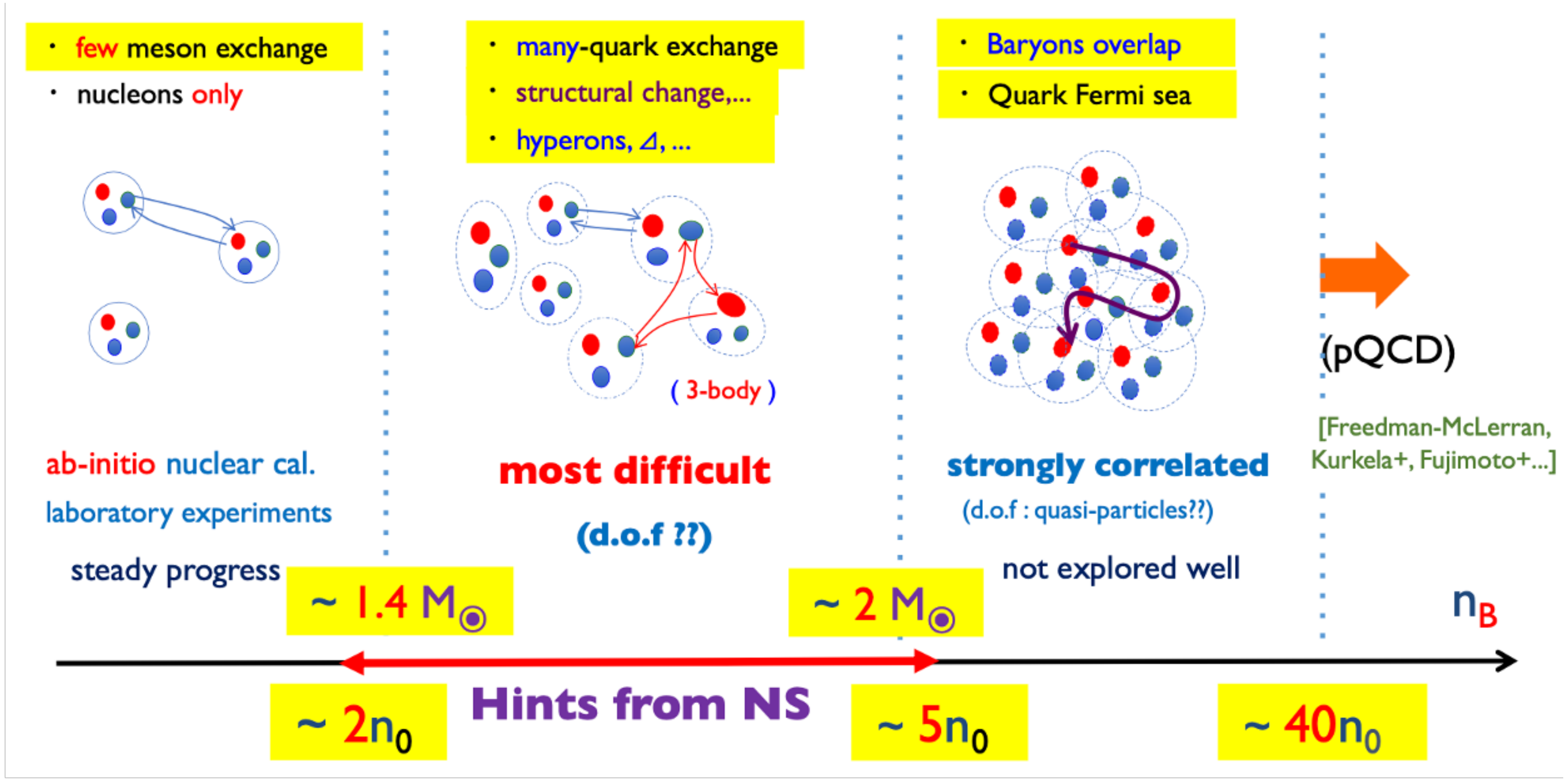
Reconciling constraints from the supernova remnant HESS J1731-347 with the parity doublet model

