Bulk viscosity in neutron star merger remnants from neutron decays to dark baryons

Steven Harris
Indiana University (NP3M Fellow)

INT workshop: EOS Measurements with Next-Generation Gravitational-Wave Detectors
September 4, 2024
SPH, Chuck Horowitz (in progress)

Outline

- Thermodynamics of neutron star mergers
- Beta equilibration and bulk viscosity in *npe* matter
- Neutron lifetime anomaly
  - Solve by introducing dark sector χ and ϕ
- Beta equilibrium and bulk viscosity in *npe*χ matter

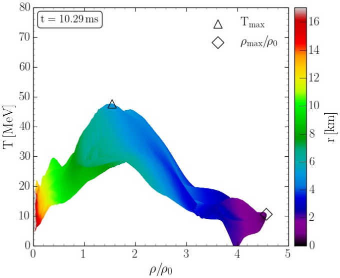
If a slowly-decaying (but thermally equilibrated[1]) particle species exists in neutron stars, what consequences does that have?

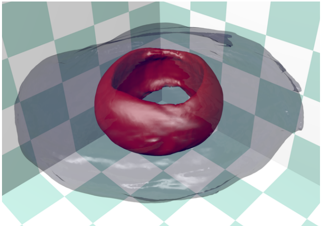
---

[1] With itself and with the *npe* matter.

Neutron star merger conditions

The collision of two neutron stars heats them from $T \sim \mathcal{O}(\mathrm{keV})$ to $T \sim 30$ MeV.

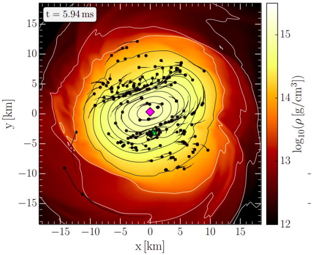




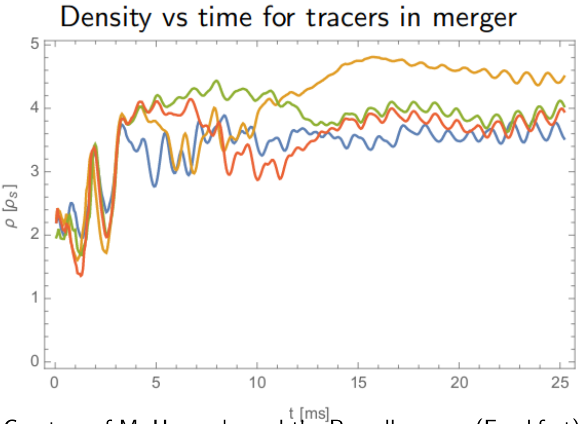
Remnant lifetime is typically tens of milliseconds. GW170817 lifetime was likely about 1 sec.

Density oscillations in neutron star mergers

Fluid elements in inviscid neutron star merger simulation:



M. Hanauske et al., Neutron Star Mergers: Probing the EoS of Hot, Dense Matter by Gravitational Waves, Particles 2 (2019) 44.



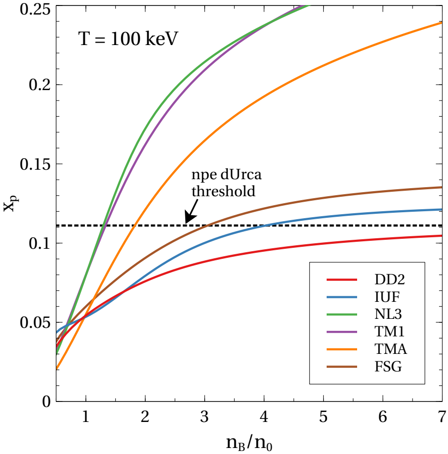
Courtesy of M. Hanauske and the Rezzolla group (Frankfurt)

Nuclear matter fluid elements change density at $\omega \approx 2\pi \times 1$ kHz.

This is related to the time sound takes to cross NS: $1/t = v/x = (c/2)/25$ km $= 6$ kHz.

Beta equilibrium in npe^- matter

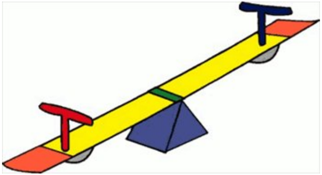
Beta-equilibrated npe^- matter is described (at a given $\{n_B, T\}$) by 1 parameter, x_p.



