Strange quark matter nucleation and Neutron stars — Quark stars coexistence

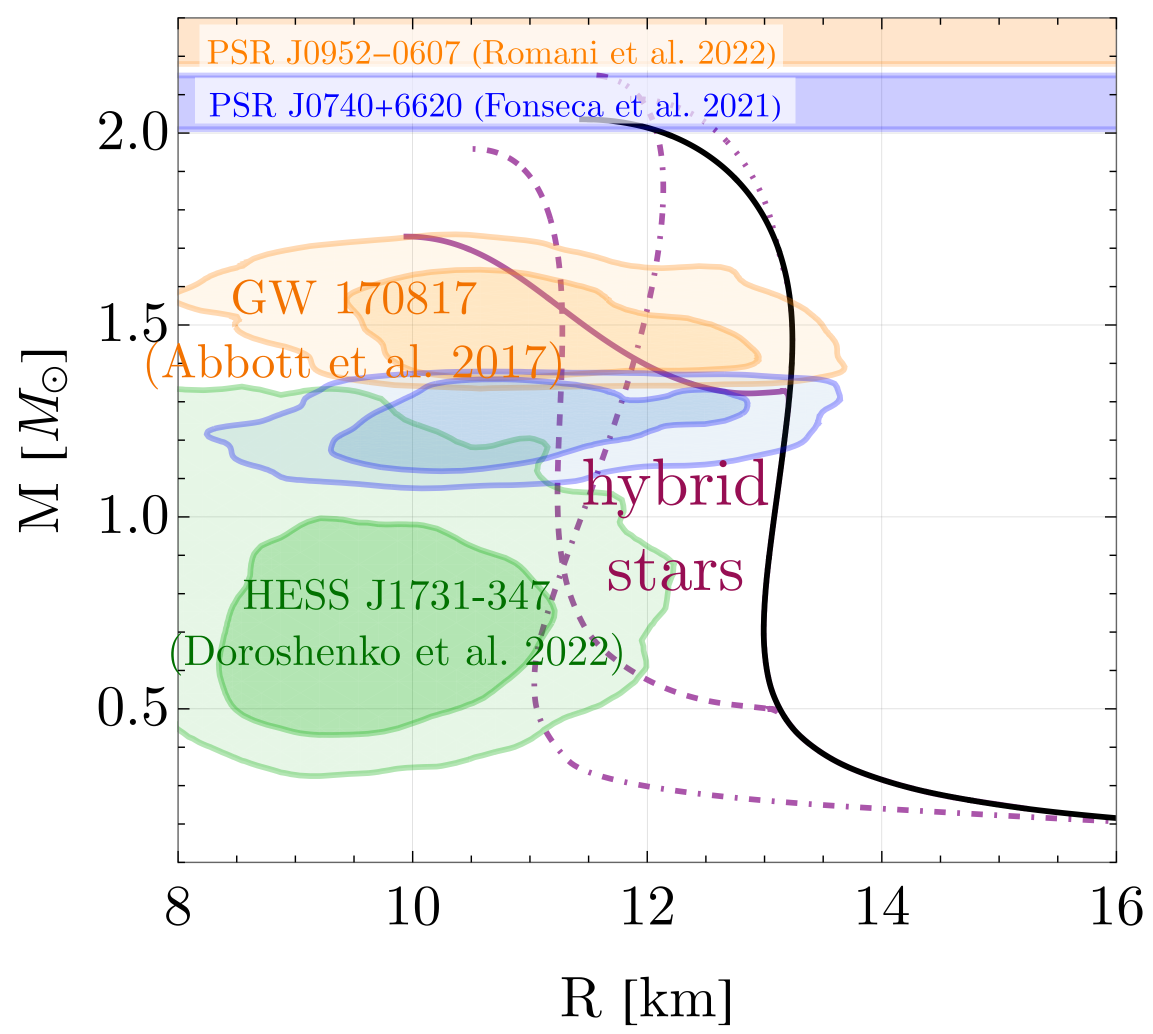
Mirco Guerrini
PhD student - University of Ferrara (Italy)
G. Pagliara (Ferrara U.), A. Drago (Ferrara U.), A. Lavagno (Poli Turin)

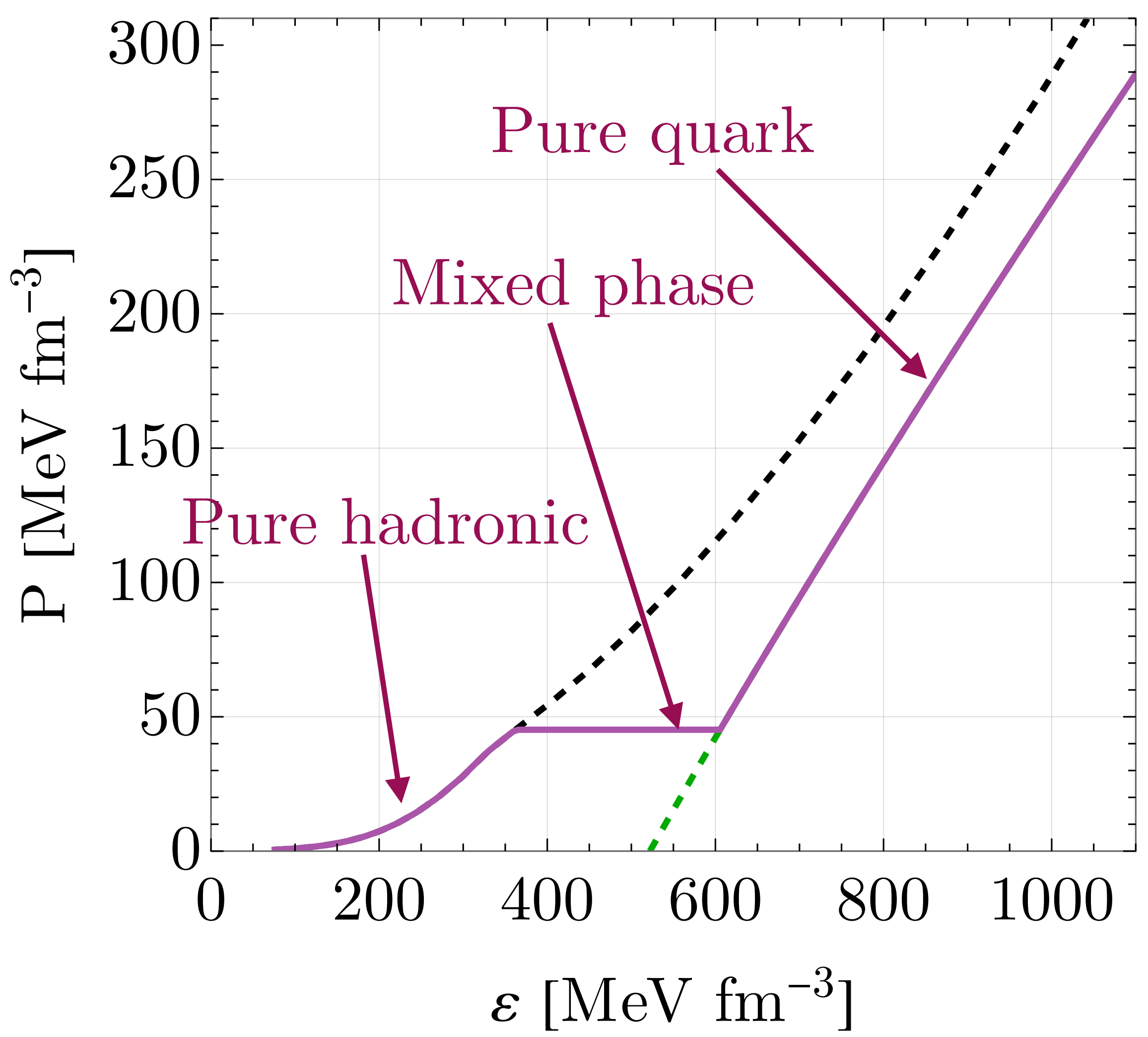
Università degli Studi di Ferrara

TNPI2025 - XX Conference on Theoretical Nuclear Physics in Italy

INFN FERRARA

SQM in compact stars: one or two families?

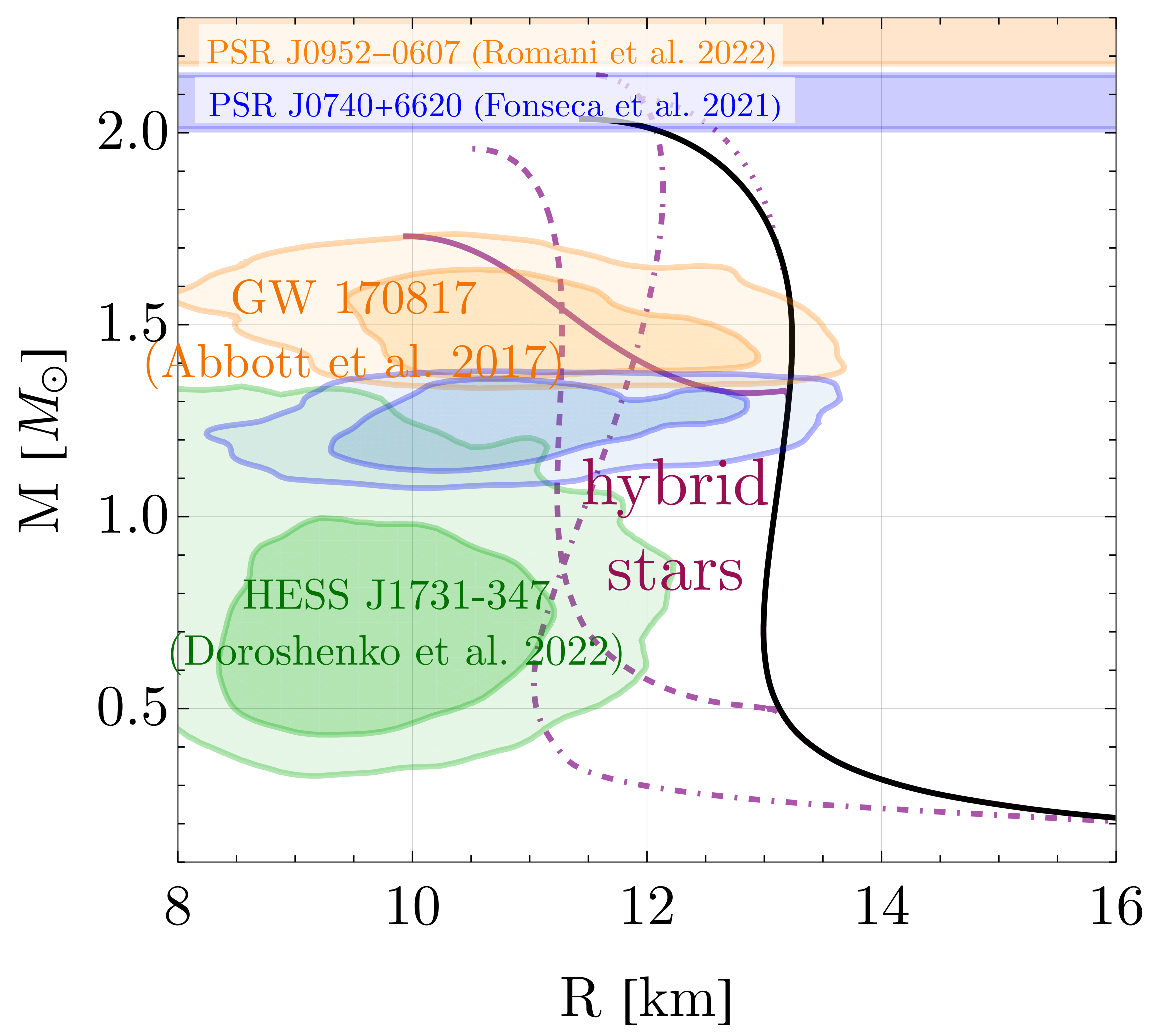


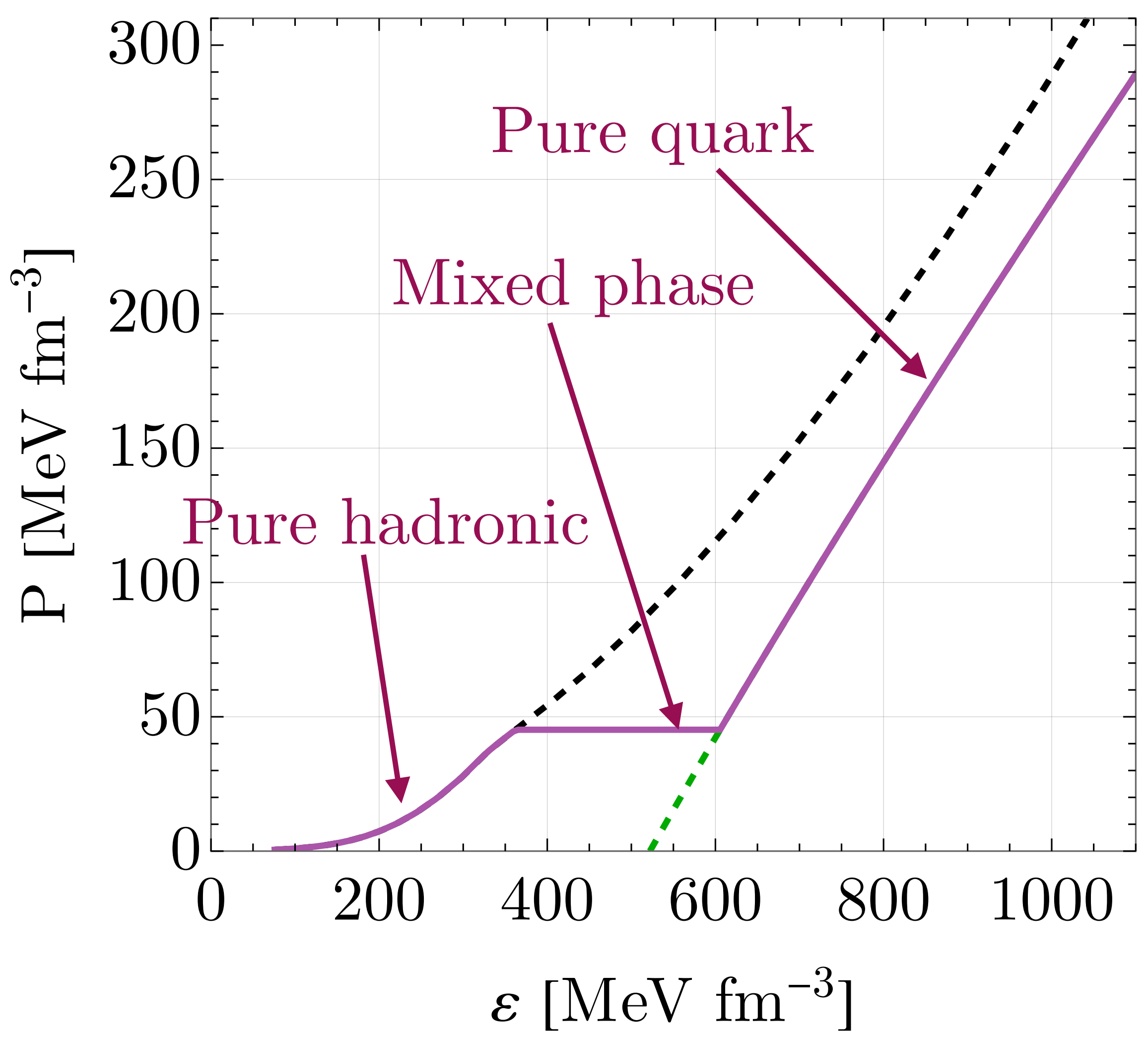


One family scenario

- 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, …

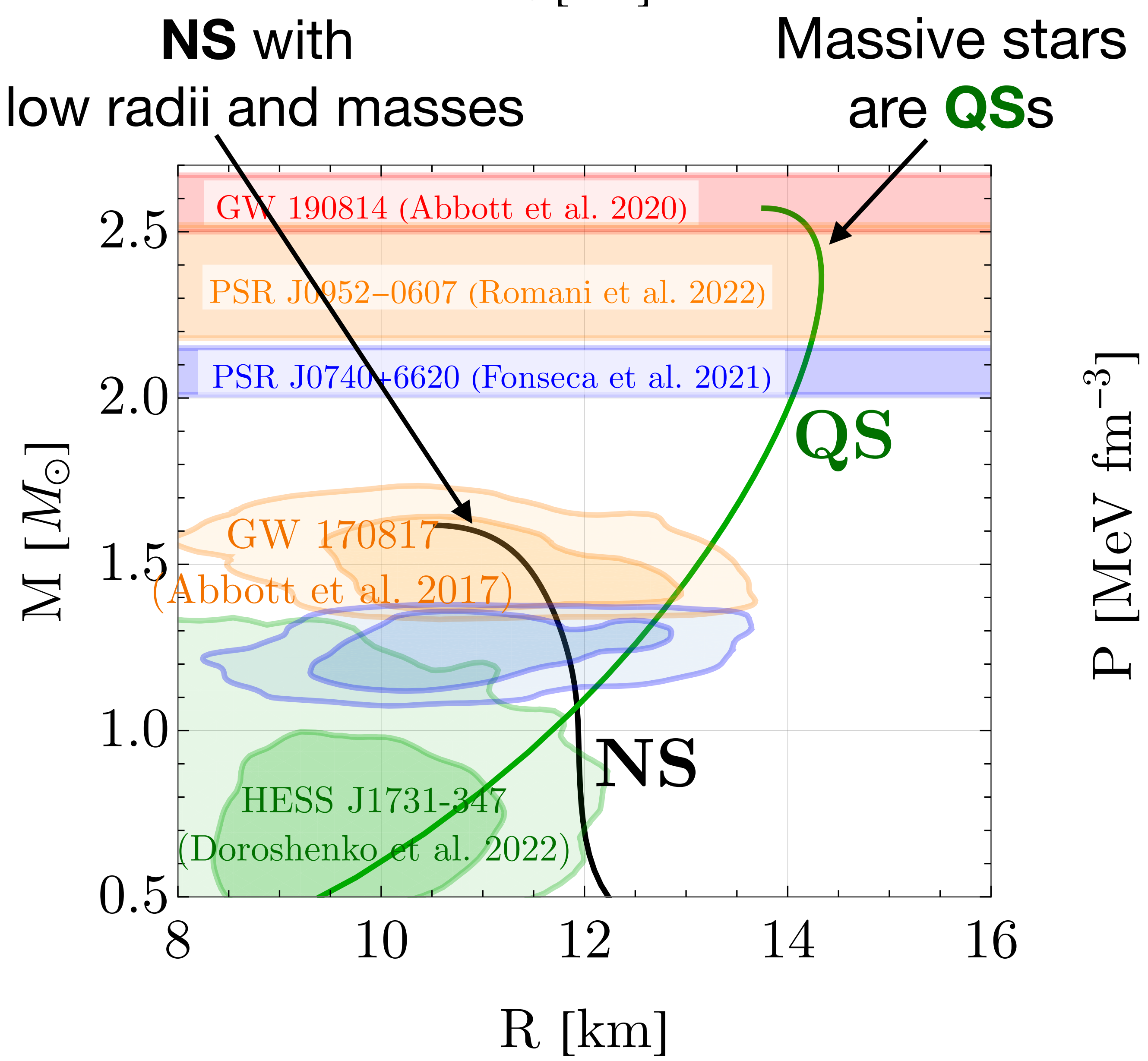
SQM in compact stars: one or two families?

