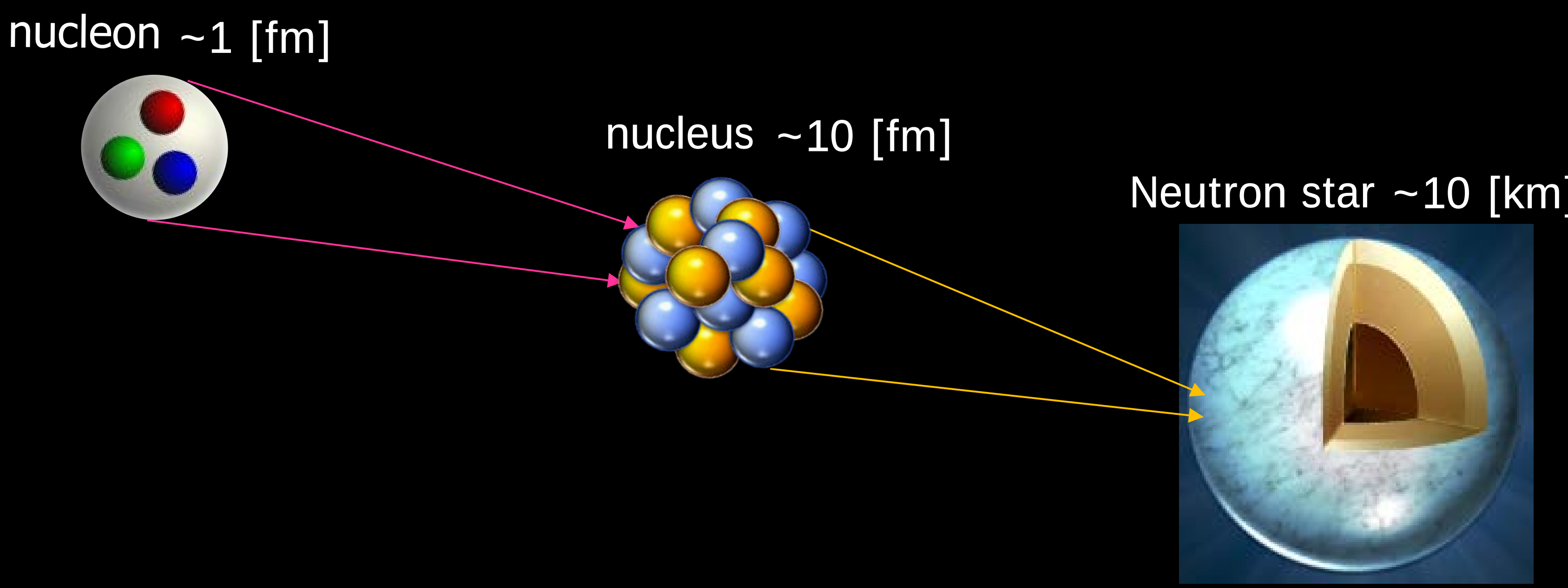
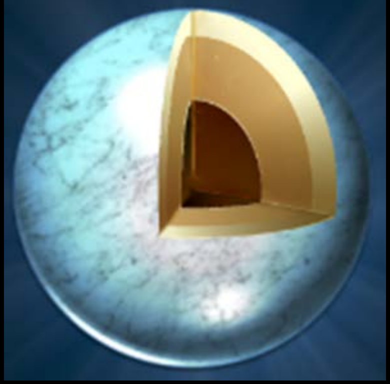
Dense QCD and Compact Stars



Matter at Extreme Conditions (Jan. 15, 2014)

