Thermal pion contribution to the bulk viscosity of dense matter

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INT program- Neutron-rich matter on heaven and earth
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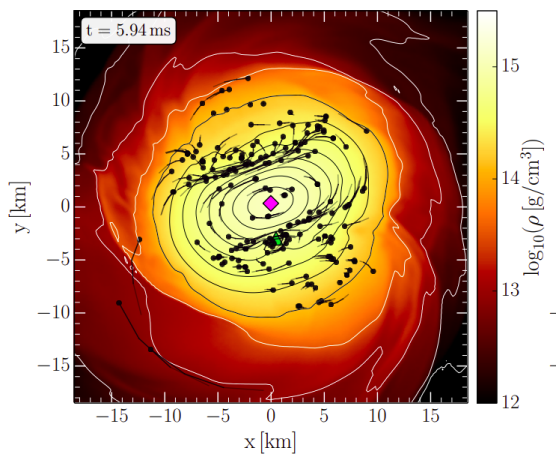
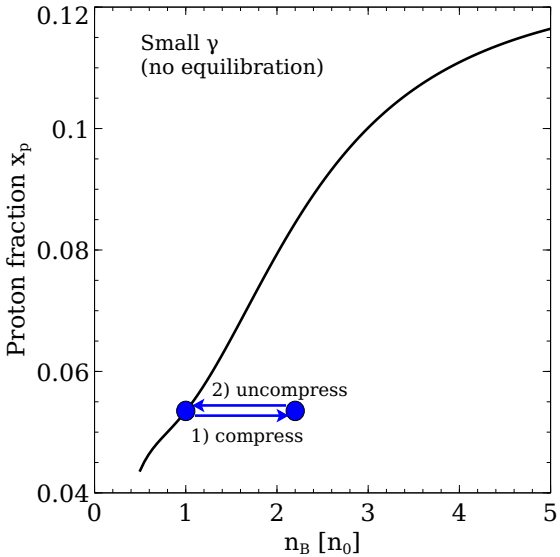
Fore, SPH, Reddy (in progress)
Most, Haber, SPH, Zhang, Alford, Noronha arXiv:2207.00442
Most, SPH, Plumberg, Alford, Noronha, *et al.* arXiv:2107.05094
Alford, SPH arXiv:1907.03795

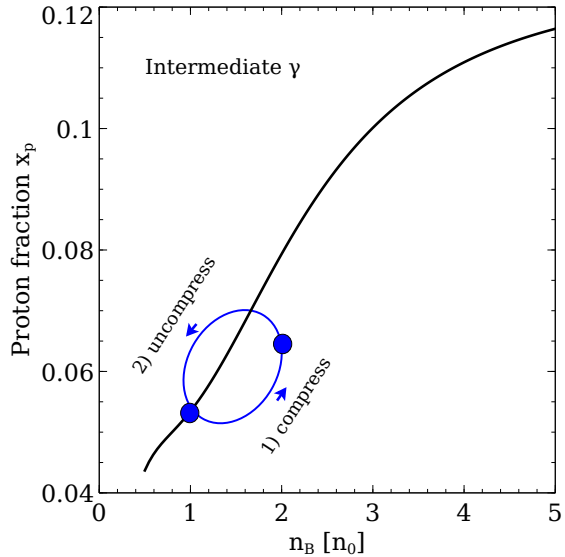


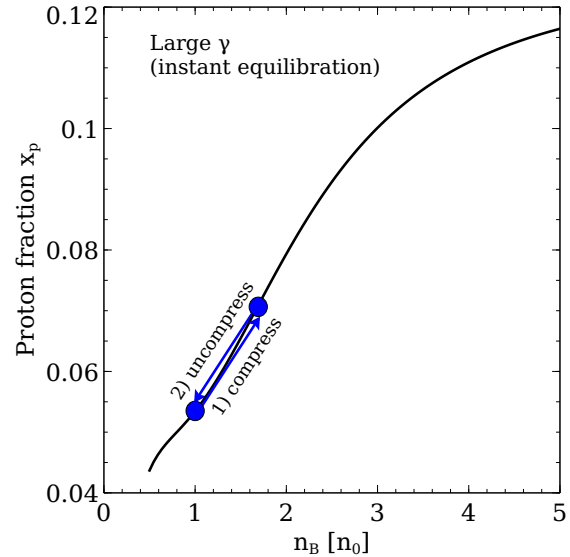
Bulk viscosity from beta equilibration

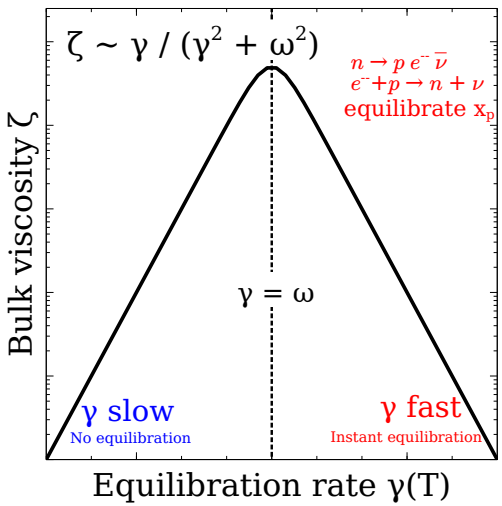
Track the path of a fluid element as it is compressed and uncompressed.

