Quark nucleation in compact stars

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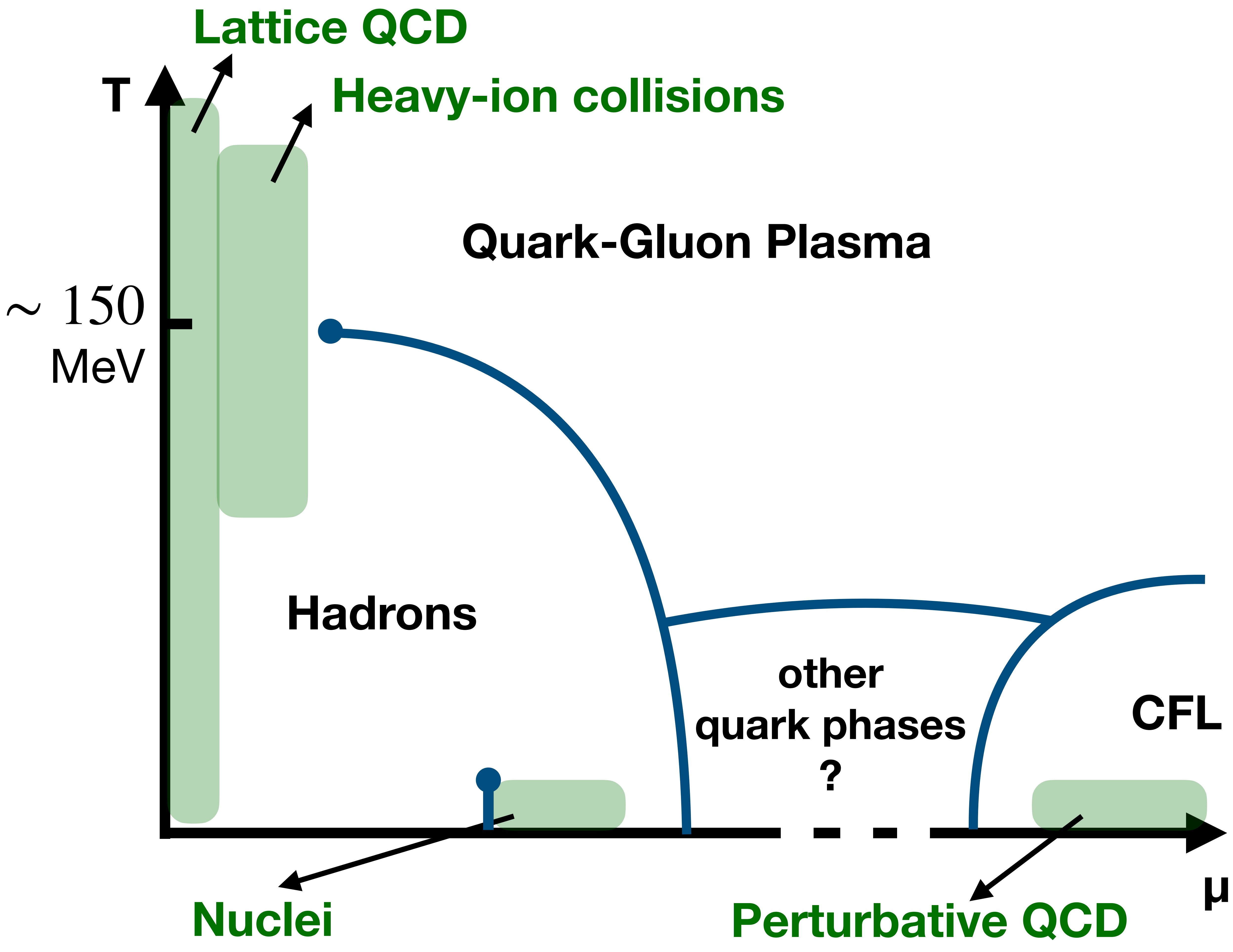
Compact Stars in the QCD phase diagram 2024
Yukawa Institute for Theoretical Physics, Kyoto

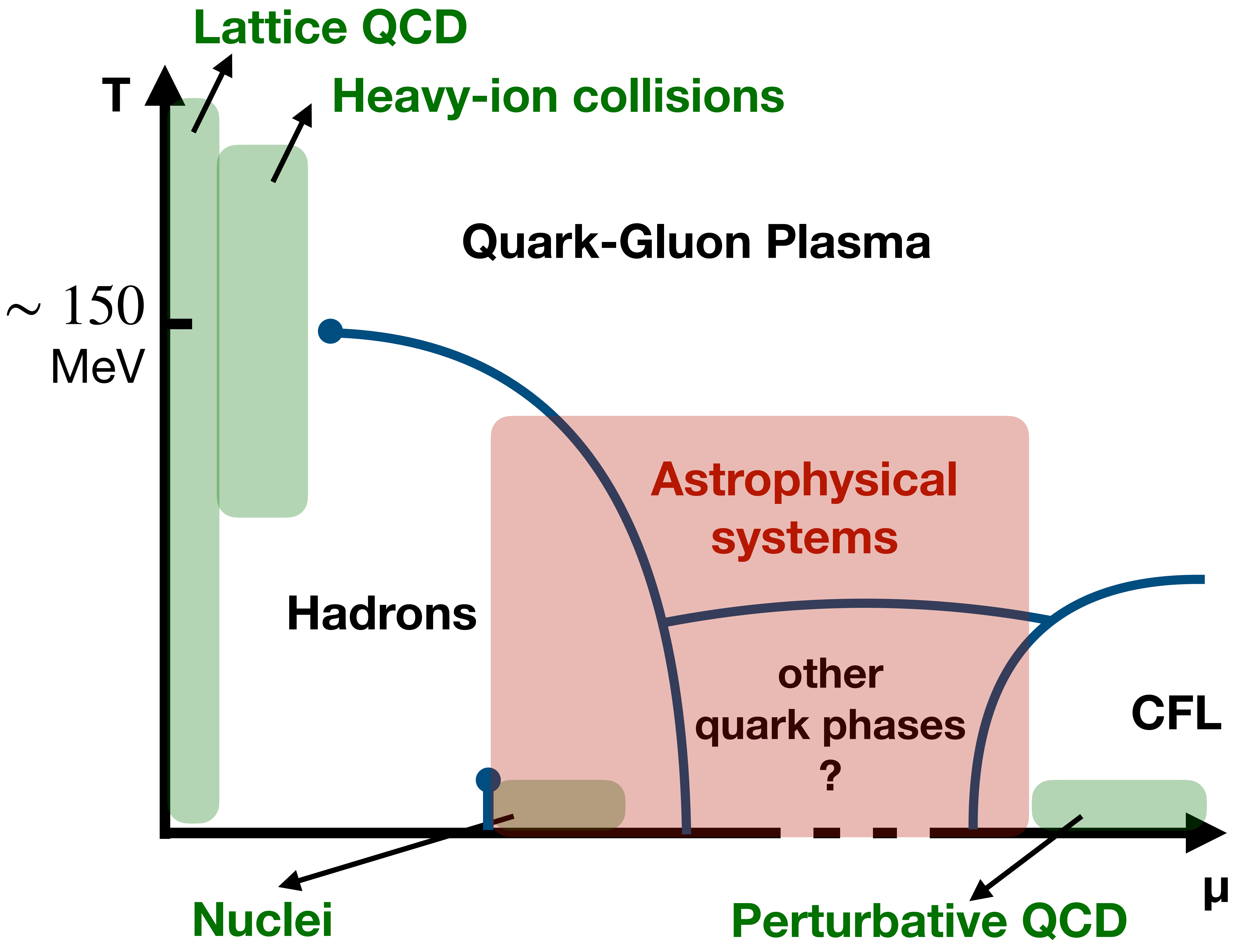
INFN FERRARA

QCD phase diagram



- the high-density regime is poorly known
- quarks d.o.f. expected at $n_B \sim$ few n_0

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

The “Two families scenario”

- new d.o.f. → EOS softening → lower NS masses
- very massive $\sim (2-2.6)\,M_\odot$ compact objects observed

$\longrightarrow$

“Hyperons Puzzle”

many different solutions have been proposed
[for a review: Vidaña (2022)]

