Transport in Neutron Star Mergers

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Washington University in St. Louis

Alford, A.H., Harris, Zhang arXiv:2108.03324
Alford, A.H., arXiv:2009.05181
Alford, Harutyunyan, Sedrakian arXiv:1907.04192
Alford, Harris arXiv:1907.03795
Alford et.al., 1707.09475

SEWM Paris, Jun. 2022

Topic of this Talk

Question of the day:

How can we use transport in neutron star mergers to study the QCD phase diagram ?

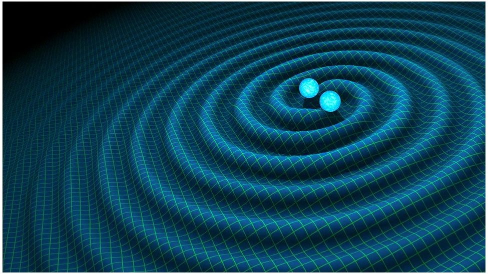
Answer:

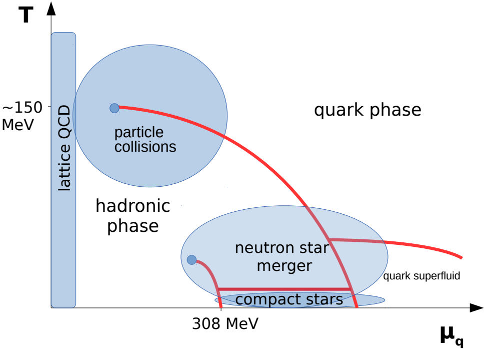
- Build better gravitational wave detectors
- Improve microscopic physics in merger simulations
- Focus on weak interactions

Motivation

Ultimate goal:

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



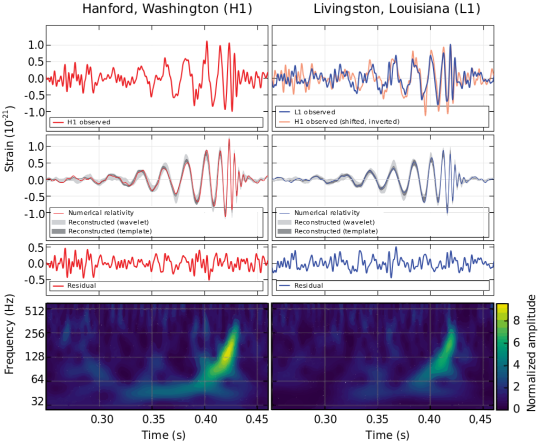


Gravitational Waves

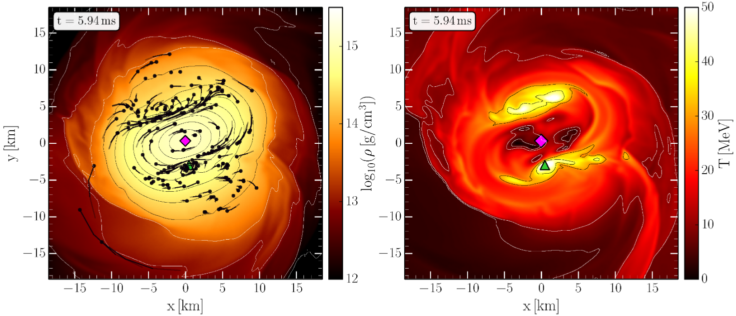
Detection requires simulations

- BNS (inspiral) can be detected with current detectors (GW170817 and GW190425)
- Signal **very noisy** - requires simulation of wave form
- Simulations provide us thermodynamic input

B. P. Abbott et al. (LIGO and Virgo Collaboration)



Neutron Star Merger

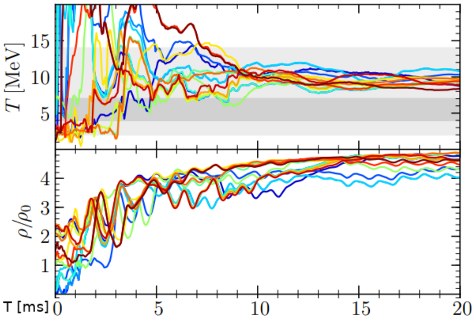


Hanauske, M.; Steinheimer, J. et al. Particles 2019

- Merger test properties of dense matter at high densities (up to $\approx 4\, n_{\text{sat}}$) and high temperatures (up to $T \approx 60 - 80$ MeV)
- If we want to use mergers to learn about nuclear matter, we need to include all the relevant physics in our simulations.

Neutron Star Merger

Thermodynamic environment



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

- Significant spatial and temporal variation in
  - temperature → thermal conductivity
  - fluid flow velocity → shear viscosity
  - density → bulk viscosity

Transport Properties in Mergers

Better discriminator of different phases than EOS

Premise

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

Estimates for transport properties: **Alford, Bovard, et.al. PRL 120 (2018)**

- Thermal transport: important if
  - neutrinos are trapped ($T > 5$ MeV)
  - there are short-distance temperature gradients on $\approx$ 0.1 km scale
- Shear viscosity similar conclusion
- **Bulk viscosity** potentially important: large enough for significant damping of oscillations in millisecond time-range?

