Effect of composition fluctuations in quark nucleation

Application to the two family scenario

Mirco Guerrini

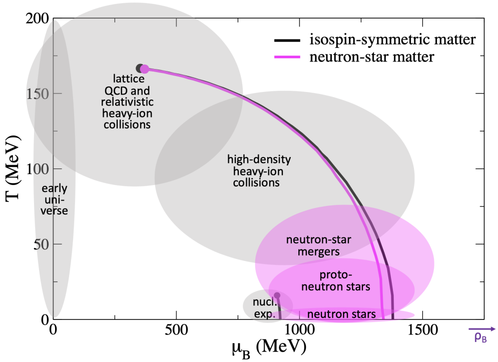
collaborators: A. Drago (UniFe), G. Pagliara (UniFe) and A. Lavagno (PoliTo)

TNPI2023 - XIX Conference on Theoretical Nuclear Physics in Italy

INFN FERRARA

Università degli Studi di Ferrara

Deconfinement in astrophysical systems



- **Quarks** d.o.f. expected at $n_B \sim$ few n_0
- Extreme densities reached in high density **astrophysical systems**
- **Deconfinement** could play a key role in astrophysical phenomena (e.g. BSGs CCSNe, *see Fischer et al. 2018*)

	n_B/n_0	T [MeV]	Y_e
Isolated NS	$10^{-8} - 8$	~ 0	0.01-0.3
Core Collapse Supernovae (CCSN)	$10^{-8} - 8$	$0 - 50$	0.25-0.55
Proto NS (PNS)	$10^{-8} - 8$	$0 - 50$	0.01-0.3
Binary NS Mergers (BNSM)	$10^{-8} - 8$	$0 - 100$	0.01-0.6

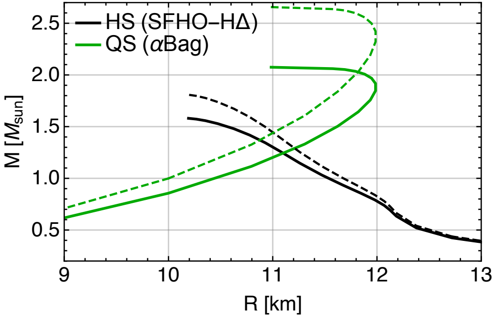
Two family scenario

New d.o.f (hyperons, delta, quarks, ...) ⇒ softening in EOS ⇒ **lower mass**

Important constraint: **very massive** $\sim 2M_{\odot}$ compact object observed

Many possible solutions proposed (e.g. see *Vidaña 2022* for a review)

...one more possible solution...



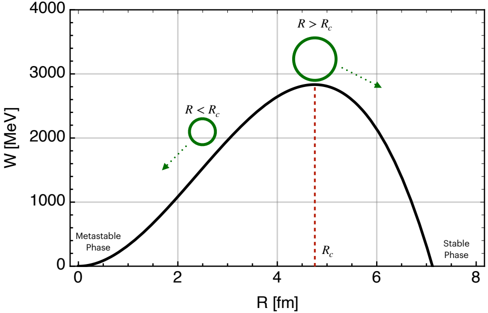
Two families scenario (*Drago et al. 2016*)

- Strange matter hypothesis (*Witten 1984*)
- Hadronic stars up to $\sim 1.6M_{\odot}$
- Quark stars up to $\sim 2M_{\odot}$
- No Hybrid stars
- β-eq Quark EOS energetically favourable

Deconfinement is triggered by a first quark seed → **Nucleation analysis**

Nucleation: the first seed of a new stable phase

if $P_H(\mu_H) < P_Q(\mu_Q) \Rightarrow H$ is a **metastable phase** $\Rightarrow$ virtual drops of Q created



$$\boxed{W(P,T) = \frac{4}{3}\pi R^3 n_Q \left[\mu_Q - \mu_H\right] + 4\pi\sigma R^2}$$

Thermal : $\mathcal{P}_{th} \sim e^{-\frac{W(R_c)}{T}}$

(*Langer et al. 1969* and *Landau et al. 1980*)

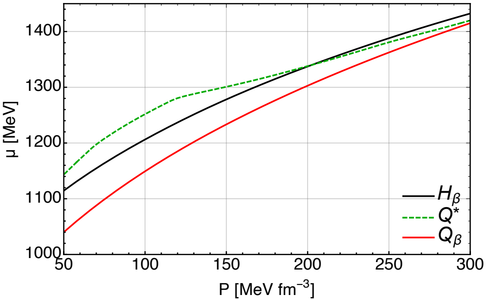
Quantum : $\mathcal{P}_q \sim e^{-\frac{A(E_0)}{\hbar}}$

