# The neutron lifetime anomaly, dark baryons, and their impact on neutron star mergers

...and some comments on the symmetry energy...

Steven Harris

Iowa State University (NP3M Fellow)

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SPH & Chuck Horowitz (in progress)

# Outline

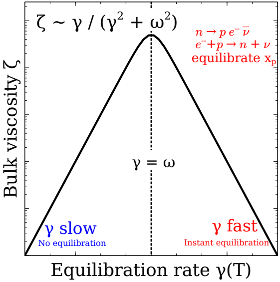
- Symmetry energy and the bulk viscosity
- Neutron decay anomaly
  - Solve by introducing dark sector $\chi$ and $\phi$
- Dark baryon effect on bulk viscosity

How do $\chi$ and $\phi$ alter transport in neutron star mergers?

# Bulk viscosity in *npe* matter

What can we learn about bulk viscosity from just knowing the symmetry energy (and $\omega$)?

- Fluid element undergoes density oscillation with frequency $\omega \approx 2\pi \times (1\text{ kHz})$
- In response, Urca process tries to restore $\beta$-eq. at rate $\gamma(T)$.
- If $\gamma \approx \omega$, $x_p$ lags behind $x_p^{\beta\text{ eq.}}$, PdV work is done on fluid element.




At a given $\omega$:

- Peak location determined by Urca rate [$\gamma(n_B, T) \approx \omega$].
- Peak height determined by properties of the EoS (susceptibilities)
  - These are determined by the symmetry energy!

# Symmetry Energy

$$\frac{E}{N_B} = \frac{E_{\text{nuc}}}{N_B}\left(n_B, x_p = \frac{1}{2}\right) + S(n_B)\left(1 - 2x_p\right)^2 + \frac{\varepsilon_e}{n_B}$$

with

$$S(n_B) = J + \frac{L}{3}\left(\frac{n_B - n_0}{n_0}\right) + \frac{K_{\text{sym}}}{18}\left(\frac{n_B - n_0}{n_0}\right)^2 + \frac{Q_{\text{sym}}}{162}\left(\frac{n_B - n_0}{n_0}\right)^3$$

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Beta equilibrium condition: $64S(n_B)^3\left(1-2x_p^{\rm eq.}\right)^3 = 3\pi^2 n_B x_p^{\rm eq.}$

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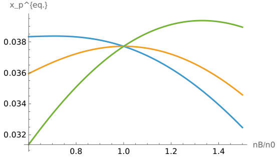
Does the *npe* EoS have any conformal points?



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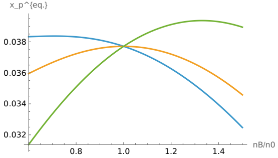


Take $d/dn_B$ and solve for $dx_p^{eq.}/dn_B$ → polynomial equation in $n_B^{\text{conf.}}$ for all conformal points of *npe* matter

$$3n_B^{\text{conf.}}\frac{dS(n_B^{\text{conf.}})}{dn_B^{\text{conf.}}} = S(n_B^{\text{conf.}}).$$

Ex. $S = J + \frac{L}{3}\left(\frac{n_B - n_0}{n_0}\right) \to \frac{n_B^{conf}}{n_0} = 1 - \frac{3}{2}\left(\frac{L-J}{L}\right)$ EoS is conformal at $n_0$ if $J = L$.