Weak interaction involved in all of these!

Bulk Viscosity

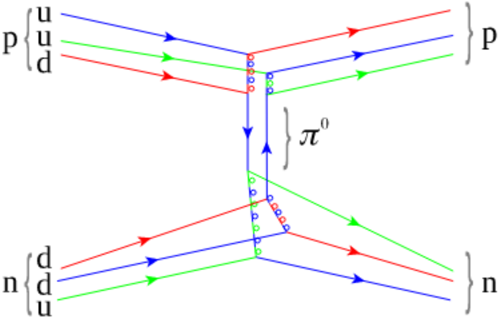
"Compression dissipation"

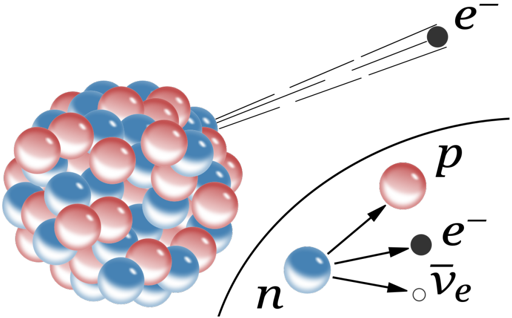
- Bulk viscosity in mergers driven by weak interactions (strong and electromagnetic too fast)
- Weak interactions equilibrate particle content

Results:

- Nuclear bulk viscosity in neutrino-transparent matter ($T \lesssim 5$ MeV):
  Alford, Harris, Phys.Rev. C100 (2019): millisecond damping times
- Nuclear bulk viscosity in neutrino-trapped matter ($T \gtrsim 10$ MeV):
  Alford, Harutyunyan, Sedrakian Phys.Rev.D100 (2019): rates too fast $\rightarrow$ low bulk viscosity
- Hyperon bulk viscosity for non-leptonic processes : Alford, A.H. PRC 103 (2021)
  - millisecond damping times only at keV temperatures
  - Hyperonic rates at higher temperatures too fast for sizeable bulk viscosity

So what do we need?





Microscopical model for nuclear matter valid at wide density and temperature range

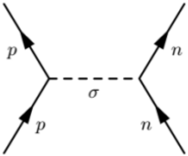
Better understanding of weak processes

New Model for Nuclear Matter

Alford, Brodie, A.H., Tews: arXiv:2205.10283

Relativistic mean field theories:

Based on meson-exchange Lagrangians:
nucleons interact via meson exchange



- ✓ Applicable to density/temperature range of NS mergers
- ✓ Fully relativistic model → always causal
- ✓ Provide microscopical model: dispersion relations, . . .

Coupling constants: fit to saturation properties of (nearly) symmetric nuclear matter

Neutron stars are ≈ 90% neutrons!

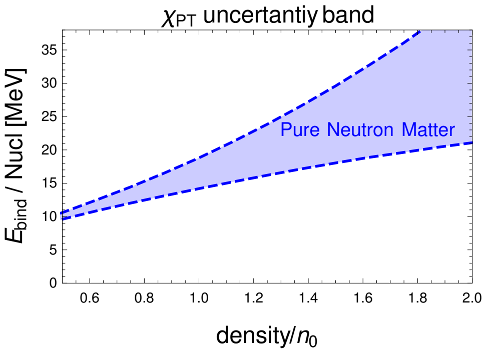
Data for Pure Neutron Matter?

Chiral Perturbation Theory

Chiral perturbation theory χ_{PT}:

Effective field theory for nucleons guided by symmetries of QCD

- ✓ Controlled approximation
- ✓ Can compute pure neutron matter
- ✗ Only $T = 0$ and valid up to $n_B \approx 2n_0$

