Reconciling constraints from the supernova remnant HESS J1731-347 with the parity doublet model

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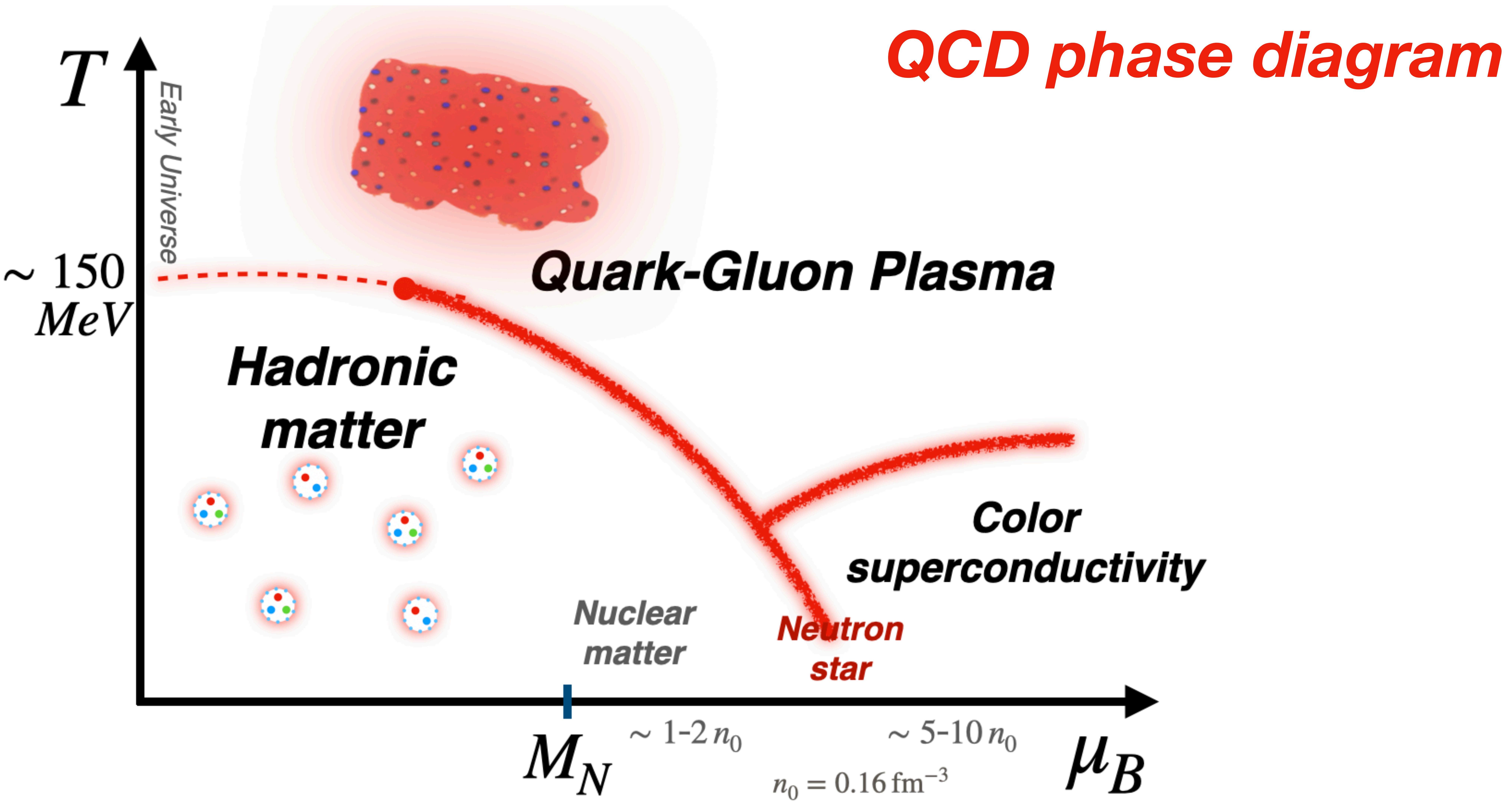
Outline

1. **Introduction** ✓

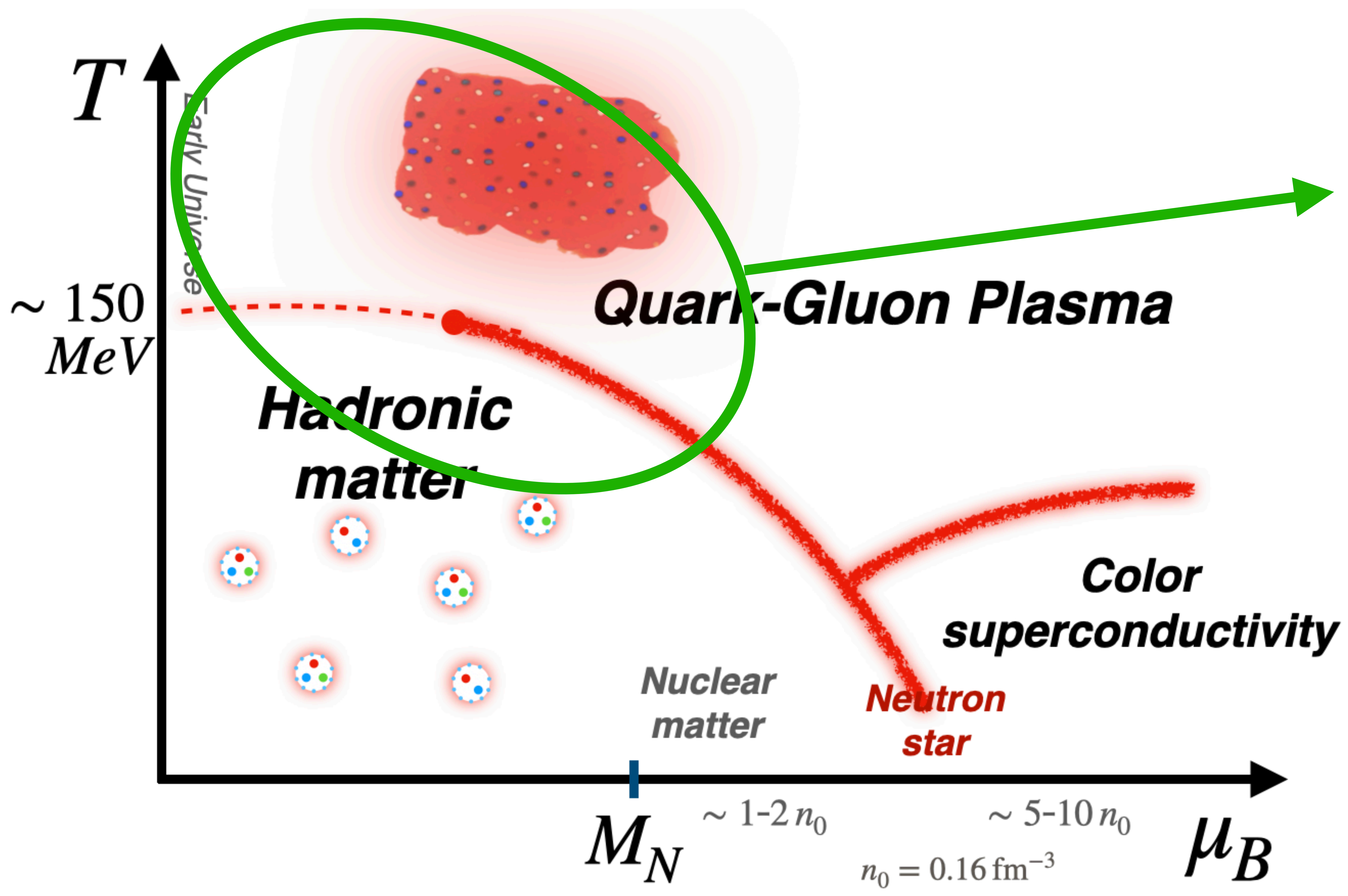
2. **Construction of Unified Equation of State**
   Parity doublet model
   NJL-type quark model

