The Modern Physics of Comapct Stars and Relativistic Gravity 2023

Quark stars in massive gravity might be candidates for the mass gap region objects

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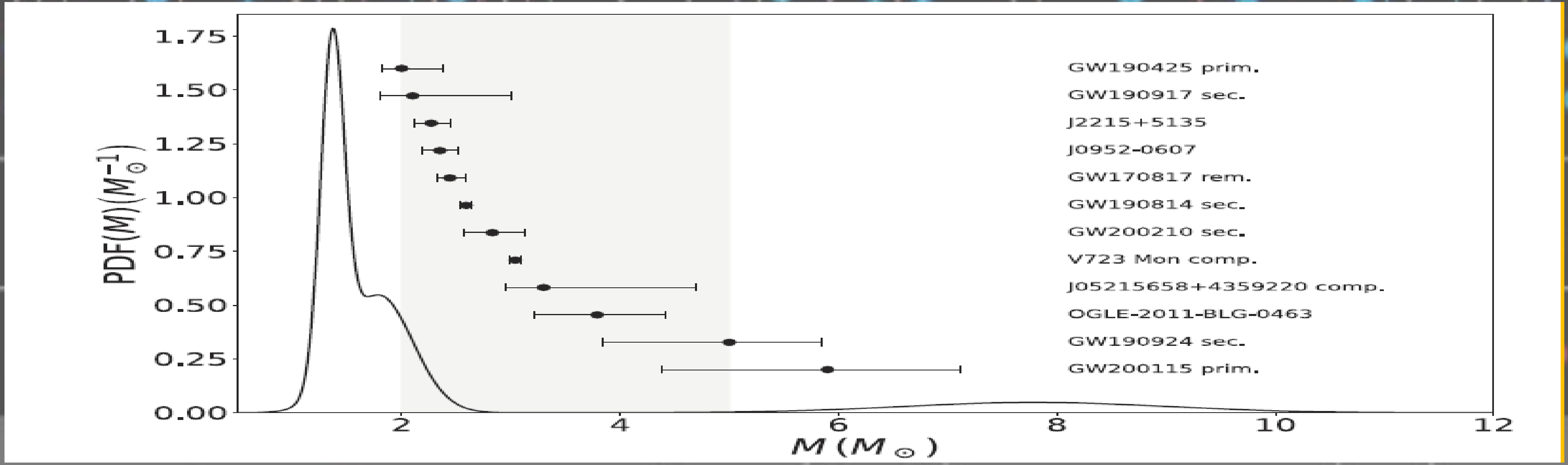
What is mass gap region?

The lack of objects between the range from 2 to 5 $M_{\odot}$ in the joint mass distribution of compact objects is called mass gap.

But



L. M. de Sá et al 2022 ApJ 941 130

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

What could be the objects that are in the mass gap region?

For non-rotating Neutron stars, the equation of state (EOS) must be very rigid. Such EOSs contrast dimensionless tidal deformability (Λ) constraints obtained from GW170817

They could be the smallest black holes or the remnants of binary mergers

We look at this from a different point of view.

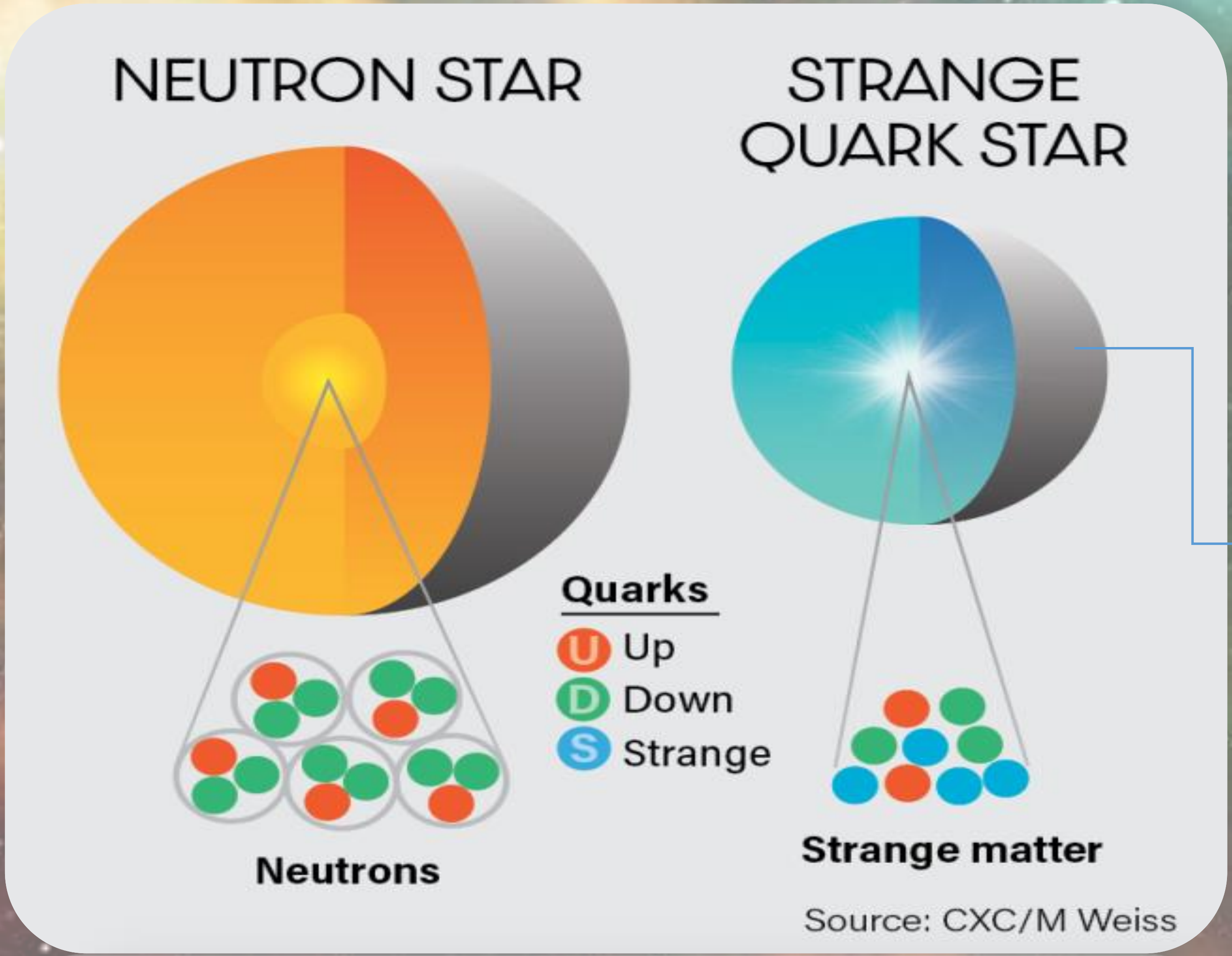
Massive Gravity

Massive Gravity is a theory of gravity which considers massive gravitons

Modified TOV equation in massive gravity

$$\frac{dP(r)}{dr} = \frac{\left(M(r) + 4\pi r^3 P - \frac{r^2 C_1}{4}\right)(\epsilon + P)}{r\left(\frac{C_1 r^2}{2} + 2M(r) + r\left(C_2 - 1\right)\right)}.$$

Strange Quark Star



The most stable state of QCD is the strange quark matter.

We have considered a modified version of the Nambu-Jona-Lasinio (MNJL) model to obtain the EOS

(Cheng-Ming Li et al, PHYSICAL REVIEW D 101, 063023 (2020))

We have used the constraint, $\Lambda_{1.4M_\odot} \lesssim 580$

$$\mathcal{L}_{\mathrm{NJL}} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + \sum_{\mathrm{i}=0}^{8} G[(\bar{\psi}\lambda_{\mathrm{i}}\psi)^2 + (\bar{\psi}i\gamma^5\lambda_{\mathrm{i}}\psi)^2] - K(\det[\bar{\psi}(1+\gamma^5)\psi] + \det[\bar{\psi}(1-\gamma^5)\psi]),$$

By performing the Fierz transformation on the Lagrangian interaction part, we get

$$\mathcal{L}_{\mathrm{F}} = \bar{\psi}(i\partial\!\!\!/ - m)\psi - \frac{1}{2}\sum_{\mathrm{a}=0}^{8} G[(\bar{\psi}\gamma^\mu\lambda_{\mathrm{a}}^C\psi)^2 - (\bar{\psi}\gamma^\mu\gamma^5\lambda_{\mathrm{a}}^C\psi)^2] - K(\det[\bar{\psi}(1+\gamma^5)\psi] + \det[\bar{\psi}(1-\gamma^5)\psi]), \quad (2)$$

The original Lagrangian and its Fierz transform are mathematically equivalent, but differ in the mean-field approximation.

$$\mathcal{L} = (1-\alpha)\mathcal{L}_{\mathrm{NJL}} + \alpha\mathcal{L}_{\mathrm{F}}$$