If the system is pushed out of beta equilibrium, the Urca process acts at rate γ to restore it

$$n \to p + e^- + \bar{\nu}_e$$

$$e^- + p \to n + \nu_e$$

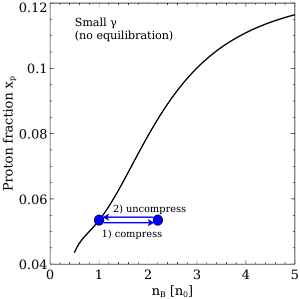


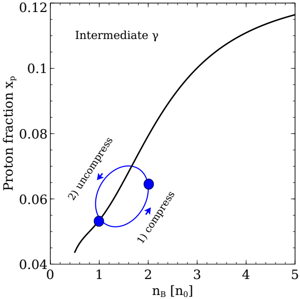
γ depends strongly on temperature.

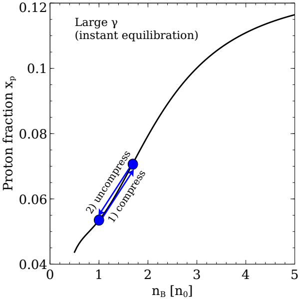
Bulk viscosity from beta equilibration

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

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



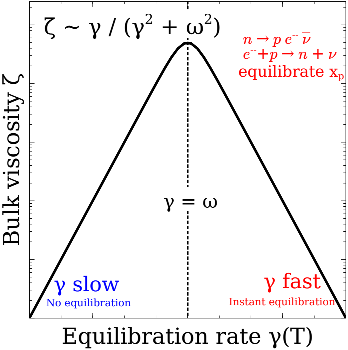




Fluid element traverses a path in the $x_p n_B$ (or, PV) plane, indicating that work is done on the fluid element. This is bulk-viscous dissipation.

$$n_B \frac{dx_p}{dt} = \Gamma_{n\rightarrow p+e^-+\bar{\nu}} - \Gamma_{e^-+p\rightarrow n+\nu}$$

npe bulk viscosity

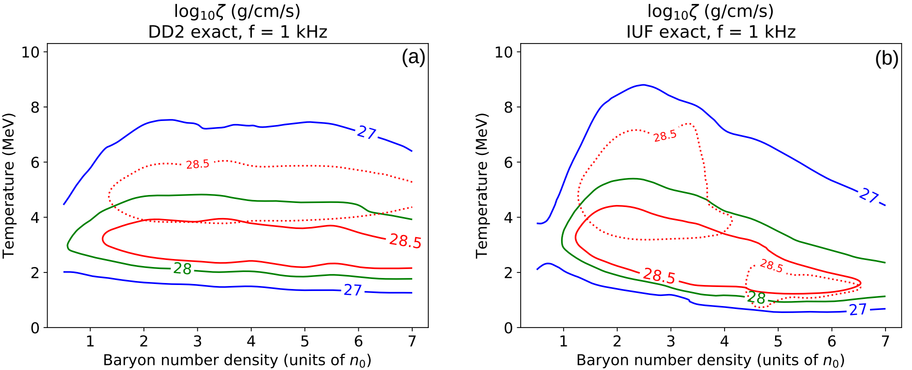


- Peak location determined by $\gamma(n_B, T) \approx \omega = 2\pi \times 1$ kHz.
- Peak height determined by ω and properties of the EoS (compressibility and sound speed)

$$c^2 \equiv \left.\frac{\partial P}{\partial \varepsilon}\right|_{x_p, T} \qquad \tilde{c}^2 \equiv \left.\frac{\partial P}{\partial \varepsilon}\right|_{\delta\mu, T}$$

$$\begin{aligned}\zeta_{\text{max}} &= \frac{1}{2\omega}\left[n_B\left(\left.\frac{\partial P}{\partial n_B}\right|_{\delta\mu, T} - \left.\frac{\partial P}{\partial n_B}\right|_{x_p, T}\right)\right] \\ &= \frac{1}{2\omega}\left[\kappa_T^{-1}\left(\frac{\tilde{c}^2 - c^2}{c^2}\right) - T\tilde{c}^2\left(\left.\frac{\partial P}{\partial T}\right|_{n_B, \delta\mu} - \left.\frac{\partial P}{\partial T}\right|_{n_B, x_p}\right)\right]\end{aligned}$$

npe bulk viscosity



Bulk viscosity is largest at $T \approx 3$ MeV.

