Dark Matter Searches Through Multi-Messenger Observations of Compact Stars

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

comp star

Outline

- A brief introduction to the physics of compact stars.
- Selected scenarios: cooling of compact stars by axions, neutron star collapse into a third family of hybrid stars, neutron star combustion into strange star, mergers of neutron stars, sexaquarks in compact stars.
- Multi-messenger astronomy measurements that could probe dark matter in compact stars.

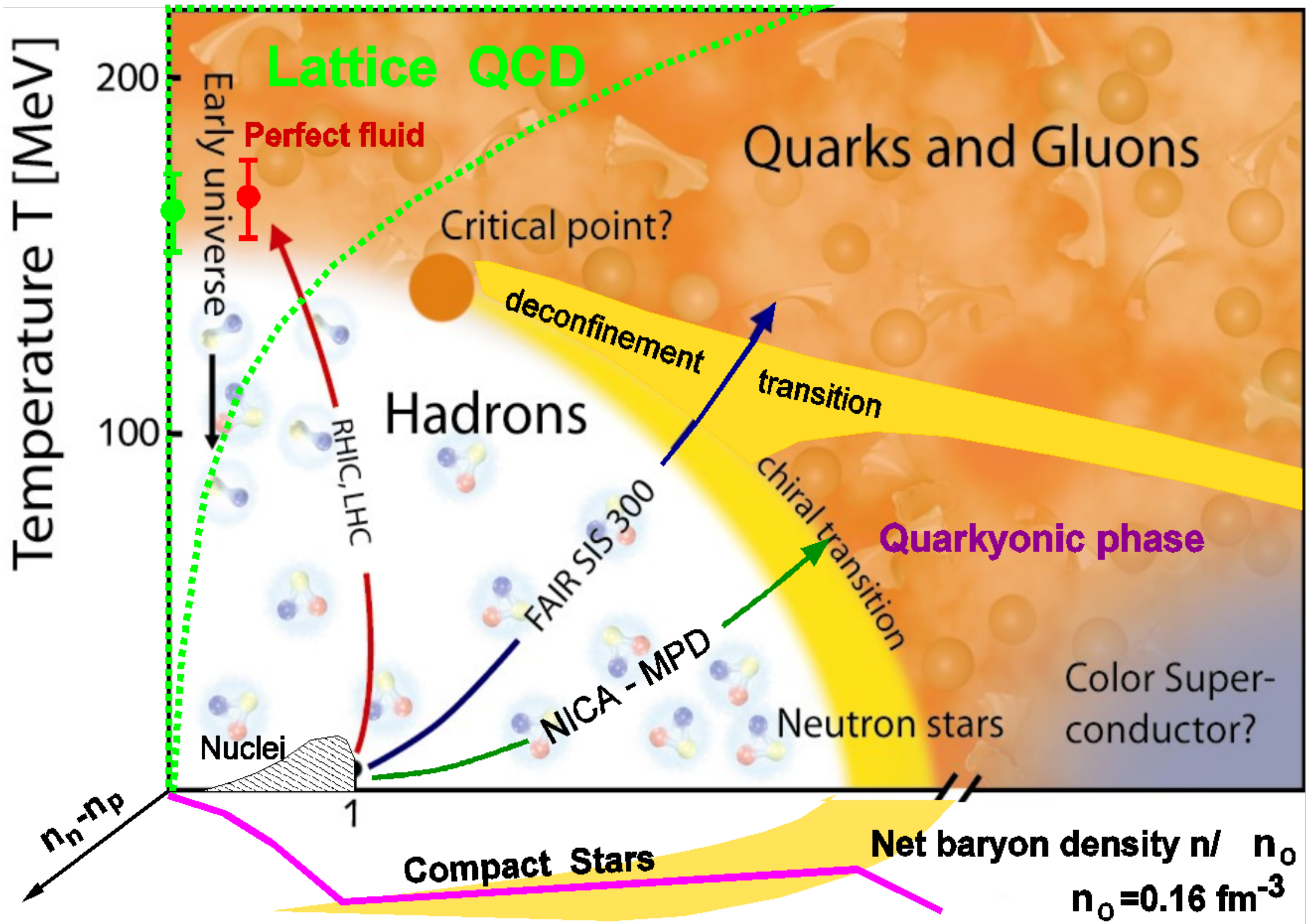
Motivation

- New channels of multi-messenger observations like gravitational radiation from merger events of binary systems of compact stars or radio and X-ray signals from isolated pulsars allow to study their most basic structural properties like mass, radius, compactness, cooling rates and compressibility of their matter.

- Nuclear measurement and experiments have narrowed the Equation of State (EoS) uncertainty in the lowest to intermediate density range.

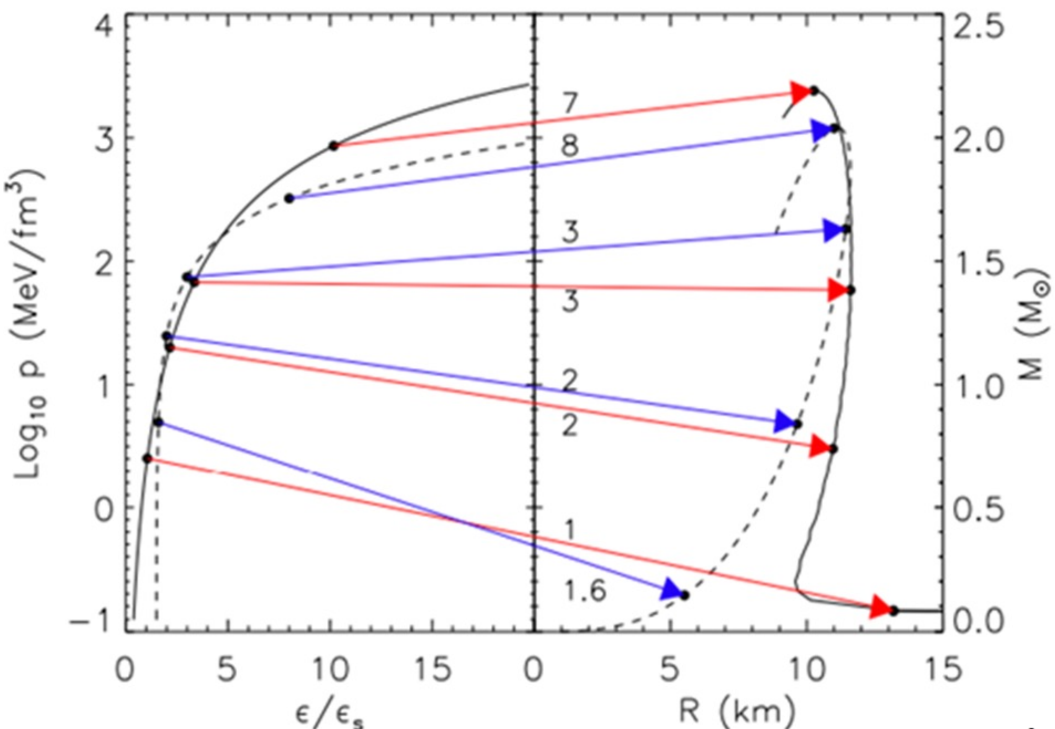
- Violent, transient energetic emissions are associated not only with the strong magnetic fields and extreme gravity in the proximity of NS but with explosive, evolutionary stages often triggered by mass accretion from companion stars. Therefore, we expect that the presence of dark matter will leave an imprint in the many kinds of expected signals to be detected.

