IEAP CTU in Prague

RAGTIME

25TH RELATIVISTIC ASTROPHYSICS GROUP MEETING

Constraints for the X17 boson from compact objects observations

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Dr. Vlasios Petousis

Institute of Experimental and Applied Physics (IEAP)
Czech Technical University in Prague (CTU)

vlasios.petousis@cvut.cz

Outline

1. Motivation
2. Equation of States (EoS's)
   Nuclear Theories - Models
   i. Relativistic Mean Field (RMF) theory
   ii. Momentum Dependent Interaction (MDI) model
   iii. Color Flavor Locked (CFL) model for Quark Stars (QS's)
3. Concluding remarks
4. Collaborators

Motivation

We wanted to investigate the hypothetical X17 boson on:

a) Neutron Stars
b) Quark Stars (QSs)

using various hadronic Equation of States (EoS's) with phenomenological or microscopic origin.

Special attention on two main phenomenological parameters of the X17 boson:

a) The coupling constant **g** that it has with hadrons or quarks
b) The in-medium effects regulator **C**

To set realistic constraints with respect to:

a) Causality
b) Various (possible) upper mass limits
c) Dimensionless tidal deformability

Motivation

Non-Newtonian Gravity model

$$V(r) = -\frac{Gm_1m_2}{r}\left(1 + \alpha_G e^{-r/\lambda}\right) = V_N(r) + V_Y(r)$$

$$\alpha_G = \pm\frac{g^2\hbar c}{4\pi G m_b^2}, \qquad \lambda = \frac{\hbar}{\mu c}$$

g^2/μ^2

λ represents the range of the Yukawa force mediated by the exchange of a boson with mass **μ**

± sign refers to **scalar(+)** and **vector(-)** boson
g is the boson-baryon coupling constant
m_b is the baryon mass

Y. Fujii, "Dilaton and Possible Non-Newtonian Gravity", Nature Physics Science, 234, 5 (1972).
doi: 10.1038/physci234005a0

Weakly Interacting Light Boson (WILB)

- Theories BSM include a number of new particles, some of which might be light and weakly coupled to ordinary matter.
- Such particles affect the EoS's of nuclear matter and can shift admissible masses of neutron stars to higher values.
- Then the internal structure of neutron stars is modified provided the ratio between coupling strength and mass squared of a weakly interacting light boson (WILB)

M.I. Krivoruchenko, F. Simkovic, and Amand Faessler, "Constraints for weakly interacting light bosons from existence of massive neutron stars", Phys. Rev. D 79, 125023 (2009).
doi: 10.1103/PhysRevD.79.125023

Equation of States (EoS's) and in-medium scaling

$$\mathcal{E} = \frac{(\hbar c)^3 g_v^2}{2(m_v c^2)^2} n_b^2 + \frac{(\hbar c)^3 (\frac{g_\rho}{2})^2}{2(m_\rho c^2)^2} \rho_I^2 + \frac{(m_s c^2)^2}{2 g_s^2 (\hbar c)^3} (m_b c^2 - m_b^* c^2)^2 + \frac{\kappa}{6 g_s^3} (m_b c^2 - m_b^* c^2)^3 + \frac{\lambda}{24 g_s^4} (m_b c^2 - m_b^* c^2)^4 + \sum_{i=n,p} \frac{\gamma}{(2\pi)^3} \int_0^{k_{Fi}} 4\pi k^2 \sqrt{(\hbar c k)^2 + (m_i^* c^2)^2} dk \quad (1)$$

$$P = \frac{(\hbar c)^3 g_v^2}{2(m_v c^2)^2} n_b^2 + \frac{(\hbar c)^3 (\frac{g_\rho}{2})^2}{2(m_\rho c^2)^2} \rho_I^2 - \frac{(m_s c^2)^2}{2 g_s^2 (\hbar c)^3} (m_b c^2 - m_b^* c^2)^2 + \frac{\kappa}{6 g_s^3} (m_b c^2 - m_b^* c^2)^3 + \frac{\lambda}{24 g_s^4} (m_b c^2 - m_b^* c^2)^4 + \sum_{i=n,p} \frac{1}{3} \frac{\gamma}{(2\pi)^3} \int_0^{k_{Fi}} \frac{4\pi k^2}{\sqrt{(\hbar c k)^2 + (m_i^* c^2)^2}} dk \quad (2)$$

$$m_v^{*2} = a_X^2 m_X^2 + (1 - a_X)^2 m_\omega^2 \quad (3)$$

RMF Theory (1–3)

$$\mathcal{E}(u, I) = \frac{3}{10} E_F^0 n_0 \left[(1+I)^{5/3} + (1-I)^{5/3}\right] u^{5/3} + \frac{1}{3} \mathcal{A} n_0 \left[\frac{3}{2} - \left(\frac{1}{2} + x_0\right) I^2\right] u^2 + \frac{\frac{2}{3} \mathcal{B} n_0 \left[\frac{3}{2} - \left(\frac{1}{2} + x_3\right) I^2\right] u^{\sigma+1}}{1 + \frac{2}{3} \mathcal{B}' n_0 \left[\frac{3}{2} - \left(\frac{1}{2} + x_3\right) I^2\right] u^{\sigma-1}} + u \sum_{i=1,2} \left[C_i (\mathcal{J}_n^i + \mathcal{J}_p^i) + \frac{(C_i - 8 Z_i)}{5} I (\mathcal{J}_n^i - \mathcal{J}_p^i) \right] \quad (6) \quad (4)$$

MDI model (4)