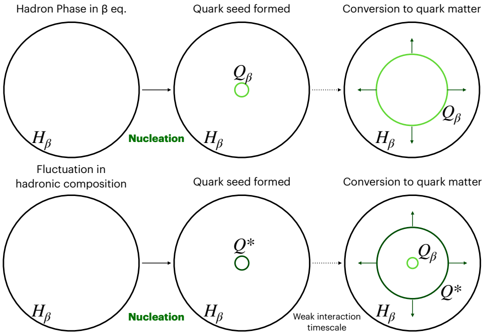
(*Iida et al. 1998*)

At the critical radius: unstable equilibrium $P_H = P_Q + \frac{2\sigma}{R}$, $T_H = T_Q$, $\mu_H = \mu_Q$

Nucleation with freezed composition

- In the past: Q seed created in equilibrium
- Now: *(Bombaci et al. 2016)*
  Strong timescale $\ll$ weak timescale
  $\Rightarrow$ **flavour composition conserved**



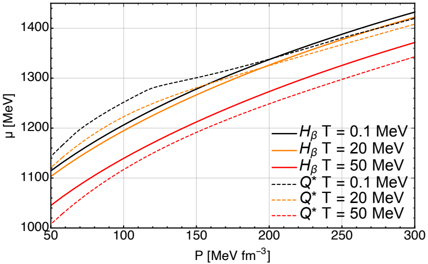


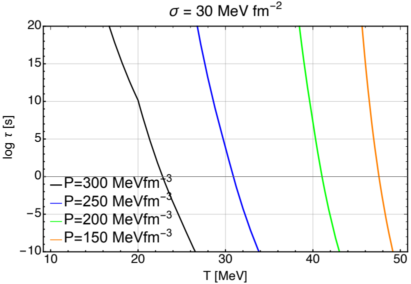
Q^* has the same flavour composition than H_β

$$N_q^{Q^*} = \sum_{q\,h} \mathcal{C}_{h\,q} N_h^{H_\beta}$$

$$\text{e.g. } N_u^{Q^*} = 2N_p^{H_\beta} + N_n^{H_\beta} + N_\Lambda^{H_\beta} + \ldots$$

Application to two family scenario





H_β is always metastable wrt Q_β but not wrt Q^*

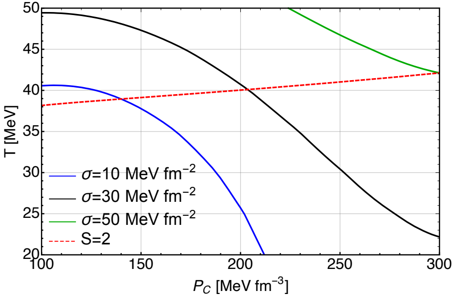
Note:

- $\tau \to \infty$ when $\mu_{Q^*}(P_{Q^*}) = \mu_{H_\beta}(P_{H_\beta})$
- P and T nucleation $\gg \mu_{H_\beta} = \mu_{Q^*}$

Existence of cold hadronic stars is insured by:

- weak interactions is slow → flavour freezed
- finite size effect → deconfinement postponed

Application to two family scenario

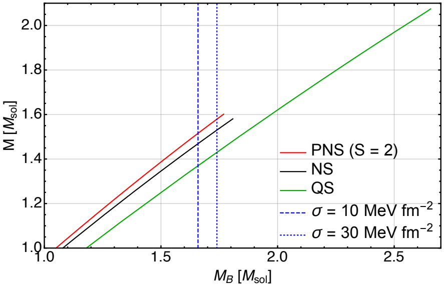


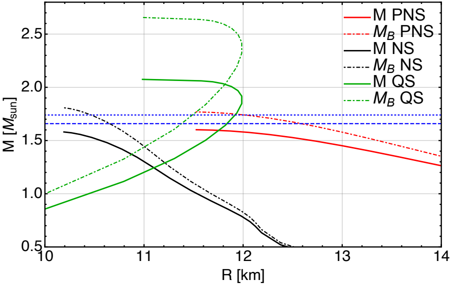
PNS after deleptonization

$Y_{Le} = 0$, $S \simeq 2$ for $\sim 10^2$ s

- T, P at which $\tau \sim 10^2$ s
- Before vertical blue line: **PNS** → **NS**
- After vertical blue line: **PNS** → **QS**

$\Rightarrow M_{PNS} \gtrsim 1.5 - 1.6\ \mathrm{M}_\odot$ converts to QS

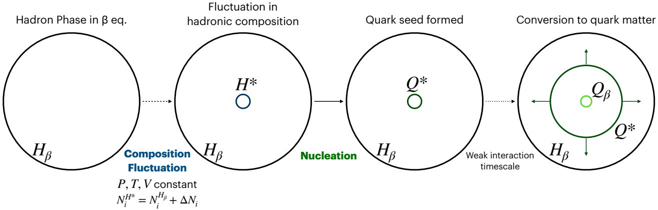




Nucleation with composition fluctuations

Key idea: at finite T hadronic composition **fluctuates** around the mean values $\left\langle N_i^{H_\beta} \right\rangle$

