# Hyperons and quarks in massive compact stars

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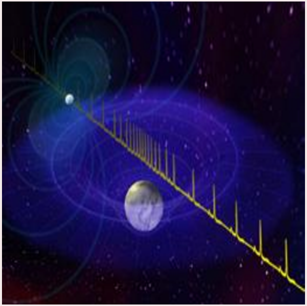
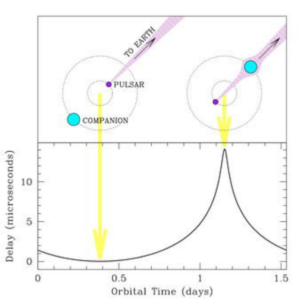
Binary Neutron Star Coalescence as a Fundamental Physics Laboratory

# Plan of this talk






- Hyperonization puzzle and hyperons in compact stars
- Color superconducting quark matter in compact stars
- Cooling and Cas A
- Rotationally induced phase transitions

# I. Hypernuclear Equation of State for Compact Stars

## Approaches to dense hypernuclear matter

- Microscopic approaches: NSC potentials + BHF theory
  *Unfortunately fail to produce massive stars, even with 3B force*
- Relativistic density functionals
  - Nuclear part is constrained by nuclear phenomenology
  - Hyperonic sector constrained by flavor symmetries of strong interactions
  - $\Lambda$-hyperon interactions can be constrained from $\Lambda$-hypernuclei

# Relativistic covariant Lagrangians for hypernuclear matter

Lagrangian for effective fields:

$$
\begin{aligned}
\mathcal{L} &= \sum_B \bar{\psi}_B \Big[ \gamma^\mu \Big( i\partial_\mu - g_{\omega BB}\omega_\mu - \frac{1}{2} g_{\rho BB} \boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu \Big) - (m_B - g_{\sigma BB}\sigma) \Big] \psi_B \\
&+ \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}^\mu \cdot \boldsymbol{\rho}_\mu \\
&+ \sum_\lambda \bar{\psi}_\lambda (i\gamma^\mu \partial_\mu - m_\lambda)\psi_\lambda - \frac{1}{4} F^{\mu\nu} F_{\mu\nu},
\end{aligned}
\tag{1}
$$

- $B$-sum is over the baryonic octet $B \equiv p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}$
- Meson fields include $\sigma$ meson, $\boldsymbol{\rho}_\mu$-meson and $\omega_\mu$-meson
- Leptons include electrons, muons and neutrinos for $T \neq 0$

# Fixing the couplings: nucleonic sector

Density dependent parametrization of couplings, no meson self-interactions:

$$g_{iN}(\rho_B) = g_{iN}(\rho_0)h_i(x), \qquad i=\sigma,\omega, \qquad h_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \tag{2}$$

$$g_{\rho N}(\rho_B) = g_{\rho N}(\rho_0)\exp[-a_\rho(x-1)]. \tag{3}$$

DD-ME2 parametrization of D. Vretenar, P. Ring et al. Phys. Rev. C 71, 024312 (2005).

| | $\sigma$ | $\omega$ | $\rho$ |
|---|---|---|---|
| $m_i$ [MeV] | 550.1238 | 783.0000 | 763.0000 |
| $g_{Ni}(\rho_0)$ | 10.5396 | 13.0189 | 3.6836 |
| $a_i$ | 1.3881 | 1.3892 | 0.5647 |
| $b_i$ | 1.0943 | 0.9240 | — |
| $c_i$ | 1.7057 | 1.4620 | — |
| $d_i$ | 0.4421 | 0.4775 | — |

Total number of parameters 8: boundary conditions on $h(x)$ at $x=1$.

# Fixing the couplings: hyperonic sector

Hyperon-vector mesons couplings: $SU(3)$-flavor symmetry and vector dominance model

$$g_{\Xi\omega} = \frac{1}{3} g_{N\omega}, \quad g_{\Sigma\omega} = g_{\Lambda\omega} = \frac{2}{3} g_{N\omega}. \tag{4}$$

$$g_{\Xi\rho} = g_{\rho N}, \quad g_{\Sigma\rho} = 2 g_{\rho N}, \quad g_{\Lambda\rho} = 0. \tag{5}$$

(Neglect heavy no strange mesons (for example $\phi$ exchanges).