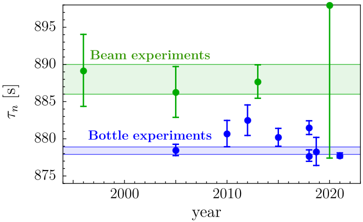
This is where $\gamma(n_B, T) \approx \omega = 2\pi \times 1$ kHz.
Damping times as small as 5 ms.

Alford & SPH arXiv:1907.03795

Neutron decay anomaly

Recently, precise neutron lifetime experiments have been conducted:

- Bottle method
  - Ultracold neutrons held in a bottle
  - Periodically counted to see how many are left
- Beam method
  - Neutron beam shot through Penning trap
  - Protons counted to see how many neutrons have decayed



Fornal arXiv:2306.11349

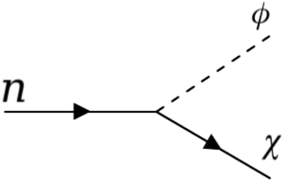
Resolution: Maybe neutrons decay into particles other than protons!

If 1% of neutron decays are into dark sector, the neutron decay anomaly is solved.

Dark matter solution to the anomaly

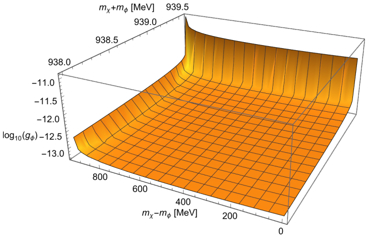
Assume the neutron can decay into a dark baryon χ and a dark scalar ϕ

$$n \to \chi + \phi$$



$$\mathcal{L} \supset g_\phi(\bar{\chi} n + \bar{n}\chi)\phi$$

$$\Gamma_{n\to\chi\phi} = \frac{{g_\phi}^2}{16\pi m_n^3}\left[(m_n + m_\chi)^2 - m_\phi^2\right]^{3/2} \times \left[(m_n - m_\chi)^2 - m_\phi^2\right]^{1/2}$$



Neutron decay anomaly is solved for $\{g_\phi, m_\chi, m_\phi\}$ such that $\Gamma_{n\to\chi\phi} = \Gamma_n/100$.

What if the χ is dark matter?

- Nucleon-DM cross section $\sigma \lesssim 10^{-45}$ cm^2
    - terrestrial experiments
- DM-DM cross section $\sigma \lesssim 10^{-25}$ cm$^2 \left(\frac{m_\chi}{1\ \text{MeV}}\right)$
    - Needed to solve core-cusp problem
- We assume the χ dark baryons are thermally equilibrated[2] with the *npe* matter and with themselves[3]. There is one *npe*χ fluid[4].

---

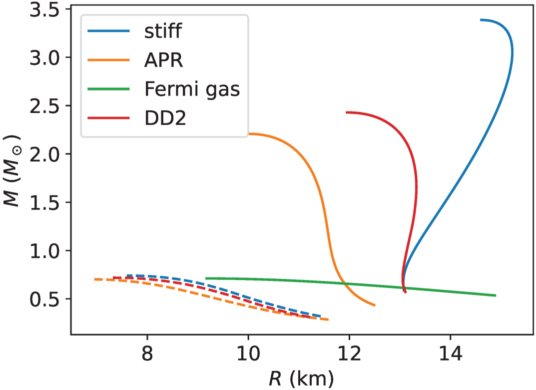
[2] But, not chemically equilibrated!

[3] In other words, both cross sections are sufficiently large

[4] Otherwise, should use 2-fluid formalism, yielding multiple bulk viscosity coefficients.

Neutron stars containing dark baryons

Free fermi gas of dark baryons χ unacceptably soften the EoS.



Zhou, Universe 2023
9(11), 484

Need to add a $\chi - \chi$ repulsion term to stiffen the EoS.

