A Few Topics in the Neutron Stars

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HaPhy, "Nuclear Physics in Various Environments"
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MKC et.al, PRC 82, 025804, (2010); PRC 83, 018802 (2011); JCAP 10, 21 (2013)…

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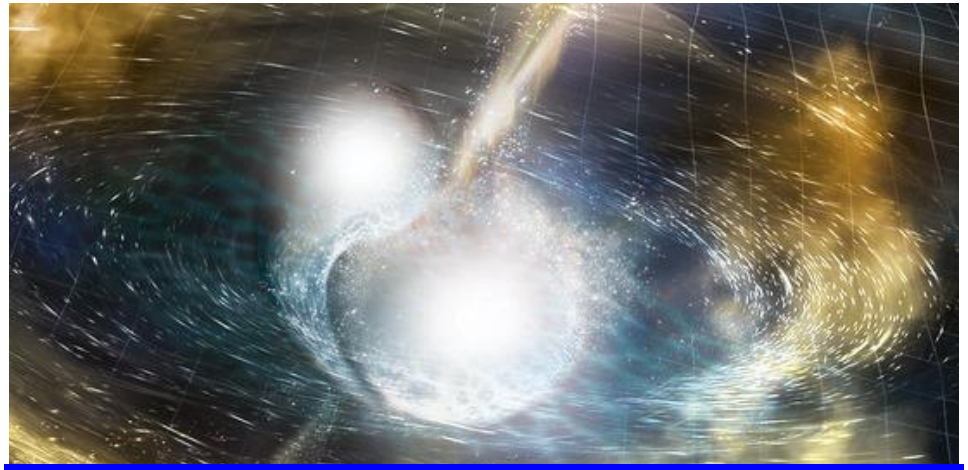
Contents II

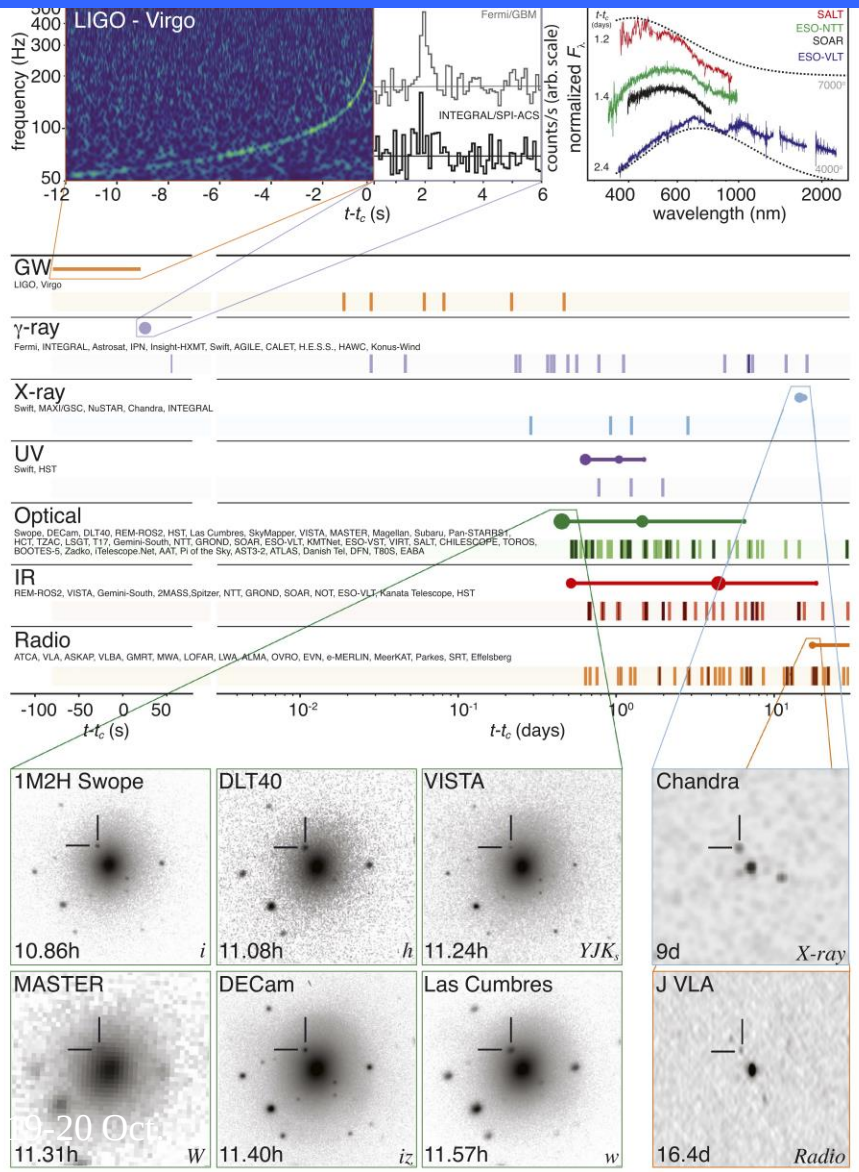
The first University in Korea Soongsil University

Seen in LIGO + 70 Observatories

GW170817/GRB170817A/ SSS17a



The EM **kilonova** indicates evidence of r-process nucleosynthesis that has implications for galactic chemical evolution and the nuclear physics of heavy nuclei.



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Deduced properties for GW170817

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

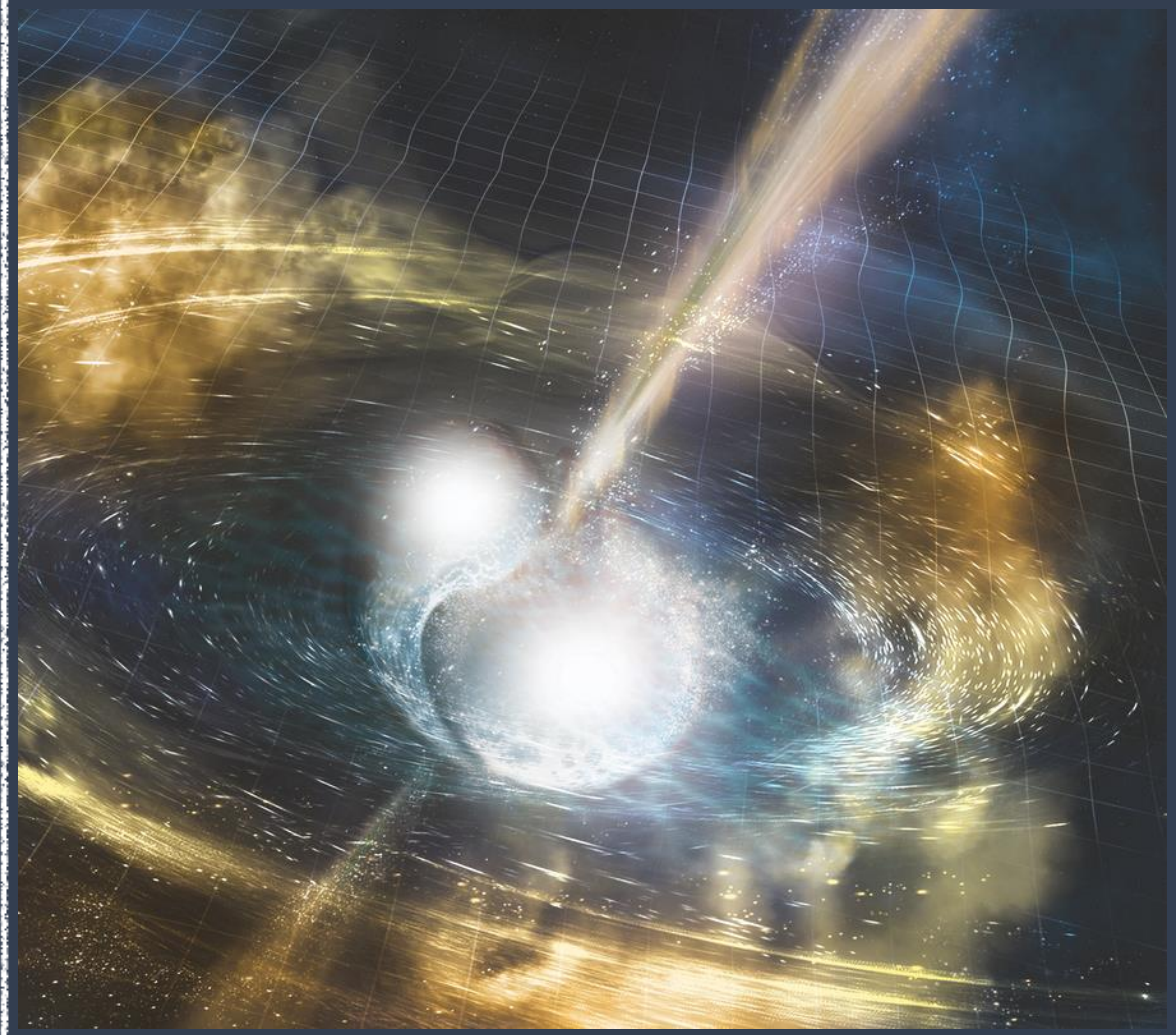
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability Λ	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Two ~1.4 $M_\odot$ neutron stars 40 Mpc distant

HaPhy, APCTP, Pohang, 19-20 Oct., 2018

By Grant Mathews

Introduction (GW170817)



NSF/LIGO/Sonoma State University/A. Simonnet
https://www.ligo.caltech.edu/image/ligo20171016d

PRL 119 161101 (2017)

Mass

$$m_1 = 1.36 - 1.60 M_\odot$$
$$m_2 = 1.17 - 1.36 M_\odot$$

Distance

$$40^{+8}_{-14} Mpc$$

Combined dimensionless tidal deformability

$$\tilde{\Lambda} \leq 800$$

Dimensionless tidal deformability

$$\Lambda(1.4 M_\odot) \leq 800$$

Introduction

$$Q = -\lambda\mathcal{E}$$

Q : Quadrupole moment of neutron star

$\mathcal{E}$: External quadrupole tidal field

λ : a constant which is related to the tidal deformability Λ

$$\Lambda = \frac{5}{2}\lambda\frac{1}{M}\left(\frac{c^2}{G}\right)^5$$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

PRD 81 123016 (2010)

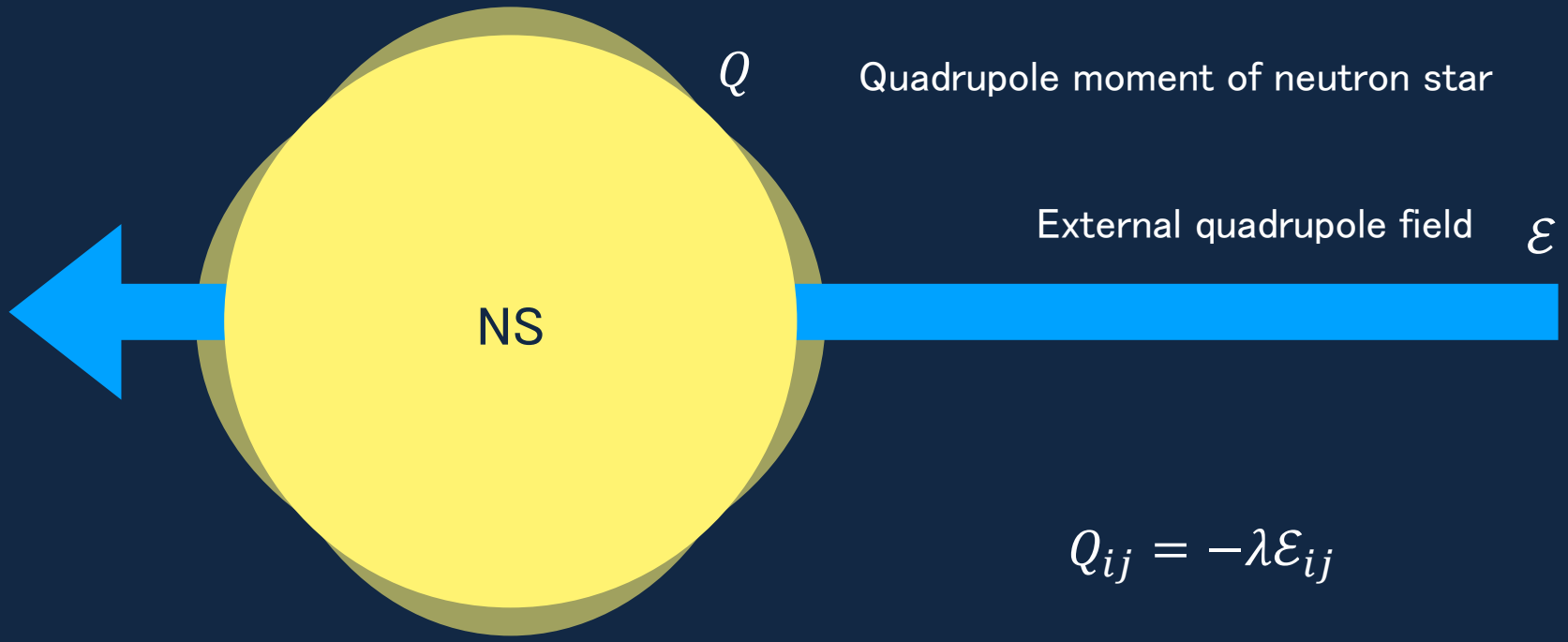
Tidal deformability

If we consider a static, spherically symmetric star of mass (m) placed in a time-independent external quadrupole tidal field.

