

Institute of High Energy Physics Chinese Academy of Sciences

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Institute of High Energy Physics, CAS

Quarks and **C**ompact **S**tars @YZU, 2023

Based on collaboration with Bob Holdom and Chen Zhang

2023-9-25

New possibilities for quark matter and compact stars

✦ **Introduction**

✦ **Quark matter may not be strange**

✦ **Hybrid stars may have an inverted structure**

✦ **Summary**

- Hadronic matter (HM) is the ground state of baryonic matter at zero *T* and *P*
- Quark matter (QM) becomes energetically favorable only in an environment like a heavy ion collider *(high T)* or deep inside a neutron star *(high P)*

✦ **Common sense**

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Quark matter in general

- Hadronic matter (HM) is the ground state of baryonic matter at zero *T* and *P*
- Quark matter (QM) becomes energetically favorable only in an environment like a heavy ion collider *(high T)* or deep inside a neutron star *(high P)*

- Quark matter (QM) *could be* the ground state of baryonic matter at zero *T* and *P*
- Specifically, the *strange quark matter (SQM) hypothesis* has been proposed back in1970s [Bodmer (1971); Terazawa (1979); Witten (1984)]

Mass Number, A

✦ **Common sense**

✦ **Quark matter hypothesis**

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Quark matter in general

SQM with comparable number of u, d, and s has lower E/A even than the most stable 56Fe

Why is "QM hypothesis" interesting? Fig. 3 *a,* Energy of the S-drop E(Z), calculated using the mass relation of ref. 7, as a function of *Z* relative to its minimum value Emin \mathbf{N} and \mathbf{N} is rather insensitive to the this rather insensitive to the third insensitive to the theory is rather insensitive to the three to the choice of Eo (in the range 900-935 MeV). We note that an S-drop *5 Az* = - 1620- 1 would have an energy *ll.E* = 40 MeV above the ground state , and *ll.E* = 20 MeV above the - 1620° state to which it will decay by tl-emission - 1620°+e- *-ve.* By scaling tabulated tl-decay rates, we . At present we do not consider it useful to put consider it useful to put constraints on the \mathcal{N} cal considerations, because, for the samples investigated here, \rightarrow \rightarrow \sim BEAM \bigcap ----- SECONDARIES Why is "OM hy" to gravitational effects and whose composition reflects and whose composition reflects \mathbf{v} primordial abundance of nuclei, may provide appropriate data studies of primitive meteorites, which have not been subjected to gravitational effects and whose composition reflects and whose composition $\mathcal{N}(\mathcal{N})$ primordial abundance of nuclei, may provide appropriate data

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Quark matter may not be strange

Strange quark matter might be the *ground state* of baryonic matter at zero *T* and *P*, which doesn't ruin the stability (or extremely long lifetime) of ordinary nuclei. [Bodmer (1971); Witten (1984)]

Strange quark matter hypothesis

Why strange quark matter *(SQM)* **rather than ud quark matter** *(udQM)?*

• Ordinary heavy nuclei will convert to udQM with the same *A* catastrophically fast

• Forming SQM needs simultaneous conversion of a sufficiently large number of

-
- down quark to strange quark via the weak interaction, so the probability is negligibly small
- In the context of MIT bag model, SQM has lower energy than udQM

Loopholes for SQM hypothesis

• **Empirical evidence?**

As the periodic table of elements ends for *A>*300, udQM could be the ground state and the catastrophic decay of ordinary nuclei would not happen as long as the minimal *Amin>*300 for udQM

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• **Theoretical prediction?**

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might not be flavor BUT the bag constant independent

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\rho = \frac{N_C}{4\pi^2} \Big(\sum_i f_i^{4/3}\Big) p_F^4 + \frac{N_C}{2\pi^2} f_s^{2/3} p_F^2 m_s^2 + B
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attains the lowest kinetic *i i i might* **not be flavor** *be the ground state of the stability of ordinary* the minimum of the total energy with m_s ~100MeV and independent SQM with comparable u, d, s

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 $\binom{2}{s}$ + $\binom{B}{s}$ (18) and *s* (18) and *s* (18) and *a* quarks (18) and *a* quarks (18) and *a* quarks (18) and *a* quarks (18) and *s* (18) and *s* (18) and *s* (18) and that udQM generally has lower bulk energy p If quark matter is energetically favored over nuclear matter at zero temperature and pressure, then it has long been expected to take the form of strange quark matter (SQM), with comparable amounts of u , d , and s quarks. The possibility of quark matter with only u and d quarks ($udQM$) is usually dismissed because of baryon than normal nuclei and SQM. This emerges in a phenomenological model that describes the spectra of the lightest pseudoscalar and scalar meson nonets. Taking into account the finite size effects, udQM can be the ground state of baryonic matter only for baryon number $A>A_{\text{min}}$ with $A_{\text{min}} \gtrsim 300$. This ensures the stability of ordinary nuclei and points to a new form of stable matter just beyond the periodic table.

$$
\rho = \frac{N_C}{4\pi^2} \left(\sum_i \hat{f}_i^{4/3}\right) p_F^4 + \frac{N_C}{2\pi^2} f_s^{2/3} p_F^2 m_s^2 + \boxed{B}
$$

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BUT the bag constant might not be flavor independent

Quark Matter May Not Be Strange

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PHYSICAL REVIEW LETTERS 120, 222001 (2018)

• Residual QCD effects subdominant on the energy similar to constituent quark model for QCD spectrum ne energy similar to ϵ cons inuent d Ω snectrum P_{C} is extended move away from small values, the fields move away from small values, the fields move away from P_{C}

- out and encoded in the parameters of meson potential *V*
-

· An effective theory describing the sub-GeV mesons: assuming other QCD degrees of freedom integrated 367.8 ± 0.0000

\mathbf{s}_c that these residual \mathbf{s}_c residual \mathbf{s}_c residual \mathbf{s}_c and \mathbf{s}_c ive theory for quark matter $\overline{\mathcal{C}}$ constituent $\overline{\mathcal{C}}$ and $\overline{\$ **Effective theory for quark matter**

Yukawa term + meson potential: $\mathcal{L}_m = \text{Tr} \left(\partial_\mu \Phi^\dagger \partial^\mu \Phi \right) - V, \quad \mathcal{L}_y = -2g \bar{\psi} \Phi \psi$

· An effective theory describing the sub-GeV mesons: assuming other QCD degrees of freedom integrated p¯ ^F can be estimated by minimizing the relativistic quark p Gall masons; assu Ig other QCD degrees of freedom integrate p¯ ^F can be estimated by minimizing the relativistic quark