3. **Results**

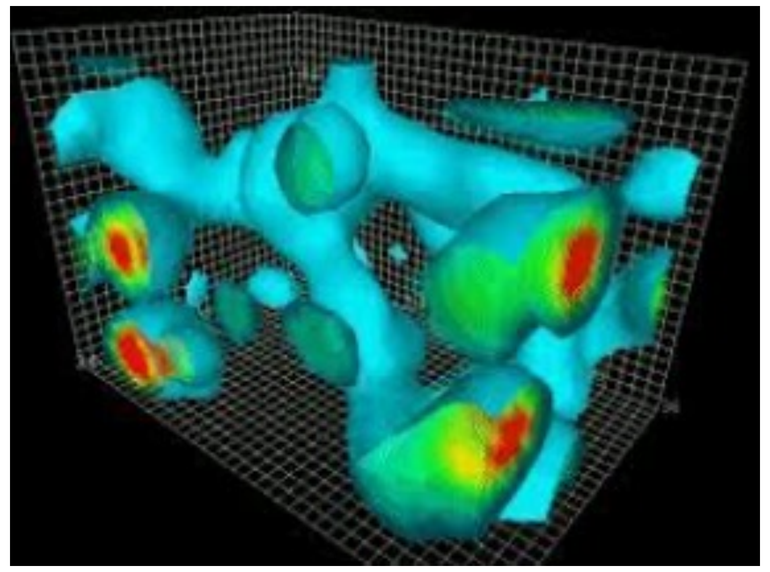
Introduction



High temperature region



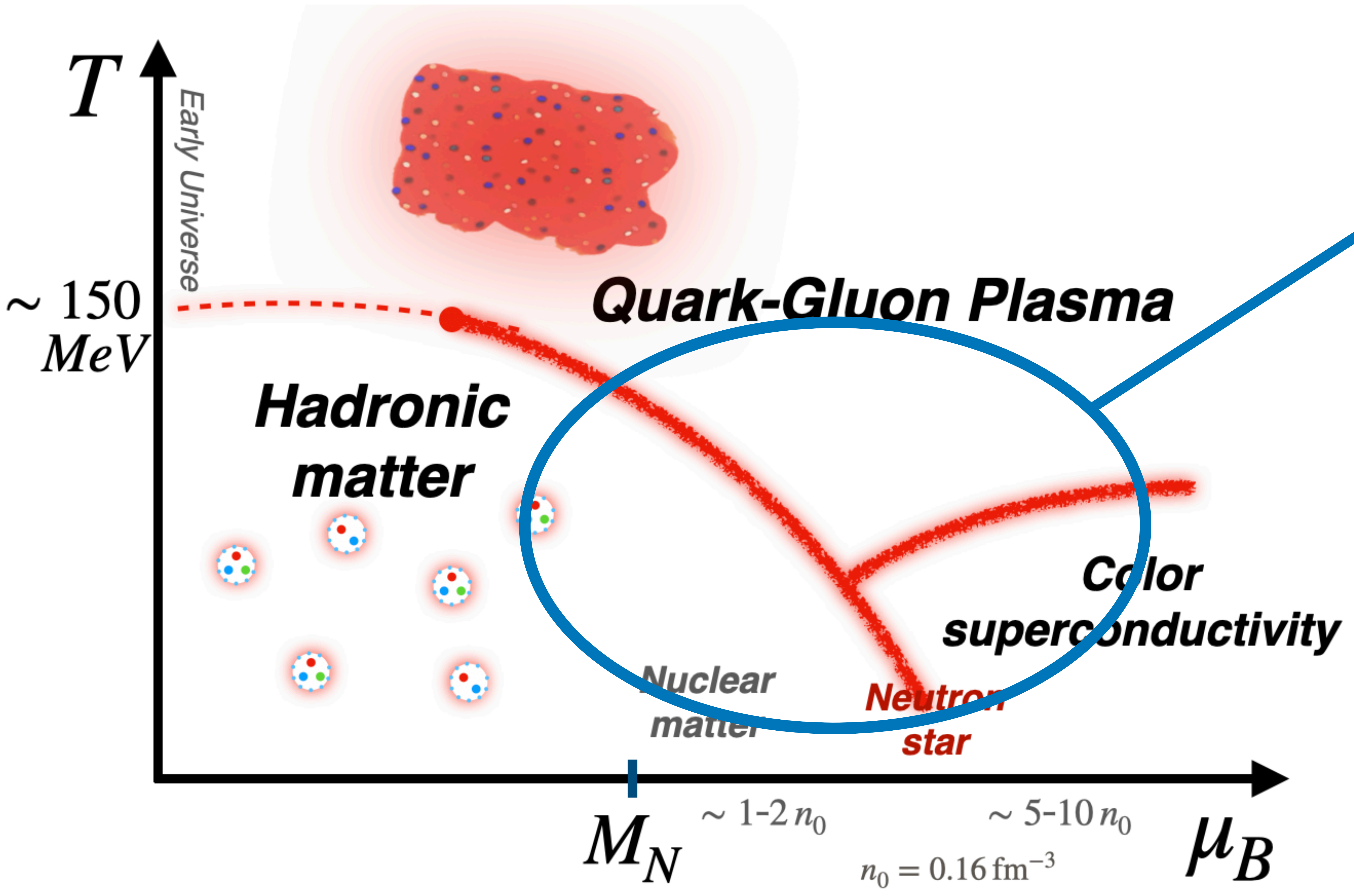
Lattice QCD;



Large Hadron Collider;

Heavy ion collision

Difficulties in high dense matter

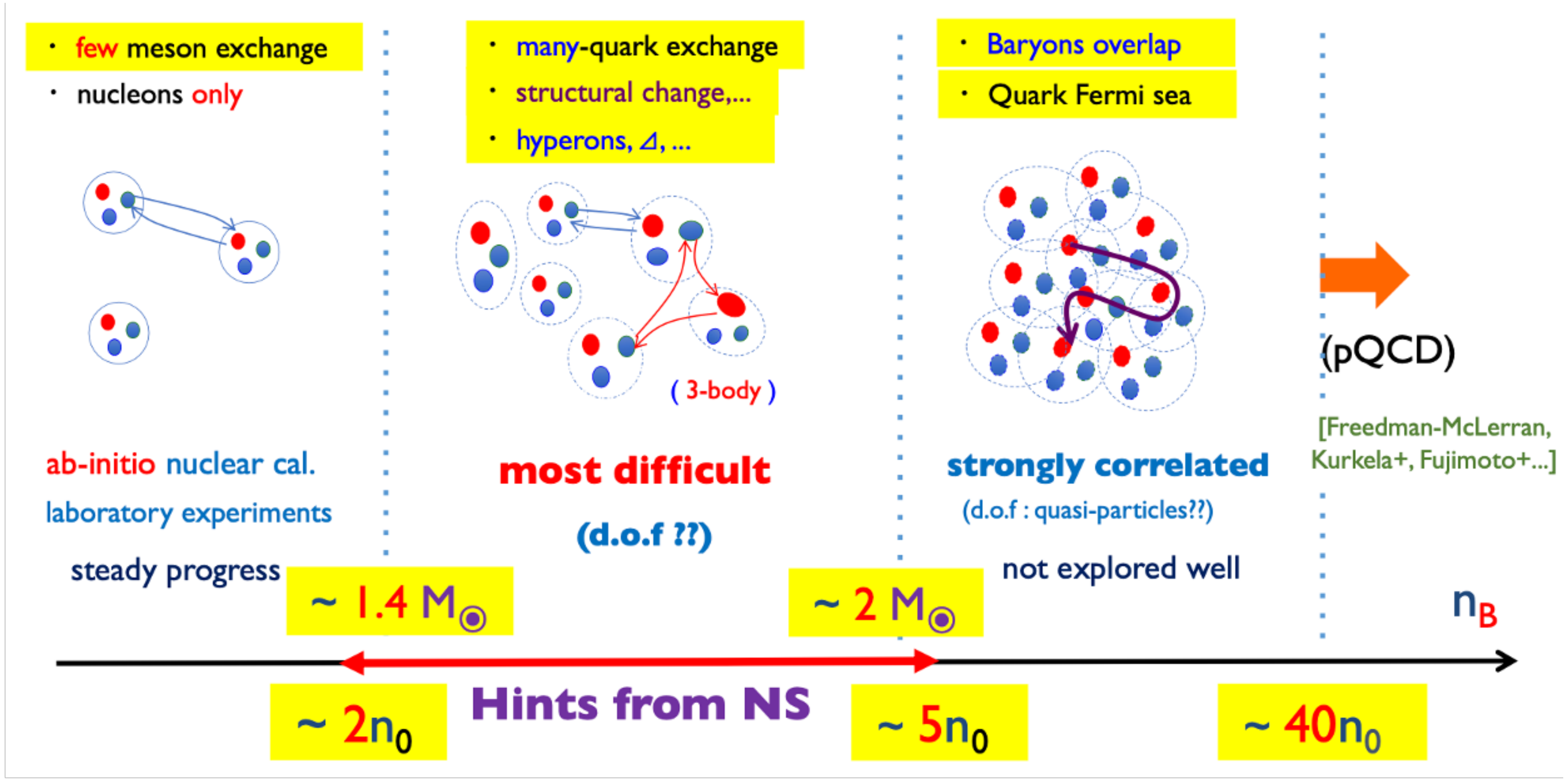


Lattice Monte-Carlo simulation Not possible(sign problem)

Cannot design laboratories, have to wait for signals (unlike heavy ion collision)

……

Fundamental questions in dense QCD



How does dense matter respond to compression, the EOS?

How hadronic matter dissolves into quark matter?

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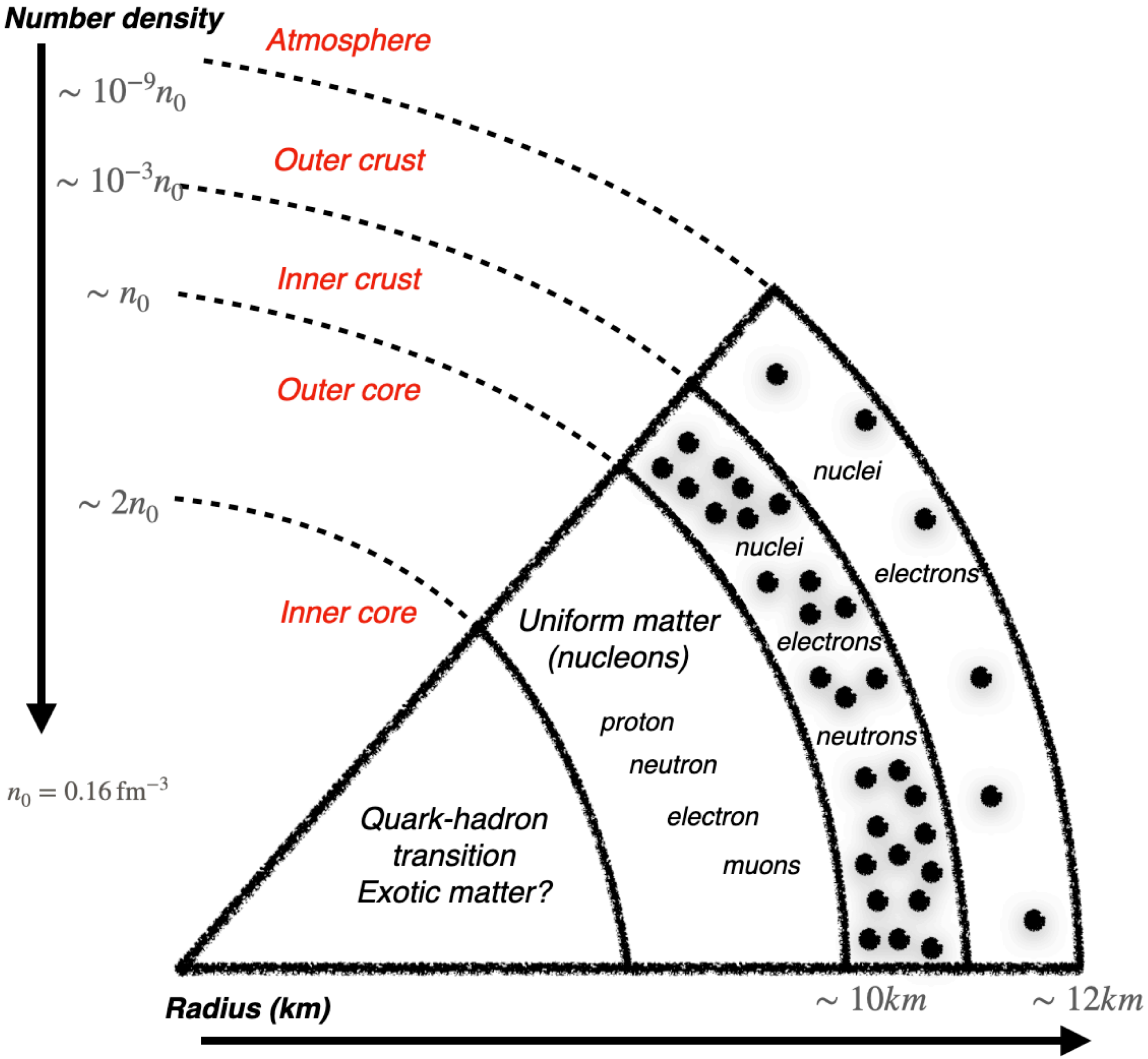
Neutron Stars(NSs) as natural laboratory