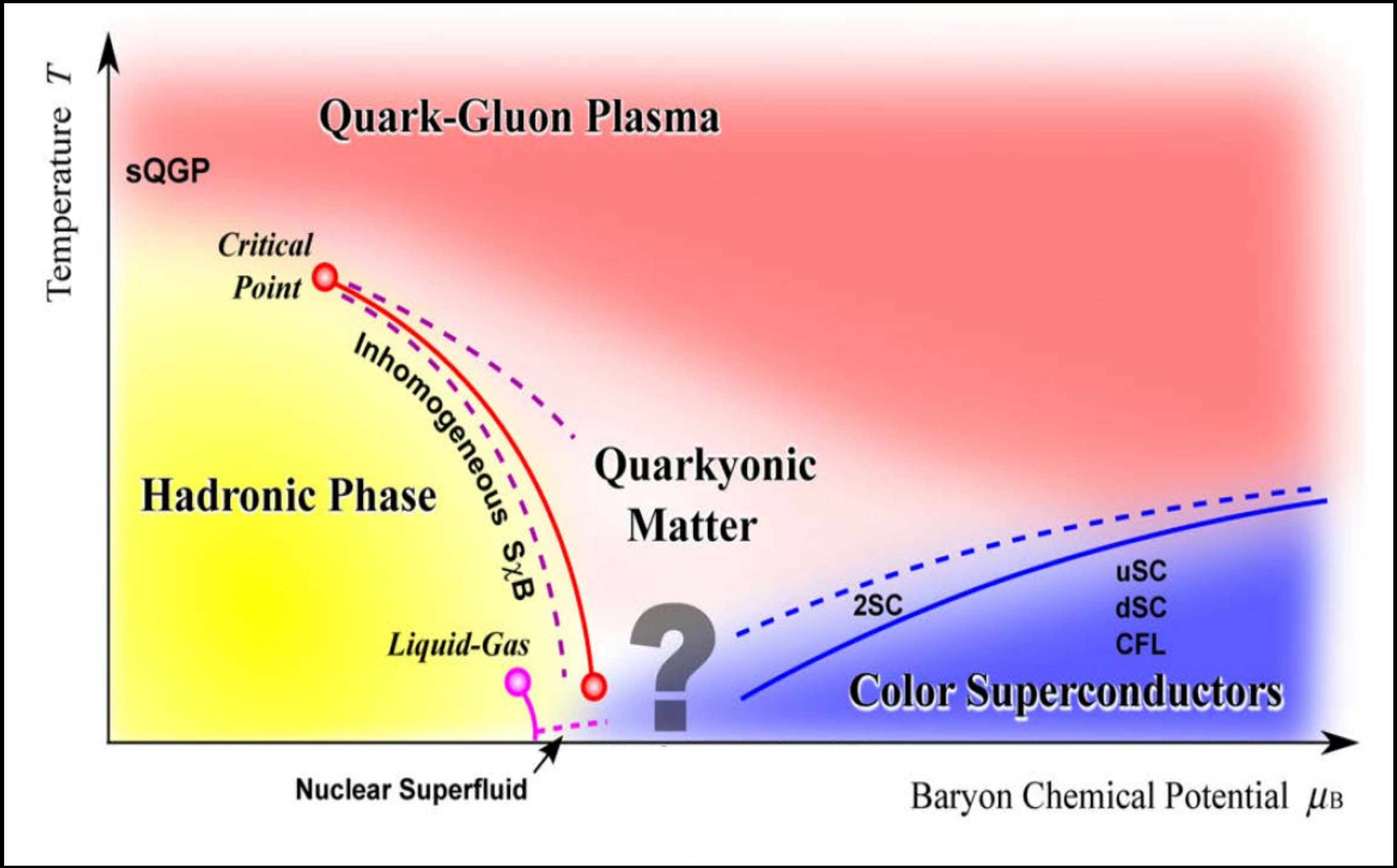
Tetsuo Hatsuda (RIKEN)