\mathbf{s}_c that these residual \mathbf{s}_c residual \mathbf{s}_c residual \mathbf{s}_c and \mathbf{s}_c ive theory for quark matter $\overline{\mathcal{C}}$ constituent $\overline{\mathcal{C}}$ and $\overline{\$ meson fields of interest are [26,27] τυι γ NP_{2} / \bullet AP_{2} \bullet AP_{2} Kitteefive fheory for a meson fields of the complete fi, for the set f benchmark with muddy \mathcal{A} and \mathcal{A} \mathbf{g} is a summatrice \mathbf{g} energy per baryon is easy of the set of \mathbf{Q} **Effective theory for quark matter**

n notont <u>nti</u> $\overline{\mathbf{e}}$ i¼u;d **Yukawa term + meson potential:** $\mathcal{L}_m = \text{Tr} \left(\partial_\mu \Phi^\dagger \partial^\mu \Phi \right) - V, \quad \mathcal{L}_y = -2 g \bar{\psi} \Phi \psi$

- out and encoded in the parameters of meson potential V $\frac{1}{2}$ rihina the s e s $h - f$ $\overline{ }$
- effects subdominant on the energy similar

$$
\nabla^2 \sigma_n(r) = \frac{\partial V}{\partial \sigma_n} + g \sum_{i=u,d} \langle \bar{\psi}_i \psi_i \rangle, \qquad \text{Quark gas densities:} \text{ depends on } p_{Fi} = p_{F} f_i, \qquad \nabla^2 \sigma_s(r) = \frac{\partial V}{\partial \sigma_s} + \sqrt{2} g \langle \bar{\psi}_s \psi_s \rangle, \qquad \text{quark masses inside} \qquad\n\begin{aligned}\nm_{u,d}(r) &= g \sigma_n(r) + m_{ud} m_{g,r} \\
m_s(r) &= \sqrt{2} g \sigma_s(r) + m_{g0}\n\end{aligned}
$$

 σ_s

- Quark densities drive meson fields. away from the vacuum
	- additional flavor symmetry breaking

tential: $\mathcal{L}_m = \text{Tr} \left(\partial_\mu \Phi^\dagger \partial^\mu \Phi \right) - V, \quad \mathcal{L}_y = -2 g \bar{\psi} \Phi \psi$ ∂σ^s $\Phi \big)$ -⁻ $\big) -V, \quad {\cal L}_{y} = -2g\bar{\psi}$ α p^ðn^Þ $\mathcal{L} = \text{Tr}(\partial \Phi^{\dagger} \partial^{\mu} \Phi) - V - \mathcal{L} = 2 \pi \overline{u} \Phi u$

2 $\sqrt{2}g\sigma_s(r)+m_{s0}$

· An effective theory describing the sub-GeV mesons: assuming other QCD degrees of freedom integrated p¯ ^F can be estimated by minimizing the relativistic quark p Gall masons; assu Ig other QCD degrees of freedom integrate p¯ ^F can be estimated by minimizing the relativistic quark

• Residual QCD effects subdominant on the energy similar to constituent quark model for QCD spectrum ne energy similar to ϵ cons the energy similar to constituent quark mode

> uark gas densities
epend on pFi=pFf depend on *p_{Fi}*=*p_F* f_i , μ_i (MeV

tential:
$$
\mathcal{L}_m = \text{Tr}(\partial_\mu \Phi^\dagger \partial^\mu \Phi) - V, \quad \mathcal{L}_y = -2g\bar{\psi}\Phi\psi
$$

\mathbf{s}_c that these residual \mathbf{s}_c residual \mathbf{s}_c residual \mathbf{s}_c and \mathbf{s}_c ive theory for quark matter $\overline{\mathcal{C}}$ constituent $\overline{\mathcal{C}}$ and $\overline{\$ meson fields of interest are [26,27] τυι γ NP_{2} / \bullet AP_{2} \bullet AP_{2} Kitteefive fheory for a meson fields of the complete fi, for the set f benchmark with muddy \mathcal{A} and \mathcal{A} \mathbf{g} is a summatrice \mathbf{g} energy per baryon is easy of the set of \mathbf{Q} **Effective theory for quark matter**

n notont <u>nti</u> $\overline{\mathbf{e}}$ i¼u;d \mathcal{L} = **Yukawa term + meson potential:**

- out and encoded in the parameters of meson potential V $\frac{1}{2}$ rihina the s e s $h - f$ $\overline{ }$ σ in the parameters of modern petermant
- momentum for each flavor, pFi \sim 9, where the quark \sim

-
-

$$
\nabla^2 \sigma_n(r) = \frac{\partial V}{\partial \sigma_n} + g \sum_{i=u,d} \langle \bar{\psi}_i \psi_i \rangle, \qquad \text{Quark gas densities:} \text{ depends on } p_{Fi} = p_{F} f_i, \qquad \nabla^2 \sigma_s(r) = \frac{\partial V}{\partial \sigma_s} + \sqrt{2} g \langle \bar{\psi}_s \psi_s \rangle, \qquad \text{quark masses inside} \qquad\n\begin{aligned}\nm_{u,d}(r) &= g \sigma_n(r) + m_{ud} m_{g,r} \\
m_s(r) &= \sqrt{2} g \sigma_s(r) + m_{g0}\n\end{aligned}
$$

i MeV

 σ_s

- $T = \frac{1}{\sqrt{2}}$ of the bound state is defined where $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ • Quark densities drive meson fields. away from the vacuum α , and α , and the contained when α
	- additional flavor symmetry breaking

$$
V = V_{\text{inv}} + V_b. \quad \boxed{\Phi = T_a(\sigma_a + i\pi_a)}
$$

pseudoscalar
scalar nonets

$$
\begin{aligned} V_{\text{inv}} & = \lambda_1 \left(\text{Tr} \, \Phi^\dagger \Phi \right)^2 + \lambda_2 \, \text{Tr} \left((\Phi^\dagger \Phi)^2 \right) + m^2 \, \text{Tr} \left(\Phi^\dagger \Phi \right) \\ & - c \left(\det \Phi + h.c. \right). \end{aligned}
$$

Explicit *SU(3)* flavor symmetry breaking incorporated in current quark masses: $\mathcal{M}=\text{diag}(m_{u0},m_{d0},m_{s0})$ $\frac{1}{2}$

$$
V_{b1} = b_1 \operatorname{Tr} (\Phi^{\dagger} \mathcal{M} + h.c.),
$$

\n
$$
V_{b2} = b_2 \epsilon_{ijk} \epsilon_{mnl} \mathcal{M}_{im} \Phi_{jn} \Phi_{kl} + h.c.,
$$

\n
$$
V_{b3} = b_3 \operatorname{Tr} (\Phi^{\dagger} \Phi \Phi^{\dagger} \mathcal{M}) + h.c.,
$$

\n
$$
V_{b4} = b_4 \operatorname{Tr} (\Phi^{\dagger} \Phi) \operatorname{Tr} (\Phi^{\dagger} \mathcal{M}) + h.c.,
$$

\n
$$
V_{b5} = b_5 \operatorname{Tr} (\Phi^{\dagger} \mathcal{M} \Phi^{\dagger} \mathcal{M}) + h.c.,
$$