The energy density and the pressure of the **WILB** (**$\mu \equiv m_B$**) in neutron star matter are given by:

$$\mathcal{E}_B = \pm \frac{(\hbar c)^3}{2} \left(\frac{g}{m_B c^2}\right)^2 n_b^2 \quad (5)$$

$$P_B = \frac{(\hbar c)^3}{2} \left(\frac{g}{m_B c^2}\right)^2 n_b^2 \left(1 - \frac{2 n_b}{m_B c^2} \frac{\partial (m_B c^2)}{\partial n_b}\right) \quad (6)$$

$$\mathcal{E} = \mathcal{E}_{\rm bar} \pm \mathcal{E}_B, \quad P = P_{\rm bar} \pm P_B \quad (7)$$

According to Brown & Rho, the in-medium modification follows the linear scaling:

$$m_B^* \equiv m_B \left(1 - C \frac{n_b}{n_0}\right) \ (\mathrm{MeV}) \quad (8)$$

We consider that the coupling **g** varies in the interval [10^{-3} - 2.2×10^{-2}] which corresponds (for 17 MeV) to the interval for **g^2/m_B^2** → [3.5×10^{-3} - 1.7] GeV^{-2}

G. E. Brown and M. Rho, "Double decimation and sliding vacua in the nuclear many-body system", Phys. Rep. 396, 1 (2004). doi: 10.1016/j.physrep.2004.02.002

Equation of States (EoS's) for Quark Stars

Color - Flavor Locked (CFL) model for Quark Stars

$$P_Q = \frac{3\mu^4}{4\pi^2(\hbar c)^3} - \frac{3(m_s c^2)^2\mu^2}{4\pi^2(\hbar c)^3} + \frac{3\Delta^2\mu^2}{\pi^2(\hbar c)^3} - B \quad (9)$$

$$\mathcal{E}_Q = \frac{9\mu^4}{4\pi^2(\hbar c)^3} - \frac{3(m_s c^2)^2\mu^2}{4\pi^2(\hbar c)^3} + \frac{3\Delta^2\mu^2}{\pi^2(\hbar c)^3} + B \quad (10)$$

$$n_b = \frac{\mu^3}{\pi^2(\hbar c)^3} - \frac{(m_s c^2)^2\mu}{2\pi^2(\hbar c)^3} + \frac{2\Delta^2\mu}{\pi^2(\hbar c)^3} = \frac{\mu^3}{\pi^2(\hbar c)^3} + \frac{3\mu\alpha}{\pi^2(\hbar c)^3} \quad (11)$$

$$\mu^2 = -3\alpha + \sqrt{9\alpha^2 + \frac{4}{3}\pi^2(P_Q + B)(\hbar c)^3} \quad (12)$$

$$\alpha = -\frac{(m_s c^2)^2}{6} + \frac{2\Delta^2}{3} \quad (13)$$

$$\mathcal{E}_B = \pm\frac{9(\hbar c)^3}{2}\left(\frac{g}{m_B c^2}\right)^2 n_b^2 \quad (14)$$

$$\mathcal{E} = \mathcal{E}_Q \pm \mathcal{E}_B, \quad P = P_Q \pm P_B \quad (15)$$

G. Lugones and J.E. Horvath,"Color-flavor locked strange matter", Phys.Rev. D 66, 074017, (2002). doi:10.1103/PhysRevD.66.074017

Z. Roupas, G. Panotopoulos, I. Lopes, "QCD color superconductivity in compact stars: Color-flavor locked quark star candidate for the gravitational-wave signal GW190814", Phys. Rev. D 103, 083015 (2021). doi: 10.1103/PhysRevD.103.083015

Shu-Hua Yang, Chun-Mei Pi, Xiao-Ping Zheng, and Fridolin Weber, "Constraints from compact star observations on non-Newtonian gravity in strange stars based on a density dependent quark mass model", Phys. Rev. D 103, 043012 (2021). doi: 10.1103/PhysRevD.103.043012

Shu-Hua Yang, Chun-Mei Pi, Xiao-Ping. Zheng, and F. Weber, "Confronting Strange Stars with Compact-Star Observations and New Physics", Universe 9, 202, (2023). doi: 10.3390/universe9050202

