Absolutely stable SQM formation in astrophysical systems

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Università degli Studi di Ferrara

2nd Workshop on modern equations of state and spectroscopy in neutron-star matter

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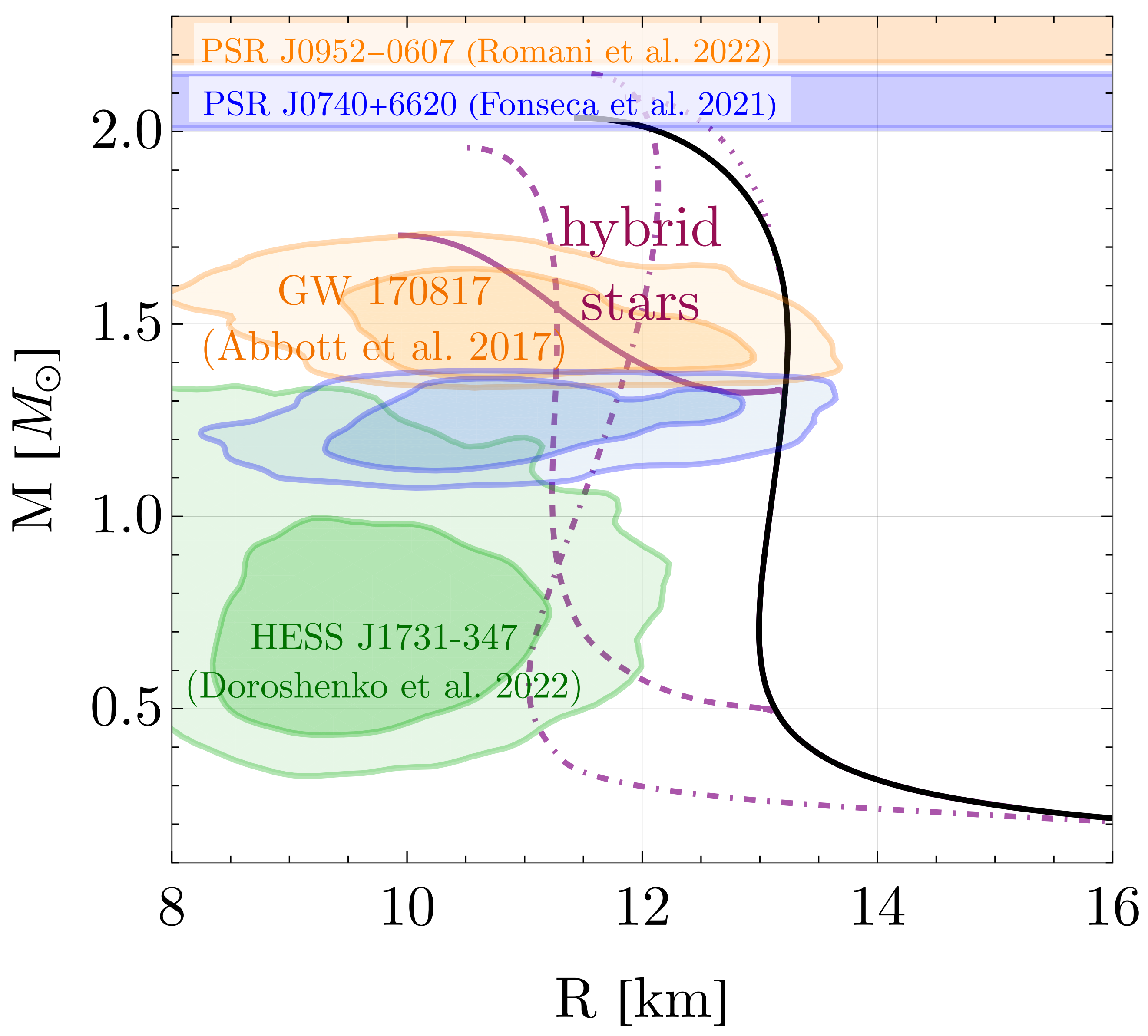
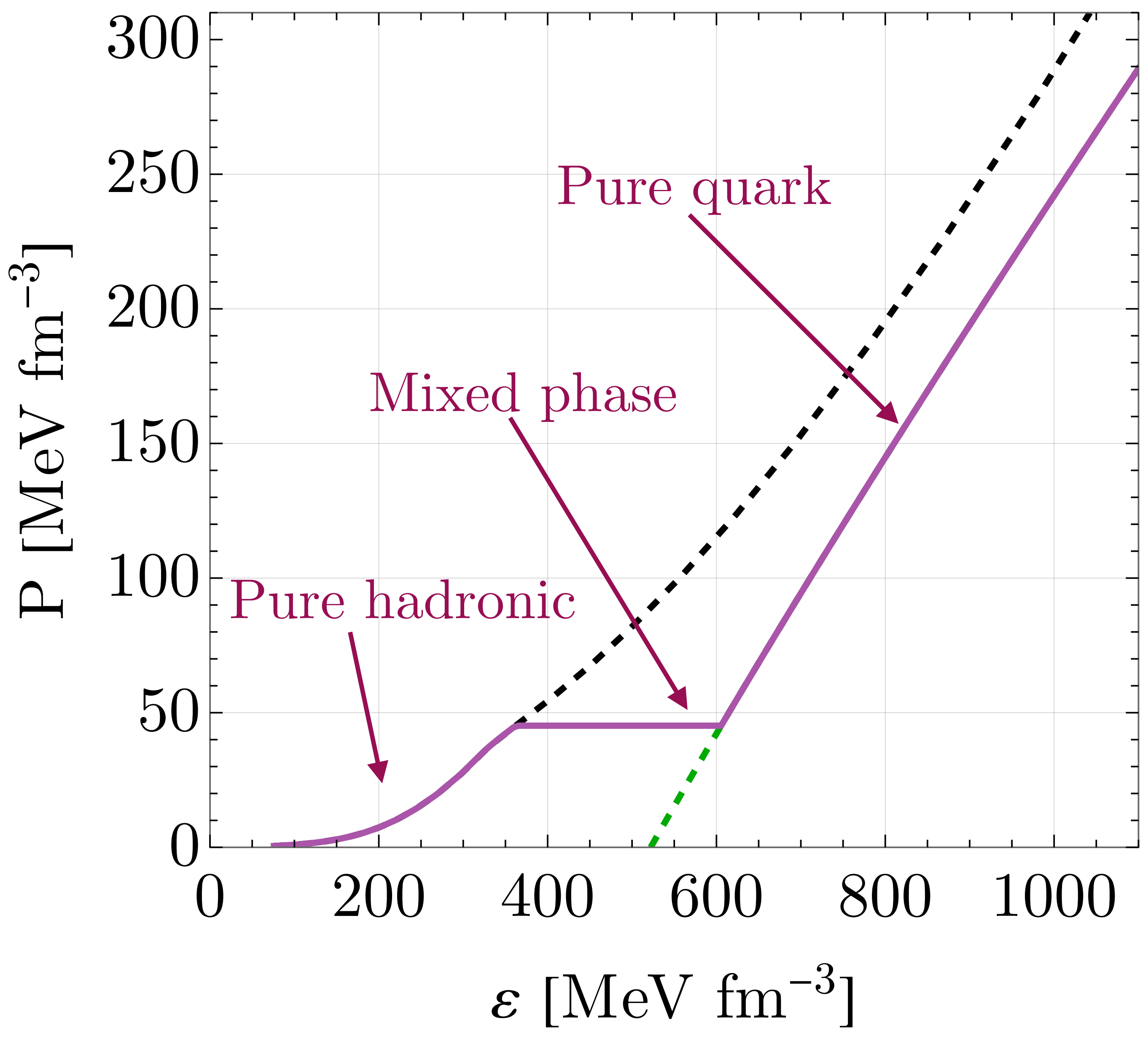
SQM in compact stars: one or two families?





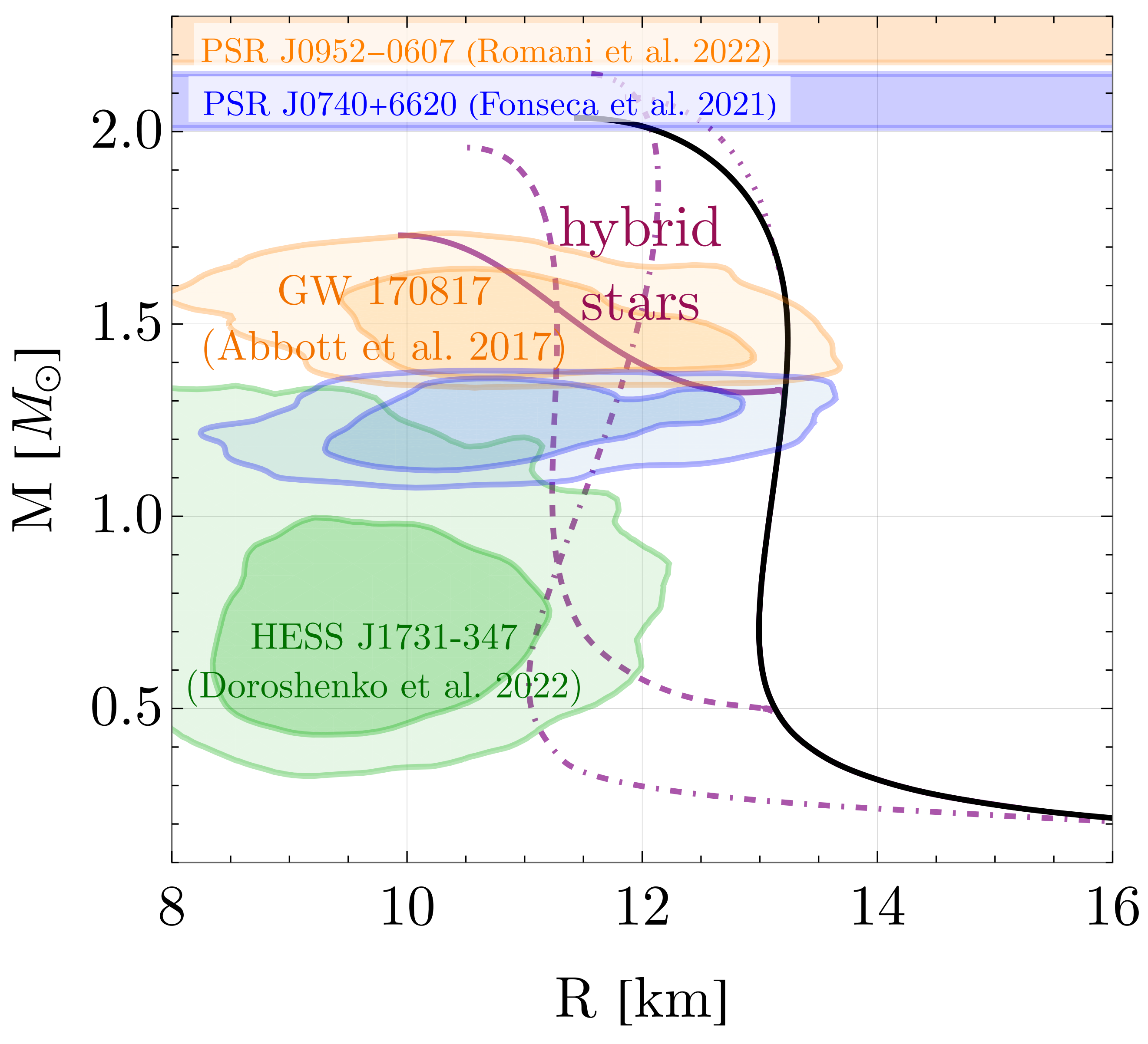
One family scenario

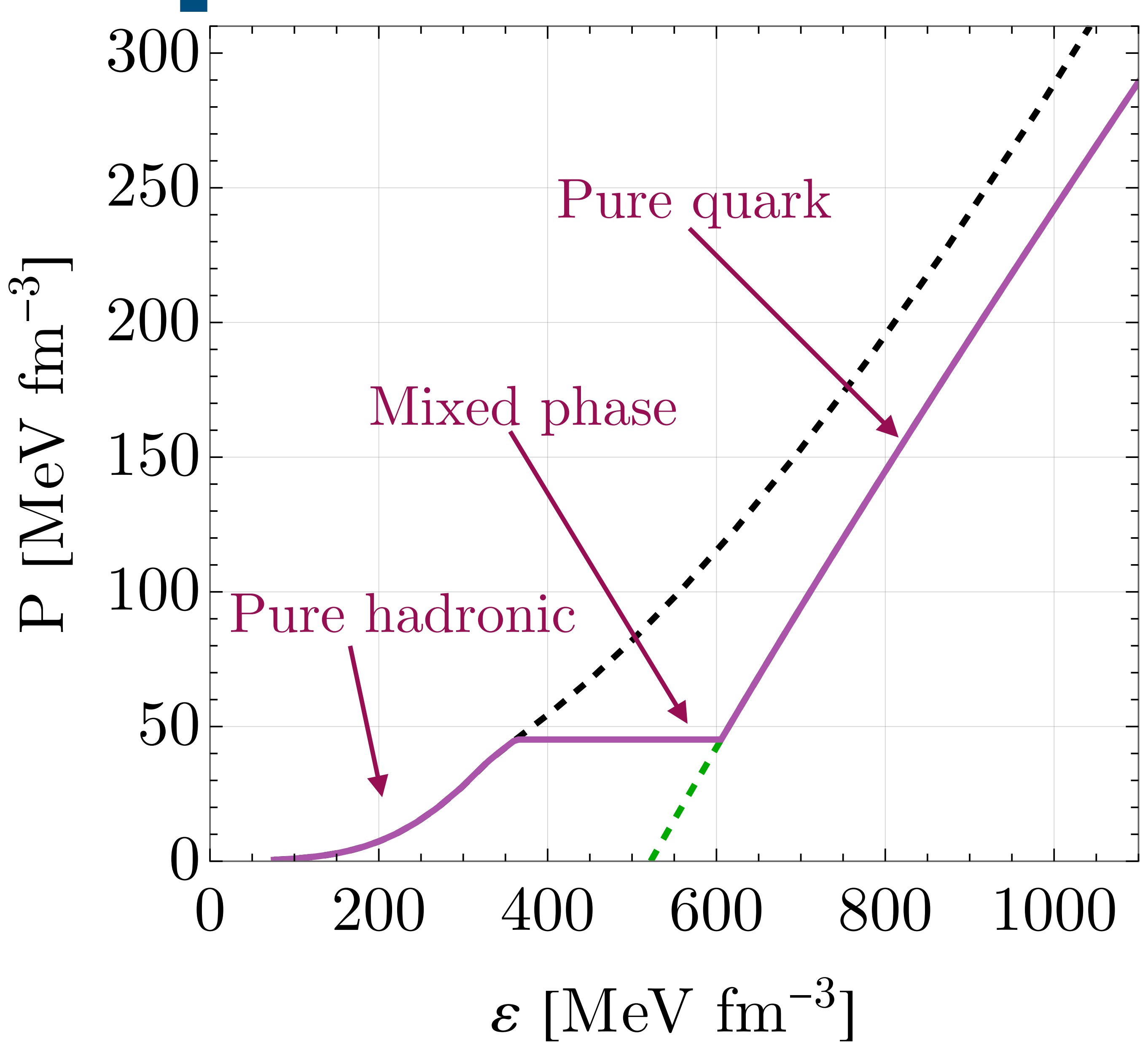
- deconfined quarks d.o.f. expected in massive compact stars
- **hybrid stars**: SQM in the core and hadrons in the outer part
- 1st order phase transition, crossover, quarkyonic, …

↓

Maxwell C., Gibbs C., mixed approach

SQM in compact stars: one or two families?





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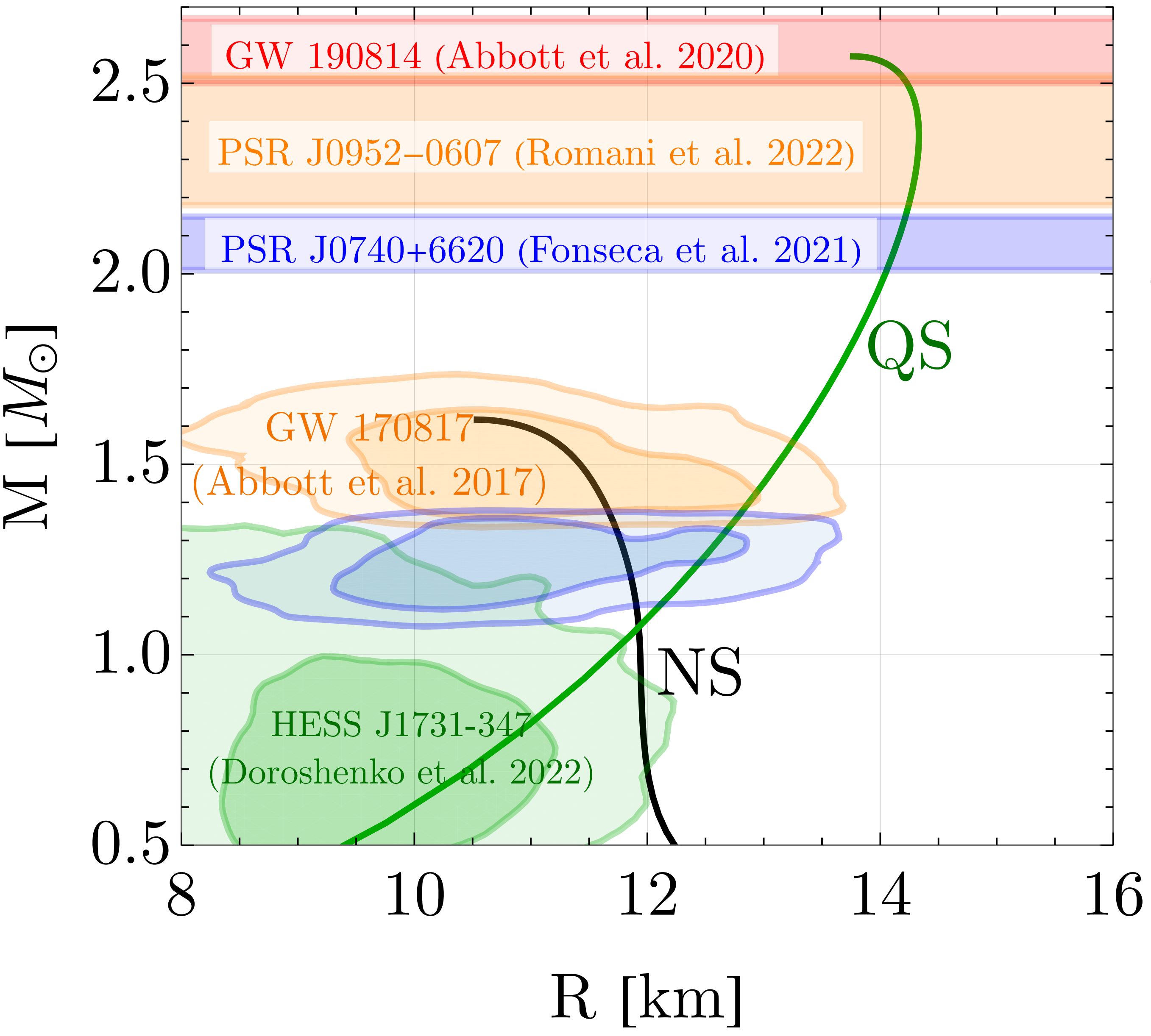
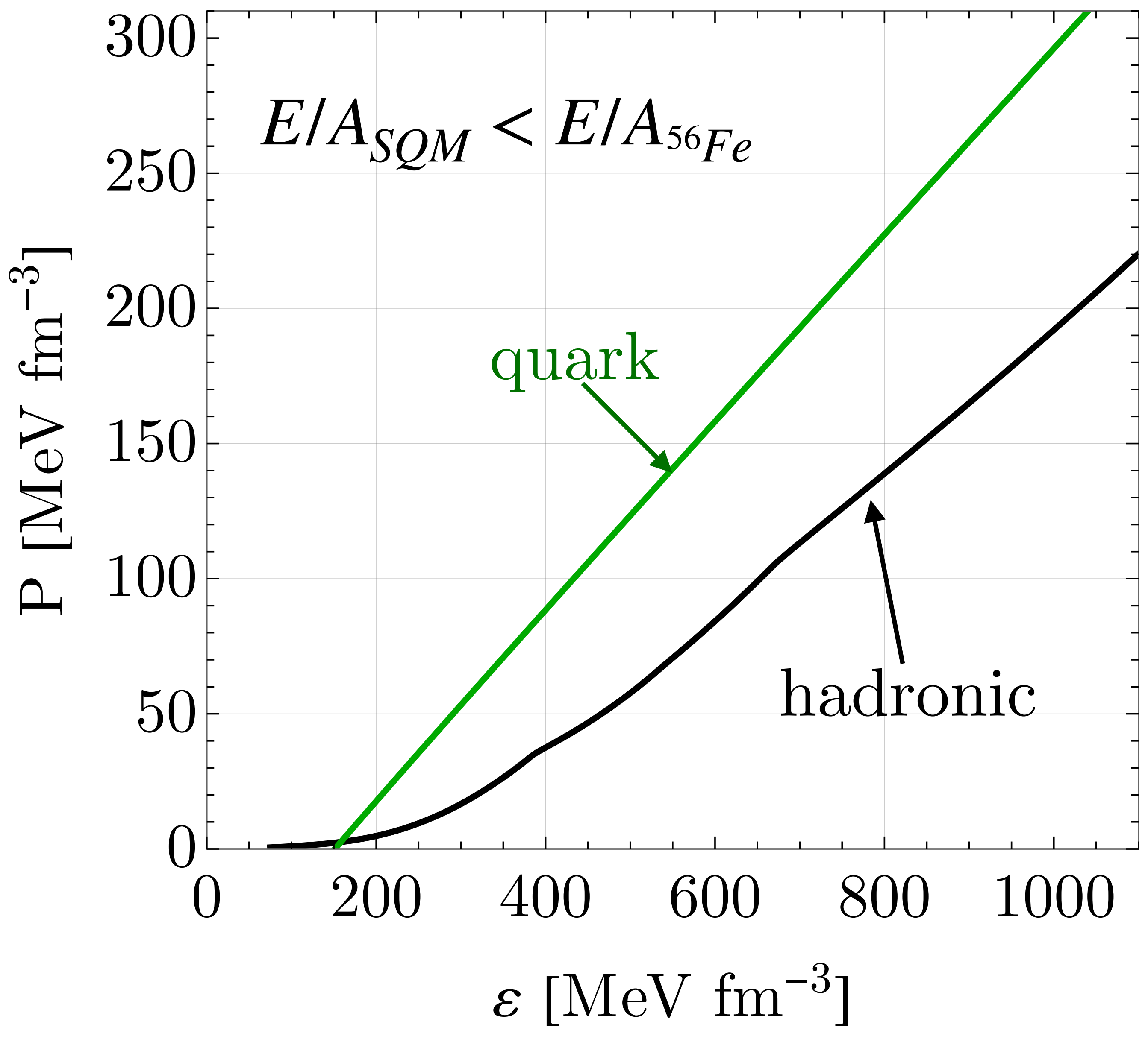