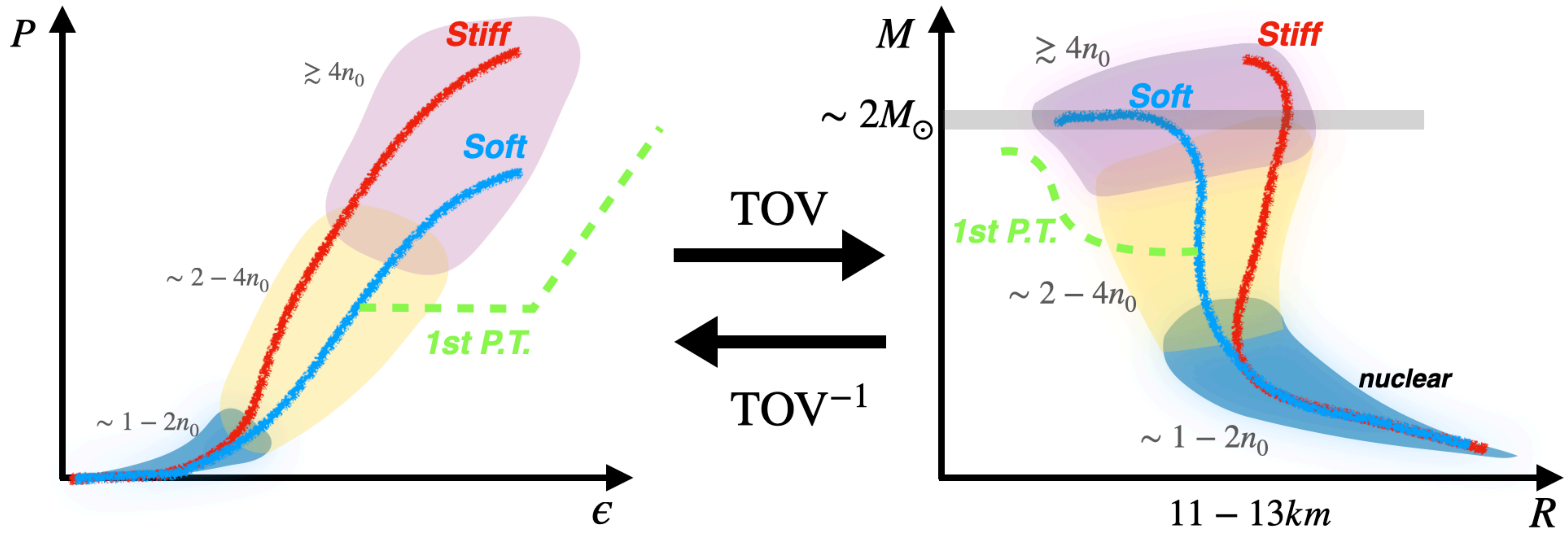
Mass: $M \sim 1 - 2\ M_{\odot}$

Radius: $R \sim 10 - 12$ Km

Nagoya, Aichi

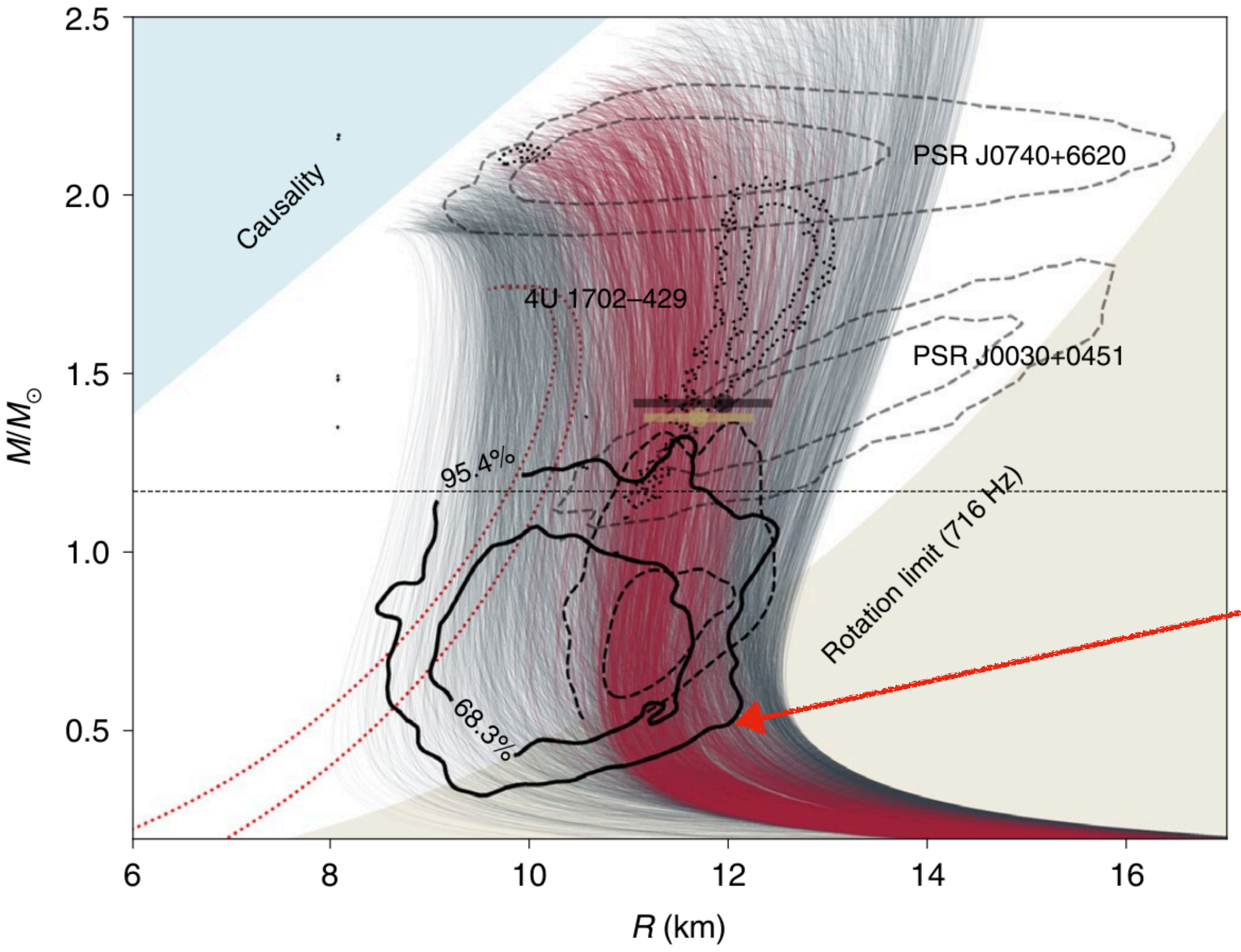


Correlation between EoS and M-R



Neutron Star	Mass (M⊙)	Radius (km)	Source
J0740+6620	2.14 ± 0.10	12.35 ± 0.75	NICER
J0030+0451	1.44 ± 0.15	12.45± 0.65	NICER
GW170817	1.33-1.60	11.9 ± 1.4	LIGO/Virgo

Strange CCO HESS J1731-347



Nature Astronomy volume **6**, 1444–1451 (2022)

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HESS J1731-347

A Strange light central compact object supernova remnant

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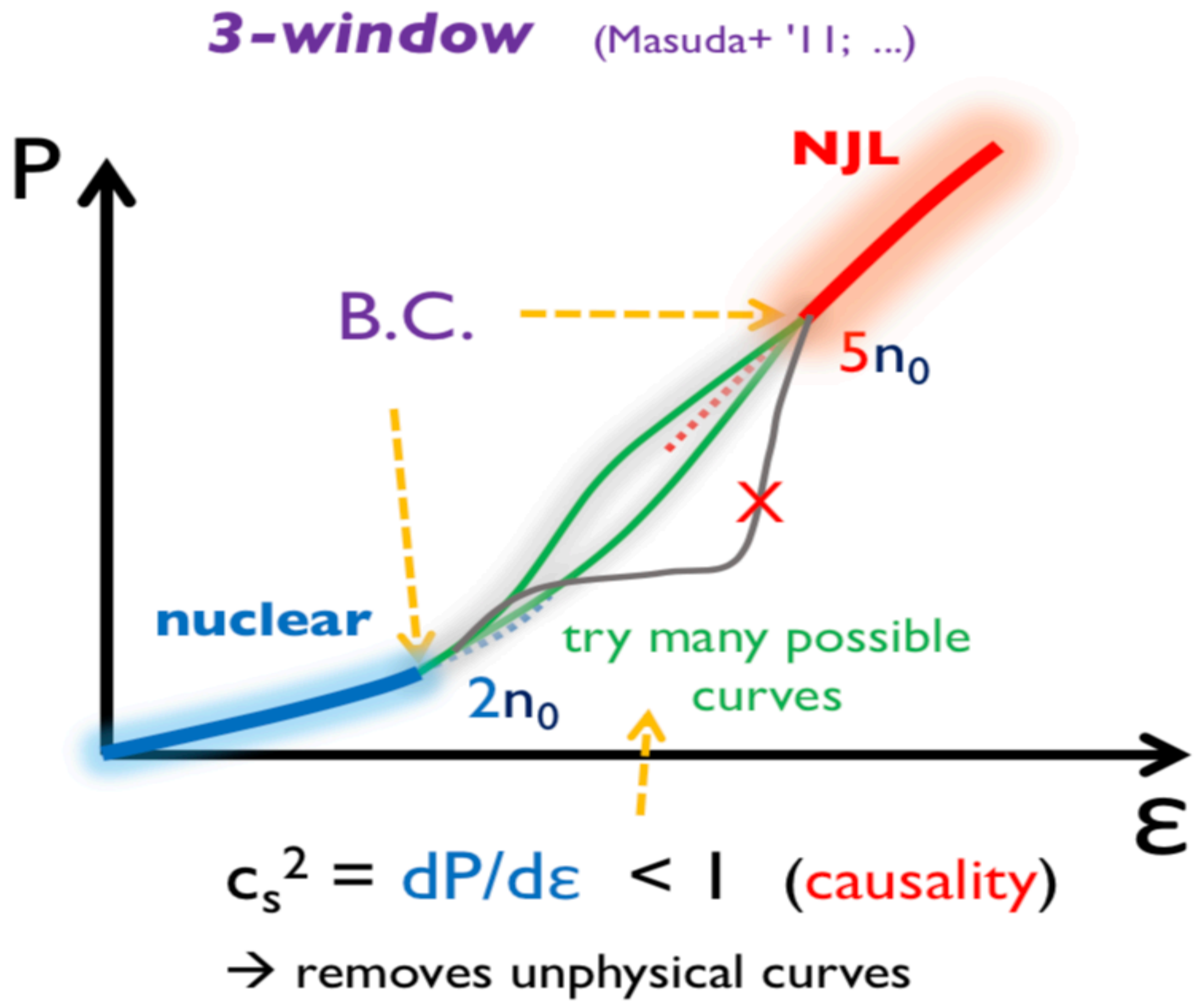
Unified Equation of State



An effective hadron model
(Parity doublet model) (n_B<=$2n_0$, blue curve)

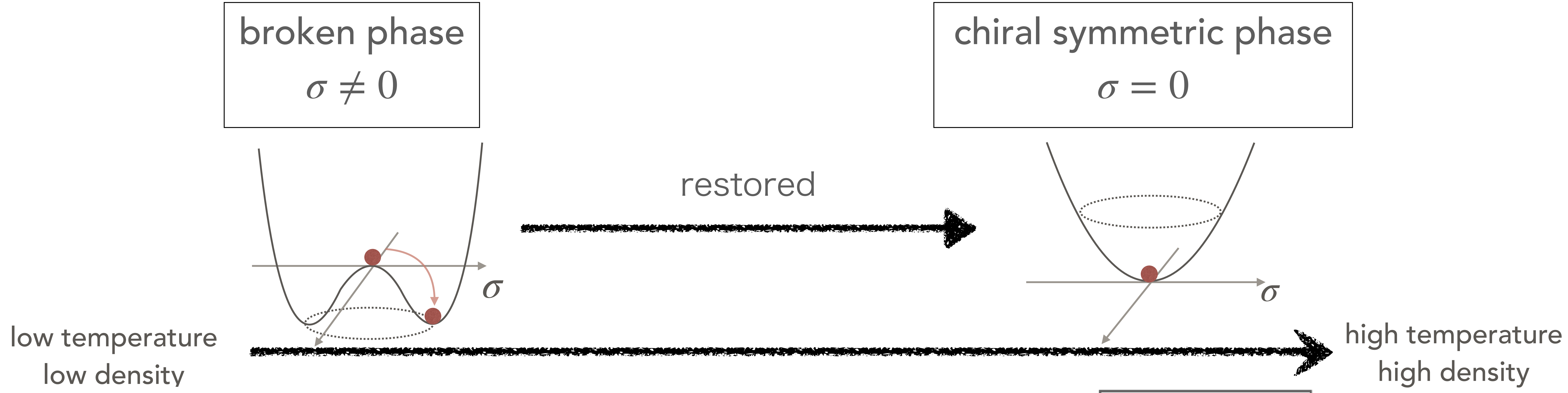
Two baryons with positive and negative-parity are introduced. They have a **degenerate chiral invariant mass** when the chiral symmetry is restored.

