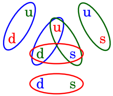
Neutrino absorption in two-flavor color-superconducting quark matter

EMMI Workshop Nov 13, 2025

Speaker: Marco Hofmann (TU Darmstadt)

Based on **arXiv:2509.04240** with Mark G. Alford, Liam Brodie, Michael Buballa, Hosein Gholami and Alexander Haber



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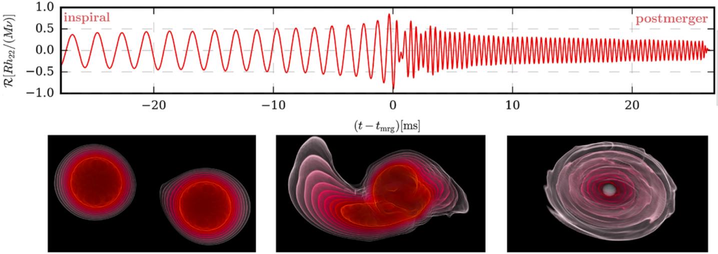
CRC-TR 211
Strong-interaction matter under extreme conditions

HGS-HIRe abroad

BNS mergers



Dietrich, Hinderer, Samajdar (2021)

- run merger simulations with different **nuclear physics input** (see talks by A. Bauswein and O. Just today) to anticipate and interpret future measurements
- post-merger: out-of-equilibrium, dynamic system: density oscillations, shocks, outflows, large gradients in density, temperature or chemical composition
- transport phenomena shape dynamics and observables of the merger

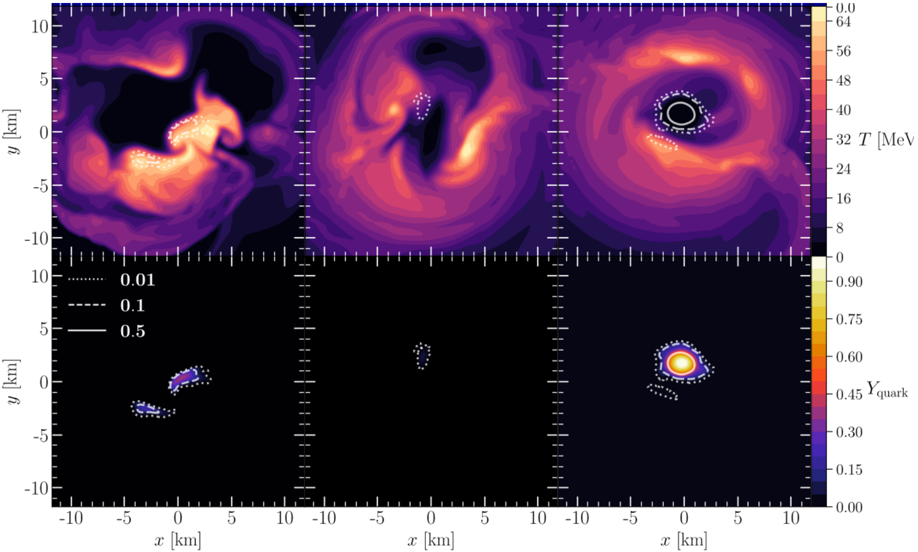
Role of neutrinos in transport

- (anti-)neutrinos are particles with the **longest mean free path** $\rightarrow$ important for transport effects
- Neutrino absorption ($+$ scattering, not in this talk)

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

- $\lambda \ll$ **system size**: neutrinos leave the system via diffusion or radiatively (*free-streaming*)
- $\lambda \ll$ **system size**: neutrinos *trapped* in the system, contribute to transport phenomena
- Hot regions in remnant ($T \simeq 10 - 100\,\text{MeV}$) become opaque to ν $\rightarrow$ **neutrino trapping**
- important phenomena:
  - Neutrino cooling
  - Re-equilibration of beta equilibrium $\mu_n = \mu_p + \mu_e$ $\rightarrow$ bulk viscosity
  - Outflows, r-process nucleosynthesis

Quark matter production in BNS mergers?



