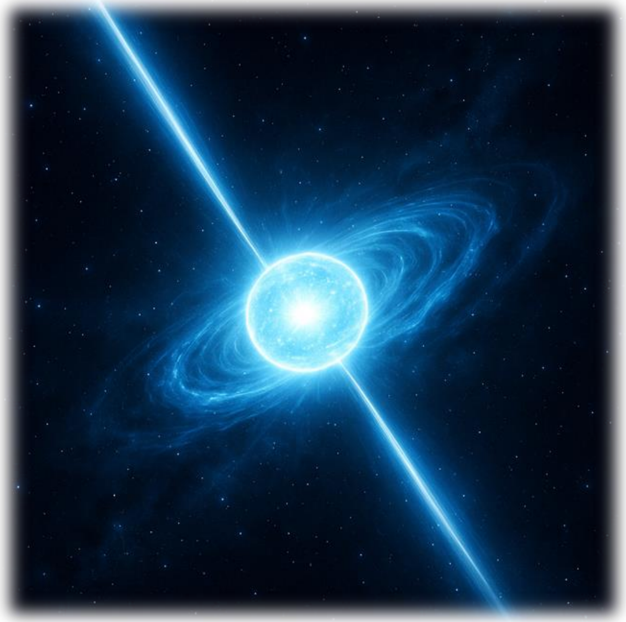
Observational Probes of the Neutron Star Equation of State with Hyperons, Sexaquarks, and Quark Matter

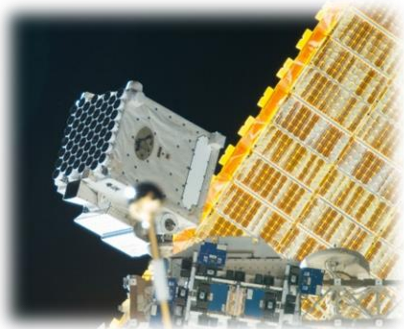
Avraham's talk: deeply bound H-dibaryon

Davood Rafiei Karkevandi

Institute of Theoretical Physics, Wroclaw University, Poland

EMMI Workshop
5th Workshop Anti-Matter, Hyper-Matter and Exotica Production at the LHC,
Nov 10-14, 2025, Salerno, Italy





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NO. 2023/48/C/ST2/00297 and 2023/51/B/ST9/02798

Observational Probes of the Neutron Star Equation of State with Hyperons, Bosonic Dark Matter, and Quark Matter

Mahboubeh Shahrbaf[1,2,3⋆], Davood Rafiei Karkevandi[1⋆⋆], Alexander Ayriyan[1,4⋆⋆⋆], and Stefan Typel[5,6]

1 Institute for Theoretical Physics, University of Wrocław, Plac Maksa Borna 9, 50-204 Wrocław, Poland
2 Incubator of Scientific Excellence, Center for Simulations of Superdense Fluids, University of Wrocław, Plac Maksa Borna 9, 50-204 Wrocław, Poland
3 Frankfurt Institute for Advanced Studies, Giersch Science Center, D-60438 Frankfurt am Main, Germany
4 Alikhanyan National Science Laboratory (Yerevan Institute of Physics), Alikhanyan Brothers St 2, 0036 Yerevan, Armenia
5 Technische Universität Darmstadt, Fachbereich Physik, Institut für Kernphysik, Schlossgartenstraße 9, D-64289 Darmstadt, Germany
6 GSI Helmholtzzentrum für Schwerionenforschung GmbH, Theorie, Planckstraße 1, D-64291 Darmstadt, Germany

arXiv:2402.18686v2

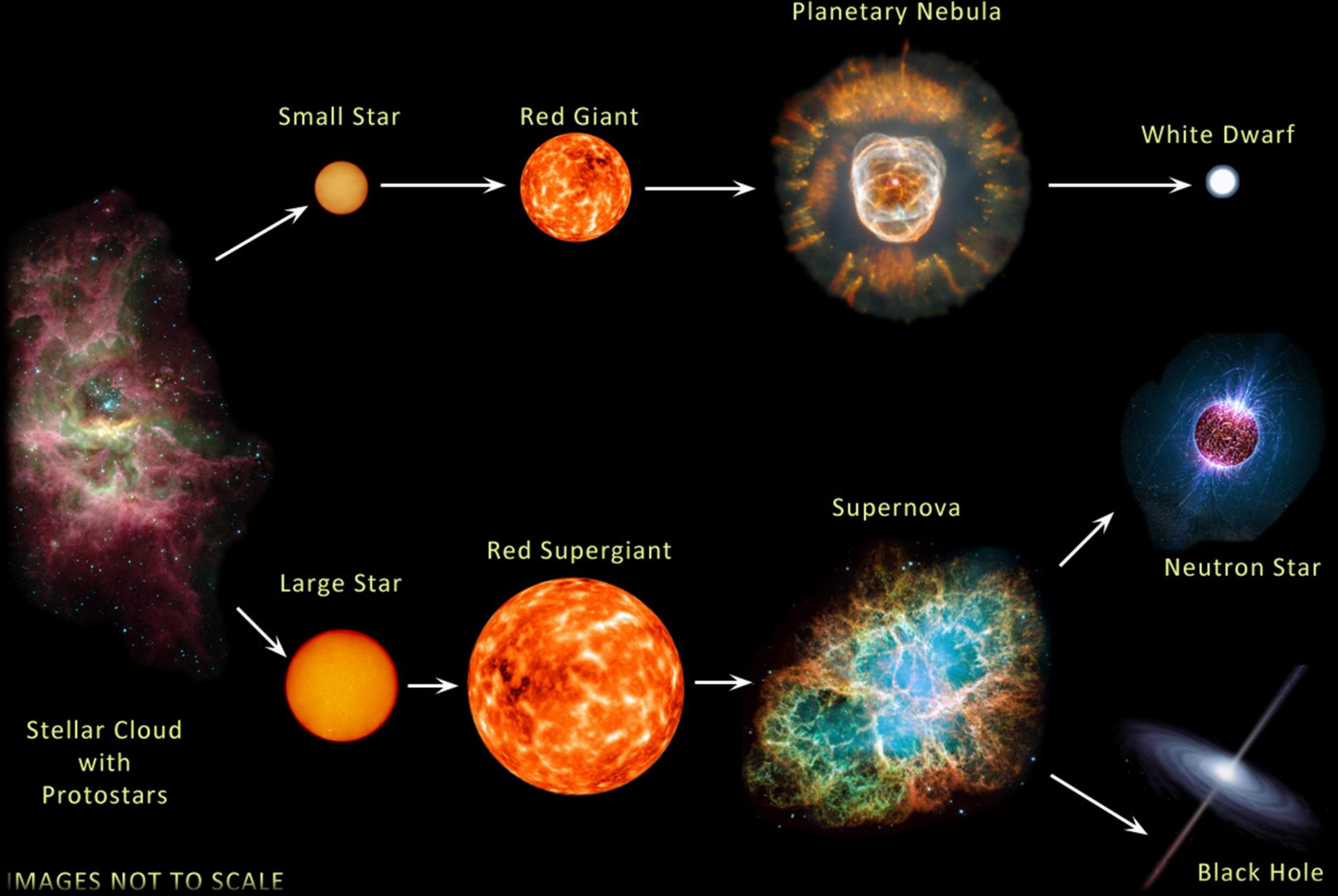
Accepted for publication in Astronomy & Astrophysics

Probing Strange Dark Matter through f-mode Oscillations of Neutron Stars with Hyperons and Quark Matter

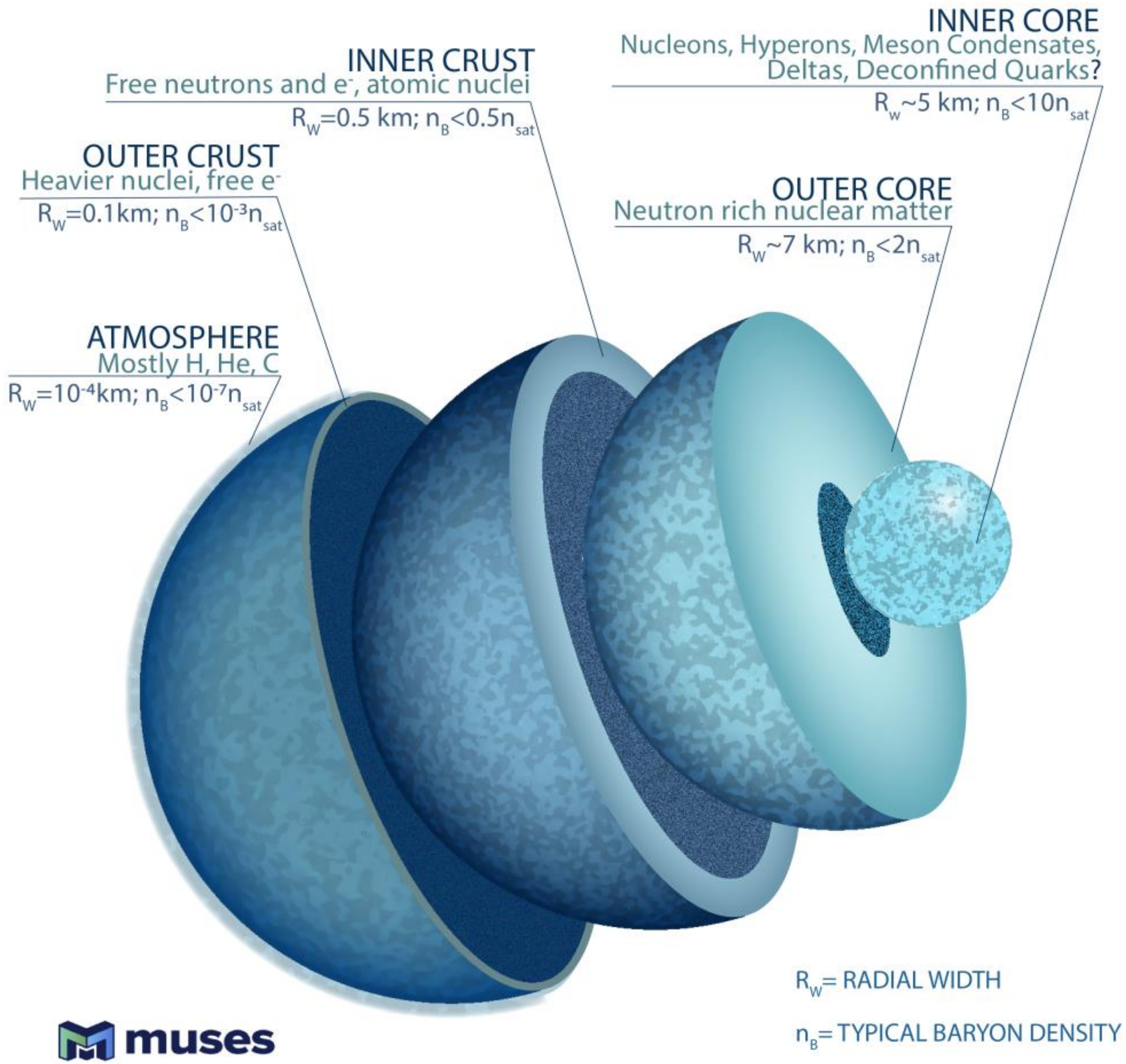
Mahboubeh Shahrbaf[1,*] Prashant Thakur[2,†] and Davood Rafiei Karkevandi[1‡]
[1] *Institute of Theoretical Physics, University of Wroclaw, 50-204 Wroclaw, Poland and*
[2] *Department of Physics, Yonsei University, Seoul, 03722, South Korea*

arXiv:2510.08115

EVOLUTION OF STARS



IMAGES NOT TO SCALE



muses

Living Rev.Rel. 27 (2024) 1, 3 (arXiv:2303.17021)

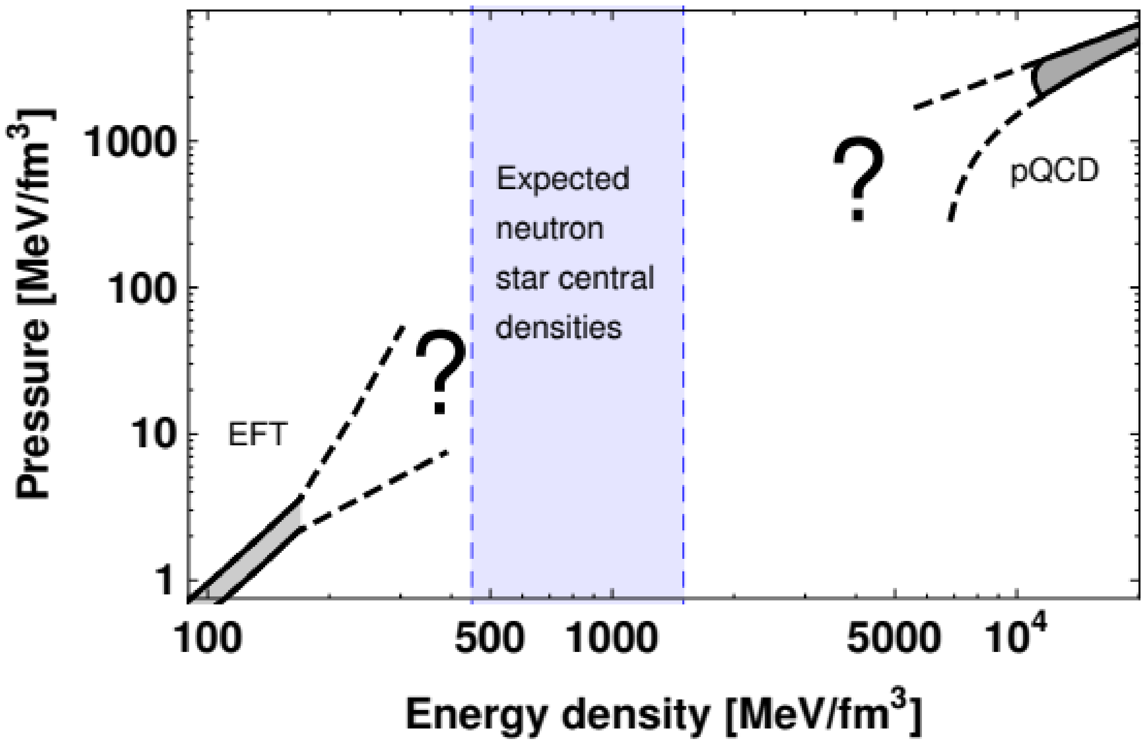
Crab Pulsar

Mass ~ 1.4 – 2 solar mass ($M_\odot$)

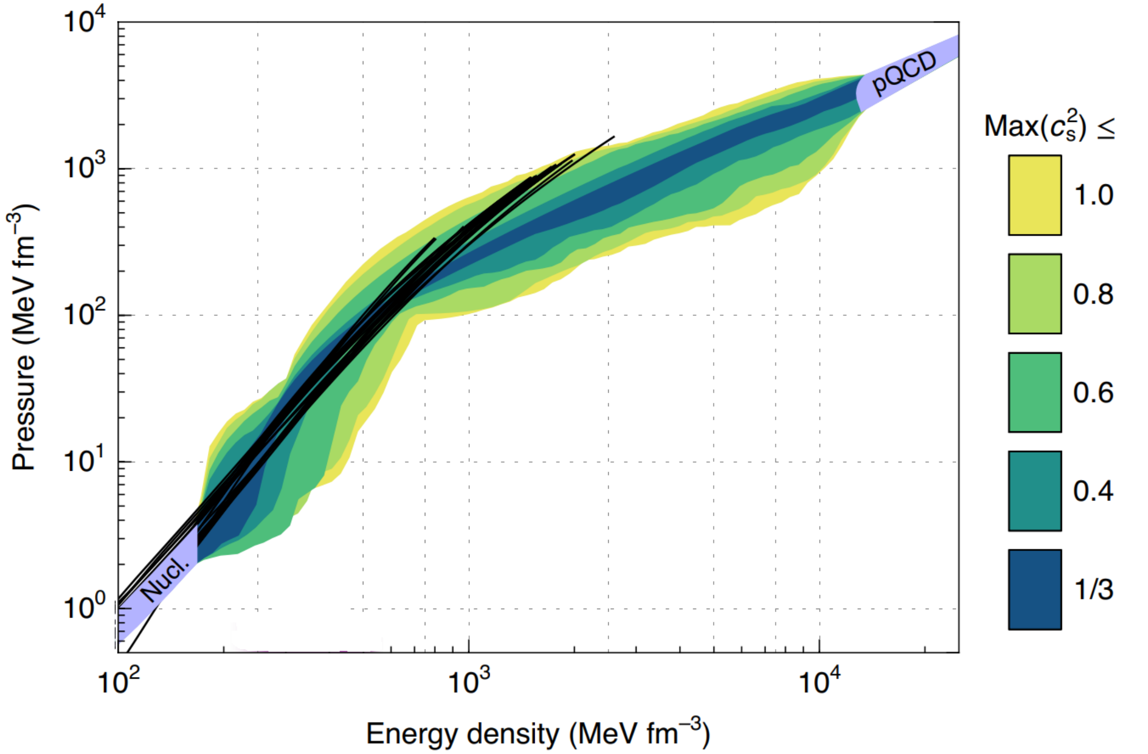
Radius ~ 10 – 13 km

Neutron stars as a natural laboratory for high density matter

Equation of state of ultra-high density matter
$P = P(\varepsilon)$



Matti Järvinen, *Eur. Phys. J. C (2022) 82:282*



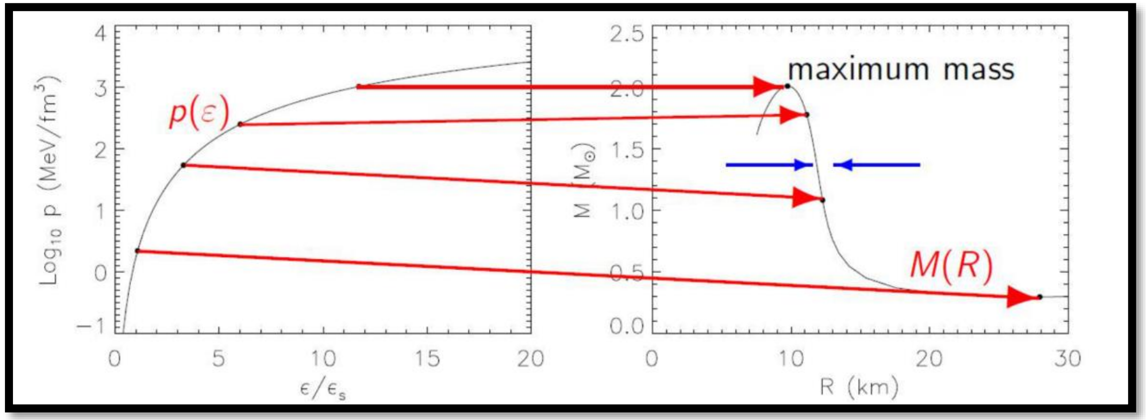
Eemeli Annala, *Nature Phys. 16 (2020) 9, 907-910*