mean-field approximation

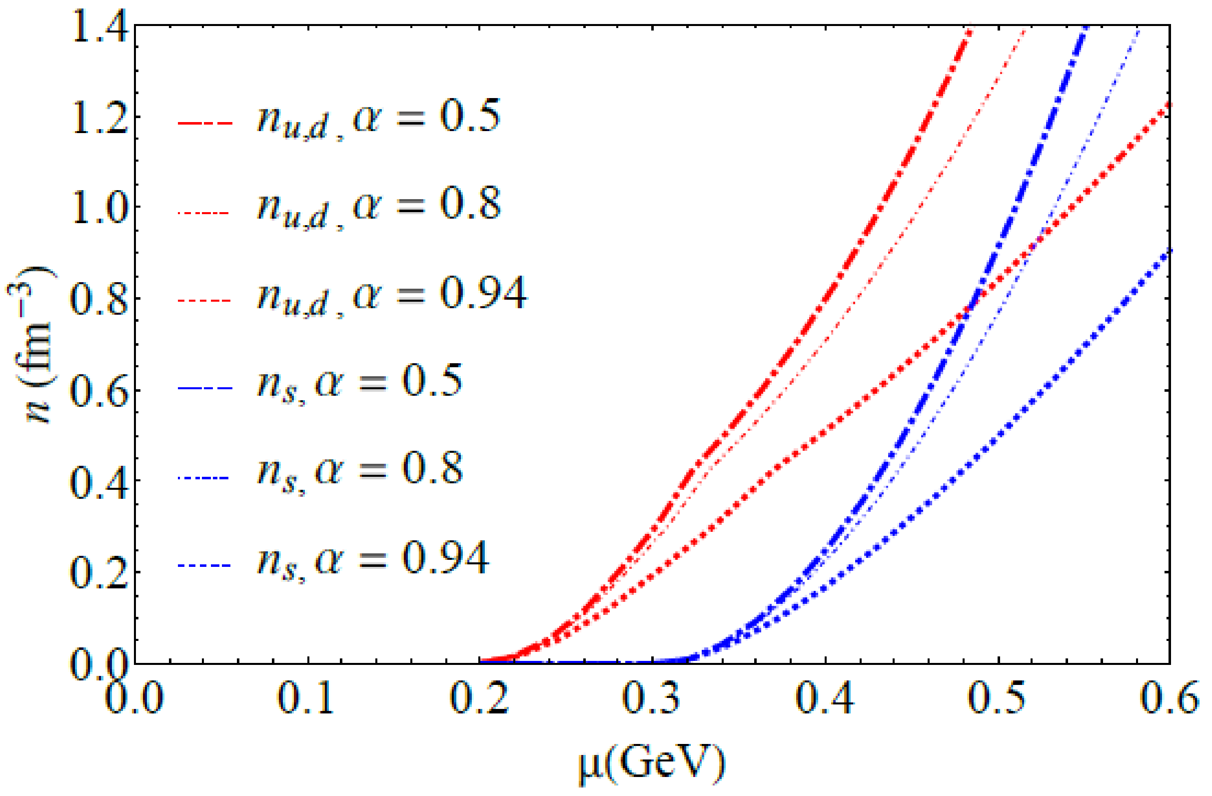
In mean-field approximation the dynamical quark mass M_i and the modified chemical potential μ_i' of flavor i are obtained respectively:

$$M_\mathrm{i} = m_\mathrm{i} - 4G\langle\bar{\psi}\psi\rangle_\mathrm{i} + 2K\langle\bar{\psi}\psi\rangle_\mathrm{j}\langle\bar{\psi}\psi\rangle_\mathrm{k},$$

$$\mu_\mathrm{i}' = \mu_\mathrm{i} - \frac{2\alpha}{N_\mathrm{c}(1-\alpha)}G\langle\psi^+\psi\rangle_\mathrm{i}.$$

Cheng-Ming Li et al, PHYSICAL REVIEW D 101, 063023 (2020)

Quark number densities



$$P(\mu) = P(\mu = 0) + \int_0^{\mu} d\mu' \rho(\mu'),$$

Constraints of SQM to obtain EOS

stability condition

$$\frac{\epsilon}{n_B}(3\ flavor) < \frac{\epsilon}{n_B}(2\ flavor)$$

Charge neutrality

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

Beta equilibrium

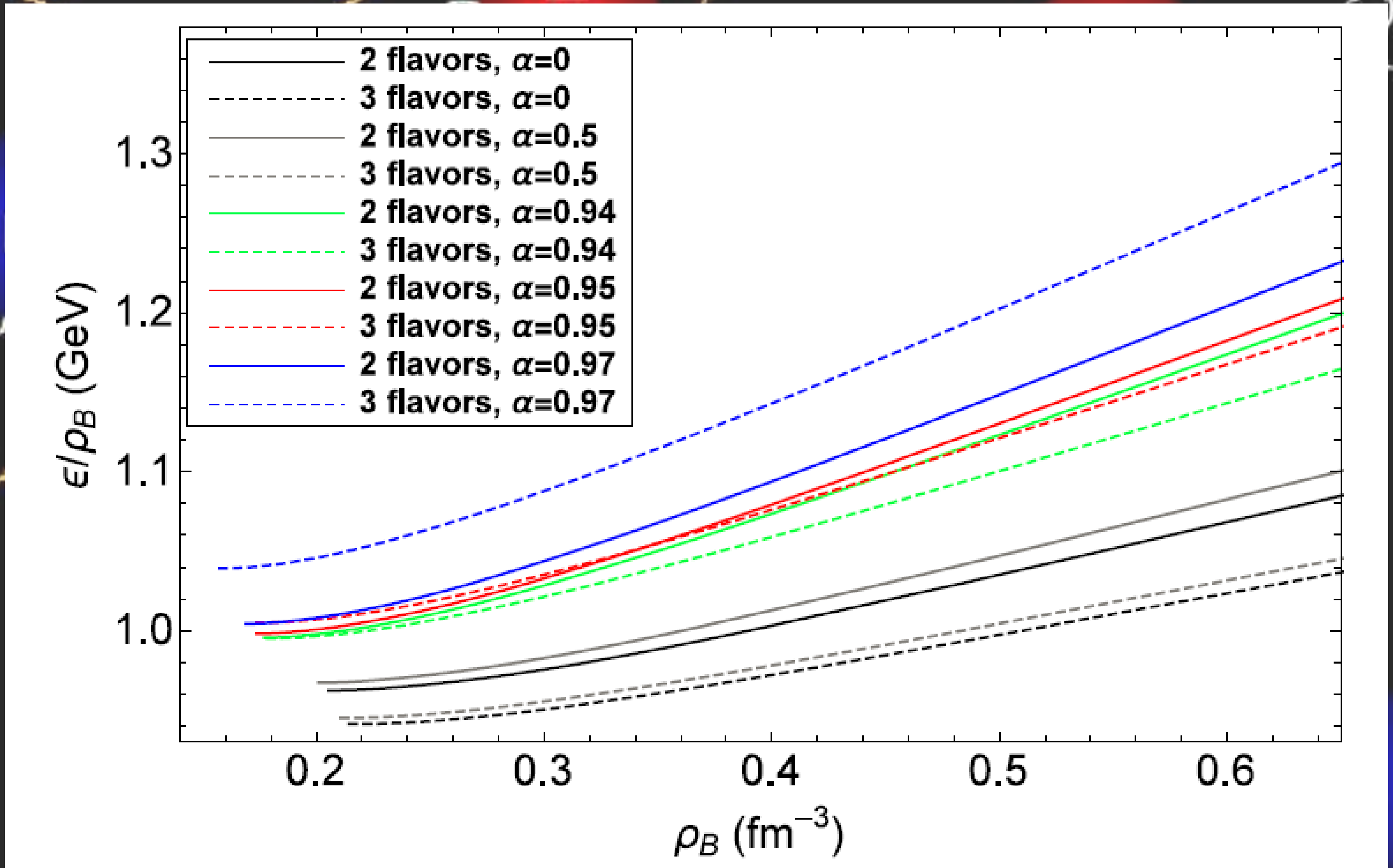
$$\mu_s = \mu_d$$

$$\mu_d = \mu_u + \mu_e$$

EOS

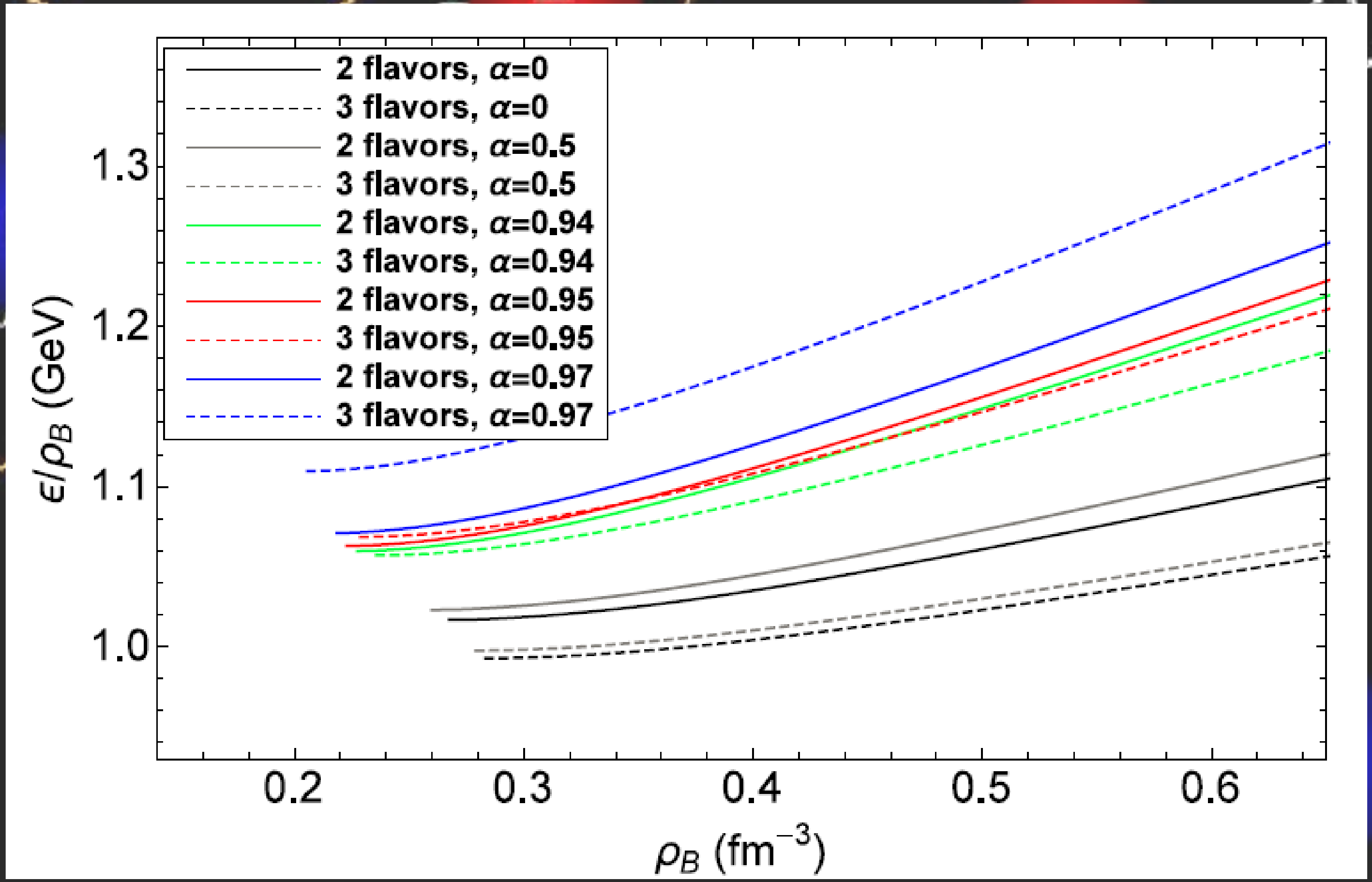
$$\epsilon = \mu_i n_i - P$$

Comparison of energy density per baryon between two-flavor and three-flavor quark matter for $B^{\frac{1}{4}} = 117 MeV$



