IEAP CTU in Prague

# Constraints for the X17 boson from compact objects observations

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# 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:

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

To set realistic constraints with respect to:

e) Causality
f) Various (possible) upper mass limits
g) Dimensionless tidal deformability

# Motivation

## Non-Newtonian Gravity model

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

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

$g^2/\mu^2$

**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

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

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

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

**RMF Theory**

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

**MDI model**

The energy density and the pressure of the **WILB** (**μ≡m$_B$**) in neutron star matter are given by:

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

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

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

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

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

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

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

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

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

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

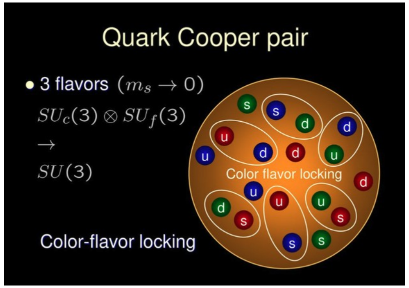
$$\alpha = -\frac{(m_s c^2)^2}{6} + \frac{2\Delta^2}{3} \quad (13)$$

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

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

In very high density, the mass of the strange quark is negligible compared to the baryonic chemical potential, leading to the same density of the three flavors of u,d and s quarks.


A. R. Bodmer, Phys. Rev. D 4, 1601 (1971)
E. Witten, Phys. Rev. D 30, 272 (1984)



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 | $g_\rho^*$ | $g_v$ | $g_s$ | $m_s[MeV]$ | $\kappa$[MeV] | $\lambda$ |
|---|---|---|---|---|---|---|
| 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 |