Tootle et al. (2022)

Our Mission

- **At which densities and temperatures should neutrinos, depending on their energy, be treated as free streaming, and when do effects of neutrino trapping become relevant?**
- $\rightarrow$ study neutrino absorption self-consistently within a model

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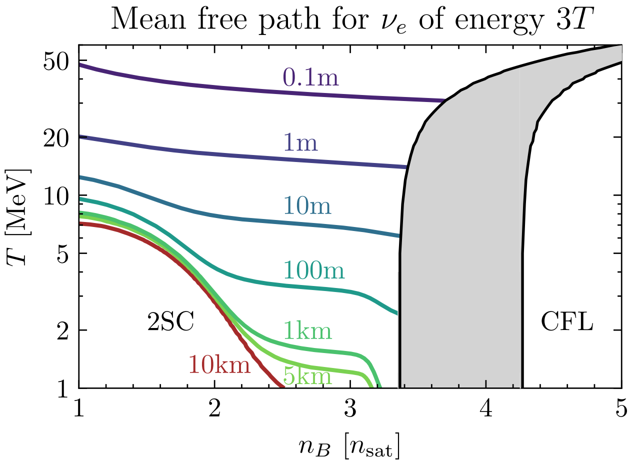
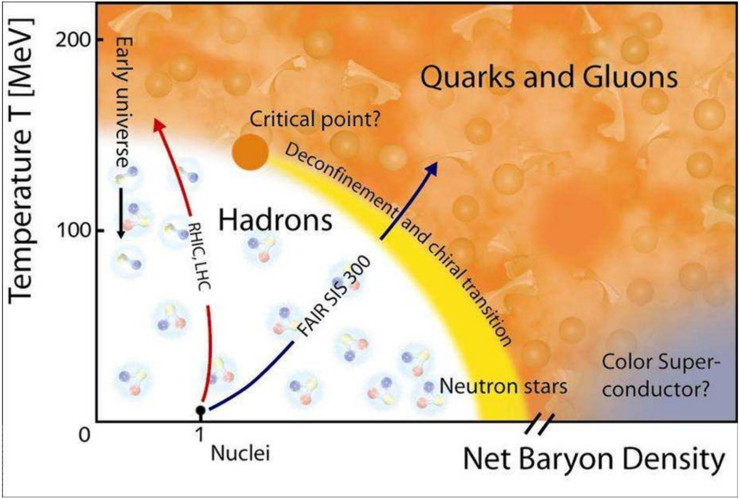
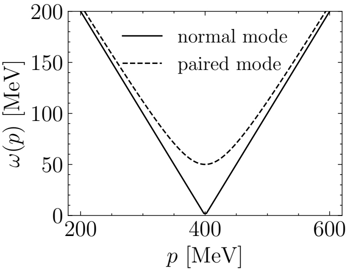


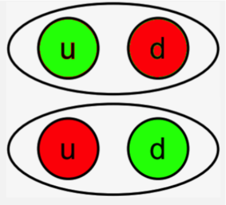

Temperature T [MeV]
200
100
0
Early universe
RHIC, LHC
Critical point?
Quarks and Gluons
Hadrons
Deconfinement and chiral transition
FAIR SIS 300
Neutron stars
Color Super-
conductor?
1
Nuclei
Net Baryon Density

- Cooper theorem: With a finite attractive interaction between particles
  - Fermi surface becomes unstable against pair creation → "Cooper pairs"
  - Bose condensation of the Cooper pairs ⇒ Energy gap Δ in exaction spectrum: $\omega = \sqrt{(E-\mu)^2 + \Delta^2}$

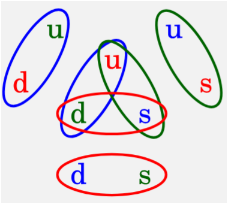


- **Color superconductor:** attractive quark-quark interaction in color anti-triplet channel

