# Chirally symmetric droplets in the core of magnetars

Daniel Kroff, Eduardo S. Fraga

*Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil*

## 1 Motivation: compact stars

- Compact stars: what's the EoS of strongly interacting matter for low temperatures and high densities?
- The order, strength and location of the strong interactions phase transitions: crucial to establish new classes of compact stars [1]
- Magnetars [2]: $B \sim 10^{19} - 10^{20}$G! $\Rightarrow$ How is the phase structure altered?

**Crucial: what are the time scales involved?**

## 2 Building the effective theory

### 2.1 The need of an effective theory description

- Surface tension, $\Sigma$: energy per unit area needed to create a bubble $\Rightarrow$ Key quantity!
- Ideally: compute $\Sigma$ in the high $\mu$ low $T$ region of the QCD phase diagram
- Reality: first principle approaches are difficult to apply in this region
  - Lattice QCD: sign problem
  - pQCD: phenomenologically interesting values of $\mu$ are already too low, 400 – 500 MeV

**Solution: Estimating Σ in an effective theory**

### 2.2 General Framework

- We describe the transition in a Chiral effective theory, The Linear Sigma Model coupled to quarks ($\mathrm{LSM_q}$) [3]. The lagrangian is given by:

$$\mathcal{L} = \bar{\psi}_f[i\gamma^\mu\partial_\mu - g(\sigma + i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})]\psi_f$$
$$+\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}) - \frac{\lambda}{4}(\sigma^2 + \boldsymbol{\pi}^2 - v^2)^2 + h\sigma$$

- Both QCD with two massless quark flavors and the $O(4)$ $\mathrm{LSM_q}$ belong to the same universality class [4]
- The model reproduces the low energy phenomenology of strong interactions $\Rightarrow$ Parameter fixing
- Spontaneous and (small) explicit break of Chiral symmetry are contained in the meson self interaction
- Coupling the system with an external magnetic field only affects the quark sector, $\partial_\mu \to \partial_\mu + ieA_\mu$
- Phase conversion is well described in the absence of pions [5].

### 2.3 Effective potential at one loop

- Quark gas: thermal bath for the long-wavelength $\sigma$ field
- Effective potential: integrating over quarks, treating $\sigma$ classically
- We take the cold and dense approximation, i.e. $T = 0$ and finite quark chemical potential:

$$V_{\text{eff}}(\bar\sigma) = U_{cl}(\bar\sigma) + U_f^{\text{vac}}(\bar\sigma, B) + U_f^{\text{med}}(\bar\sigma,\mu,B)$$

where $U_f^{\text{vac}}$ denotes the fermionic vacuum contribution,

$$U_f^{\text{vac}} = -\frac{N_c}{2\pi^2}\sum_f (q_fB)^2\left[\zeta'_H(-1,x_f) \quad + \right.$$
$$\left. -\frac{x_f^2 - x_f}{2}\log x_f + \frac{x_f^2}{4}\right],$$

and $U_f^{\text{med}}(\bar\sigma,\mu,B)$, the medium contribution,

$$U_f^{\text{med}} = -\frac{N_c}{4\pi^2}\sum_f\sum_{\nu=0}^{\nu_{\max}}(2-\delta_{\nu 0})|q_f|B\left[\mu\sqrt{\mu^2 - M_{fB}^2} \quad + \right.$$
$$\left. -M_{fB}^2\log\left(\frac{\mu + \sqrt{\mu^2 - M_{fB}^2}}{M_{fB}}\right)\right].$$

## 3 Surface tension and nucleation

- We consider homogeneous nucleation. Two possibilities:
  - Thermal activation
  - Quantum nucleation
- Physical setting [6]: $T = 10 - 20$ MeV
- Temperatures are high enough for thermal activation to take place. Quantum nucleation is negligible [1, 7, 8]
- For the chemical potential range we study, the cold approximation for the effective potential is still valid

### 3.1 Extracting nucleation parameters from the effective potential

- Our aim is to obtain the qualitative behavior, not numerical precision.
- We write the effective potential in the Ginzburg-Landau form, quartic fit [5]:

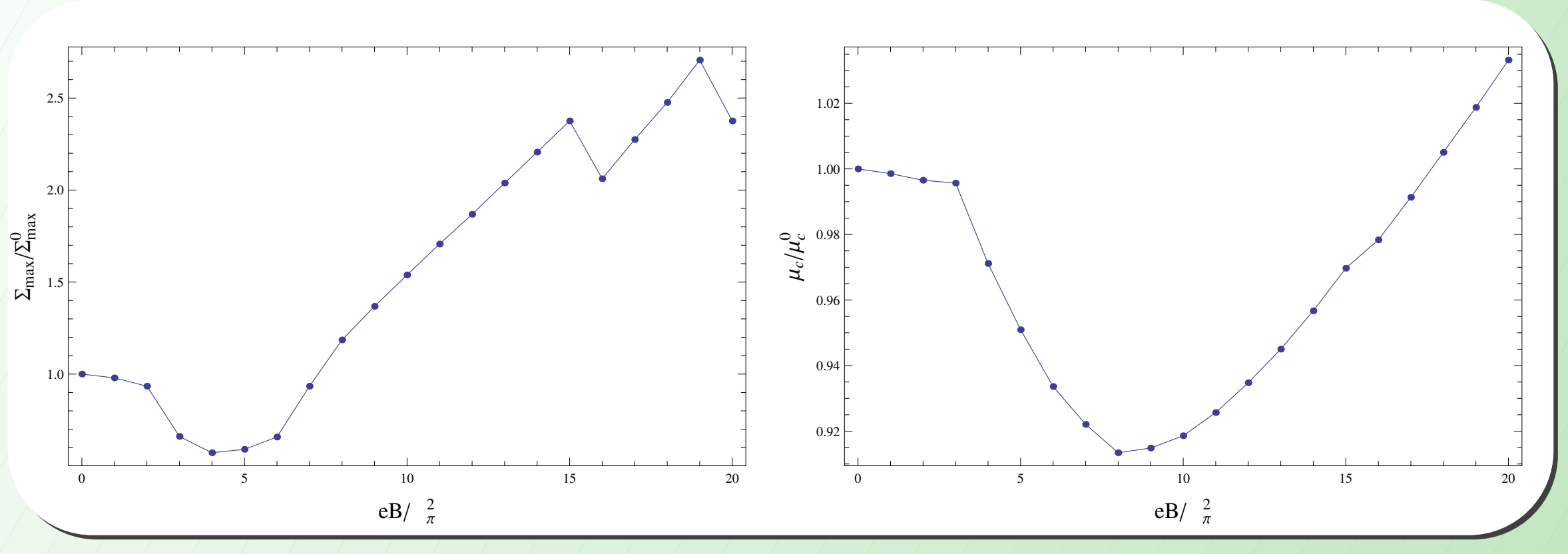
$$V_{\text{eff}} \approx \sum_{n=0}^{n=4} a_n\phi^n$$

- Although unable to reproduce all three minima, provides a good description in the region of interest for nucleation
- Simplifying limit: thin wall $\Rightarrow$ nucleation parameters are given by analytic expressions of $a_n$
- The procedure is valid for $\mu$ in the range between $\mu_c$ and $\mu_{sp}$