# Bulk viscosity peak value

$$\zeta(\omega) = \zeta_{\text{max}} \left( \frac{2\omega\gamma}{\omega^2 + \gamma^2} \right) \quad \text{where} \quad \zeta_{\text{max}}(n_B) = \left| \frac{A^2}{B} \right| \frac{1}{2\omega}.$$

$$A \equiv n_B \frac{\partial \delta\mu}{\partial n_B}\bigg|_{x_p}, \quad B \equiv \frac{1}{n_B} \frac{\partial \delta\mu}{\partial x_p}\bigg|_{n_B}.$$

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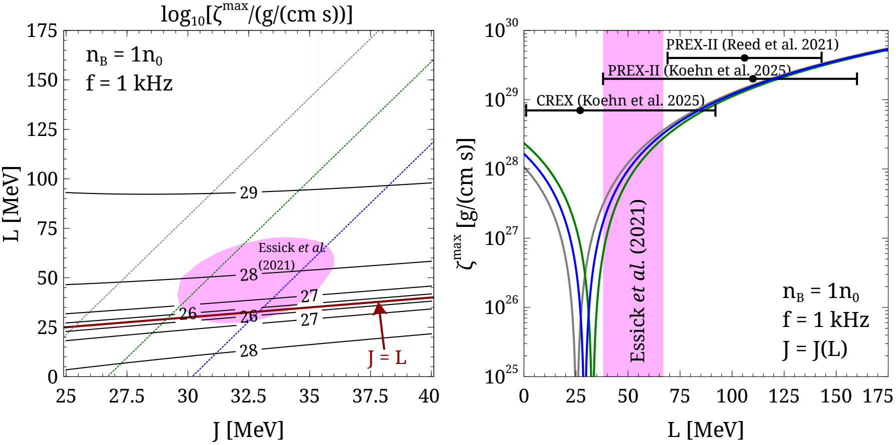
Find $A = A(J, L, K_{\text{sym}}, Q_{\text{sym}}, ...)$ and $B = B(J, L, K_{\text{sym}}, Q_{\text{sym}}, ...)$.
Calculate $A^2/B$.

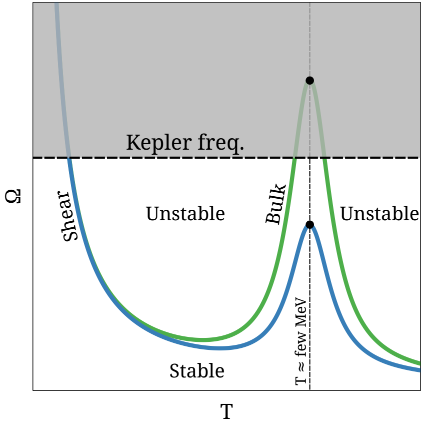
$$\zeta^{\text{max}}(n_B) = \frac{2n_0}{3\omega} x_p^{\text{eq.}} \left[ 1 - 8x_p^{\text{eq.}} + 36 \left( x_p^{\text{eq.}} \right)^2 \right] \times \left\{ \frac{(L-J)^2}{J} - \frac{L-J}{3J^2} \left( 3J^2 - 2JK_{\text{sym}} - 8JL + L^2 \right) \left( \frac{n_B - n_0}{n_0} \right) + ... \right\}$$

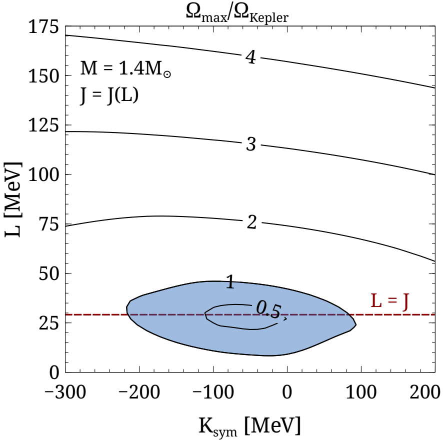
# Constraints on max bulk viscosity




*npe*-matter bulk viscosity at $n_0$ could be very small, but most likely it's large enough to cause $\tau_{\text{diss}} < 100$ ms.

# Constraints on r-mode window



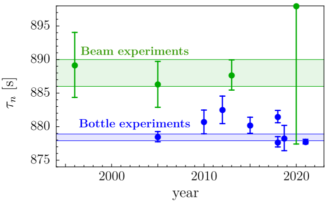




It is possible (at high $T$) that r-mode instability boundary lies below the Kepler frequency.