Bikai Gao, Yan Yan, Masayasu Harada

Dept. of Phys, Nagoya University

Fundamental questions in dense QCD

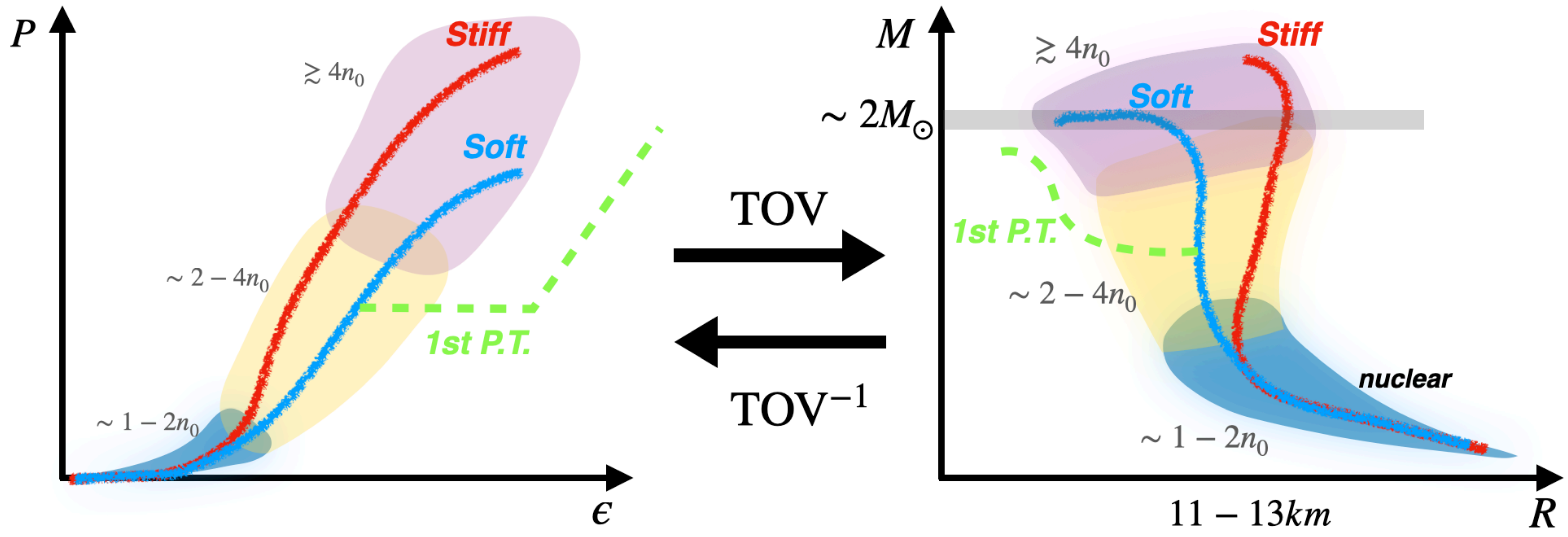


How does dense matter respond to compression, the EOS?

How hadronic matter dissolves into quark matter?

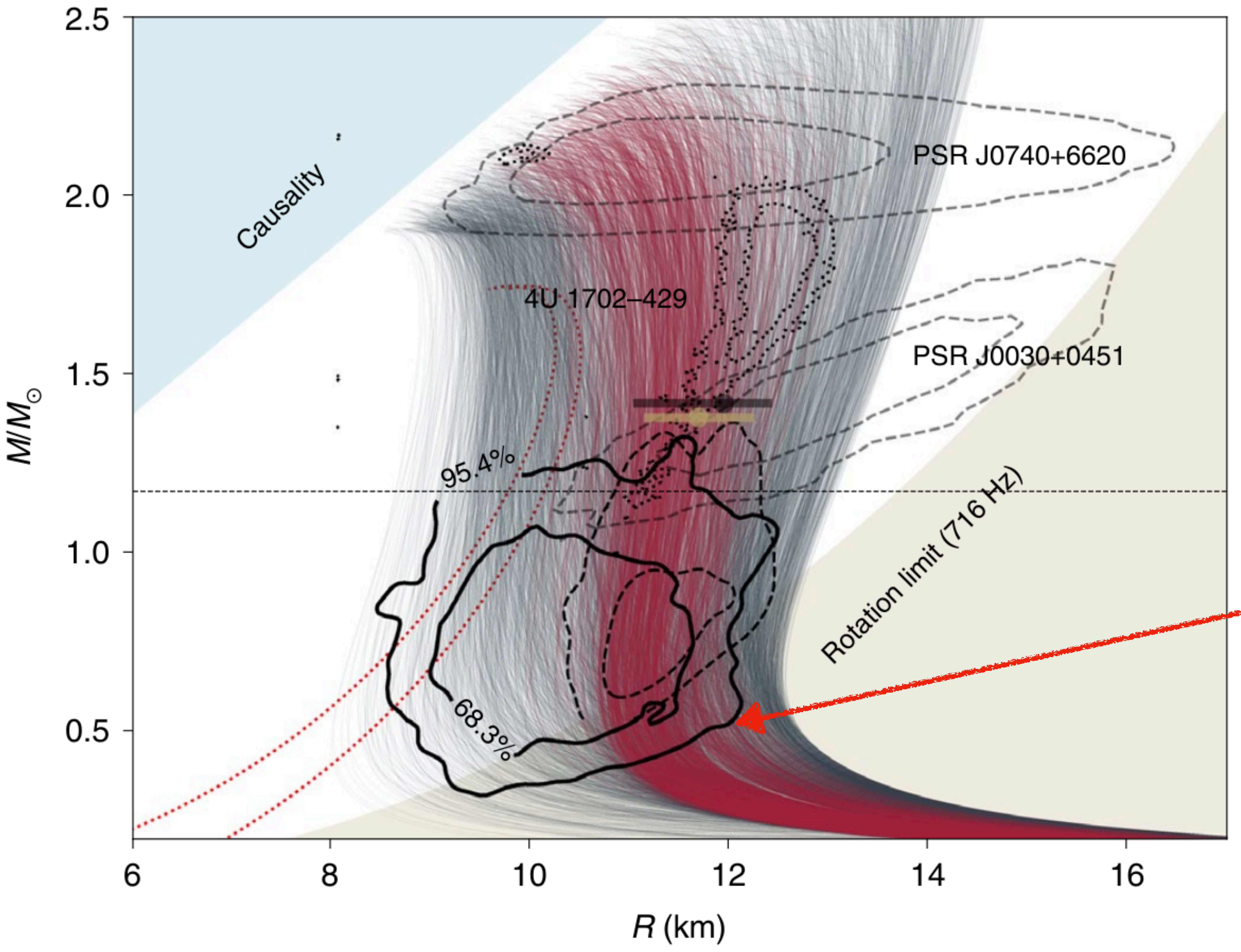
.....

