Thermal fluctuations of the composition in quark nucleation

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Introduction

At high baryonic densities, hadronic degrees of freedom are expected to be replaced by **deconfined quarks**. The order of the phase transition and its critical density are, however, totally unknown.

Such extreme densities can be reached in neutron stars (NSs) and related **astrophysical phenomena**.
Some possible scenarios for deconfinement in compact stars:

- during CCSNe explosion associated with blue supergiant stars [1]
- in the center of a PNS when neutrino untrapping sets in
- in the post-merger remnant of a BNSM

If deconfinement is a first-order phase transition, it starts with the nucleation, namely the generation of a first seed of quark matter.

Nucleation

Metastable hadronic phase

↓

fluctuations generate virtual drops of quark matter

↓

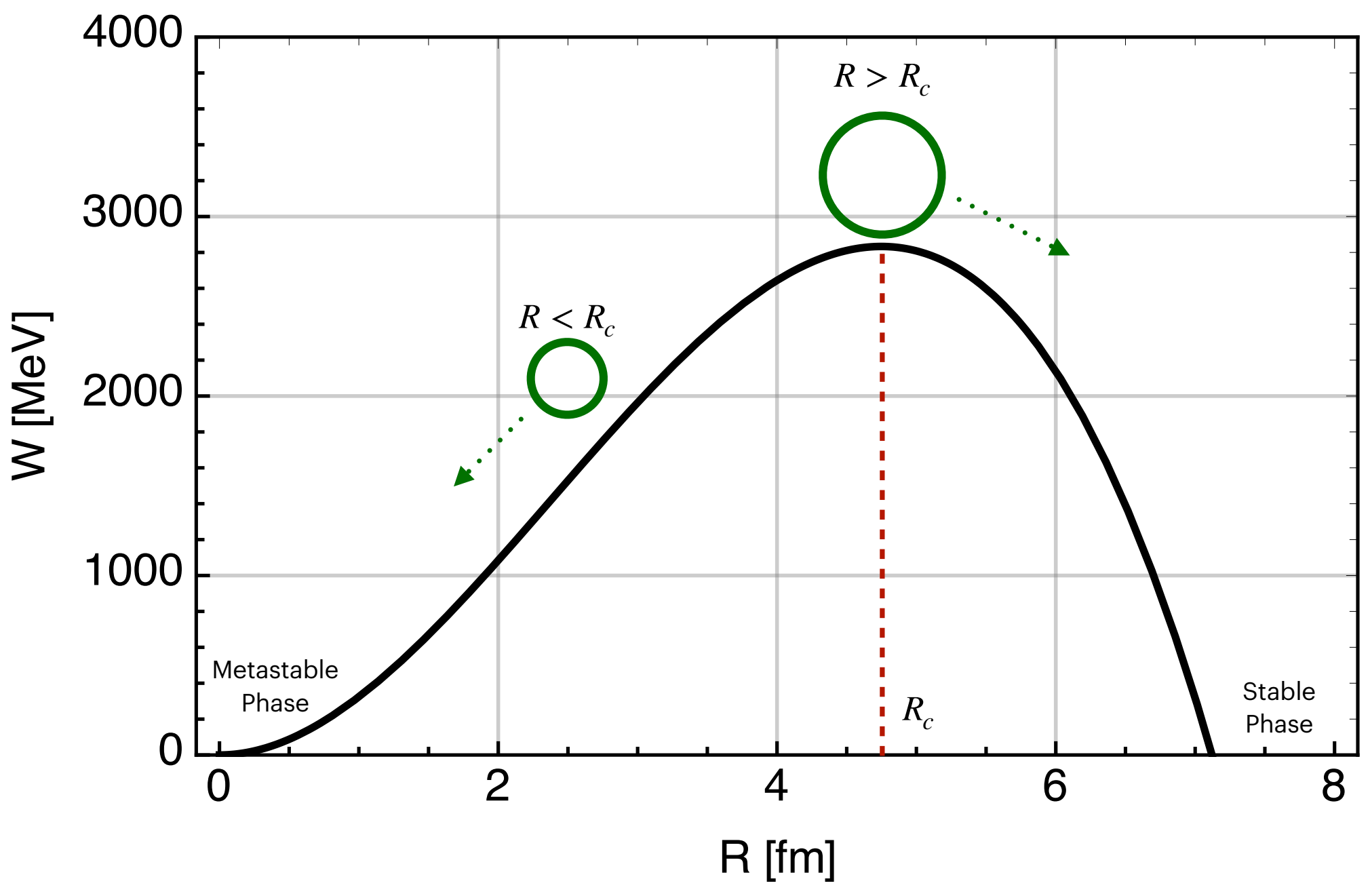
the energy gain in terms of bulk needs to compensate for the work needed to create a surface (finite-size effects)