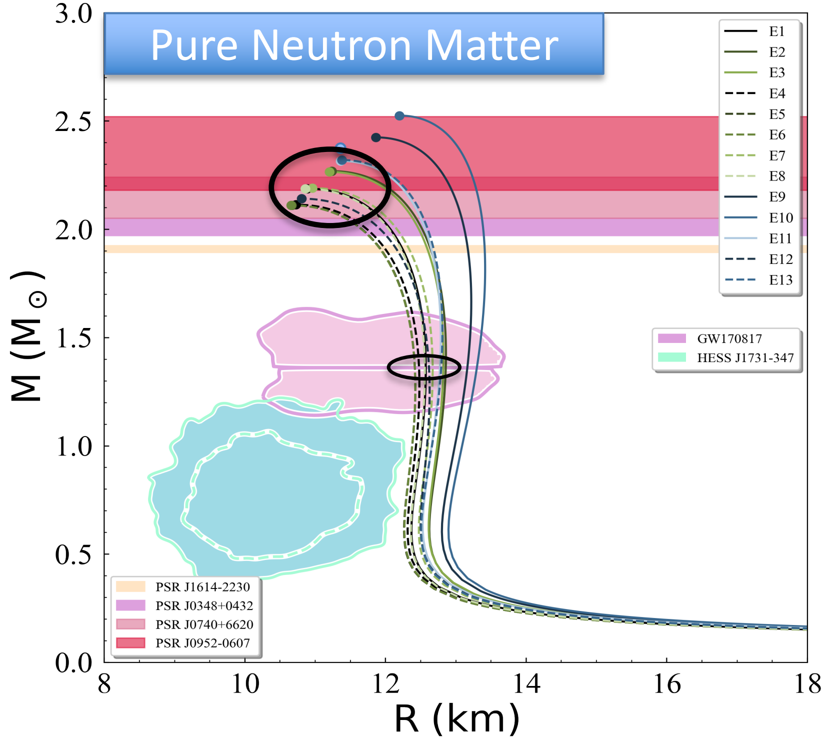
Nuclear Models – RMF theory

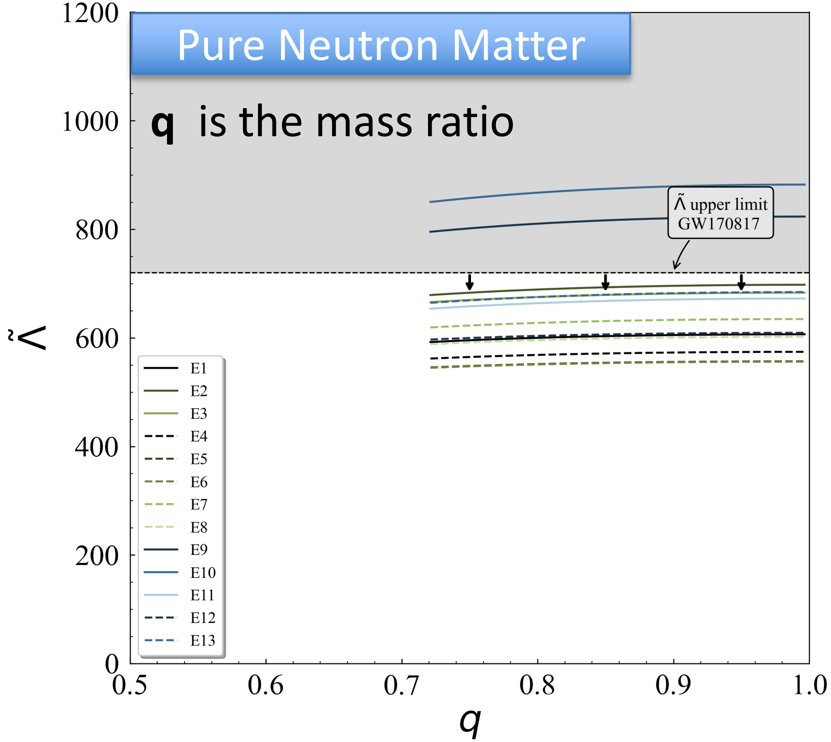
EoS	g_ρ^*	g_v	g_s	$m_s[MeV]$	κ[MeV]	λ
E1	+5%	7.61	6.78	406.6	19.0	-60.0
E2	+5%	8.00	6.76	391.4	17.0	-63.3
E3	+5%	8.00	7.03	405.6	19.5	-80.0
E4	+10%	7.23	7.27	451.9	25.0	-33.3
E5	+10%	7.23	7.27	451.9	25.5	-46.7
E6	+10%	7.23	7.51	467.0	28.5	-56.7
E7	+10%	7.61	7.03	421.7	21.0	-60.0
E8	+10%	7.61	7.03	421.7	21.5	-73.3

α_x = 20%
m^*_v = 626 MeV

EoS	g_ρ^*	g_v	g_s	m_s[MeV]	κ[MeV]	λ
E9	+5%	7.61	8.08	451.9	19.0	-103.3
E10	+5%	8.00	8.35	451.9	18.5	-123.3
E11	+5%	7.23	8.33	482.2	26.0	-150.0
E12	+10%	6.47	5.77	346.1	14.5	-33.3
E13	+10%	7.23	8.07	467.0	23.0	-123.3