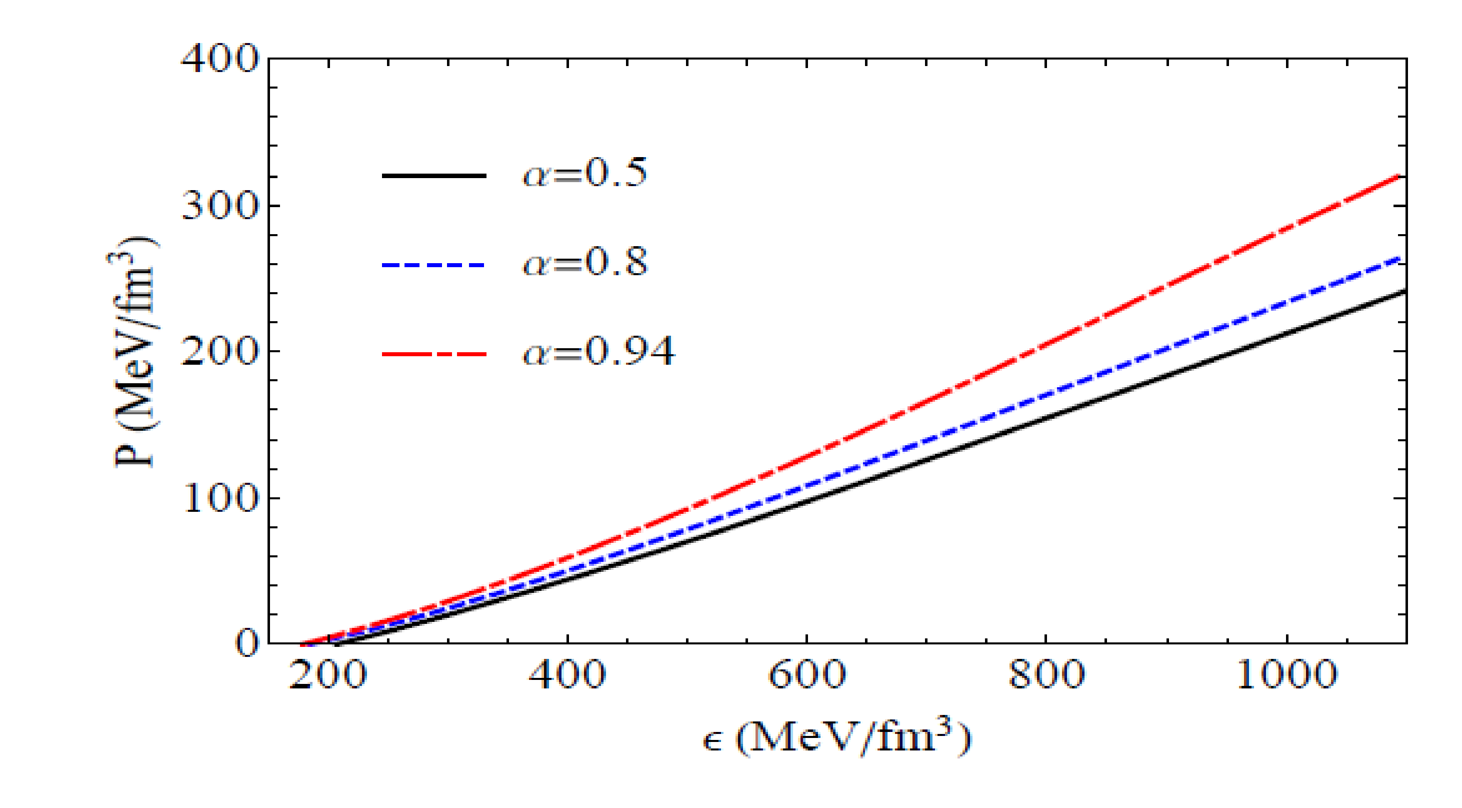
Cheng-Ming Li et al, PHYSICAL REVIEW D 101, 063023 (2020)

Comparison of energy density per baryon between two-flavor and three-flavor quark matter for $B^{\frac{1}{4}} = 130MeV$

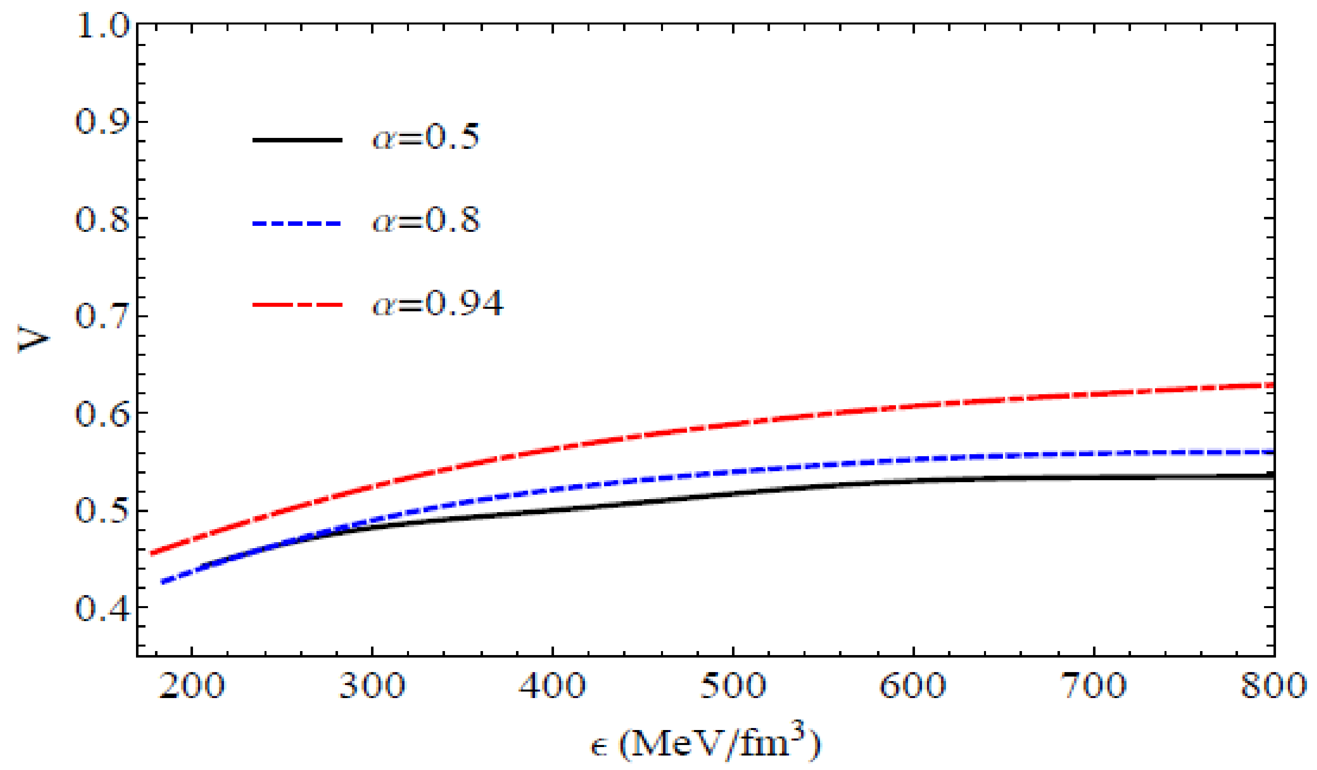


Cheng-Ming Li et al, PHYSICAL REVIEW D 101, 063023 (2020)