Plan of this Talk



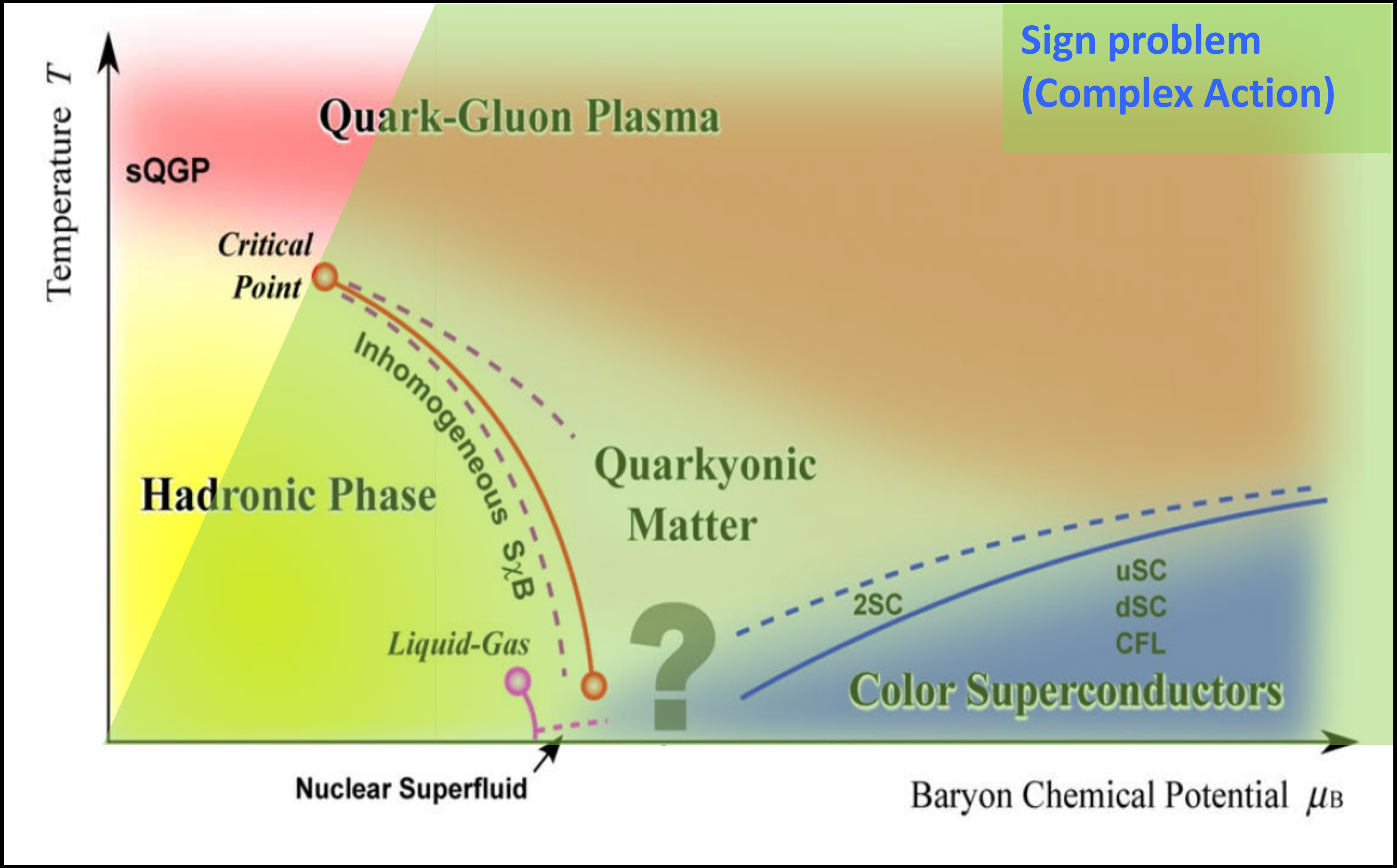
1. QCD Phase Structure
2. Dense Matter and Neutron Star
3. Lattice QCD and Neutron Star
4. Hadron-Quark Crossover and Neutron Star
5. Summary

QCD Phase Structure



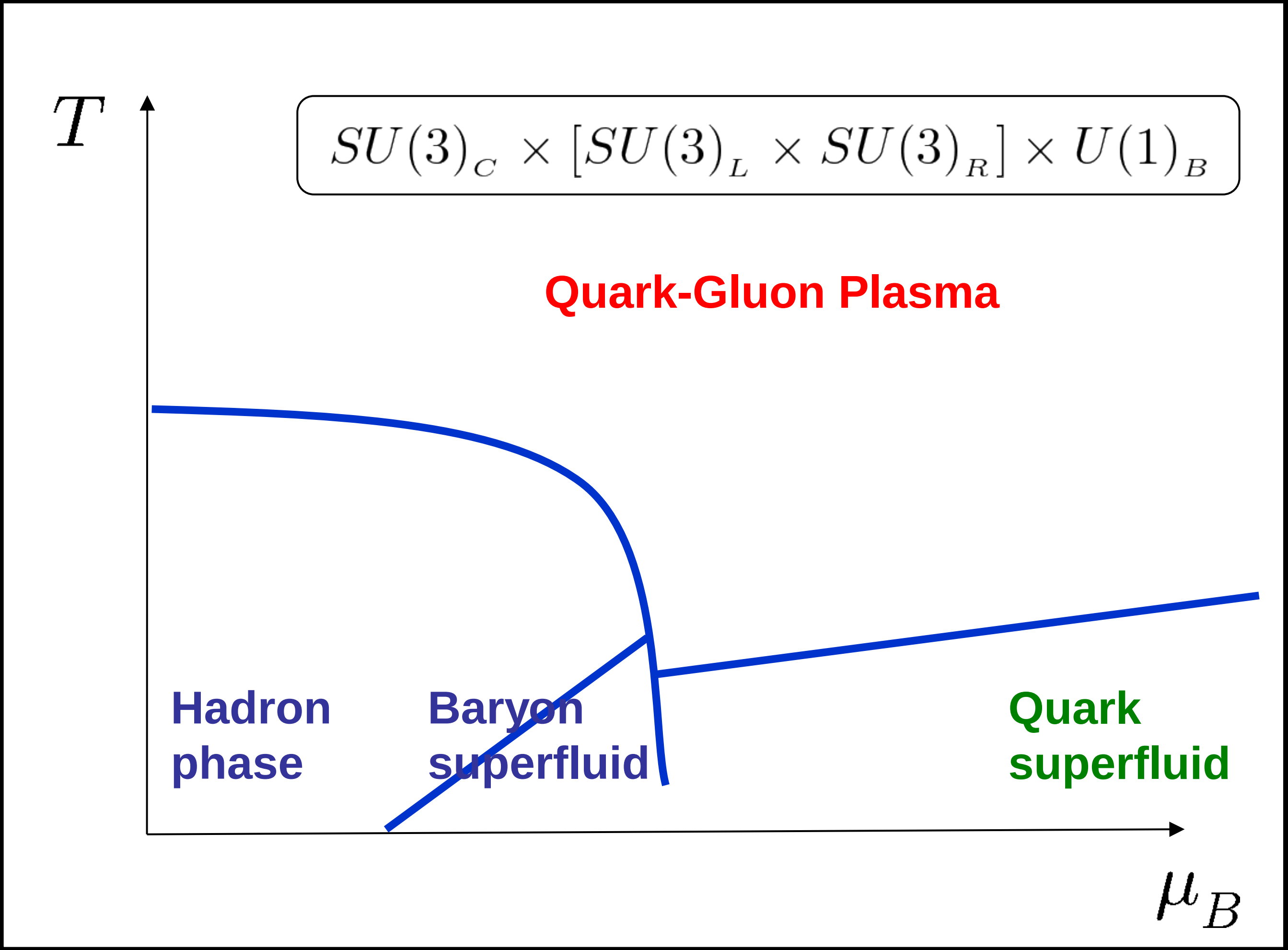
K. Fukushima and T. Hatsuda, Rep. Prog. Phys. 74 (2011) 014001