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



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

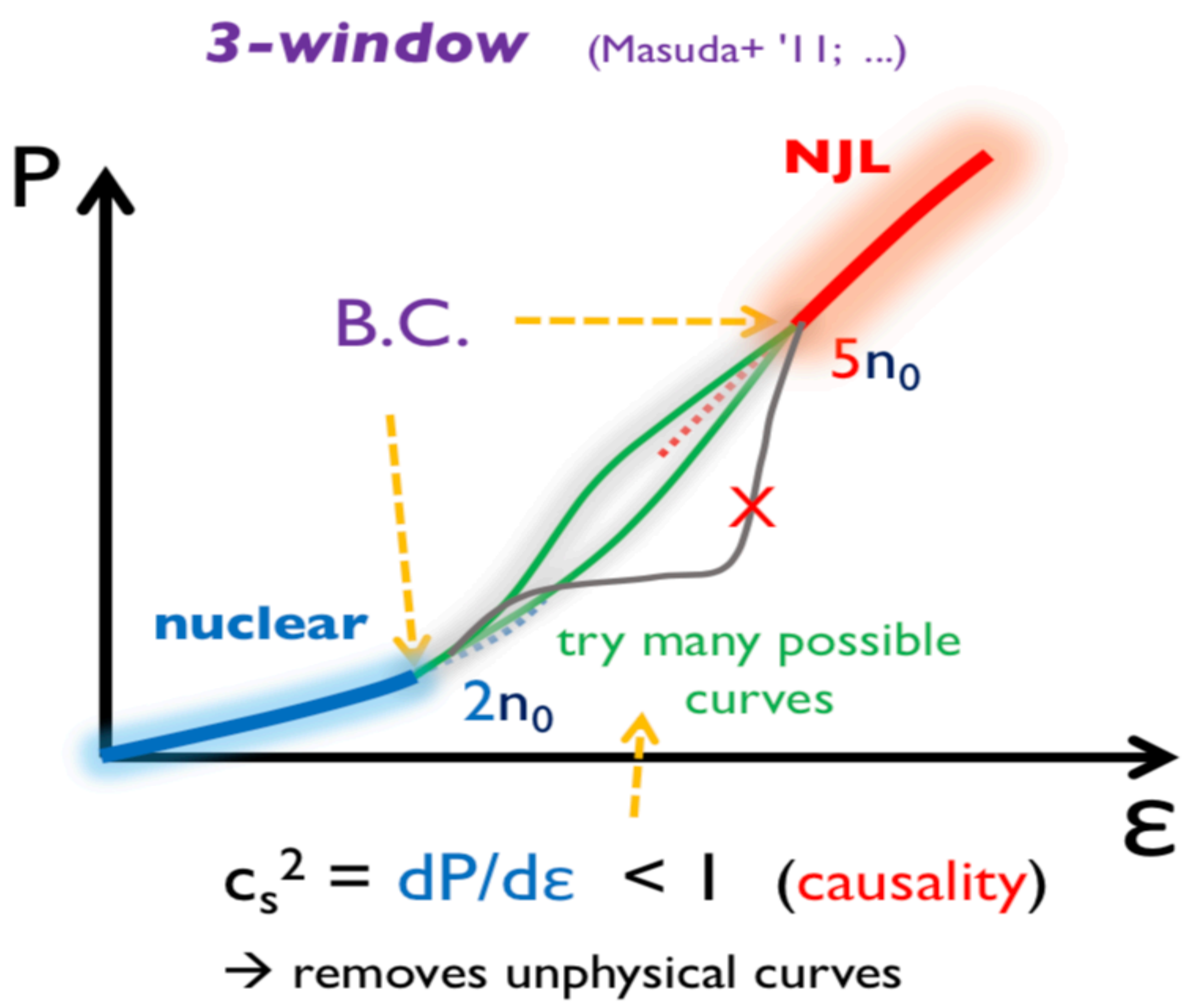
HESS J1731-347

A Strange light central compact object supernova remnant

From soft to stiff

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

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)

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

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

Parity Doublet Model

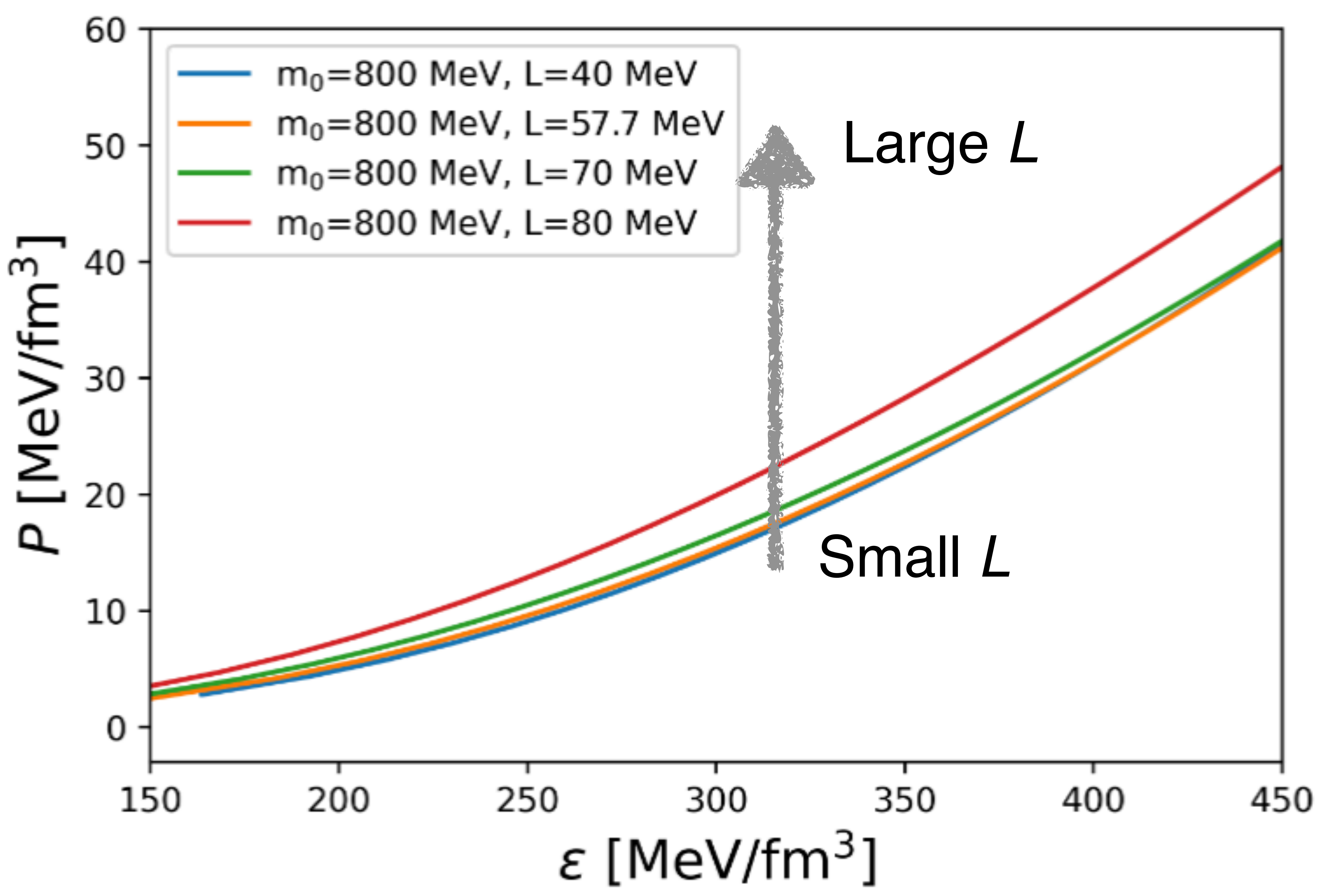
mass formula of nucleons N(939) and N*(1535)