$$n_B(t) = n_B^0 + \delta n_B \cos(\omega t)$$









- $n + \nu \leftrightarrow p + e^-$ equilibrates x_p
- $\{x_p, n_B\}$ plane is equivalent to $\{P, V\}$ plane.
- Traversing a path in $P - V$ plane indicates $p\,dV$ work

The energy dissipated from the density oscillation can be written in terms of a bulk viscosity

$$\frac{d\varepsilon}{dt} = -\zeta \underbrace{(\nabla \cdot \mathbf{v})^2}_{\text{compression of fluid}}$$

Kinetic energy is turned into heat and neutrinos

Pions in dense matter

- Hot matter in NS mergers might contain $n, p, e^-, \mu^-, \nu_e, \nu_\mu, \pi^-$.
- Pions, equilibrated by $n \leftrightarrow p + \pi^-$, have $\mu_{\pi^-} = \mu_n - \mu_p > 0$.
- π^0 and π^+ populations suppressed by $e^{-\mu_{\pi^-}/T}$ and $e^{-2\mu_{\pi^-}/T}$.
- We avoid pion condensation by staying at low densities.

Treatment of pions:

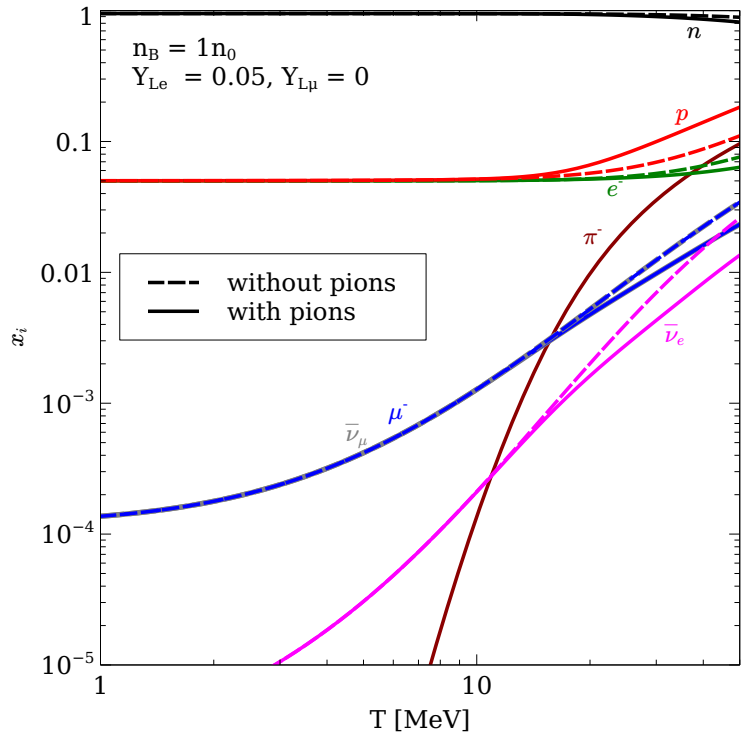
$\pi^- N$ interaction is treated with the virial expansion

$$n_{\pi^-} = n_{\pi^-}^{\text{free}} + n_{\pi^-}^{\text{interacting}}$$

$$n_{\pi^-}^{\text{interacting}} = z_n z_{\pi^-} b_2^{n\pi^-} + z_p z_{\pi^-} b_2^{p\pi^-}$$

z_i is the fugacity, b_2 is the second virial coefficient.