Tolman-Oppenheimer-Volkof (TOV) equations

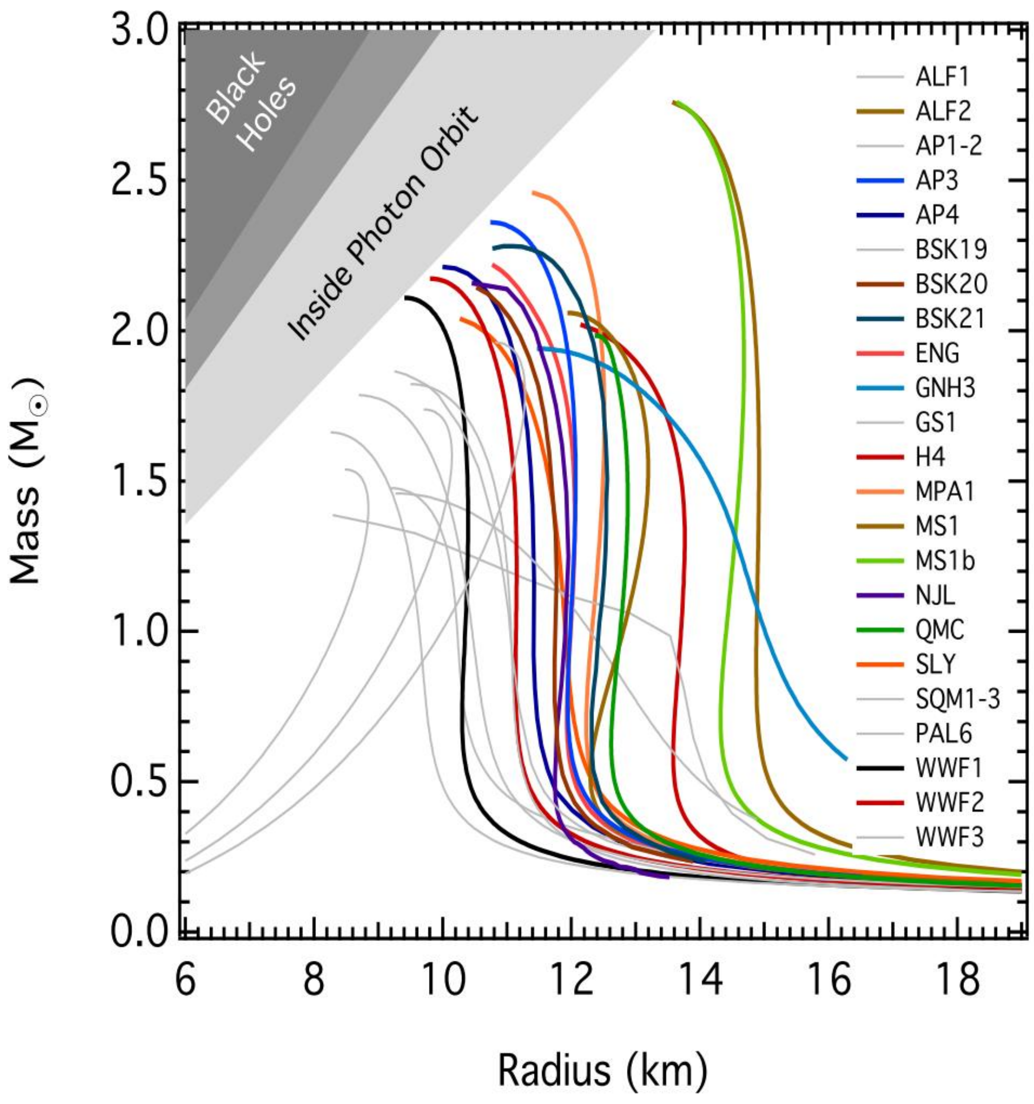
$$\frac{dP(r)}{dr} = -\frac{GM(r)\varepsilon(r)}{c^2r^2}\left[1+\frac{P(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3P(r)}{M(r)c^2}\right]\left[1-\frac{2GM(r)}{c^2r}\right]^{-1}$$

$$\frac{dM(r)}{dr} = \frac{4\pi r^2\varepsilon(r)}{c^2}$$

R. C. Tolman, *Phys. Rev. 55, 364 (1939).*
J. R. Oppenheimer and G. M. Volko, *Phys. Rev. 55,374 (1939).*

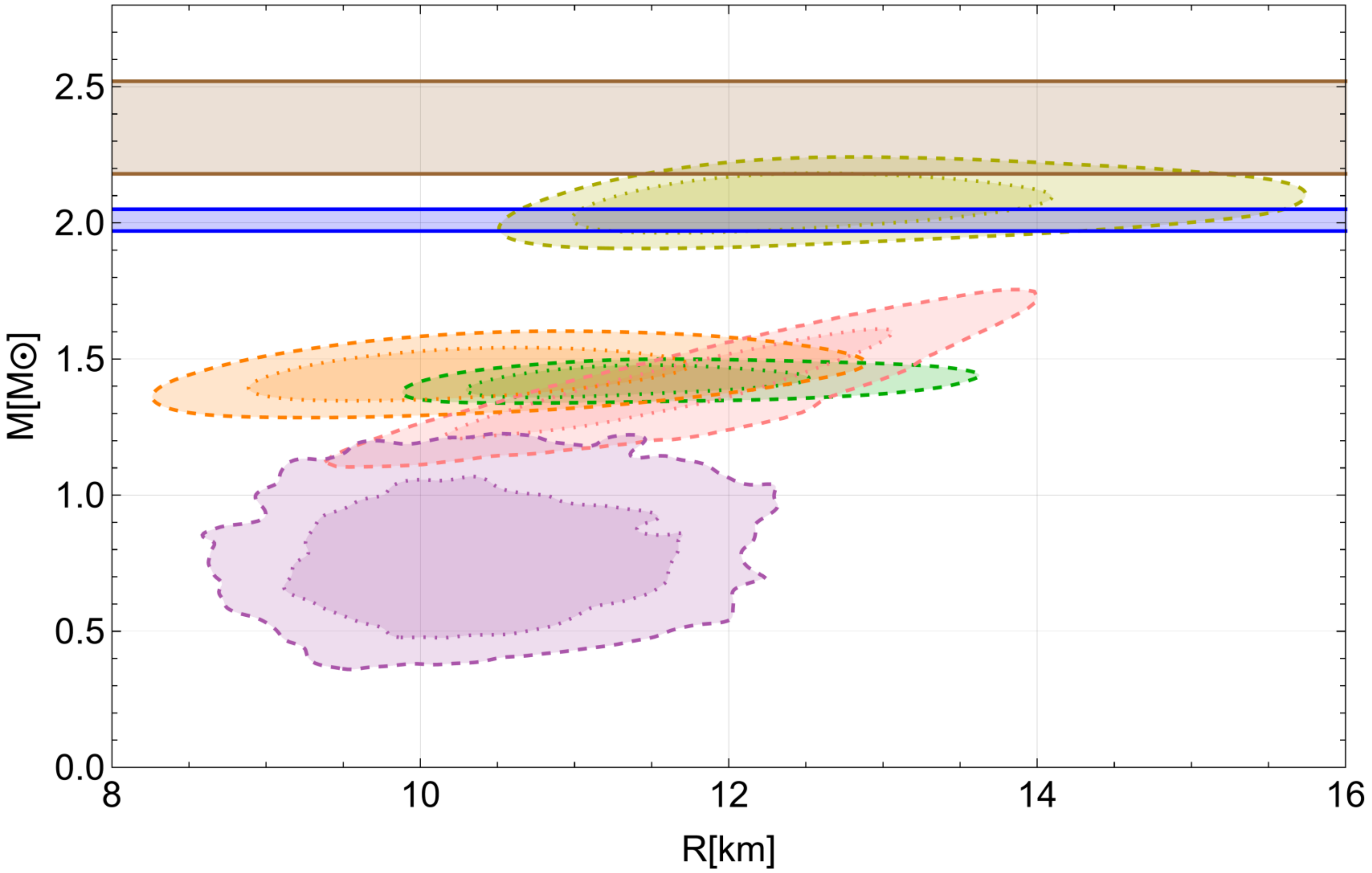


James Latimer, *EPJ Web of Conferences 109, 07004 (2016)*



Feryal Özel & Paulo Freire
Ann.Rev.Astron.Astrophys. 54 (2016) 401-440

Mass-Radius observational constraints



PSR J0348+0432, John Antoniadis et al, *Science, 26 April 2013, Vol: 340, Issue: 6131*

PSR J0030+0451, S. Vinciguerra et al., *Astrophys. J. 961, 62 (2024)*

PSR J0740+6620, T. Salmi et al., *Astrophys. J. 974, 294 (2024)*

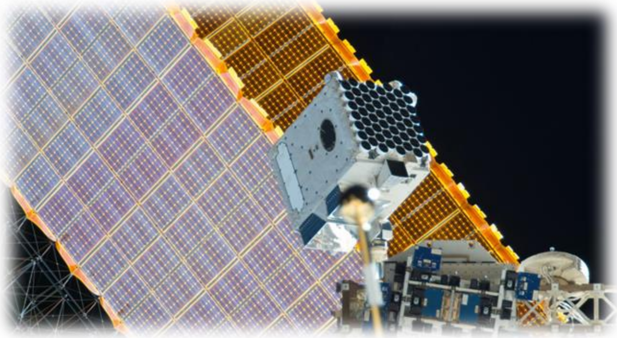
PSR J0614-3329 , Lucien Mauviard et al, *arXiv:2506.14883*

HESS J1731-347, Doroshenko et al, *Nature Astron., 6, 1444, 2022*

PSR J0437–4715, D. Choudhury et al., *Astrophys. J. Lett. 971, L20 (2024)*

PSR J0952–0607, W. Romani et al, *ApJL 934 L17, 2022*

NICER X-ray Telescope



Keck Optical Telescopes

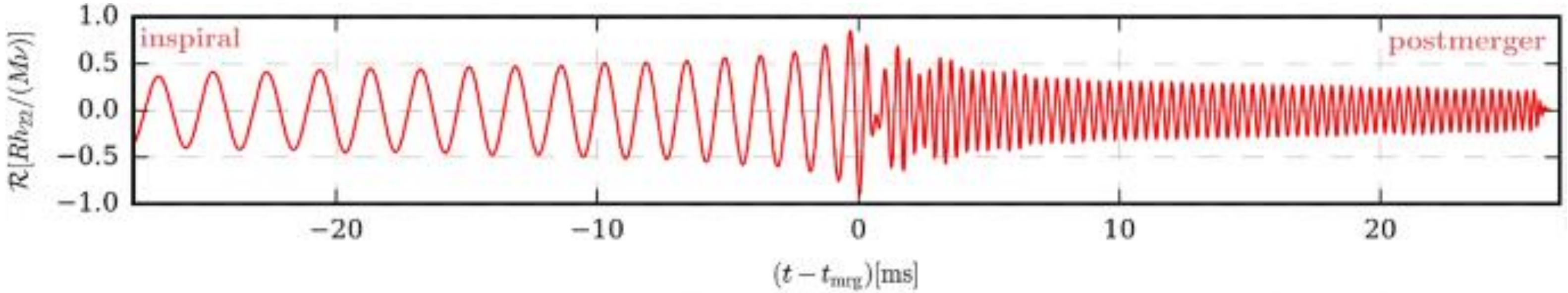
Green Bank Radio Telescope

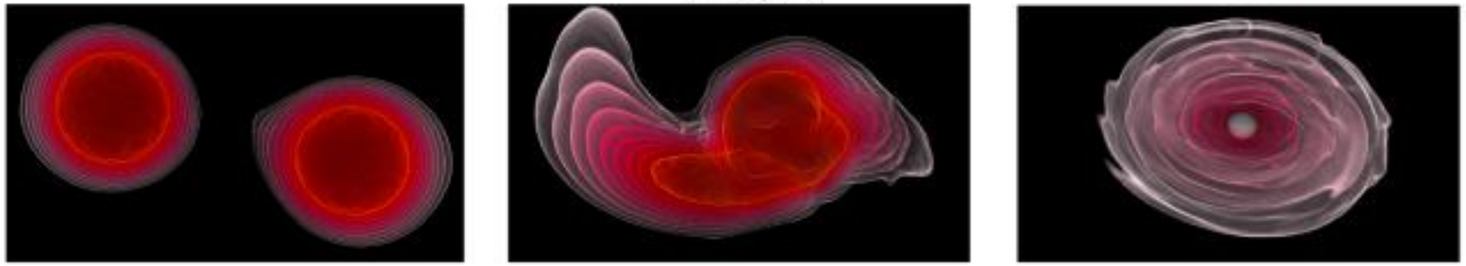
Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

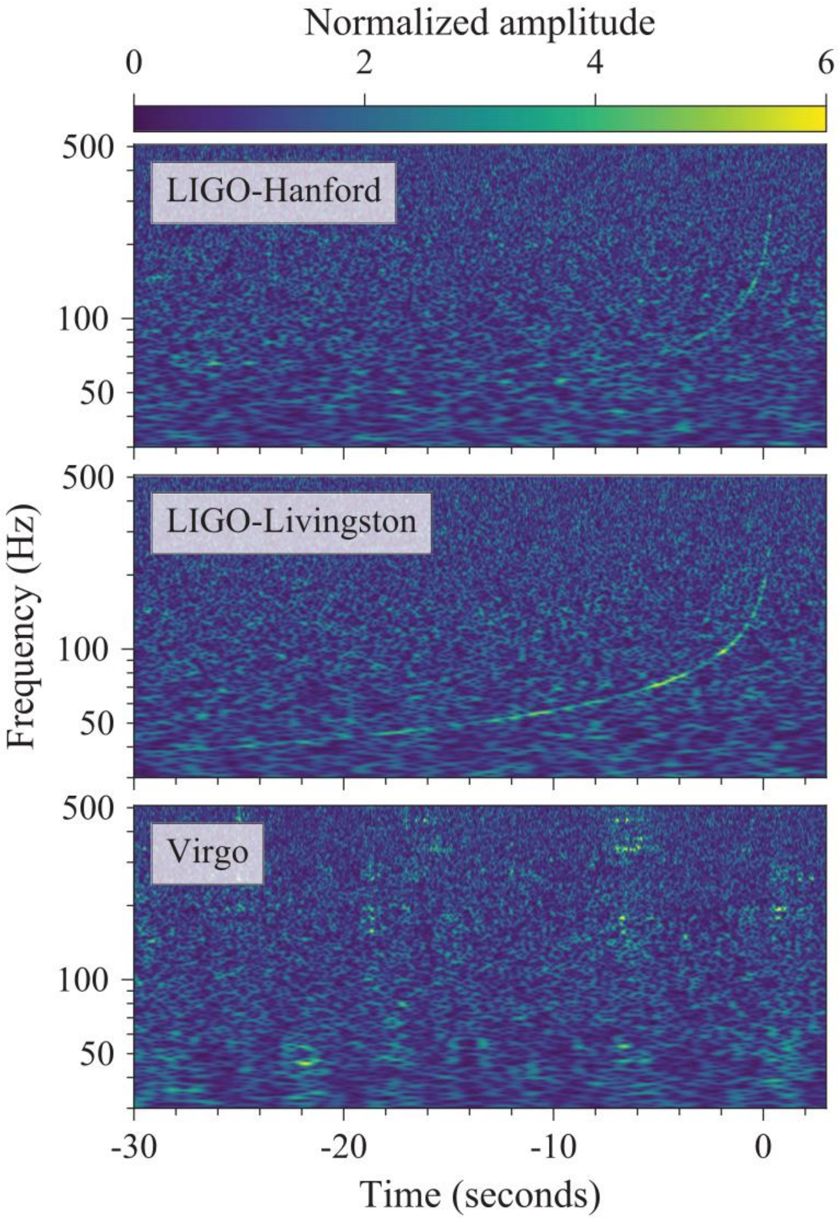
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