\n
$$
V_{b6} = b_6 \operatorname{Tr} (\Phi \Phi^{\dagger} \mathcal{M} \mathcal{M}^{\dagger} + \Phi^{\dagger} \Phi \mathcal{M}^{\dagger} \mathcal{M}),
$$

\n
$$
V_{b7} = b_7 (\operatorname{Tr} \Phi^{\dagger} \mathcal{M} + h.c.)^2,
$$

\n
$$
V_{b8} = b_8 (\operatorname{Tr} \Phi^{\dagger} \mathcal{M} - h.c.)^2.
$$

itn isospin symmetry) 12 free parameters (with isospin symmetry)

We find that a linear sigma model provides an adequate an adequate an adequate α description with the model terms: Δ minimal mod $h = h \cap \mathbb{R}$ \mathbb{Z} \sim sub-Gev mesons ^ð ffiffiffi **ad** Joy missions \mathbf{p} **A minimal model for sub-GeV mesons**

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- ⁶. Given the theoretical uncertainties associated

Vb⁶ ^¼ ^b6TrðΦΦ†MM† ^þ ^Φ†ΦM†MÞ; \blacksquare mudd \blacksquare 3.4 \blacksquare \bl V b4Trð Φ † Φ Þ Φ Þ Φ Þ Φ Þ Φ redefinition and municipal \blacksquare \blacksquare

Set 2

lynam ChSB: $\langle \Phi \rangle = T_0 v_0 + T_2 v_2 = \frac{1}{2} \text{diag}(v_x, v_x, \sqrt{2}v_z)$ $v_n = f_\pi = 92 \text{ MeV}, \quad v_s = \sqrt{2} f_\pi - f_\pi / \sqrt{2} f_\pi$ $n, \sqrt{2}v_s$
 $f = \sqrt{2} = 0$ $\sqrt{2}$ MeV MeV $v_n - \mathcal{F}_n$. $\mathbf{z} \cdot i\pi_a$) **Pseudoscalar • Dynamical ChSB:** $\langle \Phi \rangle = T_0v_0 + T_8v_8 = \frac{1}{2} \text{diag}(v_n, v_n, \sqrt{2})$ **ChSB:** $\langle \Phi \rangle = T_0 v_0 + T_8 v_8 = \frac{1}{2} \text{diag}(v_n, v_n, \sqrt{2}v_s)$ $v = f = 92$ MeV $v = \sqrt{2}f_y = f/\sqrt{2} = 90.5$ MeV $v_n = f_\pi = 92 \text{ MeV}, \quad v_s = \sqrt{2}f_K - f_\pi/\sqrt{2} = 90.5 \text{ MeV}$ 3 (a % 0; 0; 0; 0; 8) denotes the nine generators of the flavor of the flavor of the flavor of the flavor of the
The flavor of the flavor **il ChSB:** $\langle \Phi \rangle = T_0 v_0 + T_8 v_8 = \frac{1}{2} \text{diag}(v_n, v_n, \sqrt{2}v_n)$ $\sqrt{2}$ = (a) $f = 02$ MeV $v = \sqrt{2}f + \sqrt{2}$ $v_n = f_\pi = 92$ MeV, $v_s = \sqrt{2} f_K - f_\pi / \sqrt{2}$ 90.5 MeV $\overline{}$ $T_a(\sigma_a + i\pi_a)$ scalar nonets **by namical ChSB:** $\langle \Phi \rangle = T_0v_0 + T_8v_8 = \frac{1}{2}diag(v_n, v_n, \sqrt{2}v_s)$ $v_n = f_\pi = 92$ MeV, $v_s = \sqrt{2}f_K - f$ $\frac{1}{2}$ \overline{r} $v_n = f_\pi = 92 \text{ MeV}, \ \ v_s = \sqrt{2} f_K - f_\pi / \sqrt{2} = 90.5 \text{ MeV}$ dent masses are m² $p_i + i\pi_a$) scalar nonets **Dynamical ChSB:** $\langle \Phi \rangle = T_0 v_0 + T_8 v_8 = \frac{1}{2} \text{diag}(v_n, v_n, \sqrt{2}v_s)$ description with the control of the
Control of the control of the contro $h = 0^{\circ}0^{\circ} + 3^{\circ}0^{\circ}$ 2° 2° (c_n, c_n, v $=$ c_s)
= f = 92 MeV $v = \sqrt{2}f_y - f/\sqrt{2} = 0$ s)
= 90.5 MeV $U_s = \int \pi r^2 \, dx$ ivid v, $U_s = \sqrt{2} \, K = \int \pi / \sqrt{2} \, dz = \sqrt{2} \, \sqrt{2} \, \sqrt{2} \, dz$ (a α) denotes the nine generators of the nine generators of the flavor of the ChSR $\langle \Phi \rangle = T_0 v_0 + T_0 v_0 = \frac{1}{2} \text{diag}(v - v_0) \sqrt{2}v_0$ **ChSB:** $\langle \Phi \rangle = T_0 v_0 + T_8 v_8 = \frac{1}{2} \text{diag}(v_n, v_n, \sqrt{2} v_s)$ $v_n = f_\pi = 92 \text{ MeV}, \quad v_s = \sqrt{2}f_K - f_\pi/\sqrt{2} =$ amical CheR T_{11} Udi Viivb. $\sqrt{47} - 10v_0 + 18v_8 - 2$ and $\sqrt{v_n}, v_n$ $v_n = f_\pi = 92 \text{ MeV}, \ \ v_s = \sqrt{2}f_K - f_\pi$