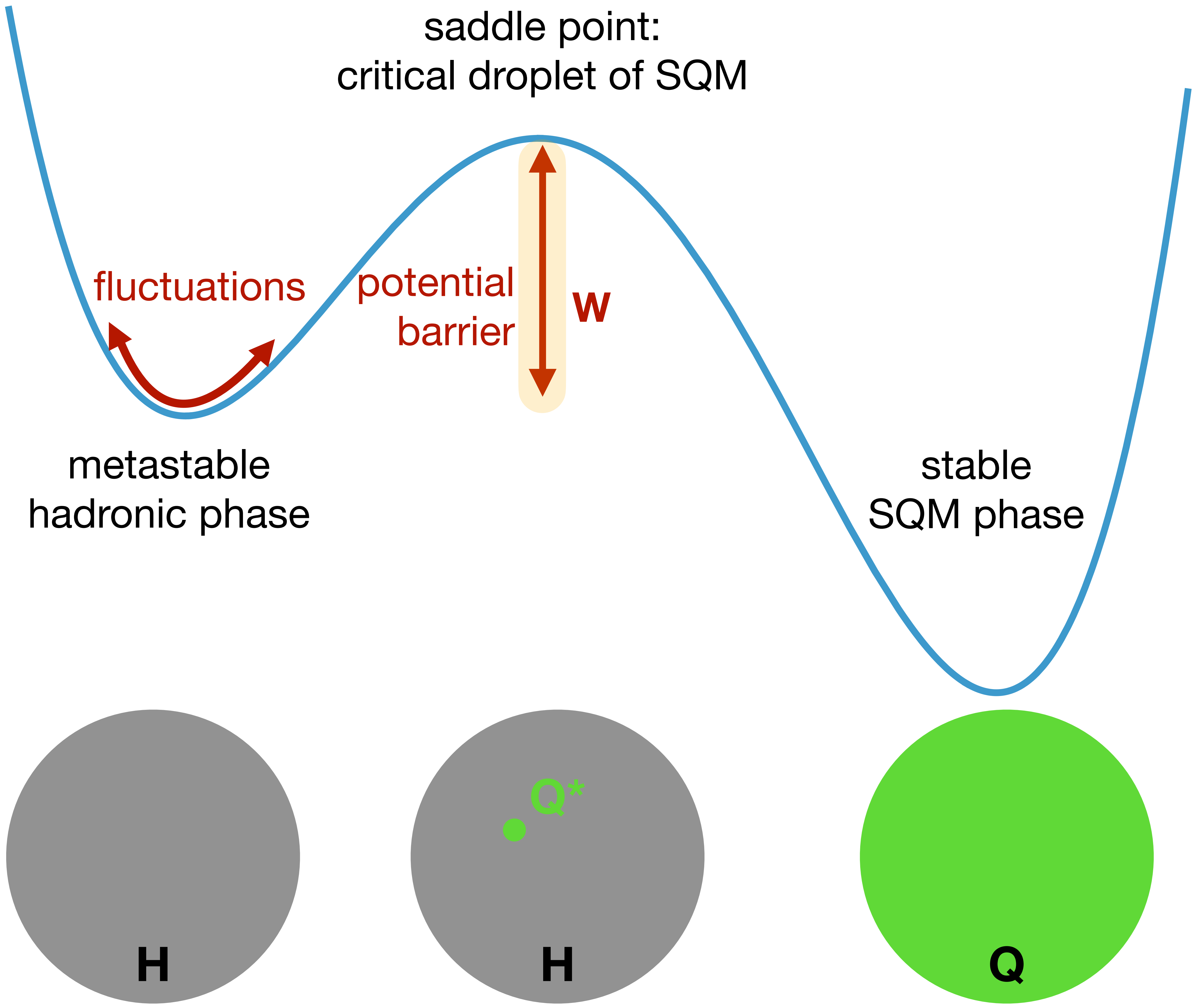


Two families scenario

[see Drago et al. (2016)]

- based on the **strange matter hypothesis** *[Witten (1984)]*
- **hadronic stars** up to $\sim 1.6\ M_\odot$ at low radius
- **quark stars** fulfill massive and subsolar objects constraints
- a **potential barrier** prevents the decay into SQM
- once reached deconfinement conditions, **HS** converts to **QS**

Nucleation: finite size effects



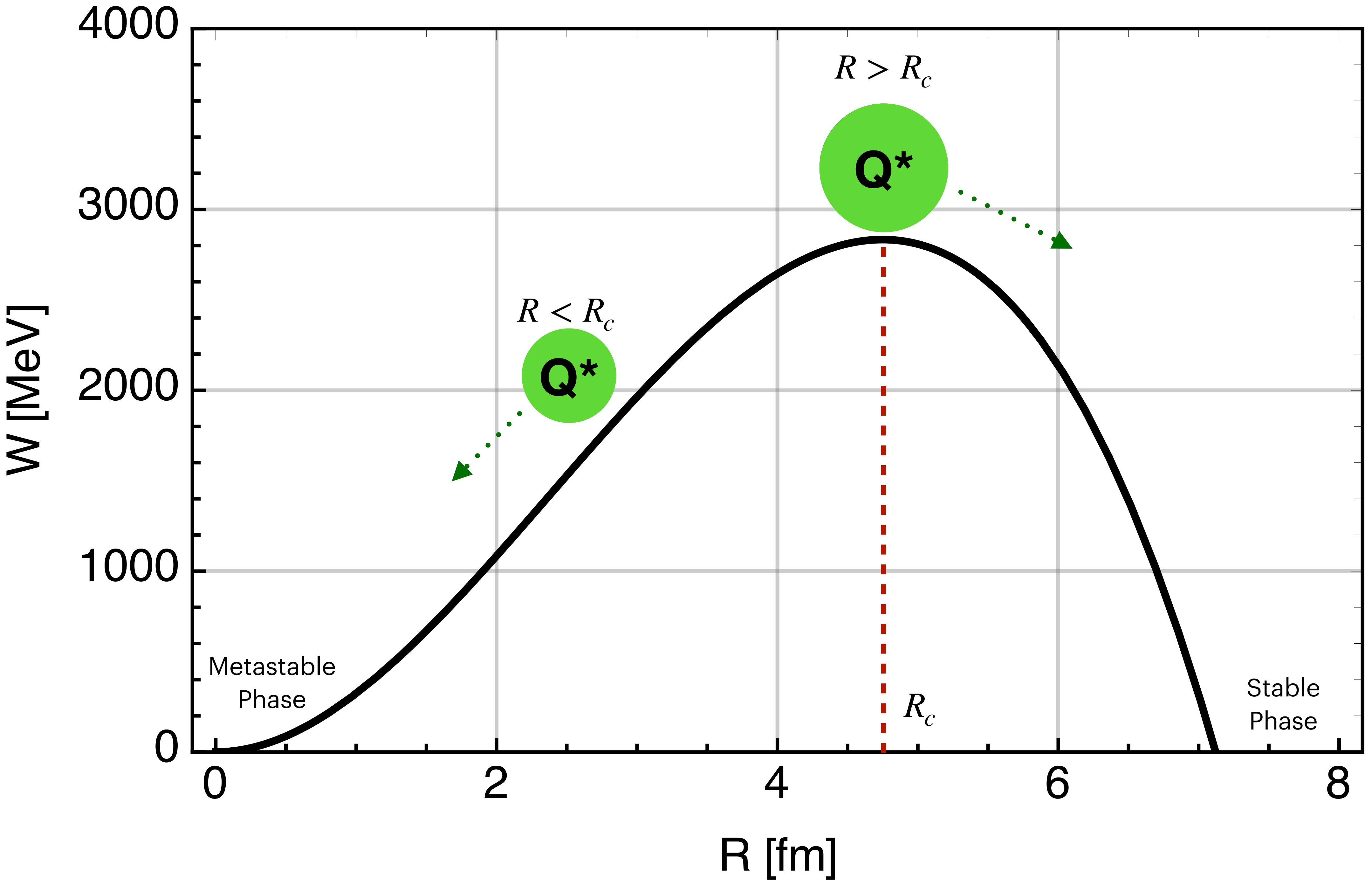
$\mathscr{P} \sim e^{-\frac{W}{T}}$ [Langer (1969)]

$$W = E_{sp} - E_H = (E_{Q*} + E_\sigma + E_{\tilde{H}}) - E_H$$

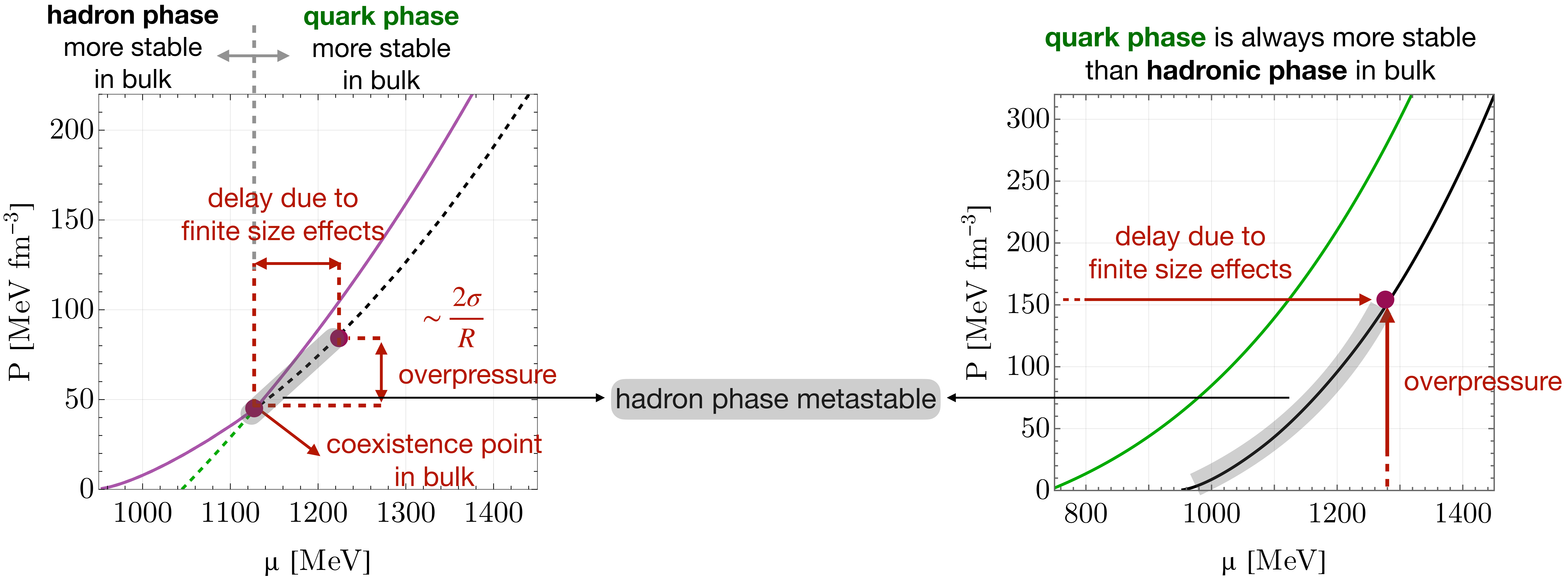
$$W = \left[-\frac{4}{3}\pi R^3 (P_{Q*} - P_H)\right] + \left[4\pi\sigma R^2\right]$$

bulk energy gain (negative if H is metastable)

surface effect (always positive)



Nucleation in compact stars



One family scenario (hybrid stars)

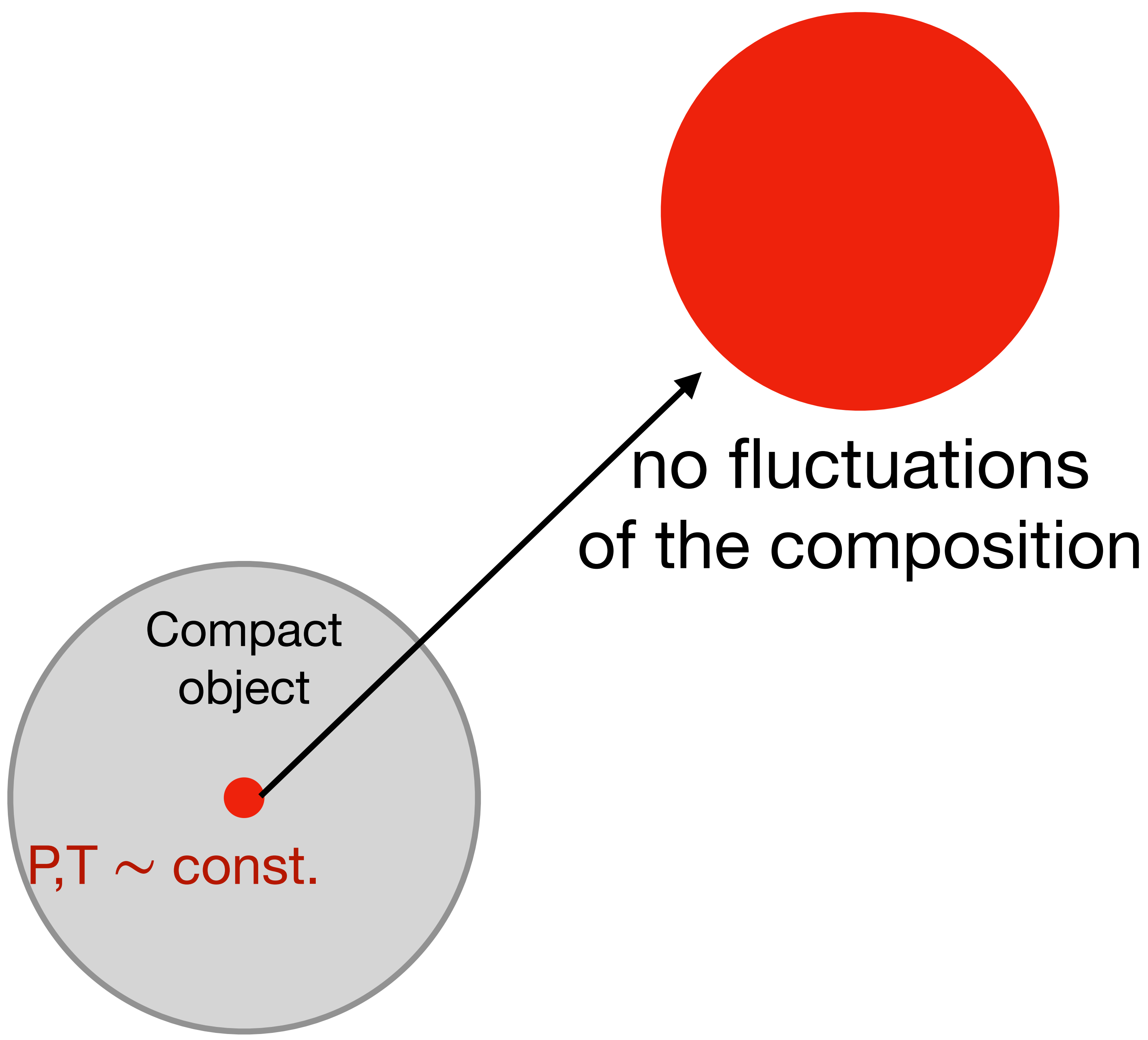
leads to a **delay** in the phase transition
with respect to the bulk mixed phase onset

