XIAMEN UNIVERSITY
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Boiling of primordial quark nuggets in the early universe

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Cf. A. Li*, T. Liu, P. Gubler and R. X. Xu, Astropart. Phys. 62, 115 (2015)

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Outline

- **Motivation**
- **Introduction**
    - The order of QCD phase transition
- **Boiling of primordial quark nuggets to hadrons**
    - Classical nucleation model; BHF for the hadron phase; CDDM for the quark phase.
    - The results
- **Summary and future plans**

Motivation: Cosmic separation of phases

Witten, *PRD* 1984

- **(proposed)** Much of the baryon(A) number of the Universe condensed into quark nuggets (QNs) during the quark-hadron phase transition;
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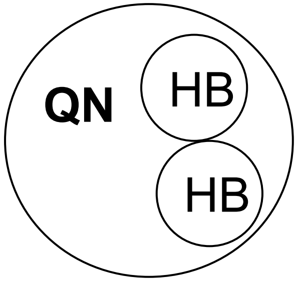
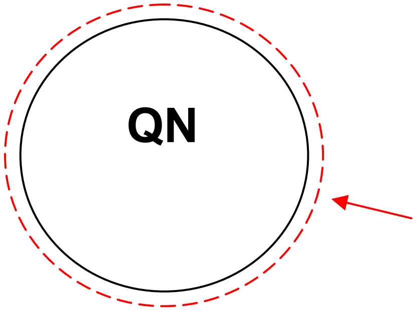


Hot QCD environment $(e^{\pm},\nu,\gamma)$

2. Surface evaporation
(depend on the dynamic of
the neutrino-driven cooling)



Baryon accumulation

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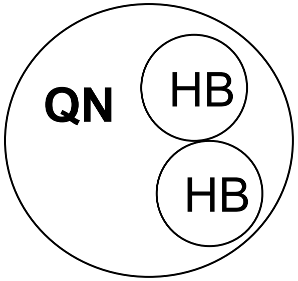

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(depend on the dynamic of the neutrino-driven cooling)

General arguments:

- Large A, easy to boil;
- Small A, easy to evaporate.

Intro: the order of QCD phase transition

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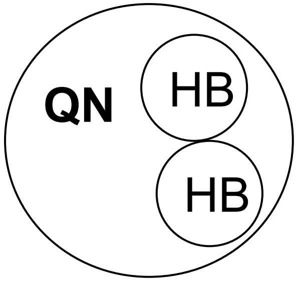

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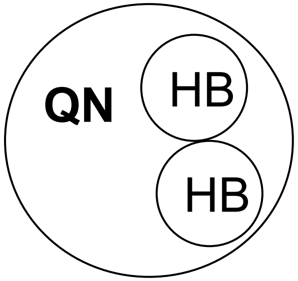

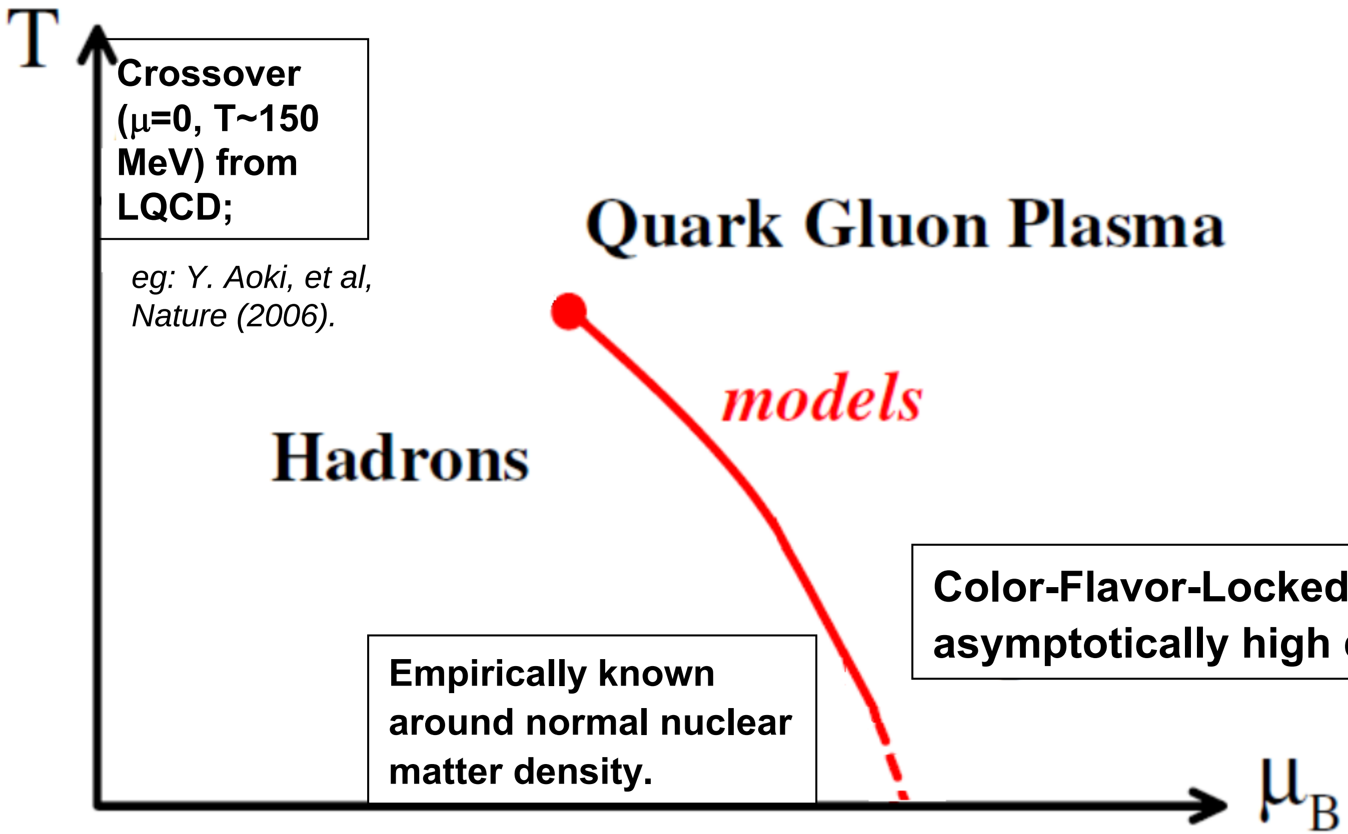

Crossover (μ=0, T~150 MeV) from LQCD;

eg: Y. Aoki, et al, Nature (2006).

Empirically known around normal nuclear matter density.

Color-Flavor-Locked phase at asymptotically high density

Fig. from C. Sasaki, NPA 2009

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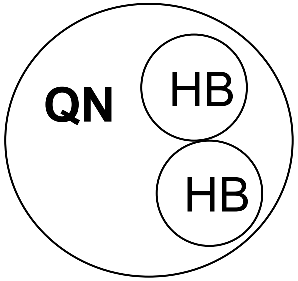

