中性子星と格子QCD

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for

HAL QCD Collaboration

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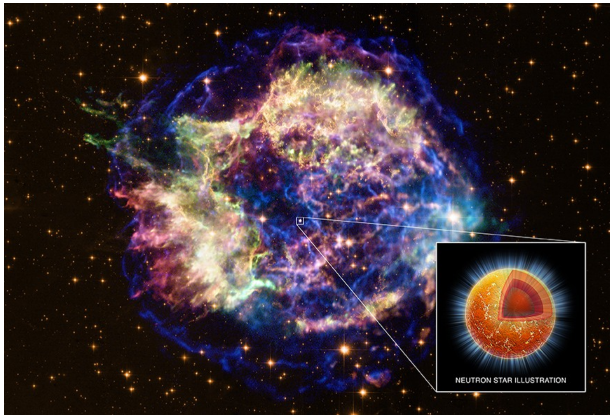
ポスト京シンポジウム，Mar 31 2016

Introduction



- Neutron Star
  - is a compact star formed after supernova explosion of massive star.
  - Typically, $M = 1.5\, M_\odot,\ R = 10$ km.
  - Temperature T $\simeq 10^8$ [K] $\simeq$ 0.01 [MeV] $\simeq$0
  - Density in core ρ = several $\times\ \rho_0$

is roughly 10^{15} [g/cm^3] !
Most dense in Universe!

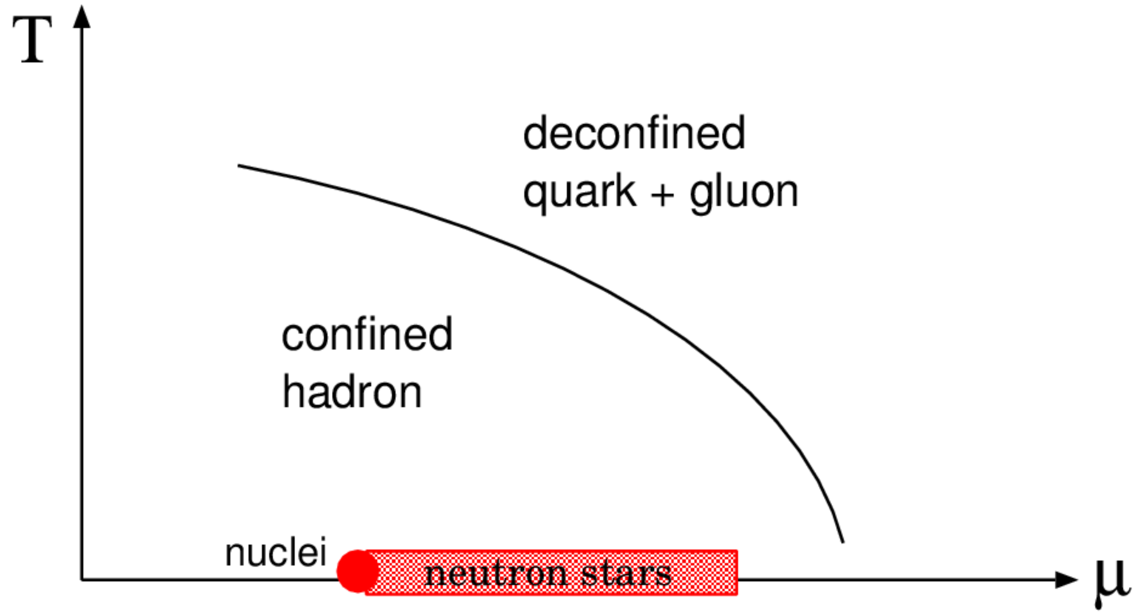
- Equation of State
  - is a relation between energy and pressure of matter

$$P(E) \text{ or } E(P) \text{ or } E(\rho) \text{ or } E(k_F) \text{ or } \ldots$$

  - EoS of dense baryonic matter is crucial for NS since it determines NS stable mass and radius, especially maximum NS mass (boundary between NS and BH).

Introduction

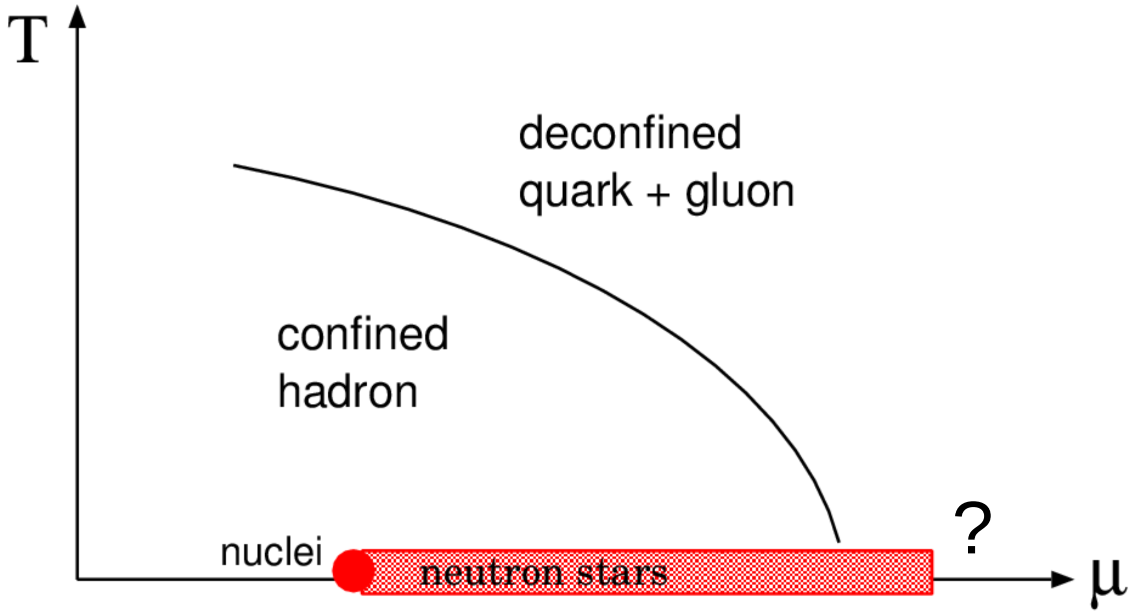
- QCD phase diagram



- NS matter has ρ = several x ρ_0 and T ≈ 0,
and corresponds to [red box] on the QCD phase-diagram.

Introduction

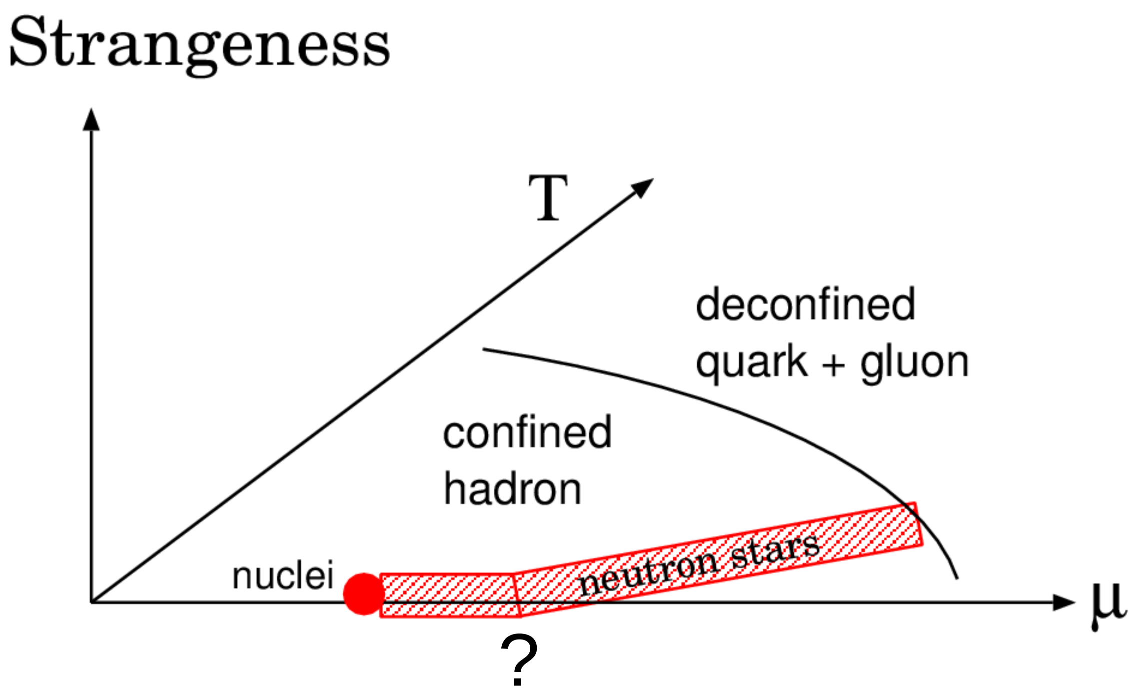
- QCD phase diagram



- NS matter has ρ = several x ρ_0 and $T \approx 0$, and corresponds to [red box] on the QCD phase-diagram.
- Perhaps, it touches the deconfined QGP phase.