• Mass spectrum: $m_{a_0}^2 = M_{s,11}^2$, $m_{\kappa}^2 = M_{s,44}^2$, $m_{\pi}^2 = M_{p,11}^2$, $m_K^2 = M_{p,44}^2$ m_{σ}^2 , $m_{\tau_0}^2$, m_{η}^2 , m_{η}^2 , $m_{\eta'}^2$ from diagonalizing (0,8) sector $\frac{3}{20}$
With isospin symmetry, the eight independent independent independent in the eight independent indep $m^2 \text{Tr} (\bar{\phi}^\dagger \bar{\phi})$ • Mass spectrum **rum:** $m_{a_0}^2 = M_{s,11}^2$, $m_{\kappa}^2 = M_{s,44}^2$, $m_{\pi}^2 = M_{p,11}^2$, $m_K^2 = M_{p,44}^2$ $\frac{2}{\sigma}$, $m_{\tilde{f}_0}^2$, $m_{\eta'}^2$, from diagonalizing (0,8) sector m^2 m^2 m^2 m^2 from diagonalizing (0.8) m_{σ} , m_{f_0} , m_{η} , $m_{\eta'}$ from diagonalizing (0,0) and $m_{f_0}^2$, m_{η}^2 , $m_{\eta'}^2$ from diagonalizing (0,8) α and α in the eight independent independent in the eight independent independent in α $\overline{\mathbf{u}}$ $(\Phi^{\dagger} \Phi)^2) + m^2 \, {\rm Tr} \left(\Phi^{\dagger} \Phi \right)$ • Mass spectrum: $m_{a_0}^2 = \mathbb{M}^2_{s,11}, \,\, m_{\kappa}^2 = \mathbb{M}^2_{s,44}, \,\, m_{\pi}^2 = \mathbb{M}^2_{p,11}, \,\, m_K^2 = \mathbb{M}^2_{p,44}$ $m_{\tilde{e}}^2$, $m_{\tilde{e}}^2$ $m_{\tilde{e}}^2$, $m_{\tilde{e}}^2$, from diagonalizing η sectors. The rotations are defined as η is a contract of η m^2 , m^2 , m^2 , m^2 , from diagonalize m_{σ} , m_{f_0} , m_{η} , $m_{\eta'}$ hom diagonalize m_σ^2 , $m_{f_0}^2$, m_{η}^2 , $m_{\eta'}^2$ from diagonalizing (0,8) sector (v, o) social p
Prijme $m^2 = M^2$ $m^2 = M^2$, $m^2 =$ $P = \mathbb{M}^2$ *m*² $\frac{1}{2}$ \mathbb{R} \mathbb{R}^2 m^2 Tr $(\Phi^{\dagger}\Phi)$ \blacksquare Mass spectrum: $m_{a_0}^2 = \mathbb{W}^2_{s,11}, m_{\tilde{k}}^2 = \mathbb{W}^2_{s,44}, m_{\tilde{n}}^2 = \mathbb{W}^2_{p,11}, m_{\tilde{k}}^2 = \mathbb{W}^2_{p,44}$ σ (-,-,-) = = = = = = $= M_{s,11}^2$, n 1, $m_{\kappa}^2 = M_{s,44}^2$, m_{κ}^2 n^{2}_{j} $m_\pi^2 = \mathbb{M}_{p,11}^2, \; m_K^2 = \mathbb{M}$ $\overline{\mathbb{M}}$ $p \cdot \left((\Phi^\dagger \Phi)^2 \right) + m^2 \, {\rm Tr} \left(\Phi^\dagger \Phi \right) \qquad \qquad$ • Mass spectrum: $m_{a_0}^2 = \mathbb{M}^2_{s,11}, \,\, m_{\kappa}^2 = \mathbb{M}^2_{s,44}, \,\, m_{\pi}^2 = \mathbb{M}^2_{p,11}, \,\, m_K^2 = \mathbb{M}^2_{p,44}$ m_c^2 , m_{ν}^2 , m_{ν}^2 , from diagonalizing (0.8) sector $m_{f_0}^2$, m_{η}^2 , $m_{\eta'}^2$ from diagonalizing (0,8) sector **UM:** $m_{a_0}^2 = M_{s+1}^2$, $m_{\kappa}^2 = M_{s+4}^2$, $m_{\pi}^2 = M_{n+1}^2$, $m_{\kappa}^2 = M_{n+1}^2$ m^2 m^2 m^2 m^2 from diagonalizing (0.8) set m_{σ} , m_{f_0} , m_{η} , $m_{\eta'}$ from diagonalizing (0,0) so m_{σ}^2 , $m_{f_0}^2$, m_{η}^2 , $m_{\eta'}^2$ from diagonalizing (0,8) sector \mathbf{c} chockum: $m^2 = M^2$ $m^2 = M^2$ $m^2 = M^2$ **s spectrum:** $m_{a_0}^2 = M_{s,11}^2$, $m_{\kappa}^2 = M_{s,44}^2$, $m_{\pi}^2 = M_{p,11}^2$, , m_{η}^2 , $m_{\eta'}^2$ from diagonalizing

> departures gives the smaller NDA couplings of set 2. \mathbf{r} and large $\pi\pi$ widths σ \overline{C} θ_s : fit small and large $\pi\pi$ widths \therefore fit small and large $\pi\pi$ widths $\int_{0}^{3} f_0$ and σ \overline{a}

$$
V = V_{\text{inv}} + V_b. \quad \boxed{\Phi = T_a(\sigma_a + i\pi_a)}
$$

pseudoscalar
scalar nonets

$$
V_{\text{inv}} = \lambda_1 \left(\text{Tr} \, \Phi^\dagger \Phi \right)^2 + \lambda_2 \, \text{Tr} \left((\Phi^\dagger \Phi)^2 \right) + m^2 \, \text{Tr} \left(\Phi^\dagger \Phi \right) \cdot \text{Mass spectrum:}
$$

- c (det Φ + h.c.).

Explicit *SU(3)* flavor symmetry breaking incorporated in current quark masses: $\mathcal{M} = \text{diag}(m_{u0}, m_{d0}, m_{s0})$ $\frac{1}{2}$ kvesking incorporated • Decay breaking incorporated **Decay widths:** The community of the community of the term is the term in the term in the set of the term is the term in the t For there to be spontaneous symmetry breaking in the For there to be spontaneous symmetry breaking in the br symmetry breaking incorporated breaking by incorporating the current quark mass mass matrix $\frac{1}{\sqrt{2}}$ (a) denotes the nine generators of the nine generators of the flavor of the flavor of the flavor of the flavor mmetry breaking incorporated **Decay widths:** cor $\begin{array}{r}\n \text{Area}(n, n, u_0, n, u_0, n, s_0) \n \end{array}$ $\text{diag}(m_{u0}, m_{d0}, m_{s0})$ $\mathcal{M}=\text{diag}(m_{u0}, m_{d0}, m_{s0})$ For the treaking in the spontaneous symmetry breaking in \mathbf{F} $\mathcal{L}(\mathbf{S}^T, \mathbf{S}^T, \mathbf{S}^$ masses: $\mathcal{M} = \text{diag}(m_{u0}, m_{d0}, m_{s0})$