Critical Endpoint in QCD



Compact Star Sequences

(M-R ⇔ EoS)



Lattimer,
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)
arXiv: 1305.3510

- TOV Equations

$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

- Equation of State (EoS)

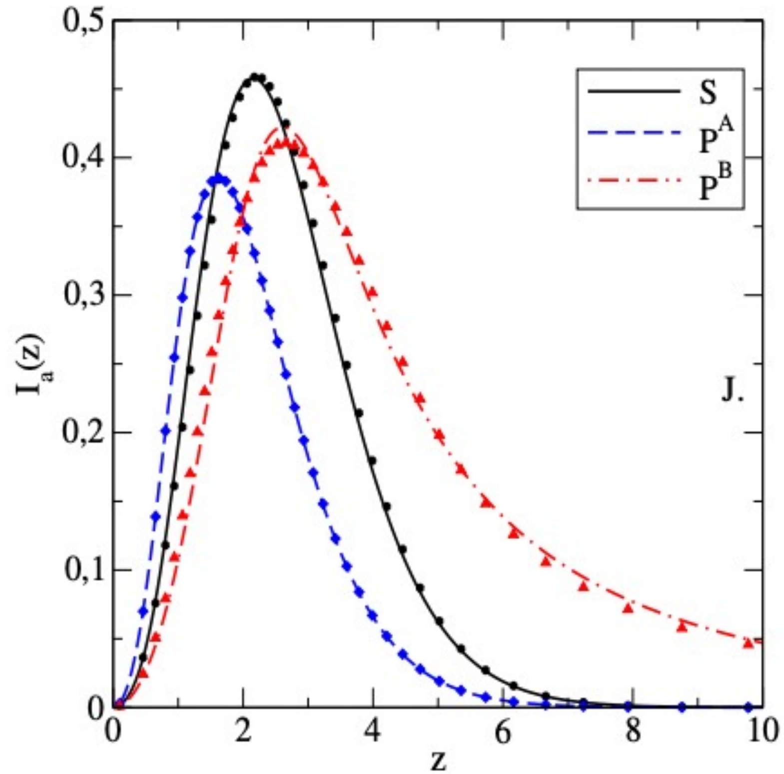
$$p(\varepsilon)$$

Effects of NS Axion Cooling

Axion emissivity for S-wave condensate

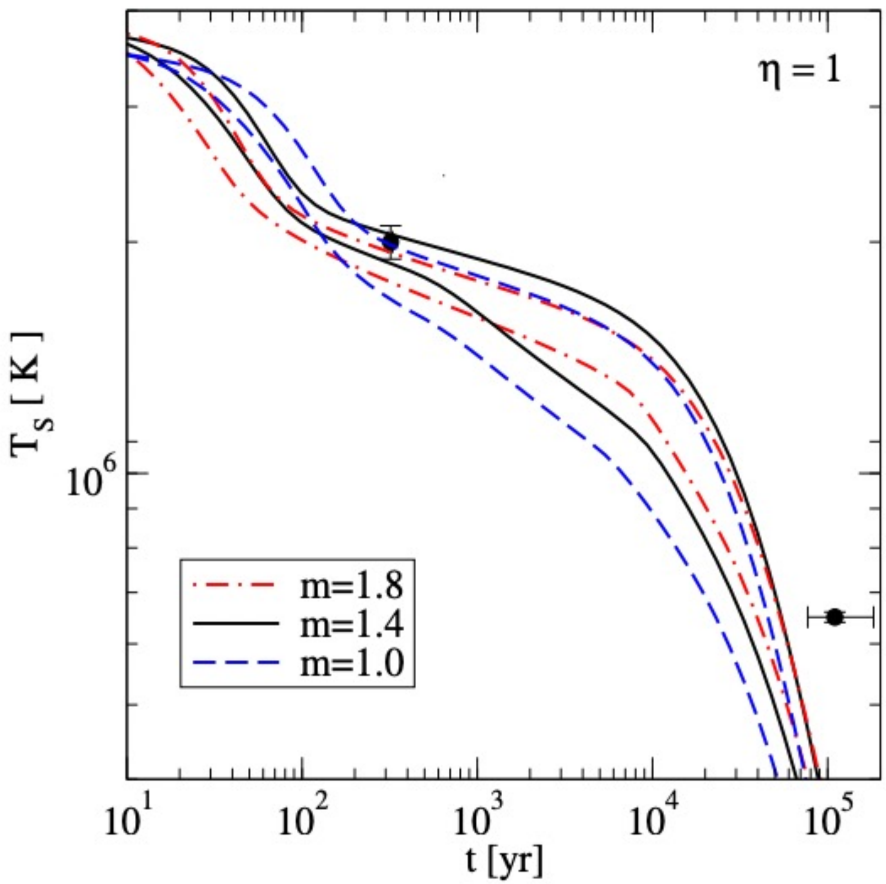
$$\epsilon^S_{aN} = \frac{2C_N^2}{3\pi} f_a^{-2}\, \nu_N(0)\, v_{FN}^2\, T^5\, I^S_{aN},$$

$$I^S_{aN} = z_N^5 \int_1^\infty dy\, \frac{y^3}{\sqrt{y^2-1}} f_F\,(z_N y)^2\,.$$



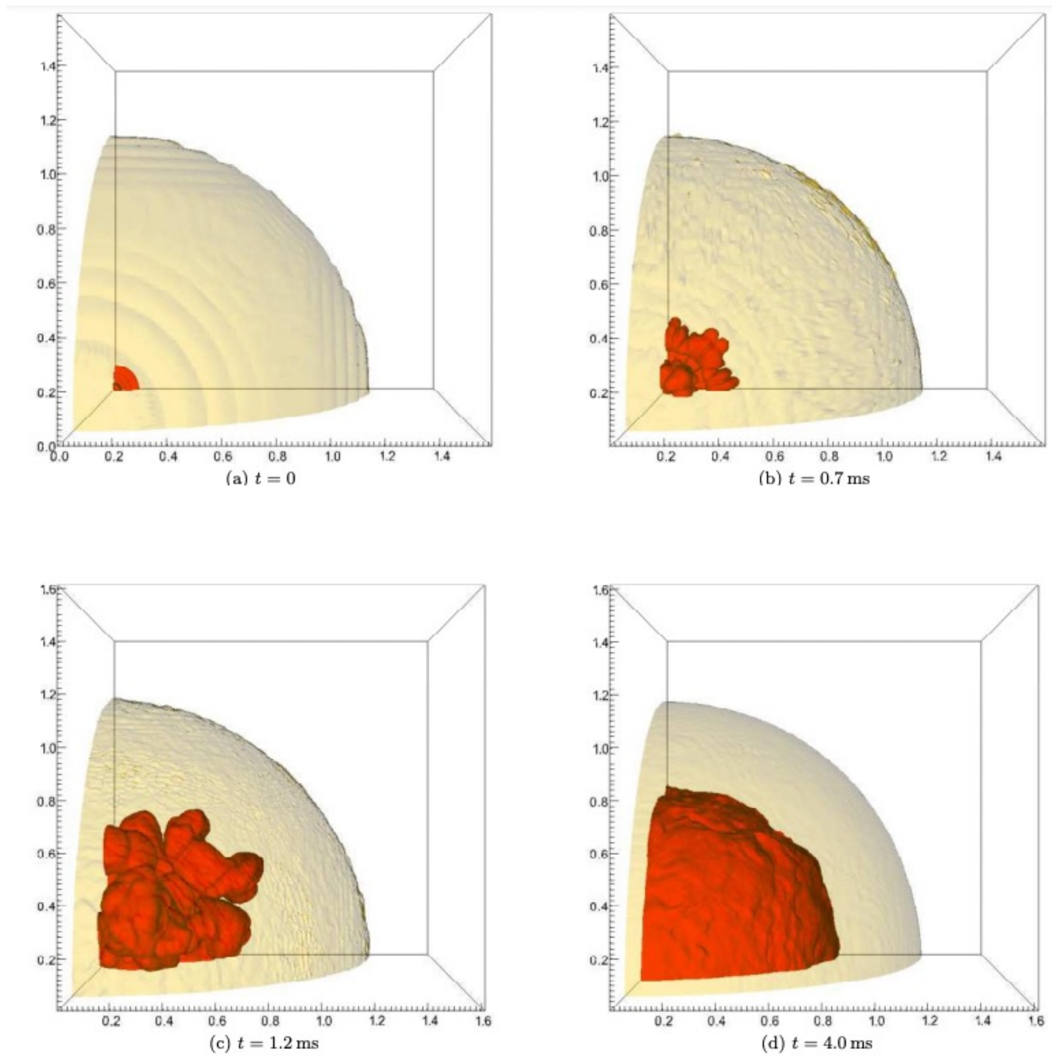
CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