Introduction

- QCD phase diagram



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Introduction

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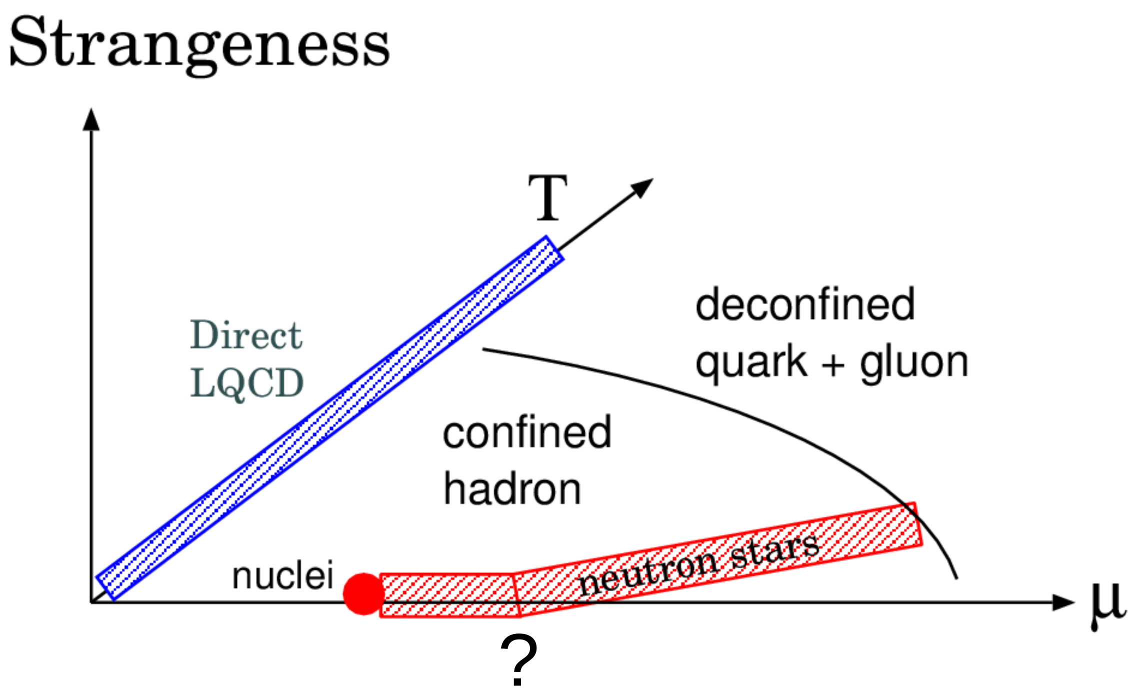

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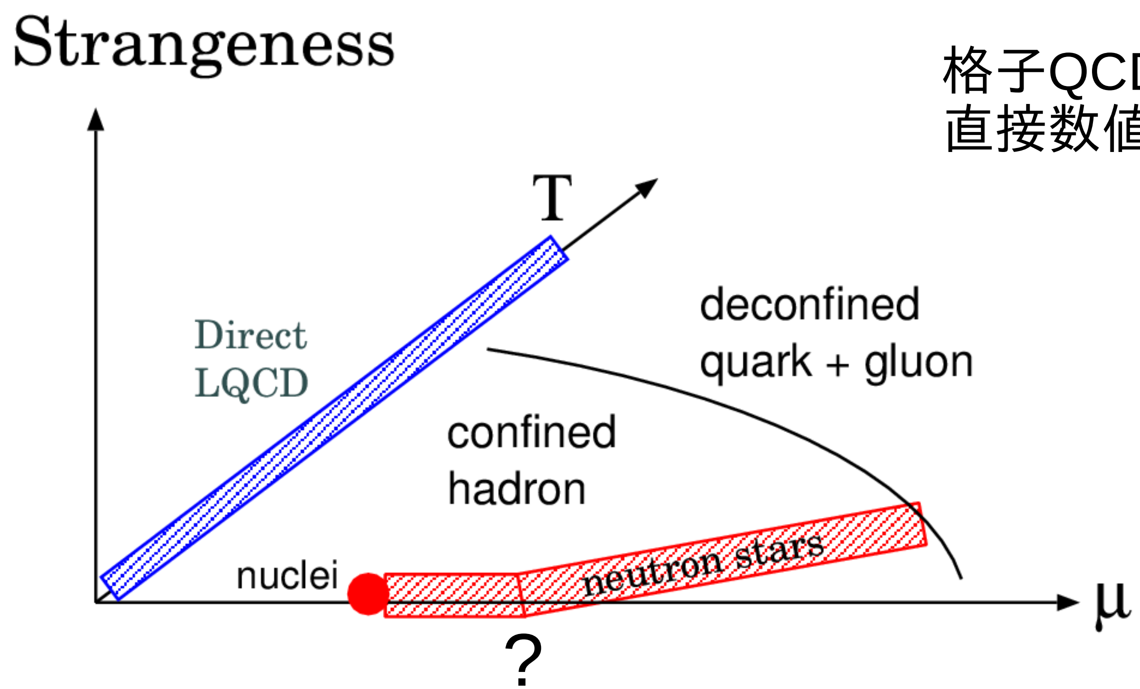
Introduction