2SC phase ($\mu \lesssim M_s$)



Color-flavor locked (CFL) phase ($\mu \gtrsim M_s$)



Three flavor Nambu–Jona-Lasinio (NJL) model

Rehberg, Klevansky, Hüfner (1996), Gastineau, Nebauer, Aichelin (2002), Klähn et al. (2006)
Includes chiral symmetry breaking and Cooper pairing of quarks self-consistently:

$$\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\partial\!\!\!/ - \hat{m})\psi + G_S \sum_a \left[(\bar{\psi}\tau_a\psi)^2 + (\bar{\psi}i\gamma_5\tau_a\psi)^2\right] && \text{Chiral-symmetry breaking} \\
&- K\left[\mathrm{det_f}(\bar{\psi}(\mathbb{1}+\gamma_5)\psi) + \mathrm{det_f}(\bar{\psi}(\mathbb{1}-\gamma_5)\psi)\right] && U_A(1) \text{ breaking} \\
&+ G_D \sum_{A,A'=2,5,7} (\bar{\psi}i\gamma_5\tau_A\lambda_{A'}\psi^c)(\bar{\psi}^c i\gamma_5\tau_A\lambda_{A'}\psi) && \text{attractive diquark int.} \\
&- G_V(\bar{\psi}\gamma^\mu\psi)^2 && \text{repulsive vector int.}
\end{aligned}$$

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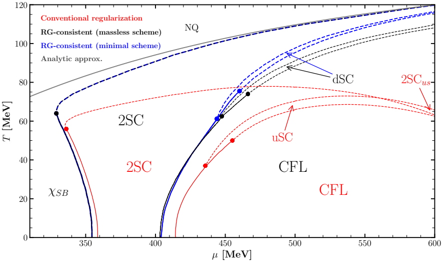
$- K \left[\det_f(\bar{\psi}(\mathbb{1}+\gamma_5)\psi) + \det_f(\bar{\psi}(\mathbb{1}-\gamma_5)\psi) \right]$	$U_A(1)$ breaking
$+ G_D \sum_{A,A'=2,5,7} (\bar{\psi}i\gamma_5\tau_A\lambda_{A'}\psi^c)(\bar{\psi}^c i\gamma_5\tau_A\lambda_{A'}\psi)$	attractive diquark int.
$- G_V (\bar{\psi}\gamma^\mu\psi)^2$	repulsive vector int.

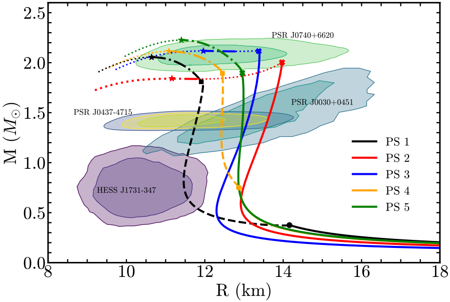
- Fitted to meson spectrum in vacuum:
  - Three-momentum cutoff λ=602.3 MeV
  - NJL-coupling $G_S = 1.835/\lambda^2$
  - $U_A(1)$-breaking $K = 12.36/\lambda^5$

Current work with the NJL model

Artifact-free phase diagrams in RG-consistent treatment → Hosein's talk



Parameters constrained for hybrid stars → Jan-Erik's talk



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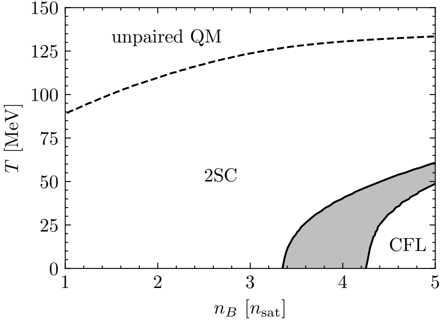
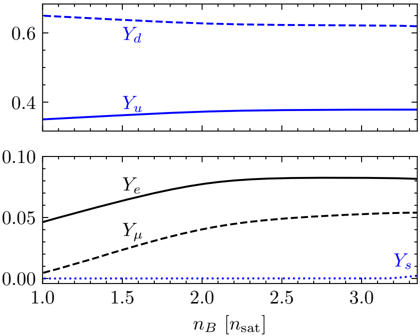
Astrophysical constraints on color-superconducting phases in compact stars within the RG-consistent NJL model