LIGO-Virgo Gravitational-Wave detectors





Tim Dietrich, et al *Gen.Rel.Grav. 53 (2021) 3, 27*



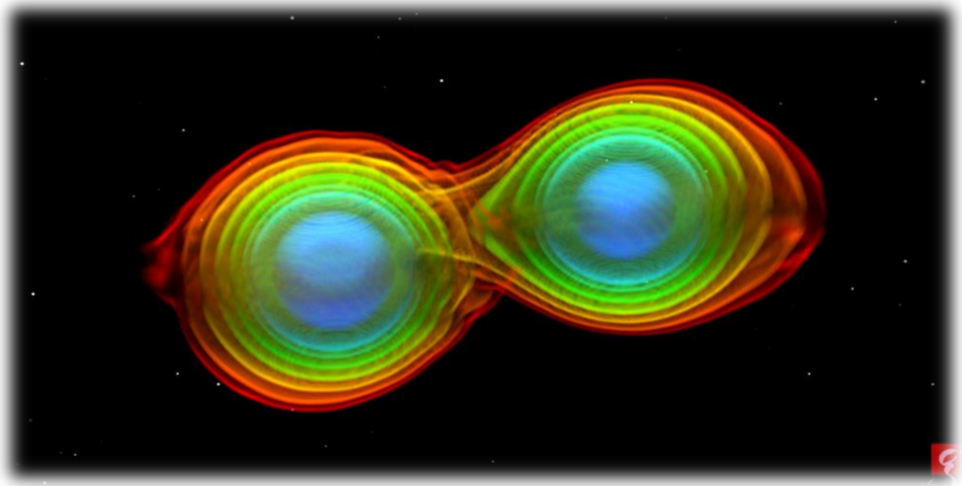
Deformation of the neutron star in the binary systems due to the tidal force

Dimensionless tidal deformability : $\Lambda = \frac{\lambda_t}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$

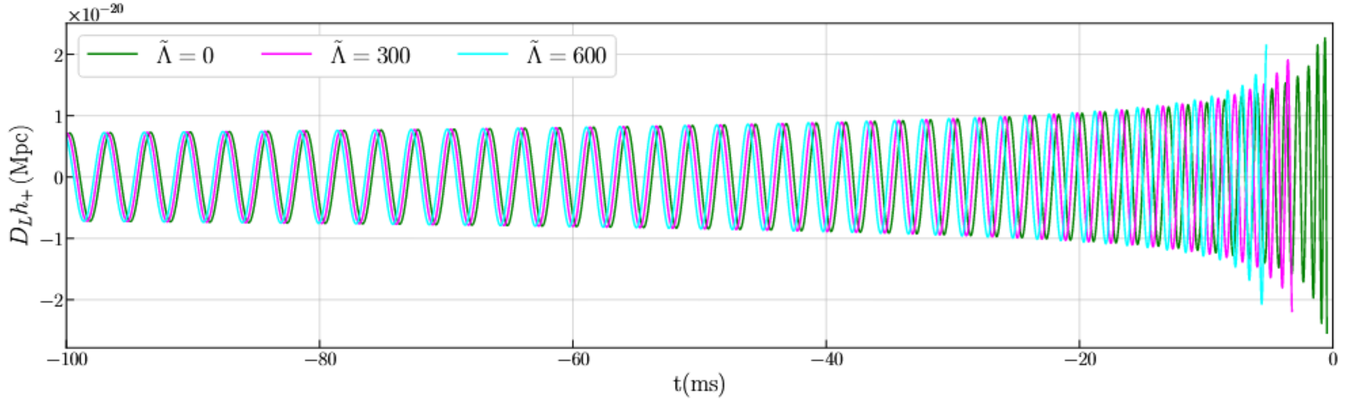
R and M are the mass and radius of star

k_2: Dimensionless tidal love number

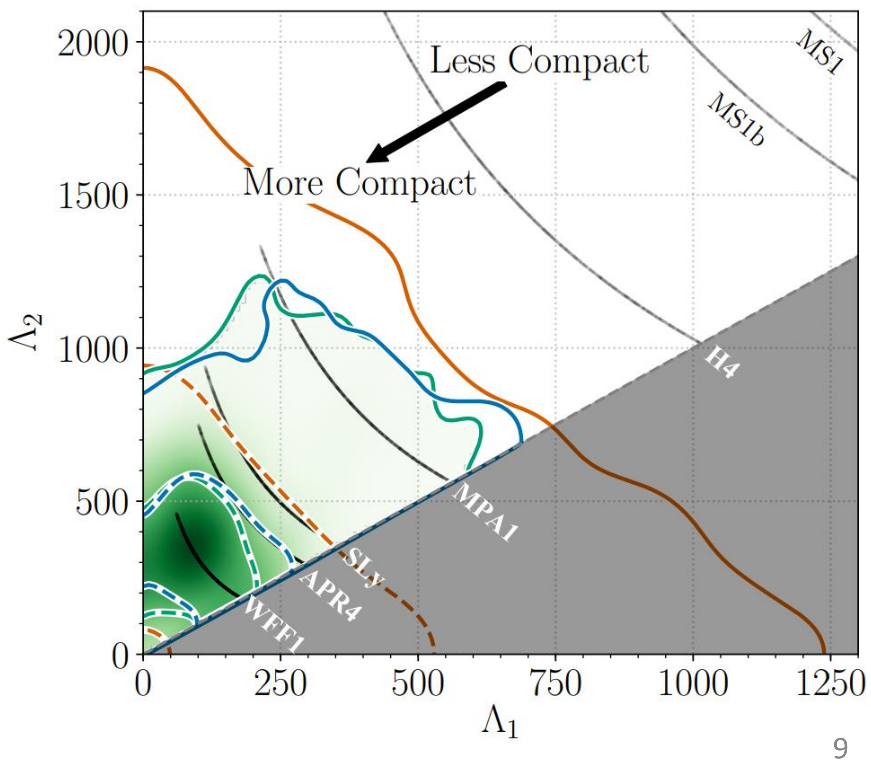
Tanja Hinderer, et al. *Phys.Rev.D81:123016,2010*



Tim Dietrich et al. Max Planck Institute



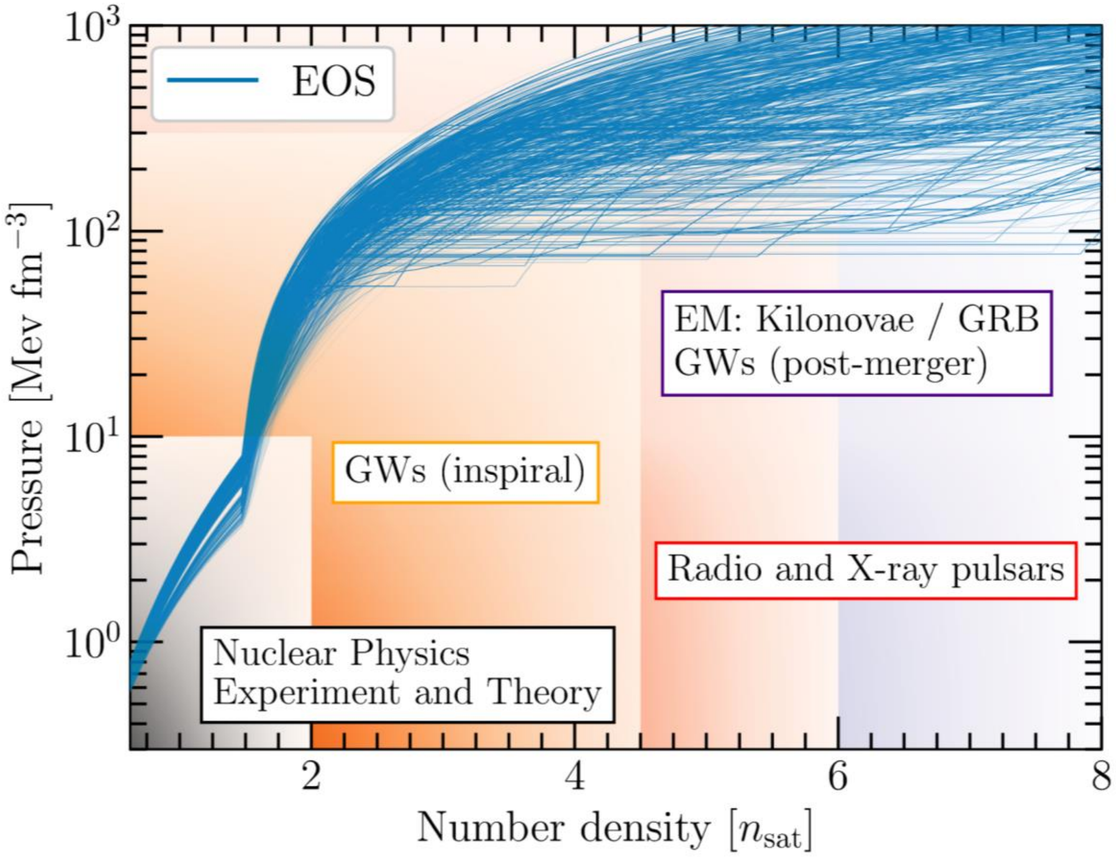
Katerina Chatziioannou, *Gen.Rel.Grav. 52 (2020) 11, 109*



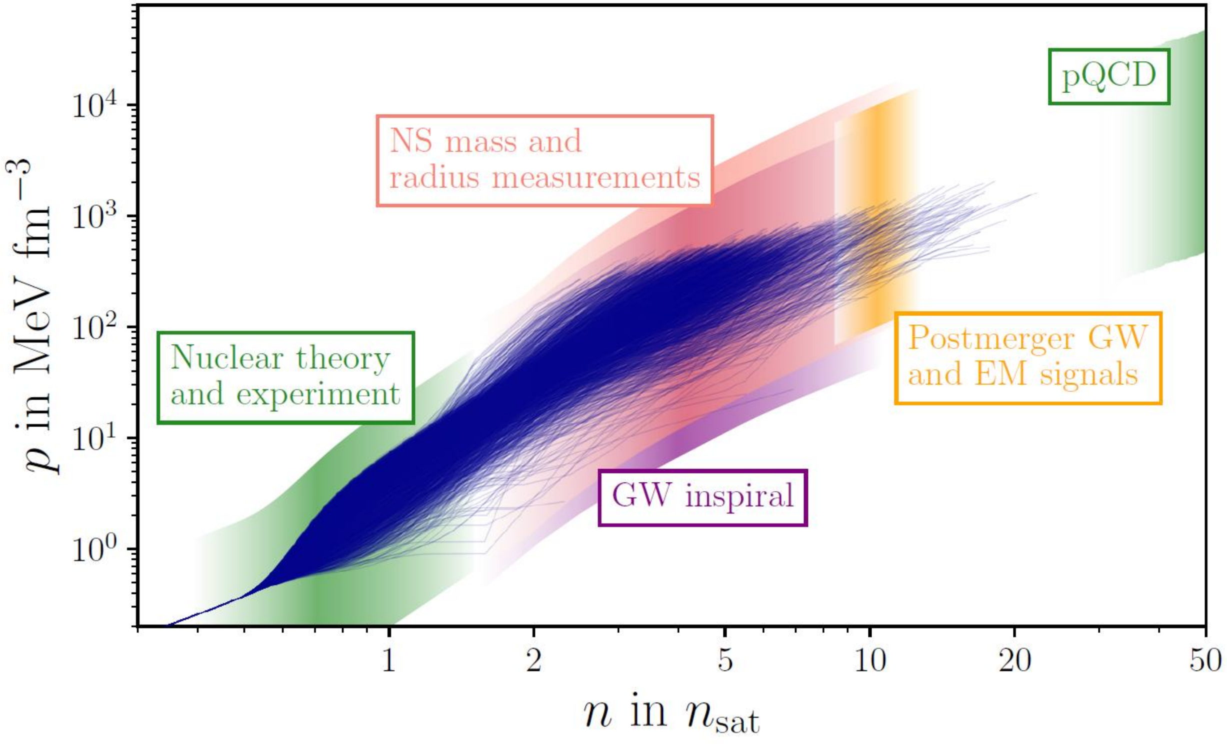
Dimensionless tidal deformability GW170817
$70 \leq \Lambda \leq 580$ for $M = 1.4M_\odot$

LIGO Scientific and Virgo Collaborations, *Phys.Rev.Lett. 121 (2018) 16*

Constraining the EOS of high-density matter by multi-messenger observations of neutron stars

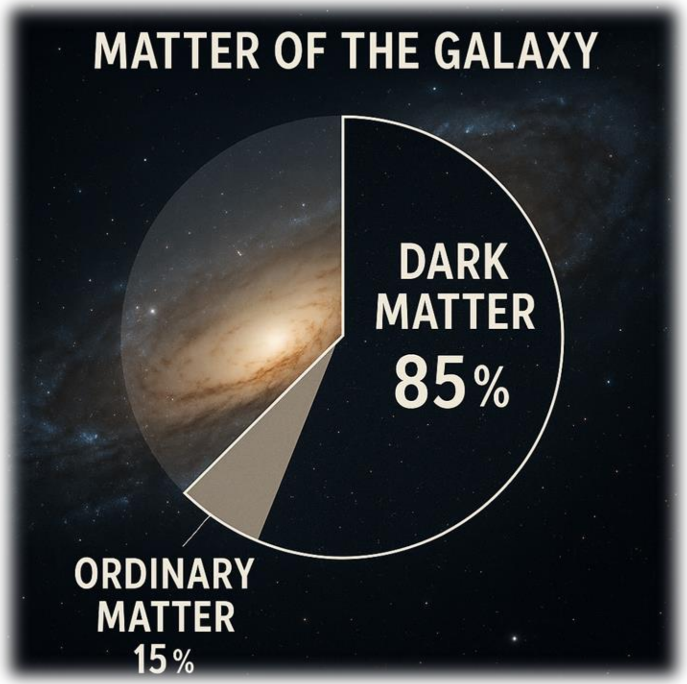


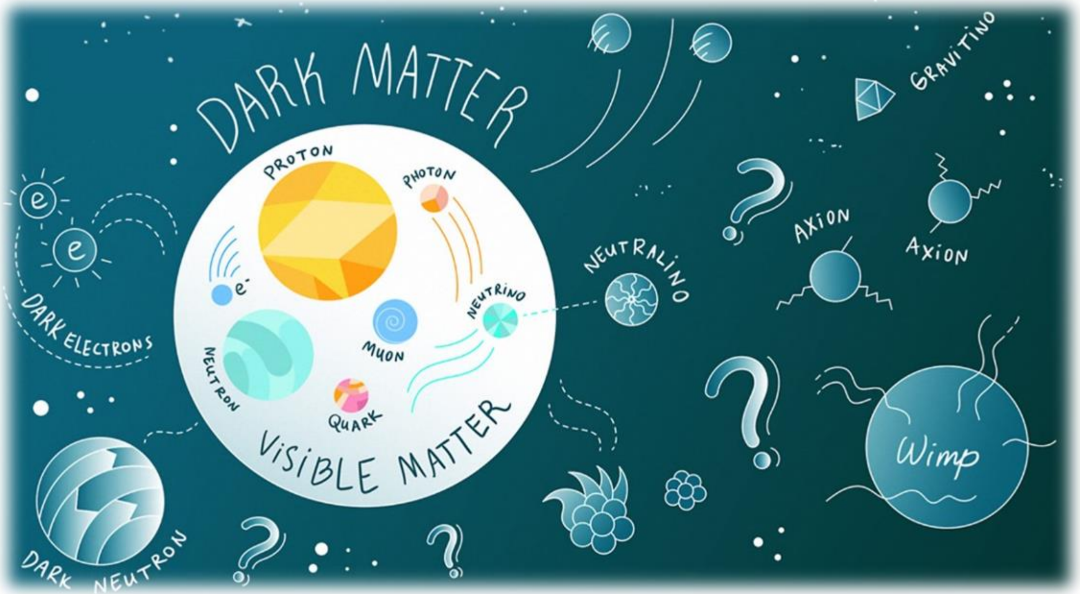
Peter T. H. Pang, et al. , *Nature Commun. 14 (2023) 1, 8352*



Hauke Koehn et al. *Phys.Rev.X 15 (2025) 2, 021014*

Dark matter constitutes about 85% of the matter in the universe, yet it remains a challenging puzzle in physics.

