Strange quark nucleation in astrophysics

thermal fluctuations of the composition

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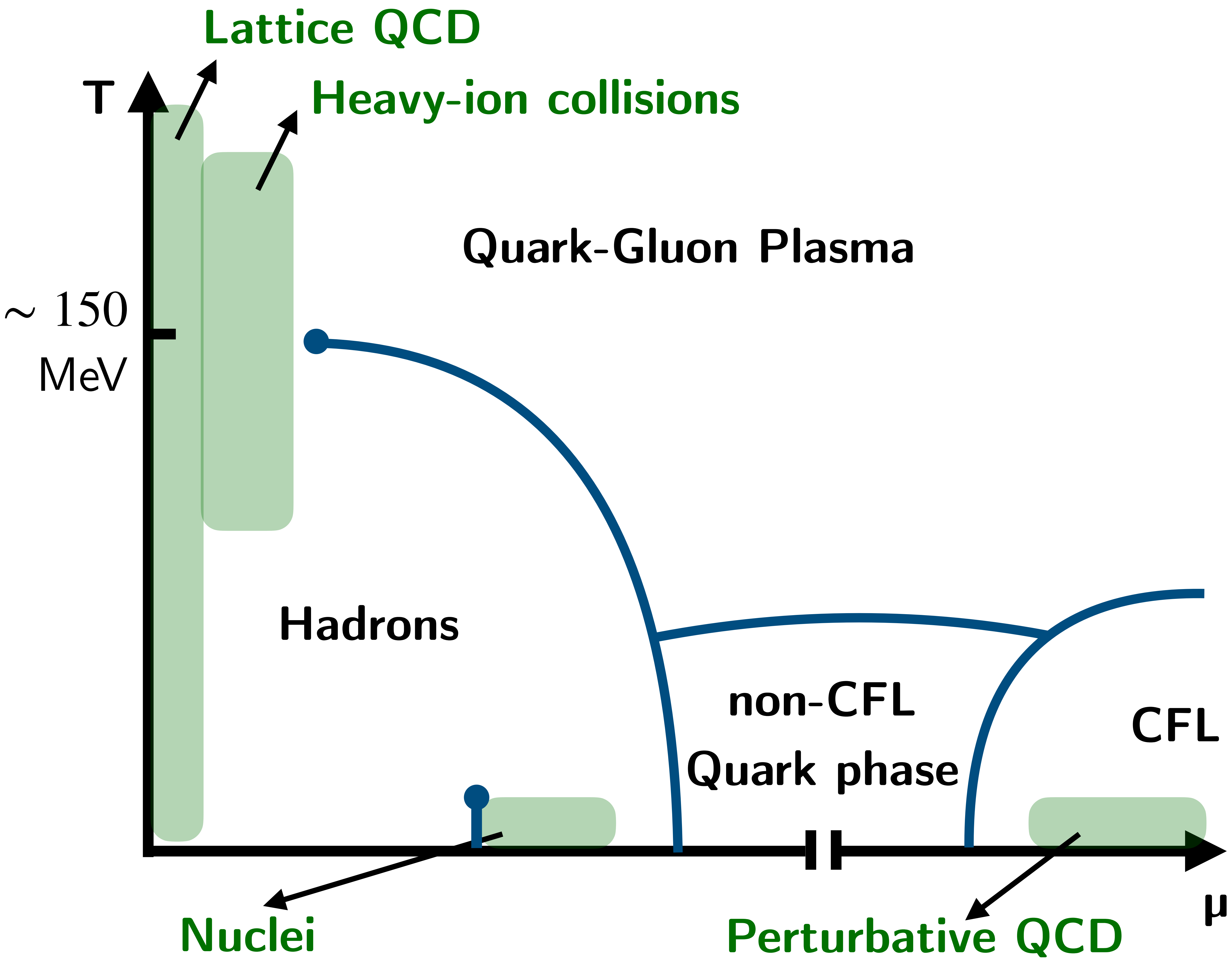
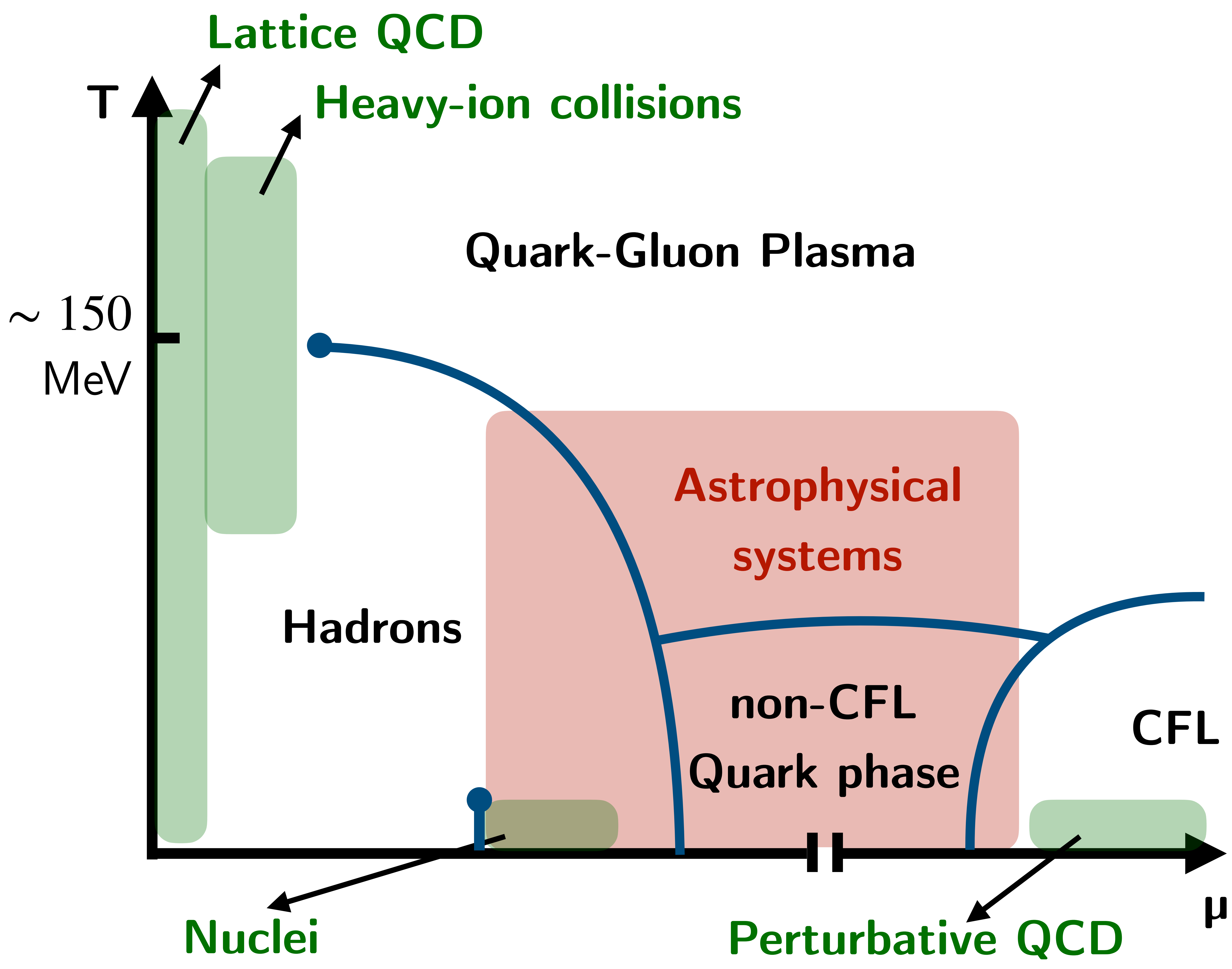
QCD phase diagram