…one more possible solution…

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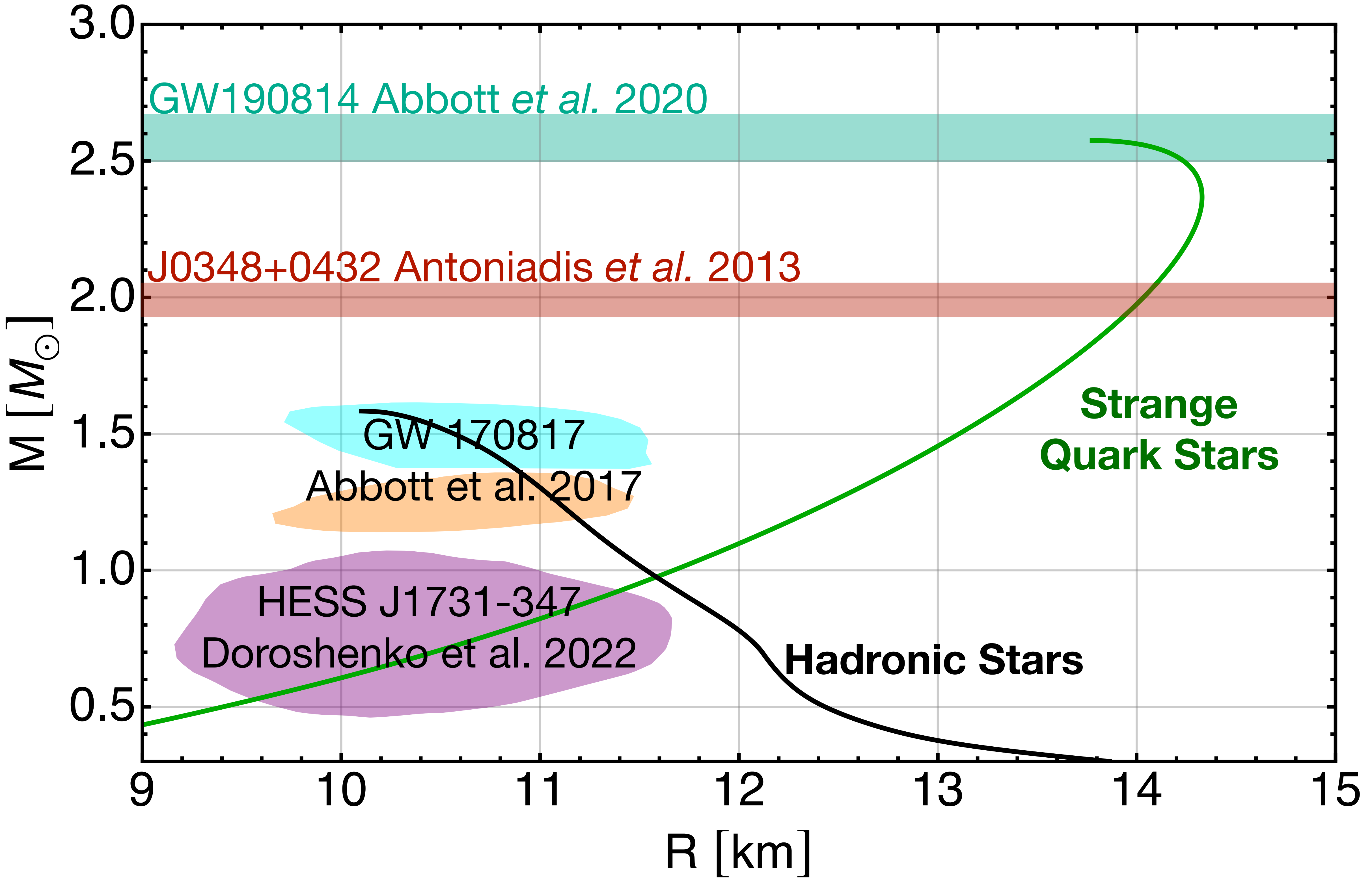

Two families scenario

[see Drago et al. (2016)]

- based on the **strange matter hypothesis** *[Witten (1984)]*
- **hadronic** stars up to ~ 1.6 M$_{\odot}$ at low radius
- **quark stars** fulfill massive and subsolar objects constraints
- once reached deconfinement conditions, **HS** converts to **QS**

Deconfinement in astrophysical systems

mergers

supernovae

mass accretion

spin down

[Berezhiani et al. (2002)]
GRBs?

Nucleation
first droplet of
quark matter

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)]

Deconfinement in astrophysical systems

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Hadronic object

Hadronic matter

Quark matter

[Berezhiani et al. (2002)]

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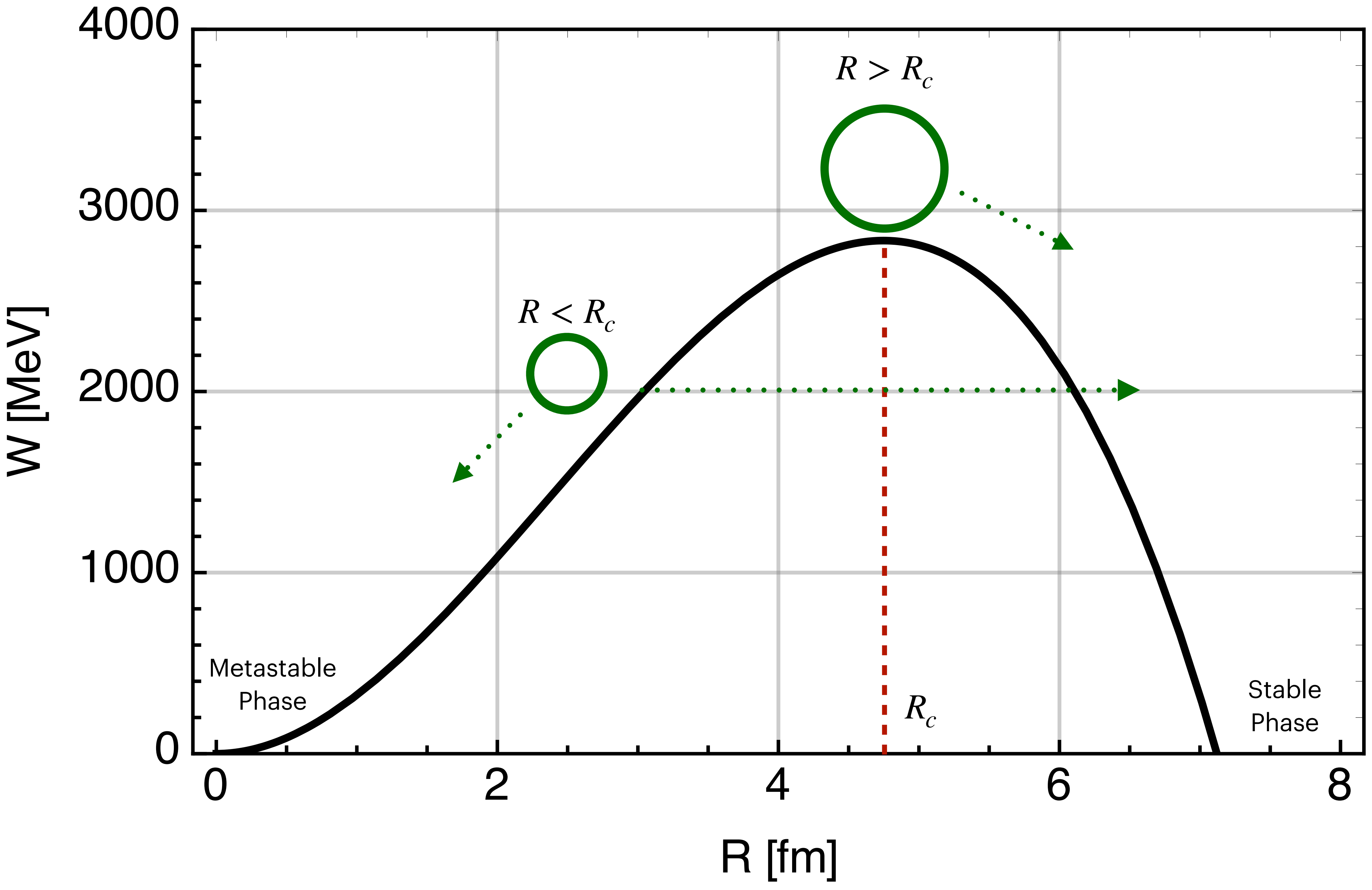
This work

goal:
identify the **thermodynamic conditions** at which **nucleation** happens in **astrophysical systems**

Nucleation

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



is a **finite-size problem**

the first seed is generated when a drop overcomes the potential barrier

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

bulk energy gain
(negative if H is metastable)

surface effect
(always positive)

The barrier can be overcome:

- Thermal: $\mathscr{P} \sim e^{\frac{-W(R_C)}{T}}$ *[Langer (1969)]*
- Quantum: $\mathscr{P} \sim e^{\frac{-A(E_0)}{\hbar}}$ *[Iida et al. (1998)]*