Effects of NS Axion Cooling



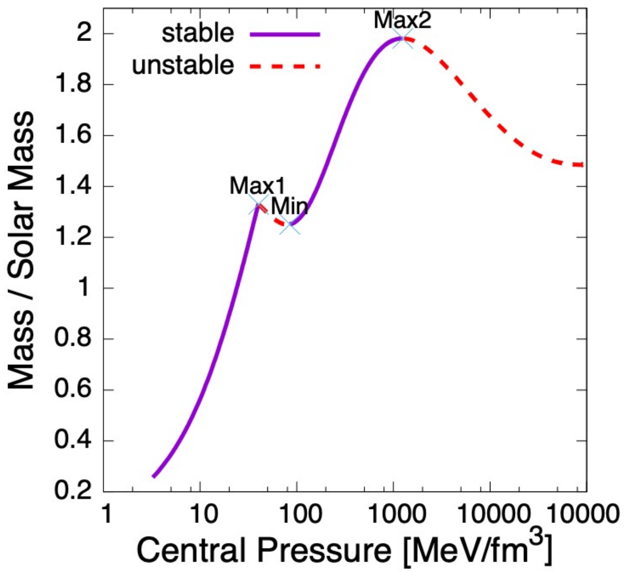
CAS A data, A. Sedrakian, Phys. Rev. D 93, 065044 (2016)

Combustion of a NS into a Strange Quark Star



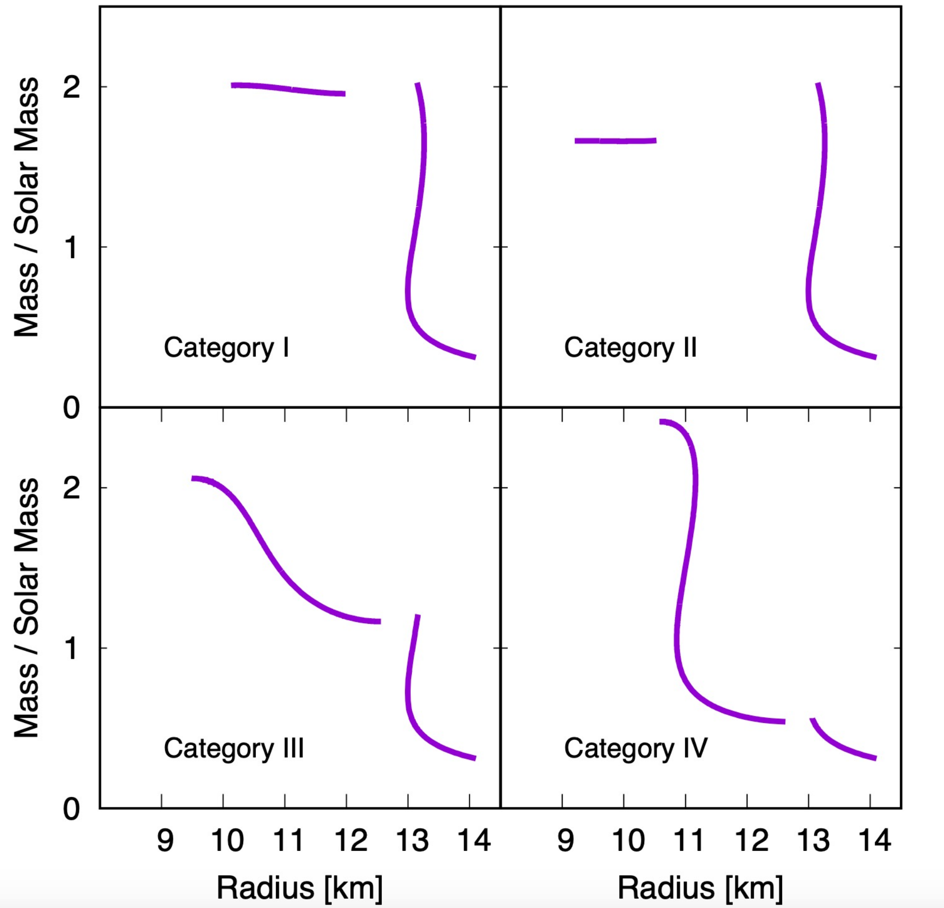
G. Pagliara, M. Herzog, F. K. Roepke, Phys. Rev. D 87, 103007 (2013)

Twin Mass Stars Compact Stars



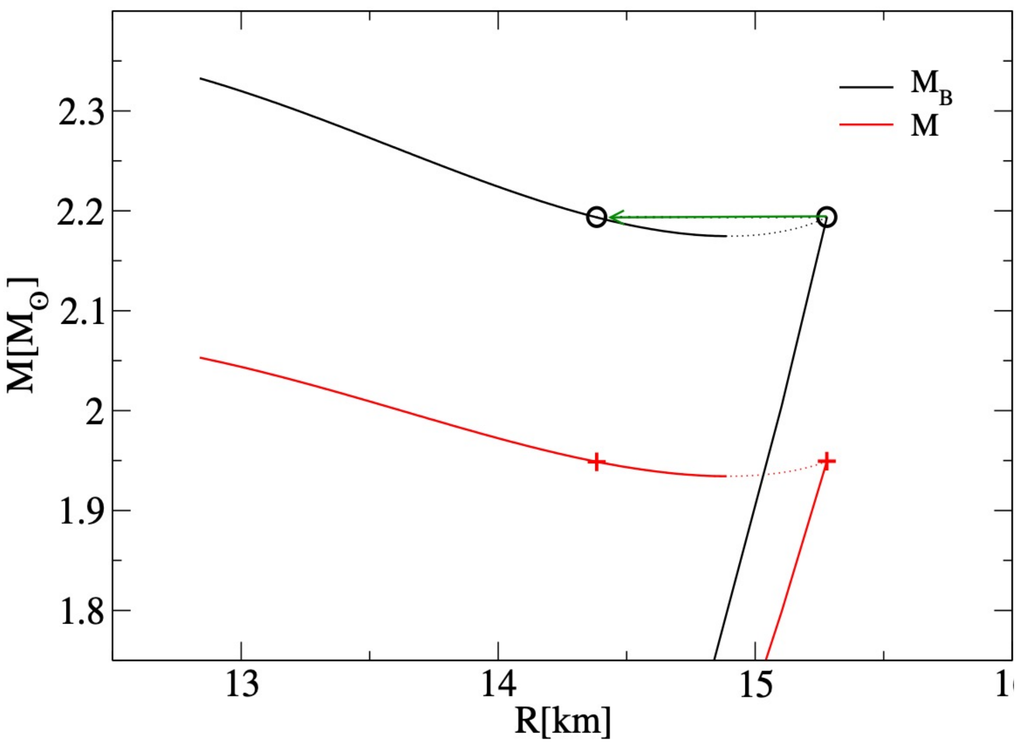
	Low p_{trans}	High p_{trans}	Low $\Delta\epsilon$	High $\Delta\epsilon$
Category I	118	184	214	375
Category II	118	136	375	725
Category III	24	117	214	368
Category IV	7	23	150	425