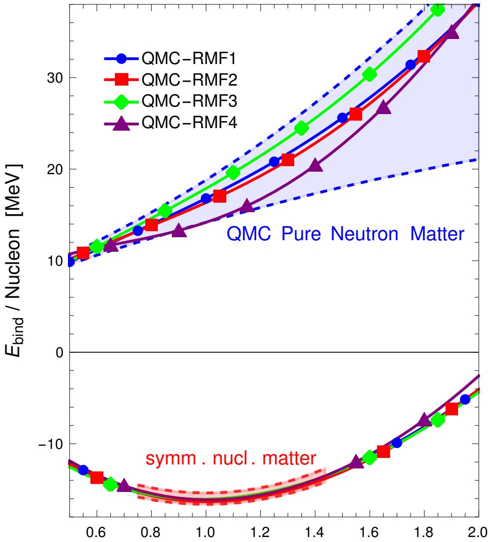


Fit RMF couplings to pure neutron matter **and** symmetric nuclear matter

QMC-RMFx EOS

Four Models

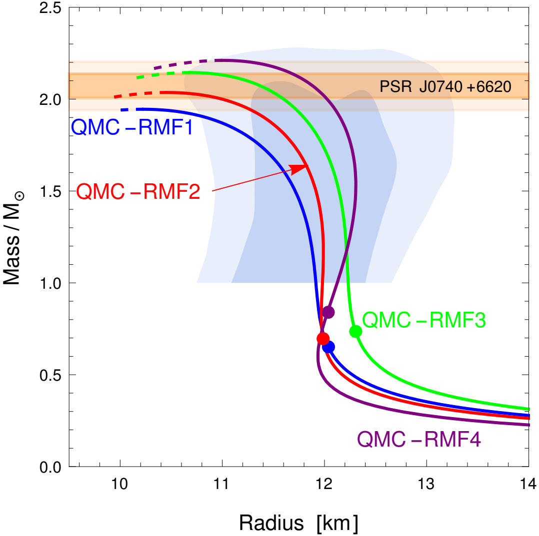
- Simultaneous fit to χ_{PT}- pure neutron matter **and** phenomenological model for symmetric matter
- Four different models: QMC-RMFx
- From soft to stiff
- Pressure = slope



QMC-RMFx EOS II

Mass-Radius Curves

- Within 2σ of PSR J0740+6620: $M = 2.072 \pm 0.066\, M_\odot$
- consistent with NICER $R_{1.34} = 12.71 \pm 1.84$ km
- consistent with NICER+XMM+multi messenger constraints from P. T. H. Pang, I. Tews, M. W. Coughlin, M. Bulla, C. Van Den Broeck, and T. Dietrich, Astrophys. J. 922, 14 (2021)



Beta Equilibrium

beta equilibrium: neutron decay and electron capture balance

$$n + \dots \to p + e^- + \dots \qquad p + e^- + \dots \to n + \dots$$

- Above $T \gtrsim 10\,\mathrm{MeV}$, neutrinos are trapped
- In this part: work in neutrino free-streaming regime

If rates balance and are inverse to each other:

cold beta equilibrium correct at $T = 0$: detailed balance

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

? Still valid at moderate, **finite temperatures** ?

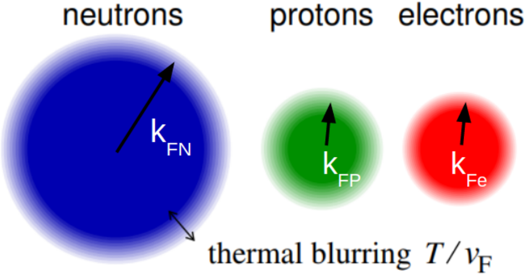
Urca Processes

Weak semi-leptonic decays in dense matter

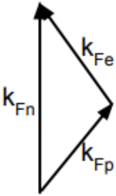
direct Urca (dU)

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

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



- 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



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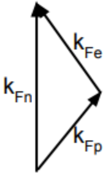


modified Urca (mU): dU with spectator

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

Direct Urca Threshold

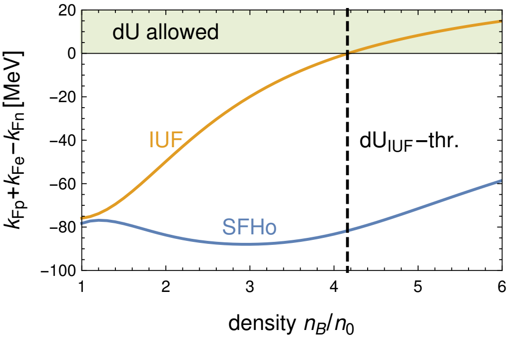
minimum density for dU on FS

direct Urca threshold:

$$k_{Fn} = k_{Fp} + k_{Fe}$$

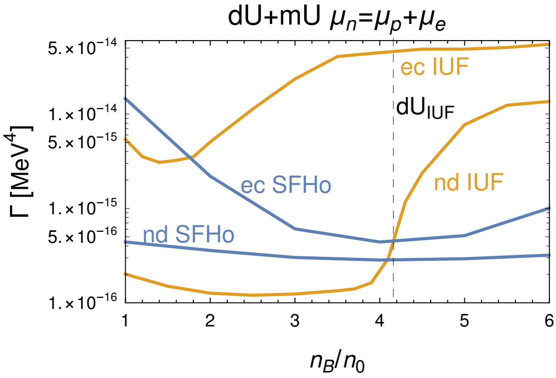
- dU requires higher proton fraction
- Nearly all equation of states (EOS) have monotonically rising proton fraction with n_B
- IUF: direct Urca threshold at $n_B \approx 4.1 n_0$

Direct Urca momentum surplus



Total Urca in Cold Beta-Equilibrium

$T = 3\,\text{MeV}$ - neutrino transparent



- IUF-results show clear dU threshold
- Electron-capture and neutron-decay differ by $1-2$ **orders of magnitude**
- Cold beta-equlibrium clearly violated

Reason:

