ANL/JINA Workshop on the EoS and it's Application in Astrophysics 8/27/2008

Argonne NATIONAL LABORATORY

Thomas Klähn

Quark Matter in Compact Stars

- CS Constraints on the EoS
- Why Quark Matter?
- NJL-model results
- In Medium QCD – Dyson-Schwinger

Some Data

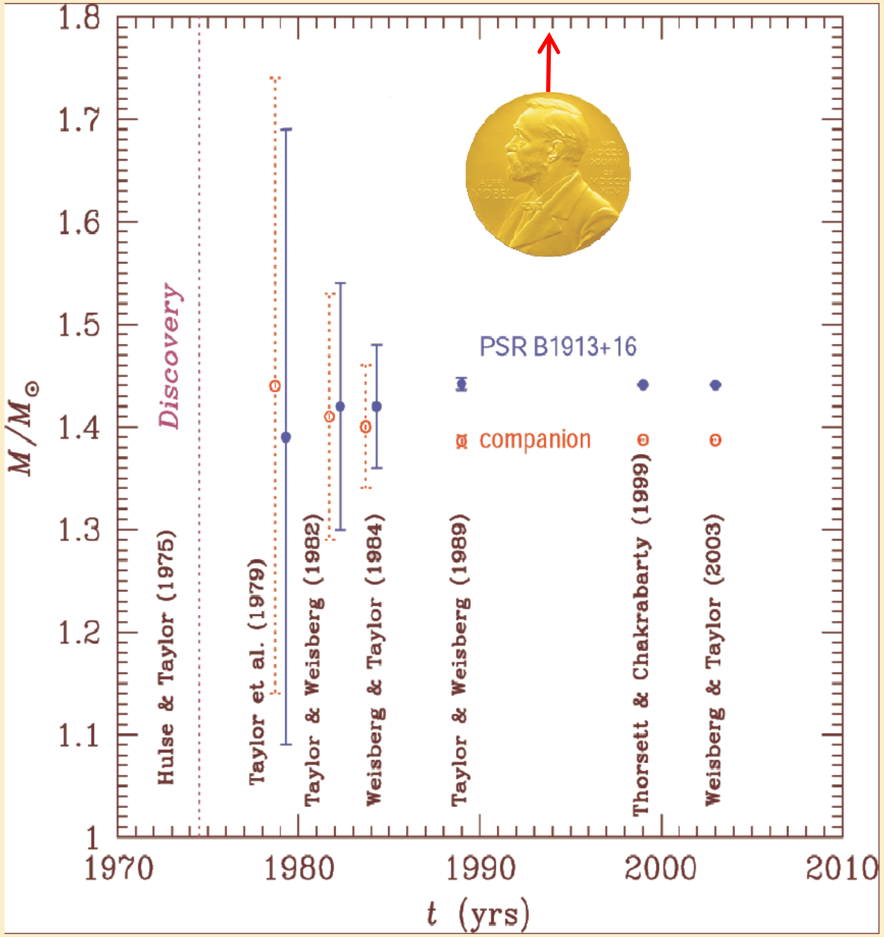
Masses $M \approx 1.35 M_{sun} \leq 2 M_{sun}$

Radii $R \geq 10\text{km}, \quad R_{\infty}^{max} \approx 17\text{km}$

Temperature /Age $T_S \approx 10^6\,\text{K} \quad \text{Age} = 0..10^6\,\text{yrs}$

Redshift $z \leq 0.8$

Rotation $P \propto \text{ms}\cdots\text{s}, \quad \dot{P} \propto 10^{-9}\cdots10^{-21}$



NEUTRON STAR SPREADSHEET

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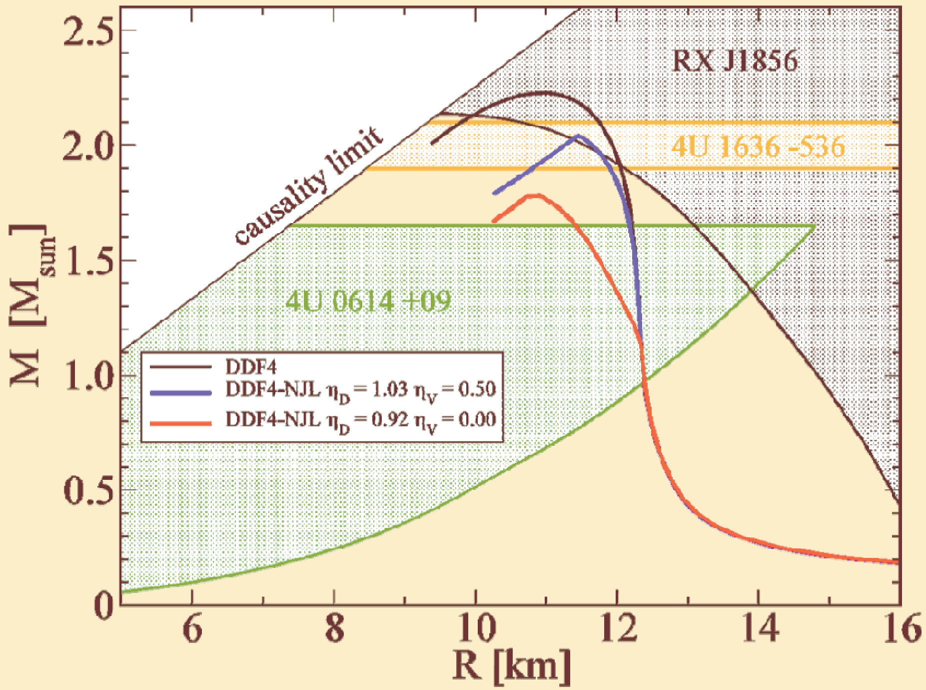

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T.K. et al., Phys.Lett.B **654**:170-176,2007.

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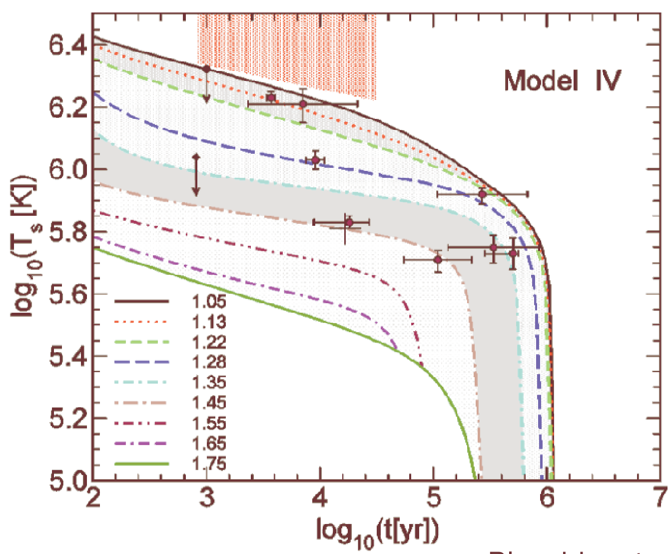

Blaschke et al. (2004)

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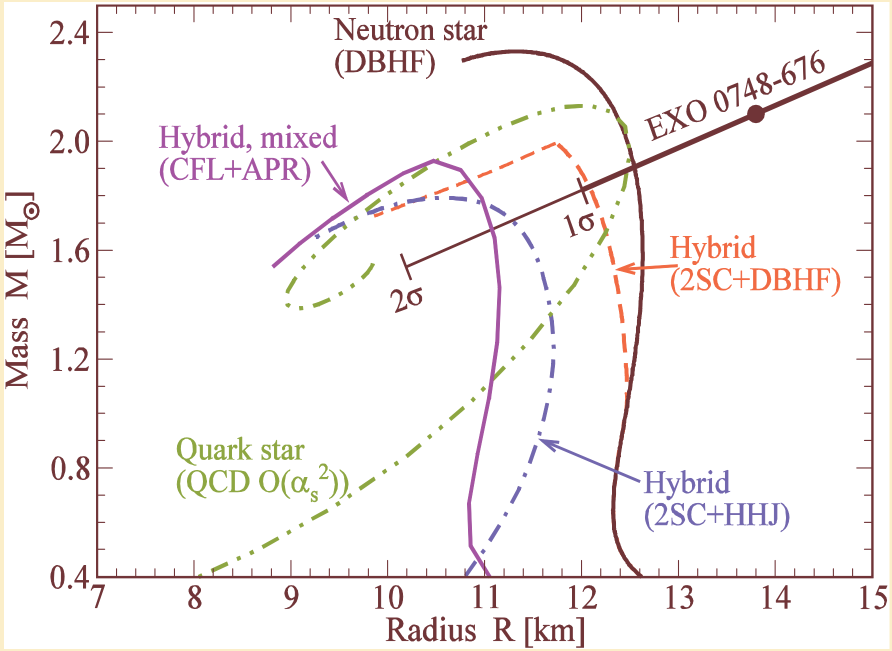

EXO 0748 z=0.35 ?