α_x = 30%
m^*_v = 547.8 MeV





Nuclear Models – RMF theory

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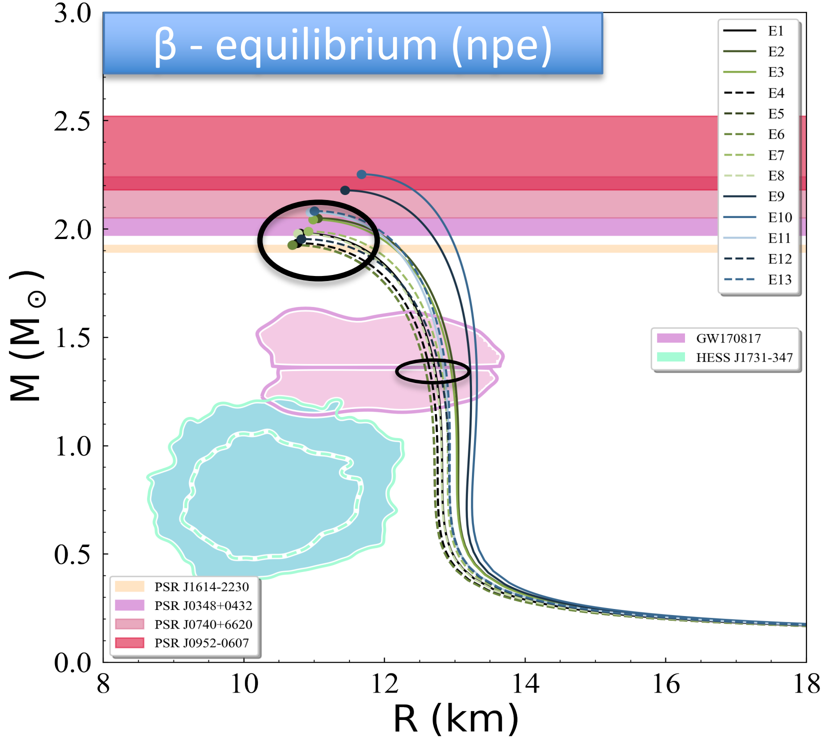
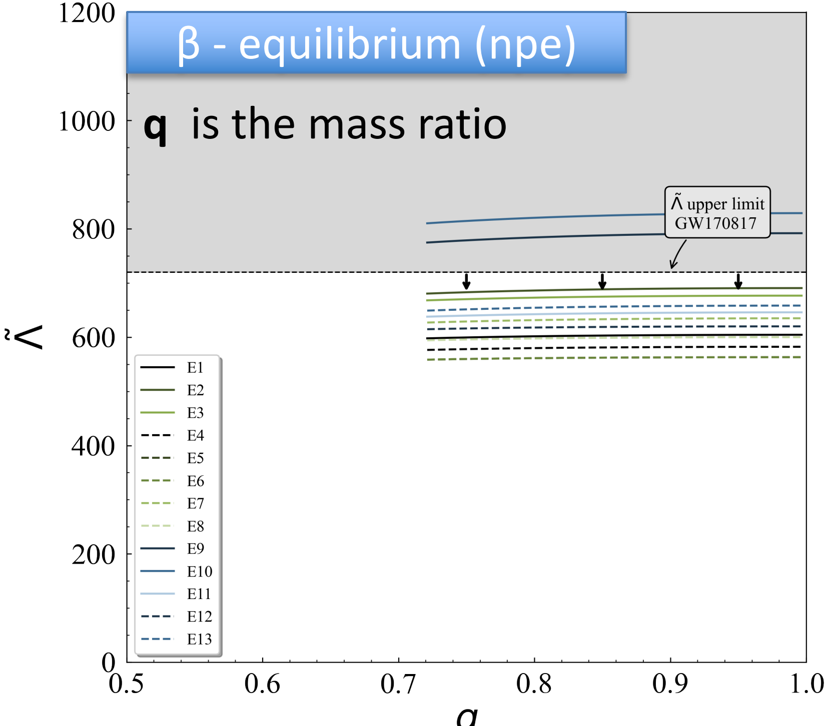
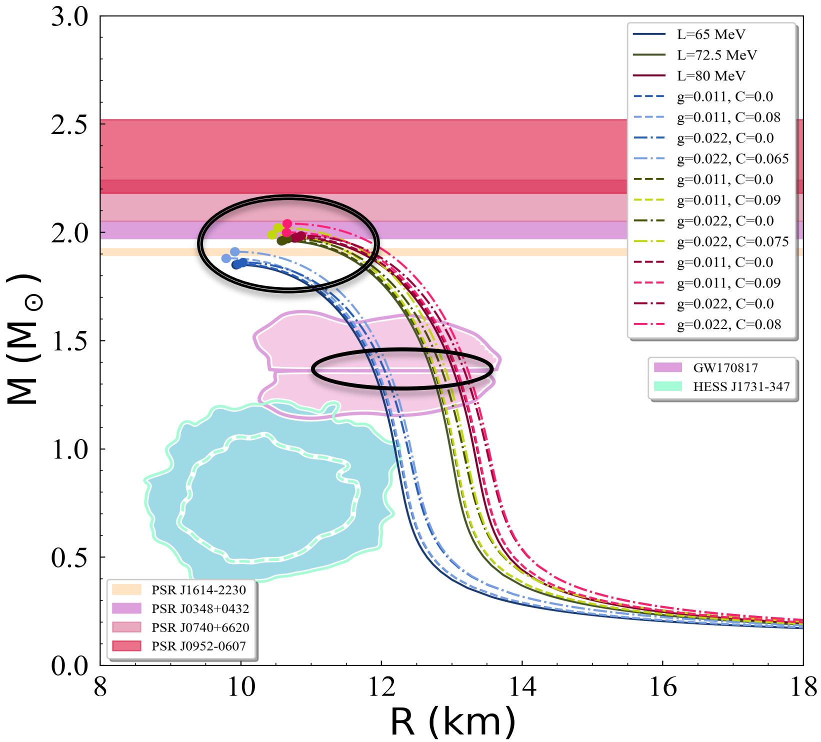


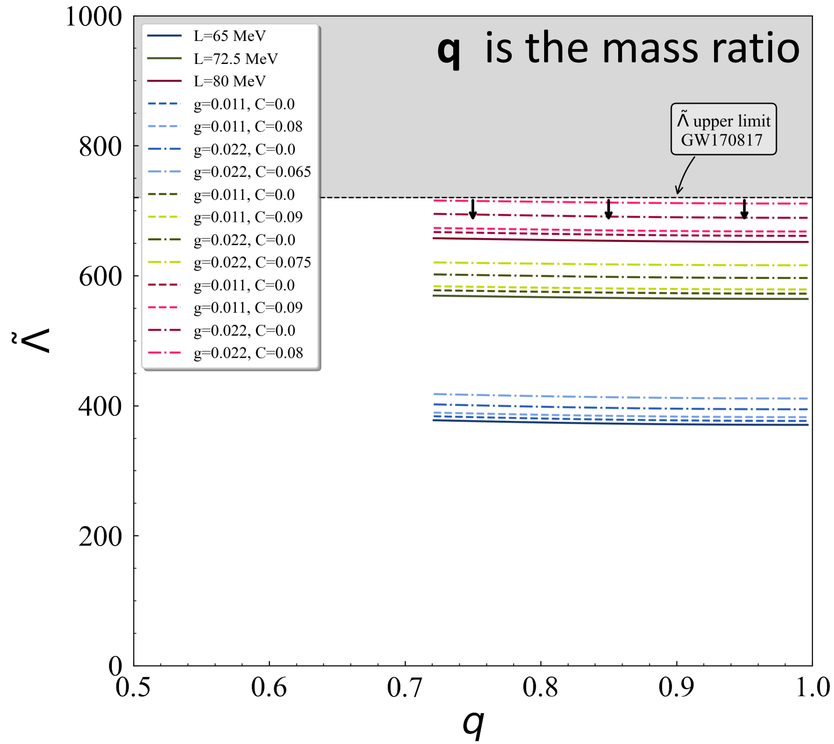


Nuclear Models – MDI model

- Solid curves correspond to the 3 initial EoS's without the X17 boson
- Dashed and dash-dotted curves correspond to the EoS's with the X17 boson for **g = 0.011** and **g = 0.022**
- All combinations resulting Max mass < 2 Solar Masses and in a good agreement with LIGO/VIRGO data

