

Transport and dissipation in neutron star mergers

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Alford, Bovard, Hanauske, Rezzolla, Schwenzer
[arXiv:1707.09475](#)

Alford, Harutyunyan, Sedrakian, [arXiv:1907.04192](#)

Alford and Harris, [arXiv:1803.00662](#), [arXiv:1907.03795](#)



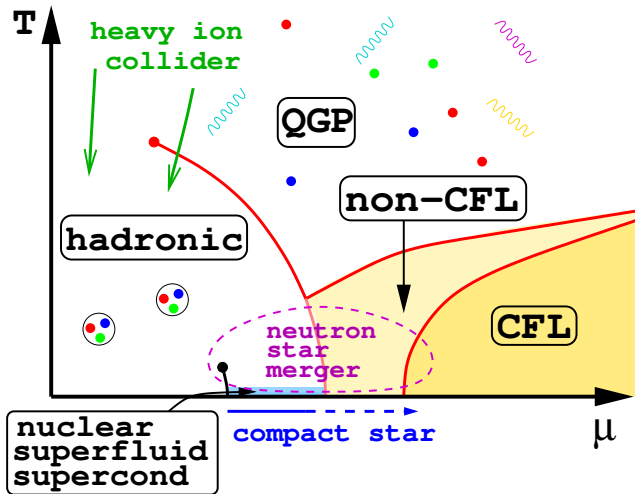
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Outline

- ▶ Neutron star mergers as a probe of dense matter
- ▶ Dissipation: thermal conductivity; shear and bulk viscosity
- ▶ Is thermal conductivity important in mergers?
Dissipation time for temperature inhomogeneities
- ▶ Is bulk viscosity important in mergers?
 - ▶ Bulk viscosity is a resonance
 - ▶ Damping time for density oscillations
- ▶ Beta equilibration:
 - ▶ Urca processes, direct and modified
 - ▶ Fermi Surface approximation
 - ▶ Detailed balance—how it can fail

Conjectured QCD Phase diagram



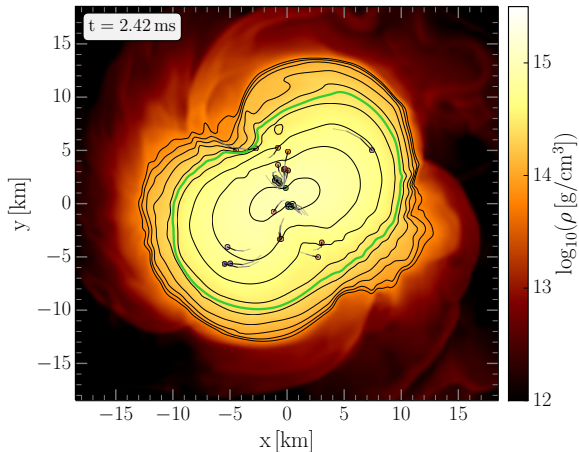
heavy ion collisions: deconfinement crossover and chiral critical point

neutron stars: quark matter core?

neutron star mergers: dynamics of warm and dense matter

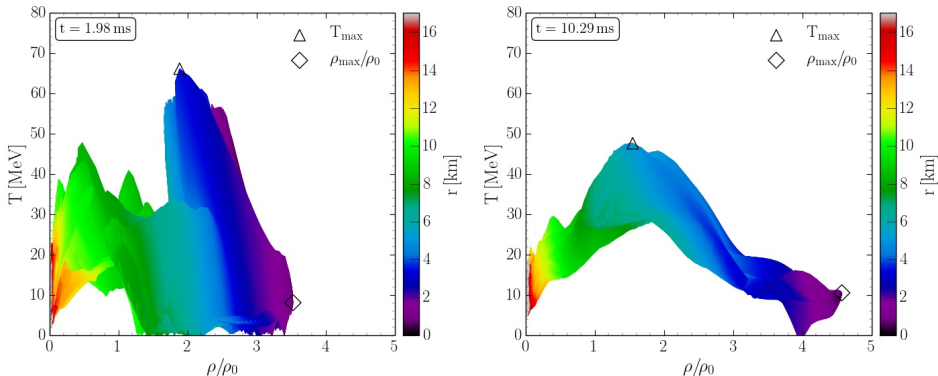
Neutron star mergers

Mergers probe the properties of nuclear/quark matter at high density (up to $\sim 4n_{\text{sat}}$) and temperature (up to ~ 60 MeV)



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

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

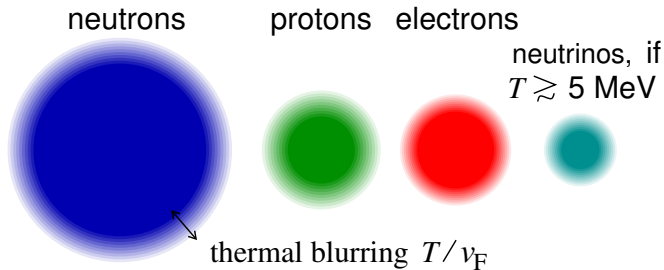
Role of transport in mergers

The important dissipation mechanisms are the ones whose equilibration time is $\lesssim 20$ ms

- ▶ **Thermal equilibration:** If neutrinos are trapped, and there are short-distance temperature gradients then thermal transport might be fast enough to play a role.
- ▶ **Shear viscosity:** similar conclusion.
- ▶ **Bulk viscosity:** could damp density oscillations on the same timescale as the merger.

Nuclear material constituents

Fermi
surfaces:



neutrons: $\sim 90\%$ of baryons

$$p_{Fn} \sim 350 \text{ MeV}$$

protons: $\sim 10\%$ of baryons

$$p_{Fp} \sim 150 \text{ MeV}$$

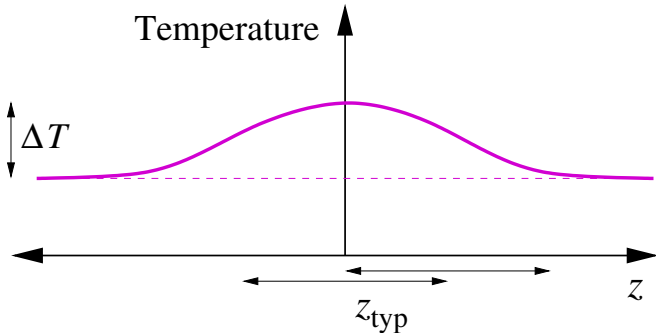
electrons: same density as protons

$$p_{Fe} = p_{Fp}$$

neutrinos: only present if $\text{mfp} \ll 10 \text{ km}$

i.e. when $T \gtrsim 5 \text{ MeV}$

Thermal equilibration



Volume

$$V \sim z_{\text{typ}}^3$$

Surface area

$$A \sim 6z_{\text{typ}}^2$$

Extra heat in region: $E_{\text{therm}} = c_V V \Delta T \approx c_V z_{\text{typ}}^3 \Delta T$

