Exploring dense nuclear matter with neutron stars

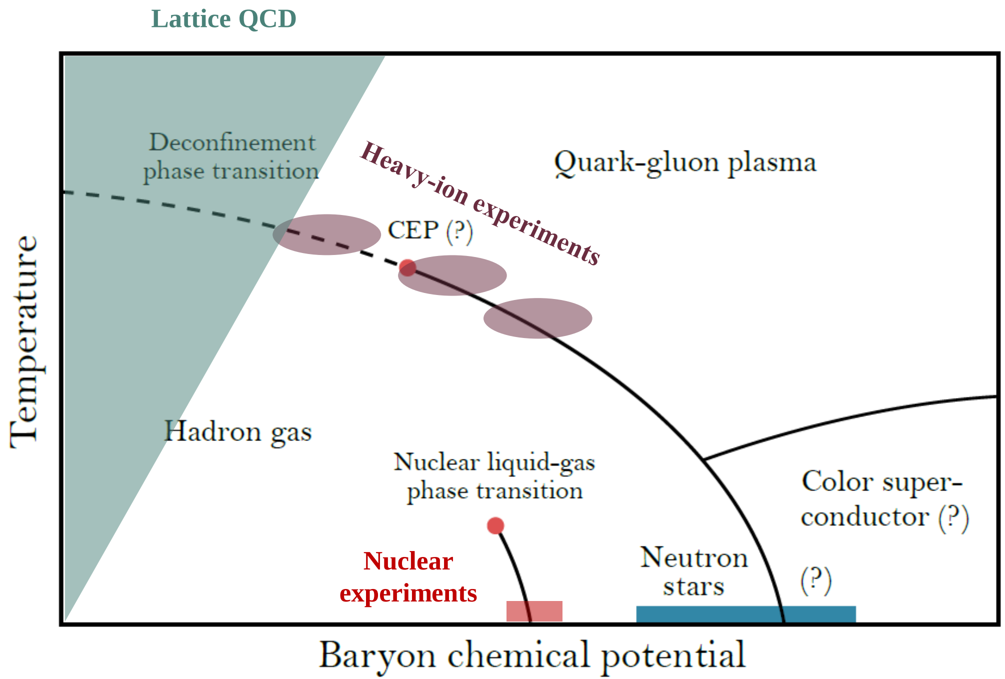
János Takátsy
Eötvös Loránd University
HUN-REN Wigner RCP

PhD supervisor:
Dr. Péter Kovács
HUN-REN Wigner RCP

Collaborators:
Prof. György Wolf, HUN-REN Wigner RCP
Prof. Jürgen Schaffner-Bielich, Goethe Universität Frankfurt
Prof. Bence Kocsis, University of Oxford

International School of Subnuclear Physics, Erice, 2024.06.17.

Why study neutron stars?



János Takátsy
takatsy.janos@wigner.hun-ren.hu

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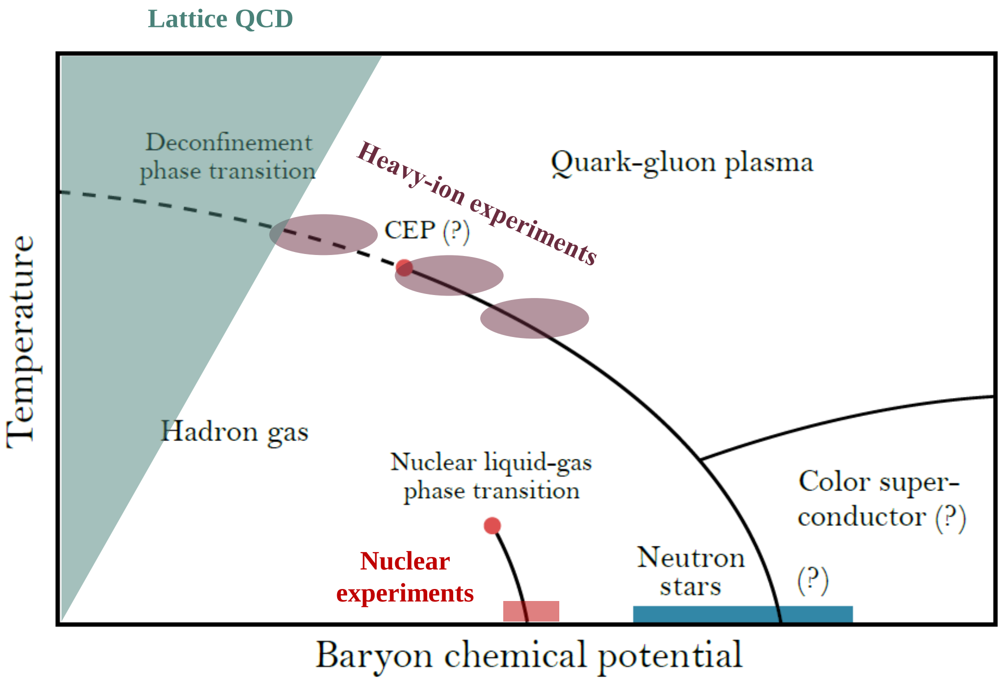

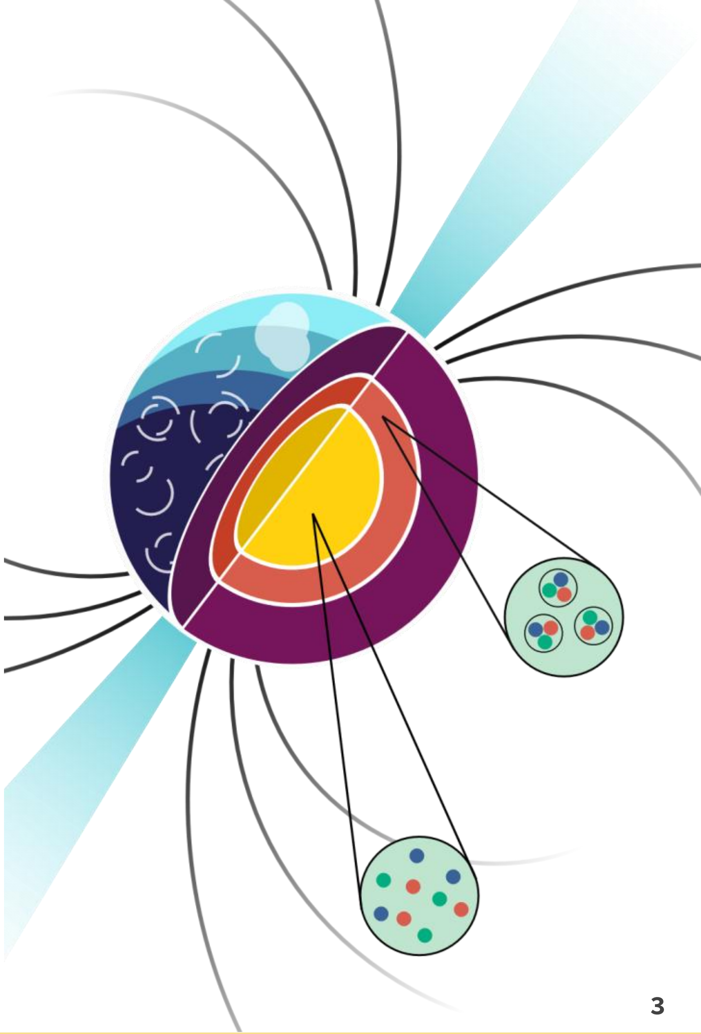

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The mass-radius relation

$$\frac{dp}{dr} = -[\varepsilon(r) + p(r)]\frac{M(r)+4\pi r^3 p(r)}{r^2 - 2M(r)r}$$