↓

The work needed to generate a seed of the new phase

$$W_{nuc}(P,T) = \frac{4}{3}\pi R^3 n_B^Q \left[\mu_Q - \mu_H\right] + 4\pi\sigma R^2$$

is a potential barrier.



The potential barrier can be overcome by

- thermal fluctuations (thermal nucleation [2])

$$\mathcal{P}_{th} \sim e^{-\frac{W(R_C)}{T}} \tag{1}$$

- quantum tunneling (quantum nucleation [3])

$$\mathcal{P}_q \sim e^{-\frac{A(E_0)}{\hbar}} \tag{2}$$

State of the art

Nucleation of quark matter is a process mediated by the **strong interaction**

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typical time scale ($\sim 10^{-23}$ s) is much smaller than that of the weak interaction

↓

weak interactions do not have sufficient time to change the flavour composition of matter

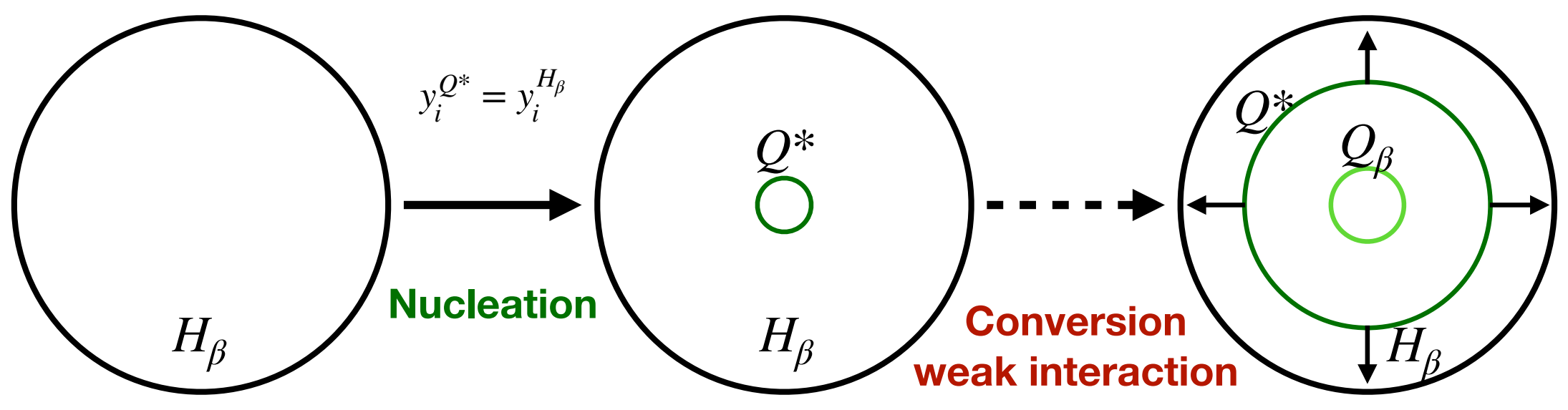
↓

the **flavour composition is frozen during the nucleation**

↓

the first quark seed will be in a out-of-equilibrium Q^* phase with the same flavour composition of H_β [4].

$$y_u^{Q^*} = y_u^H = 2y_p^H + y_n^H + \ldots$$
$$y_d^{Q^*} = y_u^H = y_p^H + 2y_n^H + \ldots$$