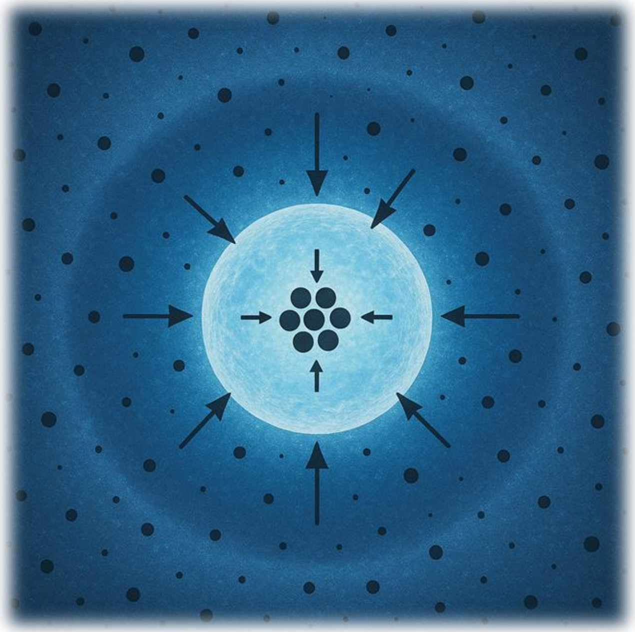


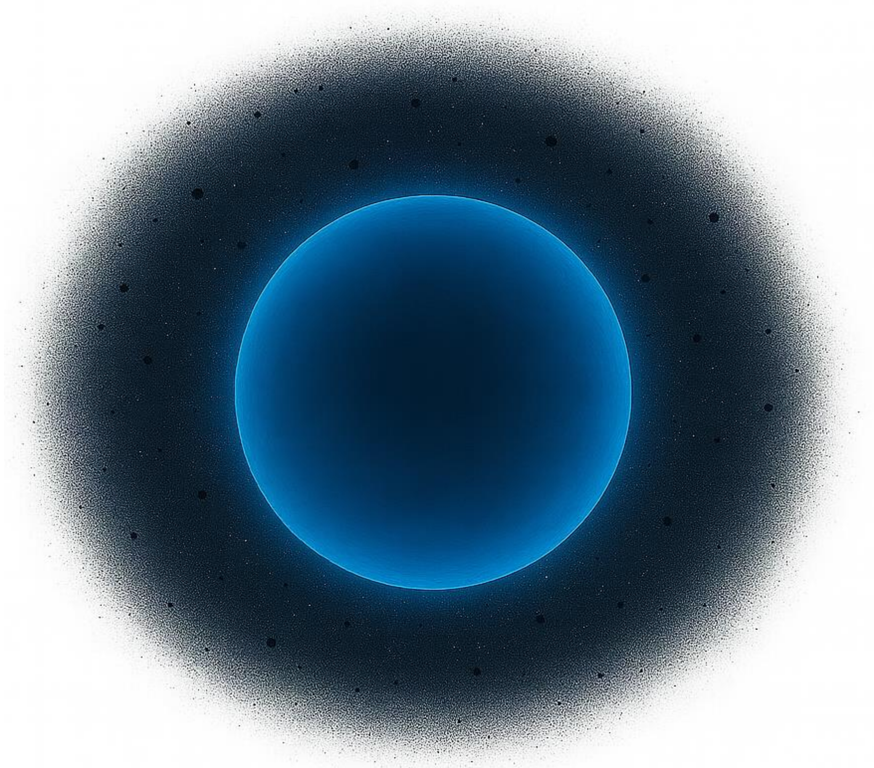


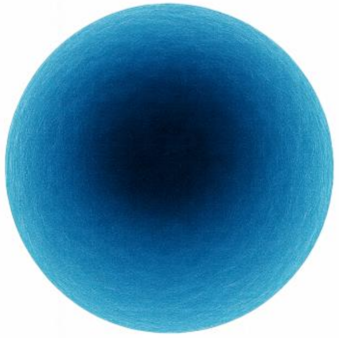
Main goal is to constrain the parameter space of the dark matter models and looking for signature

*Marco Cirelli, Alessandro Strumia, Jure Zupan, arXiv:2406.01705, **Review paper**.*

Neutron stars, due to their high densities and strong gravity, are promising astrophysical laboratories for probing the properties of dark matter.







Accretion of dark matter during different stages of stars' and neutron stars' life

Dark matter production in the neutron star matter or supernova explosions

Dark matter halo around neutron star

Dark matter core inside neutron star

Phys.Rev.D 74 (**2006**) 063003 → Jürgen → *Phys.Rev.D* 111 (**2025**) 8, 083038

Accretion of dark matter inside neutron stars

D.R.K, S. Shakeri, V. Sagun, O. Ivanytskyi,

Bosonic dark matter in neutron stars and its effect on gravitational wave signal

Phys. Rev. D 105, 023001 **(2022)** **[159 citations]**

D.R.K, S. Shakeri, V. Sagun, O. Ivanytskyi,

Tidal deformability as a probe of dark matter in neutron stars

World Scientific pp. 3713-3731 **(2023)** **[21 citations]**

S. Shakeri, D.R.K

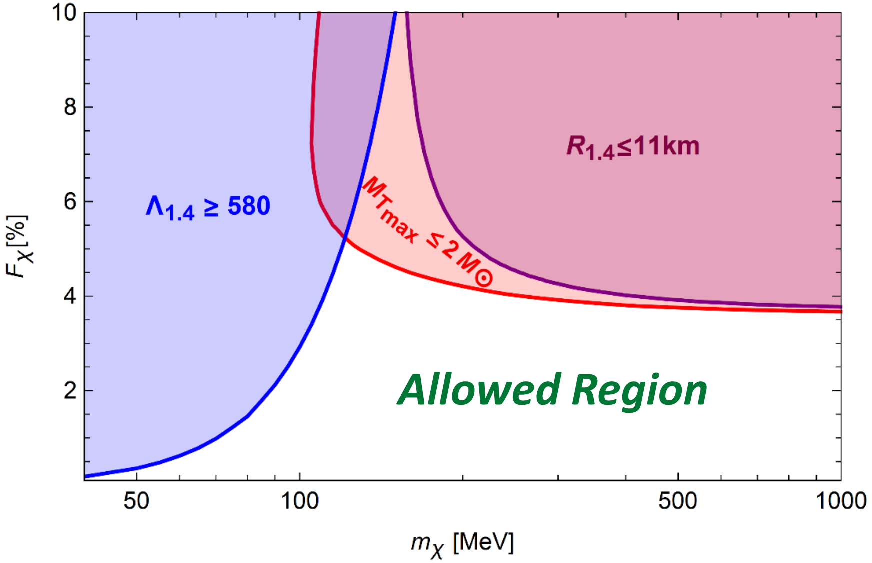
Bosonic Dark Matter in Light of the NICER Precise Mass-Radius Measurements

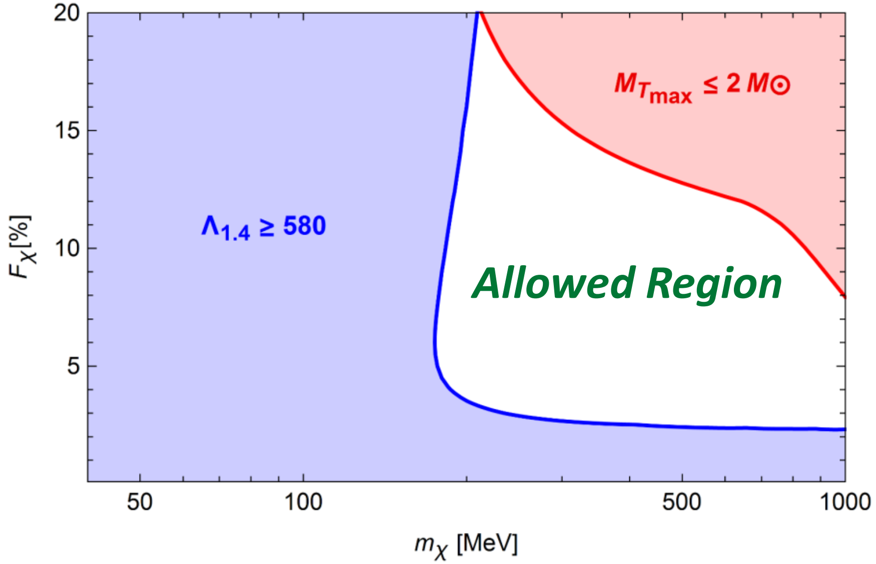
Phys. Rev. D 109, 043029 **(2024)** **[77 citations]**

D.R.K, M. Shahrbaf, S. Shakeri, S. Typel

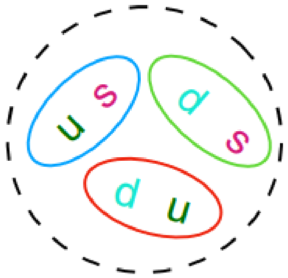
Exploring the distribution and impact of bosonic dark matter in neutron stars

Particles 7 1, 201-213 **(2024)** **[25 citations]**





Sexaquark a bosonic dark matter candidate



Glennys R. Farrar

arXiv:2201.01334, review paper

Home > International Journal of Theoretical Physics > Article

A Stable H-Dibaryon: Dark Matter, Candidate Within QCD?

Published: June 2003

Volume 42, pages 1211–1218, (2003) Cite this article

Sexaquark (Mass: ~2 GeV)

(S=uuddss): bosonic, spin-color-flavor singlet, deeply bound

Q=0, B = 2, s= −2

If $m_s \leq (m_\Lambda + m_p + m_e) = 2054$ MeV, it will decay with a lifetime more than the age of the universe.

OPEN ACCESS

Search for a Stable Six-Quark State at BABAR

J. P. Lees[1], V. Poireau[1], V. Tisserand[1], E. Grauges[2], A. Palano[3], G. Eigen[4], D. N. Brown[5], Yu. G. Kolomensky[5], M. Fritsch[6] *et al.* (BaBar Collaboration)

Show more

Phys. Rev. Lett. **122**, 072002 – **Published 22 February, 2019**

OPEN ACCESS

Coalescence production of sexaquark with three diquarks in high-energy nuclear collisions

Zhi-Lei She[1], An-Ke Lei[2,3], Dai-Mei Zhou[2,*], Larissa V. Bravina[3,†], Evgeny E. Zabrodin[3,4], Sonia Kabana[5,‡], and Vipul Bairathi[5]

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Phys. Rev. D **112**, 034002 – **Published 4 August, 2025**

Home > The European Physical Journal C > Article

Searching for a dark matter particle with anti-protonic atoms

Letter | Open access | Published: 18 December 2023

Volume 83, article number 1149, (2023) Cite this article

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Michael Doser, Glennys Farrar & Georgy Kornakov

Sexaquark cannot be a dark matter candidate

Phys. Lett. B 857 (2024) 138973

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journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

Letter

Hypernuclear constraints on the existence and lifetime of a deeply bound *H* dibaryon

Avraham Gal

Racah Institute of Physics, The Hebrew University, Jerusalem 9190401, Israel

OPEN ACCESS

Cosmology and terrestrial signals of sexaquark dark matter

Marianne Moore* and Tracy R. Slatyer†

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Phys. Rev. D **110**, 023515 – **Published 11 July, 2024**

Sexaquark dilemma in neutron stars and its solution by quark deconfinement

M. Shahrbaf[1,*], D. Blaschke[1,2,3,†], S. Typel[4,5,‡], G. R. Farrar[6,§], and D. E. Alvarez-Castillo[2,7,∥]

Show more

Phys. Rev. D **105**, 103005 – **Published 4 May, 2022**

For the first time Sexaquark dark matter (?) or exotic particle was investigated via its production in high density matter of neutron stars

Hadronic EOS:

- A generalized relativistic density functional (GRDF) approach
- **DD2Y-T** (**includes hyperons**) *Mon. Not. Roy. Astron. Soc., 502, 3476 2021*
- Exotic matter component: sexaquark (S) included in hadronic sector
- $\boldsymbol{m_S^* = m_S(1 + x_S \frac{n_b}{n_0})}$
- Parameters: $m_S \in [\mathbf{1885 - 2054}]MeV$, $x_S = \mathbf{0.03}$
- $\boldsymbol{x_S}$ **is the slope parameter and represents the coupling strength**

Quark matter EOS :

nlNJL model

- The most likely parameters were selected within a Bayesian analysis (BA)
- Mapped to the constant speed of sound (CSS) parameterization

M. Shahrbaf, et al. 2023, Phys. Rev. D, 107, 054011

- Two sets of Parameters (η_D, η_V, c_S^2) have been used

(0.70, 0.10, 0.44) & (0.70, 0.11, 0.44)

The model RIC-DD2Y-T-S_{m_S} describes a neutron star that includes Nucleons, Hyperons, Sexaquark dark matter (?) or exotic particle and Quark matter

Phase transition:

- Smooth **crossover phase transition** from hadronic matter to deconfined quark matter
- Replacement Interpolation Construction **(RIC)**

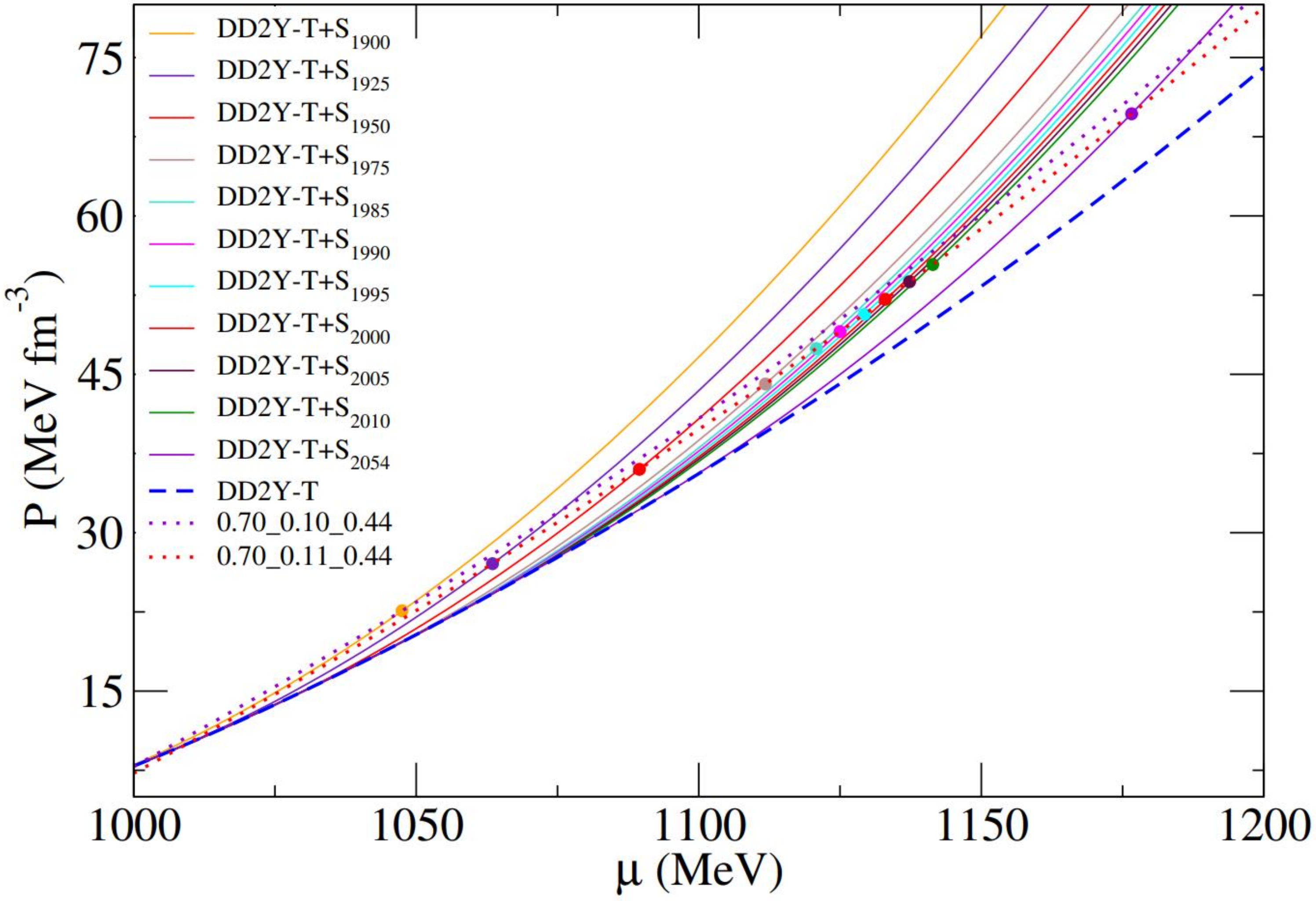
M. Shahrbaf, D. Blaschke, S. Khanmohamadi, J. Phys. G: Nucl. Part. Phys. 47 (2020) 115201