QCD Phase Structure



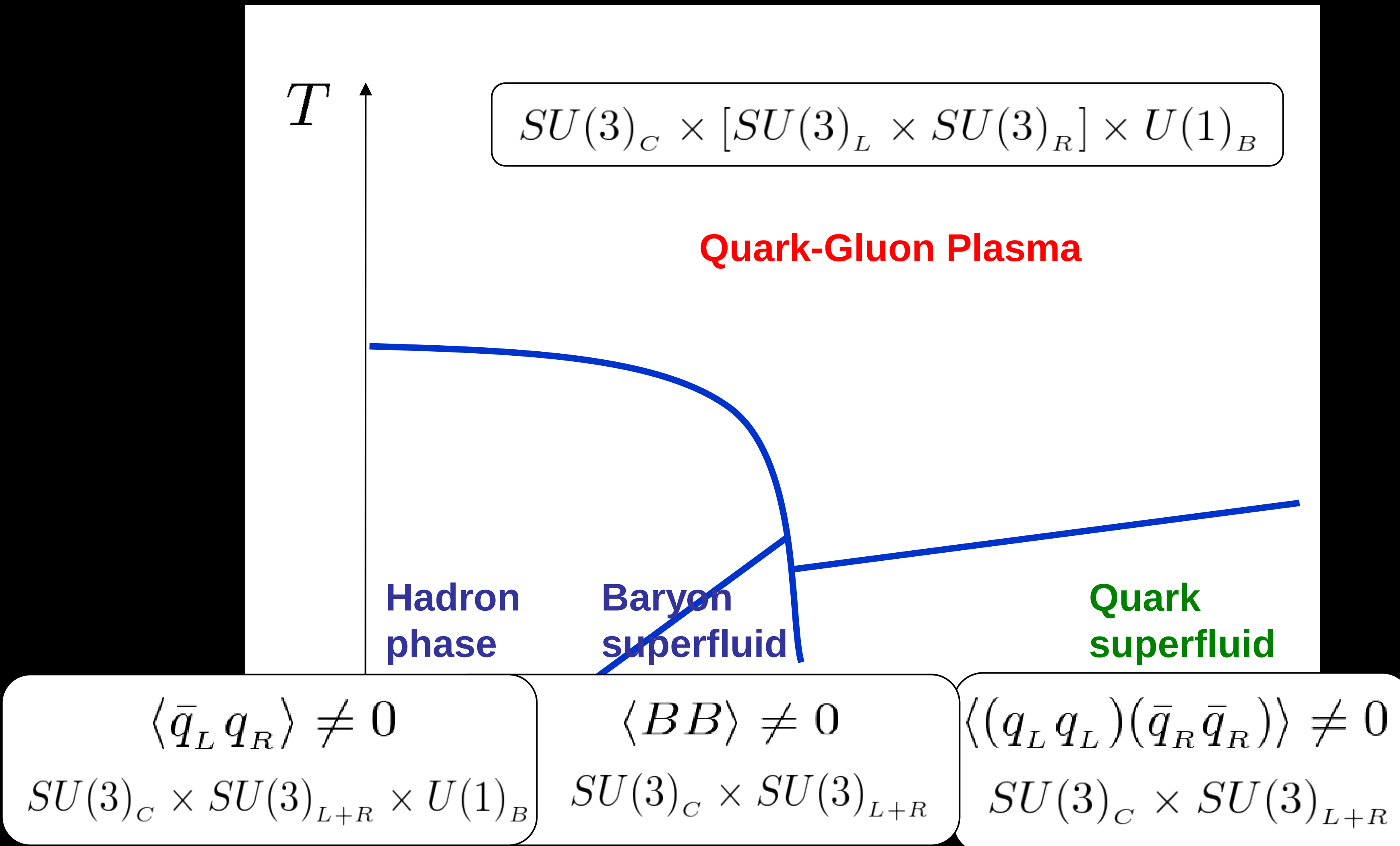
K. Fukushima and T. Hatsuda,
Rep. Prog. Phys. 74 (2011) 014001