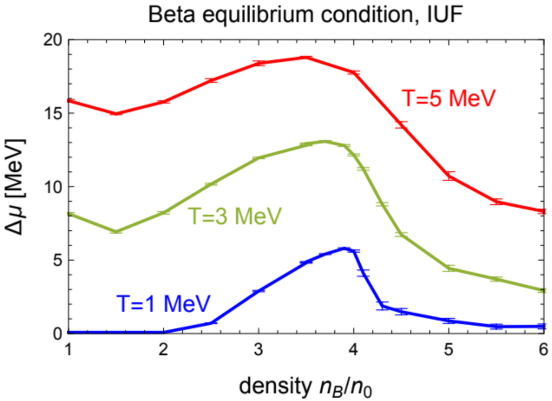
electron-capture and neutron-decay are **not** inverse processes: neutrino switches side

Warm Beta Equilibrium

Alford, Harris PRC 98 (2018), **Alford, A.H., Harris, Zhang, arXiv:2108.03324**

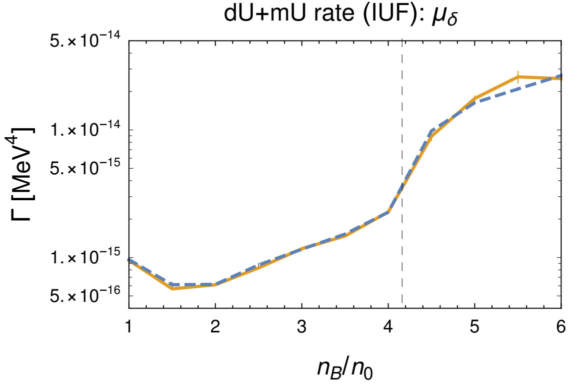
Warm Beta Equilibrium

$$\mu_n = \mu_p + \mu_e + \Delta\mu(n_B) \text{ where } \Delta\mu(n_B) \text{ is chosen s.t. } \Gamma_{nd} = \Gamma_{ec}$$



Corrected Rates: $\Delta\mu$ included

for IUF EOS at $T = 3\,\mathrm{MeV}$



Summary

What did you (hopefully) learn today?

- Merger and transport phenomena can help us studying the QCD phase diagram
- We need to improve the microphysics in simulations
- Microscopic models of nuclear matter are necessary for transport calculations
- We improve RMFs by fitting them to pure neutron matter calculations from χ_{PT}
- Traditional beta-equilibrium is violated for temperatures in the few MeV range

Thank you for your attention!

Urca Processes

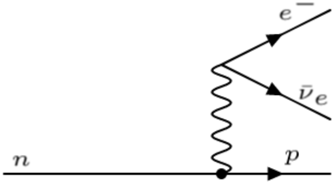
Can we improve on the Urca calculations?

- ✗ Direct and modified Urca are normally treated separately
- ✗ In-medium nature of decay mostly ignored in matrix element (only effective mass taken into account)
- ✗ Modified Urca normally computed in FS approximation with crude approximation of internal nucleon propagator

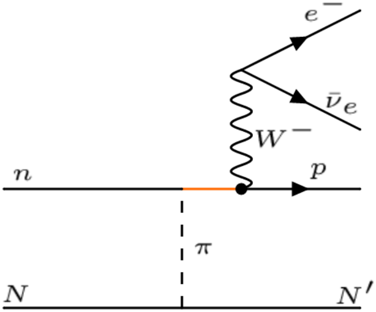
Direct Urca and Modified Urca Matrix Element

Approximations for internal propagator

direct Urca



modified Urca

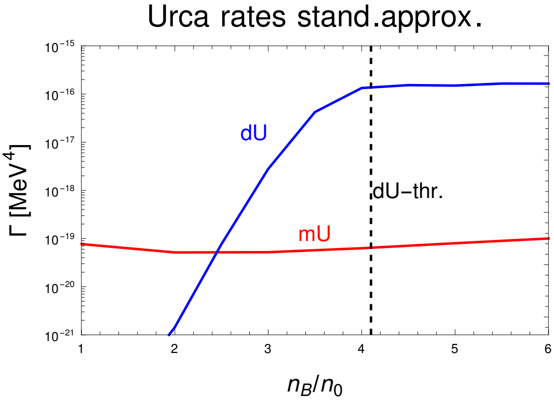


Propgator for off-shell nucleon

How to deal with propagator G_n for internal, off-shell nucleon?