A. Ayriyan et al. Phys. Rev. C 97, 045802

Observational Probes of the Neutron Star Equation of State with Hyperons, Bosonic Dark Matter, and Quark Matter

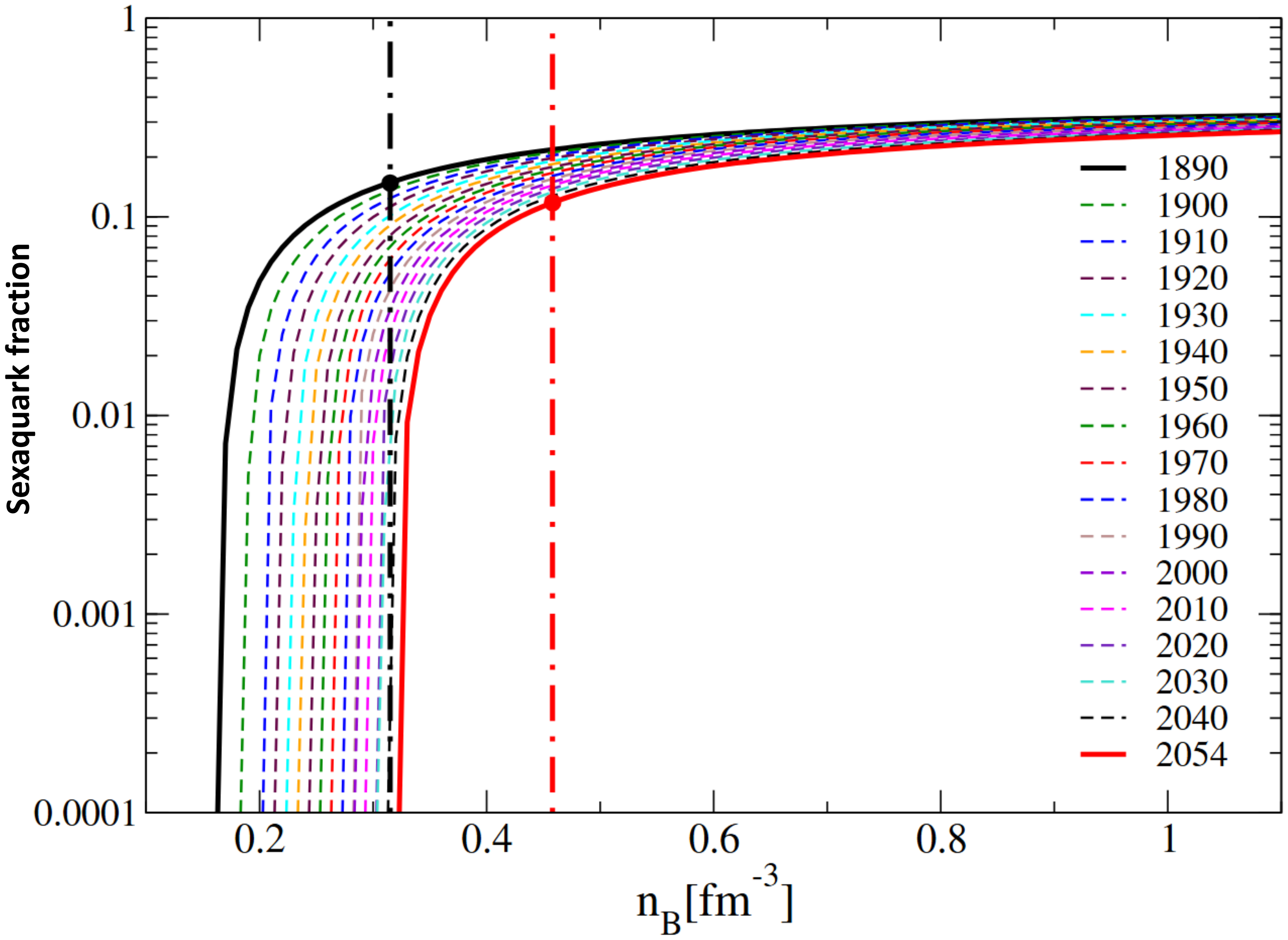
Mahboubeh Shahrbaf[1,2,3⋆], Davood Rafiei Karkevandi[1⋆⋆], Alexander Ayriyan[1,4⋆⋆⋆], and Stefan Typel[5,6]

arXiv:2402.18686v2
Accepted for publication in Astronomy & Astrophysics



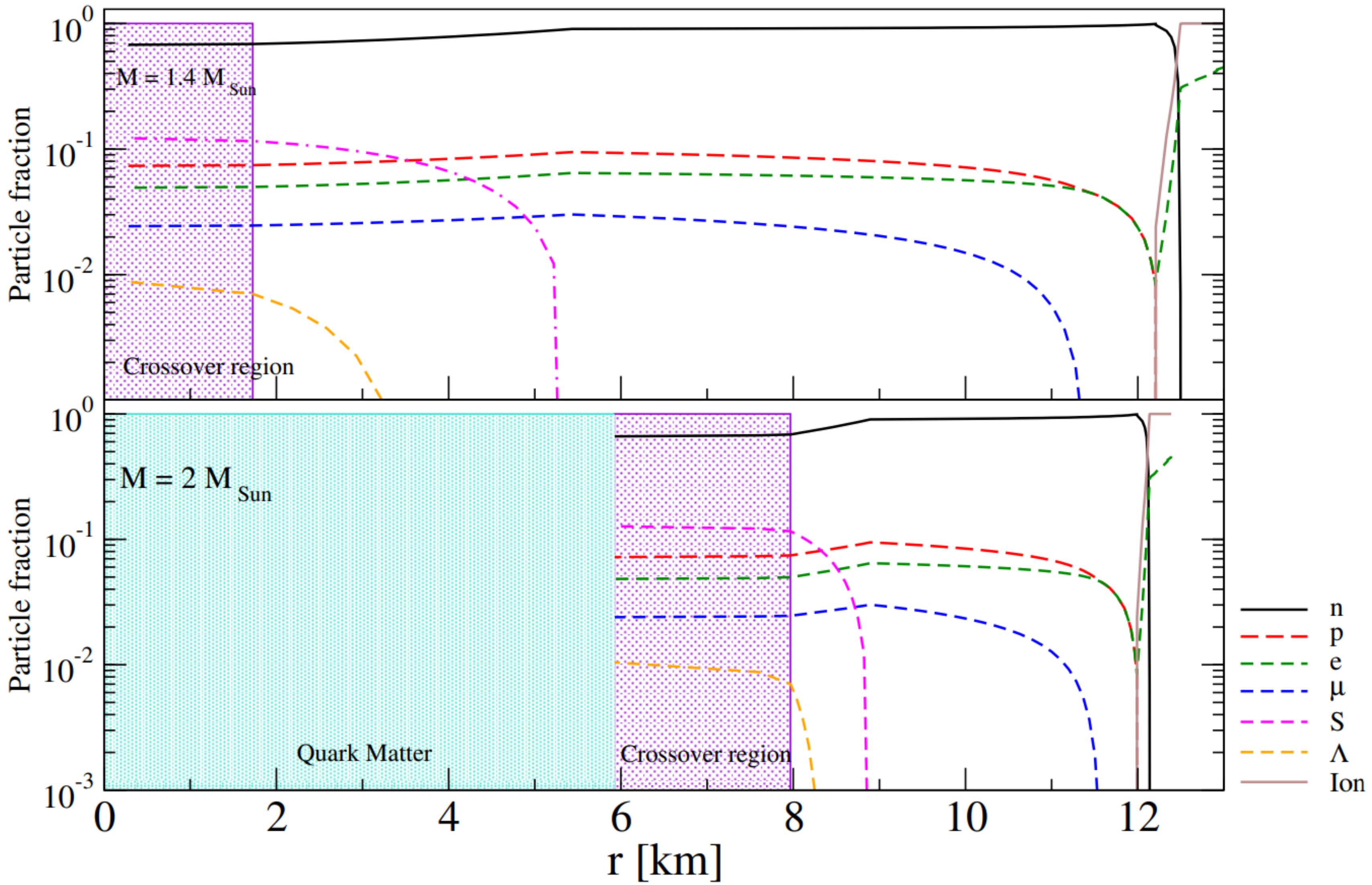
Different masses of Sexaquark particles were considered for its the lowest value of coupling strength with the medium.

The maximum Sexaquark fraction allowed in our models varies from about 12% for the highest S-particle mass to 15% for the lightest one.



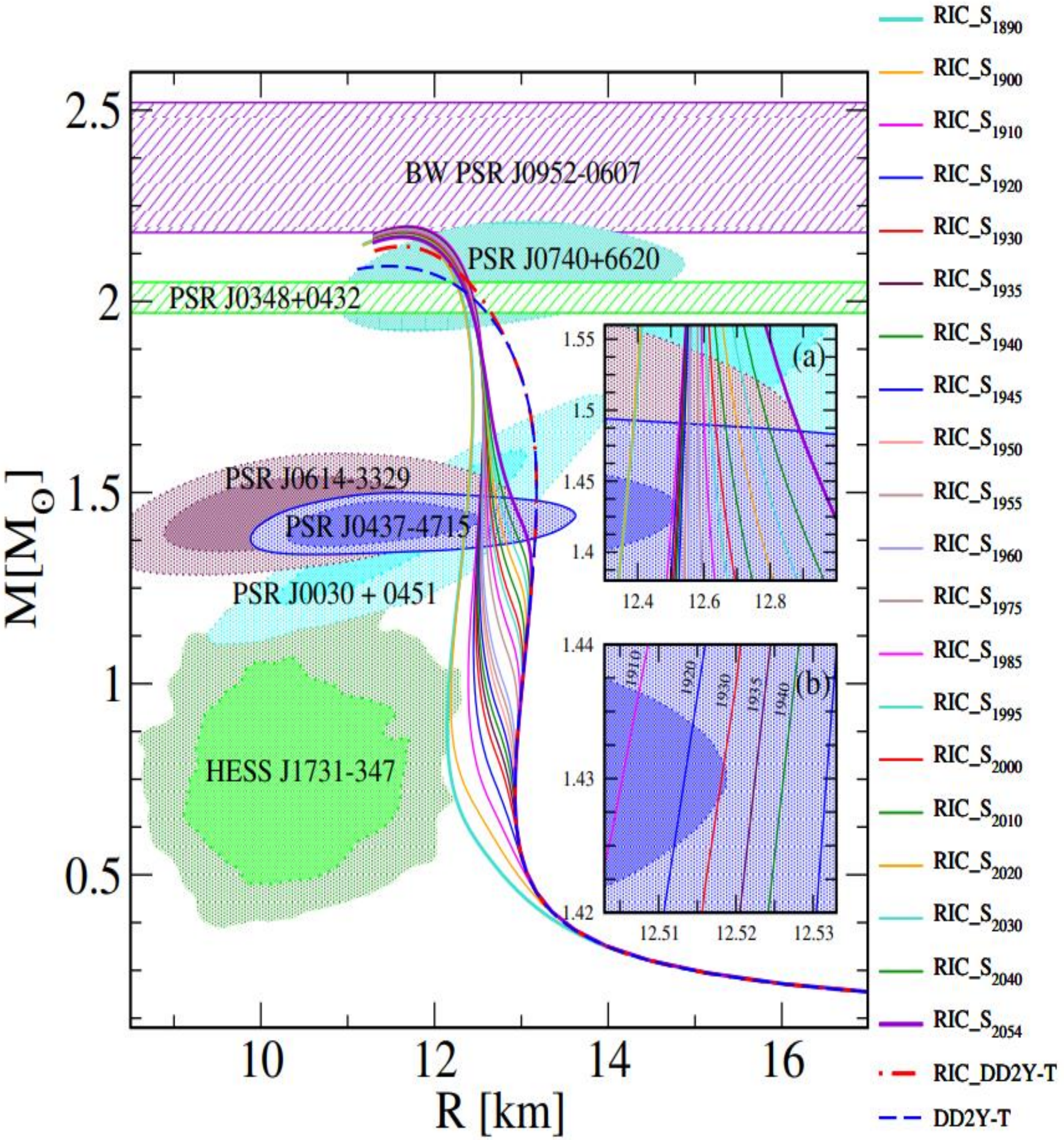
RIC-DD2Y-T+S_{2050} , x =0.03

Particle fraction inside the neutron star for $1.4M_{\odot}$ (up) and $2M_{\odot}$ (down)