# Neutron decay anomaly

Recently, precise neutron lifetime experiments have been conducted:

- Bottle method
  - Ultracold neutrons held in a bottle
  - Neutrons 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

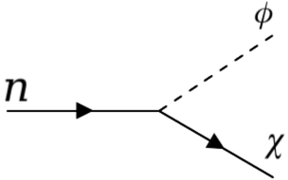
Resolution: Maybe neutrons decay into particles other than protons!

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

# Dark matter solution to the anomaly

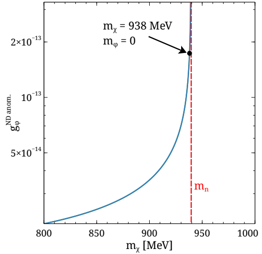
Assume the neutron can decay into a dark baryon $\chi$ and a dark scalar $\phi$

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




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

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




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

We will assume $\chi$ is heavy and $\phi$ is light.

# Neutron stars containing dark baryons

We assume the nucleon-DM cross section[a] is fairly large: NS is composed of one, thermally equilibrated, $npe\chi$ fluid.

[a] Due to some unspecified reaction, like $n\chi \to n\chi$, not $n \to \chi\phi$.

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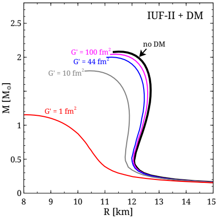
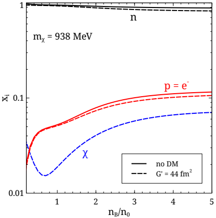
- Free Fermi gas of $\chi$'s destabilizes neutron star. Give $\chi$'s repulsive self-interaction ($G'$) to stiffen EoS to produce $2M_\odot$ NS.
- We assume $\phi$ escapes the system. Not thermalized.

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

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

$$\frac{\sigma_{\chi\chi}}{m_\chi} = 0.6 \frac{\text{cm}^2}{\text{g}} \left( \frac{G'}{10\ \text{fm}^2} \right)^2 \left( \frac{m_\chi}{\text{GeV}} \right)$$



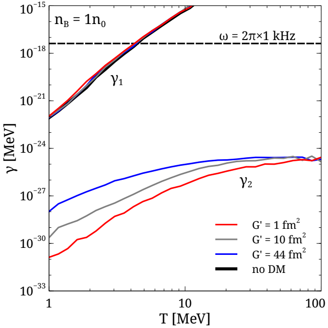




For IUF-II EoS, $G' \gtrsim 44\ \text{fm}^2$, so $\sigma/m \gtrsim 10\ \text{cm}^2/\text{g}$.

# Chemical equilibration in $npe\chi$ matter

2 independent particle fractions: $x_p$ and $x_\chi$

$$\frac{dx_p}{dt} = \frac{1}{n_B}\left(\Gamma_{n\to p+e^-+\bar{\nu}} - \Gamma_{e^-+p\to n+\nu}\right) \approx -\gamma_1(x_p - x_p^{eq.})$$
$$\frac{dx_\chi}{dt} = \frac{1}{n_B}\left(\Gamma_{n\to \chi+\phi} - \Gamma_{\chi\to n+\phi}\right) \approx -\gamma_2(x_\chi - x_\chi^{eq.})$$




- In medium, $n \to \chi\phi$ is orders of magnitude slower than Urca
  - Never reaches resonance!
- Adding $\chi$ to EoS has little effect on Urca
- Note: $n \to \chi + \phi$ was calculated in the Nucleon Width Approximation[a] (NWA).