Symmetry Realization in dense QCD（$N_c=3$, $N_f=3$）



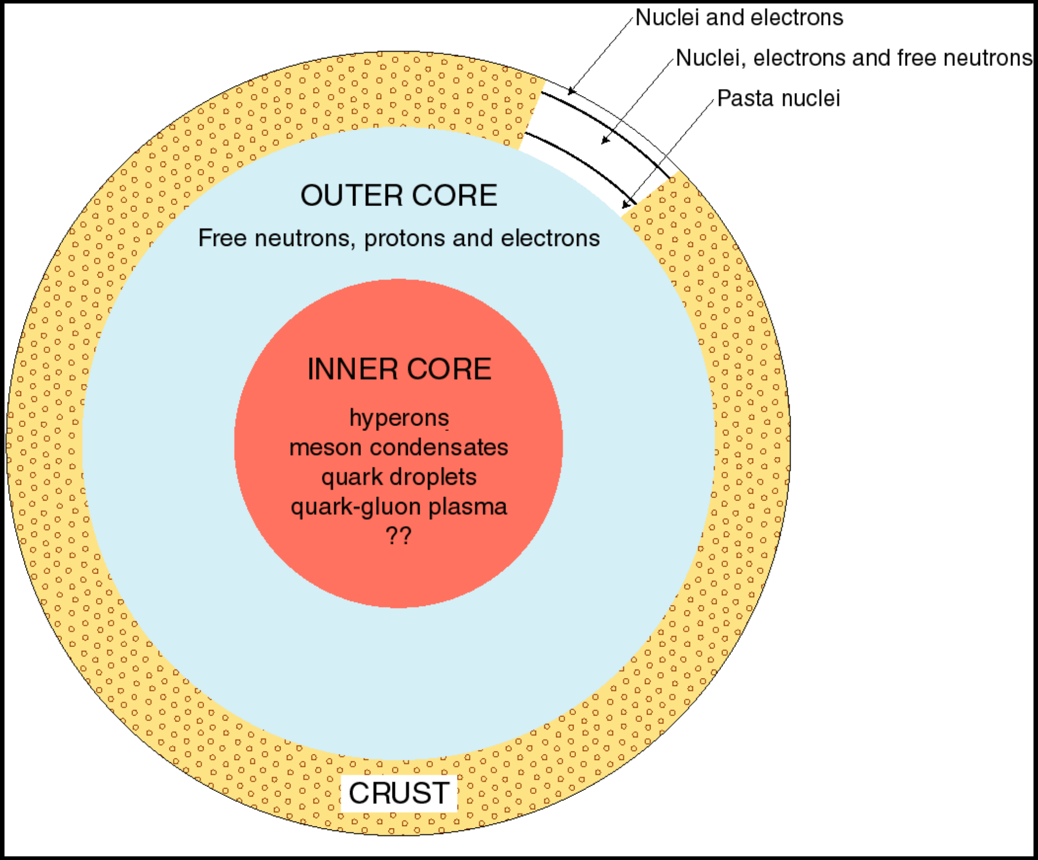
Chiral symmetry is always broken at finite density

Symmetry Realization in dense QCD (N_c=3, N_f=3)



Chiral symmetry is always broken at finite density

Dense matter and Neutron Star



- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\ \rho_0$

composition

- nuclei
- neutrons & protons
- mesons (π, K)
- hyperons (Λ, Σ^-, Ξ^-)
- quarks (u,d,s)

+ leptons (e, μ)

$N_\star$ observations

Current:

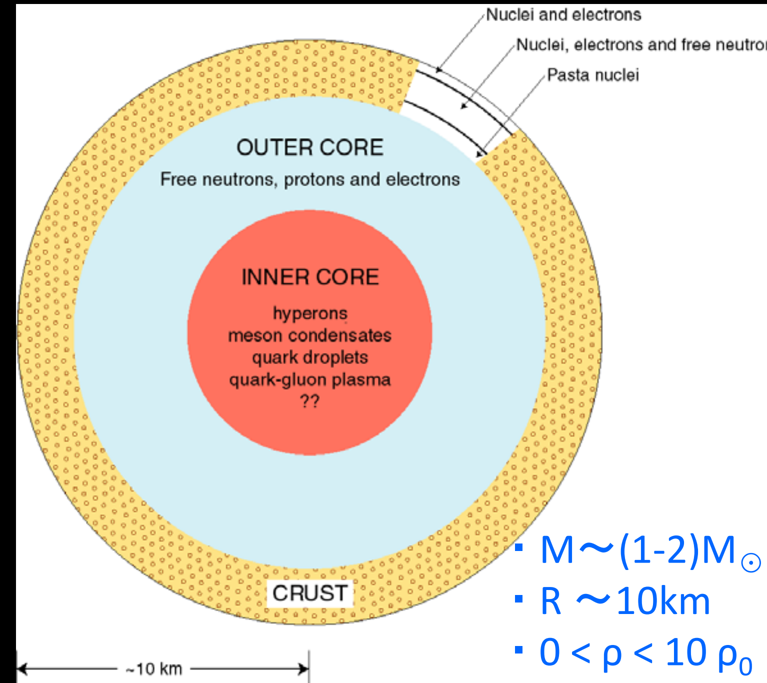
$M=(1.97\pm0.04)M_\odot$ (Nature 2010)
$M=(2.01\pm0.04)M_\odot$ (Science 2013)
⇔ cold EOS

X-ray bursts ⇔ cold EOS

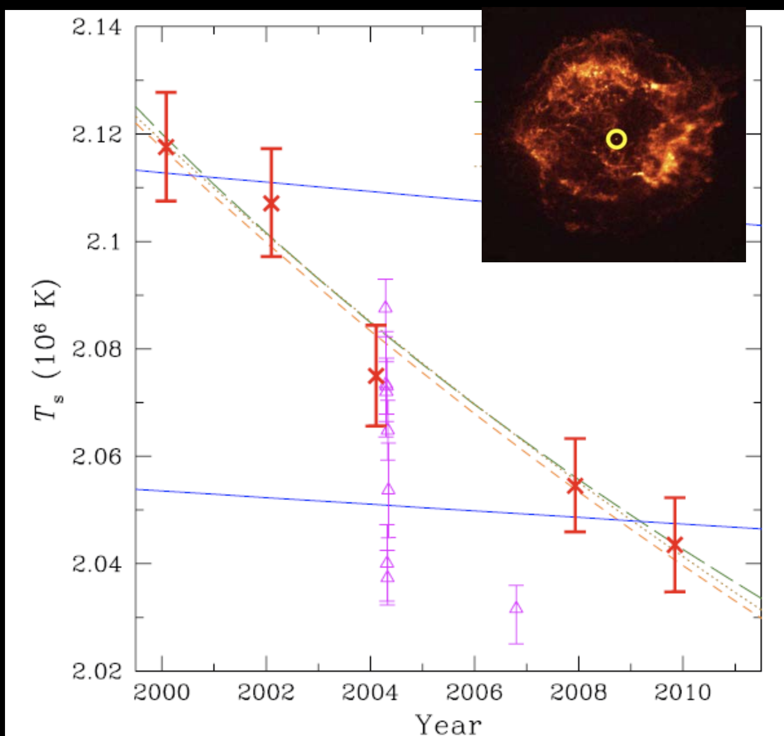
Cooling of CAS-A ⇔ $^3P_2$ superfluid?
Magnetars ⇔ ferromagnetic core?