Interpolated(red curve)

An effective quark model
(Nambu–Jona-Lasinio(NJL)-type model)
(n_B>=$5n_0$, green curve)

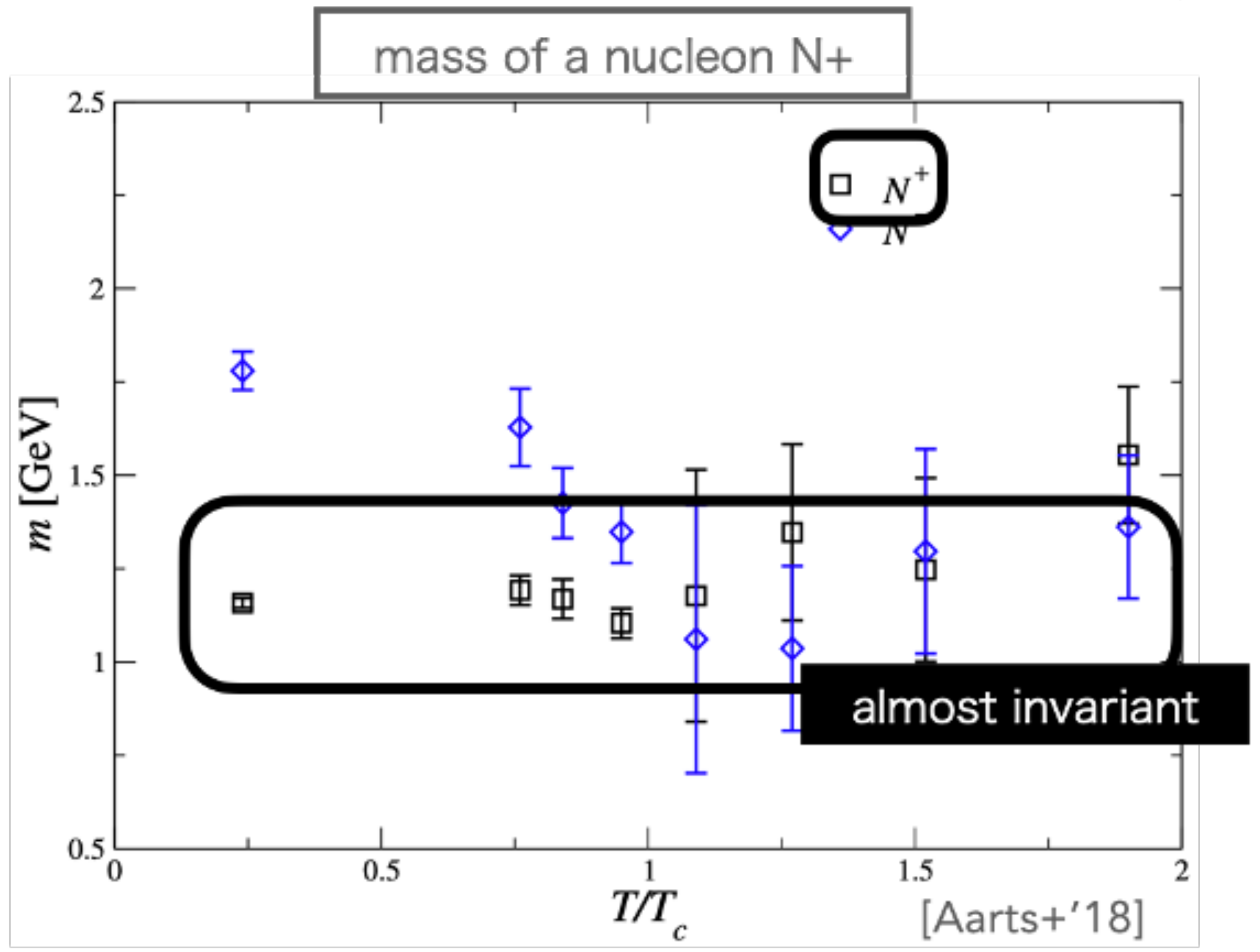
Parity Doublet Model

Contribution to mass from **spontaneously chiral symmetry breaking(SCSB)**



Contribution to mass from **chiral invariant mass m_0**

Chiral 'invariant' component?
Does not depend on temperature/density.[PhysRevD.92.014503]



Parity Doublet Model

PDM: chiral symmetric nucleon-meson effective model

DeTar, Kunihiro, 1989; Jido, Oka, Hosaka, 2001

$$\mathscr{L}_{\mathrm{PDM}} = \mathscr{L}_{\mathrm{Nucleon}}(\psi_1, \psi_2, \ldots) + \mathscr{L}_{\mathrm{Meson}}(\sigma, \pi, \underline{\omega, \rho}, \ldots)$$

vector mesons, with HLS

ordinal dirac mass term:

$$m\bar{\psi}\psi = m(\bar{\psi}^L\psi^R + \bar{\psi}^R\psi^L)$$

$$\to \underline{m(\bar{\psi}^L L^\dagger R\psi^R + \bar{\psi}^R R^\dagger L\psi^L)}$$

chiral variant

	$L \in SU(N_f)_L$ left-handed	$R \in SU(N_f)_R$ right-handed
nucleon ψ_1	$\psi_1^L \to L\psi_1^L$	$\psi_1^R \to R\psi_1^R$
nucleon ψ_2	$\psi_2^L \to R\psi_2^L$	$\psi_2^R \to L\psi_2^R$

in PDM:

$$m_0(\bar{\psi}_1\gamma_5\psi_2 - \bar{\psi}_2\gamma_5\psi_1) = m_0(\bar{\psi}_1^L\psi_2^R + \bar{\psi}_1^R\psi_2^L + \mathrm{h.c.})$$

$$\to \underline{m_0(\bar{\psi}_1^L L^\dagger L\psi_2^R + \bar{\psi}_1^R R^\dagger R\psi_2^L + \mathrm{h.c.})}$$

chiral invariant

Parity Doublet Model: Physical inputs

mass formula of nucleons N(939) and N*(1535)

DeTar, Kunihiro, 1989; Jido, Oka, Hosaka, 2001

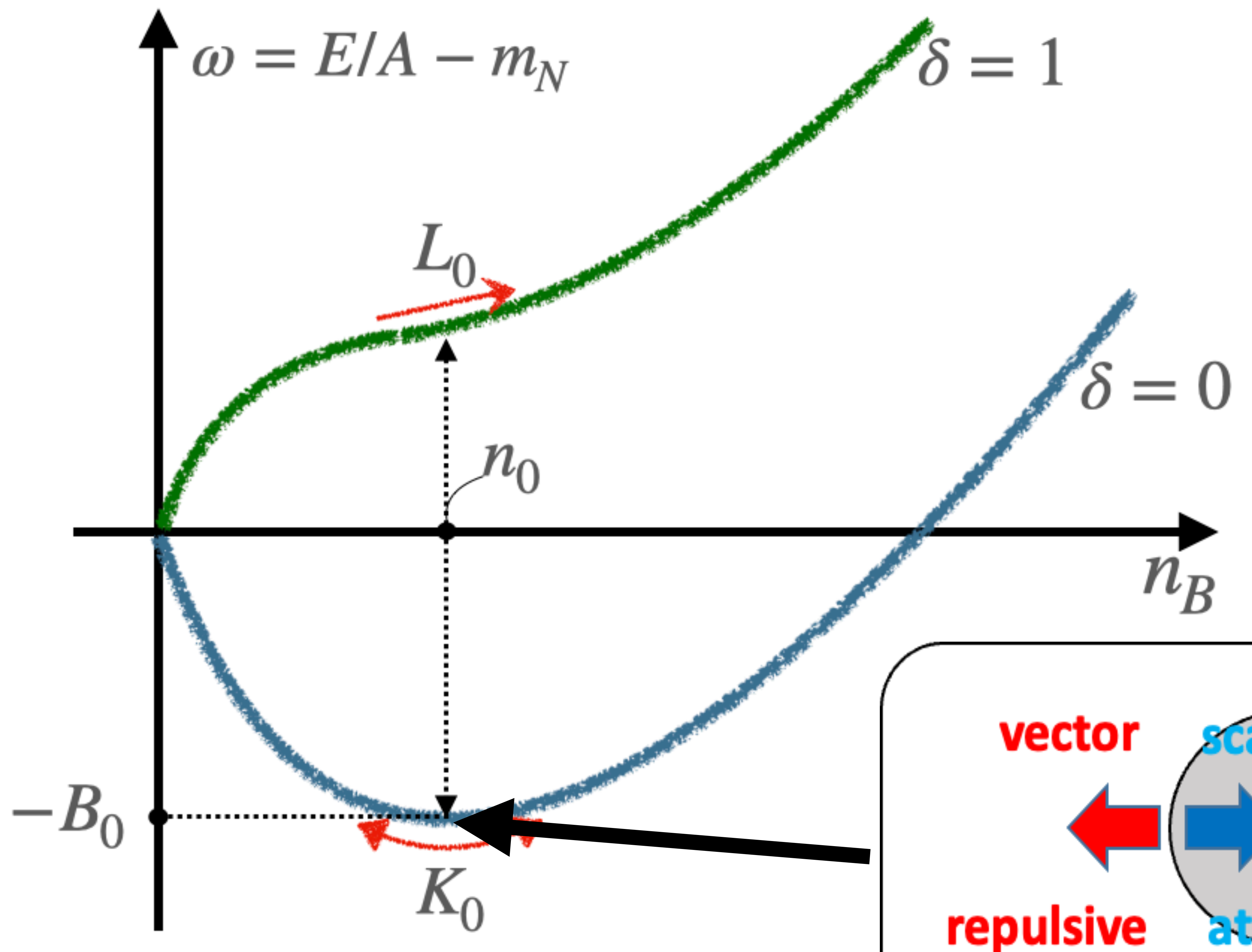
$$M_{N\pm} = \sqrt{m_0^2 + g_+^2\sigma^2} \mp g_-\sigma \quad \xrightarrow{\sigma \to 0} \quad m_0$$