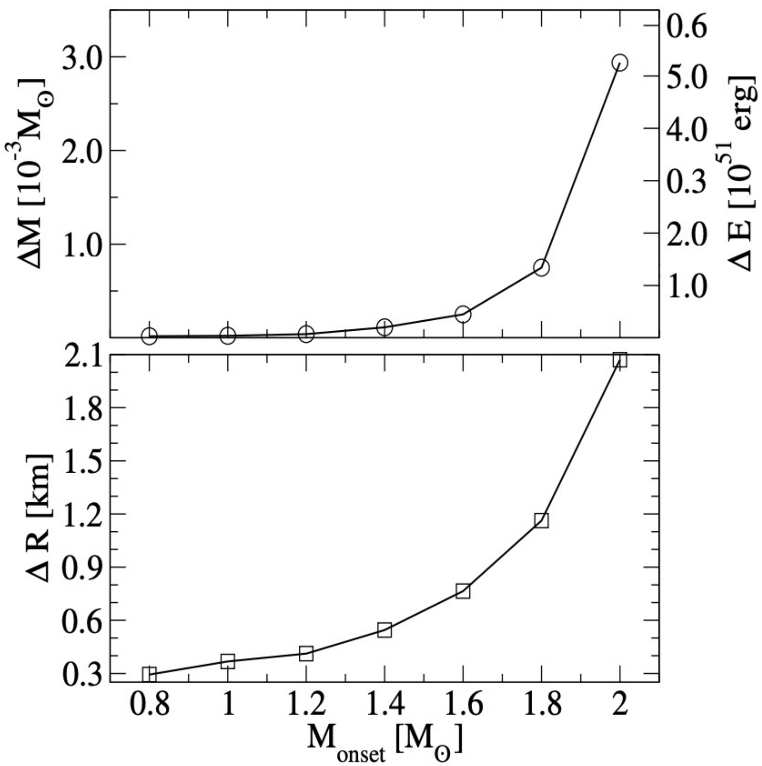
TABLE I. The four categories of twin stars defined by the masses of their maxima. All entries are given in units of MeV/fm^3. "High" and "Low" describes the upper or lower limit of p_{trans} and $\Delta\epsilon$ of the category.



Christian, J., Zacchi, A. & Schaffner-Bielich, J.
Eur. Phys. J. A **54,** 28 (2018).