Scalar $\sigma$-meson – hyperon couplings

$$g_{N\sigma} = \cos\theta_S \, g_1 + \sin\theta_S \, (4\alpha_S - 1) g_S/\sqrt{3}, \tag{6}$$

$$g_{\Lambda\sigma} = \cos\theta_S \, g_1 - 2\sin\theta_S \, (1 - \alpha_S) g_S/\sqrt{3}, \tag{7}$$

$$g_{\Sigma\sigma} = \cos\theta_S \, g_1 + 2\sin\theta_S \, (1 - \alpha_S) g_S/\sqrt{3}, \tag{8}$$

$$g_{\Xi\sigma} = \cos\theta_S \, g_1 - \sin\theta_S \, (1 + 2\alpha_S) g_S/\sqrt{3}. \tag{9}$$

# Inequalities for $\sigma$-meson couplings

For arbitrary underlying quark model we have

$$\boxed{2(g_{N\sigma} + g_{\Xi\sigma}) = 3g_{\Lambda\sigma} + g_{\Sigma\sigma}.} \tag{10}$$

e.g., for $SU(6)$ symmetric quark model $g_{\Xi\sigma} = (1/3)g_{N\sigma}$ and $g_{\Lambda\sigma} = g_{\Sigma\sigma} = (2/3)g_{N\sigma}$.

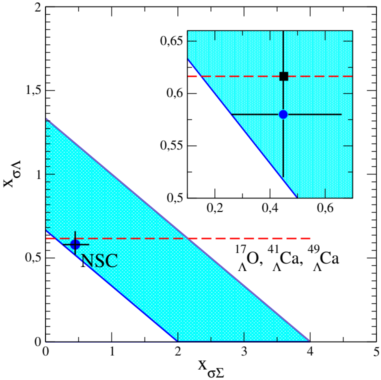
$$g_{\Xi\sigma} = \frac{1}{2}(3g_{\Lambda\sigma} + g_{\Sigma\sigma}) - g_{N\sigma}, \qquad 0 \leq g_{\Xi\sigma} \leq g_{N\sigma}, \tag{11}$$

$$\boxed{1 \leq \frac{1}{2}(3x_{\Lambda\sigma} + x_{\Sigma\sigma}) \leq 2x_{N\sigma}, \quad x_{i,\sigma} = \frac{g_{i\Sigma}}{g_{N\sigma}}} \tag{12}$$

Nijmegen soft-core potential implies that (Timmermans et al)

$$x_{\Lambda\sigma} = 0.58, \qquad x_{\Sigma\sigma} = 0.448. \tag{13}$$

# Parameter space

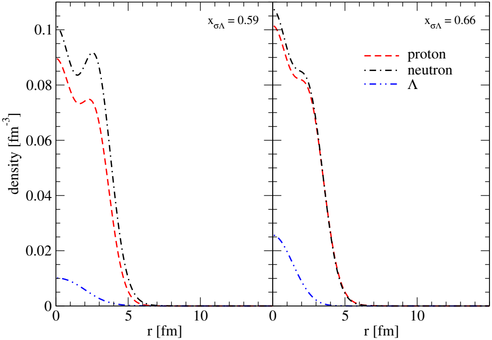



- Blue region - values allowed by the inequality
- NSC value – blue dot

| | $E_{Mass}[\Lambda\ 1s_{1/2}]$ [MeV] | $E[\Lambda\ 1s_{1/2}]$ [MeV] | $E/A$ [MeV] | $r_p$ [fm] | $r_n$ [fm] | $r_\Lambda$ [fm] |
|---|---|---|---|---|---|---|
| $^{17}_{\Lambda}O$ | −12.109 | −11.716 | −8.168 | 2.592 | 2.562 | 2.458 |
| $^{16}O$ | – | – | −8.001 | 2.609 | 2.579 | – |
| $^{41}_{\Lambda}C$ | −17.930 | −17.821 | −8.788 | 3.362 | 3.309 | 2.652 |
| $^{40}Ca$ | – | – | −8.573 | 3.372 | 3.320 | – |
| $^{49}_{\Lambda}Ca$ | −19.215 | −19.618 | −8.858 | 3.379 | 3.562 | 2.715 |
| $^{48}Ca$ | – | – | −8.641 | 3.389 | 3.576 | – |