Two families scenario (neutron and quark stars)

is the only mechanism that prevents the
decay of ordinary matter into SQM

Flavor composition can fluctuate

$Y_i^* = \langle Y_i^H \rangle$ everywhere



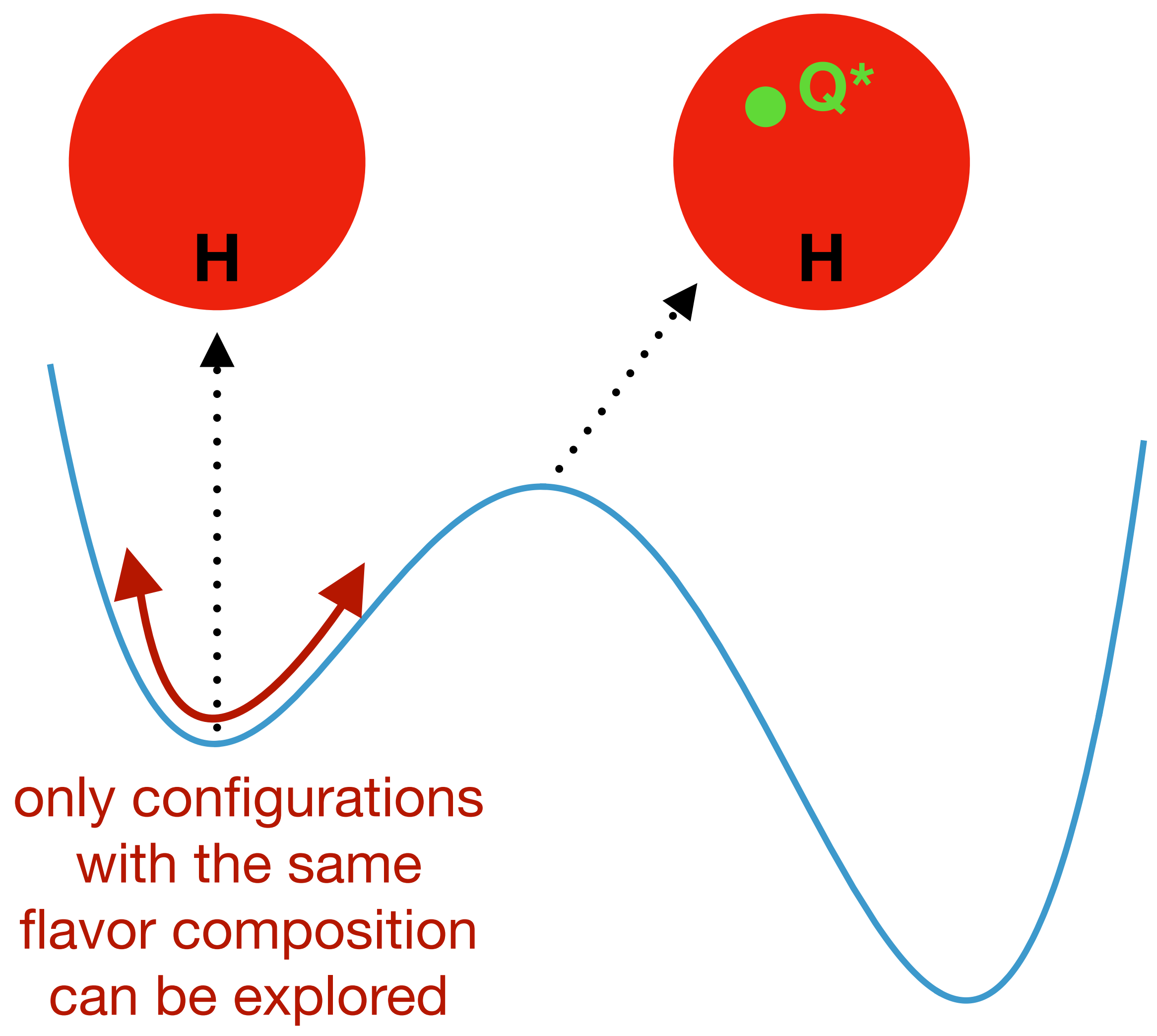
Nucleation is due to **strong interactions**
strong timescale $\ll$ weak timescale

↓

Flavor composition locally conserved
during the nucleation

[see e.g. Bombaci et al. (2016)]

$\{Y_i^{Q*}\} = \{Y_i^*\}$



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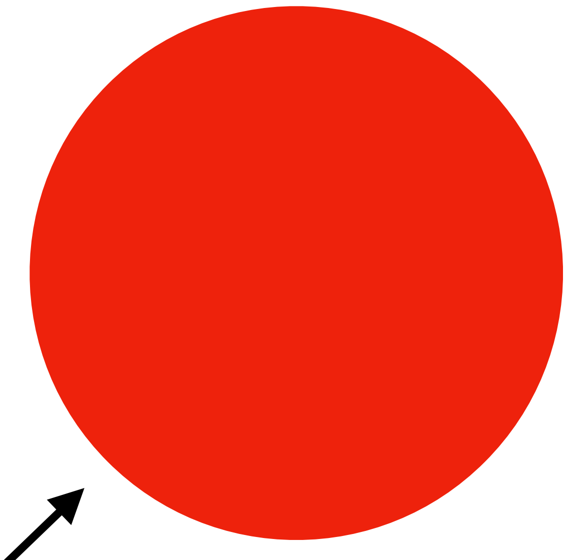
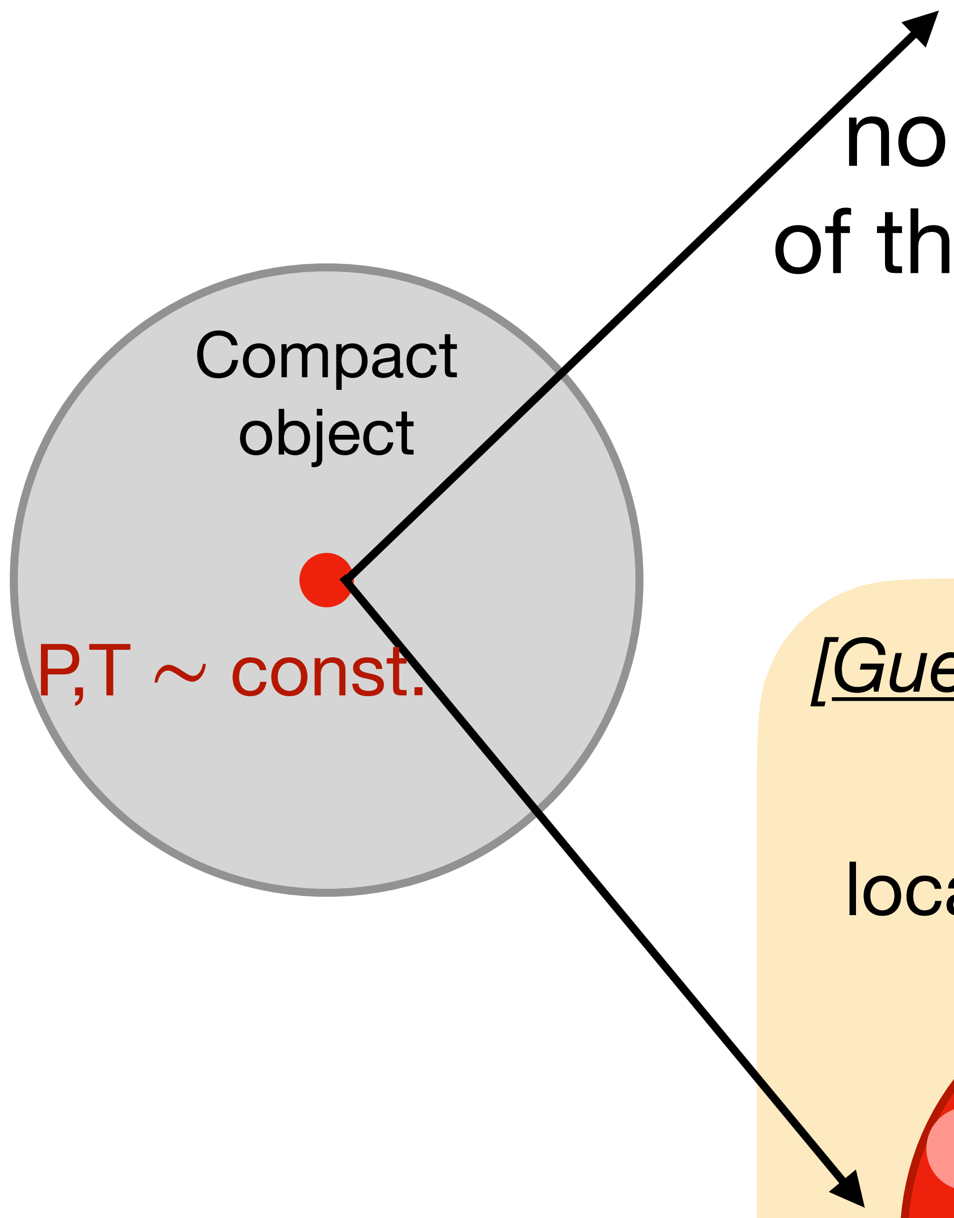


no fluctuations
of the composition



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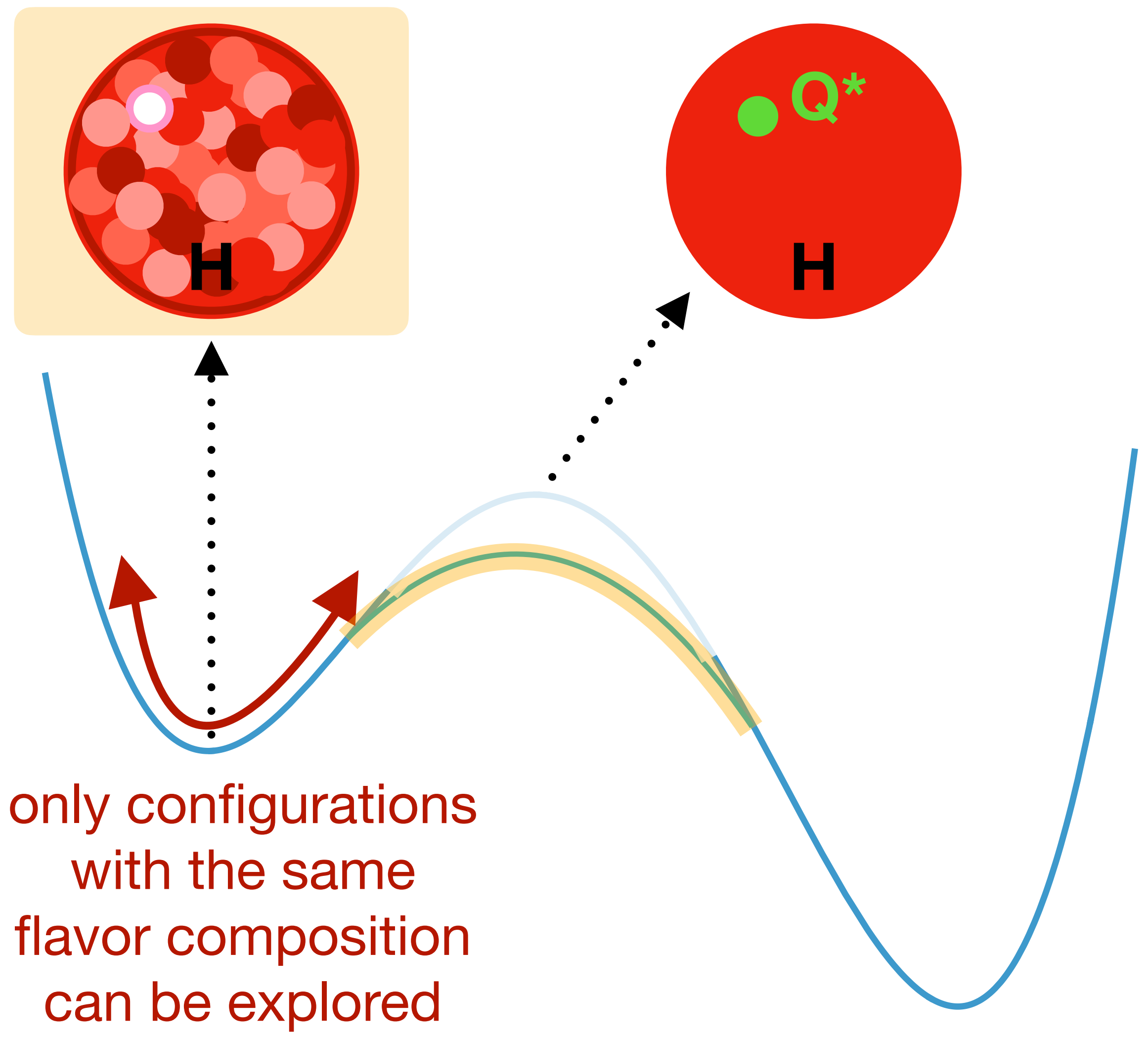
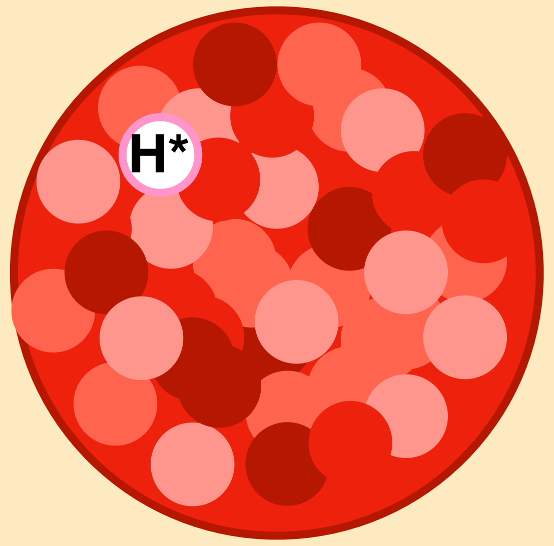


only configurations
with the same
flavor composition
can be explored

[Guerrini et al. (2024)]

locally $Y_i^* \neq \langle Y_i^H \rangle$



thermal fluctuations
of the composition

Key idea:

at $T \neq 0$ the hadronic **composition fluctuates** around the average values $\langle Y_i^H \rangle$

the nucleation is a **local process**

↓

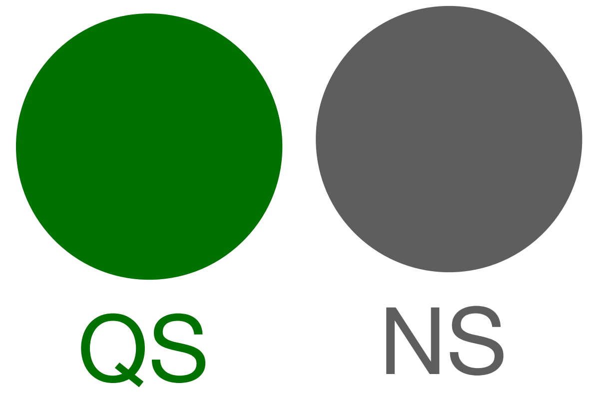
Nucleation could happen in a subsystem H* in which
the local composition $Y_i^* \neq \langle Y_i^H \rangle$ makes nucleation easier

$$\Gamma \propto \exp\left[-\frac{W_{H\to H_*}}{T}\right] \exp\left[-\frac{W_{H_*\to Q_*}}{T}\right]$$

probability of a subsystem H*

nucleation probability
in a subsystem H*

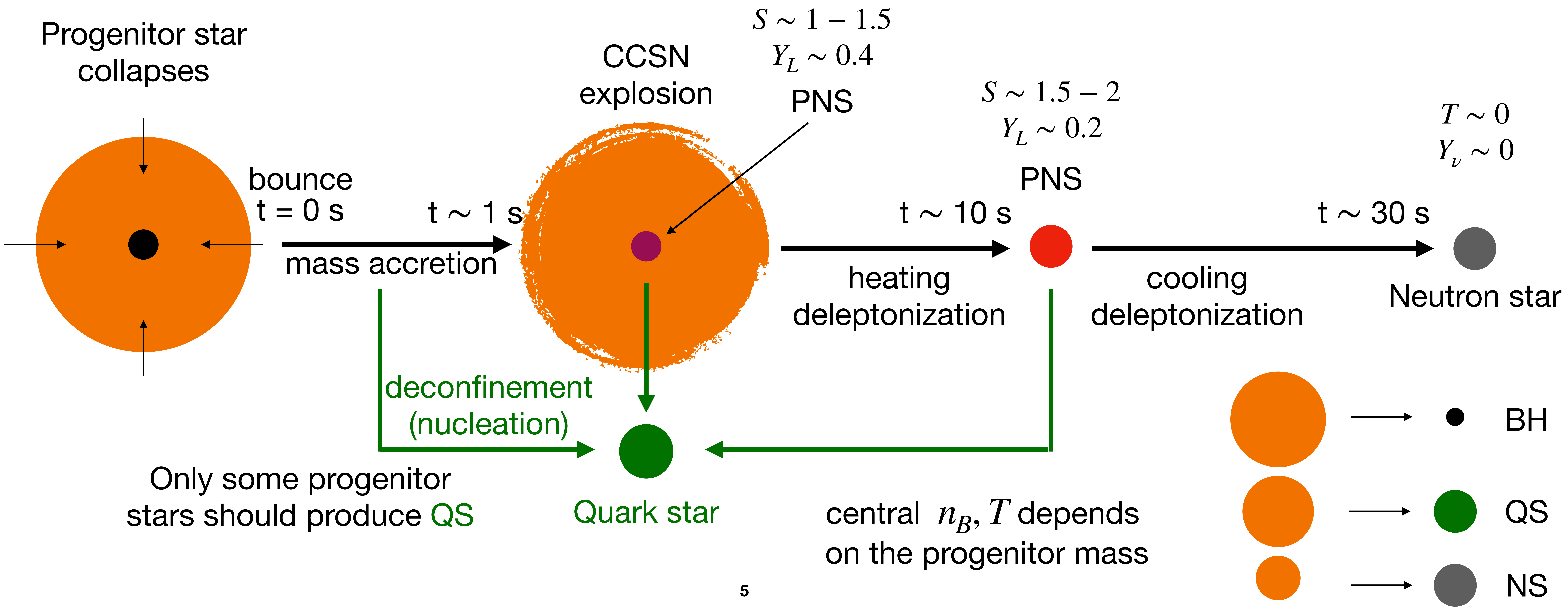
Goal: testing the two families scenario



Constraints:

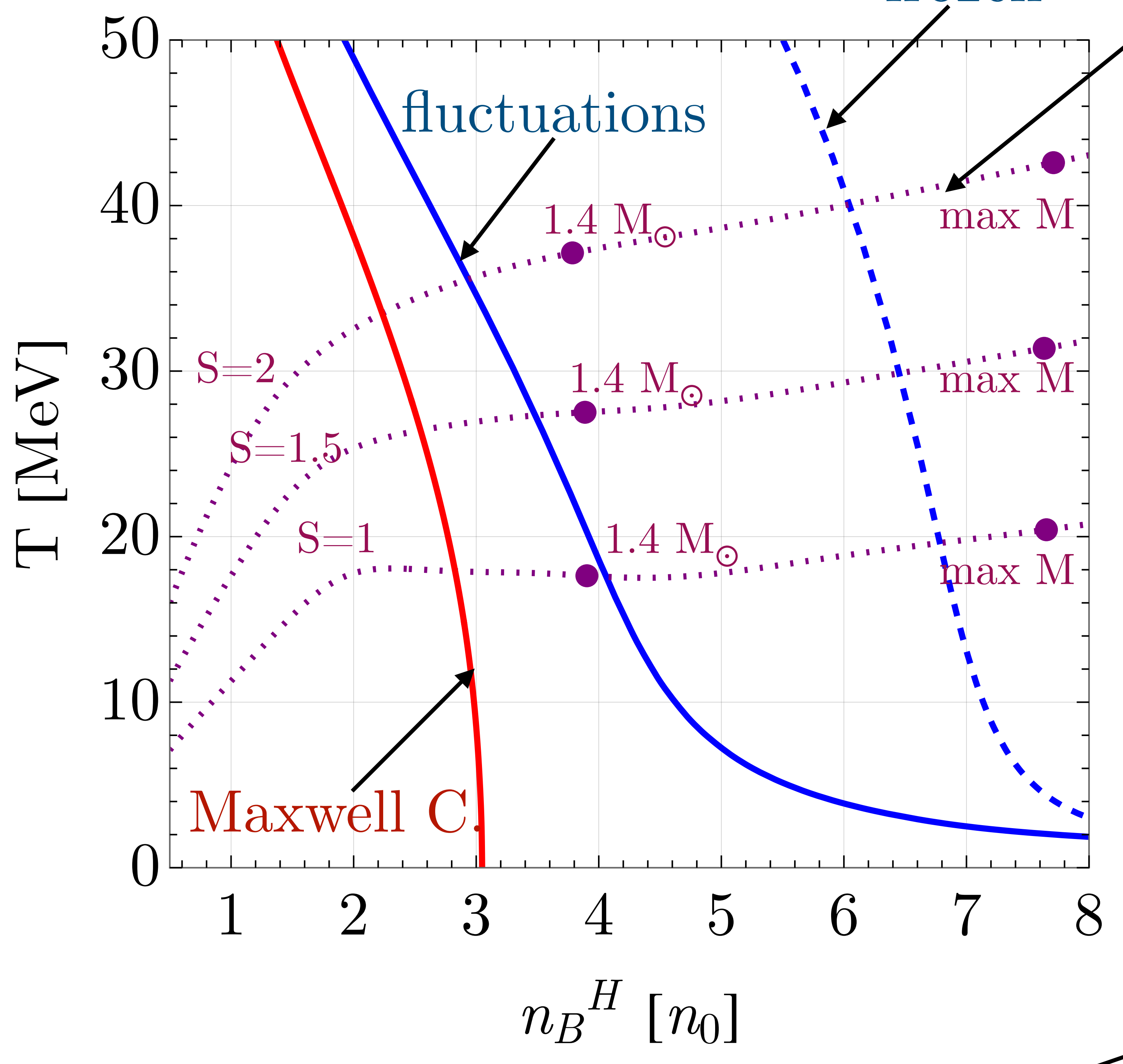
i. EOS for SQM must have a **maximum mass configuration** $M \gtrsim 2.5\, M_\odot$

ii. Some ordinary **neutron stars must survive** the evolution process (namely, **nucleation only at large enough n_B,T**)