[a] Alford, Haber, & Zhang 2406.13717

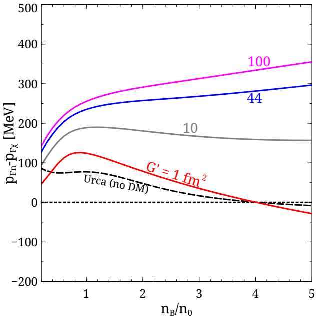
# More on the $n \to \chi + \phi$ rate in medium

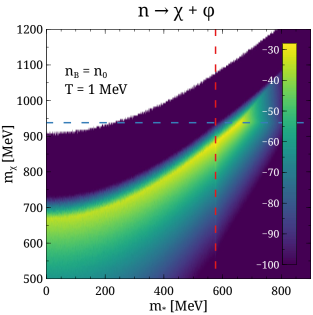
Used the nucleon width approximation (NWA), where the total rate

$$n + (N + N + ...) \to \chi + \phi + (N + N + ...)$$

is expressed as an integral of the rate $n \to \chi + \phi$ over the masses of the particles with widths $W$ ($n$ & $\chi$), weighted by a Breit-Wigner around the "real" mass.

$$W_n \sim (G_\sigma - G_\omega)^2 \, m_*^3 T^2 \quad W_\chi \sim G'^2 m_\chi^3 T^2$$



# Bulk viscosity in $npe\chi$ matter

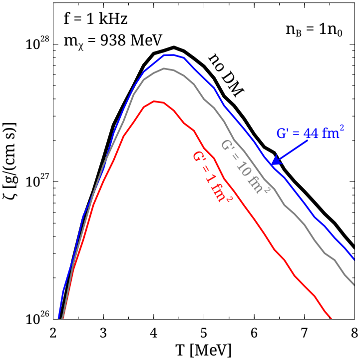
$$\zeta = \frac{\lambda_1\lambda_2\left[(A_2B_1 - A_1B_2)^2\lambda_1 + (A_2B_2 - A_1C_2)^2\lambda_2\right] + \left(A_1^2\lambda_1 + A_2^2\lambda_2\right)\omega^2}{\left(B_2^2 - B_1C_2\right)^2\lambda_1^2\lambda_2^2 + \left(B_1^2\lambda_1^2 + 2B_2^2\lambda_1\lambda_2 + C_2^2\lambda_2^2\right)\omega^2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

$n \to \chi\phi$ is so slow[a] that $\lambda_2 \approx 0$.

$$\zeta \approx \frac{A_1^2\lambda_1}{B_1^2\lambda_1^2 + \omega^2} = \frac{A_1^2}{B_1}\frac{\gamma_1}{\gamma_1^2 + \omega^2}.$$

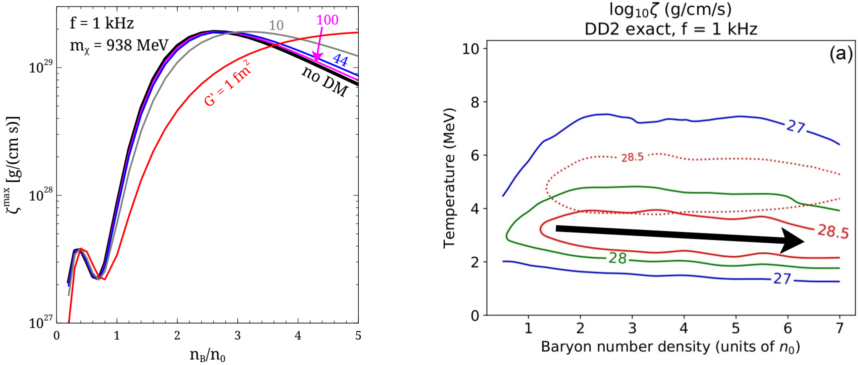
$\chi$ softens the EoS, decreasing the bulk viscosity peak.

[a] $\tau_{n\to\chi\phi} \gtrsim 40$ minutes




If $\chi$ and $\phi$ solve the neutron decay anomaly, the decay rate $n \to \chi + \phi$ is very slow $\to$ Only Urca bulk viscosity.
$\chi$ softens EoS, decreasing Urca bulk viscosity slightly.