- 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

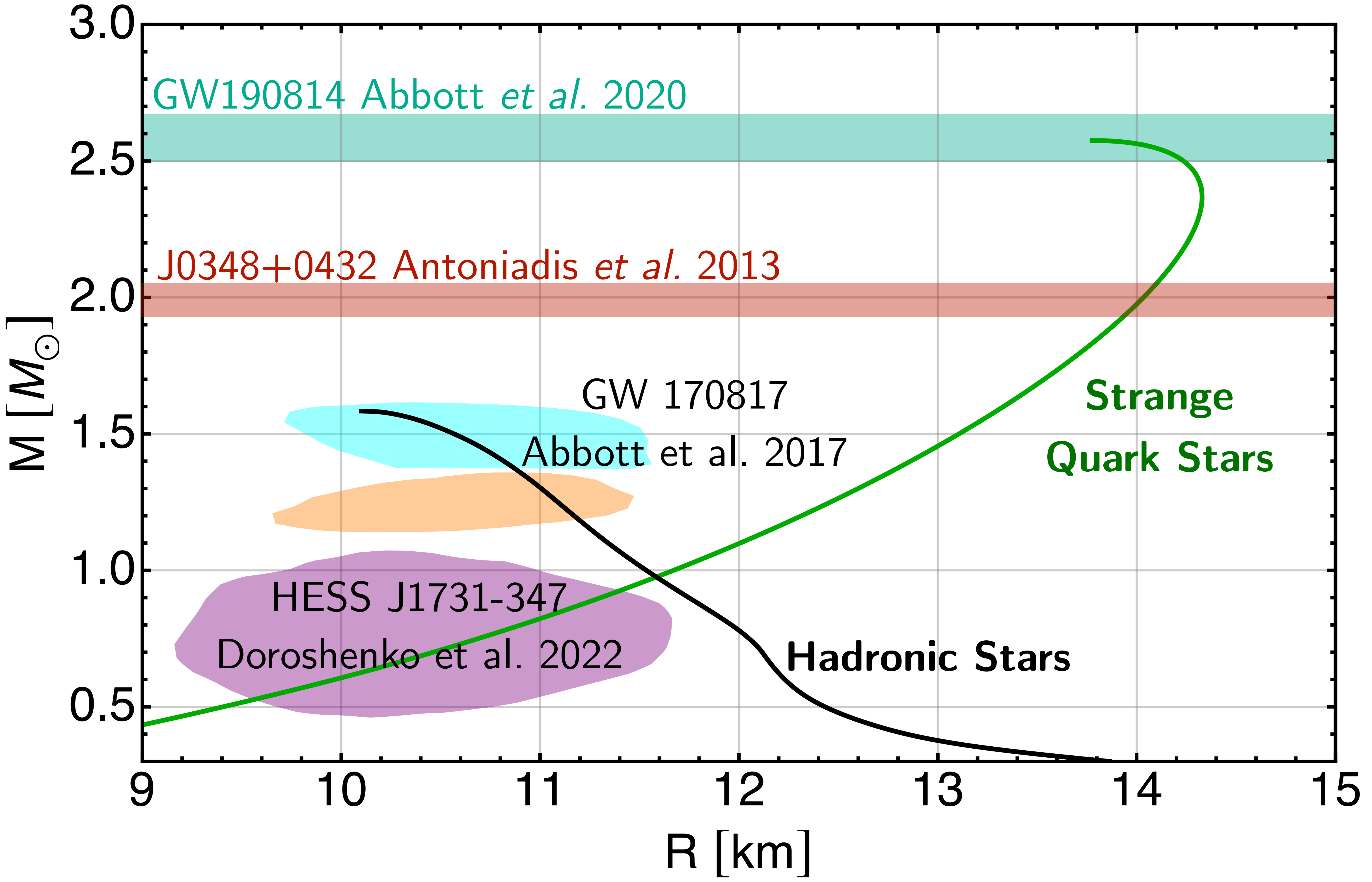
Compact objects and related phenomena may place **constraints** on **deconfinement** in the **high-density regime**

The "two families" scenario

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

→ "Hyperons Puzzle"
many different solutions have been proposed
[for a review: Vidaña, EPJ Web of Conf. 271 (2022)]

...one more possible solution...



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

[see Drago et al. Eur. Phys. J. A 52, 40 (2016)]

Deconfinement in astrophysical systems

Binary Neutron Star Merger (BNSM)

GW signal in post-merger remnant could provide deconfinement evidences

[Bauswein et al. 2019, Prakash et al. 2021]

Core-Collapse Supernova (CCSN)