L => slope parameter of nuclear symmetry energy

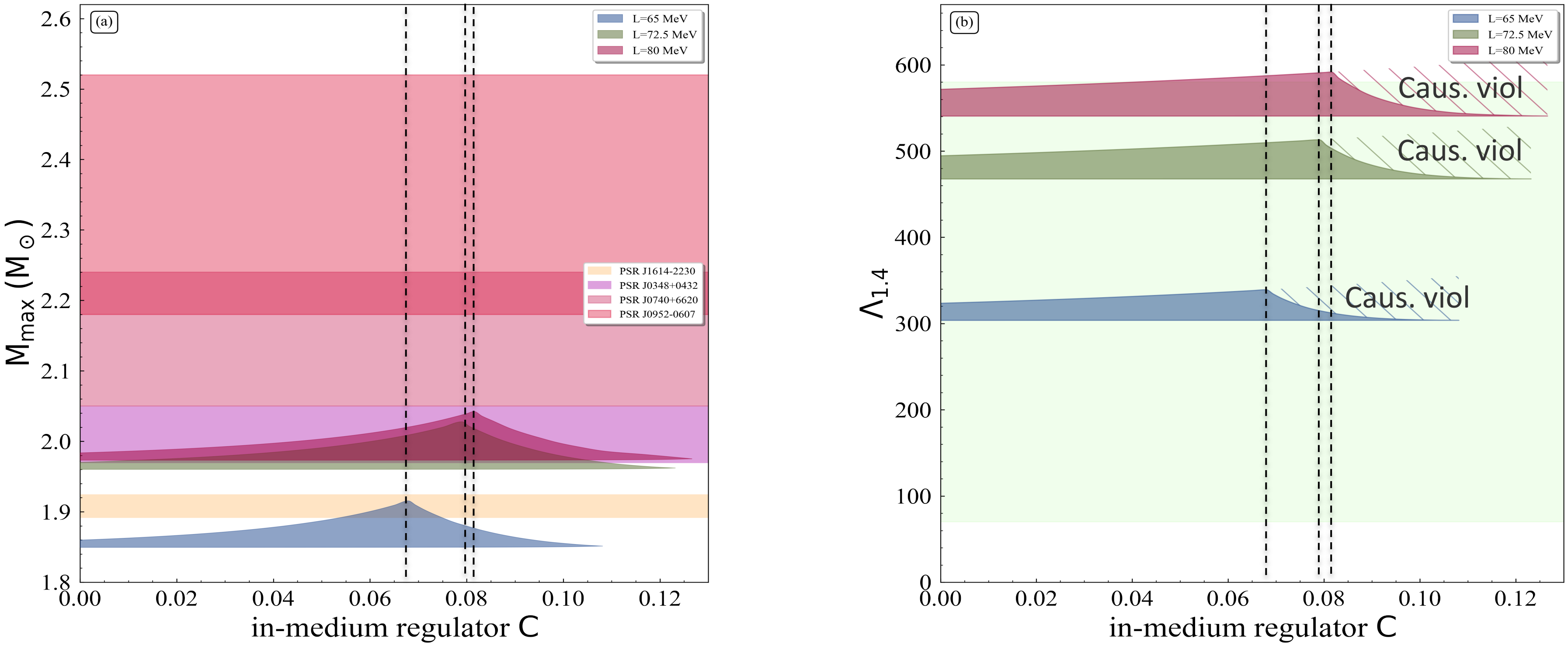




Nuclear Models – MDI model

- The **"shark-fin"** shaded region arises from the constraints that the non-violation of causality implies on the C_{max}
- The peaks corresponding to the pair of values for each one of the 3 set EoS's (**g = 0.022** and **$C = C_{max}$**)

L is the slope parameter of nuclear symmetry energy



Nuclear Models – MDI model

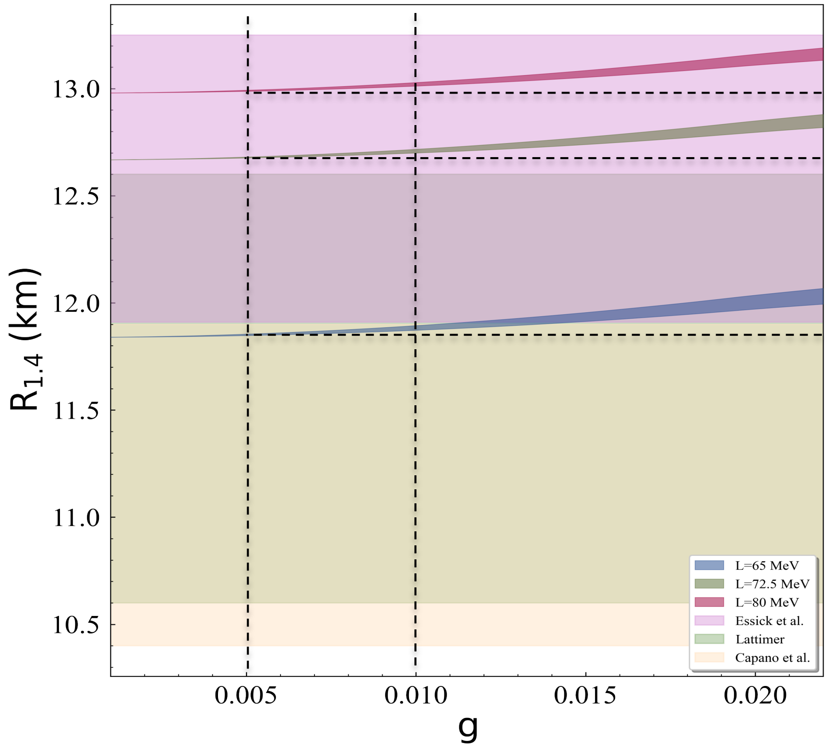
Region constraints and non-violation of causality:

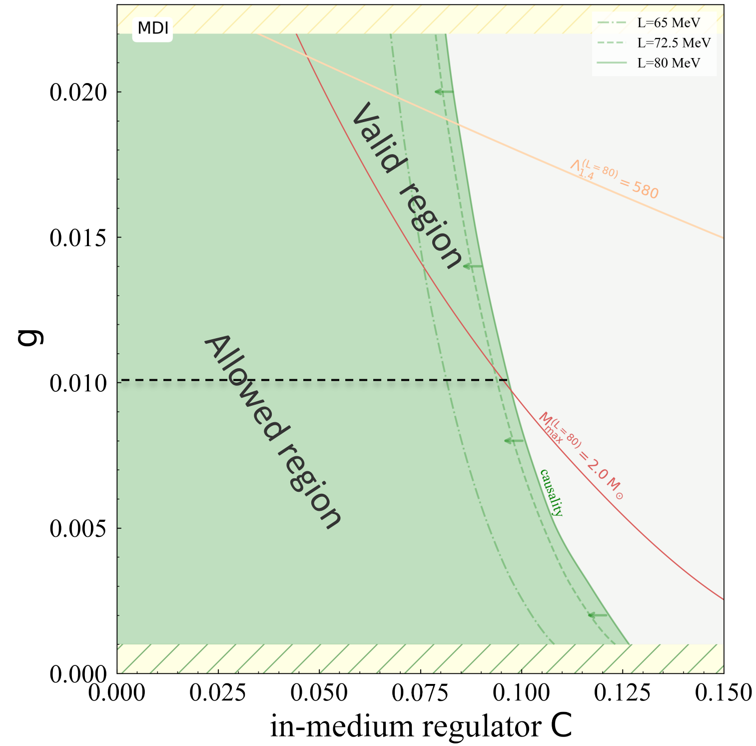
- Shaded thin inclined curves represent regions for 3 set EoS's
- The effect starts at **g > 0.005** continues **g > 0.010** (**$C = C_{max}$**)

Causality constraints for **g** and **C** for three EoS's:

- Possible upper mass limit 2 Solar masses

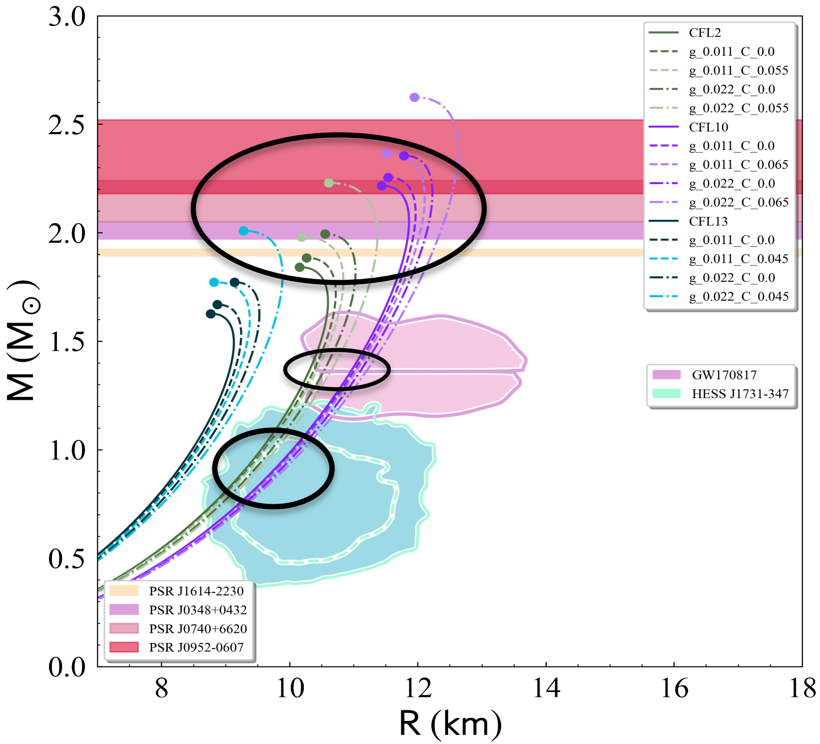
L is the slope parameter of nuclear symmetry energy