$$
V_{b1} = b_1 \text{Tr} (\Phi^{\dagger} \mathcal{M} + h.c.),
$$
\n
$$
V_{b2} = b_2 \epsilon_{ijk} \epsilon_{mnl} \mathcal{M}_{im} \Phi_{jn} \Phi_{kl} + h.c.,
$$
\n
$$
V_{b3} = b_3 \text{Tr} (\Phi^{\dagger} \Phi \Phi^{\dagger} \mathcal{M}) + h.c.,
$$
\n
$$
V_{b4} = b_4 \text{Tr} (\Phi^{\dagger} \Phi) \text{Tr} (\Phi^{\dagger} \mathcal{M}) + h.c.,
$$
\n
$$
V_{b5} = b_5 \text{Tr} (\Phi^{\dagger} \mathcal{M} \Phi^{\dagger} \mathcal{M}) + h.c.,
$$
\n
$$
V_{b6} = b_6 \text{Tr} (\Phi^{\dagger} \mathcal{M} \Phi^{\dagger} \mathcal{M}) + h.c.,
$$
\n
$$
V_{b7} = b_7 \text{Tr} \Phi^{\dagger} \mathcal{M} + h.c.
$$
\n
$$
V_{b8} = b_8 \text{Tr} \Phi^{\dagger} \mathcal{M} + h.c.
$$
\n
$$
V_{b7} = b_8 \text{Tr} (\Phi^{\dagger} \mathcal{M} + h.c.)^2,
$$
\n
$$
V_{b8} = b_8 \text{Tr} \Phi^{\dagger} \mathcal{M} - h.c.
$$
\n
$$
V_{b7} = b_7 \text{Tr} \Phi^{\dagger} \mathcal{M} + h.c.
$$
\n
$$
V_{b8} = b_8 \text{Tr} (\Phi^{\dagger} \mathcal{M} + h.c.)^2.
$$
\n
$$
V_{b9} = b_8 \text{Tr} (\Phi^{\dagger} \mathcal{M} + h.c.)^2.
$$
\n
$$
V_{b1} = b_7 \text{Tr} \Phi^{\dagger} \mathcal{M} - h.c.
$$
\n
$$
V_{b2} = b_8 \text{Tr} (\Phi^{\dagger} \mathcal{M} \mathcal{M} + h.c.)^2.
$$
\n
$$
V_{b3} = b_8 \text{Tr} (\Phi^{\dagger} \mathcal{M} \mathcal{M} + h.c.)^2.
$$
\n
$$
V_{b4} = b_4 \text{Tr} (\Phi^{\dagger} \Phi \Phi
$$

itn isospin symmetry) 12 free parameters (with isospin symmetry) symmetry) = and the symmetry \int $\frac{1}{2}$ external internal model with $\frac{1}{2}$ $\begin{array}{r} \textbf{Set 2} & 20 \\ \textbf{Set 2} & 20 \end{array}$ $\begin{CD} \text{Tr}\left(\text{WITR} \text{ isospin symmetry}\right) \end{CD}$

lhs: constrain mixing • Decay widths: constrain mixing angles s;11, m² The mass spectra for the scalar and pseudoscalar m² ^K ^¼ ^M² p;44, and m² ^σ, m² , m² ^η, m² The constrain mixing angles and the 't Hooft operator. $\mathbf{B} = \mathbf{B} \mathbf{B} + \mathbf{B} \mathbf{B}$ cos θpης της περιοχής με το θρησκοποι
Θρησκοποι av widths: constrain mixing angles y widuls. Constrain mixing angles the constrain mixing angles I**NS:** constrain mi in mixing angles hs: constrain mixing angles <u>o m</u>₀. m₂ ^η, m² at widthe: constrain mixing angles ay widths: constrain mixing angles constrain mixing angles

We find that a linear sigma model provides an adequate an adequate an adequate α description with the model terms: Δ minimal mod $h = h \cap \mathbb{R}$ \mathbb{Z} \sim sub-Gev mesons ^ð ffiffiffi **ad** Joy missions \mathbf{p} <u>iniminial miduci iði sud-oc y mics</u> p vills van de van
De van de va PHYSICAL REVIEW LETTERS 120, 222001 (2018) \mathbf{H} in \mathbf{A} and \mathbf{A} model provides and \mathbf{A} dud oc v micoul A minimal model nr s \mathbf{c} uh \mathbf{d} 7 ρ \mathbf{V} m 1 m esn $\sum_{i=1}^{n}$ p d The deformation by M natural substantial ϵ auh $\Gamma_0 V$ moone where $\frac{1}{\sqrt{2}}$ is the meson field and Ta $\frac{1}{\sqrt{2}}$ is the meson field and Table $\frac{1}{2}$ we find the complement of the state of the complete state of the com A MINIMAI MOQEI IOF SUD-GEV MESONS PHYSICAL REVIEW LETTERS 120, 222001 (2018) α r \cdot sub- \bullet 1 GeV m 1 meso n n c p S The deformation by M natural surface **A minimal model for sub-GeV mesons**

Troldom, IR and Zhang, PRL 120 G (2018)] with the neglected higher-dimensional terms, allowing the neglected higher-dimensional terms, allowing the neg
The neglected higher-dimensional terms, allowing the neglected higher-dimensional terms, allowing the neglecte Vb⁵ ^¼ ^b5TrðΦ†MΦ†MÞ þ ^H:c:; (2018) ang, PRL 120 (2018)] redefinition [15]. We adopt ms⁰ ¼ 94 MeV and mu0;d⁰ ¼ \overline{a} with form \overline{a} and \overline{a} (a0 widths have \overline{a}). and \angle hang, PRL 120 (2018)] \overline{P} and \overline{P} and \overline{P} \overline{P} and \overline{P} \overline{P} and pseudoscalar an \sum and \sum mang, the TZV (ZVTV) \sum σ PRI 120 (2018)] α , however, the leads to a rather large value for the NDA α [Holdom, JR and Zhang, PRL 120 (2018)] meson is quite close to the nonstrange direction. results of the two benchmarks, including predictions for some [Holdom, JR and Zhang, PRL 120 (2018)] 6

$^{\prime\prime}$ $\frac{1}{2}$ $\overline{}$ $\frac{1}{2}$ $\ddot{}$ cos θpης στην προσφαλία στην προσφαλία στην προσφαλία στην προσφαλία στην προσφαλία στην προσφαλία στην προσφα
Επιχειρηματικές προσφαλίες στην προσφαλία στην προσφαλία στην προσφαλία στην προσφαλία στην προσφαλία στην προ α solve the 12 free parameters (α 1 β) s;ab ∂o2V=∂a∂o∂o2∨=∂o2∨=∂o2∨ p;ab ¼ $\overline{m'_\eta}$ $\qquad \theta_p$ Find two benchmarks:

- I fit to observables with meson is quite construction. The non-terminal construction is α $\mathbf{P}^{\mathbf{a}}$ and the meson of the meson model. χ
12, m2 m2 m¹ C to the male of **The main of the parameters** and the main of the main set of t a good fi \overline{r} to obs 15.0° · a good fit to observables with \overline{a}
	- , \overline{a} , \overline{b} , \overline{c} , data; however, this leads to a rather large value for the NDA α eters ρϕ ¼ ΔV þ \mathbf{R} cho \mathbf{r} parameters with respect to the positive potential energy with respect to the positive potential energy with respect to the contract of the con

 $\frac{2}{\sqrt{2}}$ 451 $\frac{9}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$ decay of n, n' and strong decay $\frac{d}{d}$ decay with the service $\frac{d}{d}$ ecay with the neglected higher-dimensional terms, allowing the neglected higher-dimensional terms, allowing the \mathcal{L}_c d to diphoton rodictive σ' and example σ' and σ' d_1, d_1 and subling decay decay of η , η' , and strong decay σ_p : related to diphoton radiative $\frac{537}{537}$ decay or η , η , and strong decay decay of η , η , and strong decay $U_1 U_0$ $\overline{}$