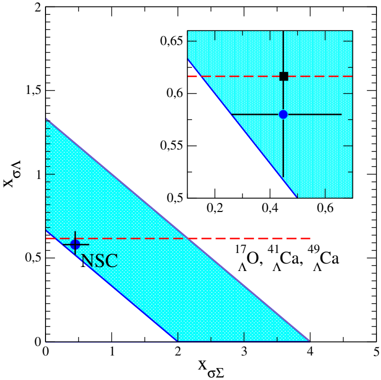
Table : Single-particle energies of the $\Lambda\ 1s_{1/2}$ states, binding energies, and rms radii of the $\Lambda$-hyperon, neutron, and proton of $^{17}_{\Lambda}O$, $^{41}_{\Lambda}C$, and $^{49}_{\Lambda}Ca$ are presented for optimal model. In addition, single-particle energies of the $\Lambda\ 1s_{1/2}$ states, i.e. separation energies of the $\Lambda$-particle, obtained from the mass formula are given for these $\Lambda$-hypernuclei. Furthermore, the properties of $^{16}O$, $^{40}Ca$, and $^{48}Ca$ are given for the optimal model; (van Dalen, Colucci, A. S., PLB 734, 383 (2014)).

# Density distribution of baryons



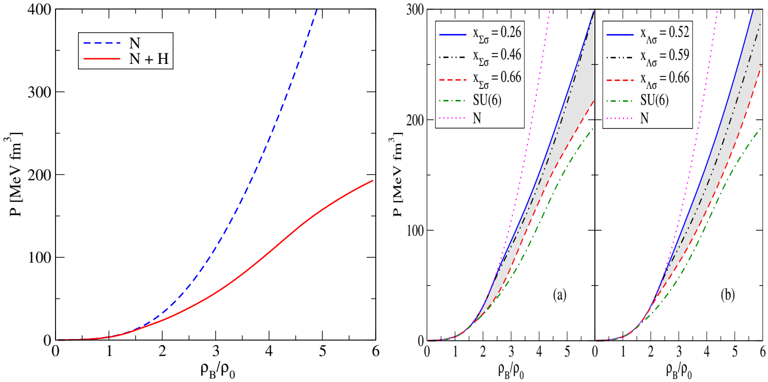

Proton (dashed), neutron (dashed dotted), and $\Lambda$ (dashed double dotted) density distributions in $^{49}_{\Lambda}$C for the models *b* (left panel) and *c* (right panel); (van Dalen, Colucci, A. S.l PLB 734, 383 (2014)).

# Parameter space



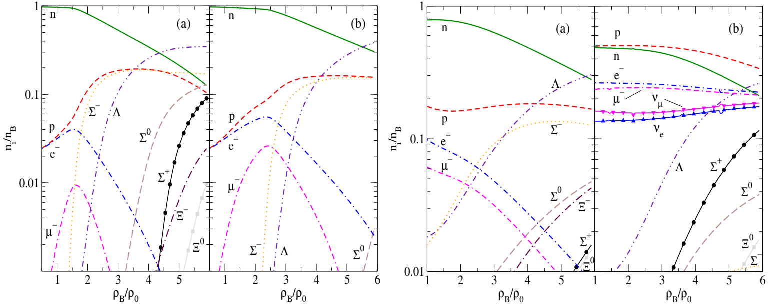

- Blue region - allowed by the inequality, NSC value - blue dot,
- red line - Λ-hypernuclei