The star will develop in response a quadrupole moment

Tidal deformability

If we consider a static, spherically symmetric star of mass (m) placed in a time-independent external quadrupole tidal field, the star will develop in response a quadrupole moment



$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

PRD 81 123016 (2010)

Tidal deformability & Masses

λ : a constant which is related to the tidal deformability Λ

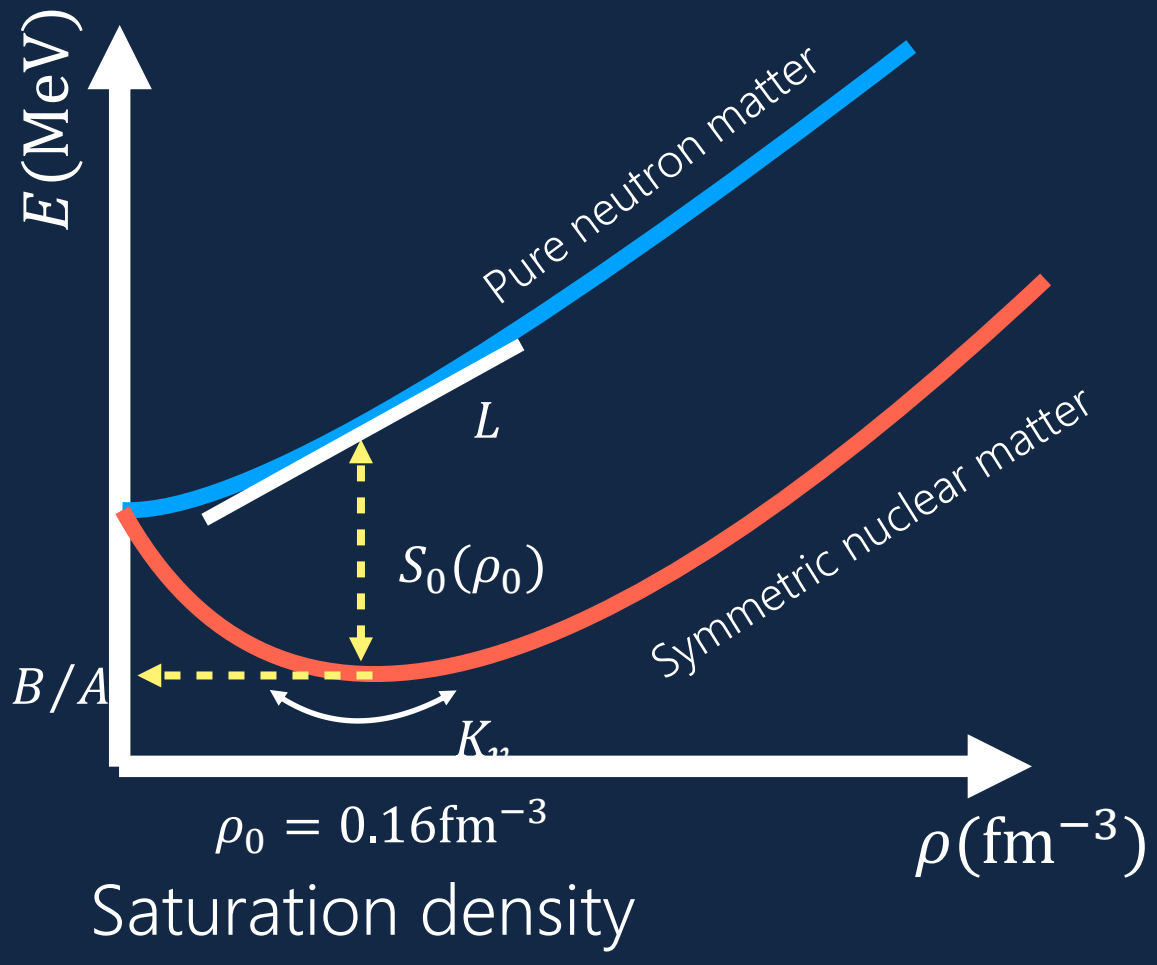
$$\Lambda = \frac{5}{2}\lambda\frac{1}{M}\left(\frac{c^2}{G}\right)^5$$

$\Lambda \leq 800$ PRL 119 161101 (2017)

$1.94M_{\odot} \leq M_{\mathrm{NS}} \leq 2.01M_{\odot}$ Nature 467 1081-1083 (2010)

By using these observation data,
we can give the constraint on slope parameter and incompressibility.

Saturation properties present



Binding energy

$$B/A \approx -16.0\mathrm{MeV}$$

Symmetry energy

$$S_0(\rho_0) = 32.5 \pm 0.5\mathrm{MeV}$$ [1]

Slope parameter

$$L = \ 50 - 100\mathrm{MeV}$$ [2]

Incompressibility

$$K = \ 180 - 260\mathrm{MeV}$$ [3]

Effective mass

$$m^*/m = 0.7 - 0.8$$ [4]

[1]PRL 108 052501 (2012)[3]PLB 778 207212 (2018)
[2]PRL 102 122501 (2009)[4]Nucl. Phys. A 950 64109 (2016)

The effect of L and K on neutron stars

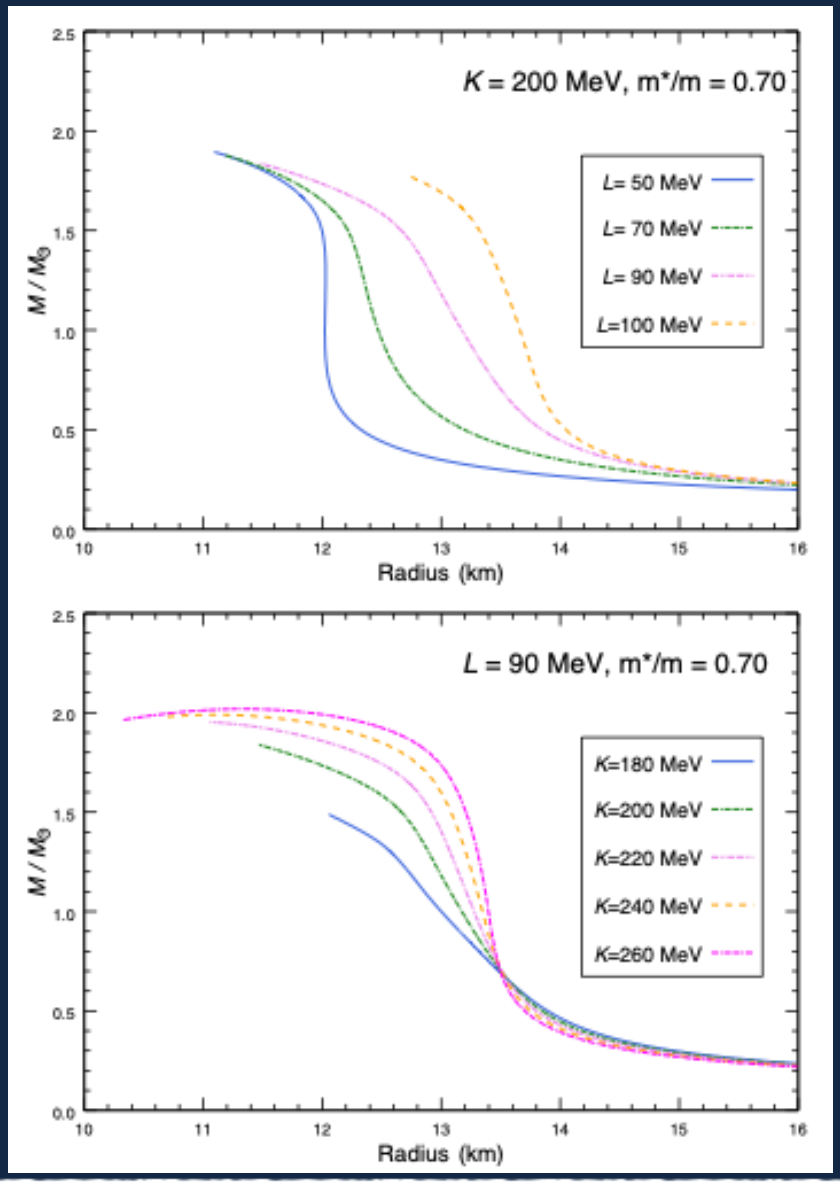
In these range,

$$L = 50 - 100\text{MeV} \quad K = 180 - 260\text{MeV}$$

neutron stars can cover wide range of mass and radius.

$$R(1.4M_{\odot}): 12 - 14\text{km}$$

Maximum mass : $1.5 - 2.1M_{\odot}$



Relativistic mean field model

Lagrangian density for static uniform nuclear matter :

$$\mathcal{L} = \sum_{B} \overline{\psi}_B \left[i\gamma_\mu \, \partial^\mu - M_B^*(\sigma_0, \sigma_0^*) - g_{\omega B}\gamma_0 \, \omega_0 - g_{\phi B}\gamma^0 \, \phi^0 - g_{\rho B}\gamma^0 \, \rho_0 \, I_{3B} \right] \psi_B$$
$$- \frac{1}{2} m_\sigma^2 \sigma_0^2 - \frac{1}{2} m_{\sigma^*} \sigma_0^{*2} + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} m_\rho^2 \rho_0^2 - U_{NL}(\sigma_0, \omega_0 \, , \rho_0 \,)$$
$$B = N, \Lambda, \Sigma^{+,0,-}, \Xi^{0,-}$$

The effective baryon mass in matter :

$$M_B^*(\sigma, \sigma^* \,) = M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*$$

The following non-linear term is also introduced in order to reproduce the saturation properties of nuclear matter :

$$U_{\mathrm{NL}}(\sigma, \omega^\mu \, \boldsymbol{\rho}^\mu \,) = \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 - \Lambda_v \, g_{\omega B}^2 g_{\rho B}^2 (\omega_0^2 \rho_0^2)$$

Coupling constants

Coupling constants, $g_{\sigma N}$, $g_{\omega N}$, and $g_{\rho N}$ are determined so as to reproduce the binding energy per nucleon, and symmetry energy at saturation density.

$$B/A = -16.0\mathrm{MeV} \qquad \rho_0 = 0.16\mathrm{fm}^{-3}$$
$$S_0(\rho_0) = 32.5\mathrm{MeV}$$

The SU(3) symmetry in the vector-meson gives the relations of the coupling constants as

$$g_{\omega\Lambda} = g_{\omega\Sigma} = \frac{1}{1+\sqrt{3}z\tan\theta_v} g_{\omega N} \qquad g_{\rho\Sigma} = 2g_{\rho N}, g_{\rho\Xi} = g_{\rho N} g_{\rho\Lambda} = 0$$

$$g_{\omega\Xi} = \frac{1-\sqrt{3}z\tan\theta_v}{1+\sqrt{3}z\tan\theta_v} g_{\omega N} \qquad g_{\phi\Lambda} = g_{\phi\Sigma} = \frac{-\tan\theta_v}{1+\sqrt{3}z\tan\theta_v} g_{\omega N} \quad g_{\phi\Xi} = -\frac{\sqrt{3}z+\tan\theta_v}{1+\sqrt{3}\tan\theta_v} g_{\omega N}$$

$$g_{\phi N} = \frac{\sqrt{3}z-\tan\theta_v}{1+\sqrt{3}z\tan\theta_v} g_{\omega N}$$

In the present calculation, we refer to the Nijmegen extended-soft-core (ESC) model [1] to fix the mixing angle (θ_v) and z as

$$\theta = 37.50^\circ, z = 0.1949$$

[1] Prog. Theor. Phys. Suppl. 185 14 (2010)

Coupling constants

We need to consider the hyperon coupling. The σ-Y and σ*-Y are determined as follows. The potential for hyperon Y in symmetric nuclear matter is calculated as

$$U_Y^{(N)} = -g_{\sigma Y}\sigma_0 + g_{\omega Y}\omega_0$$

$U_\Lambda^{(N)} = -28\text{MeV}$[1] $U_\Sigma^{(N)} = 30\text{MeV}$[2] $U_\Xi^{(N)} = -18\text{MeV}$[3]

The potential for Y in Y−hyperon matter is written as :

$$U_Y^{(Y)} = -g_{\sigma Y}\sigma_0^{(Y)} - g_{\sigma^* Y}\sigma_0^{*(Y)} + g_{\omega Y}\omega^{(Y)} + g_{\phi Y}\phi_0^{(Y)}$$

$U_\Xi^{(\Xi)} \simeq U_\Lambda^{(\Xi)} \simeq 2U_\Xi^{(\Lambda)} \simeq 2U_\Lambda^{(\Lambda)}$ [3] $U_\Lambda^{(\Lambda)} = -5\text{MeV}$ Nagara event

[1]PRC 54 1416 (1996), [2]PRC 88 015802 (2013), [3]PRC 77 025801 (2008)

Non-Linear potential

We add the following NL potential to the Lagrangian density

$$U_{\mathrm{NL}}(\sigma, \omega^{\mu}\, \boldsymbol{\rho}^{\mu}) = \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 - \Lambda_v\, g_{\omega B}^2 g_{\rho B}^2 (\omega_0^2 \rho_0^2)$$

Investigated range of incompressibility (K), and the slope parameter (L) at saturation density is

$$K = 180 - 260\mathrm{MeV}$$

$$L = 50 - 100\mathrm{MeV}.$$

We fix the effective mass ratio as

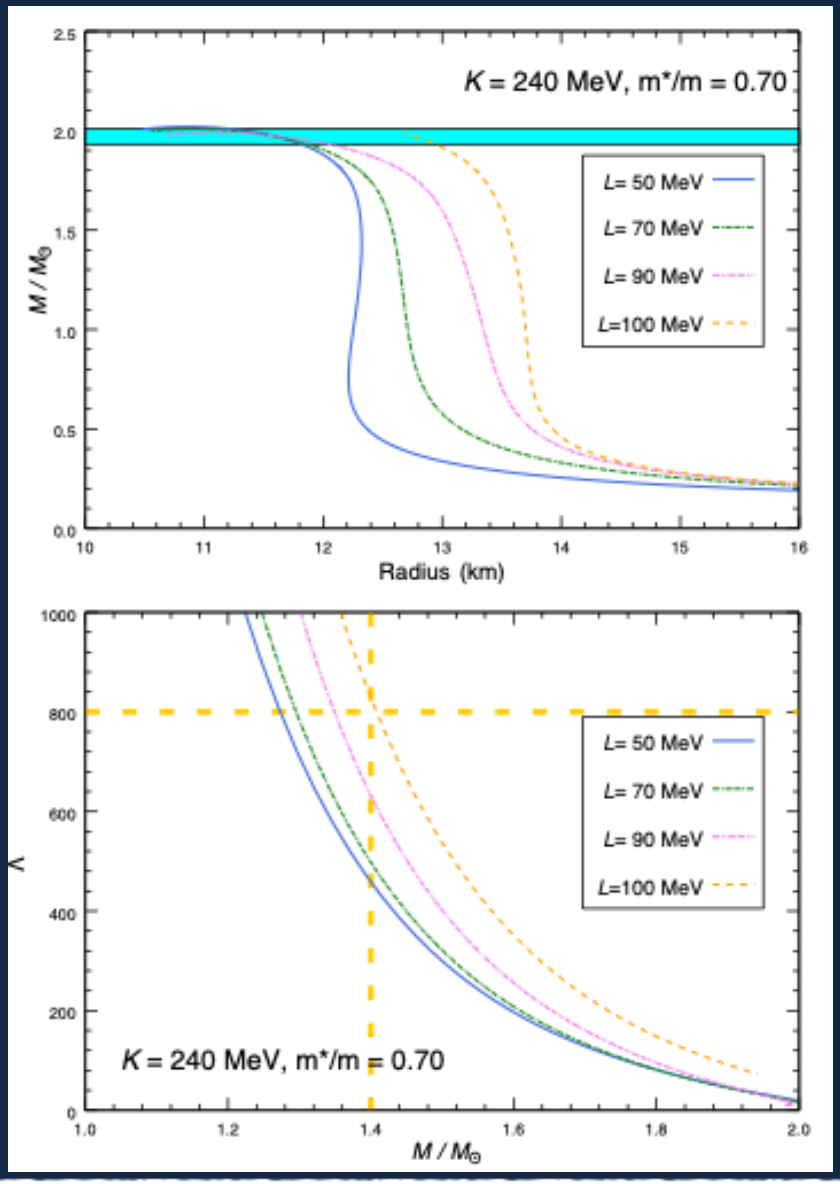
$$m^*/m = 0.7$$

Result
(Dependence on slope parameter)

- The slope parameter does not affect the maximum mass of neutron star.
- Around the 1.3 solar mass neutron star

  Slope parameter ⟶ Large

  Radius ⟶ Large
- In the tidal deformability case, the large slope parameter gives the higher tidal deformability.