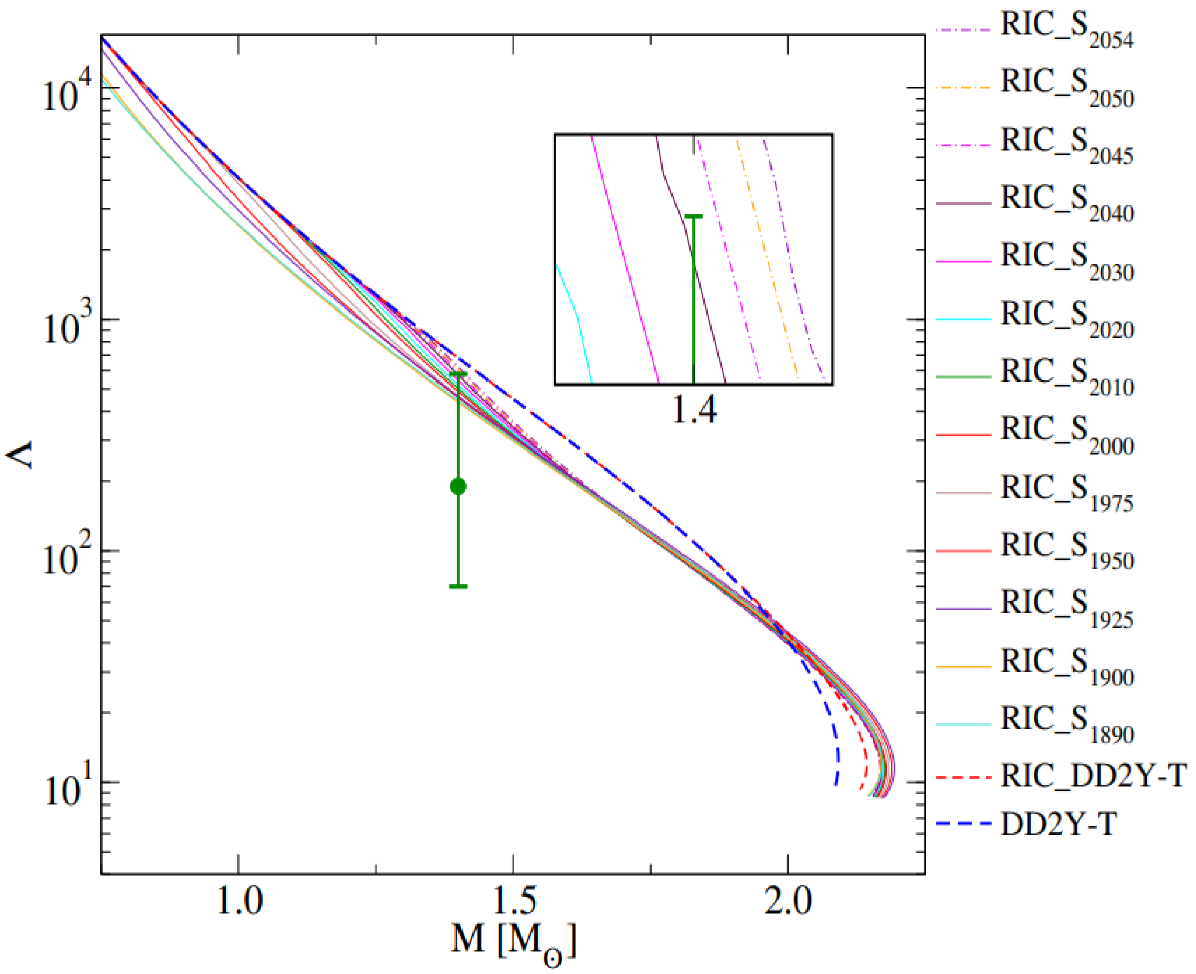


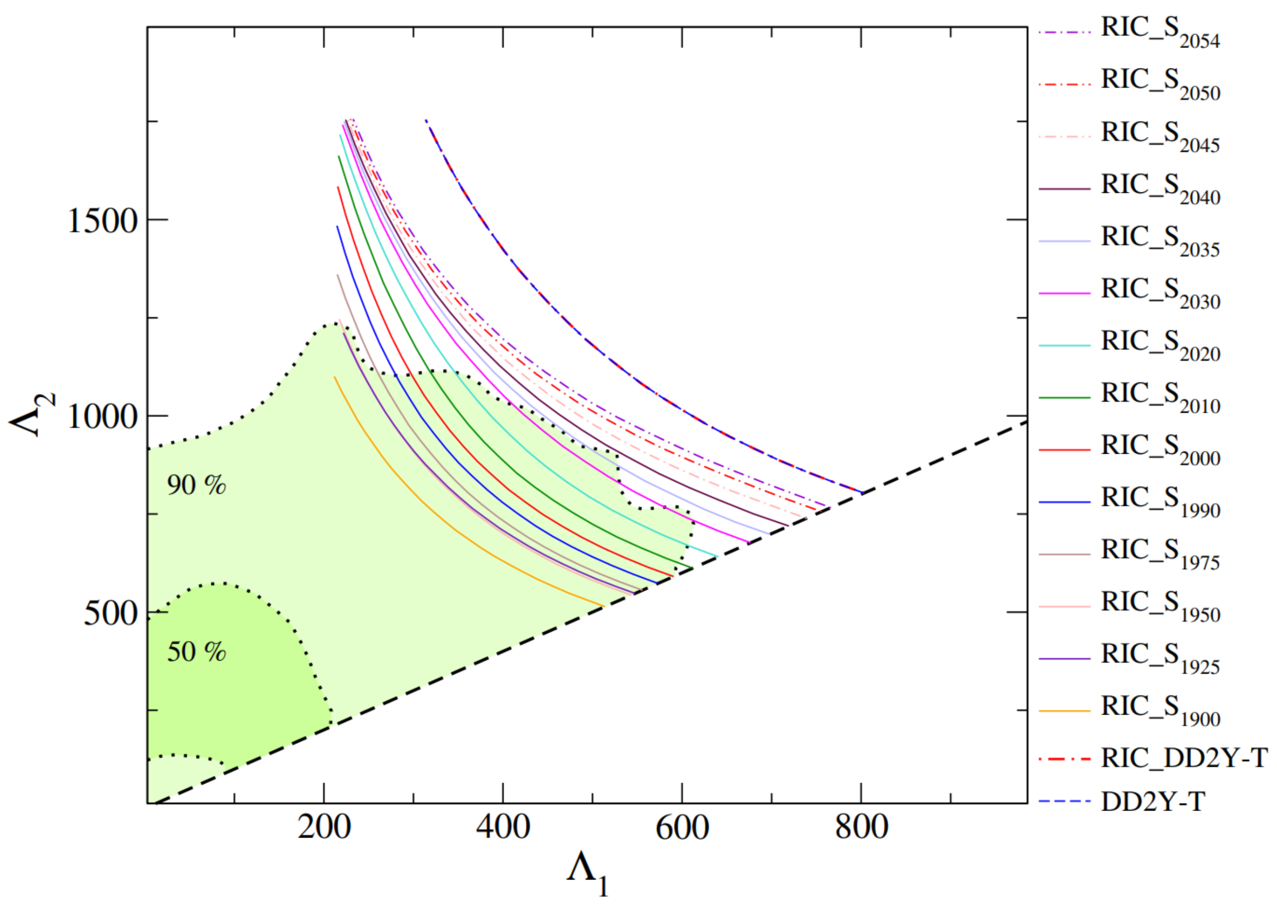
M. Shahrbaf, P. Thakur, D.R.K, *arXiv:2510.08115*

Mass-Radius observational constraints for neutron stars are considered to probe the model and different masses of Sexaquarks



Tidal deformability constraints from gravitational waves of neutron stars merger

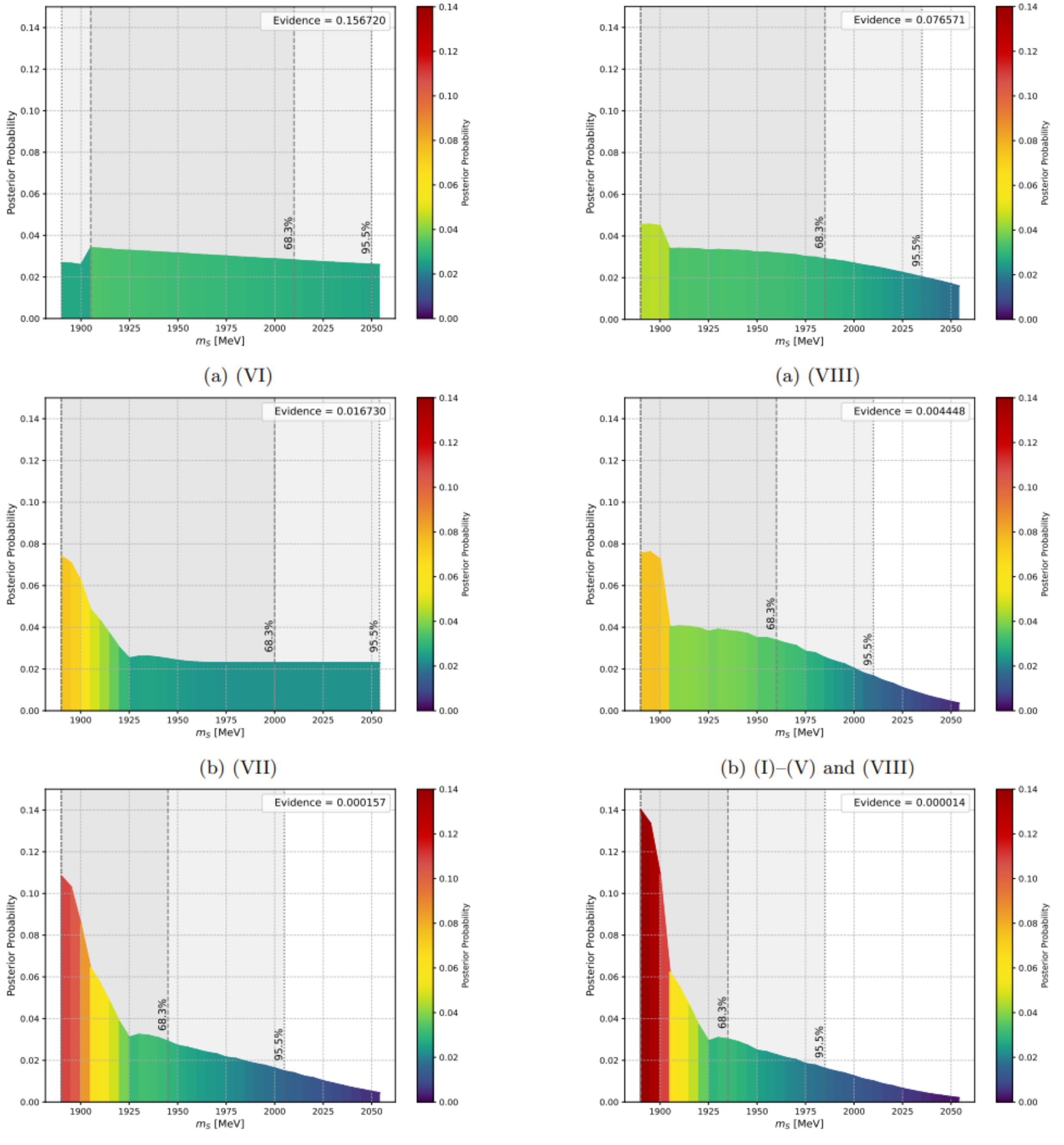




Bayesian analysis based on all available observational constraints for neutron stars

Our results disfavors Sexaquark particle masses higher than 1980 MeV

strongly favors $m_S \lesssim 1935$ MeV for the lowest of coupling strength



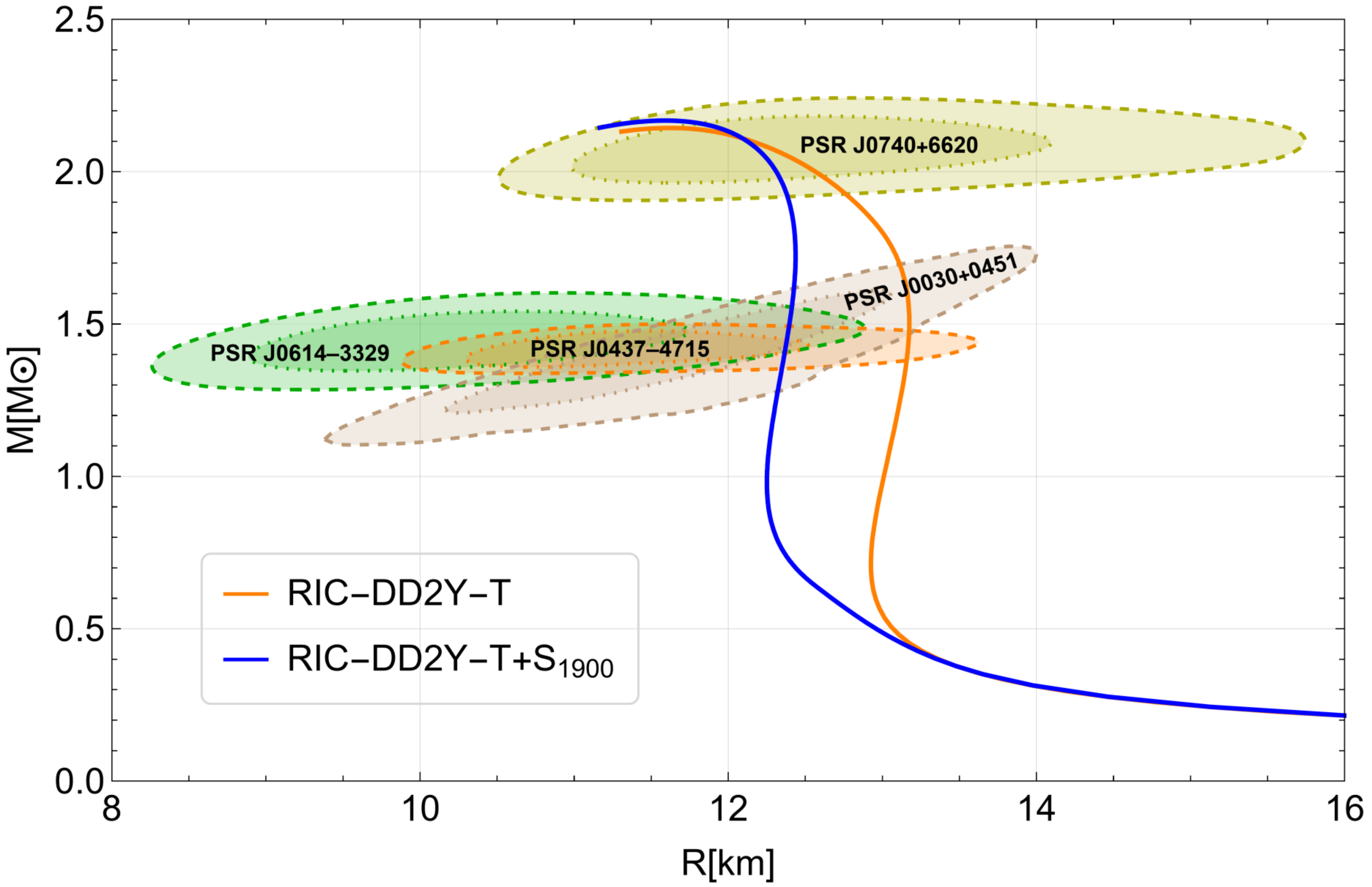
(a) (VI) (a) (VIII)

(b) (VII) (b) (I)–(V) and (VIII)

(c) (I)–(VII) (c) (I)–(VIII)

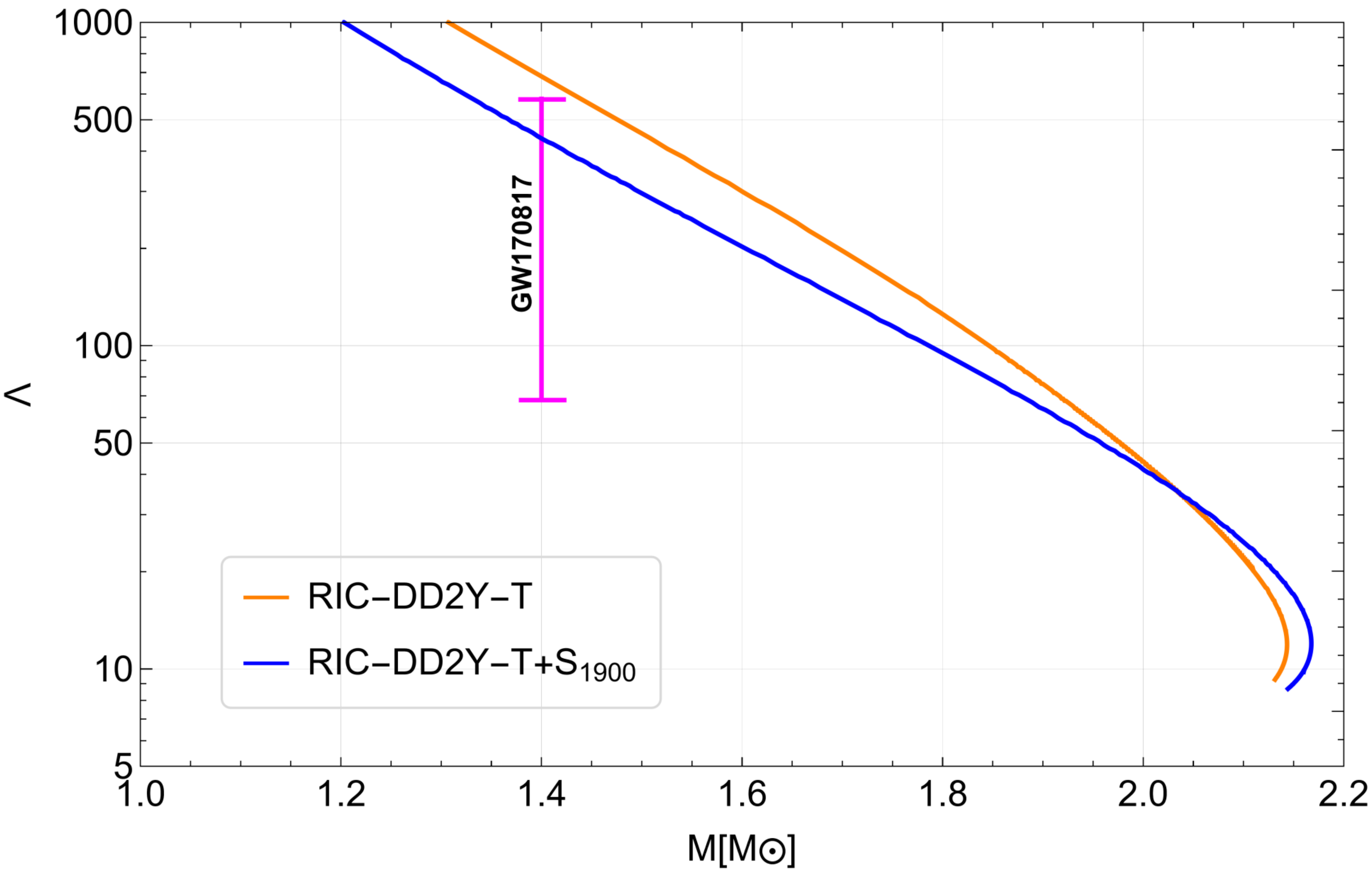
Orange curve : without Sexaquark

Blue curve : with Sexaqurak, $m_s = 1900\ MeV$ and $x_s = 0.03$



M. Shahrbaf, P. Thakur, D.R.K, ***arXiv:2510.08115***

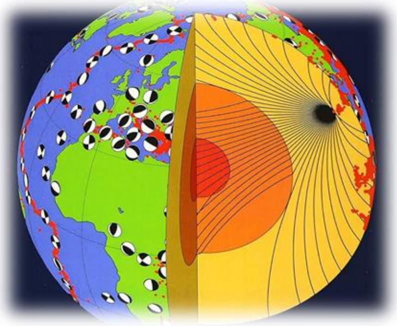
Presence of sexaquark softens the equation of the sate and make it consistent with $\Lambda_{1.4}$ limit

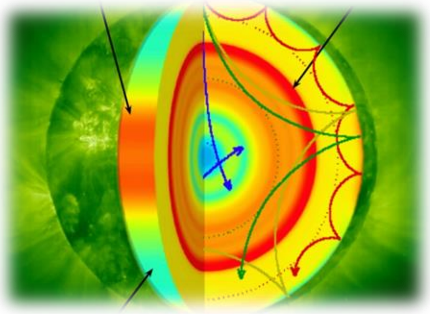


M. Shahrbaf, P. Thakur, D.R.K, ***arXiv:2510.08115***

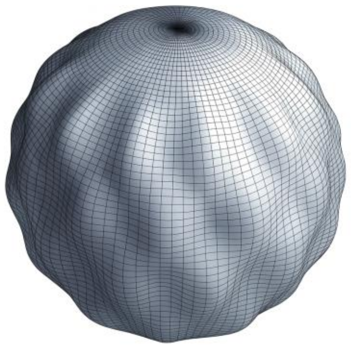
Radial and non-radial oscillations in neutron stars

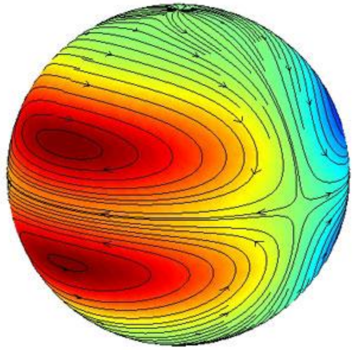
Seismology and Helioseismology for earth and sun



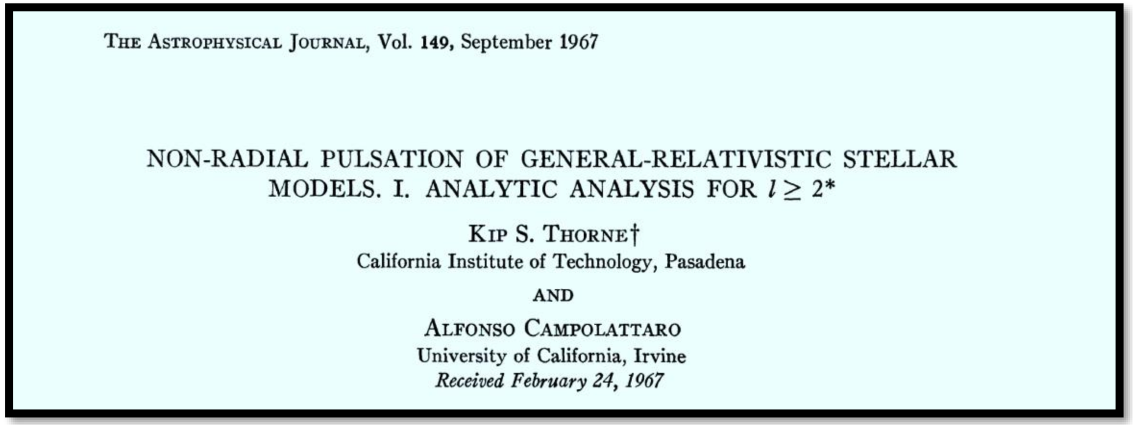


Asteroseismology for neutron stars
the interior structure and
the equation of state can be probed





Of particular interest are the non-radial modes, they distort the star's spherical shape and thus serve as a sources of gravitational waves.