Direct Urca and Modified Urca

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

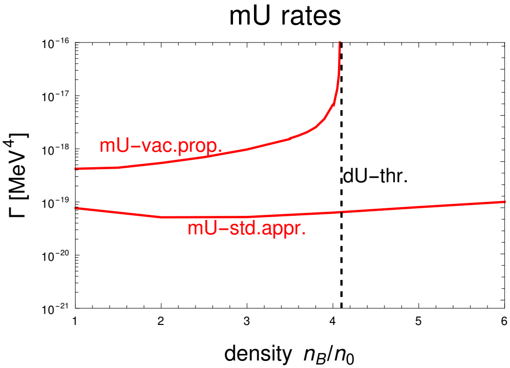


standard approximation for mU:

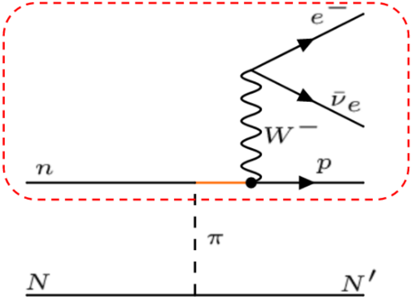
$G_n = 1/\mu_e$

Modified Urca Improved in Shternin et al. 2018

Divergent rate?

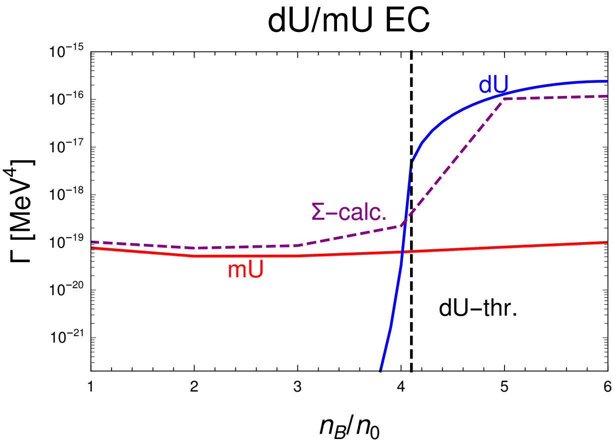


- ✓ Improved treatment: $G_n^{-1} \propto \left(E^2 - \varepsilon_N^2(k)\right)$
- ✗ Divergence at dU threshold
- ✗ Internal nucleon goes on shell!

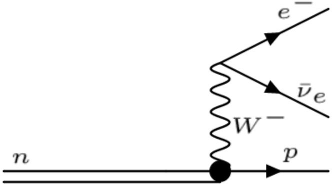


Direct Urca + Modified Urca Unified

Treat incoming neutron as particle with finite width



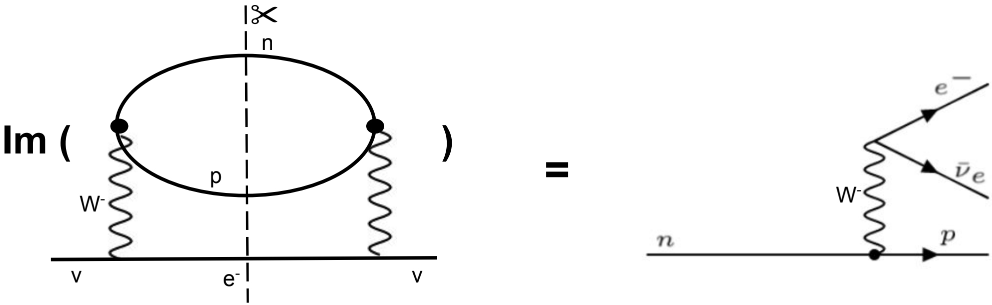
- ▶ Incoming neutron with finite width γ_n due to strong interaction (pion - nucleon nucleon-hole loop)
- ▶ $\gamma_n \approx 0.1$ MeV (FSA calculation)
- ✓ Includes direct and modified Urca



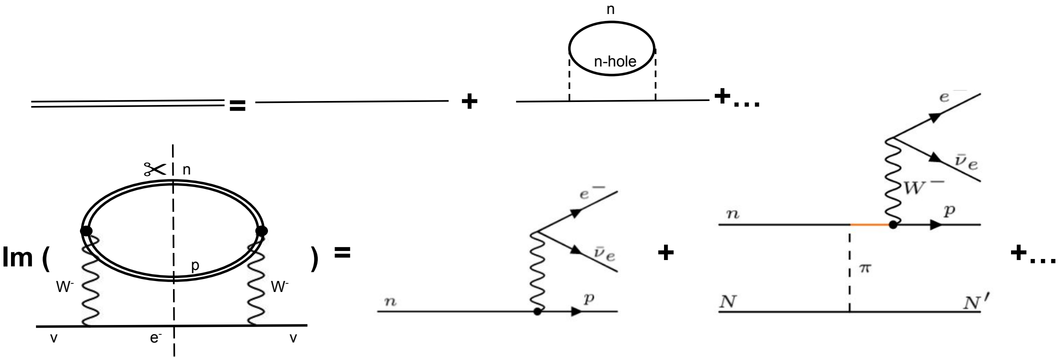
Why is this interesting?