Results for $B^{\frac{1}{4}} = 117MeV$

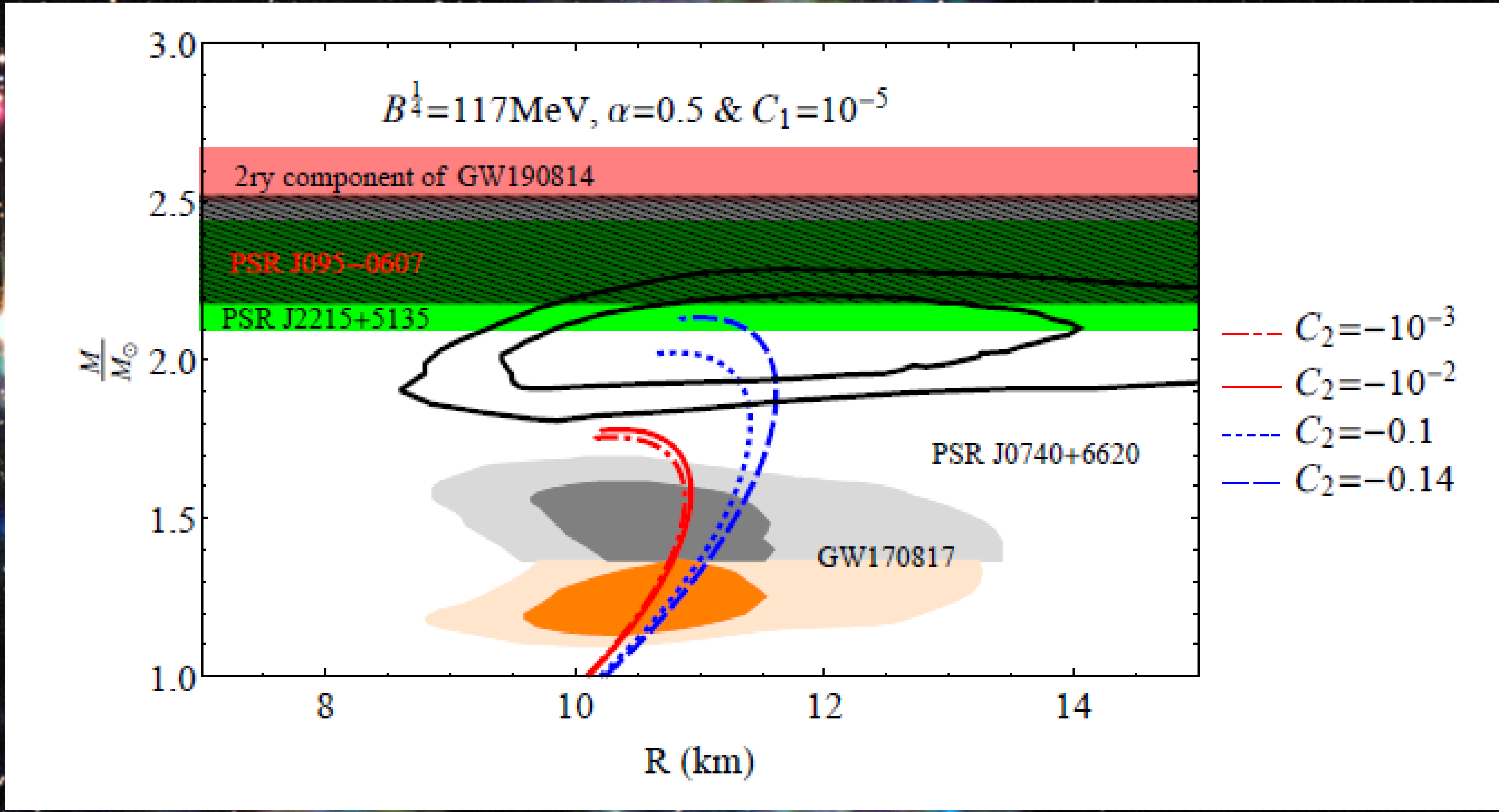


EOS

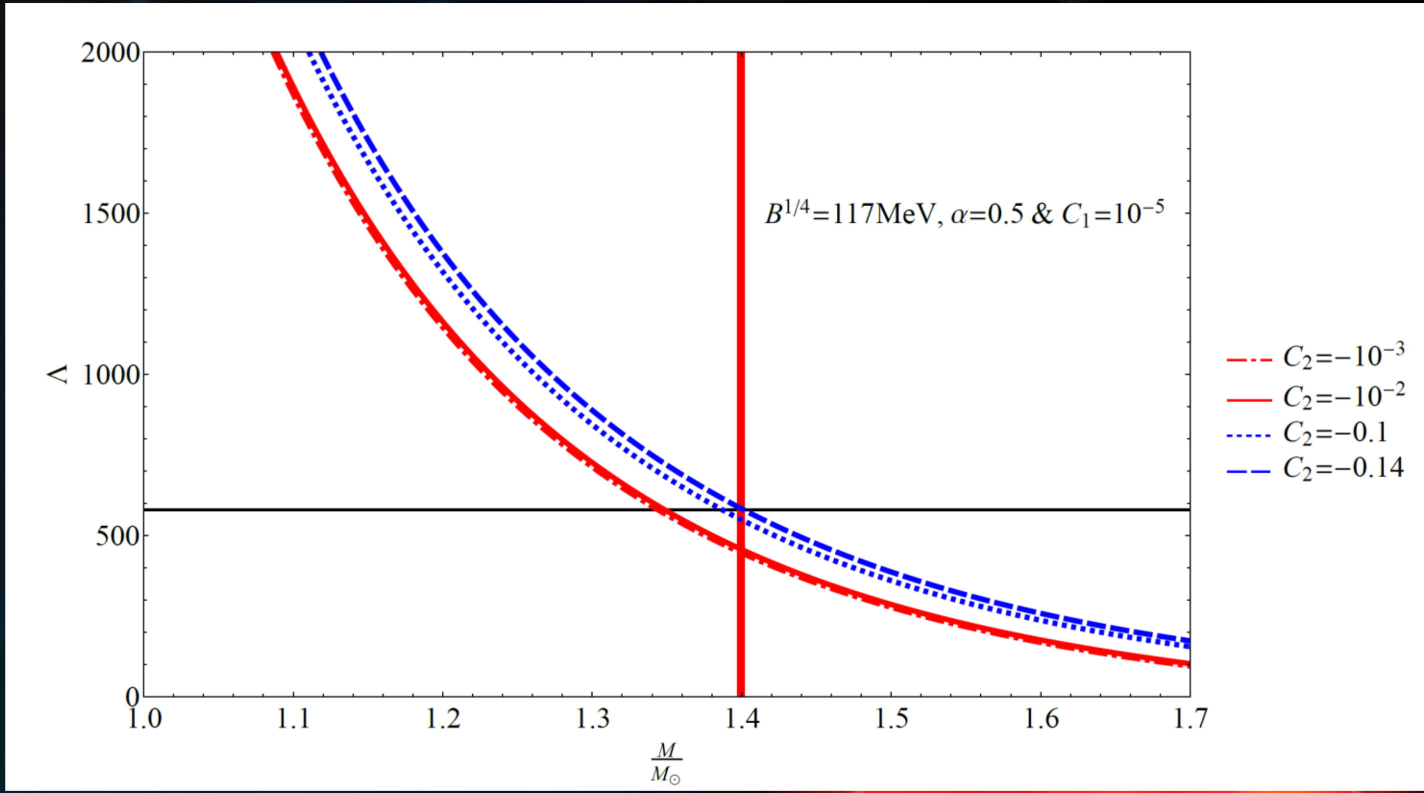


Speed of sound

$B^{\frac{1}{4}} = 117MeV$, α=0.5 , $C_1 = 10^{-5}$ & different values of C_2



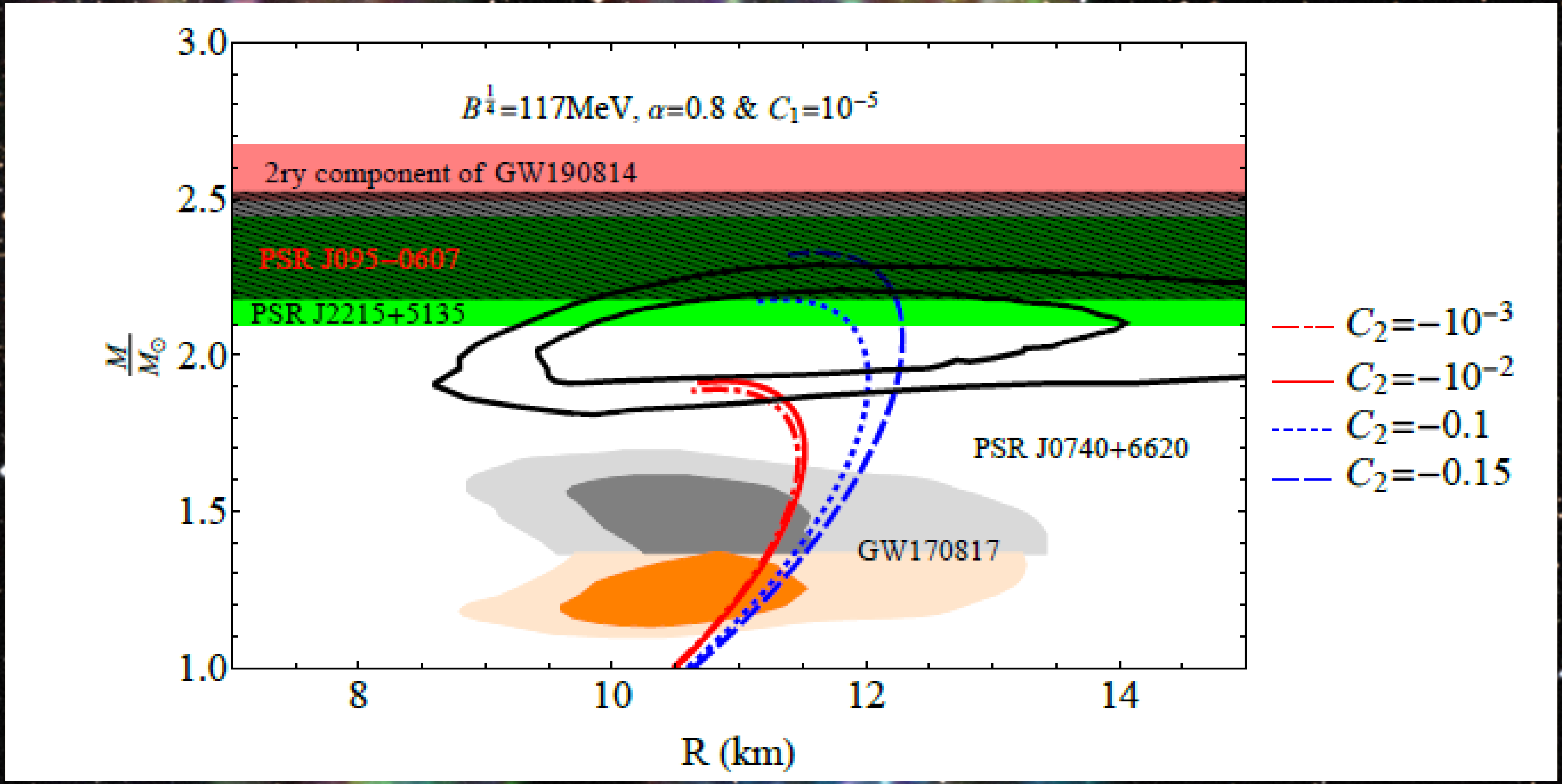
Mass – Radius diagrams



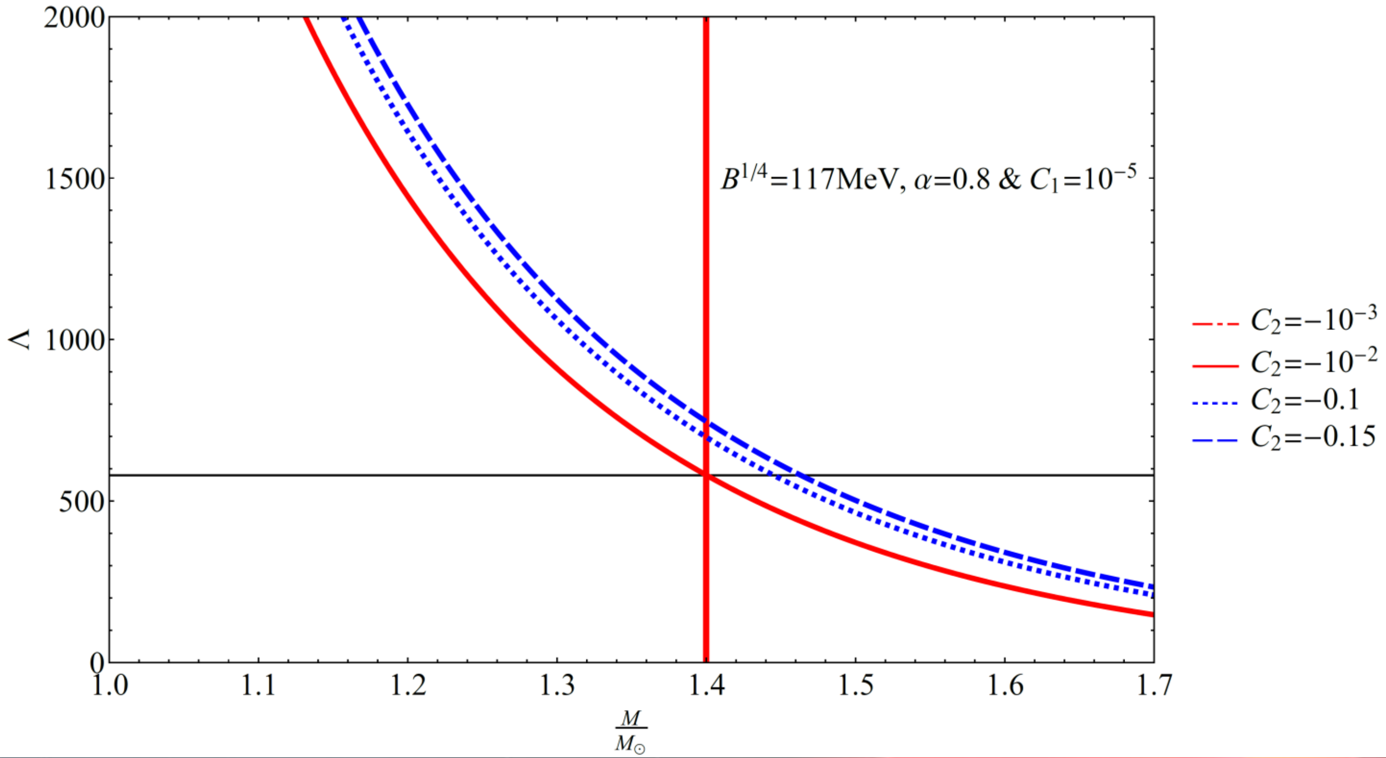
Dimensionless tidal deformability versus the mass of the star

C_2	-10^{-3}	-10^{-2}	-0.1	-0.14
