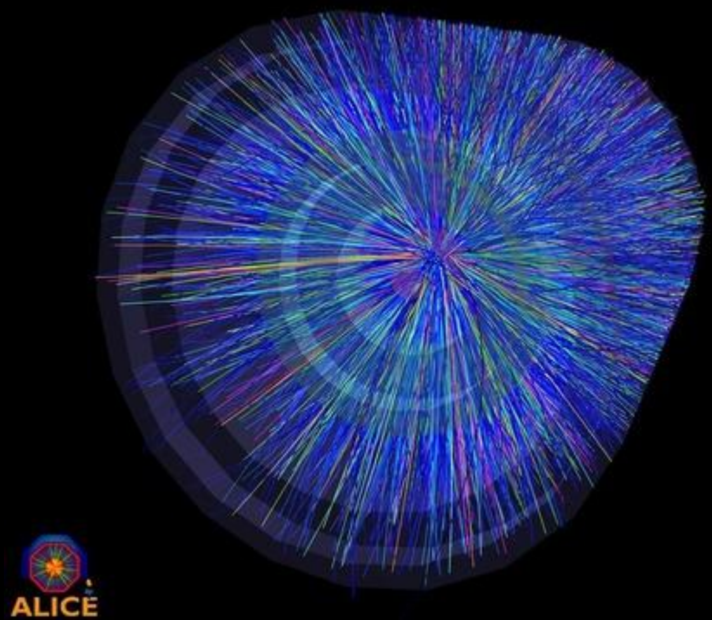
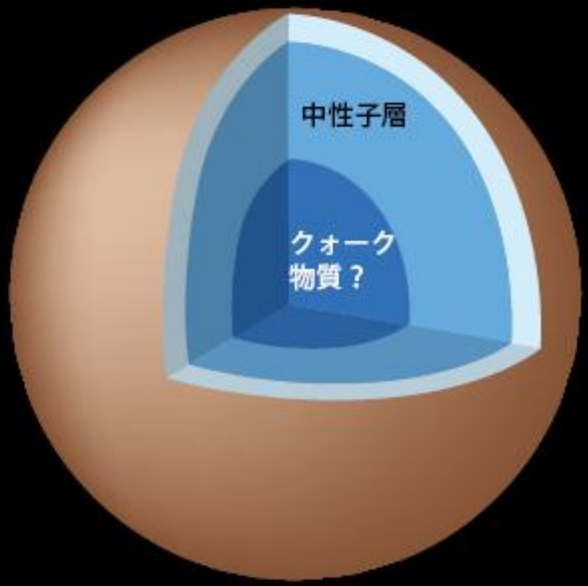
強相関ハドロンクォーク多体系





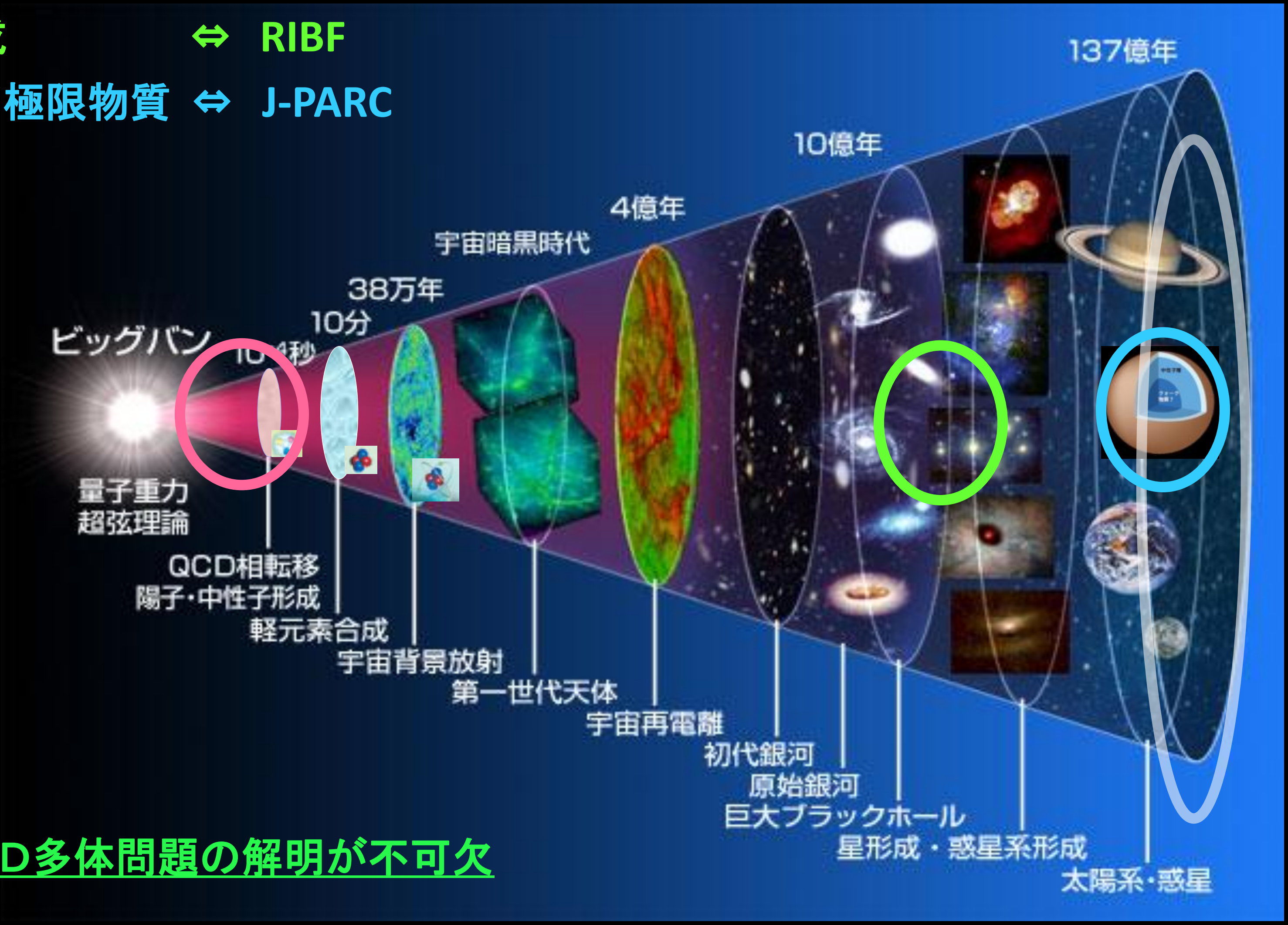
Hot matter： T ～10^{12}K

Dense matter：ρ ～ 10^{12} kg/cm^3

T. Hatsuda (Tokyo/RIKEN) June 11 (2011) at KEK

バリオン物質の起源と進化
-- 我々はどこから来てどこへ行くのか？ --

- 宇宙初期の極限物質 ⇔ RHIC, LHC
- 重元素の合成 ⇔ RIBF
- 星の終焉での極限物質 ⇔ J-PARC



いずれにもQCD多体問題の解明が不可欠

過去10年間: 着実な進歩＋新しいアイデア

1. RHICデータと相対論的流体力学 ⇔ QGP研究の精密化
2. 格子QCD計算の進展 ⇔ 高温QCD物質の状態方程式
3. CGC理論の進展 ⇔ 高エネルギーQCD反応の理解
4. ゲージ/重力対応 ⇔ 強結合QCDプラズマの性質
5. 冷却原子気体の物理 ⇔ 高密度QCDの相構造
6. 中性子星観測データ ⇔ 高密度QCDの状態方程式

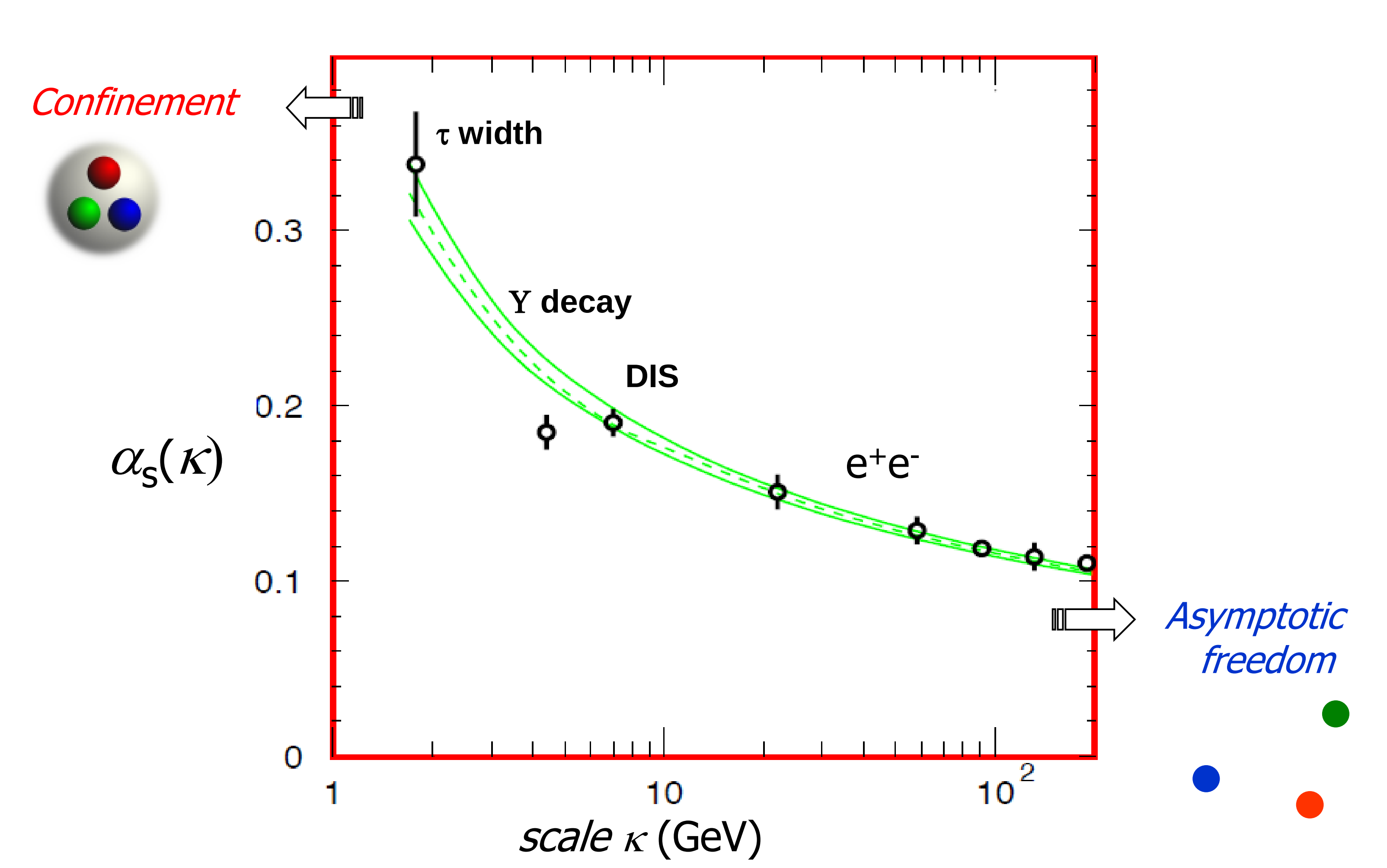
contents

1. Introduction
2. Hot QCD confronts HI experiments
3. Dense QCD confronts neutron star observations

(4. Dense QCD confronts ultracold atomic experiments ?)