Nucleation: state of the art

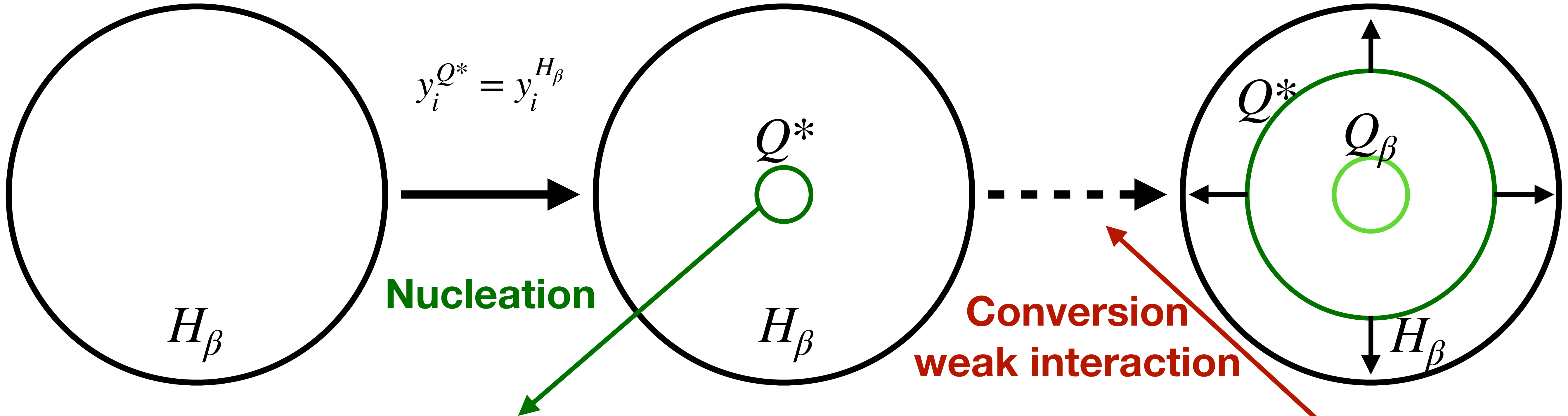
Nucleation is due to **strong interactions**

strong timescale ≪ weak timescale

→

Flavor composition is conserved during the nucleation

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



$y_i^{Q*} = y_i^{H_\beta}$

Nucleation

Conversion weak interaction

H_β

$Q*$

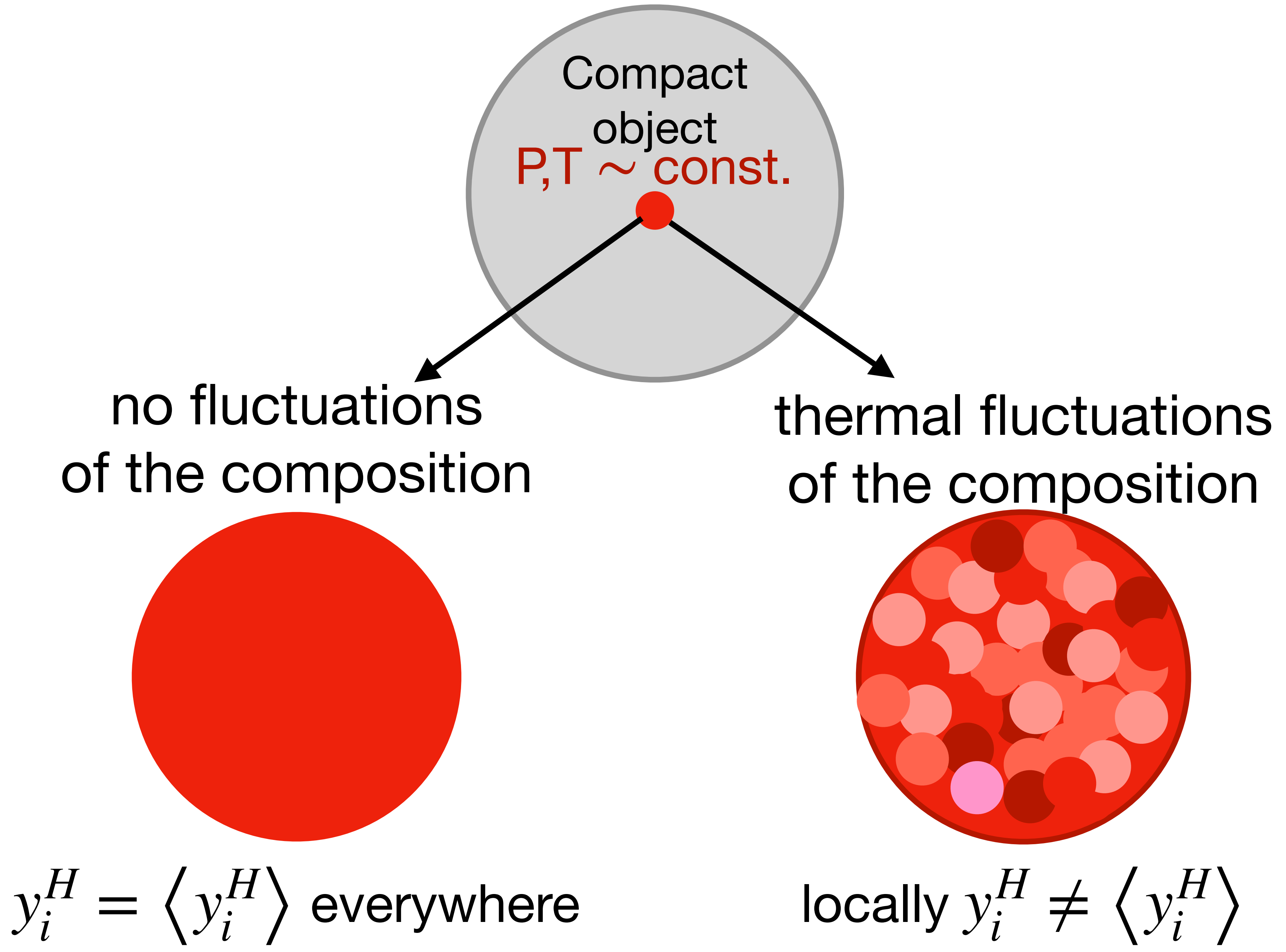
Q_β

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

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

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

Nucleation: role of thermal fluctuations



Compact object

P,T ~ const.

no fluctuations of the composition

thermal fluctuations of the composition

$y_i^H = \langle y_i^H \rangle$ everywhere

locally $y_i^H \neq \langle y_i^H \rangle$

Key idea:

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

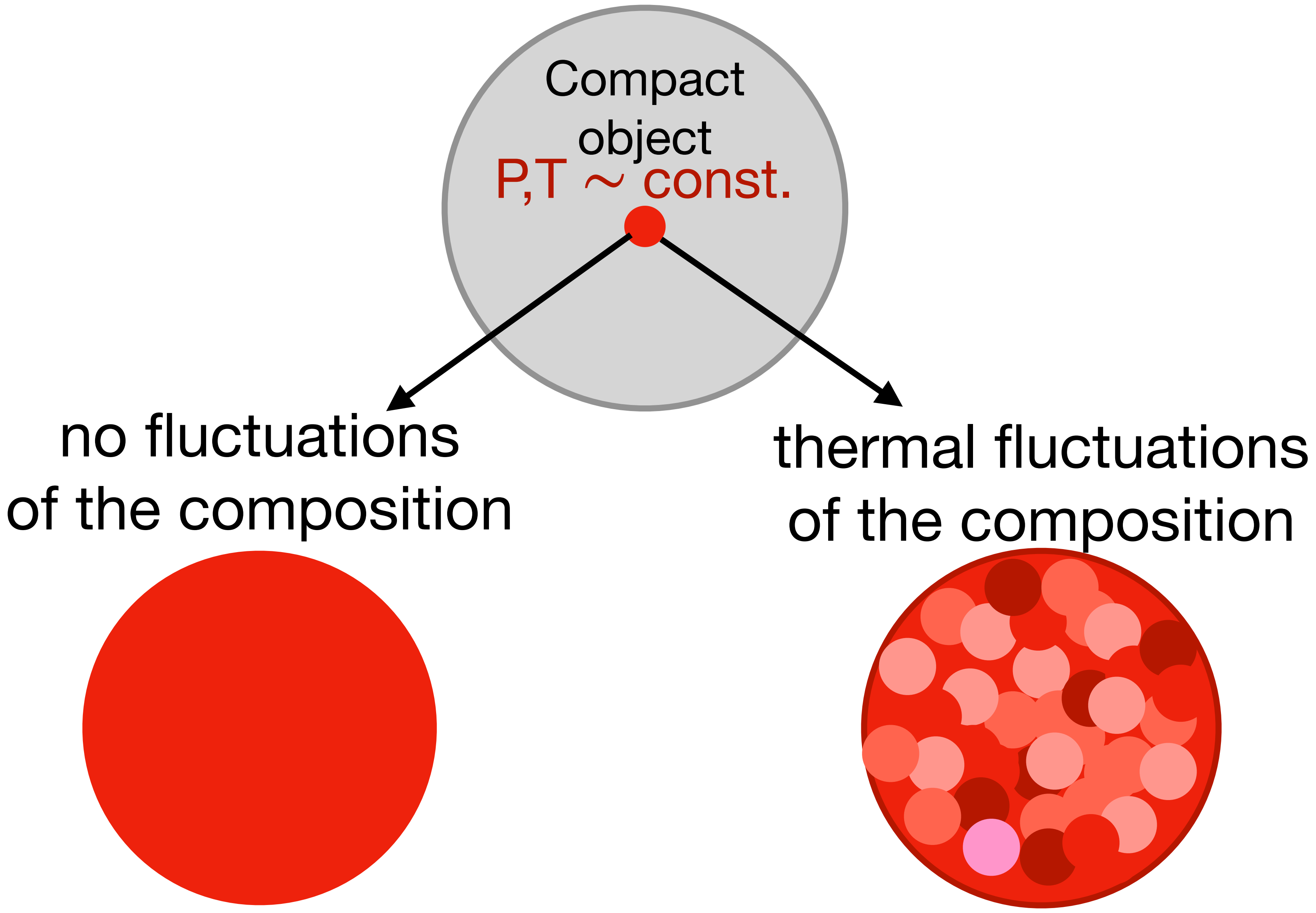
the nucleation is a **local process**

↓

Nucleation could happens in a subsystem in which the local composition makes nucleation easier

[Guerrini et al. (2024)]