$R(Km)$	10.33	10.36	10.70	11.02
$M_{TOV}(M_{\odot})$	1.76	1.78	2.02	2.13
$\Lambda_{1.4M_{\odot}}$	446.76	457.64	548.92	578.14
$\sigma(10^{-1})$	2.52	2.54	2.79	2.86
R_{Sch}	5.20	5.22	5.43	5.53

$B^{\frac{1}{4}} = 117MeV$, α=0.8 , $C_1 = 10^{-5}$ & **different values of** C_2



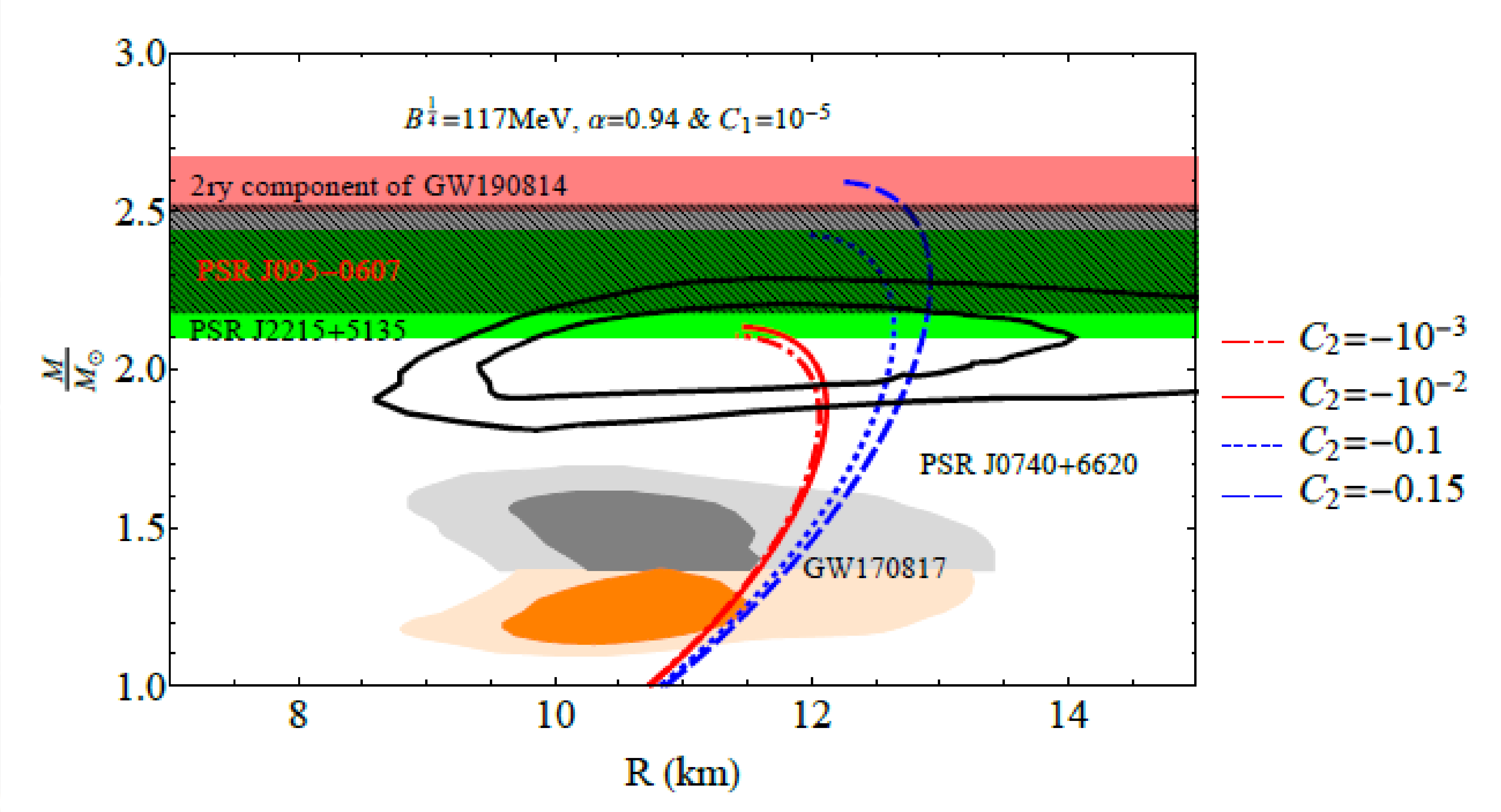
Mass – Radius diagrams



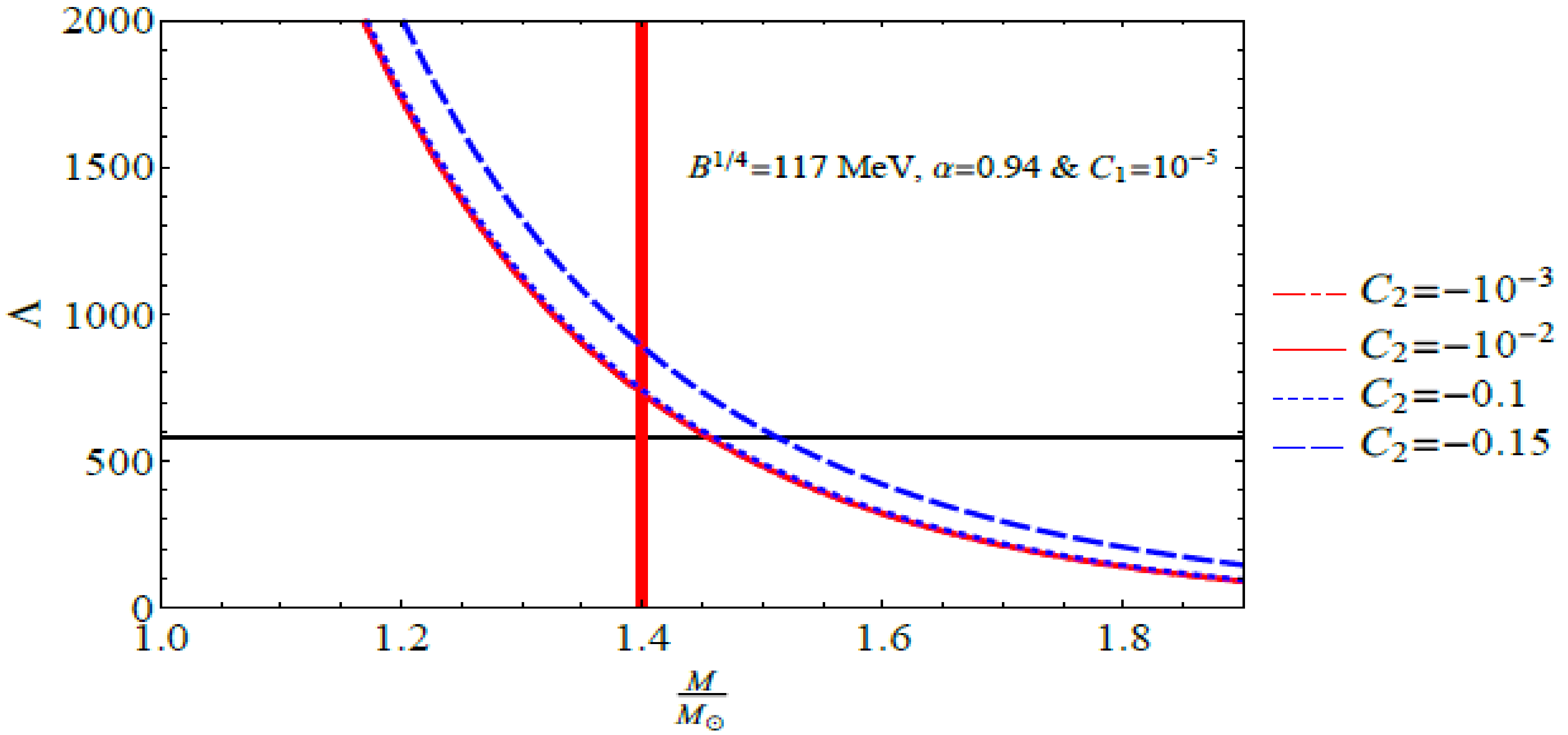
Dimensionless tidal deformability versus the mass of the star