Rate of heat outflow: $W_{\text{therm}} = \kappa \frac{dT}{dz} A \approx \kappa \frac{\Delta T}{z_{\text{typ}}} 6z_{\text{typ}}^2$

Time to equilibrate: $\tau_{\kappa} = \frac{E_{\text{therm}}}{W_{\text{therm}}} \approx \frac{c_V z_{\text{typ}}^2}{6\kappa}$

Thermal equilibration time

$$\text{Time to equilibrate: } \tau_{\kappa} = \frac{E_{\text{therm}}}{W_{\text{therm}}} \approx \frac{c_V z_{\text{typ}}^2}{6\kappa}$$

In neutron star mergers, things happen on the 20 ms timescale.

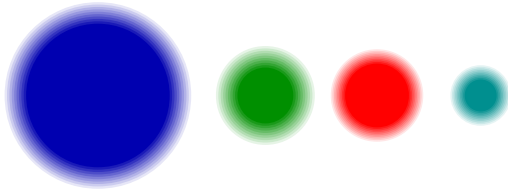
Thermal diffusion is important if $\tau_{\kappa} \lesssim 20 \text{ ms}$

To calculate the thermal equilibration time τ_{κ} , we need

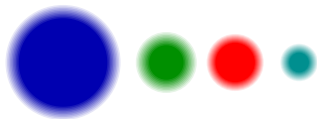
- specific heat capacity c_V
- thermal conductivity κ

Specific heat capacity

What determines the specific heat capacity?



Specific heat capacity

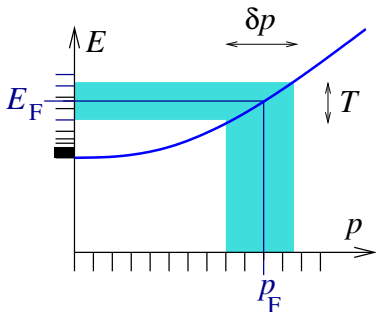


Dominated by neutrons

$c_V \sim$ number of states available
to carry energy $\lesssim T$

\sim vol of mom space with states available to carry energy $\lesssim T$

$\sim p_{Fn}^2 \delta p$



$$\delta p = \frac{T}{v_{Fn}} = T \times \frac{m_n^*}{p_{Fn}}$$

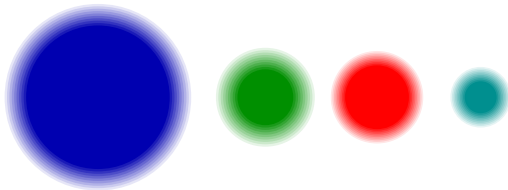
$$c_V \sim p_{Fn}^2 \delta p \sim p_{Fn}^2 \frac{m_n^*}{p_{Fn}} T \sim m_n^* p_{Fn} T$$

(Note: neutron density $n_n \sim p_{Fn}^3$)

$$c_V \approx 1.0 m_n^* n_n^{1/3} T$$

Thermal conductivity

What determines the thermal conductivity?





Thermal conductivity

Thermal conductivity $\kappa \propto n v \lambda$


Dominated by the species with the right combination of

- high density
- weak interactions \Rightarrow long mean free path (mfp) λ

neutrons: high density, but strongly interacting (short mfp) 

protons: low density, strongly interacting (short mfp) 

electrons: low density, only E&M interactions (long mfp) 

neutrinos: $\left\{ \begin{array}{l} T \lesssim 5 \text{ MeV: } \lambda > \text{ size of merged stars, so} \\ \text{they all escape, density} = 0 \\ T \gtrsim 5 \text{ MeV: } \lambda < \text{ size of merged stars,} \\ \text{but still very long mfp!} \end{array} \right.$ 



Electrons vs Neutrinos

$$\tau_{\kappa} \approx \frac{c v z_{\text{typ}}^2}{6 \kappa}$$

electron-dominated ($T \lesssim 5 \text{ MeV}$)

neutrino-dominated ($T \gtrsim 5 \text{ MeV}$)

$$\kappa^{(e)} \approx 1.5 \frac{n_e^{2/3}}{\alpha}$$

$$\kappa^{(\nu)} \approx 0.33 \frac{n_\nu^{2/3}}{G_F^2 m_n^{*2} n_e^{1/3} T}$$

Equilibration time:

$$\tau_{\kappa}^{(e)} = \boxed{5 \times 10^8 \text{ s}} \left(\frac{z_{\text{typ}}}{1 \text{ km}} \right)^2 \left(\frac{T}{1 \text{ MeV}} \right) \times \left(\frac{m_n^*}{0.8 m_n} \right) \left(\frac{n_0}{n_n} \right)^{1/3} \left(\frac{0.1}{x_p} \right)^{2/3}$$

$$\tau_{\kappa}^{(\nu)} \approx \boxed{0.7 \text{ s}} \left(\frac{z_{\text{typ}}}{1 \text{ km}} \right)^2 \left(\frac{T}{10 \text{ MeV}} \right)^2 \times \left(\frac{\mu_e}{2 \mu_\nu} \right)^2 \left(\frac{0.1}{x_p} \right)^{1/3} \left(\frac{m_n^*}{0.8 m_n} \right)^3$$

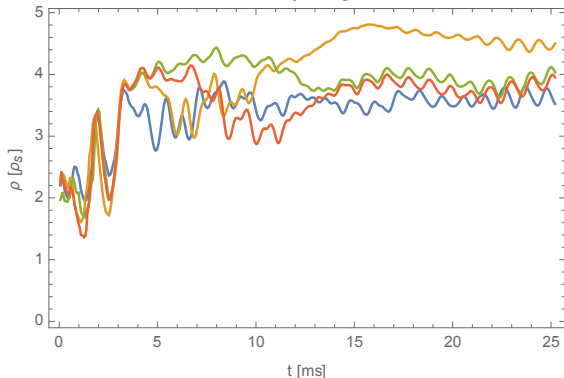
Electron thermal transport is *slow*!
electron mfp is too short

Neutrino thermal transport...
maybe if gradients on 0.1 km scale?