NEUTRON STAR SPREADSHEET

F.Özel Nature 441 (2006), Alford et al. Nature 445 (2007)

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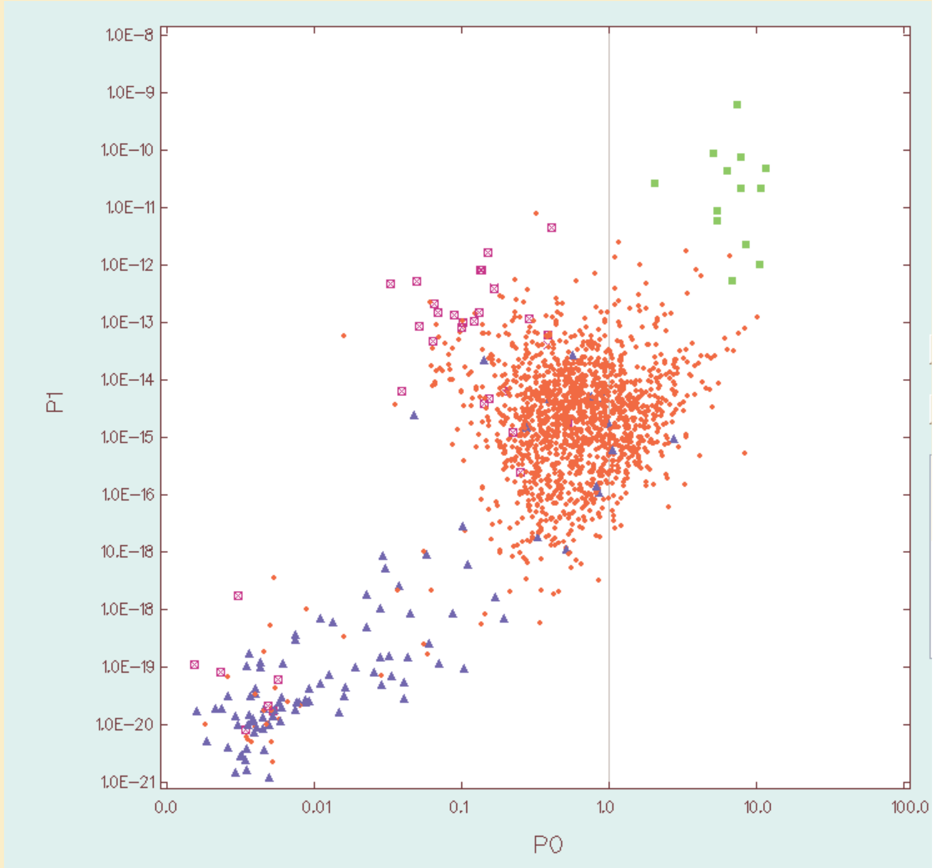

Optimum: Have all these data available for as many CS's as possible

ATNF Pulsar Database
http://www.atnf.csiro.au/research/pulsar/psrcat/

NEUTRON STAR SPREADSHEET

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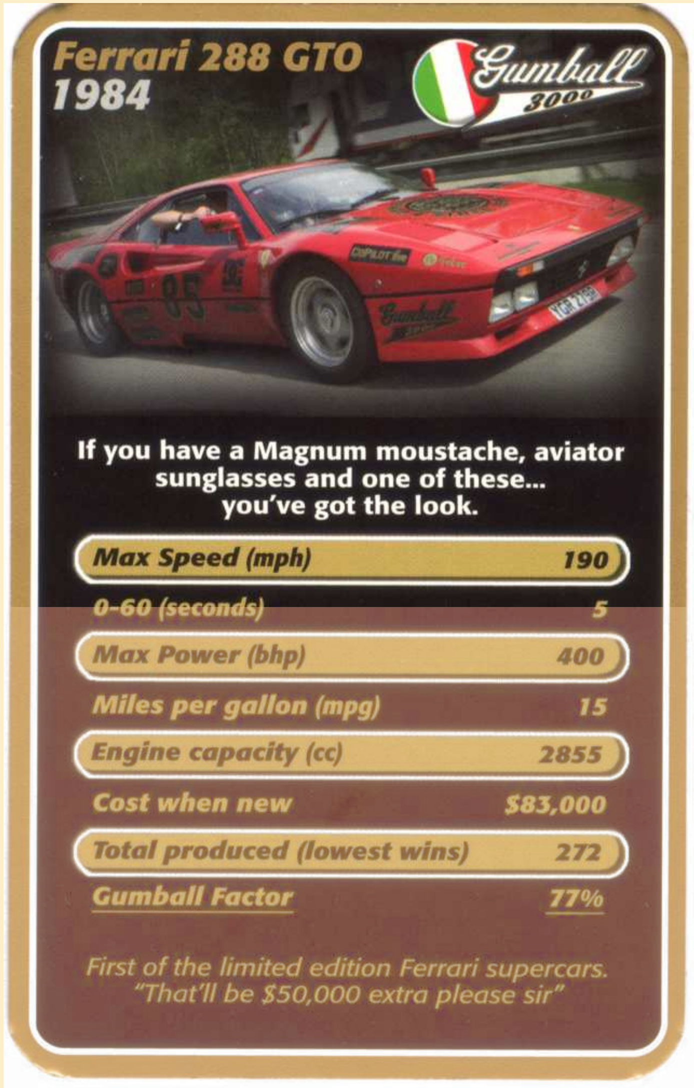

NEUTRON STAR SPREADSHEET

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Masses	$M \approx 1.35 M_{sun} \leq 2 M_{sun}$
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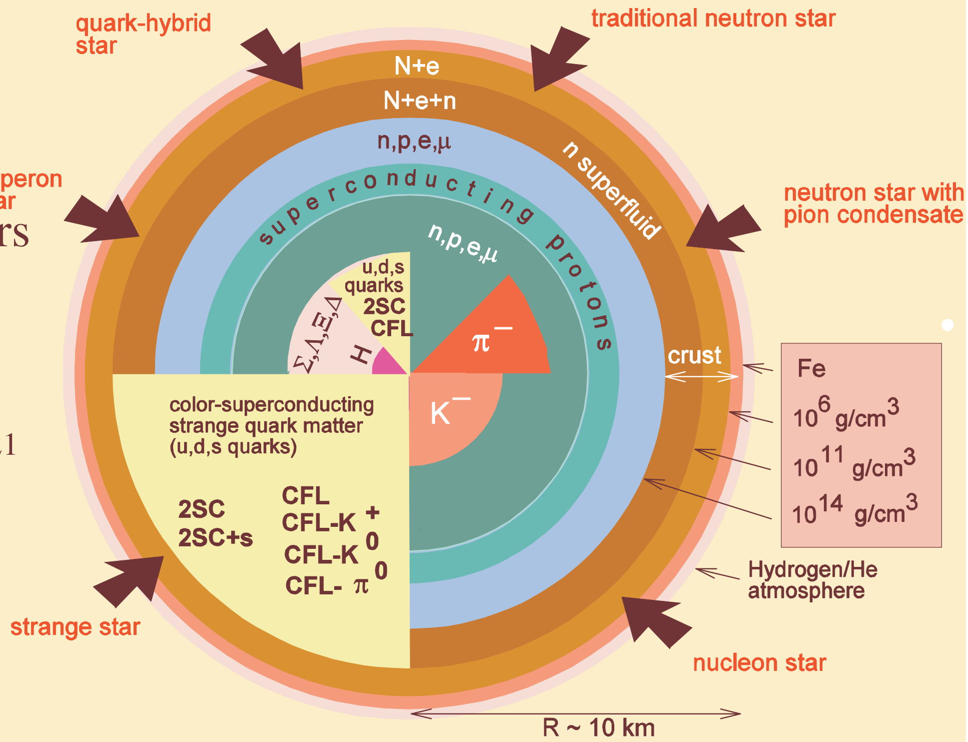

F. Weber

Much more to investigate:

- magnetic fields, T-profiles, composition
- Evolution and Dynamics
- Accretion, Binary Systems

Theorist‘s input might vary – nature‘s doesn‘t

NEUTRON STAR SPREADSHEET

- The QCD Phase Diagram
- Masquerade
- Compact Star Evolution
  - Cooling
  - Rotation

WHY TO LOOK FOR QUARK MATTER IN COMPACT STARS

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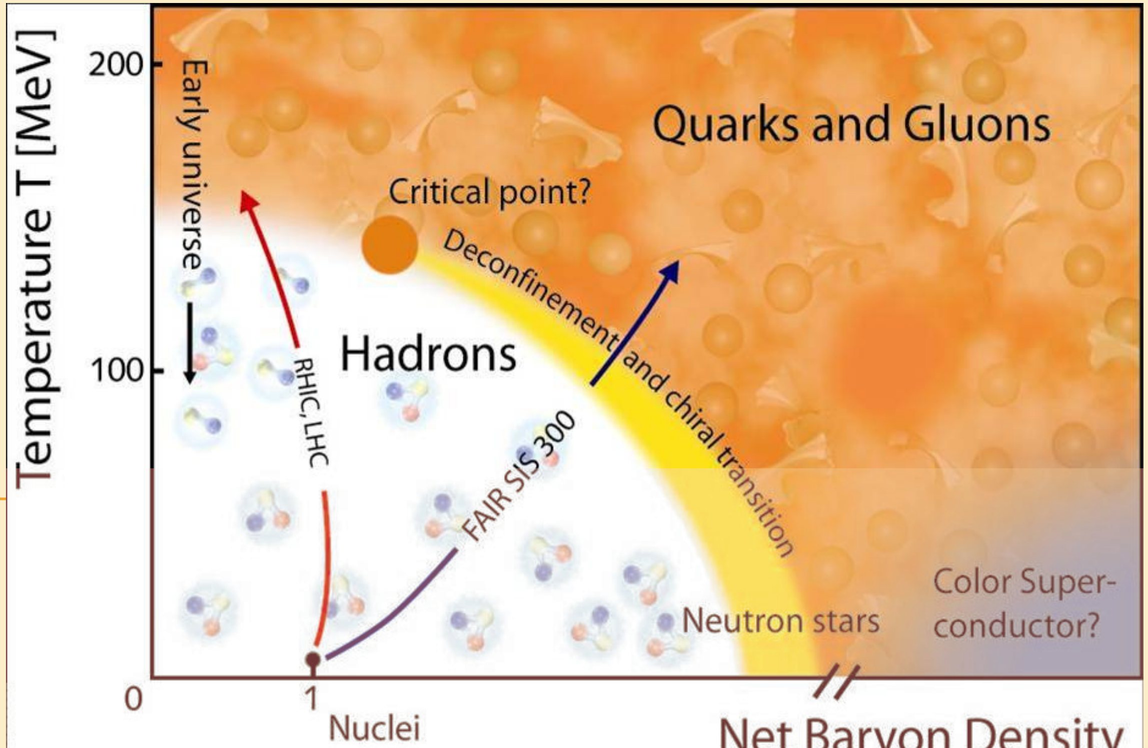