- Unified, consistent approach to modified and direct Urca
- Allows us to go beyond Fermi-surface for mU (first time)
- Matrix element for unified approach in future calculation from χ_{PT}:
  - Full in-medium nature of decay can be taken into account
  - Most complete modified Urca calculation imaginable
- Can affect cooling in proto neutron stars, bulk viscosity in mergers, ...
- Very much work in progress

dU via Self-energy Calculation

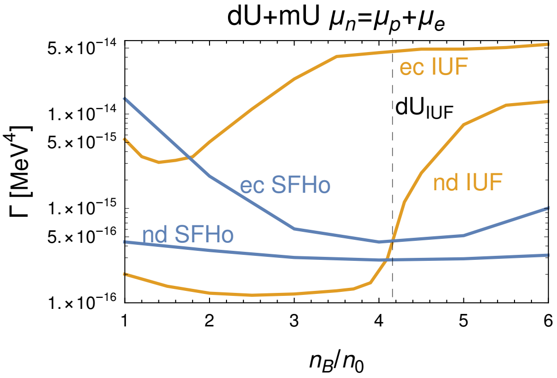


mU via Self-energy Calculation



Total Urca in Cold Beta-Equilibrium

$T = 3\,\text{MeV}$ - neutrino transparent



- IUF-results show clear dU threshold
- Electron-capture and neutron-decay differ by $1-2$ **orders of magnitude**
- Cold beta-equlibrium clearly violated

Reason:

electron-capture and neutron-decay are **not** inverse processes: neutrino switches side

Warm Beta Equilibrium

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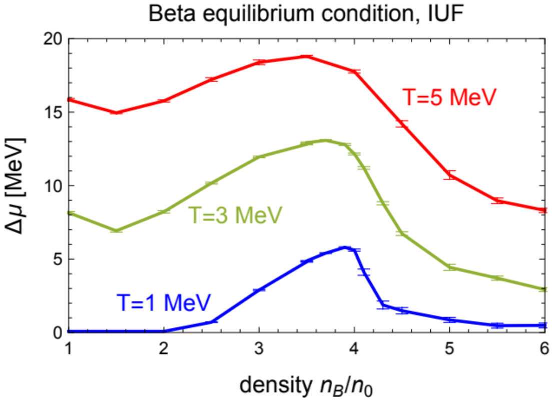
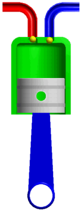
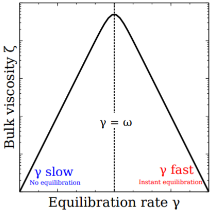


Bulk Viscosity

quick reminder





- Harmonic compression of nuclear matter with frequency ω
- Compression: work done by piston – decompression: work done by matter $\Rightarrow$ no net dissipation IF matter is the same on "way up - way down"
- Nuclear matter reacts to pressure change: e.g. change of proton fraction x_p via weak processes $n \rightarrow p^+ + e^- + \bar{\nu}_e$ and $p^+ + e^- \rightarrow n + \nu_e$
- Beta-equilibrium: rates are the same $\rightarrow x_p$ constant
- Compression $\rightarrow$ out of beta equilibrium: reequilibration time depends on difference of rates $\Delta\Gamma$

Nuclear Bulk Viscosity

neutrino trapped vs. free-streeming

- Nuclear bulk viscosity in neutrino-transparent matter ($T \lesssim 5$ MeV):
  Alford, Harris, Phys.Rev. C100 (2019): millisecond damping times
- Nuclear bulk viscosity in neutrino-trapped matter ($T \gtrsim 10$ MeV):
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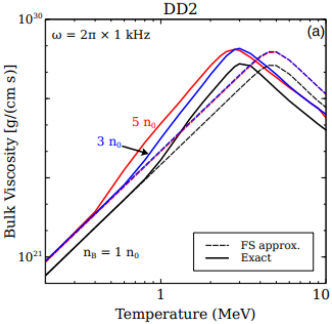
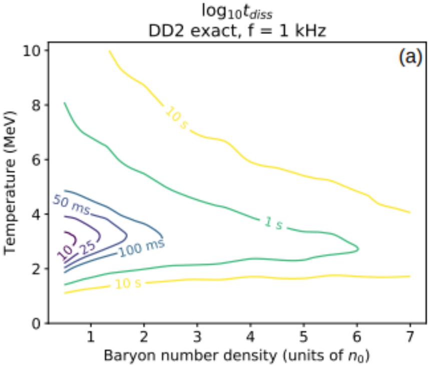




Exotic Matter Bulk Viscosity

Other weak processes

Exotic and Leptonic Matter

- Leptonic bulk viscosity: small at low temperatures
- Bulk viscosity in quark matter: color-superconductivity
- Nuclear bulk viscosity at finite magnetic field or with medium-corrections

Hyperonic Bulk Viscosity

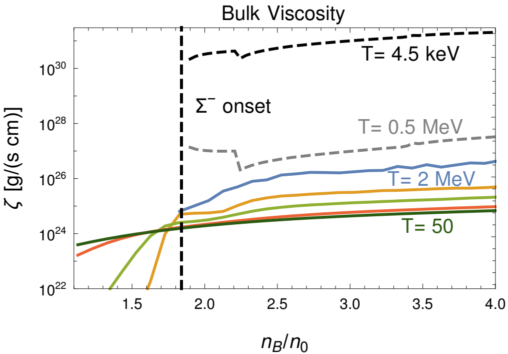
- Sizable bulk viscosity in cold matter (e.g. Lindblom, Owen Phys.Rev. D65 (2002))
- Even if hyperons non-existent in isolated star: higher densities and temperatures in merger
  - → critical density might be reached
  - → thermal population below density onset