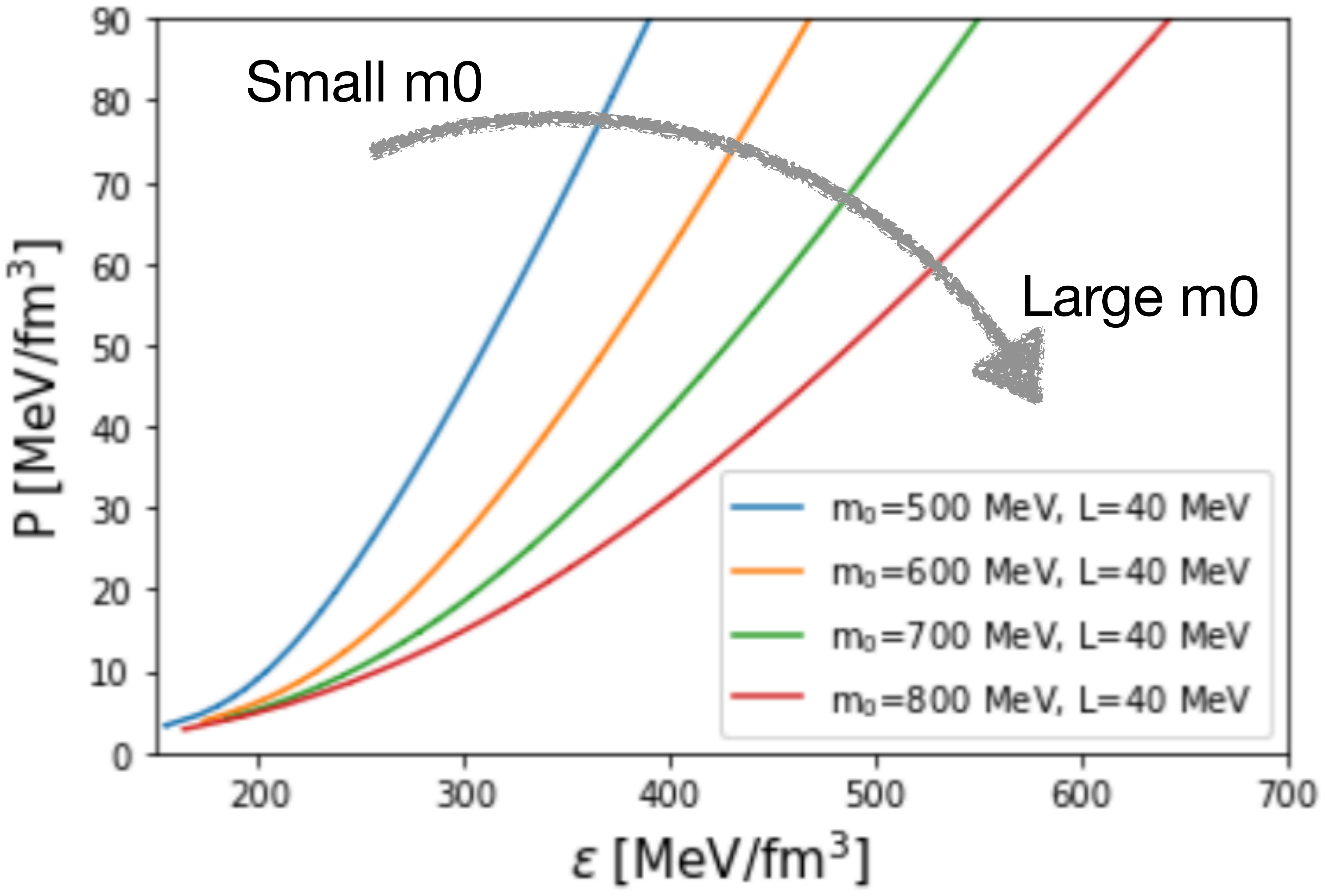
$$M_{N\pm} = \sqrt{m_0^2 + g_+^2\sigma^2} \mp g\_\sigma \quad \overset{\sigma \to 0}{\rightarrow} \quad m_0$$

Parameters in the model are determined by the saturation properties

n_0 [fm^{-3}]	B_0 [MeV]	K_0 [MeV]	S_0 [MeV]
0.16	16	240	31

Two parameters m0 , *L* (density dependence of the nuclear symmetry energy around the saturation density)