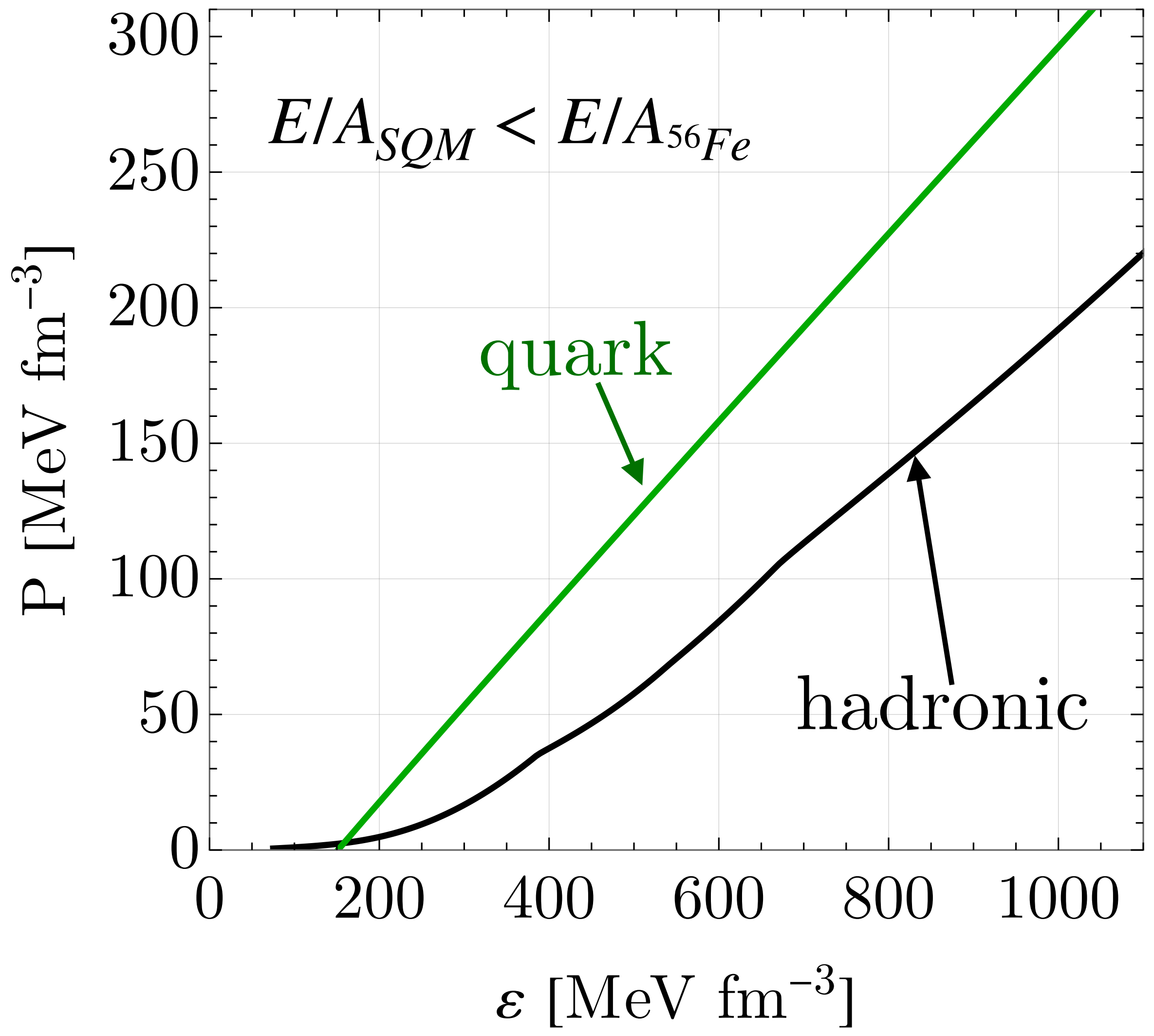




One family scenario

- 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, …

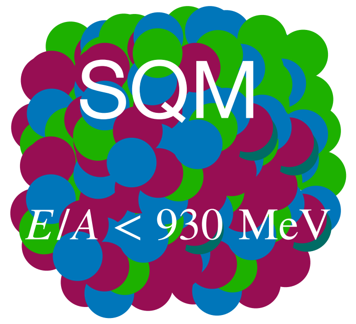


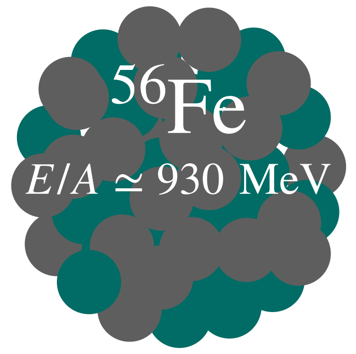


Two families scenario

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

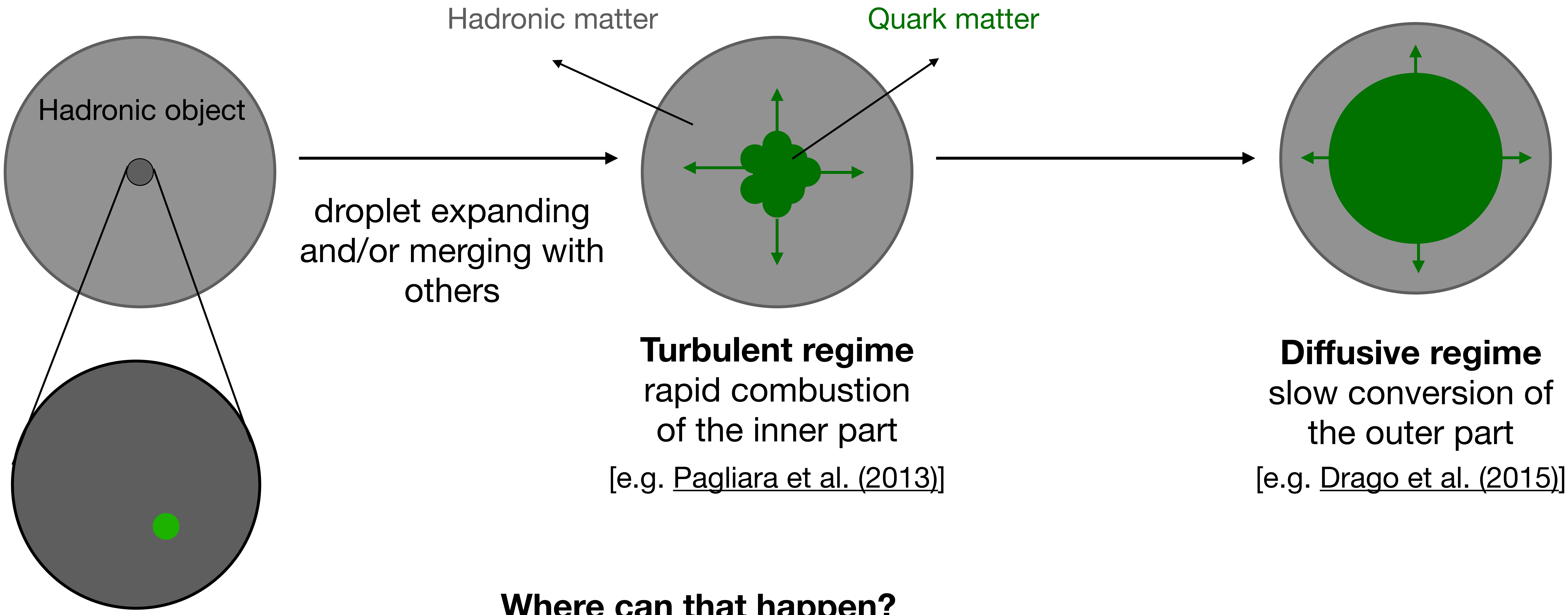
- Based on the **strange matter hypothesis** *[Witten (1984)]*





- **Quark stars (QSs)** and **Neutron stars (NSs)** coexists
- Once reached deconfinement conditions, **NS** converts to **QS**

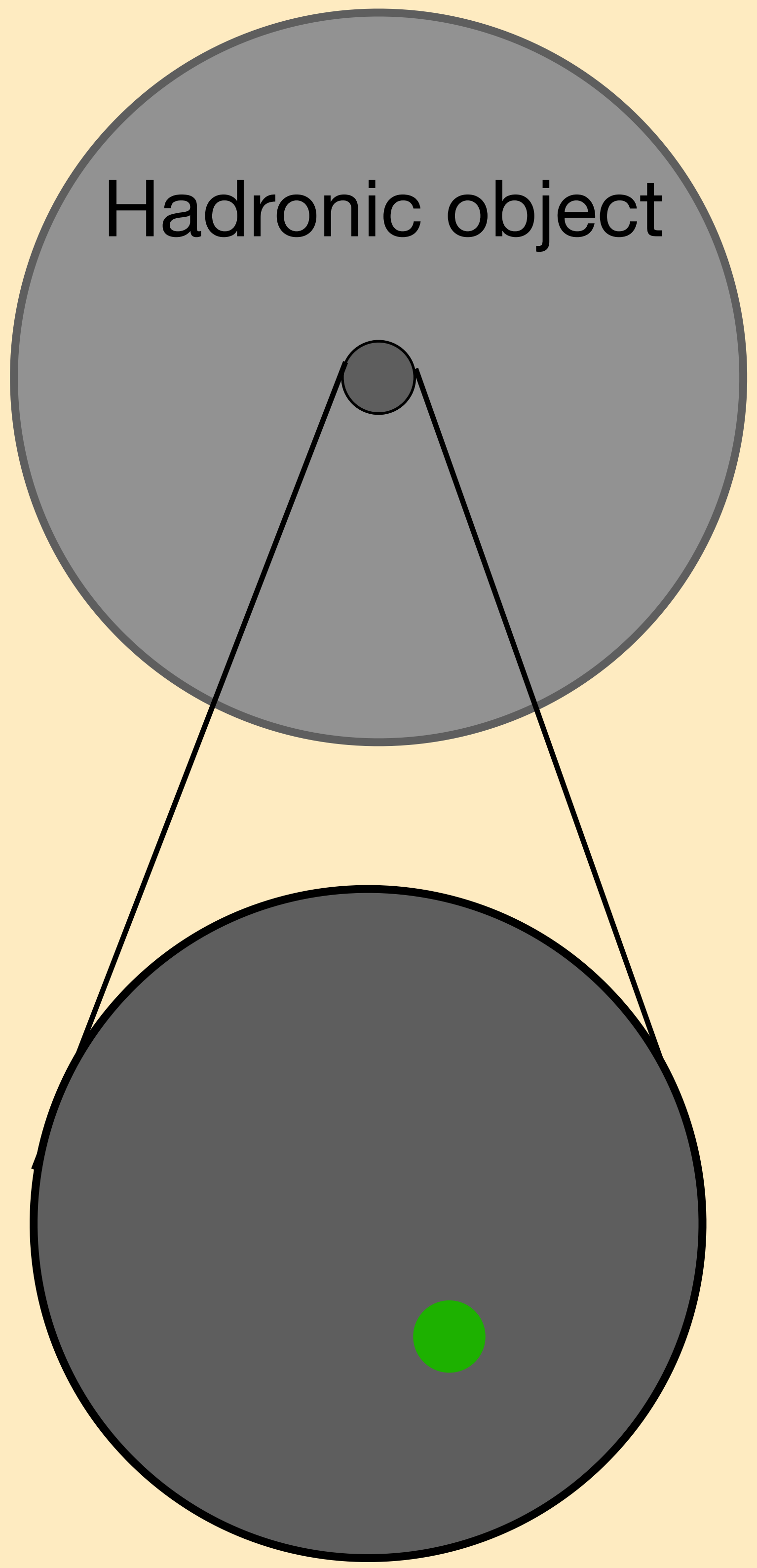
Conversion into a Quark Star



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

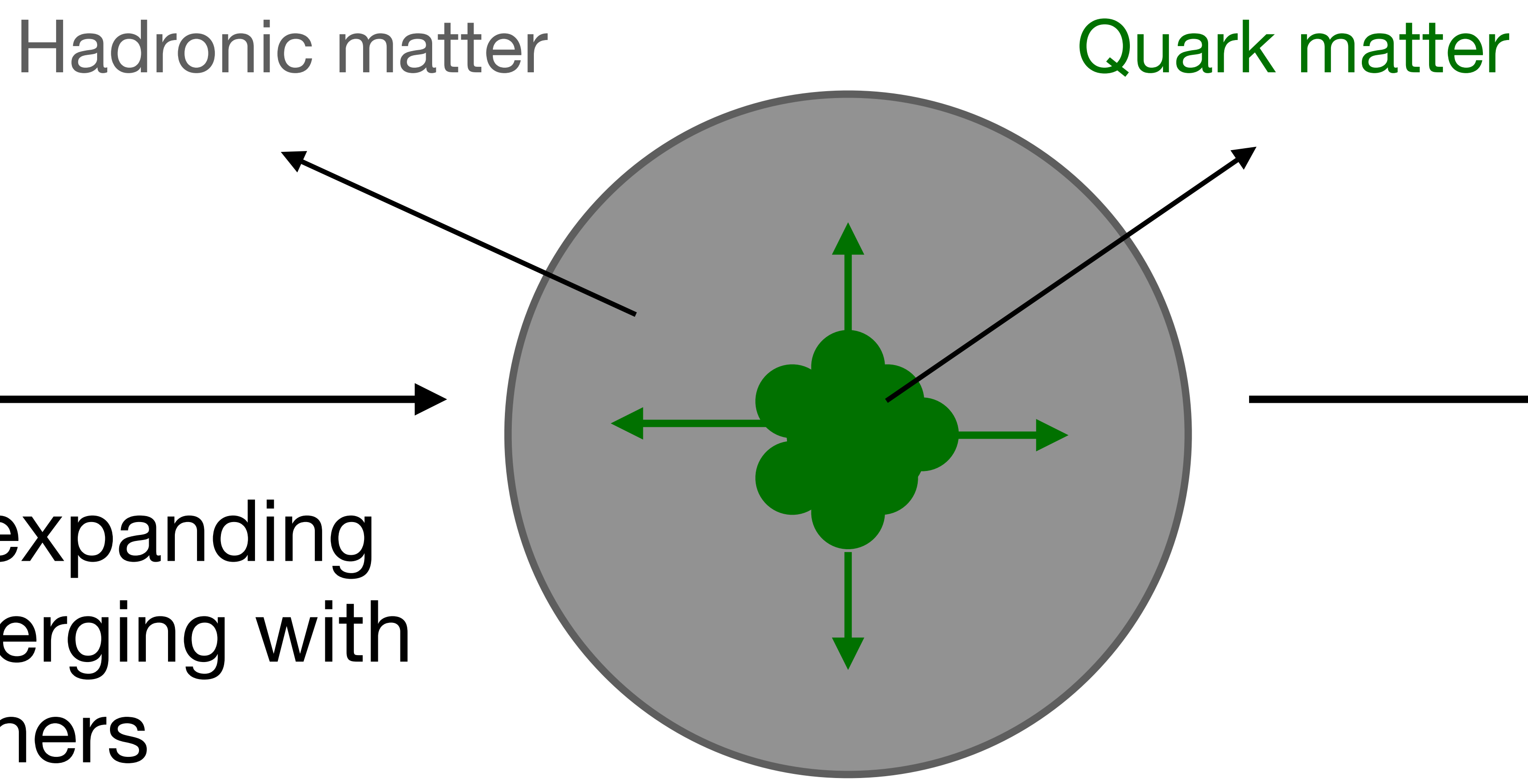
Conversion into a Quark Star



Nucleation
first droplet of
quark matter

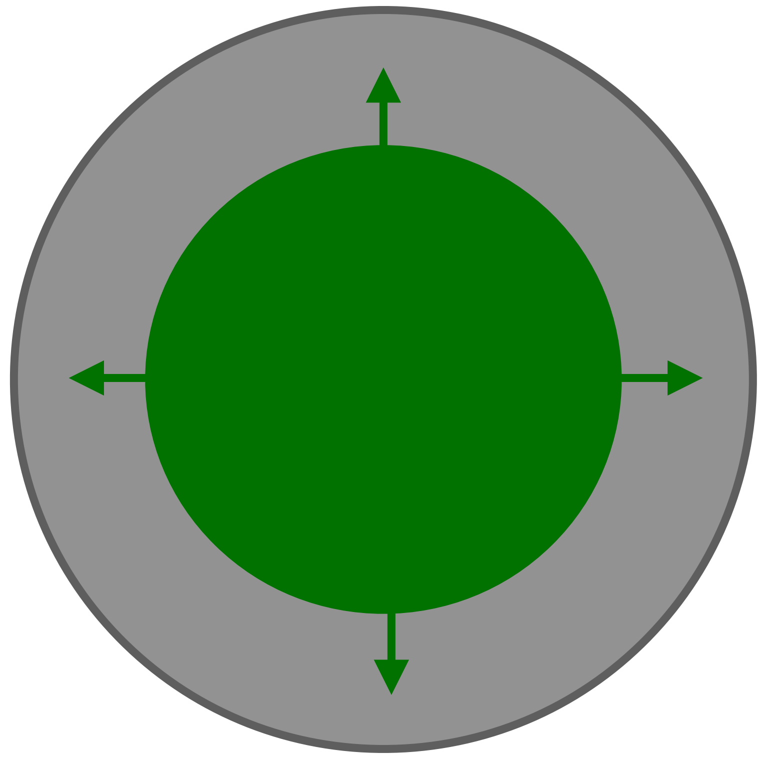
This work

droplet expanding and/or merging with others



Turbulent regime
rapid combustion
of the inner part

[e.g. Pagliara et al. (2013)]



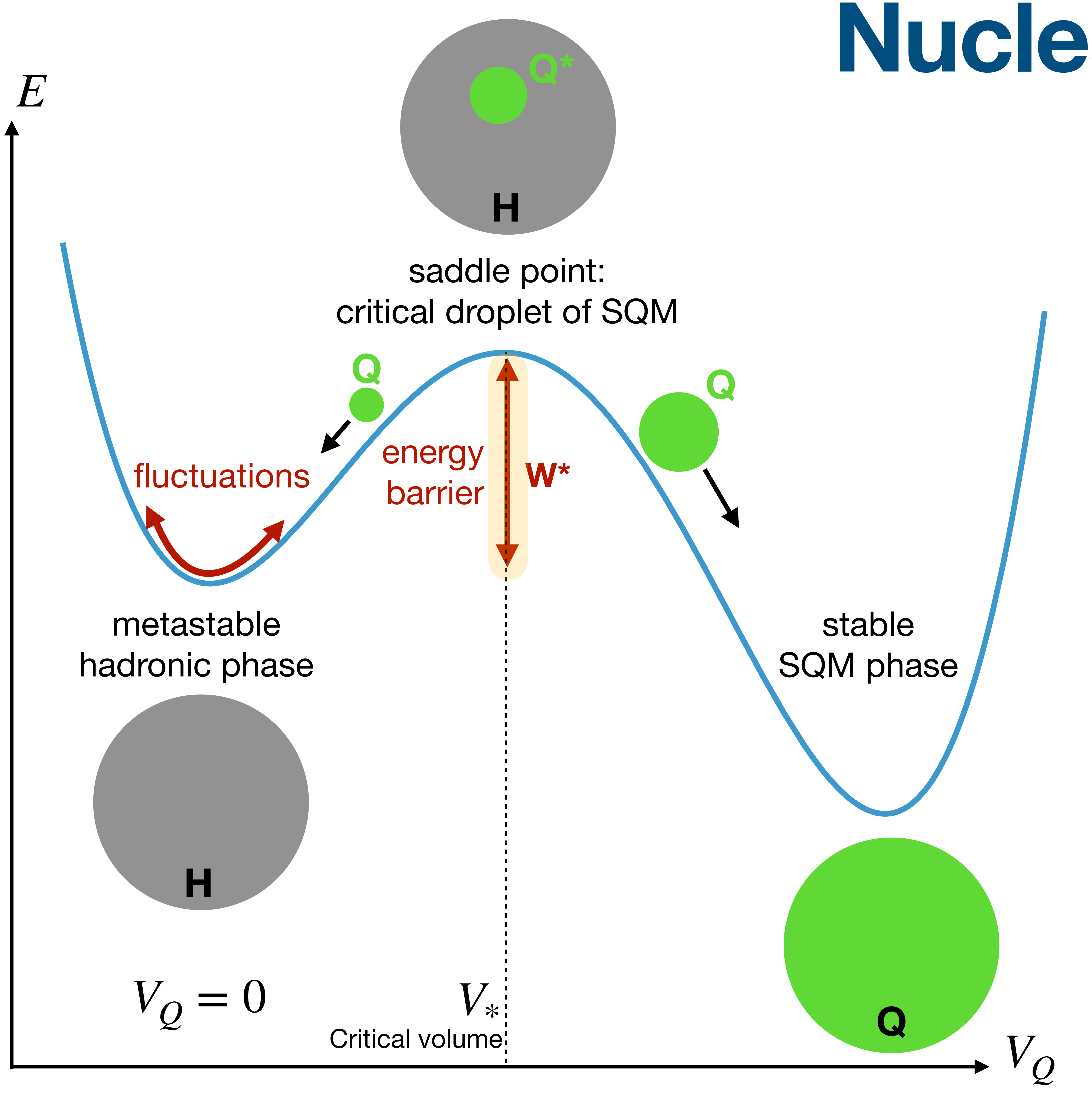
Diffusive regime
slow conversion of
the outer part