5. Exotic-hadron hunting in HIC
6. Summary

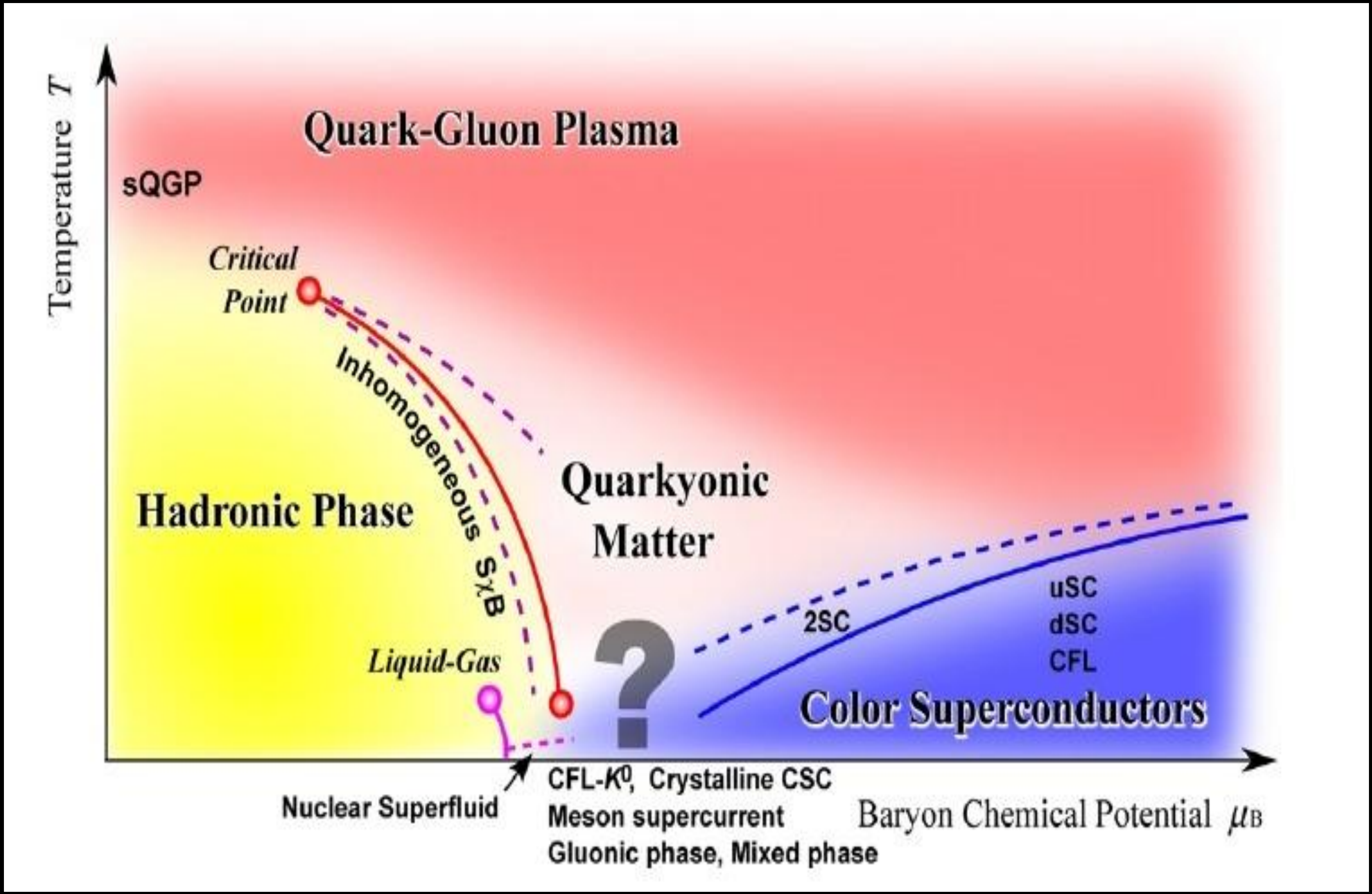
QCD running coupling



1975 Idea of quark-gluon plasma at high T (Cabbibo & Parisi)

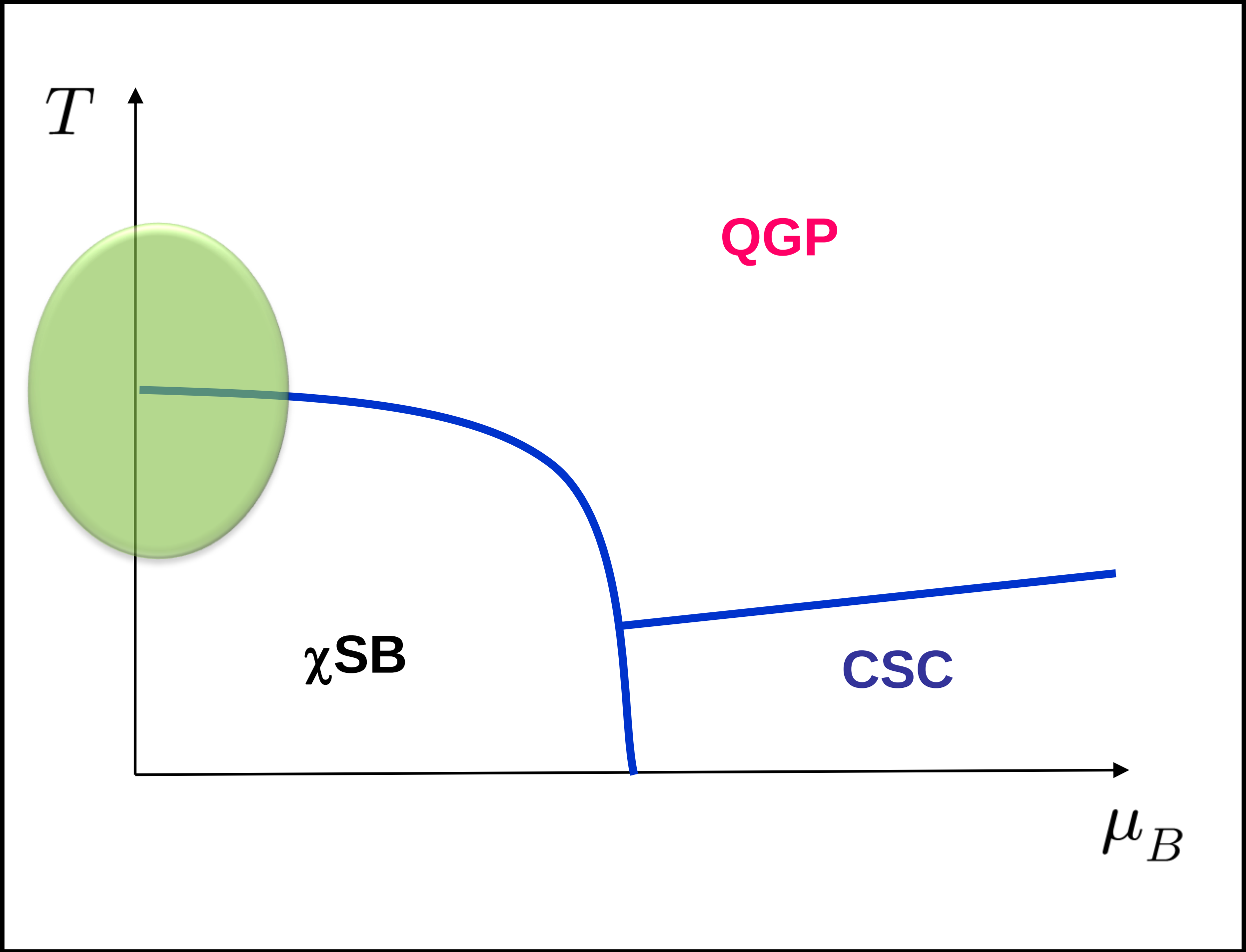
1975 Idea of quark matter at high baryon density (Collins & Perry)

QCD Phase Structure (for $m_{u,d} \neq m_s \neq 0$)

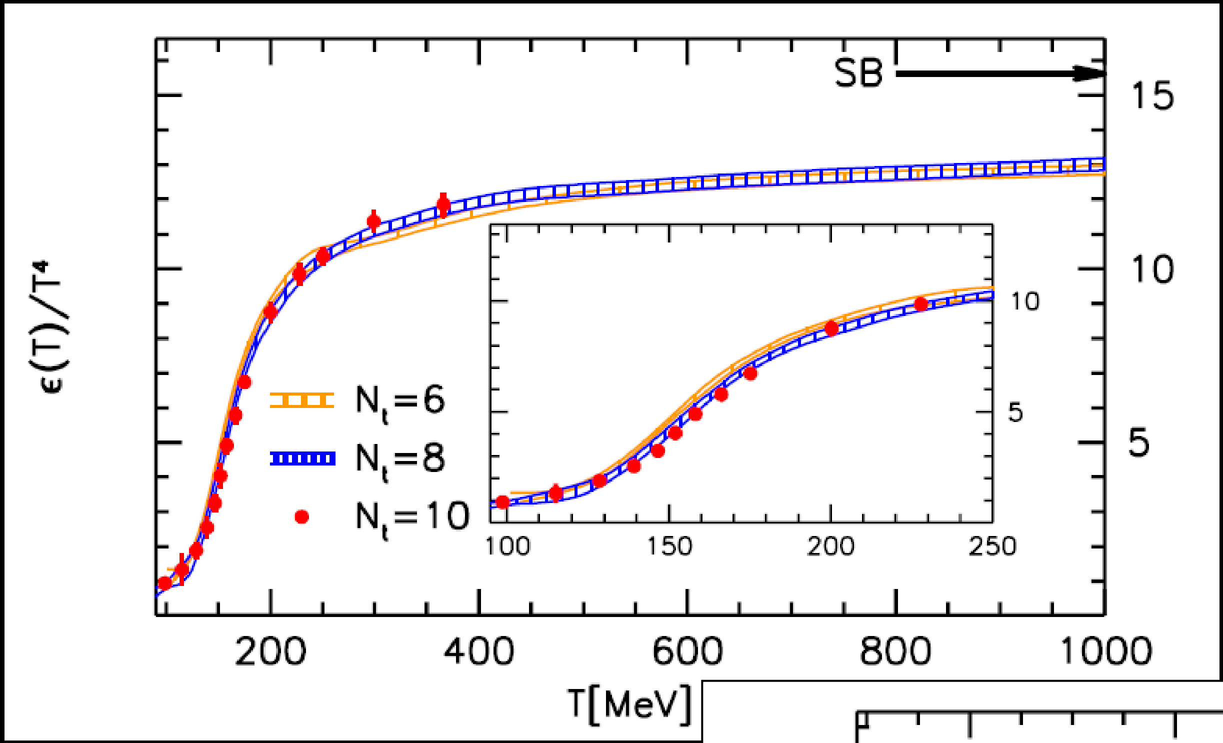


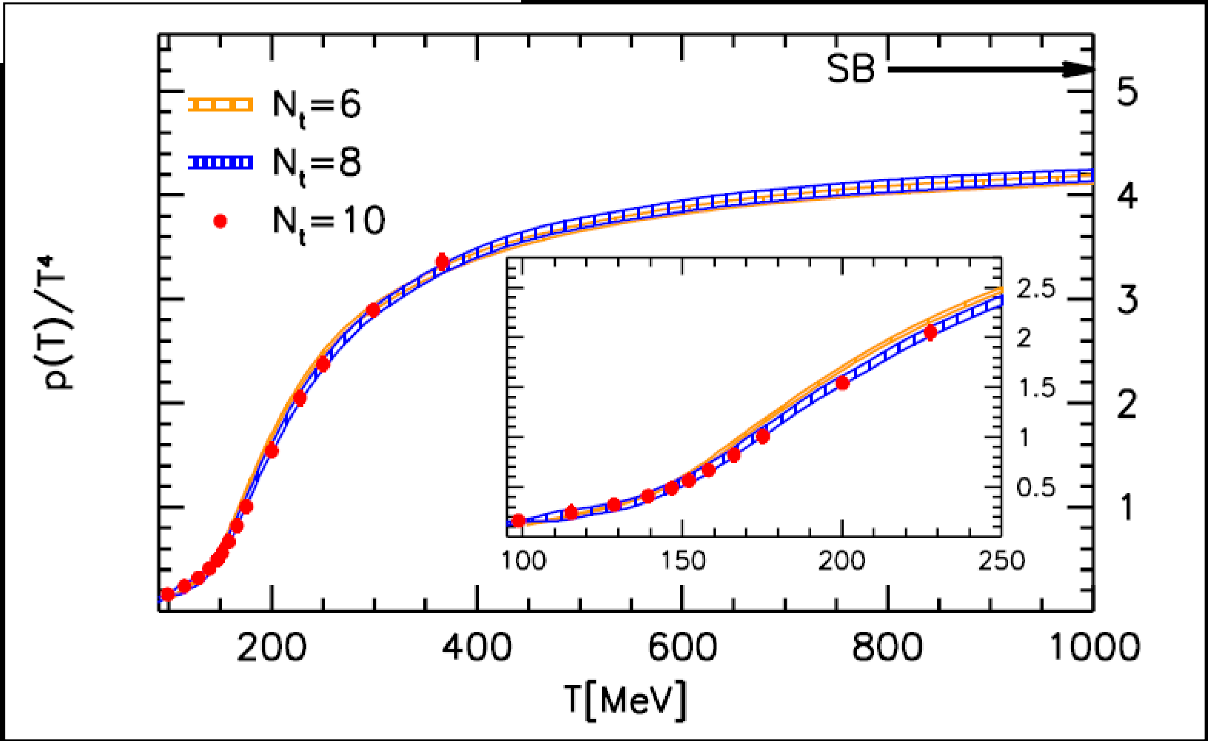
K. Fukushima + T.H.
Rep. Prog. Phys. 74 (2011) 014001

Hot QCD confronts HIC



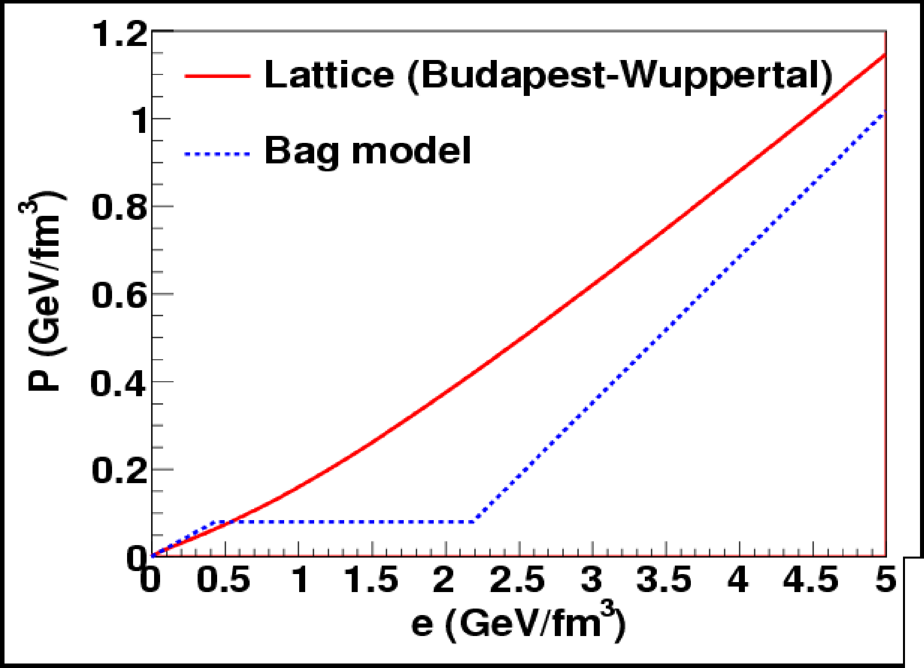
Thermal EOS in the real world





Wuppertal-Budapest Coll.
physical point simulation
with (2+1)-flavor staggard quarks
arXiv:1011.4229 [hep-lat]