# Frozen-$\chi$ bulk viscosity at higher densities

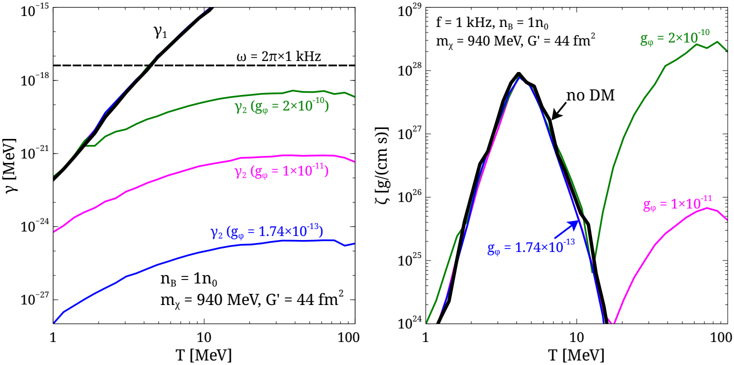



If $n \to \chi + \phi$ solves n-decay anomaly, the $\chi$s only slightly change the bulk viscosity.

- For NL3, with more $\chi$ particles, can be up to 2-3x reduction.

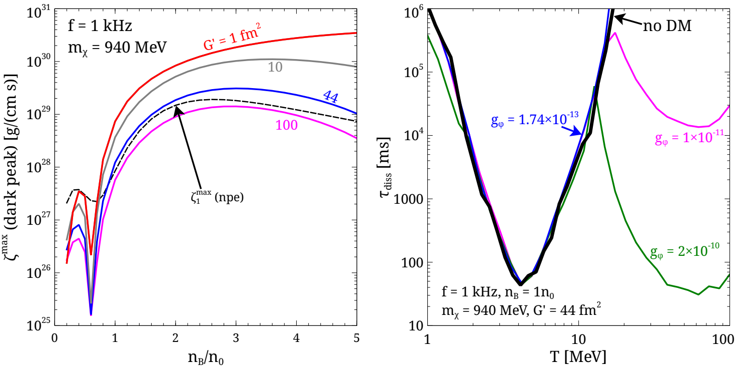
# Forget about the neutron decay anomaly!

If we abandon the desire to solve NDA, then $n \to \chi\phi$ can be faster.




- Vast separation in n-decay rates. $\zeta \approx \zeta_1 + \zeta_2$.
- Slowly (but not too slowly!) equilibrating BSM degree of freedom can strongly enhance high-T bulk viscosity!
- "Dark peak" isn't even reached! Raffelt criterion prevents it.

# How large could "dark" bulk viscosity be?




- Presumably dark bulk-viscous peak probes a sort of "dark symmetry energy".
- Dark baryons can damp an oscillation at $T = 50$ MeV in under 40 ms.

# Conclusions

Neutron decay anomaly (NDA) can be explained by introducing dark baryon $\chi$ and dark scalar $\phi$, such that $n \to \chi + \phi$.

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- If $n \rightarrow \chi + \phi$ is faster (not solving NDA), then $\zeta \approx \zeta_1 + \zeta_2$. Enhances bulk visc. at high T.

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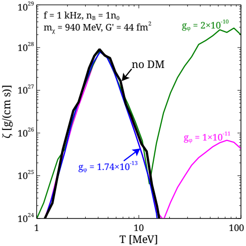
- If $n \rightarrow \chi + \phi$ is faster (not solving NDA), then $\zeta \approx \zeta_1 + \zeta_2$. Enhances bulk visc. at high T.
- Most rxns (npe Urca, quarks) are fast - $\zeta$ peaks at $T = 3 - 5$ MeV or lower. Maybe BSM physics is only way to get large $\zeta$ at $T \gtrsim 30$ MeV. Signatures??