[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

Nucleation



1st order phase transition ⇒ surface tension

↓

Small droplets are disfavoured

energy barrier

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

bulk energy gain (negative if H is metastable)

surface effect (always positive)

Thermal nucleation [Langer (1969)]

$$\Gamma \propto e^{-\frac{W}{T}}$$

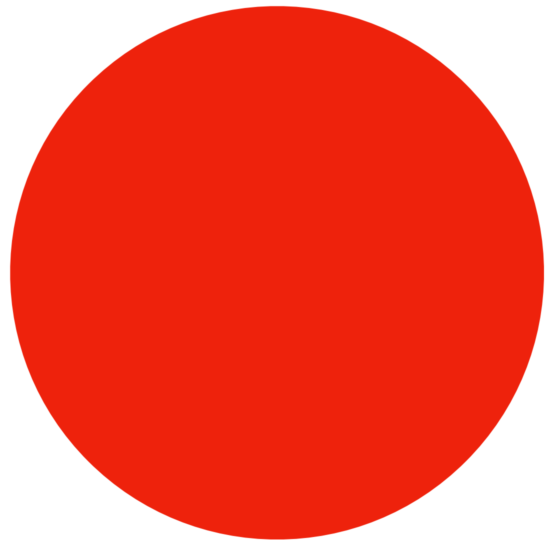
Distribution probability of a **droplet** with $R \leq R_*$ at given conditions

Quantum nucleation [Iida (1997)]

$$\Gamma \propto e^{-\frac{A(W)}{\hbar}}$$

Flavor composition can fluctuate

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



no fluctuations
of the composition

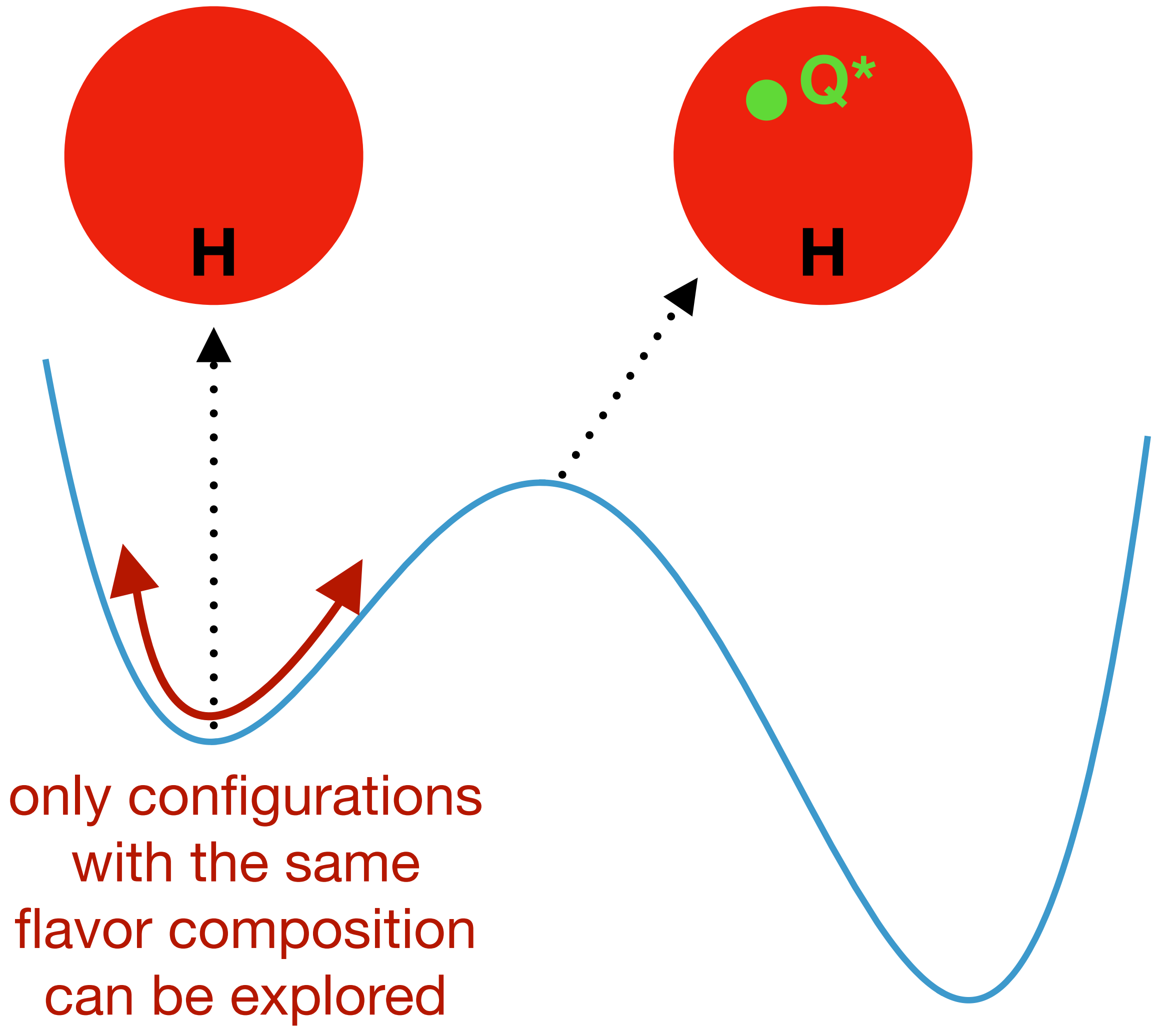
Which configurations can the system explore?

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

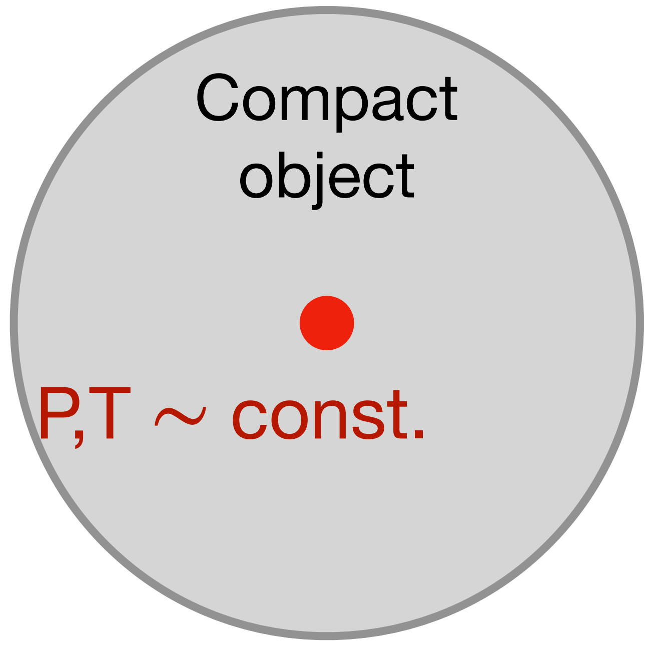
$\downarrow$

Conserved flavors
…locally?

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



only configurations
with the same
flavor composition
can be explored

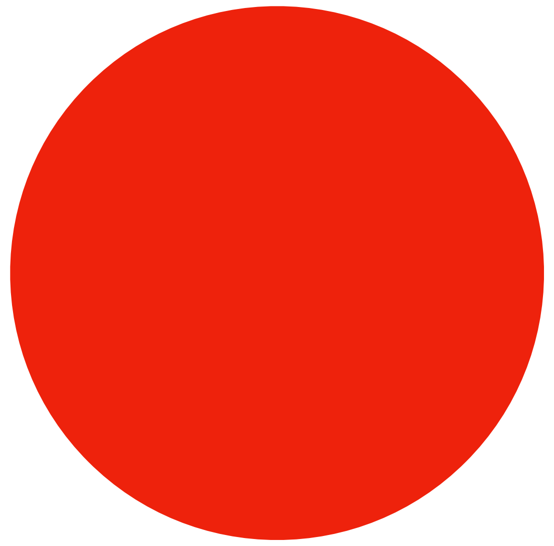


Flavor composition can fluctuate

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

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

Which configurations can the system explore?

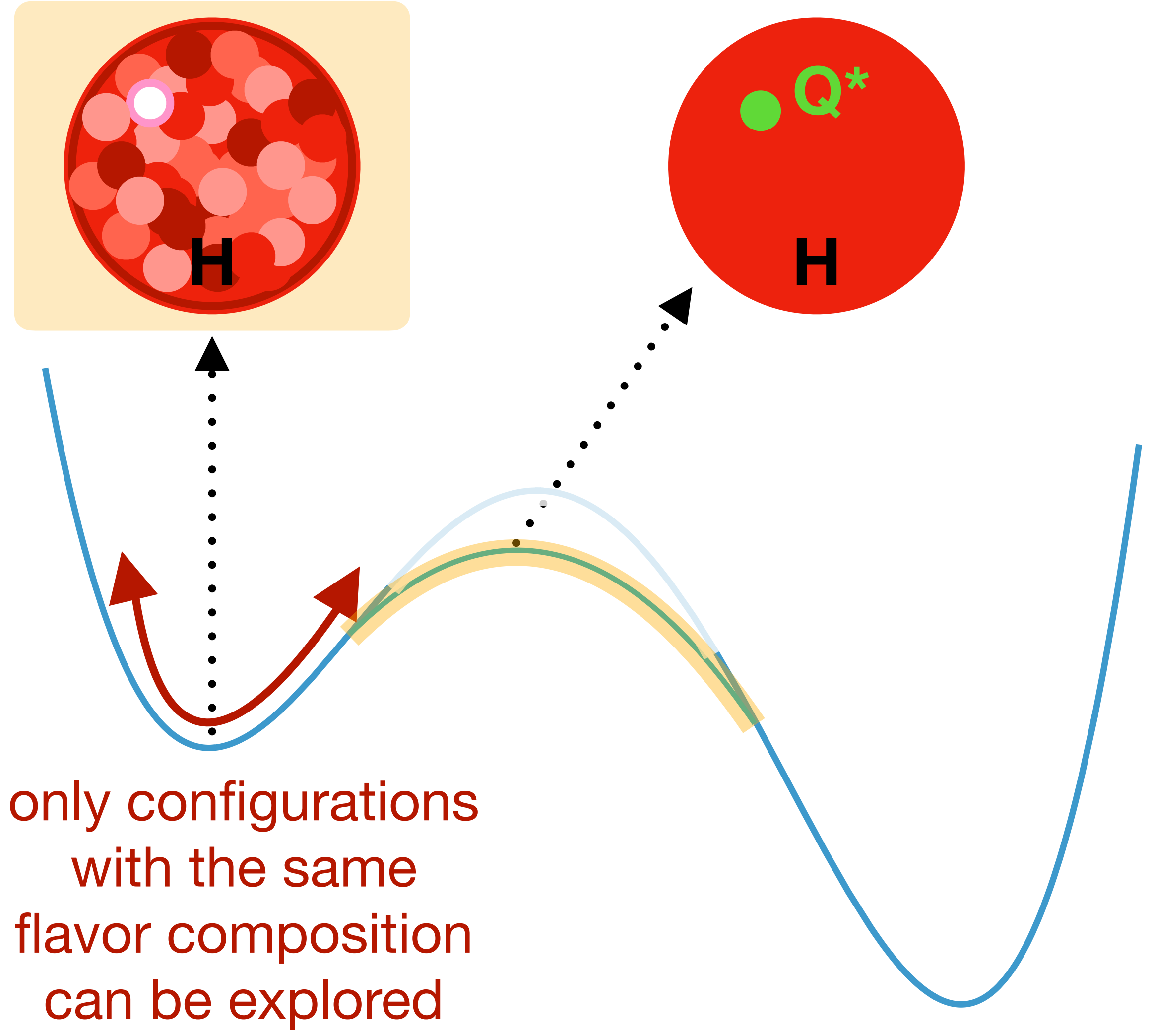


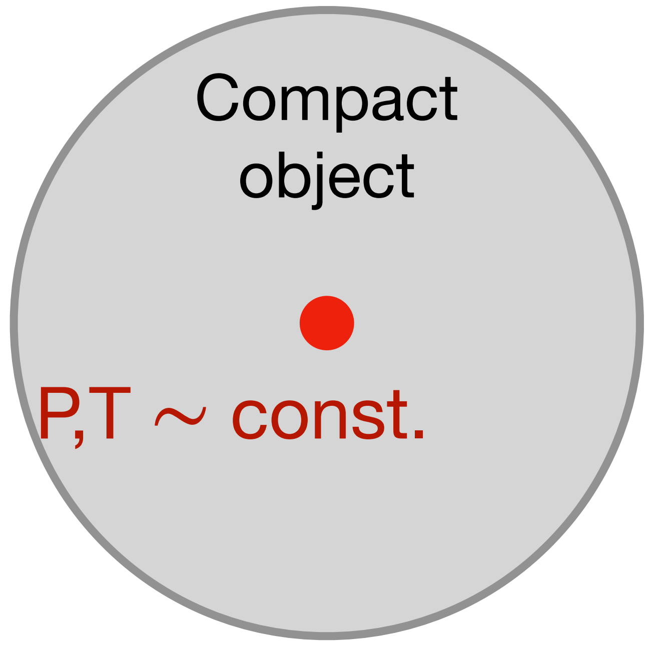
no fluctuations
of the composition

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

$\downarrow$

Conserved flavors
…locally?





[Guerrini et al. (2024)]

Key idea:

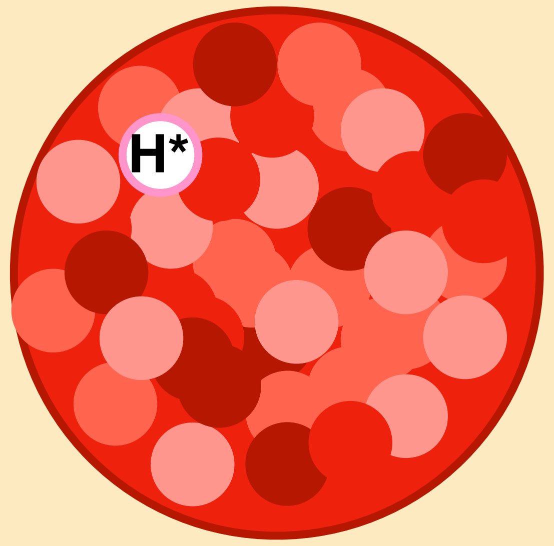
at $T \neq 0$ the hadronic **composition fluctuates** around the average values $\langle Y_i^H \rangle$

the nucleation is a **local process**

$\downarrow$

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

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



thermal fluctuations
of the composition

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

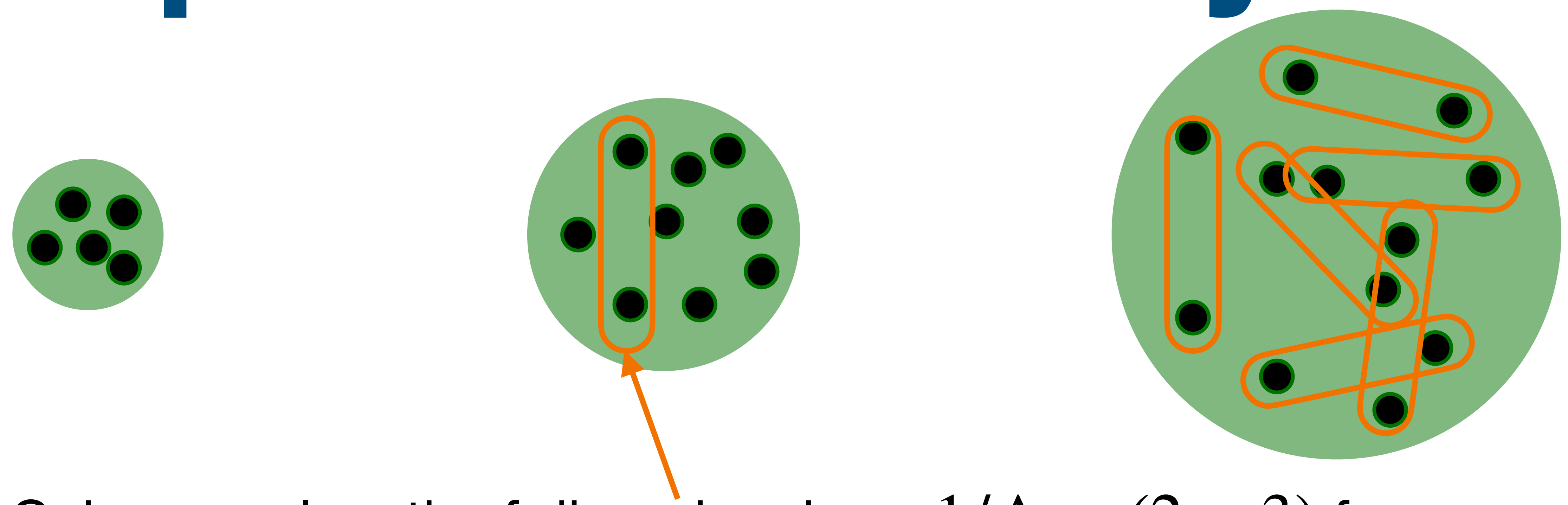
probability of a subsystem H*

nucleation probability
in a subsystem H*

Role of color-superconductivity

- to reach $\sim (2.2 - 2.5)\, M_\odot$ 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 critical quark droplet is)
  [e.g. Amore at al. (2002) PRD]