The onset of Lambda particle Kv = 240 MeV

	L = 50 MeV	70 MeV	90 MeV	100 MeV
ρ_Λ	0.450	0.440	0.410	0.380

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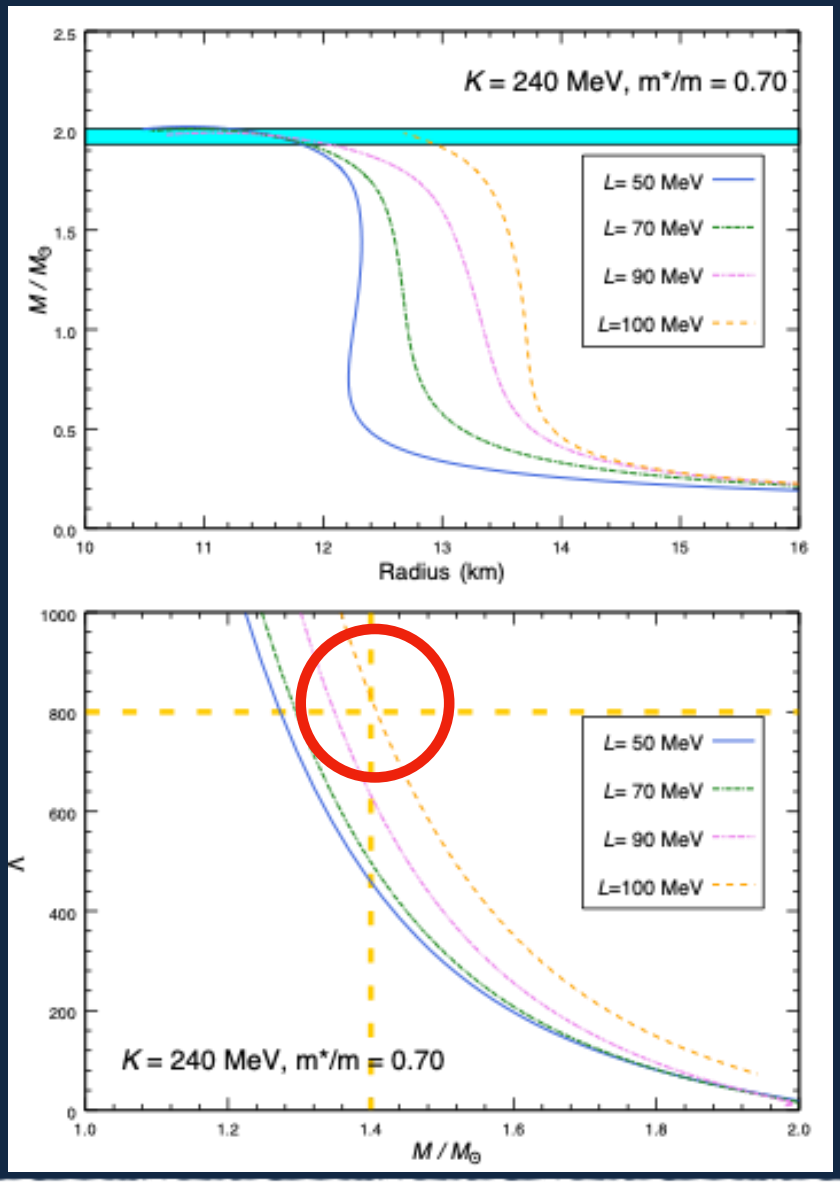

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Result

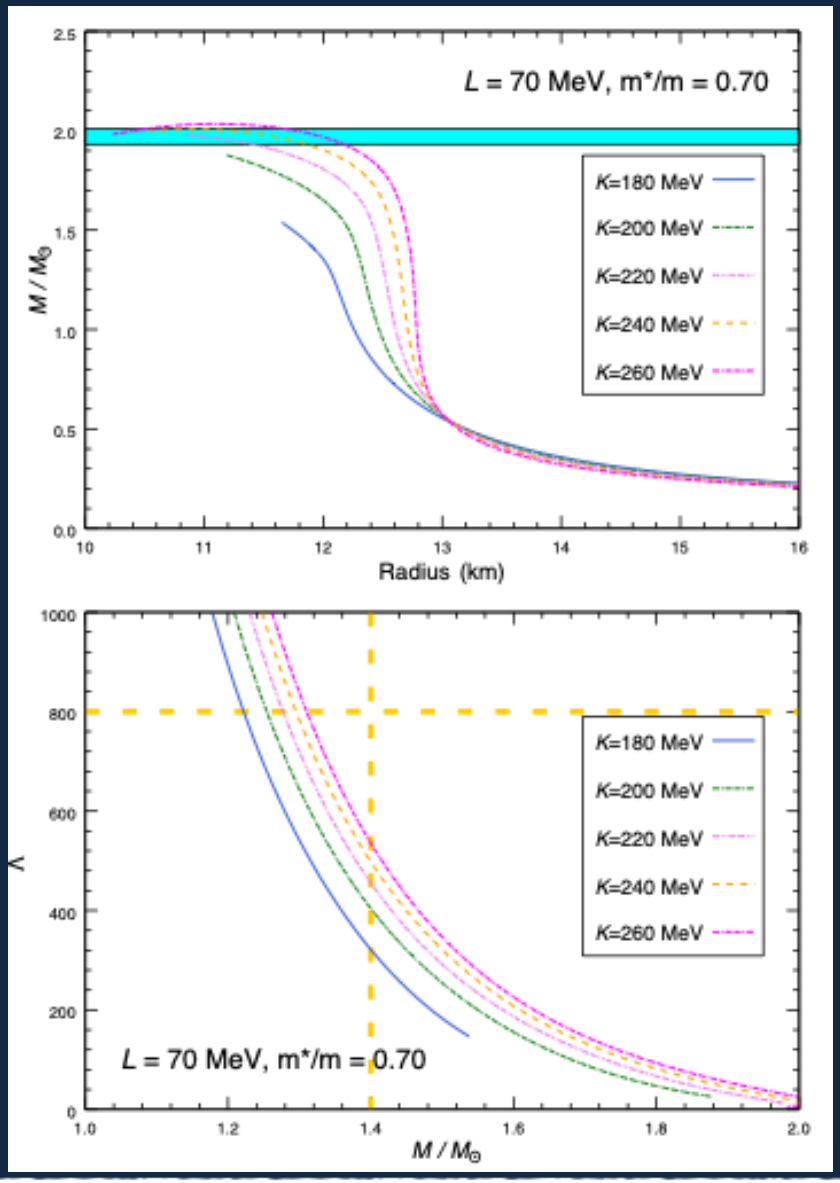
(Dependence on incompressibility)

- The incompressibility affects both maximum mass and radius.

Incompressibility ⟶ Large

maximum mass ⟶ Large

- The two-solar mass neutron star cannot be described in K = 180 and 200 MeV cases.



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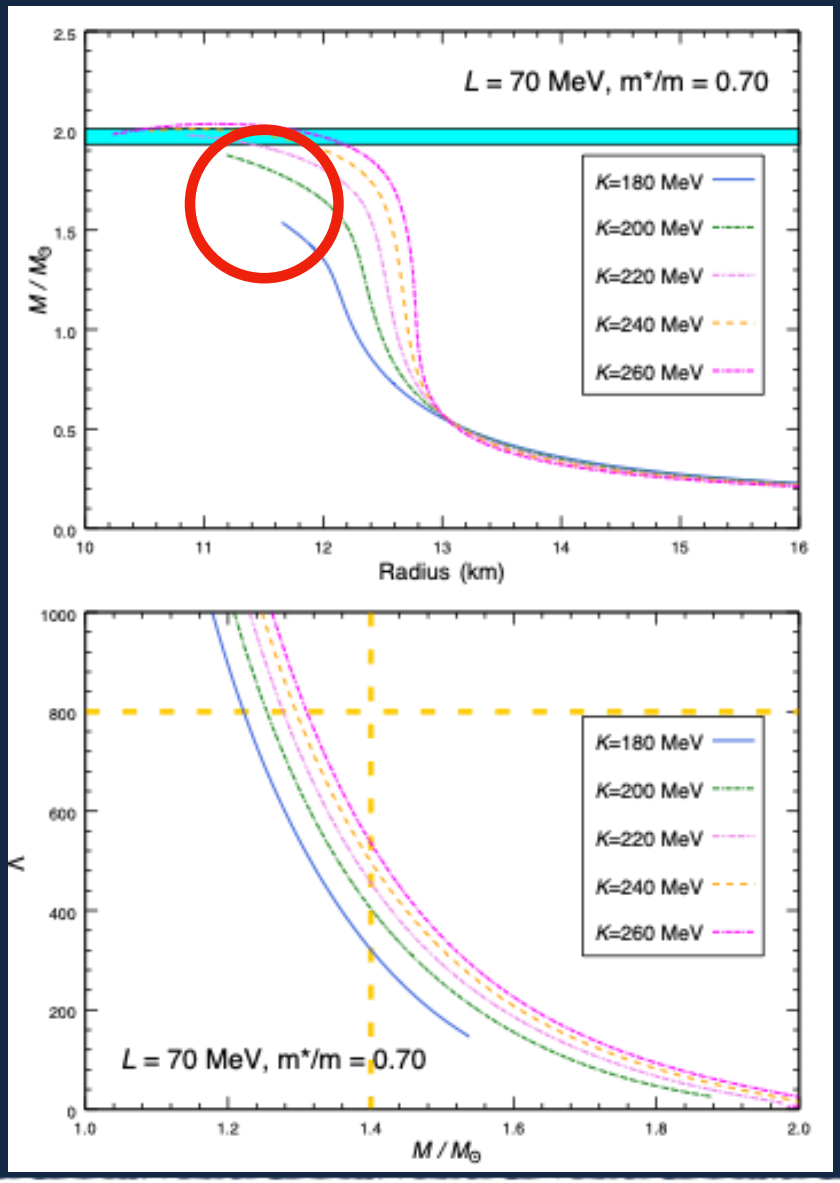

Summary I

$m^*/m = 0.7$	$K = 180$MeV	200MeV	220MeV	240MeV	260MeV
$L = 50$MeV	×	×	○	○	○
70MeV	×	×	○	○	○
90MeV	×	×	○	○	○
100MeV	×	×	×	×	×

- We changed the slope parameter and incompressibility by using RMF model with non-linear potential.
- The slope parameter affects the radius and tidal deformability.
- The incompressibility can change the maximum mass of the neutron star.
- Neutron stars prefer the high incompressibility and low slope parameter.
- **We can reduce the ambiguity of slope parameter and incompressibility by using the astronomical observation data.**

Contents

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Interaction between particles

		Two-body			Three-body			
	Type	NN	NY	YY	NNN	NNY	NYY	YYY
Y.Lim et al.,[1]	SHF	Skyrme interaction					–	–
Y. Yamamoto et al.,[2]	BHF	BHF	BHF($\Lambda\Sigma\Xi$)	BHF ($\Lambda\Lambda$)	TBR+TBA [2]			
Ours	Hybrid	SHF	BHF($\Lambda\Sigma\Xi$)	BHF ($\Lambda\Lambda$)	**SHF**	**TBR+TBA [2]**		

We suggest a hybrid model

- The ***NN* interactions** are described by the Skyrme-Hartree-Fock (SHF) [SkI4, SG1, SLy4]
- The **hyperon interactions** are treated by taking the Brueckner-Hartree-Fock approach (BHF)

Skyrme-Hartree-Fock approach

- Effective potential in the nuclear matter

Brueckner-Hartree-Fock approach

- Extending two-body interaction in free space to two-body interaction in matter

Interaction between particles

		Two-body			Three-body			
	Type	NN	NY	YY	NNN	NNY	NYY	YYY
Y.Lim et al.,[1]	SHF	Skyrme interaction					–	–
Y. Yamamoto et al.,[2]	BHF	BHF	BHF($\Lambda\Sigma\Xi$)	BHF ($\Lambda\Lambda$)	TBR+TBA [2]			
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If we use the SG1 for hybrid model, then we call H-SG1.

Type	ρ_0 (fm^{-3})	B/A (MeV)	E_{sym} (MeV)	L (MeV)	K_∞ (MeV)
SG1	0.155	−15.9	29	69	263
SkI4	0.160	−16.1	29	59	246
SLy4	0.160	−16	32	47	230
exp		−16	~30	54±19	[3]230±30

Many-body interaction for hyperon

This ESC08 is used to consider two-body interaction.

The experimental nuclear saturation properties, the density ρ_N ,

the binding energy per nucleon E/A, the compression modulus K, cannot be reproduced quantitatively with nuclear two-body interactions only.

Generally, the *N*-body local potential $W^{(N)}$ by pomeron exchange is

$$W^{(N)}(\mathbf{x_1},...,\mathbf{x_N}) = g_P^{(N)} g_p^N \left(\int \frac{d^3k_i}{(2\pi^3)} e^{-i\mathbf{k_i}\cdot\mathbf{x_i}} \right) (2\pi)^3 \left(\sum_{i=0}^{N} \mathbf{k_i} \right) \Pi_{i=1}^{N} [\exp(-\mathbf{k_i}^2)] \cdot \mathcal{M}^{4-3N}$$

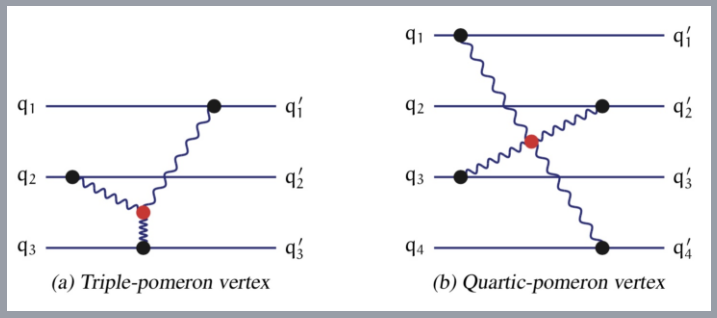
where g_p and $g_p^{(N)}$ are the two-body and *N*-body pomeron strengths, respectively.