Future work:

- Implement $n \rightarrow \chi\phi$ in NS merger and supernovae simulations
- Other NDA solutions, like $n \rightarrow \tilde{\chi}\tilde{\chi}\tilde{\chi}$

# Backup slides

# What if the $\chi$ 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 $\chi$ dark baryons are thermally equilibrated[1] with the *npe* matter and with themselves[2]. There is one *npe*$\chi$ fluid[3].

[1] But, not chemically equilibrated!

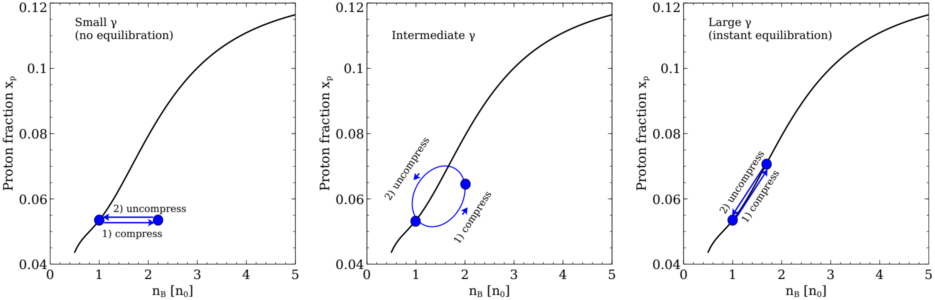
[2] In other words, both cross sections are sufficiently large

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

# Bulk viscosity from beta equilibration

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

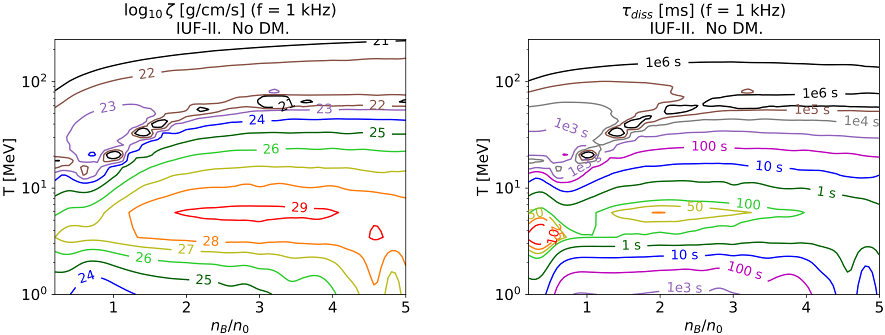
$$n_B(t) = n_B^0 + \delta n_B \cos(\omega t)$$




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.

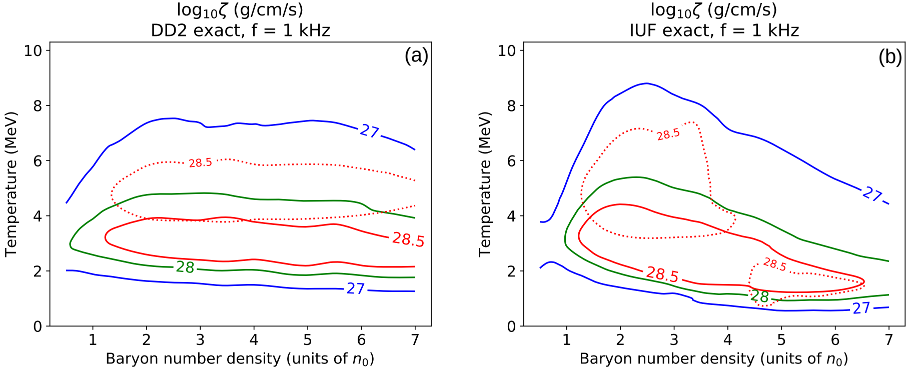
$$x_p(t) = x_p^{eq.} - \left(\frac{\delta n_B}{n_B}\right)\frac{1}{n_B}\left(\frac{A}{B}\right)\frac{\gamma}{\omega^2+\gamma^2}\left[\gamma\cos(\omega t) + \omega\sin(\omega t)\right]$$

# Bulk viscosity in *npe* matter




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

# npe bulk viscosity

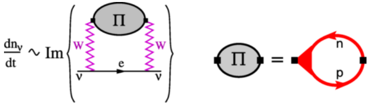



Alford & SPH arXiv:1907.03795

- Ridge-like resonance feature at $T \approx 2 - 4$ MeV, where $\gamma_{\text{Urca}} \approx 2\pi \times (1\text{ kHz})$.
- Damping times as small as 5 ms.