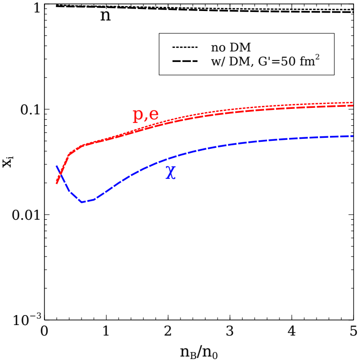
$$P_{\text{dark}} = P_{\text{kinetic}} + \frac{1}{2} G' n_\chi^2 \qquad \varepsilon_{\text{dark}} = \varepsilon_{\text{kinetic}} + \frac{1}{2} G' n_\chi^2$$

$50 \lesssim G'/(\text{fm}^2) \lesssim 1000$

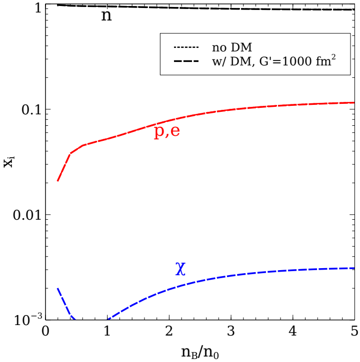
Dark baryons in neutron stars

- Use IUF-II relativistic mean field (RMF) theory for *npe*
- Add dark baryons χ ($n_B = n_n + n_p + n_\chi$ and $\mu_\chi = \mu_n$)
- vector repulsion between χ's. (Repulsion strength G'.)

Weakly repulsive DM

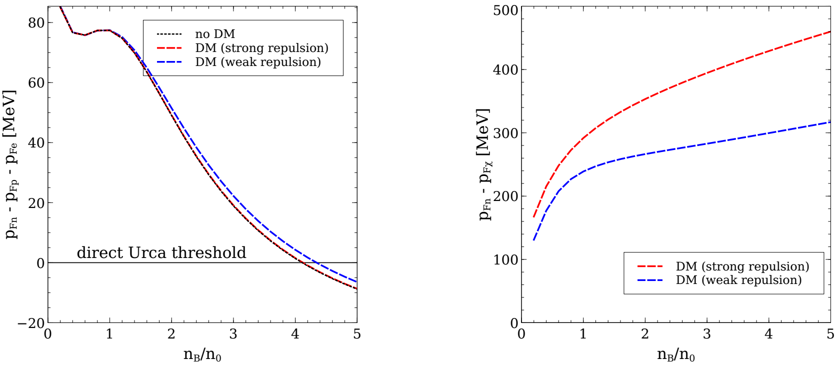


Strongly repulsive DM



Dark baryons in neutron stars

- Dark baryons slightly move direct Urca threshold
- $n \to \chi + \phi$, in medium, is strongly Boltzmann suppressed.
    - Look at *modified* processes instead: $n + n \to n + \chi + \phi$



Chemical equilibration in $npe\chi$ matter

$$n_B \frac{dx_p}{dt} = \Gamma_{n\to p+e^-+\bar{\nu}} - \Gamma_{e^-+p\to n+\nu} \sim \gamma_1(n_p - n_p^0)$$

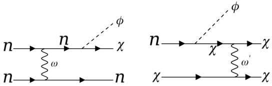
$$n_B \frac{dx_\chi}{dt} = \Gamma_{n\to \chi+\phi} - \Gamma_{\chi\to n+\phi} \sim \gamma_2(n_\chi - n_\chi^0)$$

Urca

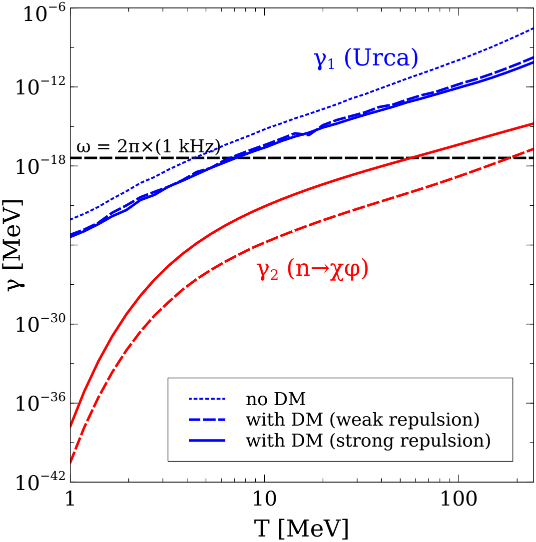
Boltzmann suppression of dUrca overcome for $T \gtrsim 1$ MeV. Do full phase space integral. Neglect modified Urca.