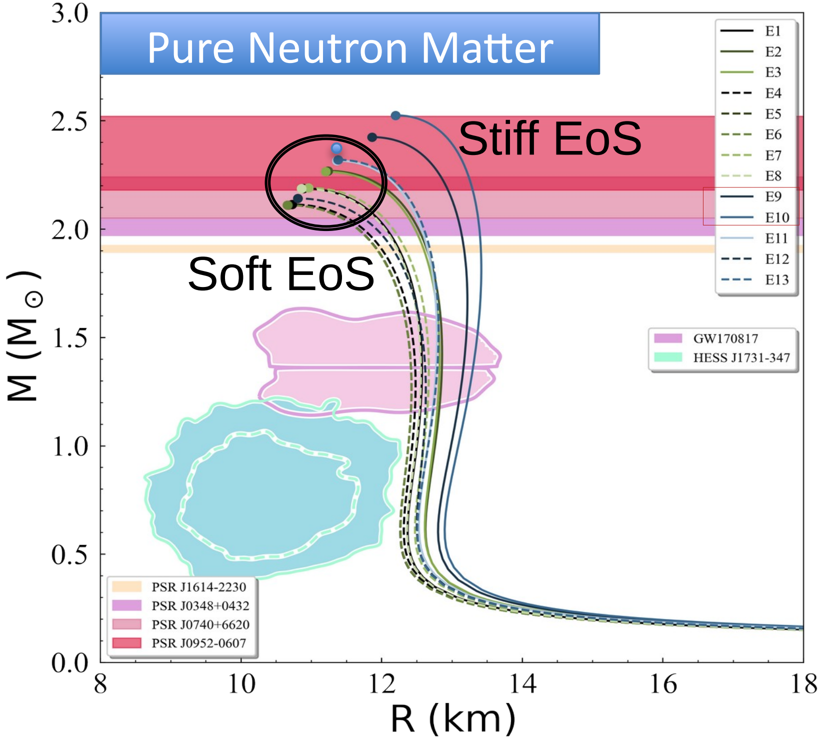
**Soft EoS**

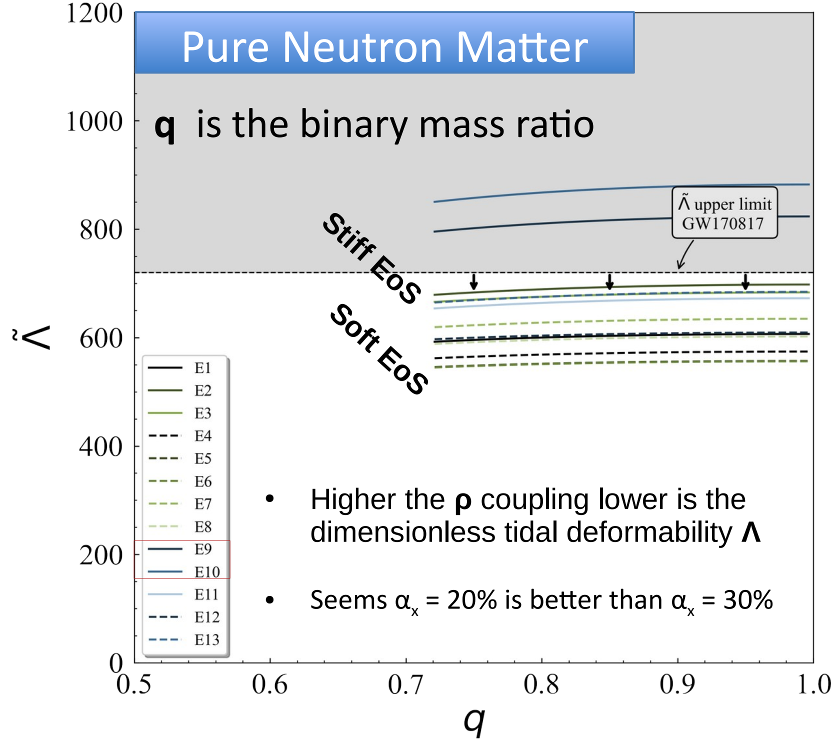
$\alpha_x$ = 20%
$m^*_v$ = 626 MeV

| EoS | $g_\rho^*$ | $g_v$ | $g_s$ | $m_s$[MeV] | $\kappa$[MeV] | $\lambda$ |
|---|---|---|---|---|---|---|
| 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 |

**Stiff EoS**

$\alpha_x$ = 30%
$m^*_v$ = 547.8 MeV




- Higher the **ρ** coupling lower is the dimensionless tidal deformability **Λ**
- Seems $\alpha_x$ = 20% is better than $\alpha_x$ = 30%