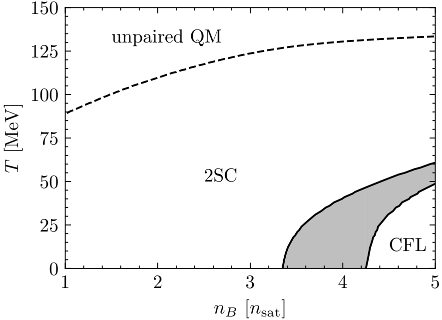
Hosein Gholami [1,*] Ishfaq Ahmad Rather [2,†] Marco Hofmann [1,‡]
Michael Buballa [1,3,§] and Jürgen Schaffner-Bielich [2,¶]

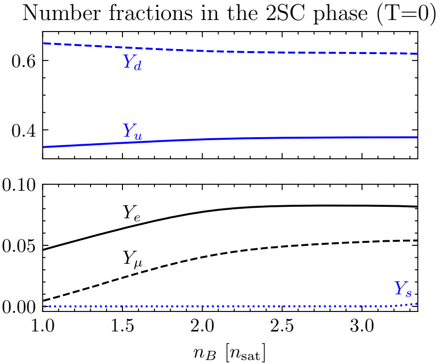


Number fractions in the 2SC phase (T=0)



Phase diagram in neutrinoless beta equilibrium ($\mu_d = \mu_u + \mu_e$)





- Tiny fraction of strange quarks ($Y_s < 0.01$) above $n_{\text{strange}}^{\text{onset}} \approx 3.2\, n_{\text{sat}}$
- Weak processes including paired quarks suppressed as $\exp(-\Delta/T)$
- High critical temperature $T_c \simeq 100\,\text{MeV} \implies$ leading contribution from unpaired blue quarks at T of interest

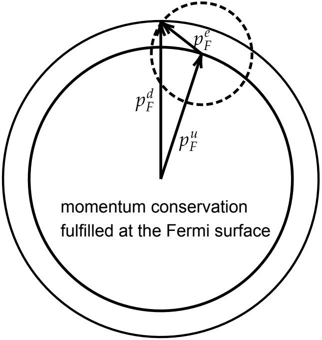
$$d \text{ capture:} \quad d_b + \nu_l \to u_b + l^-$$

$$s \text{ capture:} \quad s_b + \nu_l \to u_b + l^-$$

Kinematical constraints for neutrino absorption

At low $T \ll \mu$ all particles have momentum close to Fermi momentum:

- Momentum conservation requires triangle inequality $p_F^{d/s} \leq p_F^u + p_F^e$



$$p_F^d - p_F^u - p_F^e > 0$$

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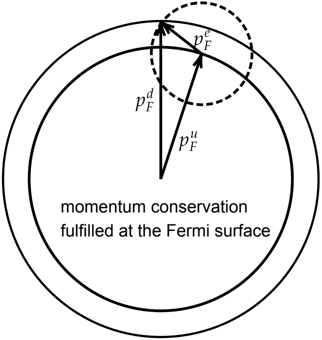
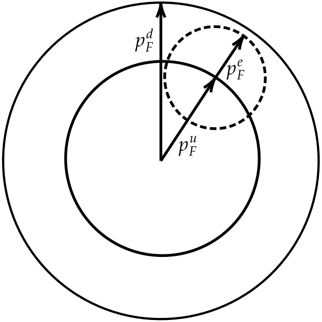