Implications for compact stars

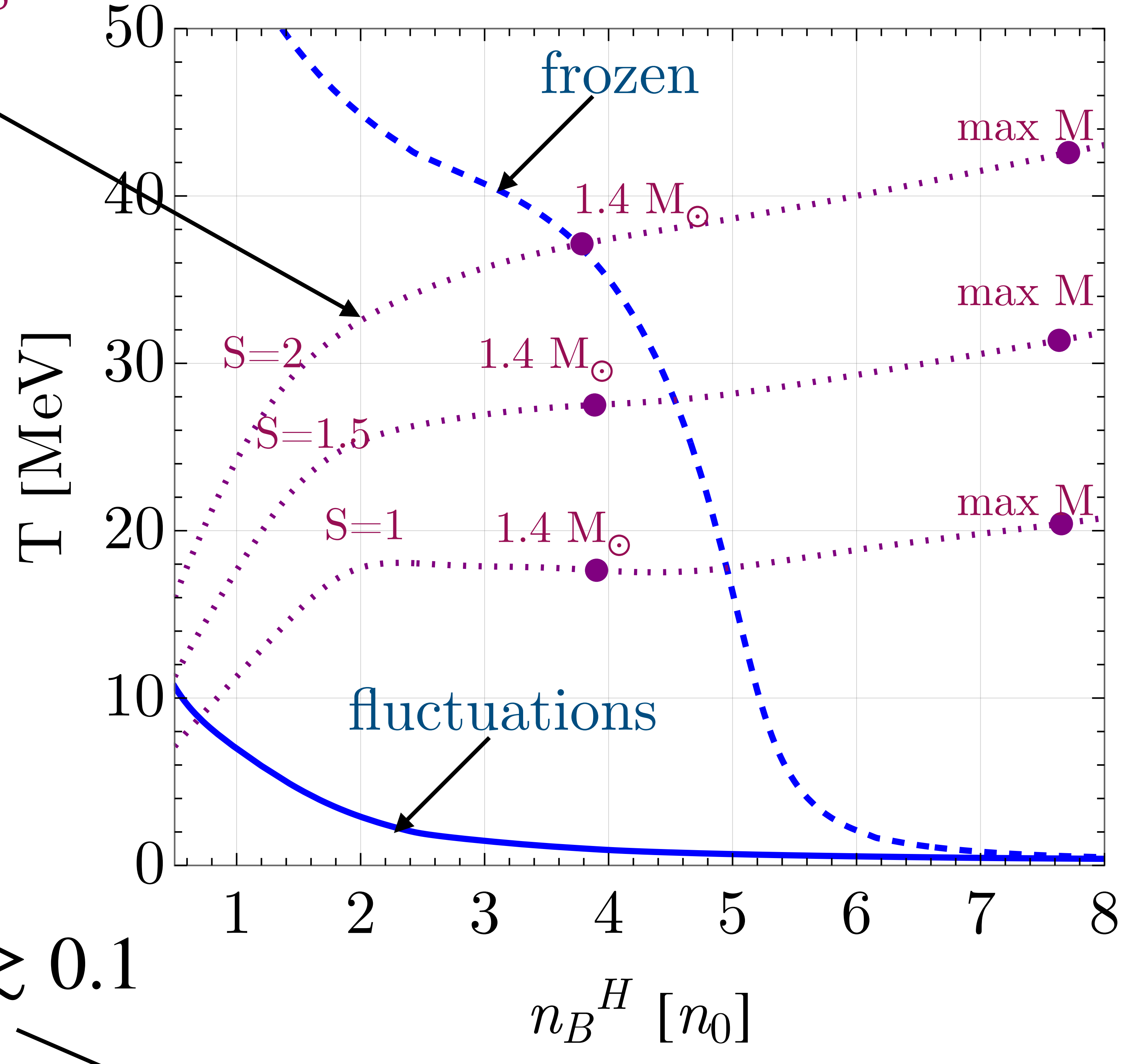
One family scenario
(hybrid stars)



PNS central conditions

Conditions at which nucleation timescale $\tau \sim 10^{-4}$ s (typical astrophysical dynamical timescale)

Two families scenario
(neutron and quark stars)



A certain amount of $Y_S^H \gtrsim 0.1$ is needed

Frozen: significant delay

Fluctuations: lower delay, only due to σ

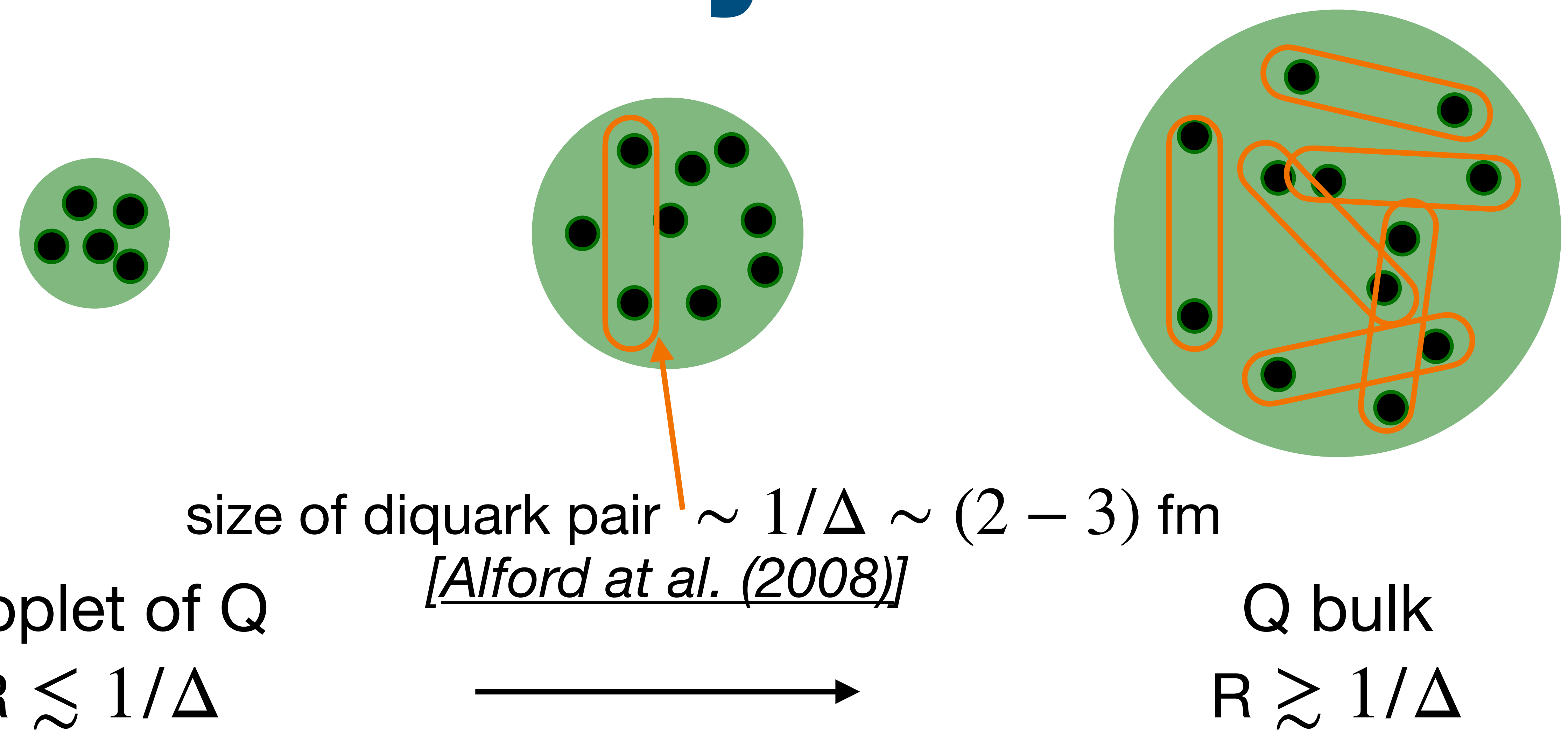
Frozen: constraints fulfilled

Fluctuations: **no NSs survive the evolution**

Role of color-superconductivity

- to reach $\sim 2.5\, M_\odot$ we need **superconducting** quark matter (e.g. **CFL**)
  [e.g. Bombaci et al. (2021), Blaschke et al. 2023]

- gaps could **vanish** in very **small systems** (as first quark seed is)
  [e.g. Amore at al. (2002) PRD]



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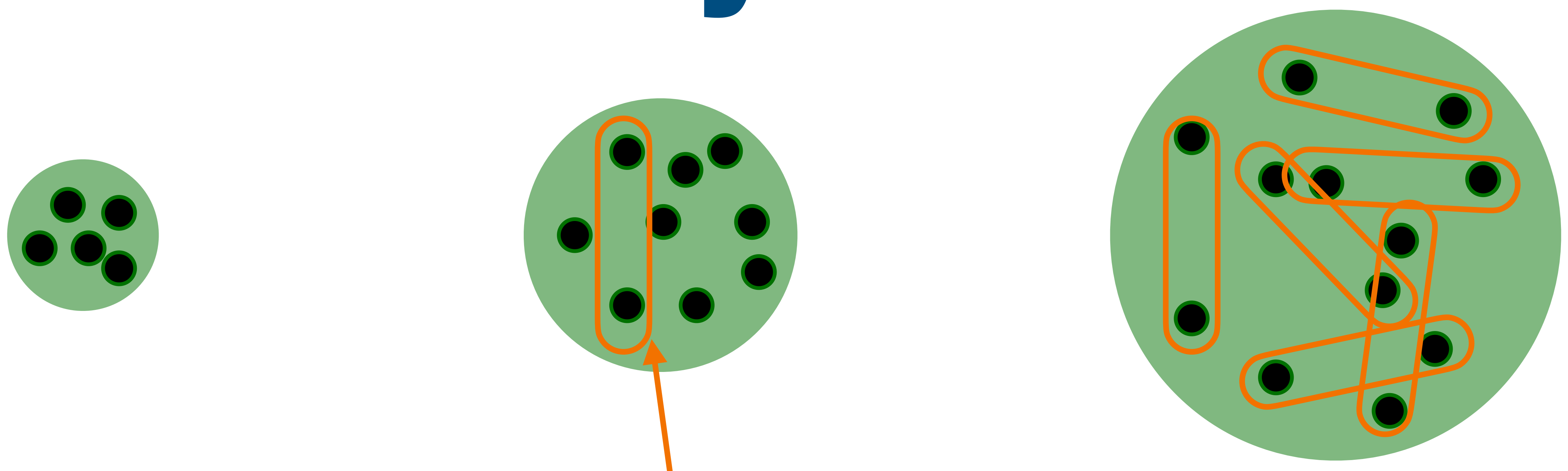
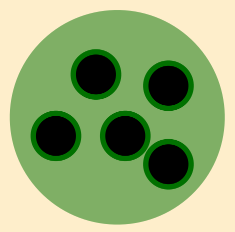


size of diquark pair $\sim 1/\Delta \sim (2-3)$ fm
[Alford at al. (2008)]

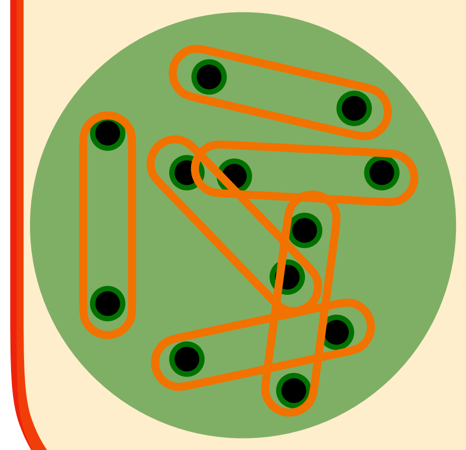
droplet of Q
R $\lesssim 1/\Delta$
unpaired phase

→

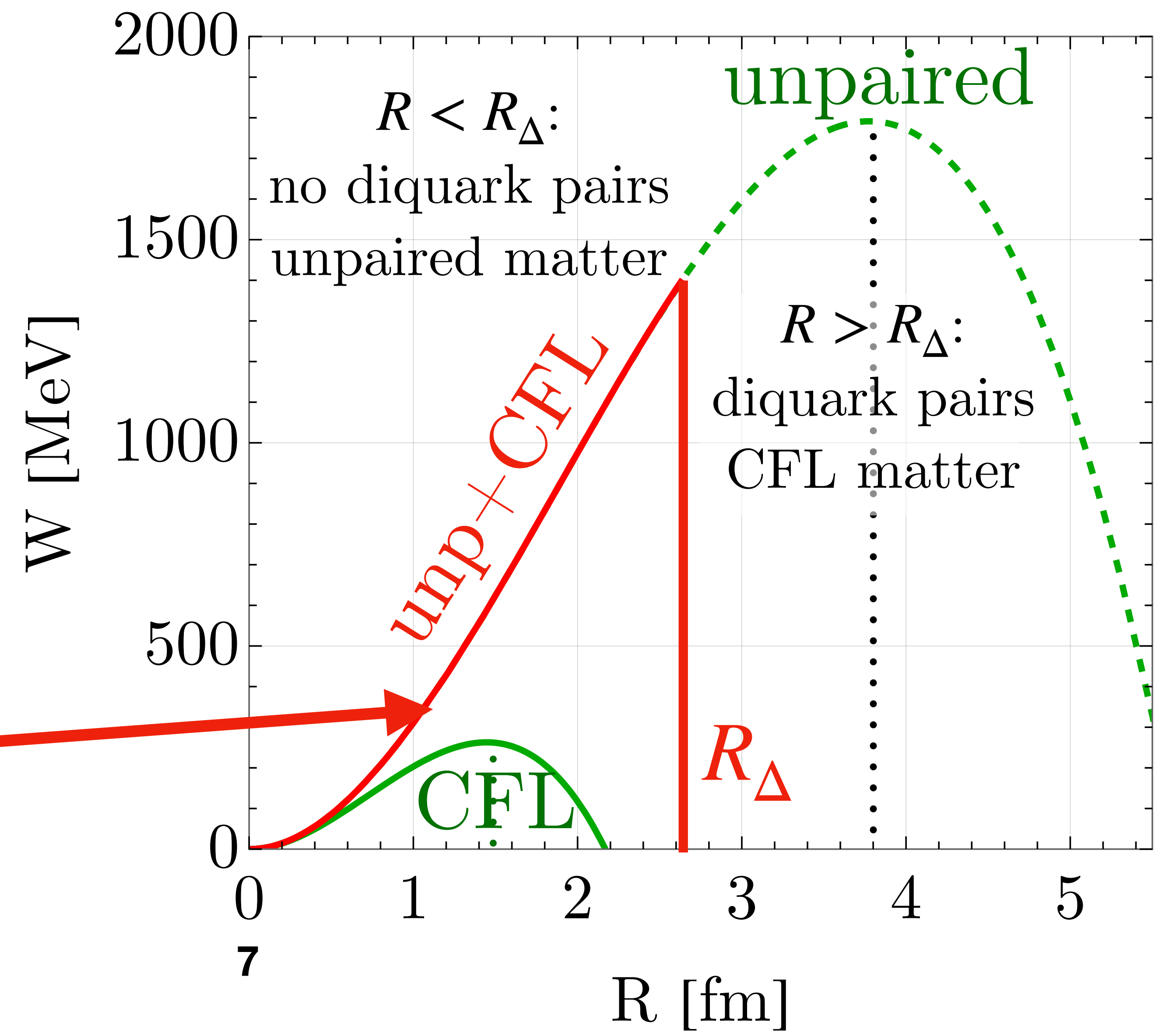
Q bulk
R $\gtrsim 1/\Delta$
color-superconducting phase