Quark matter in the bulk limit \mathbf{q} and \mathbf{q} and \mathbf{q} favorable in an analysis only becomes energetically favorable in an analysis of \mathbf{q} environment like a heavy inside a heavy inside a heavy inside a heavy inside a set of the collider or determined a

- "Force balancing" between scalar potential v.s. fermion density determines meson fields values
- Bulk properties (\bar{p}_F, \bar{f}_i) determined by minimizing the energy per baryon mined by minimizing the energy per baryon ε [Holdom, JR and Zhang, PRL 120 (2018)]
- $n \leq 1$ formal are along this proposed by ϵ as proposed for ϵ as proposed ϵ and remindri densities are roughly spatially constant, and quark matter with the matter with ϵ comparable numbers of u, and s, and s, and s, also called strange strange strange strange strange strange stra **Large** *A* **limit:** meson fields and fermion densities are roughly spatially constant, and quark

fractions are driven to approach charge neutral

Quark matter in the bulk limit \mathbf{q} and \mathbf{q} and \mathbf{q} favorable in an analysis only becomes energetically favorable in an analysis of \mathbf{q} environment like a heavy inside a heavy inside a heavy inside a heavy inside a set of the collider or determined a $f(x) = f(x) - f(x) - f(x)$ **Quark matter** energy per baryon is equipment of $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$ s \mathcal{L} for \mathcal{L} . For \mathcal{L} sets, udQM is the ground state of baryonic matter in the bulk. A s p \mathcal{A} s mall values, the fields move away \mathcal{A} is the fields move away \mathcal{A} $A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ from the vacuum along the least steep direction, which is a $v_{\rm c}$ at a close to the oriented close to the oriented close to the c $\bigcap_{n\in\mathbb{N}}\mathbb{Z}_{p^n}$ \blacksquare sets, use of baryonic matter in the ground state of bulk.

 $n \leq 1$ formal are along this proposed by ϵ as proposed for ϵ as proposed ϵ and remindri densities are roughly spatially constant, and quark matter with the matter with ϵ Large *A* limit: meson fields and fermion densities are roughly spatially constant, and quark

matter, minimizing the energy per baryon ϵ

Quark matter in the bulk limit \mathbf{q} and \mathbf{q} and \mathbf{q} favorable in an analysis only becomes energetically favorable in an analysis of \mathbf{q} environment like a heavy inside a heavy inside a heavy inside a heavy inside a set of the collider or determined a $f(x) = f(x) - f(x) - f(x)$ **Quark matter** energy per baryon is equipment of $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$, $\mathcal{L}_{\mathcal{L}}$ s \mathcal{L} for \mathcal{L} . For \mathcal{L} sets, udQM is the ground state of baryonic matter in the bulk. A s p \mathcal{A} s mall values, the fields move away \mathcal{A} is the fields move away \mathcal{A} $A = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ from the vacuum along the least steep direction, which is a $v_{\rm c}$ at a close to the oriented close to the oriented close to the c $\bigcap_{n\in\mathbb{N}}\mathbb{Z}_{p^n}$ \blacksquare sets, use of baryonic matter in the ground state of bulk.

only the scalar and pseudoscalar nonets of the sub-GeV

mesons with Yukawa coupling to quarks, we demonstrate

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udQM away from the bulk limit

Small A limit: need to include the Coulomb energy contribution and the finite size effects

$$
E = \int_0^R d^3r (\rho_\psi + \rho_\phi + \rho_Z) \hspace{1cm} 2
$$

 $\bar{\varepsilon}(A) \approx \bar{\varepsilon} + 46 \,\Sigma / (\bar{p}_F^2 A^{1/3}) + 0.31 \,\alpha \, Z^2 \bar{p}_F / A^{4/3}$

mainly surface effects minimizing the kinetic and Coulomb energies of u,d gas

 $Z = N_C A(\bar{f}_u(A) - 1/3)$

udQM away from the bulk limit

Small A limit: need to include the Coulomb energy contribution and the finite size effects

$$
E = \int_0^R d^3r (\rho_\psi + \rho_\phi + \rho_Z) \qquad \qquad \text{if}
$$

 $\bar{\varepsilon}(A) \approx \bar{\varepsilon} + 46 \,\Sigma / (\bar{p}_F^2 A^{1/3}) + 0.31 \,\alpha \, Z^2 \bar{p}_F / A^{4/3}$

minimizing the kinetic and Coulomb energies of u,d gas

Continent of Stability v.s. Island of Stability

If *A*min~300, maybe udQM with large *Z/A* could be produced by fusion of heavy elements within "continent of stability"?

mainly surface effects

 $Z = N_C A(\bar{f}_u(A) - 1/3)$

• **MoEDAL:** passive detection methodologies tuned for HIPs, good for higher charge [Acharya et al. [MoEDAL], EPJC 82 (2022)] Provention, the coupling

Collider searches of highly ionizing particles

LHC search for highly-ionizing particles (HIP): Drell-Yan

• **ATLAS:** general purpose detector by utilizing highly ionizing signature, better limits [Aad *et al.* [ATLAS], arXiv:2308.04835]

 $\mathsf D$

11

Astrophysical implications: ud quark stars (udQSs) uum constituent quark mass *Mu*⁰ = *Md*⁰ = 335 MeV and *Ms*⁰ = 527 MeV from SU(3) Nambu-Jona-Lasinio (NJL) ¹*.*00 and chirp mass *^M^c* = 1*.*186+0*.*⁰⁰¹ 0*.*001*M* for the lowg gwark stars (UGCDSS) merger, we find the unit of unit \mathcal{N} strongly violates the con-

we assume ⌫*^u* = ⌫*^d* ⌘ ⌫*ud* for simplicity, and thus we es inside hadronic stars through quantum tu note that using the isospin-dependent quark mass for-dependent quark mass for-dependent quark mass for-depende
The isospin-dependent quark mass for-dependent quark mass for-dependent quark mass for-dependent problems of-d Since ⇤˜(*q*) generally increases with *q* for a fixed *Mc*, the udQM nucleates inside hadronic stars through quantum tunneling, forming pure ud quark stars (udQSs)

enhance the *M*TOV by about 0*.*2*M* for SQSs [61]. • "All compact stars being udQSs": instantaneous transition typically predicted; consistent with observations mensionless tidal deformability and deformability $\mathcal{N}_{\mathcal{A}}$ for a $\mathcal{N}_{\mathcal{A}}$ with mass $\mathcal{N}_{\mathcal{A}}$ with mass

II. RESULT AND DISCUSSION CONTINUES OF A RESULT AND DISCUSSION CONTINUES OF A RESULT AND DISCUSSION OF A RESULT AN [Zhao, *et al.* PRD 100 (2019), Ren and Zhang, PRD 102 (2020)]

 $[$ UdO, UHEN, UNU dNU ZNOU, END TOO (ZUZZ)] [Cao, Chen, Chu and Zhou, PRD 106 (2022)]

 $GMM100814$ as $1dOS$ (confin GW190814 as udQS (confining quark matter)

b. "Two family scenario": high-mass stars are **ordinal substitute is a parameter set in the parameter set is denoted as units denoted as uses in the parameter set is denoted as uses in the parameter set is denoted as uses in the parameter set is denoted as uses in the** udQSs and low-mass ones are hadronic stars • **"Two family scenario":** high-mass stars are

mula (2020) with one more parameter can help to α *u* α *d* α *u* α *d* α [JR and Zhang, PRD 102 (2020)]

Hybrid stars may have an inverted structure

Hybrid stars: maybe an inverted structure?