How to get a mass-radius relation:

→ get an equation of state p(ε)

→ start with a specific central density: ε_c, p_c, M(0) = 0

→ integrate the TOV equations until p(R) = 0 → R is the radius of the NS

→ M(R) is the mass of the NS

→ change ε_c and repeat → M-R relation

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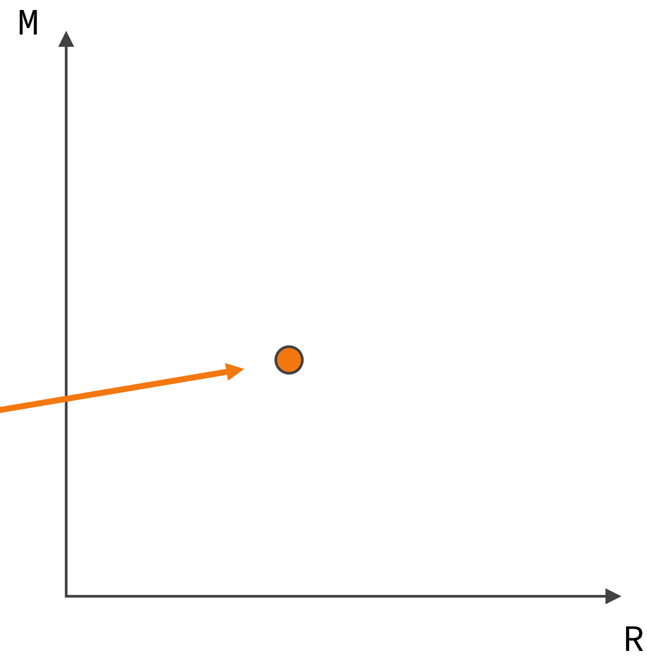

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How to get a mass-radius relation:

→ get an equation of state $p(\varepsilon)$

→ start with a specific central density: ε_c, p_c, $M(0) = 0$

→ integrate the TOV equations until $p(R) = 0$ → R is the radius of the NS

→ M(R) is the mass of the NS

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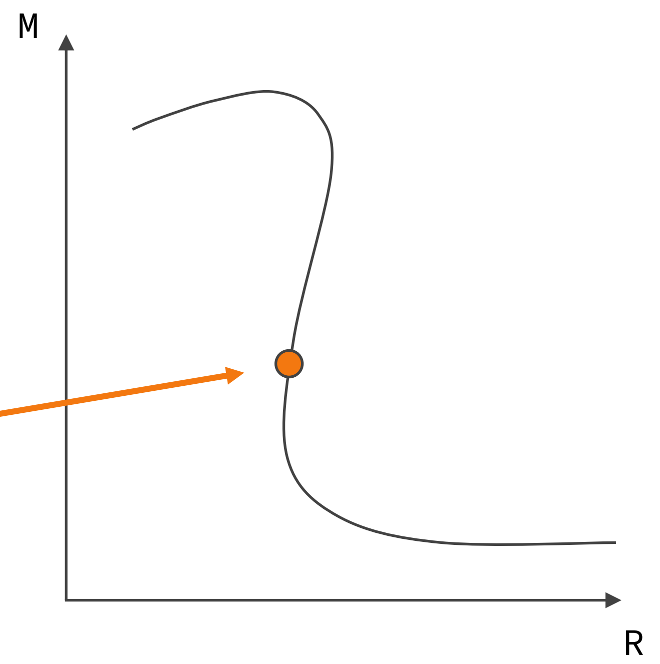

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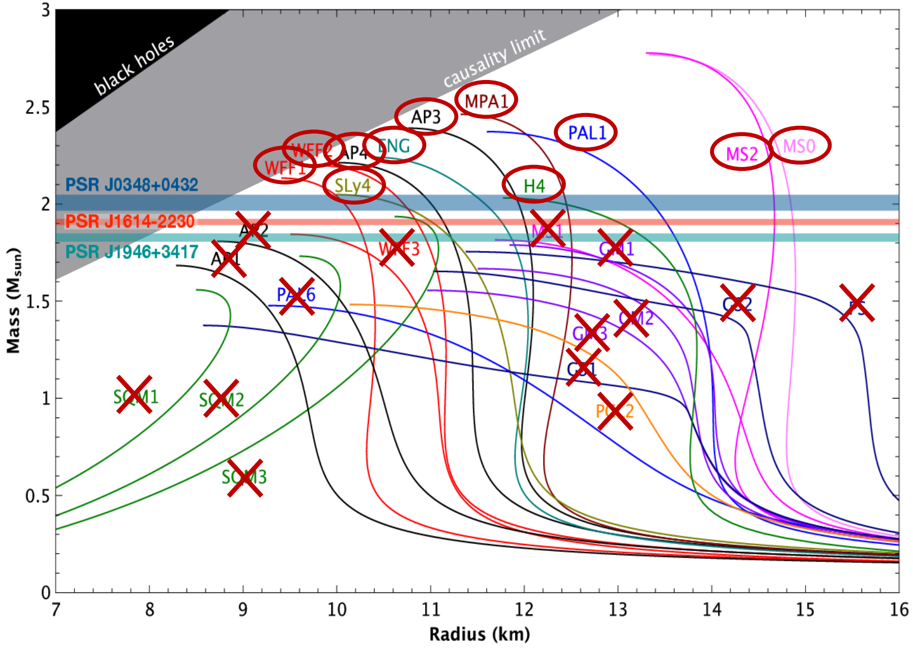
Astrophysical measurements