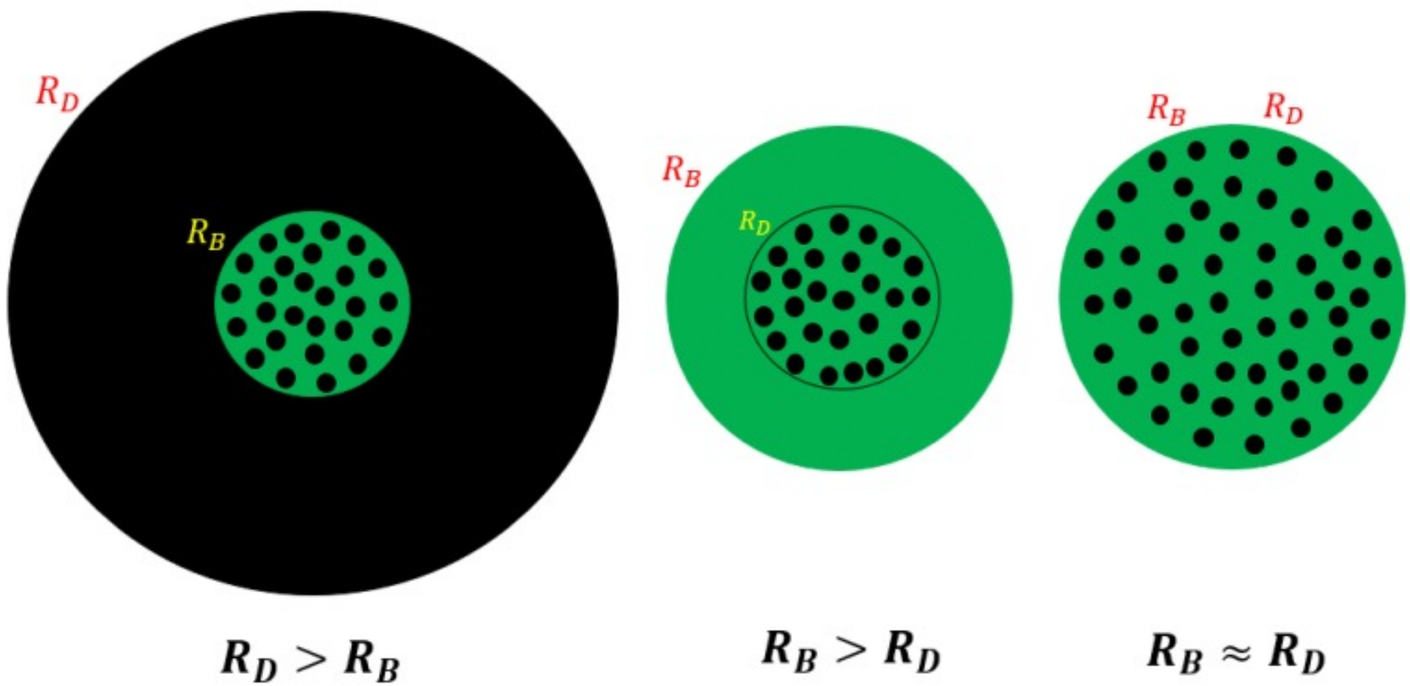
Mass Twins – Energy Released





DD2MEV-CSS EoS, D. A-C, Astronomischen Nachrichten (2021) 1–6, arXiv: 2011.11145

Bosonic Dark Matter in NS



D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Bosonic Dark Matter in NS

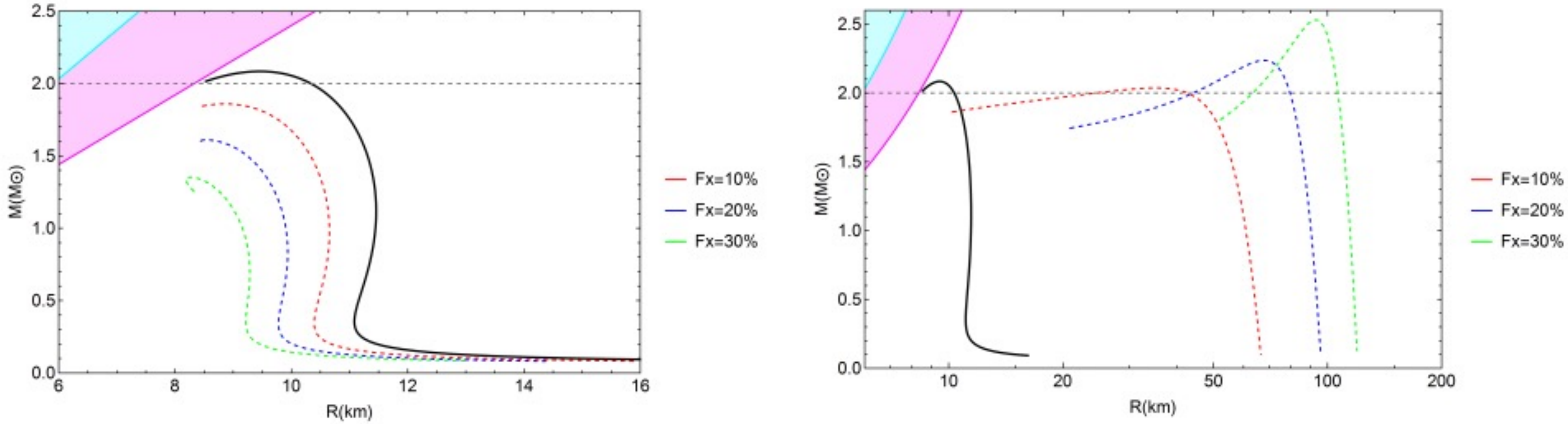
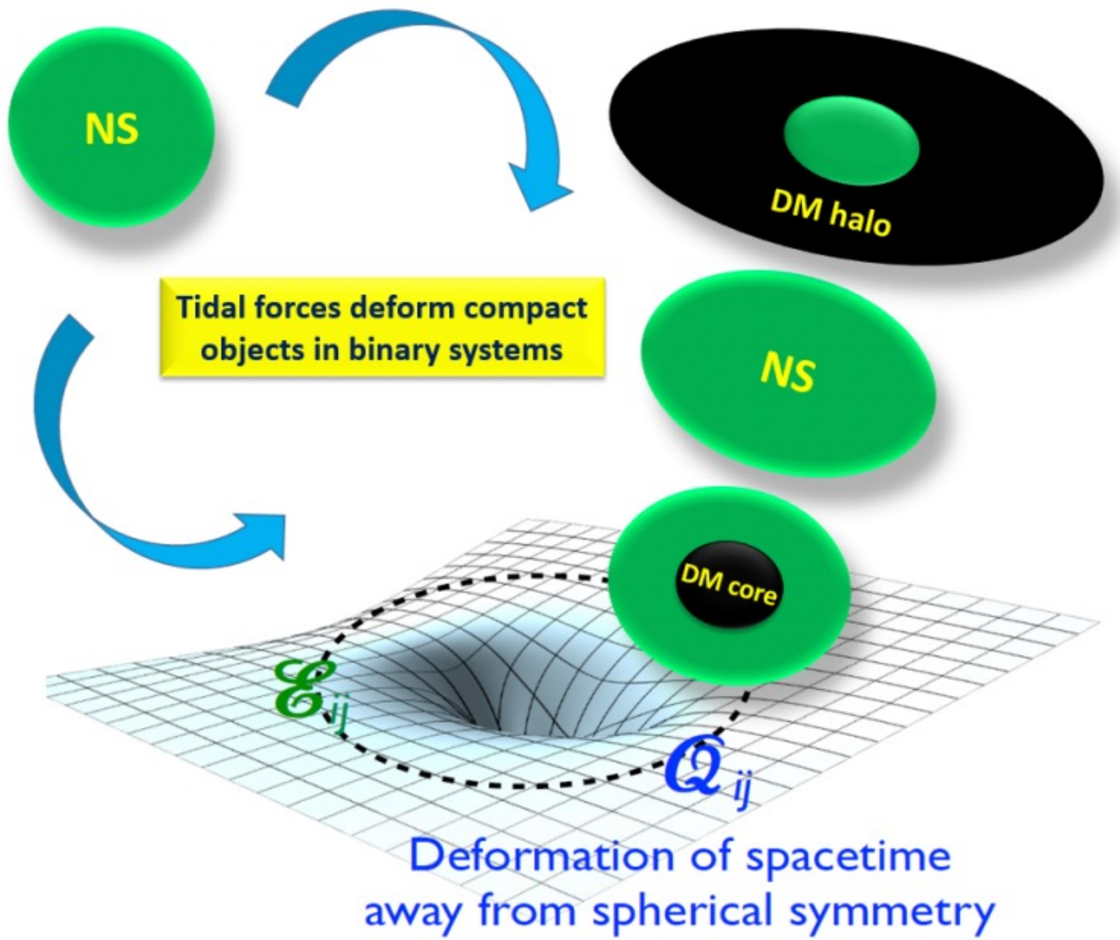


Fig. 7. Mass-Radius profiles for DM admixed NSs for $m_\chi = 400$ MeV (left) which corresponds to a DM core formation and $m_\chi = 100$ MeV (right) that represents an extended DM halo formation around a NS. Coupling constant is fixed to $\lambda = \pi$ and different F_χ are considered as labeled.

$$\frac{dp_{\mathrm{B}}}{dr} = -\left(p_{\mathrm{B}} + \epsilon_{\mathrm{B}}\right) \frac{M + 4\pi r^3 p}{r(r - 2M)},$$
$$\frac{dp_{\mathrm{D}}}{dr} = -\left(p_{\mathrm{D}} + \epsilon_{\mathrm{D}}\right) \frac{M + 4\pi r^3 p}{r(r - 2M)},$$

D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Bosonic Dark Matter in NS



D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Bosonic Dark Matter in NS

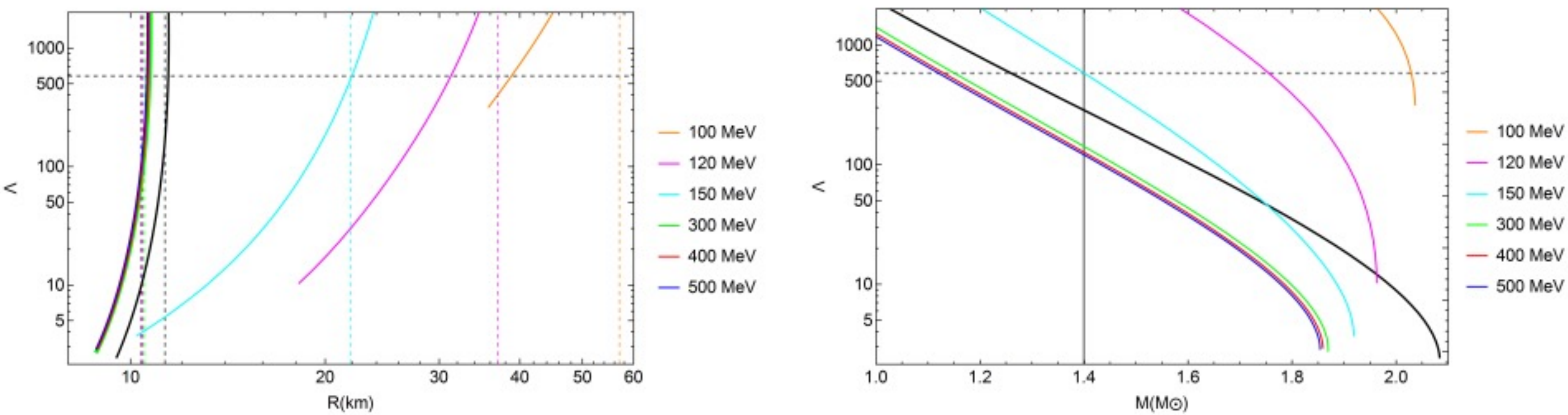
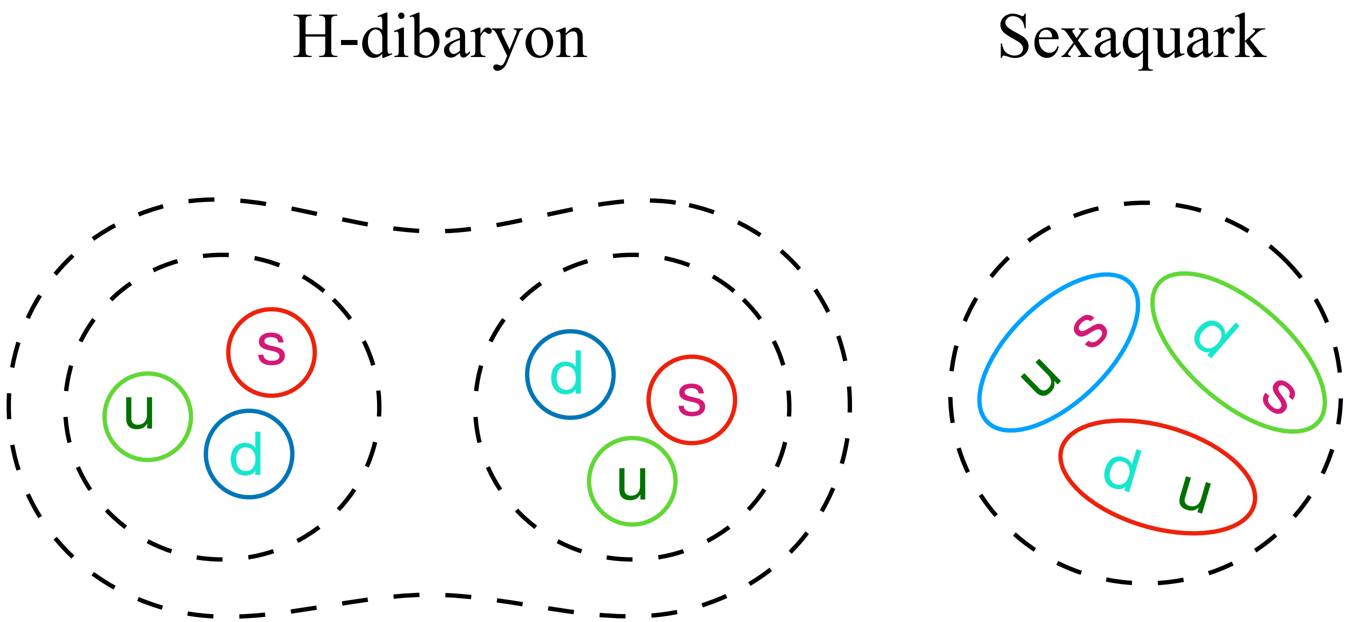