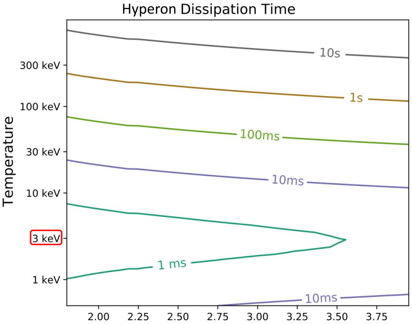
Hyperonic Bulk Viscosity: Equilibration of Strangeness

Alford, A.H. 2009.05181

Contributing processes: change strangeness by 1

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



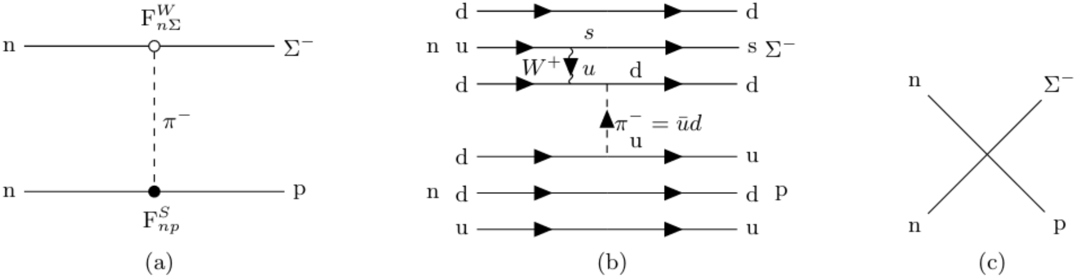


Strangeness changing rates might play role in local heating + phase conversion dissipation.

Hyperon Bulk Viscosity II

Calculating the matrix element

Combined weak-strong vertex with one meson exchange (OME) vs. contact interaction



- Full momentum dependent matrix element using one meson exchange interaction instead of contact interaction:
  - → significant processes (3+4) can be included (no contact-interaction matrix element)
    Phys.Rev.C69 (2004), Phys.Rev.D 100 (2019)

Beta Equilibrium

Cold vs warm beta equilibrium

- Beta-equilibrium = chemical equilibrium: composition of matter (e.g. proton fraction) stays constant with time
- "Chemical composition" (particle fractions) change via weak interactions

beta equilibrium: neutron decay and electron capture balance

$$n + \dots \to p + e^- + \dots \qquad p + e^- + \dots \to n + \dots$$

- Above $T \gtrsim 10\,\mathrm{MeV}$, neutrinos are trapped
- In this part: work in neutrino free-streaming regime

If rates balance and are inverse to each other:

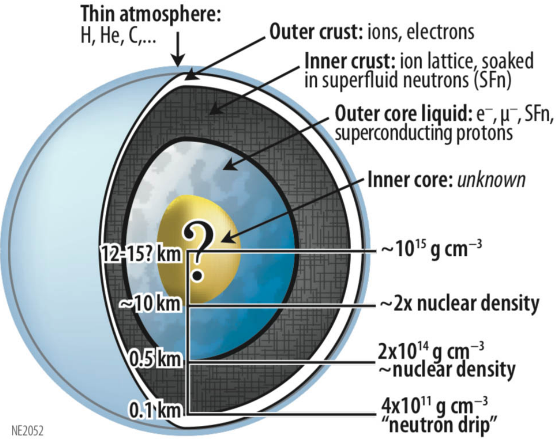
cold beta equilibrium: correct at $T = 0$

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

? Still valid at moderate, **finite temperatures** ?

Isolated Neutron Star

Expected composition



A particle physicist's dream/nightmare

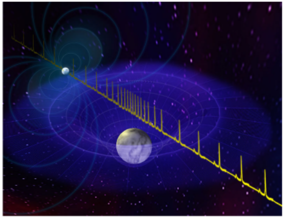
Neutron stars require understanding of **all fundamental interactions**

- **Gravity:** formation and stability, gravitational waves
- **Electromagnetism:** strong magnetic fields, EM signals
- **Weak interaction:** cooling via neutrino emissivity, beta equilibrium, bulk viscosity
- **Strong interaction:** pressure of matter, composition,...

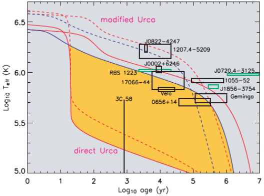
Gendreau et.al., vol. 8443 of Proceedings of SPIE, p. 844313. Sept., 2012.

What can we measure?