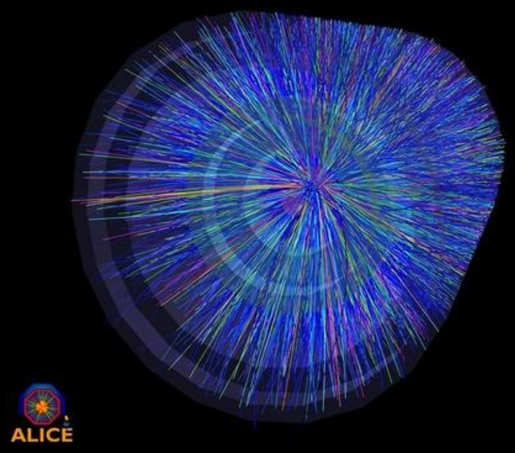
3D ideal-hydrodynamics with lattice EOS

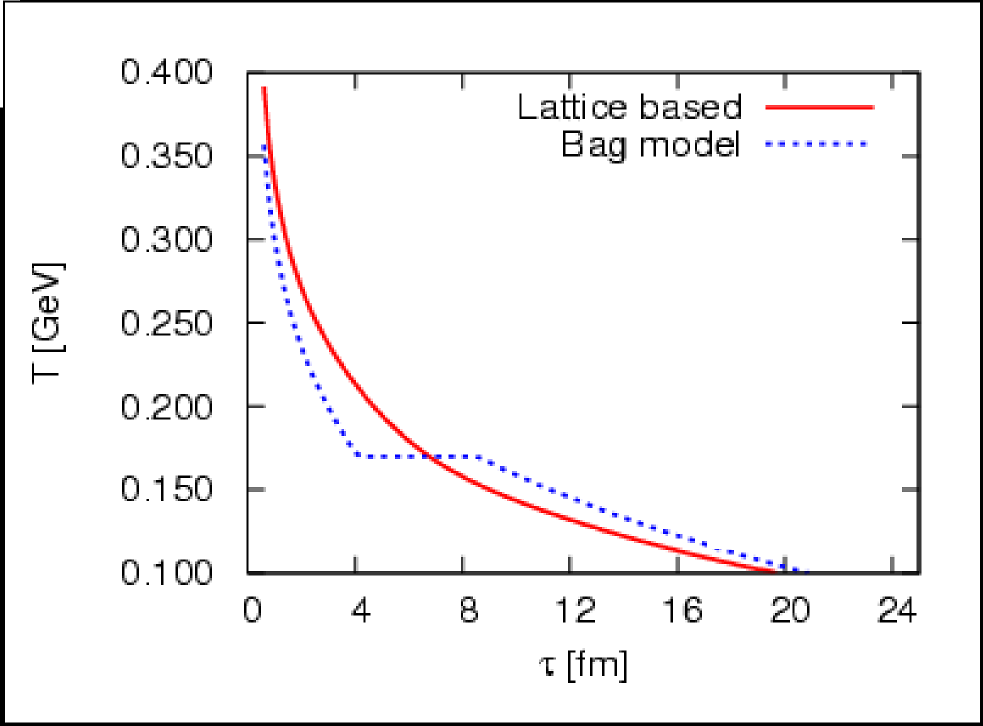


State-of-the-art lattice EOS
\+ Full 3D ideal-hydrodynamics

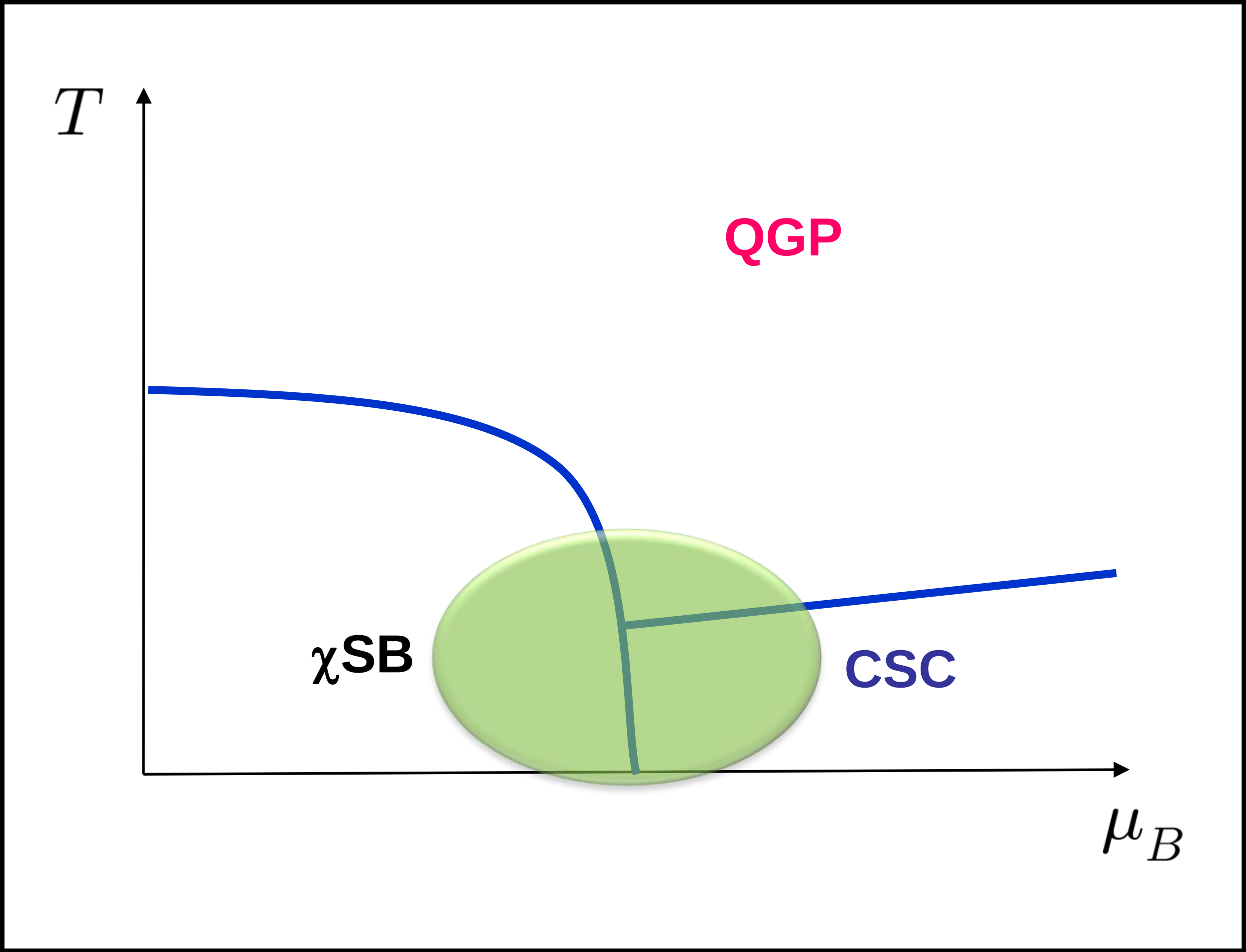
$$\partial_\mu T^{\mu\nu}(e,p)=0$$

Akamatsu, Hirano, Hamagaki, Hatsuda
in preparation

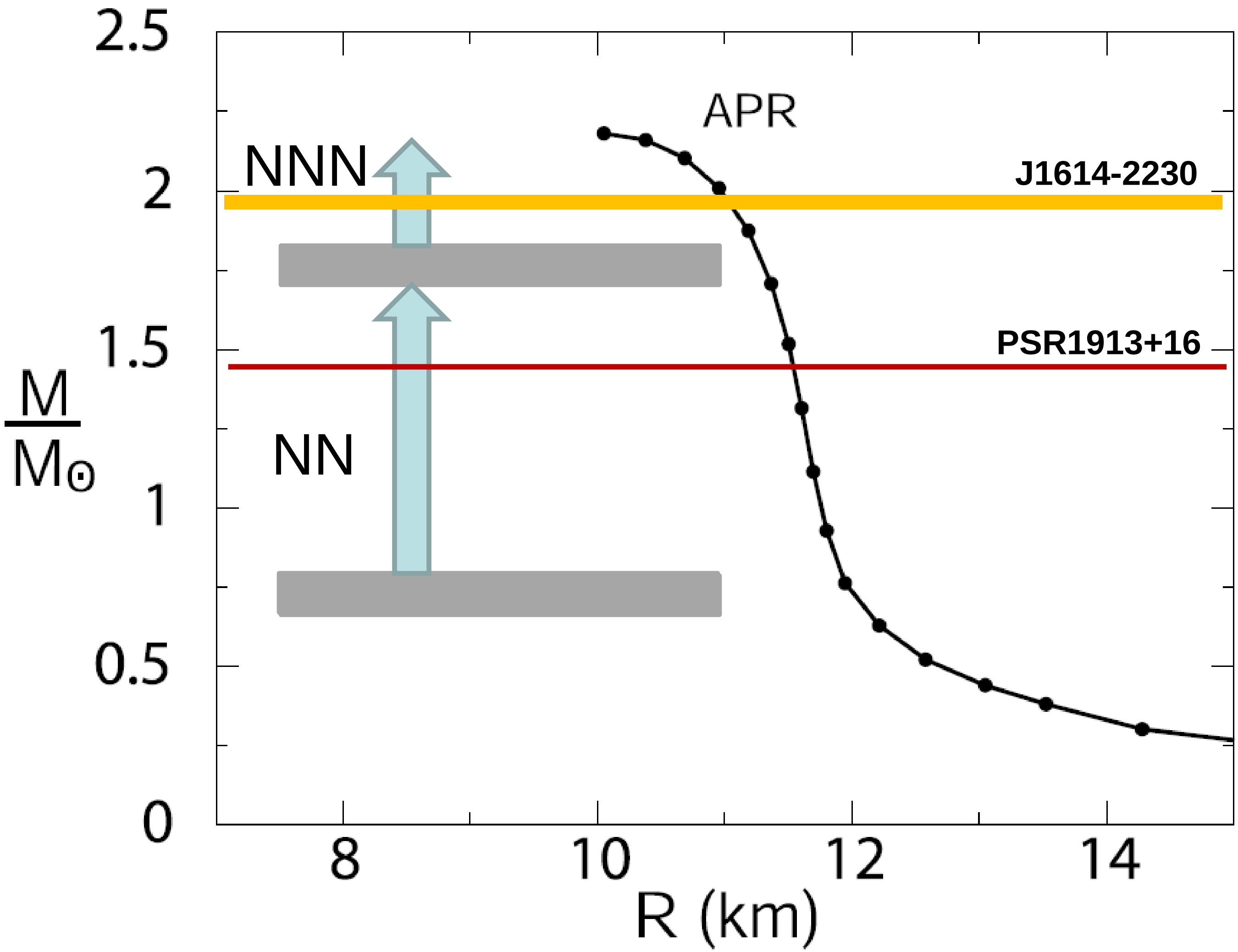


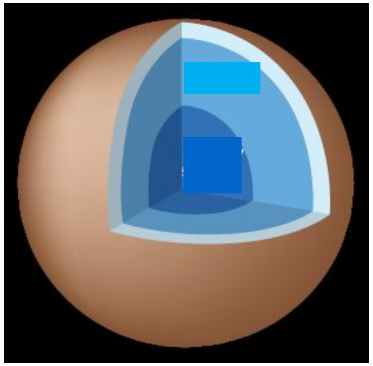


Dense QCD confronts N$_\star$

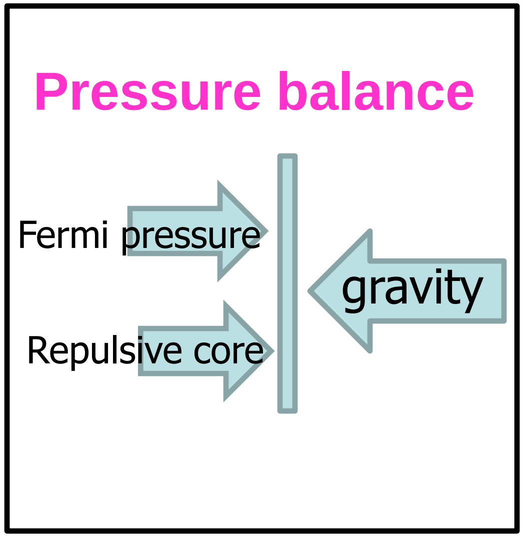


Neutron star, BB force & Takatsuka problem





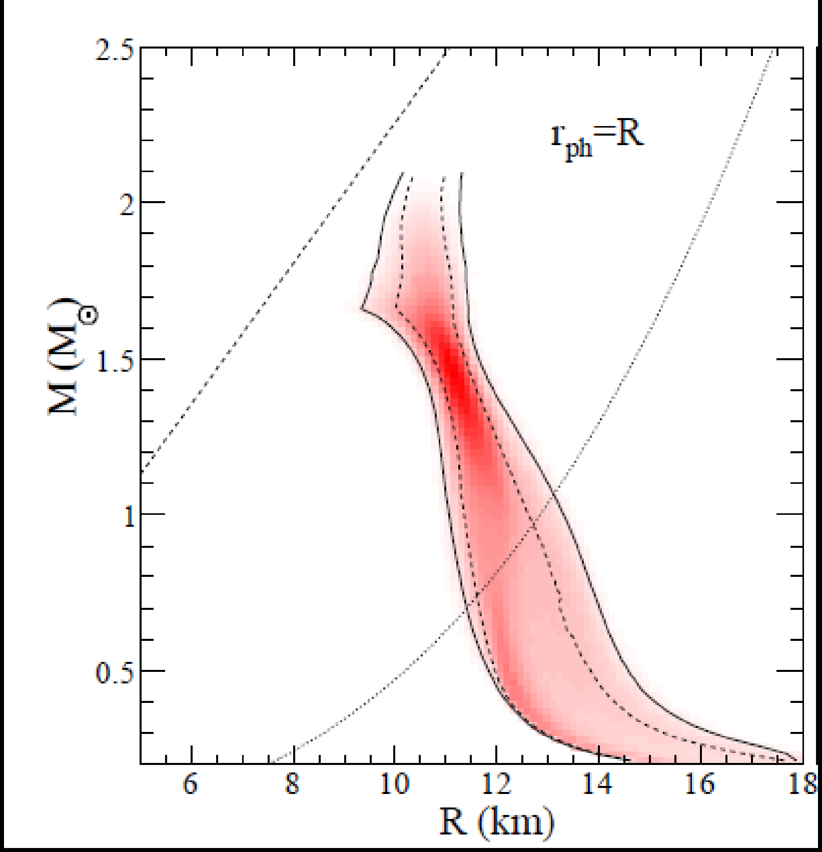
(ρ_{max} ~ $6\rho_0$)

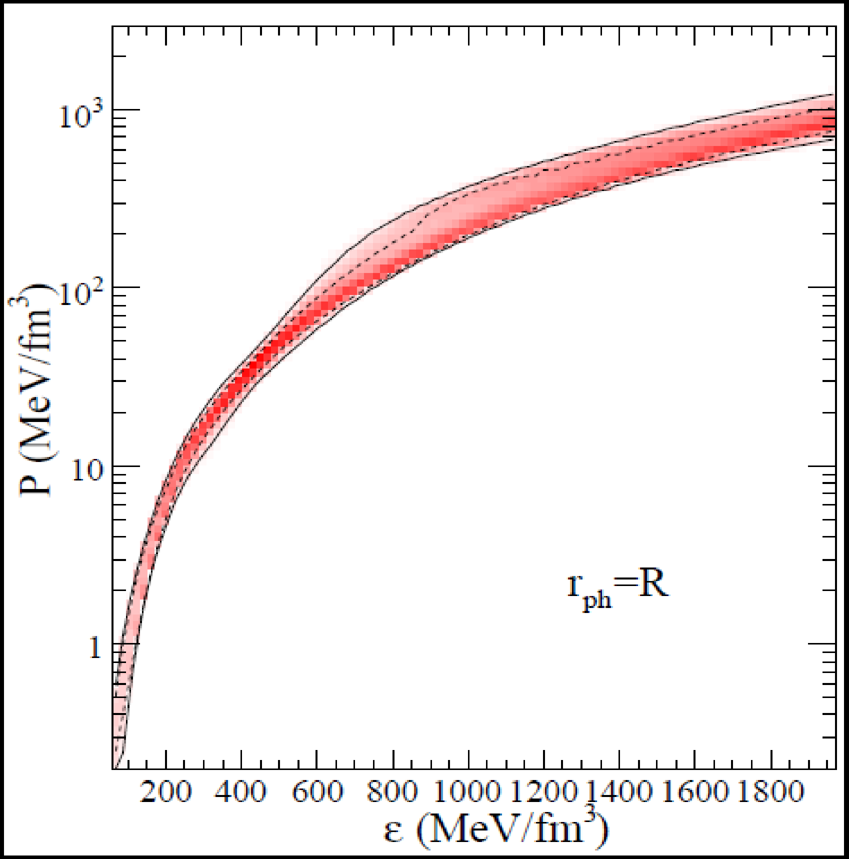


From TOV to EOS

Ozel, Baym & Guver, arXiv: 1002.3153 [astro-ph.HE]
Steiner, Luttimer & Brown, arXiv: 1005.0811 [astro-ph.HE]