THE ASTROPHYSICAL JOURNAL, Vol. 149, September 1967

NON-RADIAL PULSATION OF GENERAL-RELATIVISTIC STELLAR MODELS. I. ANALYTIC ANALYSIS FOR $l \geq 2$*

KIP S. THORNE†
California Institute of Technology, Pasadena

AND

ALFONSO CAMPOLATTARO
University of California, Irvine

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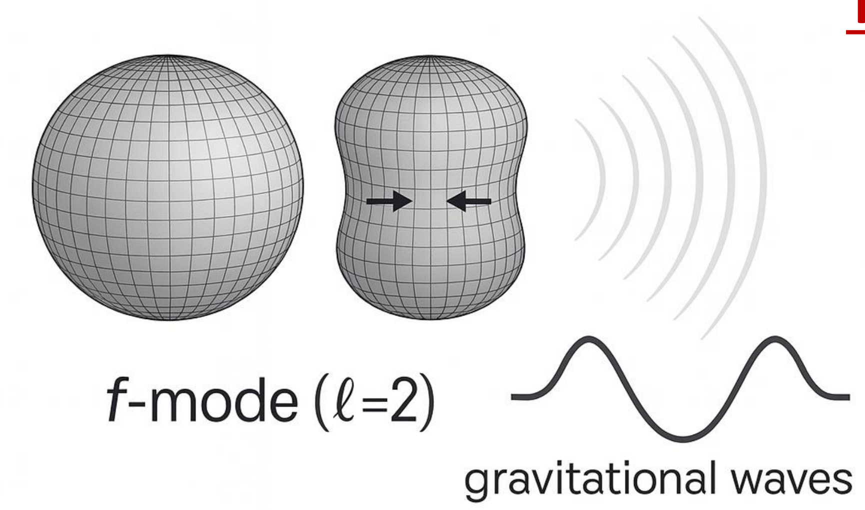

The fundamental mode (f-mode) oscillation in a neutron star

The frequency is between 1.3 and 2.8 kHz

could be detectable by current and future gravitational wave detectors

The f-mode oscillations are expected to be damped over time

mainly through the emission of gravitational waves

The damping time is predicted to be relatively short, around 0.1–0.5 seconds.

Gravitational wave asteroseismology

By calculating the universal relation between the f-mode frequency (and damping time) and the star's fundamental properties (mass, radius, tidal, EOS).


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JOURNAL ARTICLE

Towards gravitational wave asteroseismology FREE

Nils Andersson, Kostas D. Kokkotas

Monthly Notices of the Royal Astronomical Society, Volume 299, Issue 4, October 1998, Pages 1059–1068, https://doi.org/10.1046/j.1365-8711.1998.01840.x

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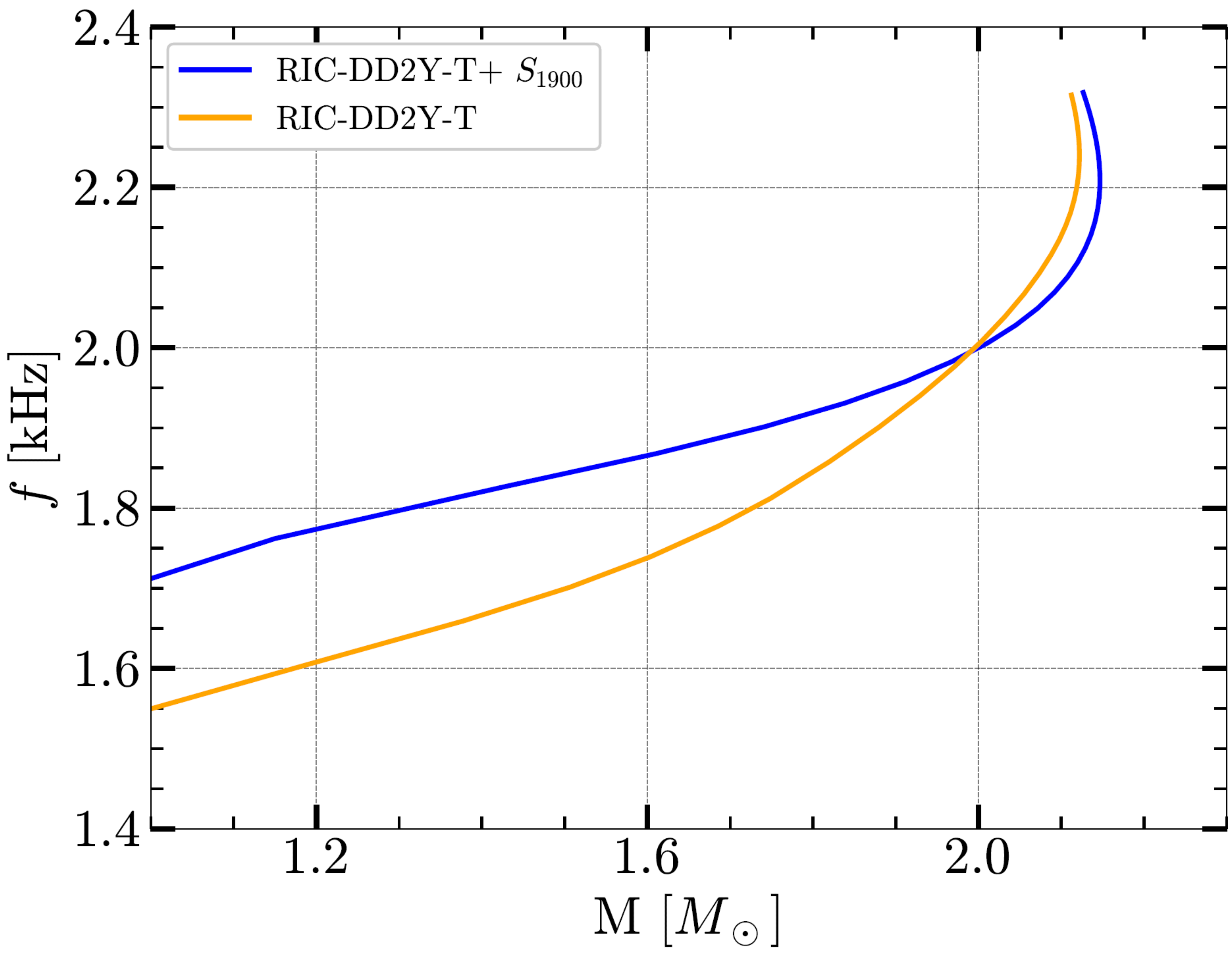
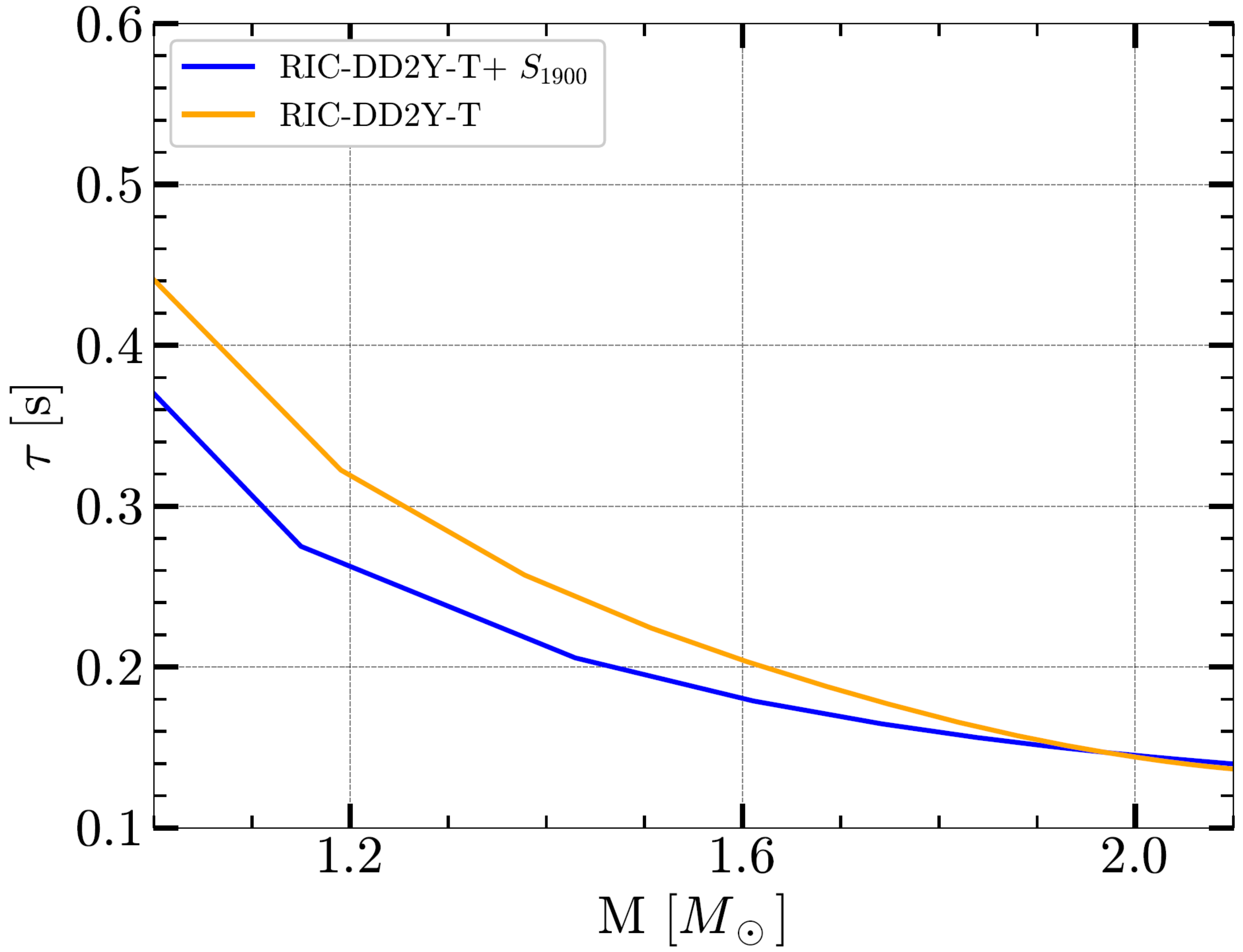
Andersson and Kokkotas opening up the field of gravitational wave asteroseismology in which they propose the first **asteroseismological universal relations for oscillation modes of neutron stars.**

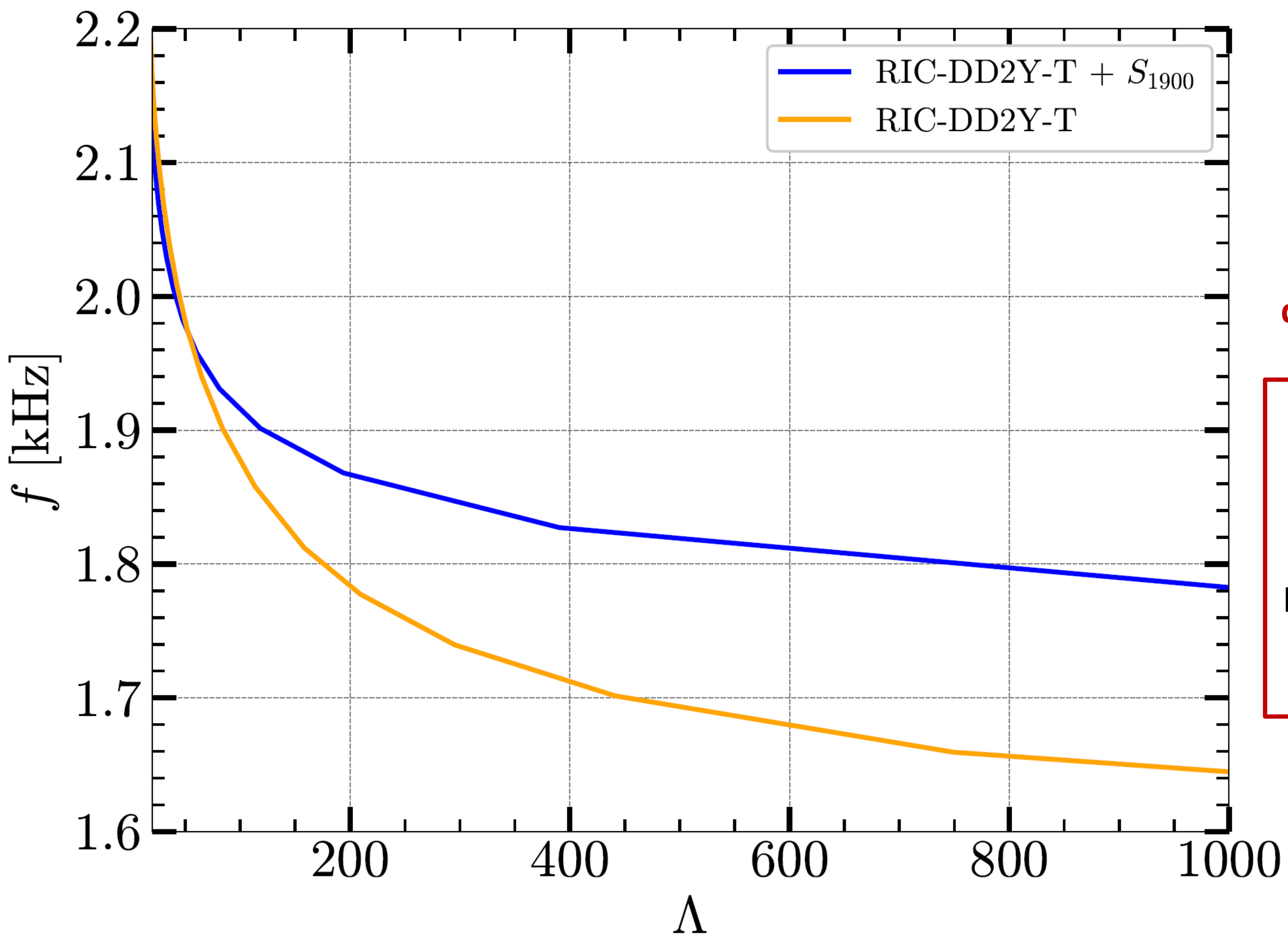


The presence of **Sexaquark** directly contributes to the **softening of the EOS** and **higher f-mode frequencies**.