# Nuclear Models – RMF theory

| EoS | $g^*_\rho$ | $g_v$ | $g_s$ | $m_s[MeV]$ | $\kappa$[MeV] | $\lambda$ |
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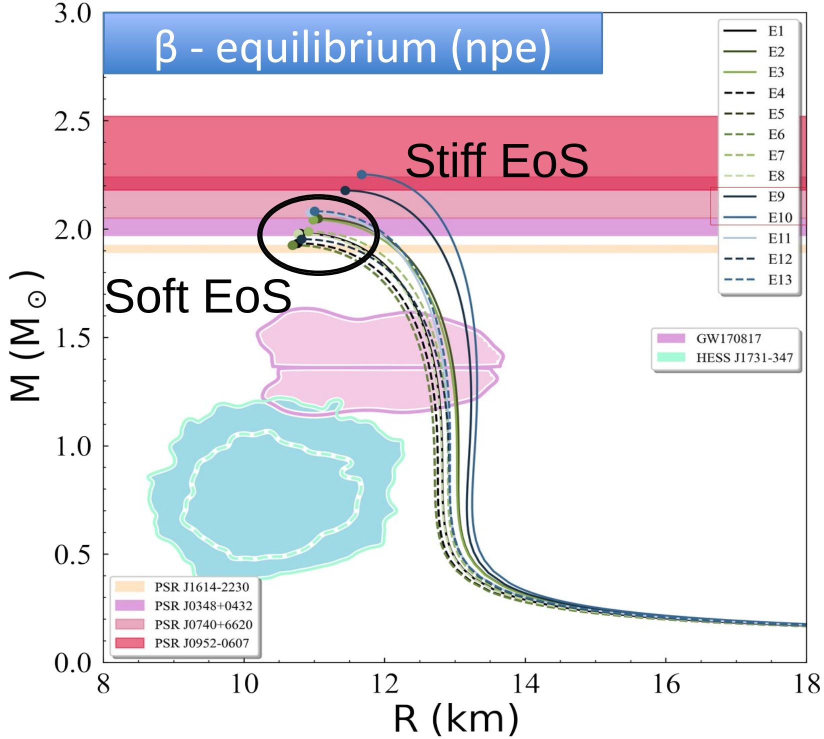
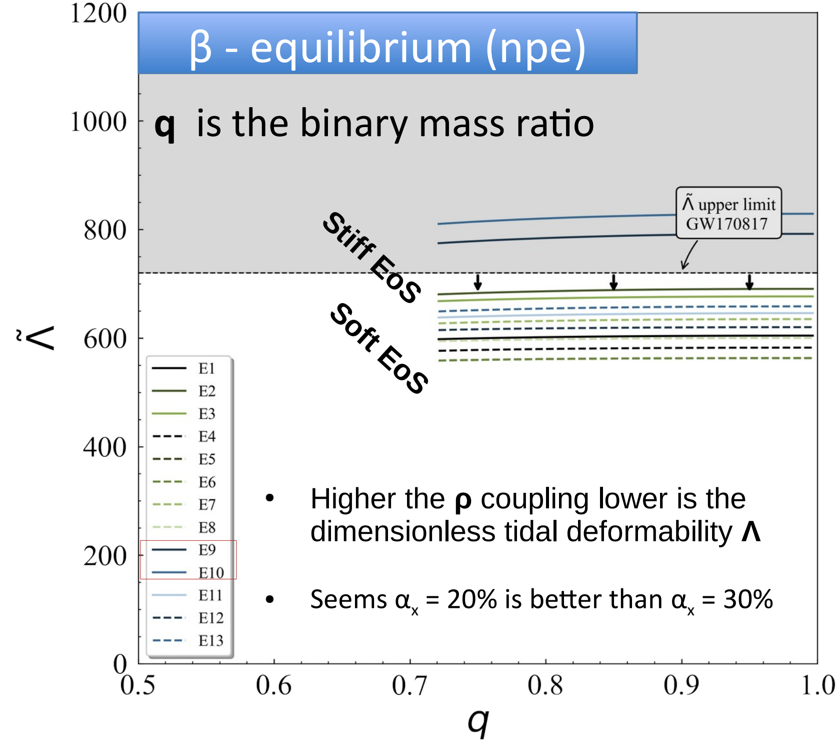
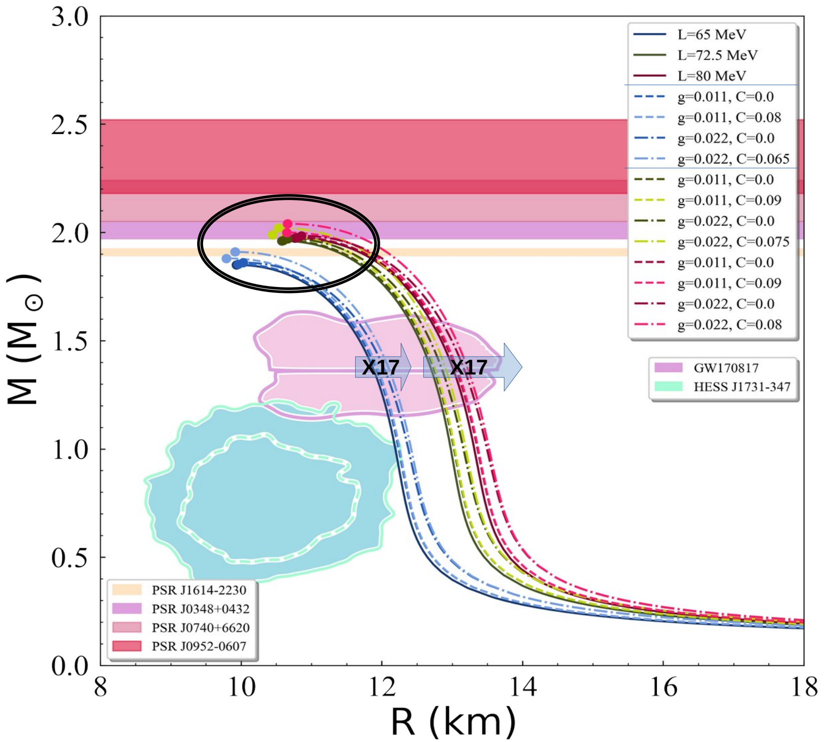