$$E_{\pi^-}(p) = \sqrt{p^2 + m_{\pi^-}^2} + \Sigma_{\pi^-}(p)$$

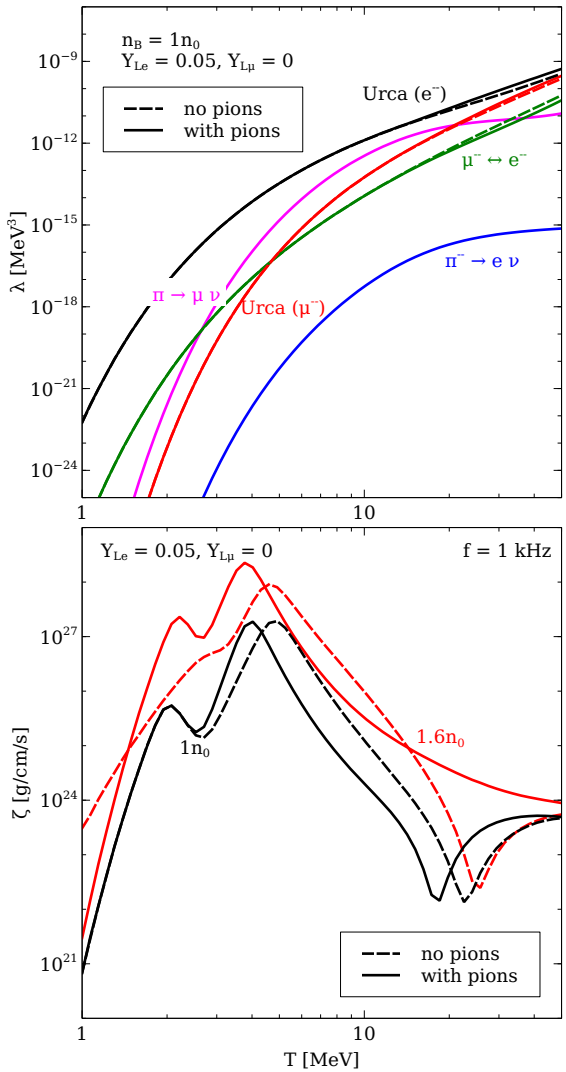


Fore, SPH, Reddy (in progress)
Fore, Reddy arXiv:1911.02632

Pion bulk viscosity (inf. $n \leftrightarrow p + \pi^-$ rate)

System described by x_p, x_μ, x_π (or $\delta\mu_1, \delta\mu_2, \delta\mu_3$).

1. $\delta\mu_1 \equiv \mu_n + \mu_{\nu_e} - \mu_p - \mu_e$
   - $n \leftrightarrow p + e^- + \bar{\nu}_e$
   - $n + \nu_e \leftrightarrow e^- + p$
2. $\delta\mu_2 \equiv \mu_n + \mu_{\nu_\mu} - \mu_p - \mu_\mu$
   - $n \leftrightarrow p + \mu^- + \bar{\nu}_\mu$
   - $n + \nu_\mu \leftrightarrow \mu^- + p$
3. $\delta\mu_3 \equiv \mu_n - \mu_p - \mu_\pi$
   - $n \leftrightarrow p + \pi^-$ (strong int!)
4. $\delta\mu_4 \equiv \mu_\pi + \mu_{\nu_e} - \mu_e = \delta\mu_1 - \delta\mu_3$
   - $\pi^- \leftrightarrow e^- + \bar{\nu}_e$
   - $\pi^- + \nu_e \leftrightarrow e^-$
5. $\delta\mu_5 \equiv \mu_\pi + \mu_{\nu_\mu} - \mu_\mu = \delta\mu_2 - \delta\mu_3$
   - $\pi^- \leftrightarrow \mu^- + \bar{\nu}_\mu$
   - $\pi^- + \nu_\mu \leftrightarrow \mu^-$
6. $\delta\mu_6 = \mu_\mu + \mu_{\nu_e} - \mu_e - \mu_{\nu_\mu} = \delta\mu_1 - \delta\mu_2$
   - $\mu^- \leftrightarrow e^- + \bar{\nu}_e + \nu_\mu$
   - $\mu^- + \bar{\nu}_\mu \leftrightarrow e^- + \bar{\nu}_e$
   - $\mu^- + \nu_e \leftrightarrow e^- + \nu_\mu$
   - $\mu^- + \nu_e + \bar{\nu}_\mu \leftrightarrow e^-$



Fore, SPH, Reddy (in progress)

Pion bulk viscosity (finite $n \leftrightarrow p + \pi^-$ rate)