⋆ QCD phase diagram



格子QCDから中性子星を攻めるには、
直接数値計算とは別のアプローチが必要！

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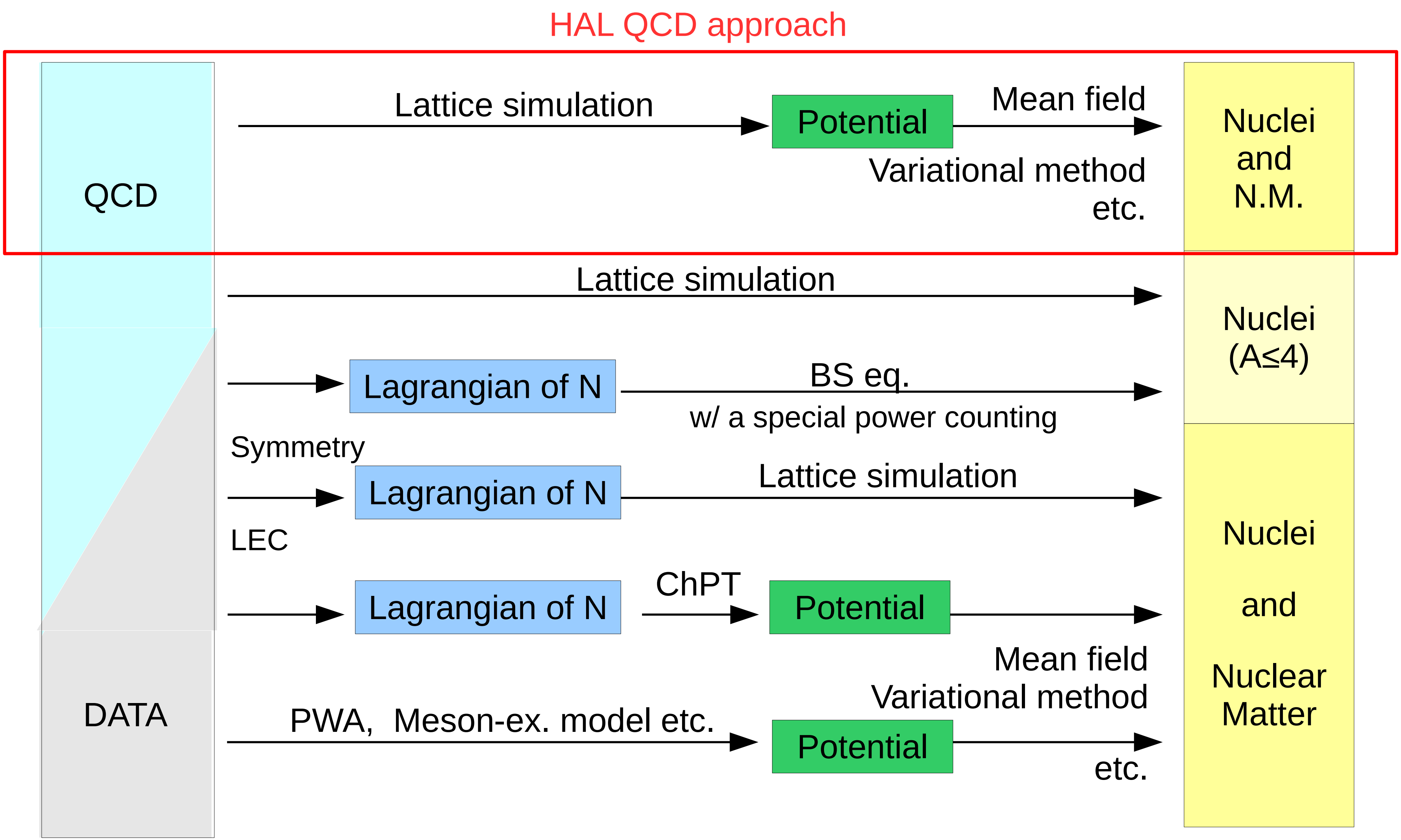
Various approaches in nuclear phys.



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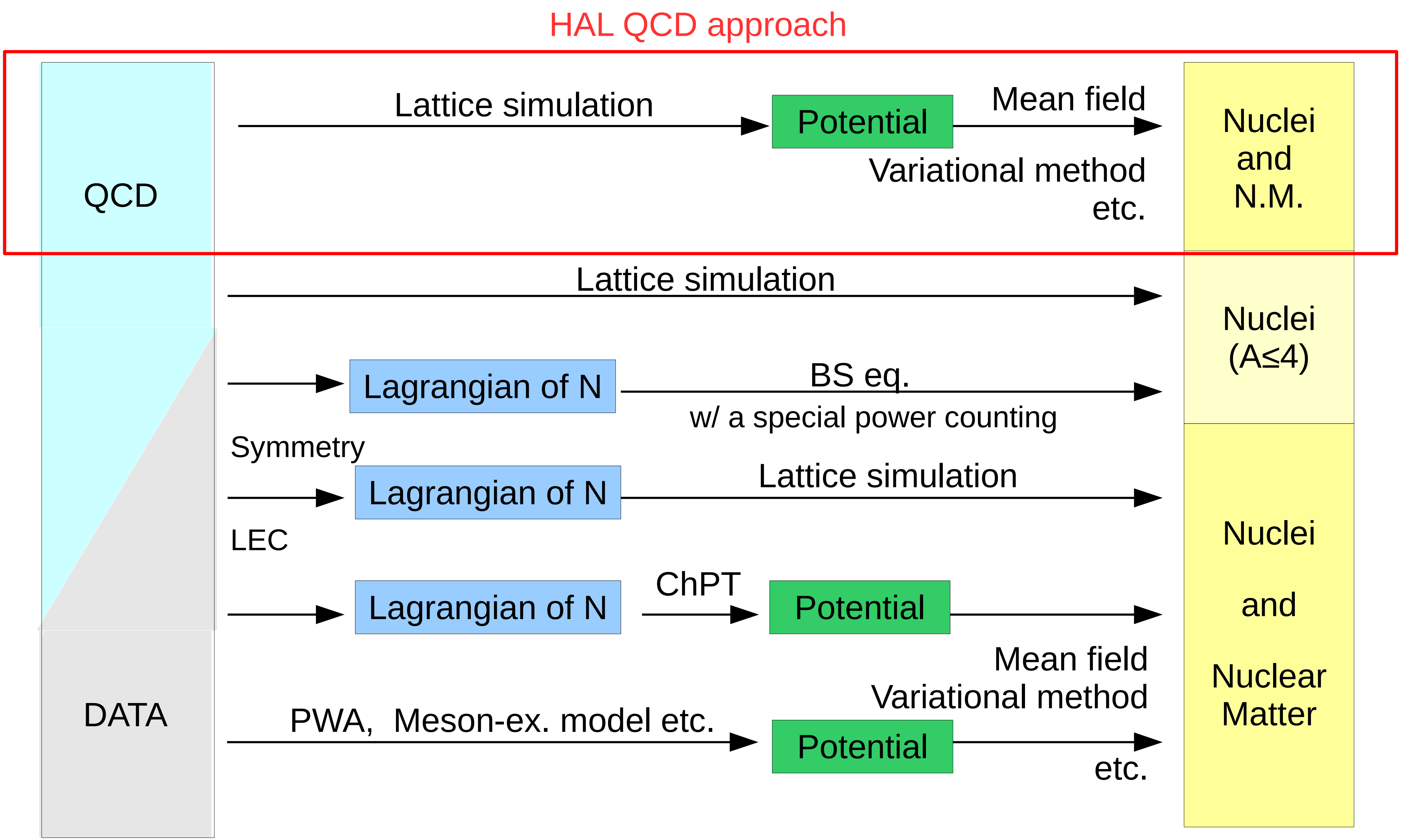
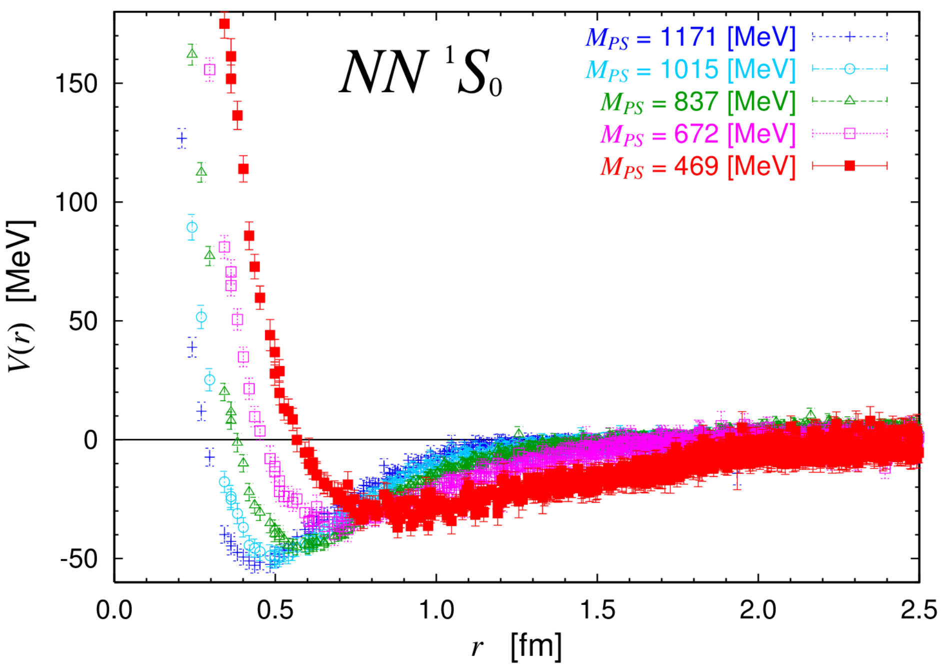
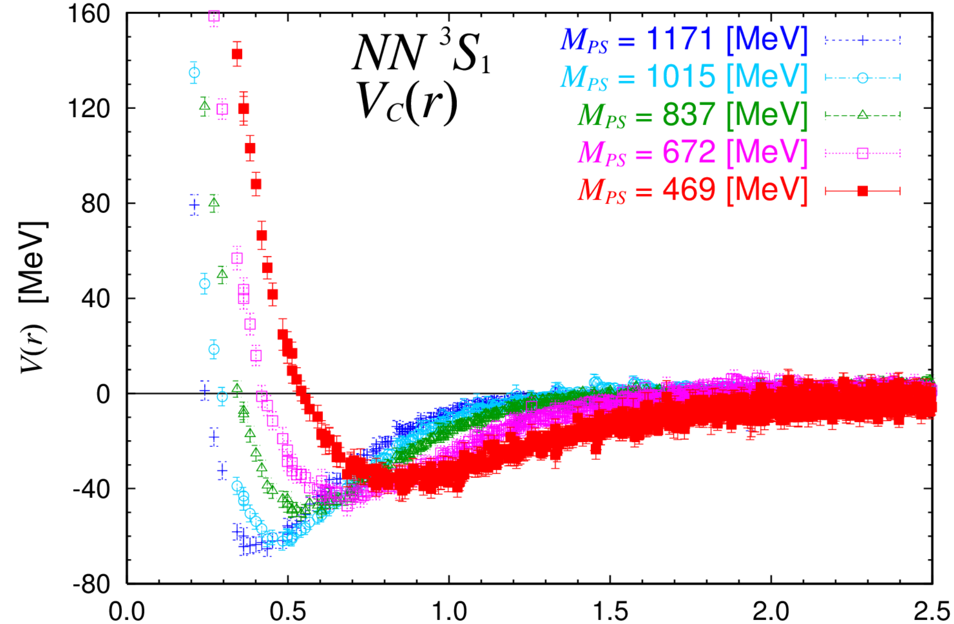