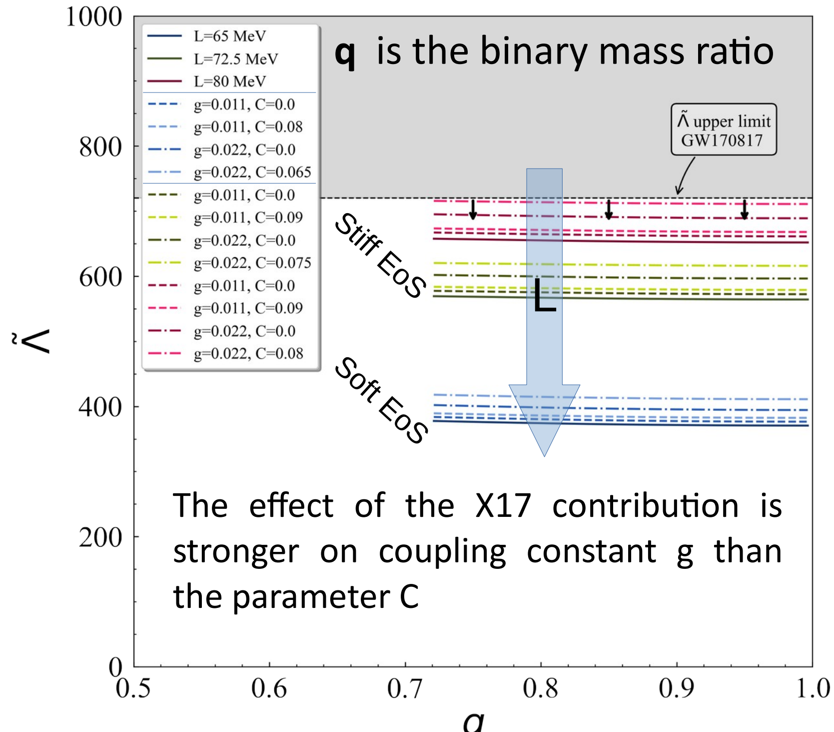



# Nuclear Models – MDI model

- 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

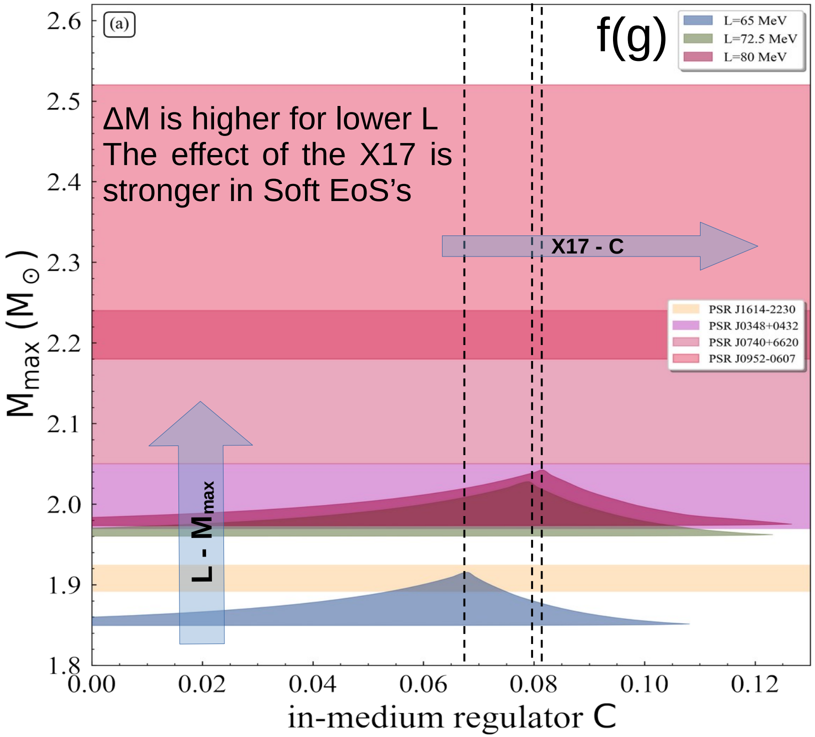


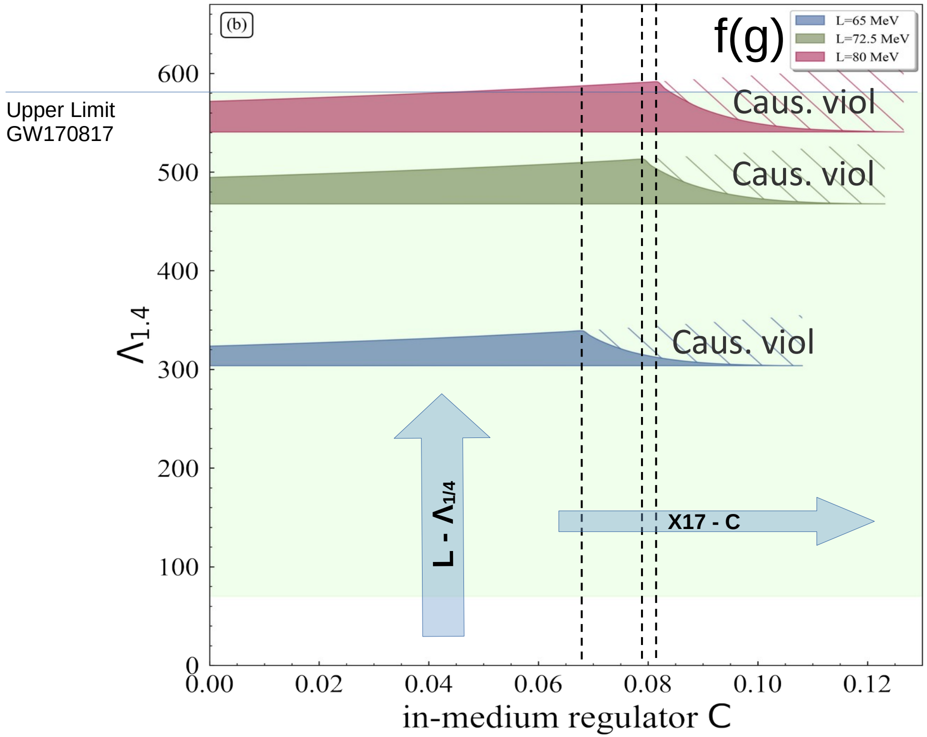



# Nuclear Models – MDI model

- 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 **$C = C_{max}$**) Hight X17 Contribution