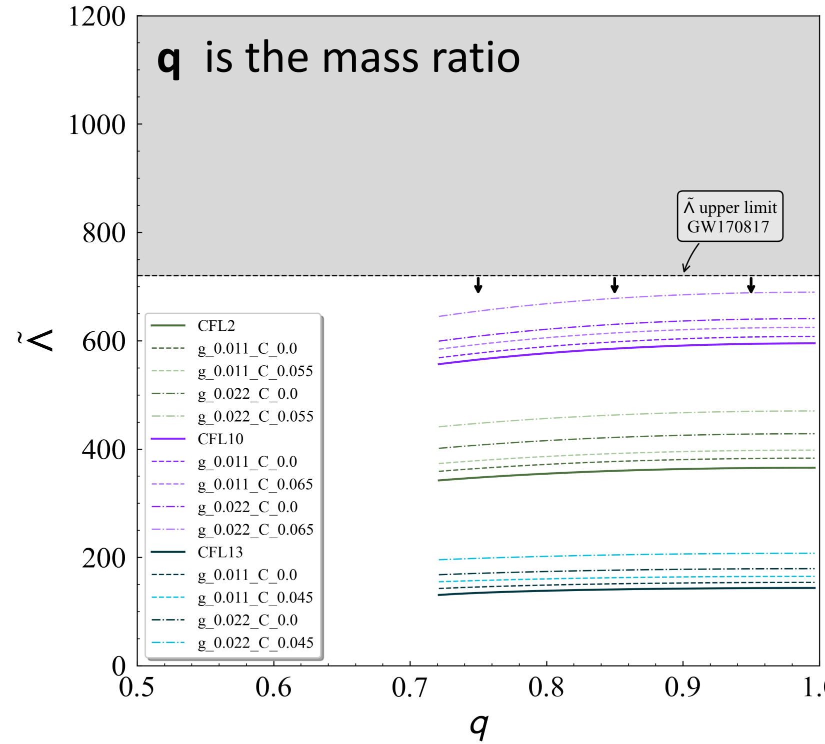




Color Flavor Locked (CFL) model - Quark Stars

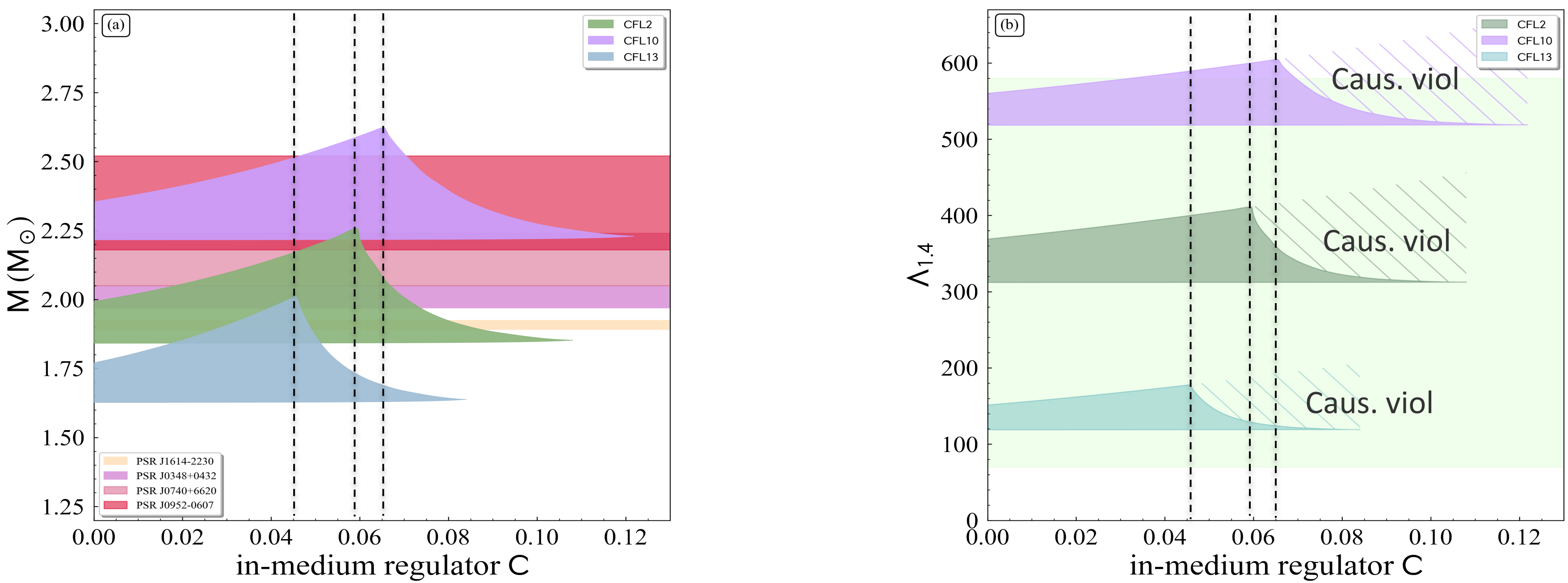
3 different parametrization sets of EoS's
- Soft (CFL13)
- Medium (CFL2)
- Stiff (CFL10)





Color Flavor Locked (CFL) model - Quark Stars

- The **"shark-fin"** shaded region arises from the constraints that the non-violation of causality implies on the C_{max}
- The peaks corresponding to the pair of values for each one of the 3 set EoS's (**g = 0.022** and **$C = C_{max}$**)



Color Flavor Locked (CFL) model - Quark Stars

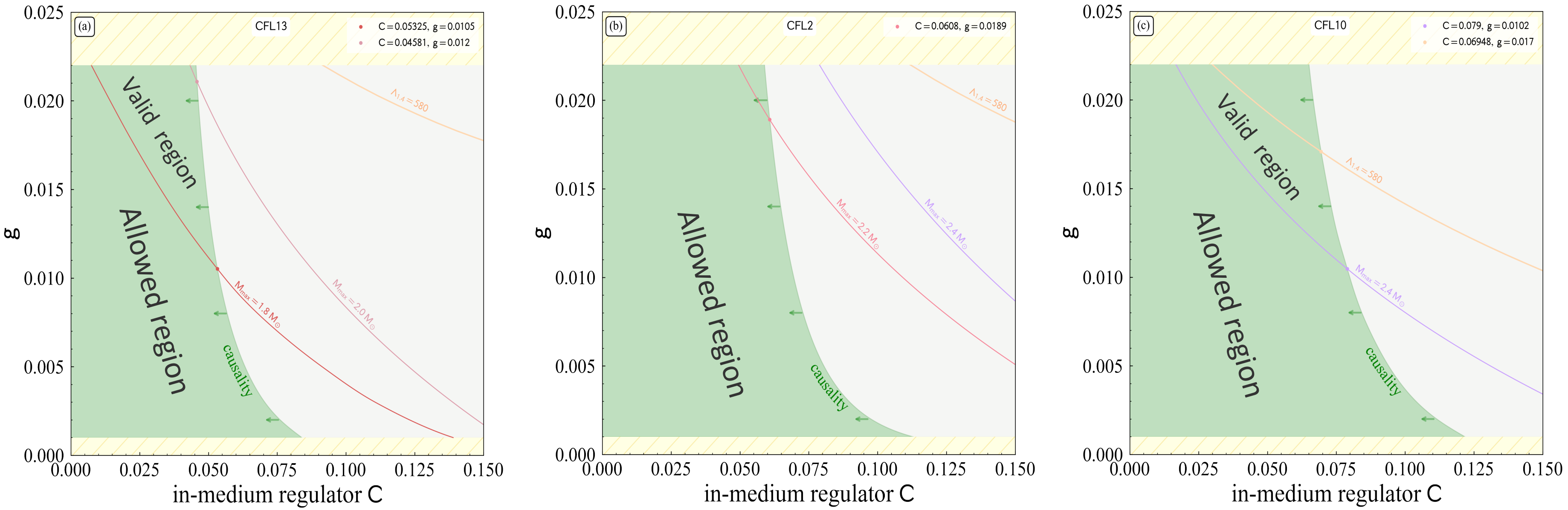
Causality constraints for **g** and **C** for three EoS's