M-R relation from
thermonuclear Burst in X-ray Binaries

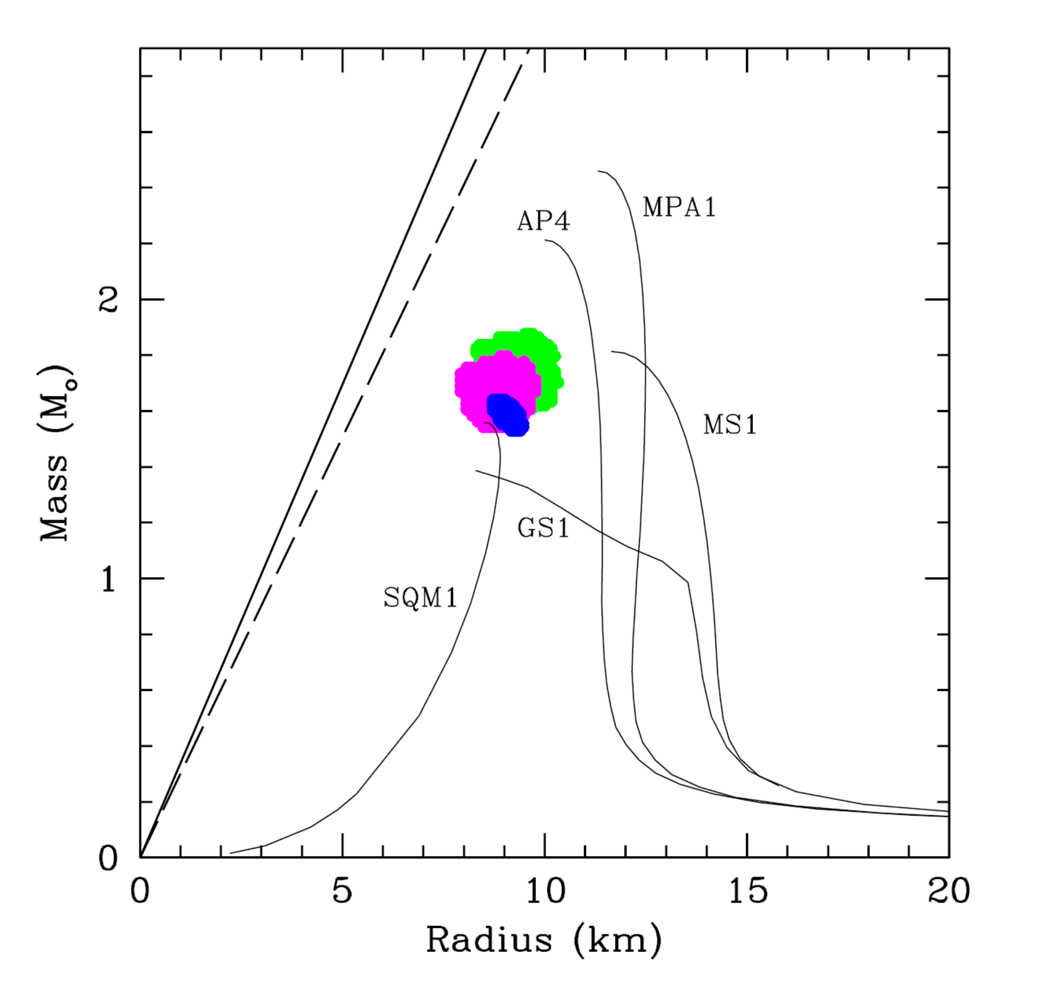




Mass-Radius relation of Neutron Stars and dense EOS

Thermonuclear Burst in X-ray Binaries

4U 1608-248 EXO 1745-248 4U 1820-30



(i) Apparent surface area

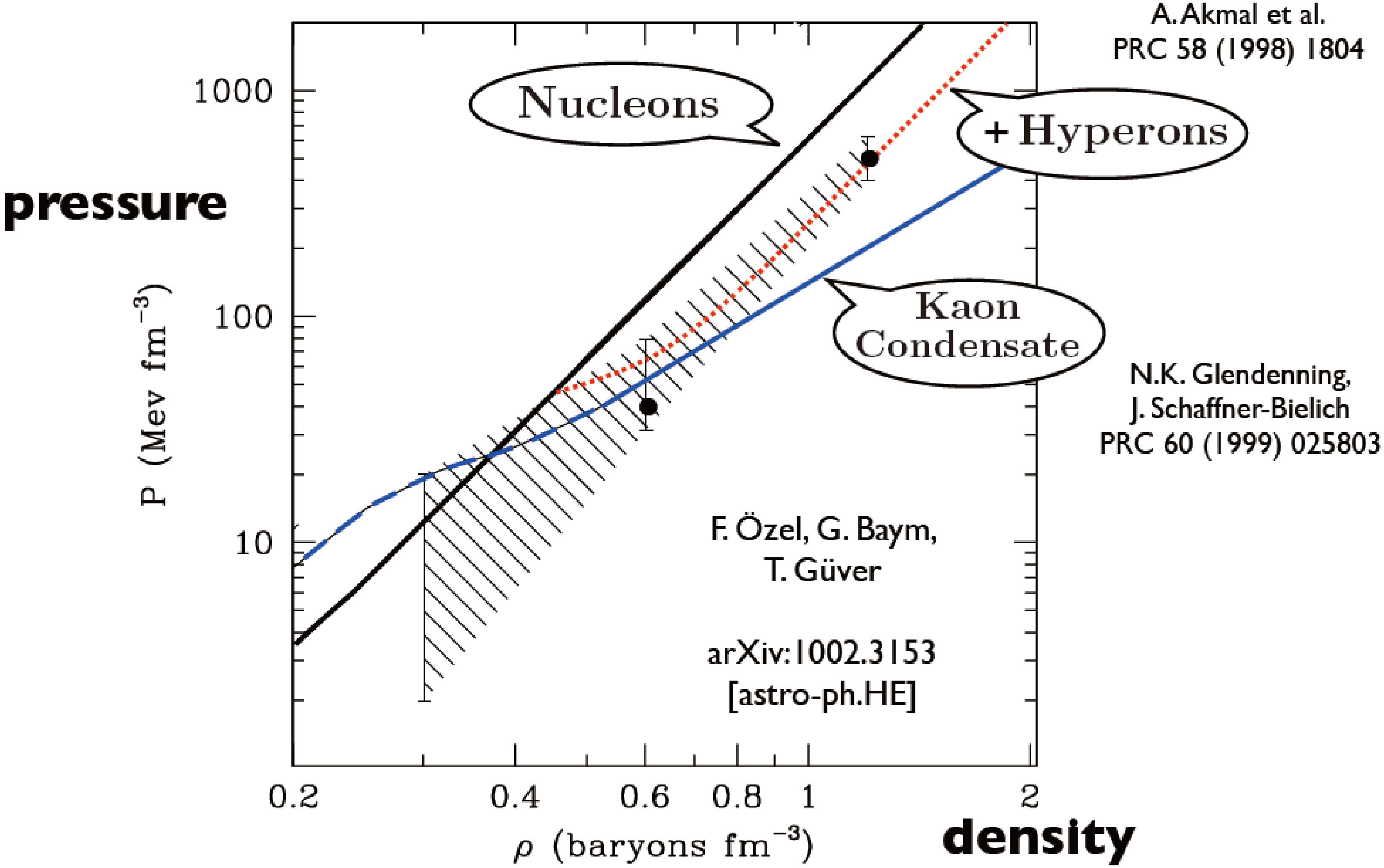
$$A = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{R}\right)^{-1}$$

(ii) Eddington limit

$$F_{edd} = \frac{4\pi GM}{\kappa_{cs} D^2}\left(1 - \frac{2GM}{R}\right)^{1/2}$$

Ozel, Baym & Guver, arXiv: 1002.3153 [astro-ph.HE]

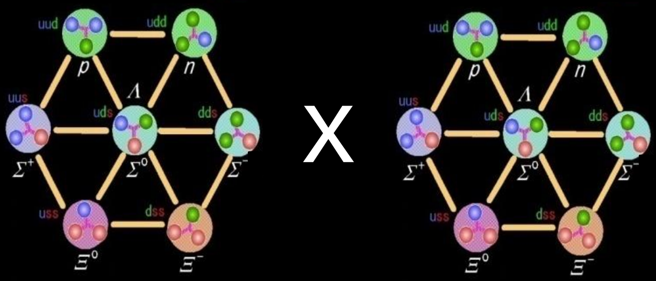
Implications for the **EQUATION of STATE**



- **Nucleons + Hyperons** more likely than **Kaon Condensate** or **Quark Matter**