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

Outline

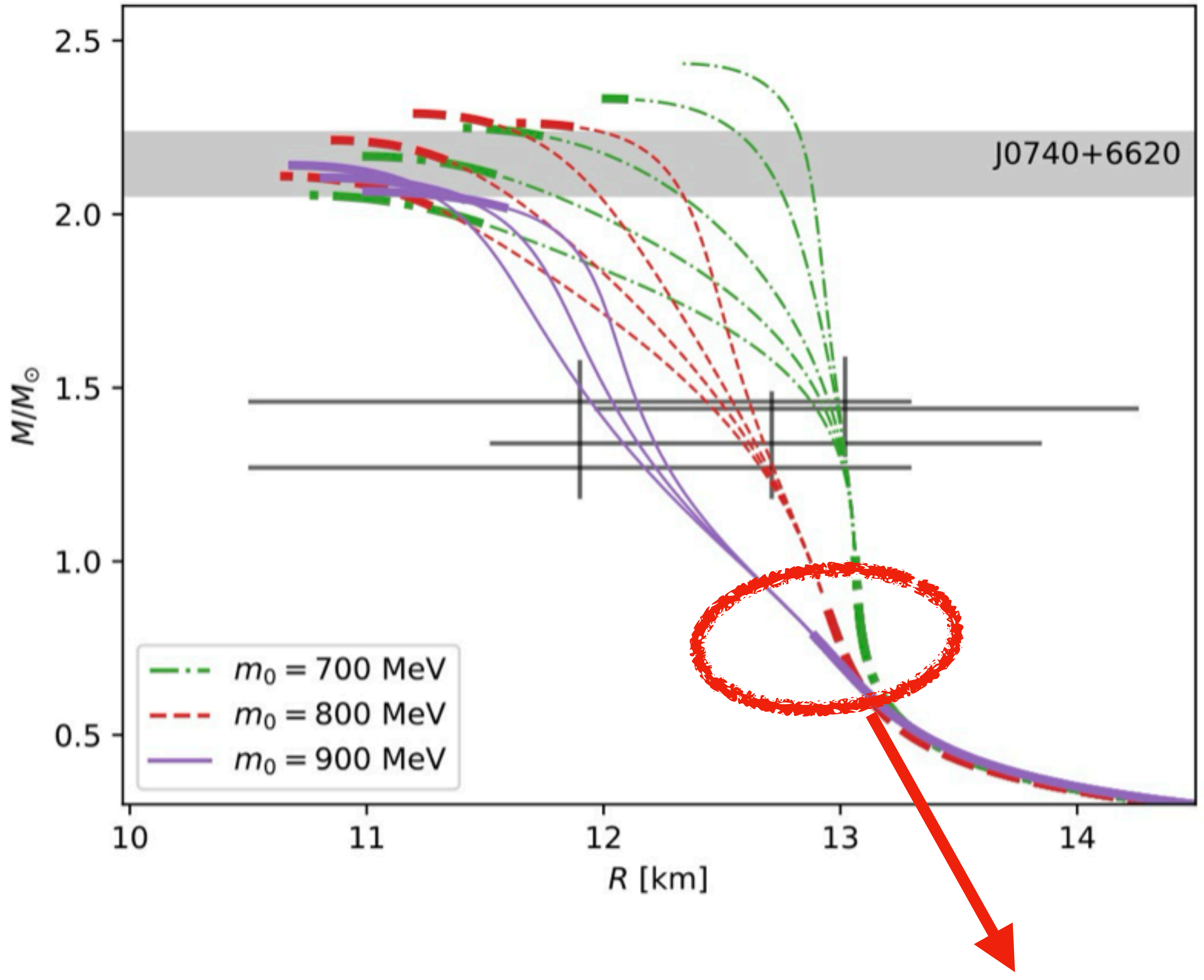
1. **Introduction** ✓

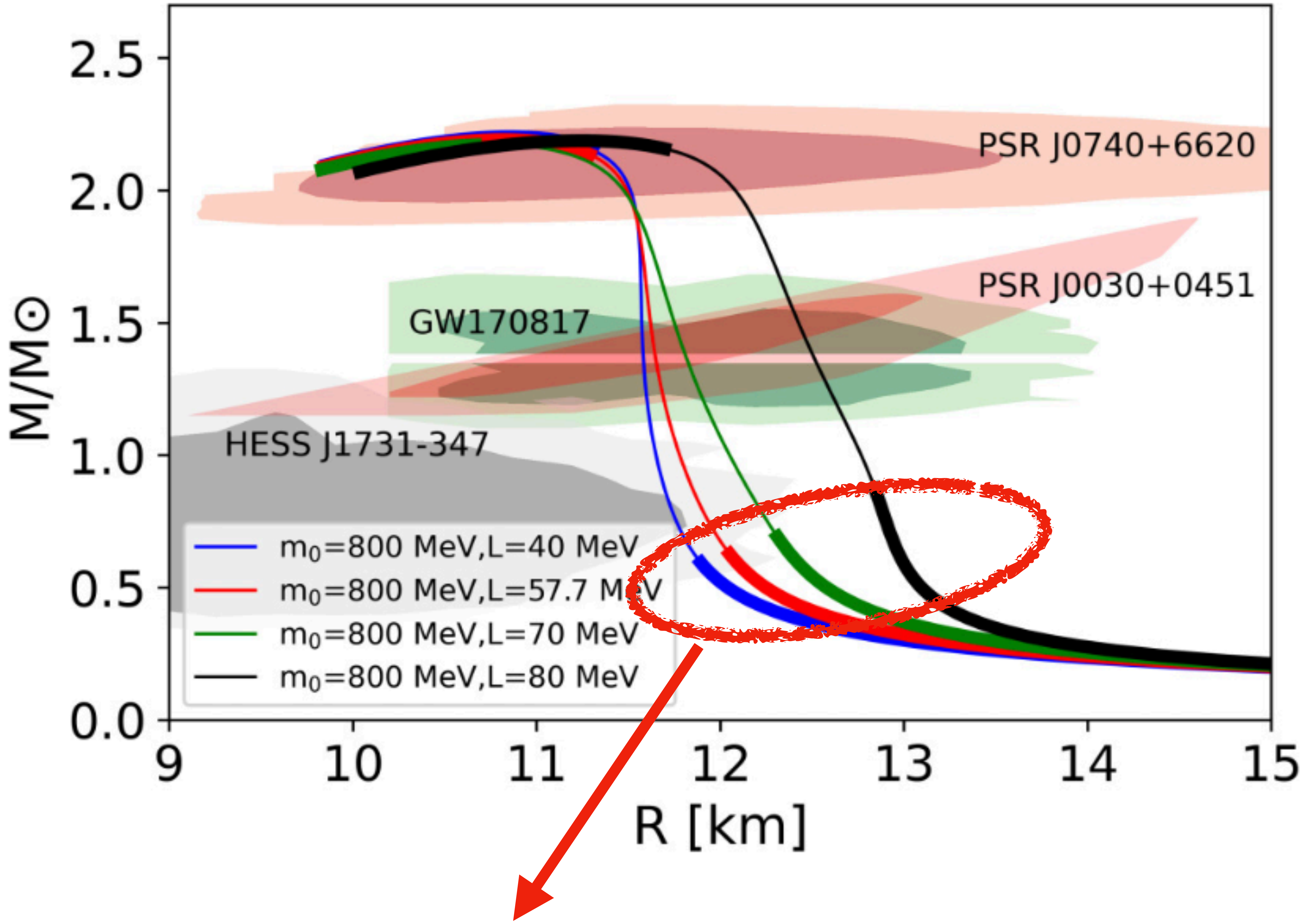
2. **Construction of Unified Equation of State** ✓
   - Parity doublet model
   - NJL-type quark model