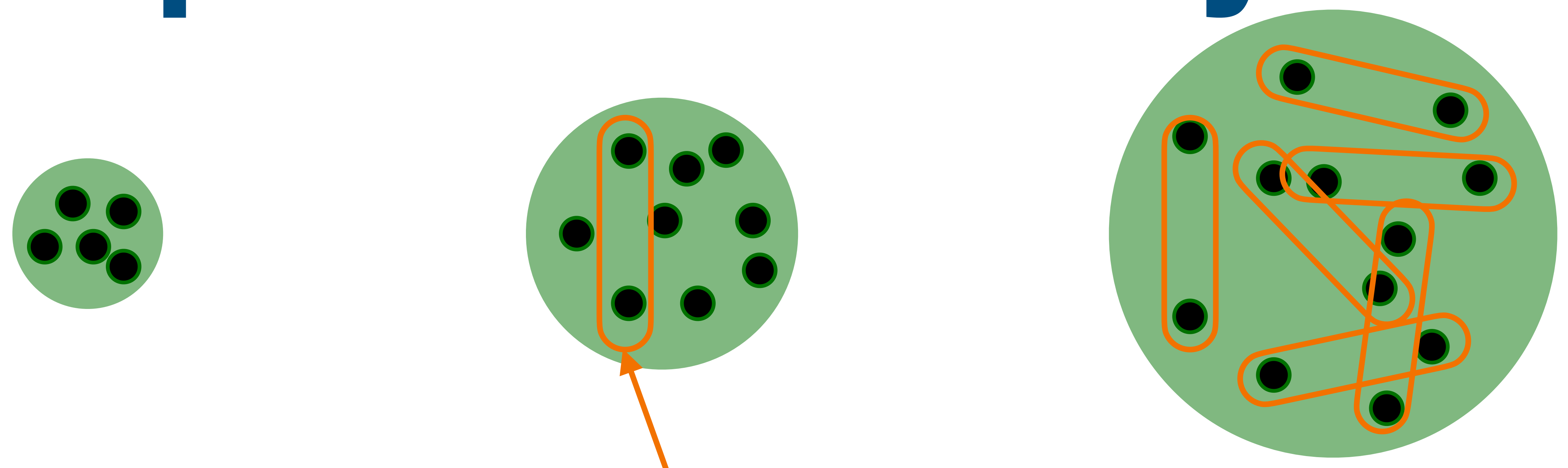
Coherence length of diquark pair $\sim 1/\Delta \sim (2-3)$ fm
[Alford at al. (2008)]

droplet of Q		Q bulk
R $\lesssim 1/\Delta$	$\longrightarrow$	R $\gtrsim 1/\Delta$
unpaired phase		**color-superconducting phase**

Role of color-superconductivity

- to reach $\sim (2.2 - 2.5)\, M_\odot$ 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 critical quark droplet is)
  [e.g. Amore at al. (2002) PRD]

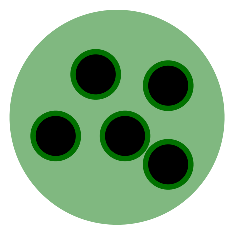


Coherence length of diquark pair $\sim 1/\Delta \sim (2-3)$ fm
[Alford at al. (2008)]

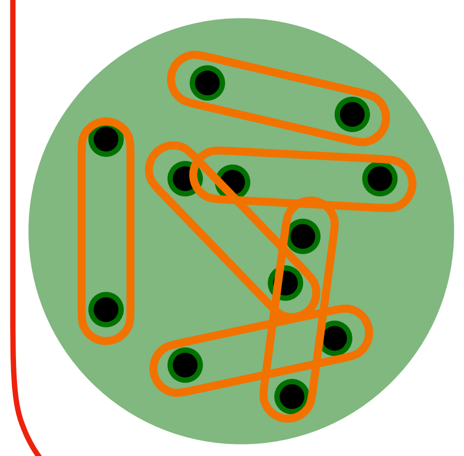
droplet of Q
R $\lesssim 1/\Delta$
unpaired phase

$\longrightarrow$

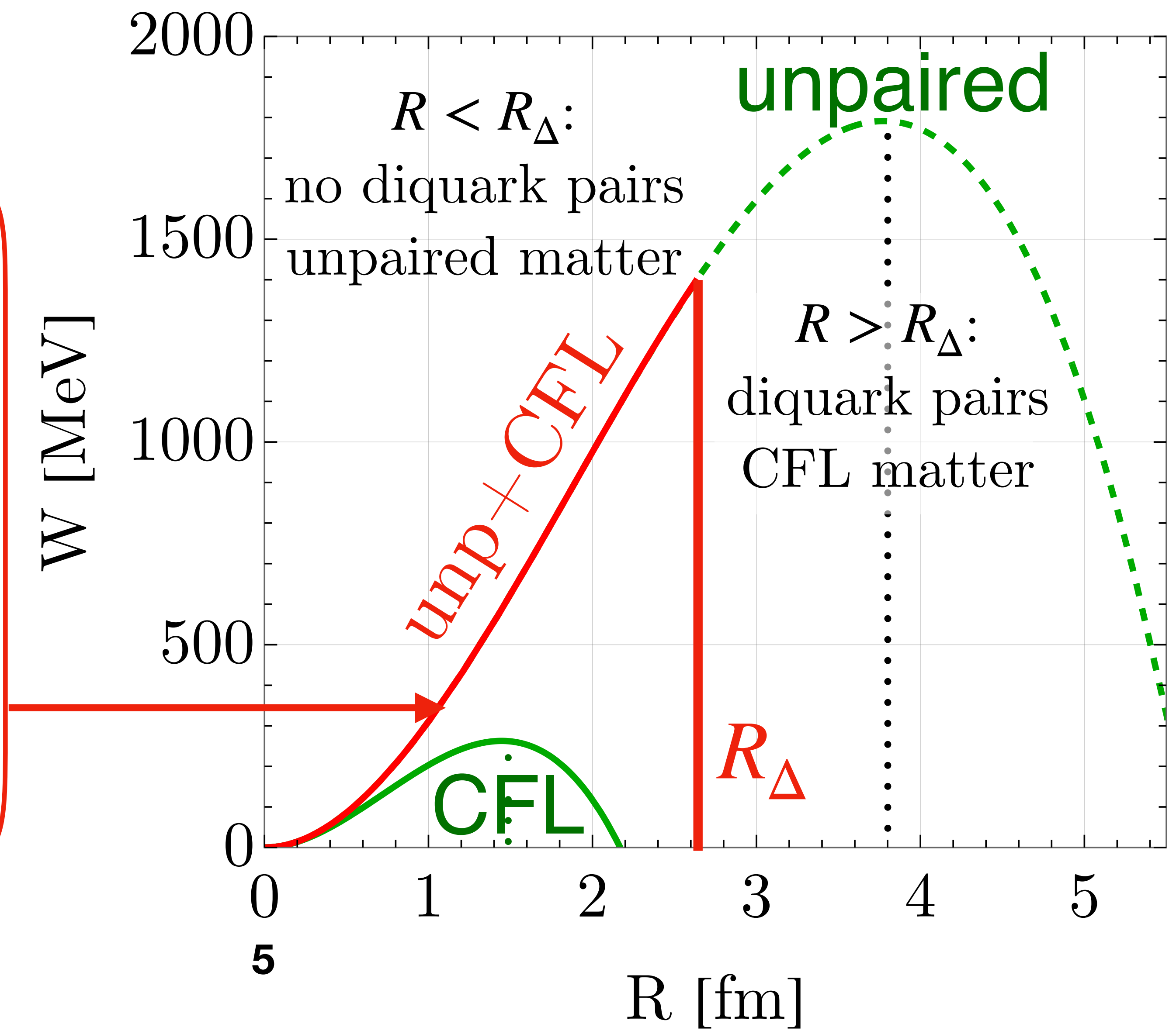
Q bulk
R $\gtrsim 1/\Delta$
color-superconducting phase

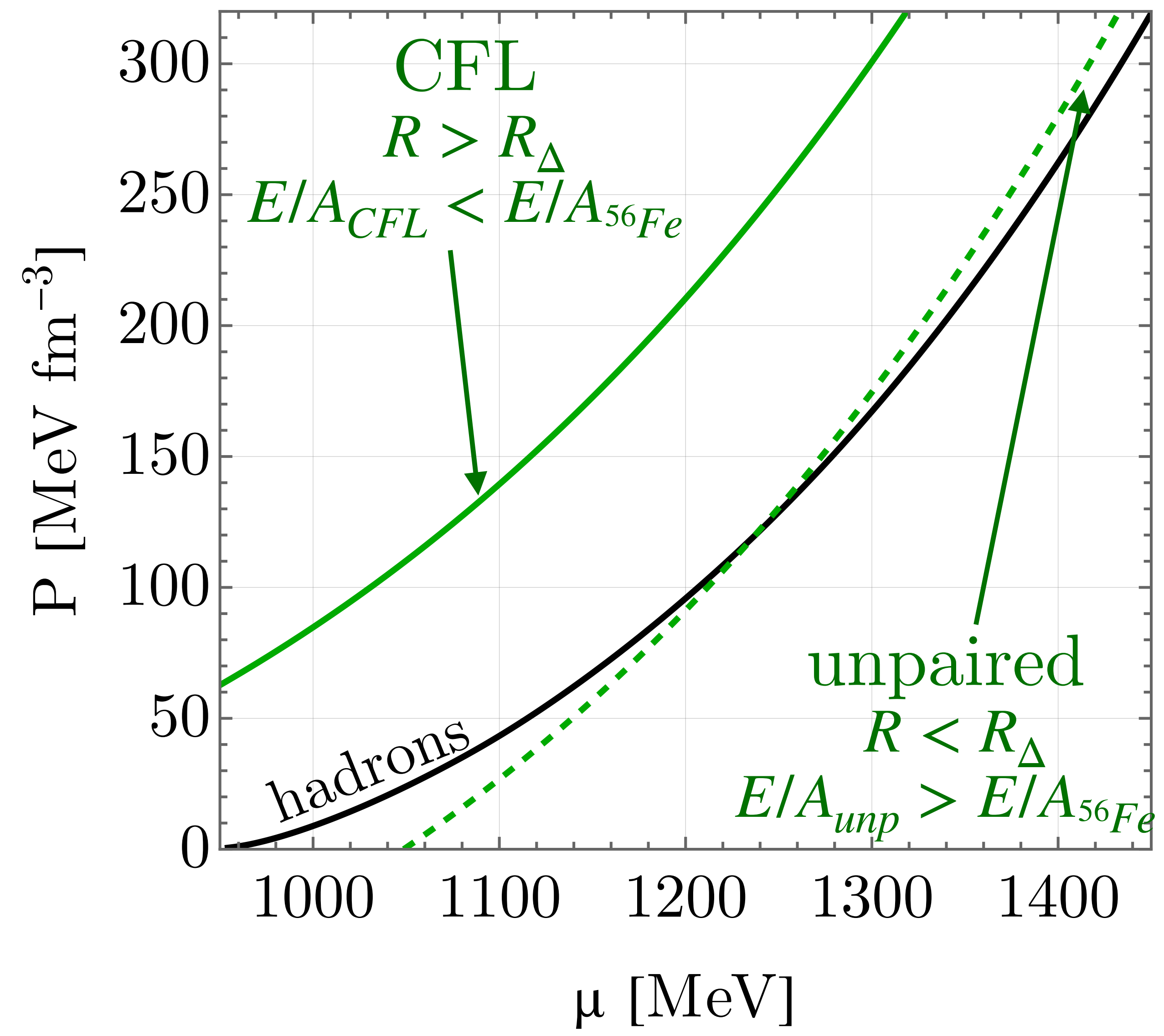


$R < R_\Delta = 1/\Delta(T)$: **unpaired matter non absolutely stable**



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



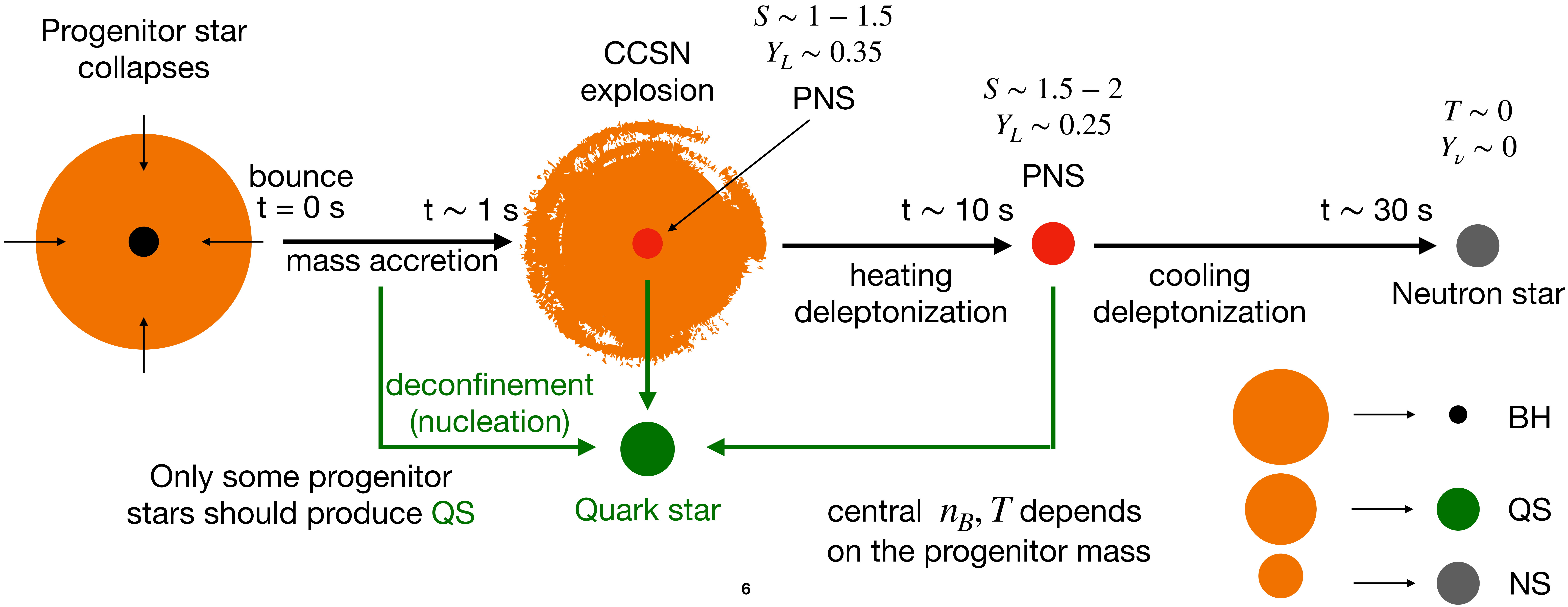


Evolution of PNSs

Constraints:

i. EOS for SQM must have a **maximum mass configuration** $M \gtrsim (2.2 - 2.6)\, M_\odot$

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



Nucleation in astrophysical systems

Astrophysical simulation

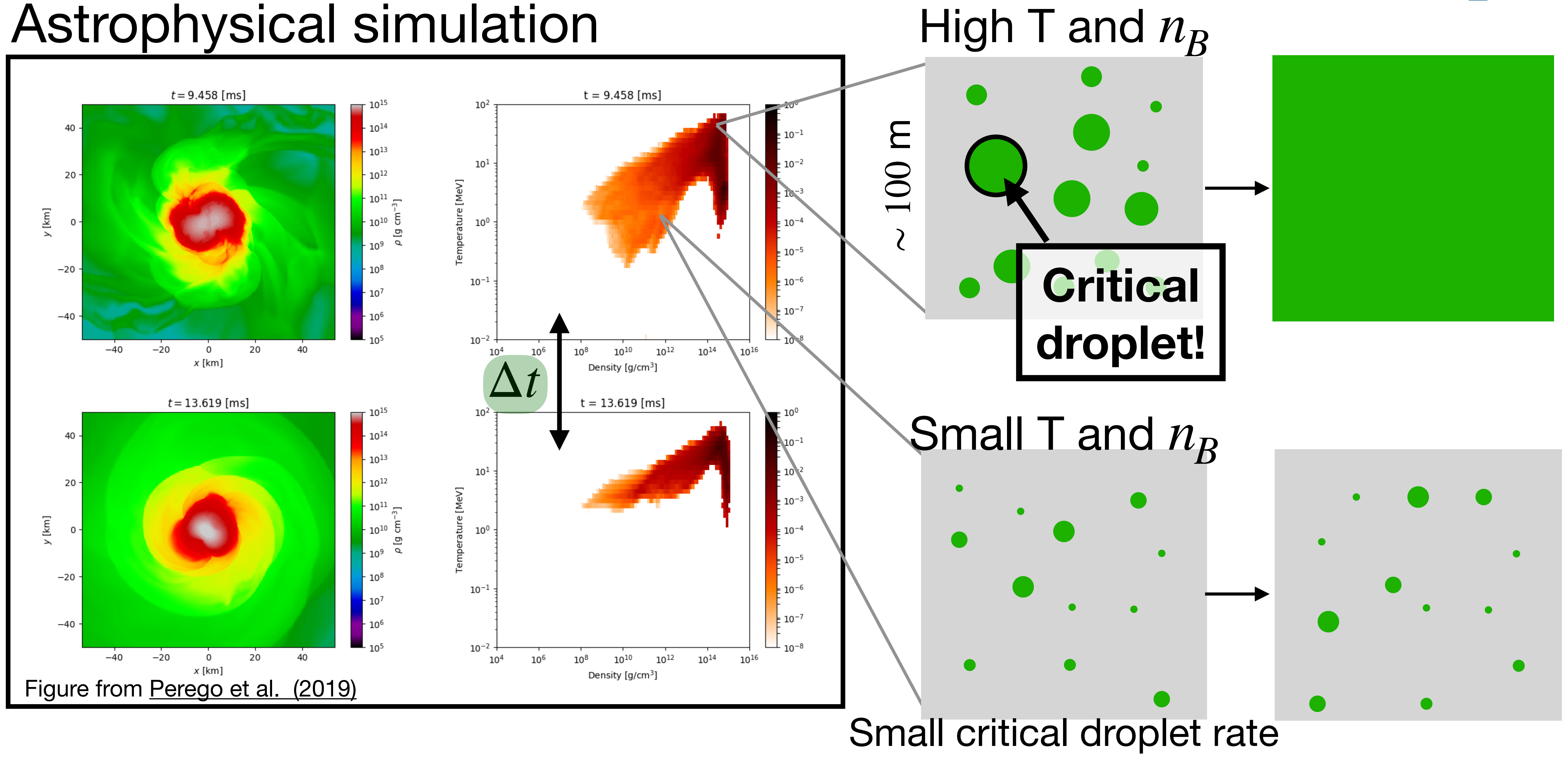


Figure from Perego et al. (2019)

Simulation output: n_B, Y_e, T
in each space-cell and
in each time-step

$$\sum_{\substack{\text{every}\\ \text{cell}}} \sum_{\substack{\text{every}\\ \text{time}}} V_{\text{cell}}\, \Delta t\, \Gamma(n_B^H, Y_e, T) \geq 1$$