www.gsi.de

- cold, asymmetric matter
- nature of phase transition
- superconducting phases

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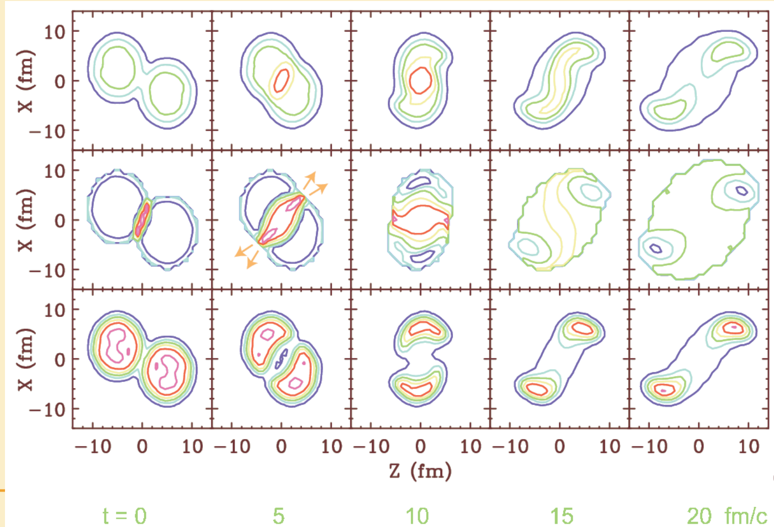
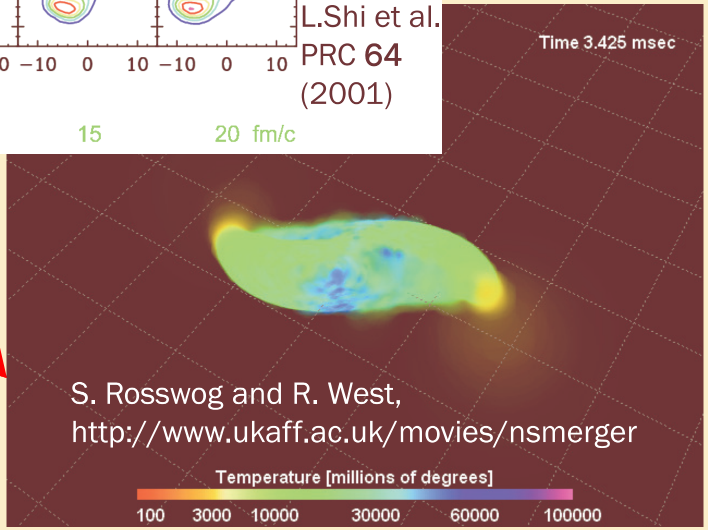


L.Shi et al. PRC **64** (2001)



S. Rosswog and R. West, http://www.ukaff.ac.uk/movies/nsmerger

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- superconducting phases

→ <u>natural HIC complement</u>

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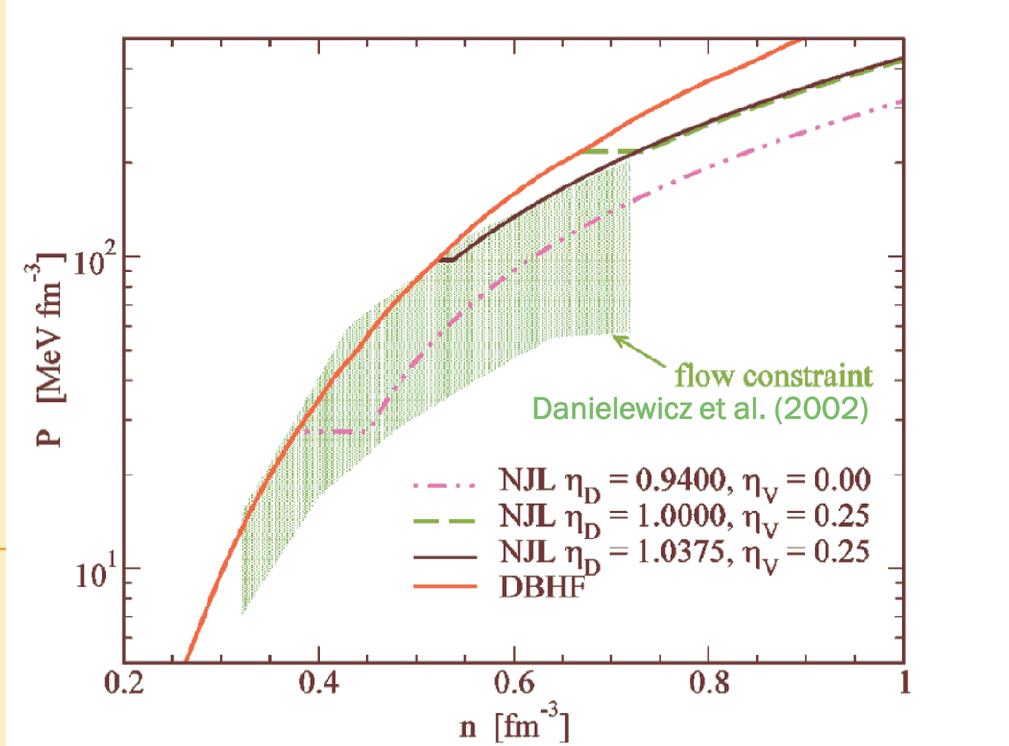

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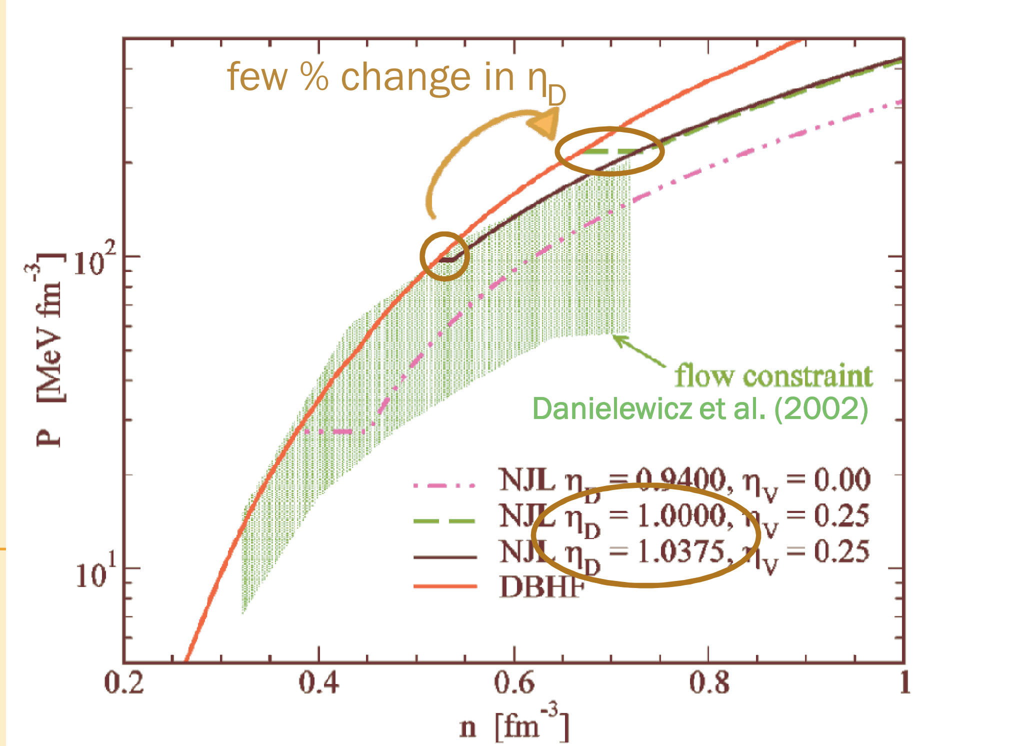

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WHY TO LOOK FOR QUARK MATTER IN COMPACT STARS

- The QCD Phase Diagram
- Masquerade Alford et al., APJ 629, 969 (2005)
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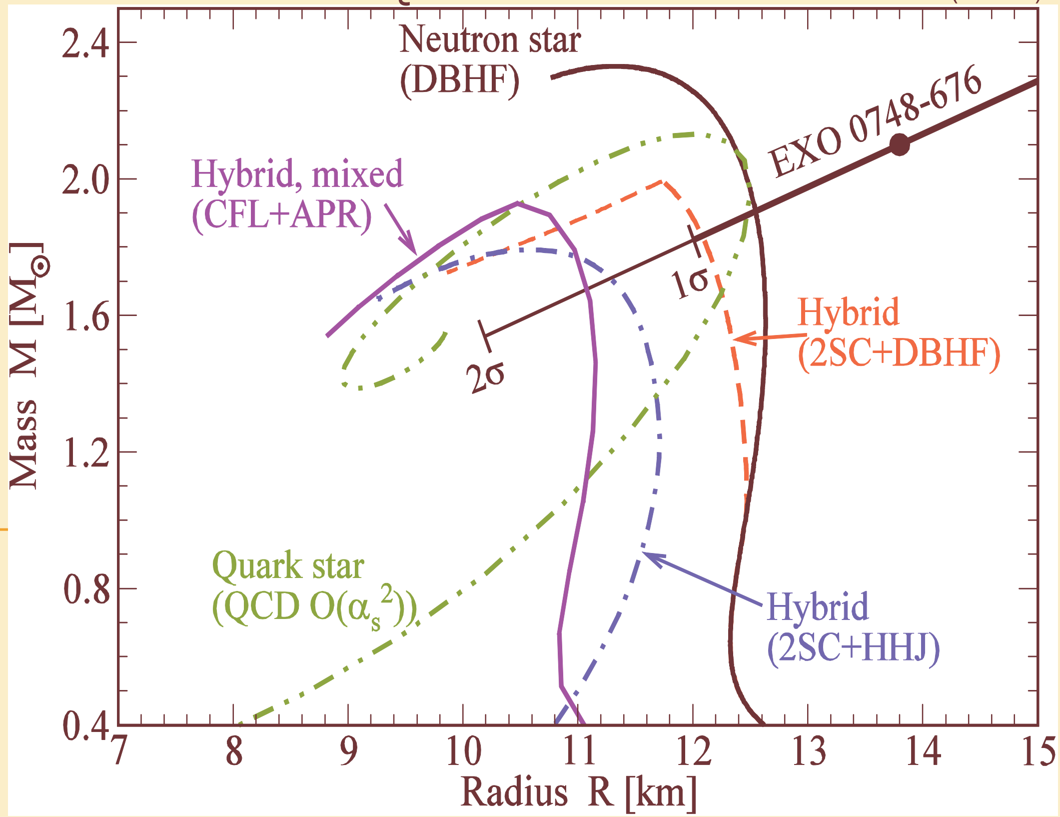
EXO constraint: no QM in CSs? F.Özel Nature 441 (2006)