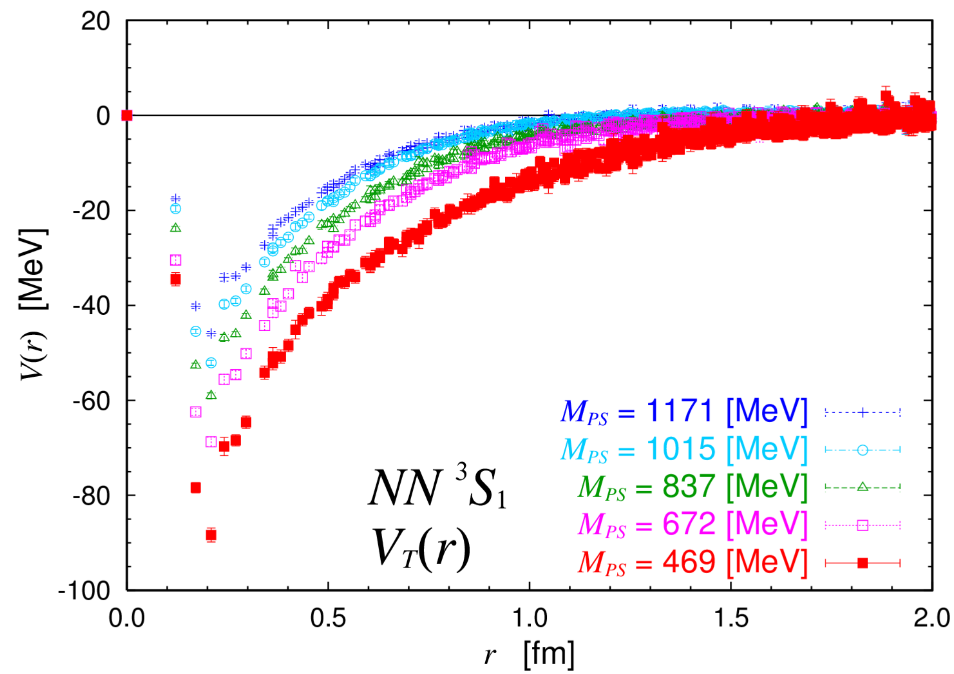
今日は、だいぶ前に、このアプローチで中性子星を調べた話をします。

Nuclear force from QCD

NN potentials from QCD







- At SU(3)$_F$ limit which is useful to capture essential feature of BB int.

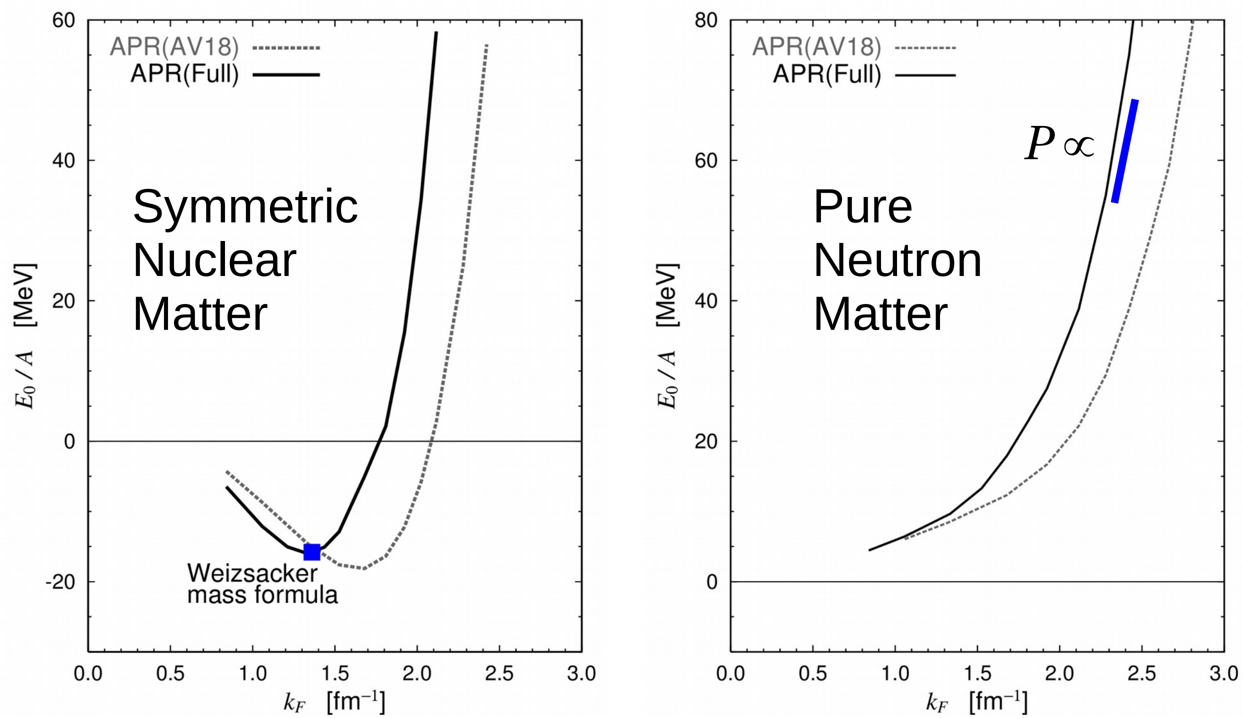
size	β	C_{SW}	a [fm]	L [fm]
32^3 x 32	1.83	1.761	0.121(2)	3.87

- Thanks to PACS-CS collaboration for their DDHMC/PHMC code.

EoS of nuclear matter and Neutron star from QCD

Equation of State

- Ground state of interacting infinite nucleon system
  - Relativistic Mean Field — J. D. Walecka, Ann. Phys. 83 (1974) 491
  - Fermi Hyper-Netted Chain — A. Akmal, V.R. Phandharipande, D.G. Ravenhall Phys. Rev. C 58 (1998) 1804



They used phenomenological Argonne NN force & “Urbana” NNN force.