## 4 Results

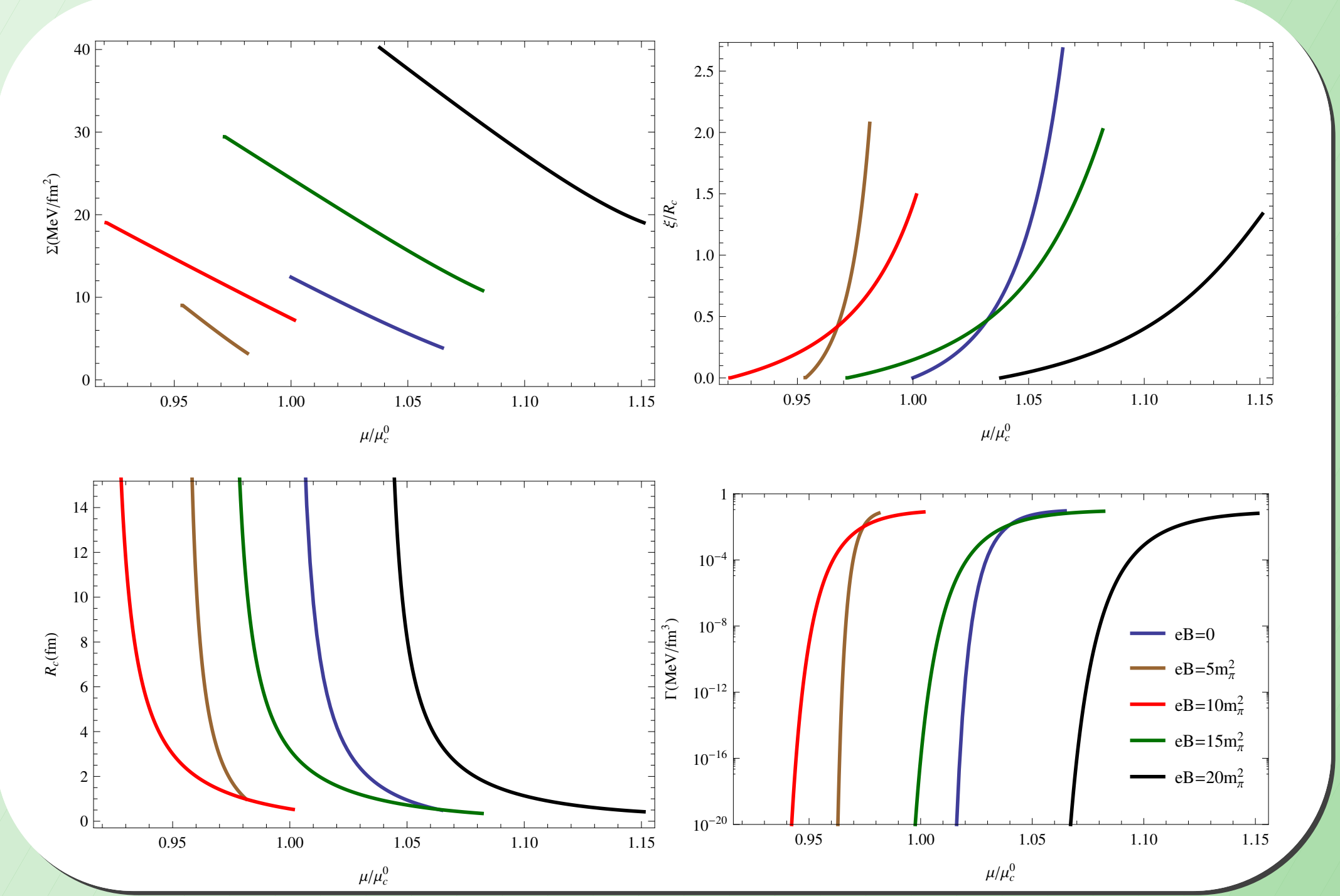
### 4.1 Landau level filling and oscillations

- Last occupied Landau level: $\nu_{\max} = \left\lfloor \frac{\mu^2 - g^2\sigma^2}{2|q_f|B} \right\rfloor$
- Varying $B$, the number of filled Landau levels change $\Rightarrow$ oscillations
- Similar to the ones found in the NJL model [9]