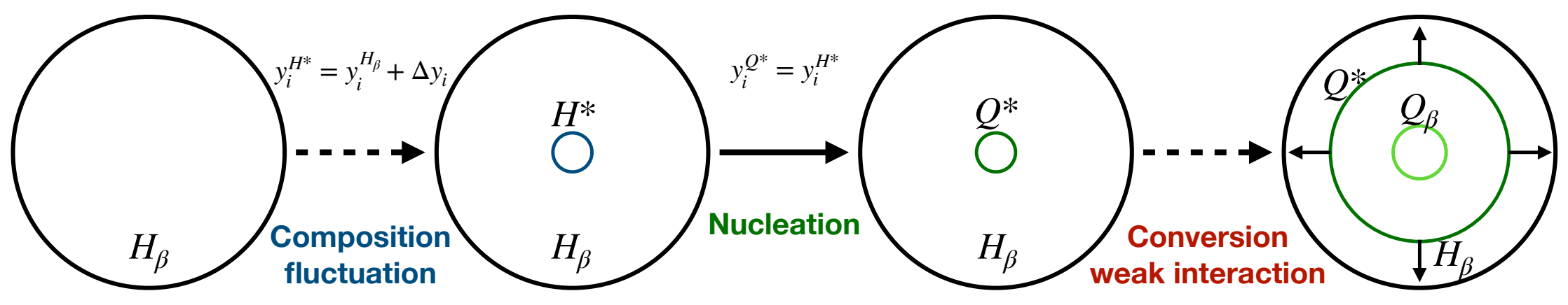
Method

Key idea

The average particle fraction composition in β-equilibrium is $\{y_i^{H_\beta}\}$.

However, if we divide the system into several small subsystems, the actual composition $\{y_i^{H^*}\}$ in each of these subsystems at finite temperature is not necessarily identical to the average values.

Since nucleation is a local process, it is possible that it occurs in a subsystem whose composition makes the formation of a stable seed of the new phase more convenient than if average values are taken into account.



$$\mathcal{P}(P,T,\Delta y_i) \sim \mathcal{P}_{fluc}^{H_\beta \to H^*} \times \mathcal{P}_{nuc}^{H^* \to Q^*} \tag{3}$$

where

- $\mathcal{P}_{fluc}^{H_\beta \to H^*}$: probability that a subsystem H^* has a composition $y_i^{H^*} = y_i^{H_\beta} + \Delta y_i$
- $\mathcal{P}_{nuc}^{H^* \to Q^*}$: probability to nucleate a quark seed Q^* from a subsystem H^* with the same composition $y_i^{Q^*} = y_i^{H^*}$.

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Application to two flavours

In this work, we are focused on the two flavour case. The used EOS models are described in [5]. We consider only two extreme cases:

- ($\beta*$) is $\{\Delta y_i = 0\}$ (i.e. no fluctuations in the hadronic composition as in [4])
- ($\beta\beta$) is based on a choice of $\{\Delta y_i\}$ such that $\{y_i^{Q^*}\} = \{y_i^{Q_\beta}\}$ (i.e. in the hadronic subsystem, the flavour composition is identical to the flavour composition of quark matter in β-equilibrium)

Results and conclusions

- at high T, the thermal fluctuations of the hadronic composition are important and lead to a much faster nucleation
- at small T the thermal fluctuations are negligible