Fig. 8. Tidal deformability (Λ) as a function of total mass (right) and outermost radius (left) for stable sequences of DM admixed NSs. Various boson masses are considered, $m_\chi = 100, 120, 150$ MeV correspond to a DM halo formation while for $m_\chi = 300, 400, 500$ MeV a DM core is formed inside NS. Coupling constant and DM fraction are fixed at π and 10%, respectively.

D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, arXiv:2112.14231

Sexaquarks in NS



M. Shahrbaf, D. Blaschke, S. Typel, D. A-C, and G. R. Farrar, *in preparation*, (2022)

Sexaquarks in NS

- An S with mass below 2054 MeV is either absolutely stable or has a lifetime greater than the age of the Universe. Two separate baryons with the same quark content as the *S* have a mass $\geq 2m_{\Lambda} = 2231.36$ MeV. Thus for the *S* to be effectively stable, its quarks must be more deeply bound by at least 176.9 MeV.

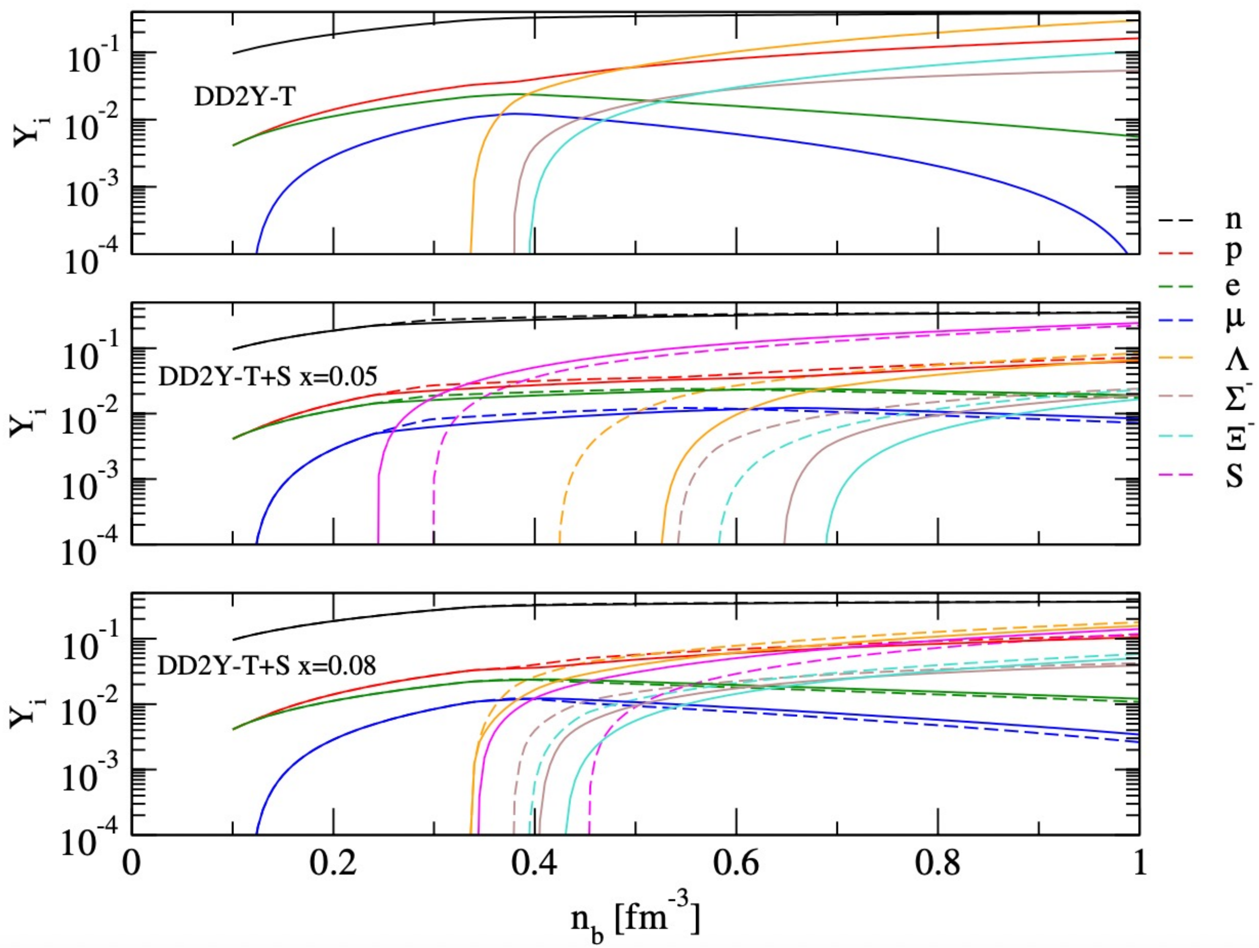
- The observed dark matter to baryon ratio is $\Omega_{DM} / \Omega_B = 5.3 \pm 0.1$. An abundance of *S* dark matter (SDM) in agreement with this observation has been obtained within a statistical model on the basis of the assumptions for the quark masses and an effective temperature $T_{eff} = 156$ MeV of the transition from the quark-gluon plasma to the hadronic phase when $m_S = 1860$ MeV.

- *S* might be a deeply bound state with low enough mass to be stable so that it can not decay on the weak interaction timescale and is therefore a dark matter (DM) candidate.

- The fact that the light S cannot decay and that it is electrically neutral explains why it has so far evaded detection in laboratory experiments. For an overview and detection strategies, see arXiv:2201.01334.

M. Shahrbaf, D. Blaschke, S. Typel, D. A-C, and G. R. Farrar, *in preparation*, (2022)

Sexaquarks in NS



M. Shahrbaf, D. Blaschke, S. Typel, D. A-C, and G. R. Farrar, *in preparation*, (2022)

TABLE IV: The opted parameters of hadronic matter as well as quark matter which have been investigated as a hybrid solution with MC.