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Hybrid stars: maybe an inverted structure?

If HM is more stable than QM at intermediate density, inverted structure can be formed by NSs hit by QM or quantum nucleation of QM (HM) inside NSs (QSs)

may easily fall into the unstable branch of compact stars.

Institute of High Energy Physics, Chinese Academy Physics, Chinese Academy of High Energy Physics, Chinese Academy of Academy of High Energy Physics, Chinese Academy of Academy of Academy of Academy of Academy of Academy o

absolute stability condition of QM at zero pressure. Since $\mathcal{L}_{\mathcal{A}}$

The parameter space of \mathbb{R}^n after space of \mathbb{R}^n are constrained by the constrained by the constrained by the constraints of \mathbb{R}^n

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under the conventional assumption of a flavor-independent of a flavor-independent of a flavor-independent of a

Considering a sharp phase transition (Maxwell construction), QM to HM transition occurs when $\mu_{\sf Q}$ and $\mu_{\sf H}$ cross, i.e. a softer HM EOS and stiffer QM EOS at low densities, given mass regime meeting the PSR J0740 þ 6620 one. This Considering a sharp phase transition (Maxwell con Considering a sharp phase transition (Maxwell construction), QM to HIN transition occurs when μ_Q and μ_H cross, i.e. **QM EOS at low densities, given** $\mu(P) \approx \mu(Q) + \int_0^P dP' \frac{1}{n(P')}$ [Zhang and JR, PRD 108 (2023)] [50] M. G. Alford, K. Rajagopal, S. Reddy, and F. Wilczek, $n(P')$ a softer HM EOS and stiffer QM EOS at low densities, given $\mu(P) \approx \mu(Q) + \int_0^P dP' \frac{1}{n(P')}$ [Zhang and JR, PRD 108 (2023)] $\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ on the reduction (Maxwell construction). OM to HM transition occurs when μ_0 and μ_1 cross i.e. ven $u(P) \approx u(0) + \int_{0}^{P} dP' \frac{1}{\sqrt{2\pi}}$ (*zhone and IP PPP 100 (0000)*) $\frac{1}{2}$ d'origip prigod transition (ividavion constituction) t ivi E UJ and sun e i Qivi E UJ at luw densities, giv t U and μ to the stability of μ ordinary μ and μ ordinary μ $u(P) \approx \mu(Q) + J_0$ $dP \overline{n(P')}$ [Zhang and JR, PRD 108 (2023)] $T_{\rm eff}$ is the EOS of using the EOS of using the $P_{\rm eff}$ is the P $_{\rm eff}$ 3 ðþeir 1938 - 4Bb.
1938 - 4Bb. The Eoster 1940 - 4Bb.
1940 - 4Bb. The Eoster 1940 - 4Bb. ponsidering a sharp phase transition (Maxwe ϵ ofter HM EOS and etiffer OM EOS at low a $\frac{1}{2}$ $\mathcal{L}_{\mathcal{A}}$, the latter for $\mathcal{A}_{\mathcal{A}}$ is the latter from the latter sharp phase transition (Maxwell construction effect induced by the residual and stifter $\bigcap_{n=1}^{\infty}$ at low densities aive the dividence color color superconductivity for superconductivity for simulations of the simulation of the simulat θ QM to HNP transition occurs when μ_Q μ _imarsition occurs when μ _Q and μ _F $\mu(P) \approx \mu(Q) + J_0^f dP' \frac{1}{n(P')}$ [Zhang and JR, PRD 108 (2023)]

Crossing from QM to HM and GW170817 constraints and CrSs residing in the large-APPENDIX VARIATIONS OF HADRONIC EOSS \sim I. Bombach, D. Logotta, I. Vidaña, and C. Providencia, I. Vidaña, and C. Providencia, and C. Providence and C. rossing trom [49] K. Iida and K. Sato, Phys. Rev. C 58, 2538 (1998). $\sum_{\alpha} R_{\alpha}$ and GW170817 constraints and CrSs residing in the largemass regime meeting the PSR J0740 þ 6620 one. This ARPENDIX A: VARIATIONS OF HADRONIC EOSS context of specific holographic models Γ WE START BY THE PROPERTY OF TH \sim most stabilizer nucleus, \sim 56Fe, has an energy per baryon p \Box Number of \Box 10 MeV, the stability condition \Box \sim and a lower bound on a lower bound on a set \sim ð2Þ α = α α α = α α α = α The value of ξ⁴ depends on the flavor composition of QM. For udQM, ^ξ⁴ ¼ ½ð1=3Þ⁴=³ þ ð2=3Þ⁴=³& [−]³ ≈ 1.86, bag constant. Requiring assume that the constant of to a window B to a window B ⊆ ₹15.5; 222 $\mathcal{L} = \{ \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1$

[47] E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984).

may easily fall into the unstable branch of compact stars.

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ponsidering a sharp phase transition (Maxwe ϵ ofter HM EOS and etiffer OM EOS at low a

Crossing from QM to HM and GW170817 constraints and CrSs residing in the large-APPENDIX VARIATIONS OF HADRONIC EOSS \sim I. Bombach, D. Logotta, I. Vidaña, and C. Providencia, I. Vidaña, and C. Providencia, and C. Providence and C. rossing trom [49] K. Iida and K. Sato, Phys. Rev. C 58, 2538 (1998). $\sum_{\alpha} R_{\alpha}$ and GW170817 constraints and CrSs residing in the large-ARPENDIX A: VARIATIONS OF HADRONIC EOSS context of specific holographic models Γ WE START BY THE PROPERTY OF TH \sim most stabilizer nucleus, \sim 56Fe, has an energy per baryon p \Box Number of \Box 10 MeV, the stability condition \Box \sim and a lower bound on a lower bound on a set \sim ð2Þ α = α α α = α α α = α The value of ξ⁴ depends on the flavor composition of QM. For udQM, ^ξ⁴ ¼ ½ð1=3Þ⁴=³ þ ð2=3Þ⁴=³& [−]³ ≈ 1.86, bag constant. Requiring assume that the constant of to a window B to a window B ⊆ ₹ 15.5; 222 $\mathcal{L} = \{ \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1}, \mathbf{1}, \ldots, \mathbf{1$

[47] E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984).