Nucleation rate

Nucleation in astrophysical systems

Astrophysical simulation

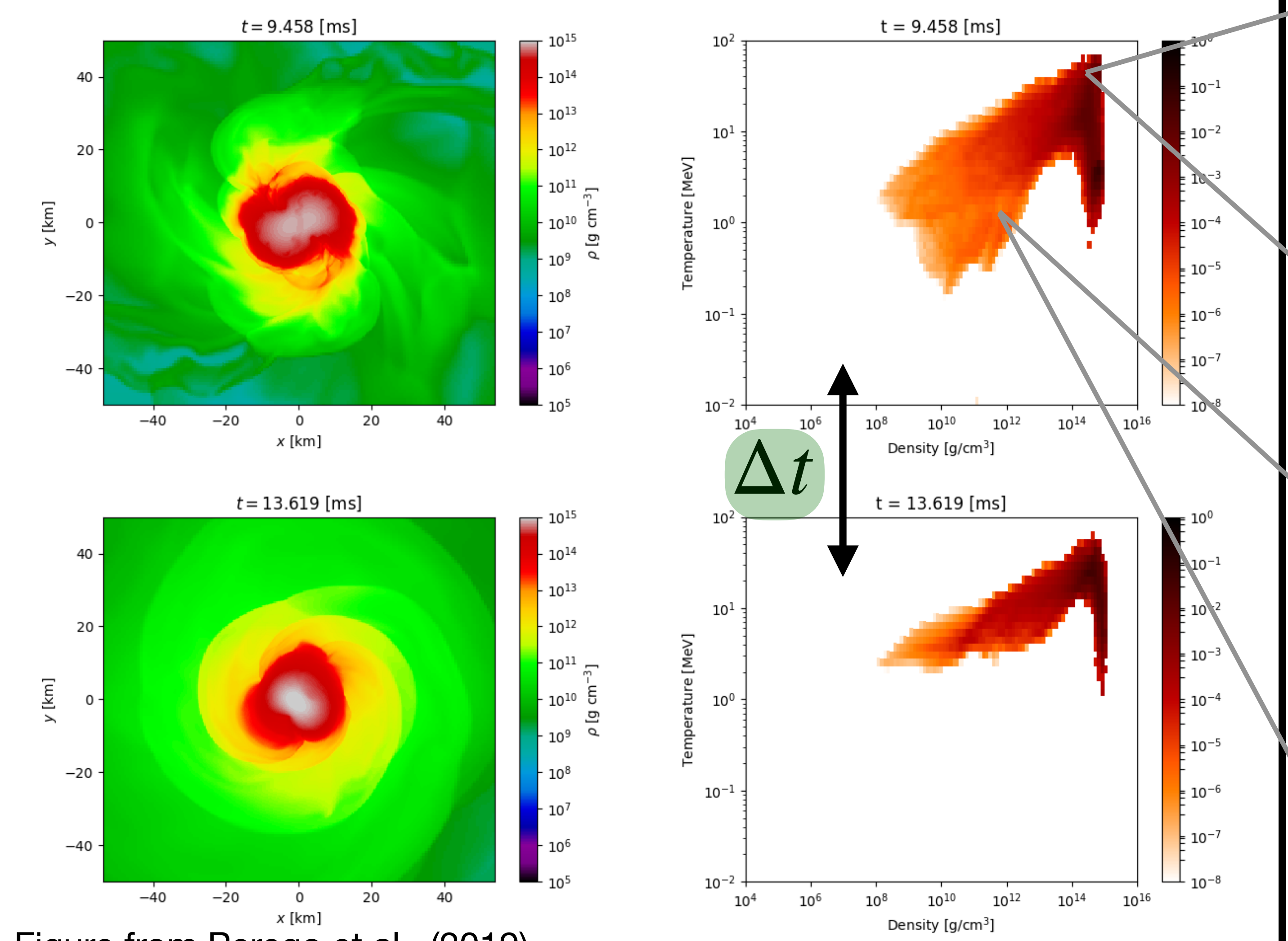
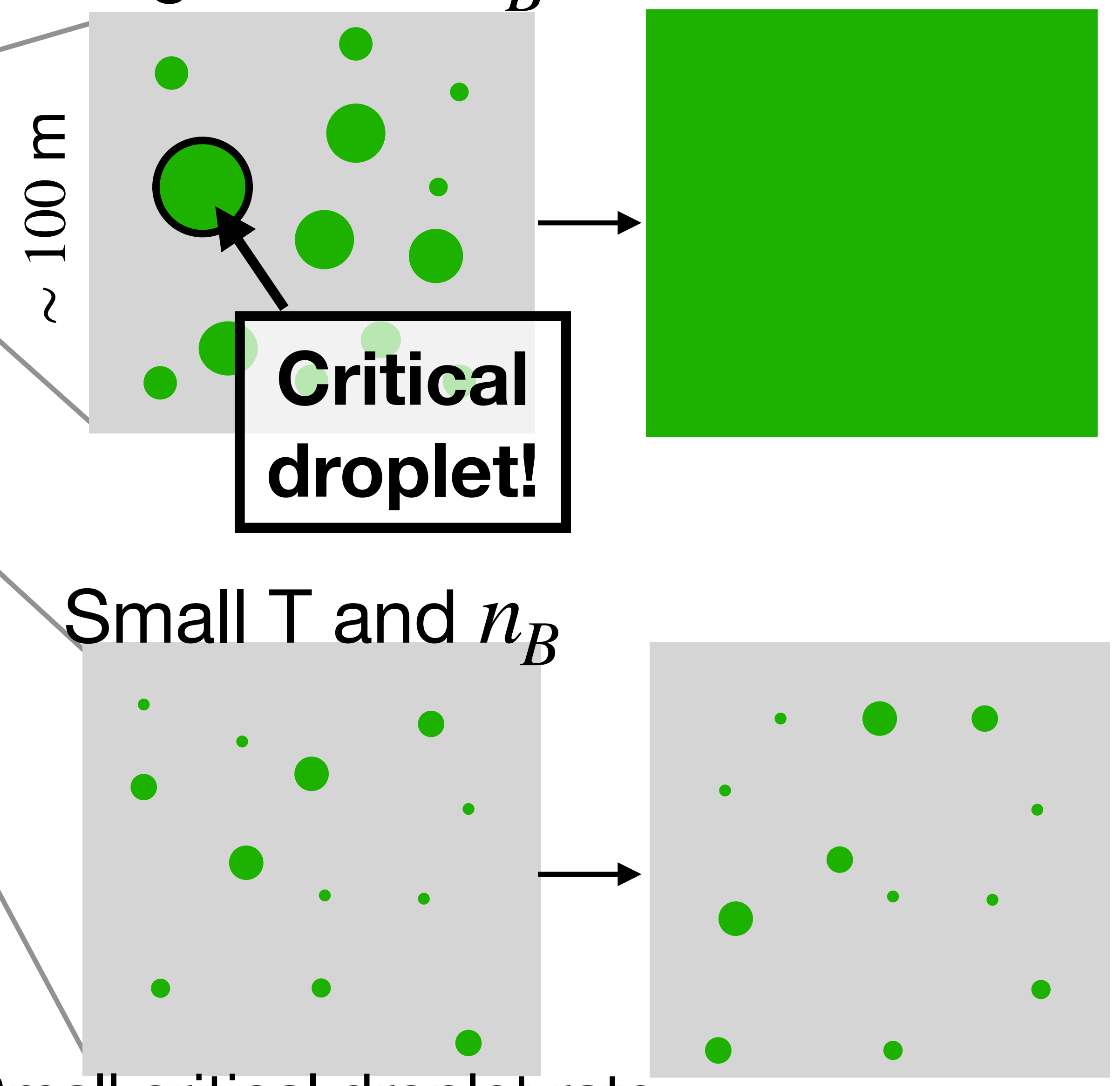


Figure from Perego et al. (2019)

High T and n_B



Small T and n_B

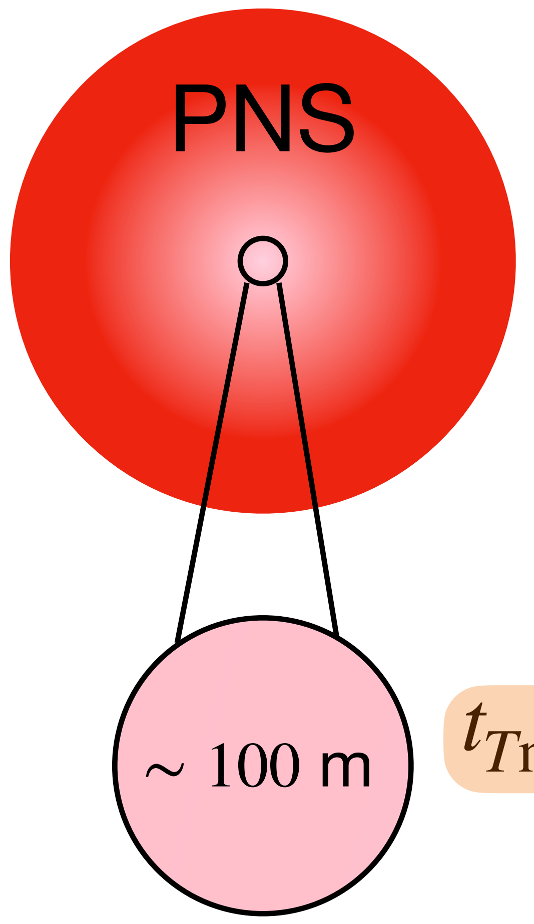
Small critical droplet rate

Simulation output: n_B, Y_e, T
in each space-cell and
in each time-step

$$\underbrace{\sum}_{\text{every cell}} \underbrace{\sum}_{\text{every time}} V_{\text{cell}}\, \Delta t\, \Gamma(n_B^H, Y_e, T) \geq 1$$

Nucleation rate

Approximate approach

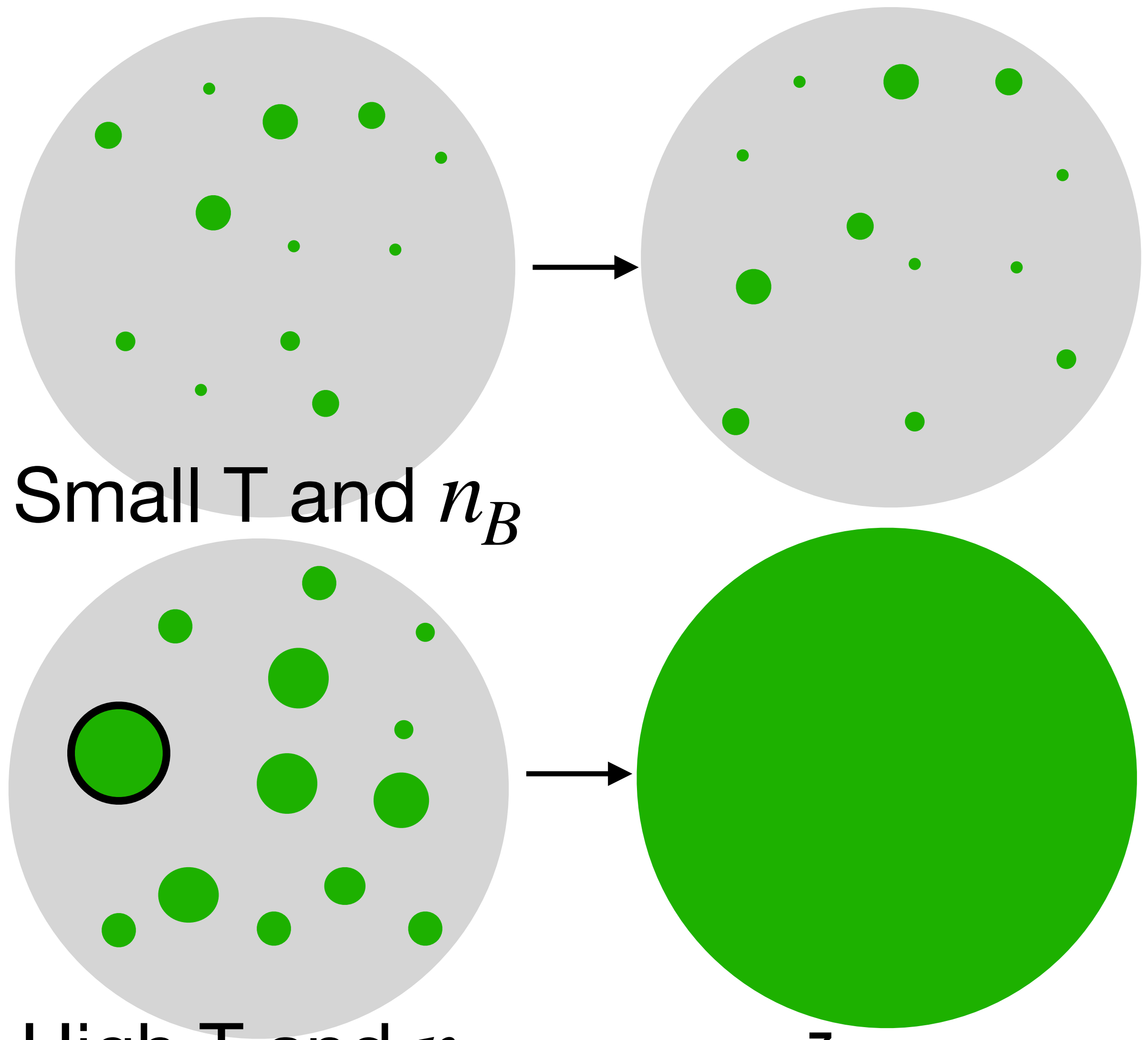


Focus on a certain region
In certain snapshots

t_0 : $S = 1.5,\ Y_L^H = 0.35$

$t_{T\max}$: $S = 2.0,\ Y_L^H = 0.25$

t_{T_0} : $T \simeq 0,\ Y_\nu^H = 0$



Small T and n_B

High T and n_B

We have some snapshots with fixed Y_L, S

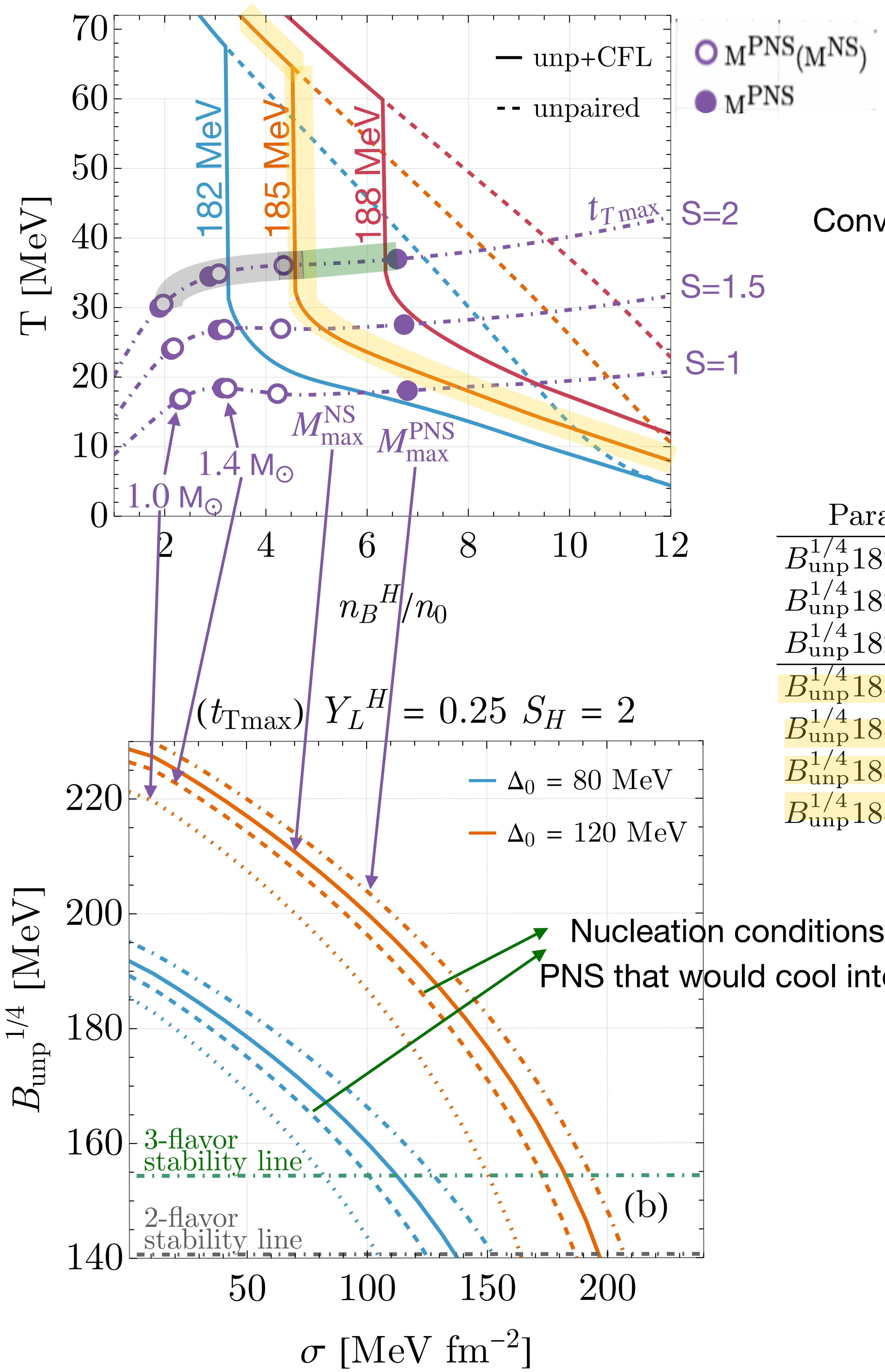
n_B fixed as central density of a given M^{PNS}

$$\left[V_{\text{core}}\Gamma(n_B^H, Y_e, T)\right]^{-1} \equiv \tau_{\text{nuc}} \leq \tau_{\text{dyn}}$$

Typical time after which a critical droplet is statistically expected

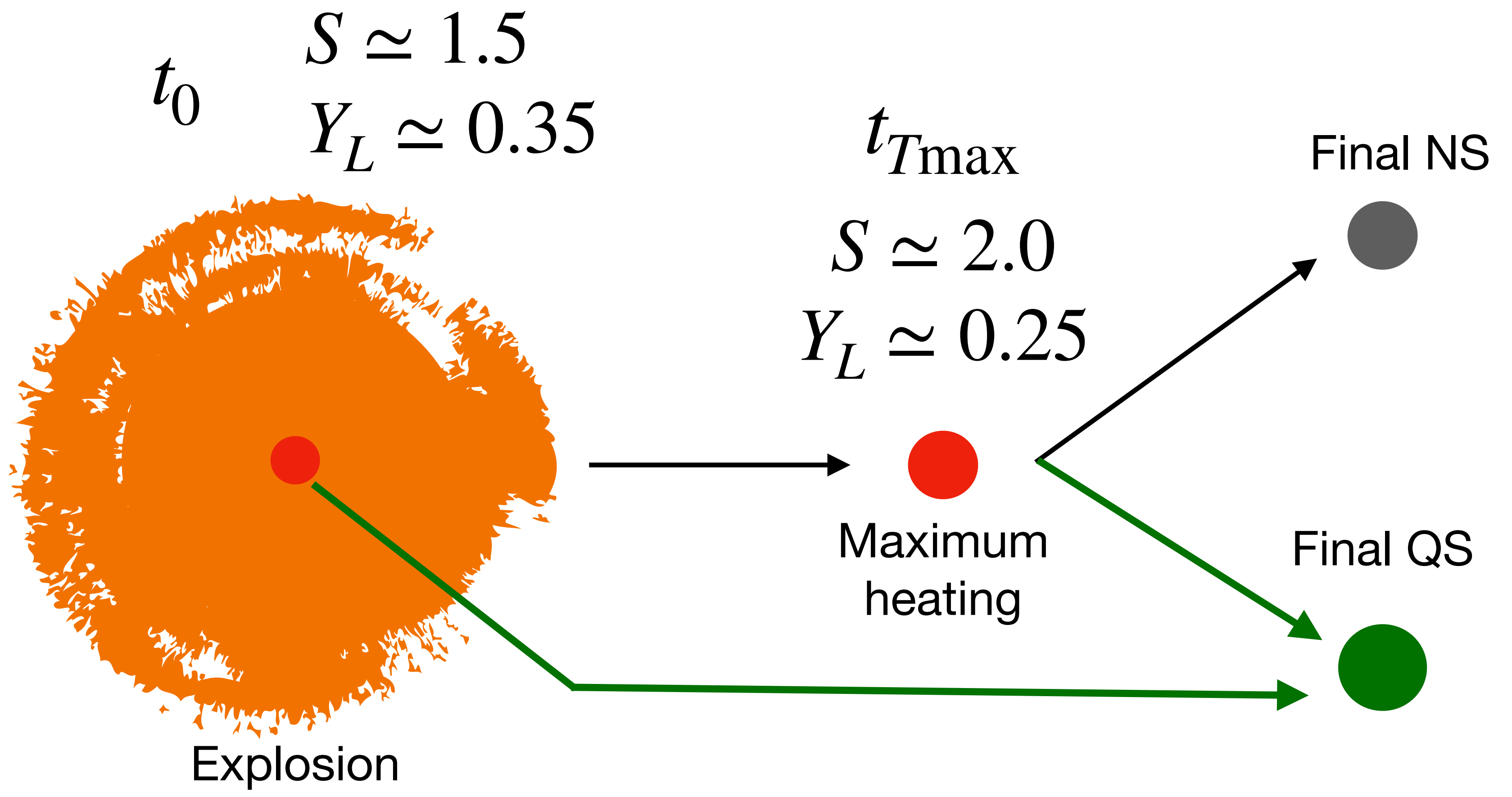
Results

nucleating conditions at $Y_L^H = 0.25$



Nucleation conditions reached for PNS that would cool into >1.4 M☉ NS

Conversion for all the $n_B^H >$ **nucleating line**



Parameters	PNS at t_0: M^{PNS} [M☉]	M_B^{PNS} [M☉]	$n^H_{B,c}$ [n_0]	$Y^H_{S,c}$	PNS at $t_{T\max}$: M^{PNS} [M☉]	$n^H_{B,c}$ [n_0]	$Y^H_{S,c}$	Remnant: remnant	M [M☉]	E_{conv} [$\times 10^{53}$erg]
$B^{1/4}_{unp}$182-Δ80-σ30	1.40	1.48	2.85	0.02	1.39	2.87	0.04	NS	1.34	-
$B^{1/4}_{unp}$182-Δ80-σ30	1.60	1.72	3.53	0.05	1.59	3.70	0.11	QS	1.32	4.98
$B^{1/4}_{unp}$182-Δ80-σ30	1.80	1.97	5.40	0.31	-	-	-	QS	1.49	7.22
$B^{1/4}_{unp}$185-Δ80-σ30	1.60	1.72	3.53	0.05	1.59	3.70	0.11	NS	1.53	-
$B^{1/4}_{unp}$185-Δ80-σ30	1.70	1.84	4.08	0.10	1.69	4.48	0.20	BH	-	-
$B^{1/4}_{unp}$185-Δ80-σ30	1.75	1.90	4.52	0.16	1.74	5.31	0.33	QS	1.45	5.32
$B^{1/4}_{unp}$185-Δ80-σ30	1.80	1.97	5.40	0.31	-	-	-	BH	-	-

Conversion energy
GRB after CCSN?
other phenomenology?