Credits: Norbert Wex

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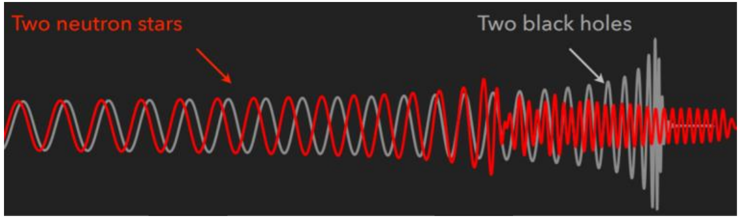
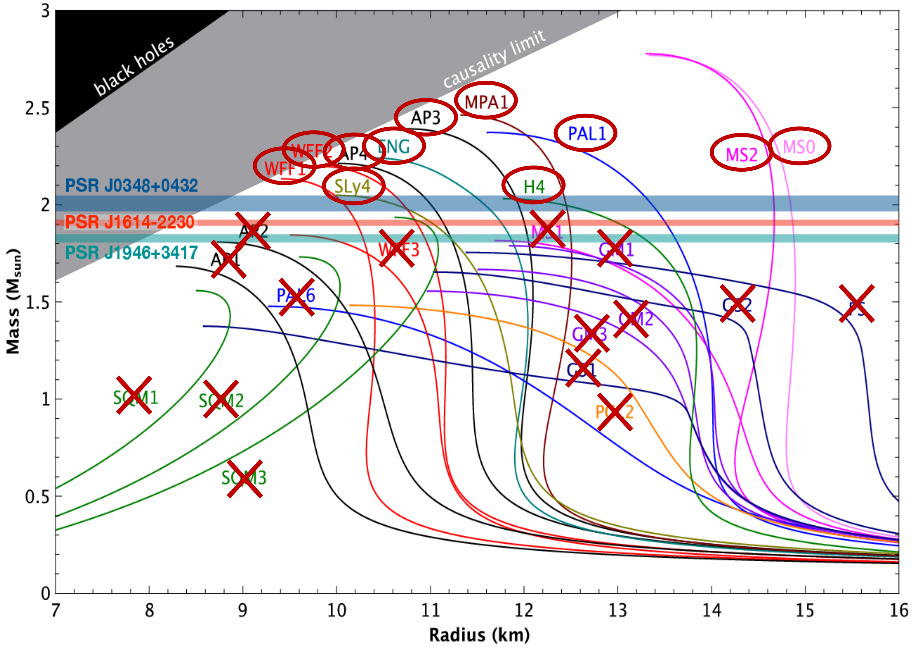
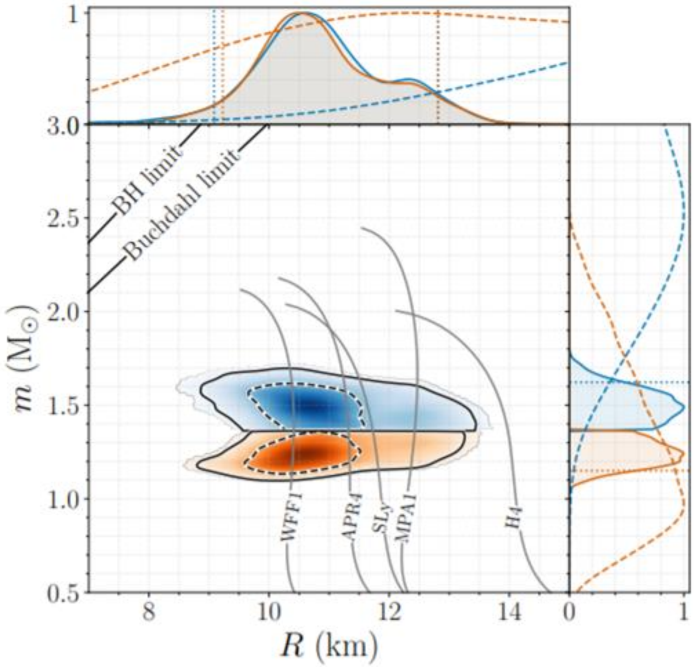




Credits: Norbert Wex



Source: LVC, Phys.Rev.Lett. 121, 161101 (2018)

Hybrid stars

Hybrid stars also have a hadronic crust and quark matter core:

- at low densities we use hadronic EoSs:
  - ↪ the SFHo EoS as a soft hadronic EoS
  - ↪ the DD2 as a stiff EoS
- effective quark-meson model consistent with meson phenomenology and lattice QCD
- we connect the two phases smoothly:
  - ↪ $\varepsilon(n_B)$ interpolation with polynomial

Observations → Bayesian statistics

$$p(\vartheta|\text{data}) = \frac{p(\text{data}|\vartheta)p(\vartheta)}{p(\text{data})}$$

$$p(\text{data}|\vartheta) = p(M_{\text{max}}|\vartheta)p(\text{NICER}|\vartheta)p(\tilde{\Lambda}|\vartheta)$$

↪ Lower limit on maximum mass from massive pulsars

↪ NICER mass-radius constraints

↪ Tidal deformability measurement from GW170817

↪ Upper mass constraint from hypermassive neutron star hypothesis

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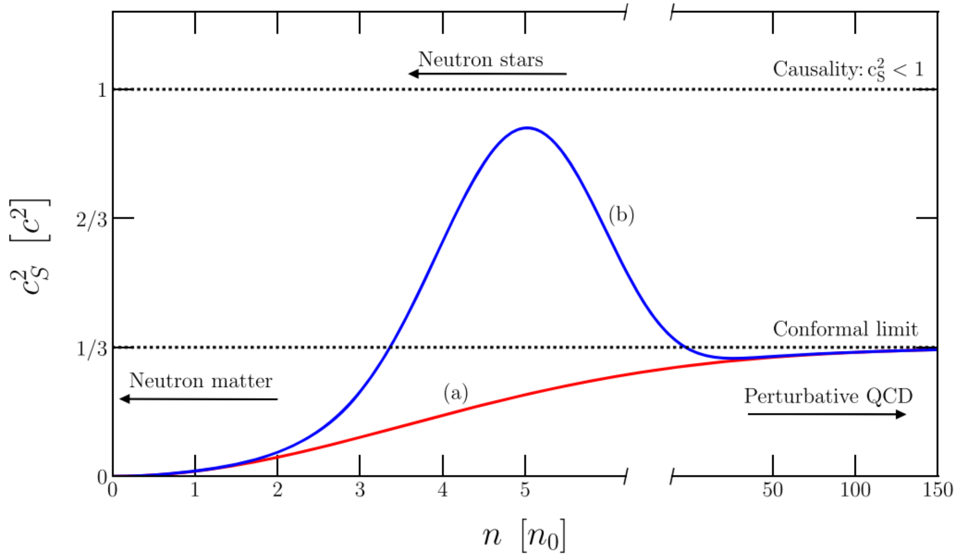
Speed of sound and conformality



Source: I. Tews, et al. In: Astrophys.J. 860, 149 (2018)

Important measure: speed of sound

$$c_s^2 = \frac{\mathrm{d}p}{\mathrm{d}\varepsilon}$$

In the conformal limit (high density):

$$p \to \frac{1}{3}\varepsilon \qquad c_s^2 \to \frac{1}{3}$$

Empirical conformality measures:

$$\Delta = \frac{1}{3} - \frac{p}{\varepsilon} \qquad d_c = \sqrt{\Delta^2 + \Delta'^2}$$