# EOS Nuclear vs Hypernuclear Matter



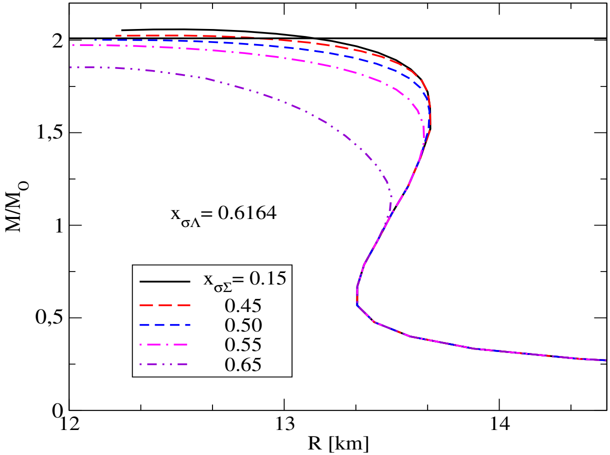

- Dashed (blue) - nuclear, full (red) - hypernuclear + variation of the scalar $\sigma$ meson - hypernuclear couplings.
- Parameters of nuclear functional: $\rho_0 = 0.152$ fm$^{-3}$, binding energy per nucleon $E/A = -16.14$ MeV, incompressibility $K_0 = 250.90$ MeV, symmetry energy $J = 32.30$ MeV, symmetry energy slope $L = 51.24$ MeV, and symmetry incompressibility $K_{sym} = -87.19$ MeV all taken at saturation density

# Abundances of hyperons



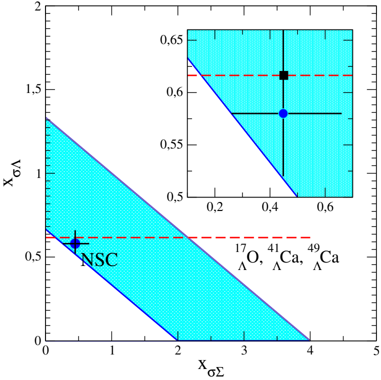

- Left panel: $T = 0$, soft vs hard EOS
- Right panel: $T = 50$ MeV, neutrino-less vs neutrino-full matter

# Mass vs Radius relationship




The solid (blue) lines show the cases $x_{\Sigma\sigma} = 0.26$ and $x_{\Lambda\sigma} = 0.58$ (upper panel) and $x_{\Sigma\sigma} = 0.52$ and $x_{\Lambda\sigma} = 0.448$ (lower panel). The (red) dots show the cases $x_{\Sigma\sigma} = 0.66$ and $x_{\Lambda\sigma} = 0.58$ (upper panel) and $x_{\Sigma\sigma} = 0.66$ and $x_{\Lambda\sigma} = 0.448$ (lower panel).

# Parameter space




- Blue region - allowed by the inequality, NSC value - the blue dot
- red line - Λ-hypernuclei,
- left of square (inset) along red line – constraint from stars
- Best values of parameters

$$x_{\sigma\Lambda} = 0.6164, \qquad 0.15 \leq x_{\sigma\Sigma} \leq 0.45. \tag{14}$$

# II. Quark Matter Equation of State for Compact Stars

# Quark phases

**Nambu-Jona-Lasinio Lagrangian:**

$$\begin{aligned}\mathcal{L}_Q &= \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_V(\bar{\psi}i\gamma^0\psi)^2 + G_S\sum_{a=0}^{8}[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2] \\ &+ G_D\sum_{\gamma,c}[\bar{\psi}^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta][(\bar{\psi}_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^8_\sigma] \\ &- K\left\{\det{}_f[\bar{\psi}(1+\gamma_5)\psi] + \det{}_f[\bar{\psi}(1-\gamma_5)\psi]\right\}, \end{aligned} \quad (15)$$

quark spinor fields $\psi^a_\alpha$, color $a = r, g, b$, flavor ($\alpha = u, d, s$) indices, mass matrix $\hat{m} = \mathrm{diag}_f(m_u, m_d, m_s)$, $\lambda_a$ $a = 1, ..., 8$ Gell-Mann matrices. Charge conjugated $\psi_C = C\bar{\psi}^T$ and $\bar{\psi}_C = \psi^T C$ $C = i\gamma^2\gamma^0$.

- $a$ sum is over the 8 gluons
- $G_S$ is the scalar coupling fixed from vacuum physics; $G_D$ is the scalar coupling, which is related to the $G_S$ via Fierz transformation
- $G_D$ is treated as a free parameter

# Quark phases

Pairing patterns: Order parameter

$$\Delta \propto \langle 0|\psi^a_{\alpha\sigma}\psi^b_{\beta\tau}|0\rangle$$

- Antisymmetry in spin $\sigma, \tau$ for the BCS mechanism to work
- Antisymmetry in color $a, b$ for attraction
- Antisymmetry in flavor to avoid Pauli blocking