Nucleation: role of thermal fluctuations



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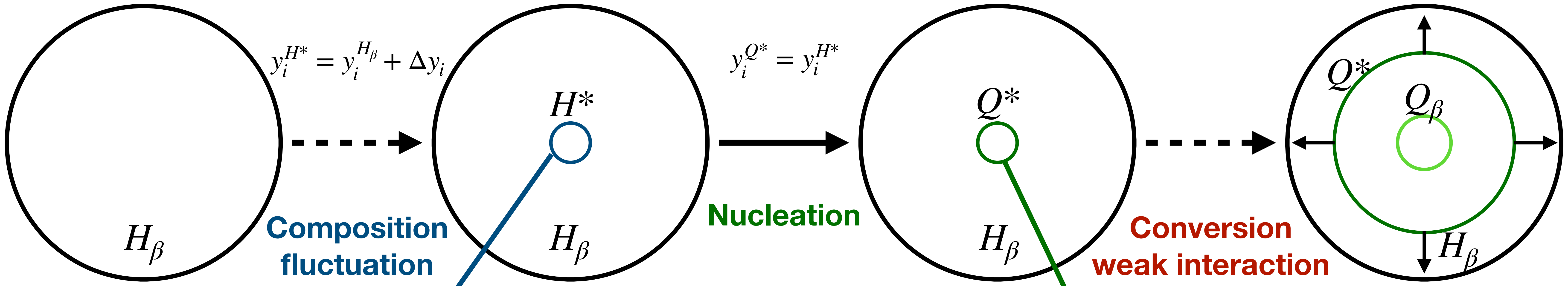


Composition fluctuation

Nucleation

Conversion weak interaction

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

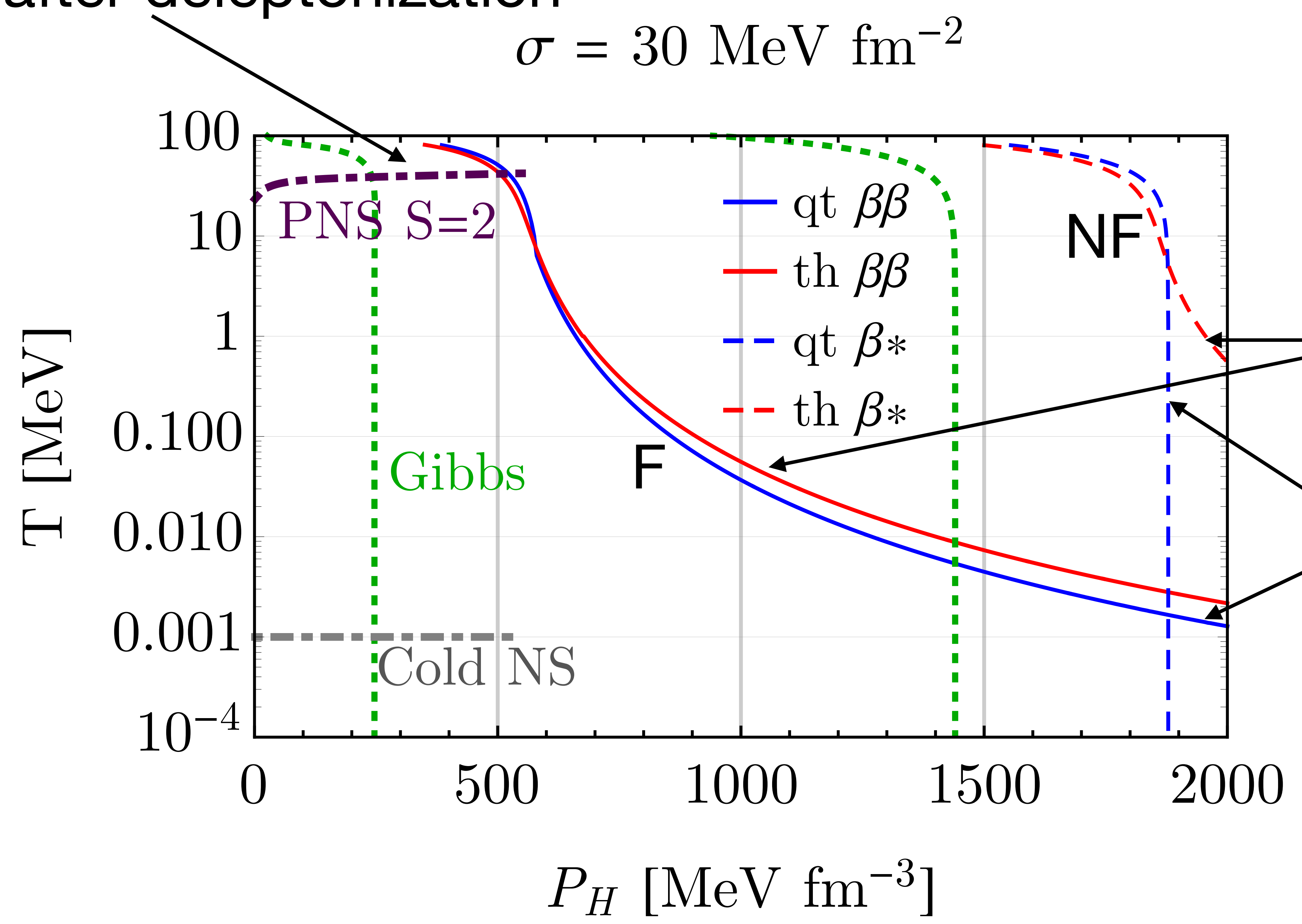
$$y_f^{H*} = y_f^H + \Delta y_f$$

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

Results: two flavors case

[Guerrini et al. (2024)]

PNS after deleptonization



Thermal nucleation

Quantum nucleation

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

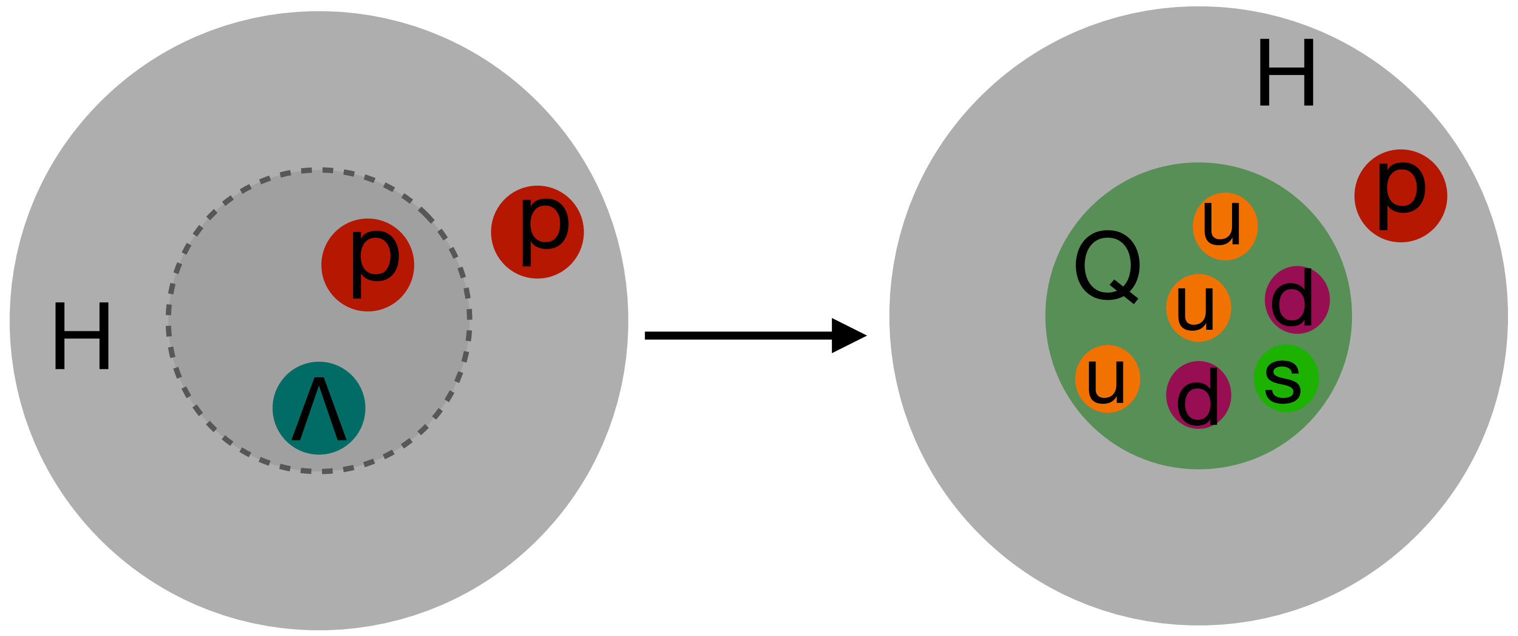
1 keV $\lesssim T \lesssim 10$ MeV:
- nucleation at lower P than NF case
- PSNs can not nucleate

$T \lesssim 1$ 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

[work in progress]

More ingredients: global conservation?