3. **Results** ✓

Results

For fixed slope parameter *L=80* MeV





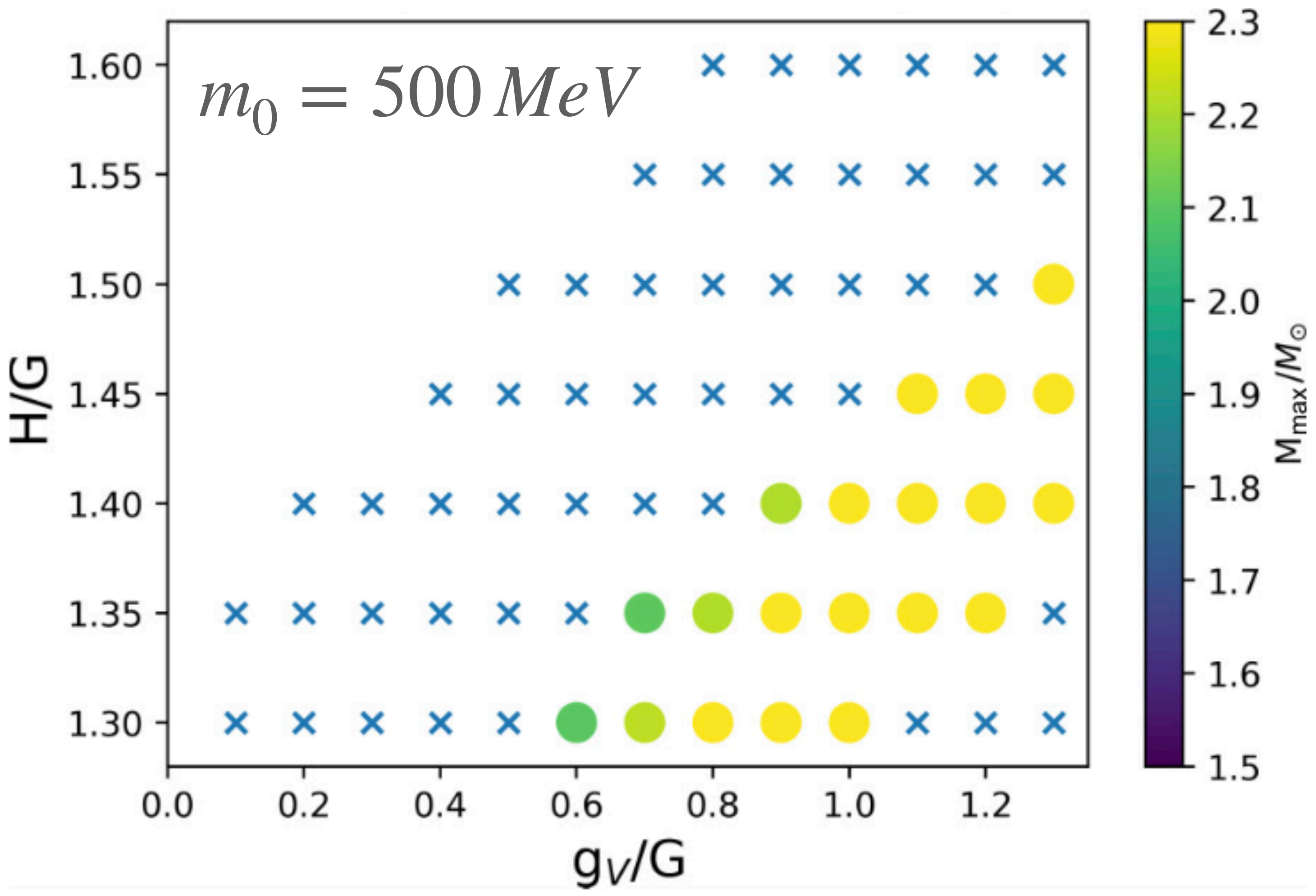
The hadronic matter EoS is crucial to determine the radius of a NS.
(From soft to stiff)