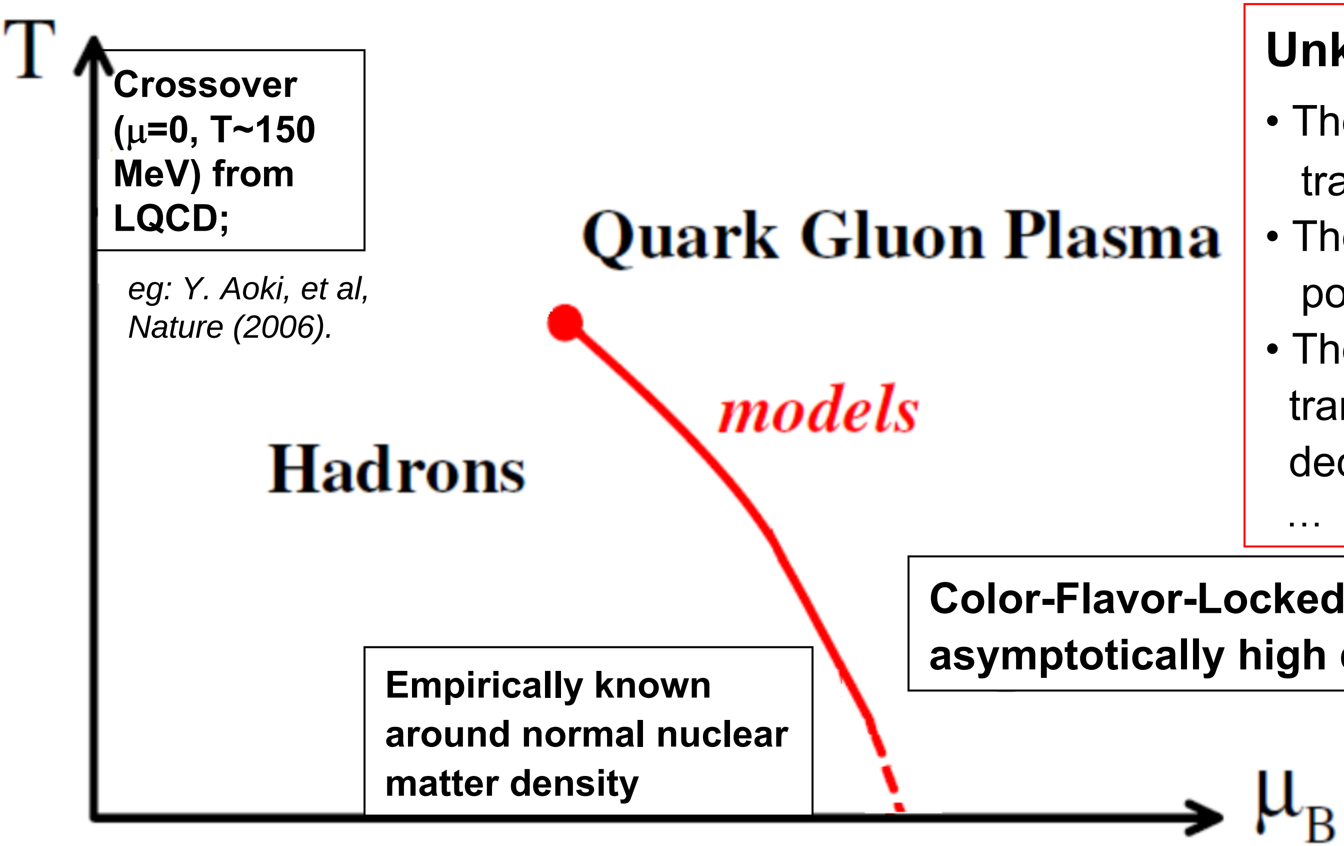

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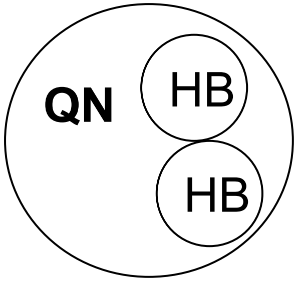
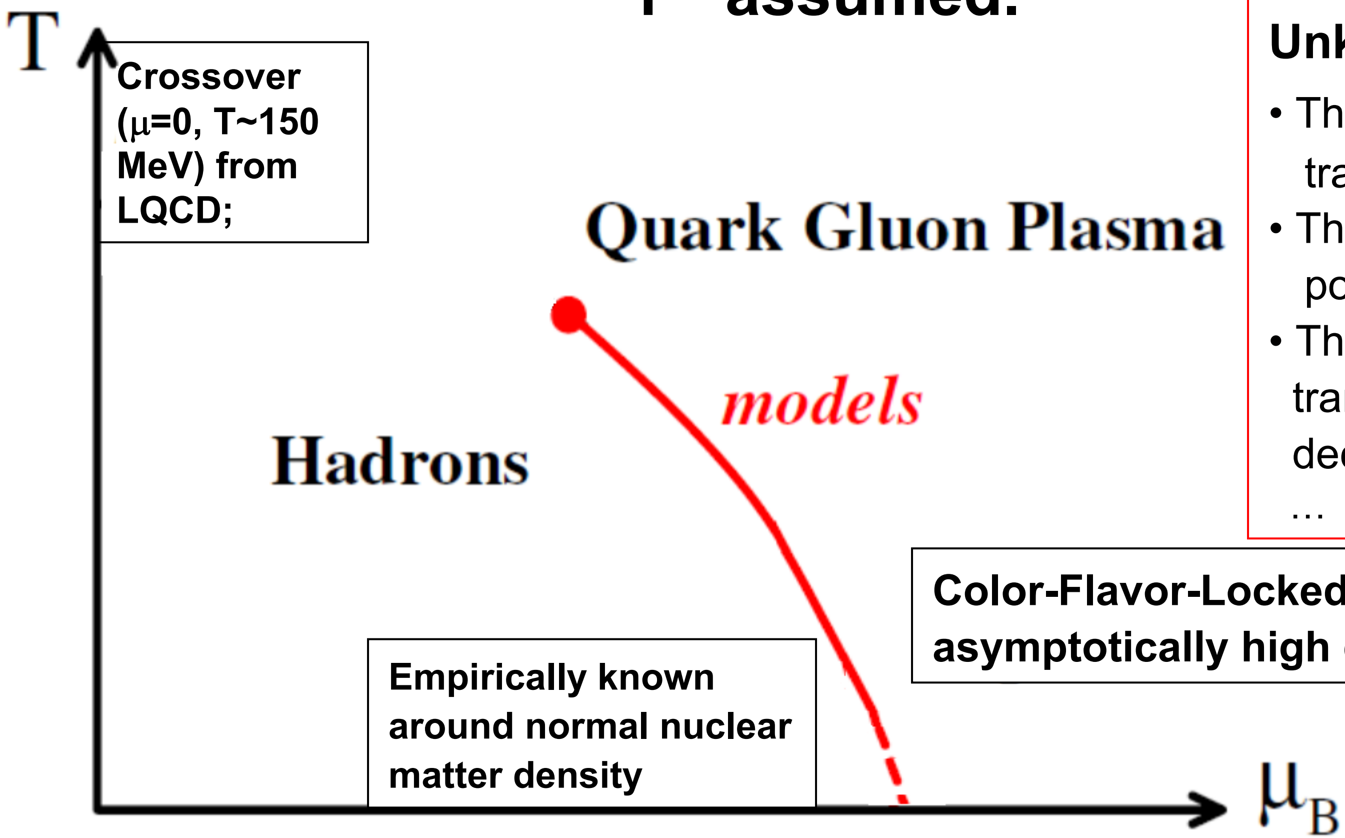


1^{st} assumed.



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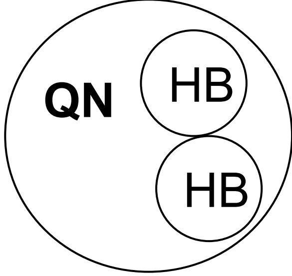
Boiling of primordial quark nuggets

in the early universe ($\mu \neq 0$)

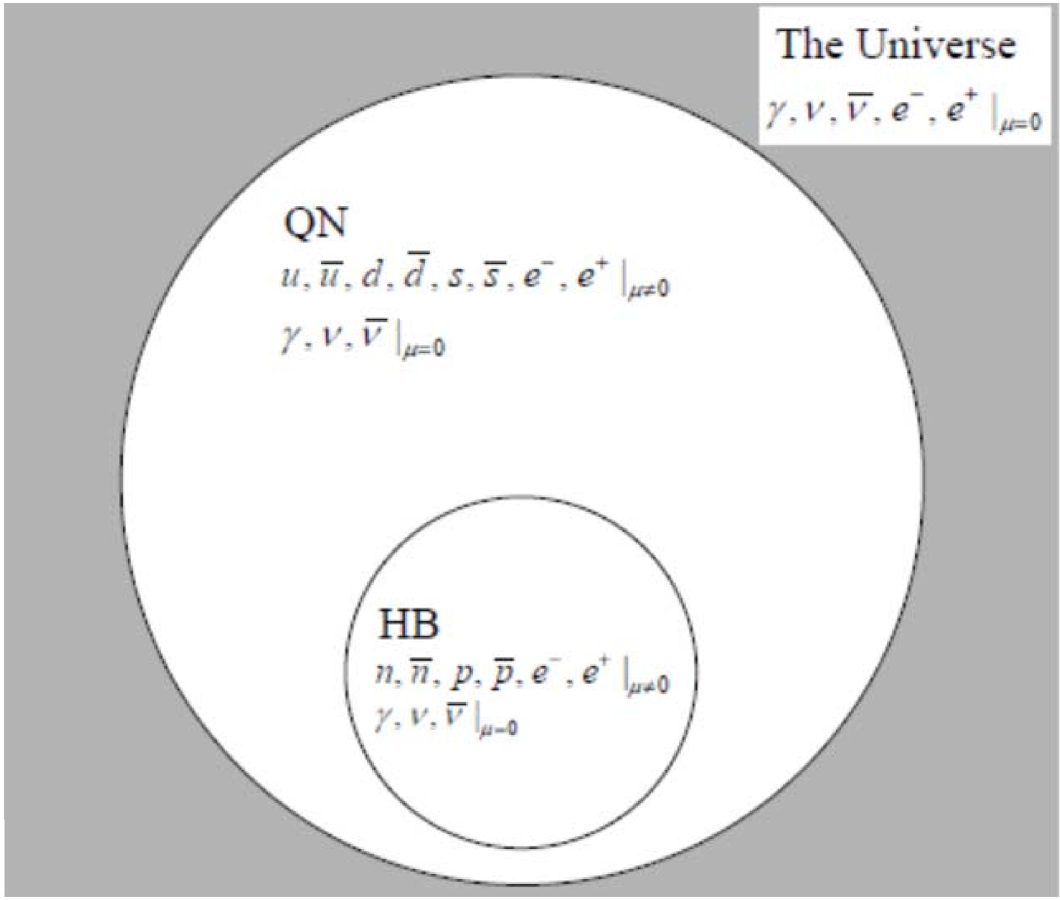
The boiling of quark nuggets



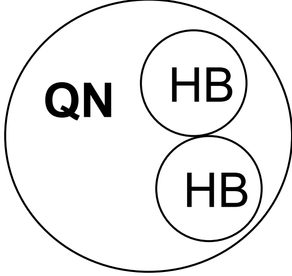
- **Earlier studies** **ignored** interactions between quarks and used phenomenological models for the hadron phase.