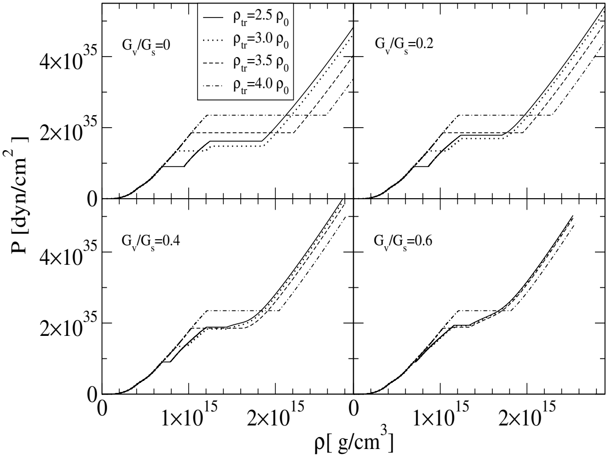
At low densities 2SC phase (Bailin and Love '84)

$$\Delta \propto = \Delta\epsilon^{ab3}\epsilon_{\alpha\beta}$$

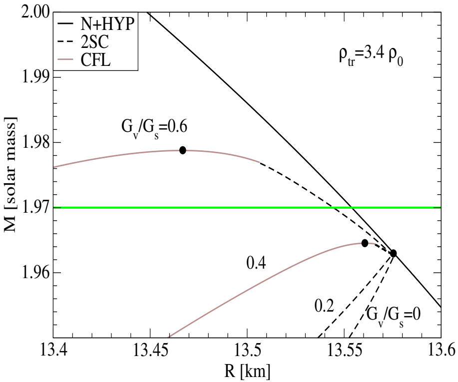
At high densities we expect 3 flavors of $u, d, s$ massless quarks. The ground state is the color-flavor-locked phase (Alford, Rajagopal, Wilczek '99)

$$\Delta \propto \langle 0|\psi^a_{\alpha L}\psi^b_{\beta L}|0\rangle = -\langle 0|\psi^a_{\alpha R}\psi^b_{\beta R}|0\rangle = \Delta\epsilon^{abC}\Delta\epsilon_{\alpha\beta C}$$

# EoS with equilibrium among nuclear, hyperonic, 2SC- and CFL-quark phases

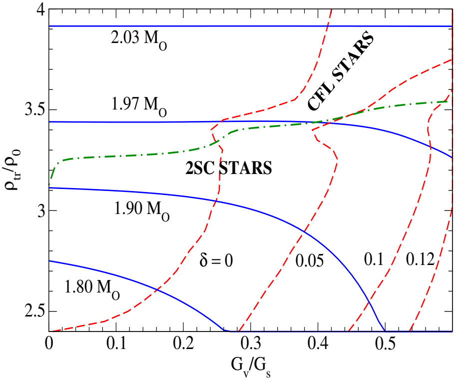


# Mass vs Radius relationship




- Dashed only 2SC, grey includes CFL.
- Stability is achieved for $G_V > 0.2$ and transition densities few $\rho_0$
- Left panel rapidly rotating stars

# Parameter space



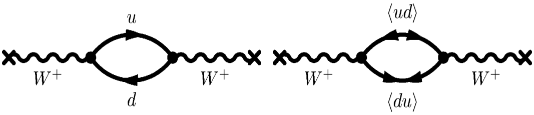

- Below dashed-dotted: 2SC stars are stable
- To the right of dashed curves CFL are stable few $\rho_0$

III. Non-standard (exotic) cooling of neutron stars

# Cooling processes in quark matter

Quark cores of NS emit neutrons via: $d \to u + e + \bar{\nu}_e \quad u + e \to d + \nu_e$. The rate of the process is

$$\epsilon_{\nu\bar{\nu}} \quad \propto \quad \Lambda^{\mu\lambda}(q_1, q_2) \Im \Pi^R_{\mu\lambda}(q).$$




(a) (b)