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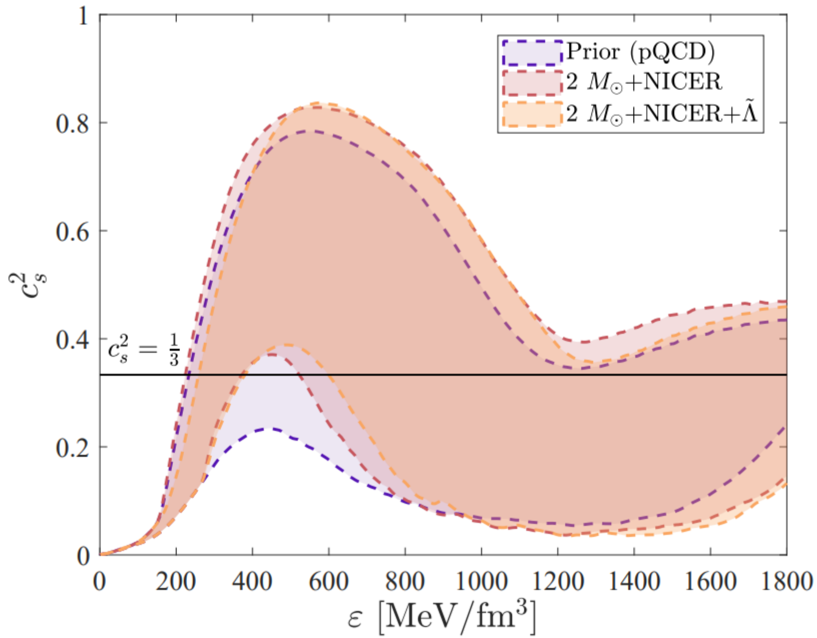
Speed of sound and conformality



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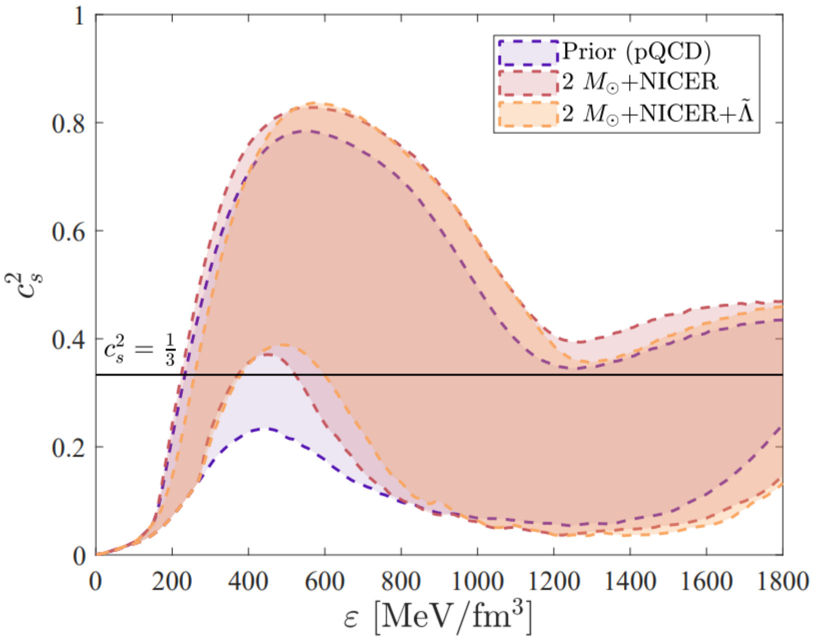
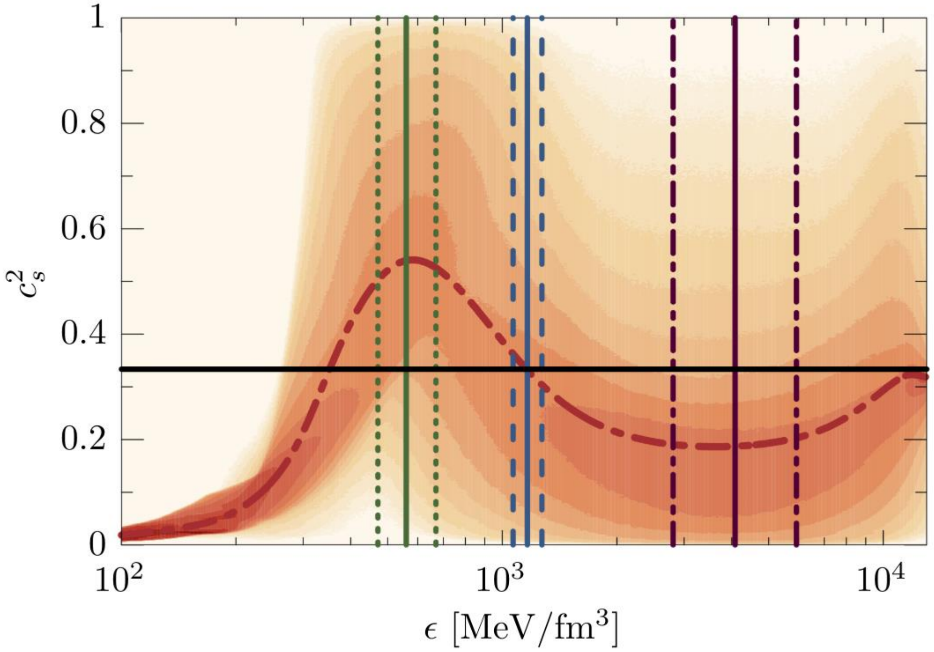
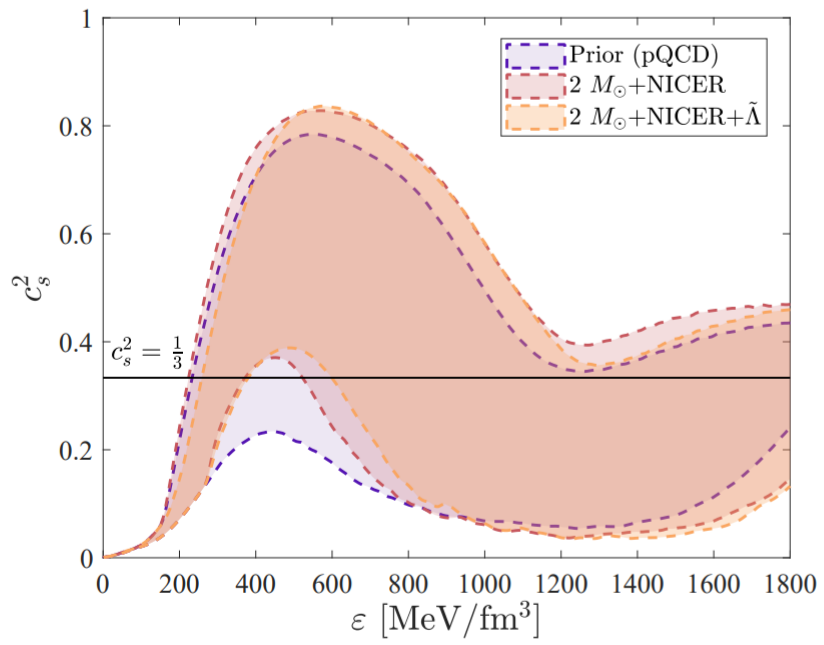