C_2	-10^{-3}	-10^{-2}	-0.1	-0.15
$R(Km)$	10.80	10.92	11.33	11.61
$M_{TOV}(M_\odot)$	1.89	1.92	2.18	2.33
$\Lambda_{1.4M_\odot}$	578.35	578.69	700.07	745.67
$\sigma(10^{-1})$	2.59	2.60	2.85	2.97
R_{Sch}	5.59	5.63	5.87	6.00

$B^{\frac{1}{4}} = 117MeV$, α=0.94 , $C_1 = 10^{-5}$ & different values of C_2



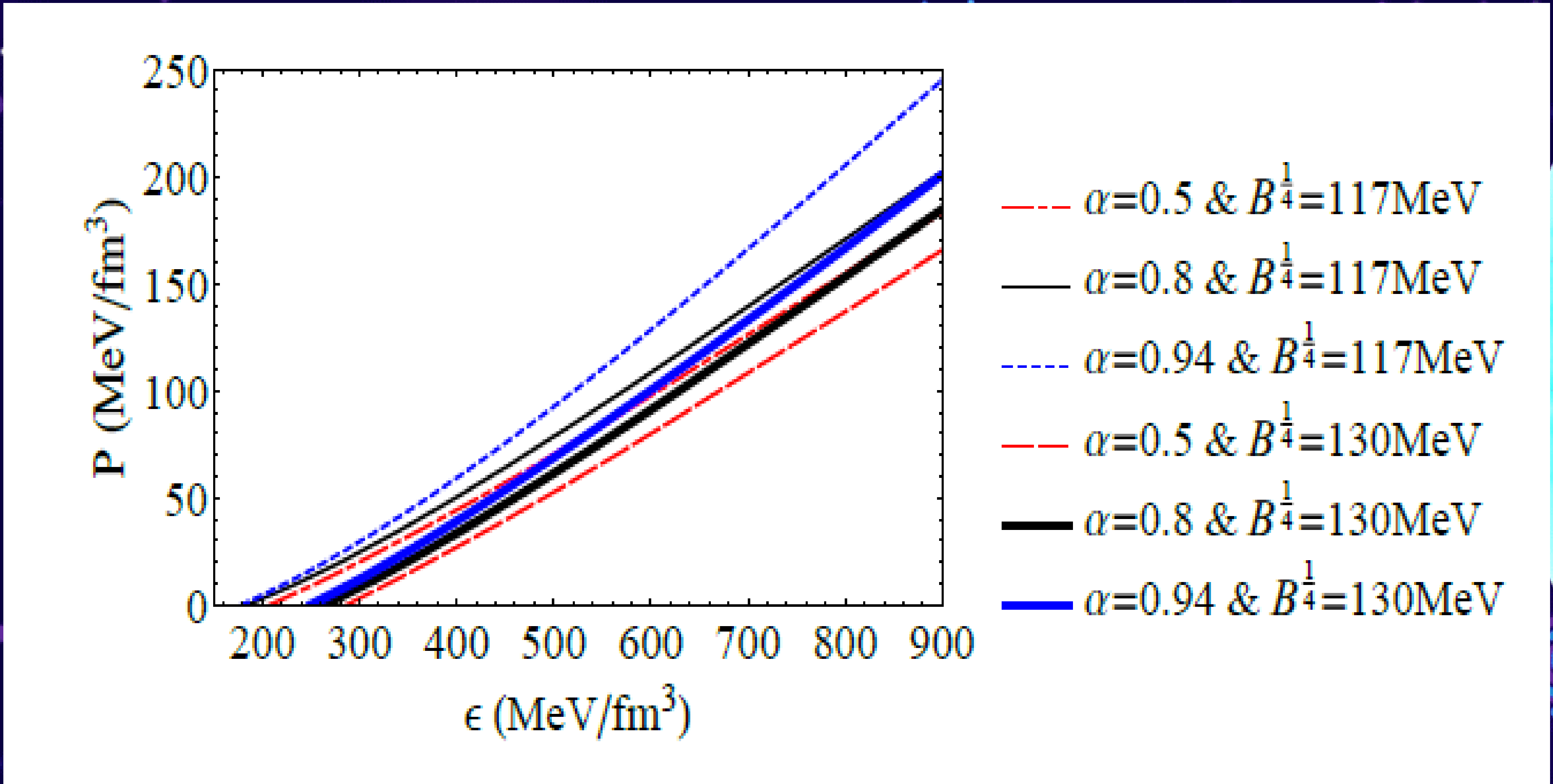
Mass – Radius diagrams



Dimensionless tidal deformability versus the mass of the star

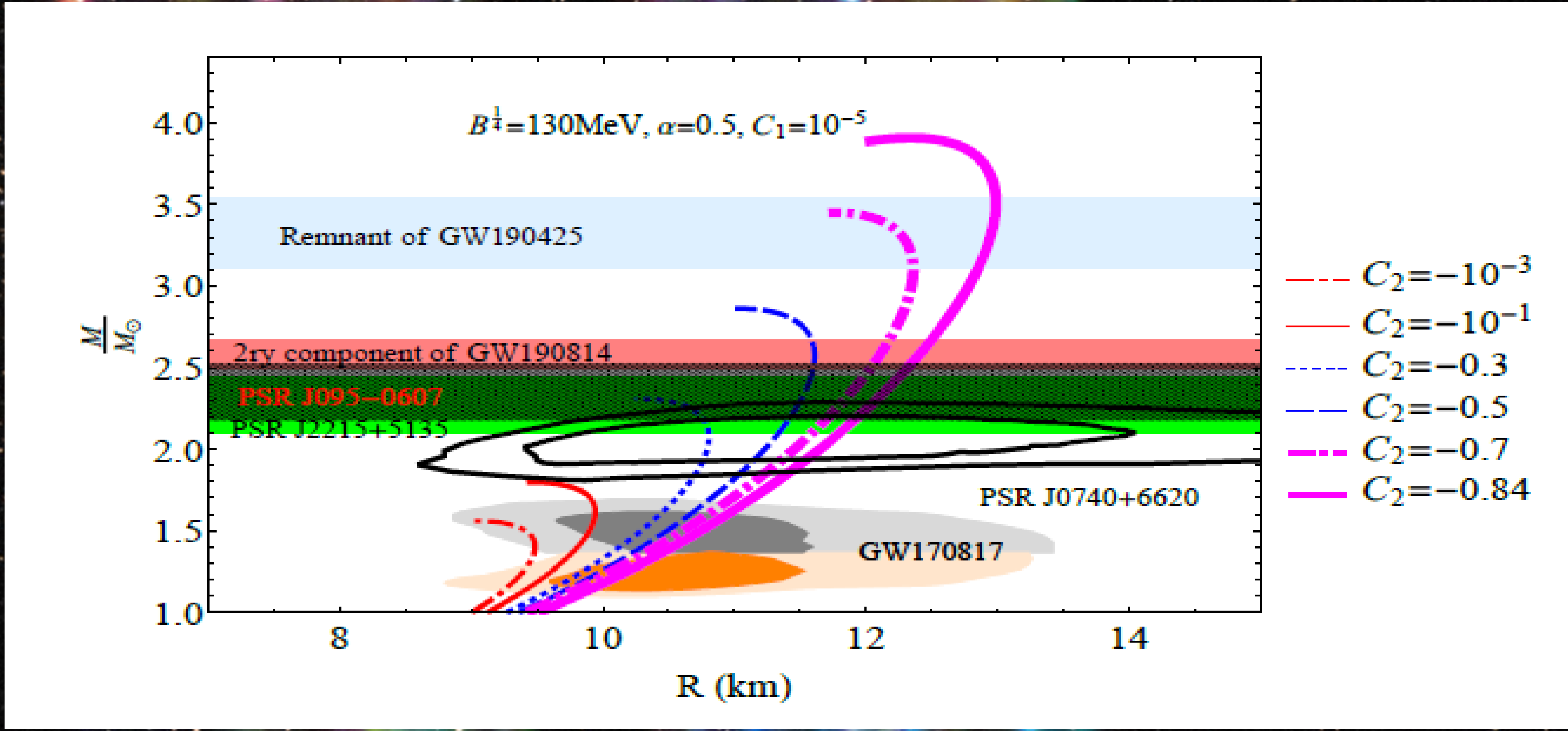
C_2	-10^{-3}	-10^{-2}	-0.1	-0.15
$R(Km)$	11.41	11.46	12.06	12.23
$M_{TOV}(M_\odot)$	2.11	2.13	2.43	2.60
$\Lambda_{1.4M_\odot}$	728.30	733.20	747.51	887.92
$\sigma(10^{-1})$	2.74	2.75	2.98	3.09
R_{Sch}	6.24	6.30	6.54	6.70