If we integrate the above equation by $\mathbf{x_3},...,\mathbf{x_N}$, then

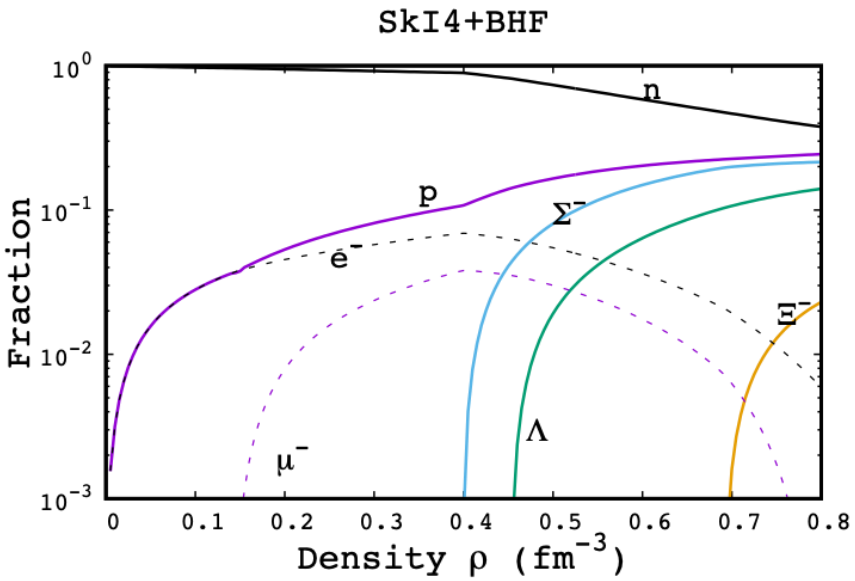
$$V_{\text{eff}}^{(N)}(\mathbf{x_1},\mathbf{x_2})$$

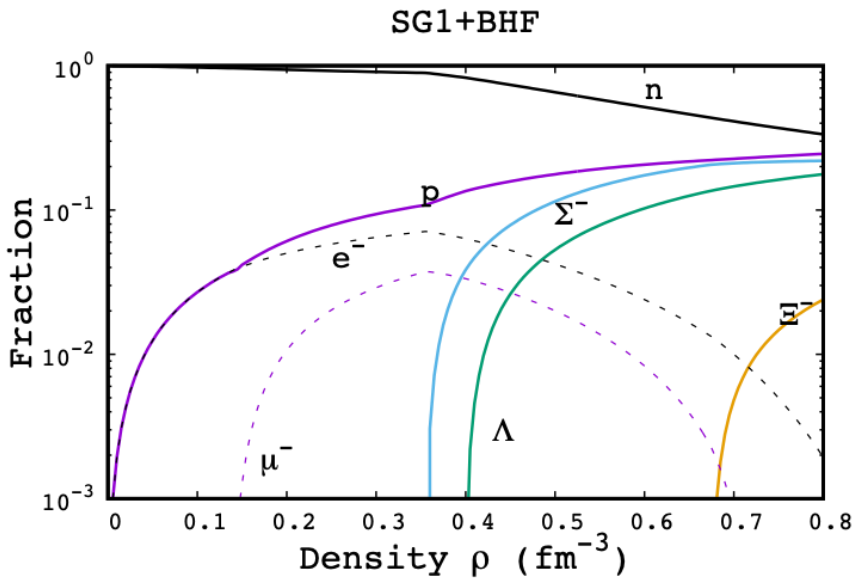
$$= \rho^{N-2} \int d^3x_3 ... \int d^3x_N W^{(N)}(\mathbf{x_1},\mathbf{x_2},...,\mathbf{x}_N)$$

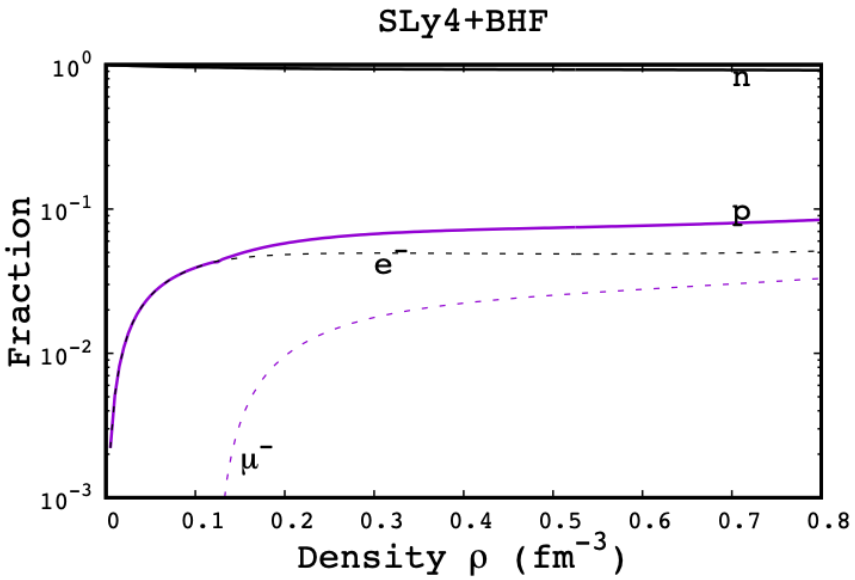
$$= g_p^{(N)} g_p^N \frac{\rho^{N-2}}{\mathcal{M}^{3N-4}} \left(\frac{m_P}{\sqrt{2\pi}} \right)^3 \exp\left(-\frac{1}{2} m_P^2 r_{12}^2 \right)$$



Particle profile





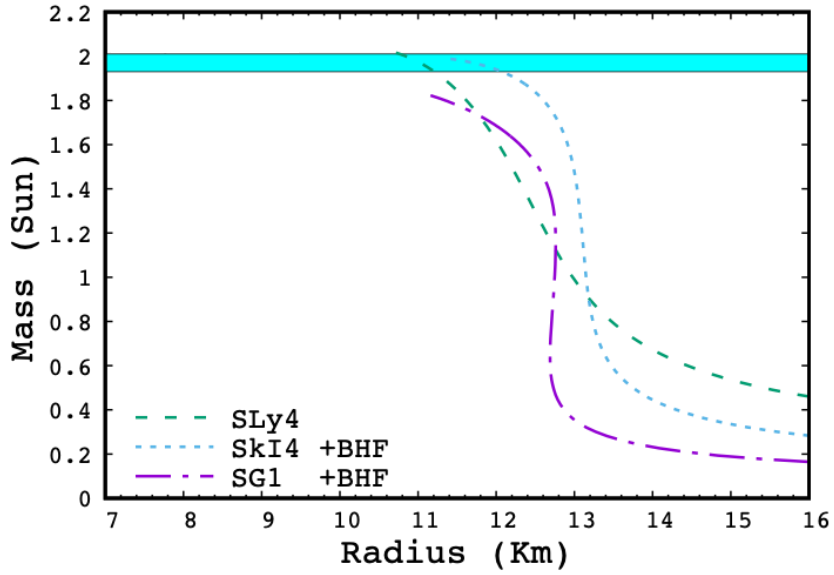


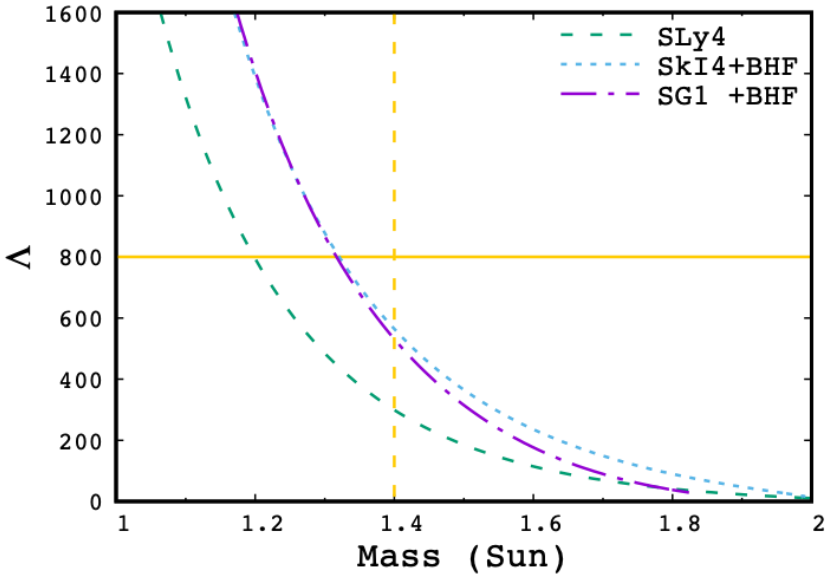
If we input the center density, then

we can obtain the neutron star properties

mass, radius and Λ

Mass–radius relation and tidal deformability



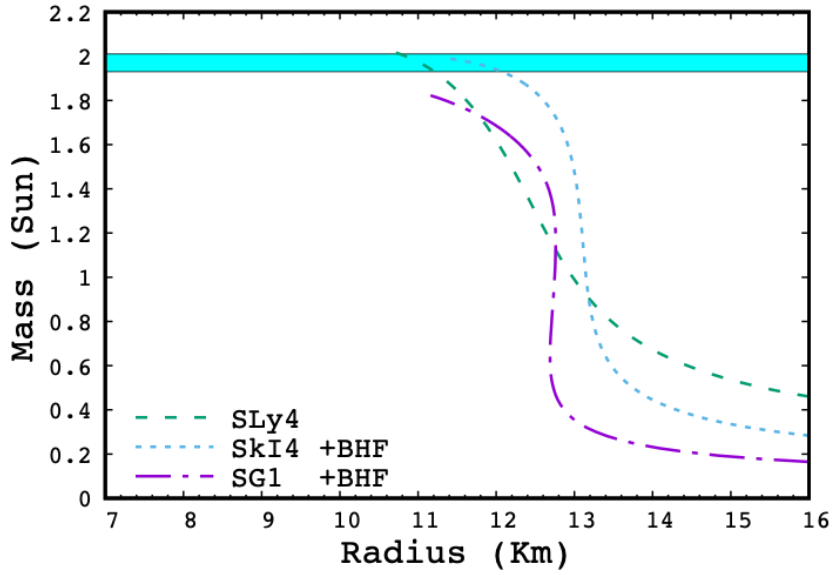


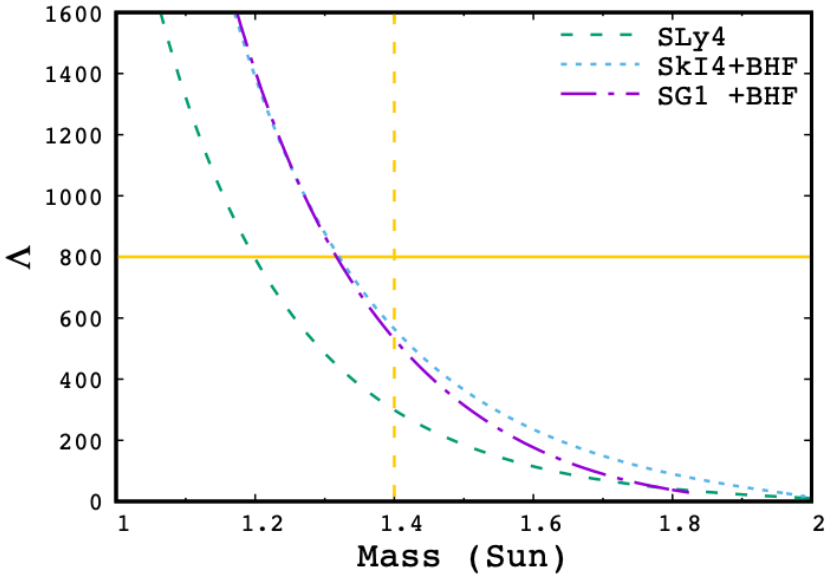
SkI4 + BHF case can reach
the two–solar mass neutron star.

The same mass The large Λ

The pressure is large

Mass–radius relation and tidal deformability





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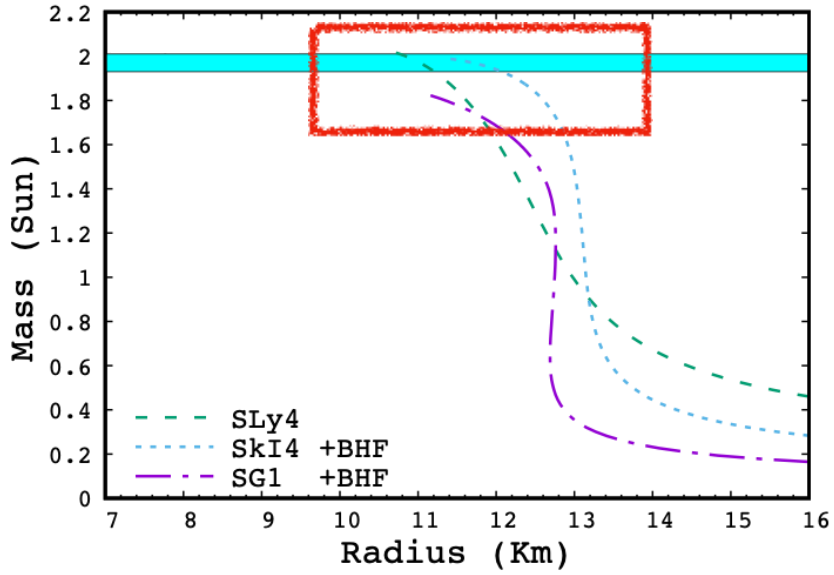
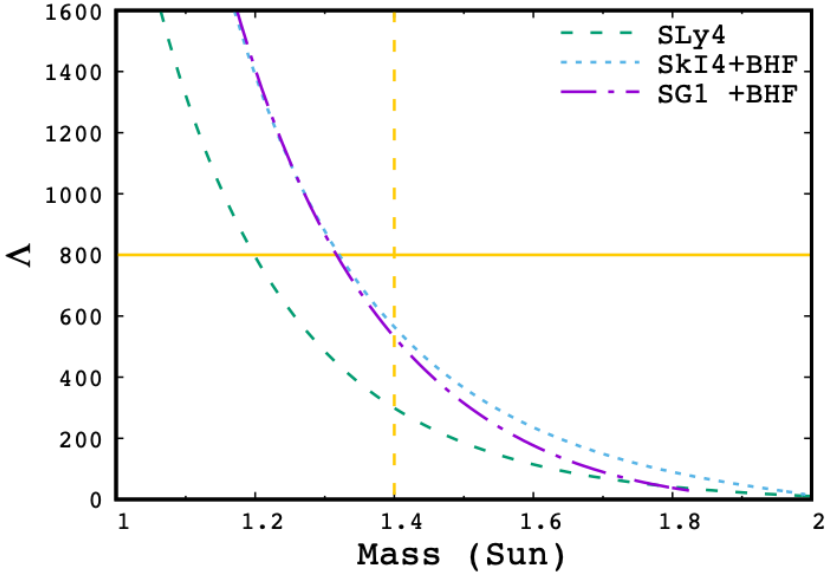
preliminary

	Λ_1	Λ_2	$\tilde{\Lambda}$
SLy4	202	560	343
H–SkI4	400	980	629
H–SG1	345	1023	611

$$\tilde{\Lambda} \leq 800$$

Mass–radius relation and tidal deformability





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Summary II

- The density of neutron star is very high.
  hyperons can be generated in the core.
- The gravitational waves from binary neutron star merge
  gives the **tidal deformability** and masses of NS
- To get mass and tidal deformability,
  we need equation of state for neutron star.
- Our hybrid model can describe the 2 solar mass NS and
  measured tidal deformability.

Contents

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Soongsil University

The Astrophysical Journal, 813:135 (13pp), 2015 November 10 doi:10.1088/0004-637X/813/2/135

EQUATION OF STATE FOR NEUTRON STARS WITH HYPERONS AND QUARKS IN THE RELATIVISTIC HARTREE–FOCK APPROXIMATION

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$$\mathcal{L}_H = \mathcal{L}_B + \mathcal{L}_M + \mathcal{L}_{\rm int}, \tag{1}$$

where

$$\mathcal{L}_B = \sum_B \bar{\psi}_B\left(i\gamma_\mu\partial^\mu - M_B\right)\psi_B, \tag{2}$$

with ψ_B being the baryon field and M_B being the baryon mass in a vacuum. The sum B runs over the octet baryons: proton (p), neutron (n), Λ, Σ^{+0-}, and Ξ^{0-}. For the free baryon masses, we take $M_N = 939$ MeV, $M_\Lambda = 1116$ MeV, $M_\Sigma = 1193$ MeV, and $M_\Xi = 1318$ MeV, respectively. Lepton Lagrangian is introduced in Section 4.

