Transport in Neutron Star Mergers

An attempt at an introduction

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INT workshop "Nuclear Physics in Mergers - Going Beyond the Equation of State", Sep.9$^{\mathrm{th}}$ 2025

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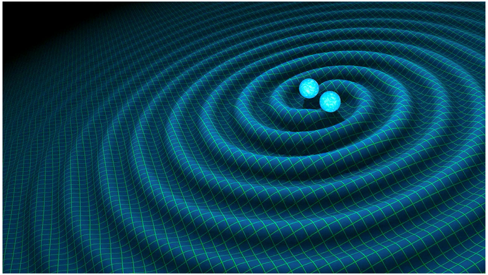
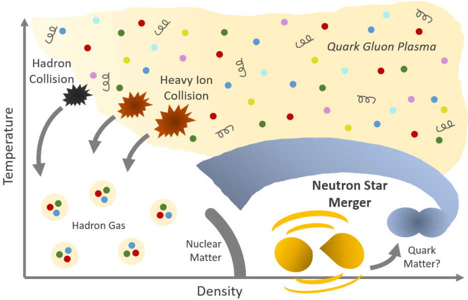
Motivation

Ultimate goal:
Understanding the **phase diagram of fundamental matter** as described by QCD using **gravitational waves from neutron star mergers**



R. Hurt/Caltech-JPL

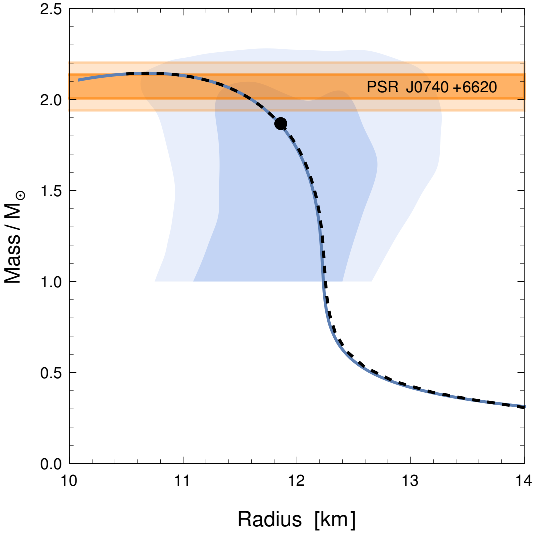


We probably have to go beyond the equation of state to do this!

Masquerade Problem

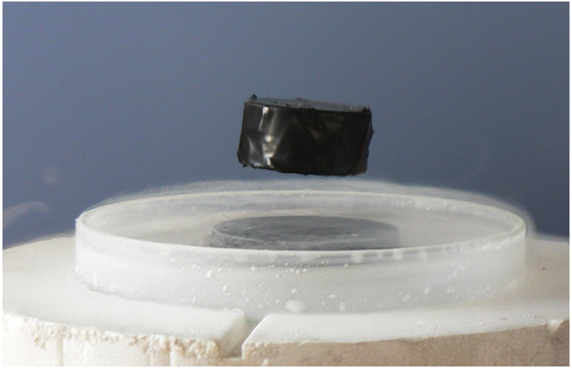
We need to go **beyond the Equation of State**

- EoS might be able to “hide” underlying degrees of freedom
- Need observables that depended on phases of matter
- Dynamical properties: transport, viscosity, chemical equilibration,...



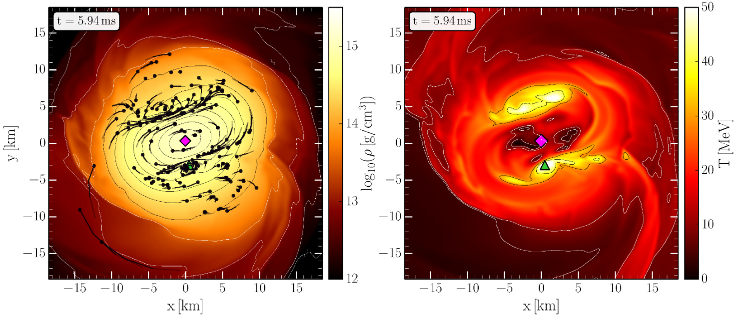
Transport as better discriminator of different phases

Equation of State = Pressure(energy density)



What would you measure?