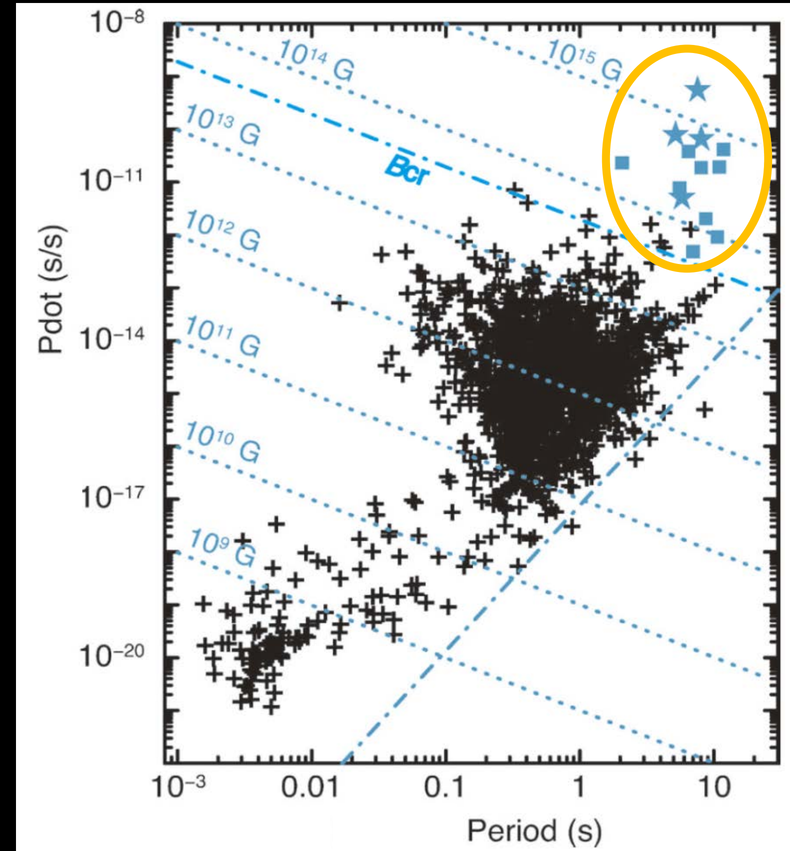
Near Future:

GW from $N_\star$ merger ⇔ hot EOS



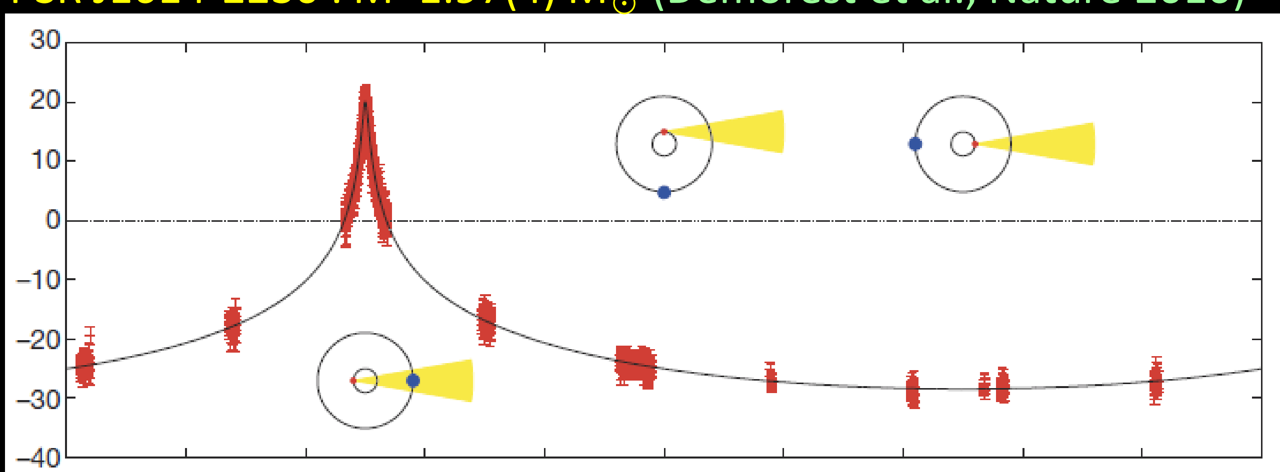
Cassiopeia A cooling: T decreases by 4% in 9 years
(Heinke & Ho, ApJ 2010)





Magnetars: B~$10^{14\text{-}15}$ G
(from Enoto, 2012)
Bs=$3.2\times10^{19}\sqrt{(P\dot{P})}$ [G]

PSR J1614-2230 : M=1.97(4) $M_\odot$ (Demorest et al., Nature 2010)