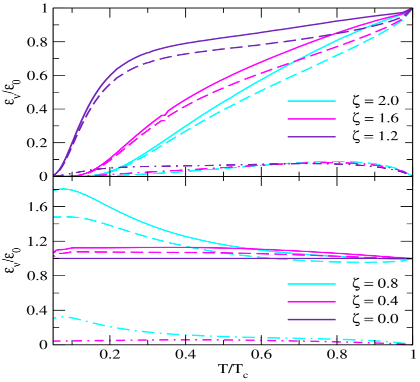
via the response function

$$\Pi_{\mu\lambda}(q) = -i \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[(\Gamma_-)_\mu S(p)(\Gamma_+)_\lambda S(p+q)\right], \quad \Gamma_\pm(q) = \gamma_\mu(1-\gamma_5) \otimes \tau_\pm$$

with propagators

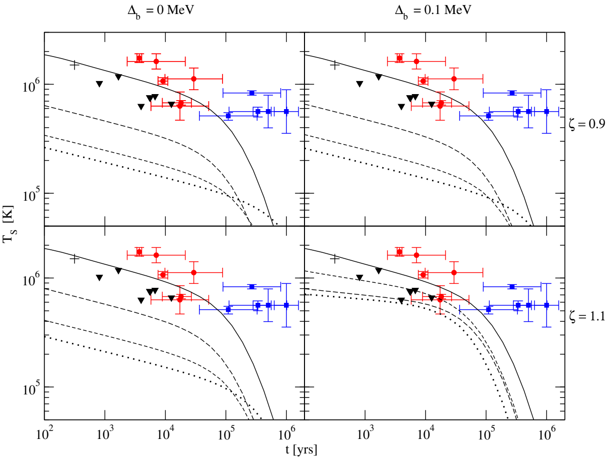
$$S_{f=u,d} = i\delta_{ab} \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}(\not{p} - \mu_f \gamma_0), \quad F(p) = -i\epsilon_{ab3}\epsilon_{fg}\Delta \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}\gamma_5 C$$

## CSC phases show non-trivial dependence on gap



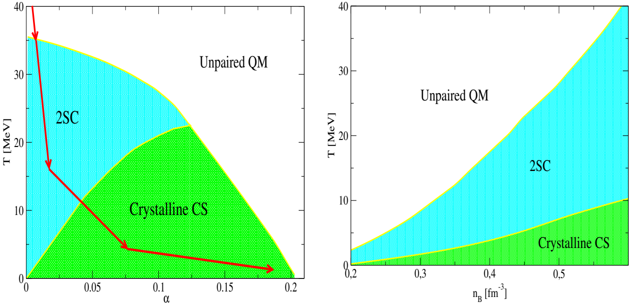

- Two-flavor phase (2SC) - No gapless excitations - suppressed emissivities
- Crystalline (LOFF) phase - Gapless excitations - unsuppressed emissivities

# Temperature evolution



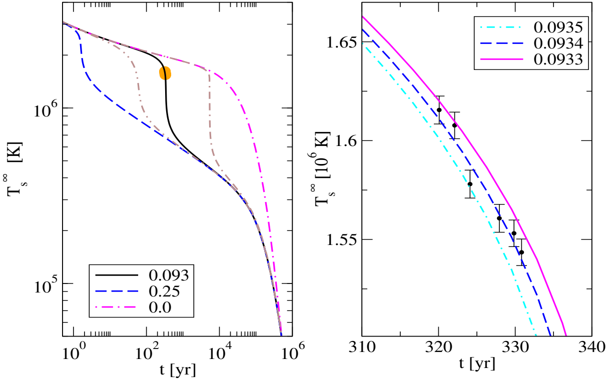

Cooling simulation of stars with quark matter cores, (D. Hess, A. Sedrakian, Phys. Rev. D 84, 063015 (2011))

# Phase diagram




- Can Cas A be a massive compact star with a quark core?
- Cas A cooling can be explained by a $1.4M_{\odot}$ star using as a cooling agent the pair-breaking processes.

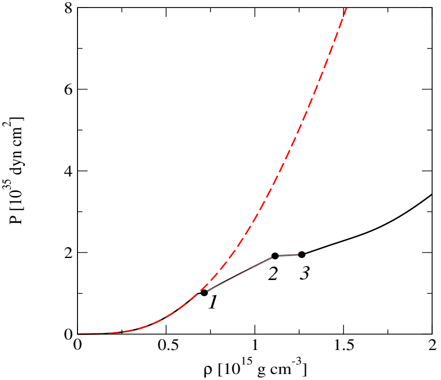
# CAS A: a cooling quark star?




- Two-parameter fit to the Cas A: $w$ - the width of the transition and $T^*$ the temperature of the transition
- The blue quark gap is a further parameter.