Neutron Star Mergers



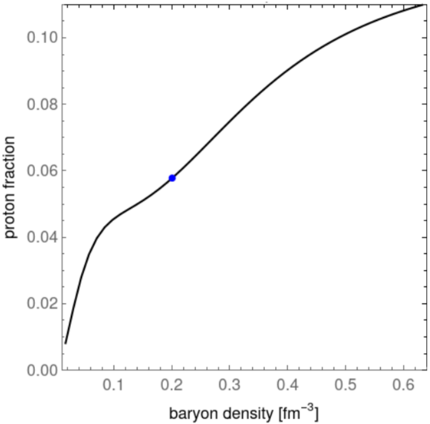
Hanauske, M.; Steinheimer, J. et al. Particles 2019

- Mergers test properties of dense matter at high densities (up to $\approx 4 - 7\, n_{\text{sat}}$) and high temperatures (up to $T \approx 60 - 80$ MeV)
- "$T = 0$ common knowledge" needs to be reevaluated: especially **weak interactions**

Flavor equilibrium: neutron decay and electron capture balance

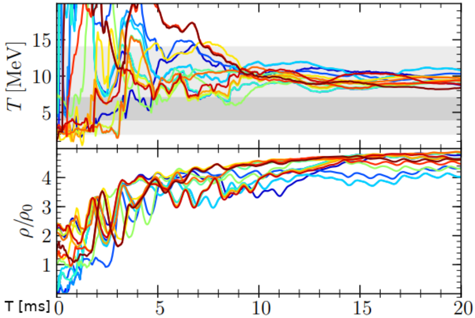
$$n + \cdots \to p + e^- + \ldots \qquad p + e^- + \cdots \to n + \cdots$$

- Only weak interactions can change particle content
- Cold equilibrium: $\mu_n = \mu_p + \mu_e$
- finite T correction:
  Alford, Harris: 1803.00662,
  Alford, Haber, (Harris), Zhang:
  2108.03324 , 2306.06180



Neutron Star Mergers

Prime environment for transport effects



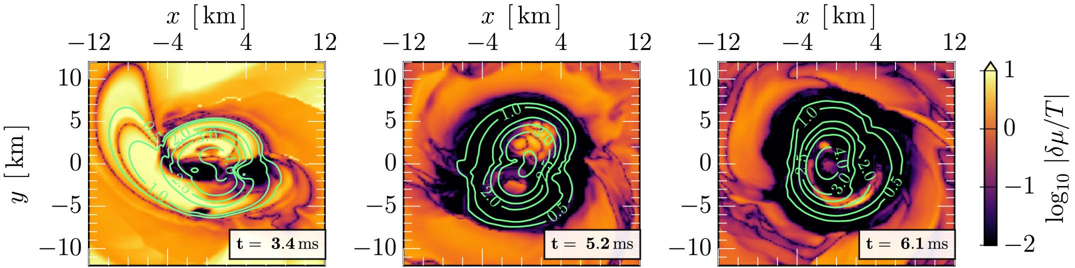
Alford, Bovard et.al., PRL 120 (2018)

- Tidal interactions will drive us out of equilibrium (g-modes)
- Oscillations in merger drive matter out of equilibrium
- Weak interactions try to drive matter back to equilibrium
- impact depends on timescale of oscillations and equilibration times
- Linear response probably insufficient

Include Equilibration in Simulations

Most, A.H., Harris, Zhang, Alford, Noronha; ApJL 967 2024 arXiv:2207.00442

$$\delta\mu = \mu_n - (\mu_p + \mu_e)$$



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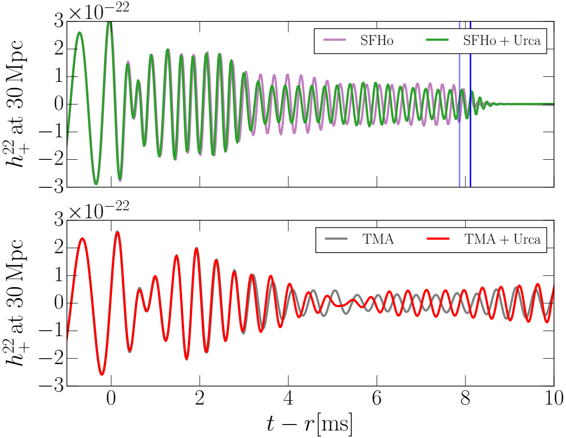
Gravitational Wave Signal

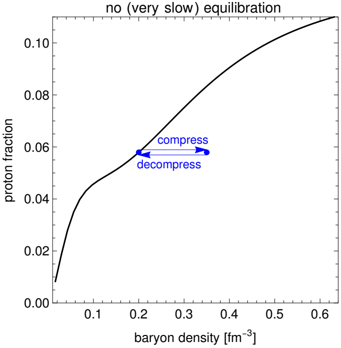


Difference same order as finite T, resolution effects, **uncertainty in EOS**, ...