Coexistence of QS-NS

There exists a parameter space in which some PNSs will not convert into QSs but instead cool down into NS.

Summary and conclusions

Any other questions
or suggestions?
mirco.guerrini@unife.it

Background

- **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 **NS** can **convert** into **QS**

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 possible coexistence of NSs and QSs: Can at least some NSs survive the PNS evolution?

Results: a parameters space for the two-families scenario exists

Outlooks

- Use more sophisticated EOSs for the quark phase and estimate surface tension
- How to include those **finite-size effects in simulations**?
- Complete study of related phenomenology (e.g., deconfinement-driven CCSN with two families scenario? Accretion?)

Backup

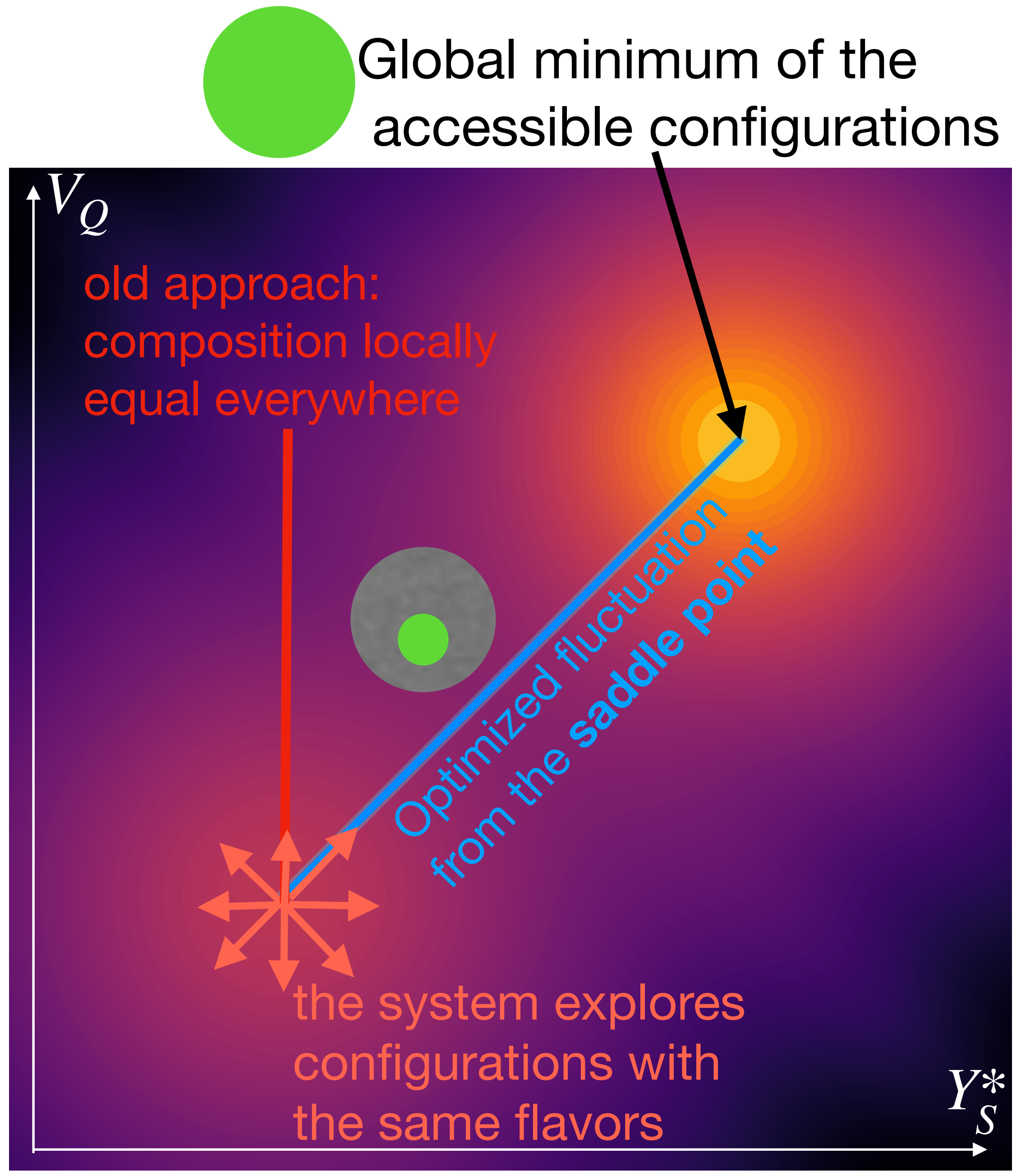
Fluctuations and nucleation

$\propto e^{-\frac{W}{T}}$

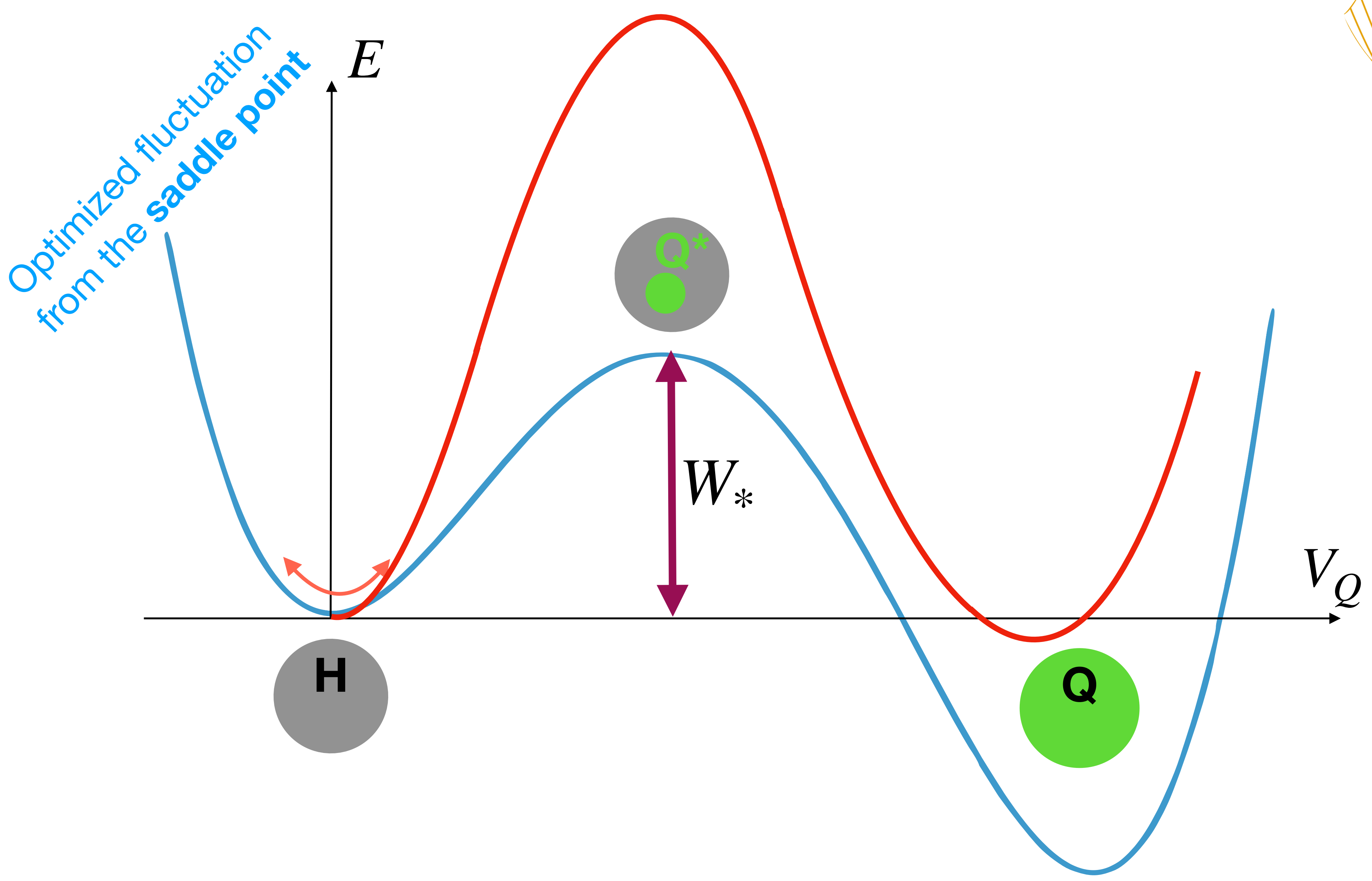
Configurations with high W are negligible

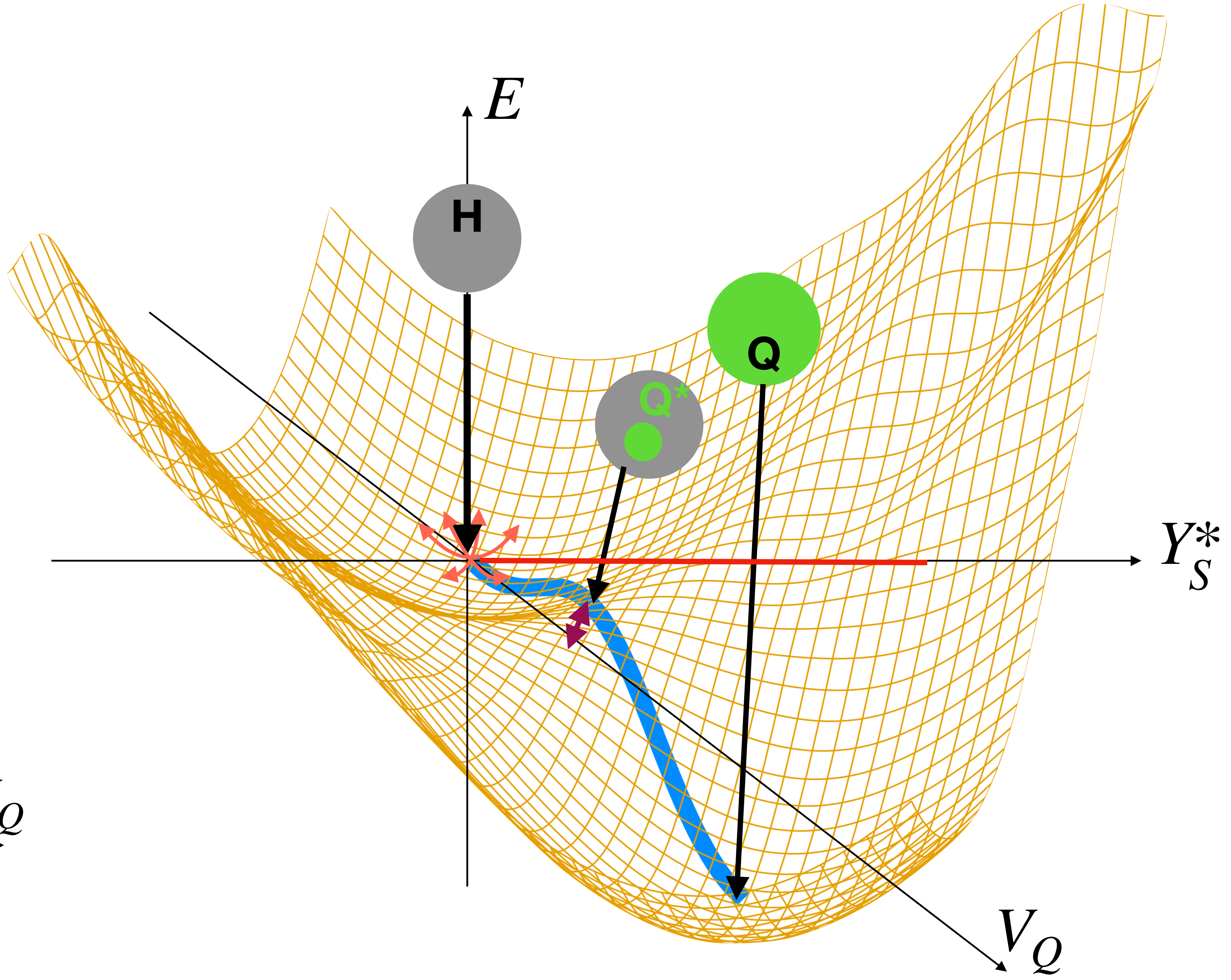
$$\min_{n_B^{Q*},\{Y_i^*\},T_{Q*}} \left[W(R, n_B^{Q*}, \{Y_i^*\}, T_{Q*}, n_B^H, \{Y_i^H\}, T)\right] \to W(R, n_B^H, \{Y_i\}, T)$$

$$\max_R \left[W\left(R, n_B^H, \{Y_i^H\}, T\right)\right] = W(R_*, n_B^H, \{Y_i^H\}, T) \equiv W_*$$



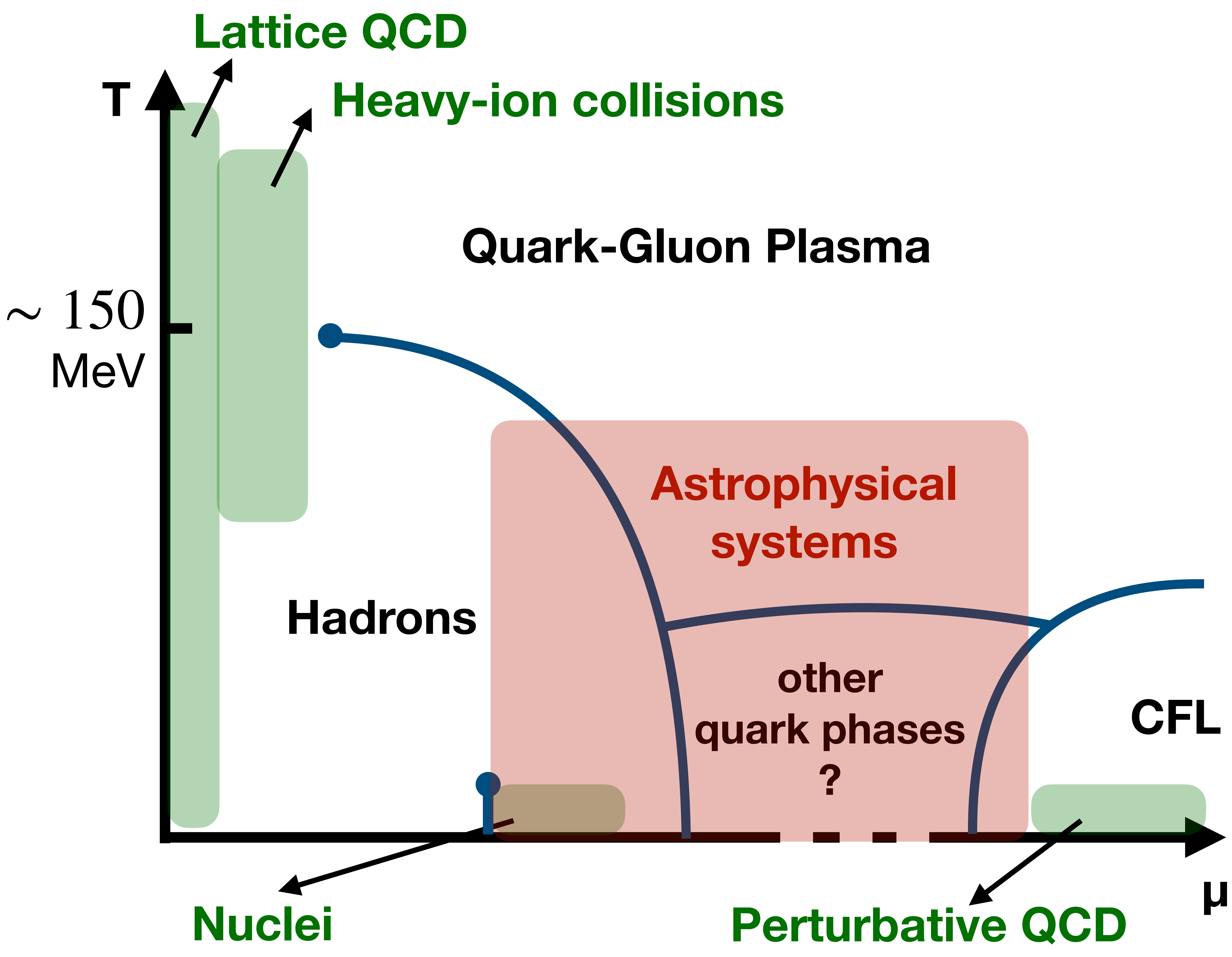
Local minimum:
The entire system is in the **H phase** ($V_Q = 0$)
with the composition locally equal everywhere





3D representation of a N-D plot of the **energy** of the system as a function of all the **variables**