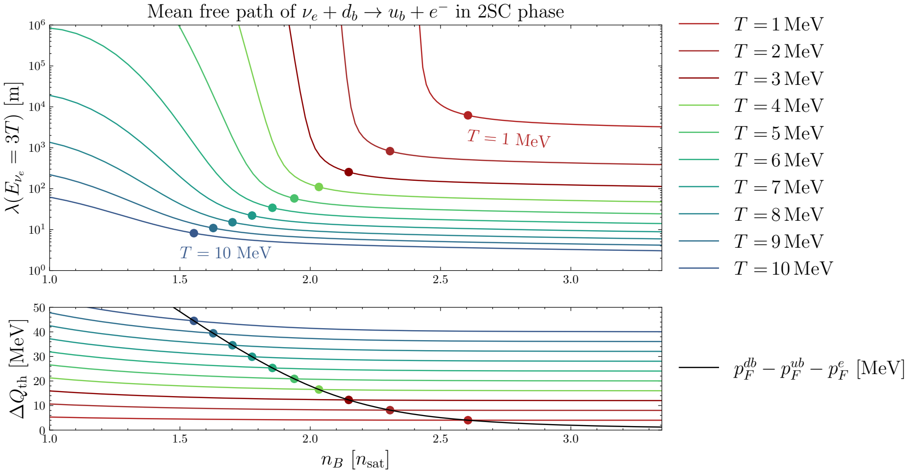


no phase space at Fermi surface

$$p_F^d - p_F^u - p_F^e > 0$$

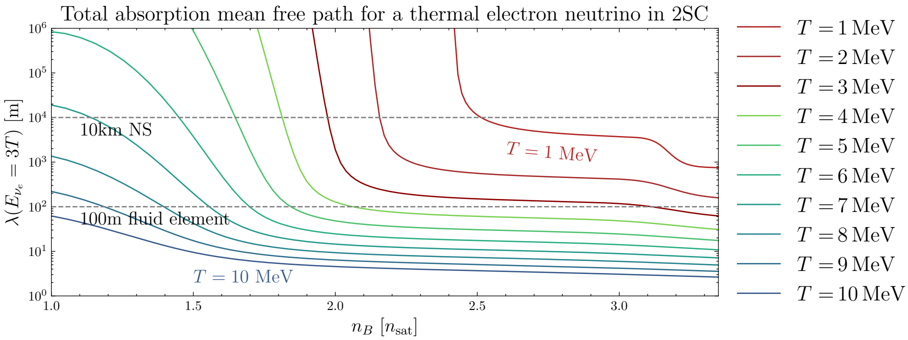
$$p_F^d - p_F^u - p_F^e \leq 0$$

Absorption of thermal ν_e through d capture

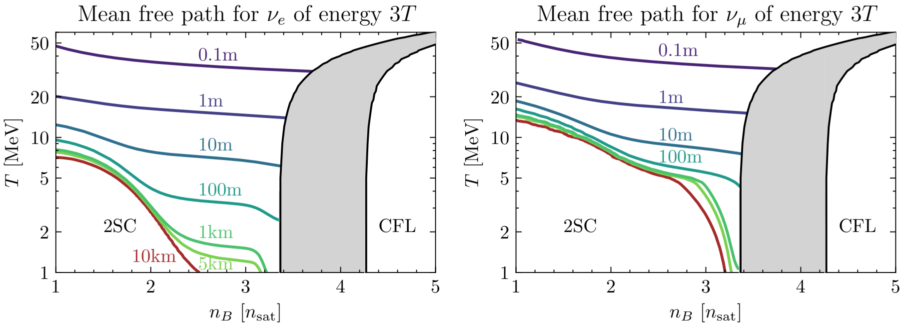


- Mean free path decreases sharply where thermal phase space $\Delta Q_{\mathrm{th}} = \dfrac{T}{v_F^{ub}} + E_{\nu_e}$ compensates momentum deficit