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)

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

Compression dissipation rate:
(ζ = bulk viscosity)

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

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

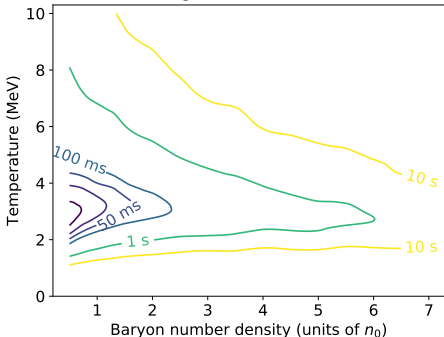
Bulk visc is only important if $\tau_\zeta \lesssim 20$ ms

Damping time results (ν -transparent)

Results for two eqns of state:

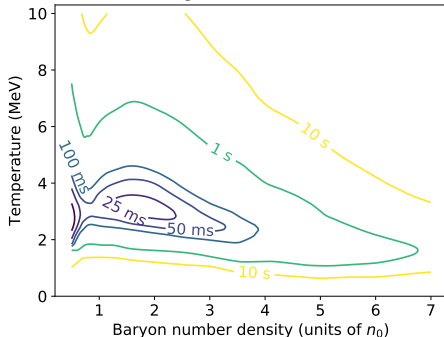
name	type	M_{\max}	$R_{1.4 M_{\odot}}$	d-Urca threshold
HS(DD2)	stiffer	$2.42 M_{\odot}$	13.3 km	none
IUFSU	softer	$1.96 M_{\odot}$	12.8 km	$4n_{\text{sat}}$

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



No direct Urca

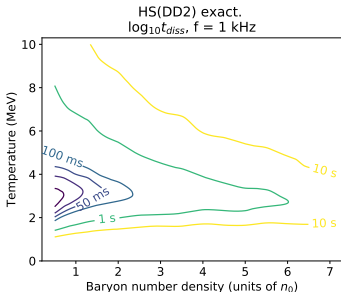
IUFSU exact.
 $\log_{10} t_{\text{diss}}, f = 1 \text{ kHz}$



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



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

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 \Rightarrow slower to damp

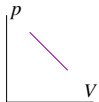
Bulk viscosity: phase lag in system response

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

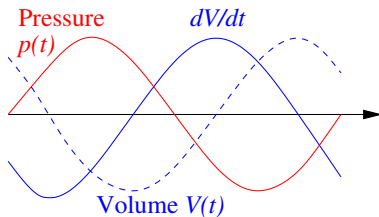
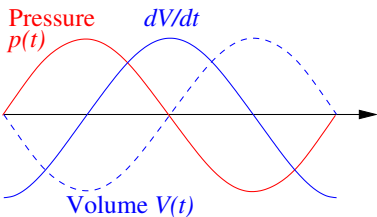
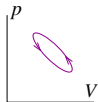
Baryon density n and hence fluid element volume V gets out of phase with applied pressure p :

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

No phase lag.
Dissipation = 0



Some phase lag.
Dissipation > 0



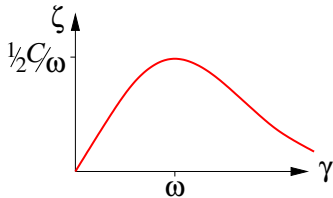
Bulk viscosity: a resonant phenomenon

Bulk viscosity is maximum when

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

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

C is a combination of susceptibilities

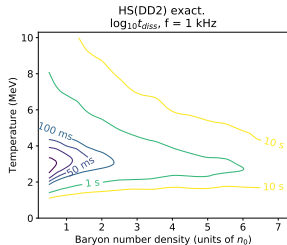
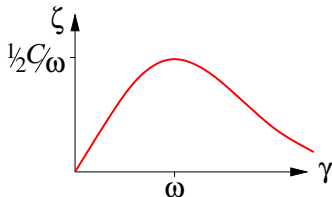


- ▶ **Fast equilibration:** $\gamma \rightarrow \infty, \zeta \rightarrow 0$
System is always in equilibrium. No pressure-density phase lag.
- ▶ **Slow equilibration:** $\gamma \rightarrow 0, \zeta \rightarrow 0$.
System does not try to equilibrate: proton number and neutron number are both conserved.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

Resonant peak in bulk viscosity

We now see why bulk visc is a non-monotonic fn of 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
equilibration rate matches typical compression frequency $f \approx 1$ kHz.
I.e. when $\gamma \sim 2\pi \times 1$ kHz

Why does bulk visc reach resonant maximum at $T \approx 3$ MeV?

What goes out of equilibrium, and how is it re-equilibrated?

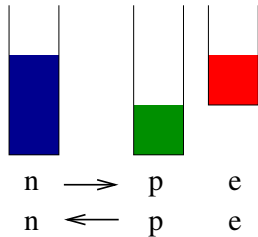
Bulk viscosity and beta equilibration

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

We'll see why in the next section

Only **weak interactions** can change proton fraction

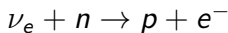
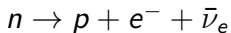
But which processes, exactly?



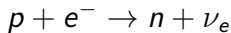
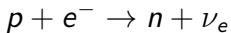
neutrino-transparent
($T \lesssim 5 \text{ MeV}$)*

neutrino-trapped
($T \gtrsim 5 \text{ MeV}$)*

neutron decay



electron capture



forward \neq backward



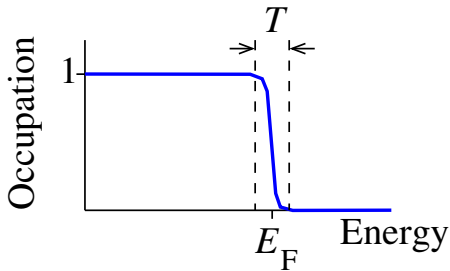
* Neutrino transparency is a finite volume effect, which occurs when the neutrino mean free path is greater than the size of the system. Our system is a neutron star, $R \sim 10 \text{ km}$

Fermi Surface approximation

If the temperature is low enough, we can analyse beta equilibration processes in a simple way using the *Fermi Surface* (FS) approximation.

$$T \ll (E_F - m)$$

or $(\mu - m)$



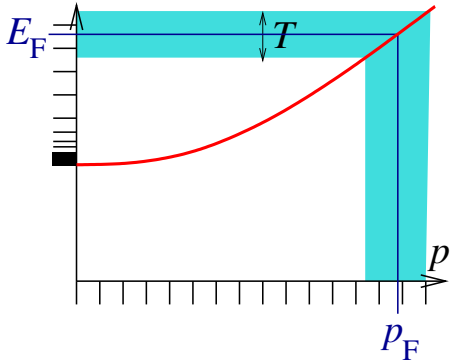
In the FS approximation, all the particles participating in beta equilibration processes are close to their Fermi surfaces.