Alcock & Olinto, PRD 1989
Madsen & Olesen, PRD 1991
Lugones & Horvath, PRD 2004

- **Boiling possible or not still uncertain.**



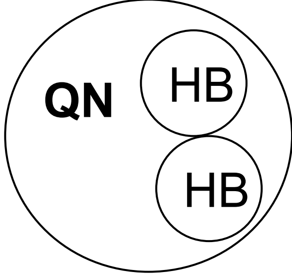
Zero chemical potential $(\mu = 0)$ represents that the relevant particles are thermally produced.



Classical nucleation theory

L. D. Landau and E. M. Lifschitz, <Statistical Physics>

- Whether boiling is important or not depends on the formation rate of **critical** bubbles;



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- Whether boiling is important or not depends on the formation rate of **critical** bubbles;

- Formulas:

the work done to form a bubble of radius r: $W=\frac{4\pi}{3}r^3(P_q-P_h)+4\pi\sigma r^2$

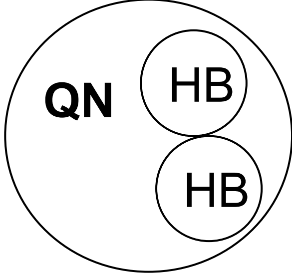
The work of a critical-size bubble can be obtained by maximizing W w.r.t. r:

$$r_c=\frac{2\sigma}{P_h-P_q}$$

Formation rate of critical bubbles:

$p\approx\epsilon^4\exp(-W_c/T)$ ϵ is a "characteristic energy" in the kinetics;

$\epsilon\sim T$



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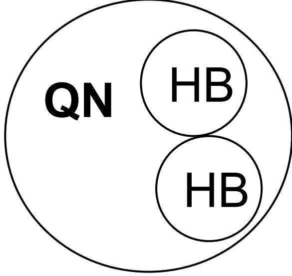

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$$\alpha_b \approx V n_b 4\pi r_c^2 \quad \begin{array}{l} V \sim A \ \mathrm{MeV}^{-3} \\ n_b \approx 0.1 M_P T^2 \exp(-W_c/T) \end{array}$$

Constant baryon density assumed in the nuggets.

where $0.1 M_P / T^2$

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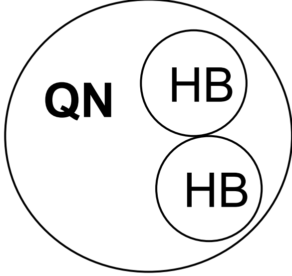

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$$\boxed{A_{\text{boil}} \approx 7.90 \times 10^{-61} \frac{\Delta P^6}{T^6 \sigma^6} \exp\left[16\pi \frac{\sigma^3}{T \Delta P^2}\right]}$$

✓ High powers and exponential term in Eq. would result in a **rapid** dependence on parameters (ΔP, σ, T).

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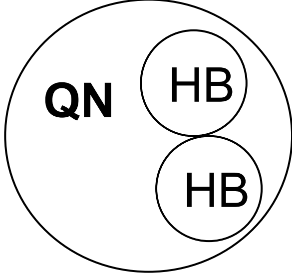

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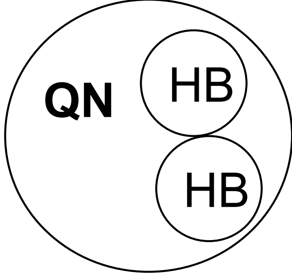

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✓ High powers and exponential term in Eq. would result in a **rapid** dependence on parameters (ΔP, σ, T).

- **Pressure difference** between the phases calculated from the equation:

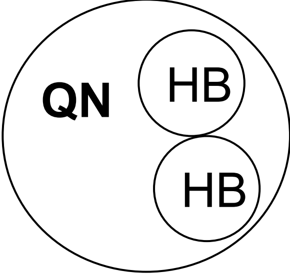
$$\mu_q(T, P_q) = \mu_h(T, P_h)$$

- **Surface tension** σ of QN can be calculated consistently as the free energy per unit surface area, from all fermion species (i =u; d; s; e).

L. D. Landau and E. M. Lifschitz, <Statistical Physics>

$$\sigma_i = \frac{3T}{8\pi} \times \int_0^\infty \left(1 - \frac{2}{\pi}\arctan\frac{k}{m_i}\right) \ln\left[1 + \exp\left(-\frac{e_i(k) - \mu_i}{T}\right)\right] k dk.$$

Pressure difference between the phases



- Based on our previous calculations of hybrid neutron stars (Peng, AL, Lombardo, *PRC* 2008)：
  - Using the **BHF** nuclear many-body approach for hadron phase;
  - Using the **CDDM** model for quark phase;

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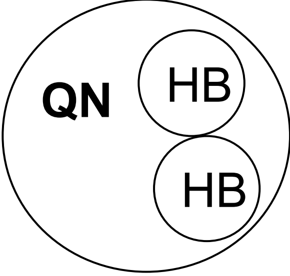

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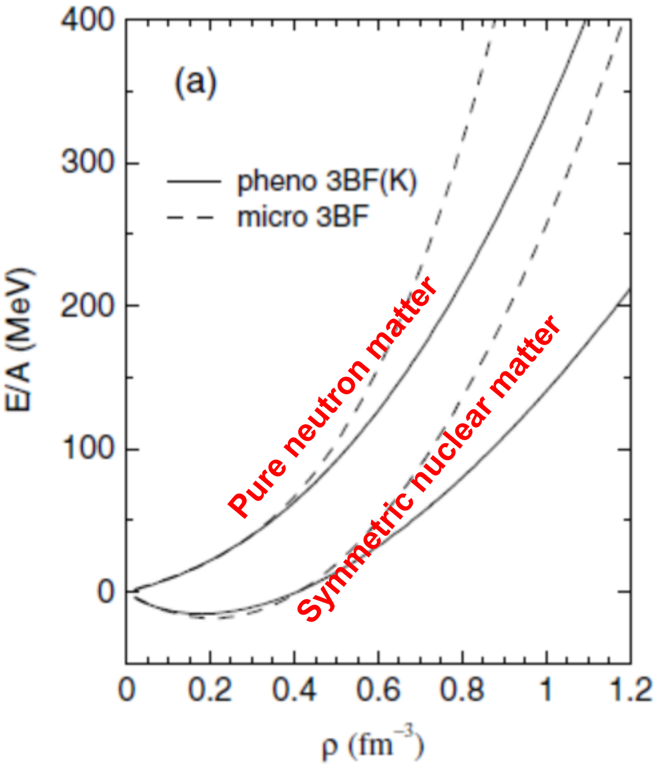
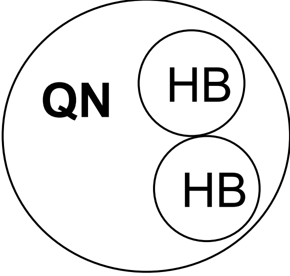
NNN 3 body force (3BF) included in non-rel. BHF



- 3BF substantially improve saturation;
- Micro 3BF stiffer than pheno 3BF at high densities: **Hadron EoS dependence**.

A. Li, G. F. Burgio, U. Lombardo, and W. Zuo, PRC 2006

Pressure difference between the phases



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Confined-density-dependent-mass (**CDDM**) model

$$m_q = m_{q0} + \frac{\langle H_{\mathrm{I}} \rangle_{n_b} - \langle H_{\mathrm{I}} \rangle_0}{\sum_q \left[\langle \bar{q} q \rangle_{n_b} - \langle \bar{q} q \rangle_0 \right]}$$

$$\equiv m_{q0} + m_{\mathrm{I}},$$

***G.X. Peng** et al, PRC 1999*

X. J. Wen, et al., PRC 2005

***C. J. Xia**, G. X. Peng, et al. PRC 2014*

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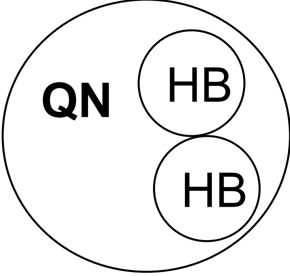

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$$\equiv m_{q0} + m_\mathrm{I},$$

$$m_I(n_b, T) = \frac{D}{n_b^z}\left[1 - \frac{8T}{\lambda T_c}\exp\left(-\lambda\frac{T_c}{T}\right)\right]$$

- Stability window for $D^{1/2}$: (**158- 270**)MeV;
- **Lower** limit from nuclear physics,

at $P = 0$, non-strange nuclear matter should be stable against decay to (ud) quark matter.

Upper limit from vacuum quark condensation.

- LQCD favored area (161 MeV~195 MeV).