W. Weise (2010)

BB force in SU(3) world



1. First step to study YN, YY interactions not accessible in exp.
2. Origin of the short range repulsion
3. Fate of H-dibaryon in the ideal limit

$$8 \times 8 = \underbrace{27 + 8s + 1}_{\text{Symmetric}} + \underbrace{10^* + 10 + 8a}_{\text{Anti-symmetric}}$$

Six independent potentials in flavor-basis

$$V^{(27)}(r),\ V^{(8s)}(r),\ V^{(1)}(r) \rightarrow {}^1S_0$$

$$V^{(10^*)}(r),\ V^{(10)}(r),\ V^{(8a)}(r) \rightarrow {}^3S_1$$

irreducible BB source operator

$$\overline{BB}^{(27)} = +\sqrt{\frac{27}{40}}\,\overline{\Lambda\Lambda} - \sqrt{\frac{1}{40}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{12}{40}}\,\overline{N\Xi} \quad \text{or} \quad +\sqrt{\frac{1}{2}}\,\overline{p\,n} + \sqrt{\frac{1}{2}}\,\overline{n\,p}$$

$$\overline{BB}^{(8s)} = -\sqrt{\frac{1}{5}}\,\overline{\Lambda\Lambda} - \sqrt{\frac{3}{5}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{1}{5}}\,\overline{N\Xi}$$

$$\overline{BB}^{(1)} = -\sqrt{\frac{1}{8}}\,\overline{\Lambda\Lambda} + \sqrt{\frac{3}{8}}\,\overline{\Sigma\Sigma} + \sqrt{\frac{4}{8}}\,\overline{N\Xi}$$

with

$$\overline{\Sigma\Sigma} = +\sqrt{\frac{1}{3}}\,\overline{\Sigma^+\Sigma^-} - \sqrt{\frac{1}{3}}\,\overline{\Sigma^0\Sigma^0} + \sqrt{\frac{1}{3}}\,\overline{\Sigma^-\Sigma^+}$$

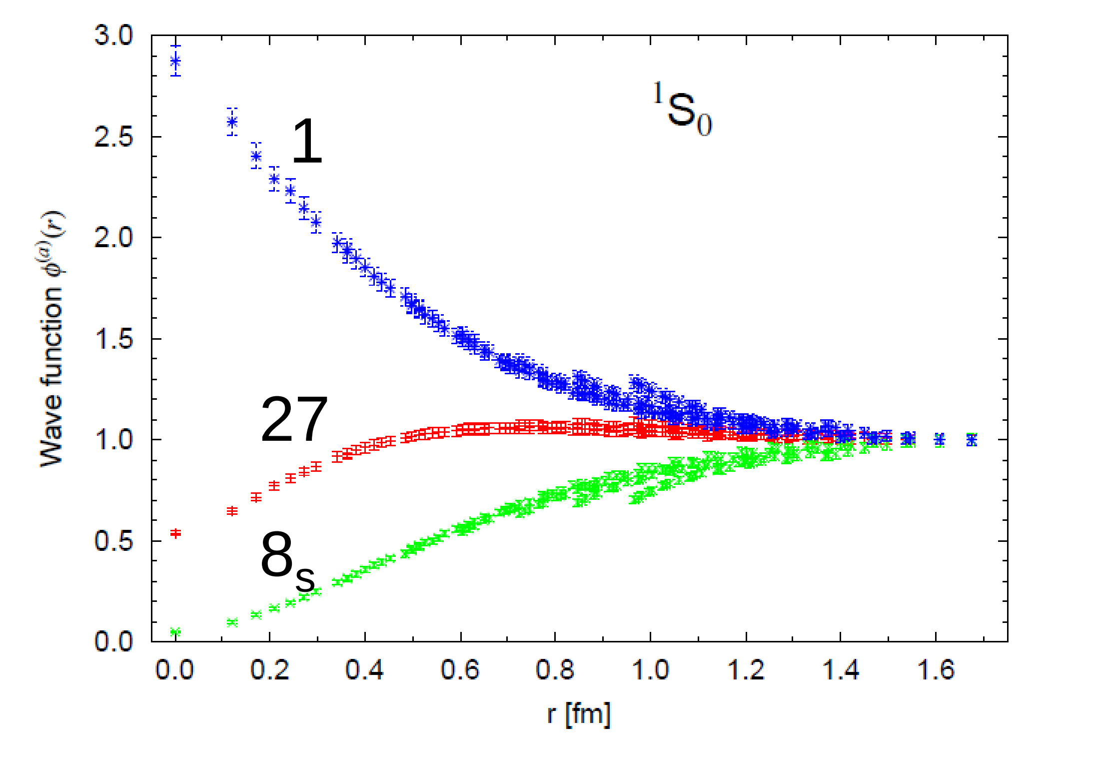
$$\overline{N\Xi} = +\sqrt{\frac{1}{4}}\,\overline{p\,\Xi^-} + \sqrt{\frac{1}{4}}\,\overline{\Xi^-\,p} - \sqrt{\frac{1}{4}}\,\overline{n\,\Xi^0} - \sqrt{\frac{1}{4}}\,\overline{\Xi^0\,n}$$

$$\overline{BB}^{(10^*)} = +\sqrt{\frac{1}{2}}\,\overline{p\,n} - \sqrt{\frac{1}{2}}\,\overline{n\,p}$$

$$\overline{BB}^{(10)} = +\sqrt{\frac{1}{2}}\,\overline{p\,\Sigma^+} - \sqrt{\frac{1}{2}}\,\overline{\Sigma^+\,p}$$

$$\overline{BB}^{(8a)} = +\sqrt{\frac{1}{4}}\,\overline{p\,\Xi^-} - \sqrt{\frac{1}{4}}\,\overline{\Xi^-\,p} - \sqrt{\frac{1}{4}}\,\overline{n\,\Xi^0} + \sqrt{\frac{1}{4}}\,\overline{\Xi^0\,n}$$

BB wave functions in flavor-basis ($^1S_0$ channel)



Iwasaki + clover (CP-PACS/JLQCD)
L=1.9 fm, a=0.12 fm, 16^3x32
m_π=835 MeV, m_B=1752 MeV

Inoue et al. (HAL QCD Coll.)
Prog. Theor. Phys. 124 (2010) 591

Pauli principle at work !

Oka, Yazaki, Shimizu, Morimatsu, Takeuchi, Fujiwara, Nakamoto, Suzuki, ….

1 : allowed
27 : partially blocked
8_s : almost blocked

Otsuki, Tamagaki and Wada, "Nuclear Interaction of Core region", PTP 32 (1964) 220

A hypothetical interpretation on the substantial carrier of the degrees of freedom is proposed based on an analogy with nucleus that the carrier is a many-body-system of ur-fermions. The core is interpreted as the exchange repulsion due to the antisymmetrization among the ur-fermions.

H-dibaryon is Hot now

Physics
spotlighting exceptional research

American Physical Society
APS physics

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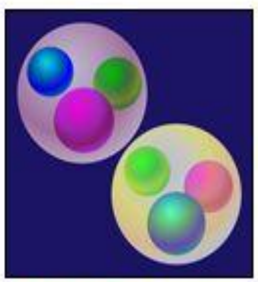
APS » Journals » Physics » Synopses » Binding baryons on the lattice

Binding baryons on the lattice



Credit: Alan Stonebraker

Evidence for a Bound *H* Dibaryon from Lattice QCD

S. R. Beane, E. Chang, W. Detmold, B. Joo, H. W. Lin, T. C. Luu, K. Orginos, A. Parreño, M. J. Savage, A. Torok, and A. Walker-Loud (NPLQCD Collaboration)

Phys. Rev. Lett. **106**, 162001 (Published April 20, 2011)

Bound *H* Dibaryon in Flavor SU(3) Limit of Lattice QCD

Takashi Inoue, Noriyoshi Ishii, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Keiko Murano, Hidekatsu Nemura, and Kenji Sasaki (HAL QCD Collaboration)

Phys. Rev. Lett. **106**, 162002 (Published April 20, 2011)

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Coming Soon in *Physics*

- New materials: Topological semimetals

Now in Focus

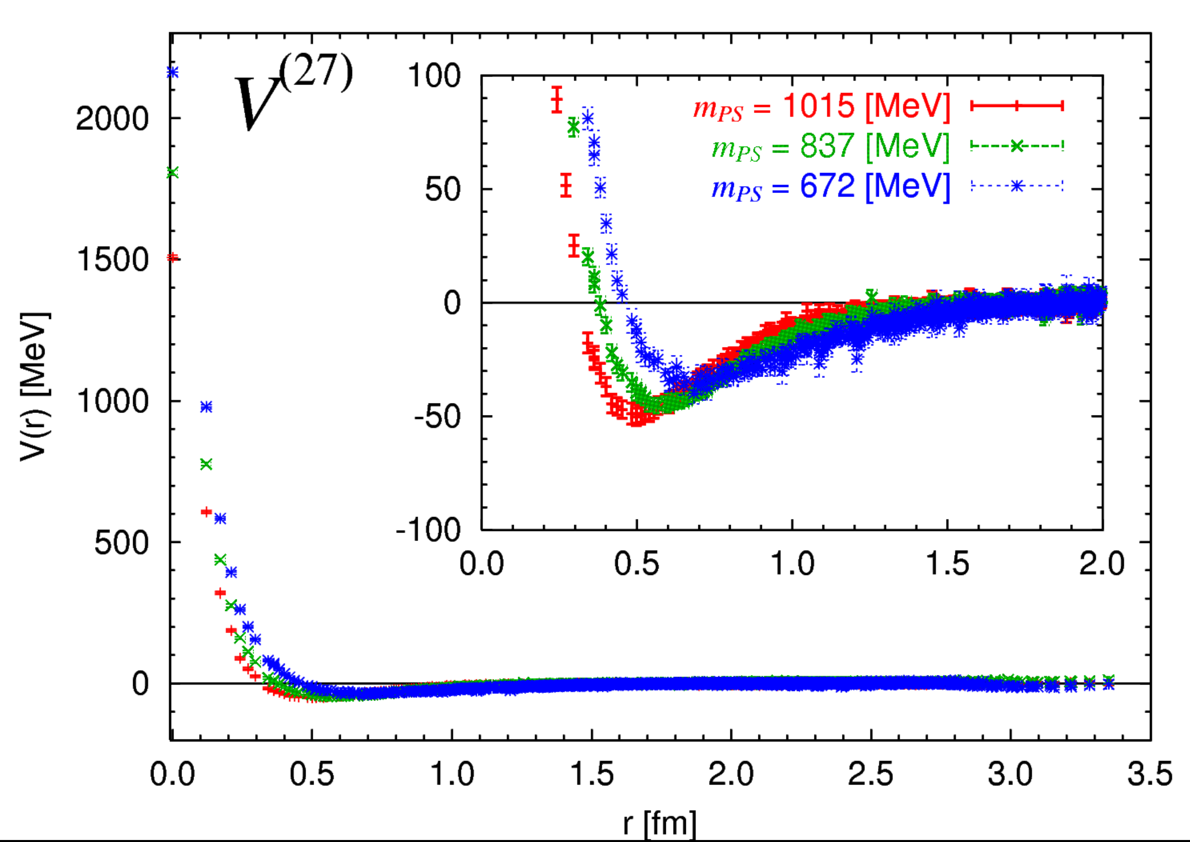
Liquid Magnet: Stirred, not Shaken

April 29, 2011

Liquid sodium agitated gently in a rotating tank can significantly amplify a magnetic field. The experiment is the first step toward demonstrating a

APS Physics Synopsis (April 26, 2011)