When is the FS approx valid?

neutrons

$$p_F \sim 350 \text{ MeV}$$

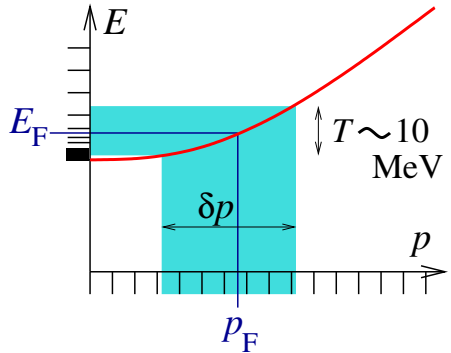
$$E_F - m \sim 60 \text{ MeV}$$



protons

$$p_F \sim 150 \text{ MeV}$$

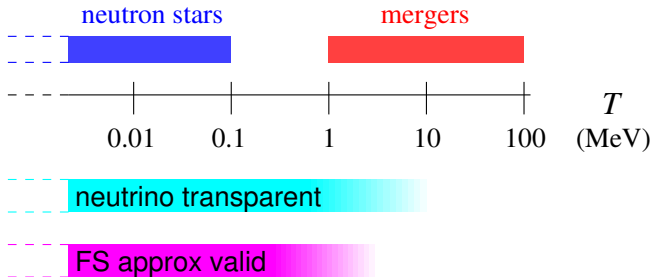
$$E_F - m \sim 10 \text{ MeV}$$



Fermi Surface approx clearly becomes invalid as T rises to 10 MeV.

But we will see that it becomes misleading above $T \sim 1 \text{ MeV}$.

Temperature regimes for neutron stars



We want to understand bulk viscosity in mergers.

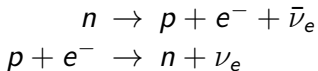
Bulk viscosity arises from beta equilibration on the 1 ms timescale.

- ▶ First, understand beta equilibrium in the “cold” regime where FS approx is valid
- ▶ Then, for mergers, do the “warm” regime where the star is still neutrino transparent but FS approx is unreliable

“Cold” beta equilibration

At $T \lesssim 1 \text{ MeV}$:

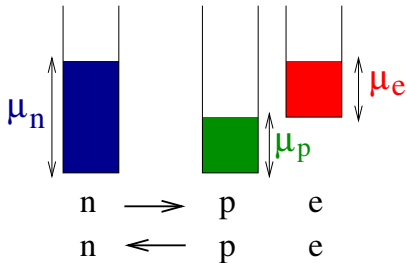
- Fermi surface approximation is valid
- neutrinos escape, so it is the “neutrino-transparent” regime



Neutrino energy $\sim T$ is negligible compared to μ_n, μ_p, μ_e .

Beta equilibrium condition is

$$\mu_n = \mu_p + \mu_e$$



- ▶ Why does a density change drive the proton fraction out of beta equilibrium?
- ▶ What goes wrong with the Fermi Surface approximation as T approaches 1 MeV?

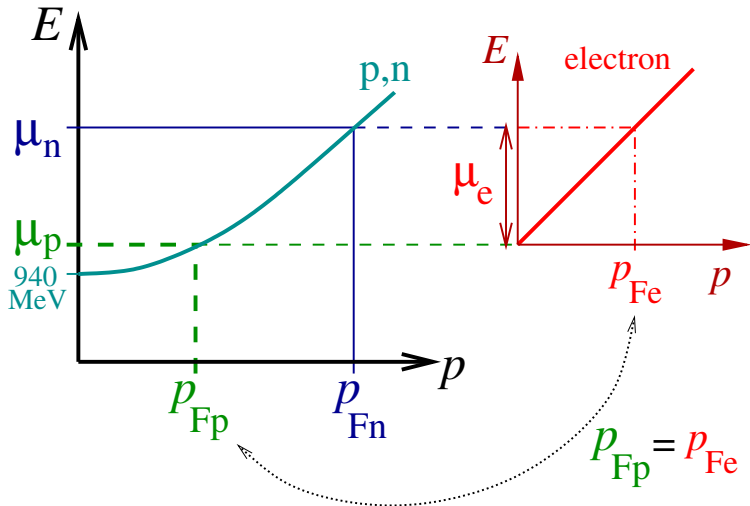
“Cold” beta equilibrium

In the cold regime, beta equilibrium means

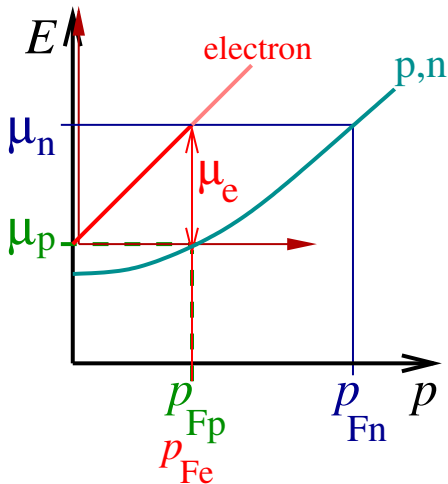
$$\mu_n = \mu_p + \mu_e$$

Electrical neutrality means

$$n_p = n_e \Rightarrow \rho_{Fp} = \rho_{Fe}$$



“Cold” beta equilibrium

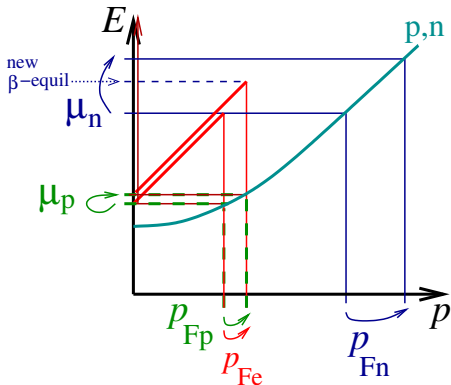


- Choose proton density ρ_{Fp} . This fixes μ_p and $\rho_{Fe} = \rho_{Fp}$
- Superimpose electron dispersion relation with energy zero at μ_p : this automatically adds μ_e to μ_p to give the beta-equilibrated value of μ_n .
- From μ_n we get ρ_{Fn} which fixes the neutron density.

Now, what happens if we compress this β -equilibrated nuclear matter? Does the proton fraction need to change?