**L** is the slope parameter of nuclear symmetry energy



# Nuclear Models – MDI model

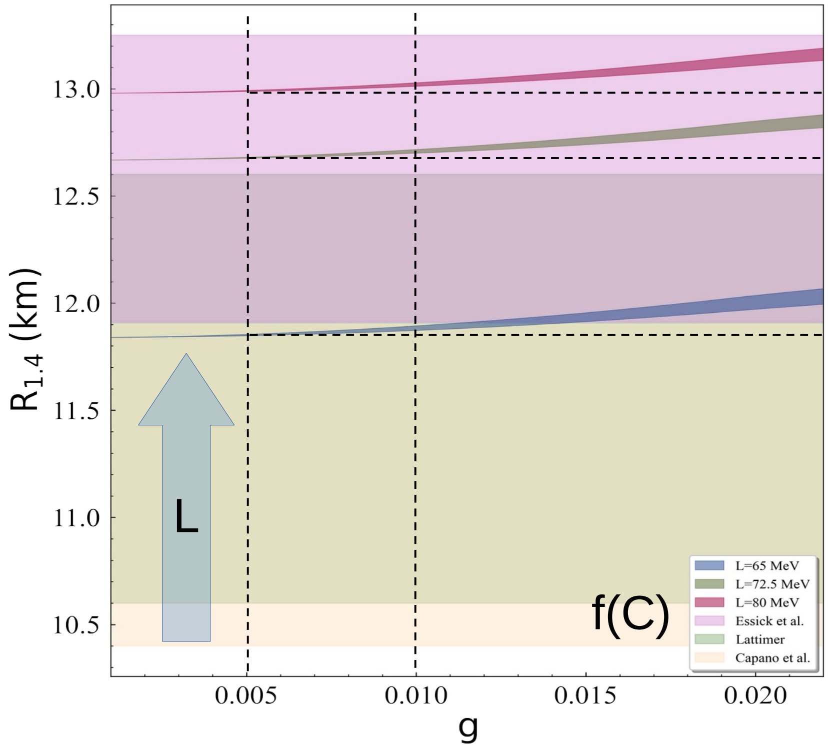
Region constraints and non-violation of causality:

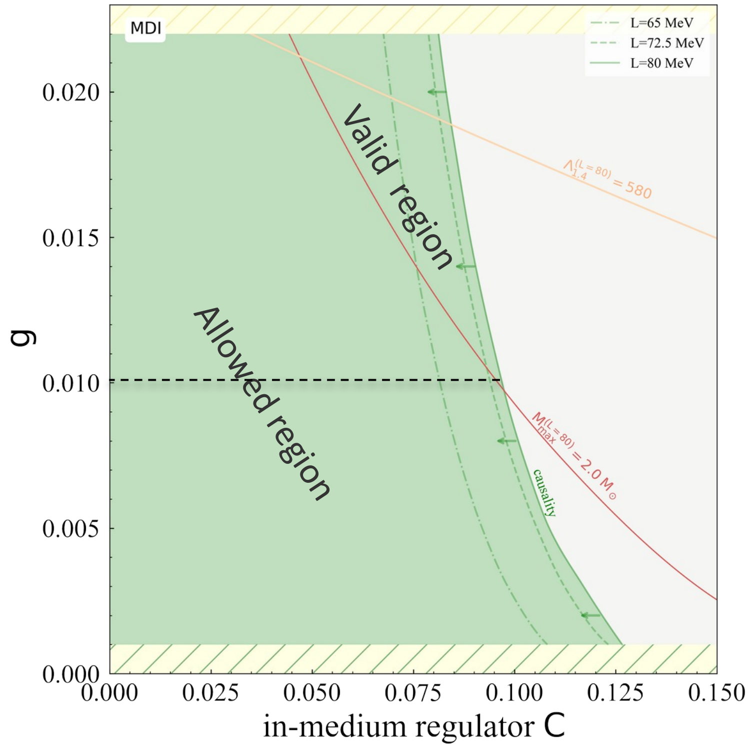
- Shaded thin inclined curves represent regions for 3 set EoS's
- The effect starts at **g > 0.005** continues **g > 0.010** (**C = $C_{max}$**)