Neutron dark decay

$n \to \chi\phi$ is Boltzmann suppressed even at high temperatures. Calculate *modified* process



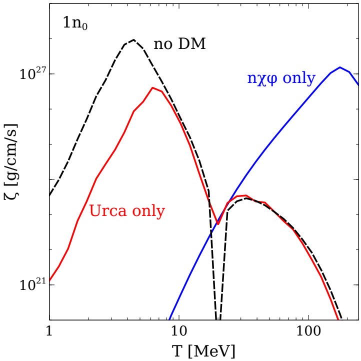
Chemical equilibration in $npe\chi$ matter



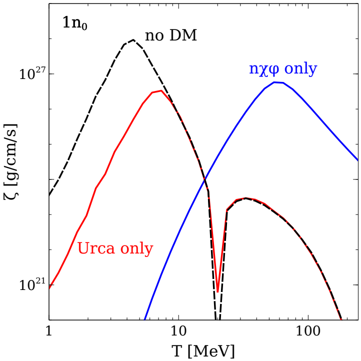
Bulk viscosity in *npe*χ matter

$$\zeta = \frac{\lambda_1\lambda_2\left[\left(A_2B_1 - A_1B_2\right)^2\lambda_1 + \left(A_2B_2 - A_1C_2\right)^2\lambda_2\right] + \left(A_1^2\lambda_1 + A_2^2\lambda_2\right)\omega^2}{\left(B_2^2 - B_1C_2\right)^2\lambda_1^2\lambda_2^2 + \left(B_1^2\lambda_1^2 + 2B_2^2\lambda_1\lambda_2 + C_2^2\lambda_2^2\right)\omega^2 + \omega^4}.$$

Weakly repulsive DM



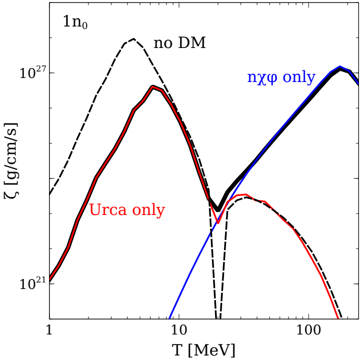
Strongly repulsive DM



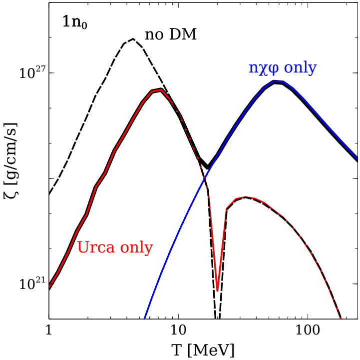
Bulk viscosity in $npe\chi$ matter

$$\zeta = \frac{\lambda_1\lambda_2\left[\left(A_2B_1 - A_1B_2\right)^2\lambda_1 + \left(A_2B_2 - A_1C_2\right)^2\lambda_2\right] + \left(A_1^2\lambda_1 + A_2^2\lambda_2\right)\omega^2}{\left(B_2^2 - B_1C_2\right)^2\lambda_1^2\lambda_2^2 + \left(B_1^2\lambda_1^2 + 2B_2^2\lambda_1\lambda_2 + C_2^2\lambda_2^2\right)\omega^2 + \omega^4}.$$