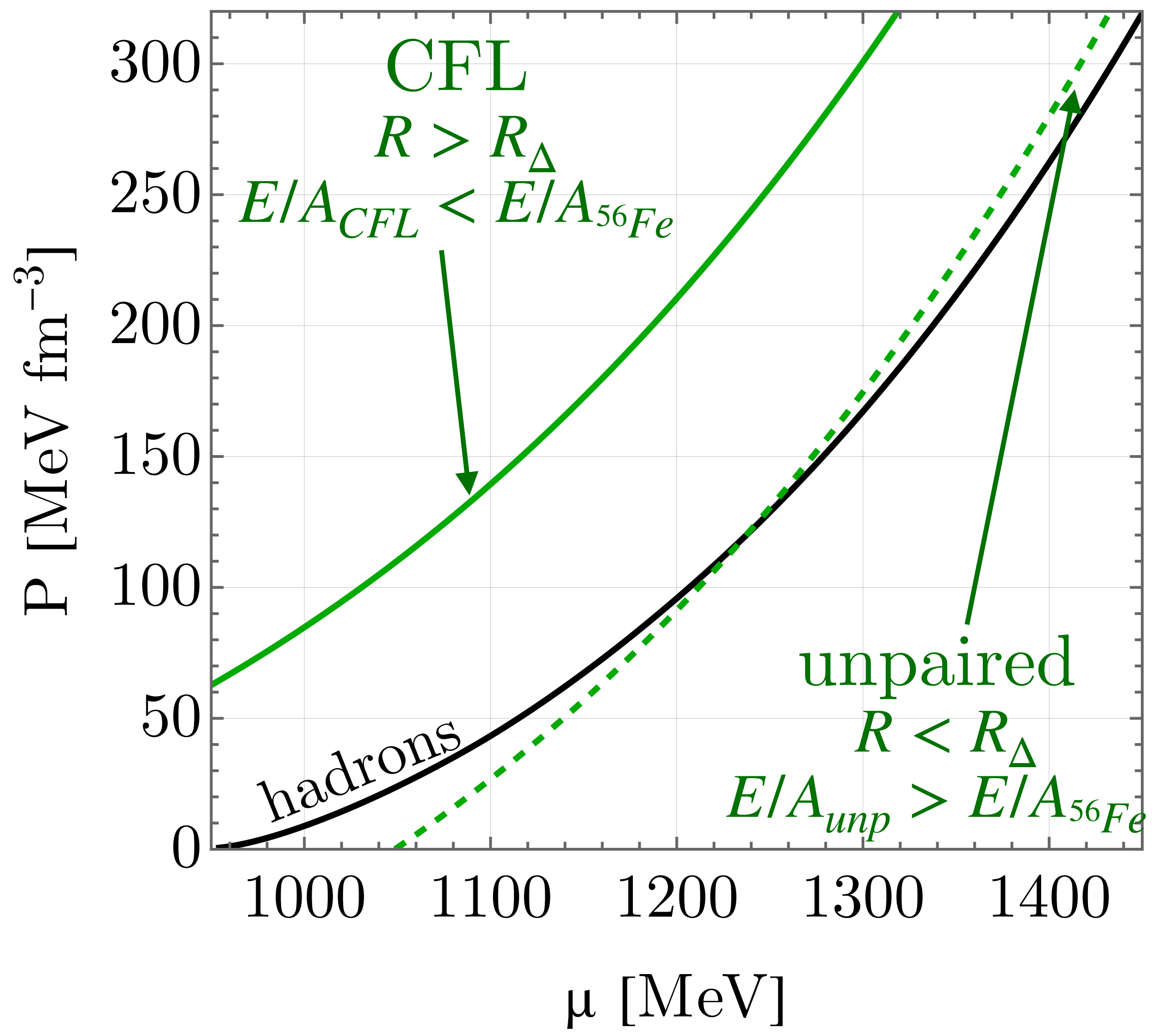


$R < R_{\Delta} = 1/\Delta(T)$: **unpaired matter**
non absolutely stable

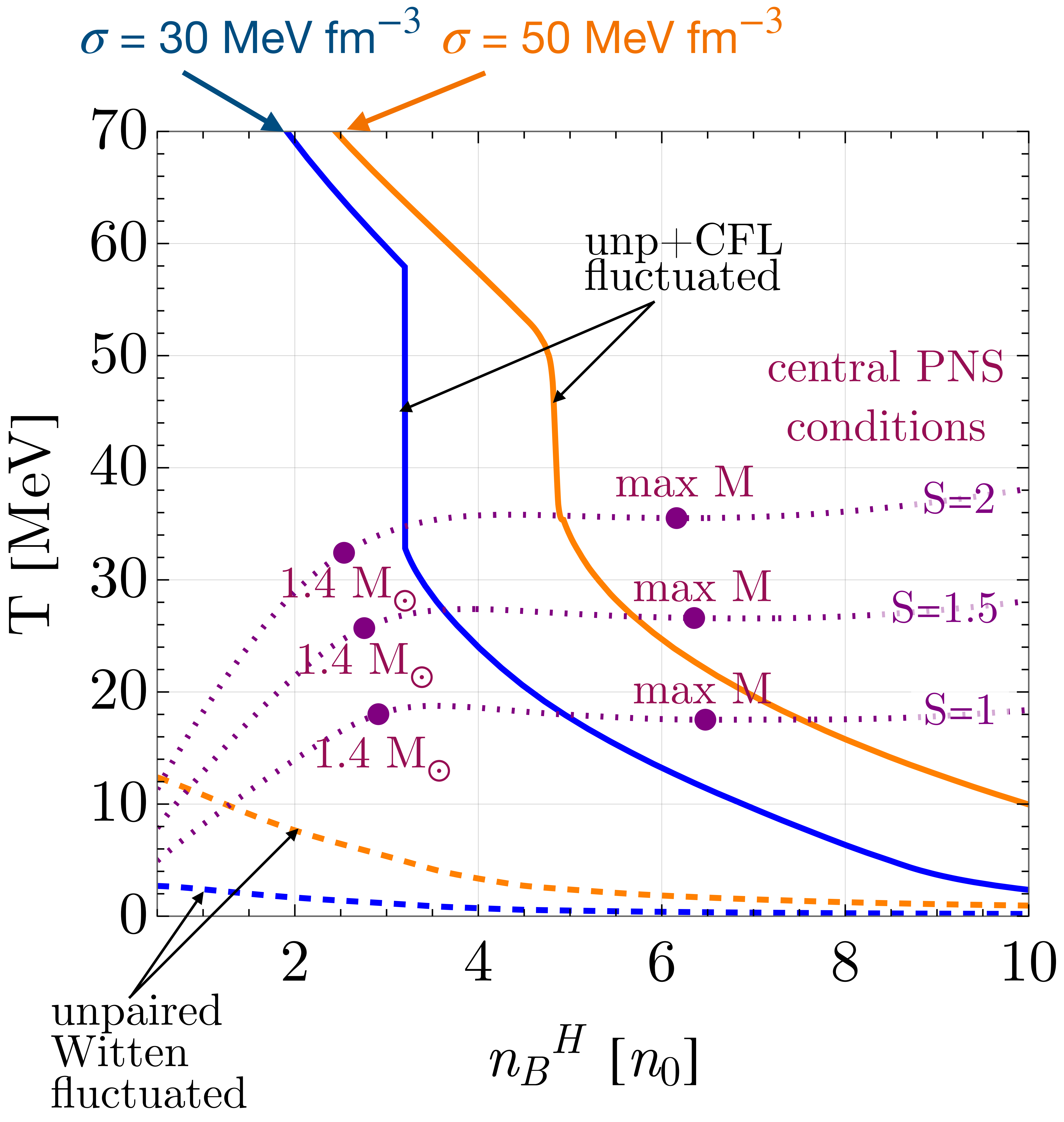


$R > R_{\Delta} = 1/\Delta(T)$: **CFL matter**
absolutely stable



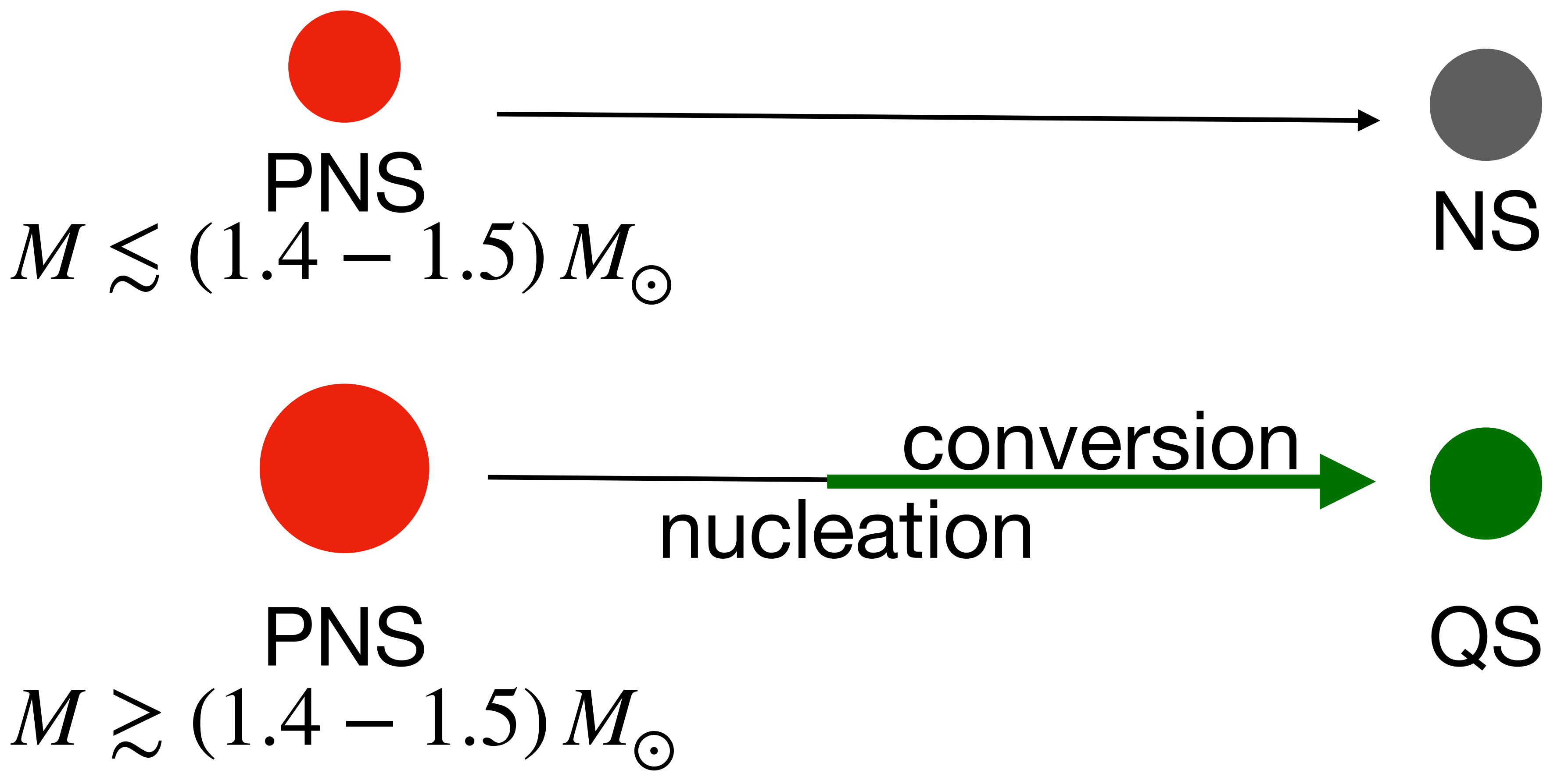


Results



Conditions at which nucleation timescale $\tau \sim 10^{-4}$ s (typical astrophysical dynamical timescale)

only PNS with $M_{PNS} \gtrsim 1.4 M_\odot$ nucleate and convert into QSs, while the less massive ones will become NSs



Any other questions or suggestions?
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Summary and conclusions

Background

- **deconfined quark d.o.f.** are expected to appear during the born and evolution of (some) **compact objects**
- **two families** of compact objects may exist if the **Witten hypothesis** is correct (absolute stability of SQM in bulk)
- **nucleation** is key for understanding under which conditions ordinary compact stars can convert into **QS**
- **color-superconducting** phases can help to explain the very massive observed compact objects

Method

- we added the contribution of **thermal fluctuations of the composition** in computing the nucleation time
- we propose a framework for **color-superconductivity in nucleation:**
    1. CFL is absolutely stable, unpaired matter is not
    2. diquark pairs form only in systems large enough (unpaired in $R < 1/\Delta$, CFL in $R > 1/\Delta$)

Goal: testing the compatibility of two families scenario

Results

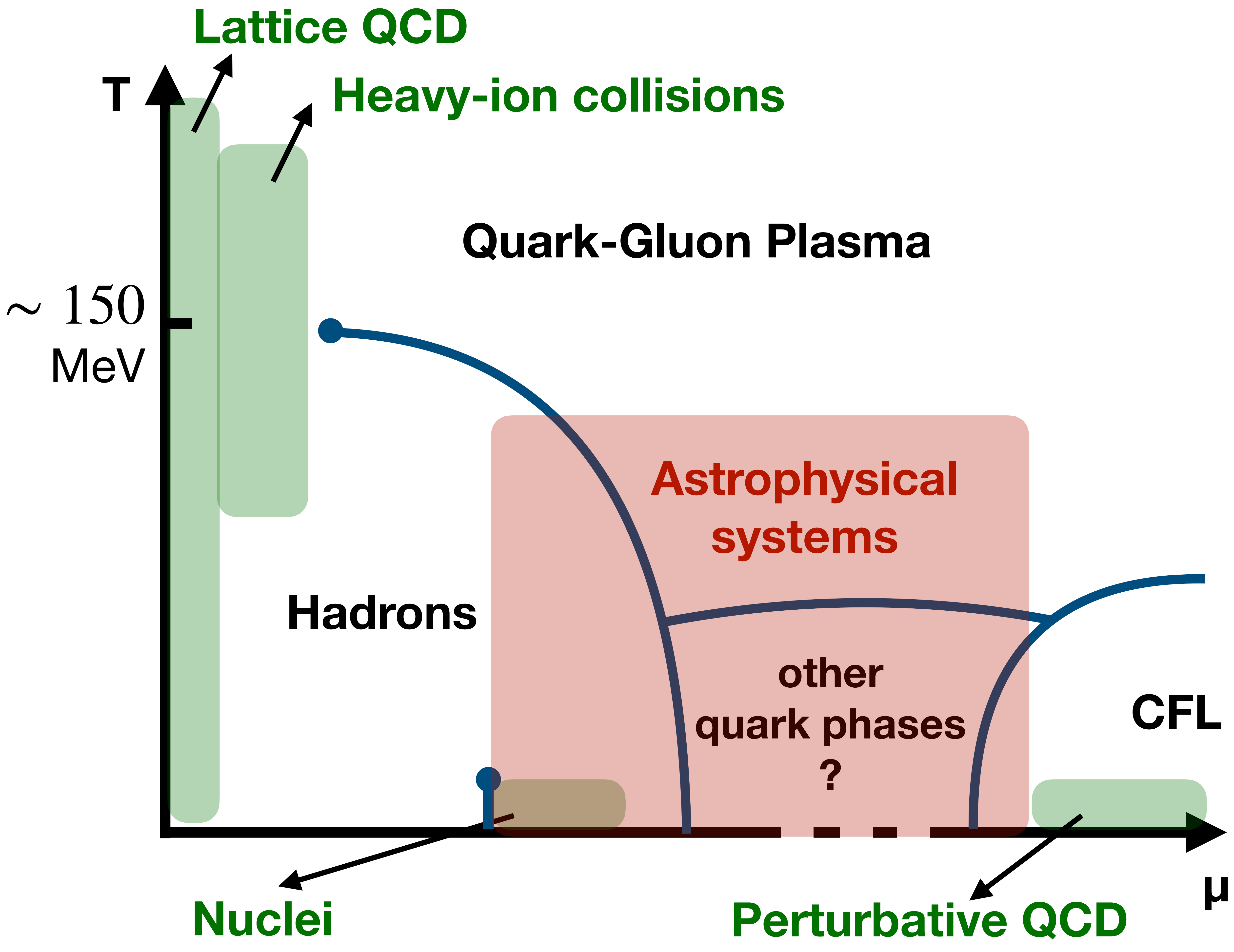
- including matter **composition fluctuations**, all the PNSs convert into QSs (**two families scenario does not work**)
- including color-superconductivity, the **two families scenario is compatible** with observations

Outlooks

- use more sophisticated EOSs for the quark phase
- how to include those **finite-size effects in simulations**?

Backup

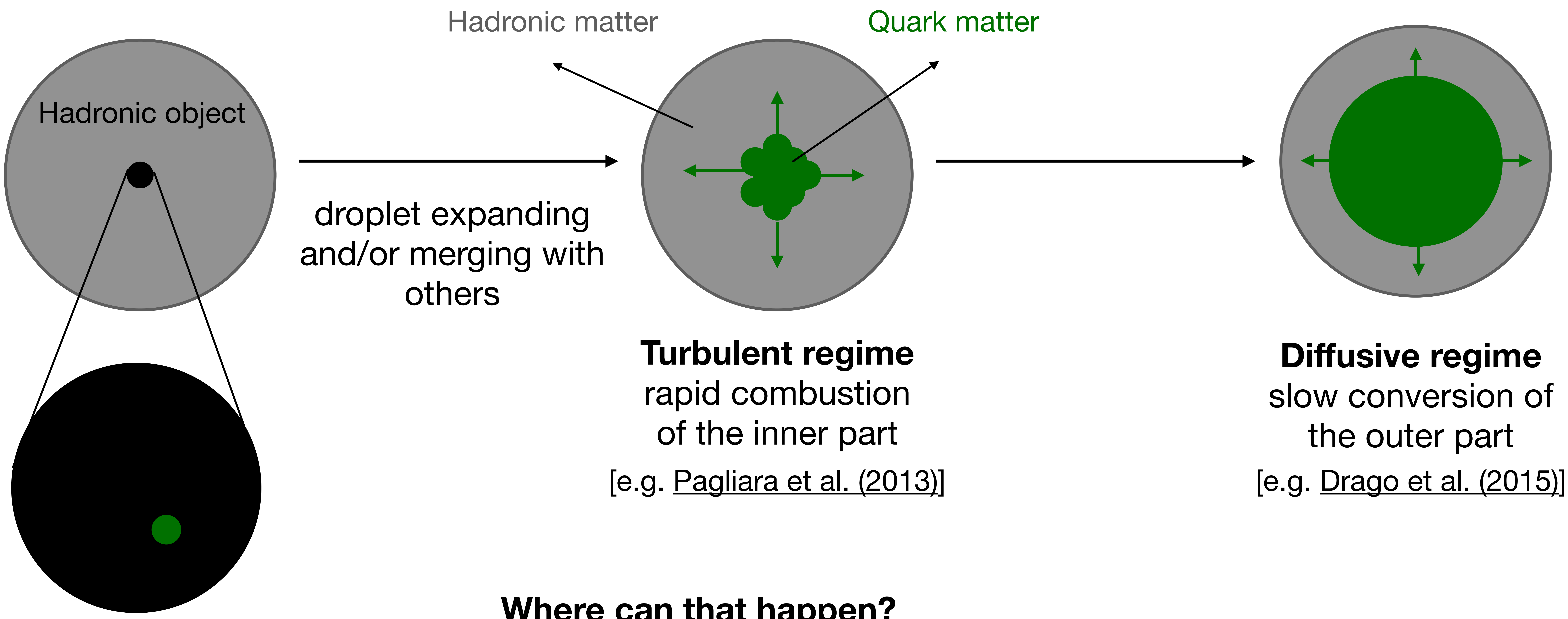
QCD phase diagram



- the high-density regime is poorly known
- quarks d.o.f. expected at $n_B \sim$ few n_0
- extreme densities are reached in astrophysical phenomena related to **compact objects**