# Nucleon Width Approximation

The Urca rate is the imaginary part of the neutrino self-energy.




"The propagator for a fermion with nonzero width can be written as a mass-spectral decomposition in terms of propagators with zero width"

For a particle with width $W$,

$$G^{\text{NWA}} = \int_{-\infty}^{\infty} \frac{dm}{2\pi} G^{\text{MF}} \frac{W}{(m - m^{\text{vac}})^2 + (W/2)^2}$$

As $W \to 0$, $G^{\text{NWA}} \to G^{\text{MF}}$.

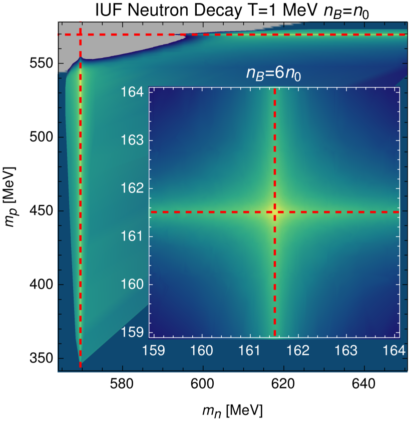
$$\Gamma_{\text{dUrca}} \sim \int d^3p \ldots \delta^4\left(\sum p\right) \sum_{\text{spins}} |\mathcal{M}|^2 f_n \left(1 - f_p\right)\left(1 - f_e\right)$$

$$\Gamma^{\text{NWA}} = \int_{-\infty}^{\infty} \frac{dm_n}{2\pi} \frac{dm_p}{2\pi} \Gamma_{\text{dUrca}} \left[\frac{W_n}{(m_n - m_n^{\text{vac}})^2 + (W_n/2)^2}\right]\left[\frac{W_p}{(m_p - m_p^{\text{vac}})^2 + (W_p/2)^2}\right]$$

Alford, Haber, & Zhang 2406.13717

# Nuclear Width Approximation (2)

Urca:

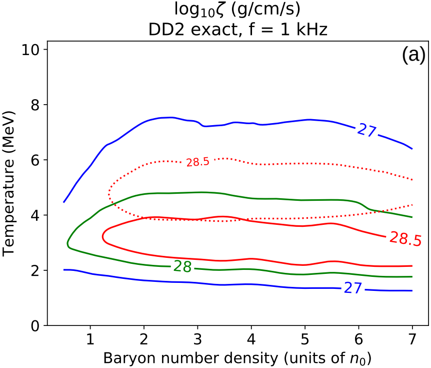


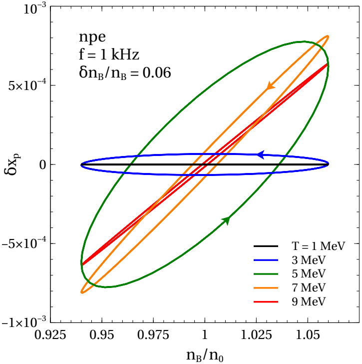

Below threshold: Masses away from vacuum mass dominate. Suppression.
Above threshold: Masses at vacuum mass dominate. No suppression.

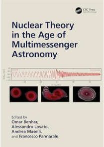
Alford, Haber, & Zhang 2406.13717

# npe bulk viscosity

Alford & SPH
arXiv:1907.03795




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.

SPH, Ch. 8 and arXiv:2407.16157

# Dark baryon affect on symmetry energy