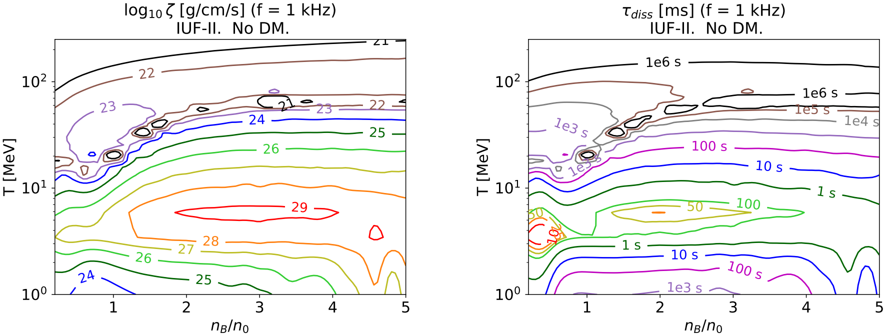
Weakly repulsive DM



Strongly repulsive DM

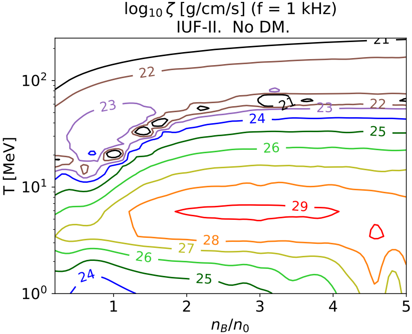


Bulk viscosity in *npe* matter

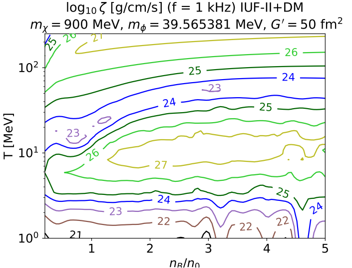


- Bulk viscosity exceeds 10^{29} g/cm/s.
- 1 resonant peak
- Damping times as small as 10 ms.

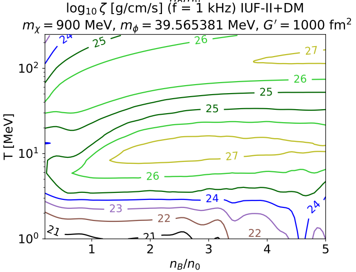
Bulk viscosity in $np e\chi$ matter



$\log_{10}\zeta$ [g/cm/s] (f = 1 kHz)
IUF-II. No DM.



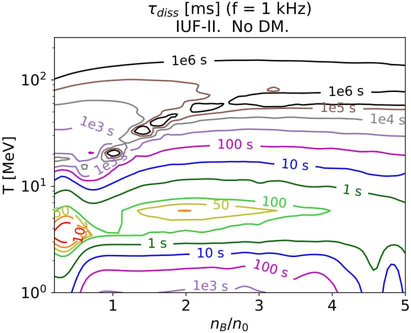
$\log_{10}\zeta$ [g/cm/s] (f = 1 kHz) IUF-II+DM
$m_\chi = 900$ MeV, $m_\phi = 39.565381$ MeV, $G' = 50$ fm^2



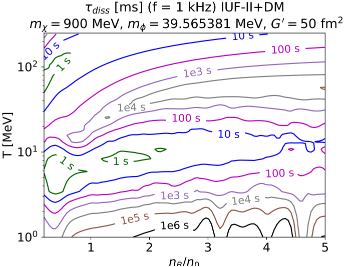
$\log_{10}\zeta$ [g/cm/s] (f = 1 kHz) IUF-II+DM
$m_\chi = 900$ MeV, $m_\phi = 39.565381$ MeV, $G' = 1000$ fm^2

- χ dark baryons suppress the Urca peak in the bulk viscosity
- $n \to \chi\phi$ reaction yields new peak in ζ at $T \gtrsim 50$ MeV

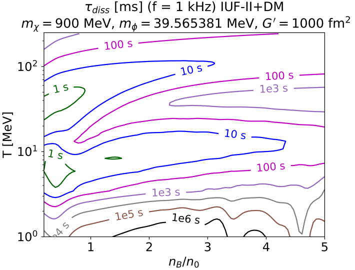
Damping times in $npe\chi$ matter



τ_{diss} [ms] (f = 1 kHz)
IUF-II. No DM.



τ_{diss} [ms] (f = 1 kHz) IUF-II+DM
$m_\chi = 900$ MeV, $m_\phi = 39.565381$ MeV, $G' = 50$ fm^2



τ_{diss} [ms] (f = 1 kHz) IUF-II+DM
$m_\chi = 900$ MeV, $m_\phi = 39.565381$ MeV, $G' = 1000$ fm^2

- Presence of χ particles
  - Increases damping time to (at least) hundreds of ms
  - Quickens damping at high temperatures

Conclusions

- Neutron decay anomaly can be solved by introducing dark baryon χ and dark scalar ϕ such that $n \to \chi + \phi$. What are the consequences of χ in neutron stars?
  - $n \to \chi + \phi$ is slow (even in medium), giving rise to a second peak in the bulk viscosity at $T \gtrsim 50$ MeV. Its effect on the EoS also reduces the Urca peak in the bulk viscosity.
- Future:
  - Improve $n + n \to n + \chi + \phi$ rate calculation (c.f. Alex Haber's talk)
  - Implement $n \to \chi + \phi$ in NS merger simulation
  - Other neutron decay anomaly solutions, like $n \to \tilde{\chi} + \tilde{\chi} + \tilde{\chi}$