Aoki, et al. hep-lat/13108555

***G.X. Peng** et al, PRC 1999*

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***C. J. Xia**, G. X. Peng,et al. PRC 2014*

Parameter

- Two hadron EoSs: Stiff (with Micro 3BF) and Soft (with Pheno 3BF);
- $D^{1/2}$ = 158MeV: Absolutely stable strange quark matter;

  170MeV: LQCD favored area (161 MeV~195 MeV);

  225MeV: Near the upper limit of *D* parameter.

Results

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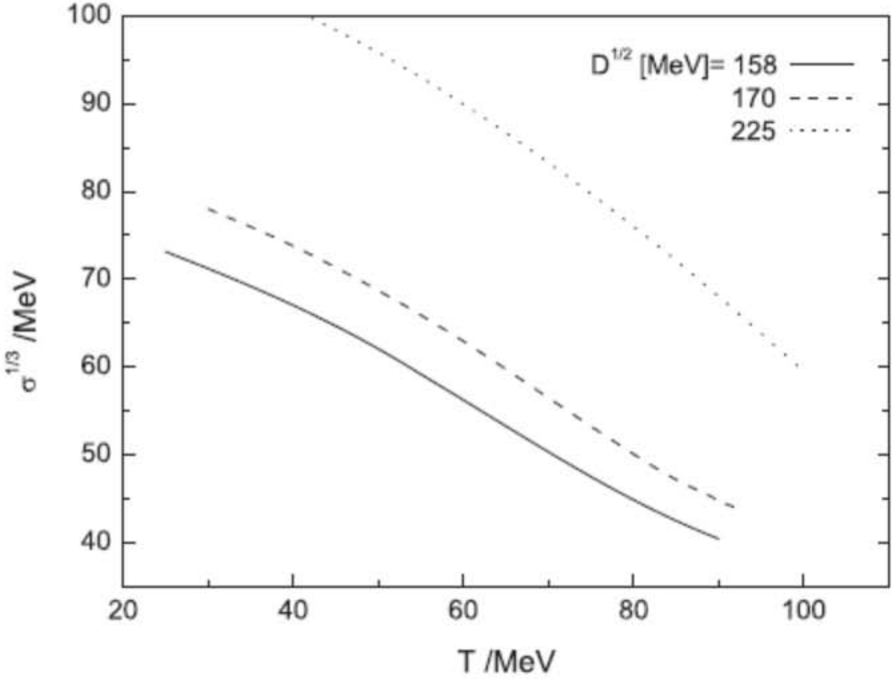
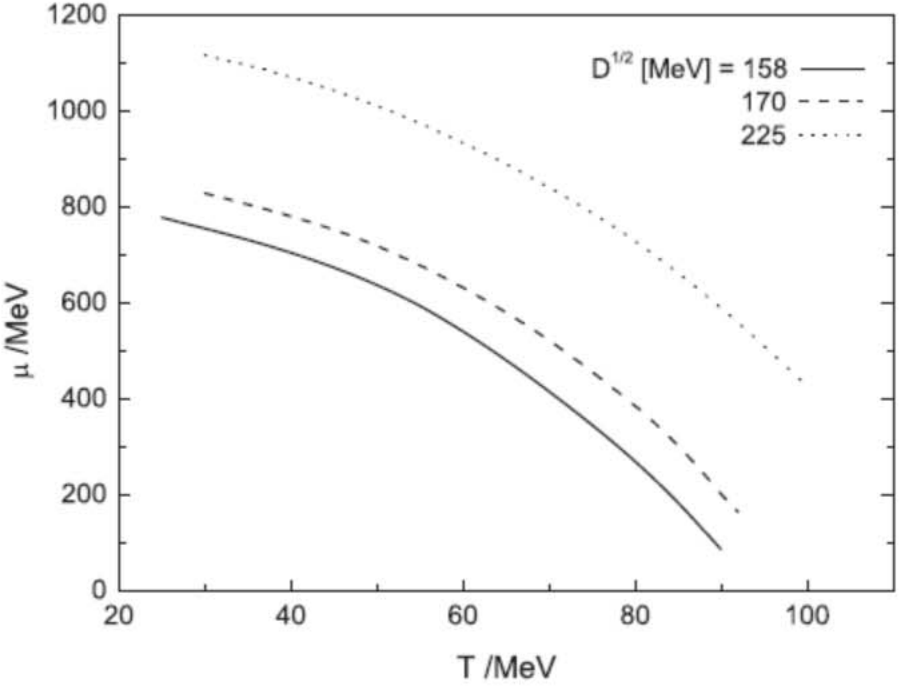
Surface tension



Baryon chemical potential



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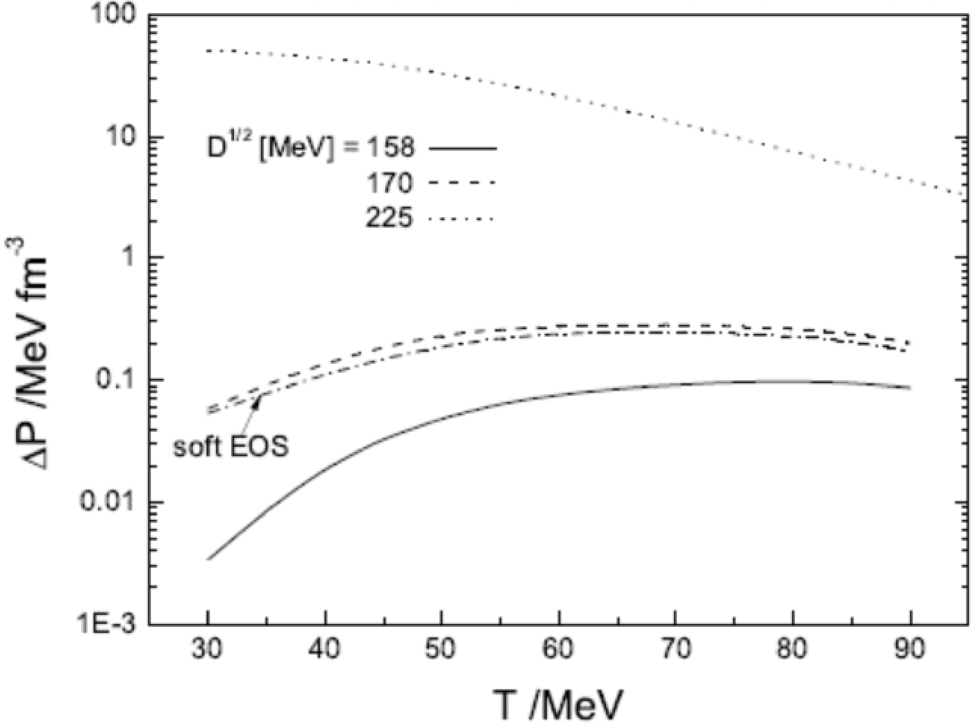
Pressure differences



Softer Hadron EoS

↓

Smaller pressure gap

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- More sensitive to *D* parameter, than to the hadron EoS.

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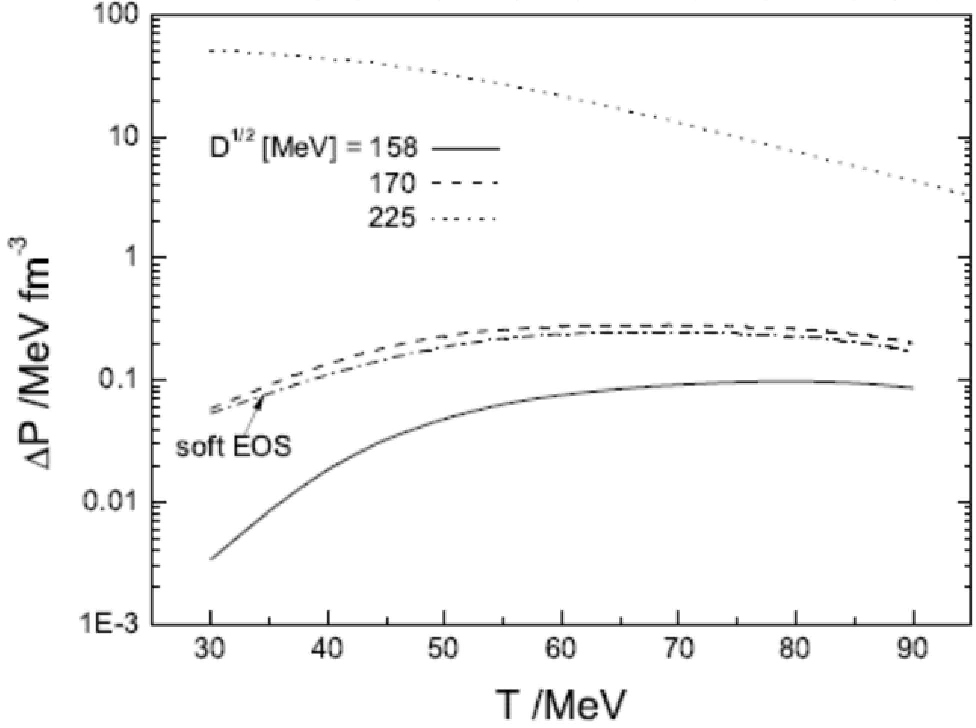