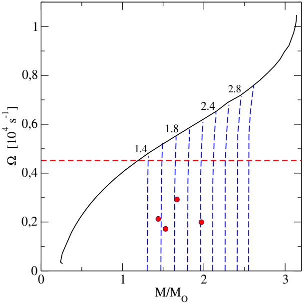
# IV. Rotation Induced Phase Transition to Color Superconducting State

## Improved equation of state: DD-ME2 +3f NJL model




Improves on Bonanno-Sedrakian (2012) by using more realistic nuclear equation of state (DD-ME2).

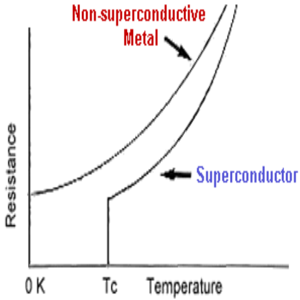
# Frequency vs mass for rapidly rotating stars

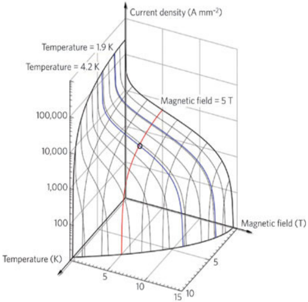


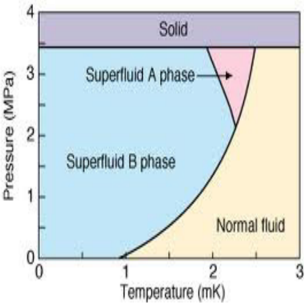

| Pulsar | $M/M_\odot$ | $P$(ms) |
|---|---|---|
| J1740 − 5340 | 1.53 ± 0.19 | 3.65 |
| J1903 + 0327 | 1.67 ± 0.01 | 2.15 |
| J1909 − 3744 | 1.44 ± 0.024 | 2.95 |
| J1614 − 2230 | 1.97 ± 0.04 | 3.15 |
| J1748 − 2446ad | − | 1.395 |

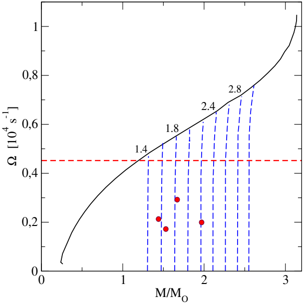
No constraints from rotation so far, but many more (millisecond)-pulsars will be observed 2.000 → 10.000 with the operation of SKA by 2020.

# A new path to (color) superconductivity

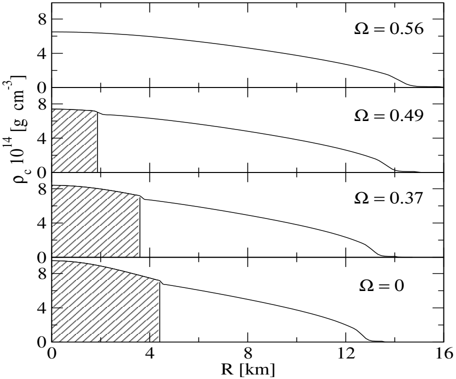


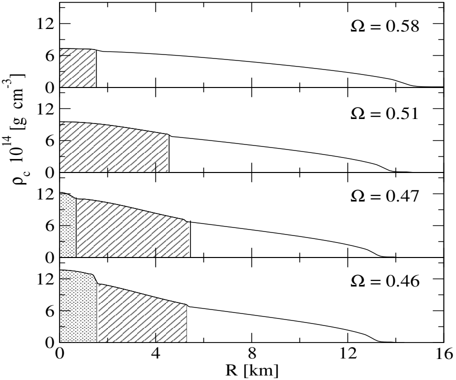



# Rotation induced phase transition to superfluid state




The star shrinks, density in the center increases overcoming the threshold for nucleation of color superconducting quark matter.

## Phase transition *within* the QCD phase diagram




For very massive stars there might be a phase transition between the two color superconducting phases of QCD: CFL $\rightarrow$ 2SC.

# Conclusions

Neutron stars with hyperonic cores are not excluded by currently available data.

Combined with the hypernuclear data we can constrain some of the couplings in hypernuclear sector.

Cas A behavior may be explained as a phase transition within the QCD phase diagram.

The core of decelerating or spinning-up star can undergo transition from and to superconducting quark matter.

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