Alford et al., Nature 445:E7-E8,2007

- no contradiction
- no (easy) distinction

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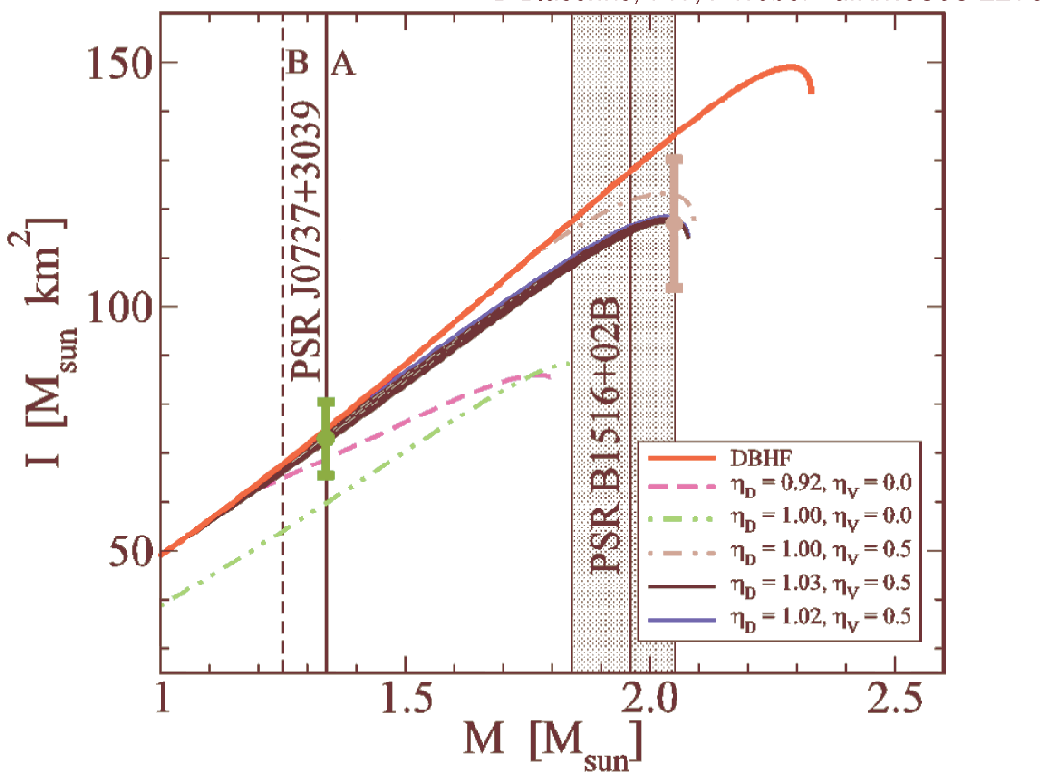
D.Blaschke, T.K., F.Weber - arXiv:0808.1279



MoI, M, R, z - QM affects high massive CSs only

- no contradiction
- no (easy) distinction

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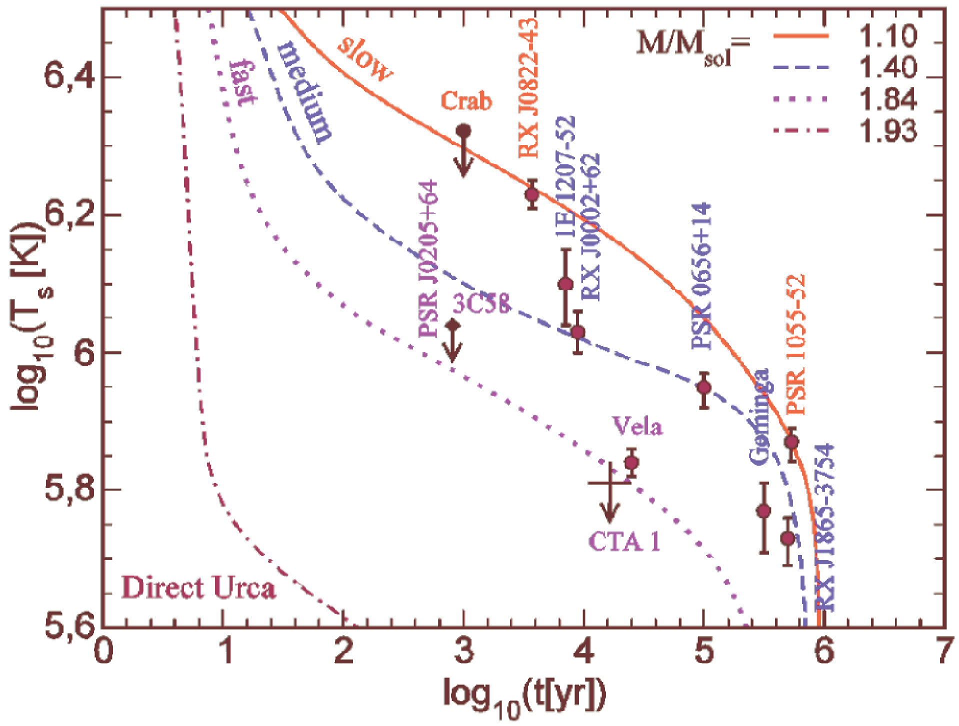

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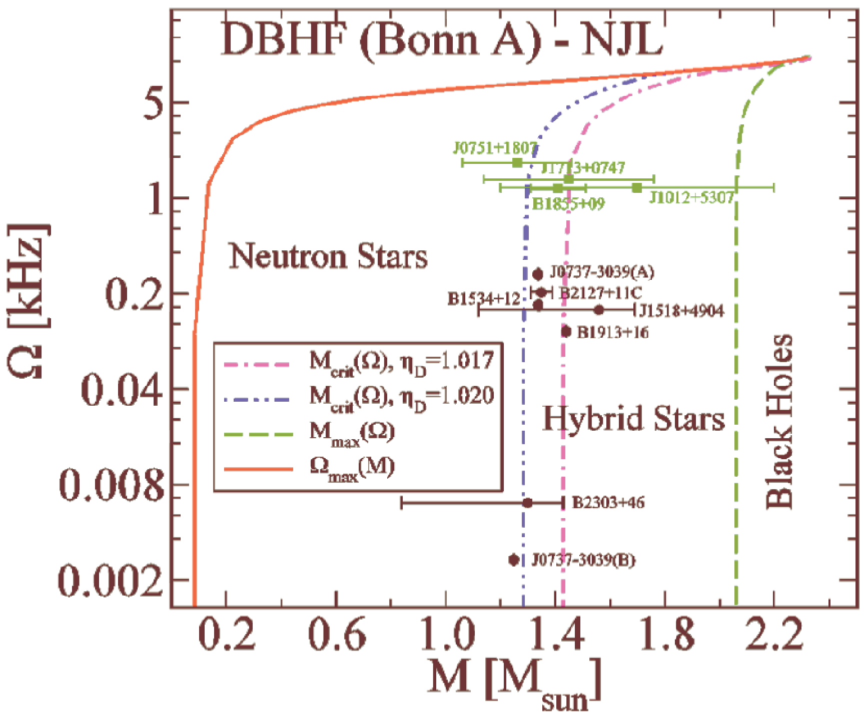
Poghosyan, Grigorian, Blaschke , Astrophys.J.551:L73 (2001)
Blaschke, Poghosyan, Grigorian (in preparation)



Accreting Neutron Stars: Waiting Point at Phase Transition?

WHY TO LOOK FOR QUARK MATTER IN COMPACT STARS

Describing hadrons as quark bound states is a challenge! Solve QCD at finite densities...

Traditional approach: model nuclear and quark matter independently

⟹ two-phase (Maxwell/Gibbs)-construction: physically realised phase... minimum t.-d. potential

Both phases are β-equilibrated : $\mu_n = \mu_p + \mu_e$ $\mu_d = \mu_u + \mu_e$

Both phases are charge neutral : $0 = n_p - n_e$ $0 = \frac{2}{3} n_u - n_e - \frac{1}{3} n_d$

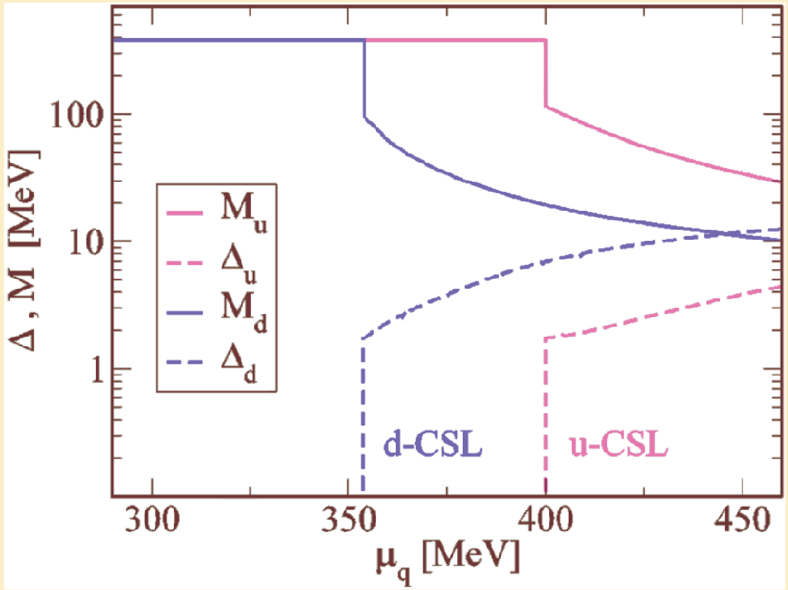
NJL model study:

There is no neutral quark flavor

⟹ despite $\mu_d \geq \mu_\chi$ d-quarks not realized

u-quarks required to neutralize QM-phase

D. Blaschke, F. Sandin, T.K., J. Berdermann
J. Phys. G: Nucl. Part. Phys. In press (2008)
[arXiv:0807.0414]



THE QUARK-HADRON PHASE TRANSITION

Another point of view

D. Blaschke, F. Sandin, T.K., J. Berdermann

J. Phys. G: Nucl. Part. Phys. In press (2008) [arXiv:0807.0414]

Nucleonic matter ... n,p,e

n, p as QM-boundstates → mixed phase?

conditions for β-equilibrium: $\mu_n = 2\mu_d + \mu_u$

$\mu_p = 2\mu_u + \mu_d$

global charge neutrality $\sum_{i=p,e,u,d} Q_i n_i = 0$

in particular: protons (+1) ↔ d-quarks (-1/3)

Sequential ‚deconfinement‘:

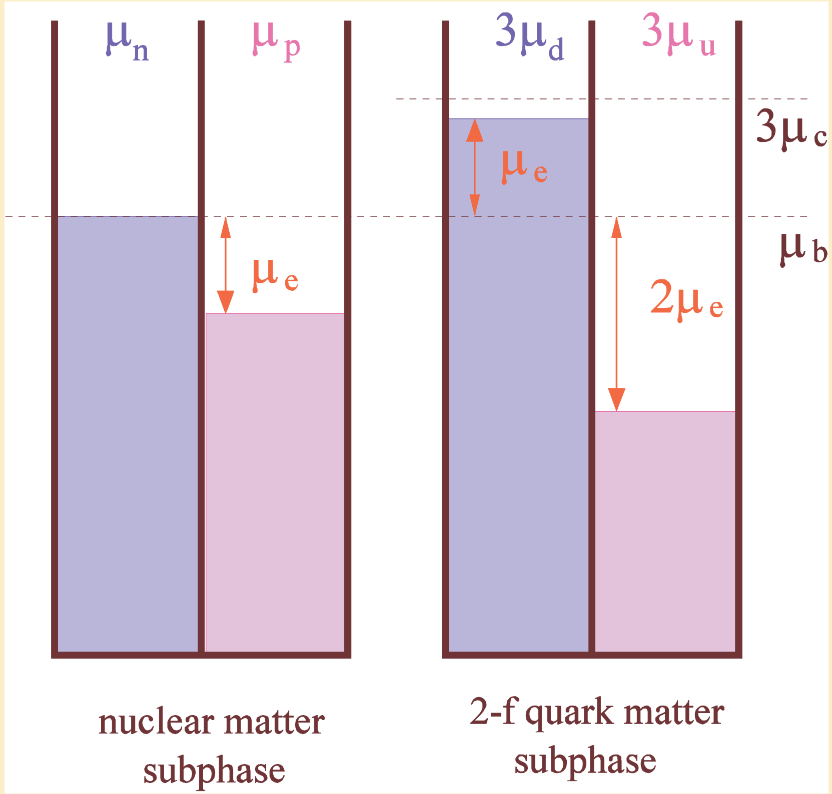
analogous to the dissociation of nuclear clusters

⟹ d-quark drip line

mixture of nucleons and 1f d-quark-matter

Pre-condition: $\mu_e \geq 0$ (asymmetry driven effect!)

$x_p^{crit} < 0.2$



$\mu_n = \mu_p + \mu_e$ $\mu_d = \mu_u + \mu_e$

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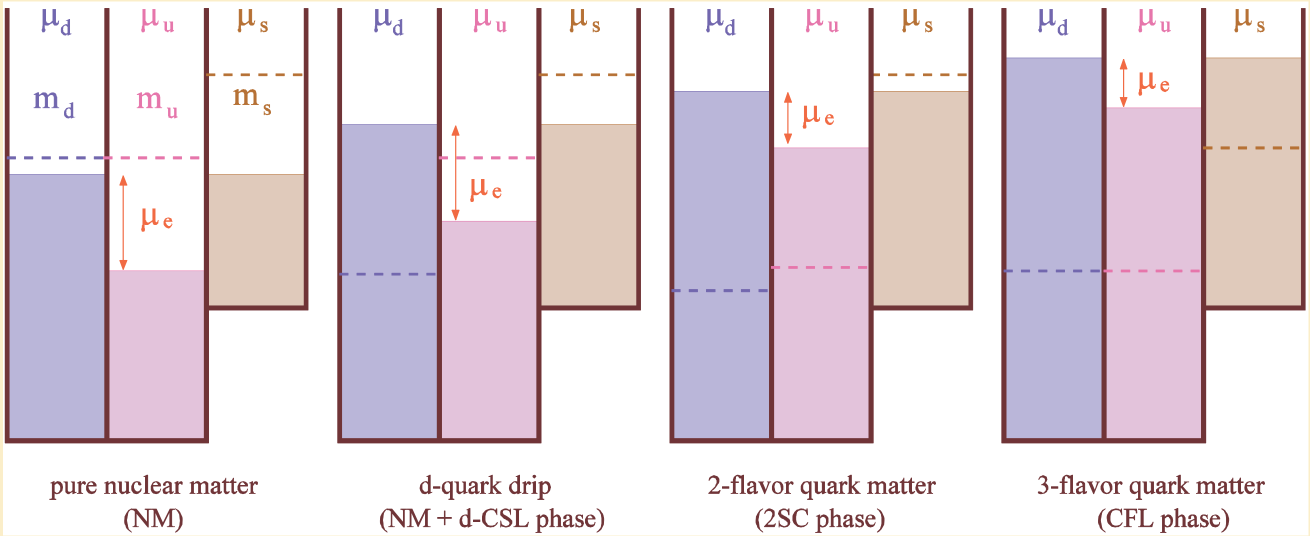

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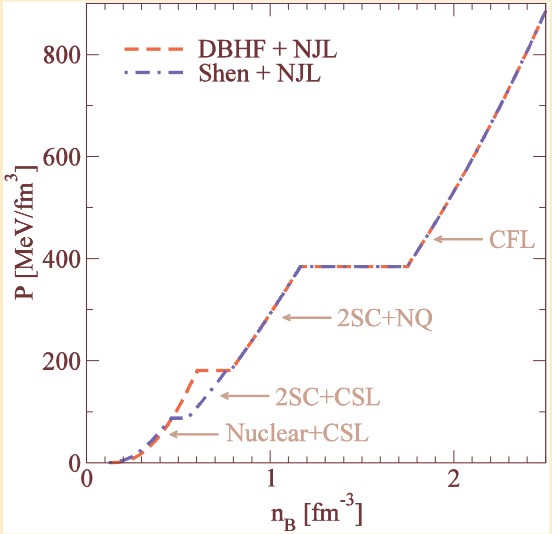
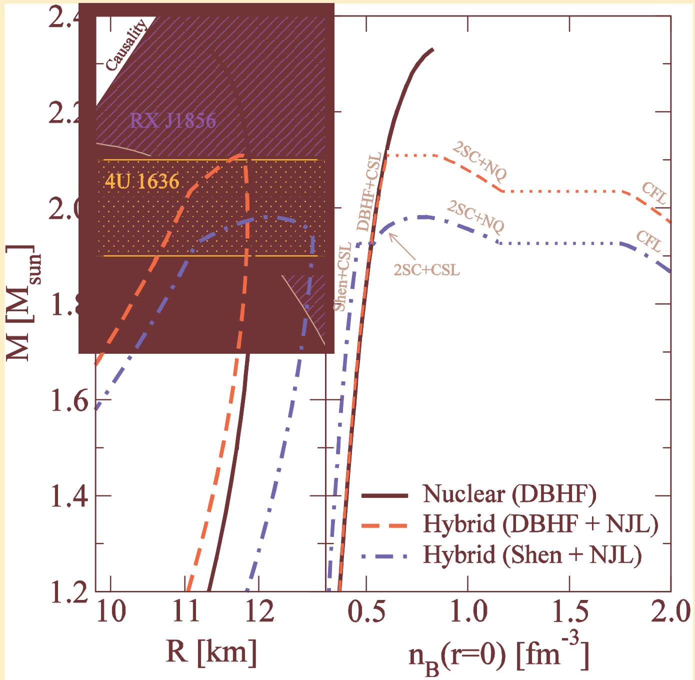


Actual sequence depends on nuclear EoS

In any case...
Large Masses and Radii



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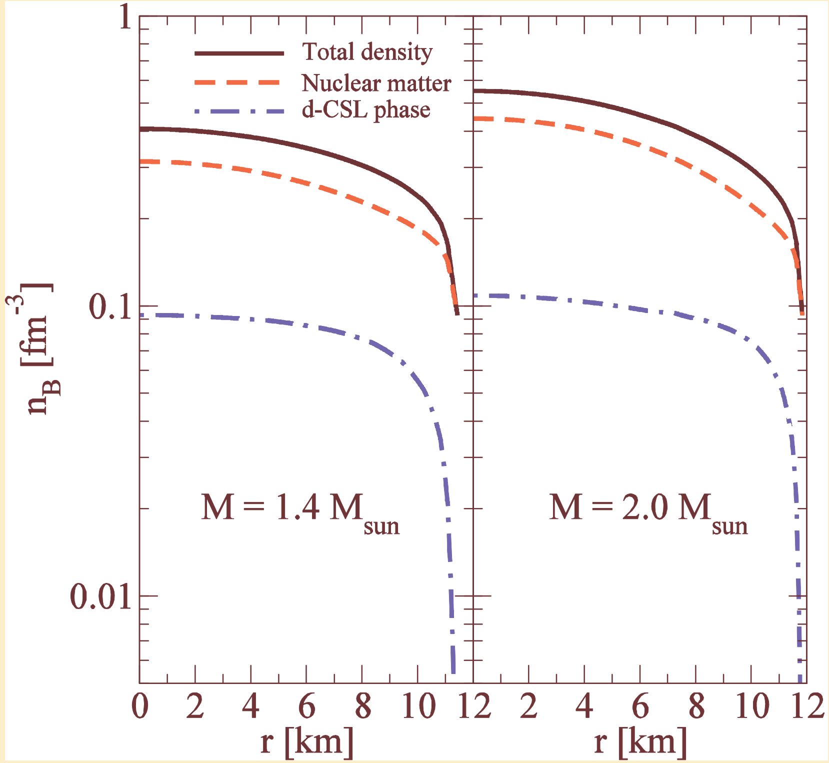
Density profiles: *1f-d-QM basically everywhere!*

Superbursts?