In the present calculation, we study the effects of direct and exchange contributions on hadronic matter through not only the exchanges of non-strange mesons (σ, ω, π, and ρ) but also those of strange mesons (σ^* and ϕ). Thus, the meson term reads

$$\begin{aligned}\mathcal{L}_M =& \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) + \frac{1}{2}\left(\partial_\mu\sigma^*\partial^\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2}\right)\\ &+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}P_{\mu\nu}P^{\mu\nu}\\ &+ \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu - \frac{1}{4}\boldsymbol{R}_{\mu\nu}\cdot\boldsymbol{R}^{\mu\nu}\\ &+ \frac{1}{2}\left(\partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi} - m_\pi^2\boldsymbol{\pi}^2\right),\end{aligned} \tag{3}$$

The interaction Lagrangian is given by

$$\begin{aligned}\mathcal{L}_{\rm int} = \sum_B \bar{\psi}_B\Big[& g_{\sigma B}(\sigma)\sigma + g_{\sigma^* B}(\sigma^*)\sigma^*\\ &- g_{\omega B}\gamma_\mu\omega^\mu + \frac{f_{\omega B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu\omega^\mu\\ &- g_{\phi B}\gamma_\mu\phi^\mu + \frac{f_{\phi B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu\phi^\mu - g_{\rho B}\gamma_\mu\boldsymbol{\rho}^\mu\cdot\boldsymbol{I}_B\\ &+ \frac{f_{\rho B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu\boldsymbol{\rho}^\mu\cdot\boldsymbol{I}_B - \frac{f_{\pi B}}{m_\pi}\gamma_5\gamma_\mu\partial^\mu\boldsymbol{\pi}\cdot\boldsymbol{I}_B\Big]\psi_B,\end{aligned} \tag{7}$$

$$g_{\sigma B}(\sigma) = g_{\sigma B}b_B\left[1 - \frac{a_B}{2}(g_{\sigma N}\sigma)\right], \tag{8}$$

$$g_{\sigma^* B}(\sigma^*) = g_{\sigma^* B}b_B'\left[1 - \frac{a_B'}{2}\left(g_{\sigma^*\Lambda}\sigma^*\right)\right], \tag{9}$$

where $g_{\sigma N}$ and $g_{\sigma^*\Lambda}$ are, respectively, the σ-N and σ^*-Λ coupling constants at zero density. The effect of the variation of baryon structure at the quark level can be described with the parameters a_B and a_B'. In addition, the extra parameters, b_B and b_B', are necessary to express the effect of hyperfine interaction between two quarks (Nagai et al. 2008; Miyatsu & Saito 2009; Saito 2010). The couplings in the CQMC model are invariant

$$M_B^*(k) = M_B + \Sigma_B^s(k), \tag{12}$$

$$k_B^{*\mu} = \left(k_B^{*0}, \boldsymbol{k}_B^*\right) = \left(k^0 + \Sigma_B^0(k), \boldsymbol{k} + \hat{k}\Sigma_B^v(k)\right), \tag{13}$$

$$E_B^*(k) = \left[k_B^{*2} + M_B^{*2}(k)\right]^{1/2}. \tag{14}$$

3. QUARK MATTER DESCRIPTION

We briefly present a description of uniform quark matter. The thermodynamic potential can be simply expressed by (Freedman & McLerran 1978; Farhi & Jaffe 1984; Alcock et al. 1986; Haensel et al. 1986)

$$\Omega = \sum_q \Omega_q + B, \tag{41}$$

with the quark term, Ω_q, and the bag constant, B. The sum q runs over three-flavor quarks (u, d, and s), and the quark thermodynamic potential is given by a sum of the kinetic term and the interaction term due to the OGE (Freedman & McLerran 1978):

$$\Omega_q = -\frac{g_q(2J_q+1)}{24\pi^2}\left[F(\mu_q, m_q) - \frac{2\alpha_c}{\pi}G(\mu_q, m_q)\right], \tag{42}$$

The quark number density is related to Ω_q via $\rho_q = -\partial\Omega_q/\partial\mu_q$, and the baryon density and the charge density in quark matter are given by $n_B = \frac{1}{3}\sum_q \rho_q$ and $n_C = \frac{2}{3}\rho_u - \frac{1}{3}(\rho_d + \rho_s)$, respectively. The energy density and pressure for quark matter are then written as

$$\varepsilon_Q = \sum_q \left(\Omega_q + \mu_q\rho_q\right) + B, \tag{45}$$

$$P_Q = -\sum_q \Omega_q - B. \tag{46}$$

Instead of hadronic matter, quark matter is expected to exist at very high densities such as at the center of a neutron star. However, the exact value of the transition density from hadron phase (HP) to quark phase is still unknown. In the present calculation, in order to study the effect of quark matter on neutron stars, we introduce a density-dependent bag constant, which is assumed to be given by a Gaussian parametrization (Burgio et al. 2002a, 2002b)

$$B(n_B) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\frac{n_B}{n_0}\right)^2\right], \tag{47}$$

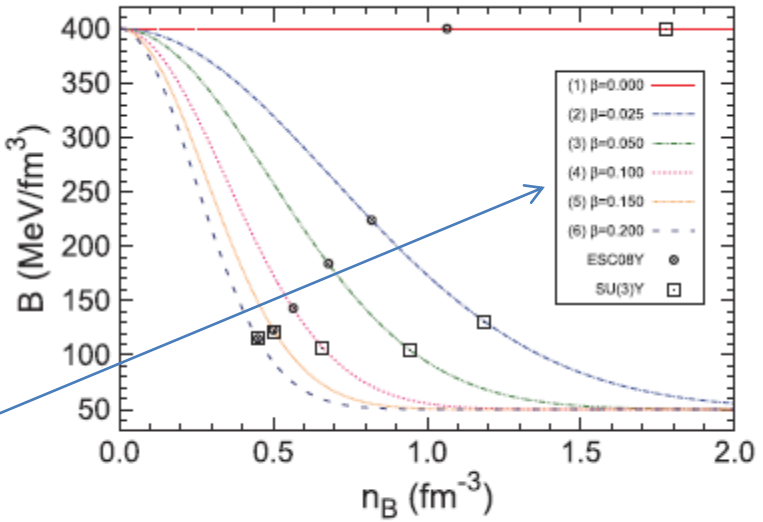


Figure 6. Density-dependence of bag constant given in Equation (47). The circles (squares) show the critical points in ESC08Y (SU(3)Y) (see also Table 6).

$$\mathcal{L}_\ell = \sum_\ell \bar{\psi}_\ell \left(i\gamma_\mu \partial^\mu - m_\ell \right) \psi_\ell, \tag{50}$$

with ψ_ℓ being the lepton field and m_ℓ being its mass. The sum ℓ is for e^- and μ^-. The lepton energy density, pressure, and number density are then given by

$$\epsilon_\ell = \sum_\ell \frac{2J_\ell + 1}{2\pi^2} \int_0^{k_{F_\ell}} dk\, k^2 \sqrt{k^2 + m_\ell^2}, \tag{51}$$

$$P_\ell = \frac{1}{3} \sum_\ell \frac{2J_\ell + 1}{2\pi^2} \int_0^{k_{F_\ell}} dk\, \frac{k^4}{\sqrt{k^2 + m_\ell^2}}, \tag{52}$$

$$\rho_\ell = \frac{2J_\ell + 1}{2\pi^2} \int_0^{k_{F_\ell}} dk\, k^2 = \frac{2J_\ell + 1}{6\pi^2} k_{F_\ell}^3, \tag{53}$$

where J_ℓ is the spin degeneracy factor of lepton ℓ. The total energy density and pressure for hadronic (quark) matter are given by the sum of the hadron (quark) and lepton parts, namely, $\epsilon = \epsilon_{H(Q)} + \epsilon_\ell$ and $P = P_{H(Q)} + P_\ell$. Furthermore, the condition of β equilibrium is expressed as (Glendenning 1992, 2001; Maruyama et al. 2007)

$$\mu_n = \mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_u + 2\mu_d, \tag{54}$$

$$\mu_n + \mu_e = \mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_d = \mu_s, \tag{55}$$

$$\mu_n - \mu_e = \mu_p = \mu_{\Sigma^+}, \tag{56}$$

$$\mu_e = \mu_\mu, \tag{57}$$

In order to describe the coexistence of hadrons and quarks, we impose Gibbs criterion for chemical equilibrium (Glendenning 1992, 2001). Under Gibbs criterion, in the mixed phase (MP), pressure in the HP must balance with that in the quark phase (QP) to ensure mechanical stability as follows,

$$P_{\rm HP}(\mu_n, \mu_e) = P_{\rm QP}(\mu_n, \mu_e). \tag{58}$$

In the MP, where the condition, Equation (58), is satisfied, the charge neutrality can be expressed as

$$(1 - \chi) n_C^{\rm HP} + \chi n_C^{\rm QP} = 0, \tag{59}$$

with $n_C^{\rm HP}$ ($n_C^{\rm QP}$) being the charge density in the HP (QP), and χ being a volume fraction for the QP. The total energy density and baryon number density in the MP are then given by

$$\epsilon_{\rm MP} = (1 - \chi)\epsilon_{\rm HP} + \chi \epsilon_{\rm QP}, \tag{60}$$

$$n_B^{\rm MP} = (1-\chi) n_B^{\rm HP} + \chi n_B^{\rm QP}. \tag{61}$$

$$U_Y^{(B)} = \Sigma_Y^{sH} - \Sigma_Y^{0H} + \frac{1}{2M_Y} \left[\Sigma_Y^{sH} - \Sigma_Y^{0H} \right]^2, \tag{63}$$

where $\Sigma_Y^{s(0)H}$ is the direct term of the baryon self-energy for the scalar (the time component of the vector) part. Then, we can determine the coupling constants, $g_{\sigma Y}$, following the values of potential depth around n_0 suggested from the experimental data of hypernuclei: $U_\Lambda^{(N)} = -28$ MeV, $U_\Sigma^{(N)} = +30$ MeV, and $U_\Xi^{(N)} = -18$ MeV (Schaffner et al. 1994). The scalar strange coupling constants, $g_{\sigma^* Y}$, are restricted by the relation $U_\Xi^{(\Xi)} \simeq U_\Lambda^{(\Xi)} \simeq 2U_\Xi^{(\Lambda)} \simeq 2U_\Lambda^{(\Lambda)}$ (Schaffner et al. 1994; Schaffner & Mishustin 1996; Yang & Shen 2008). We here take $U_\Lambda^{(\Lambda)} \simeq -5$ MeV, which has been implied by the Nagara event (Takahashi et al. 2001).

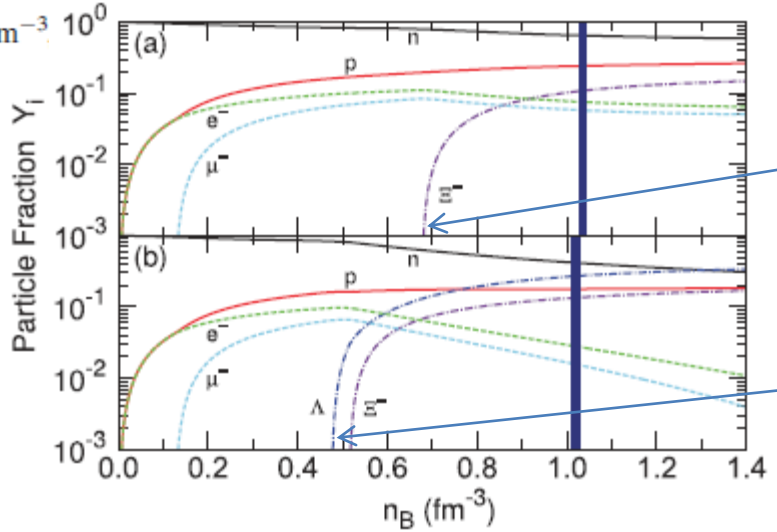


Figure 1. Particle fractions, Y_i, for hadronic matter in ESC08Y and SU(3)Y, which is defined as $Y_i = \rho_i/n_B$ with ρ_i being the number densities of particle species $i = B, \ell$. The upper panel (a) is for the case of ESC08Y, and the lower panel (b) is for the case of SU(3)Y. The thick vertical line shows the density at which a neutron star reaches the maximum-mass point by solving the TOV equation.

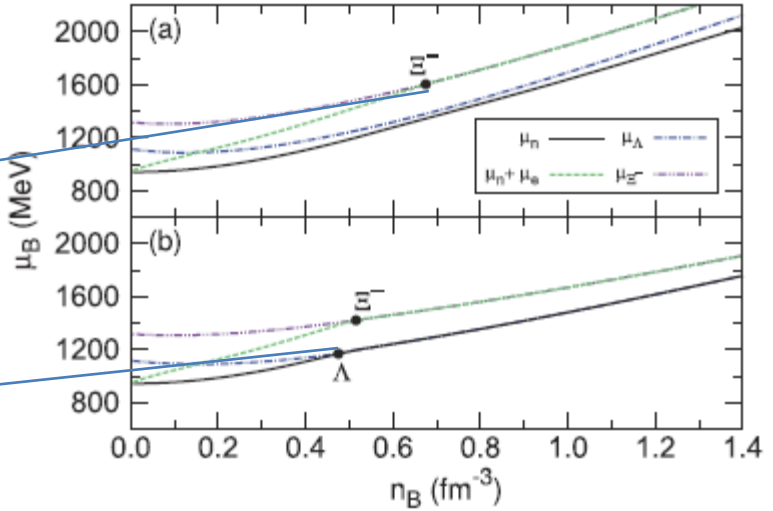


Figure 2. Chemical potentials for the n, Λ, Ξ^-, and e^- in ESC08Y and SU(3)Y. The filled circle denotes the onset of Λ or Ξ^-. The labels (a) and (b) are the same as in Figure 1.

In contrast, in ESC08Y, we adopt the values of $(g_{\omega N}, g_{\rho N})$ presented in Table IV of Rijken et al. (2010) in the calculation of coupling constants for hyperons. The couplings related to the hyperons are listed in Table 5.

5.2. Neutron Star Properties

The properties of neutron stars are, in general, estimated by solving the Tolman–Oppenheimer–Volkoff (TOV) equation (Oppenheimer & Volkoff 1939; Tolman 1939). Since the radius of a neutron star is remarkably sensitive to the EoS at very low densities, we use the EoS for nonuniform matter below $n_B = 0.068\,\mathrm{fm}^{-3}$, where nuclei are taken into account using the Thomas–Fermi calculation (Miyatsu et al. 2013b).

In Figure 1, we illustrate the particle fractions for hadronic matter in ESC08Y and SU(3)Y. Although all octet baryons are

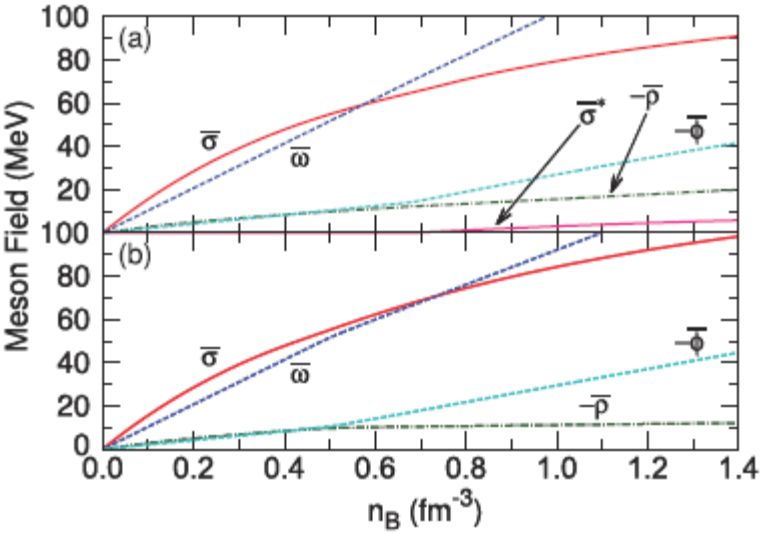


Figure 3. Meson fields in ESC08Y and SU(3)Y. The labels (a) and (b) are the same as in Figure 1.