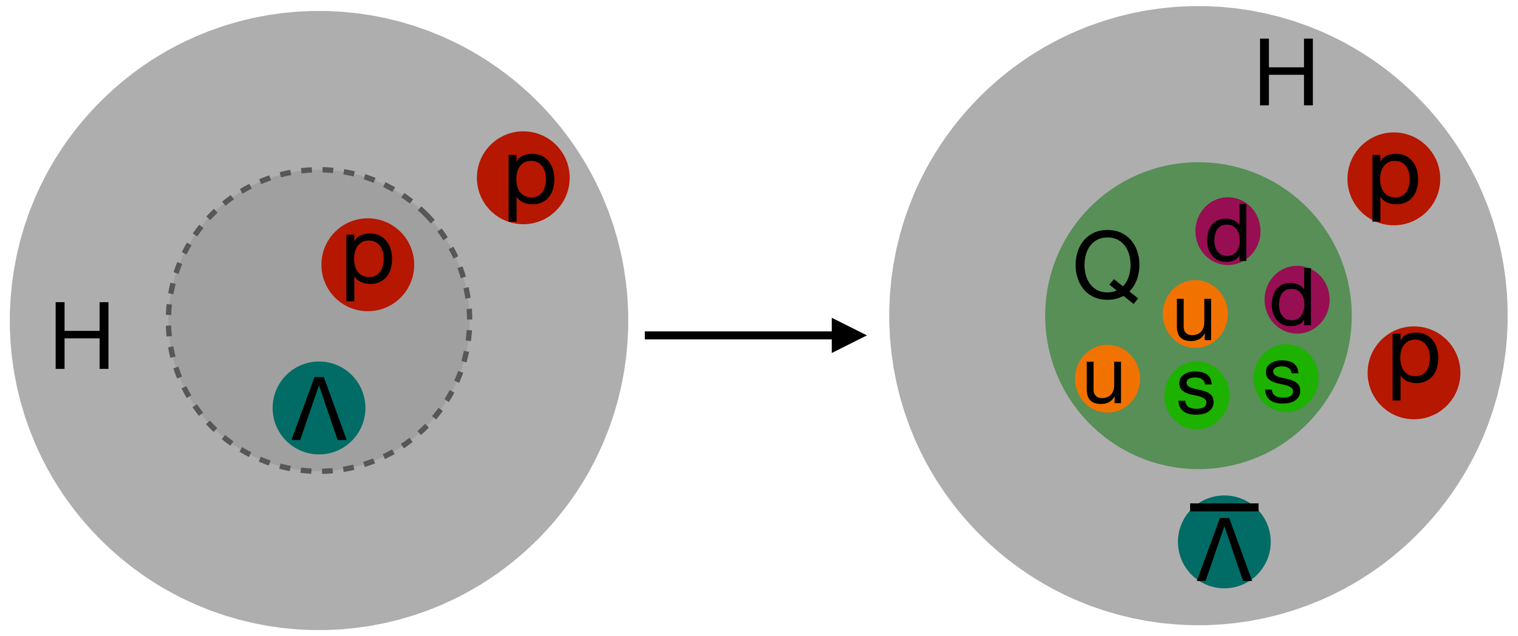
Nucleation mediated by **strong interaction** → flavors are **conserved** in nucleation (or baryon number, isospin, strangeness)

Local conservation $N_i^Q = N_i^H$

$i = u, d, s$ or B, I, S

Global conservation $N_i^Q + N_i^H = N_i \rightarrow \mu_i^Q = \mu_i^H$

e.g. $s\bar{s}$ can be created, s inside the Q droplet, $\bar{s}$ in the H background



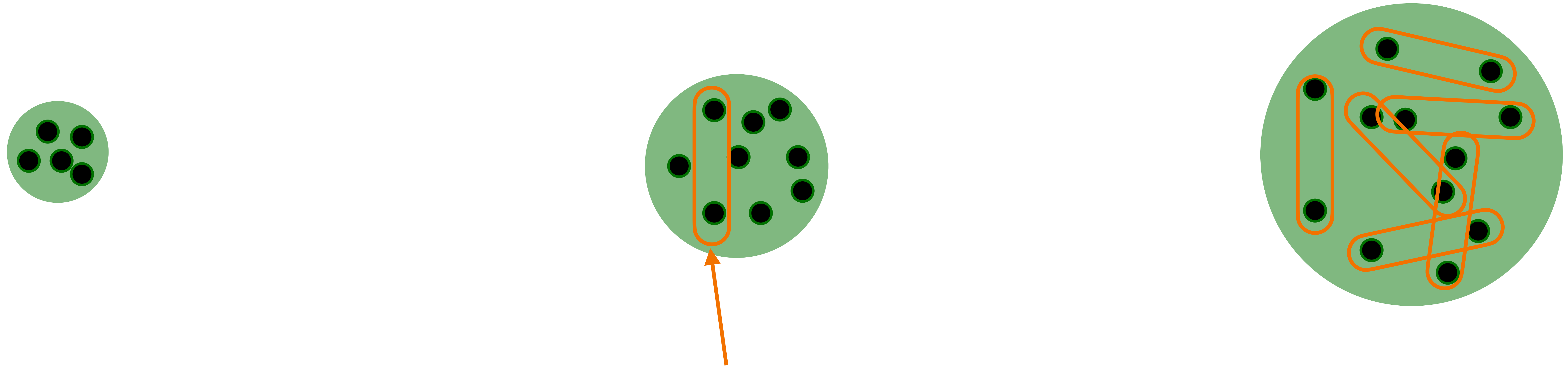
[work in progress]

More ingredients: color-superconductivity

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

…but…

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



size of Cooper pairs $\sim 1/\Delta \sim (2-3)$ fm

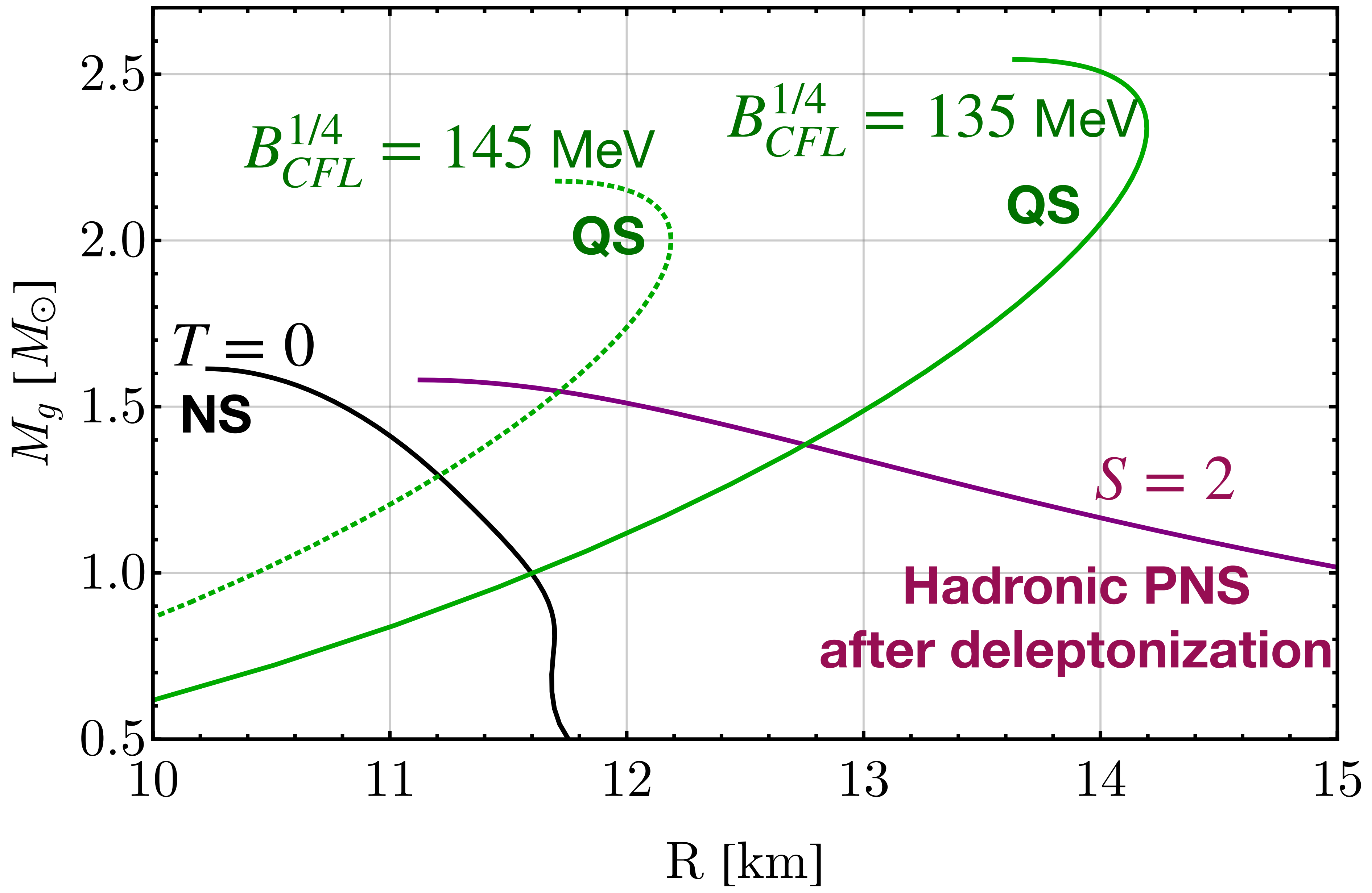
droplet of Q
R $\lesssim 1/\Delta$
unpaired phase

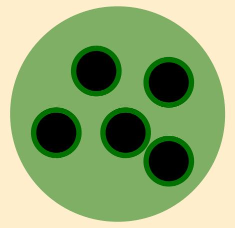
$\longrightarrow$

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

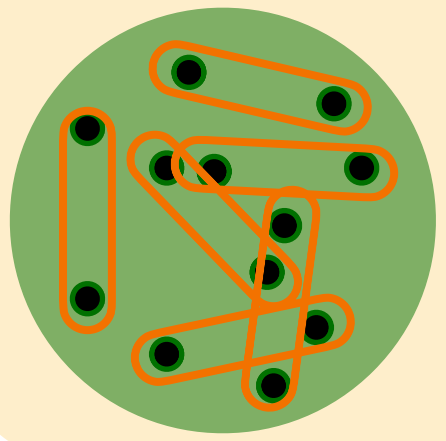
[work in progress]

Nucleation in “two families scenario”?