Caveats:
- surface tension, Coulomb force
- DS : CFL energetically prefered *Nickel et al.*(2008)
- mixture of quarks and nucleons? NJL is chiral model. Confinement?
- and still... no consistent picture



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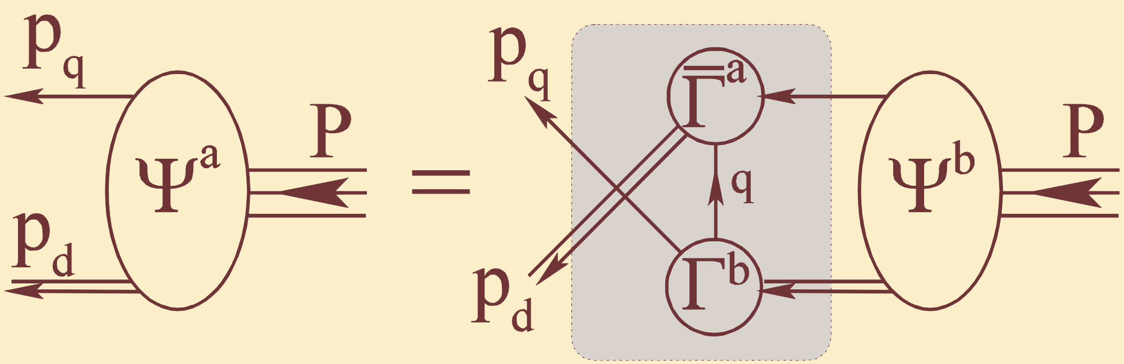
THE QUARK-HADRON PHASE TRANSITION

HADRONS AS QUARK BOUNDSTATES

Problem is not unknown

Faddeev Equations



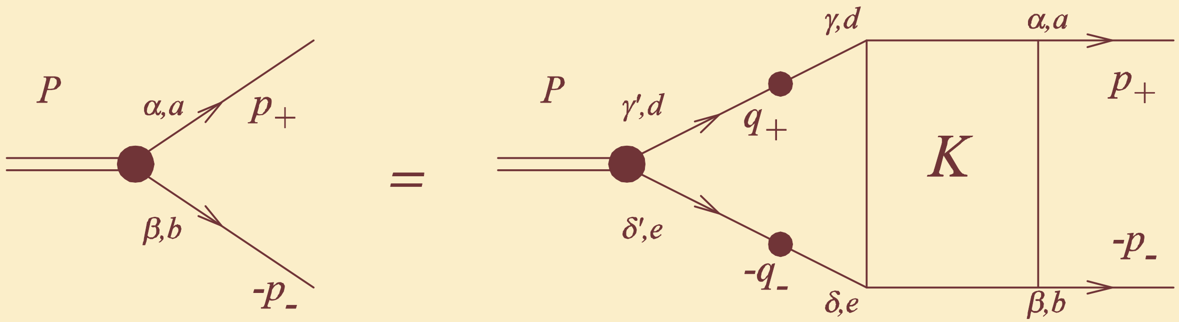
Cloet et al. (2008)
Current quark mass dependence of nucleon magnetic moments and radii

Eichmann et al. (2008)
The nucleon as a QCD bound state in a Faddeev approach.

Baryons as composites of confined quarks and diquarks

$\longrightarrow$ q-propagator, $\Longrightarrow$ d-propagator, Γ Bethe-Salpeter-Ampl., Ψ Faddeev Ampl.

Bethe Salpeter Equations



P. Maris (2002)
Effective masses of diquarks.

Bhagwat et al. (2007)
Flavour symmetry breaking and meson masses

Inverse Quark Propagator:

$$S(p;\mu)^{-1} = Z_2(\underbrace{i\,\vec{\gamma}\vec{p} + i\,\gamma_4 p_4}_{=i\,\gamma p} \underset{\downarrow}{+ i\mu} + m_{\rm bm}) + \Sigma(p;\mu)$$

revokes Poincaré covariance

Renormalised Self Energy:

$$\Sigma(p;\mu) = Z_1 \int_q^\Lambda g^2(\mu) D_{\rho\sigma}(p-q;\mu) \frac{\lambda^a}{2} \gamma_\rho S(q;\mu) \Gamma_\sigma^a(q,p;\mu)$$

Loss of Poincaré covariance increases complexity of propagator...

General Solution:

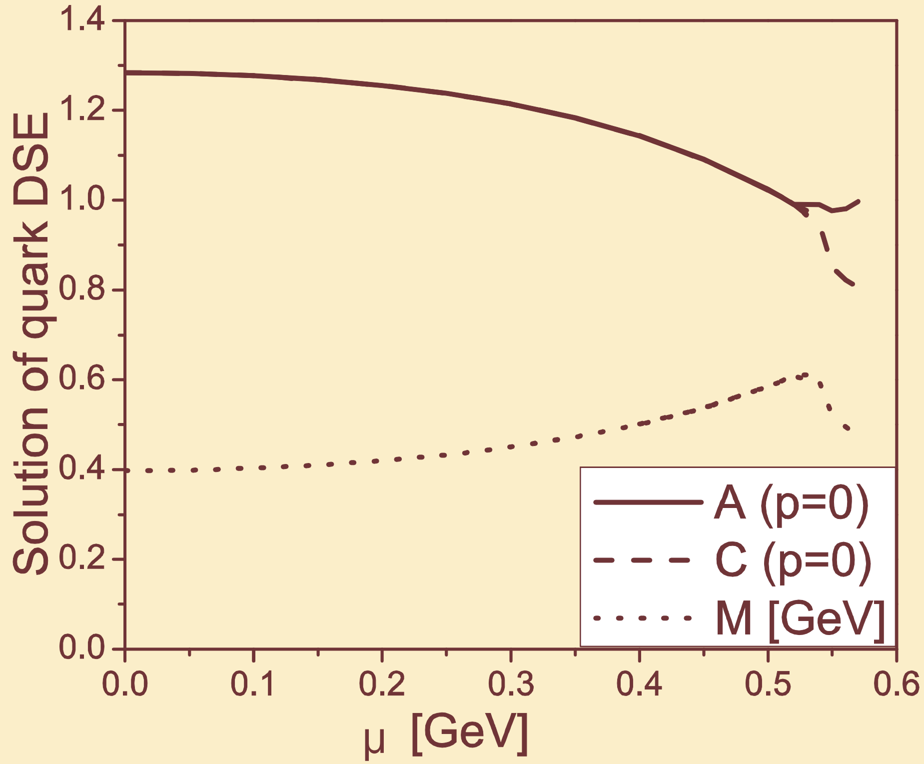
$\mu = 0$ $\quad S(p^2)^{-1} = i\,\gamma p\, A(p^2) + B(p^2)$ $\quad S(p^2) = i\,\gamma p\, \sigma_A(p^2) + \sigma_B(p^2)$

$\mu \neq 0$ $\quad S(p^2, p_4;\mu)^{-1} = i\,\vec{\gamma}\vec{p}\, A(p^2, p_4, \mu) + i\,\gamma_4(p_4 + i\mu)\, C(p^2, p_4, \mu) + B(p^2, p_4, \mu)$

$S(p^2, p_4;\mu) = \ldots$

1. One more Gap
2. Gaps depend on energy and chemical potential

IN MEDIUM QCD



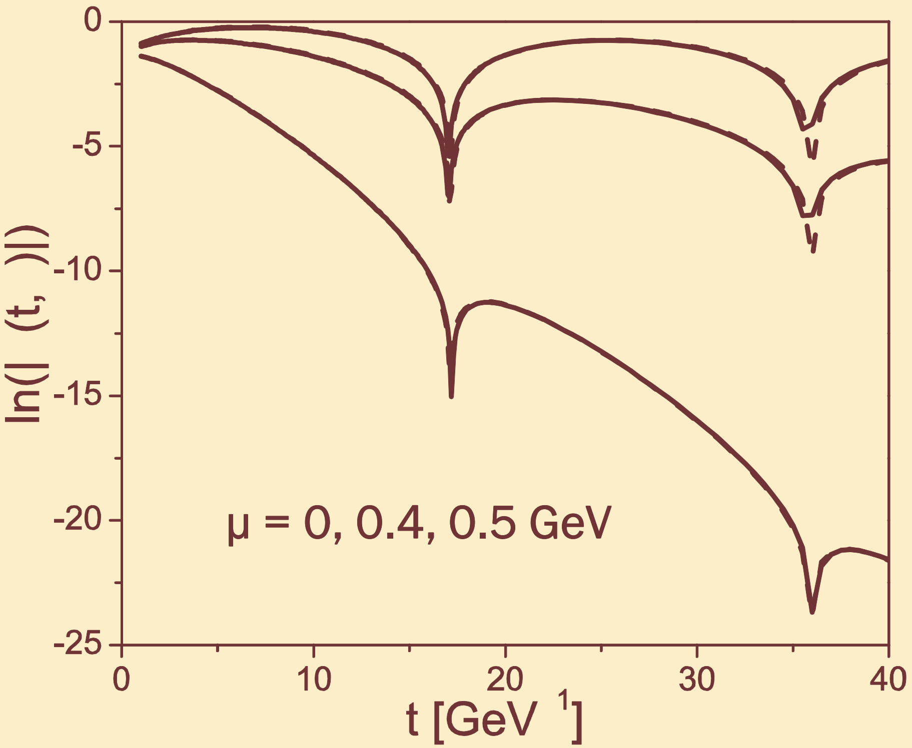
Result for μ < 0.53 GeV

- A = C
- M= B/A increases monotonically

What happens at 0.53 GeV ?

IN MEDIUM QCD

H. Chen, W. Yuan, L. Chang, Y.-X. Liu, T.K., C.D. Roberts arXiv:0807.2755



Schwinger Function

$$\Delta(\tau,\mu)=\int \frac{d^4p}{(2\pi)^4}\exp(i\vec{p}\vec{x}+ip_4\tau)\delta(p)\sigma_B(p,\mu)$$

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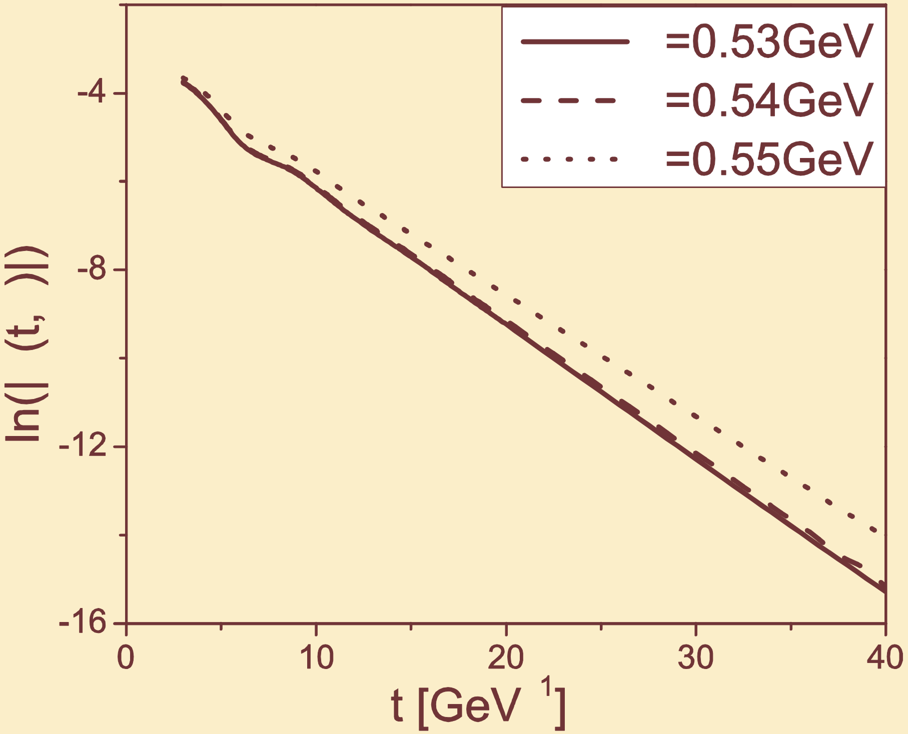