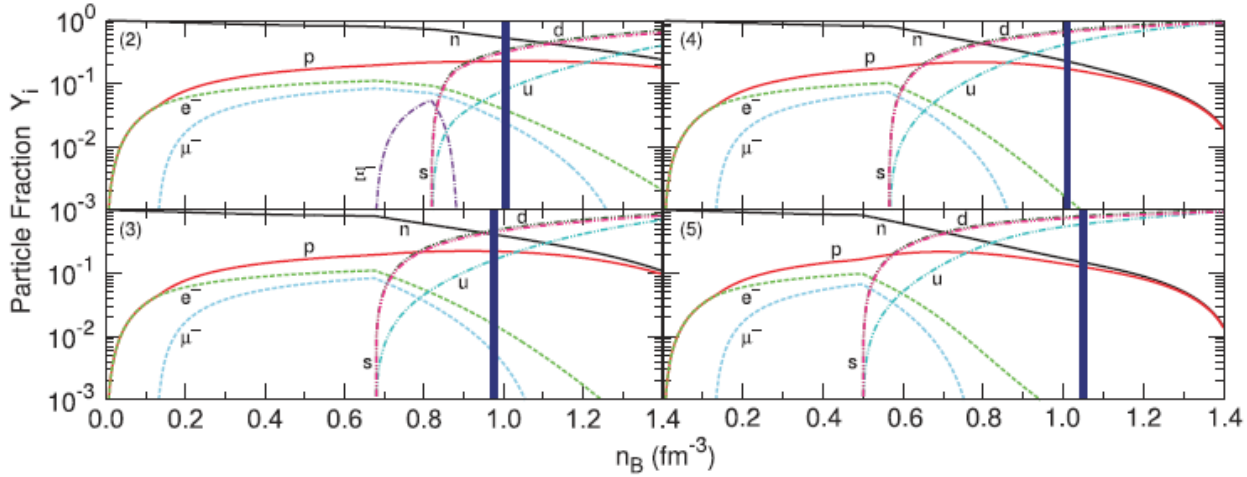


Figure 7. Particle fractions, Y_i, for hybrid-star matter in ESC08Y. The labels (2)–(5) designate the case number in Table 6.

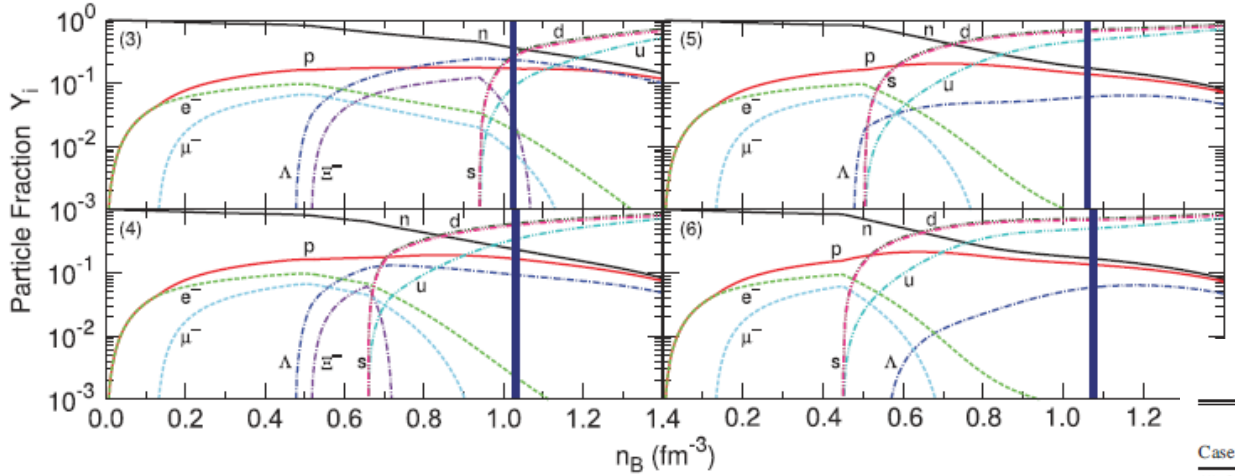


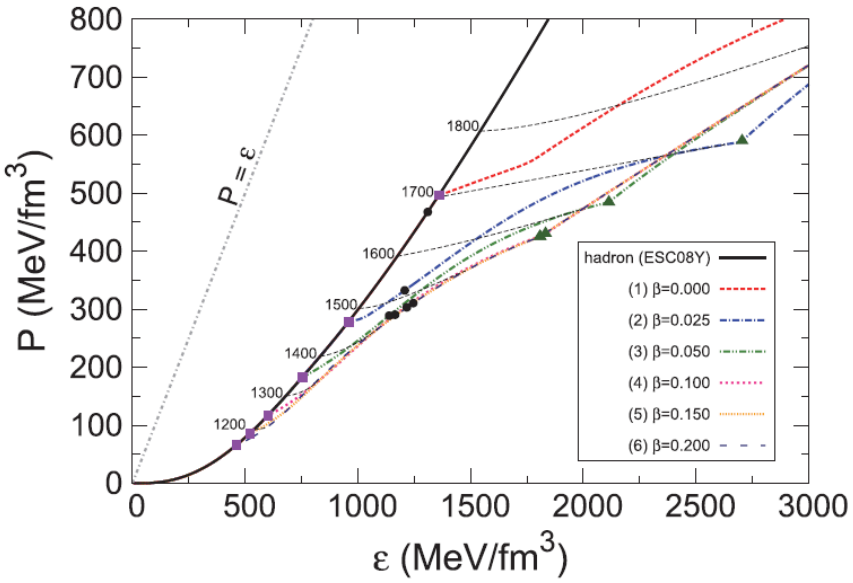
Figure 8. Particle fractions, Y_i, for hybrid-star matter in SU(3)Y. The labels (3)–(6) designate the case number in Table 6.

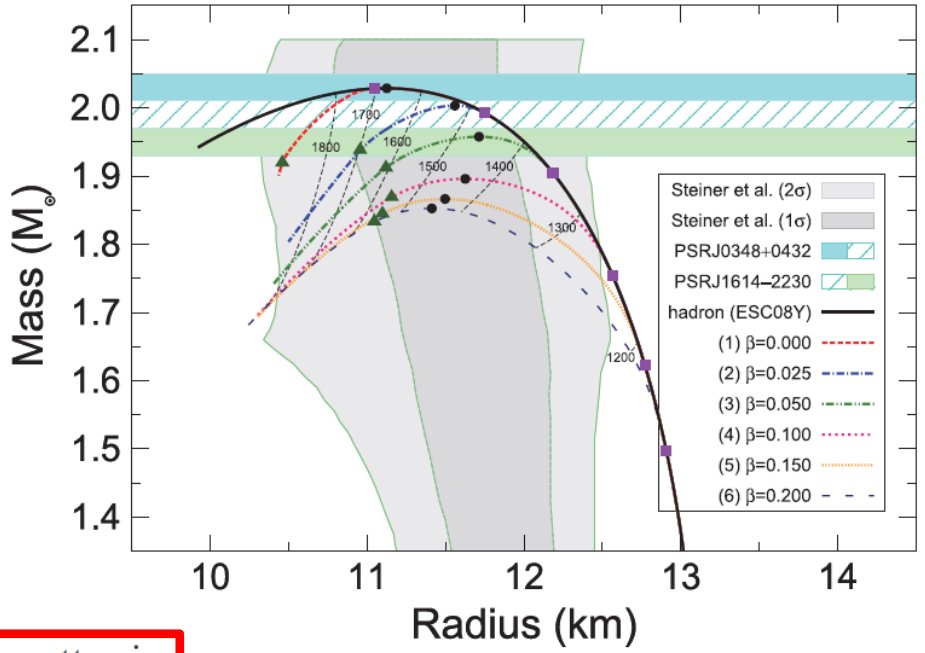
Table 6
Phase Transition Properties at the Critical Density, $n_B^{(c)}$ (fm^{-3})

	ESC08Y			SU(3)Y		
Case (β)	$n_B^{(c)}$	$B^{(c)}$	$\mu_B^{(c)}$	$n_B^{(c)}$	$B^{(c)}$	$\mu_B^{(c)}$
(1) 0.000	1.065	400	1702	1.775	400	2031
(2) 0.025	0.820	224	1474	1.185	131	1605
(3) 0.050	0.680	184	1350	0.945	105	1444
(4) 0.100	0.565	143	1246	0.660	107	1274
(5) 0.150	0.500	123	1188	0.505	121	1188
(6) 0.200	0.450	115	1147	0.450	115	1147

Note. We list six cases, where the parameter β varies between 0 and 0.2, for ESC08Y and SU(3)Y. The critical bag constant, B^c, and the critical chemical potential, $\mu_B^{(c)}$, which are in the unit of MeV, are calculated by Equation (47).

RMF with CQMC in H-F scheme by SU(3)+q





In Figure 9, we present the EoS for hybrid-star matter in ESC08Y. In general, the quark productions soften the EoS, as is well known. Increasing the parameter β, the EoS becomes softer because the threshold densities of the quarks move toward lower densities, as seen in Table 6 and Figure 7. Furthermore, the pure QP emerges at lowe
the parameter β increases.

ss–radius relations for hybrid stars in ESC08Y. The shaded
s are the same as in Figure 5. The filled circles, squares, and
e contours of the nucleon chemical potential are explained in
Figure 9.

before the QP transition. In case (2) of ESC08Y, the maximum mass reaches $2.003M_\odot$ even if quark matter appears in the core of a neutron star. Therefore, the present EoS for hybrid-star matter can reasonably explain the recent mass constraint from astrophysical observations even if hyperons and quarks are included. As the properties of hybrid stars in SU(3)Y are

Case (β)	
(1) 0.000	
(2) 0.025	
(3) 0.050	
(4) 0.100	
(5) 0.150	
(6) 0.200	

Note. We list the neutron-star radius, R_{max} (in km), the ratio of the neutron-star mass to the solar mass, $M_{max}/M_\odot$, and the central density, n_c (in fm^{-3}), at the maximum-mass point.

Contents

The first University in Korea
Soongsil University

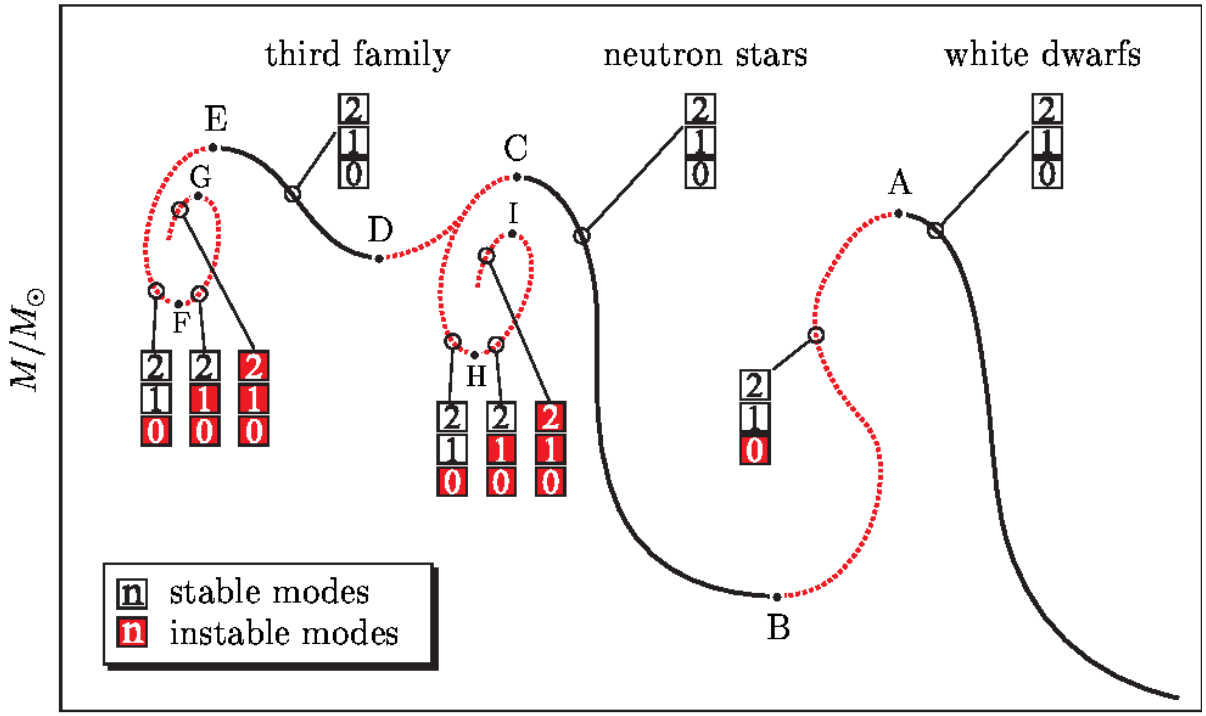
What process would bring about a quark star? (Intermediate)

"What process would bring about a quark star? How would that differ from a neutron star?

A neutron star is the remnant core of a massive, normal star after it has undergone a supernova explosion. It consists mostly of neutrons and is held up against gravitational collapse by "neutron degeneracy pressure" - this is a quantum mechanical effect that resists two neutrons being in the same place and therefore tends to push them apart when they get too close together.

If the remnant core of the original star is massive enough (greater than a few times the mass of the sun) then the force of gravity will be stronger than the force of neutron degeneracy pressure and so the star will continue to collapse right on past the neutron star stage. Currently, we think that the star will continue to collapse indefinitely past this point and eventually become a black hole. However, it is possible that there is another effect which comes into play - "**quark degeneracy pressure**". Quarks are the ultimate building blocks of protons and neutrons - each neutron is made up of three quarks - so it could be the case that as gravity overcomes neutron degeneracy pressure and causes the neutrons to "implode", the quarks put up some resistance of their own, and if the star isn't massive enough for its gravity to overcome that, then you would be left with a quark star instead of a black hole.

It is not yet known whether quark stars actually exist in nature because the details of what happens at such high densities are difficult to calculate. There has been some tentative evidence put forward for the existence of one quark star but it is by no means considered conclusive.