QCD phase diagram

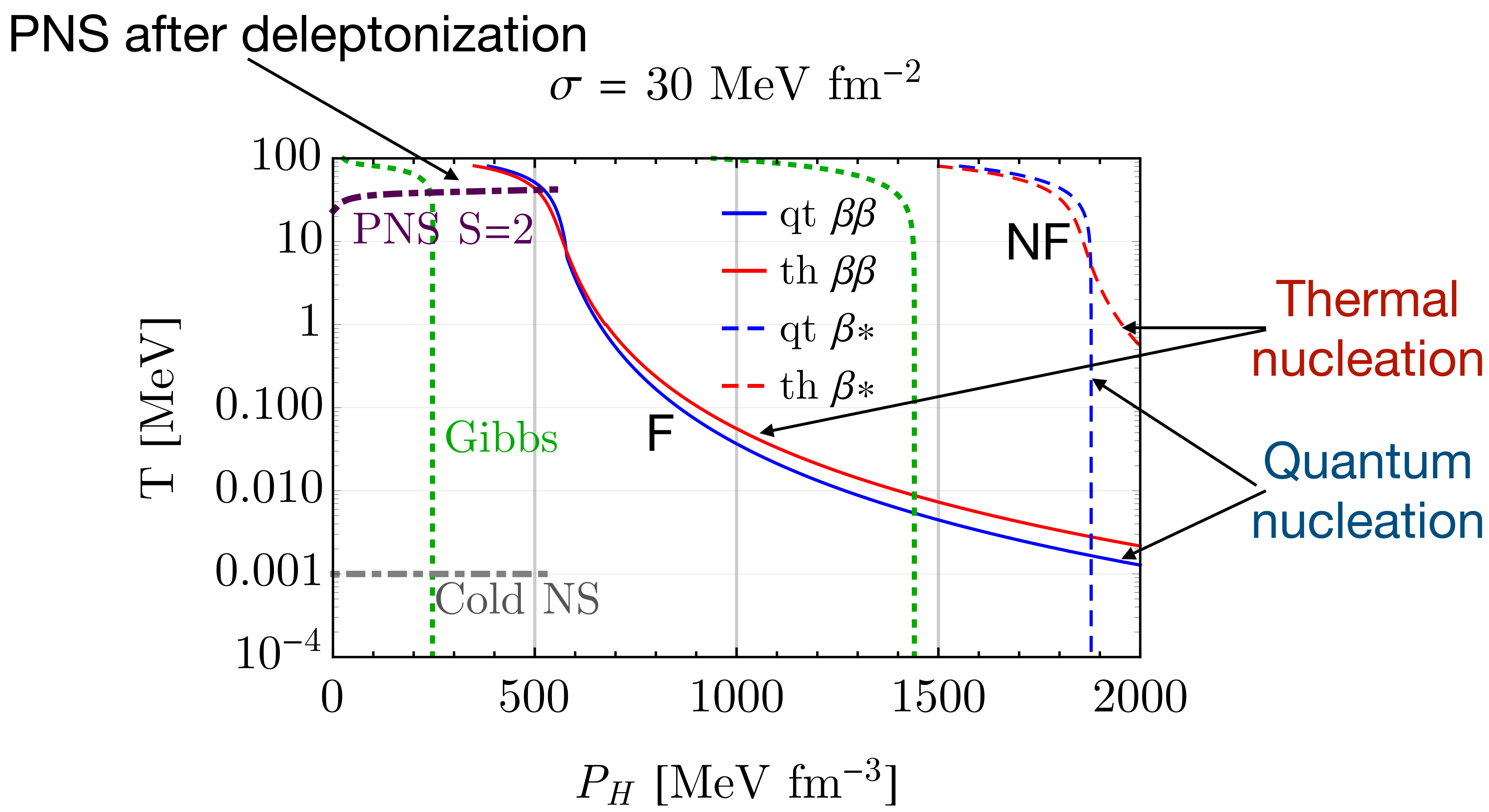


- the high-density regime is poorly known
- quarks d.o.f. expected at $n_B \sim$ few n_0
- extreme densities are reached in astrophysical phenomena related to **compact objects**

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

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

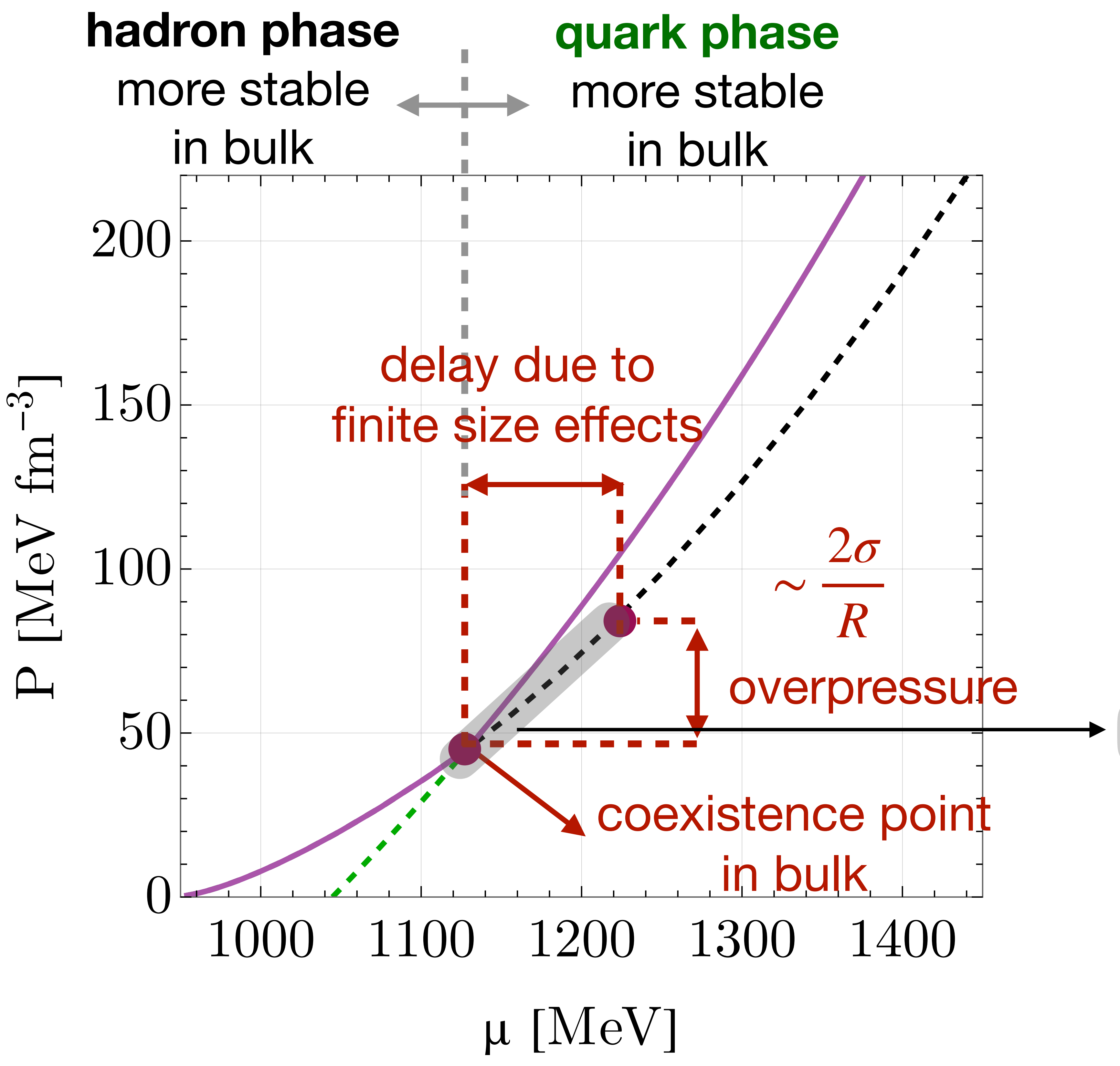
$T \gtrsim 10$ MeV:
- nucleation at lower P than no fluc. (NF) case
- most massive PSNs could nucleate

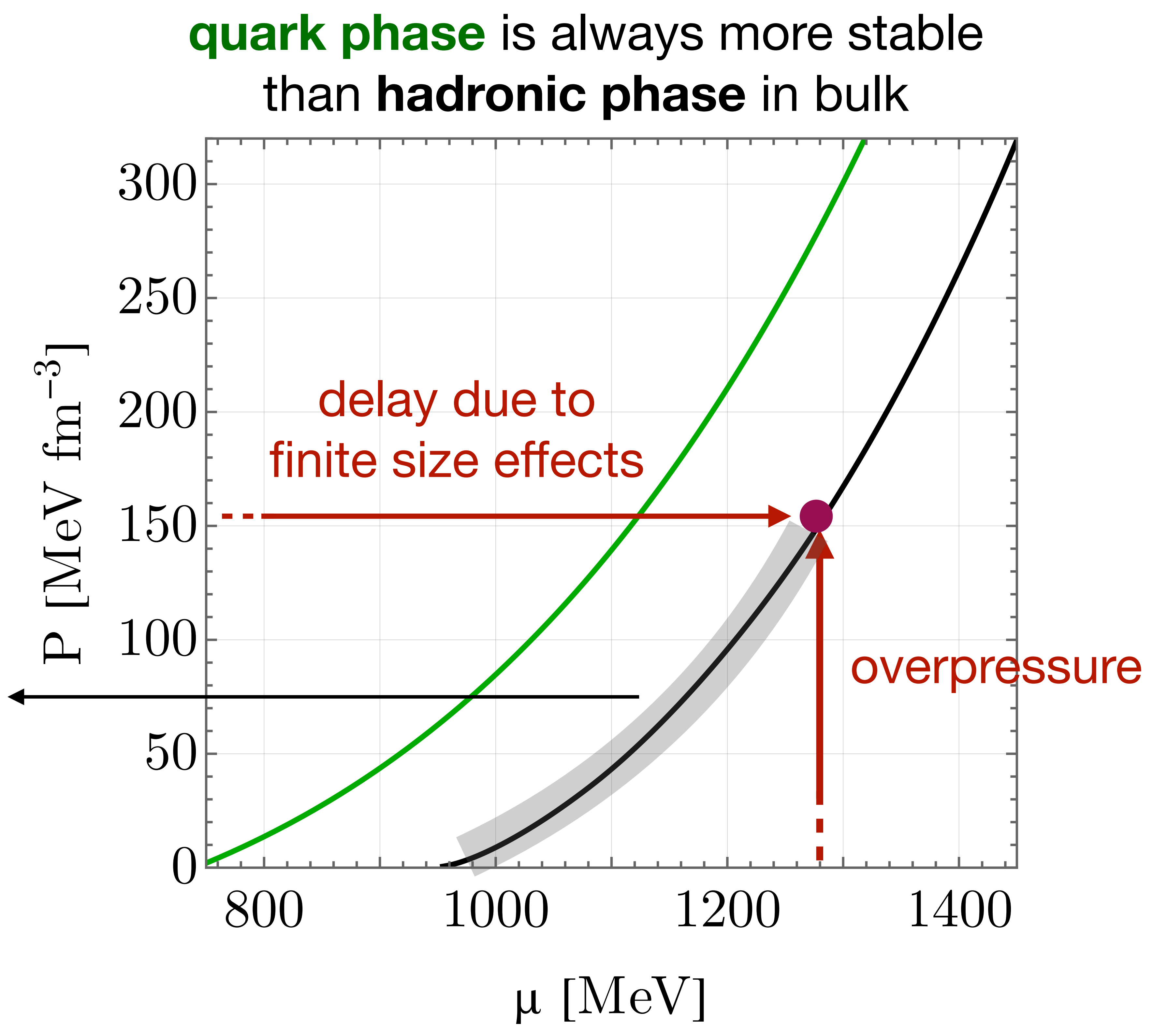
1 keV $\lesssim T \lesssim 10$ MeV:
- nucleation at lower P than NF case
- PSNs can not nucleate

$T \lesssim 1$ 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

Nucleation in compact stars





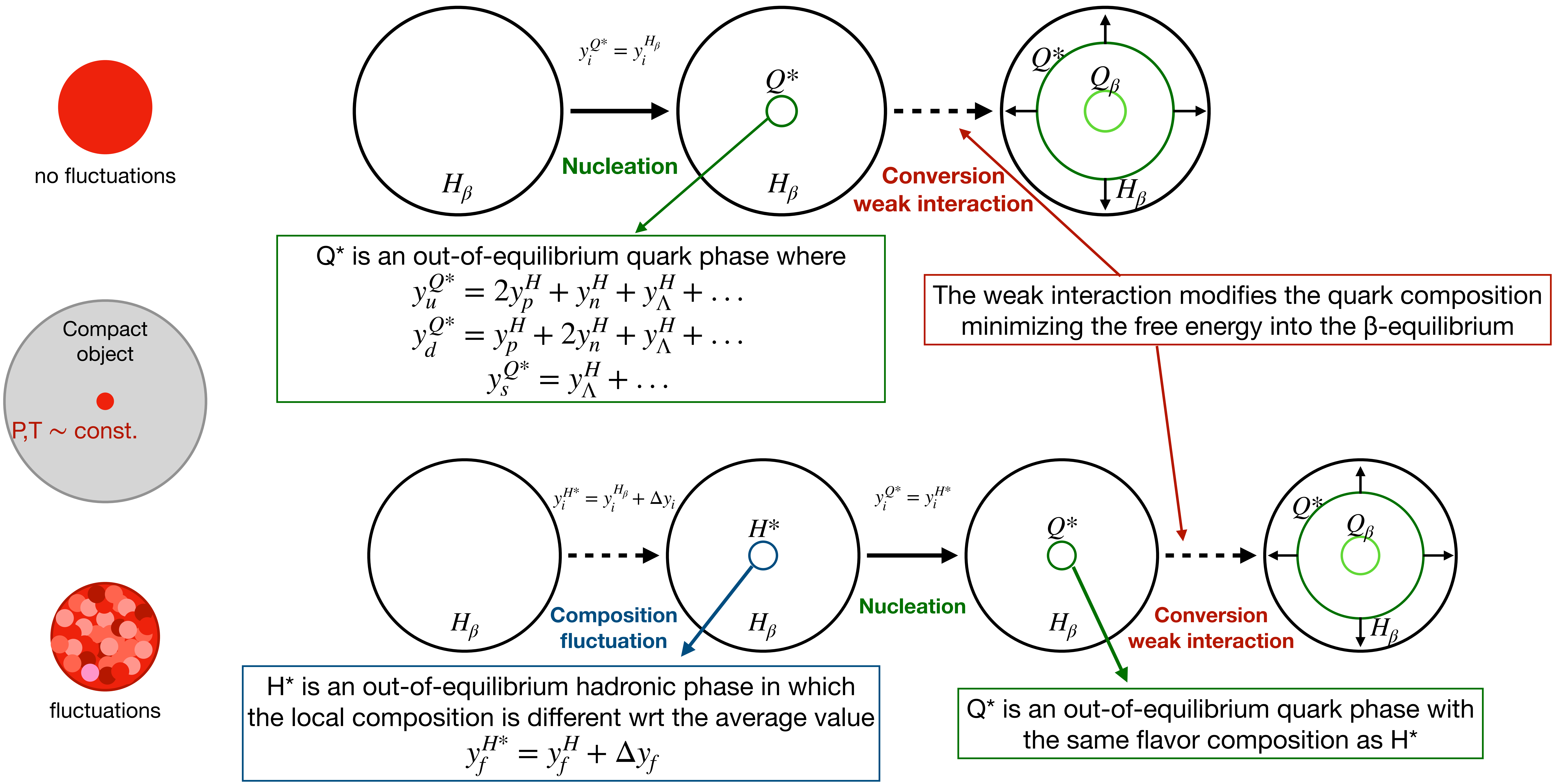
One family scenario (hybrid stars)

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

Nucleation: calculations setup



Backup: nucleation

$$\Gamma = \Gamma_0 \, e^{-W/T} \qquad R_* = \frac{2\sigma}{P_{Q*} - P_H} \qquad W = \frac{16}{3}\pi \frac{\sigma^3}{(P_{Q*} - P_H)^2}.$$

$$\tau = \frac{1}{V\Gamma} \qquad W = -\frac{4}{3}\pi R_*^3 \left[P_{Q*} - P_H\right] + 4\pi\sigma R_*^2.$$