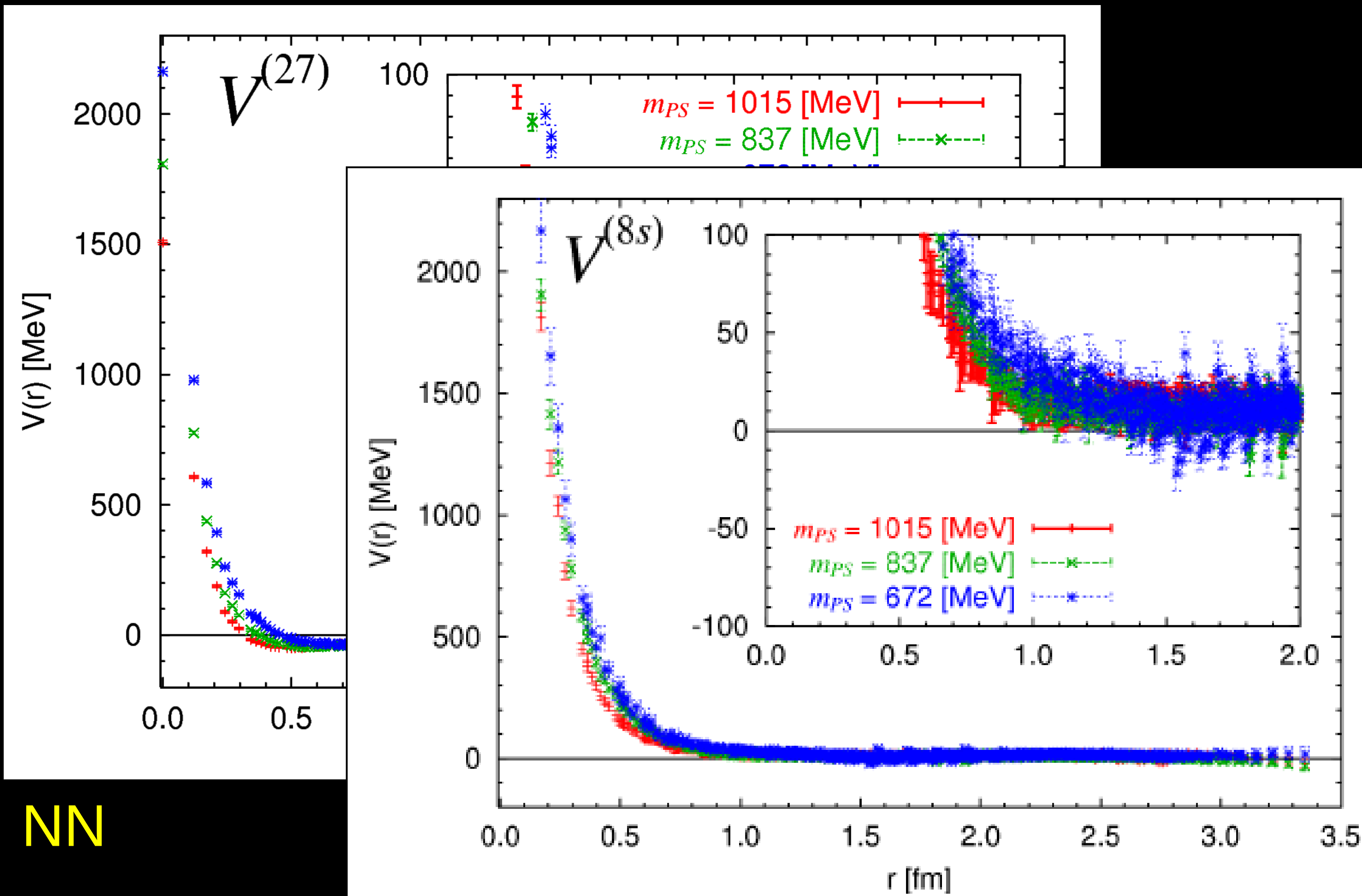
BB potentials in flavor-basis ($^1S_0$ channel)



NN

Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

BB potentials in flavor-basis ($^1S_0$ channel)



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Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

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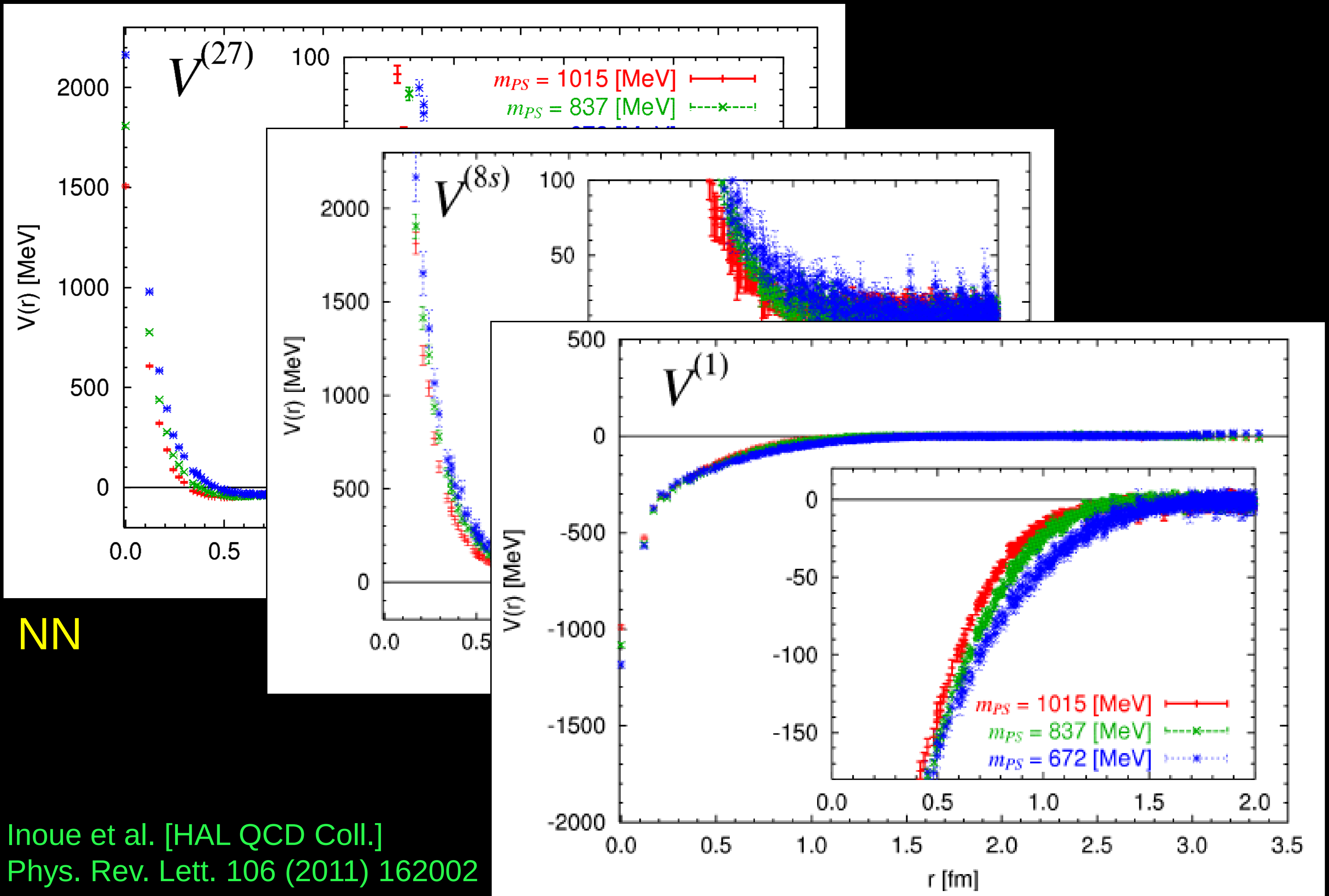
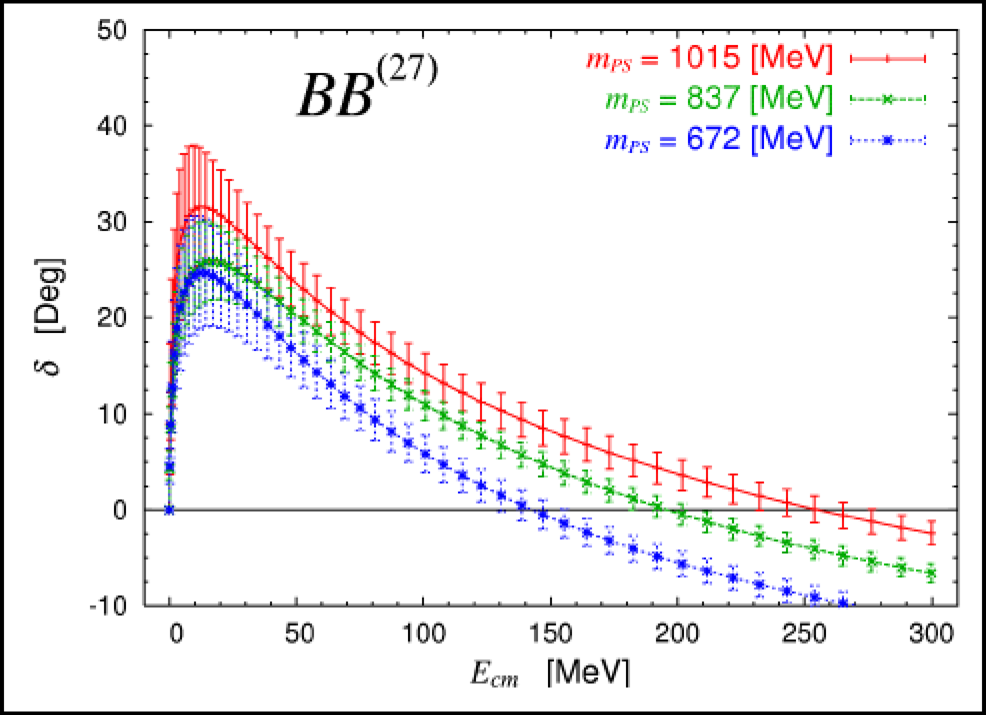


NN

Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

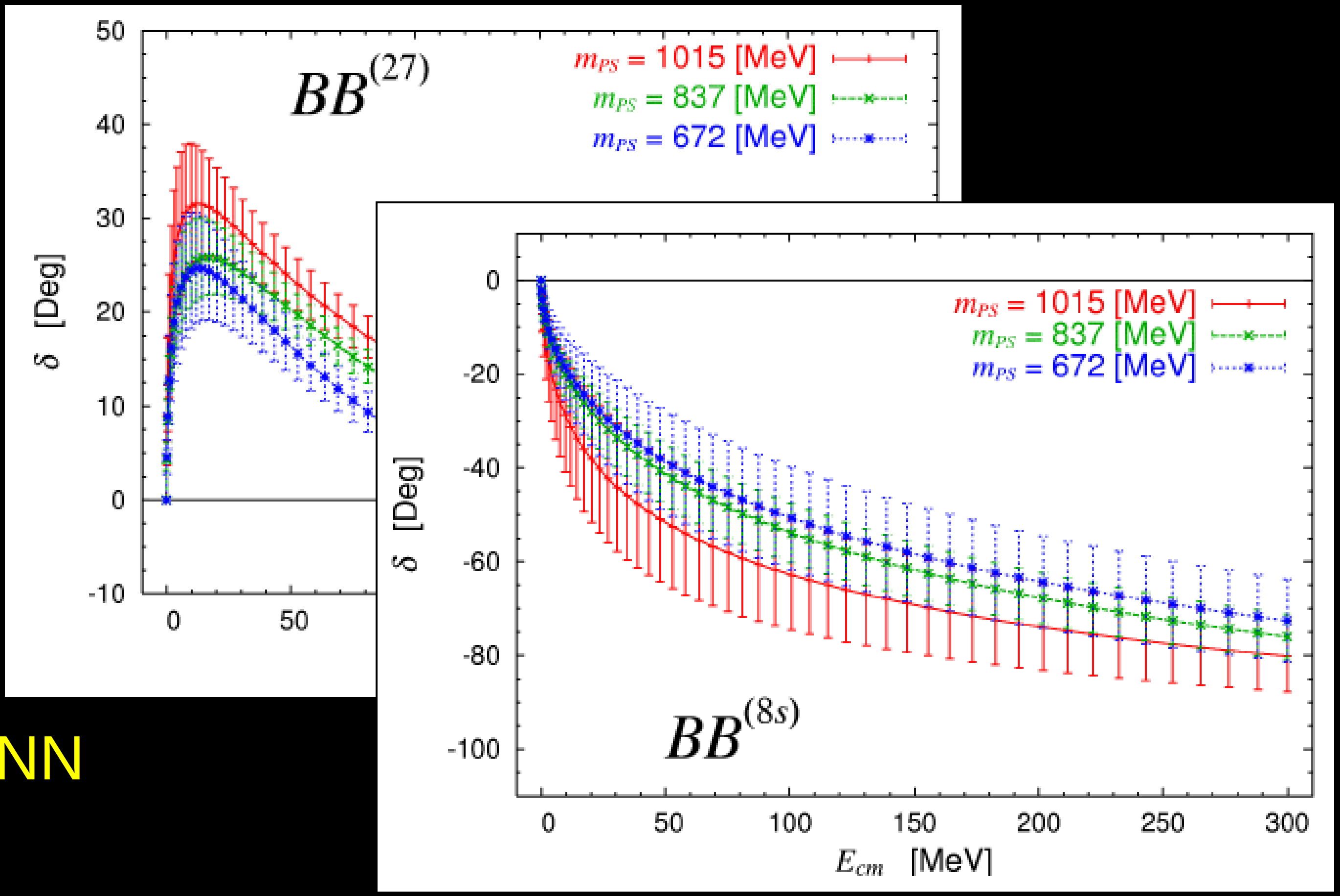
BB phase shifts in flavor-basis ($^1S_0$ channel)



NN

Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

BB phase shifts in flavor-basis ($^1S_0$ channel)



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Phys. Rev. Lett. 106 (2011) 162002