Bulk Viscosity from Flavor Equilibration

Path of fluid element as it is compressed and decompressed

Density Oscillations in merger drive matter out of equilibrium



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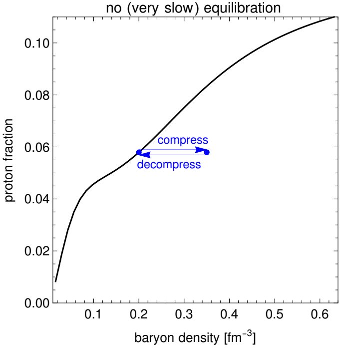

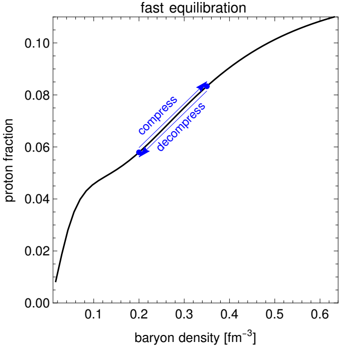

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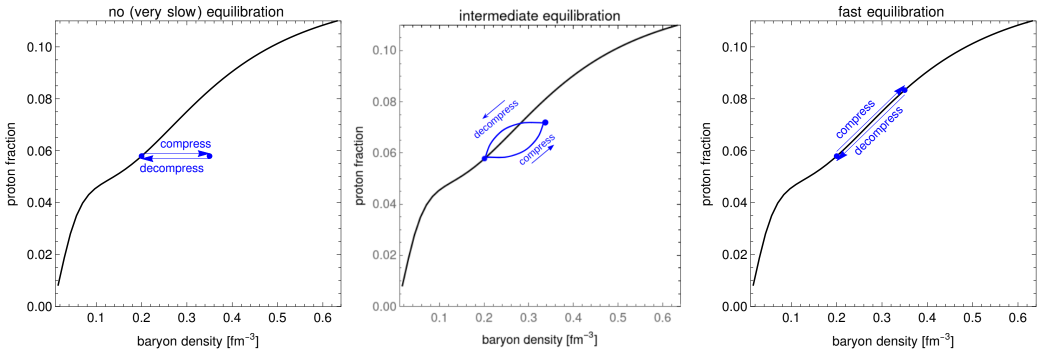


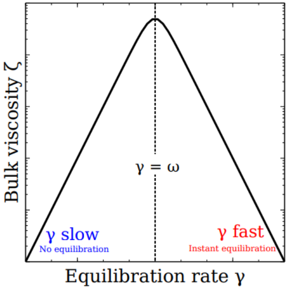
$\{x_P, n_B\}$ plane equiv. to $\{P, V\}$ plane $\rightarrow$ traversing a path in P-V plane leads to $\int PdV$ - **work**

Bulk viscosity

Resonace effect between 2 competing time scales

driving force: external density oscillation ω $\Longleftrightarrow$ response: internal re-equilibration γ

$$\zeta \sim \frac{\gamma}{\omega^2+\gamma^2}$$

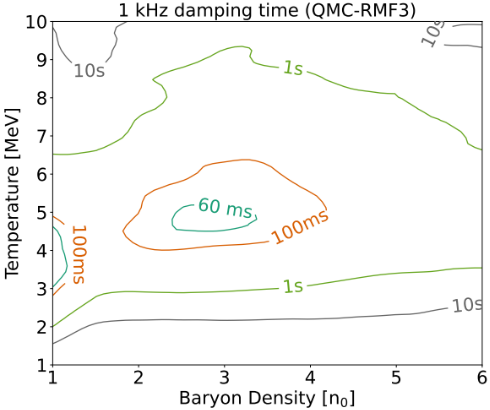


What influences the rate?