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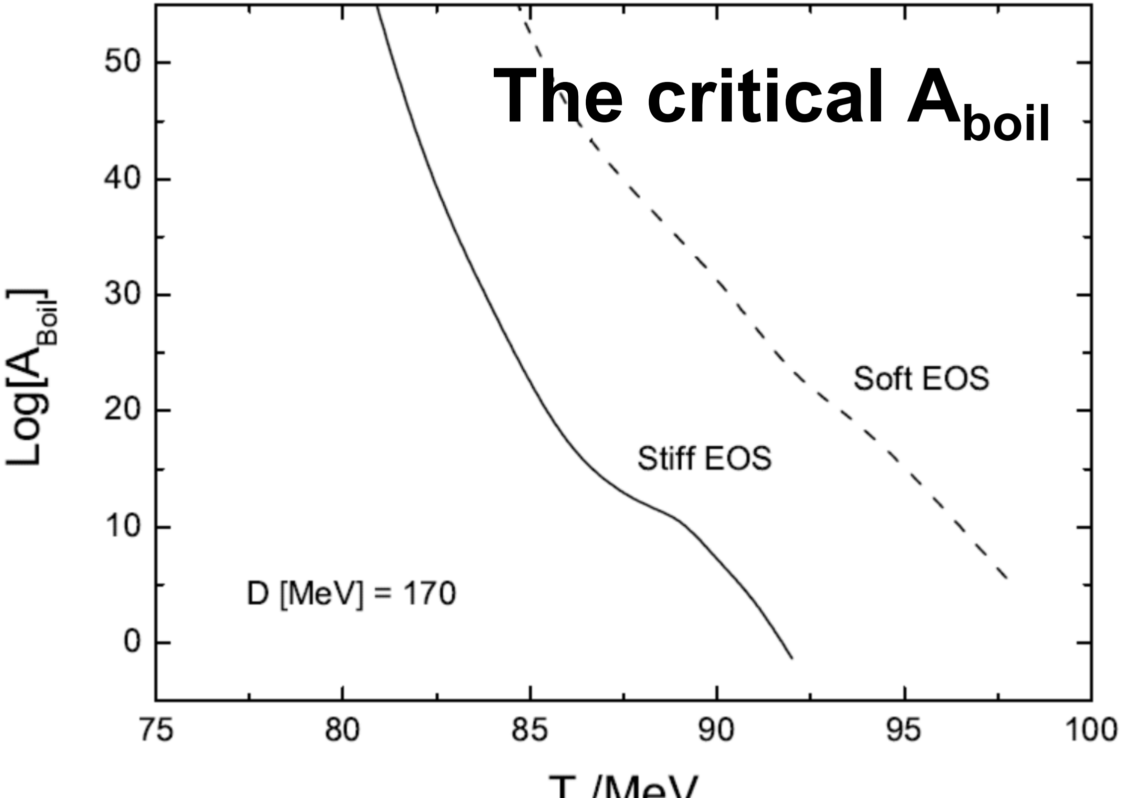

The critical A_{boil}

Softer Hadron EoS

↓

Smaller pressure gap

↓

Larger work for
a critical-size bubble

↓

Lower probability
of bubbles nucleation

↓

Larger A_{boil}

Results

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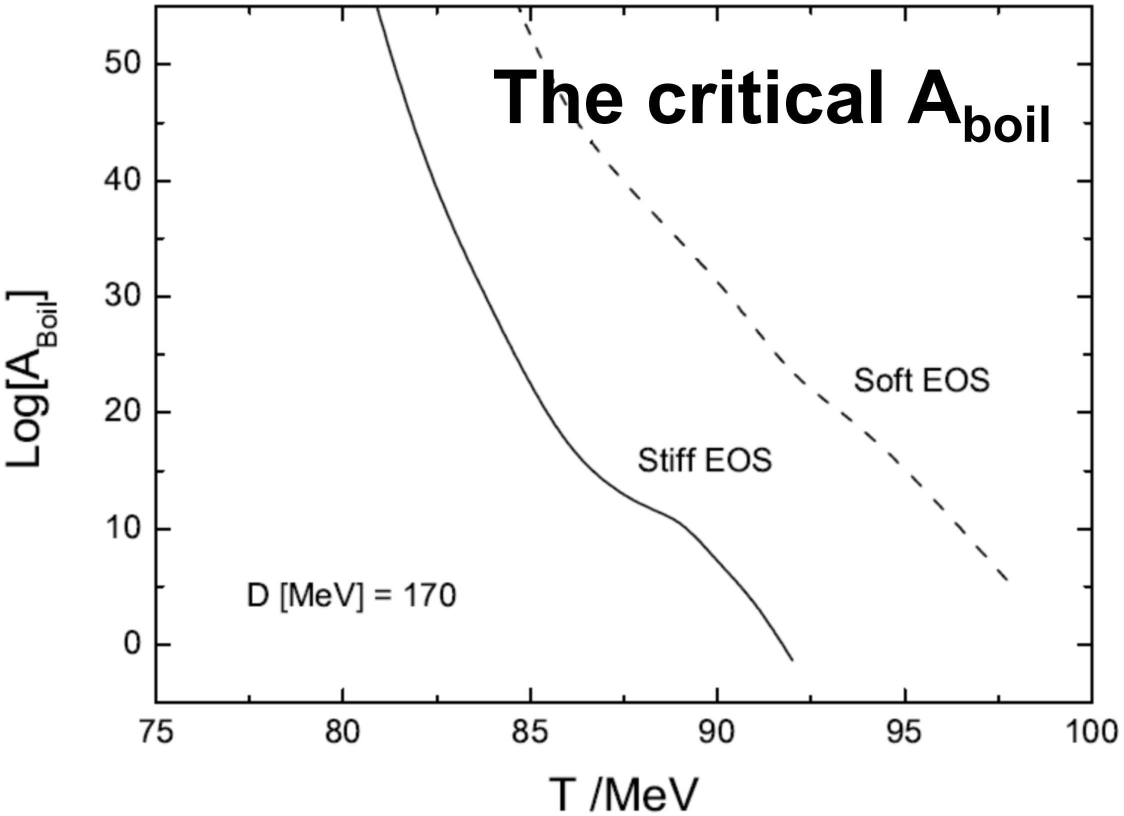


The critical A_{boil}

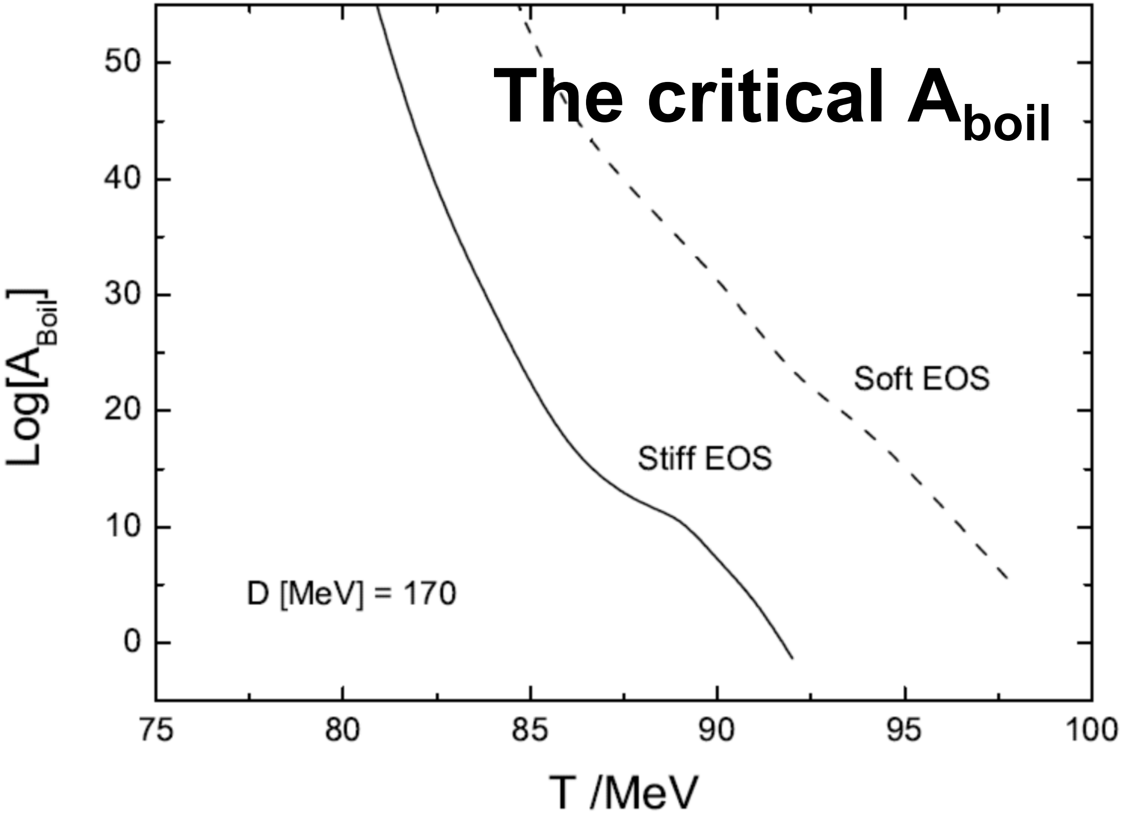
- **Surprisingly!**

  Other *D* values result in an extremely large A_{boil}, and boiling might not happen;
- Boiling might be important only **~170MeV** (values from Lattice).