Comparison to conventional hybrid stars

a generic QM equation of state allowing for a first order phase transition between HM and QM and Q = 40 to 60 Q = 40 to 60 Q = 40 \math **p** a sense its QM equation gonono givi oquation. i at arder phases. st utron pridse $T_{\rm eff}$ so Ω so for nuclear favoring a soft EoS for nucle

CONSIDERATION AND CONSIDERATION **• Conventional hybrid stars**

$T_{\rm eff}$ parametrizations $T_{\rm eff}$ parametrizations \sim 10] parameterizations \sim 10] parameterizations \sim Constant-sound-speed (CSS) parametrizations

[Alford, Han and Prakash, PRD 88 (2013)]

 $\rho(P) = \begin{cases} \rho_{\text{HM}}(P) & P < P_{\text{trans}} \\ \rho_{\text{max}} + \Delta \rho + c^{-2} (P - P) & P > P \end{cases}$ $\rho_{\text{trans}} + \Delta \rho + c_s^{-2} (P - P_{\text{trans}}) P > P_{\text{trans}}$ $,$

a generic QM equation of state allowing for a first order phase transition between HM **p** a sense its QM equation gonono givi oquation. i at arder phases. neutron stars that are larger maximum stars that are larger maximum stars and can reach a higher maximum stars $T_{\rm eff}$ so Ω so for nuclear favoring a soft EoS for nucle and QM and Q = 40 to 60 MeV we incorporate the configuration of CrSs, we include the configuration of a generic QM equation

$$
\rho_{\text{trans}} = \rho_{\text{QM}}(P_{\text{trans}})
$$

$$
\rho(P) = \begin{cases} \rho_{\text{HM}}(P) & P < P_{\text{trans}} \\ \rho_{\text{trans}} + \Delta \rho + c_s^{-2} (P - P_{\text{trans}}) & P > P_{\text{trans}} \end{cases},
$$

$$
\rho(P) = \begin{cases} \rho_{\text{QM}}(P) & P < P_{\text{trans}} \\ \rho_{\text{HM}}(P) & P \gtrsim P_{\text{trans}} \end{cases}, \quad \sum_{\text{new of } P} \neq 0.01
$$

$$
\Delta \rho = \rho_{\rm HM}(P_{\rm trans}) - \rho_{\rm QM}(P_{\rm trans})
$$

Comparison to conventional hybrid stars \bullet is a stars may have an inverted structure phys. Rev. \bullet 108, 063012 (2023)

CONSIDERATION AND CONSIDERATION **• Conventional hybrid stars**

[Alford, Han and Prakash, PRD 88 (2013)]

063012-6 phase transition takes place when Δρ > 0. \cdot inverted hybrid stars $\begin{array}{ccc} \bullet\end{array}$ e in posted nverted hyhrid stars **• Inverted hybrid stars**

Comparison to conventional hybrid stars \bullet is a stars may have an inverted structure phys. Rev. \bullet 108, 063012 (2023) iventional hybrid stars may be a structure of the control of the control of HM- \bullet HYBRID STARS MAY HAVE AN INVERTED STRUCTURE PHYS. REV. D 108, 063012 (2023) IV GHIUNUHAI HIY DI 1U. STAI S

• Conventional hybrid stars CONSIDERATION AND CONSIDERATION

[Alford, Han and Prakash, PRD 88 (2013)]

• Inverted hybrid stars 063012-6 phase transition takes place when Δρ > 0. \cdot inverted hybrid stars $\begin{array}{ccc} \bullet\end{array}$ e in posted nverted hyhrid stars

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$$
\rho_{\text{trans}} = \rho_{\text{QM}}(P_{\text{trans}})
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$$
\rho(P) = \begin{cases} \rho_{\text{HM}}(P) & P < P_{\text{trans}} \\ \rho_{\text{trans}} + \Delta \rho + c_s^{-2} (P - P_{\text{trans}}) & P > P_{\text{trans}} \end{cases},
$$

$$
\rho(P) = \begin{cases} \rho_{\text{QM}}(P) & P < P_{\text{trans}} \\ \rho_{\text{HM}}(P) & P \gtrsim P_{\text{trans}} \end{cases}, \quad \sum_{\text{new of } P} \neq 0.01
$$

$$
\Delta \rho = \rho_{\rm HM}(P_{\rm trans}) - \rho_{\rm QM}(P_{\rm trans})
$$

Astrophysical implications of inverted hybrid stars λ large and large and the existence of the exist **DILYSICAL IMPHCAULONS OF INVERTE** order phase transition as discussed. In contrast transition as discussed. In contrast to contrast to convenience \mathcal{L} cion limit setteng of intu sical milphications of Mrvt ted hyhrid stars LCU HYDI IU Stal S

- Its *M* larger than HSs of the those for QSs and HSs of the same *M*
- Interplay between HM and QM constraints at low and high masses
- "Twin star" configurations exist in cases of small B and large a4
- The new stellar structure leaves more space open for EOS of both HM and QM

•

✦ Quark matter may not be strange

✦ Hybrid stars may have an inverted structure

- udQM generally has lower bulk E/A than normal nuclei and SQM; serve as ground stater at zero *T* and *P* for *A>*300; ensure stability of ordinary nuclei
- Production of udQM by the fusion of heavy elements within the new "continent of stability"…

- Under the QM hypothesis, inverted hybrid stars naturally arise (no need to fine-tune) when the HM becomes more stable in the intermediate density
- Astrophysical implications of inverted hybrid stars deserve further study…

See Yudong Luo's talk for GW asteroseismology of inverted hybrid stars

Thank you!

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Comparing udQM and SQM hypothesis HSs of the same radii, while the radii and tidal deformhynothesis II y poulesis \mathbf{p} benchmark set in \mathbf{p} in \mathbf{p} and \mathbf{p} mparing uu Qivi anu dQ HSS of the same radii, while the same radii, while the radii and tidal deformation and tidal deformation of ti
HSS of the radii and tidal deformation and tidal deformation and tidal deformation and tidal deformation and t relation construction construction construction construction of PSR J0740 μ and PSR μ **THAD POINTED**

The dot-dashed lines denote the dot-dashed lines denote the hadronic cores with the radius recreation of the r

The dot-dashed lines denote the dot-dashed lines denote the hadronic cores with the radius records with the ra

and mass mðrcrÞ.

- Transition usually takes place at a higher pressure for SQM compared to udQM, and thus less parameter space exists to realize stable inverted hybrid stars in the SQM hypothesis
- The parameter space for inverted hybrid stars with a SQM crust is more constrained by the astrophysical observations, especially for hadronic EOSs that are relatively stiffer than APR at low pressure like SLy4

•

and mass mðrcrÞ.