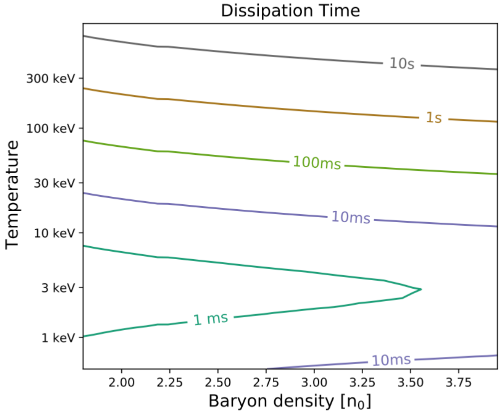
- Composition of matter: nuclear matter (Yang), hyperons, pions, quark matter (Harutyunyan), dark matter (Harris)
- Thermodynamic conditions: **Temperature**, density, particle fractions, magnetic fields (Tambe, Kumamoto)
- Neutrino opacities: trapped, free-streaming, in-between (Lin, Brodie)

Composition and Bulk Viscosity

Ripley et al. 2312.11659, Ghosh et al. 2306.14737



Alford, Haber, Zhang 2306.06180



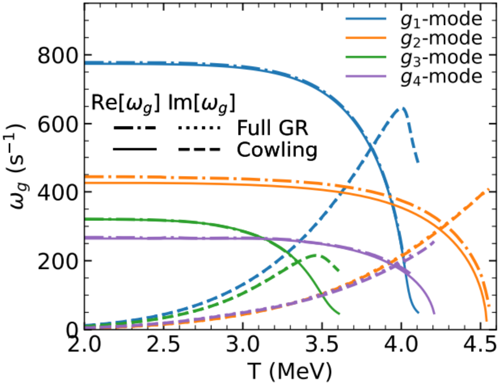
Alford, Haber 2009.05181

If we see damping in inspiral $\rightarrow$ exotic matter

Falvor Equilibration and g-modes

Zhao, Rau, Haber, Harris, Constantinou, Han 2504.12230

- g-modes are driven by composition gradient
- equilibration rates first damp, then kill off the modes

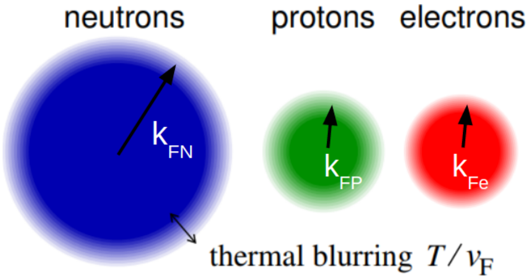


Urca processes in npe - matter

direct Urca (dU)

neutron decay: $n \rightarrow p + e^- + \bar{\nu}_e$ electron capture: $p + e^- \rightarrow n + \nu_e$

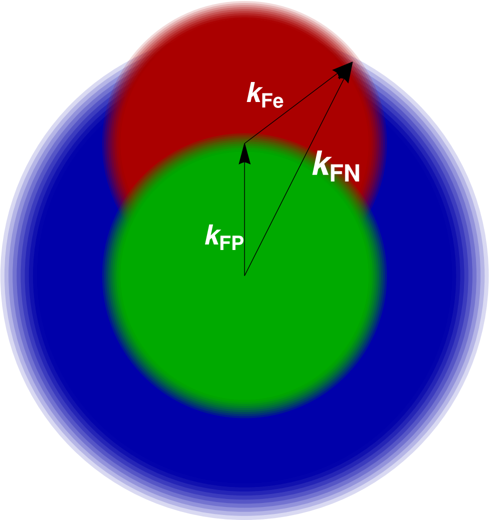
- Strongly degenerate npe-matter:
  dominated by particles on their Fermi surface (FS)



$$\Gamma_{dU,ND} \propto \prod_{i=1}^{4} \int \frac{d^3 p_i}{2E_i} \sum_{\text{spins}} |M|^2 \delta^4(E-p) \times f_n(1-f_p)(1-f_e)$$

Direct Urca Threshold

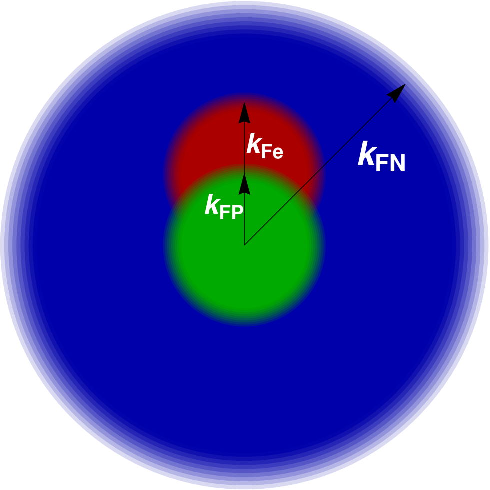
Above threshold: proton fraction $\geq 11\%$