Results

- **Further comments:**

  QNs might **unlikely** a candidate for DM, since only boiling can destroy them very sufficiently (Companied by yet unknown consequences for the spectrum of the emitted photons).



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Summary and and future plans

- Boiling revisited using updated micro. many-body theory;
- Boiling very possibly important for destroying (large) primordial QN;
- + Evaporation;
- Hyperon effect;
- Color superfluity effect (for $T<T_{\Delta}$);
- Other important aspects from the audience.

Thank you very much!

校園鳥瞰

backup

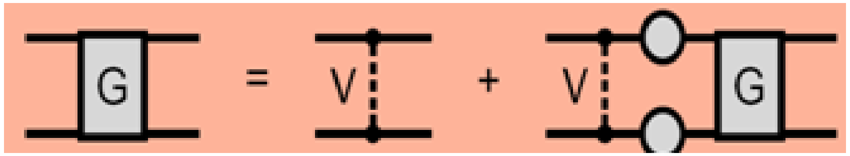
Brueckner-Hartree-Fock (BHF) model

58 -present

(P. Ring's lectures)

Input quantities

- Interaction V
- Baryon density $\rho = \rho_n + \rho_p$
- Asymmetry parameter $\beta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$



$$G(\rho,\beta;\omega) = v + v\sum_{k_a k_b} \frac{|k_a k_b\rangle Q(k_a,k_b)\langle k_a k_b|}{\omega - e(k_a) - e(k_b) + i\eta} G(\rho,\beta;\omega)$$

- *G*: In-medium effective Interaction matrix
- *Q*: Pauli operator $Q(k_a,k_b) = [1 - n(k_a)][1 - n(k_b)]$
- ω: Starting energy
- *e*: s.p. energy

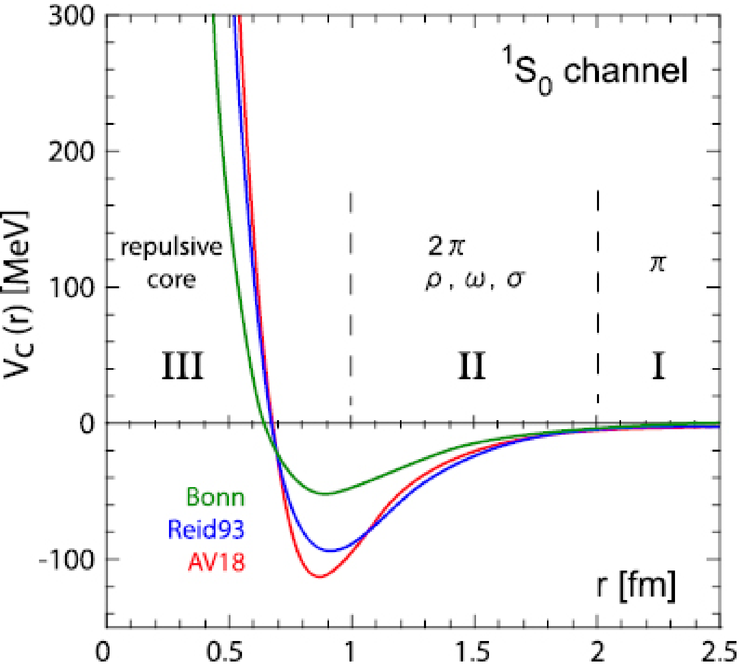
$$e(k) = \frac{\hbar^2 k^2}{2m} + \sum_{k'} n(k')\,\mathrm{Re}\langle kk'|G[e(k)+e(k')]|kk'\rangle_A$$

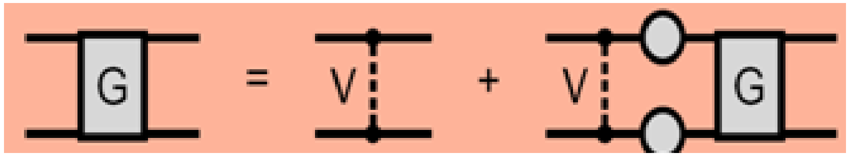
- A theory based on independent nucleon pair, for handling the repulsive core of nuclear force.

Brueckner-Hartree-Fock (BHF) model

70 -present

(P. Ring's lectures)





$$G(\rho,\beta;\omega)=v+v\sum_{k_ak_b}\frac{|k_ak_b\rangle Q(k_a,k_b)\langle k_ak_b|}{\omega-e(k_a)-e(k_b)+i\eta}G(\rho,\beta;\omega)$$

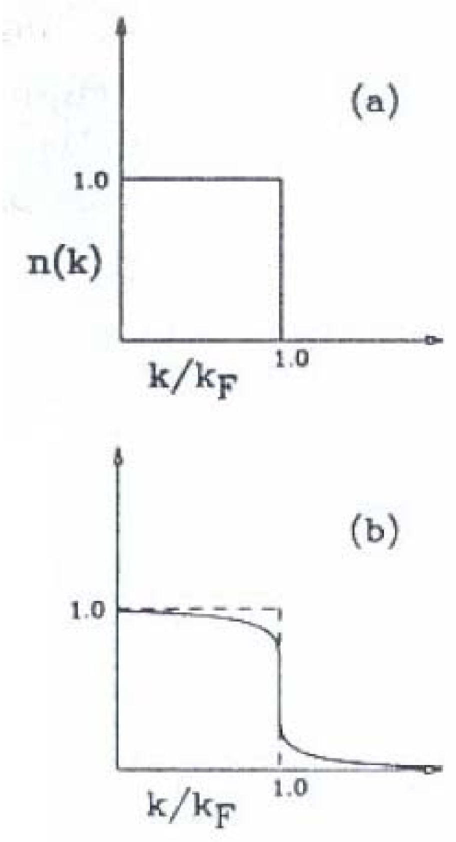
- *G*: In-medium effective Interaction matrix
- *Q*: Pauli operator $Q(k_a,k_b)=[1-n(k_a)][1-n(k_b)]$
- ω: Starting energy
- *e*: s.p. energy

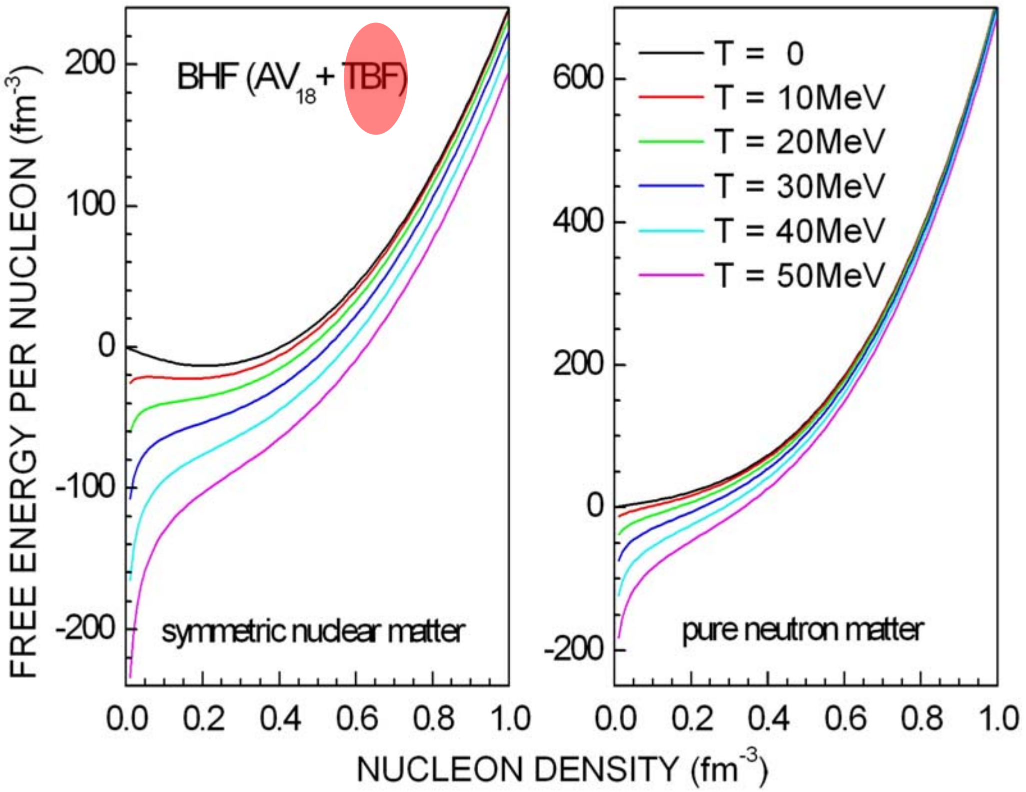
$$\boxed{e(k)=\frac{\hbar^2k^2}{2m}+\sum_{k'}n(k')\,\mathrm{Re}\langle kk'|G[e(k)+e(k')]|kk'\rangle_A}$$

- A theory based on independent nucleon pair, for handling the repulsive core of nuclear force.