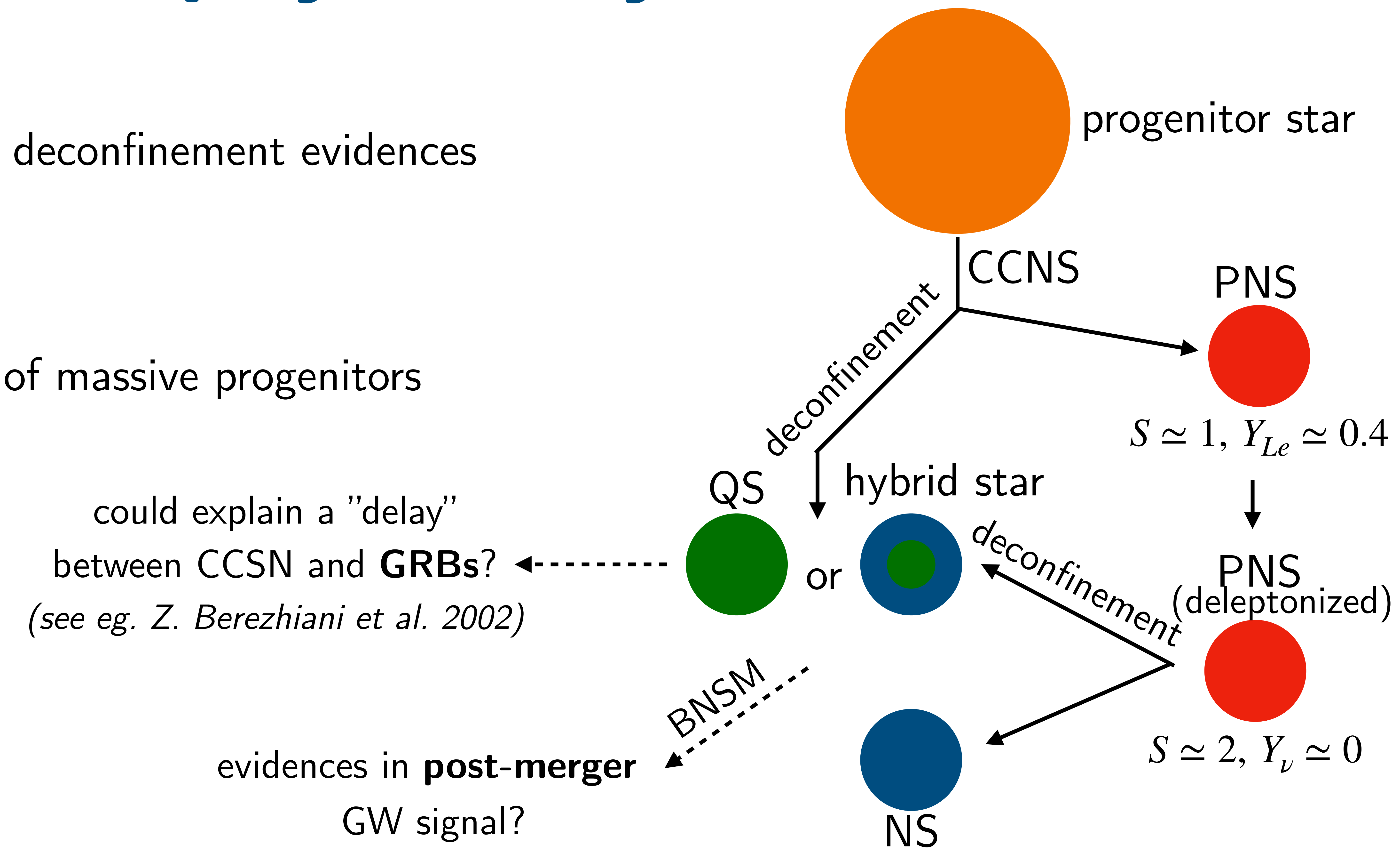
deconfinement as a mechanism for SN explosion of massive progenitors

[Fischer et al. 2018]

Proto Neutron Star (PNS)

deconfinement after neutrino untrapping

[Pons et al. 2001, Bombaci et al. 2016]



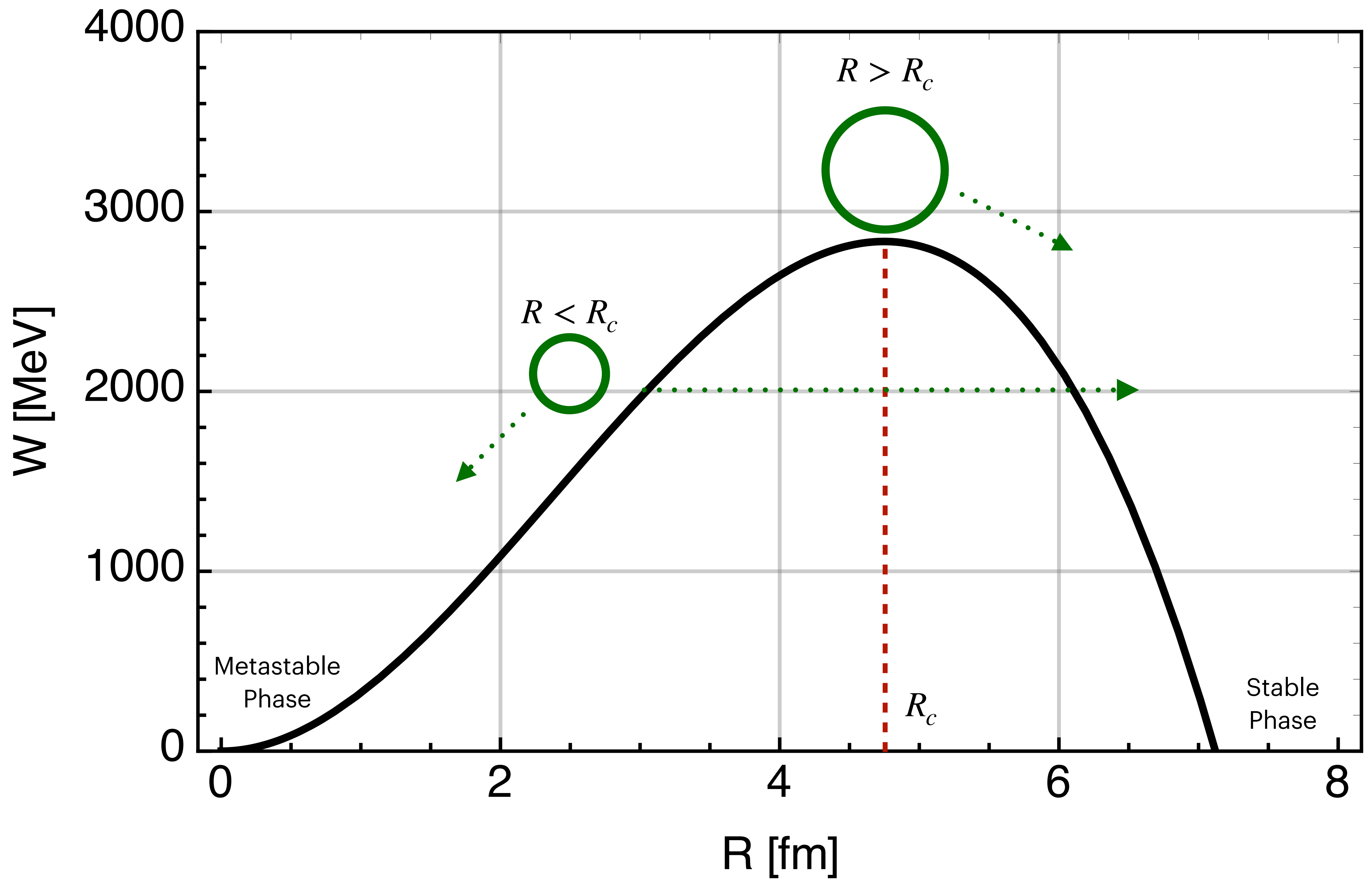
goal: identify the **thermodynamic conditions** at which **deconfinement** starts in **astrophysical systems**

↓

deconfinement is triggered by a first quark seed (**nucleation**)

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

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

bulk energy gain (negative if H is metastable)

surface effect (always positive)

The barrier can be overcome:

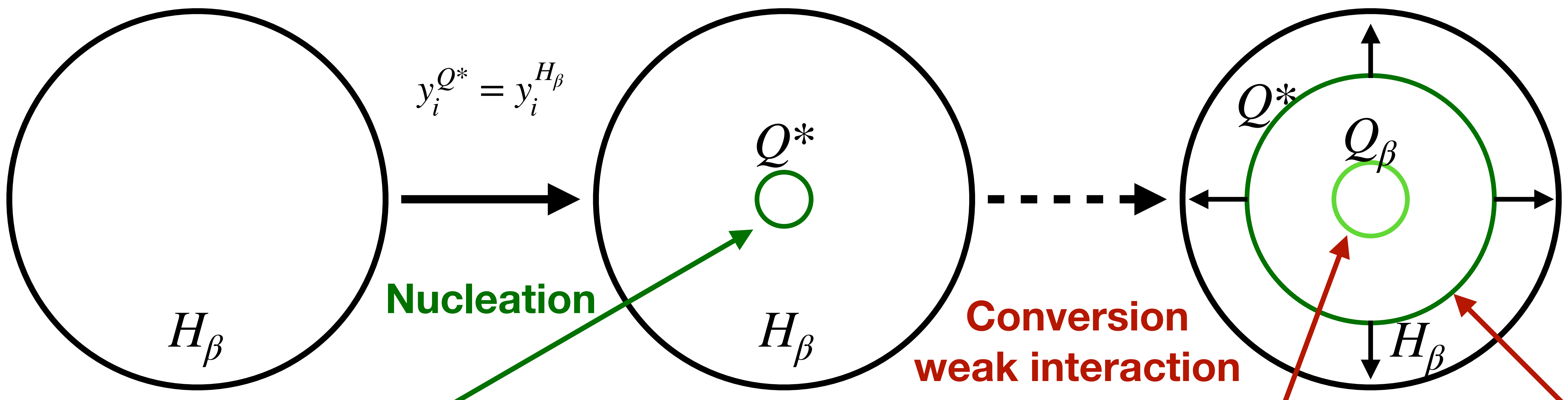
- Thermal: $\mathscr{P} \sim e^{\frac{-W(R_C)}{T}}$ *(Langer et al. 1969)*
- Quantum: $\mathscr{P} \sim e^{\frac{-A(E_0)}{\hbar}}$ *(Iida et al. 1998)*

Nucleation: state of the art

in the past: nucleation computed assuming Q seed created already in equilibrium **... but ...**

Nucleation is due to **strong interactions**
strong timescale ≪ weak timescale → Flavour composition can not change during the nucleation

[see e.g. Bombaci et al. Eur. Phys. J. A 52, 58 (2016)]



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

After the nucleation, the conversion starts

Nucleation: role of the thermal fluctuations

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**

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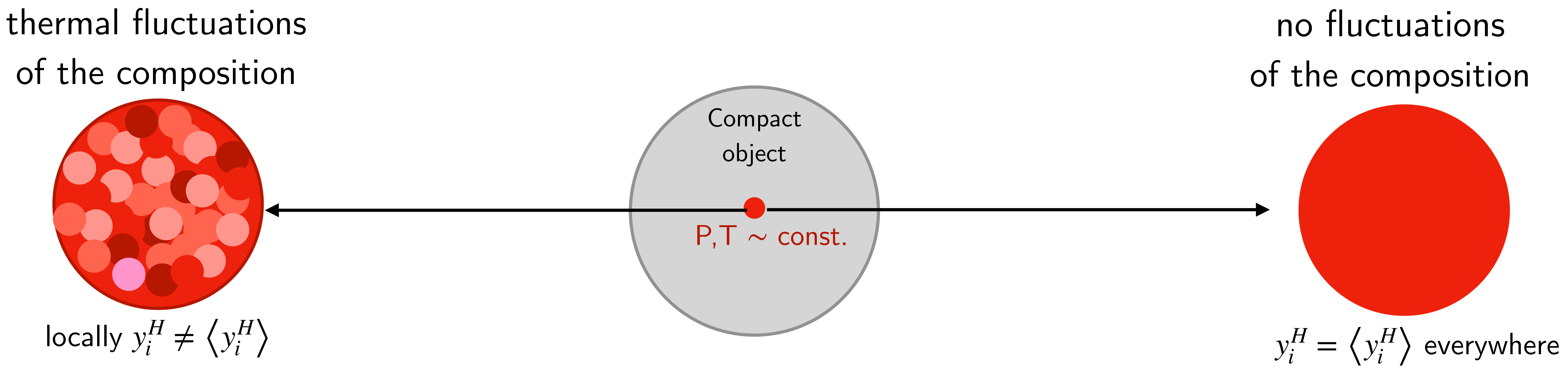
Nucleation could happens in a subsystem in which the local composition makes nucleation easier