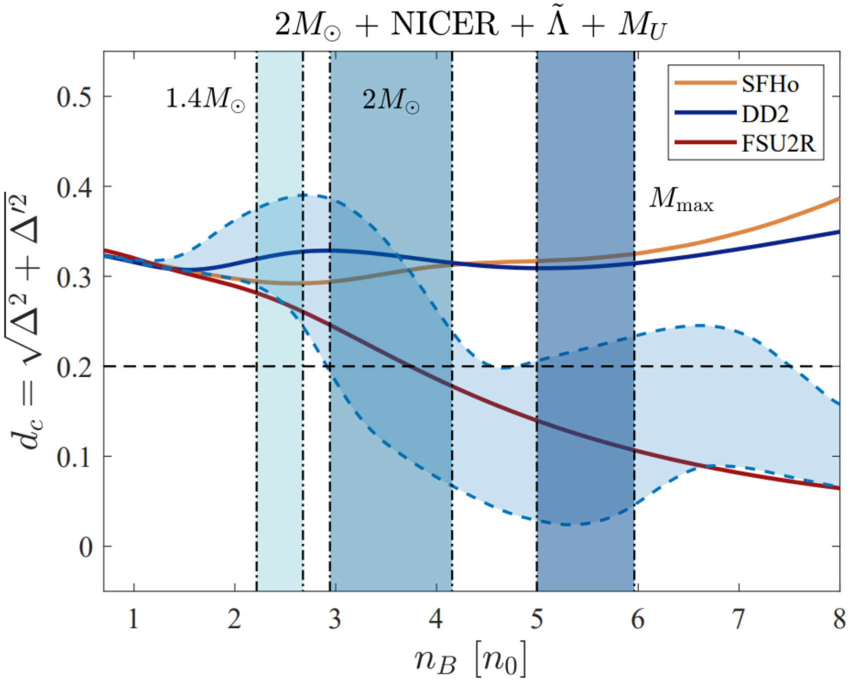


Source: *M. Marczenko, et al., Phys.Rev.C 107, 025802 (2023)*

János Takátsy takatsy.janos@wigner.hun-ren.hu

Speed of sound and conformality





Source: J. Takátsy, et al. In: ***Phys.Rev.D 108, 043002 (2023)***

János Takátsy
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Thank you for your attention!

References to some of our works

[1] P. Kovács, Zs. Szép, Gy. Wolf. In: Phys.Rev.D 93, 114014 (2016)

[2] J. Takátsy, P. Kovács. In: Phys.Rev.D 102, 028501 (2020)

[3] P. Kovács, J. Takátsy, J. Schaffner-Bielich, Gy. Wolf. In: Phys.Rev.D 105, 103014 (2022)

[4] P. Kovács, Gy. Kovács, F. Giacosa. In: Phys.Rev.D 106, 116016 (2022)

[5] J. Takátsy, P. Kovács, Gy. Wolf, J. Schaffner-Bielich. In: Phys.Rev.D 108, 043002 (2023)

[6] Gy. Kovács, P. Kovács, Gy. Wolf, P. M. Lo, K. Redlich. In: Phys.Rev.D 108, 076010 (2023)

János Takátsy takatsy.janos@wigner.hun-ren.hu

Backup slides

The quark-meson model

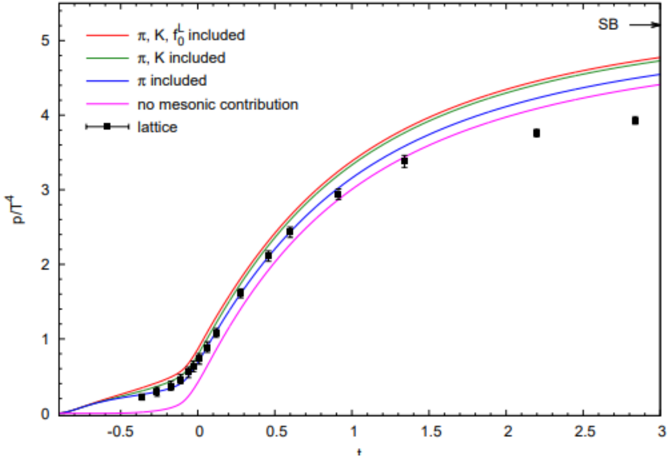
———

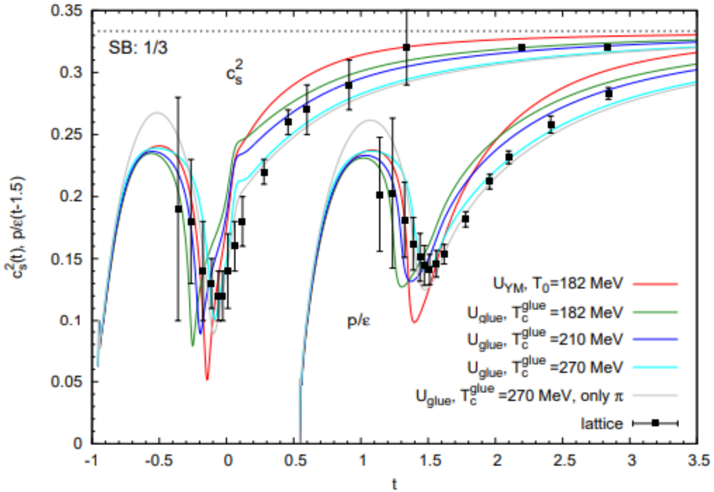
We use the (axial)vector meson extended linear sigma model

↪ three-flavour constituent quark-meson model with the complete (pseudo)scalar and (axial)vector meson nonets

↪ parameterized with meson vacuum masses and decay widths

↪ agrees well with lattice results at finite temperature





Source: P. Kovács, et al. In: **Phys.Rev.D 93, 114014 (2016)**

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The eLSM Lagrangian

The eLSM Lagrangian is constructed based on linearly realized global $U(3)_L \times U(3)_R$ chiral symmetry and its explicit breaking

$$
\begin{aligned}
\mathcal{L} = & \operatorname{Tr}[(D_\mu\Phi)^\dagger(D_\mu\Phi)] - m_0^2\operatorname{Tr}(\Phi^\dagger\Phi) - \lambda_1[\operatorname{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\operatorname{Tr}(\Phi^\dagger\Phi)^2 \\
& + c_1(\det\Phi + \det\Phi^\dagger) + \operatorname{Tr}[H(\Phi+\Phi^\dagger)] - \frac{1}{4}\operatorname{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) \\
& + \operatorname{Tr}\left[\left(\frac{m_1^2}{2}\mathbb{I} + \Delta\right)(L_\mu^2 + R_\mu^2)\right] + i\frac{g_2}{2}(\operatorname{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \operatorname{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
& + \frac{h_1}{2}\operatorname{Tr}(\Phi^\dagger\Phi)\operatorname{Tr}(L_\mu^2 + R_\mu^2) + h_2\operatorname{Tr}[(L_\mu\Phi)^2 + (\Phi R_\mu)^2] + 2h_3\operatorname{Tr}(L_\mu\Phi R^\mu\Phi^\dagger) \\
& + \bar{\Psi}i\gamma_\mu D^\mu\Psi - g_F\bar{\Psi}(\Phi_S + i\gamma_5\Phi_{PS})\Psi - g_V\bar{\Psi}(\gamma^\mu(V_\mu + \gamma_5 A_\mu))\Psi
\end{aligned}
$$