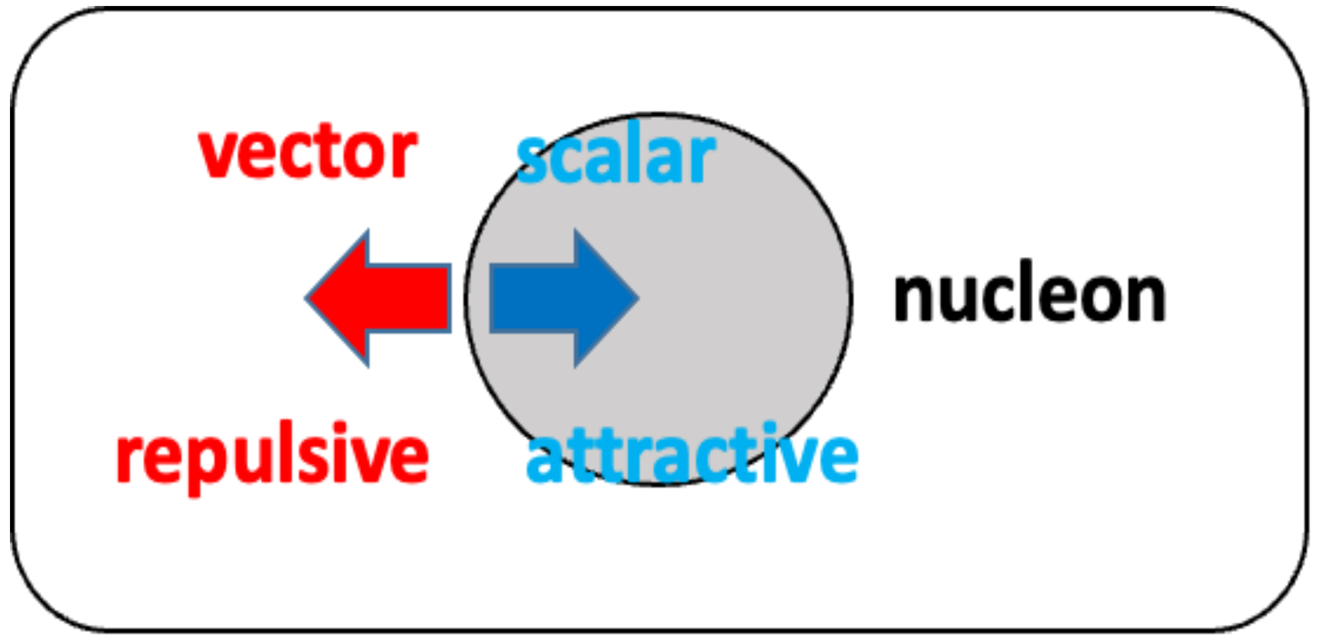
n_0=0.16 fm^{-3} (**normal nuclear density**),

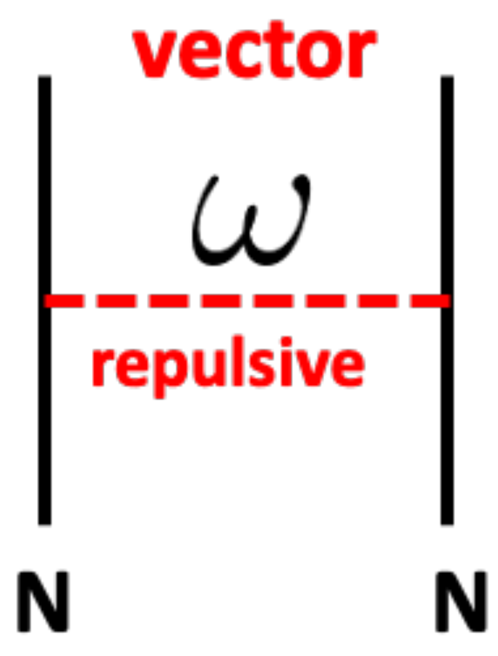
K_0=240 MeV (**incompressibility**)

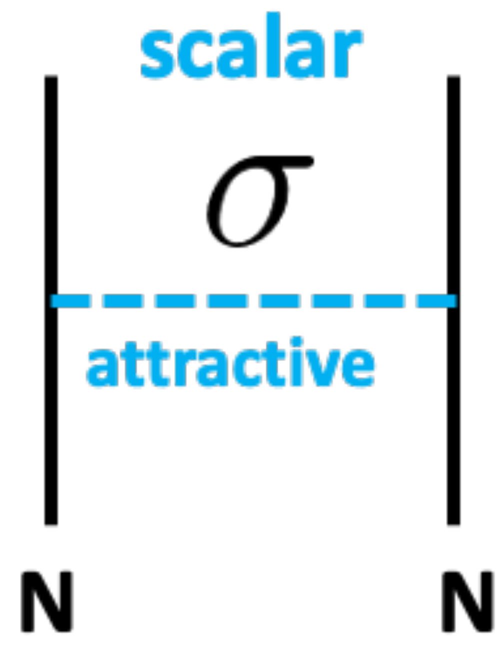
S_0=31 MeV (**symmetry energy**),

B_0=16 MeV (**bounding energy**)









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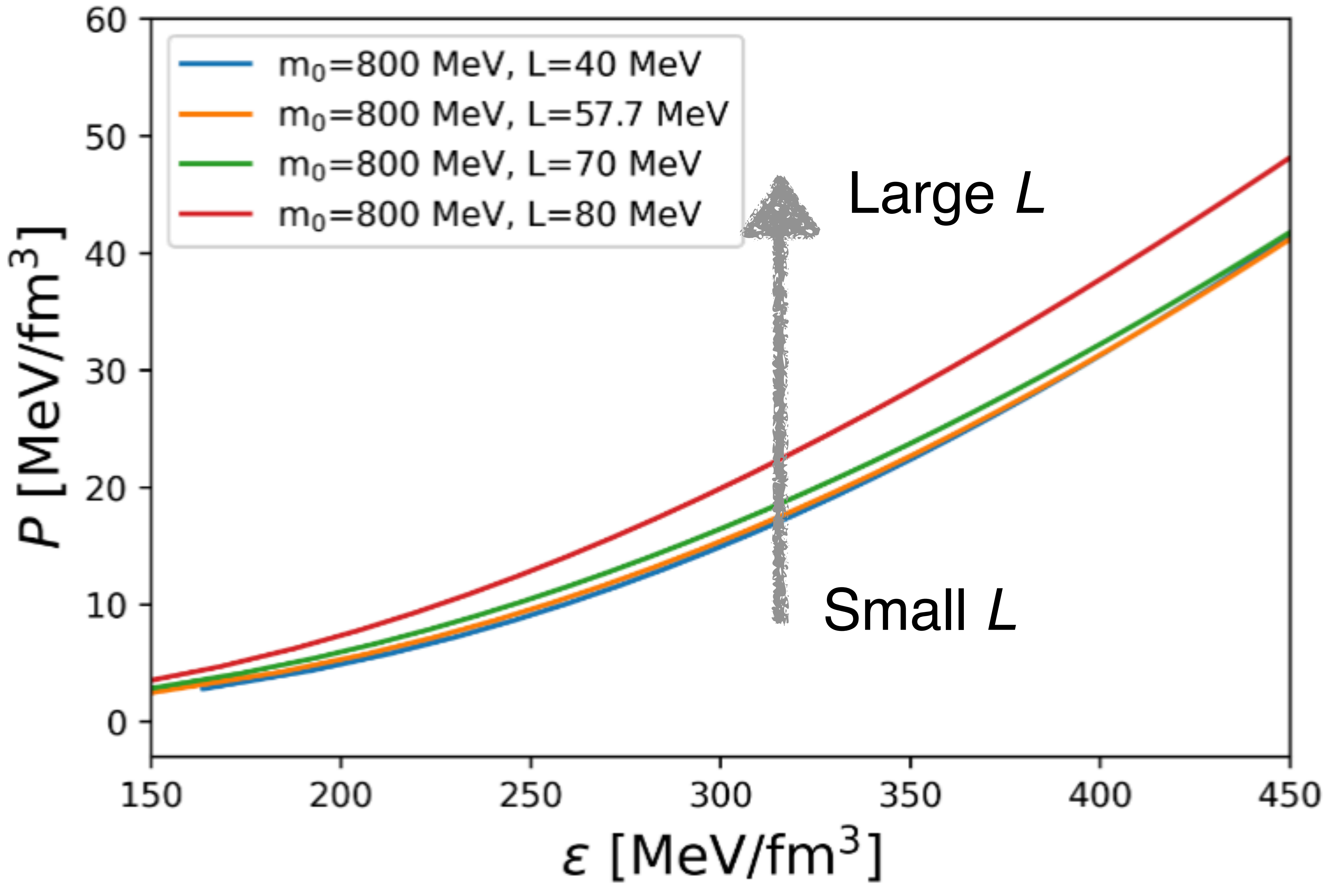