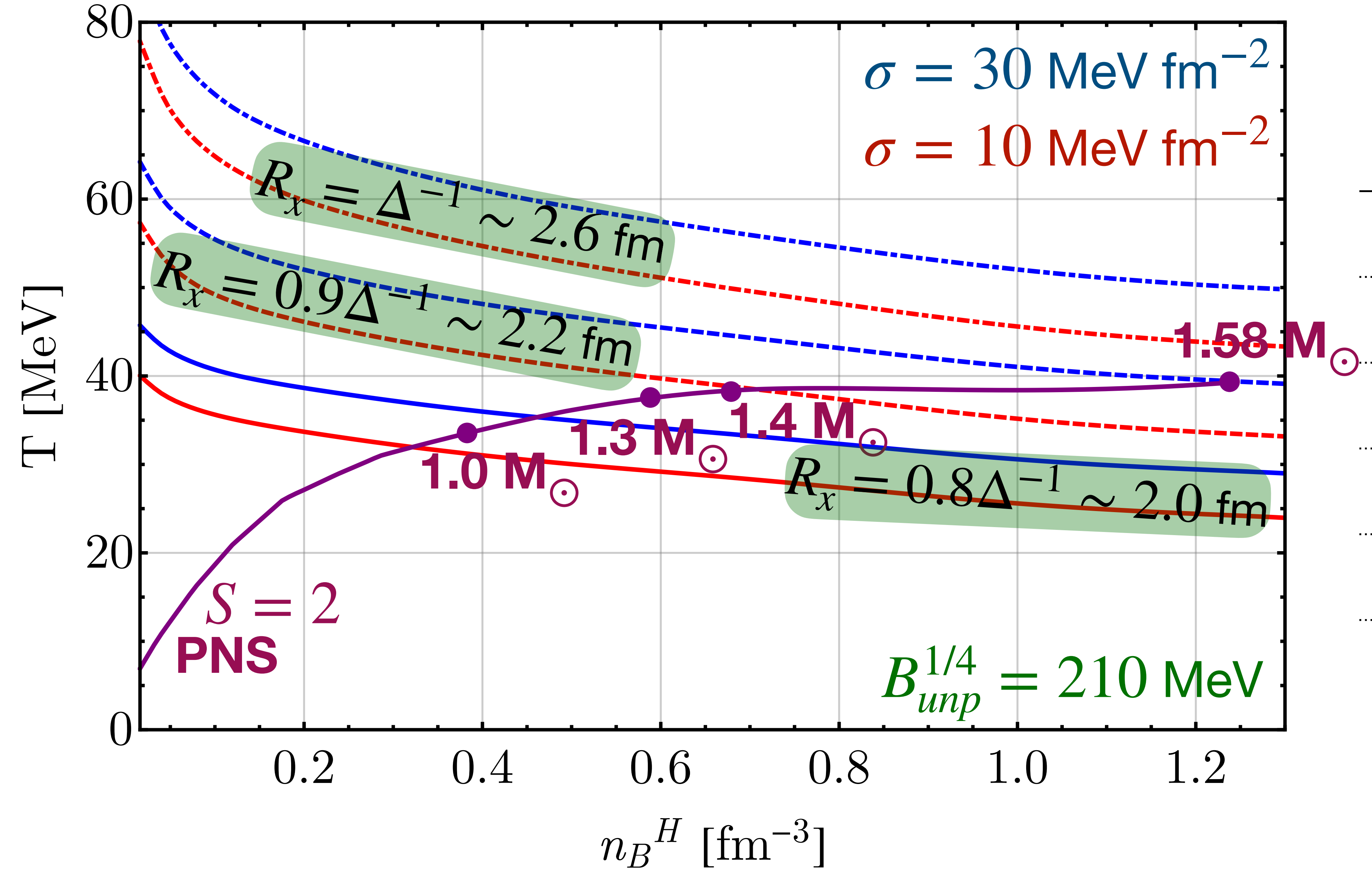
$R < R_x$: **unpaired matter**, B_{unp} , $\alpha = 0.1\pi/2$, $\Delta = 0$ MeV



$R > R_x$: **CFL matter**, B_{CFL} , $\alpha = 0.1\pi/2$, $\Delta = 80$ MeV

Can (some) PNS be converted into QS?

Is the two fam. scenario compatible with our nucleation calculations?



$B_{unp}^{1/4}$ [MeV]	$B_{CFL}^{1/4}$ [MeV]	R_x [Δ^{-1} fm]	σ [MeV fm^{-2}]	Y_S	M_{PNS}^{crit} [M$_\odot$]	M_{QS} [M$_\odot$]	E_{conv} [10^{53} erg]	Two fam?
210	135	0.8	10	0.02	0.89	0.69	3.6	all QSs
210	135	0.9	10	0.15	1.43	1.12	5.4	QSs+NSs
210	135	1.0	10	1.03	X	X	X	no QSs after PNS
210	145	0.9	10	0.15	1.43	1.19	4.1	QSs+NSs
180	135	1.2	30	0.04	1.11	0.87	4.4	all QSs

We are working on that!

Any other questions or suggestions?
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Summary and conclusions

Background

- **exotic d.o.f.** expected at **compact object** densities
- **nucleation** is the starting point for first order phase transitions
- “**two families**” of compact objects may exist if the **Witten hypothesis** is correct
- flavor composition is conserved during **nucleation**

Method

- State of the art: the first droplet of **Q matter** has the **same flavor composition** as the initial **bulk H phase**
- Guerrini et al. 2024: take into account that at finite T the hadronic composition **fluctuates**

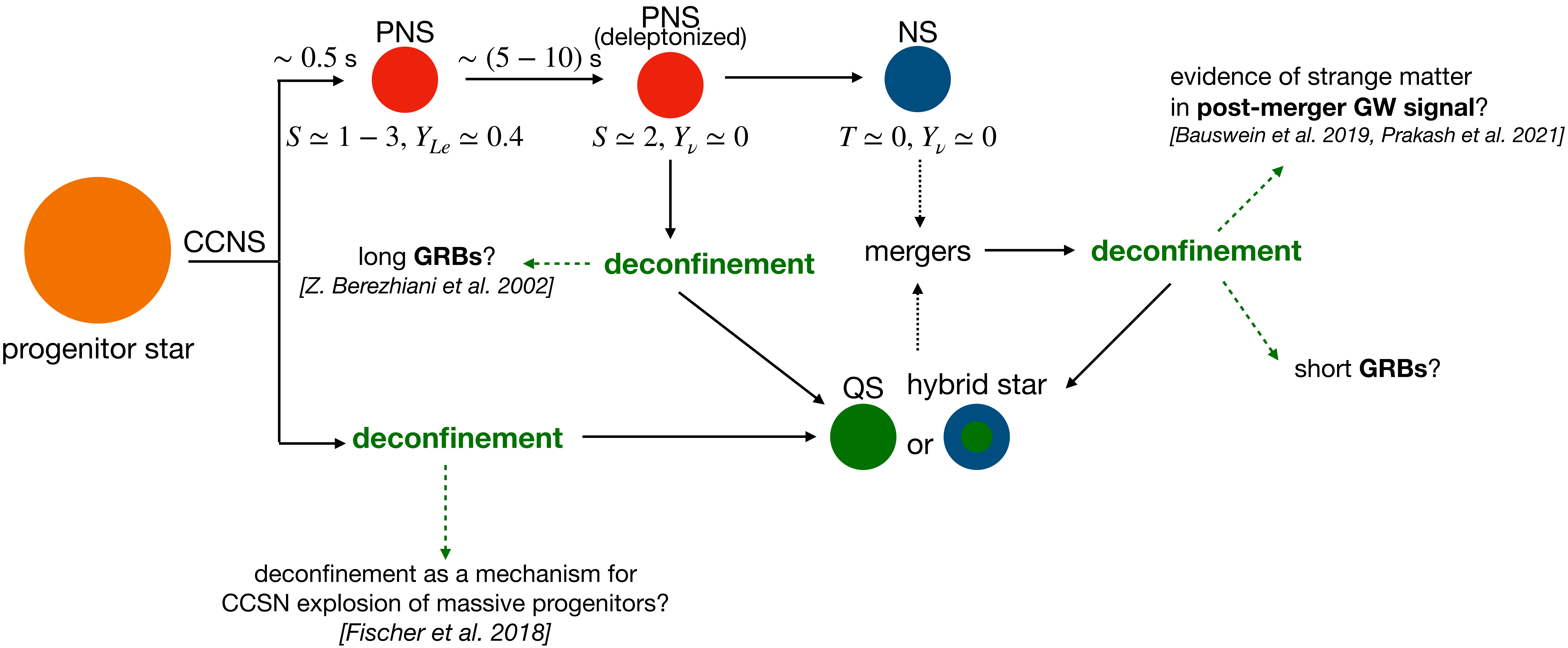
Results

- two flavors: **composition fluctuations** lead to **faster nucleation** (i.e. deconfinement can start at lower P) at intermediate and high T
- three flavors: work in progress

Outlooks

- **global** or **local** flavor conservation in nucleation?
- behavior and role of **color-superconducting** matter in nucleation
- using nucleation to study the **phenomenology** of the “**Two families scenario**”
- how to include those **finite-size effects in simulations**?