Total ν_e absorption

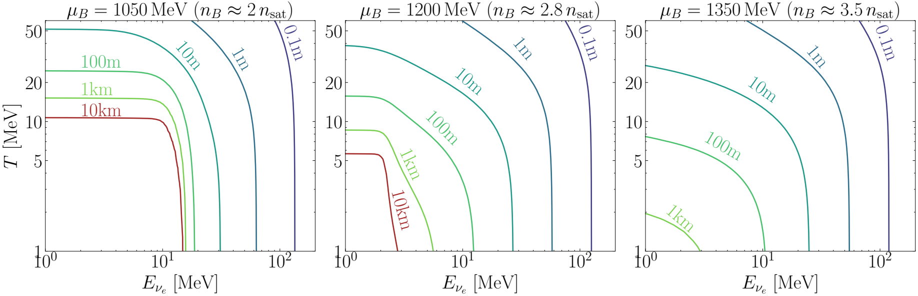


- if $\lambda \ll$ system size: neutrinos become trapped gas which quickly equilibrates
  $\implies$ conservation of lepton number relevant
- tiny s quark fraction dominates absorption at small window of densities above $3\,n_{\text{sat}}$



- neutrino trapping relevant at T of more than a few MeV, depending on n_B
- ν_μ absorption at higher only at higher T

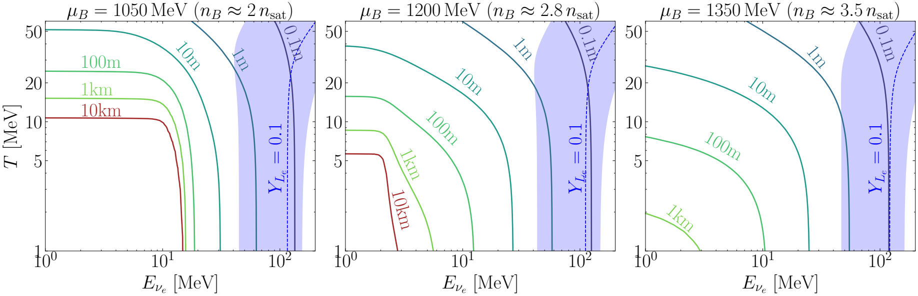
- So far: assumed an average thermal neutrino energy $E_\nu \approx 3T$
- Now: MFP for different neutrino energies



- Low energy neutrinos diffuse out of the system at low densities and energies ($\lambda \gtrsim 10\,\mathrm{km}$)

Neutrino energy dependence of the MFP

- Scenario: leptonized region in a neutron star merger with fluid elements that have $Y_{L_e} = 0.1$ (blue band)
- Equilibrium neutrino distribution with $Y_{L_e} = 0.1 \implies \mu_{\nu_e} \approx 100\,\mathrm{MeV}$ remains trapped ($\lambda < 10\,\mathrm{m}$)



Next step: isovector interaction opens phase space?

- So far: d capture was suppressed due to

$$p_F^d - p_F^u - p_F^e \approx (\mu_d - \mu_u)\frac{M^2}{2\mu_u\mu_d} > 0$$

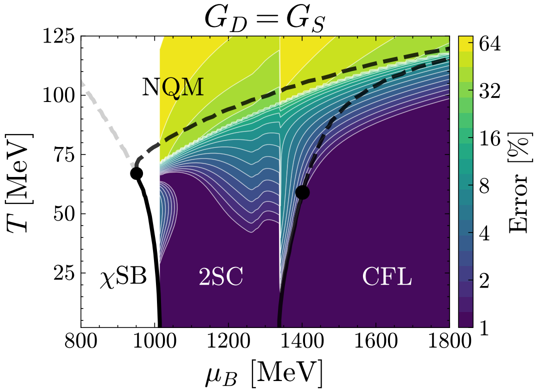
- But: inclusion of isovector channel (ρ meson) could open up phase space:

$$p_F^d - p_F^u - p_F^e \approx (\mu_d - \mu_u)\frac{M^2}{2\mu_u\mu_d} + \underbrace{\alpha_{\text{isov.}}(n_u - n_d)}_{<0}$$