set	m_S [MeV]	x	η_V	c_s^2/c^2	A [MeVfm^{-3}]	B [MeVfm^{-3}]	B$_0$ [MeVfm^{-3}]	B$_1$ [MeVfm^{-3}]	$\mu_<$ [MeV]	$\Gamma_<$ [MeV]	scenario
MC-S$_{1941}$-1	1941	0.05	0.11	0.45	93.49	81.73	9.0	0	0	0	S$_{1941}$DY
MC-S$_{1941}$-2	1941	0.05	0.14	0.48	94.99	85.50	5.7	0	0	0	S$_{1941}$DY
MC-S$_{1941}$-3	1941	0.05	0.17	0.52	96.85	90.18	0	7.0	1020	110	S$_{1941}$DY
MC-S$_{1941}$-4	1941	0.08	0.14	0.48	94.99	85.50	0	10.0	1250	100	YS$_{1941}$D
MC-S$_{1941}$-5	1941	0.05	0.17	0.52	96.85	90.18	0	0	0	0	DS$_{1941}$Y
MC-S$_{1885}$-6	1885	0.030	0.14	0.48	94.99	85.50	0	0	0	0	S$_{1885}$DY
MC-S$_{1885}$-7	1885	0.035	0.13	0.47	94.45	84.14	0	0	0	0	DS$_{1885}$Y
MC-S$_{1885}$-8	1885	0.040	0.13	0.47	94.45	84.14	1.8	0	0	0	DS$_{1885}$Y
MC-S$_{1885}$-9	1885	0.050	0.13	0.47	94.45	84.14	3.5	0	0	0	DS$_{1885}$Y

TABLE V: Parameter sets characterizing hybrid EoS which have been investigated as a solution for RIC when S_1 is included in hadronic matter. In different sets, A corresponds to $x = 0.03$, B corresponds to $x = 0.04$ and C corresponds to $x = 0.05$.

set	m_S [MeV]	x	η_V	c_s^2/c^2	A [MeVfm^{-3}]	B [MeVfm^{-3}]	B$_0$ [MeVfm^{-3}]	Δ_p	μ_H [MeV	μ_Q MeV]	scenario
RIC-A-1	1885	0.03	0.14	0.48	94.99	85.50	0	-3%	1027.76	1121.92	S$_{1885}$DY
RIC-A-2	1885	0.03	0.14	0.48	94.99	85.50	0	-5%	1019.32	1261.74	S$_{1885}$YD
RIC-A-3	1885	0.03	0.14	0.48	94.99	85.50	0	-7%	1012.81	1418.92	S$_{1885}$YD
RIC-B-1	1885	0.04	0.14	0.48	94.99	85.50	-4	-7%	1064.10	1335.80	S$_{1885}$YD
RIC-C-1	1885	0.05	0.12	0.46	93.95	82.88	0	-3%	1122.39	1286.74	S$_{1885}$YD
RIC-C-2	1885	0.05	0.12	0.46	93.95	82.88	0	-5%	1097.33	1398.25	S$_{1885}$YD

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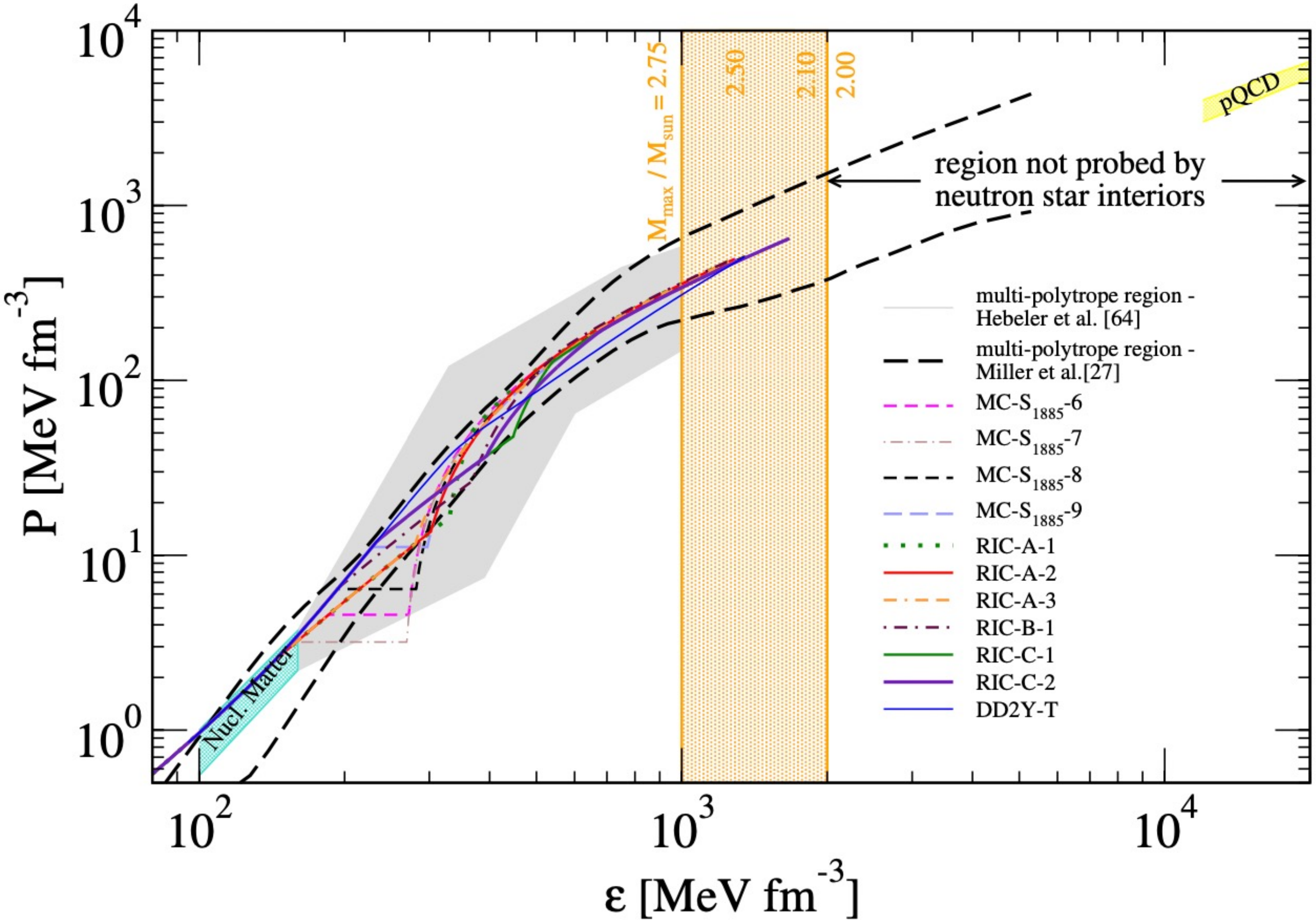
Sexaquarks in NS