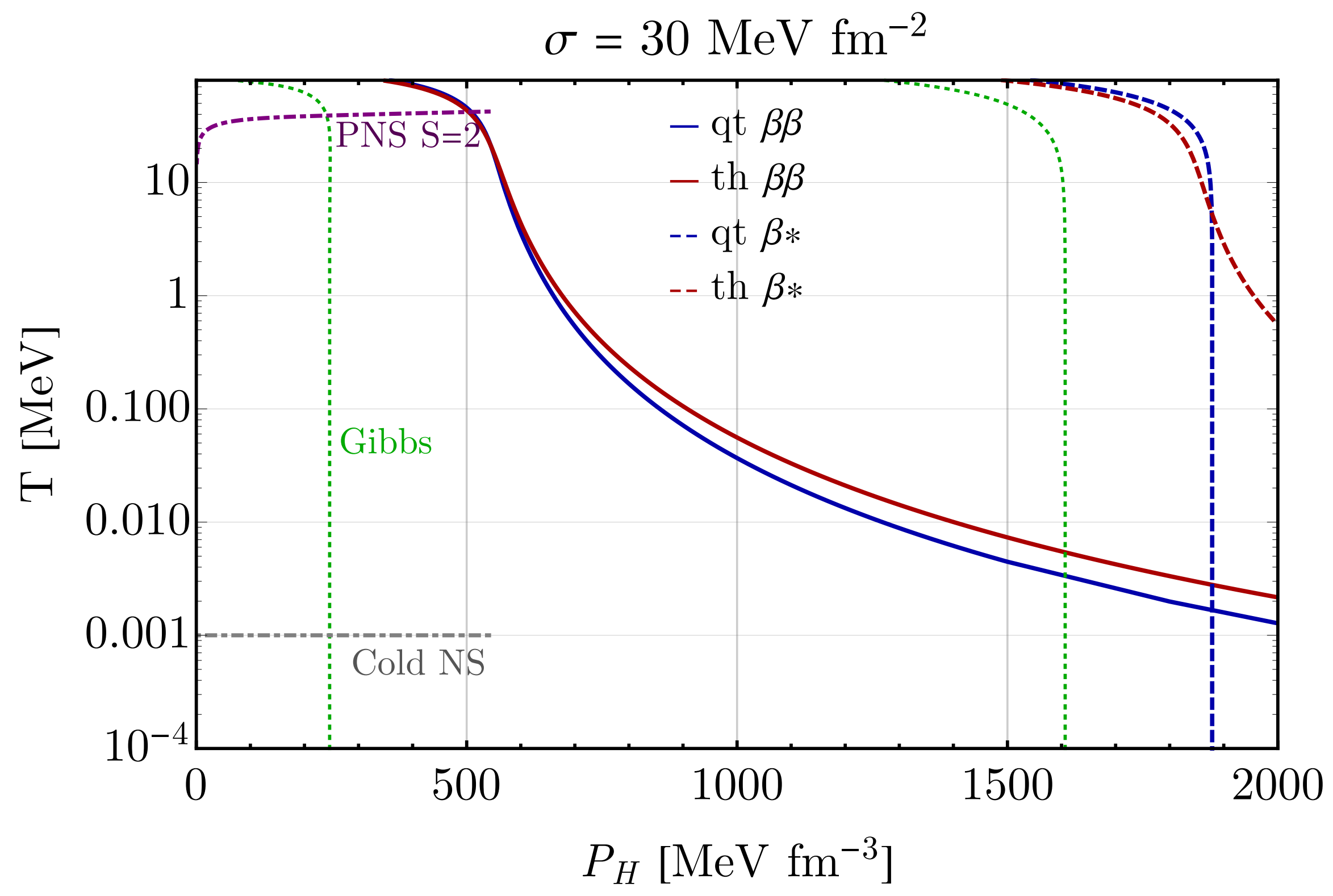

Figure 1:Temperature and pressure for which the nucleation time is 1 s. The mixed phase boundaries of the two-flavour Gibbs construction are reported for comparison (dotted green). The purple dot-dashed curve represents the pressure and temperature of the core of PNSs, assuming a $s/n_B = 2$ hadronic and neutrino-free matter (i.e. approximately the conditions 10 − 60 s after the core collapse). The endpoint of this curve corresponds to the PNS maximum mass configuration. The gray dot-dashed curve in the left panel indicates the range of pressures reached in the core of cold NSs (assumed to have a uniform temperature $T = 1$ keV).

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Conditions in the PNS core after deleptonization allow for nucleation in the most massive PNSs

References

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[4] I. Bombaci *et al. The European Physical Journal A*, vol. 52, mar 2016.

[5] C. Constantinou *et al. in preparation*, 2024.