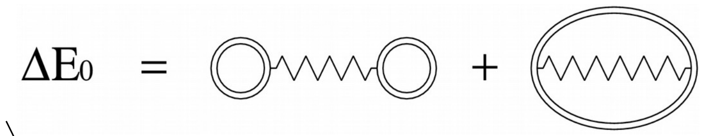
- For SNM, most important feature is the saturation.
- For PNM or NSM, the slope at large k_F is important.

BHF for nuclear matter

K.A. Brueckner and J.L.Gammel
Phys. Rev. 109 (1958) 1023

M.I. Haftel and F. Tabakin,
Nucl. Phys. A158(1970) 1-42

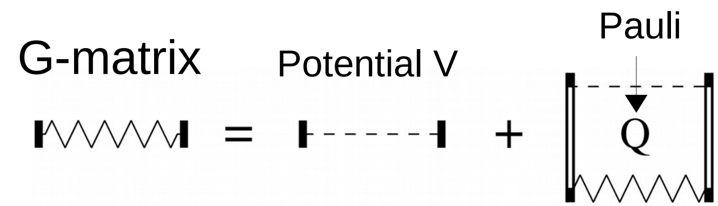
- Ground state energy in BHF framework



$$E_0 = \gamma \sum_{k}^{k_F} \frac{k^2}{2M} + \frac{1}{2} \sum_{i}^{N_{ch}} \sum_{k,k'}^{k_F} \mathrm{Re} \langle G_i(e(k)+e(k')) \rangle_A$$

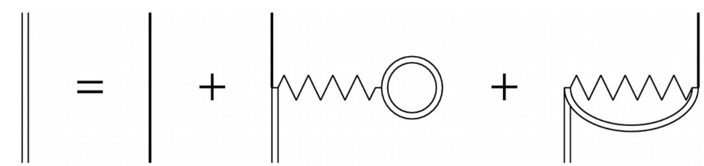
- G-matrix

LQCD V_{NN}



$$\langle k_1 k_2 | G(\omega) | k_3 k_4 \rangle = \langle k_1 k_2 | V | k_3 k_4 \rangle + \sum_{k_5, k_6} \frac{\langle k_1 k_2 | V | k_5 k_6 \rangle Q(k_5, k_6) \langle k_5 k_6 | G(\omega) | k_3 k_4 \rangle}{\omega - e(k_5) - e(k_6)}$$

- Single particle spectrum & potential



$$e(k) = \frac{k^2}{2M} + U(k)$$

LQCD M_N

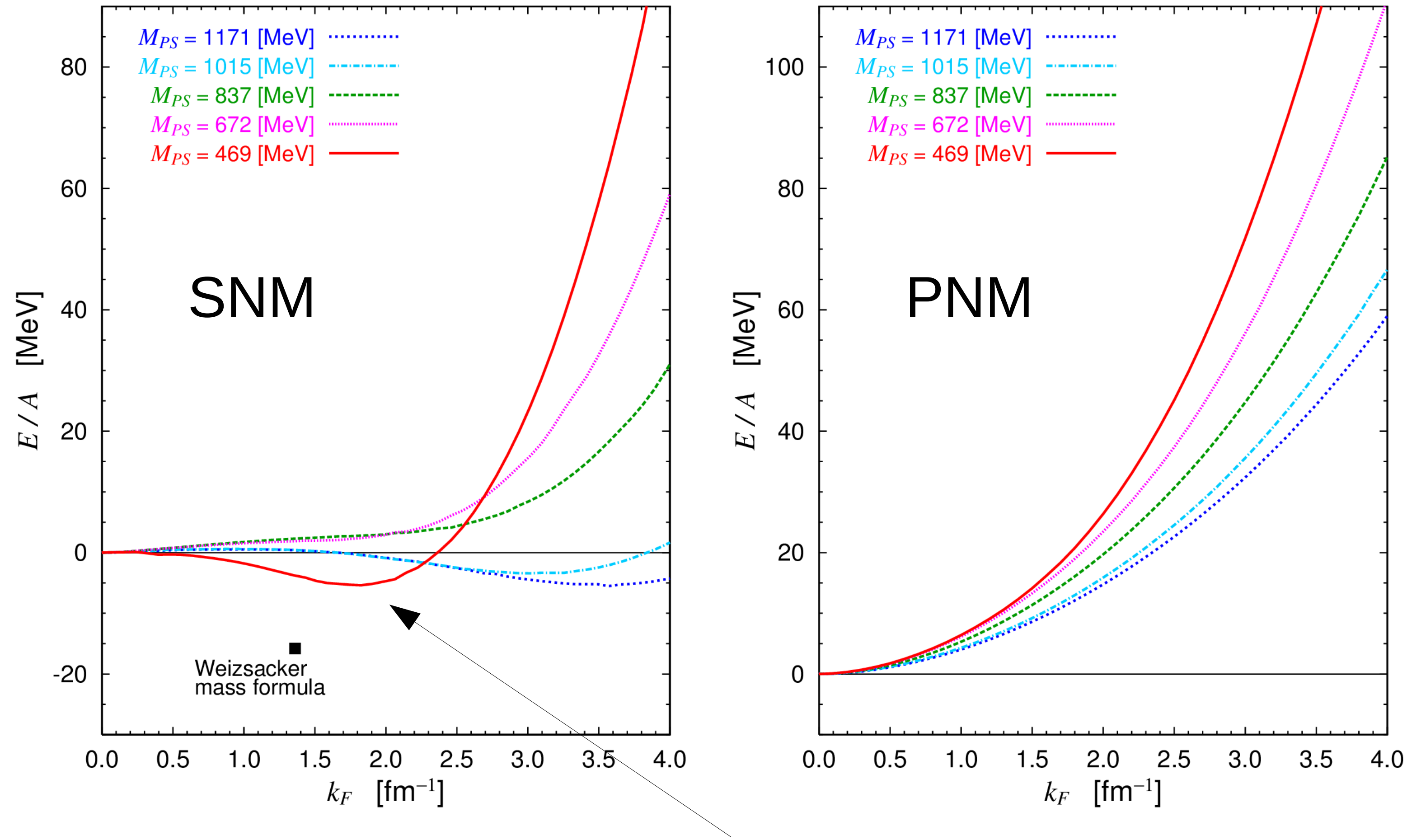
$$U(k) = \sum_{i} \sum_{k' \leq k_F} \mathrm{Re} \langle k k' | G_i(e(k)+e(k')) | k k' \rangle_A$$

limitation

- p.w. decomposition & truncation $^{2S+1}L_J = {}^1S_0, {}^3S_1, {}^3D_1, {}^1P_1, {}^3P_J \cdots$
- Continuous choice w/ parabolic approximation, Angle averaged Q-operator