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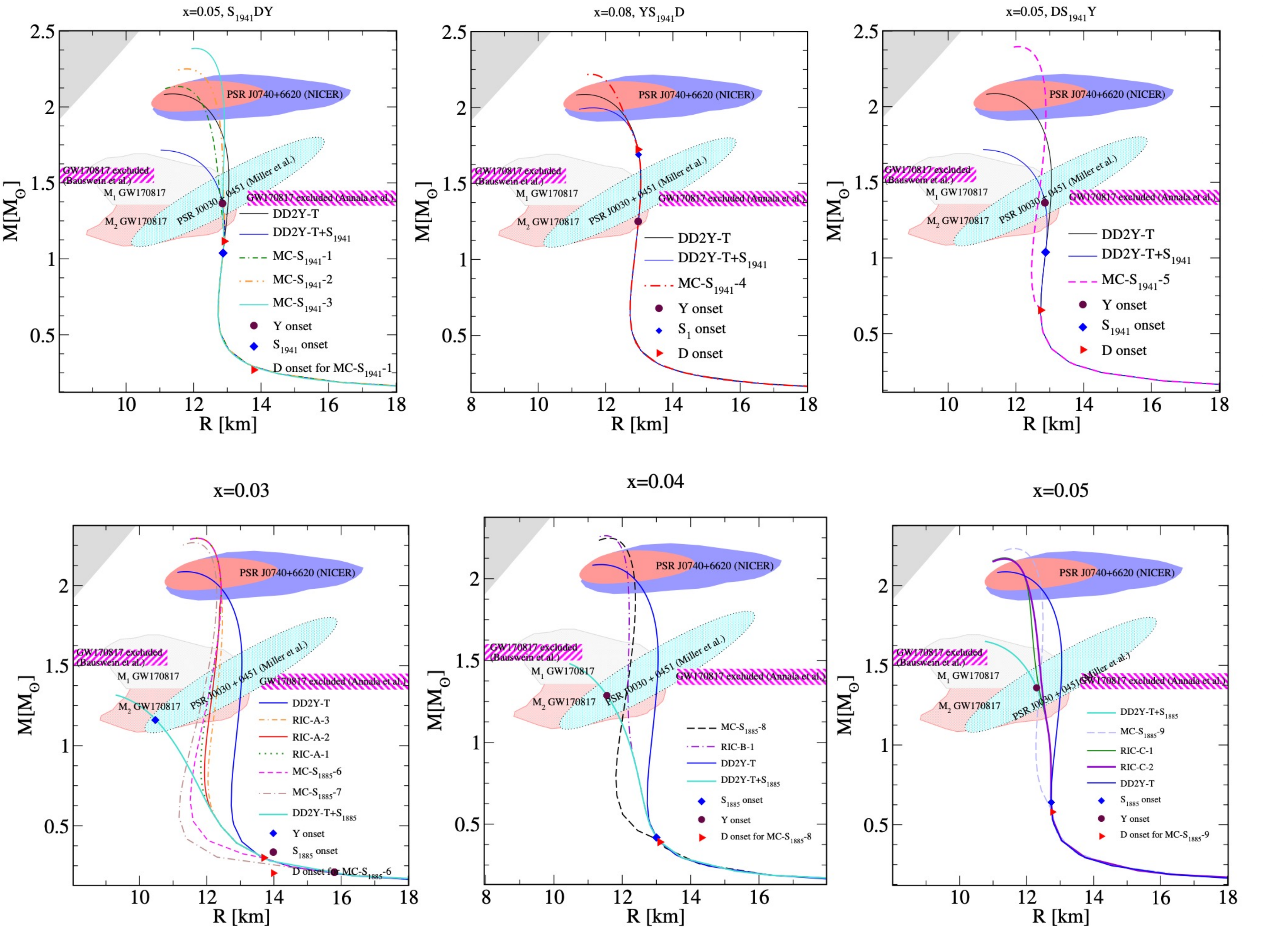
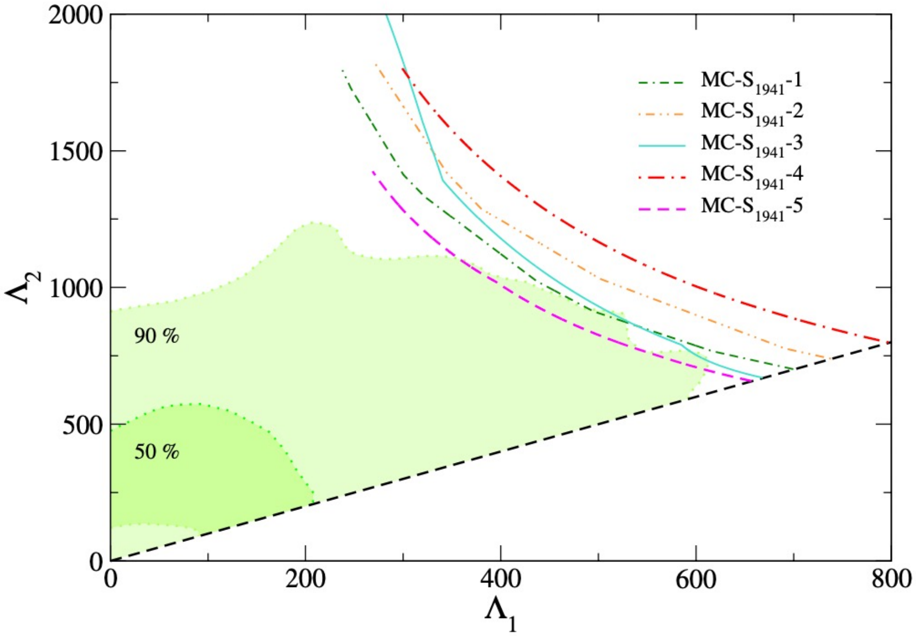
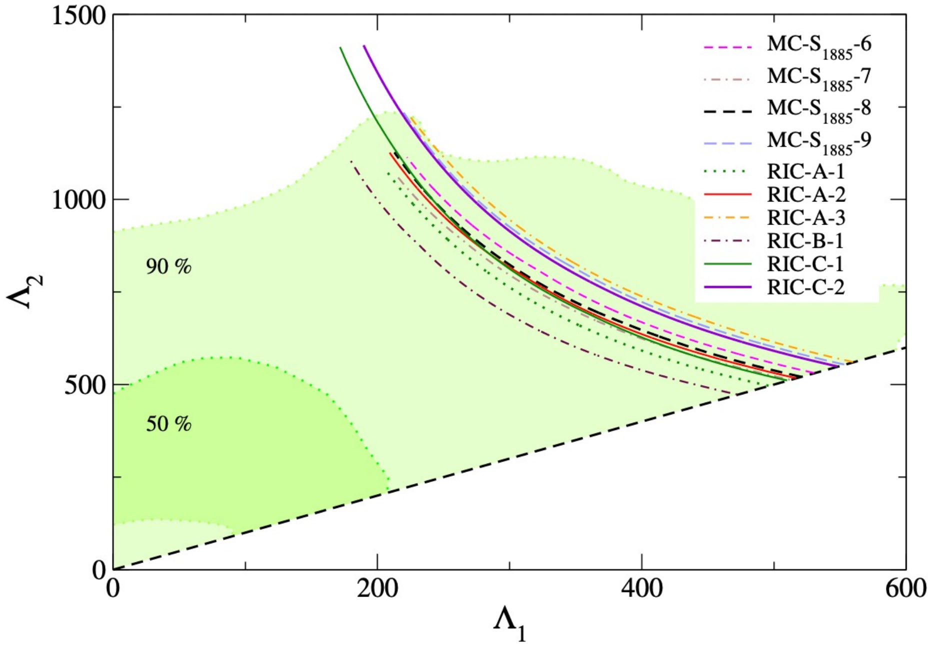

x=0.05, S1941DY
x=0.08, YS1941D
x=0.05, DS1941Y
x=0.03
x=0.04
x=0.05
PSR J0740+6620 (NICER)
PSR J0030 + 0451 (Miller et al.)
GW170817 excluded (Bauswein et al.)
GW170817 excluded (Annala et al.)
M1 GW170817
M2 GW170817
DD2Y-T
DD2Y-T+S1941
MC-S1941-1
MC-S1941-2
MC-S1941-3
MC-S1941-4
MC-S1941-5
Y onset
S1941 onset
S1 onset
D onset
D onset for MC-S1941-1
RIC-A-3
RIC-A-2
RIC-A-1
MC-S1885-6
MC-S1885-7
DD2Y-T+S1885
S1885 onset
D onset for MC-S1885-6
MC-S1885-8
RIC-B-1
D onset for MC-S1885-8
MC-S1885-9
RIC-C-1
RIC-C-2
D onset for MC-S1885-9
M[M⊙]
R [km]

Tidal deformabilities from GW170817





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Outlook

- Multi-messenger astronomy and collider experiments will continue probing the properties of dense matter.
- As we advance on the quest for clarification of the neutron star internal content, we will be able to reveal or discard the existence of dark matter in the corresponding stellar interiors and environments.
- Bayesian Analysis and Machine Learning methods are useful for estimation of unknown physical parameters, specially for simultaneously studying the various physical processes involving dark matter.


NICER
Neutron Star Interior Composition Explorer
LIGO
KAGRA
Virgo
ATHENA
ET
EINSTEIN
TELESCOPE
STROBE-X
SK
A
SKA AFRICA
SQUARE KILOMETRE ARRAY
MeerKAT
ngvla
eXTP
enhanced X-ray Timing and Polarimetry Mission