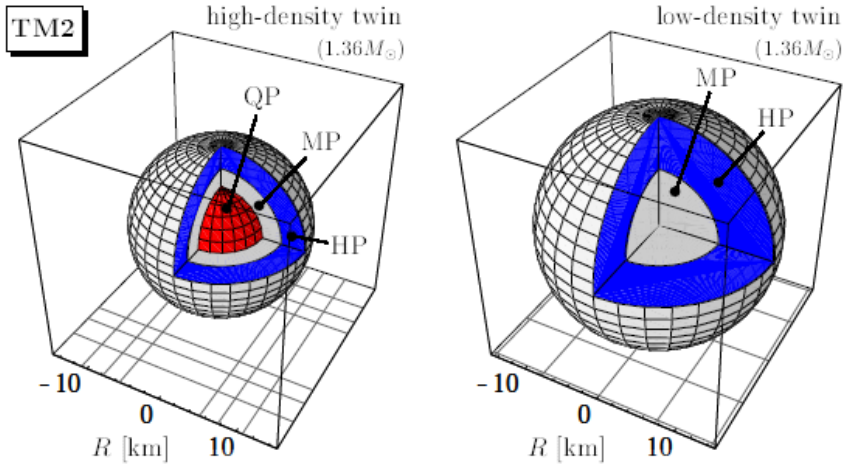


Figure 17: Schematic gross structure of the non identical neutron star twins marked in Fig. 16. Both stars have $M = 1.36M_\odot$ and belong the same EOS (TM2 hybrid star EOS, $B^{1/4} = 182\,\mathrm{MeV}$, $g = 0$).

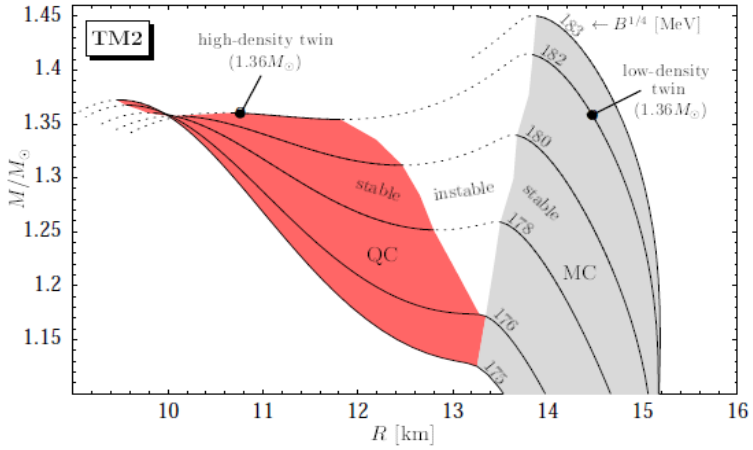
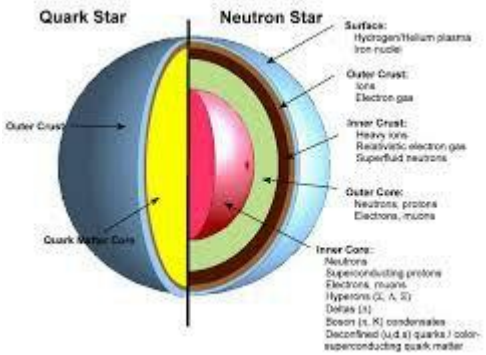


Figure 16: Mass-radius relation using the TM2 EOS for the HP for different bag constants B and $g = 0$. For this EOS a third family only exists in the narrow parameter range of $176\,\mathrm{MeV} < B^{1/4} \leq 182\,\mathrm{MeV}$. Obviously the stars of the third family possess approximately the same minimal radii as an "ordinary" hybrid star with pure QC as given by $B^{1/4} = 175\,\mathrm{MeV}$.



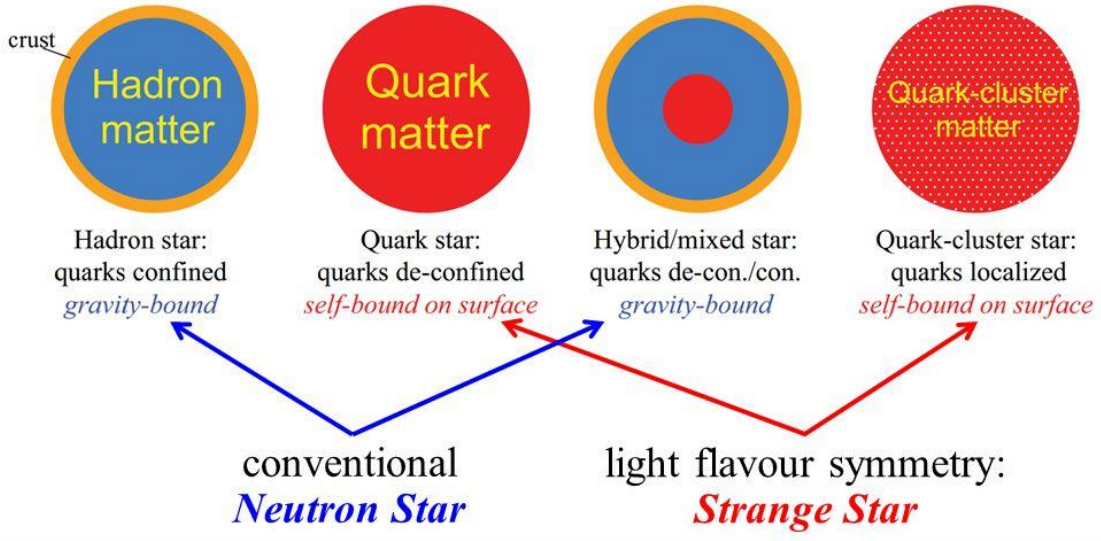
$$\frac{dP}{dr} = -\frac{[P(r)+\varepsilon(r)][M(r)+4\pi r^3 P(r)]}{r[r-2M(r)]}$$

4 Neutron star structure

With the evaluated hybrid star EOS presented in the last section we now turn to analyse the structure of the corresponding non-rotating neutron stars by solving the Tolman-Oppenheimer-Volkoff (TOV) equations [44]. These equations describe the balance between the gravitational force and the pressure given by the Fermi pressure of the particular EOS. This leads to a relation between the mass M and the radius R of the neutron star in general relativistic hydrostatic equilibrium.

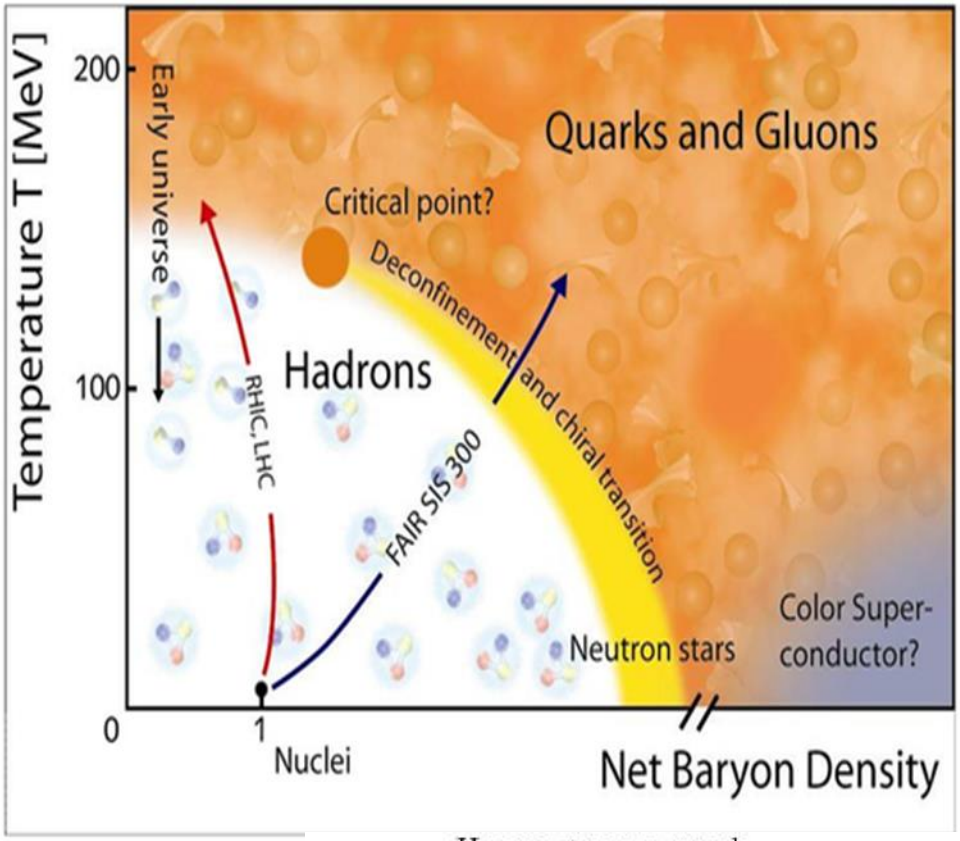
Observational hints from SM?

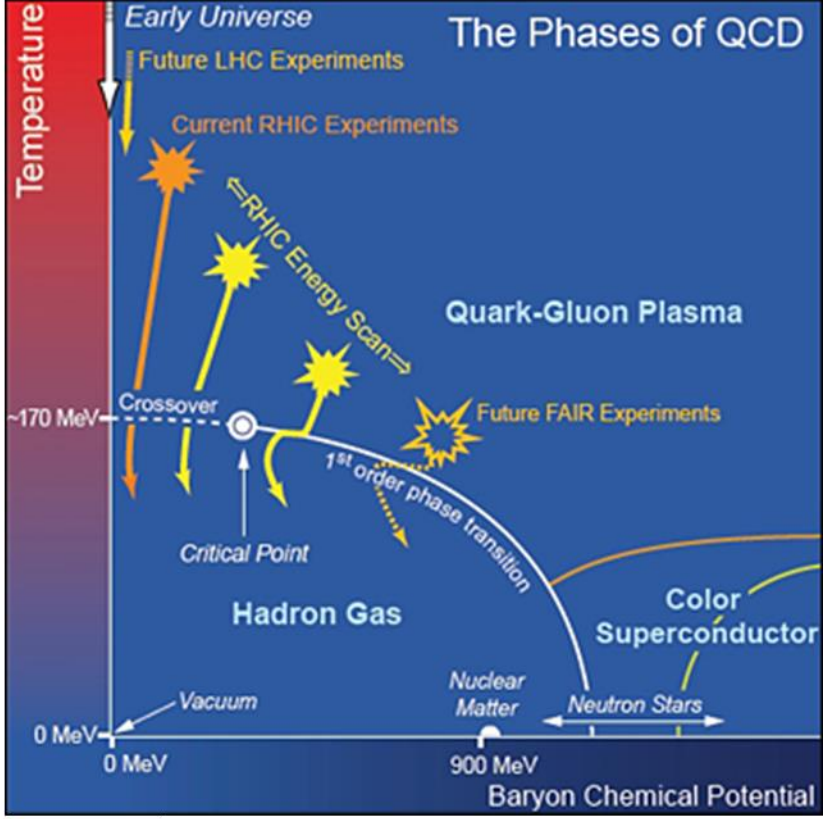
•**Pulsars**: different models in the market…



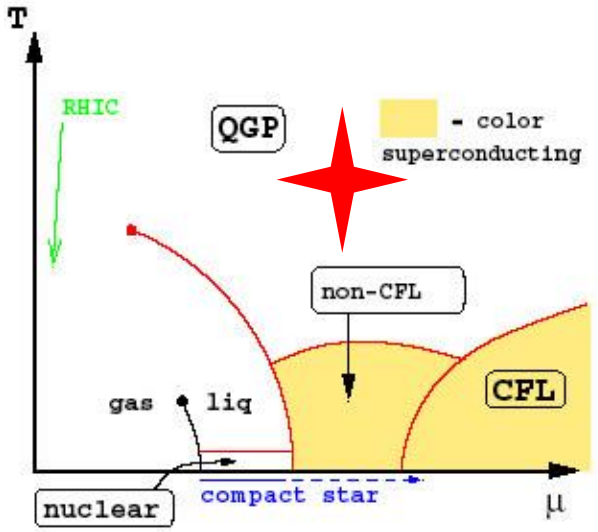
SN-*nuclei* http://www.phy.pku.edu.cn/~xurenxin/ R. X. Xu

inner structure of pulsars. Traditionally speaking, quarks are confined in hadrons of neutron stars, while a quark star is composed of de-confined quarks. While a solid quark star is a condensed object of quark clusters, which distinguishes from conventional both neutron and quark stars (Xu 2003, 2010, 2013). The solid quark star (i.e. quark cluster star) is quite different from the traditional quark stars. The properties which are common in traditional quark stars, e.g. colour superconductivity with colour-flavour locking (Ouyed et al. 2006), are not expected in solid quark stars as the quarks in such stars cannot be treated as free fermion gas any more. The magnetic field of a solid quark star will also be quite different (Xu 2005) from that of a traditional quark star (Iwazaki 2005) because of the different magnetic origins (Xu 2005; Chen, Yu & Xu 2007).

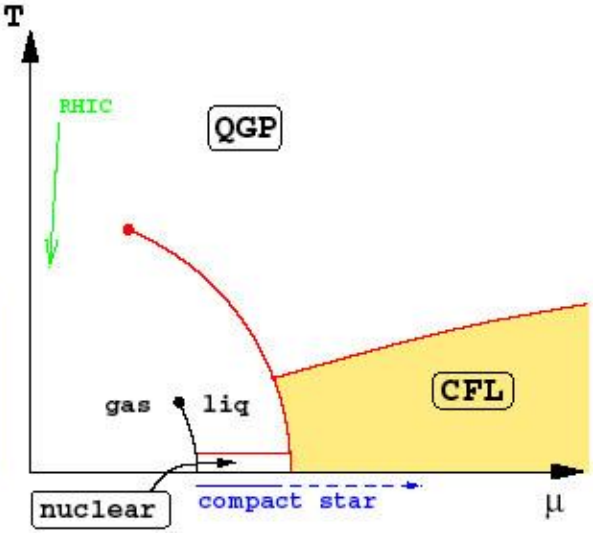




Heavy strange quark



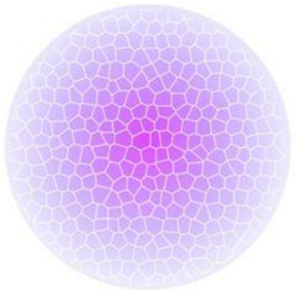
Light strange quark



EoS of compressed BM: specu. & obs.