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



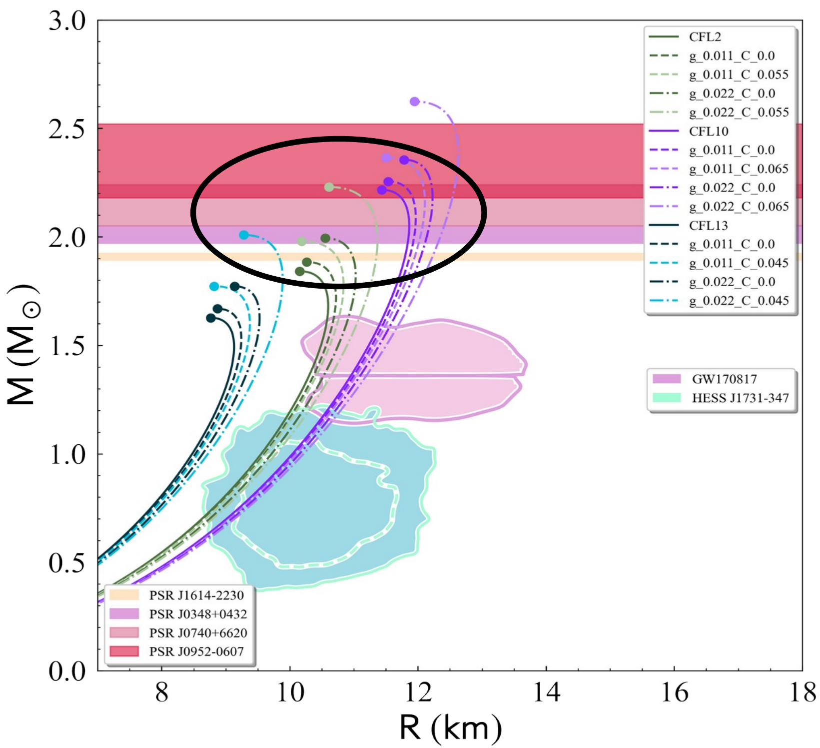



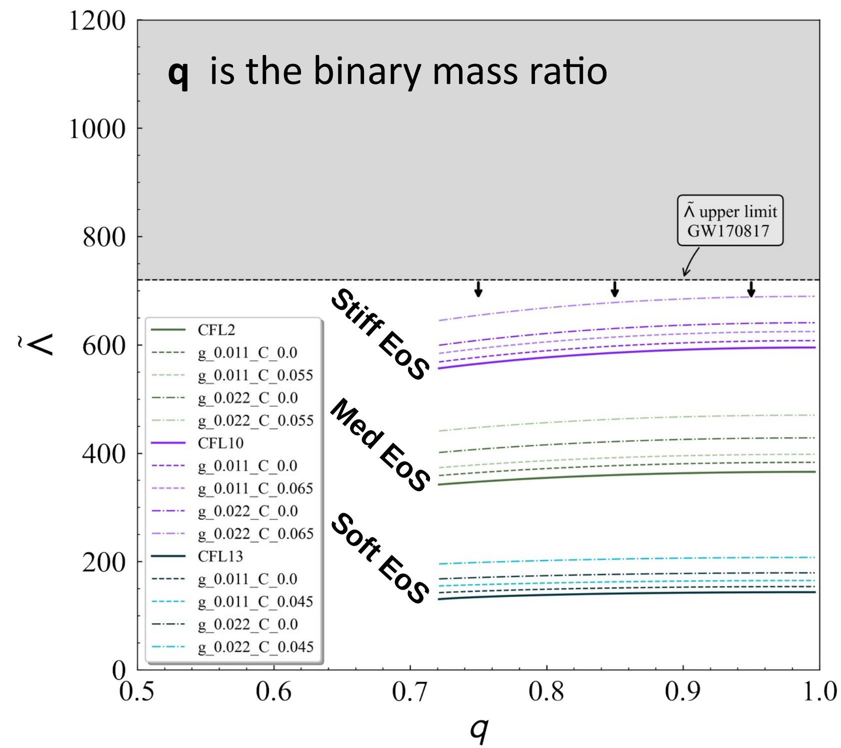
# Color Flavor Locked (CFL) model - Quark Stars

3 different parametrization sets of EoS's

- Soft (CFL13)
- Medium (CFL2)
- Stiff (CFL10)