- Possible mass limits:

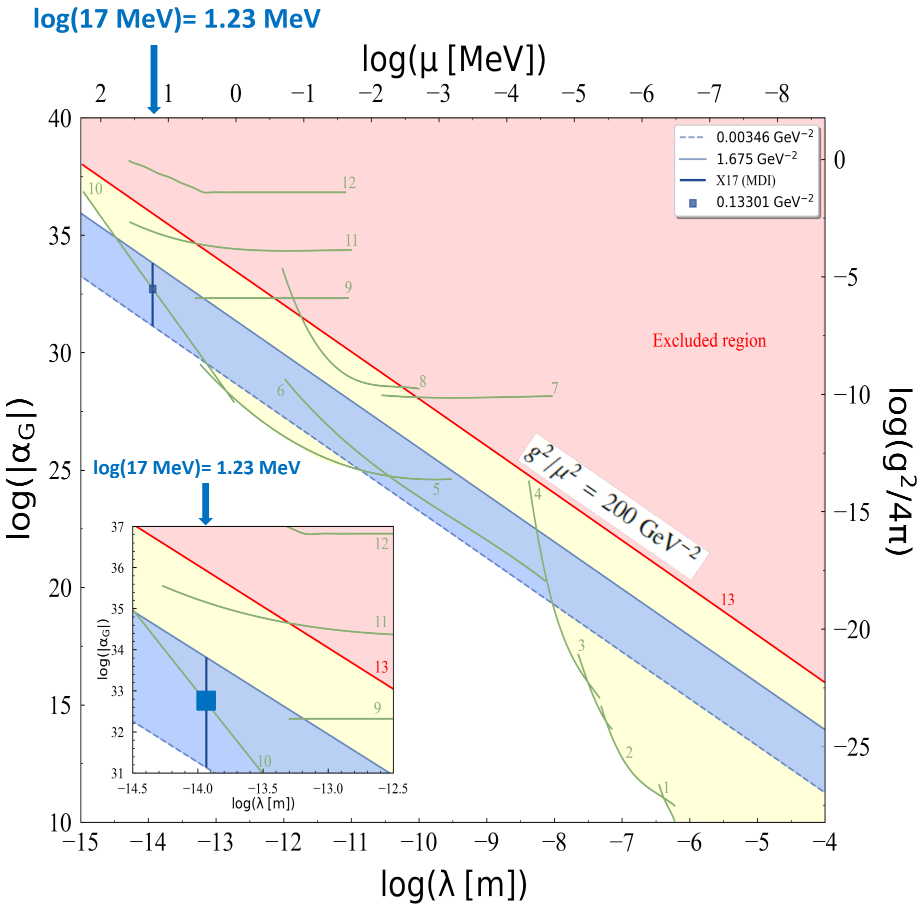
  1.8 Solar Masses (CFL13 Soft)

  2.2 Solar Masses (CFL2 Medium)

  2.4 Solar Masses (CFL10 Stiff)



Concluding Remarks (MDI model)



- Specific range for the X17 boson in the MDI model is shown with **blue vertical line** among constraints from different experiments.
- The **square blue dot** indicate the constraints on the X17 boson settled by the experiment of low-energy n - ^{208}Pb scattering (number 10).
- The extrapolation of our settled constraints to other masses indicated by the **blue-shaded band**.

Concluding Remarks

- We payed attention on two main phenomenological parameters of the hypothetical X17 boson:
  a) the coupling constant **g** of its interaction with hadrons or quarks
  b) the in-medium effects through a regulator **C**
- Extensive analysis concerning the contribution on the total energy density and pressure of combat objects.
- We suggested that it's possible to provide constraints on these parameters, with respect to causality, various possible upper mass limits and dimensionless tidal deformability.
- We found that stiffer is the EoS (hadronic or quark), the more indiscernible are the effects on the properties of compact objects.
- The effectiveness of the X17 boson in compact objects properties, is more sensitive on the coupling g than the regulator C
- The effects of the hypothetical X17 boson, are more pronounced, in the case of QSs, concerning all the bulk properties.
- It will be possible from both terrestrial and astrophysical observations, to make the best possible estimate of the properties concerning the WILB particles.

Collaborators

A. Kanakis-Pegios[1]
Ch. Moustakidis[1]
V. Petousis[2]
M. Veselsky[2]
J. Leja[3]

ARISTOTLE UNIVERSITY OF THESSALONIKI SCHOOL OF PHYSICS

IEAP CTU in Prague

STU SjF

(1) Department of Theoretical Physics, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
(2) Institute of Experimental and Applied Physics, Czech Technical University, Prague, 110 00, Czechia
(3) Faculty of Mechanical Engineering - Slovak University of Technology in Bratislava, Bratislava, 812 31, Slovakia

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Thank you