$$n + n \leftrightarrow n + p + \pi^-$$

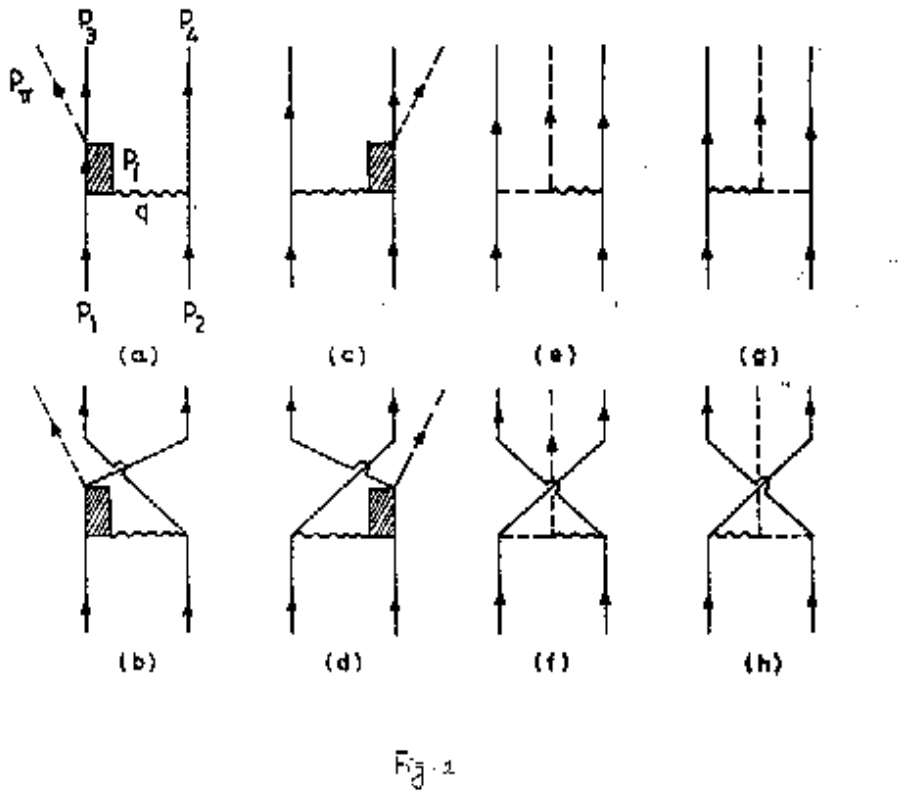
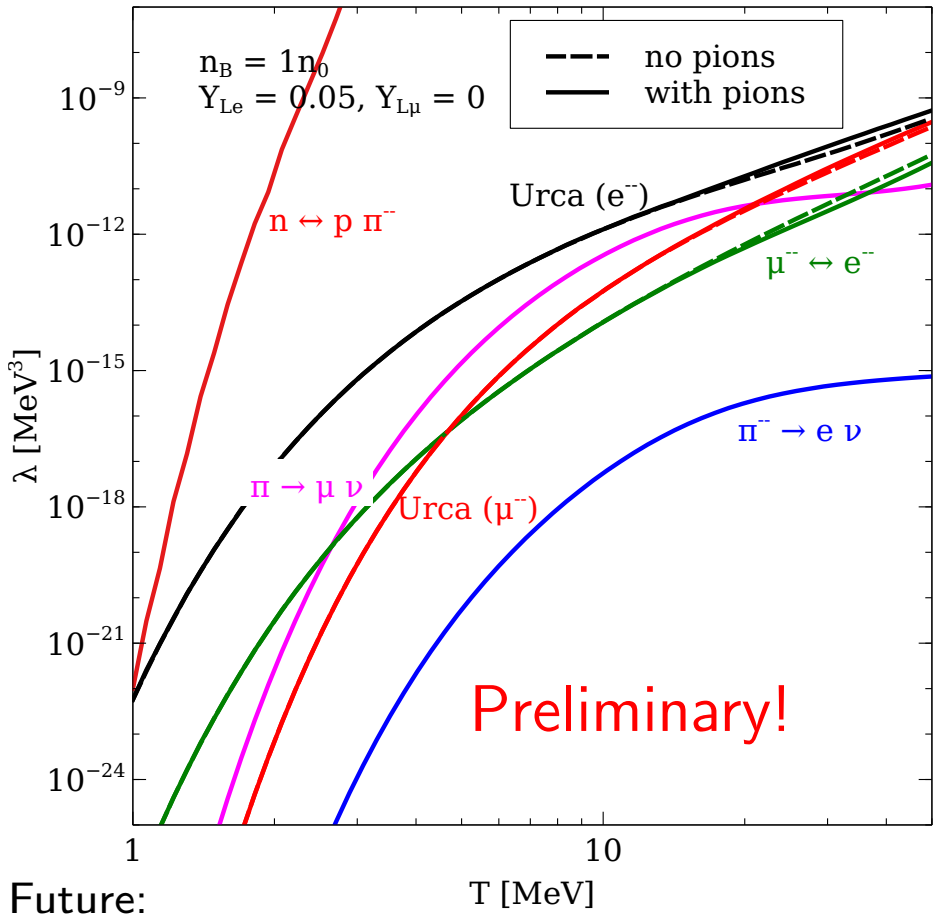


Fig. 1

Engel, Dutt-Mazumder, Shyam, Mosel arXiv:nucl-th/9601026



Future:

- See how finite $n \leftrightarrow p + \pi^-$ rate impacts bulk viscosity
- Neutrino-transparent regime