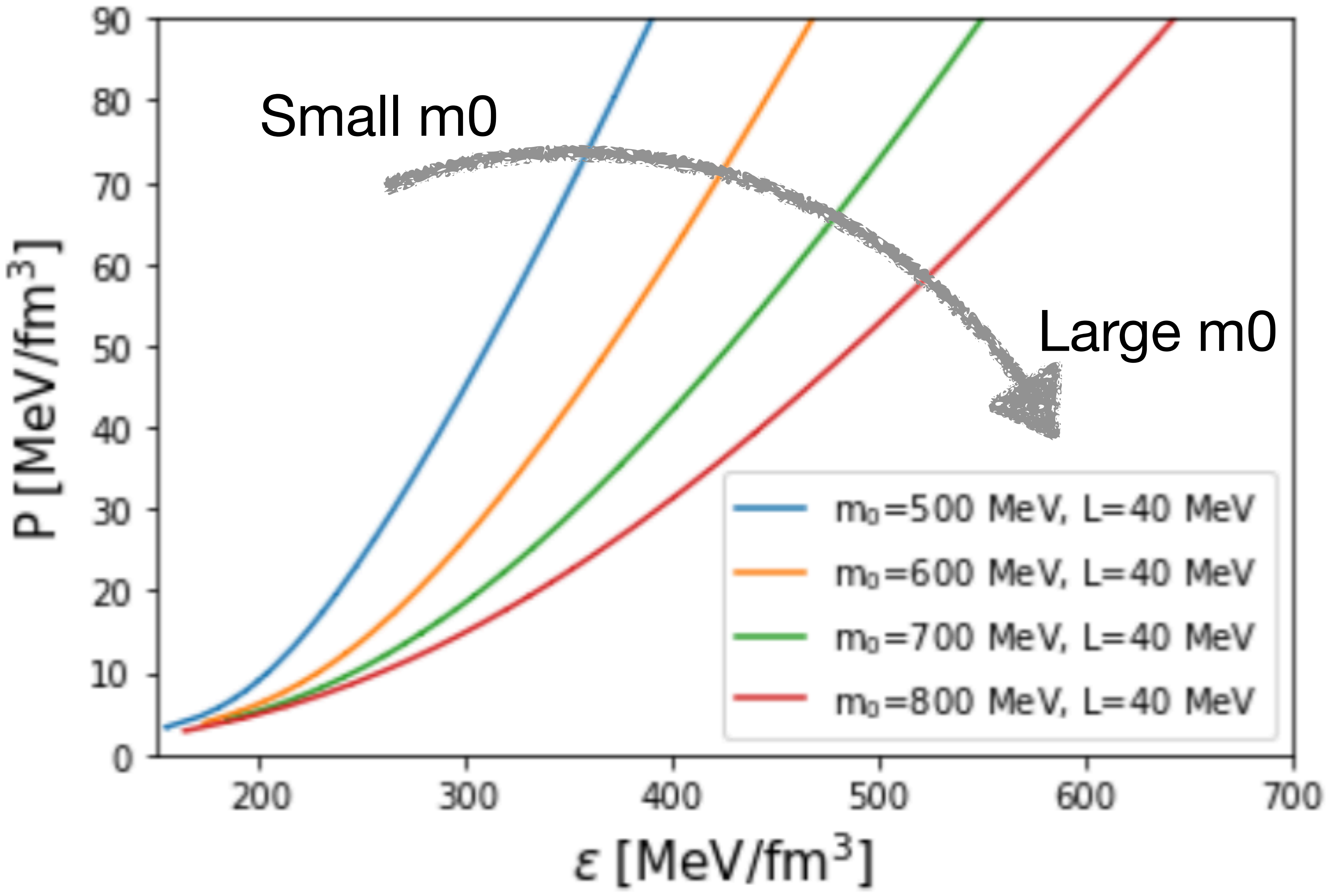

NJL-type quark model

$$\mathscr{L} = \mathscr{L}_{\mathrm{NJL}} - H(q^T\Gamma_A q)(\bar{q}\Gamma^A\bar{q}^T) + g_V(\bar{q}\gamma^0 q)^2 \quad + \sum_i \mu_i Q_i$$

- Original NJL-type model(Hatsuda and Kunihiro) includes four point interaction $+G(\bar{\psi}\psi)^2$
- U(1) axial anomaly $-K\det(\bar{\psi}\psi)$

HK parameters: $G\Lambda^2 = 1.835, \quad K\Lambda^5 = 9.29$

$\Lambda = 631.4\mathrm{MeV}$

H: coupling for diquark condensates
gV: coupling for vector (repulsive) interaction

(H,gV): not well-constrained before
→ survey wide range for given nuclear EOS + NS constraints

NJL-type quark model

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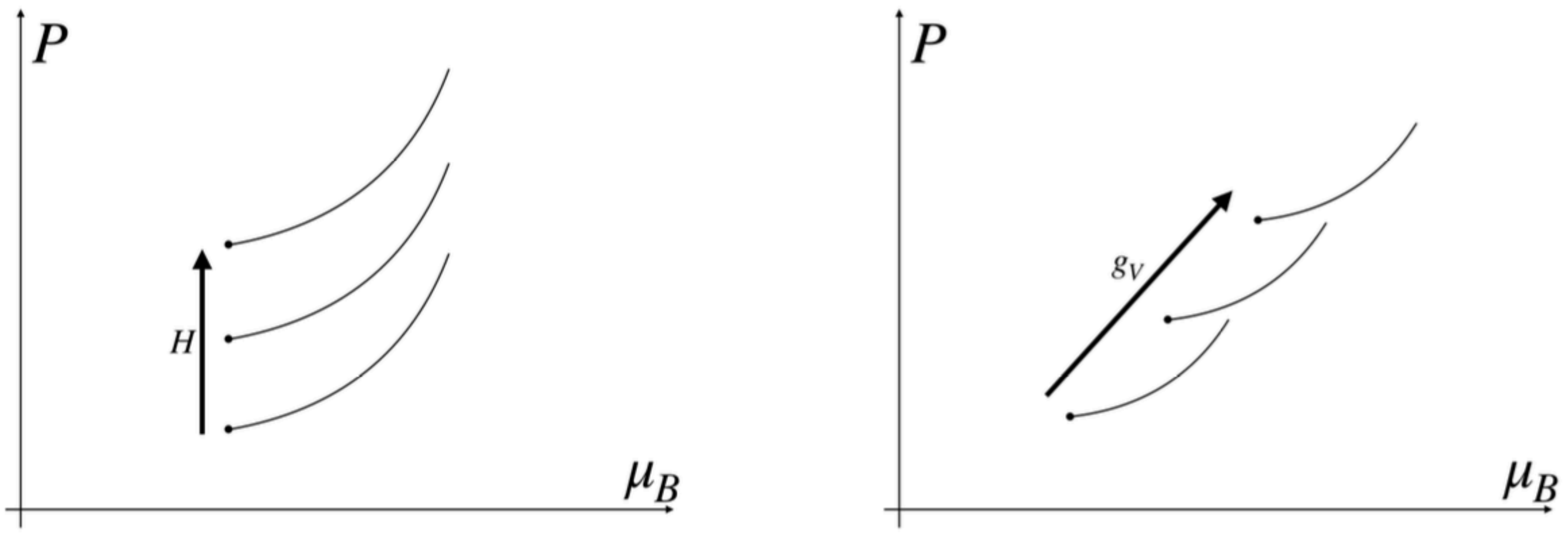
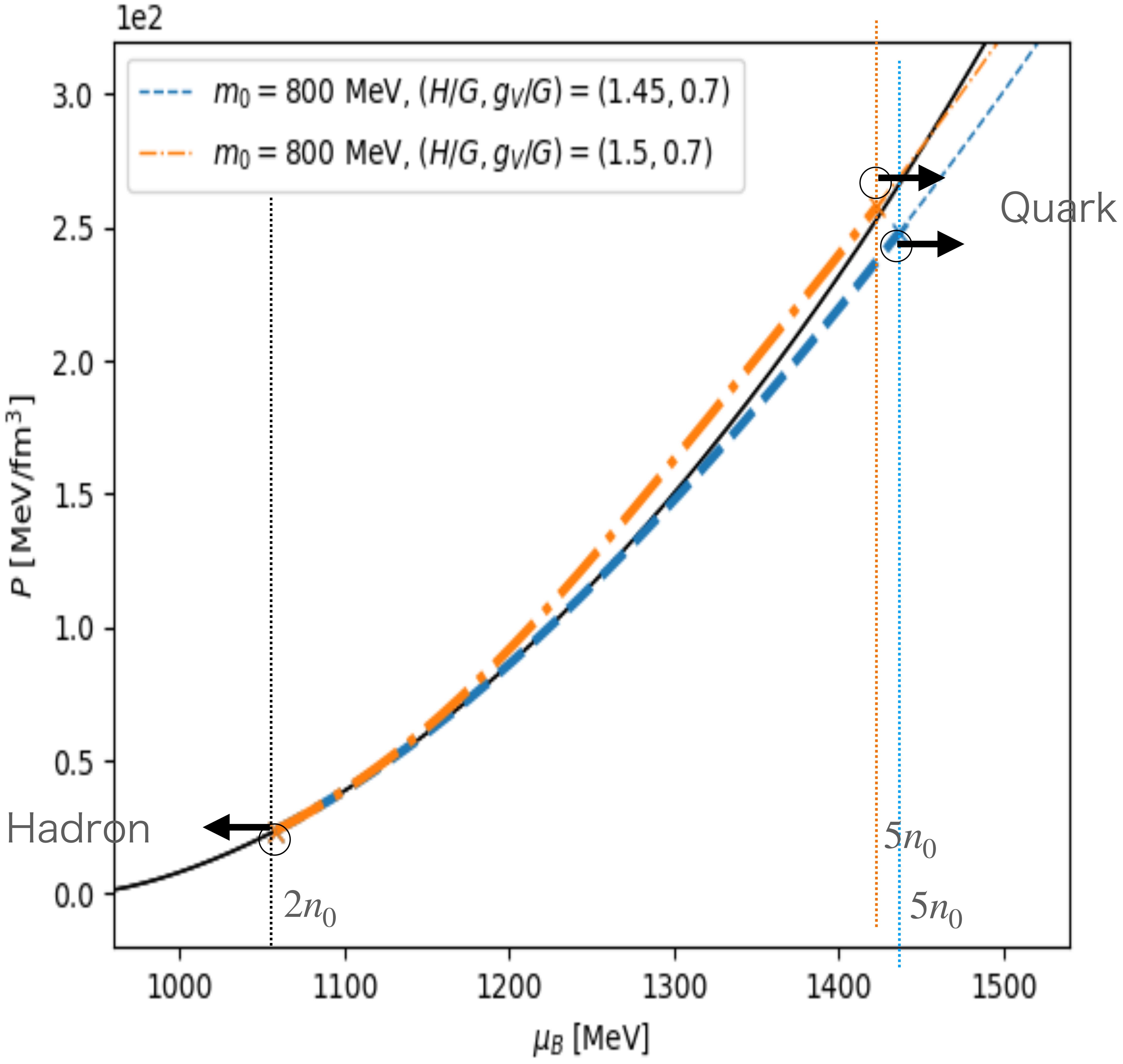


Schematic diagram showing the changes in pressure and chemical potential while changing *H* and *gV*

Interpolated EoS



$0 \leqslant n_B < 0.5n_0$	$0.5n_0 \leqslant n_B \leqslant 2n_0$	$2n_0 < n_B < 5n_0$	$n_B \geqslant 5n_0$
Crust	PDM	Interpolation	NJL

interpolate w/ polynomial: $P = \sum_{n=0}^{5} c_n \mu_B^n$

(six) Boundary Conditions => (six) coefficients c_n

$$\left.\frac{d^n P_I}{(d\mu_B)^n}\right|_{\mu_{BL}} = \left.\frac{d^n P_H}{(d\mu_B)^n}\right|_{\mu_{BL}},$$

$$\left.\frac{d^n P_I}{(d\mu_B)^n}\right|_{\mu_{BU}} = \left.\frac{d^n P_Q}{(d\mu_B)^n}\right|_{\mu_{BU}}, \quad (n = 0, 1, 2),$$