$$
\begin{aligned}
D^\mu\Phi &= \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu) - ieA_e^\mu[T_3, \Phi], \\
L^{\mu\nu} &= \partial^\mu L^\nu - ieA_e^\mu[T_3, L^\nu] - \{\partial^\nu L^\mu - ieA_e^\nu[T_3, L^\mu]\}, \\
R^{\mu\nu} &= \partial^\mu R^\nu - ieA_e^\mu[T_3, R^\nu] - \{\partial^\nu R^\mu - ieA_e^\nu[T_3, R^\mu]\}, \\
D^\mu\Psi &= \partial^\mu\Psi - iG^\mu\Psi, \quad \text{with} \quad G^\mu = g_s G_a^\mu T_a.
\end{aligned}
$$

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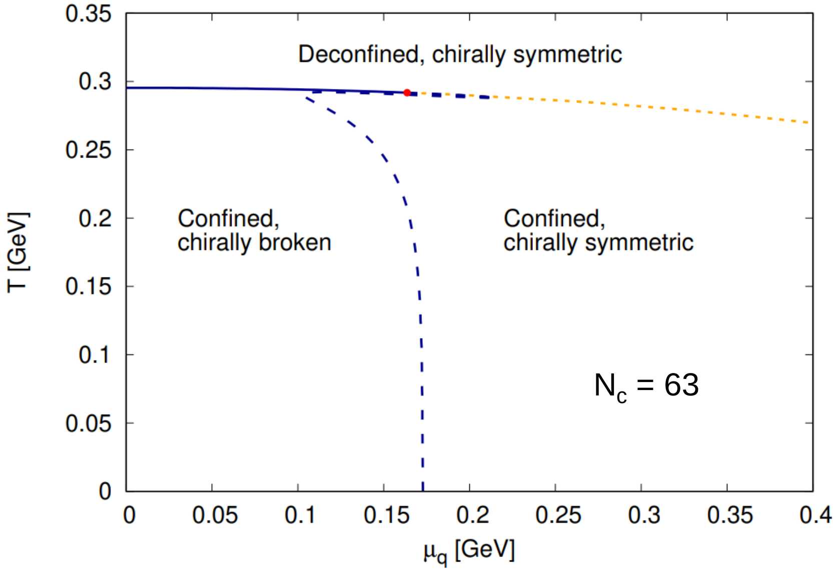
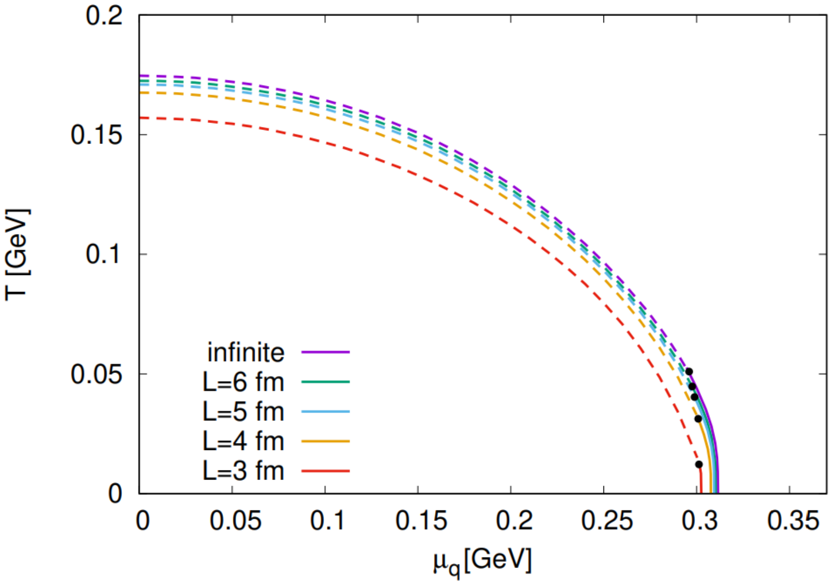
Large-N_c limit and finite volume effects



Source: P. Kovács, et al. In: **Phys.Rev.D 106, 116016 (2022)**



Source: Gy. Kovács, et al. In: **Phys.Rev.D 108, 076010 (2023)**

↪ large-N_c solution can be very different from N_c=3 solution

↪ the CEP tempreature is reduced for finite-size systems

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Mass measurement

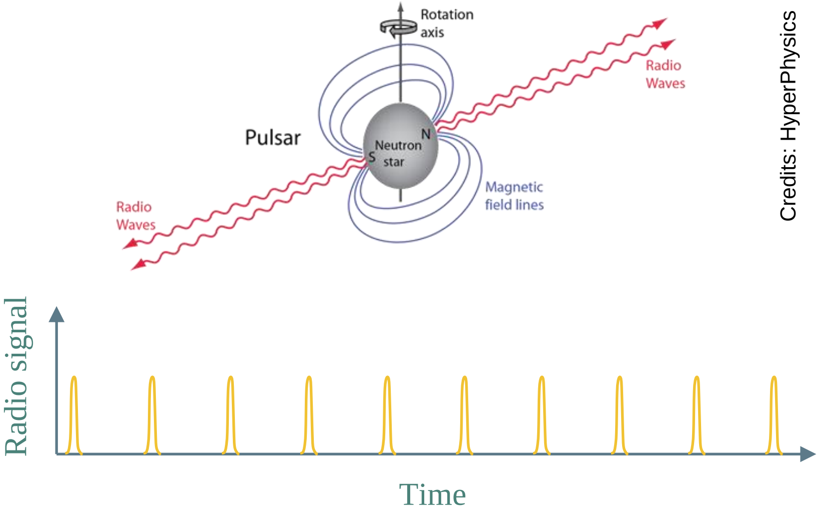
→ Pulsars in binary systems + Doppler shift