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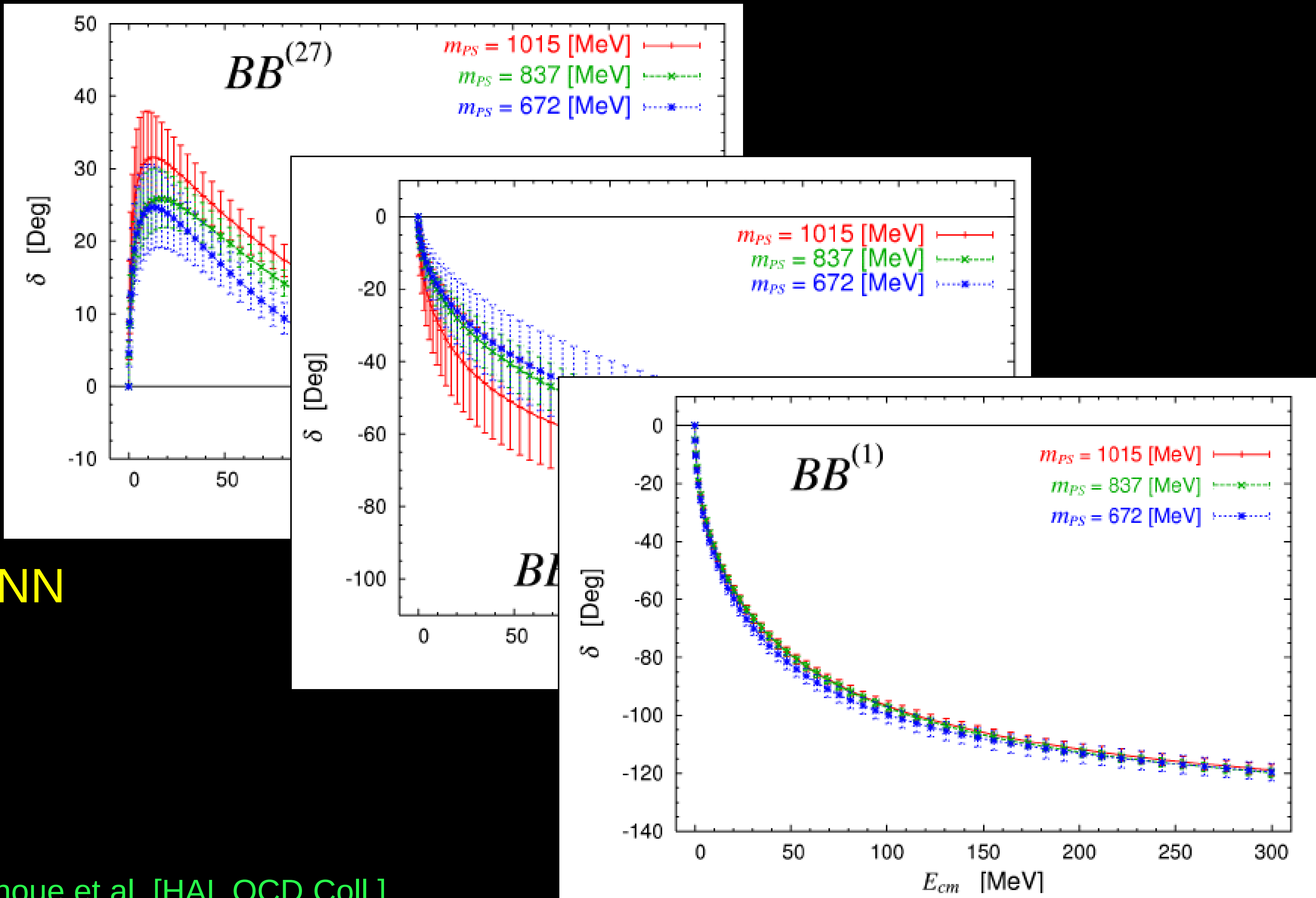
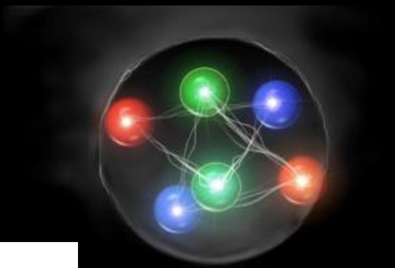
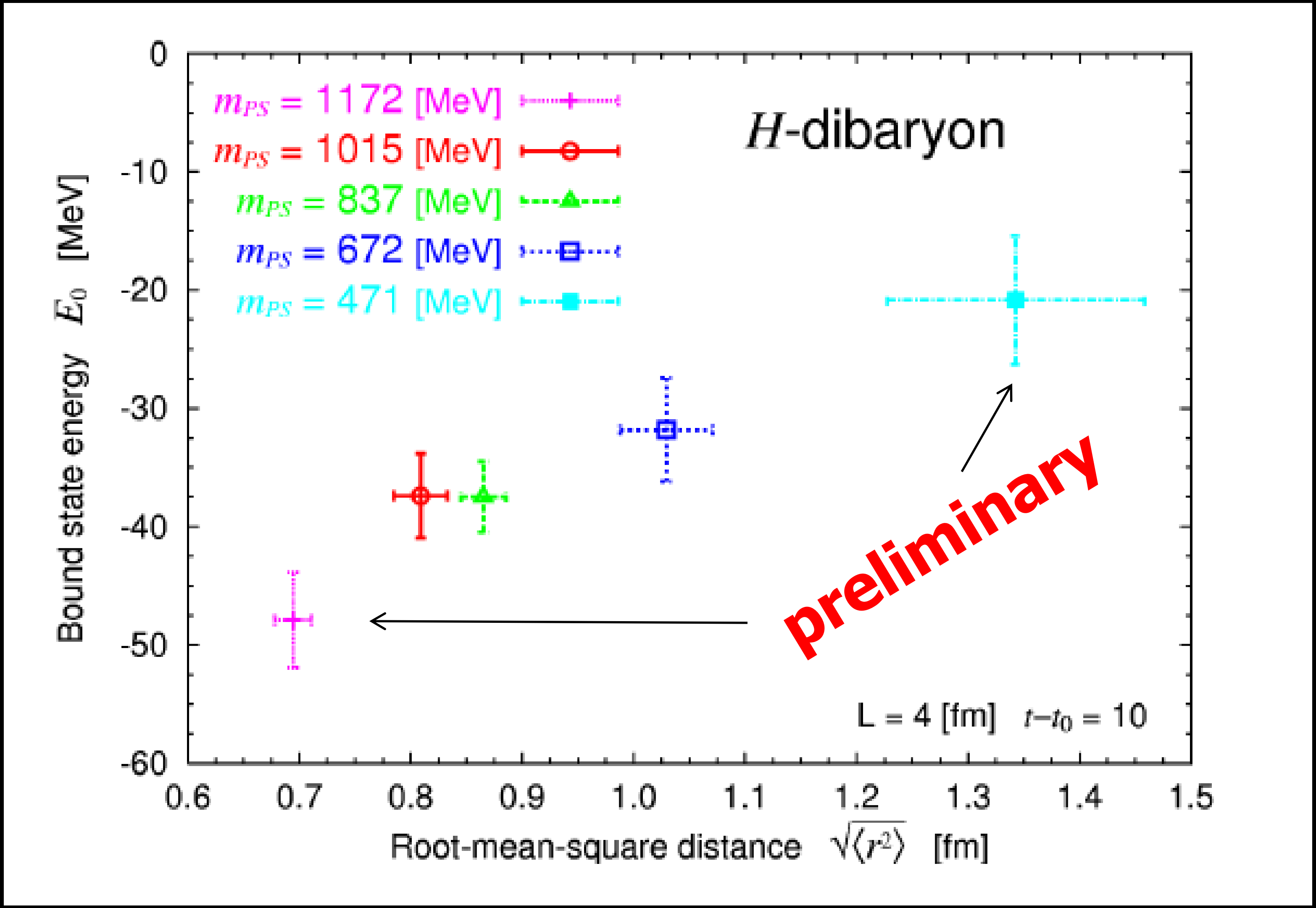


NN

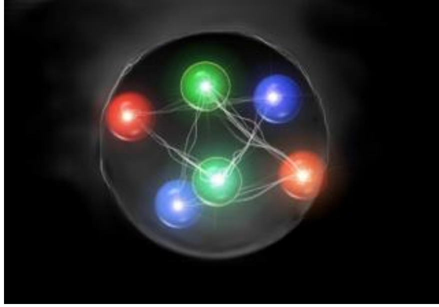
Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