Finite-temperature BHF model with TBF

$$n(k) = \begin{cases} 1 & k \le k_F \\ 0 & k > k_F \end{cases} \quad \Longrightarrow \quad f_\tau(k, T, \rho, \beta) \equiv [1 + \exp(\frac{e_\tau(k) - \mu_\tau}{T})]^{-1}$$





W. Zuo, Z. H. Li, AL, U. Lombardo, HJ Schulze, 2004-

TBF (Three body force)

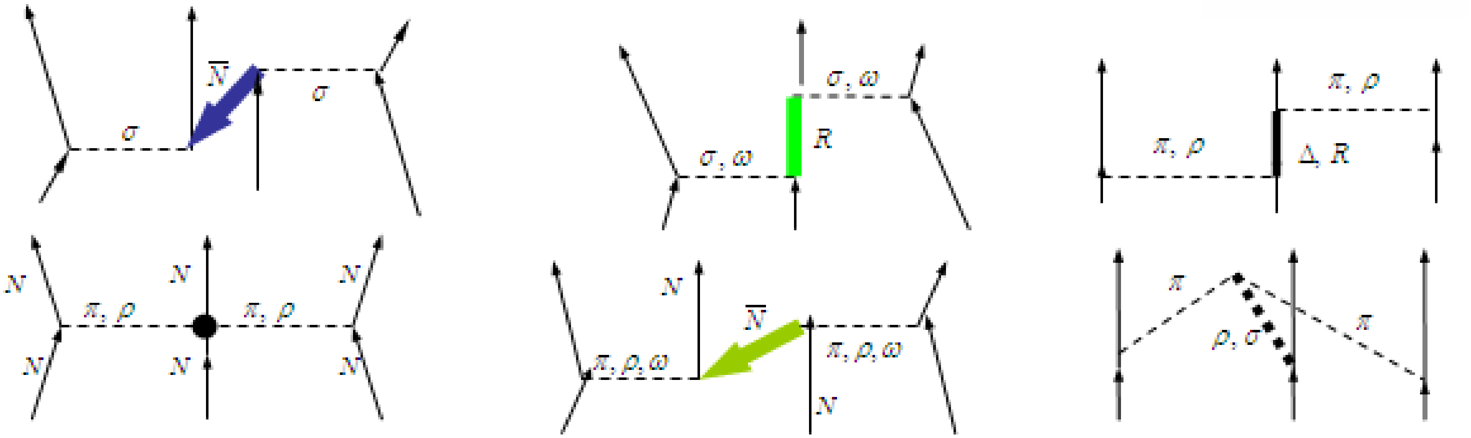
(Schulze's talk)

- **Microscopic TBF;**

  Exchange of π, ρ, σ, ω via Δ (1232), *R*(1440), *N*$\underline{N}$

  with parameters compatible with 2BF (Paris,V18,...)

P. Grangé et al., *PRC* 1989



- **Phenomenological TBF.**

  Directly add the TBF operators $V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R},$

  Only 2π-TBF + phenomenological repulsion

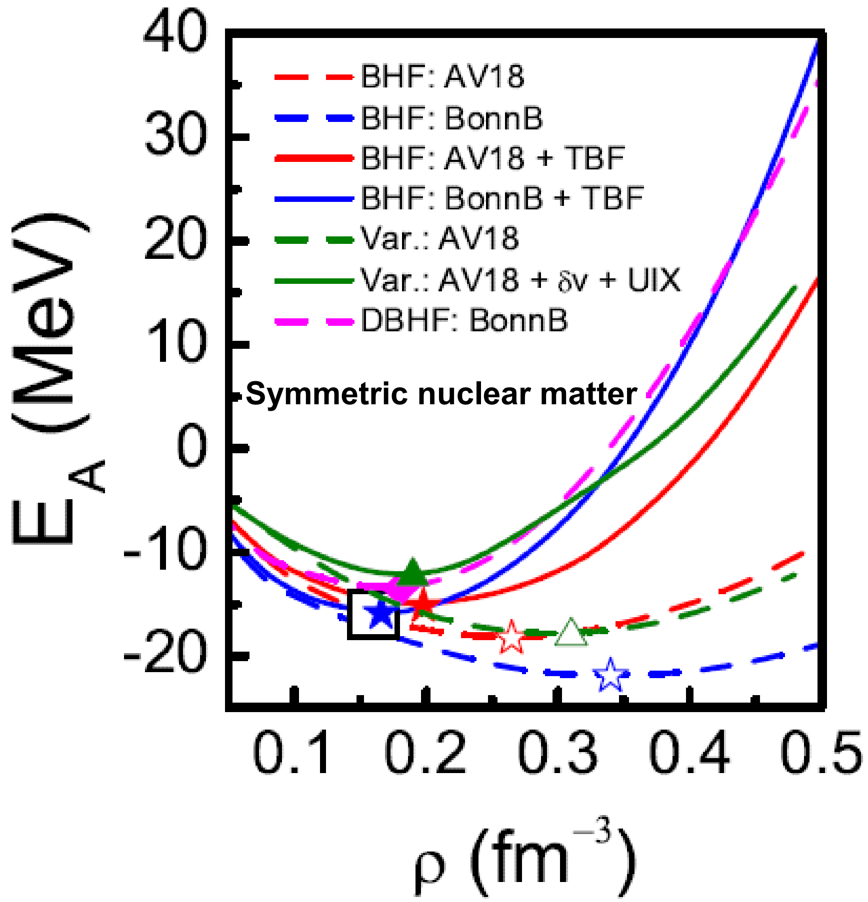
  Parameters fitted from saturation point.

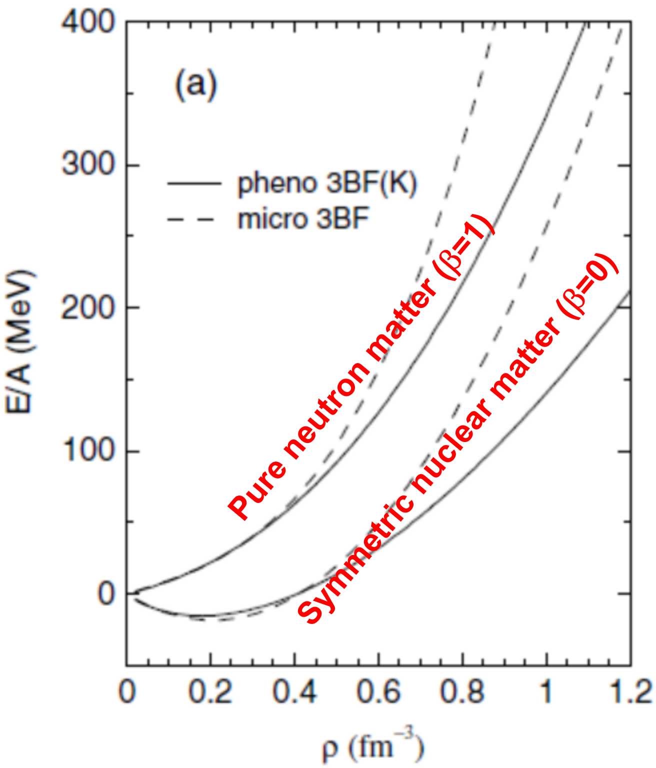
TBF: Nucleon structure effect + Relativistic effect