- Motivation: Finite T expansion for quark matter, including color-superconducting phases based on $T = 0$ EoS

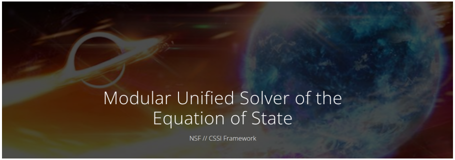
$$P(T, \mu_B) = P_{T=0,\mu_B} + \frac{1}{2}\frac{\partial s}{\partial T}\bigg|_{T=0,\mu_B} \cdot T^2 + \mathcal{O}(T^3)$$ **Mroczek et al. (2024)**

- Contribution of paired modes suppressed as $P \propto T^2 \sqrt{\Delta/T} \exp(-\Delta/T)$

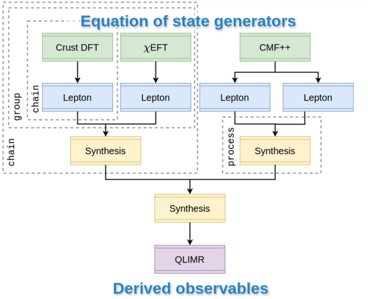


Quark matter at home: The MUSES NJL module

with H. Gholami, M. R. Pelicer and Y. Yang



- NJL module provides solver for the equation of state with adjustable diquark and vector channels and different regularizations
- Interpolation along 4 axes (T, μ_B, μ_Q, μ_S) possible
- Compatible with synthesis and QLMR modules to calculate hybrid star observables

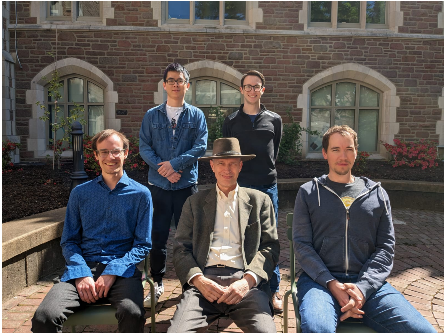


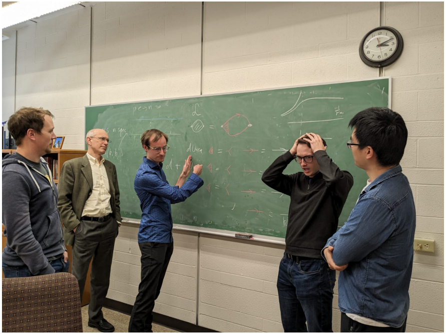
Summary

- d quark capture suppressed by a momentum deficit of a few MeV in our model, must be overcome by T or E_ν, study with isovector channels in future
- s capture kinem. allowed $\implies$ dominates absorption at very low T
- 2SC phase can support a population of trapped, equilibrated neutrinos
- Open-source module to calculate full chain from model to astrophysics at home available soon

Outlook:

- Extend study to antineutrinos and scattering (neutral current interactions) and also to CFL phase
- Explore impact of **specific thermal properties of color-superconducting phases**
- Include thermal and weak interaction effects in **quark matter consistently in a BNS merger simulation**





Special thanks to HGS-HIRe (Helmholtz) for sponsoring

HGS-HIRe abroad

Appendix

- **massless, non-interacting quarks**: $p_F^{d/s} = p_F^u + p_F^e$
  $\Longrightarrow$ collinear momenta, processes **suppressed** at low T