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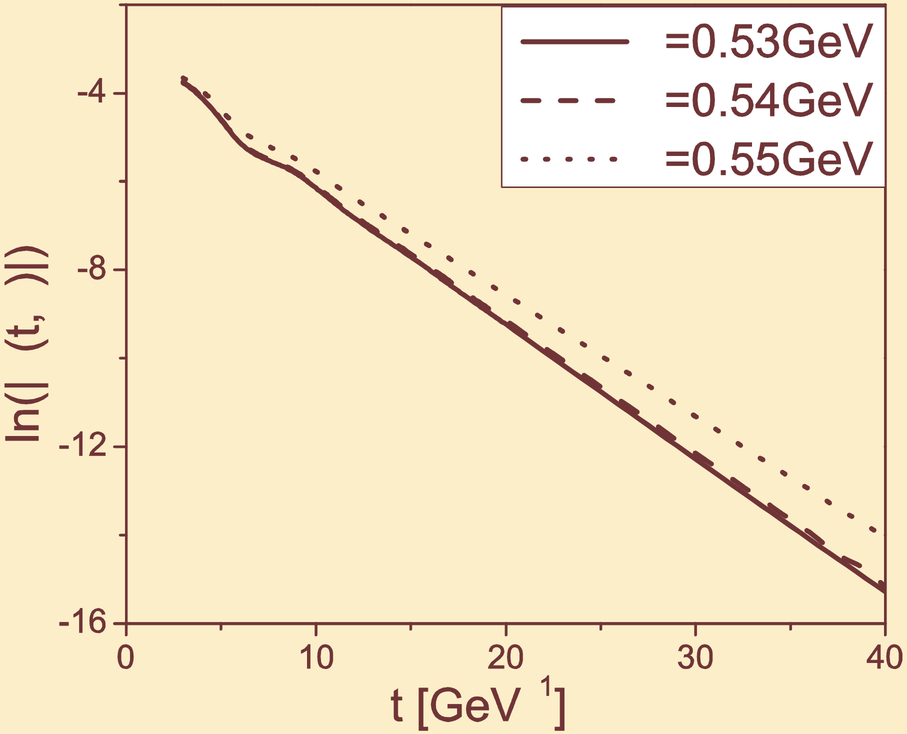

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Mass pole expansion

$$S_N(p)=\sum_{i=1}^{N}\frac{r_i}{2}\left(\frac{1}{i\gamma p+z_i}+\frac{1}{i\gamma p+z_i^*}\right)$$

$$\Delta_N(\tau,\mu)=\sum_{i=1}^{N}\frac{r_i}{2}e^{-(\Re(z_i)-\mu)\tau}\cos\left(\Im(z_i)\tau\right)\theta\left(\Re(z_i)-\mu\right)$$

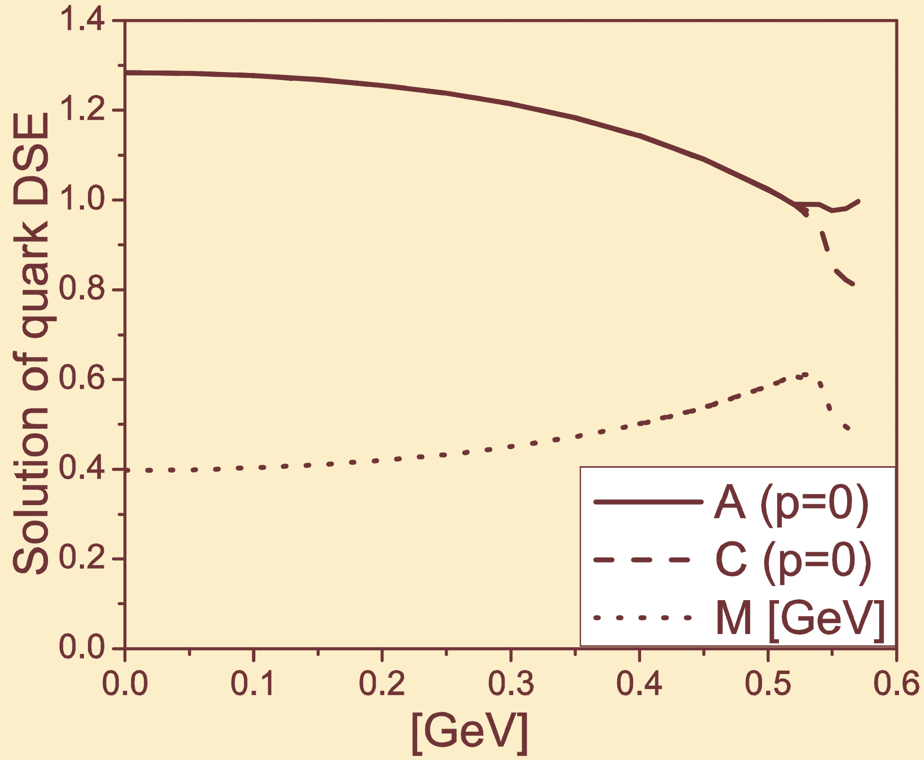
$$z_1=(0.53+i\,0.17)\text{ GeV}$$

$$z_2=(0.82+i\,0.00)\text{ GeV}$$

↑

inverse lifetime ... deconfinement

H. Chen, W. Yuan, L. Chang, Y.-X. Liu, T.K., C.D. Roberts arXiv:0807.2755



Deconfinement for μ > 0.53 GeV

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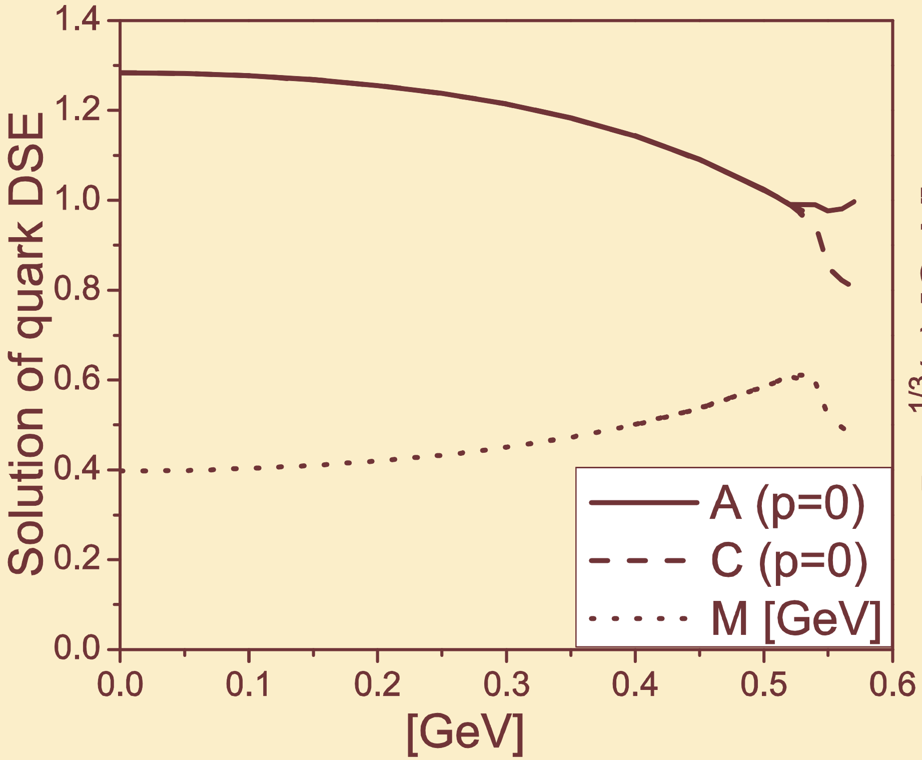

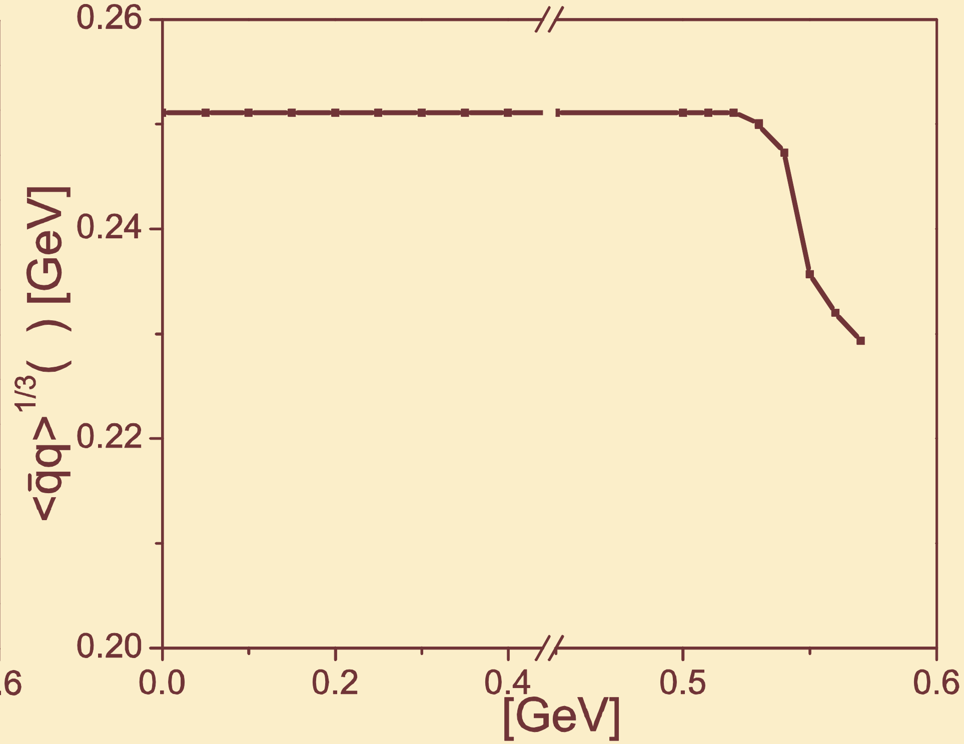

Deconfinement for μ > 0.53 GeV

Melting of Vacuum Quark Condensate:

$$-\langle\bar{q}q\rangle_{\zeta}^{0} = N_c Z_4 \int \frac{d^4p}{(2\pi)^4} \mathrm{tr}_D S(p;\mu)$$