Astrophysical systems	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

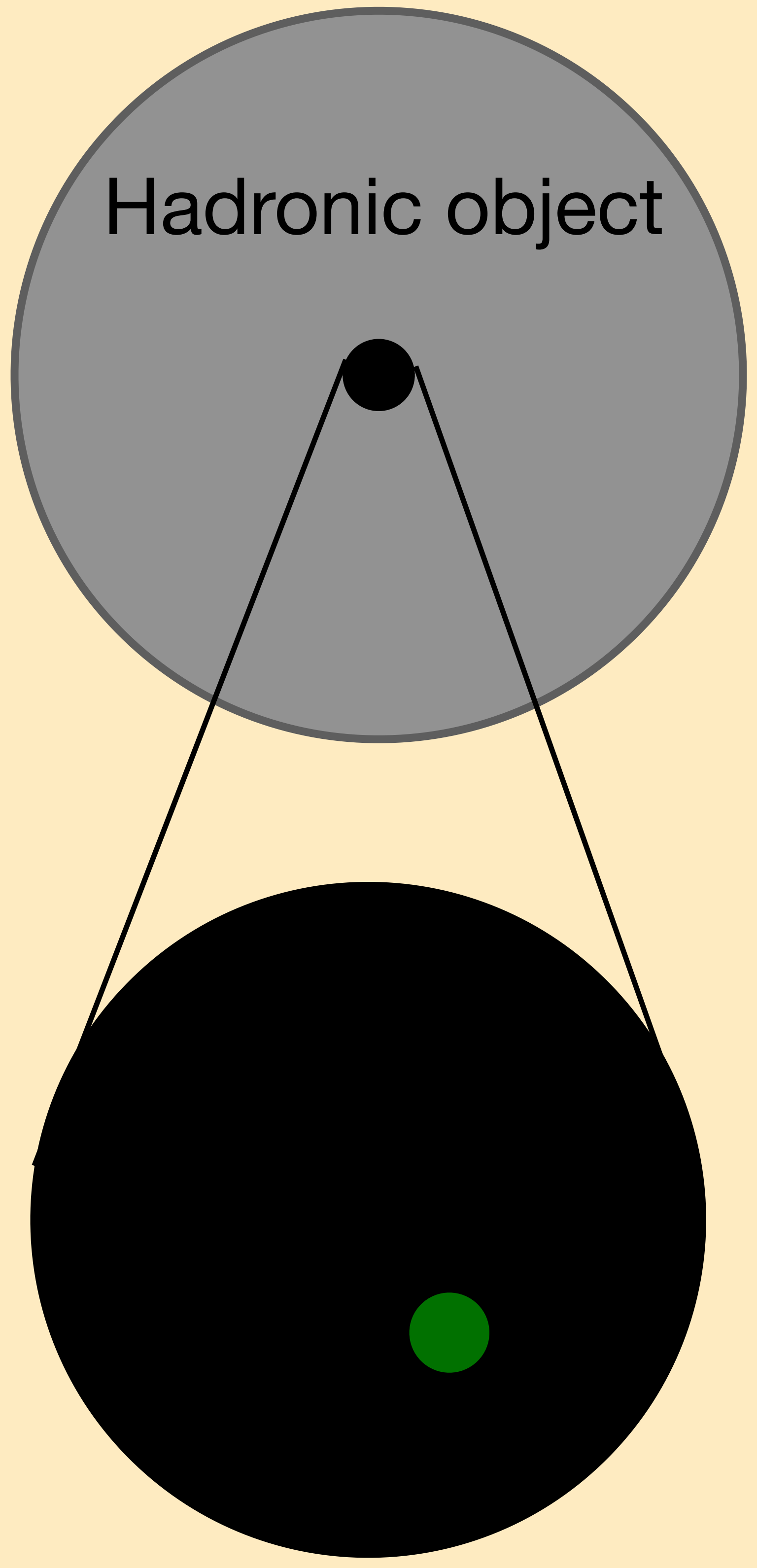
SQM in compact stars: formation



Nucleation
first droplet of quark matter

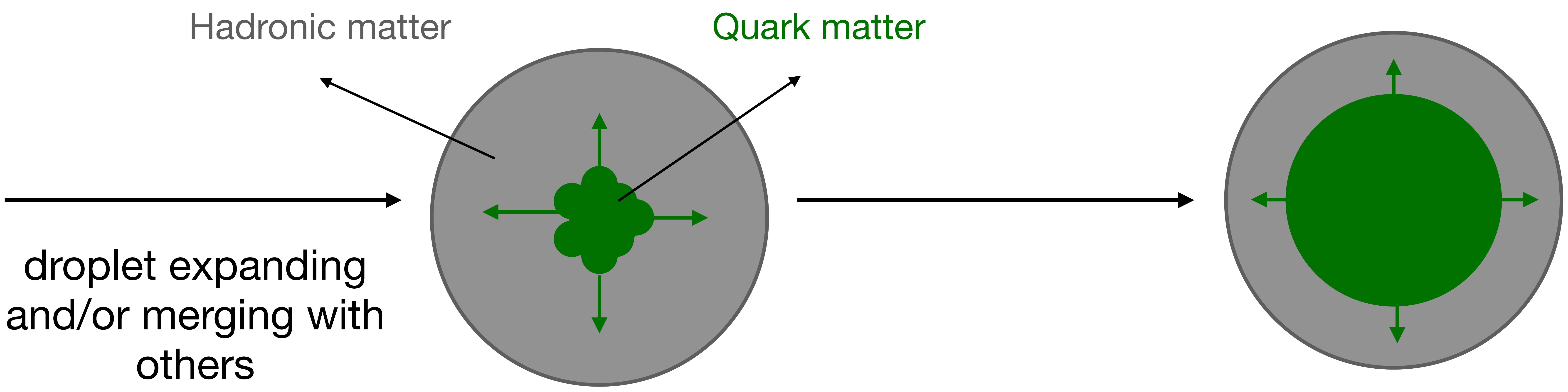
Where can that happen?
- CCSN (could be the mechanism leading to the explosion)
- evolution of a PNS
- matter accretion from a companion
- BNSM or in the remnant

SQM in compact stars: formation



Nucleation
first droplet of
quark matter

This work



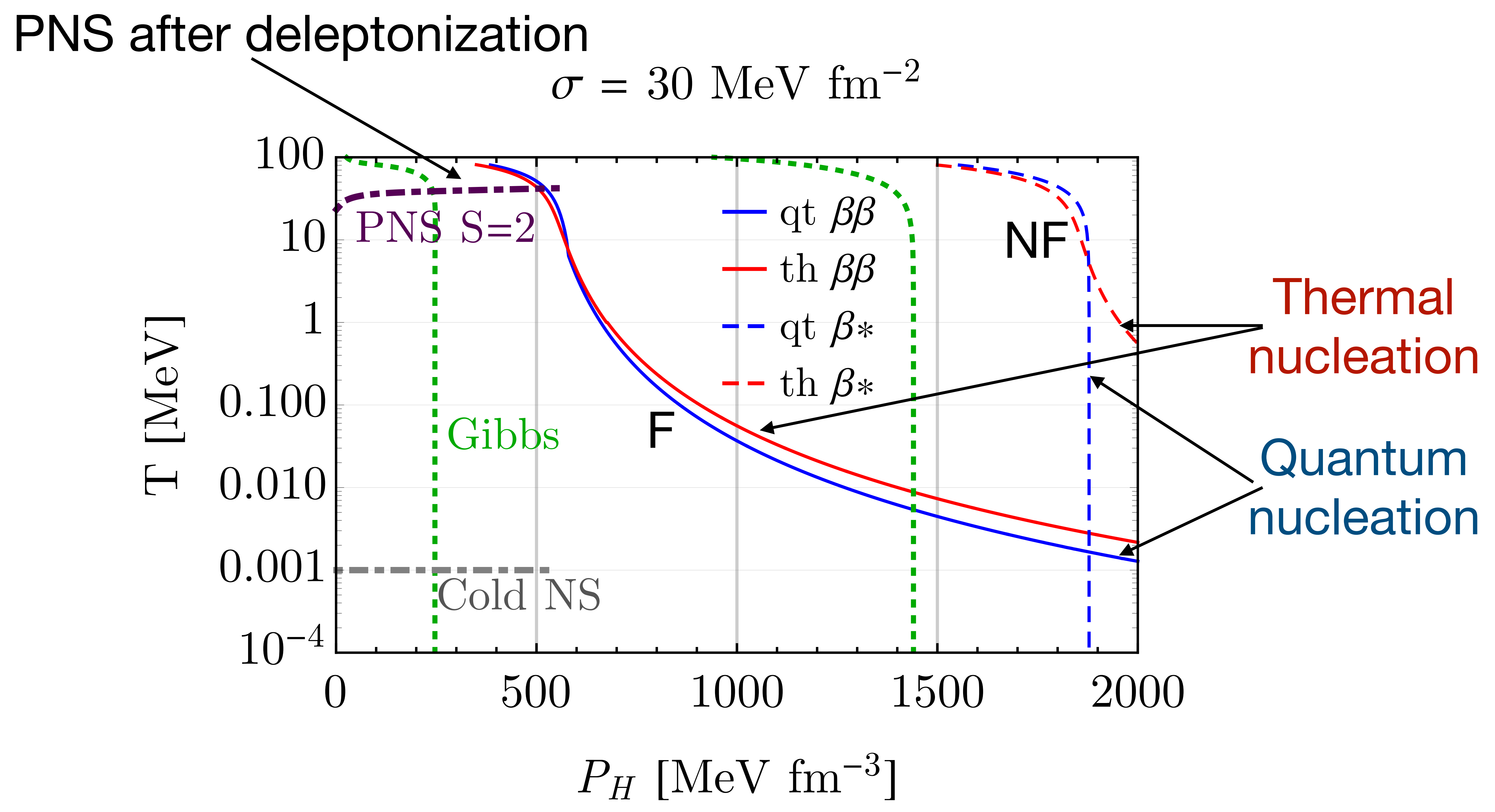
Turbulent regime
rapid combustion
of the inner part
[e.g. Pagliara et al. (2013)]

Diffusive regime
slow conversion of
the outer part
[e.g. Drago et al. (2015)]

Where can that happen?
- CCSN (could be the mechanism leading to the explosion)
- evolution of a PNS
- matter accretion from a companion
- BNSM or in the remnant

Results: two flavors case

[Guerrini et al. (2024)]



P and T at which the typical nucleation time is ~ 1 s

Effect of thermal fluctuation (F) in the hadronic composition

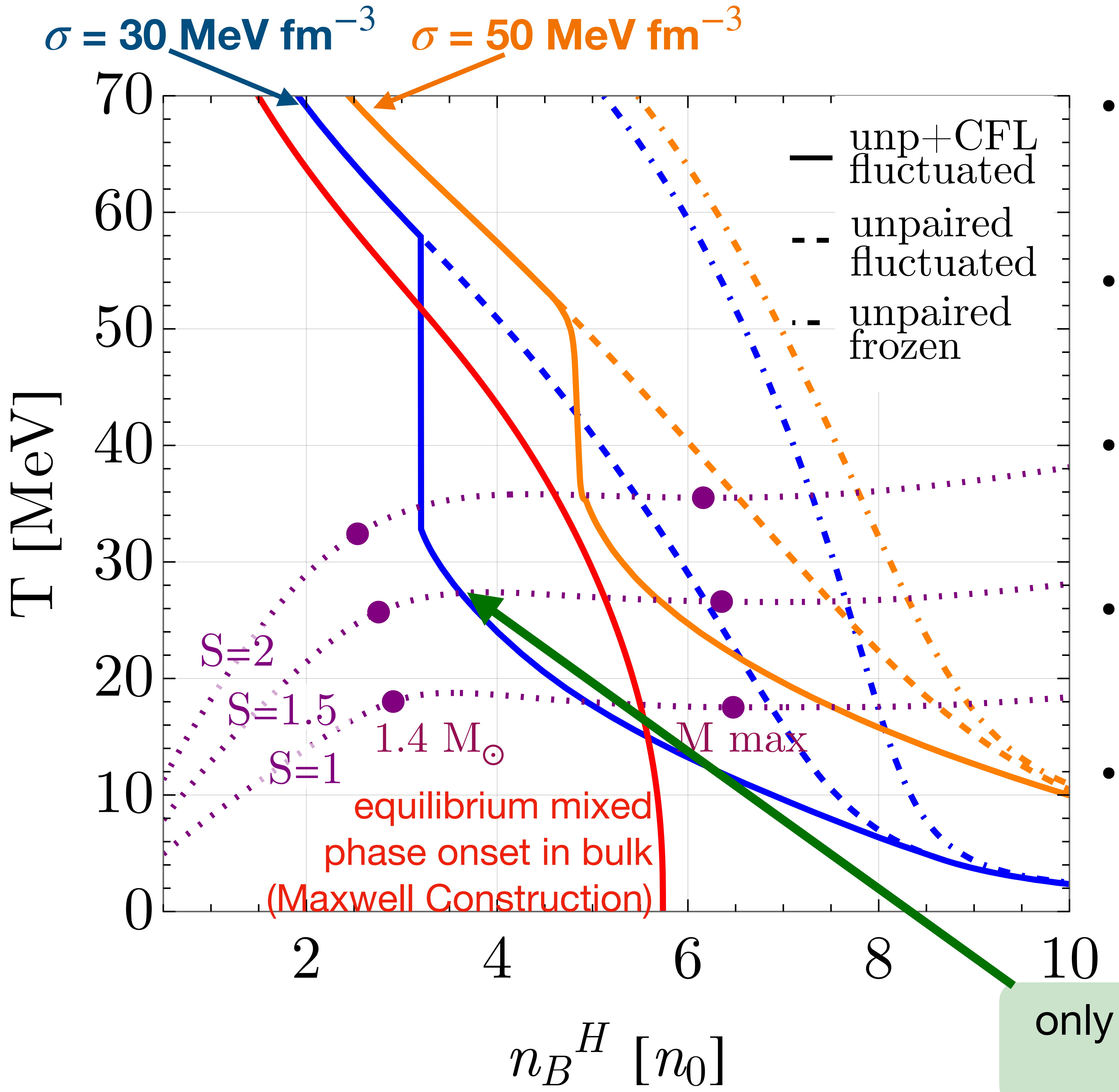
$T \gtrsim 10$ MeV:
- nucleation at lower P than no fluc. (NF) case
- most massive PSNs could nucleate

1 keV $\lesssim T \lesssim 10$ MeV:
- nucleation at lower P than NF case
- PSNs can not nucleate

$T \lesssim 1$ keV:
- negligible contribution

Take home message:
composition fluctuations lead to a much faster nucleation (i.e. deconfinement can start at lower P) in compact objects at intermediate and high temperature

Results

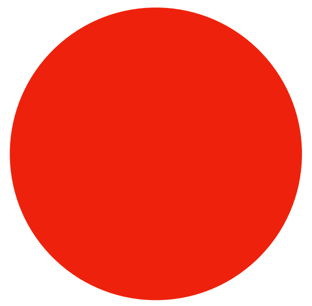


Conditions at which nucleation timescale $\tau \sim 10^{-4}$ s (typical astrophysical dynamical timescale)

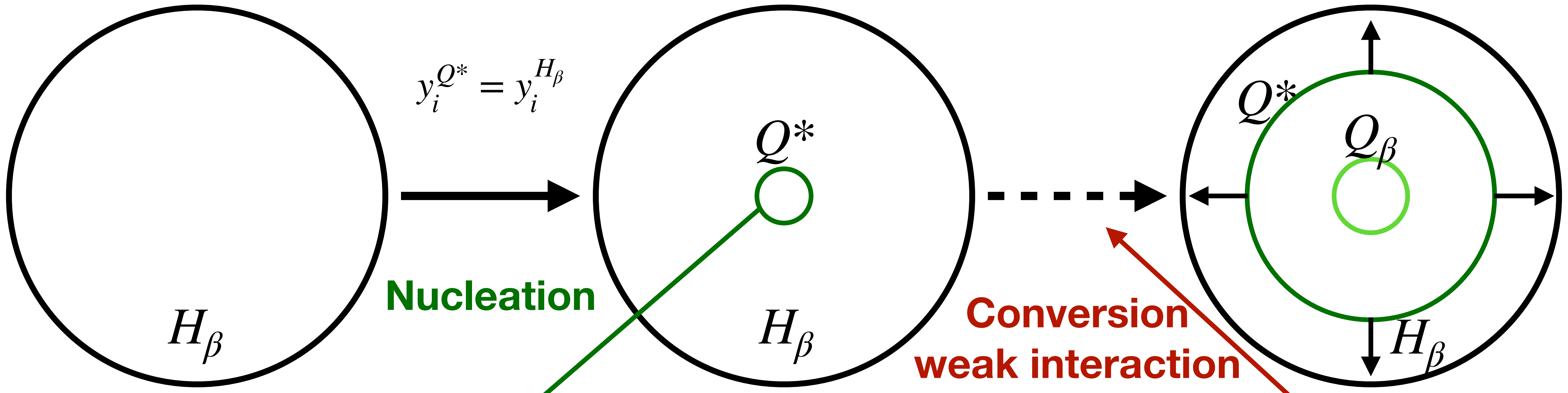
- Thermal fluctuations of matter composition lead to nucleation at lower n_B, thus T(fluctuated) < T(frozen)
- At low n_B we have high T, $\Delta \to 0$ thus the unpaired results are restored
- At intermediate n_B diquark pairs lead to a lower nucleation temperature
- At high n_B critical droplet form before diquark pairs, thus unpaired = unp+CFL
- At high n_B hadronic composition is similar to the equilibrium quark composition, thus frozen $\sim$ fluctuated

only PNS with $M_{PNS} \gtrsim 1.5 M_\odot$ nucleate and convert into QSs, while the less massive ones will become NSs

Nucleation: calculations setup



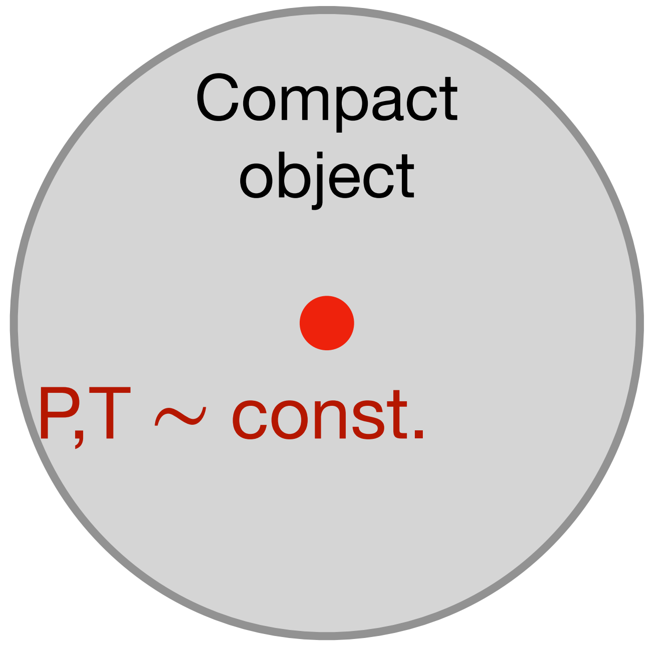
no fluctuations

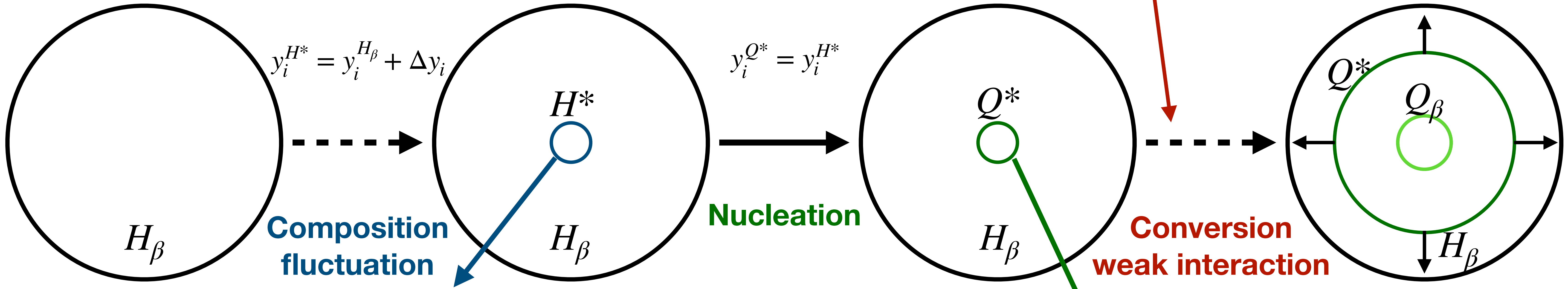


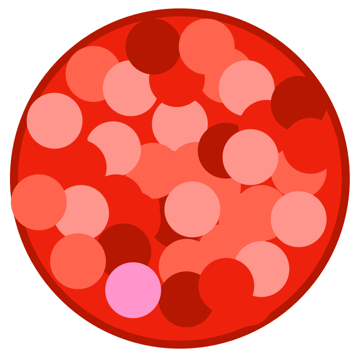
Q* is an out-of-equilibrium quark phase where

$$y_u^{Q*} = 2y_p^H + y_n^H + y_\Lambda^H + \dots$$
$$y_d^{Q*} = y_p^H + 2y_n^H + y_\Lambda^H + \dots$$
$$y_s^{Q*} = y_\Lambda^H + \dots$$