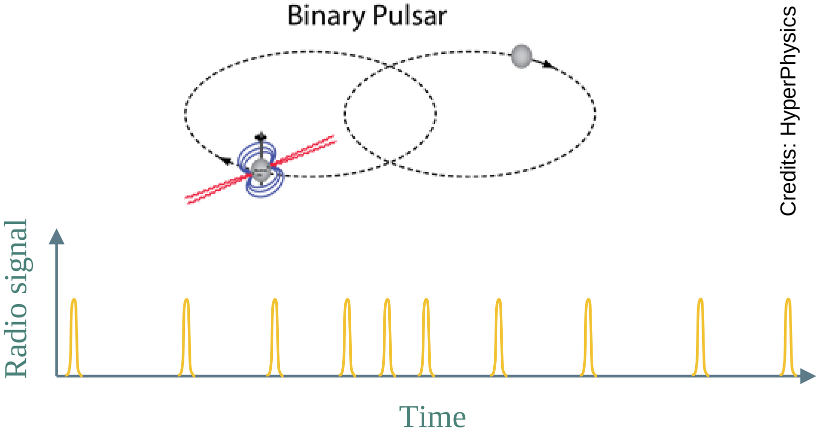
→ Degeneracies → only projected semi-major axis is measured

$$\left(\frac{2\pi}{P_{\rm orb}}\right)^2 \frac{(a_{\rm ns}\sin i)^3}{G} = \frac{(M_{\rm c}\sin i)^3}{M_{\rm T}^2}$$

$$q = \frac{M}{M_{\rm c}} = \frac{(a_{\rm c}\sin i)^3}{(a_{\rm ns}\sin i)^3}$$

→ Observation of the companion object: another pulsar, white dwarf (+X-ray binaries)





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Mass measurement

$$f_{ns} = \left(\frac{2\pi}{P_{orb}}\right)^2 \frac{(a_{ns}\sin i)^3}{G} = \frac{(M_c \sin i)^3}{M_T^2}$$

$$q = \frac{M}{M_c} = \frac{(a_c \sin i)}{(a_{ns} \sin i)}$$

Two other measurements:

1) Projected semi-major axis of the companion star → mass ratio

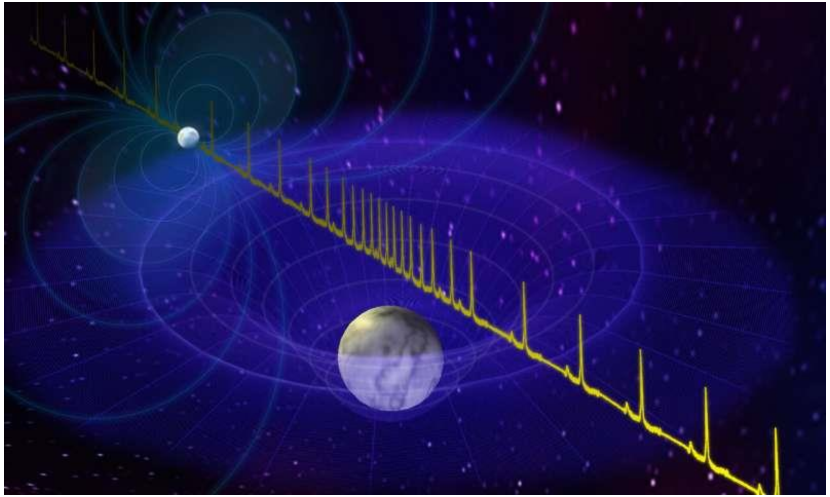
a) White dwarf → optical measurements

b) Another pulsar

2.1) Eclipses → observed edge-on

2.2) Independent mass measurement of the companion: Shapiro-delay

2.3) Relativistic effects: precession, gravitational radiation



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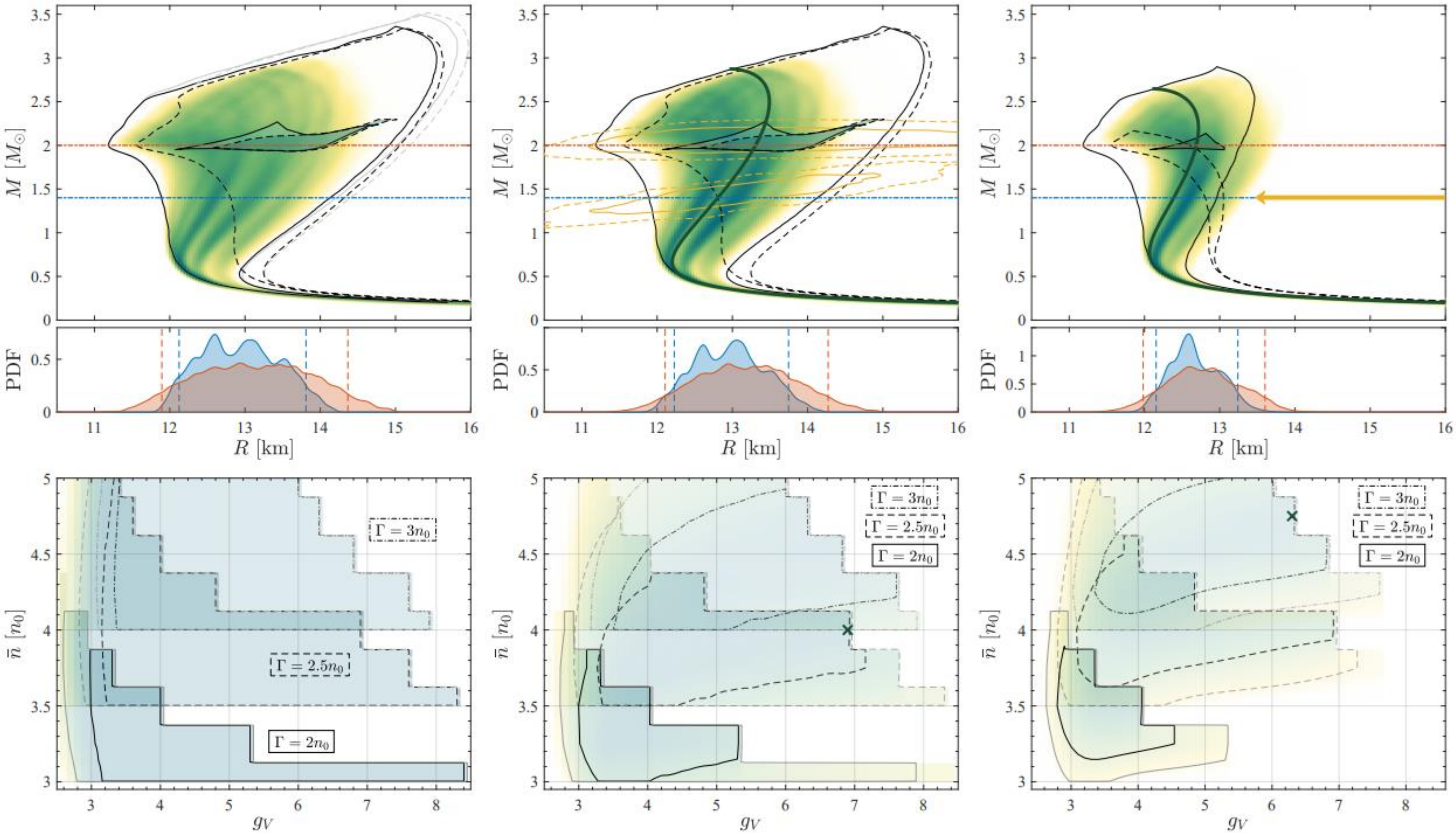
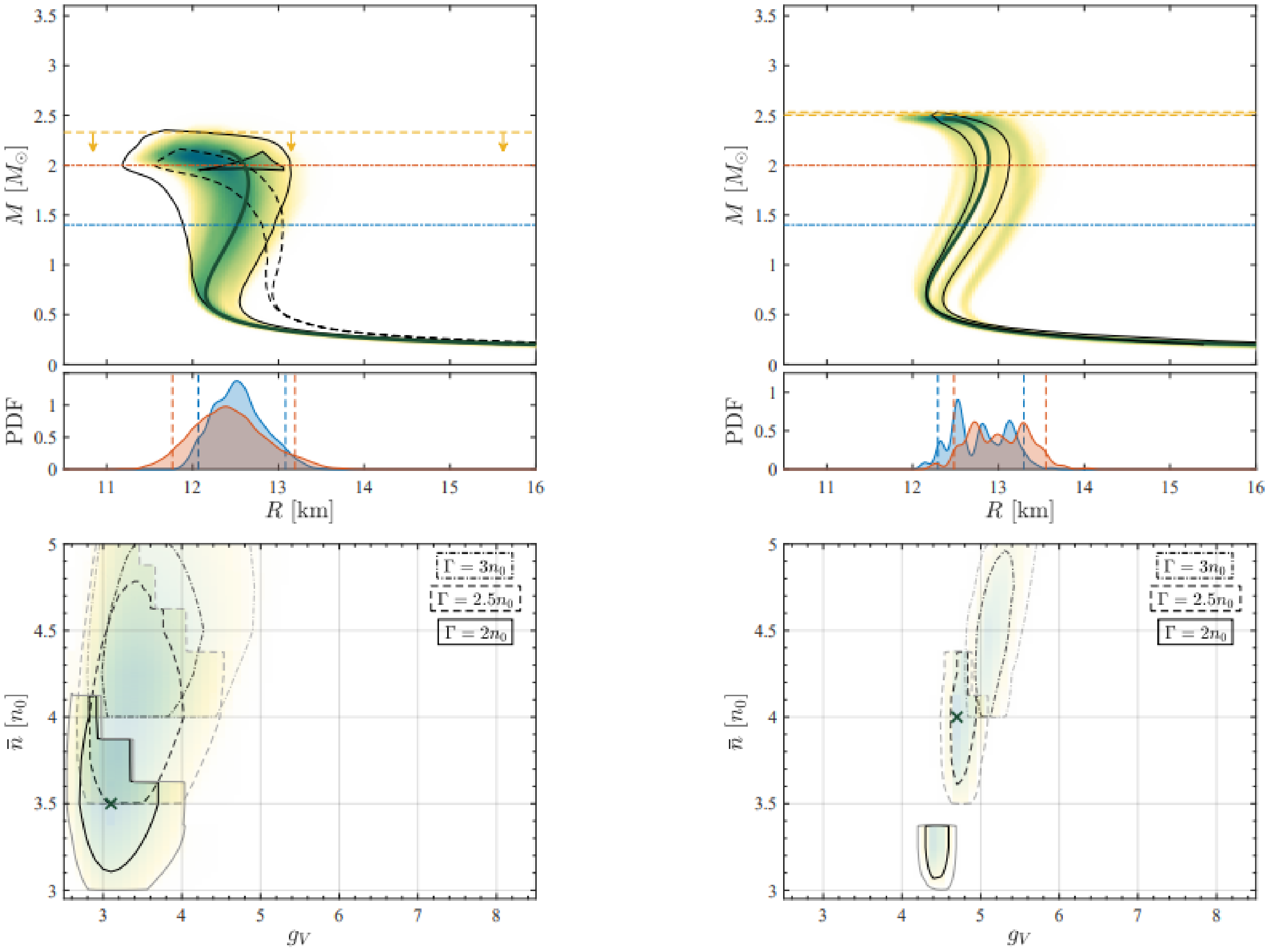


M $[M_\odot]$
PDF
R [km]
$\bar{n}$ $[n_0]$
g_V
$\Gamma = 3n_0$
$\Gamma = 2.5n_0$
$\Gamma = 2n_0$



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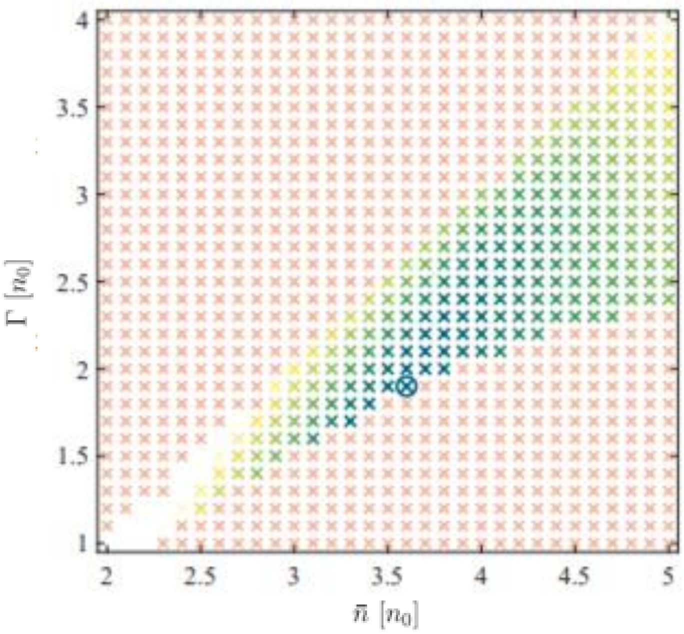
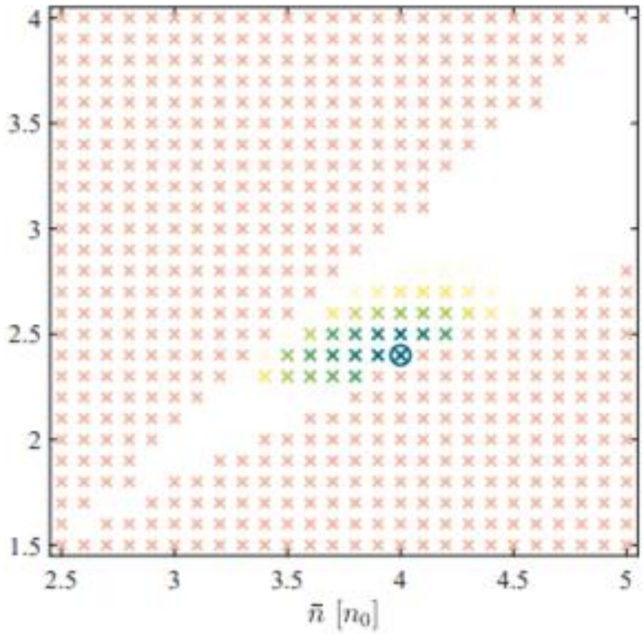
Constraints on concatenation parameters





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