... Wigner Phase: $B \equiv 0 \Rightarrow \mathrm{tr}_D S(p;\mu) = 0$

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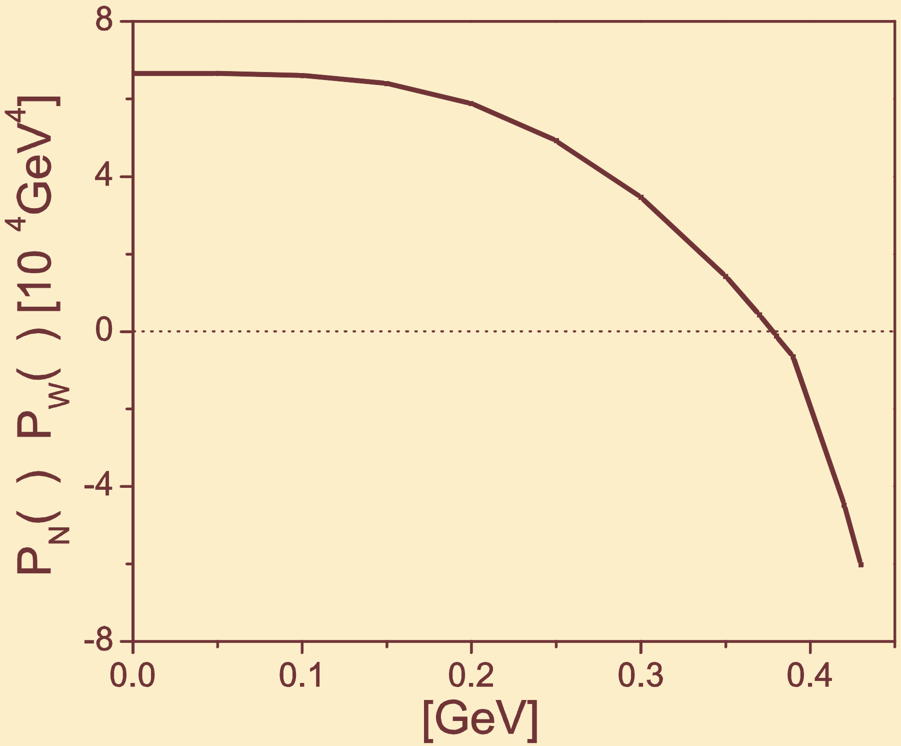
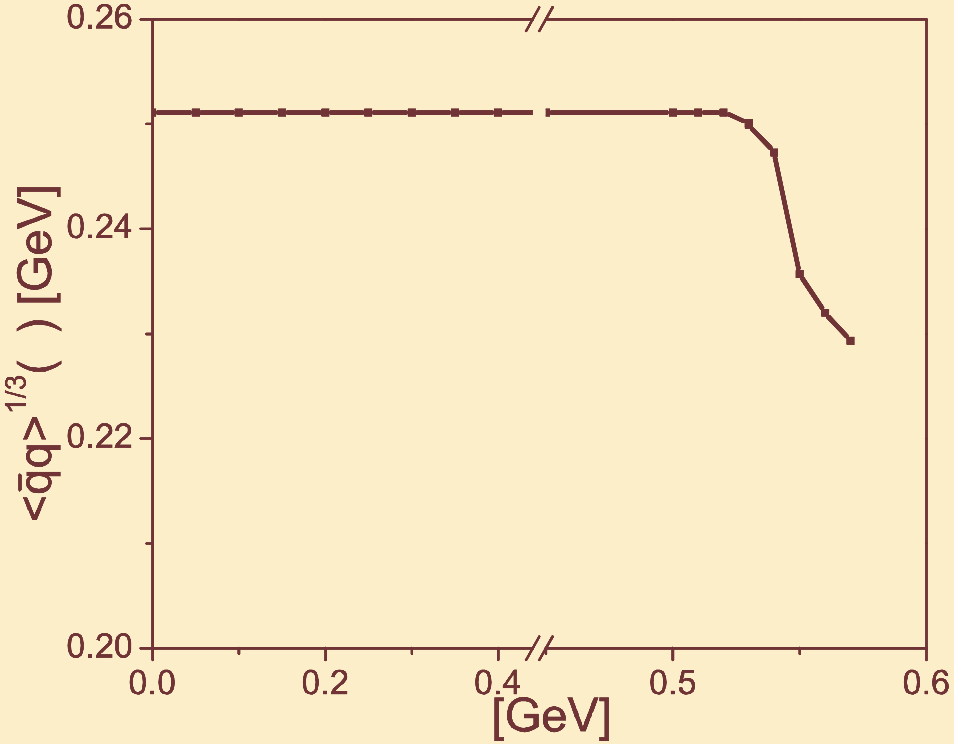
H. Chen, W. Yuan, L. Chang, Y.-X. Liu, T.K., C.D. Roberts arXiv:0807.2755





μ > 0.53 GeV:

deconfinement in Nambu-Goldstone phase

μ > 0.38 GeV:

chiral-limit Wigner phase favored (B=0)

Melting of Vacuum Quark Condensate:

$$-\langle \bar{q}q \rangle_{\zeta}^{0} = N_c Z_4 \int \frac{d^4p}{(2\pi)^4} \mathrm{tr}_D S(p;\mu)$$

IN MEDIUM QCD

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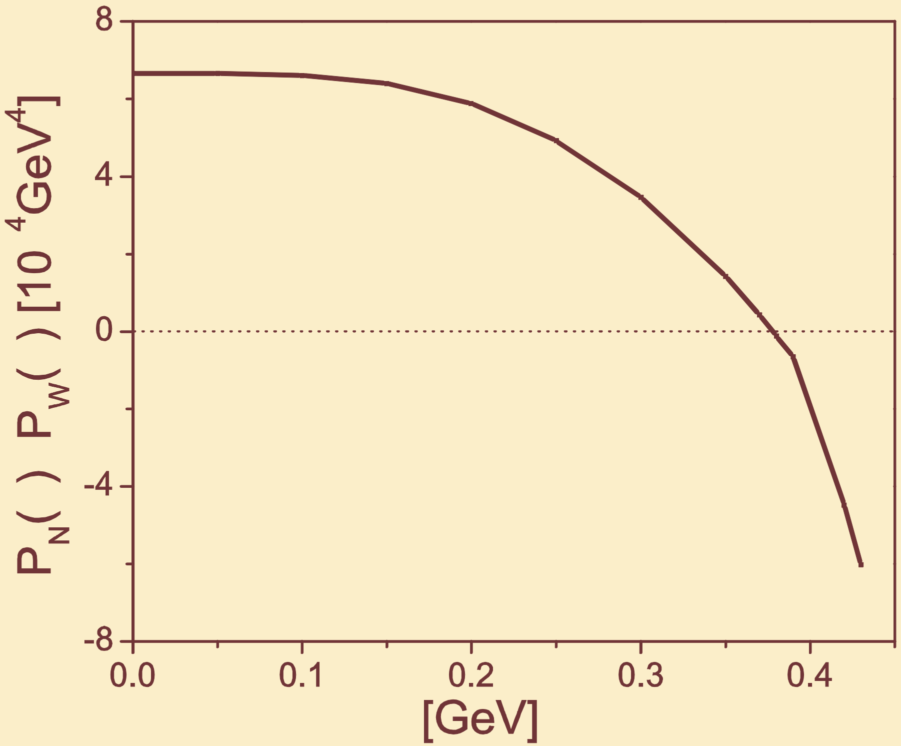

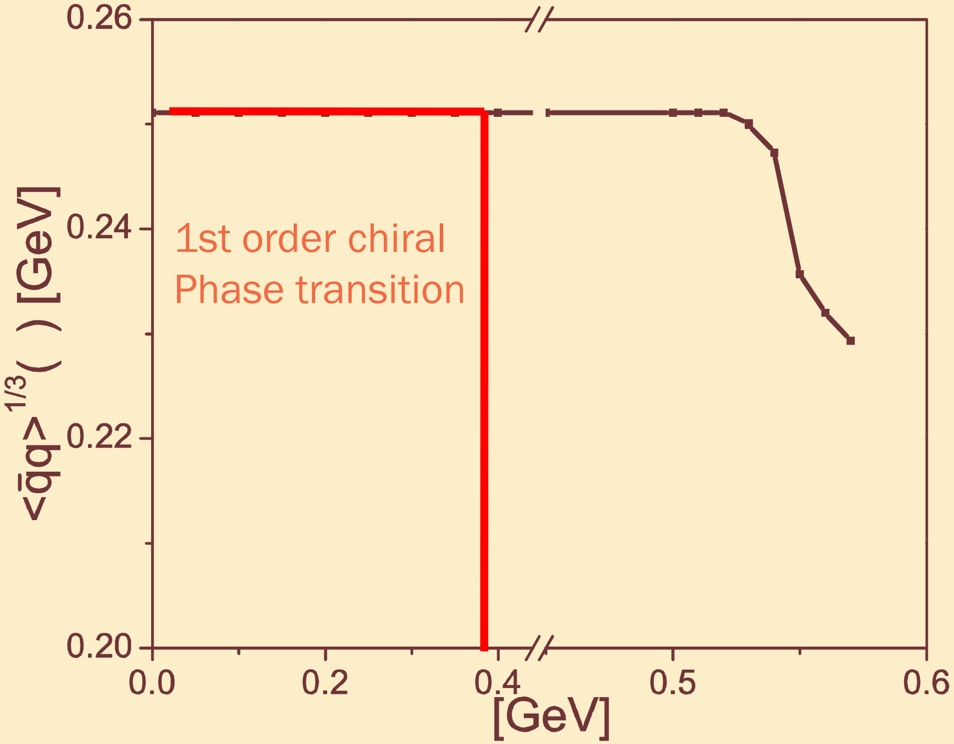

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CSs as natural complement to HICs
- no indication against QM in CS's
- vice versa: hard to disprove
- potentially usefull to fix QM-model EoS parameters

Possible scenario:
- 1f-QM in nuclear medium
- d-quark dripline

In medium QCD / Dyson-Schwinger
- deconfinement
- chiral symmetry restauration

... compact stars are a fascinating playground.

CONCLUSIONS

Argonne: C.D. Roberts
Beijing: L. Chang, H. Chen, Y.-X. Liu , W. Yuan
Liège: F. Sandin
Wrocław: D. Blaschke
Zeuthen: J. Berdermann

... compact stars are a fascinating playground.

THANK YOU!