Compressing nuclear matter

Suppose we compress β -equilibrated nuclear matter by a factor of 2. All Fermi momenta rise by 26% ($2^{(1/3)} = 1.26$). Is the matter still in β equilibrium?



- p_{Fp} rises by 26%. μ_p hardly changes.
- p_{Fe} rises by 26%. Superimpose electron dispersion relation with energy zero at new μ_p . Read off new β -equilibrated value of $\mu_n = \mu_p + \mu_e$
- But actually p_{Fn} rose by 26%, giving actual new μ_n : larger than the β -equilibrated value.

After compression the system is out of β equilibrium; $\mu_n - \mu_p - \mu_e > 0$
 There are too many neutrons: proton fraction x needs to rise.

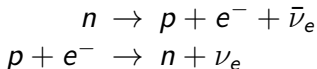
Compression \Rightarrow β -equilibration

Density oscillations in cold ($T \lesssim 1$ MeV) nuclear matter

- ▶ Does compression/rarefaction drive nuclear matter out of β -equilibrium? **Yes**
- ▶ **Why?**

Neutrons are semi-relativistic so under compression their E_F rises quite a bit, but protons are very nonrelativistic so their E_F doesn't change much, so the neutrons can decay into protons.

- ▶ What process re-establishes β equilibrium? Urca process.



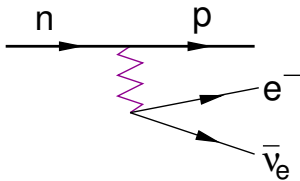
- ▶ At what temperature does the resultant equilibration rate match the frequency of density oscillations in mergers, ~ 1 kHz?

How do we calculate the rate of these processes?

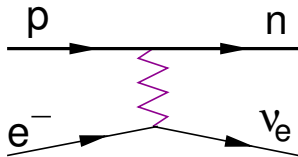
Beta equilibration: direct Urca

The obvious Feynman diagrams to evaluate are the “direct Urca” ones

neutron decay



electron capture

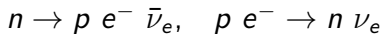


direct Urca threshold

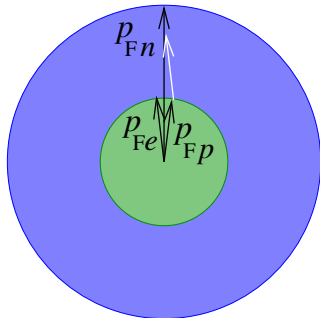
In the “cold” regime, where the Fermi Surface approx is valid, some equations of state have a direct Urca threshold density n_{dU} .

If the density is below n_{dU} then the direct Urca rate drops to zero!

When can direct Urca happen?

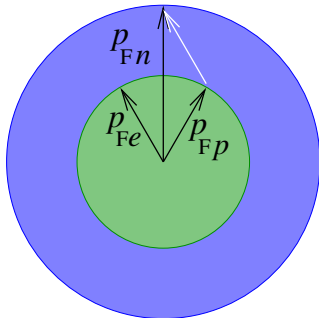


Low density
Low proton fraction
Direct Urca closed



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

High density
High proton fraction
Direct Urca open



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

Direct Urca rate

$$\Gamma_{n \rightarrow p e^- \bar{\nu}_e} = \int \frac{d^3 p_n}{(2\pi)^3} \frac{d^3 p_p}{(2\pi)^3} \frac{d^3 p_e}{(2\pi)^3} \frac{d^3 p_\nu}{(2\pi)^3} \frac{\sum_{\text{spins}} |\mathcal{M}_{\text{dU}}|^2}{2^4 E_n^* E_p^* E_e E_\nu} \\ \times (2\pi)^4 \delta^4(p_n - p_p - p_e - p_\nu) f_n (1 - f_p) (1 - f_e)$$

$$\Gamma_{p e^- \rightarrow n \nu_e} = \text{same, with } f_i \rightarrow 1 - f_i$$

where $f_i \equiv \frac{1}{1 + e^{\frac{E_i - \mu_i}{T}}}$ (Fermi-Dirac distributions).

Matrix element is (Yakovlev et. al., astro-ph/0012122)

$$\sum_{\text{spins}} |\mathcal{M}_{\text{dU}}|^2 = 32 G^2 E_n^* E_p^* E_e E_\nu \left(1 + 3g_A^2 + (1 - g_A^2) \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} \right)$$

where $G^2 = G_F^2 \cos^2 \theta_c$ and $g_A = 1.26$.

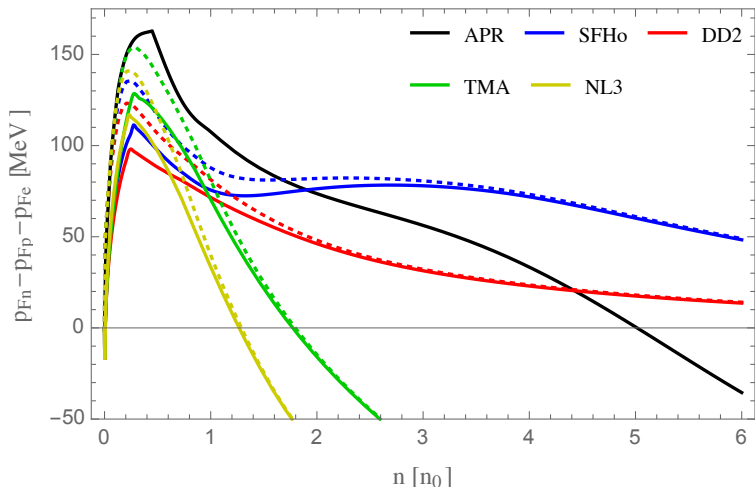
But direct Urca is not always allowed...

Direct Urca threshold

Some examples of the direct Urca kinematic constraint

$$\Delta p \equiv p_{Fn} - p_{Fp} - p_{Fe}$$

When $\Delta p < 0$ direct Urca can happen.



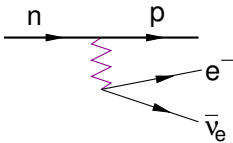
At $T \ll 1$ MeV we will get wildly different rates depending on the EoS.

Other Urca processes

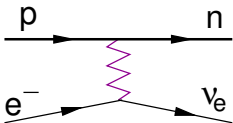
What happens when the density is below the direct Urca threshold?
A subleading process becomes relevant: “modified Urca”.