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$$p_F^d - p_F^u - p_F^e \approx (\mu_d - \mu_u)\frac{M^2}{2\mu_u\mu_d} > 0$$

due to $\mu_d - \mu_u > 0$ in neutral matter

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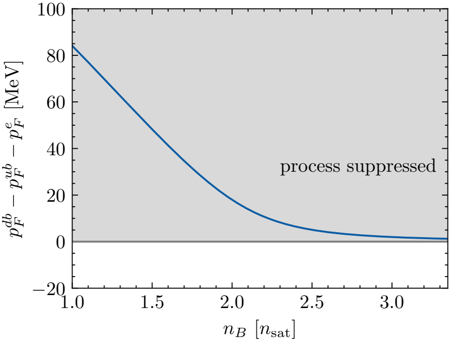
- **suppressed** phase space **for** d **quark capture**



Neutrino absorption in a 2SC phase

- Consider direct Urca-type processes $\nu + d/s \to u + e^-$
- Inverse mean free path λ^{-1} is cross section per volume

$$\lambda^{-1} = g \left(\Pi_{i=d/s,u,e} \int \frac{d^3\boldsymbol{p}_i}{(2\pi)^3} \right) (2\pi)^4 \delta^4(P_\nu + P_{d/s} - P_u - P_e) \times W_{fi} f_{d/s}(1 - f_u)(1 - f_e)$$

- Angular integrals can be calculated analytically **Gupta (1995)**, 2d momentum integral left

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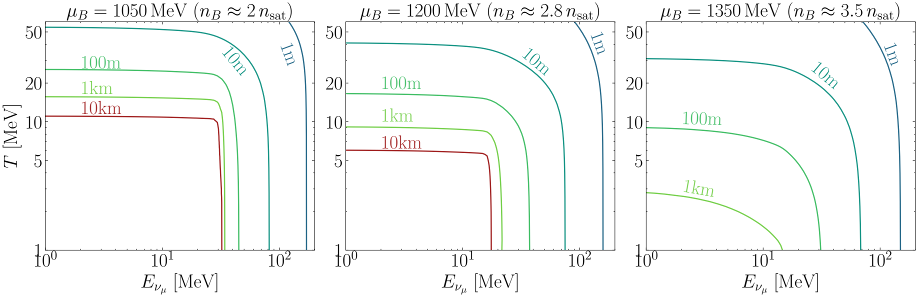
- Angular integrals can be calculated analytically **Gupta (1995)**, 2d momentum integral left
- EoS enters via dispersion relations of unpaired quarks

$$\omega_{f,c} = \sqrt{p^2 + M_f^2} + 6G_V n_B - \mu_{f,c}$$

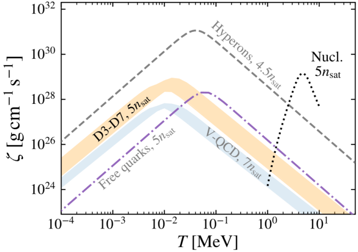
- Approximation: Only consider ungapped blue quarks (gapped contributions suppressed as $\exp(-\Delta/T)$ for $T \ll T_c$ **Jaikumar, Roberts, Sedrakian (2006)**)

Neutrino energy dependence of the MFP

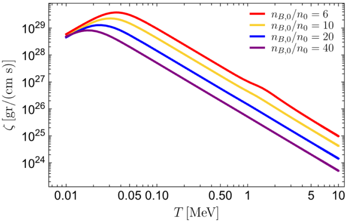


- Muon neutrino absorption requires higher neutrino energies at densities before $n_{\mathsf{strange}}^{\mathsf{onset}} = 3.2\,n_{\mathsf{sat}}$

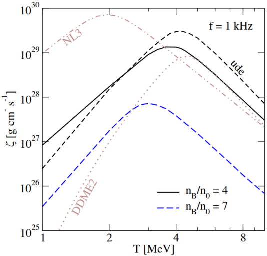
CRC-TR 211



Rojas et al. (2024)



Hernandez, Manuel, Tolos (2024)



Alford et al. (2024)