Approach: let divide the process in two intermediate steps



Step 2: **Nucleation** with flavour freezed between H^* and Q^* starting from a hadronic phase having a composition $\{N_i^{H^*}\}$ locally different wrt the mean equilibrium values

Step 1: Prob. that in a certain volume the composition is $N_i^{H^*} = \left\langle N_i^{H_\beta} \right\rangle + \Delta N_i$

Nucleation with composition fluctuations

$$W = \Delta E - T_0 \Delta S + P_0 \Delta V - \sum_i \mu_{i,0} \Delta N_i$$

$$W_2 = \tfrac{4}{3}\pi R^3 n_{Q^*} \left[\mu_{Q^*} - \mu_{H^*}\right] + 4\pi\sigma R^2 \qquad W_1 = \tfrac{4}{3}\pi R^3 n_{Q^*} \left[\mu_{H^*} - \textstyle\sum_i \mu_i^{H_\beta} y_i^{H^*}\right]$$

$$\boxed{\mathcal{P}(P, T, \Delta N_i) \sim \mathcal{P}_{nuc}^{H^* \to Q^*} \times \exp\left[-\frac{W_1(R_c, \Delta N_i)}{T}\right]}$$

Note:

- $\exp\left[-\frac{W_1(R_c, \Delta N_i)}{T}\right]$ can be interpreted as the probability that $N_i = N_i^{H_\beta} + \Delta N_i$
- for small ΔN_i, $\exp\left[-\frac{W_1(R_c, \Delta N_i)}{T}\right]$ is a gaussian + non diag. terms
- with $\Delta N_i = 0$ we turn in the *Bombaci et al. 2016* case

Nucleation with composition fluctuations

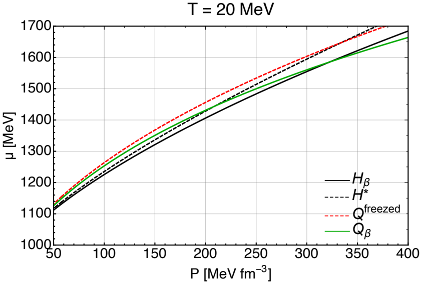
$$\boxed{\mathcal{P}(P,T,\Delta N_i) \sim \mathcal{P}_{nuc}^{H^*\to Q^*} \times \exp\left[-\frac{W_1(R_c,\Delta N_i)}{T}\right]}$$

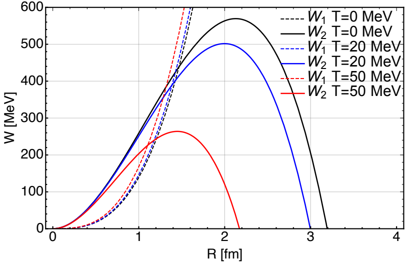
What should we expect?

If we choose "convenient" $\{\Delta N_i\}$ such that $W^{H_\beta \to Q^*} > W_2^{H^* \to Q^*}$

- The **potential barrier** will be **lower**
- We have to "pay" a W_1 **energy cost** to fluctuate H composition by $\{\Delta N_i\}$
- High T: nucleation faster wrt the *Bombaci et al. 2016* approach
- Small T: high fluctuations are suppressed, *Bombaci et al. 2016* is restored

Application to two flavour case





A "toy" application with two quark flavours:

- H_β: p, n, e in β-eq, ZL (Zhao et al. 2020)
- Q_β: u, d, e in β-eq, αBag
- H^*: fluctuation st flavours are equal to Q_β
- Q^*: equal to Q_β by construction
- $Q^{freezed}$: flavours freezed from H_β

As expected:

- lower potential barrier (W_2)
- cost to pay to fluctuate by ΔN_i (W_1)

Summary

Introduction

- Exotic degrees of freedom expected at compact object densities
- Nucleation is the starting point for the deconfinement process

Application to two family scenario in PNS

- HS existence insured by flavour freezing and finite size effect
- QS could be generated from $\sim 1.5 - 1.6$ $\mathrm{M}_{\odot}$ PNS after deleptonization

Role of the fluctuations

- at finite T hadronic composition fluctuates around $N_i^{H_\beta}$
- One more step: I. Fluctuation in hadronic composition, II. Nucleation

Outlooks

- Complete the "fluctuation in hadronic phase" frameowork
- Test the two family scenario in more astrophysical conditions
- Search observables for the deconfinement (e.g. AT2018cow delayed signal wrt SN)