TBF included in BHF

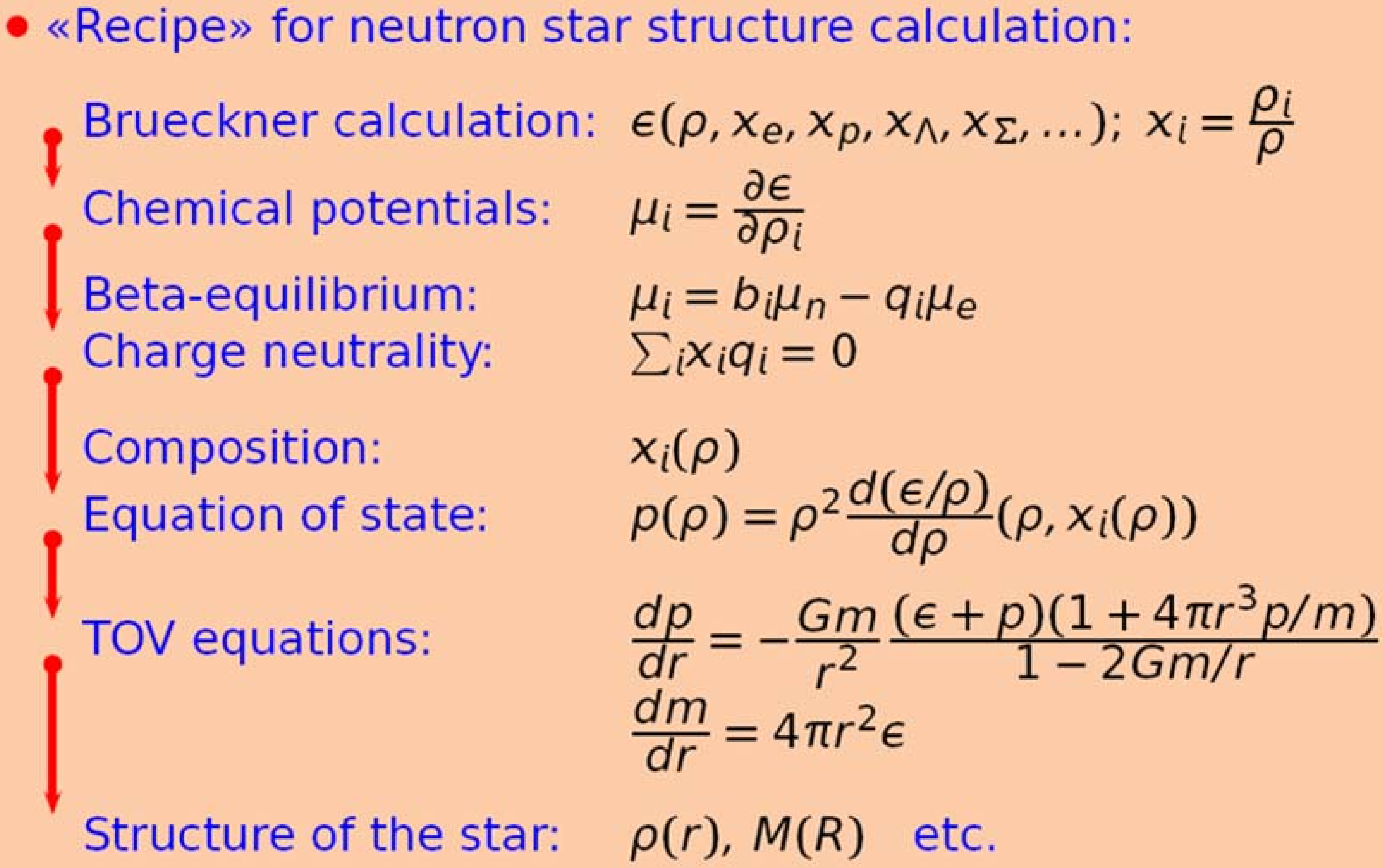
(Lombardo’s talk)

- TBF substantially improve saturation;
- Micro TBF more stiffer than pheno TBF at high densities.





(Bombaci's talk)



- «Recipe» for neutron star structure calculation:

Brueckner calculation: $\epsilon(\rho, x_e, x_p, x_\Lambda, x_\Sigma, \ldots)$; $x_i = \frac{\rho_i}{\rho}$

Chemical potentials: $\mu_i = \frac{\partial \epsilon}{\partial \rho_i}$

Beta-equilibrium: $\mu_i = b_i \mu_n - q_i \mu_e$

Charge neutrality: $\sum_i x_i q_i = 0$

Composition: $x_i(\rho)$

Equation of state: $p(\rho) = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}(\rho, x_i(\rho))$

TOV equations:

$$\frac{dp}{dr} = -\frac{Gm}{r^2} \frac{(\epsilon + p)(1 + 4\pi r^3 p/m)}{1 - 2Gm/r}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Structure of the star: $\rho(r)$, $M(R)$ etc.

- M(R) relation is **unique** to the underlying EoS;
- Very **massive** NS observed recently.

Demorest et. al, Nature 2010
Antoniadis et al., Science 2013

Confined-density-dependent-mass (**CDDM**) model

$$H_{\mathrm{QCD}} = H_k + \sum_q m_{q0}\bar{q}q + H_I,$$

The variation of the quark mass with density mimics the strong interaction between quarks.

$$H_{\mathrm{eqv}} = H_k + \sum_q m_q \bar{q}q$$

$$m_q = m_{q0} + \frac{\langle H_I\rangle_{n_b} - \langle H_I\rangle_0}{\sum_q [\langle\bar{q}q\rangle_{n_b} - \langle\bar{q}q\rangle_0]}$$

$$\equiv m_{q0} + m_I.$$

Quark confinement $\lim_{n_b\to 0} m_I = \infty$

Asymptotic freedom $\lim_{n_b\to\infty} m_I = 0$

$$m_I = \frac{D}{n_b^z}$$

G.X. Peng et al, *PRC* (1999)

$$< H_I >_{n_b} - < H_I >_0 \;=\; \frac{1}{2V}\iint_V v(r)(3n_b dr_1)(3n_b dr_2) \qquad (1)$$

$$\sum_q [< \bar{q}q >_{n_b} - < \bar{q}q >_0] \;=\; \sum_q [1 - < \bar{q}q >_0 /\rho_q']n_b \equiv A n_b \qquad (2)$$

a linear confinement potential $v(r) = \alpha r$ (3)

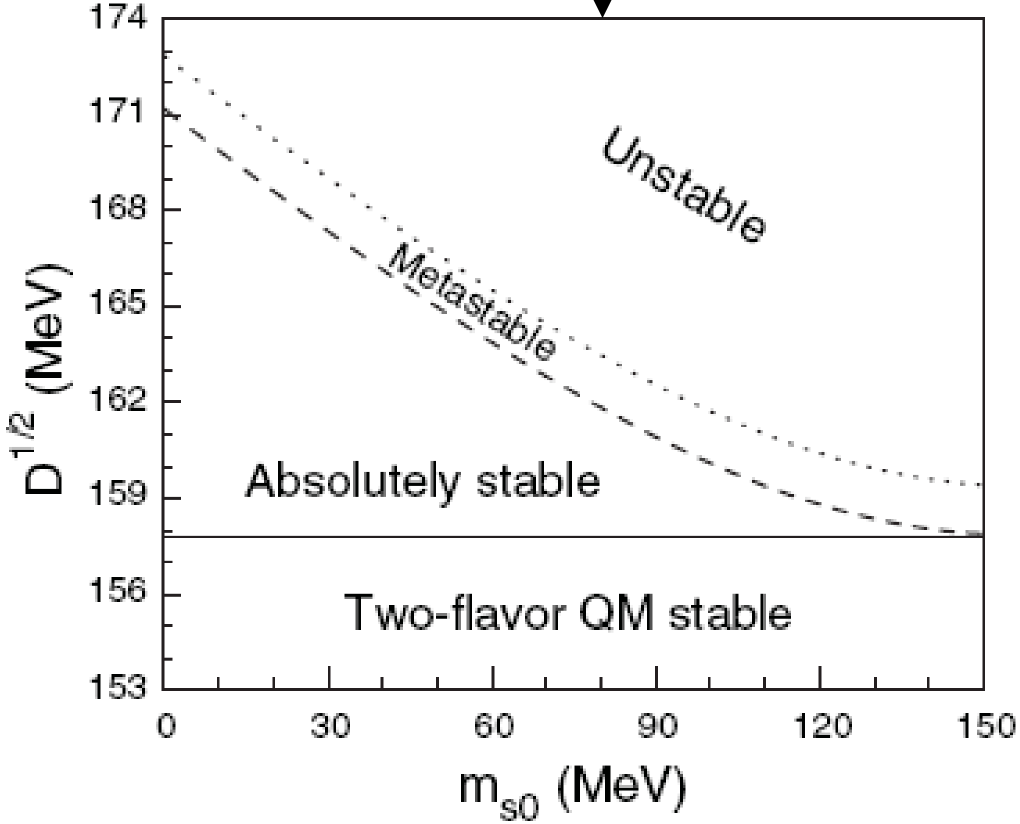
$$m_I = \frac{18\pi}{A} n_b \frac{R^4}{4} \propto \frac{1}{n_b^{1/3}}$$

Quark model with chiral mass scaling

High-order perturbative interactions included, see *C. J. Xia, G. X. Peng,et al. PRC 2014*

Confined-density-dependent-mass (**CDDM**) model

- Stability window for $D^{1/2}$: (**158- 270**)MeV;
- **Lower** limit from nuclear physics, **Upper** limit from vacuum quark condensation;



Peng, AL, Lombardo, *PRC* 2008

$$\boxed{D = \frac{3(2/\pi)^{1/3}\sigma_0 m_\pi^2 f_\pi^2}{-\sigma_N \sum_q \langle\bar{q}q\rangle_0}}$$

- Finite-temperature extension

X. J. Wen, et al., *PRC* 2005

$$m_I(n_b, T) = \frac{D}{n_b^z}\left[1 - \frac{8T}{\lambda T_c}\exp\left(-\lambda\frac{T_c}{T}\right)\right]$$

Cosmic separation of phases

Witten, *PRD* 1984

H: High-temperature **quark** phase;

L: Low-temperature **hadron** phase;