Deconfinement in astrophysical systems



progenitor star

CCNS

~ 0.5 s

PNS

$S \simeq 1-3,\ Y_{Le} \simeq 0.4$

$\sim (5-10)$ s

PNS
(deleptonized)

$S \simeq 2,\ Y_\nu \simeq 0$

NS

$T \simeq 0,\ Y_\nu \simeq 0$

long **GRBs**?
[Z. Berezhiani et al. 2002]

deconfinement

mergers

deconfinement

evidence of strange matter
in **post-merger GW signal**?
[Bauswein et al. 2019, Prakash et al. 2021]

short **GRBs**?

deconfinement

QS

hybrid star

or

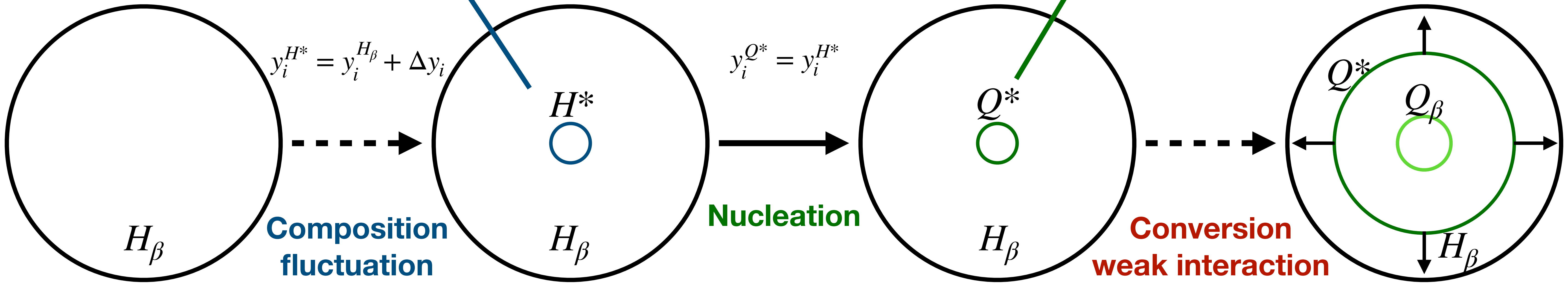
deconfinement as a mechanism for
CCSN explosion of massive progenitors?
[Fischer et al. 2018]

Backup: role of thermal 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*



$$\mathscr{P}(P, T, \Delta y_f) = \mathscr{P}_{fluc} \times \mathscr{P}_{nuc}$$

Prob. that in a subsystem the composition is y_i^{H*} due to a thermal fluctuation

$$\mathscr{P}_{fluc} \sim e^{-\frac{W_{fluc}}{T}}$$

Nucleation prob. in a subsystem H* keeping constant the flavor composition

[complete calculations in Guerrini et al. (2024), arXiv:2404.06463]

Backup: two flavors EOSs

Numerical Fermi Integrals: Johns Ellis Lattimer (1996) ApJ

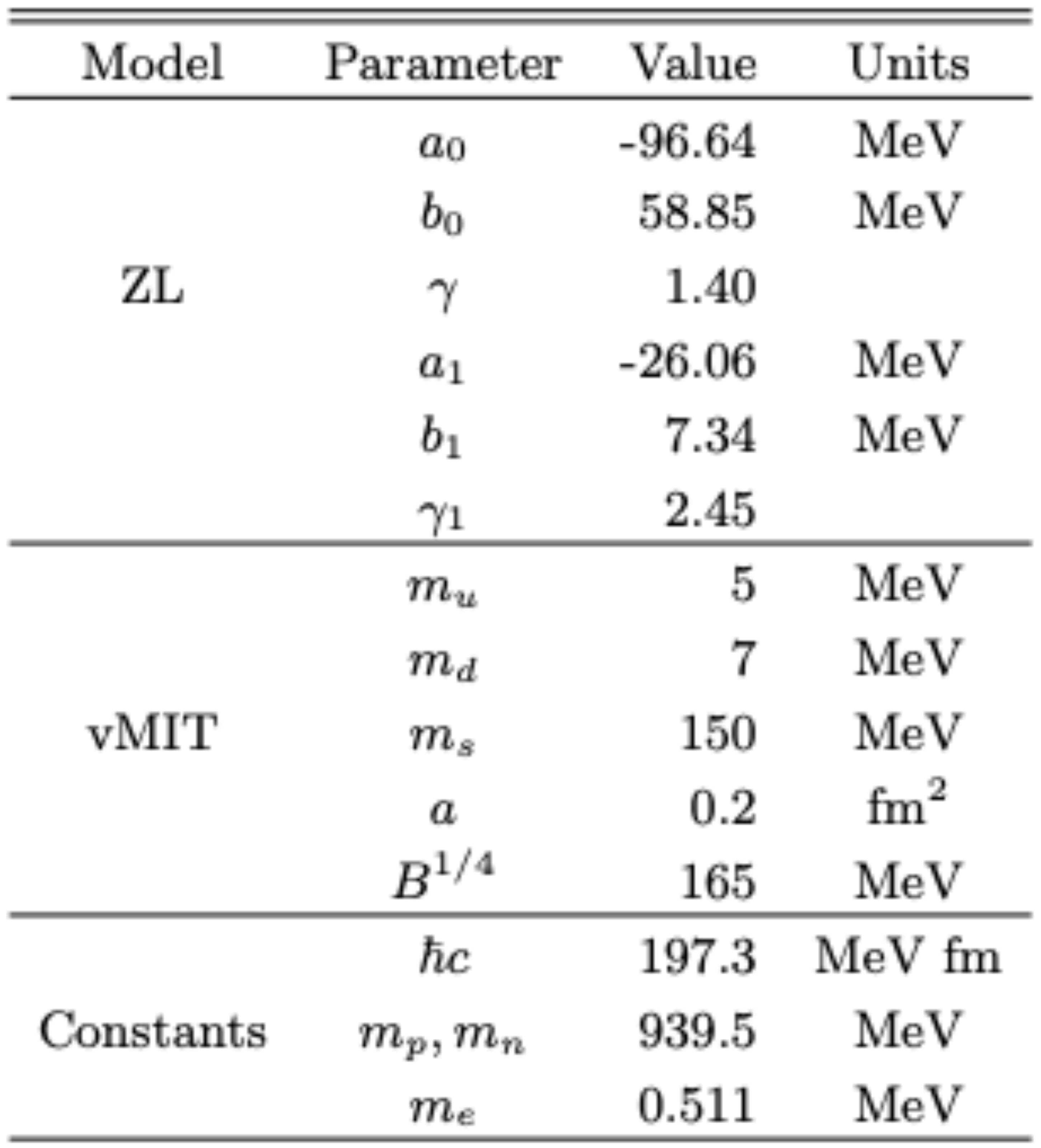
$$\varepsilon_j = \gamma_j \int_0^\infty \frac{d^3k_j}{(2\pi)^3} \frac{E_{k_j}}{e^{(E_{k_j}-\mu_{K,j})/T}+1} + V_j$$

Zhao-Lattimer EOS: Zhao, Lattimer (2020) PRD

$$\begin{aligned} V_H &= V_p + V_n \\ &= 4n_B^2 y_n y_p \left\{ \frac{a_0}{n_0} + \frac{b_0}{n_0^{\gamma}} [n_B(y_n + y_p)]^{\gamma-1} \right\} \\ &+ n_B^2 (y_n - y_p)^2 \left\{ \frac{a_1}{n_0} + \frac{b_1}{n_0^{\gamma_1}} [n_B(y_n + y_p)]^{\gamma_1 - 1} \right\} \end{aligned}$$

vMIT EOS: Gomes et al. (2019) ApJ

$$\begin{aligned} V_Q &= \sum_q V_q \\ &= \frac{1}{2} a \left[n_B \left(\sum_q y_q \right) \right]^2 + B \end{aligned}$$



Model	Parameter	Value	Units
ZL	a_0	-96.64	MeV
	b_0	58.85	MeV
	γ	1.40	
	a_1	-26.06	MeV
	b_1	7.34	MeV
	γ_1	2.45	
vMIT	m_u	5	MeV
	m_d	7	MeV
	m_s	150	MeV
	a	0.2	fm^2
	$B^{1/4}$	165	MeV
Constants	$\hbar c$	197.3	MeV fm
	m_p, m_n	939.5	MeV
	m_e	0.511	MeV