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Results

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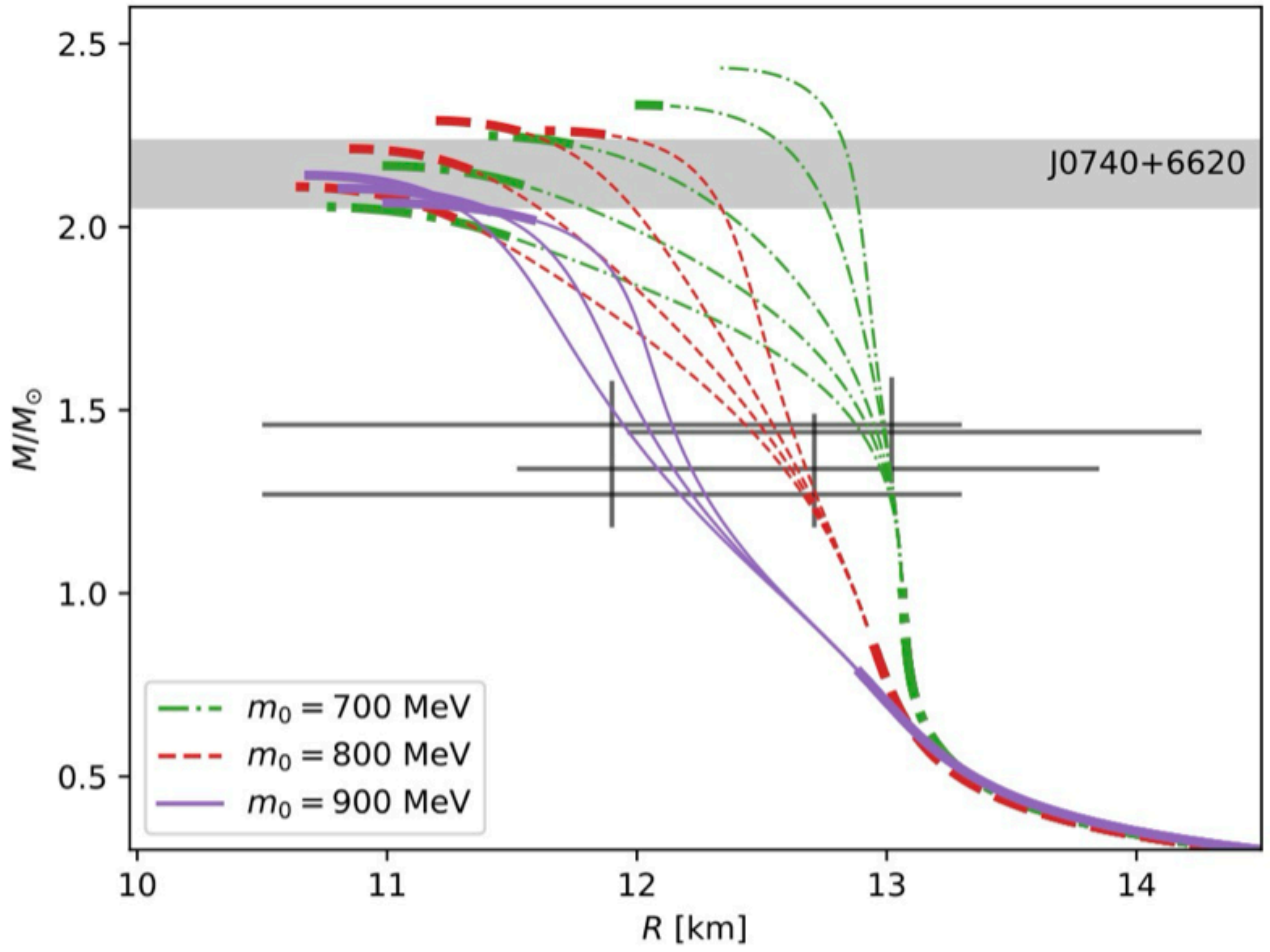

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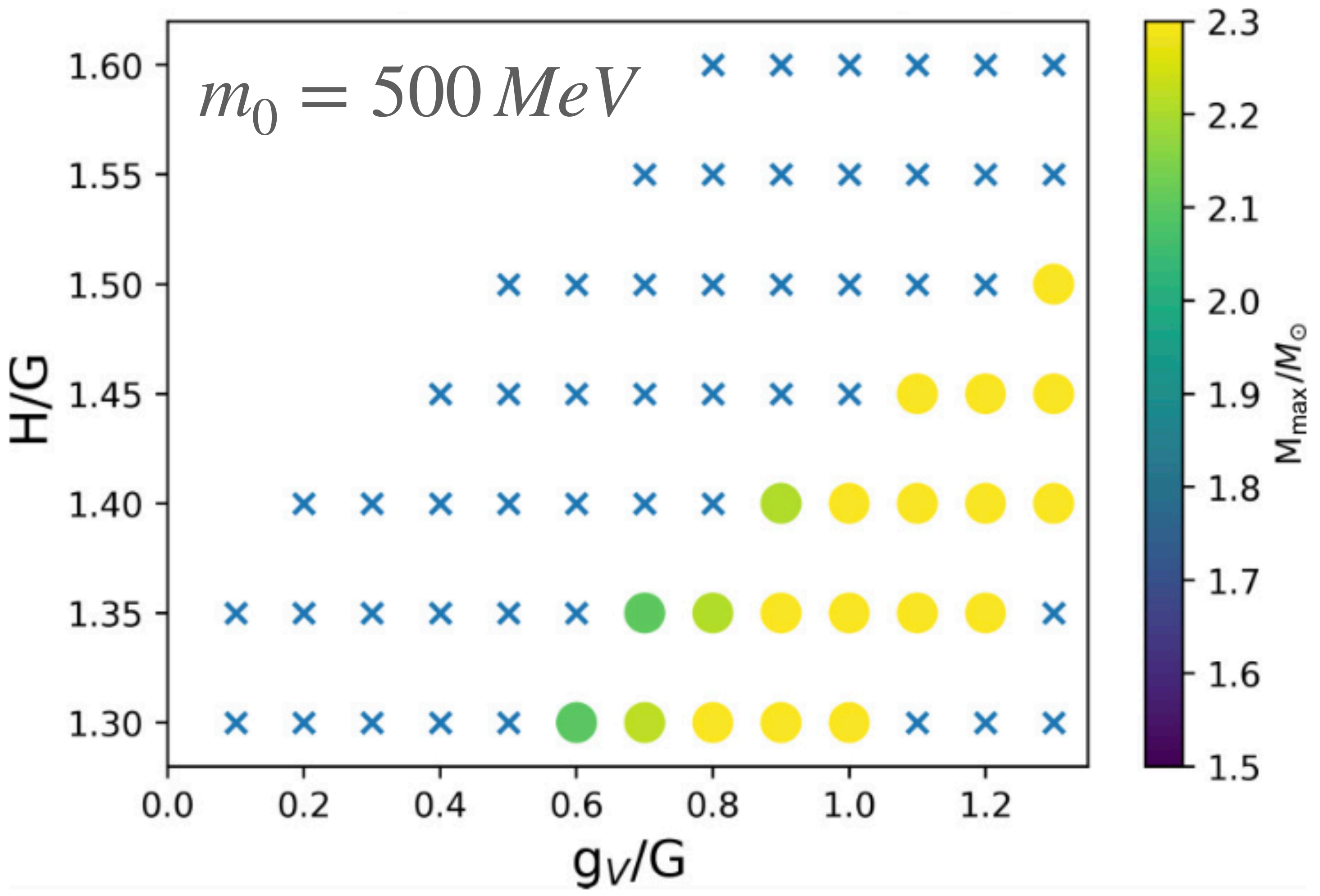
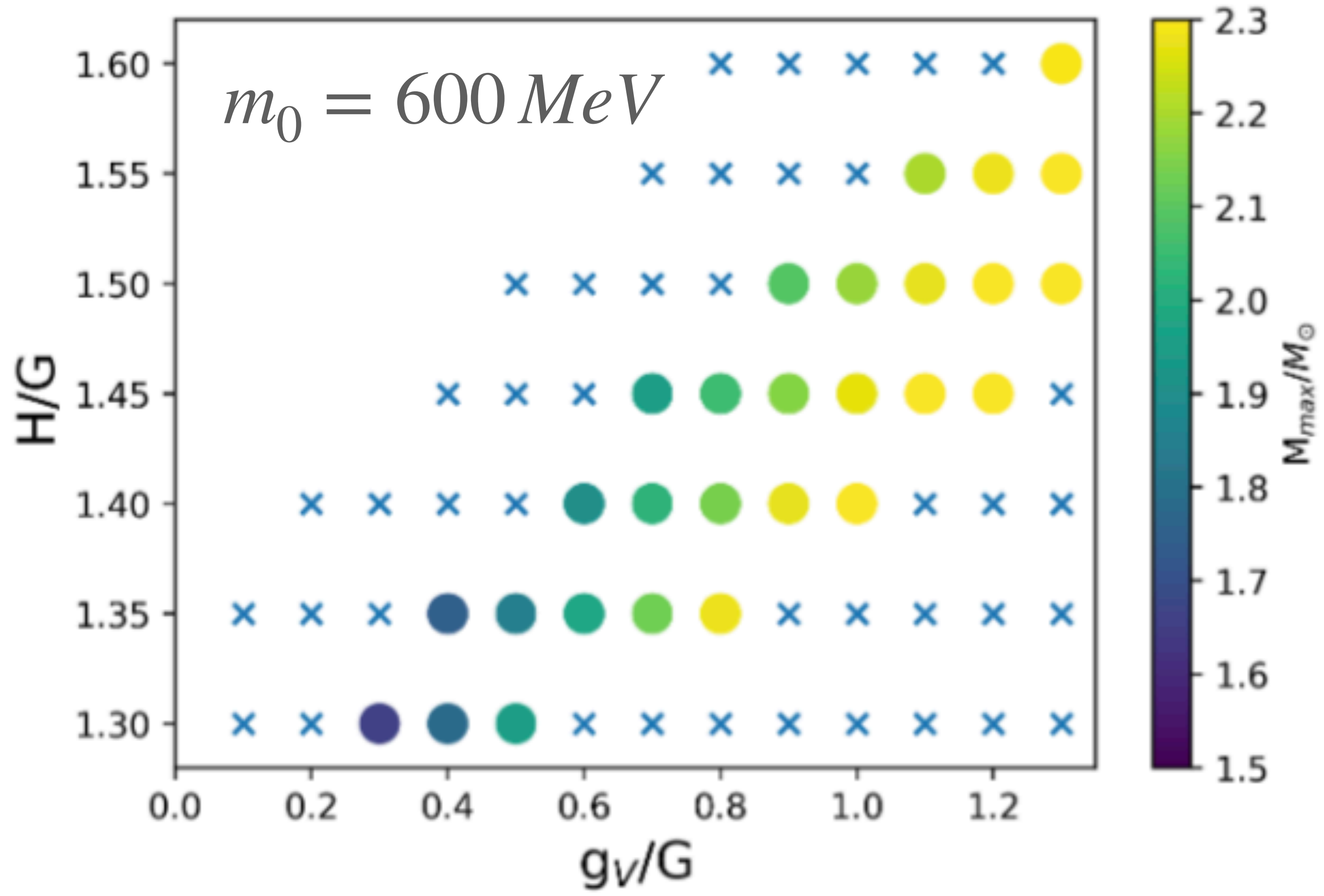
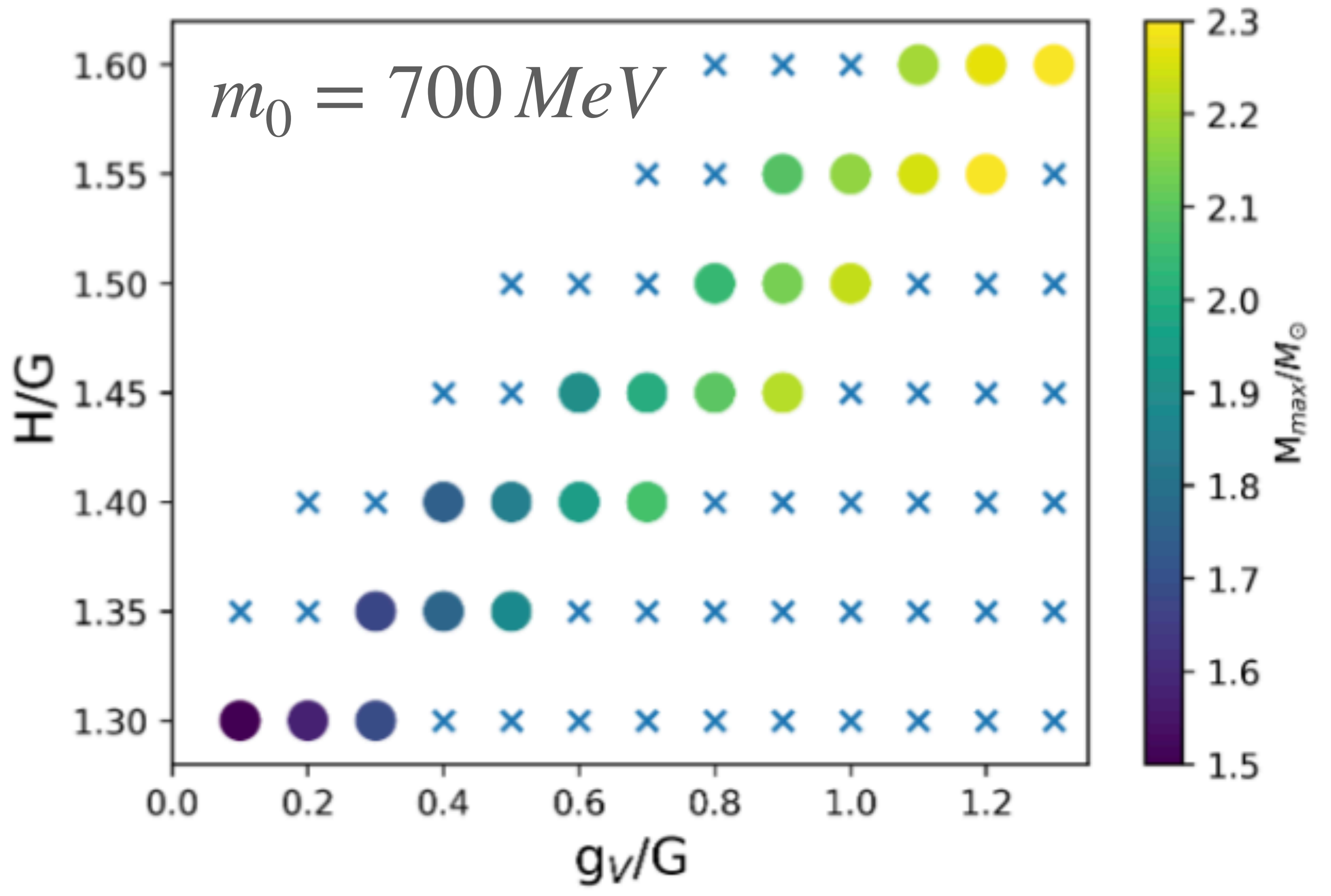