Matter EoS from QCD

T. Inoue etal. PRL 11, 112503 (2013)



M_N = 2274 MeV
M_N = 2031 MeV
M_N = 1749 MeV
M_N = 1484 MeV
M_N = 1161 MeV

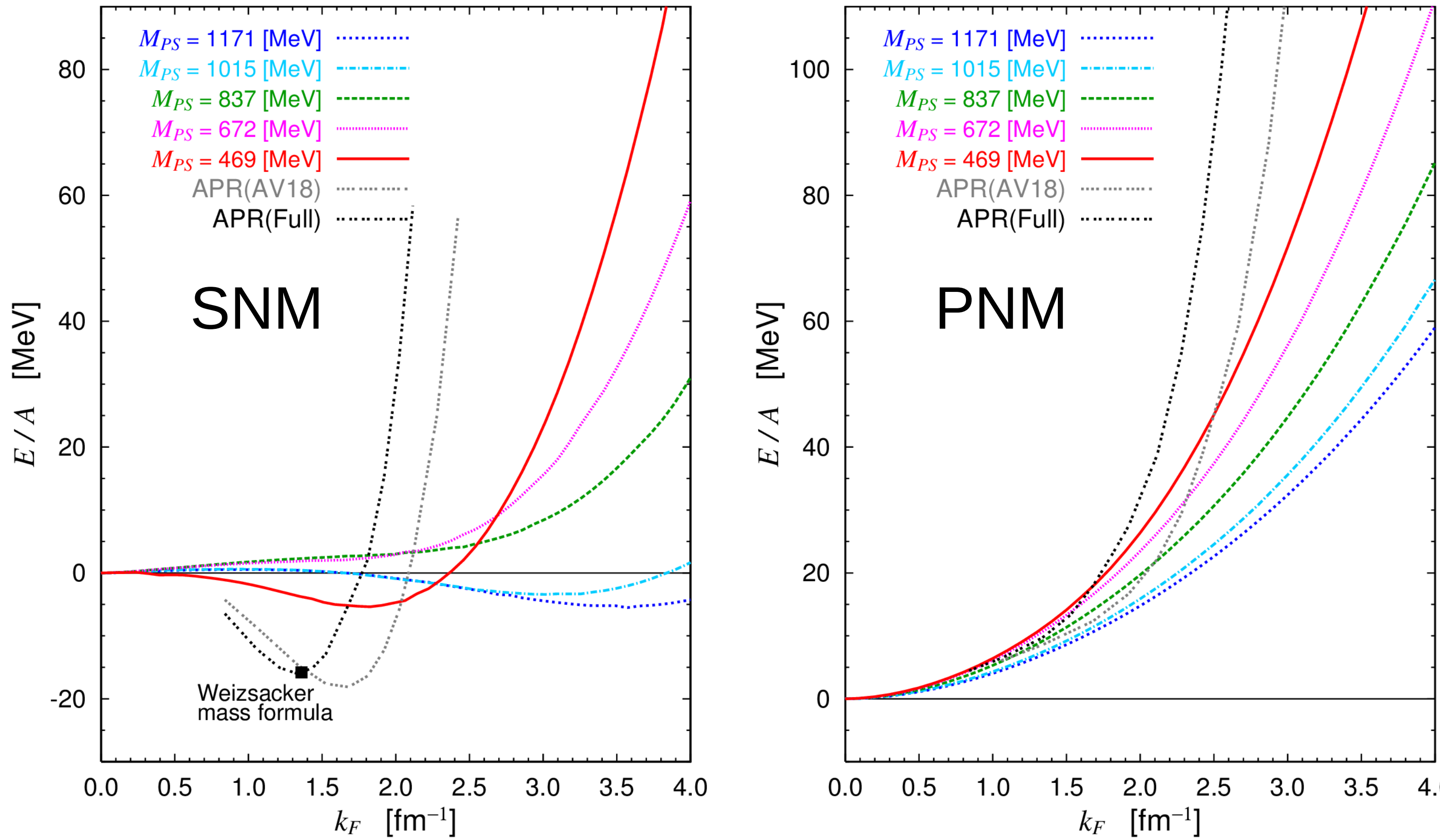
limitation

No NNN force.

- SNM is bound and the saturation occurs at M_{PS} = 469 MeV.
  - Saturation is very delicate against change of quark mass.
- PNM is unbound as normal.
  - PNM become stiff at high density as quark mass decrease.

Matter EoS from QCD

T. Inoue etal. PRL 11, 112503 (2013)



M_N = 2274 MeV
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limitation

No NNN force.

- "APR" curves are EoS of the matter in the physical world, obtained with a variational method and experimental data.
  phenomenological force
- HALQCD EoS largely deviate from the empirical ones, primarily due to the heavy u, d quark in our calculation.

We expect more compatible results from the physical point LQCD.

Stable Neutron Star (spherical & non-rotating)

- Tolman-Oppenheimer-Volkoff equation

$$\frac{dP(r)}{dr} = -\frac{G\,(E(r)+P(r))\,(M(r)+4\pi r^3 P(r))}{r\,(r-2GM(r))}$$

R. C. Tolman, Phys Rev. 55(1939) 364

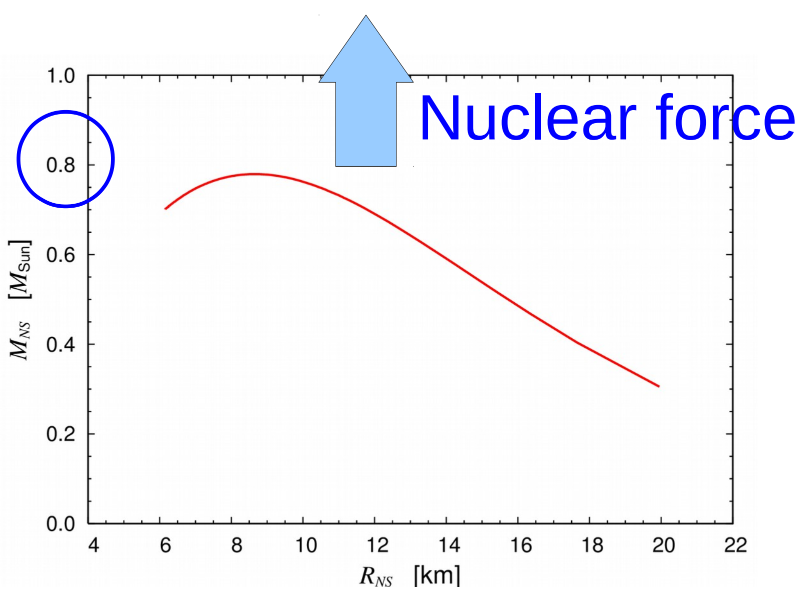
J. R. Oppenheimer and G. M. Volkoff
Phys. Rev. 55 (1939) 374

$$\frac{dM(r)}{dr} = 4\pi r^2 E(r)$$

$P(r)$: Pressure
$E(r)$: Mass-energy density
$M(r)$: Enclosed mass

Gravitational constant
$G = 6.6743 \times 10^{-11}$ [$m^3\ kg^{-1}\ s^{-2}$]

- with $P(E)$ (EoS) for a cold Fermi gas of neutrons.