Direct Urca

n decay

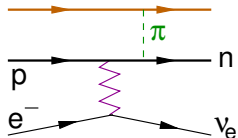
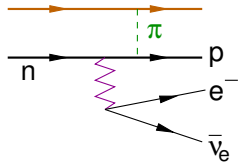


e^- capture



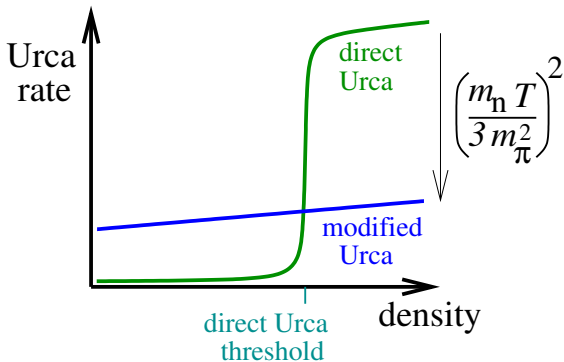
direct Urca only occurs above
direct Urca threshold density

Modified Urca



Urca in the cold regime

So in the cold regime, $T \ll 1$ MeV, the picture is

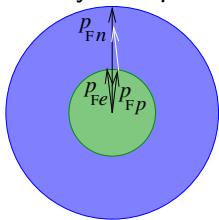


Is this picture still valid at merger temperatures: $T = 1$ to 100 MeV?

Thermal resurgence of direct Urca

At what temperature is there enough thermal blurring of the proton Fermi surface so that direct Urca becomes comparable to modified Urca, even below the direct Urca threshold density?

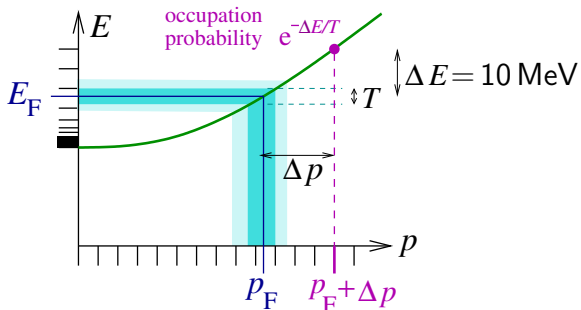
Low density, low p fraction



To do $p + e^- \rightarrow n + \nu_e$ we would need a proton with momentum above its Fermi surface by

$$\Delta p = p_{Fn} - p_{Fp} - p_{Fe}$$

typical EoS: $\Delta p \sim 50 \text{ MeV}$



Probability of finding a proton 50 MeV above its Fermi surface is suppressed by $\sim \exp(-\Delta E/T)$

At what T does that become large enough to compete with modified Urca?

Direct vs Modified Urca

At what T does direct Urca become comparable to modified Urca?

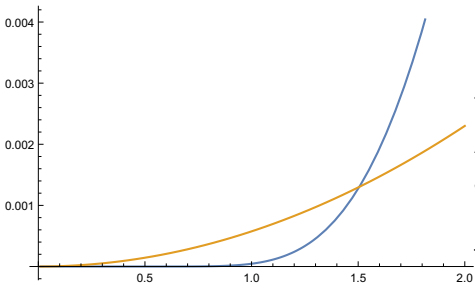
Direct Urca is suppressed by $\exp(-\Delta E/T)$

$$\Delta E = 10 \text{ MeV}$$

(for $\Delta p = 50 \text{ MeV}$)

Modified Urca suppressed by $\left(\frac{m_n T}{3m_\pi^2}\right)^2$

They are comparable when $\exp(-\Delta E/T) = \left(\frac{m_n T}{3m_\pi^2}\right)^2$



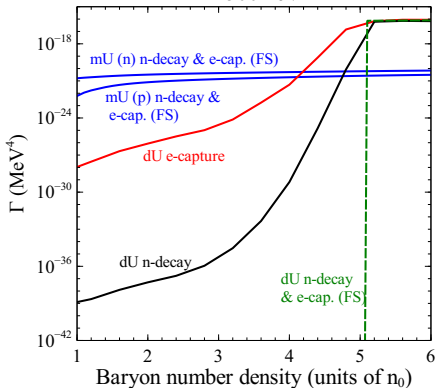
$$T \sim 1.5 \text{ MeV}$$

The “cold” regime is $T \lesssim 1 \text{ MeV}$.
At $T \gtrsim 1 \text{ MeV}$ the Fermi Surface approx is no longer valid: Direct Urca involving particles far from their Fermi surface is comparable to modified Urca.

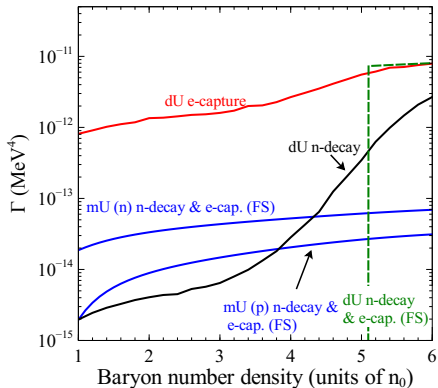
Rethinking β -equilibrium, I

In the “warm” regime, $1 \text{ MeV} \lesssim T \lesssim 5 \text{ MeV}$,
is the β -equilibrium condition still $\mu_n = \mu_p + \mu_e$?

APR EoS, $\mu_n = \mu_p + \mu_e$
 $T = 500 \text{ keV}$



APR EoS, $\mu_n = \mu_p + \mu_e$
 $T = 5 \text{ MeV}$



When $\mu_n = \mu_p + \mu_e$, the forward (n decay) and backward (e^- capture) rates are not equal!

Rethinking β equilibrium, II

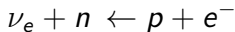
Typical equilibration scenario:



$$\mu_A + \mu_B = \mu_C + \mu_D$$

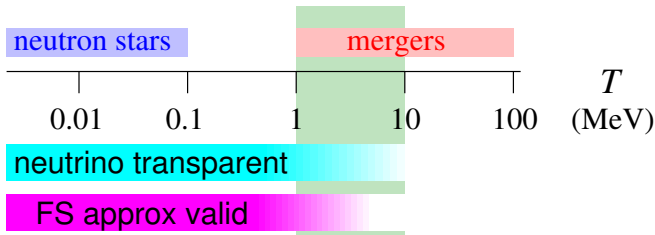
“Detailed balance”: energy cost is the same for the forward and backward reactions.

Urca equilibration in neutrino-transparent regime:



Forward and backward reactions are *not the same*.

Detailed balance does not apply.