Results for $B^{\frac{1}{4}} = 130MeV$

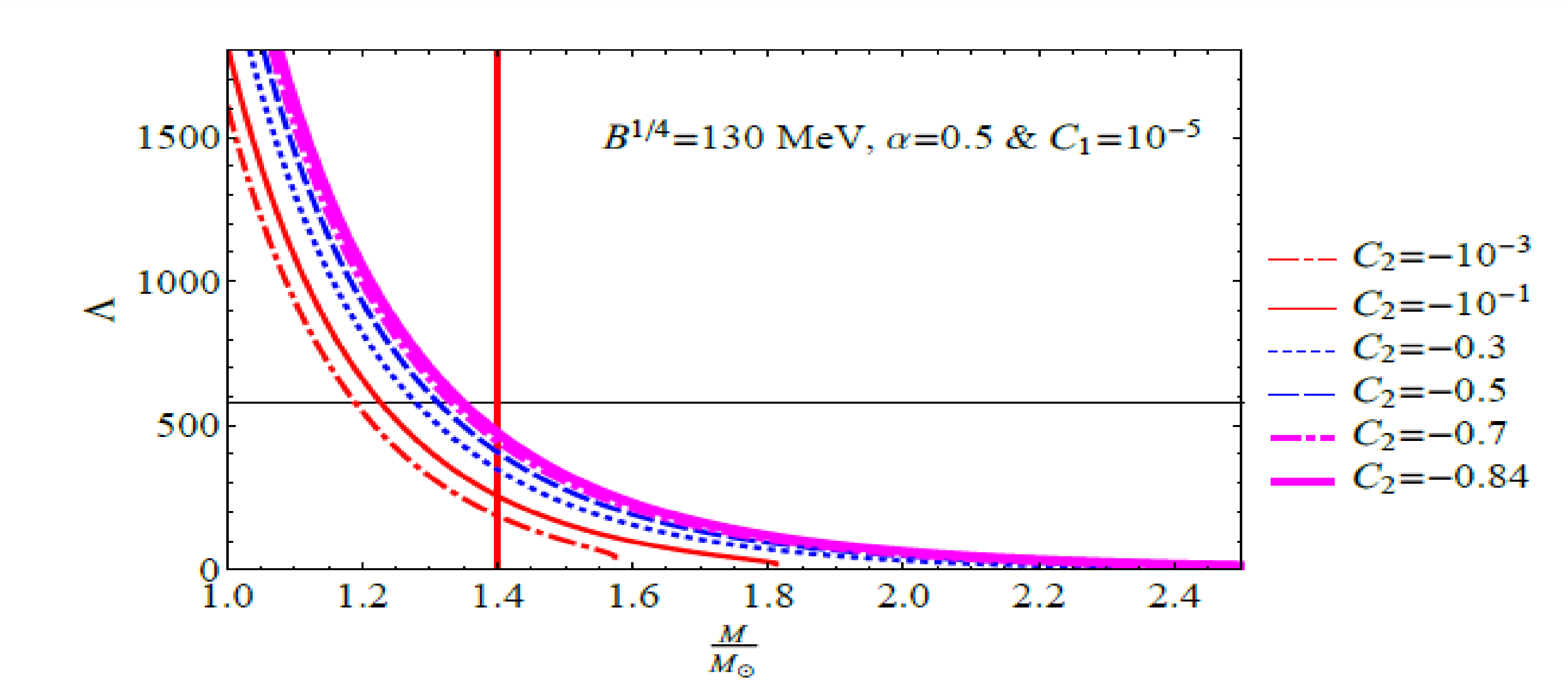


EOS

$B^{\frac{1}{4}} = 130MeV$, α=0.5 , $C_1 = 10^{-5}$ & different values of C_2



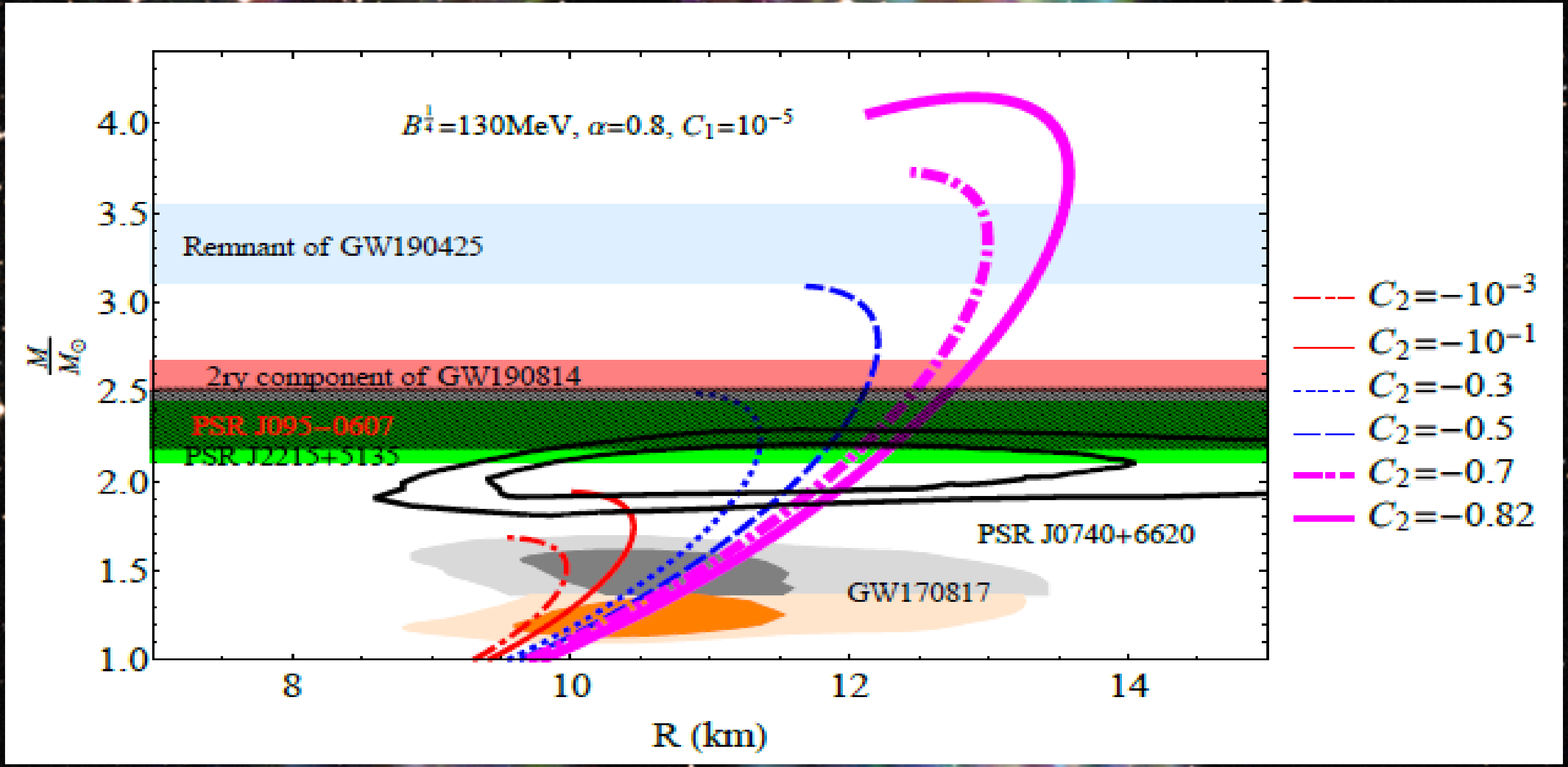
Mass – Radius diagrams



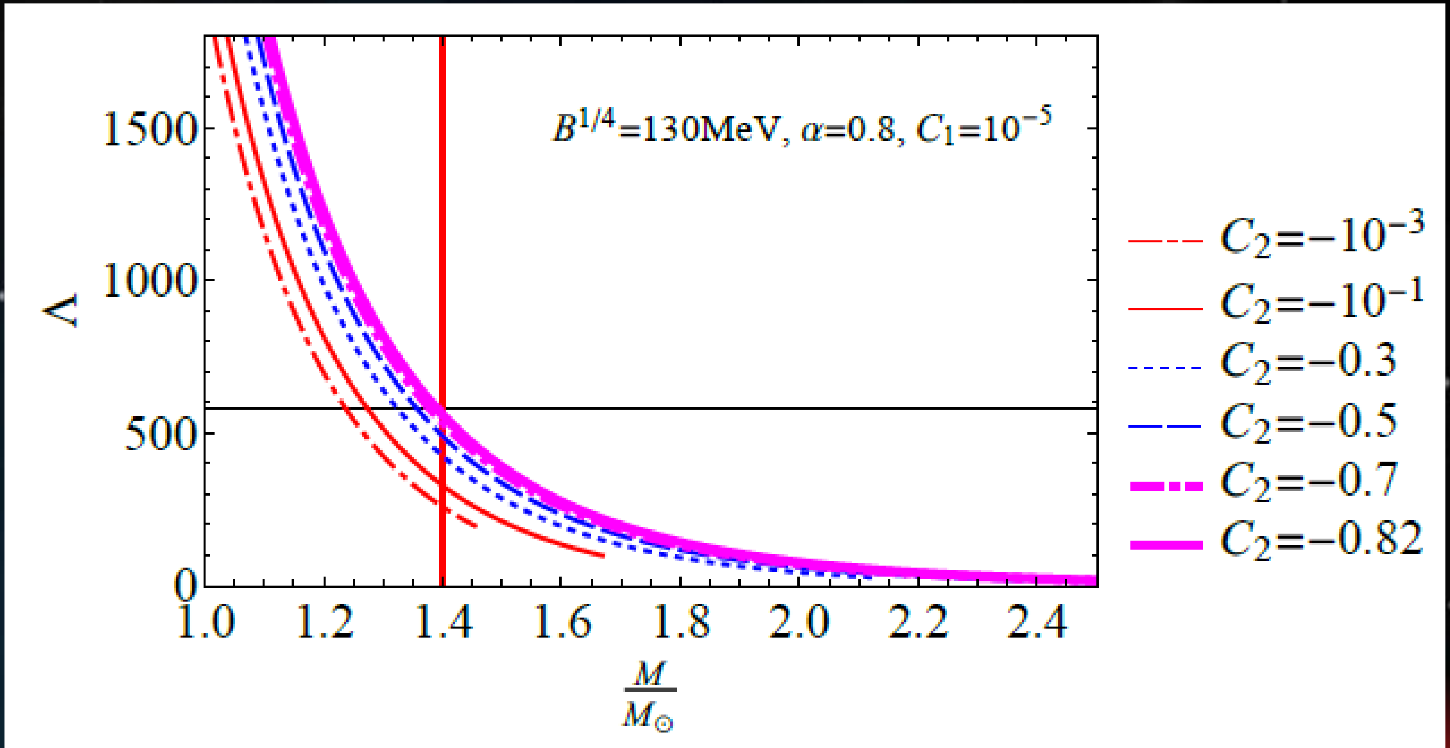
Dimensionless tidal deformability versus the mass of the star

	none mass gap				mass gap				
C_2	-10^{-3}	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.84
$R(Km)$	9.04	9.46	9.85	10.24	10.66	11.06	11.40	11.75	12.34
$M_{TOV}(M_\odot)$	1.56	1.80	2.05	2.31	2.57	2.86	3.15	3.45	3.91
$\Lambda_{1.4M_\odot}$	185.80	255.06	307.00	348.34	379.38	403.35	431.03	449.16	480.18
$\Lambda_{M_{TOV}}$	59.11	26.20	12.74	6.20	3.30	1.42	0.64	0.26	0.02
$\sigma(10^{-1})$	2.55	2.82	3.08	3.34	3.57	3.83	4.09	4.34	4.69
R_{Sch}	4.61	4.84	5.06	5.26	5.43	5.64	5.83	6.00	6.29