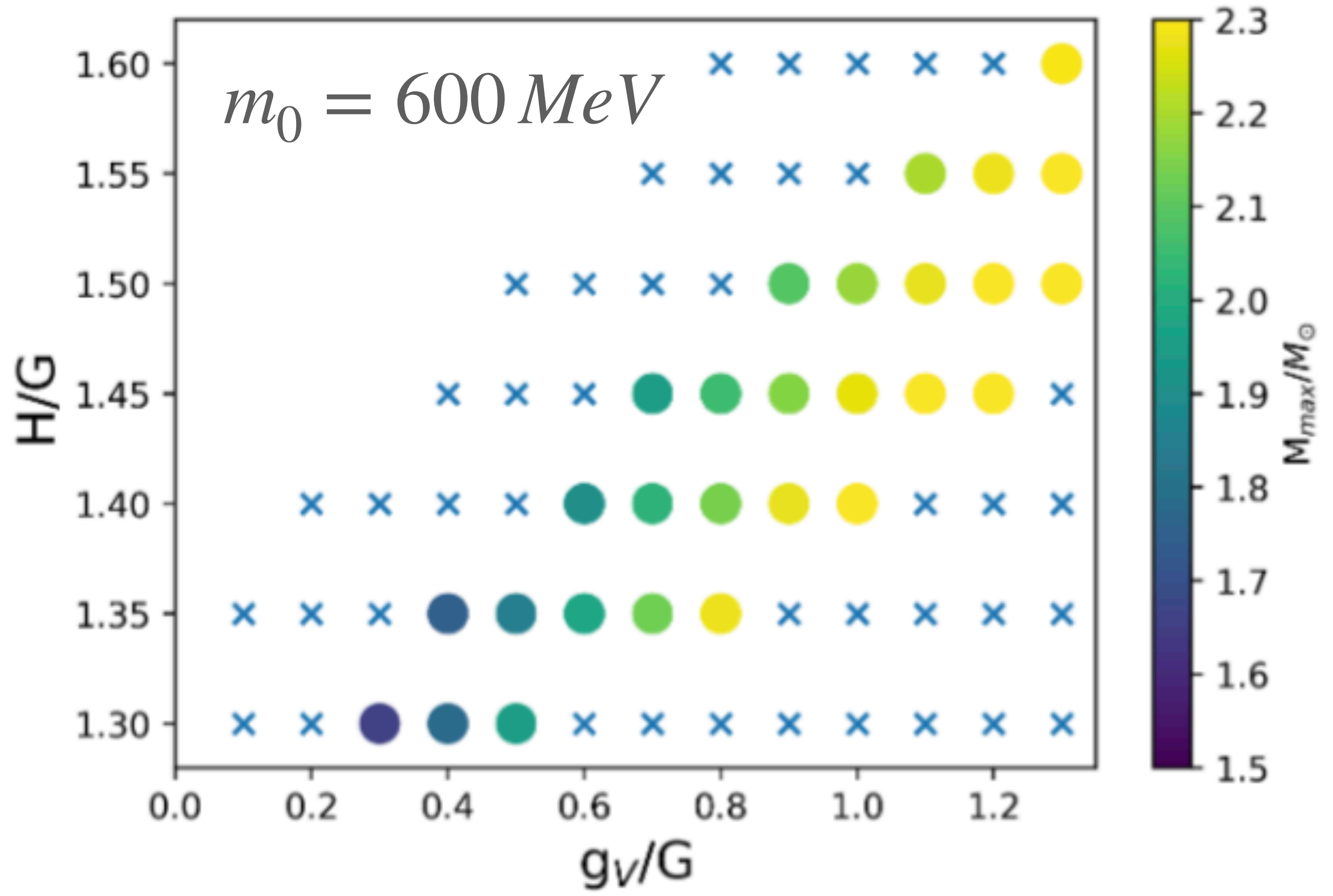
Results

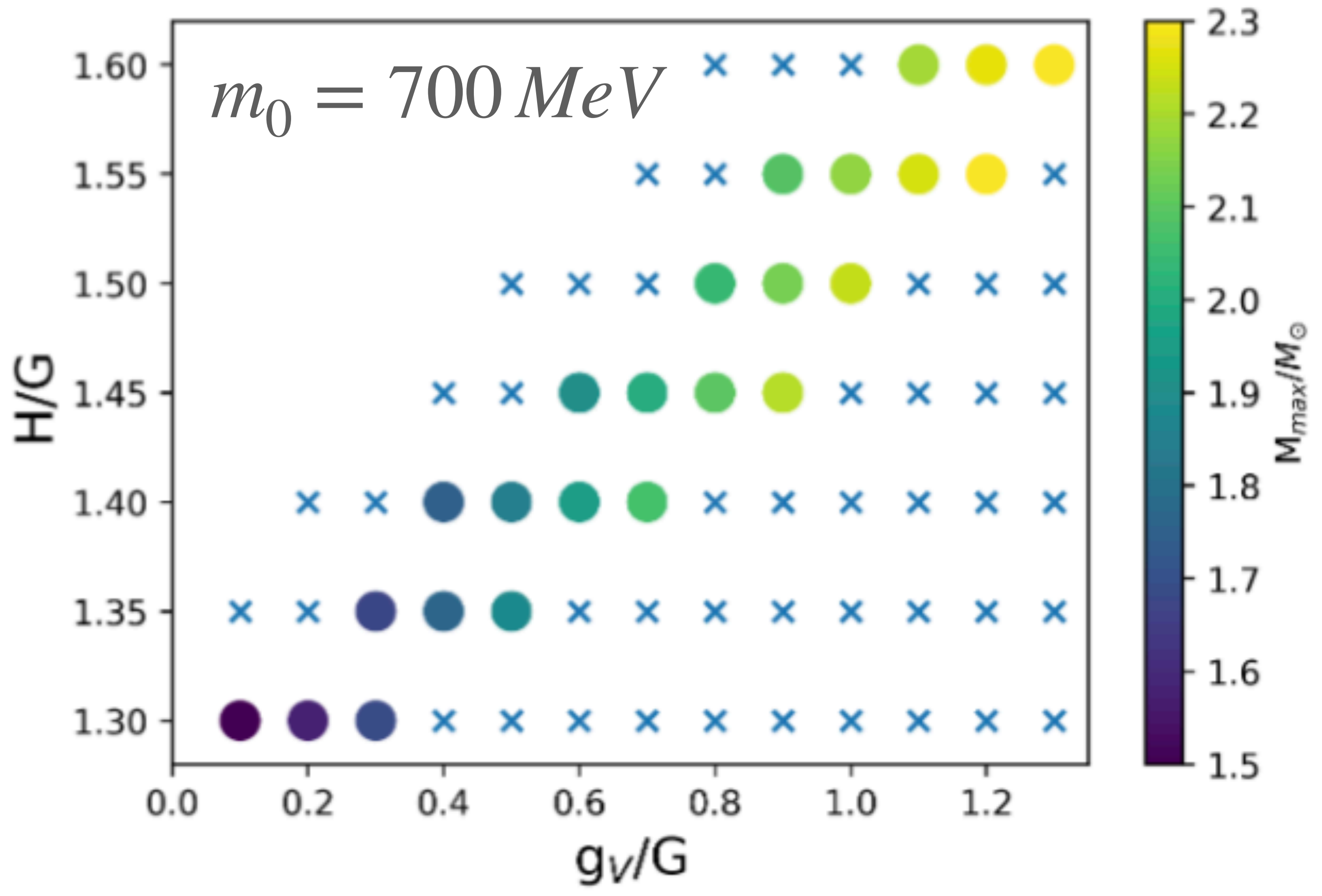
H: coupling for diquark condensates

gV: coupling for vector (repulsive) interaction

Slope parameter L =40 MeV







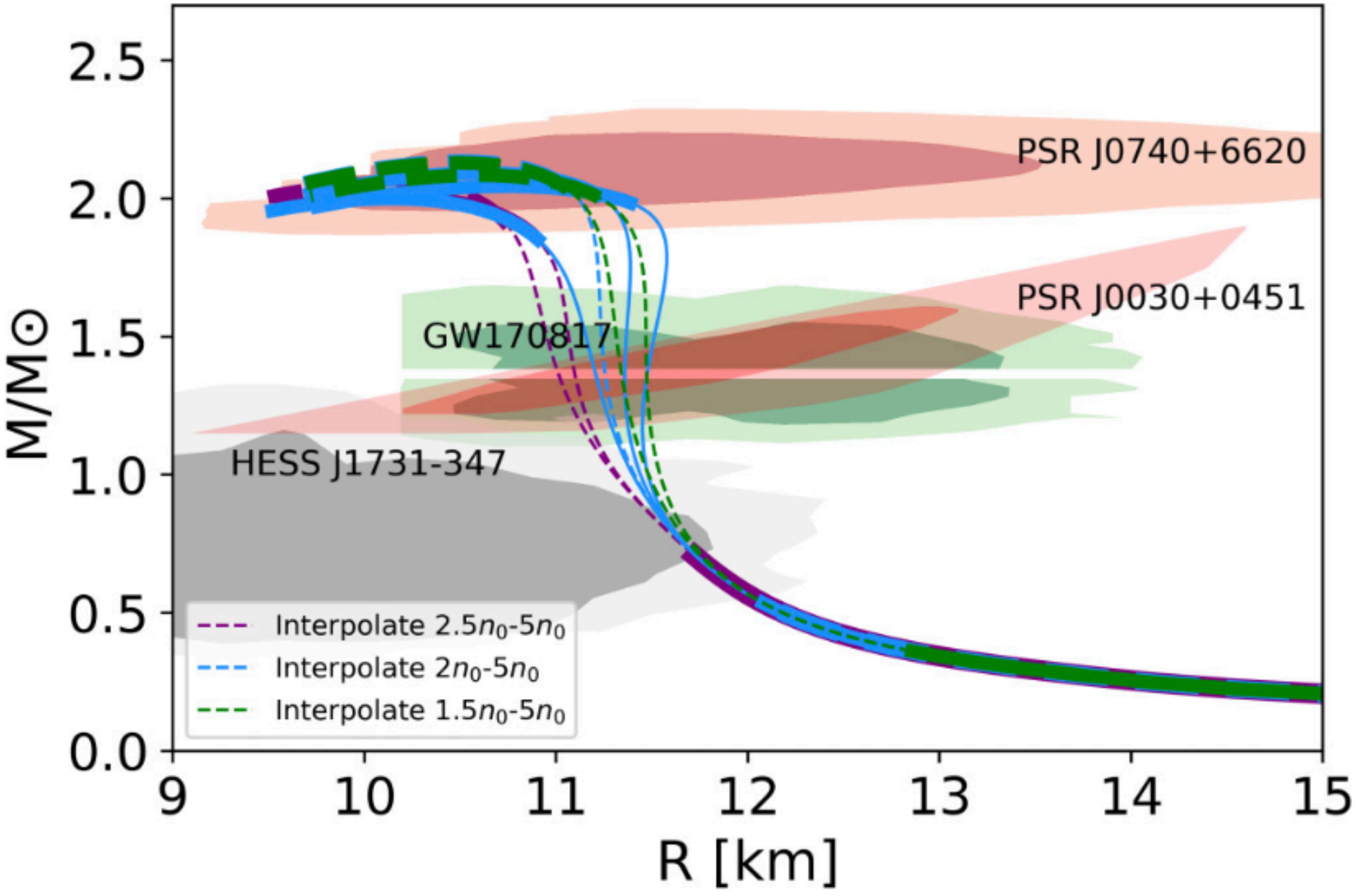
(m_0, L) ⟷ (H,gV)

constrain each other

Causality + Mmax

Results

$m_0 = 850\ \text{MeV}, L = 40\ \text{MeV}$



Check for the ambiguity from the interpolation range:

At $M \sim 1M_\odot$

Radius only change around 0.3 km

At $M \sim 1.4M_\odot$

Radius only change around 0.6 km

Our approach is robust!

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

Thank you for your attention!