Correct criterion for β equilibrium

The real criterion for β equilibrium in neutrino-transparent matter is

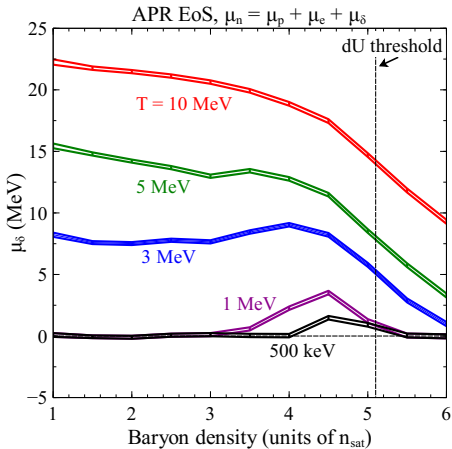
$$\Gamma(n \rightarrow p e^- \bar{\nu}_e) = \Gamma(p e^- \rightarrow n \nu_e)$$

If the forward and backward reactions are not the same, this will occur at a non-zero value of

$$\mu_\delta = \mu_n - \mu_p - \mu_e$$

- At $T \ll 1$ MeV the Fermi Surface approx is valid, neutrino energy can be ignored, so the reaction is approximately $n \leftrightarrow e^- + p$ so β equilibrium is when μ_δ is negligible, i.e. $\mu_n = \mu_p + \mu_e$.
- At $1 \text{ MeV} \lesssim T \lesssim 5 \text{ MeV}$, μ_δ is not negligible.
- At $T \gtrsim 5 \text{ MeV}$, neutrinos are trapped, the reaction is $\nu_e + n \leftrightarrow p + e^-$, and detailed balance holds again, beta equilibrium is when $\mu_n + \mu_\nu = \mu_p + \mu_e$.

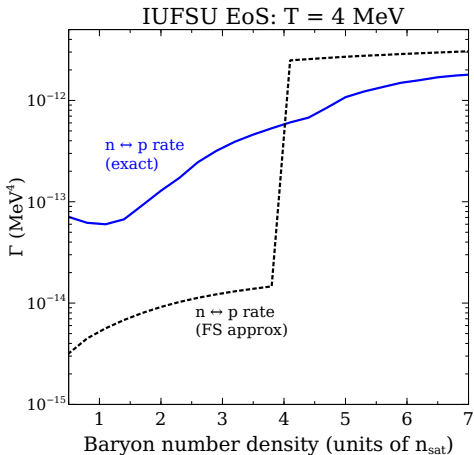
Beta equilibrium in warm matter



As T rises above 1 MeV, FS approx breaks down and the value of μ_δ needed to achieve β equilibrium gets larger.

What does the breakdown of FS approx mean for β equilibration rates?

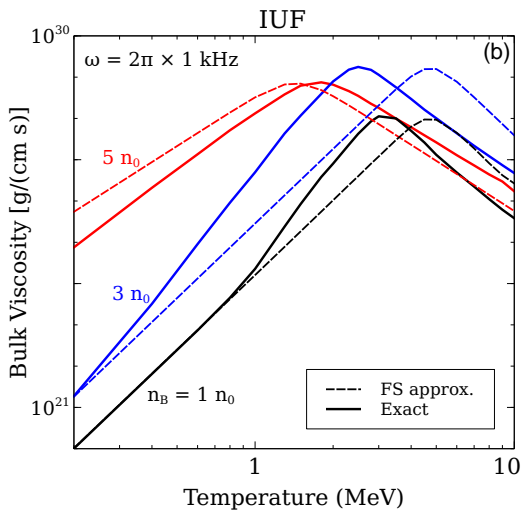
Beyond the Fermi Surface approx



At $T \gtrsim 1$ MeV the proton Fermi surface is sufficiently thermally blurred to smooth out the switch-on of direct Urca.

This is why the direct Urca threshold is not clearly visible in the contour plots of the dissipation time.

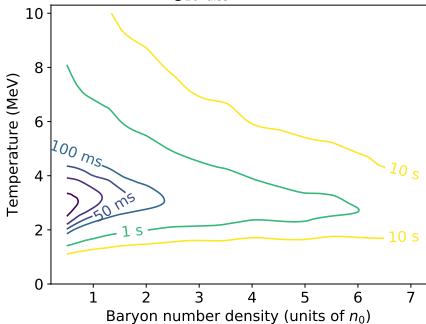
Bulk viscosity (IUF EoS)



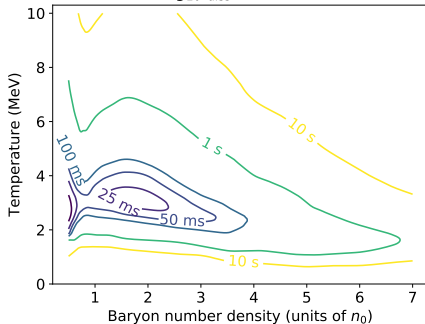
- ▶ resonant peak when equilibration rate matches density oscillation frequency, $\gamma = \omega$
- ▶ IUF EoS has direct Urca threshold at density $n = 4n_0$
- ▶ For $n < 4n_0$, FS approx underestimates γ , so it needs higher T to reach resonant peak.
- ▶ For $n > 4n_0$, FS approx overestimates γ , so it reaches resonant peak at lower T

Damping time

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



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

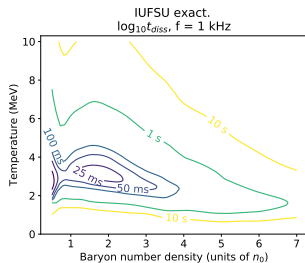
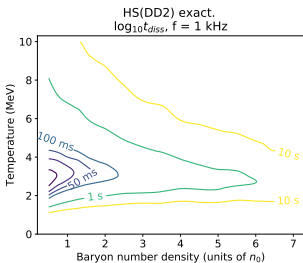


The damping time for density oscillations is shortest around $T \sim 3 \text{ MeV}$, independent of the EoS.

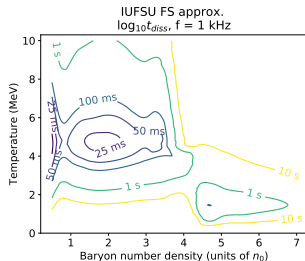
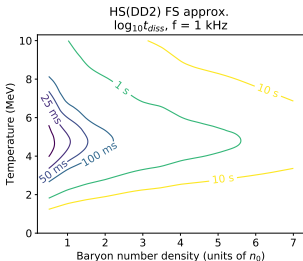
It is short enough to be relevant for neutron star mergers, especially at low density.