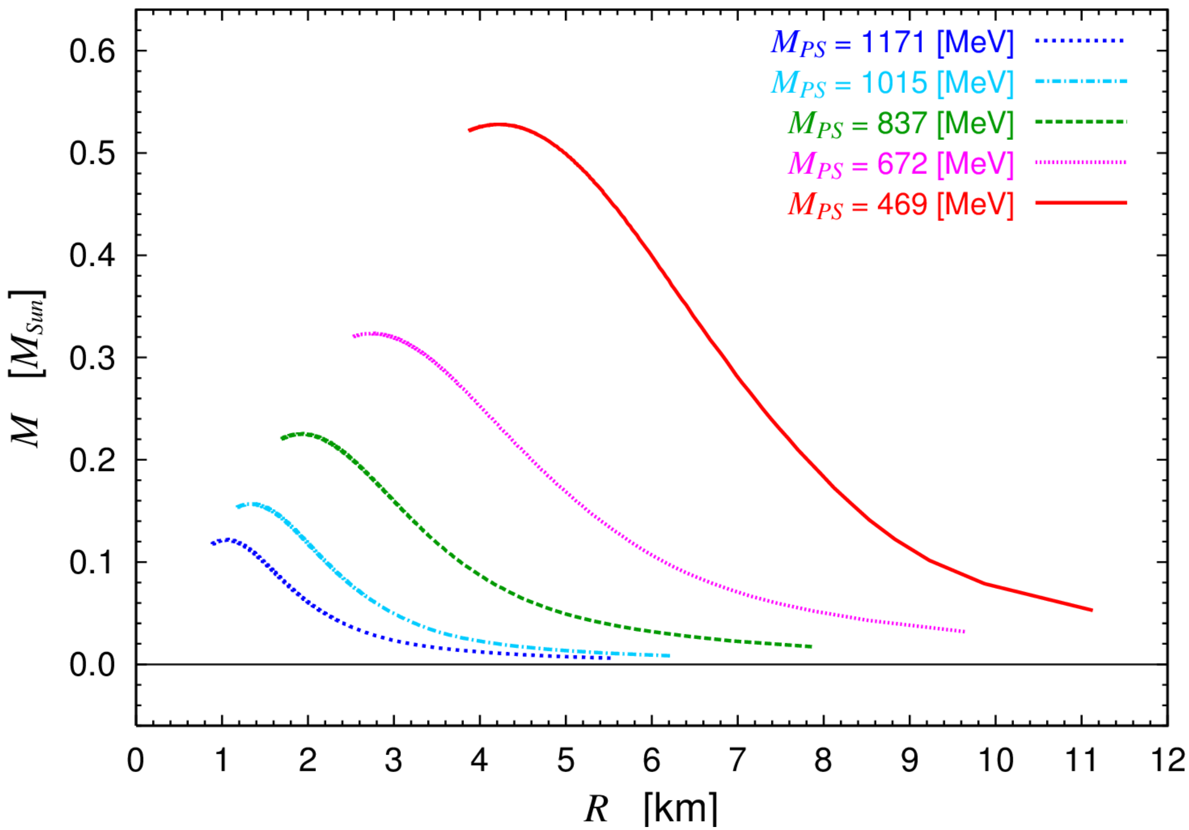


QCD is essential for NS!

Let us apply our LQCD EoS to neutron stars.

Neutron Star M-R relation

T. Inoue etal. PRL 11, 112503 (2013)



M_N = 2274 MeV
M_N = 2031 MeV
M_N = 1749 MeV
M_N = 1484 MeV
M_N = 1161 MeV

No crust.
Uniform matter only.

- Mass-radius curve of neutron stars at five value of mq.
  - M^{max} = 0.12 – 0.52 [$M_\odot$] for M_{ps} = 1171 – 469 [MeV].
  - due to heavy nucleon and weaker repulsion at short distance.
  - M^{max} will be much bigger with lighter u,d quark.

We expect more compatible results from the physical point LQCD.

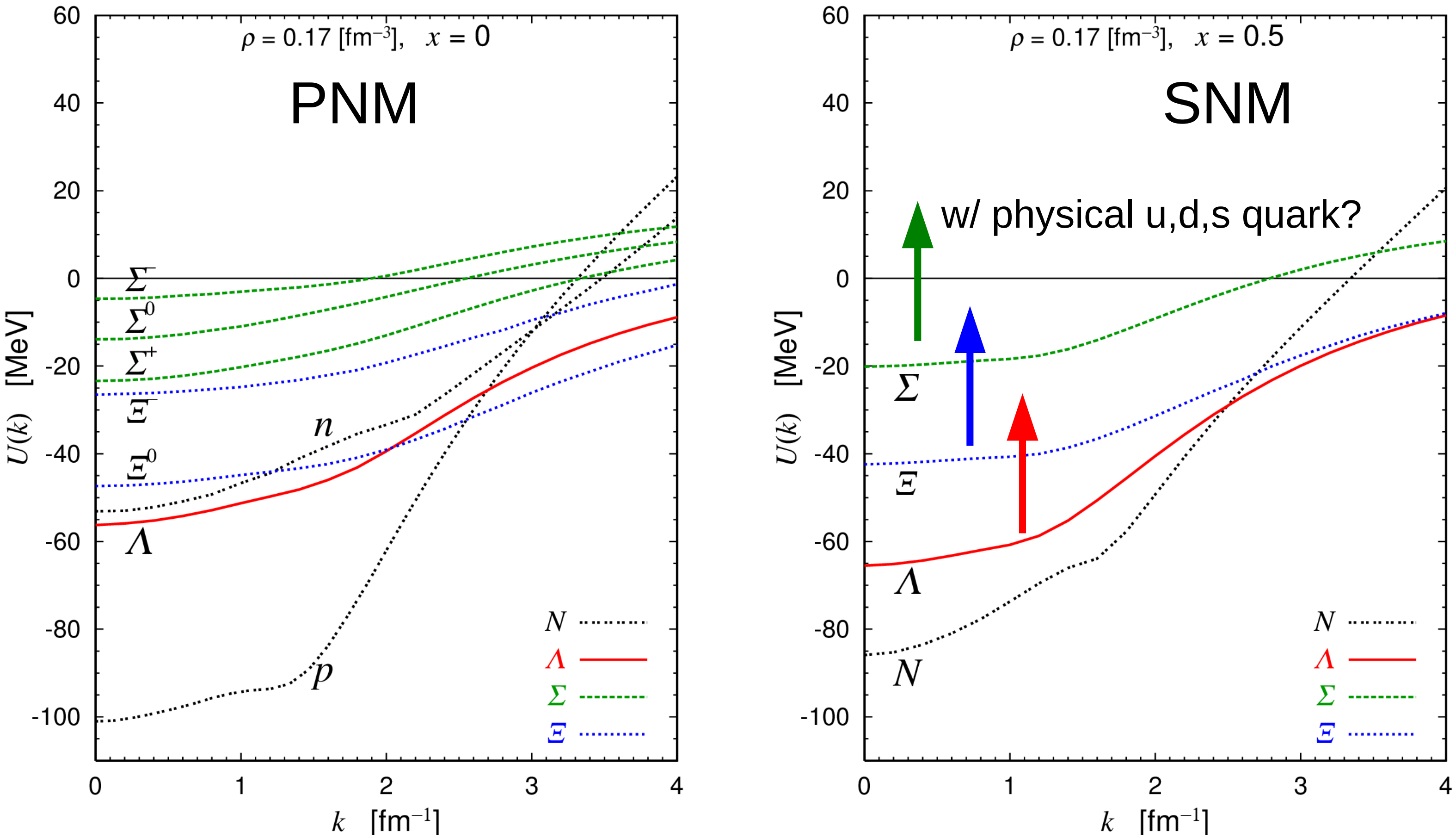
More on Neutron star and QCD

Strangeness in neutron star

- Probably, hyperons exist in core of NS.
- How EoS of NS mater can be stiff with hyperon?
- Tough problem due to ambiguity of YN, YY force.
  - ambiguity due to shortage of experimental data.
- But, we can study hyperon in nuclear medium by basing on YN, YY force extracted from QCD.
- Hyperon chemical potential $\mu_Y(\rho)$ in matter and onset density are given by single-particle potential

Hyperon spectrum in nuclear medium $$e_Y(k) = \frac{k^2}{2M_Y} + \underline{U_Y(k)}$$