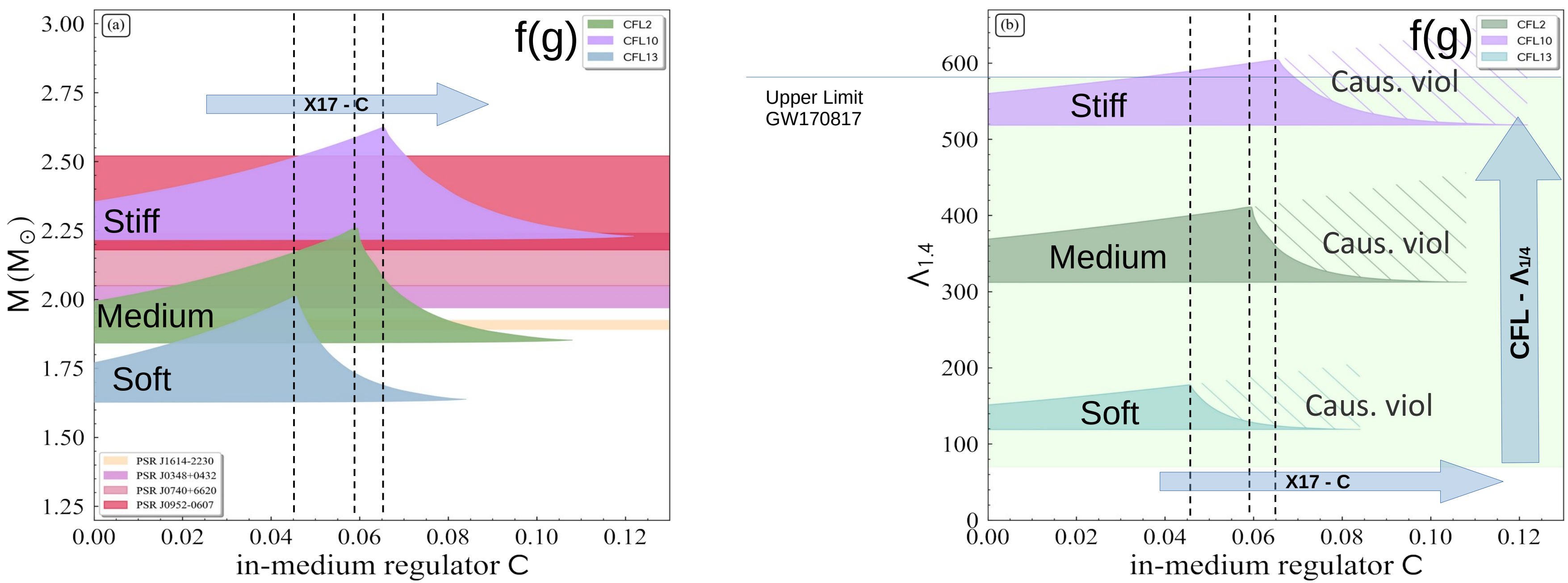
The effect of the X17 contribution is stronger on coupling constant g than the parameter C



# 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 **$C = C_{max}$**) Hight X17 Contribution

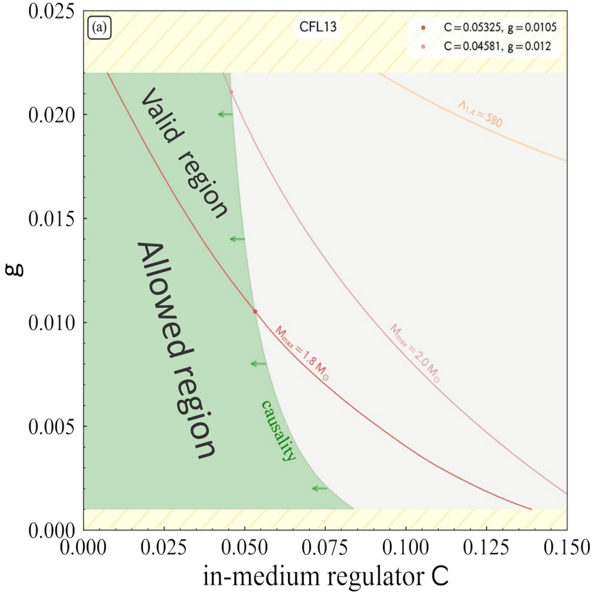


# Color Flavor Locked (CFL) model - Quark Stars

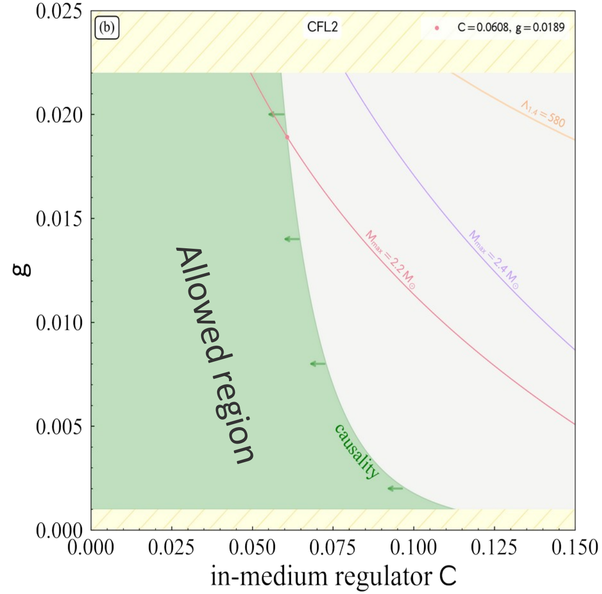
Causality constraints for **g** and **C** for three EoS's