$B^{\frac{1}{4}} = 130 MeV, \alpha=0.8, C_1 = 10^{-5}$ & different values of C_2



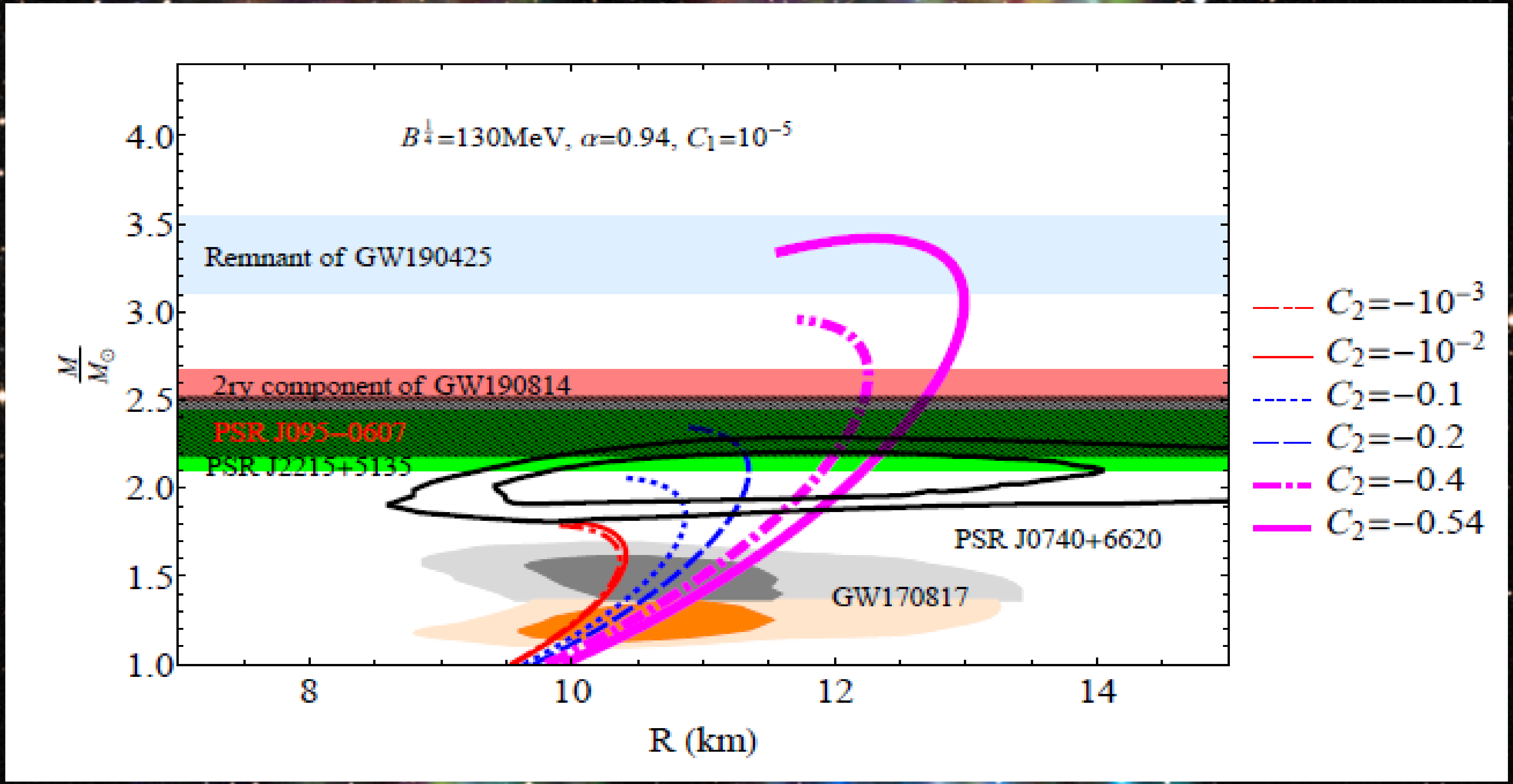
Mass – Radius diagrams



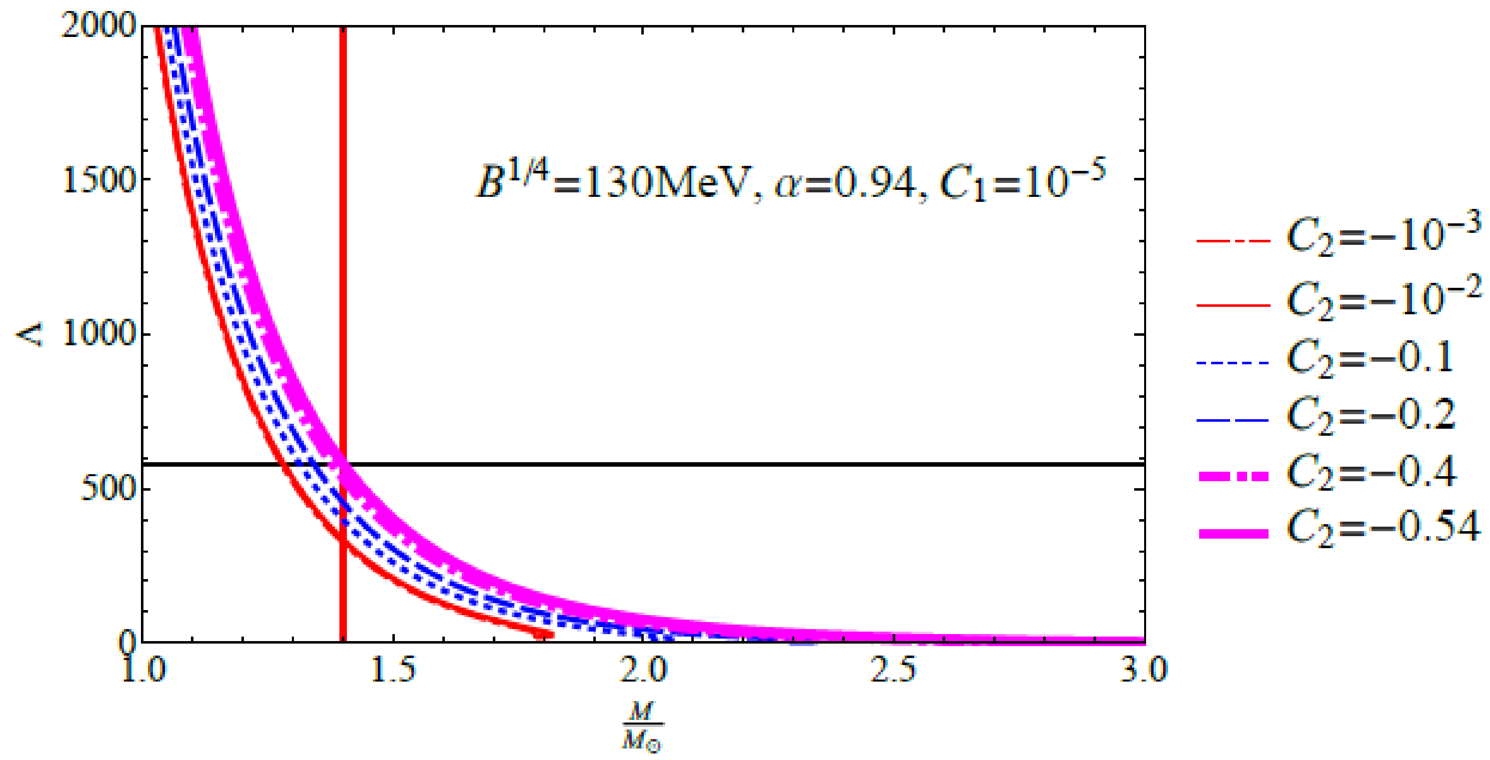
Dimensionless tidal deformability versus the mass of the star

none mass gap				mass gap					
C_2	-10^{-3}	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.82
$R(Km)$	9.46	9.94	10.40	10.78	11.15	11.60	11.97	12.36	12.80
$M_{TOV}(M_\odot)$	1.68	1.94	2.21	2.49	2.79	3.09	3.40	3.73	4.14
$\Lambda_{1.4M_\odot}$	257.98	329.76	383.76	427.33	461.80	487.14	515.31	536.06	559.21
$\Lambda_{M_{TOV}}$	47.04	20.43	9.64	2.70	1.95	0.92	0.39	0.14	0.01
$\sigma(10^{-1})$	2.63	2.89	3.14	3.42	3.70	3.94	4.20	4.47	4.79
R_{Sch}	4.97	5.22	5.45	5.67	5.90	6.10	6.29	6.49	6.73

$B^{\frac{1}{4}} = 130MeV$, α=0.94 , $C_1 = 10^{-5}$ & different values of C_2



Mass – Radius diagrams



Dimensionless tidal deformability versus the mass of the star

	none mass gap				mass gap			
C_2	-10^{-3}	-10^{-2}	-0.1	-0.2	-0.3	-0.4	-0.54	-0.55
$R(Km)$	9.81	9.85	10.30	10.77	11.23	11.63	12.32	12.35
$M_{TOV}(M_\odot)$	1.79	1.81	2.06	2.35	2.65	2.96	3.42	3.45
$\Lambda_{1.4M_\odot}$	326.43	333.26	398.93	452.51	499.87	532.37	578.95	580.64
$\Lambda_{M_{TOV}}$	32.25	32.26	15.20	6.51	2.92	1.36	0.35	0.32
σ (10^{-1})	2.70	2.72	2.96	3.23	3.49	3.77	4.11	4.13
R_{Sch}	5.29	5.30	5.54	5.80	6.03	6.26	6.57	6.59

Conclusion

In GR, the soft EOSs give small masses for quark stars, and the stiff EOSs do not satisfy the constraint of tidal deformability. We have shown that in massive gravity, it is possible to have quark stars that not only cover the mass gap region objects, but also satisfy the constraint of tidal deformability.

Thank you for giving time