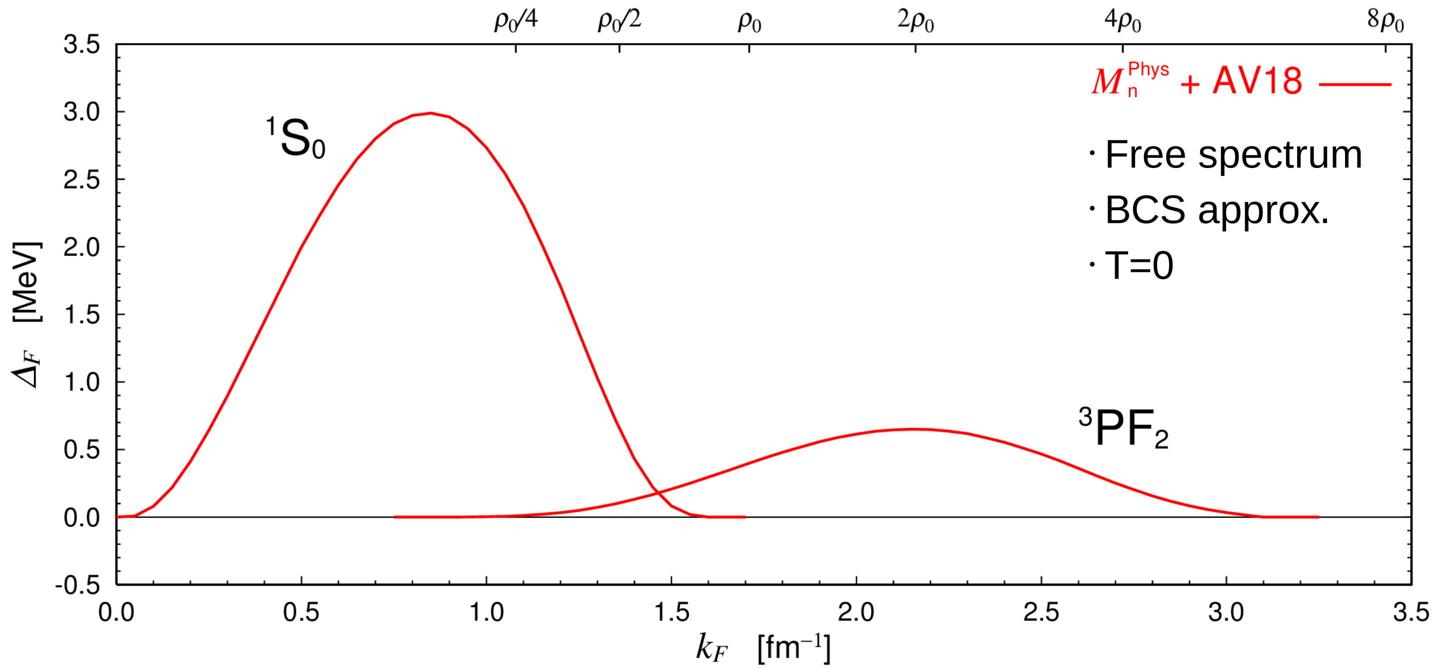
M_B^{Phys} + AV18 NN + LQCD YN,YY



at the normal nuclear density

- LQCD result $U_\Lambda(k) < U_\Xi(k) < U_\Sigma(k)$ is consistent to data.
- LQCD $U_Y(k)$ are deeper than data and model predictions.
- Due to unphysically heavy u,d quark and light s quark. (?)

Neutron pairing gap in PNM



$$\Delta_F = \Delta(k_F) \quad \text{where}$$

$$E(p) = \sqrt{\epsilon(p)^2 + \Delta(p)^2}$$

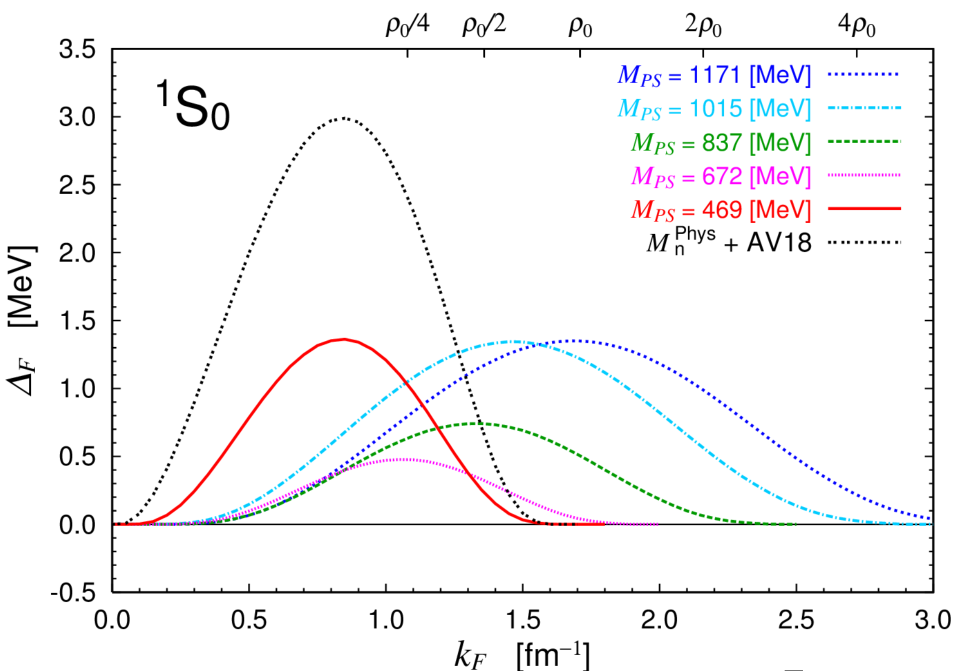
Elementary excitation
(Bogolon) spectrum

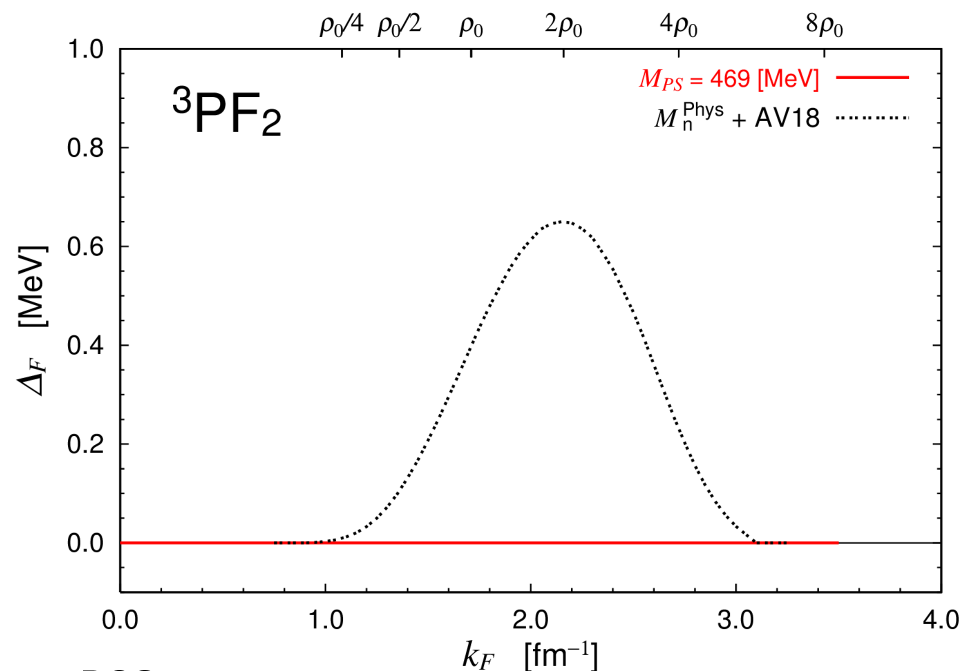
- Neutron superfluid may exist in crust and core of NS due to paring gap in $^1S_0$ and $^3PF_2$ channel, respectively.

T. Takatsuka and R. Tamagaki, Prog. Theo. Phys. 46 (1971) 114, Suppl. 112 (1993) 27

- Surface superfluid may be origin of the glitch phenomenon.
- Core superfluid affects ν production rate and cooling rate.
    - It is already observed in NS in Cassiopeia A (?)

Neutron pairing gap from QCD





・ Free spectrum, BCS approx.

- Left: $^1S_0$ pairing gap in PNM at T=0.
  - QCD derive finite gap at all the five m_q. → Super
  - Nontrivial m_q dependence. Peak moves to lower density.
- Right $^3PF_2$ pairing gap in PNM at T=0.
  - QCD derive no gap at that quark mass. → Normal

Summary and Outlook

まとめと展望

- 中性子星とバリオン物質と格子QCDの関係
  - バリオン物質の高密度での状態方程式の必要性
  - 実験データが不足しているハイペロン力の必要性
  - 格子QCDの直接数値計算の困難
- HALQCDアプローチで中性子星への例
  - クォークが重い世界で格子QCD数値計算 ⇨ 核力の導出。
  - BHF で EoS の計算。SNMの飽和性を再現。
  - TOV方程式 ⇨ M-R 曲線。最大質量のクォーク質量依存性。
  - ハイペロンの出現や超流動の有無の研究にも有力。

重いクォーク、足りない部分波、平均場 etc.

- 今日紹介した例は第一歩に過ぎない（要改善な点が多々ある）。今後このアプローチを発展させる事によって、より確かな基礎を基に中性子星の理論研究が可能になる時代が来ると信じている。