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

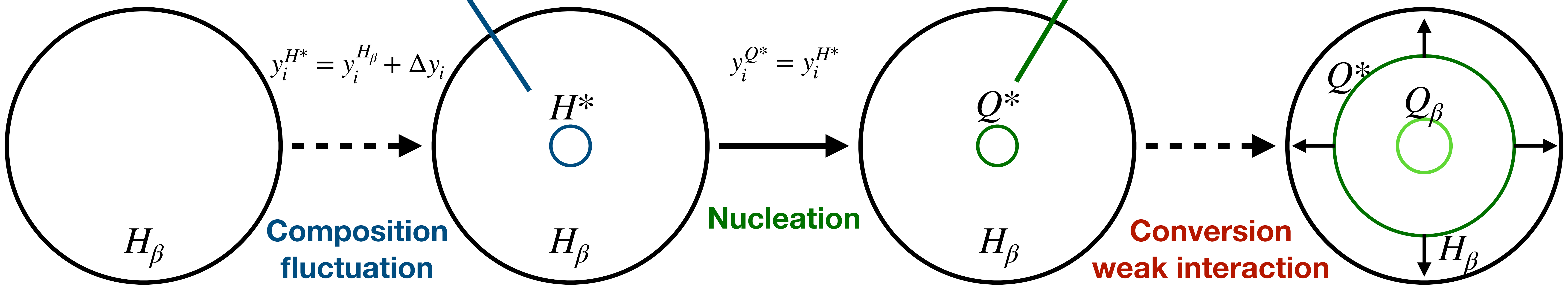


Nucleation: role of the thermal fluctuations

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

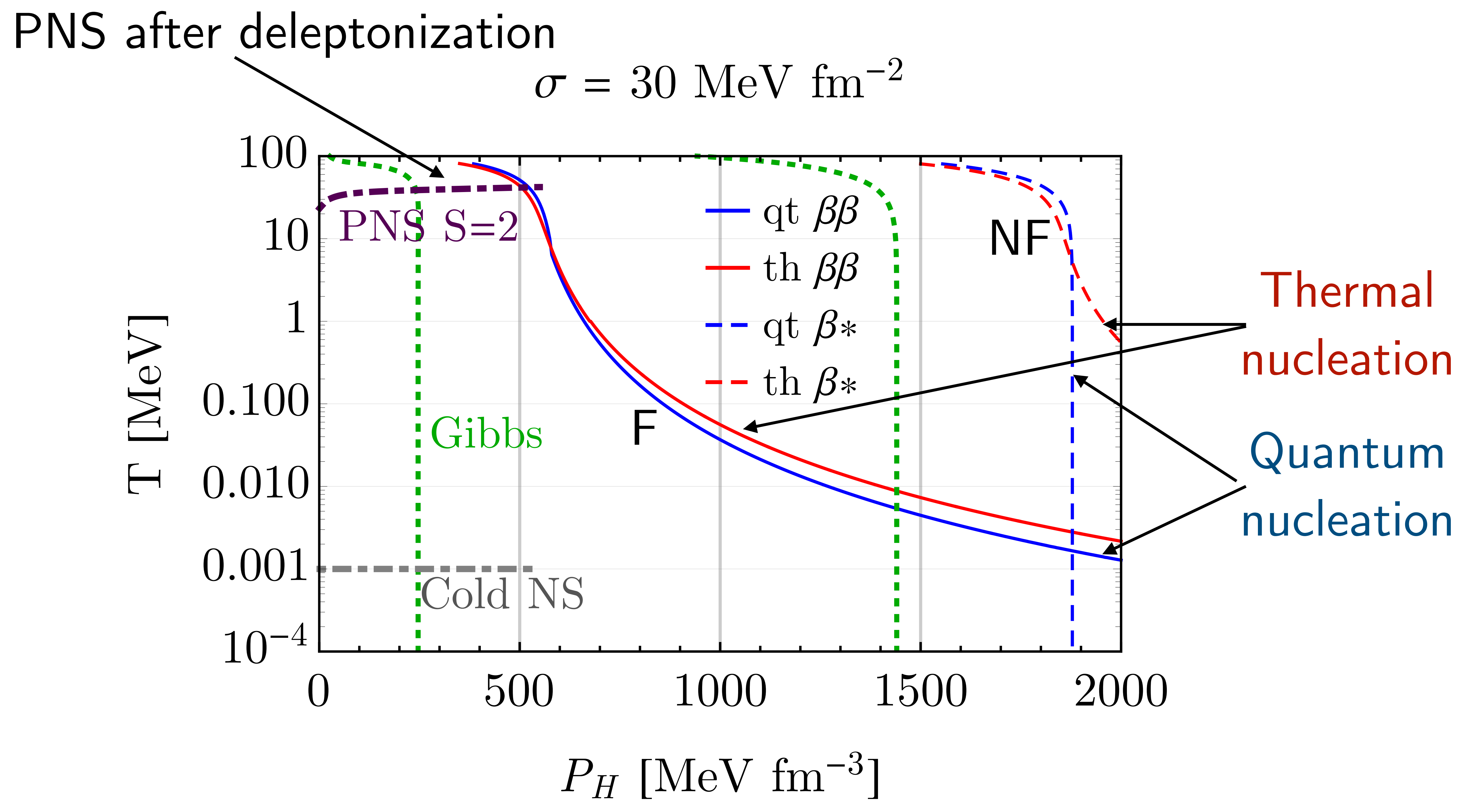
$$\mathscr{P}_{fluc} \sim e^{-\frac{W_{fluc}}{T}}$$

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

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

Results: two flavors case

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



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

Effect of thermal fluctuation (F)
in the hadronic composition

<u>$T \gtrsim 10$ MeV:</u>

- nucleation at lower P than no fluc. (NF) case
- most massive PSNs could nucleate

<u>1 keV $\lesssim T \lesssim 10$ MeV:</u>

- nucleation at lower P than NF. case
- PSNs can not nucleate

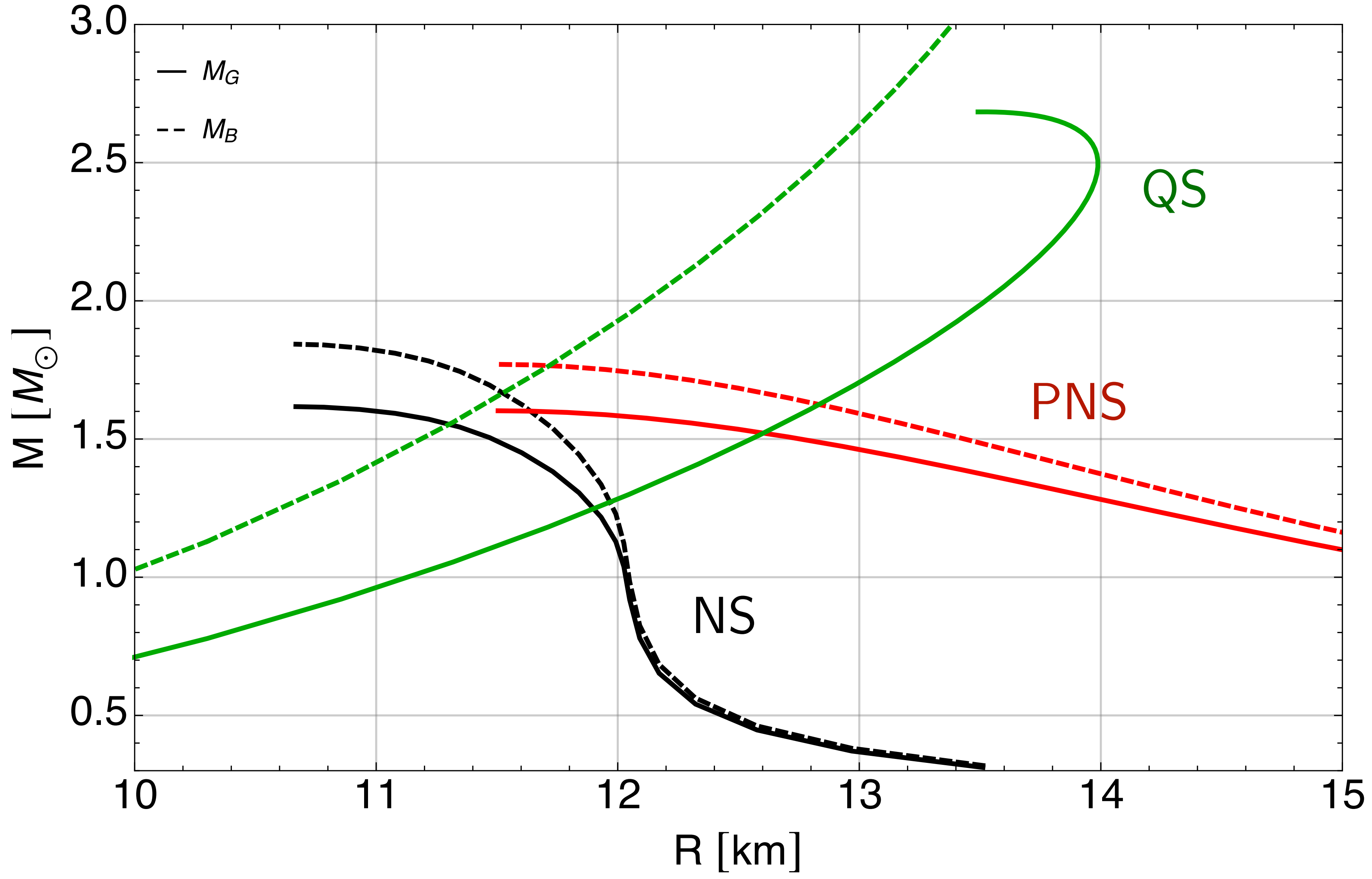
<u>$T \lesssim 1$ keV:</u>

- negligible contribution

Results: two families scenario

(No definitive results … we are still working on that!)