- A quark-cluster star looks like a ***big*** metal ball

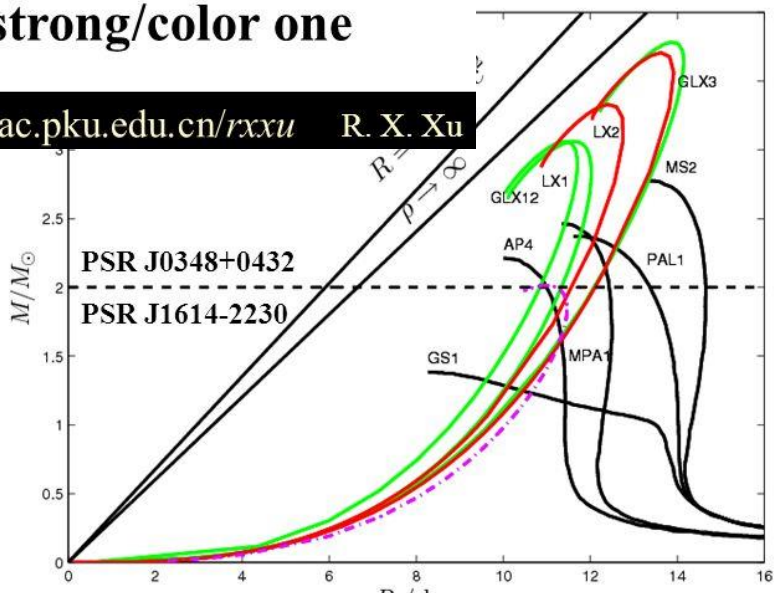
Metal ball *V.S.* **Quark-cluster star**



ions/nuclei ⟷ **quark clusters**

E-M interaction ⟷ **strong/color one**

tion of States



Gravity bound

Hadron star

Hybrid star

Hyperon Core ($R > 13$ km)

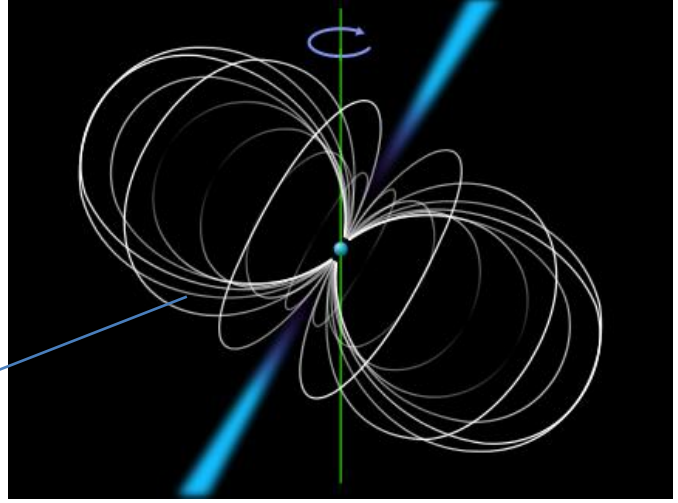
Fortin et al.(2014)

Self-bound

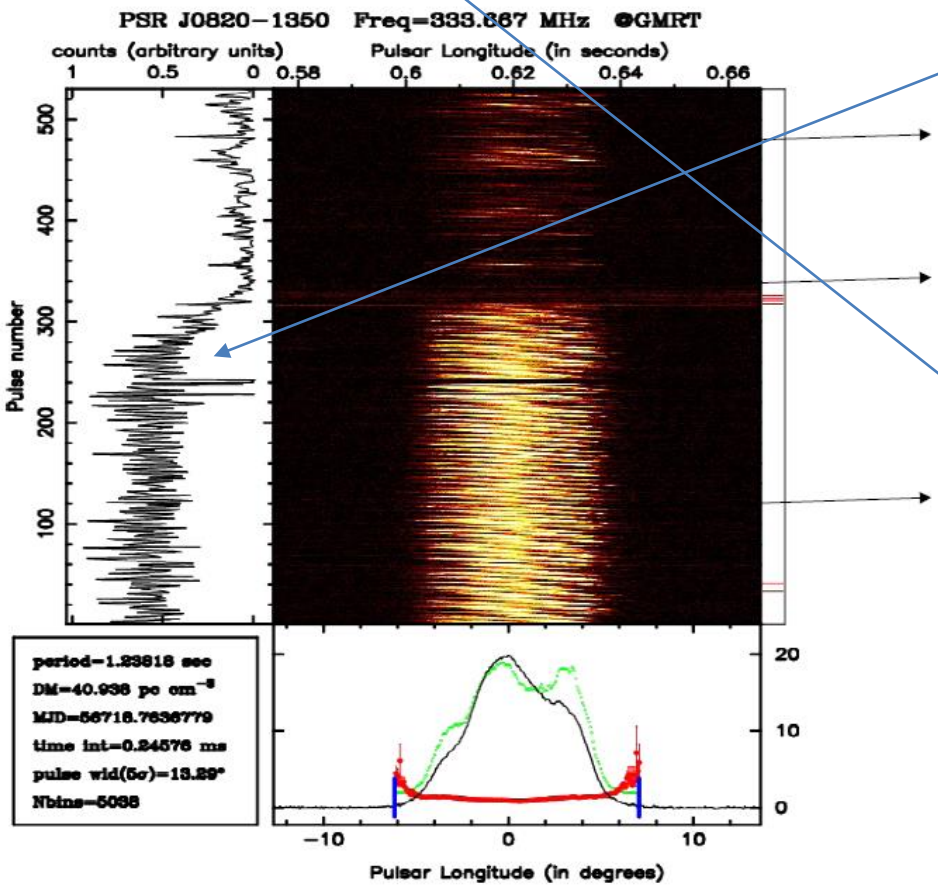
Quark star

Quark-cluster star

Observational Data
1. Drifting subpulsar



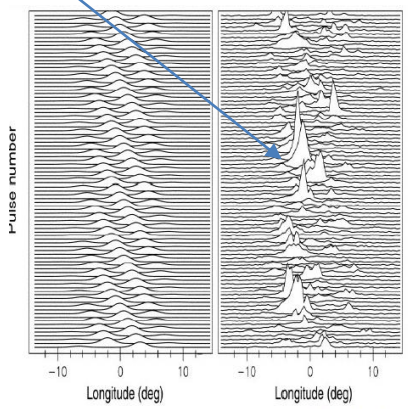
The Phenomenon

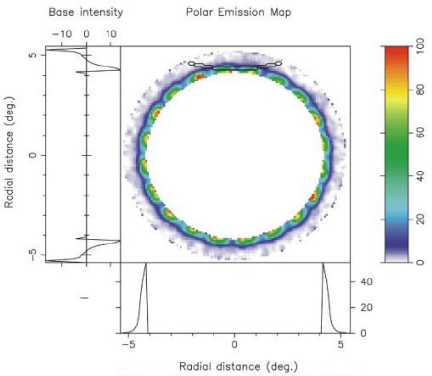


MODING

NULLING

The Case of PSR B0943+10



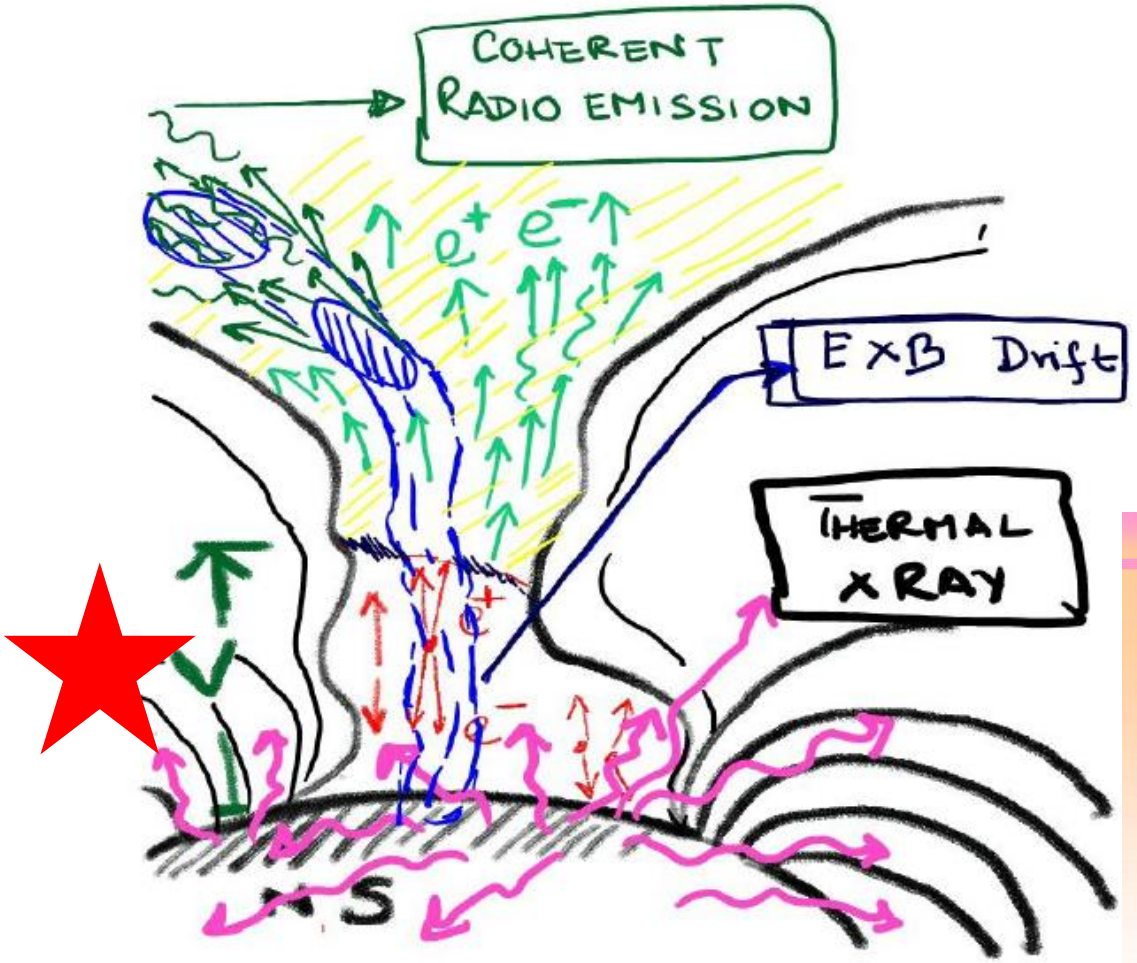


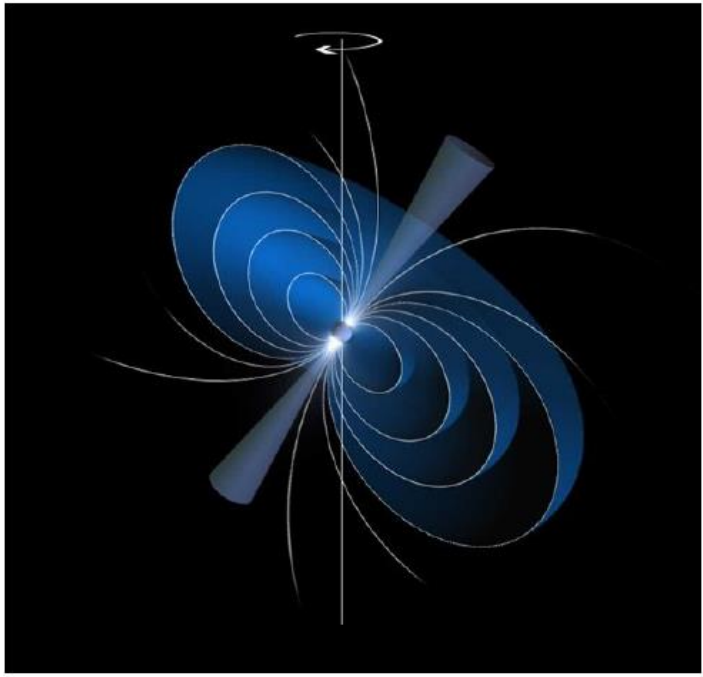
(Deshpande Rankin 99)

Explained by EXB drift of plasma (RS75)

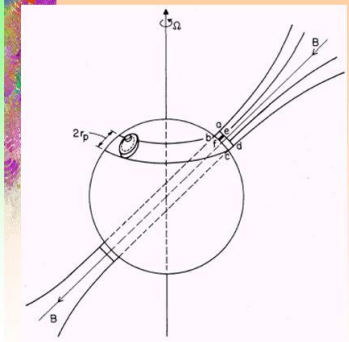
(e.g. Deshpande and Rankin 1999, Gil & Sendyk 2000, Asgekar Deshpande Backus Mitra Rankin 2012)

Xray/Radio emission





Drifting sub-pulses



Accelerators:

- Inner vacuum gap (Ruderman & Sutherland 1975)

requiring high binding energy of charges on stellar surface

Xu,Qiao Zhang, 1999,ApJL,522,L112

Deshpannde & Rankin, 1999,ApJ, 524,1008

For drifting subpulsar, we need electric field or very high voltage between surface and outside. But normal NS could not produce enough E field Compared to quark solid star because of some charged particles (or nuclei) on the Surface of normal NS.

Observational Data
2. Another accelerating mechanism for SN explosion

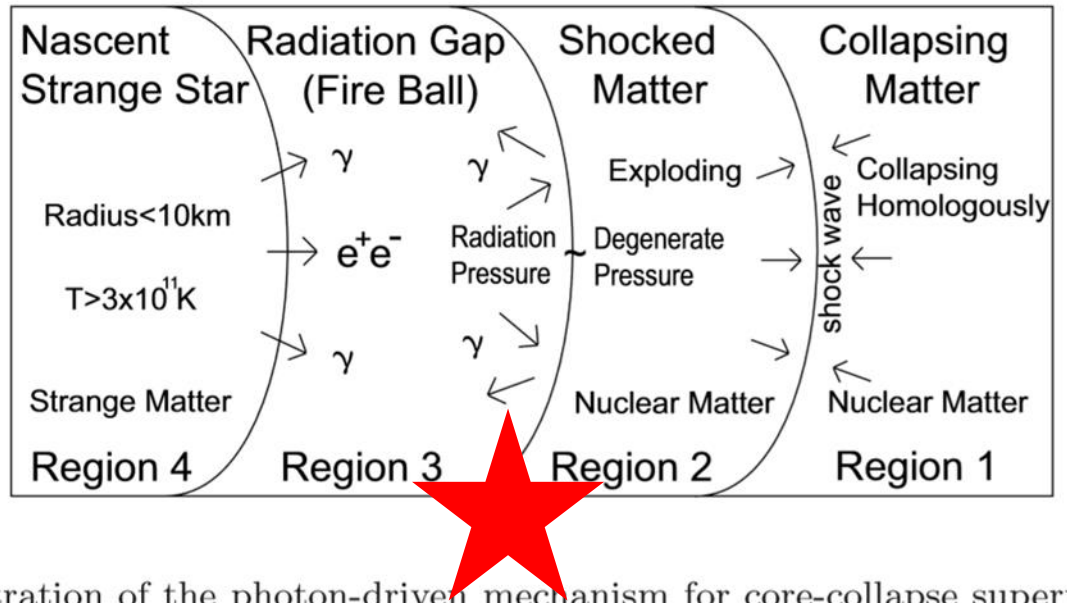


Fig. 2. An illustration of the photon-driven mechanism for core-collapse supernova (Chen et al. 2007). The outermost region 1 consists of the unshocked normal matter which is still in-falling, assembled to the homologous solution. Behind the shock front which serves as the border and increases in thickness, region 2 comprises the shocked nuclear matter whose motion has been reversed by the shock. Between the nascent strange quark-cluster star in the center of the original collapsing core and region 2 is a fireball (region 3), a gap filled up with high energy photons and e^+e^- pair plasma, similar to the fireball of gamma-ray bursts.

Summary

The first University in Korea
Soongsil University

1. **Tidal Deformation from GW by Neutron Star Merge**
1-1. Tidal Deformation from GW
1-2. **Results** by Various Models for NS

2. A Hybrid model for Neutron Star
2-1. **Many-Body Interactions in Dense Matter**
2-2. **Hyperon Puzzles** of Neutron Stars
2-3. **Pomeron Exchange Model with SHF sets of** Neutron Stars

3. **Quark cluster star**
3-1. Quark Matter inside Neutron Star
3-2. **Quark Star and Quark Cluster Star**


Thanks for your
Attention !!