The weak interaction modifies the quark composition minimizing the free energy into the β-equilibrium







fluctuations

H* is an out-of-equilibrium hadronic phase in which the local composition is different wrt the average value

$$y_f^{H*} = y_f^H + \Delta y_f$$

Q* is an out-of-equilibrium quark phase with the same flavor composition as H*

Backup: nucleation

$$\Gamma = \Gamma_0 \, e^{-W/T}$$

$$R_* = \frac{2\sigma}{P_{Q*} - P_H} \qquad W = \frac{16}{3}\pi \frac{\sigma^3}{(P_{Q*} - P_H)^2}.$$

$$\tau = \frac{1}{V\Gamma}$$

$$W = -\frac{4}{3}\pi R_*^3 \left[P_{Q*} - P_H\right] + 4\pi\sigma R_*^2.$$

$$\begin{aligned} W_1 &= \sum_{i=B,C,S,e} N_i^* (\mu_i^{H*} - \mu_i^H) \\ &= \frac{4}{3}\pi R_*^3 n_B^{Q*} \sum_{i=B,C,S,e} Y_i^* (\mu_i^{H*} - \mu_i^H) \end{aligned}$$

$$\begin{aligned} \mu_B^Q(n_B^{Q*}, \{Y_i^{Q*}\}, T) &= \mu_B^H(n_B^H, \{Y_i^H\}, T) \\ \mu_C^Q(n_B^{Q*}, \{Y_i^{Q*}\}, T) + \mu_e^Q(n_B^{Q*}, Y_e^{Q*}, T) &= \mu_C^H(n_B^H, \{Y_i^H\}, T) + \mu_e^H(n_B^H, Y_e^H, T) \\ \mu_S^Q(n_B^{Q*}, \{Y_i^{Q*}\}, T) &= \mu_S^H(n_B^H, \{Y_i^H\}, T) \\ \mu_\nu^Q(n_B^{Q*}, Y_{\nu_e}^{Q*}, T) &= \mu_\nu^H(n_B^H, Y_{\nu_e}^H, T) \\ Y_C^{Q*} - Y_e^{Q*} &= 0. \end{aligned}$$

Backup: CFL+unp

$$P_Q(n_B^Q, \{Y_i^Q\}, T, R) = \begin{cases} P_{Qunp}(n_B^Q, \{Y_i^Q\}, T) & \text{if} \quad R \leq R_\Delta \\ P_{QCFL}(n_B^Q, T) & \text{if} \quad R > R_\Delta \end{cases}$$

$$R_*(n_B^H, \{Y_i^H\}, T) = \begin{cases} R_{unp*}(n_B^H, \{Y_i^H\}, T) & \text{if} \quad R_{unp*}(n_B^H, \{Y_i^H\}, T) \leq R_\Delta \\ \max\left[R_\Delta, R_{CFL*}(n_B^H, T)\right] & \text{if} \quad R_{unp*}(n_B^H, \{Y_i^H\}, T) > R_\Delta \end{cases}$$

$$\Delta(T) = \Theta(T_c - T)\Delta_0\sqrt{1 - \frac{T}{T_c}}$$

$$T_c \simeq 2^{1/3} 0.57 \Delta_0$$

Schmitt (2010) Lec. Not. Phys

Backup: three flavors EOSs

$$P_q(\mu_i, T, m_i, \alpha_s = 0) = \frac{6}{2\pi^2}\frac{1}{3}\int_0^{+\infty}\frac{k^4}{E(k,m_i)}[\mathbf{f}(k,\mu_i,T,m_i) + \mathbf{f}(k,-\mu_i,T,m_i)]dk$$

$$P_i^Q(\mu_i, T) = P_q(\mu_i, T, m_i, \alpha_s = 0) - \frac{5\pi\alpha_s}{18}T^4 - \frac{2\alpha_s}{\pi}\left(\frac{1}{2}T^2\mu_i^2 + \frac{1}{4\pi^2}\mu_i^4\right)$$

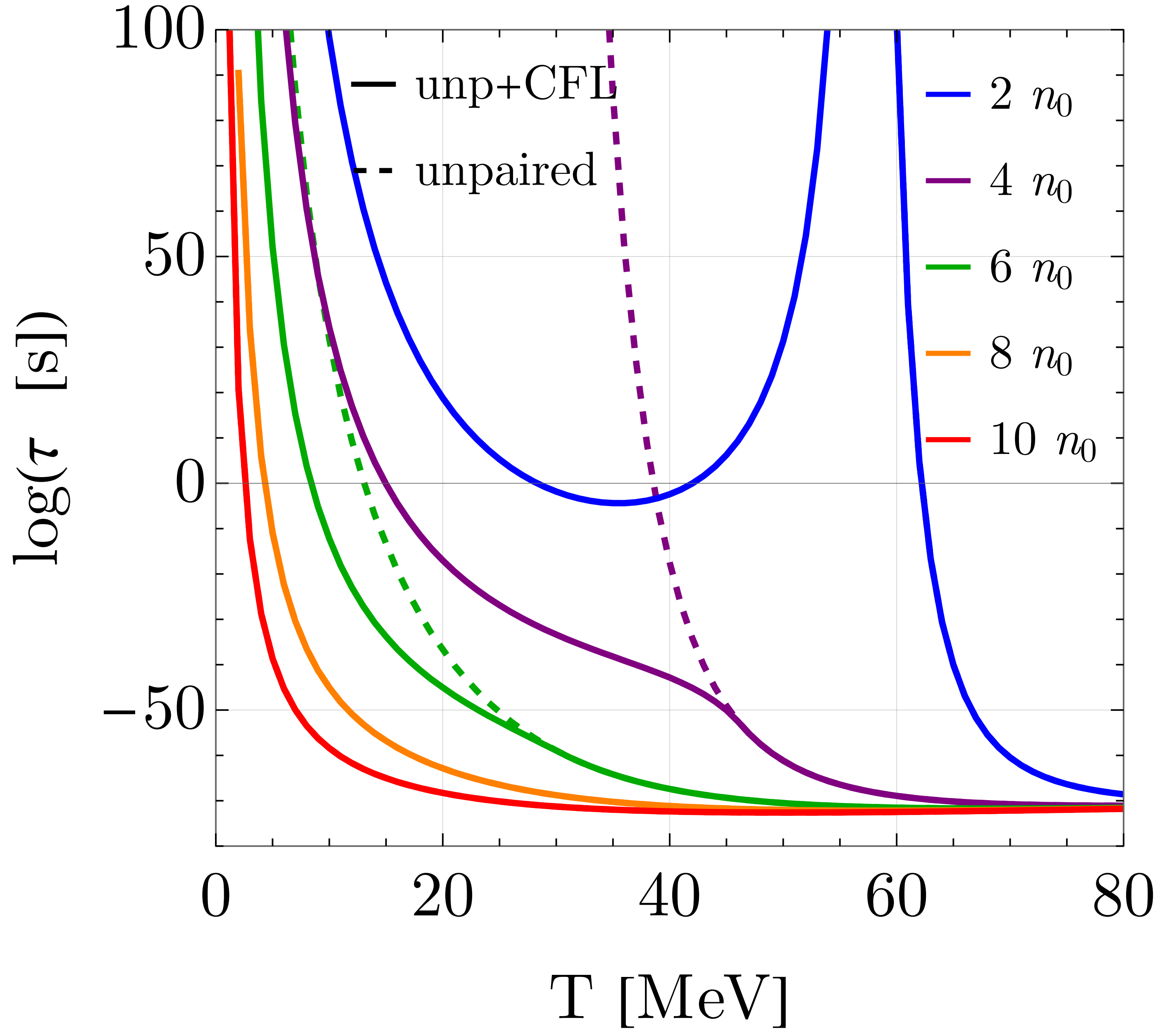
Fischer et al. (2011) ApJ

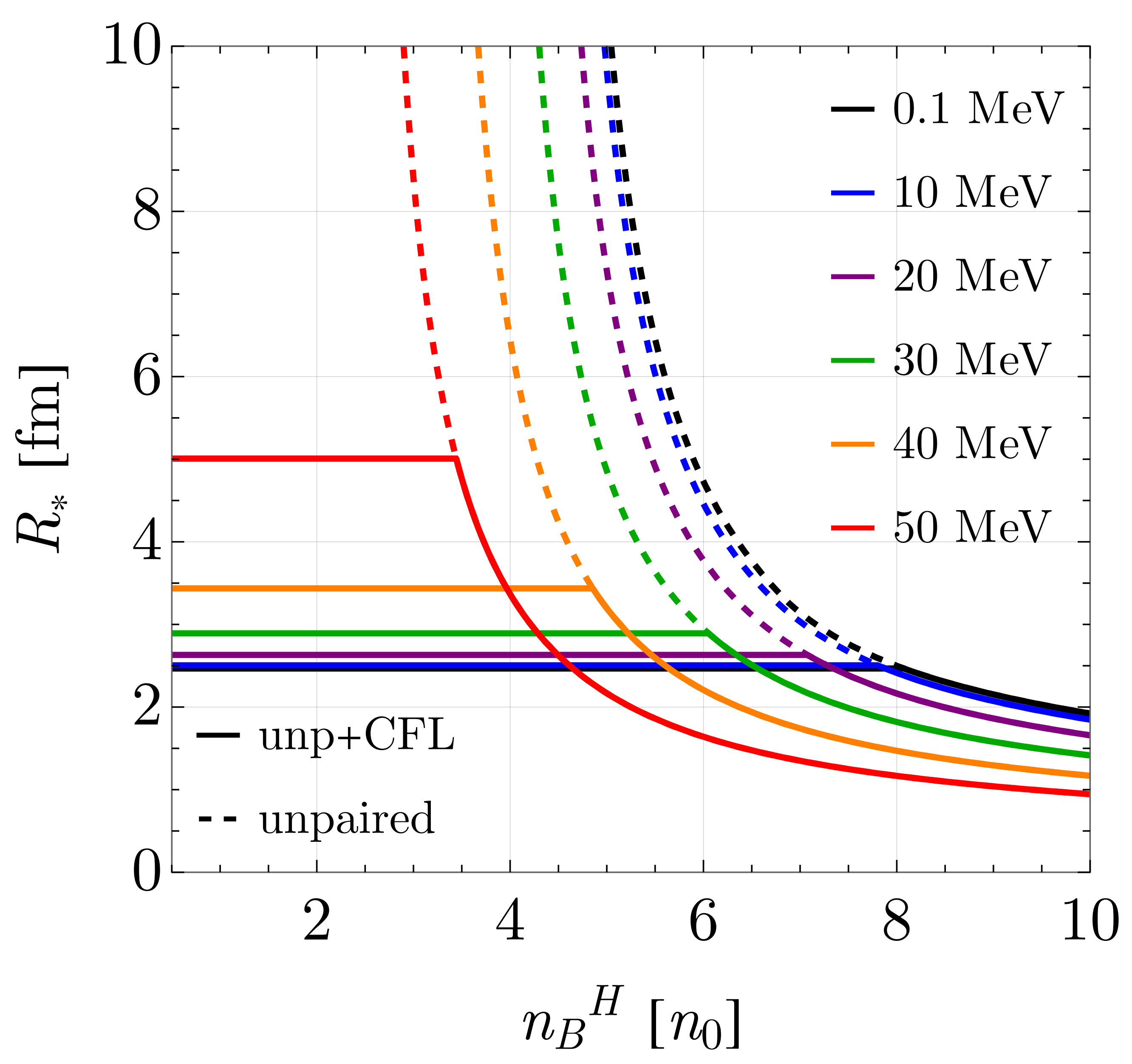
$$\Delta(T) = \Theta(T_c - T)\Delta_0\sqrt{1 - \frac{T}{T_c}}$$