Testing the two families scenario: can the core of a PNS nucleate strange quark matter?



some relevant points:

to reach $\sim 2.5\ M_\odot$ we need gapped quark matter (e.g. CFL)
[see e.g. Bombaci et al. Phys. Rev. Lett. 126, 162702 (2021)]

↓

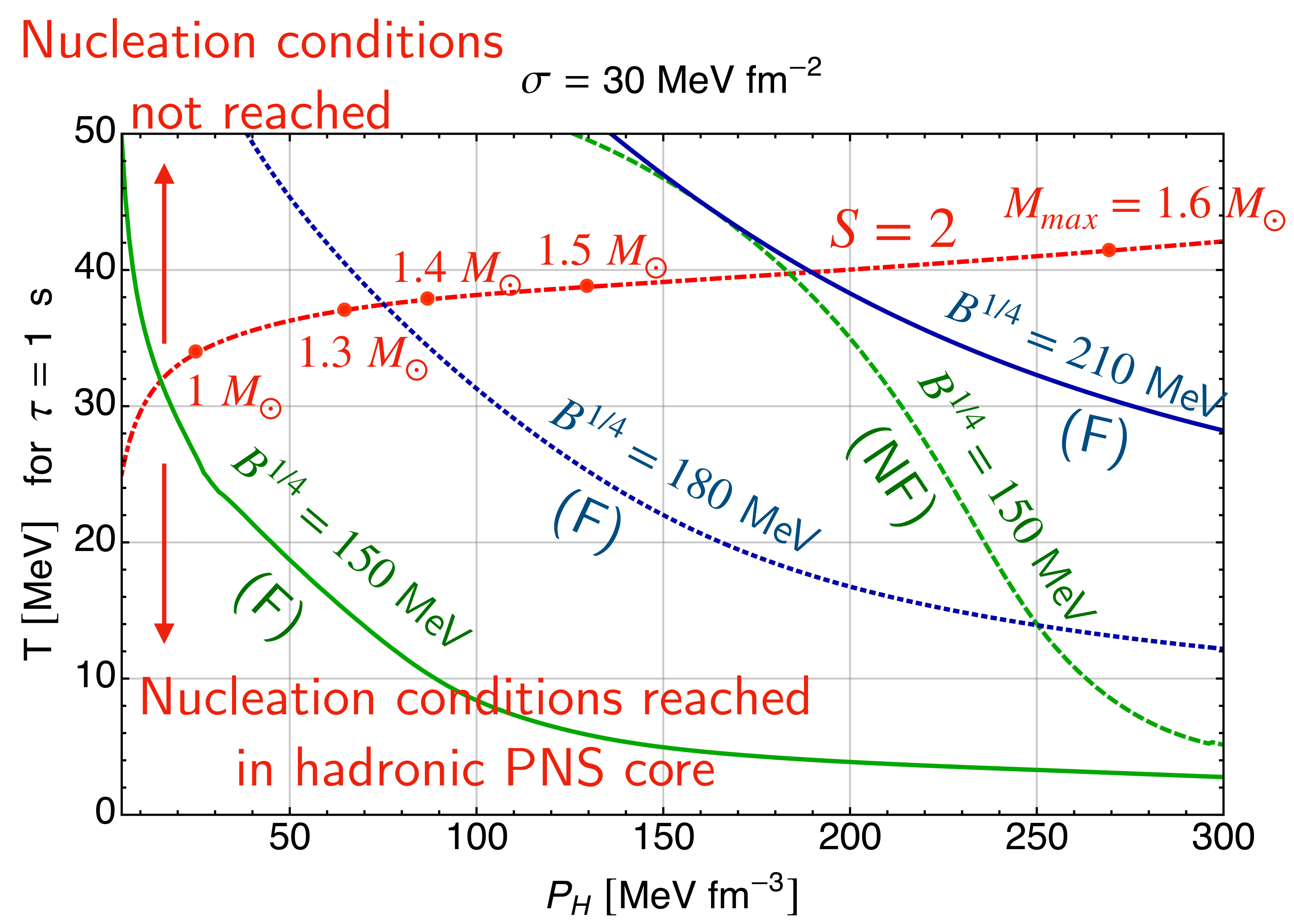
gaps could vanish in very small systems (as first quark seed is)
[see eg. Amore at al. Phys. Rev. D 65, 074005 (2002)]

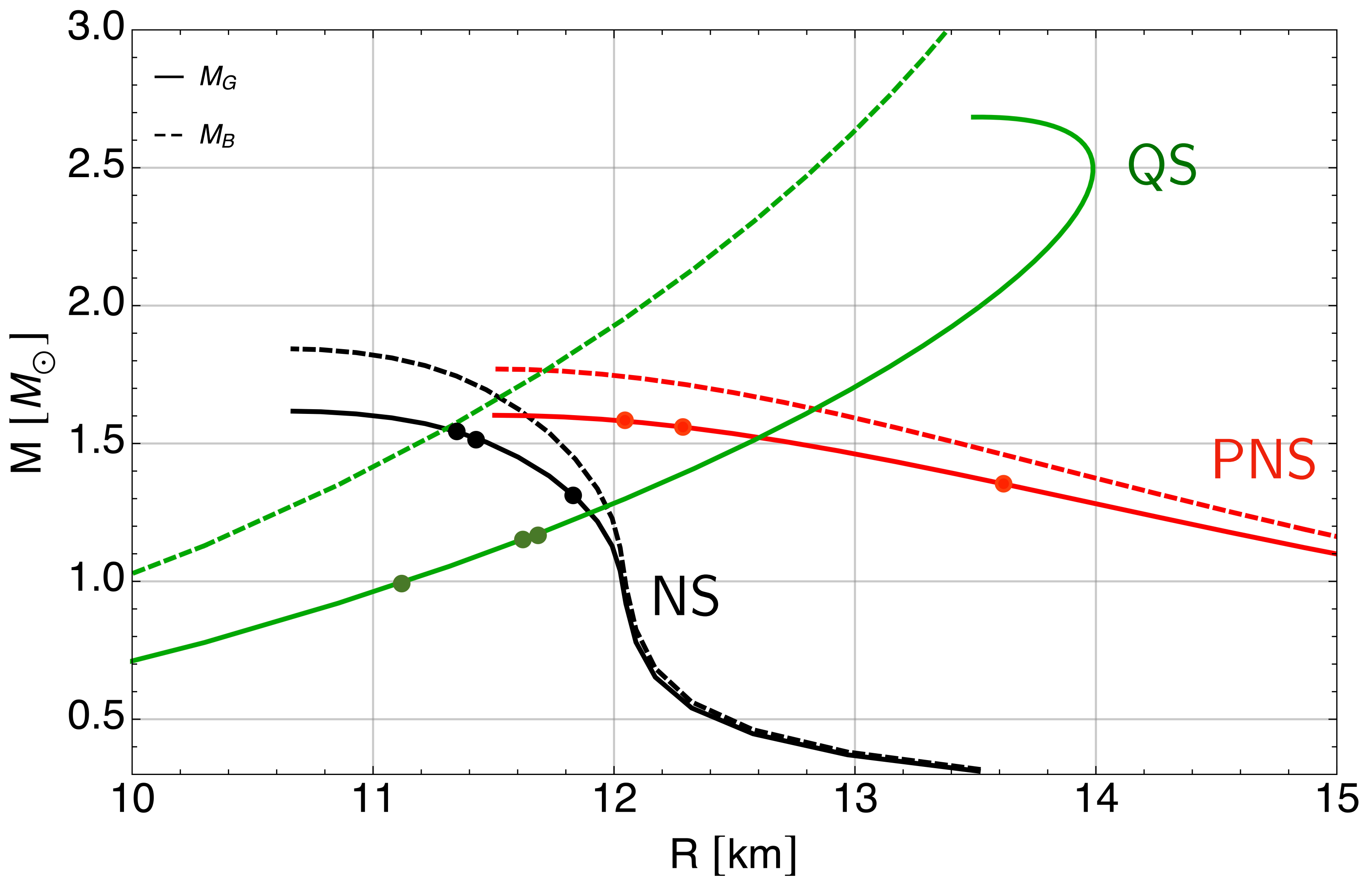
One possible approach:

- Quark CFL phase respects the Witten hypothesis ($\mu_Q(P) < \mu_H(P)$ also at P=0), while the unpaired phase does not
- CFL needs to fulfill $\sim 2.5\ M_\odot$ QS, unpaired phase needs to fulfill heavy ions and lattice QCD constraints
- switching function depending on the seed size $\mu_{Q*}(R, P, T) = [1 - \chi(R)]\mu_{Q_{unpaired}}(P, T) + \chi(R)\mu_{Q_{CFL}}(P, T)$

Results: two families scenario

(No definitive results … we are still working on that!)





$B^{1/4}$ (unpaired) [MeV]	$B^{1/4}$ (CFL) [MeV]	with fluc?	PNS mass for nucleation	emitted energy [erg]
150	150	NF	$\gtrsim 1.57\ M_\odot$	7×10^{53}
		F	$\gtrsim 0.83\ M_\odot$	4×10^{53}
180	150	NF	never	-
		F	$\gtrsim 1.35\ M_\odot$	6×10^{53}
210	150	NF	never	-
		F	$\gtrsim 1.57\ M_\odot$	7×10^{53}

…thus…

- hadronic PNS could be converted in $\lesssim 1.2\ M_\odot$ QSs
- $\gtrsim 1.2\ M_\odot$ QSs could be produced in other phenomena (BNSM or CCSN)

Do these calculations suggest that all the PNS should be converted to QS?

it strongly depends on how gapped matter appears in small systems

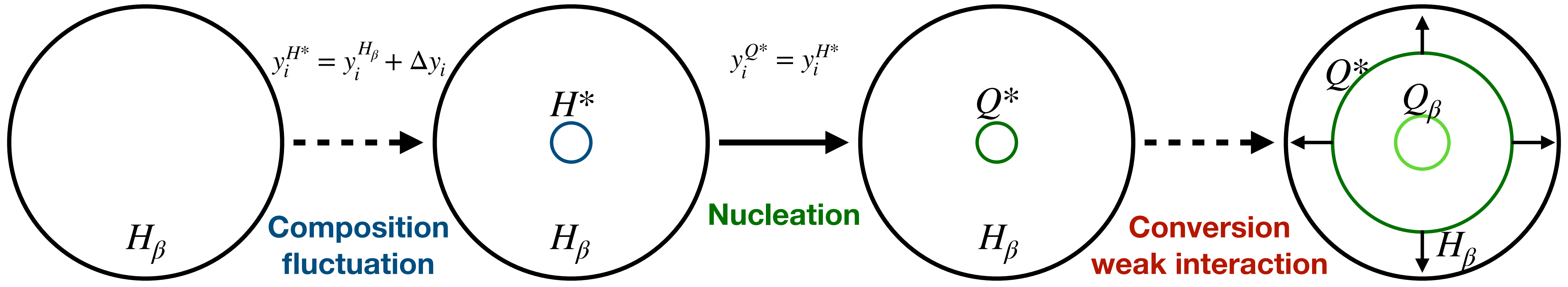
Summary and conclusions

Background

- exotic d.o.f. expected at compact object densities
- nucleation is the starting point for the deconfinement
- "two families" of compact objects may exist if the Witten hypothesis is correct
- goal: identify conditions at which deconfinement starts considering the thermal fluctuations of the composition and the related compact objects phenomenology

Method

- flavor composition is conserved during **nucleation**
- at finite T the hadronic composition **fluctuates**
- the nucleation is a local process



Results

- composition fluctuations lead to a much faster nucleation (i.e. deconfinement can start at lower P) in compact objects at intermediate and high temperatures
- the phenomenology of the QS formation in the two families scenario strongly depends on how gapped matter behaves in nucleation (i.e. in small systems)

Outlooks

- complete the analysis in the three-flavors case
- how to include those finite-size effects in simulations?
- can the deconfinement be linked with astrophysical signals?
- is the two families scenario compatible with the observations?
- behavior of gapped matter in nucleation