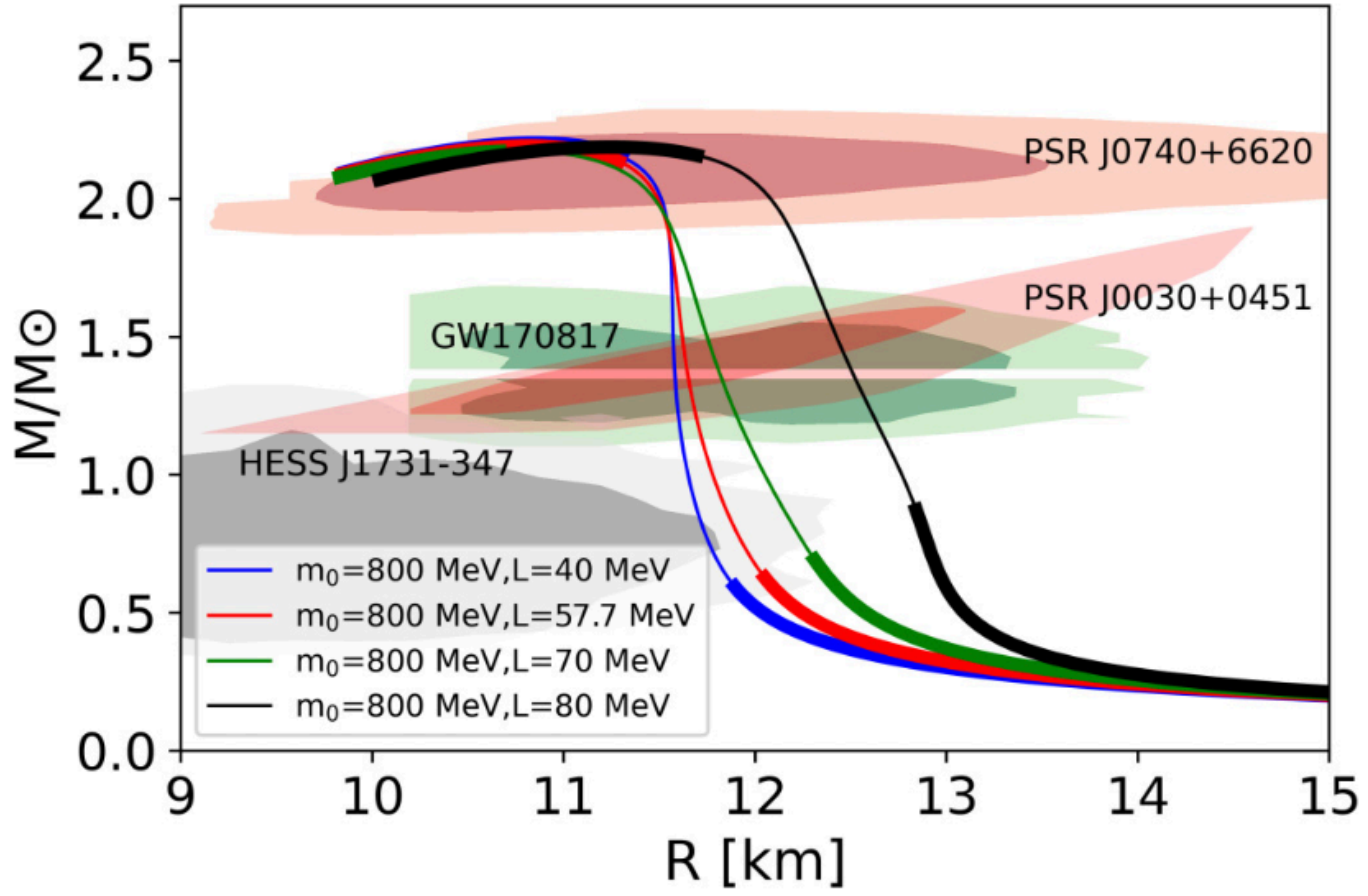


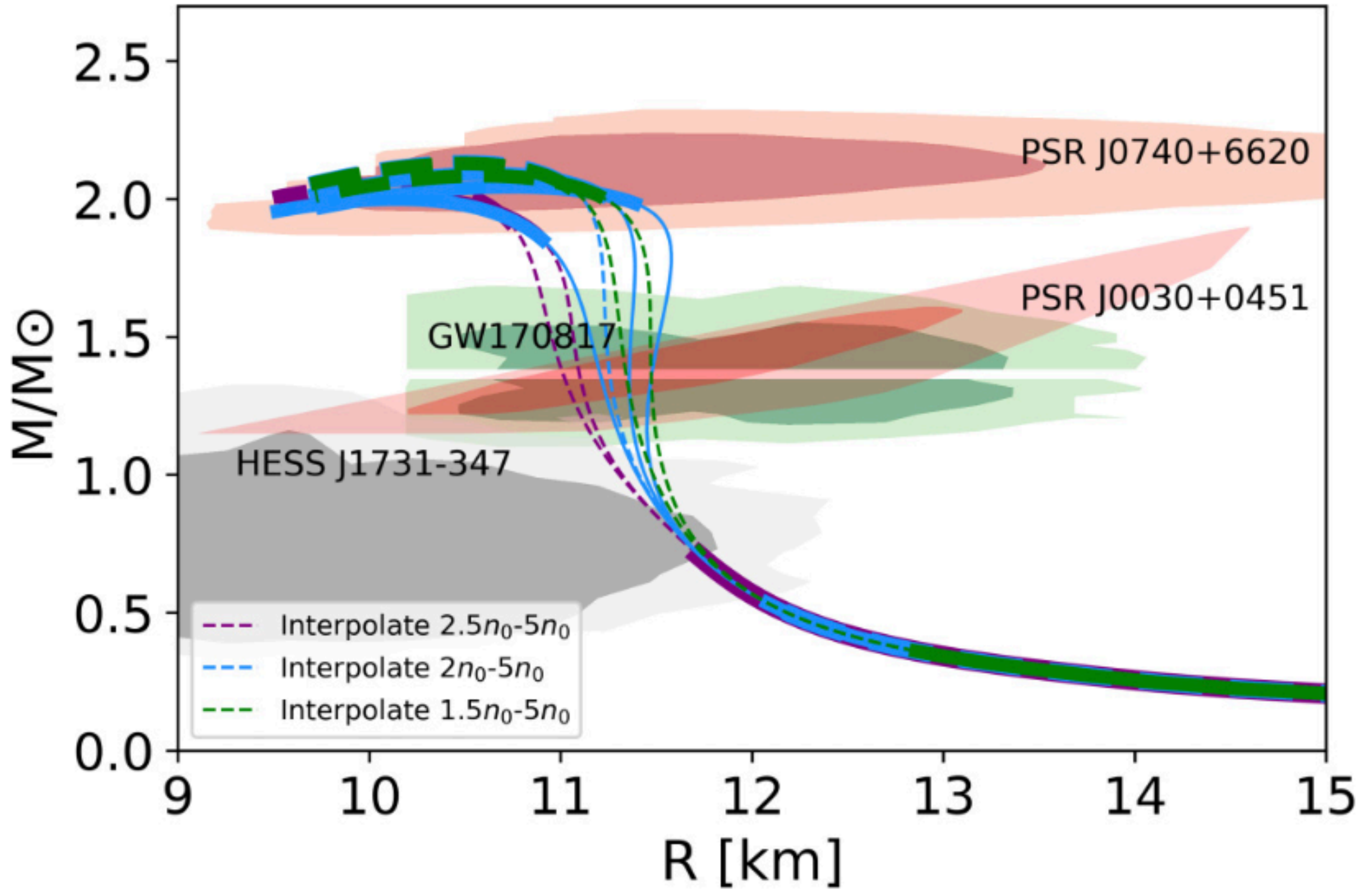
m_0 ⟷ (H,gV)

constrain each other

Causality + Mmax

Results





The hadronic matter EoS is crucial to determine the radius of a NS.

Summary

We use the parity double model together with the NJL-type quark model to construct the unified EoS.

The outer core EoS (described by PDM) is crucial to determine the radius of a NS.

We successfully reconcile with the multi-messenger constraints at the same time and the best fitted value is

$$m_0 \cong 850 \text{ MeV}$$

for L =40 MeV