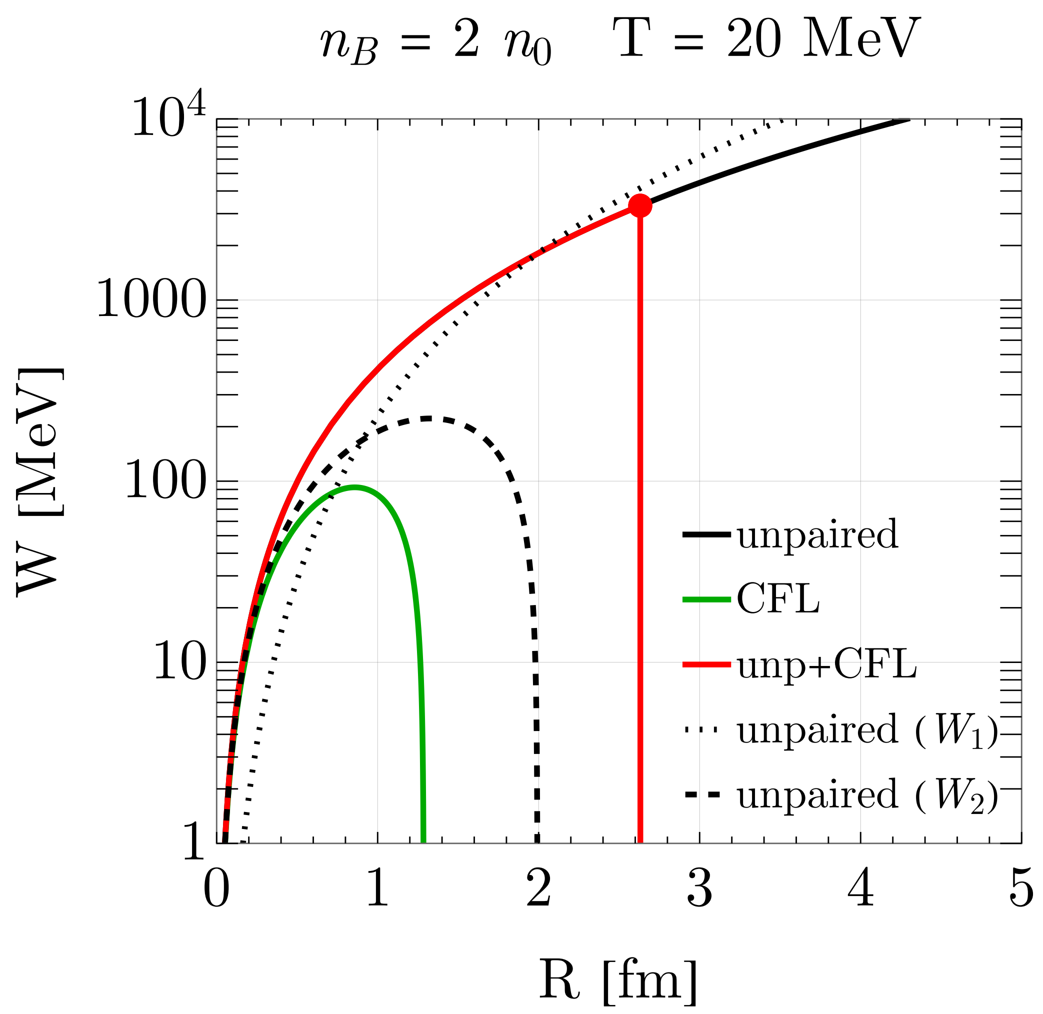
$$T_c \simeq 2^{1/3} 0.57 \Delta_0$$

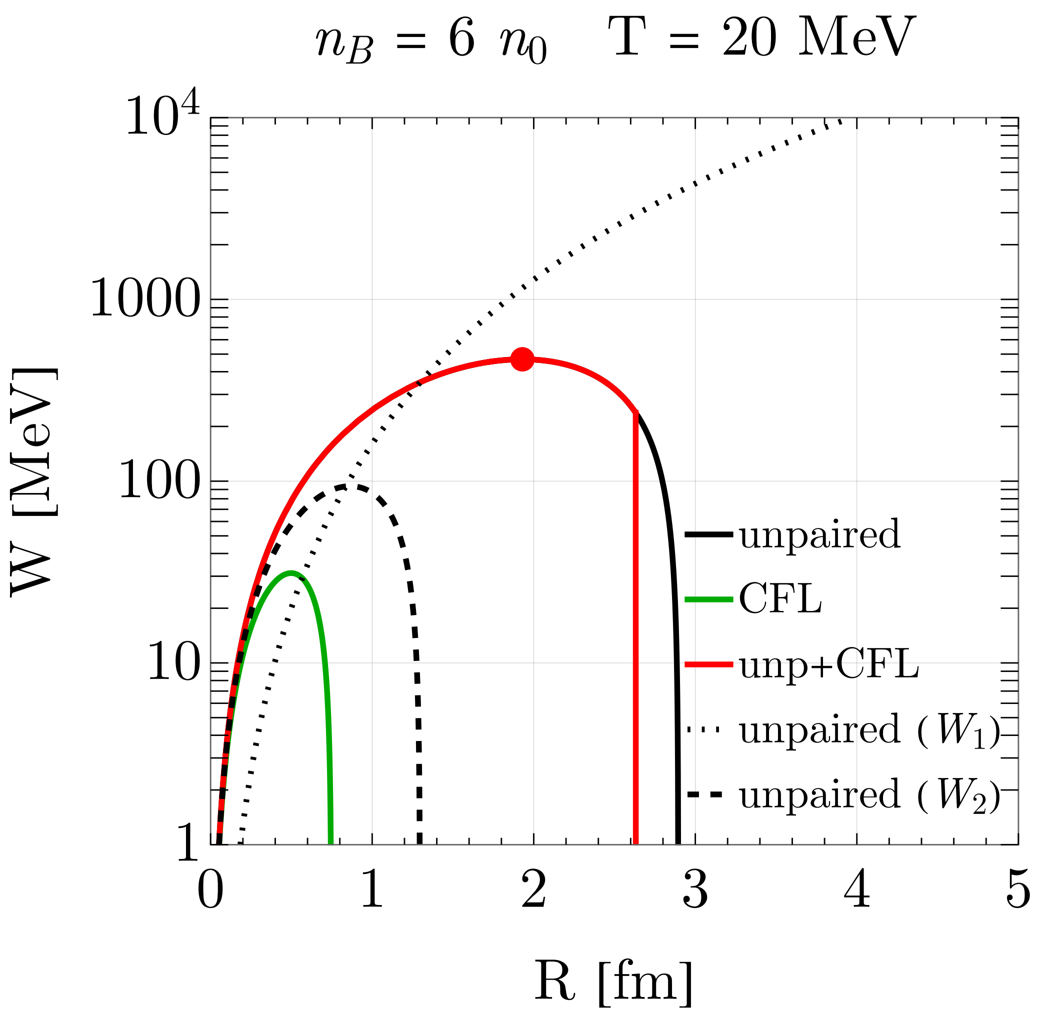
Schmitt (2010) Lec. Not. Phys

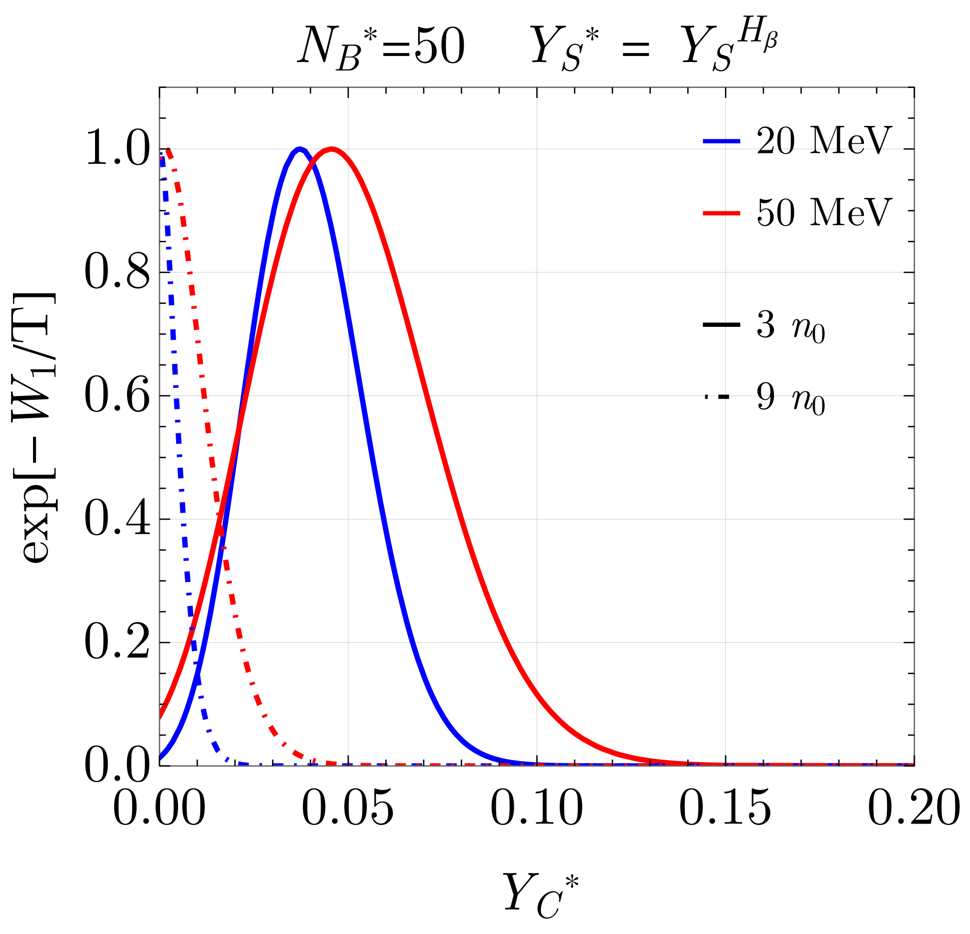
Backup: more on three flavors

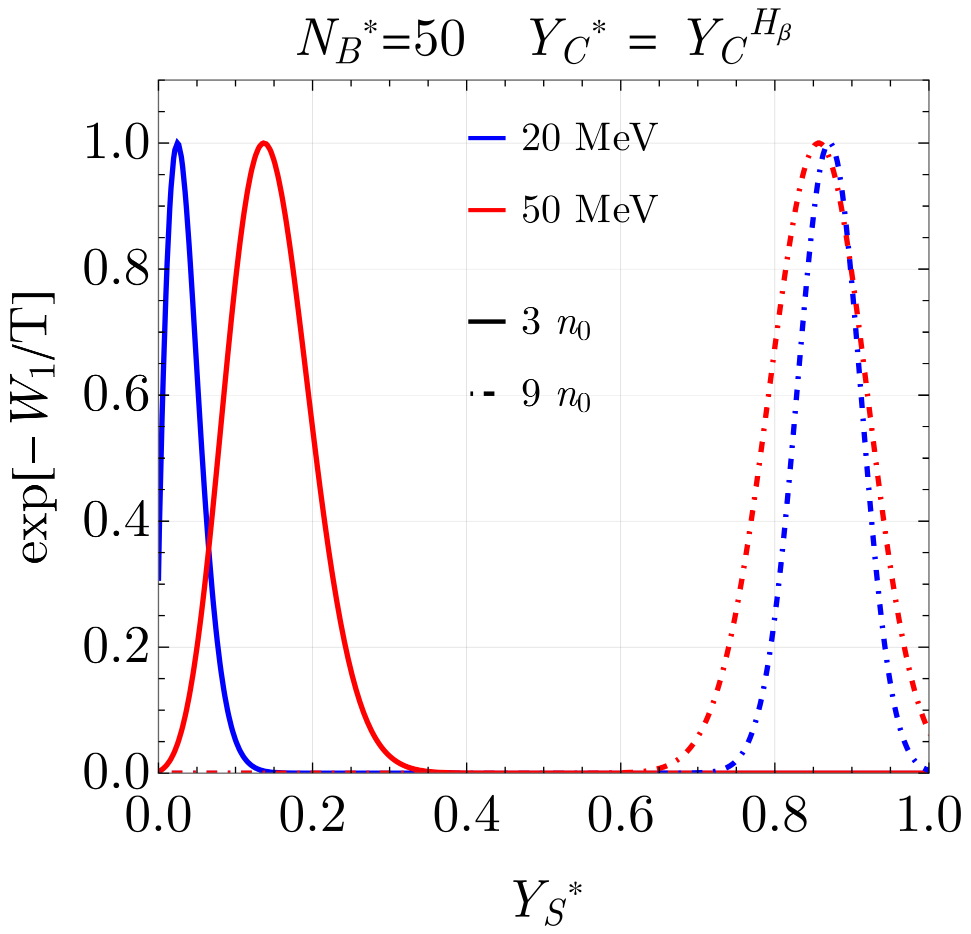












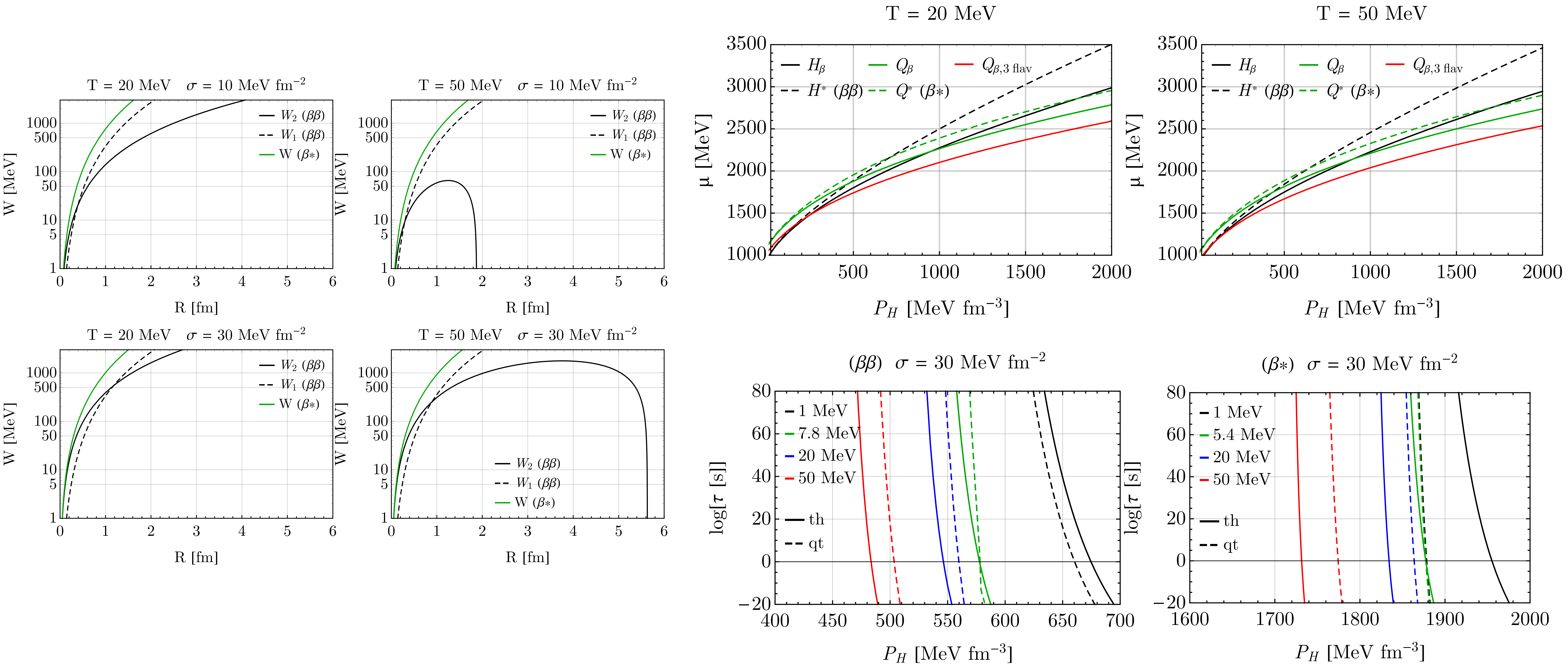
Backup: more on two flavors

$$W_1 = n_{B,Q^*} V_{Q^*} \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*} \right)$$
$$= n_{B,Q^*} \frac{4}{3} \pi R^3 \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*} \right).$$

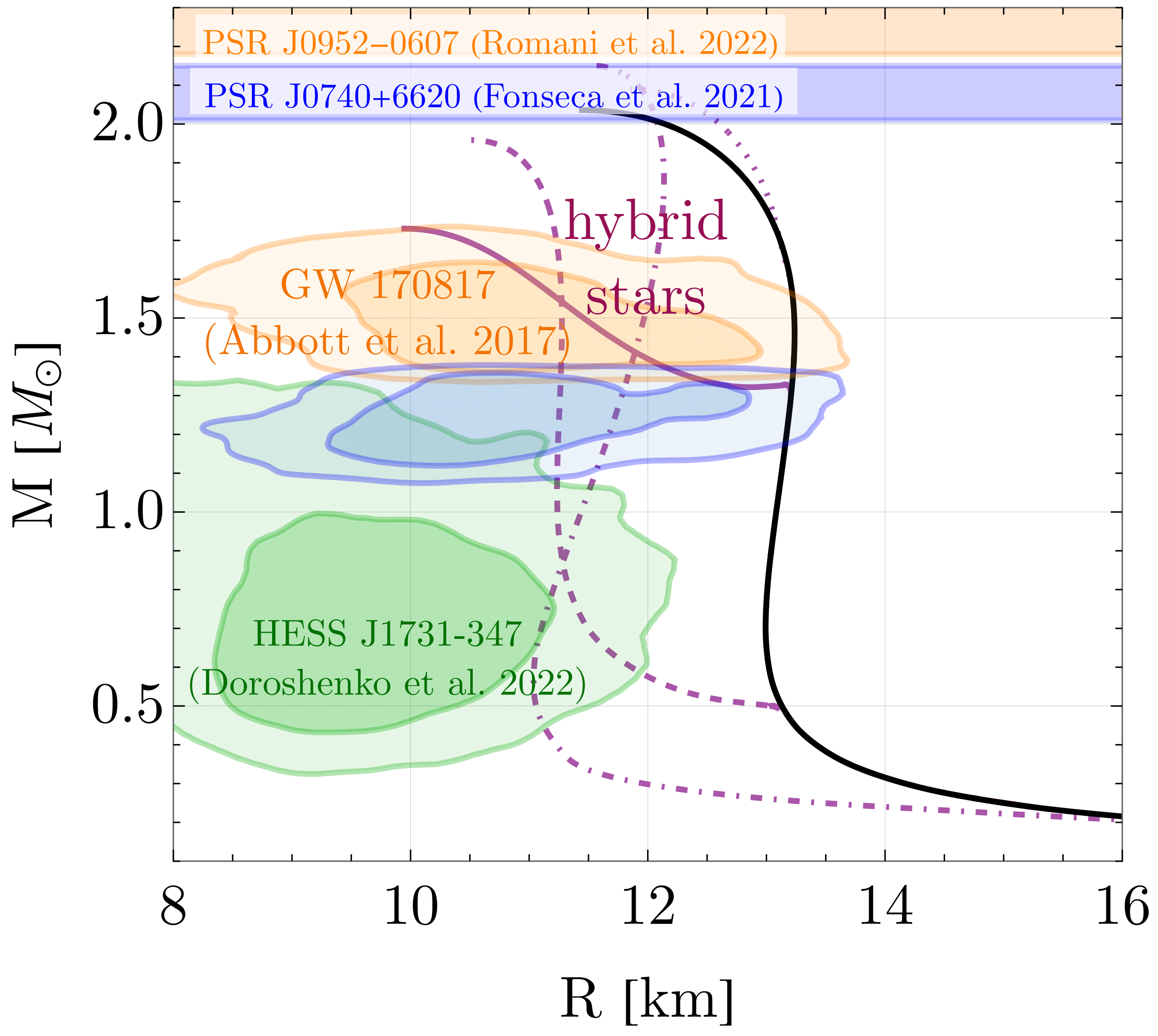
$$W_2 = \frac{4}{3} \pi R^3 n_{B,Q^*} \left(\mu_{Q^*} - \mu_{H^*} \right) + 4\pi\sigma R^2.$$

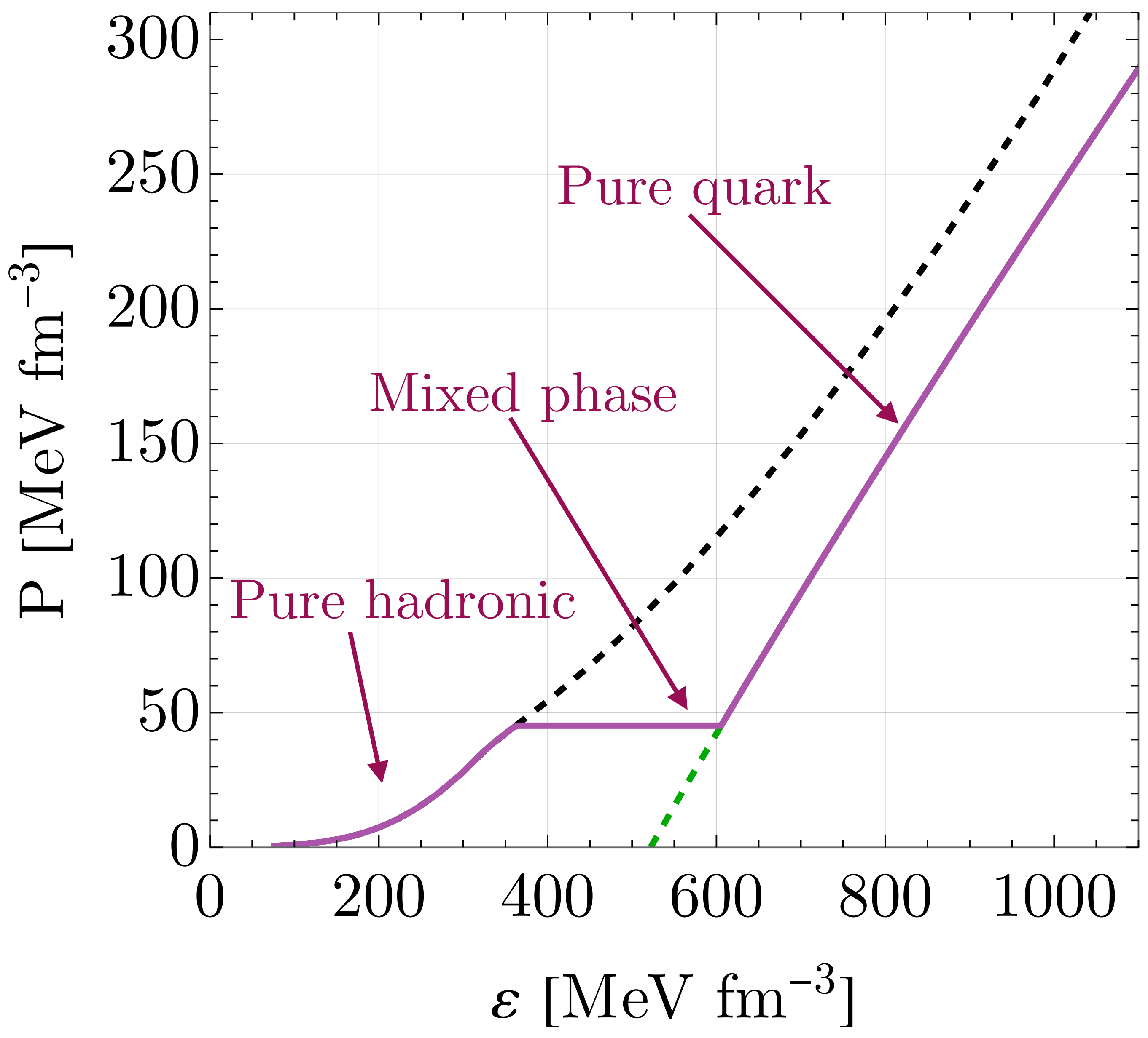
$$\tau^{th}(P_H, \{\Delta y_i\}, T) = \left[V_{nuc} \frac{\kappa}{2\pi} \Omega_0 \mathcal{P}_1^{th} \mathcal{P}_2^{th} \right]^{-1}$$

Backup: more on two flavors results



SQM in compact stars: one or two families?

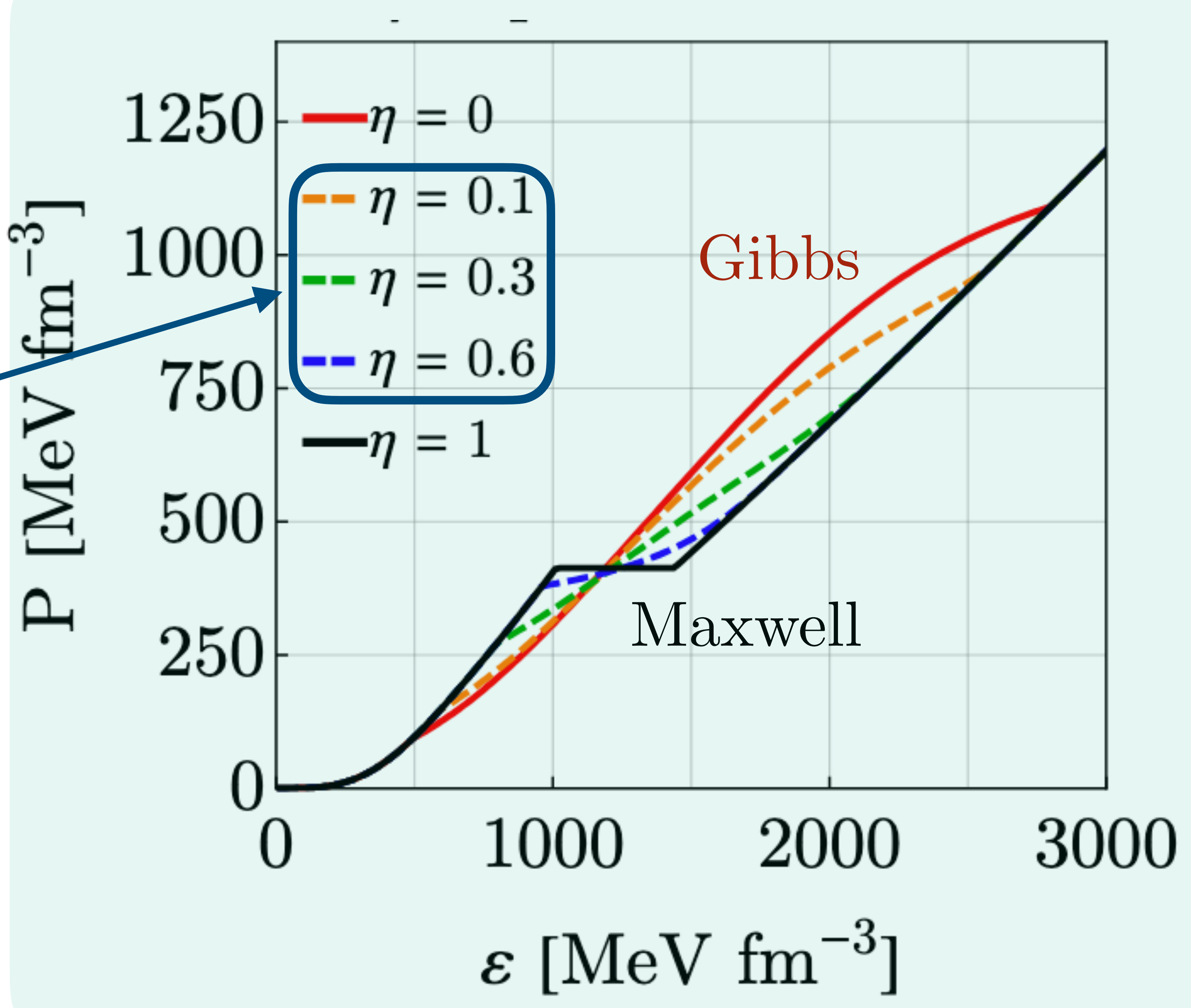




One family scenario

- deconfined quarks d.o.f. expected in massive compact stars
- **hybrid stars**: SQM in the core and hadrons in the outer part
- 1st order phase transition, crossover, quarkyonic, …

Maxwell C., Gibbs C., mixed approach



[Constantinou et al. 2024]

(soon at finite temperature)