- Momentum conservation on FS demands $\vec{k}_{Fn} \leq \vec{k}_{Fp} + \vec{k}_{Fe}$
- If momentum cons. on FS possible: rate dominated by direct Urca
- fast cooling, low bulk viscosity, $\gamma \propto T^4$

Direct Urca Threshold

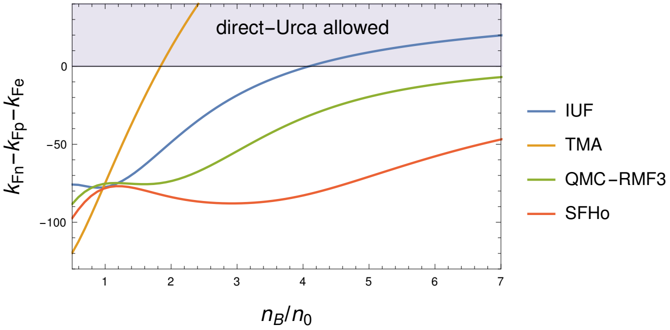
Below threshold: proton fraction too low



- Momentum conservation on FS demands $\vec{k}_{Fn} \leq \vec{k}_{Fp} + \vec{k}_{Fe}$
- If momentum cons. on FS not possible: rate heavily suppressed
- In-medium corrections important: modified Urca, NWA Alford, Haber, Zhang arXiv:2406.13717 (See Alford talk)
- slow cooling, higher bulk viscosity, $\gamma \propto T^6$

Direct Urca Threshold

strongly EOS depended



- Momentum conservation on FS demands $\vec{k}_{Fn} \leq \vec{k}_{Fp} + \vec{k}_{Fe}$
- Proton fraction x_p is monotonic with density
- Need $x_p \approx 11\%$ for $k_{Fn} = k_{Fp} + k_{Fe}$
- Threshold density = direct Urca threshold
- Impact on cooling, bulk viscosity, ...

The Nucleon Width Approximation (NWA) 2406.13717

Simple, improvable, consistent

- Nucleons in medium undergo constant collisions

→ Nucleons in medium are **unstable** to strong interaction "decays"

- Should include nucleon lifetime/width as imaginary mass component

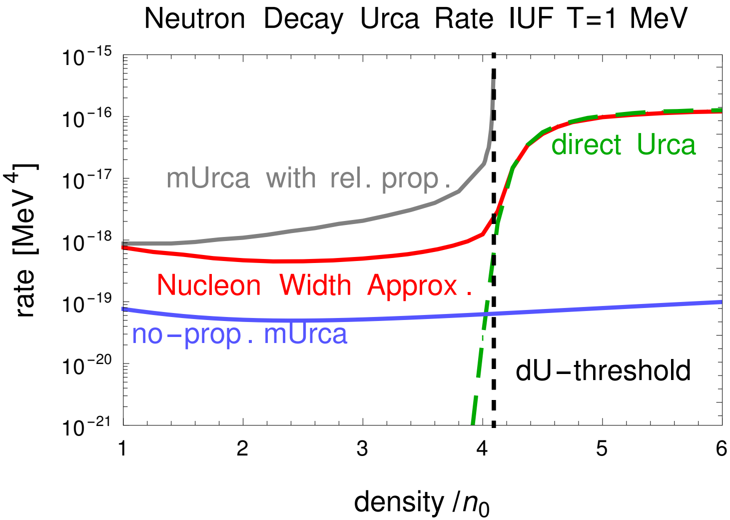
Nucleon Width Approximation - NWA

$$\Gamma^{\mathrm{NWA}} = \int_{-\infty}^{\infty} dm_{\mathrm{n}} dm_{\mathrm{p}} \Gamma^{\mathrm{dUrca}}(m_{\mathrm{n}}, m_{\mathrm{p}}) \, R_{\mathrm{n}}(m_{\mathrm{n}}) R_{\mathrm{p}}(m_{\mathrm{p}}) \ .$$

with the Breit-Wigner spectral function

$$R_a(m) \equiv \frac{1}{\pi} \frac{W_a/2}{(m - M_a^*)^2 + W_a^2/4} \ .$$

NWA rates



Neutron Decay Urca Rate IUF T=1 MeV
rate [MeV^4]
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
1
2
3
4
5
6
density / n_0
mUrca with rel. prop.
direct Urca
Nucleon Width Approx.
no-prop. mUrca
dU-threshold