Details will be in Constantinou, Guerrini, Zhao, Prakash (in preparation) and references therein

Backup: three flavors EOSs

$$P_Q = \sum_{q=u,d,s} P_{k,q} + \frac{1}{\pi^2}\left(\sum_{q=u,d,s} \mu_q^2\right)\Delta^2 - B \qquad Y_u = Y_d = Y_s$$

$$\Delta(T) = \Theta(T_c - T)\Delta_0\sqrt{1 - \frac{T}{T_c}} \qquad T_C = 2^{1/3}\cdot 0.57\Delta_0$$

Schmitt (2010) Lec. Not. Phys

Fischer et al. (2011) ApJ

$$\underset{\text{K}}{p_i}(m_i, T, \mu_i, \alpha_s) = \underset{\text{K}}{p_i}(m_i, T, \mu_i, 0)$$

$$+ \left[\underset{\text{K}}{p_i}(0, T, \mu_i, \alpha_s) - \underset{\text{K}}{p_i}(0, T, \mu_i, 0)\right]$$

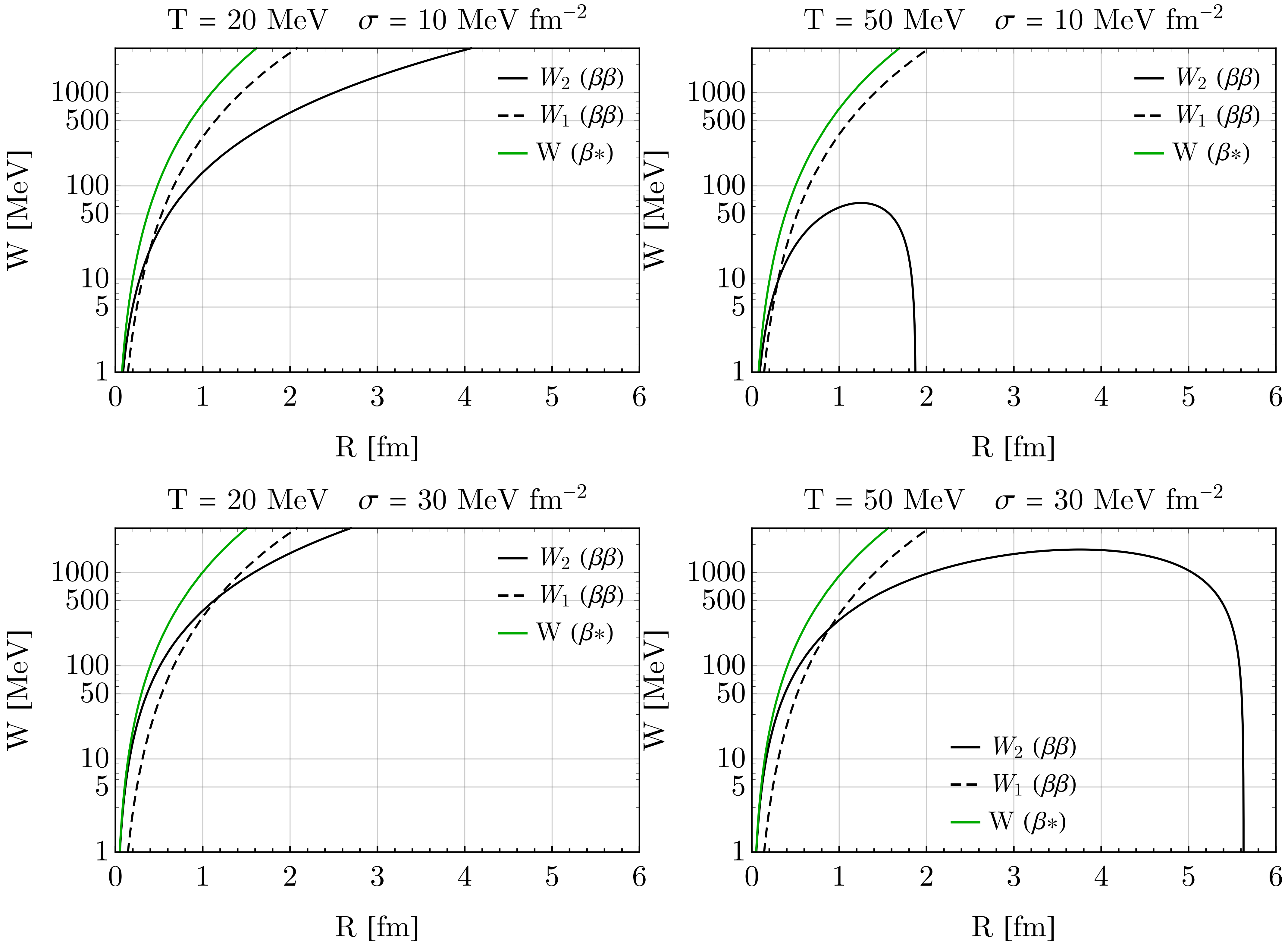
Backup: more on two flavors

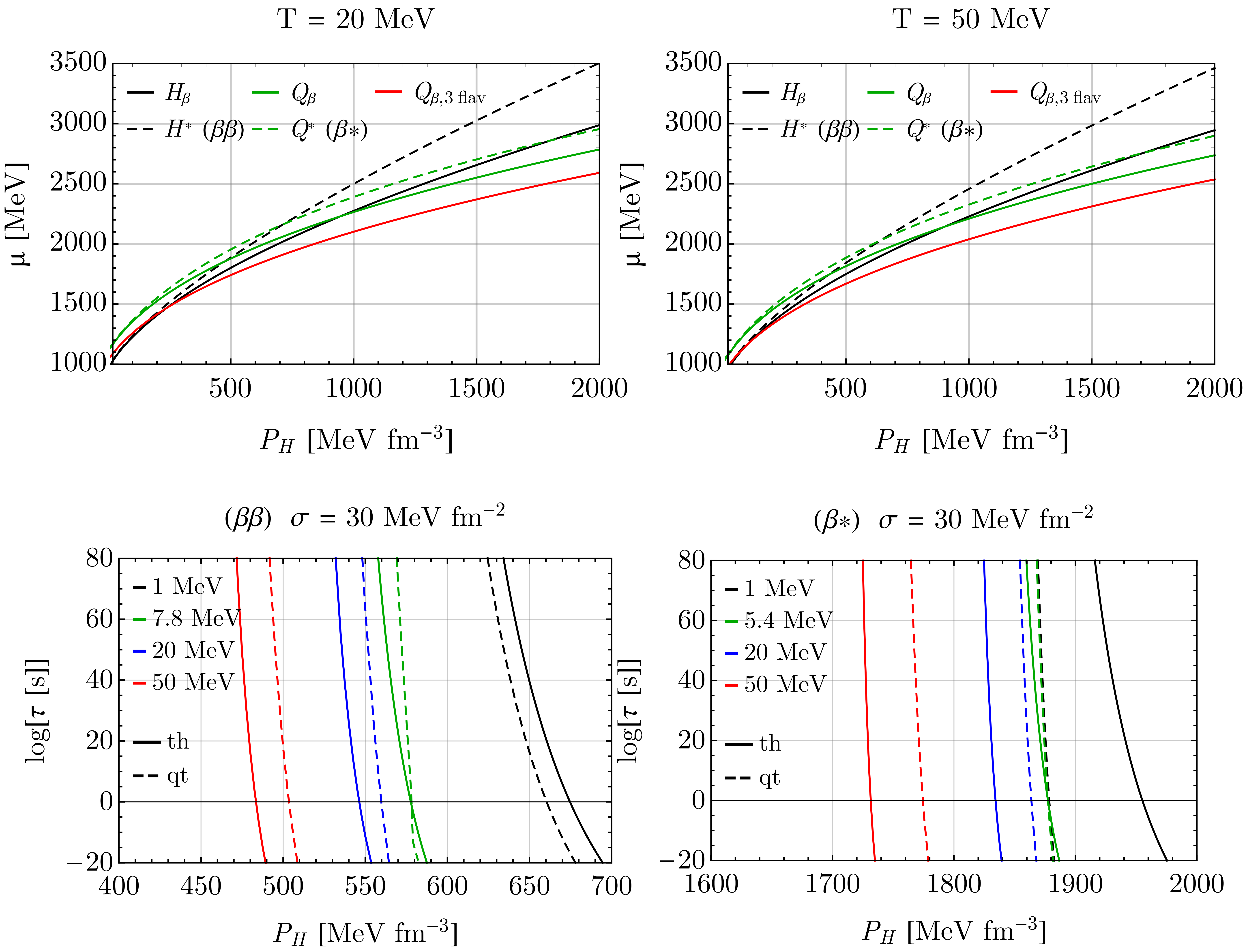
$$
\begin{aligned}
W_1 &= n_{B,Q^*} V_{Q^*} \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*} \right) \\
&= n_{B,Q^*} \frac{4}{3} \pi R^3 \sum_i y_i^{H^*} \left(\mu_i^{H_\beta} - \mu_i^{H^*} \right).
\end{aligned}
$$

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

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

Backup: more on two flavors results





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