### 4.2 Nucleation parameters

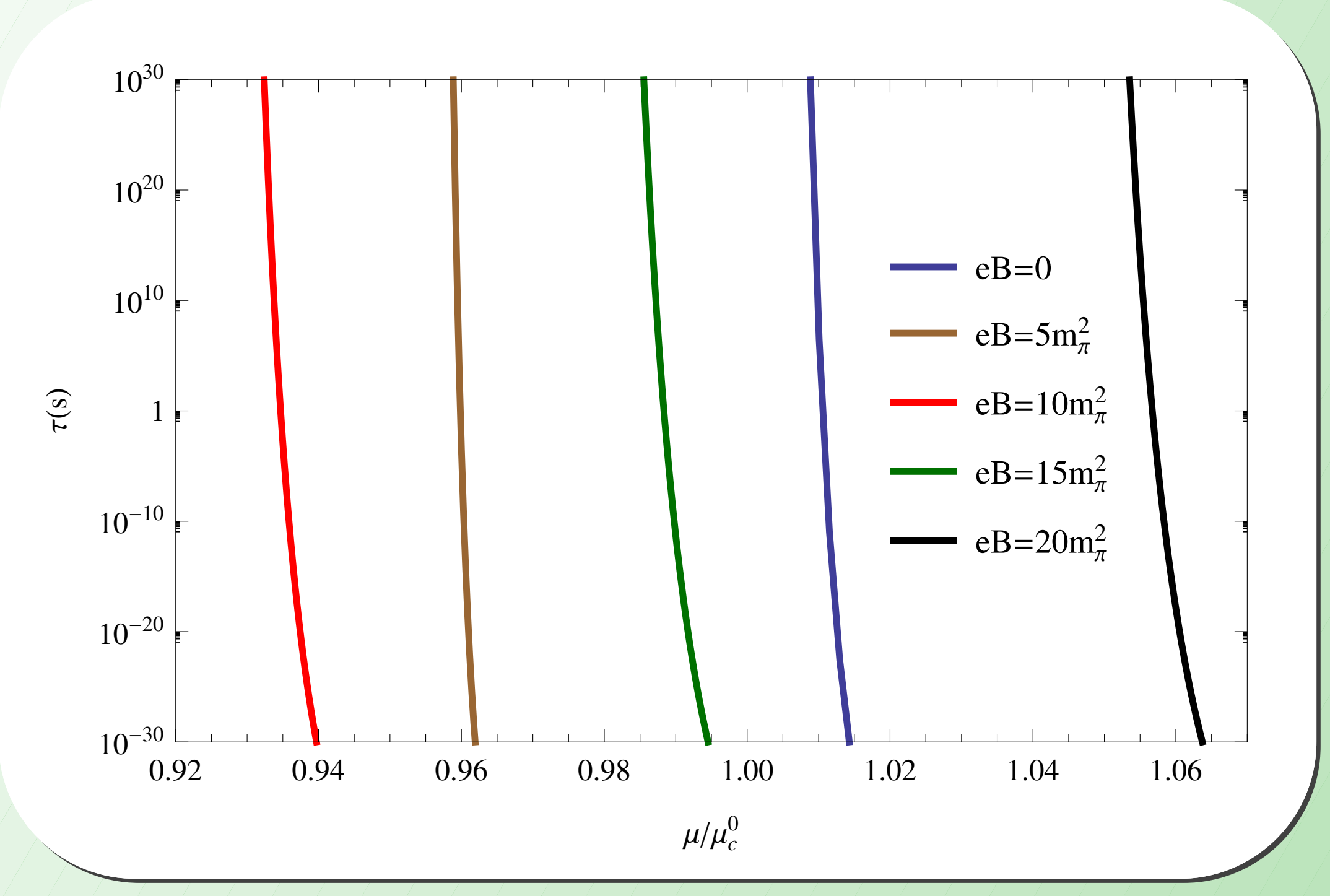
- Nucleation of chirally symmetric droplets
- Thin-wall is a good approximation for $\xi/R_c$ small
- Nucleation rate: $\Gamma \sim T_f^4 e^{-F_b/T_f}$, for $T_f = 30$ MeV
- All plot lines begin at $\mu_c$ and end at $\mu_{sp}$



### 4.3 Nucleation time

- Extremely Important information!
- Time needed to nucleate a single critical bubble in a volume of 1km$^3$:

$$\tau \equiv \left(\frac{1}{\text{km}^3}\right)\frac{1}{\Gamma}$$



## 5 Conclusion

- For magnetic fields up to 5 $m_\pi^2$: decrease of the metastable region

  $\Rightarrow$ phase conversion via spinodal explosion facilitated
- Non trivial competition between $\Sigma$ and $R_c$: surface tension may increase and the the nucleation time still decrease

  **⇒The surface tension alone is not able to give all the needed information about nucleation in magnetar matter!**
- Nucleation is favored for $eB \approx 10\ m_\pi^2$
- All these interesting features take place in the phenomenologically interesting region of magnetic fields for magnetars

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