- Possible mass limits:
  - **1.8** Solar Masses (CFL13  Soft)
  - **2.2** Solar Masses (CFL2 Medium)
  - **2.4** Solar Masses (CFL10 Stiff)

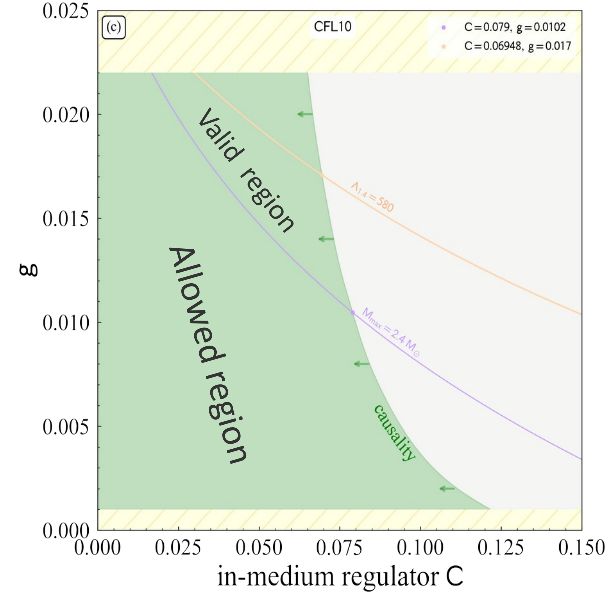
Soft EoS



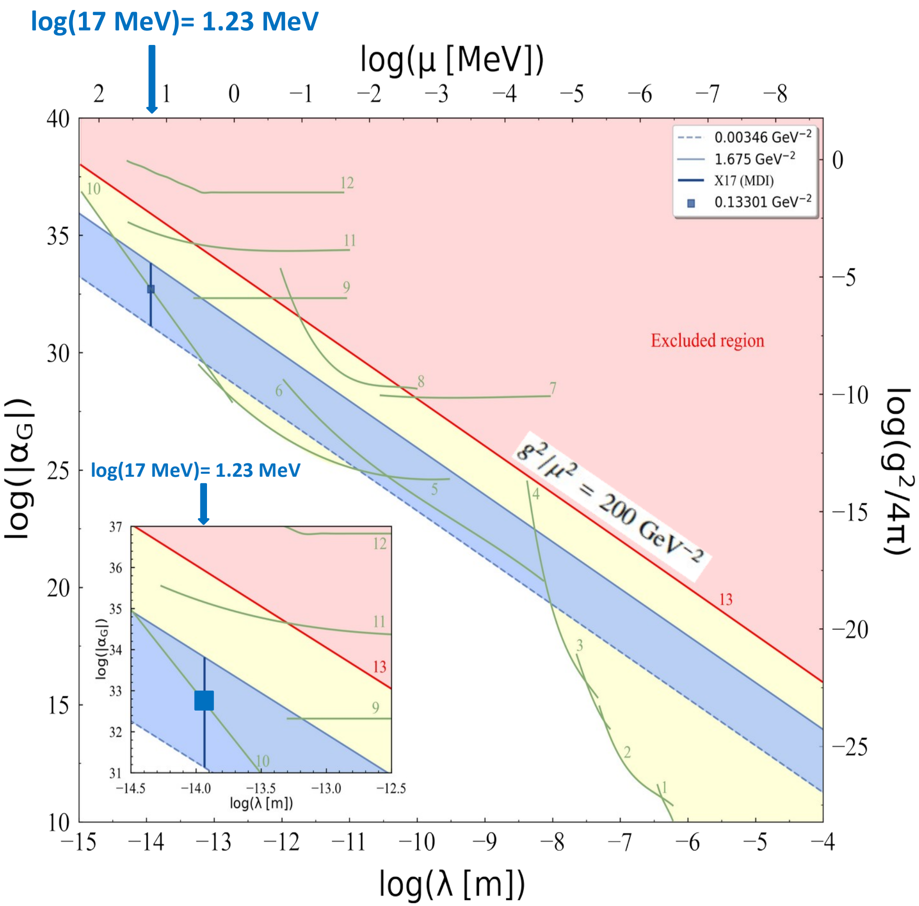

Medium EoS




Stiff EoS



# 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

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(3) Faculty of Mechanical Engineering - Slovak University of Technology in Bratislava, Bratislava, 812 31, Slovakia

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IEAP CTU in Prague

HINP ΕΙΠΦ

# Thank you