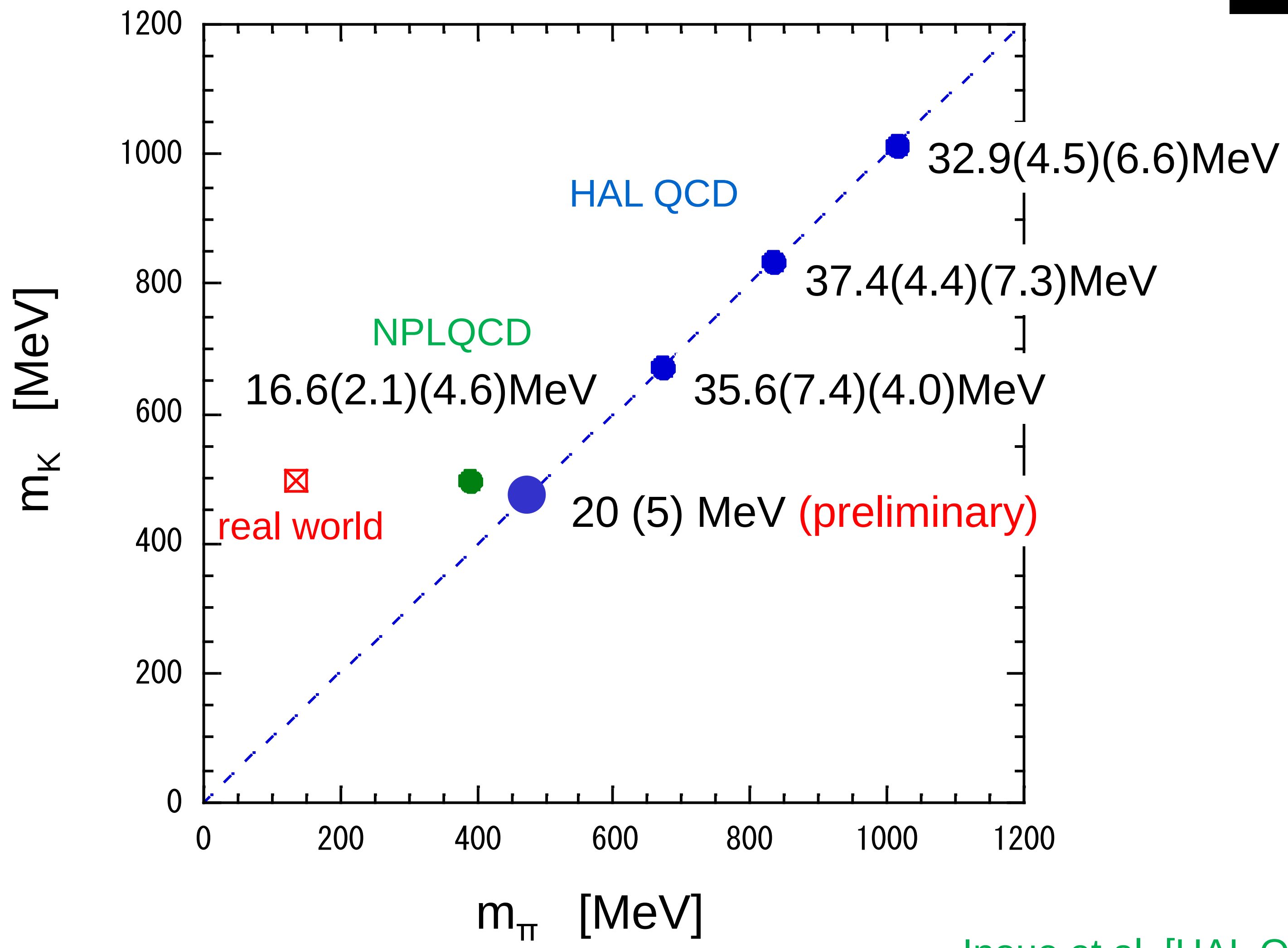




Inoue et al. [HAL QCD Coll.] Phys. Rev. Lett. 106 (2011) 162002

Binding energy of H dibaryon in full QCD

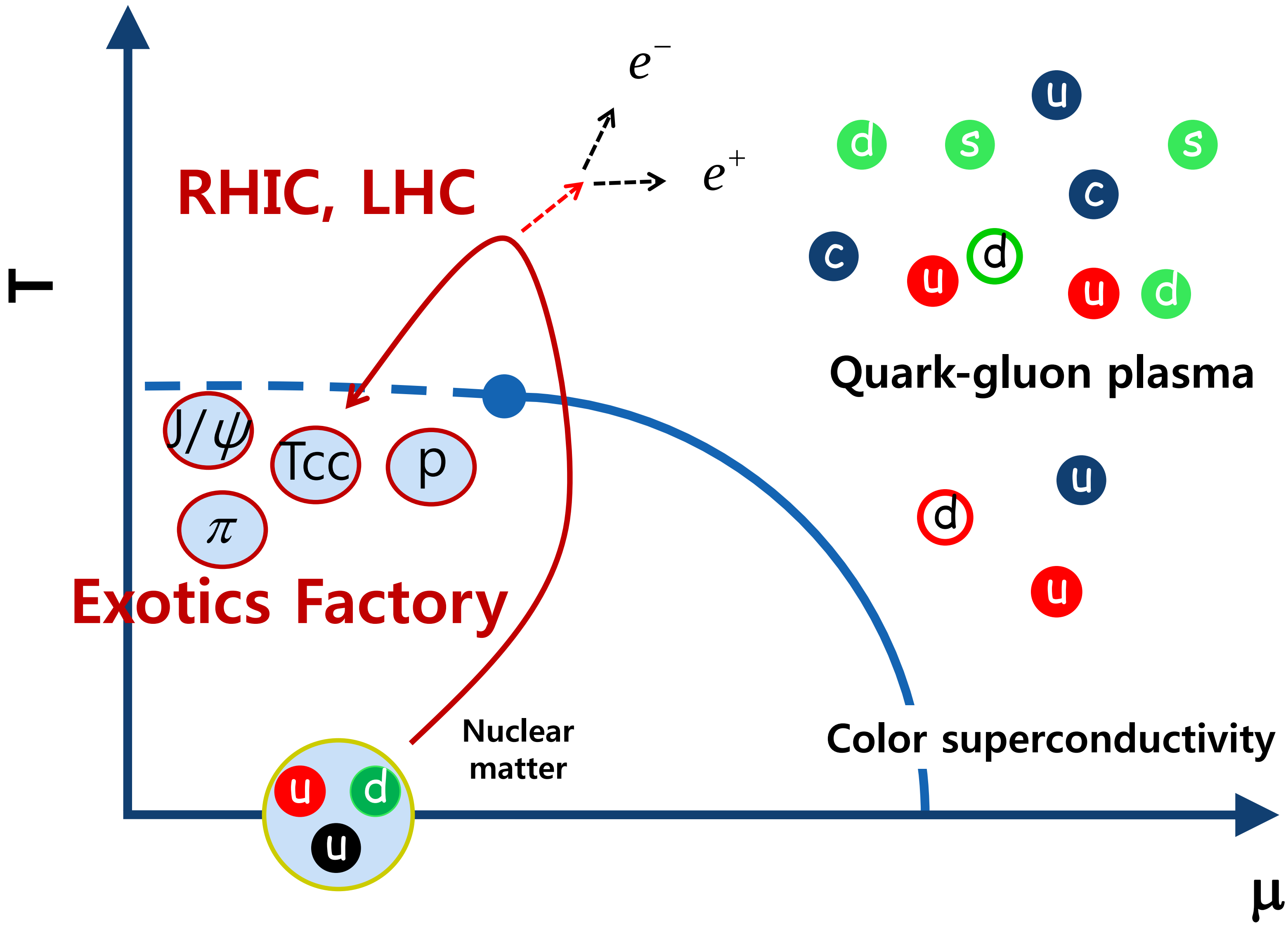




Inoue et al. [HAL QCD Coll.]
Phys. Rev. Lett. 106 (2011) 162002

Exotics Factory

Cho, Furumoto, Hyodo, Jido, Ko, Lee,
Nielsen, Ohnishi, Sekihara, Yasui, Yazaki [ExHIC Coll.]
arXiv:1011.0852 [nucl-th] PRL 106 (2011) 212001



S. H. Lee @ 15th Heavy Ion Café (June 26, 2010)

（過去10年間） 着実な進歩＋新しいアイデア

1． RHICデータと
相対論的流体力学 ⇔ QGP研究の精密化

2． 格子QCD計算の進展 ⇔ 高温QCD物質の状態方程式

3． CGC理論の進展 ⇔ 高エネルギーQCD反応の理解

4． ゲージ/重力対応 ⇔ 強結合QCDプラズマの性質

5． 冷却原子気体の物理 ⇔ 高密度QCDの相構造

6． 中性子星観測データ ⇔ 高密度QCDの状態方程式

今後５－１０年の期待

1． LHC:　pp, pA, AAの系統的測定、新現象
2． 相対論的流体力学:　粘性流体シミュレーション
3． 格子QCD計算:　輸送係数、スペクトル関数、有限密度
4． CGC理論:　LHCでの精密テスト
5． ゲージ/重力対応:　“面白いアプローチ”の域を越えられるか？
6． 冷却原子気体:　multi-component系での相構造の解明
7． 中性子星観測:　観測データからの状態方程式導出
合体時の重力波観測
8． 有限密度QCDの非一様相:　どこでテストできるか？

BB interactions: Current and Future

- HAL QCD method for BB Interaction s

  lattice wave func. → NN, YN, YY forces → observables → nuclear physics

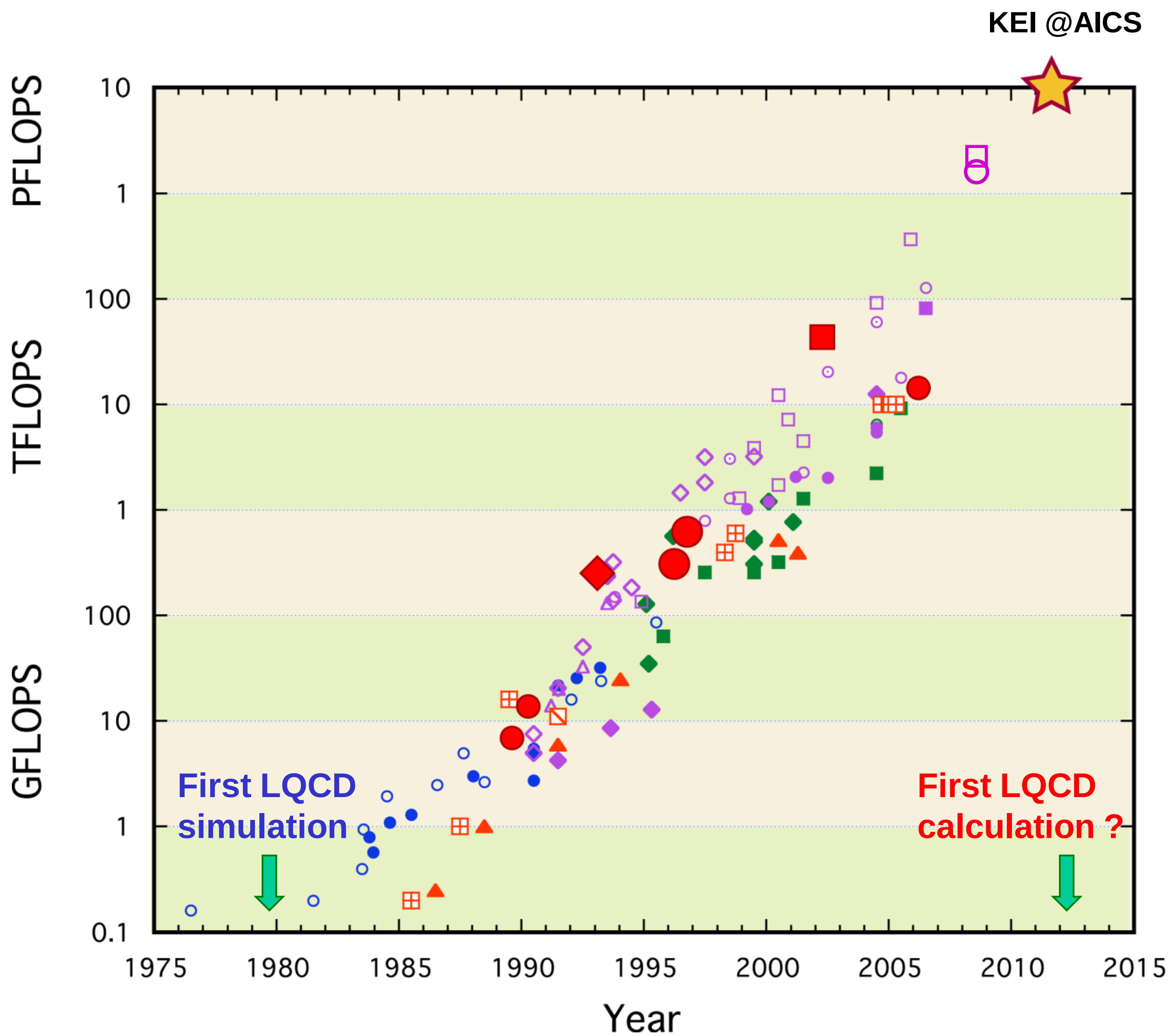
- Full QCD with m_π=135 MeV and L= 6fm, 9fm

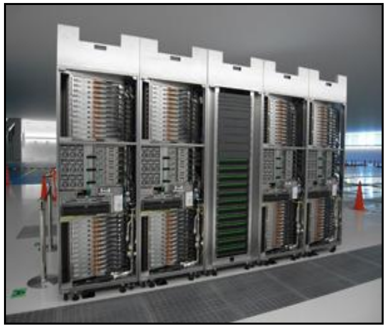
  "KEI" (10 Pflops supercomputer at AICS) : full operation from 2012

AICS@Kobe

- Physics
  - YN force, LS forces, 3N force, lattice nuclei with SU(3) breaking
  - exotic hadrons (H dibaryon, pentaquark, etc) with SU(3) breaking
  - + many more

Supercomputer peak performance





Hadrons to Atomic nuclei

HAL

from Lattice QCD

Tohoku Univ. H. Nemura

Univ. Tsukuba S. Aoki, T. Doi, N. Ishii, K. Sasaki

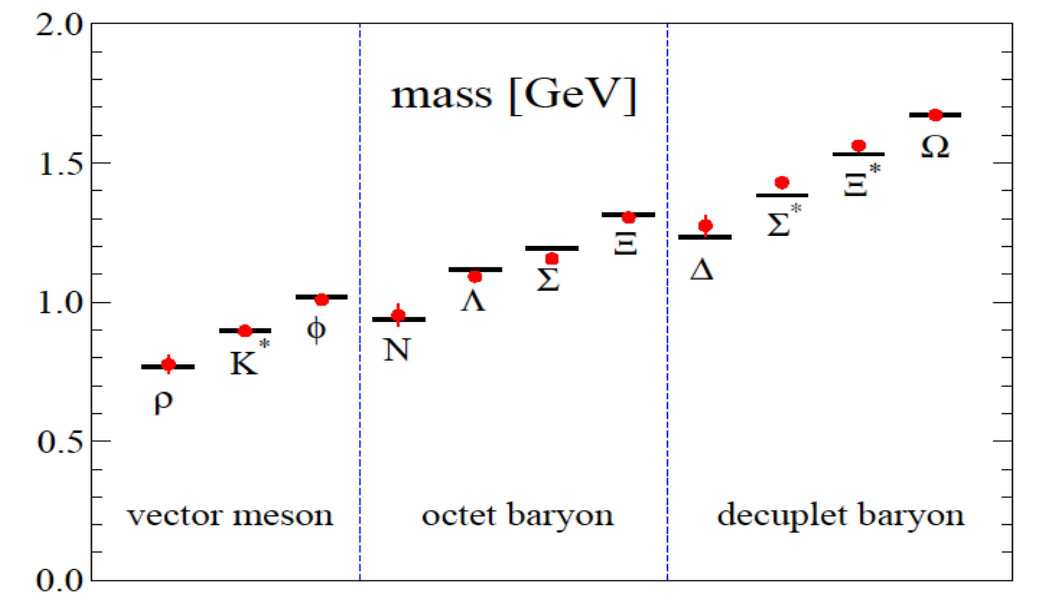
RIKEN K. Murano, T. Hatsuda

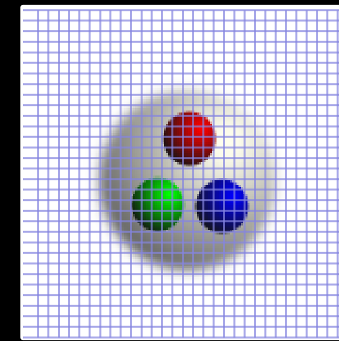
Nihon Univ. T. Inoue

Tokyo Inst. Tech. Y. Ikeda

Backup slides

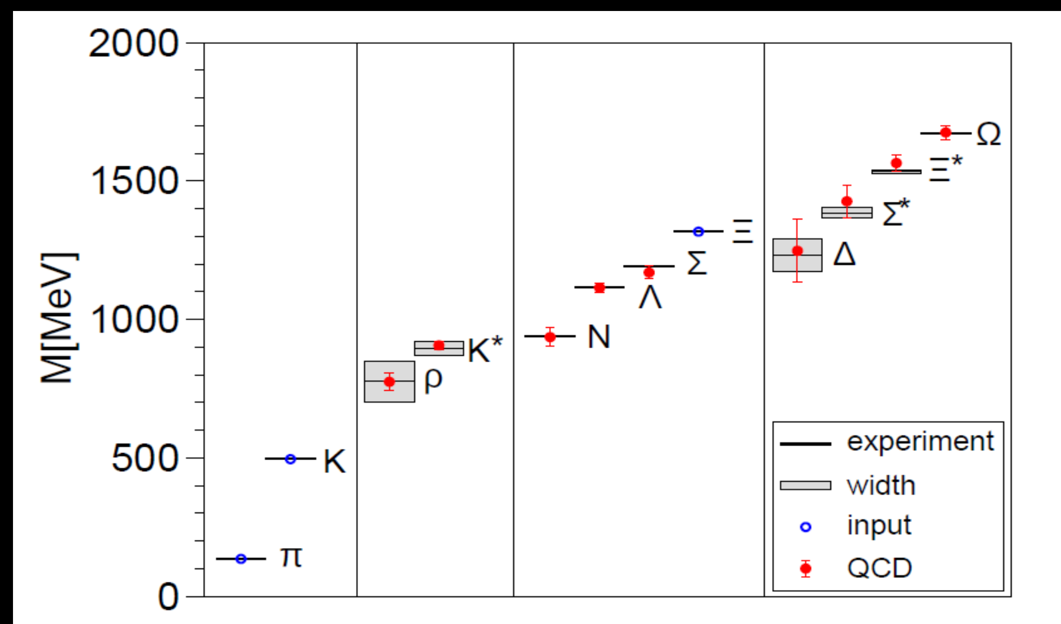
Light Hadrons in full QCD





BMW Coll.,
Science 322, 1224 (2008)
[arXiv:0906.3599 [hep-lat]]

PACS-CS Coll.,
Phys. Rev. D79 (2009) 034503
[arXiv:0807.1661 [hep-lat]].



QCD-*light* has only
4 parameters ($m_{u,d,s}$, Λ_{QCD})