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

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

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

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

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

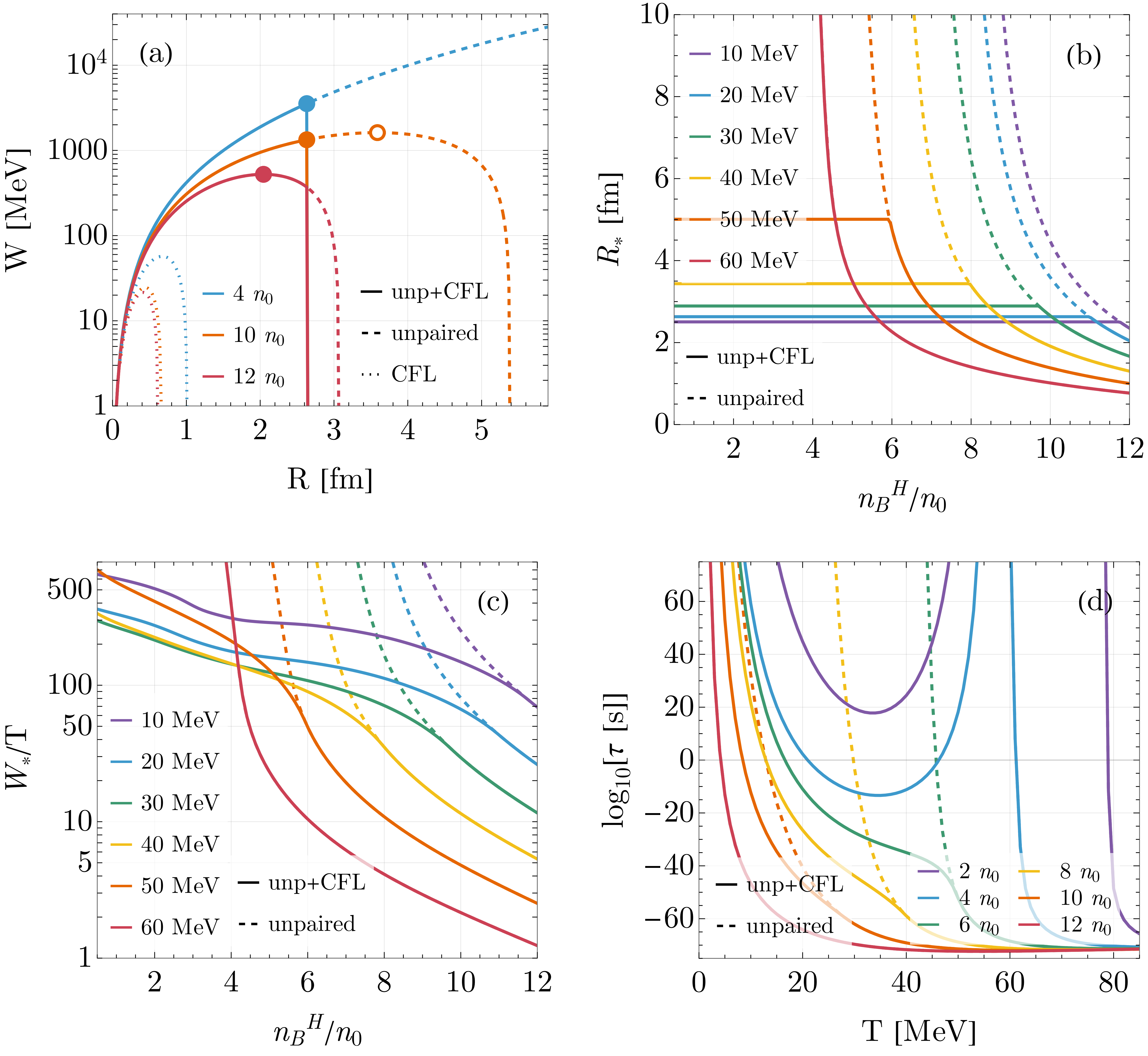
Fischer et al. (2011) ApJ

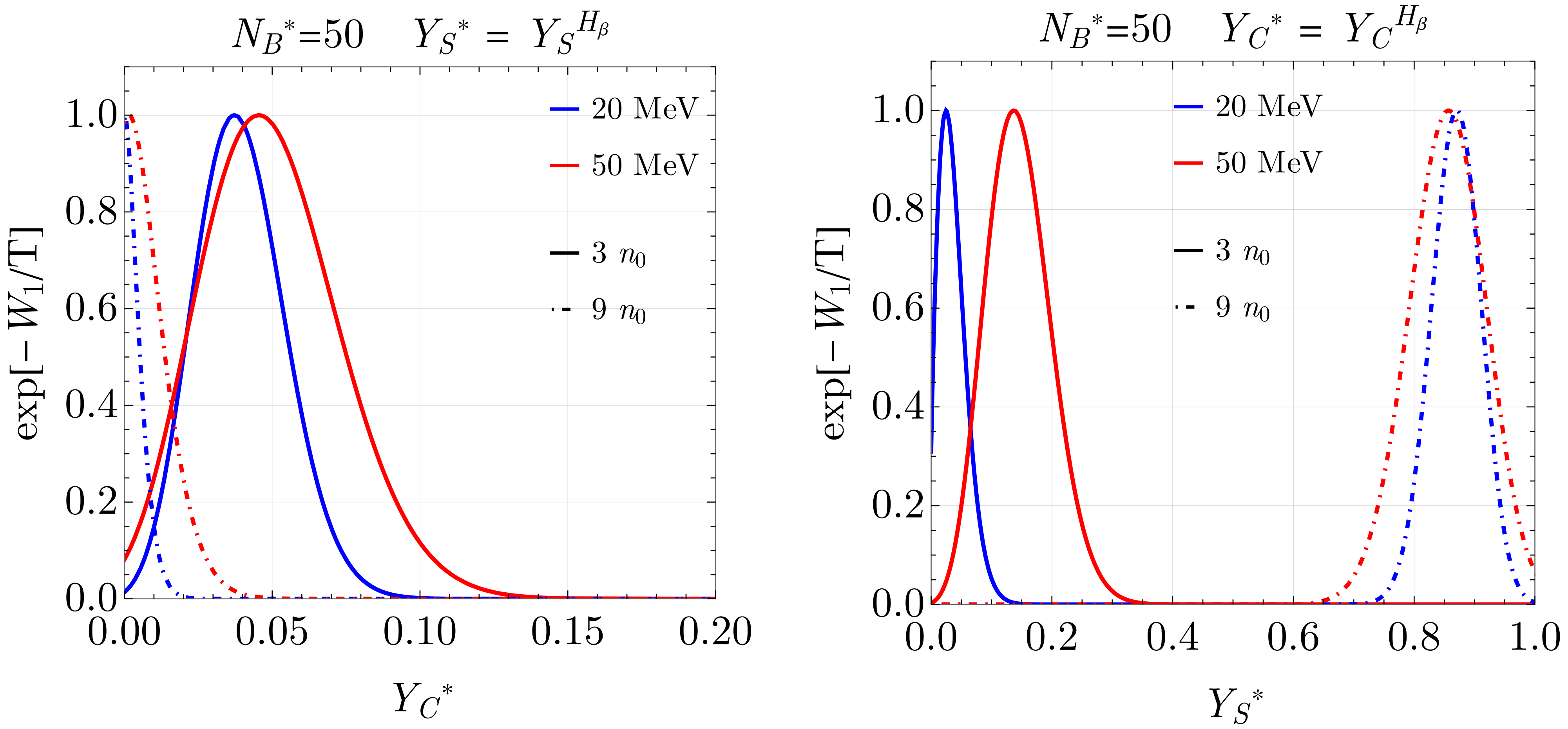
$$\Delta(T) = \Theta(T_c - T)\Delta_0\sqrt{1 - \frac{T}{T_c}}$$

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

Schmitt (2010) Lec. Not. Phys

Backup: more on three flavors





Backup: more on two flavors

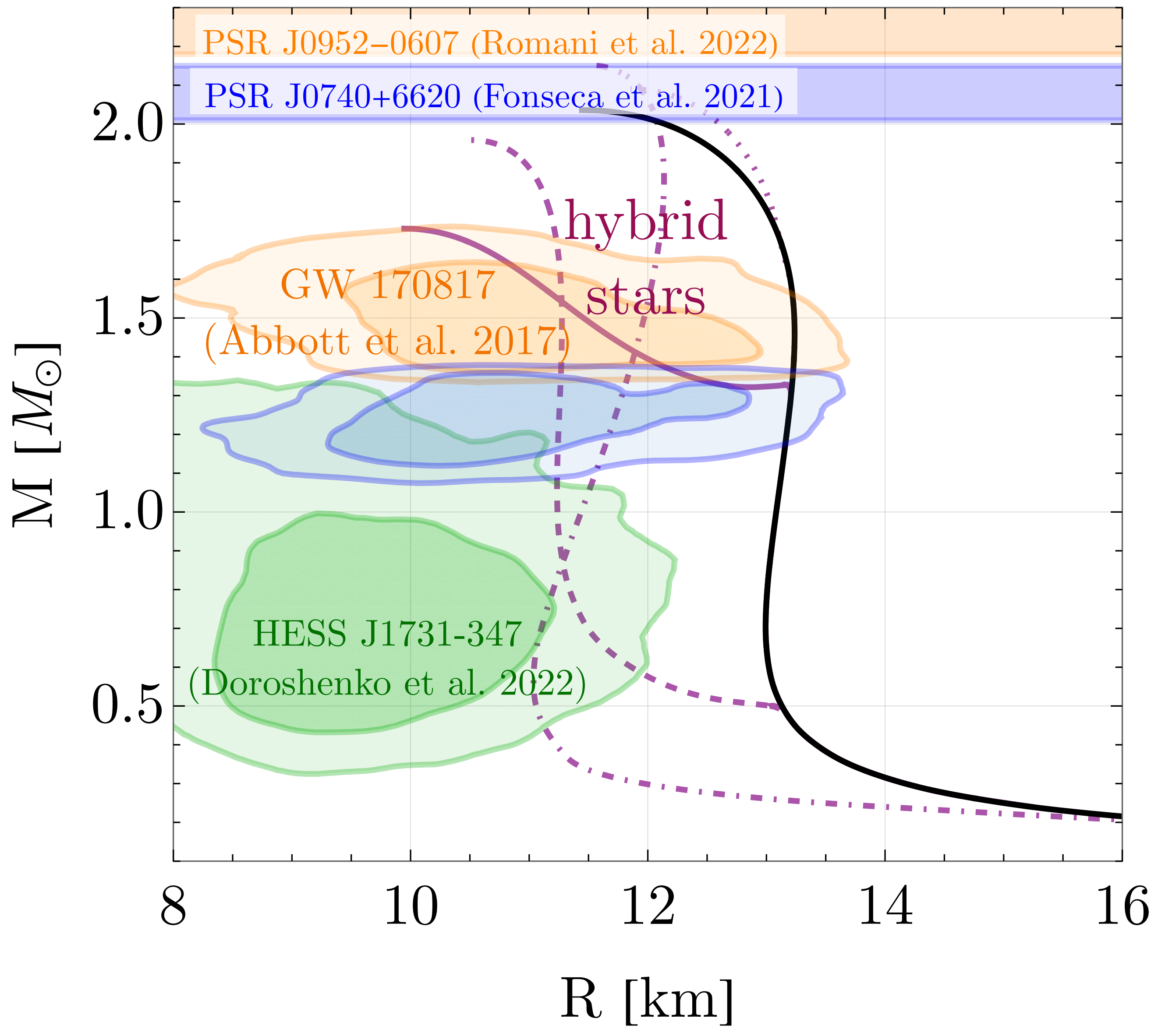
$$W_1 = n_{B,Q^*} V_{Q^*} \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*}\right)$$
$$= n_{B,Q^*} \frac{4}{3}\pi R^3 \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*}\right).$$

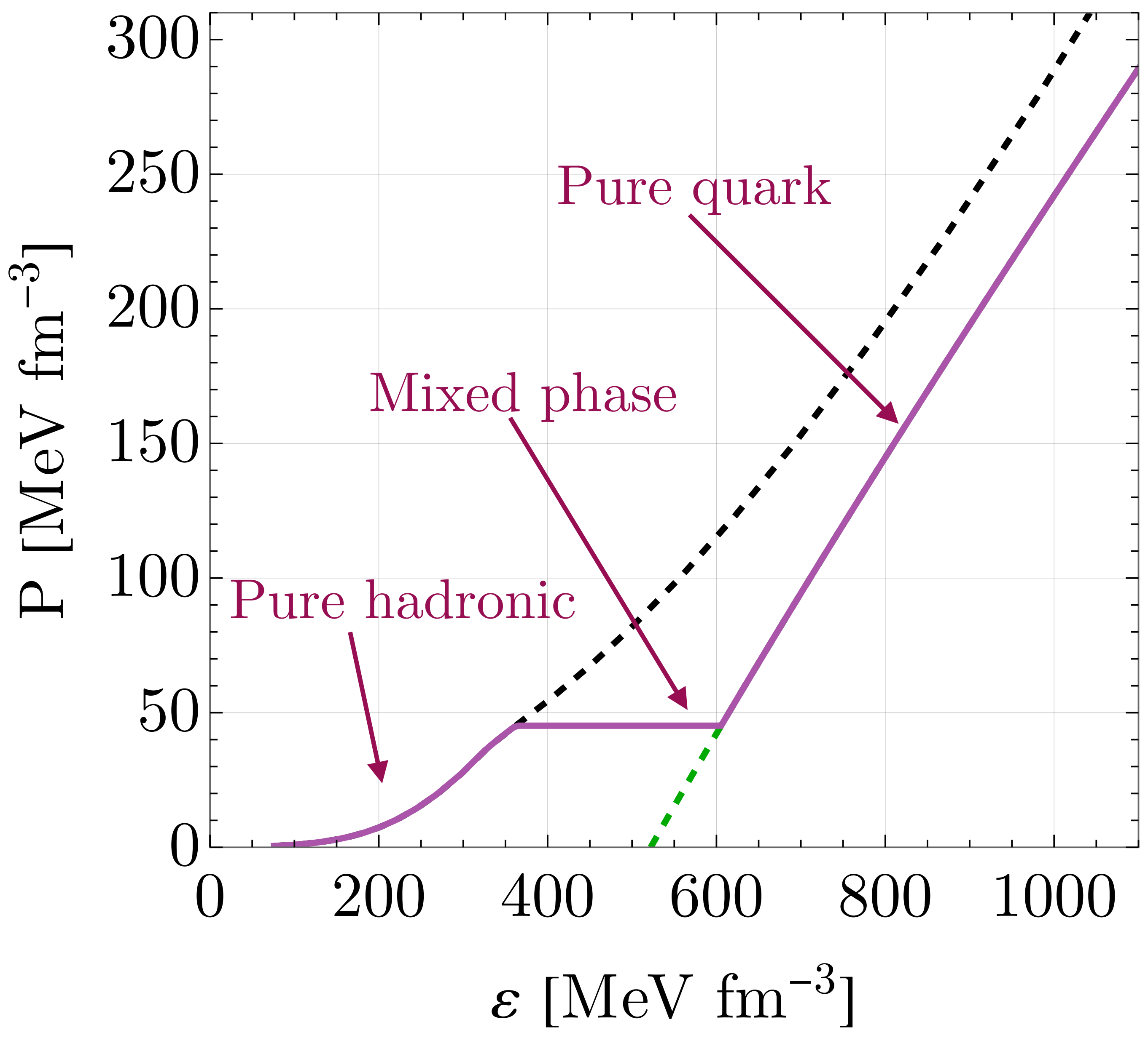
$$W_2 = \frac{4}{3}\pi R^3 n_{B,Q^*} \left(\mu_{Q^*} - \mu_{H^*}\right) + 4\pi\sigma R^2.$$

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

Backup: more on two flavors results

SQM in compact stars: one or two families?

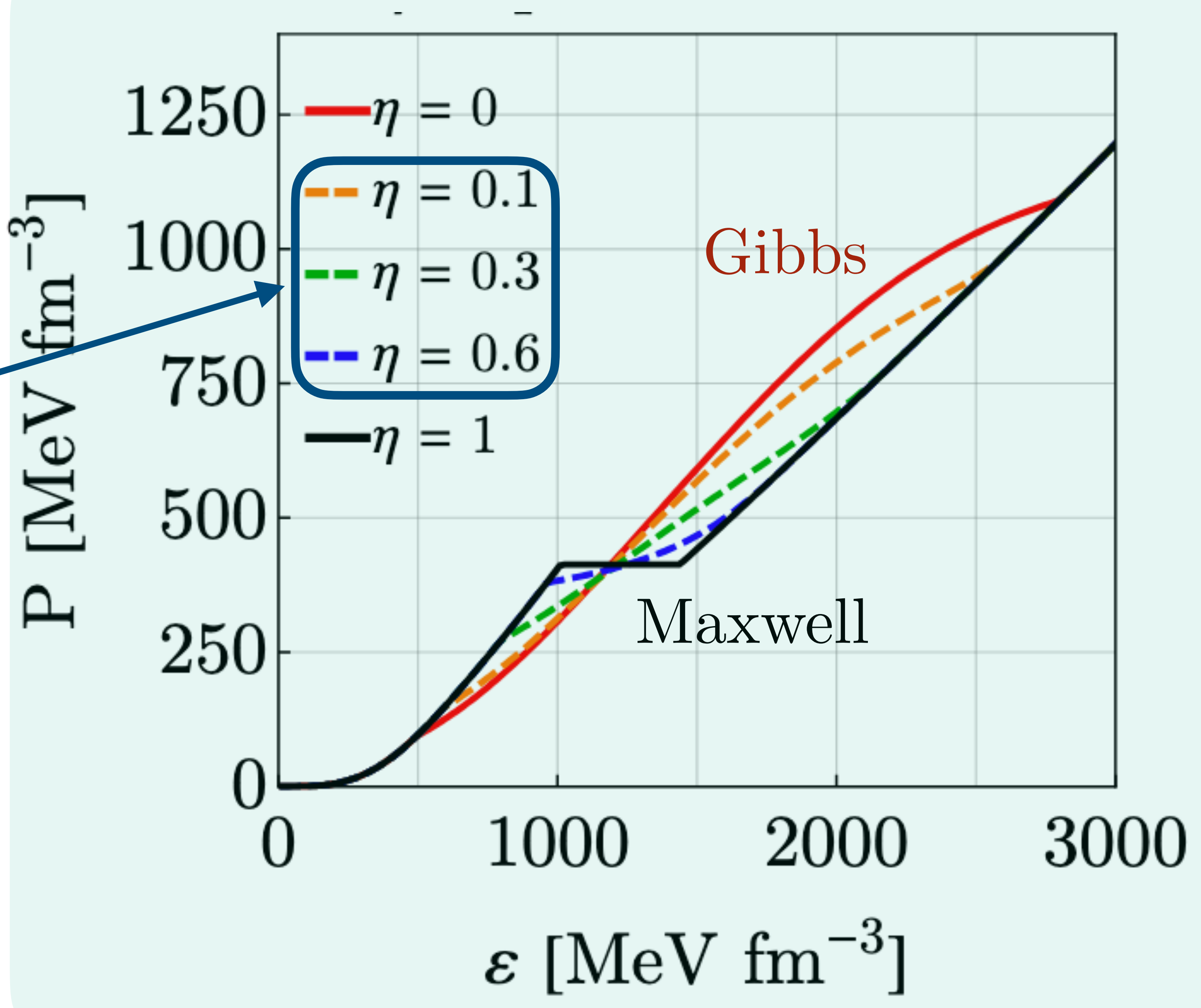




One family scenario

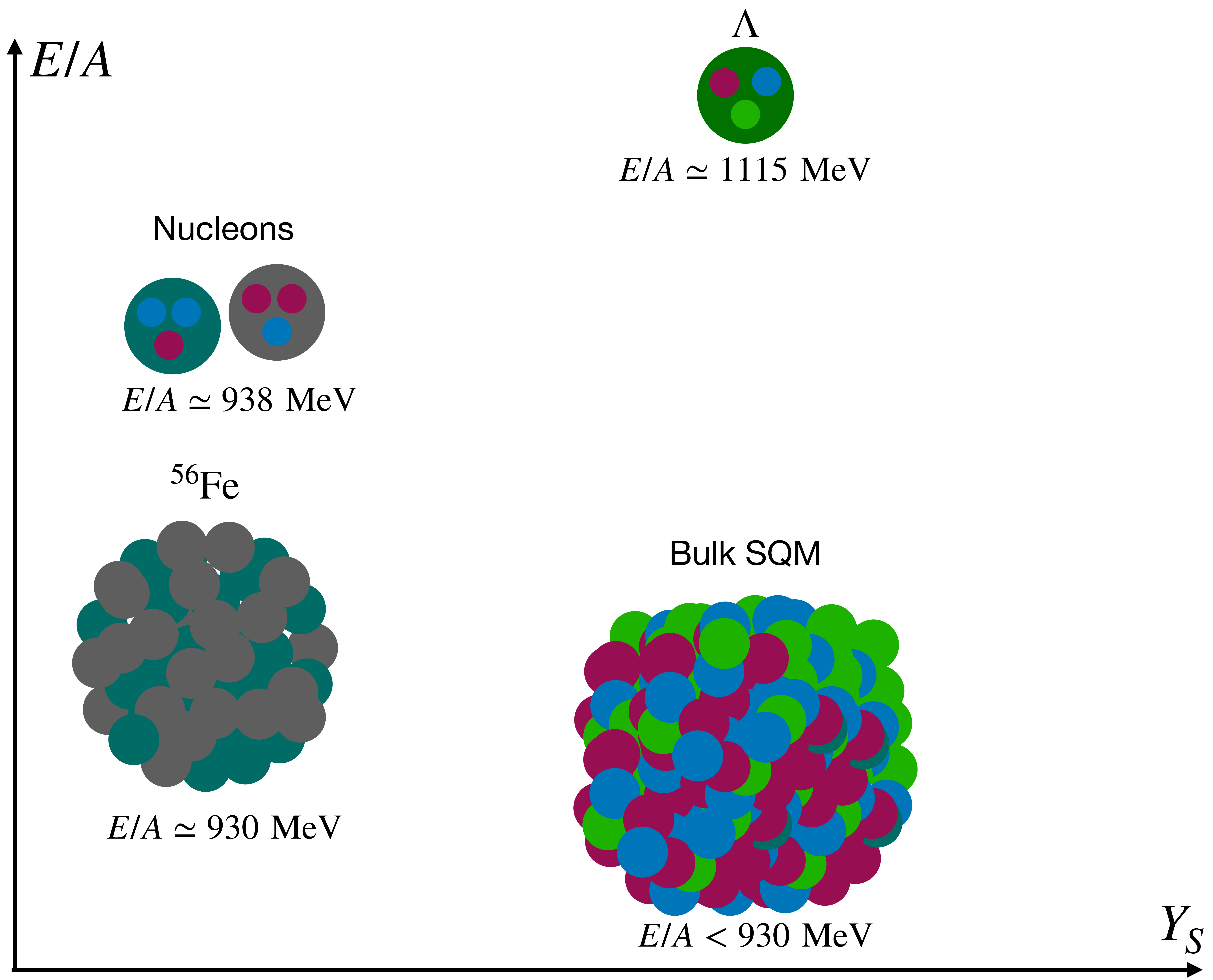
- deconfined quarks d.o.f. expected in massive compact stars
- **hybrid stars**: SQM in the core and hadrons in the outer part
- 1st order phase transition, crossover, quarkyonic, …

Maxwell C., Gibbs C., mixed approach



[Constantinou et al. 2024]

(soon at finite temperature)



E/A
Λ
$E/A \simeq 1115$ MeV
Nucleons
$E/A \simeq 938$ MeV
^{56}Fe
$E/A \simeq 930$ MeV
Bulk SQM
$E/A < 930$ MeV
Y_S