M. Shahrbaf, P. Thakur, D.R.K, ***arXiv:2510.08115***

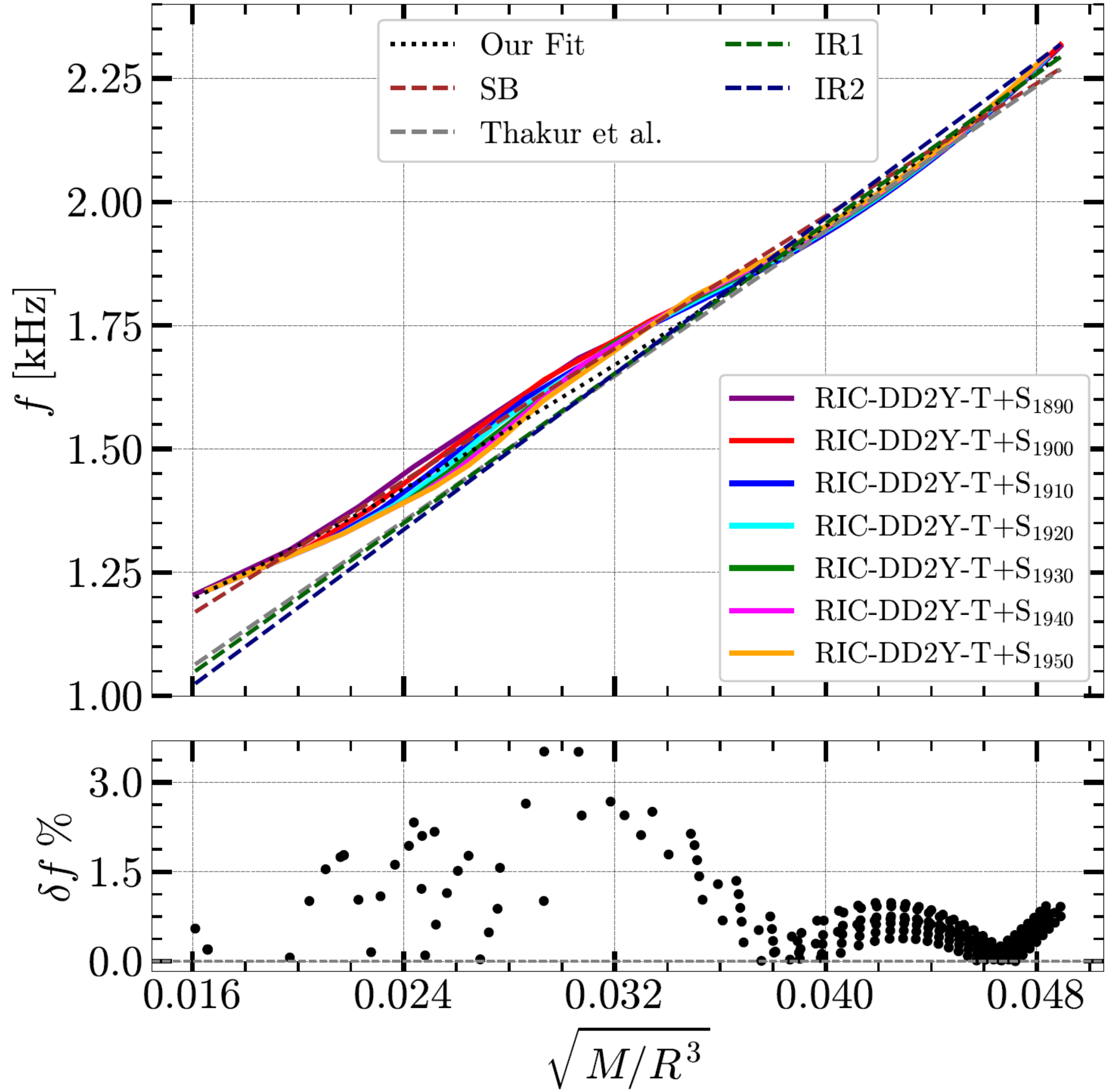


The increased compactness caused by Sexaquark enhances metric perturbations, and enables more efficient emission of gravitational waves, so that shortens the damping time



The f-mode has close connection with the tidal deformability of neutron stars

<u>**Independent or simultaneous**</u> measurements of the **f-mode frequency and tidal deformability** can therefore provide valuable constraints on the EOS and the underlying composition of NSs.

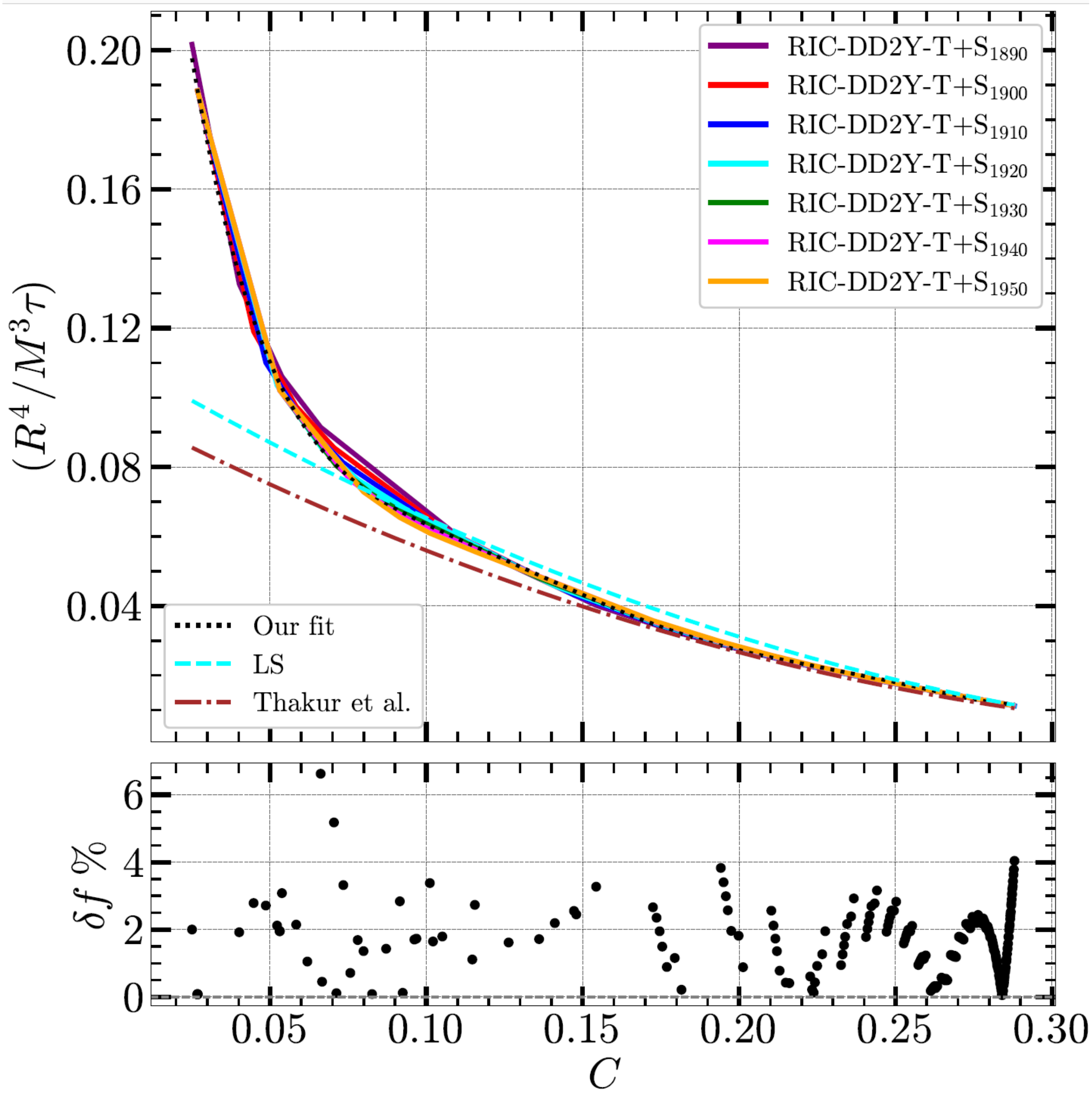


The **f-mode frequency** scales approximately with the **square root of the neutron star's average density**.

$$\frac{f}{\text{kHz}} = a + b\left(\sqrt{\frac{M}{R^3}}\right) + c\left(\sqrt{\frac{M}{R^3}}\right)^2$$

where $a = 0.840846$, $b = 18.569058$ and $c = 229.339724$

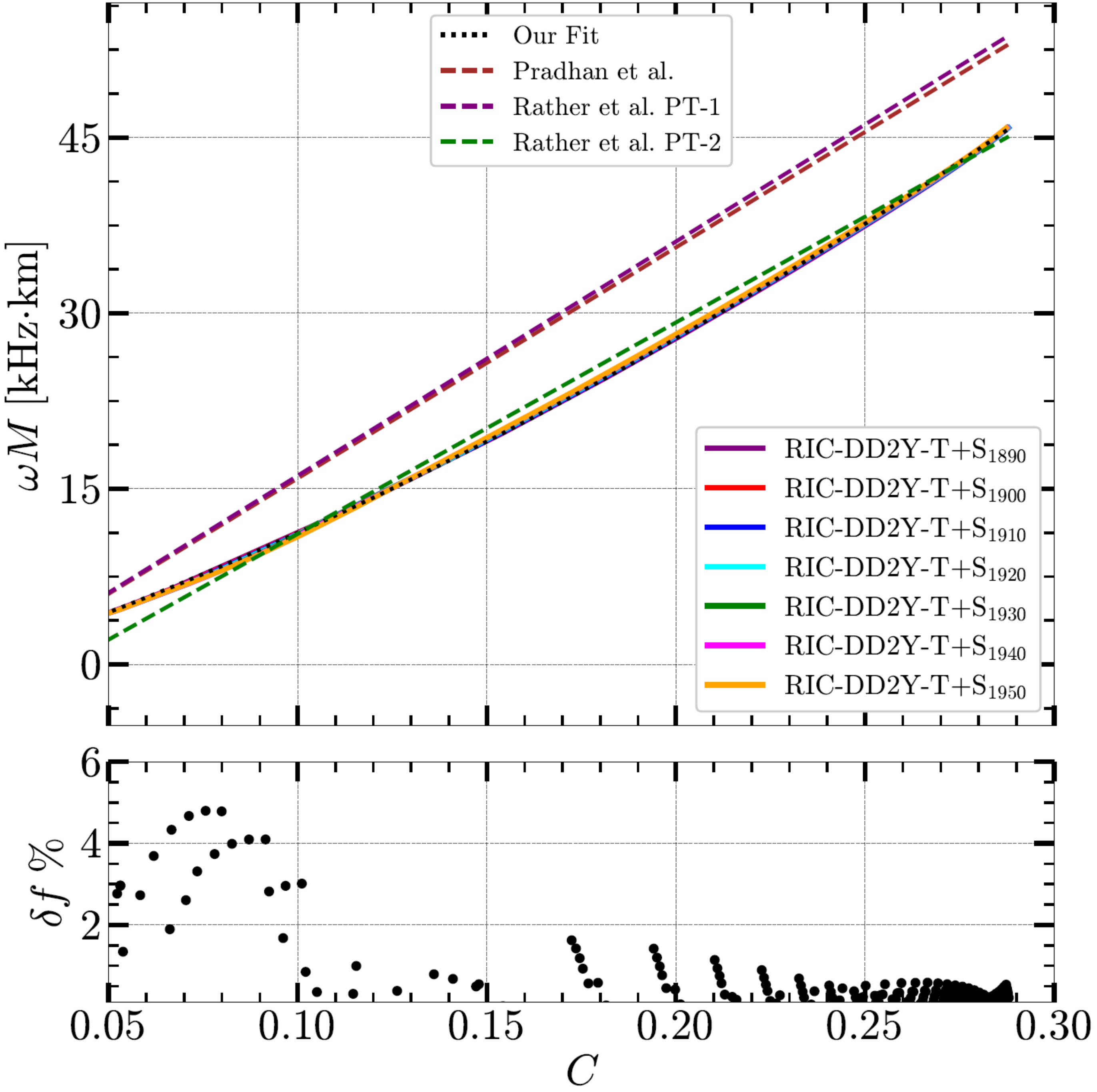
M. Shahrbaf, P. Thakur, D.R.K, ***arXiv:2510.08115***



The quasi-universal relation between the scaled damping-time variable and the compactness

$$\frac{R^4}{M^3\tau} = a + b\,C + c\,C^2 + d\,C^3 + e\,C^4 + f\,C^5 + g\,C^6$$

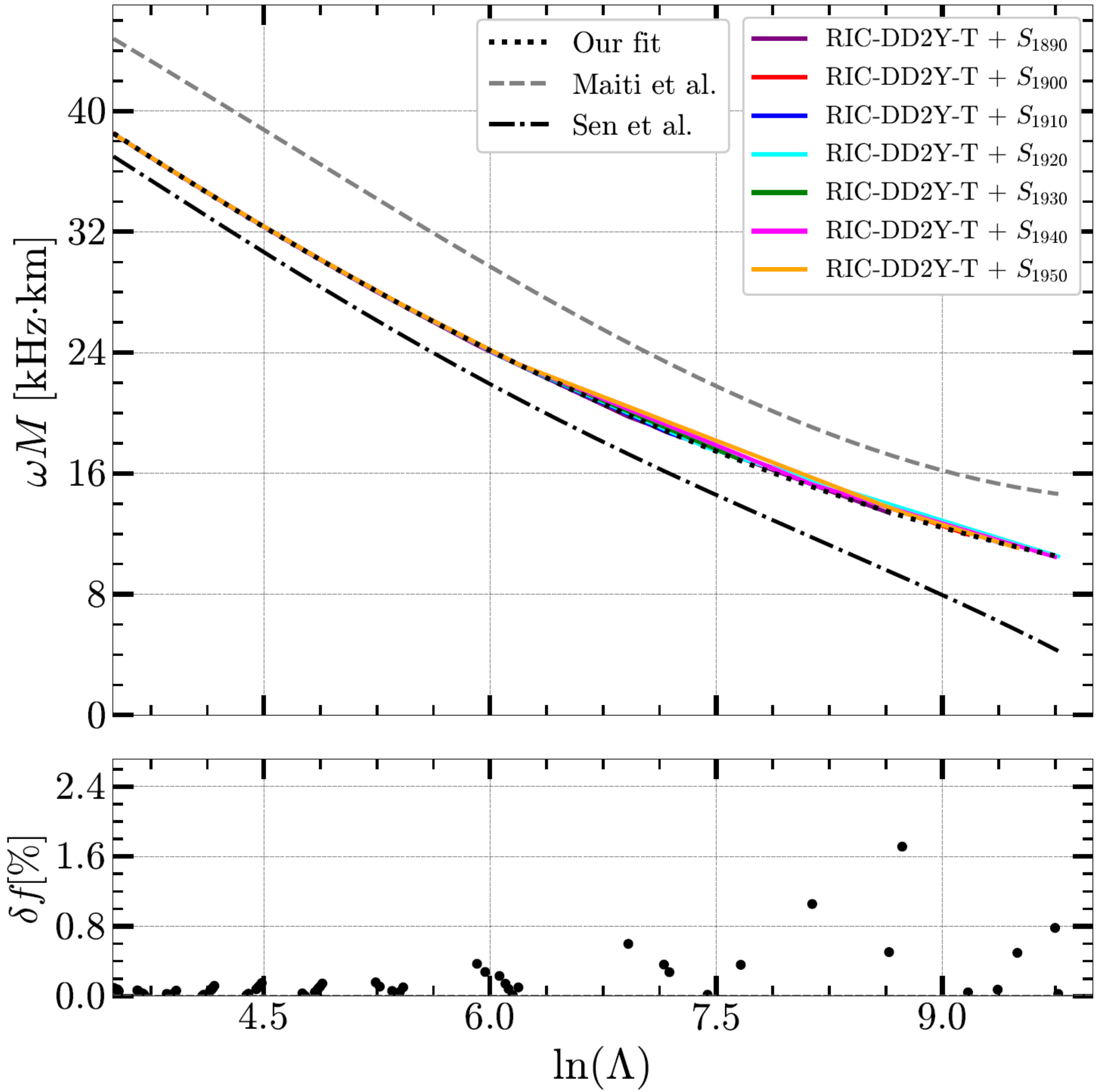
where, $a = 0.4095642$, $b = -12.26236$, $c = 186.0756$, $d = -1505.978$, $e = 6603.648$, $f = -14837.04$ and $g = 13389.98$



The mass scaled angular frequency of f-mode, ωM (with ω = 2πf), as a function of the stellar compactness

$$\omega M = a\,C^2 + b\,C + c$$

where a = 199.734977, b = 106.082697, c = - 1.365759 have units of kHz·km



The variation of the scaled frequency, ωM, as a function of the dimensionless tidal deformability parameter (Λ)

$$\omega M = a + b\,(\ln\Lambda) + c\,(\ln\Lambda)^2 + d\,(\ln\Lambda)^3$$

where $a = 67.426668$, $b = -9.797683$, $c = 0.470981$, and $d = -0.006726$

Golden Age of neutron stars research

Investigating the properties of ultra high density matter

We may shed light on the nature of dark matter

Tomb of Cyrus the Great in Pasargad Iran

Photo by Sepehr Moeini

What we know is a drop
What we do not know is an ocean