Summary

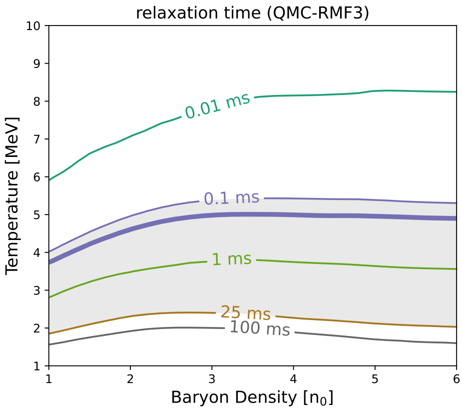
- EOS might not tell us what dense matter is made of
- Transport properties are more sensitive to phases of matter
- Neutron star mergers are extremely dynamical - transport matters
- Some dissipative effects can be directly captured by implementing the underlying microscopic processes
- Flavor equilibration strongly depends on composition and thermodynamic environment

There is a lot of work ahead of us on the theory front!

Flavor Equilibration Time

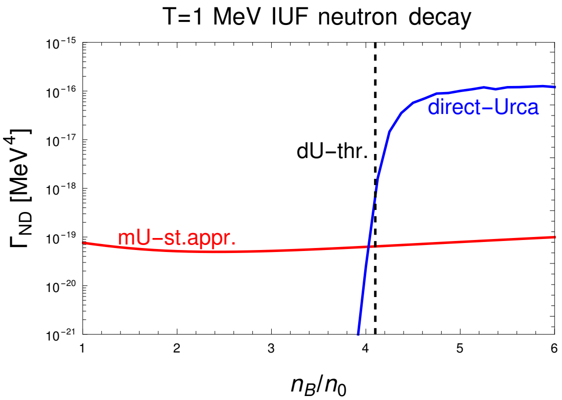
Alford, Haber, Zhang, 2306.06180

- kHz oscillation $\sim$ ms timescale
- Three distinct regimes: frozen - resonant - instantaneous equilibration
- QMC-RMF models: Alford, Brodie, Haber, Tews: 2205.10283 (Compose)



Direct Urca and Modified Urca

$T = 1$ MeV - neutrino transparent, IUF-EOS



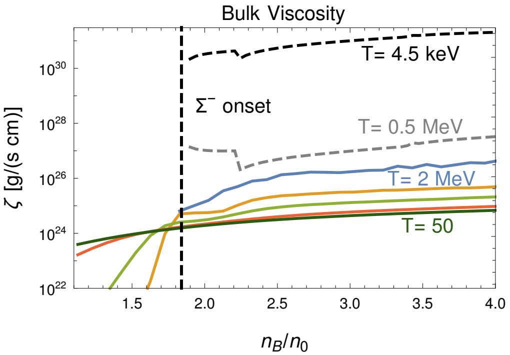
- standard calculation of mU:
  - Widely used in cooling codes, all over the field
  - Completely missing in neutrino opacities tables (NuLib,...) for mergers
  - **crude, inconsistent, not systematically improvable, wrong**, but easy
- Full phase space calculation for direct Urca: **arXiv:2306.06180, arXiv:2108.03324**

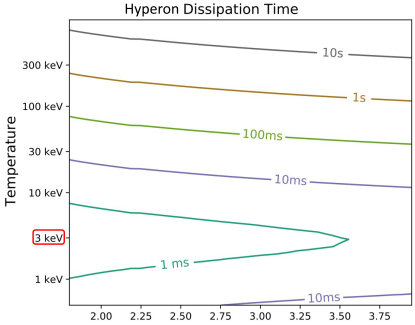
Hyperonic Bulk Viscosity: Equilibration of Strangeness

Alford, A.H. 2009.05181

Contributing processes: change strangeness by 1

(1) $n + n \Leftrightarrow p^+ + \Sigma^-$ (2) $n + p^+ \Leftrightarrow p^+ + \Lambda$ (3) $n + n \Leftrightarrow n + \Lambda$ (4) $\Lambda + \Lambda \Leftrightarrow \Lambda + n$





Strangeness changing rates might play role in local heating + phase conversion dissipation.