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

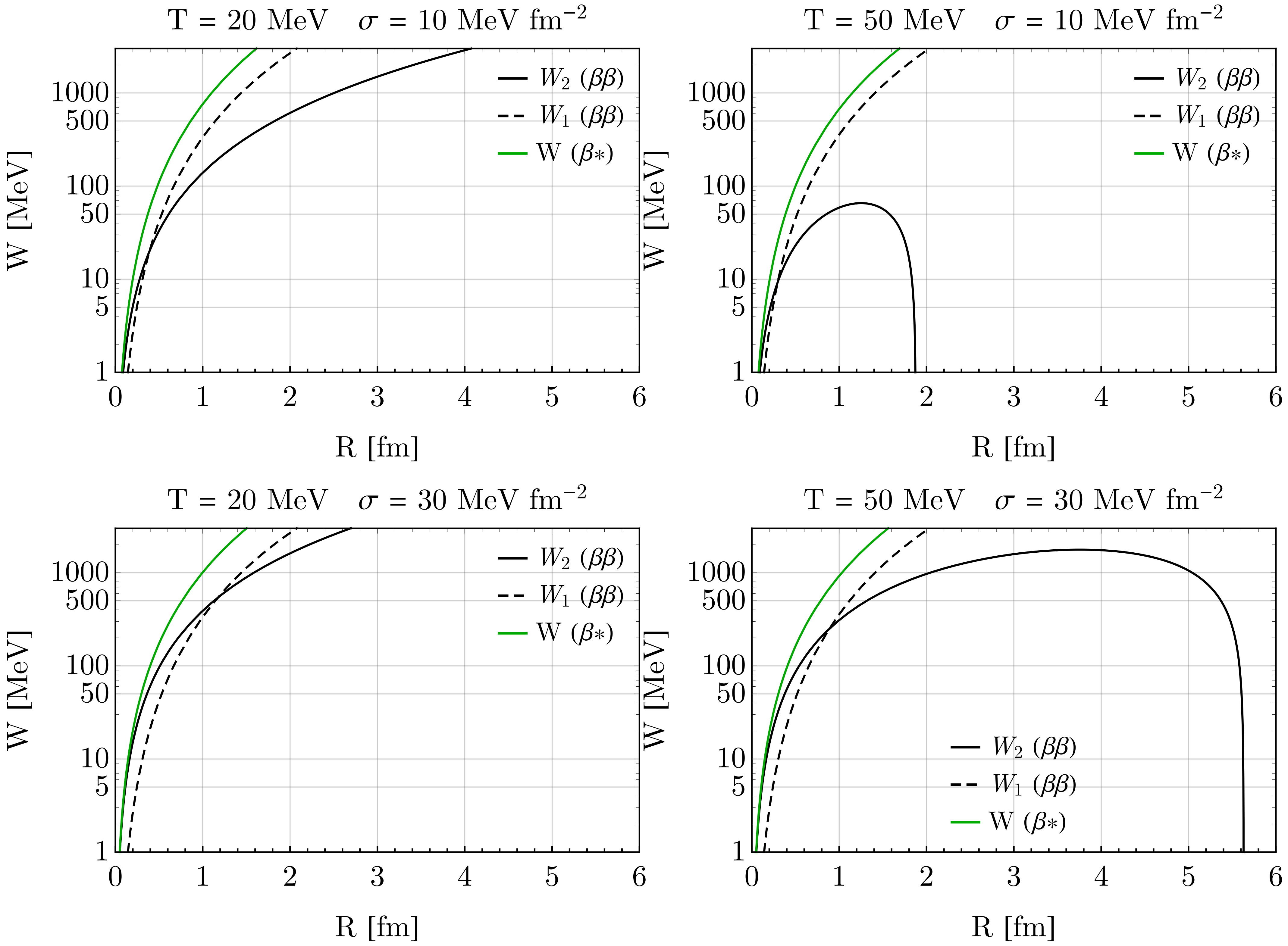
Backup

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

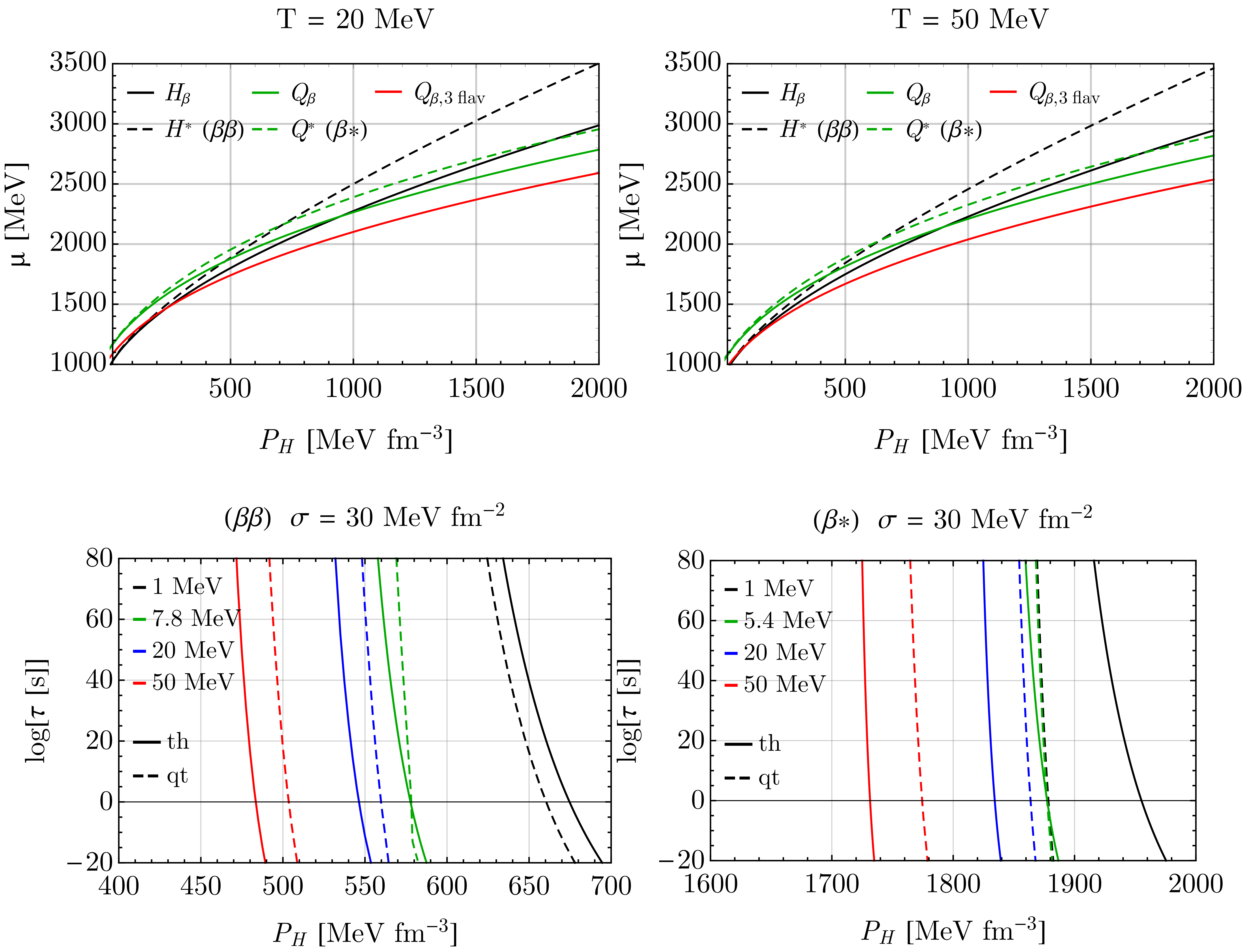
$$W_2 = \frac{4}{3} \pi R^3 n_{B,Q^*} \left(\mu_{Q^*} - \mu_{H^*} \right) + 4\pi\sigma R^2.$$

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

Backup



T = 20 MeV σ = 10 MeV fm^{-2}
T = 50 MeV σ = 10 MeV fm^{-2}
T = 20 MeV σ = 30 MeV fm^{-2}
T = 50 MeV σ = 30 MeV fm^{-2}
W_2 (ββ)
W_1 (ββ)
W (β∗)
W [MeV]
R [fm]



T = 20 MeV
T = 50 MeV
H_β
Q_β
$Q_{\beta,3\ \mathrm{flav}}$
H^* (ββ)
Q^* (β∗)
μ [MeV]
P_H [MeV fm^{-3}]
(ββ) σ = 30 MeV fm^{-2}
(β∗) σ = 30 MeV fm^{-2}
1 MeV
7.8 MeV
5.4 MeV
20 MeV
50 MeV
th
qt
log[τ [s]]