- Mass: Best in binary systems via Shapiro delay, other systems very model dependent
- Radii: Hard to measure (nano Arcs), X-ray bursts, NICER mission, twin stars?
- Temperature: Analysis of the electromagnetic spectrum, cooling from neutrino emissivity (except very old stars)
- Rotation frequency: Measurement of Pulsar frequency, determination of magnetic field possible, pulsar glitches, r-modes
- Gravitational waves: Inspiral detected by advanced LIGO/VIRGO



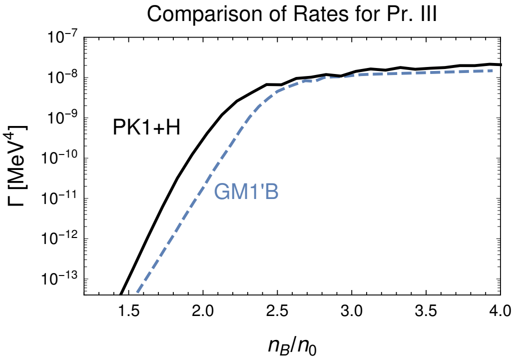
Shapiro delay



Goal: Find particle composition of NS and equation of state (EOS)

Hyperon Rates

Comparison to GM1'B



- GM1'B: first hyperon to appear $=$ $\Lambda-$hyperon
- onset at higher densities than PK1+H

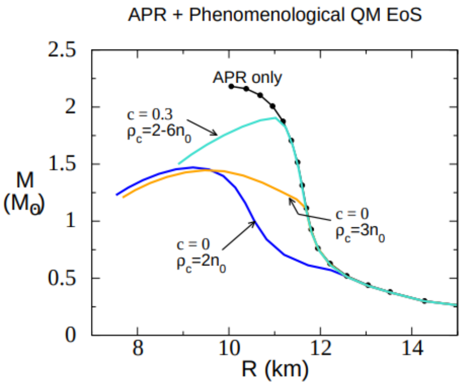
→ rates are shifted but otherwise show same behavior

→ expect comparable bulk viscosity for different EOS, but at slightly different n_B, T

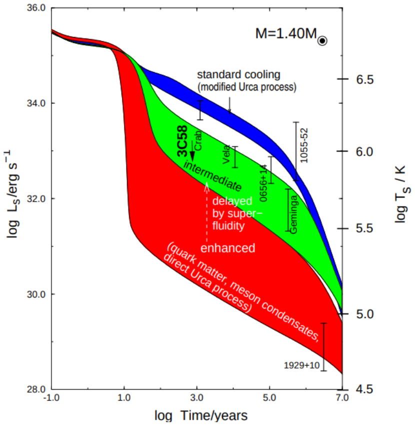
Why Transport?

The "masquerade problem"

Transport properties are more sensitive to fundamental physics than the EOS



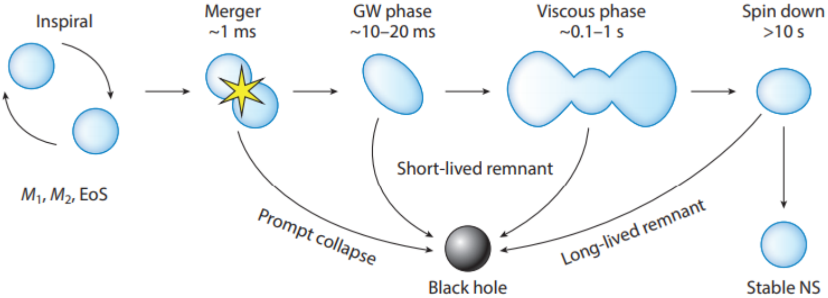
Alford, Braby 2004



Weber, Prog. Part. Nucl. Phys. 54

GW170817 and GW190425

What have we seen so far?



Radice, D., Bernuzzi, S. Perego, A.,Annu.Rev.Nucl.Part.Sci.70(2020)

- Observation of kilonova for GW170817 $\rightarrow$ short-lived remnant
- Tidal deformability $\tilde{\Lambda} < 800$
- $M_{TOV} \approx 2.17$? H_0? strong model dependence!

QMC-PSx EOS

Properties for Symmetric Nuclear Matter

Name	n_{sat} $[\mathrm{fm}^{-3}]$	$\mathcal{E}(n_{\text{sat}})$ [MeV]	$\kappa(n_{\text{sat}})$ [MeV]	$J(n_{\text{sat}})$ [MeV]	$L(n_{\text{sat}})$ [MeV]
Fit	**0.16**	**-16**	**240**	-	-
QMC-RMF1	0.159	-16.03	258	32.8	44.4
QMC-RMF2	0.160	-16.03	258	32.6	40.4
QMC-RMF3	0.158	-15.99	229	33.7	49.2
QMC-RMF4	0.162	-16.05	275	30.4	31.2

QMC-RMFx EOS

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Exp.				31.6 ± 3.2	58.7 ± 28.1
QMC-RMF1	0.159	-16.03	258	32.8	44.4
QMC-RMF2	0.160	-16.03	258	32.6	40.4
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