Fermi Surface Approx

Exact:



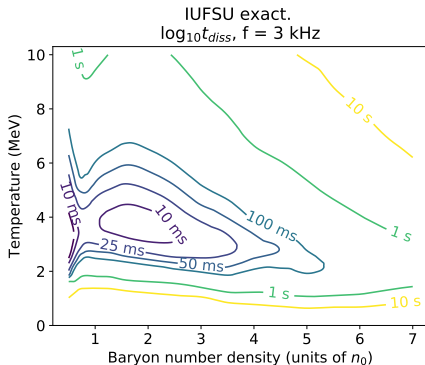
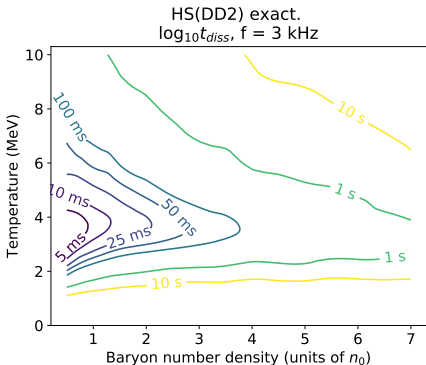
FS approx:



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

Higher frequency oscillations

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



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

Why is resonance with 1 kHz at $T \sim \text{MeV}$?

Let's estimate $\gamma(T)$ and see when it is $2\pi \times 1 \text{ kHz}$.

$$\frac{dn_a}{dt} = -\gamma (n_a - n_{a,\text{equil}})$$
$$\Gamma_{n \rightarrow p} - \Gamma_{p \rightarrow n} \sim -\gamma \frac{\partial n_a}{\partial \mu_a} \mu_a$$

In FS approx, at β -equilibrium,

$$\Gamma_{n \rightarrow p} = \Gamma_{p \rightarrow n} \sim G_F^2 \times (p_{Fn}^2 T) \times (p_{Fp} T) \times T^3$$

If we push it away from β equilibrium by adding μ_a , the leading correction is to replace one power of T with μ_a

$$\Gamma_{n \rightarrow p} - \Gamma_{p \rightarrow n} \sim G_F^2 (p_{Fn}^2 T) \times (p_{Fp} T) \times T^2 \mu_a$$

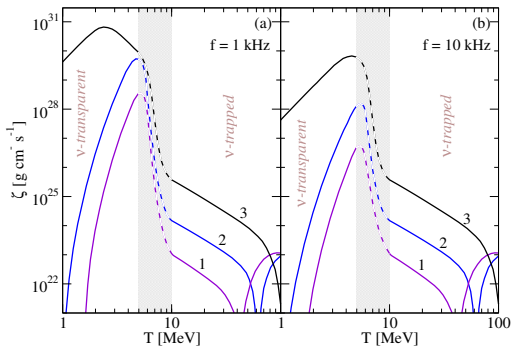
So

$$\gamma \sim \frac{\partial \mu_a}{\partial n_a} G_F^2 p_{Fn}^2 p_{Fp} T^4 \sim \frac{1}{(30 \text{ MeV})^2} \frac{(350 \text{ MeV})^2 (150 \text{ MeV})}{(290 \text{ GeV})^4} T^4$$

Solve for when $\gamma = 2\pi \times 1 \text{ kHz} = 4 \times 10^{-18} \text{ MeV}$:

$$T \sim 1 \text{ MeV}$$

The neutrino-trapped regime



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

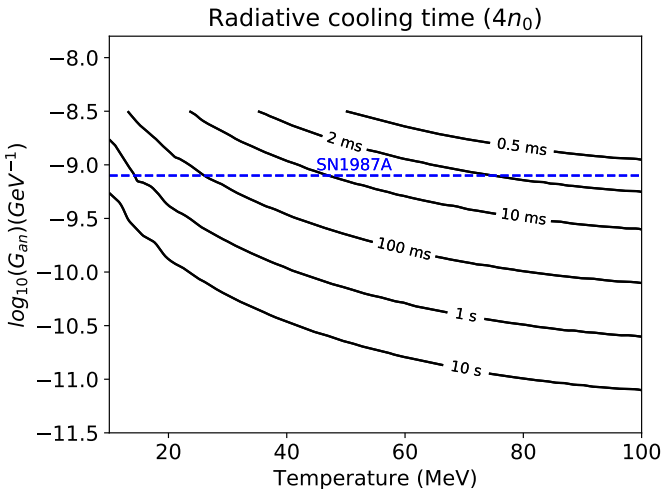
- ▶ β equilibration is too fast, above resonant temperature.
- ▶ The relevant susceptibilities are smaller, so the peak bulk visc is smaller

Summary

- ▶ Some forms of dissipation are probably physically important for neutron star mergers.
- ▶ Thermal conductivity and shear viscosity may become significant in the neutrino-trapped regime ($T \gtrsim 5 \text{ MeV}$) if there are fine-scale gradients ($z \lesssim 100 \text{ m}$).
- ▶ In neutrino-transparent nuclear matter (at low density and $T \sim 3 \text{ MeV}$) bulk viscosity will be significant in damping density oscillations.
- ▶ Under these conditions, the Fermi Surface approximation and detailed balance are not valid.
Rate calculations must include the whole phase space.

Cooling by axion emission

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

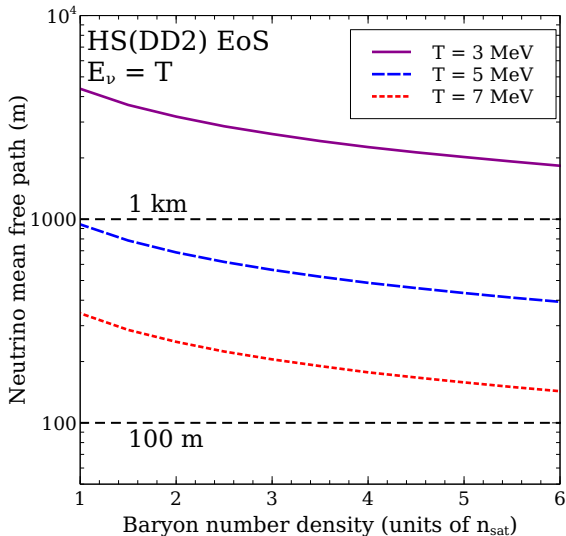


PRELIMINARY

Harris, Fortin, Kuver, Alford, work in progress

Extra slides

Neutrino mean free path



When does neutrino trapping begin?

mfp \sim 3 km: $T = 2-3$ MeV

mfp \sim 1 km: $T = 4-5$ MeV

mfp \sim 0.3 km: $T = 6-7$ MeV