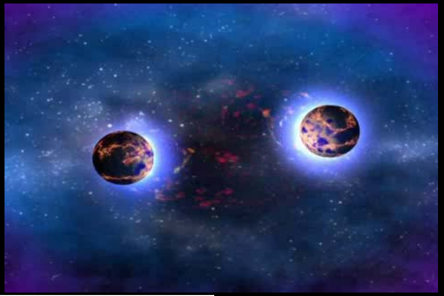
T, B, M

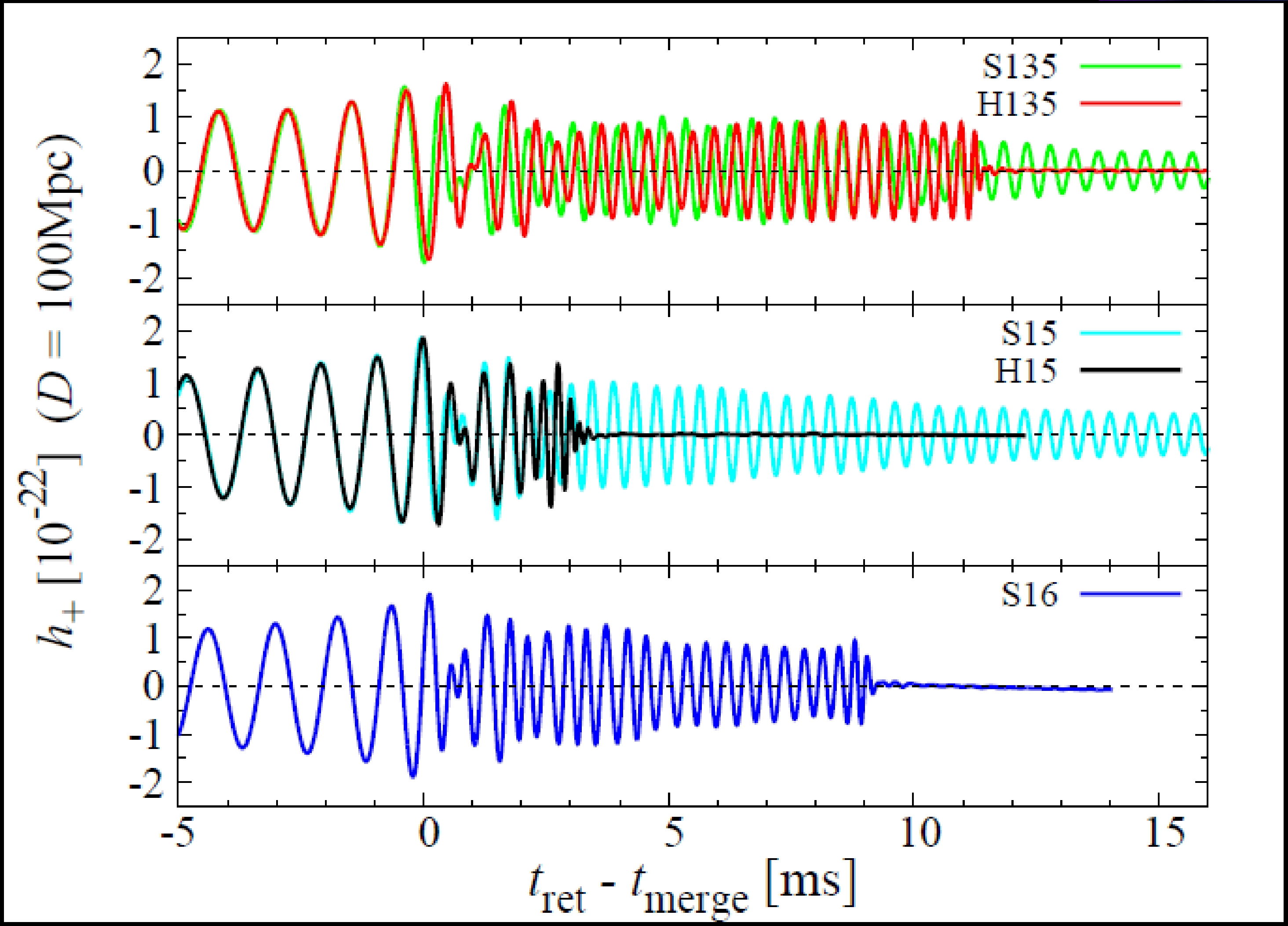
Gravitational wave from $N_{\star}$ merger
-- Detectors --

Berger et al., arXiv:1306.3960[astro-ph.HE] (June 17, 2013)
Animation in Harvard-Smithonian press release (July 17, 2013)

M. Shibata (YITP)

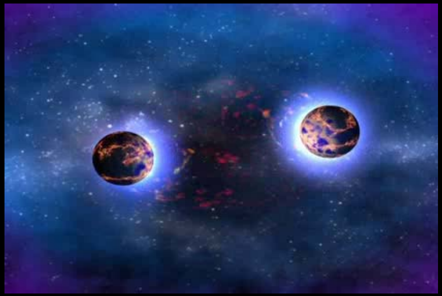
Gravitational wave from N☆ merger
-- Expected signal --

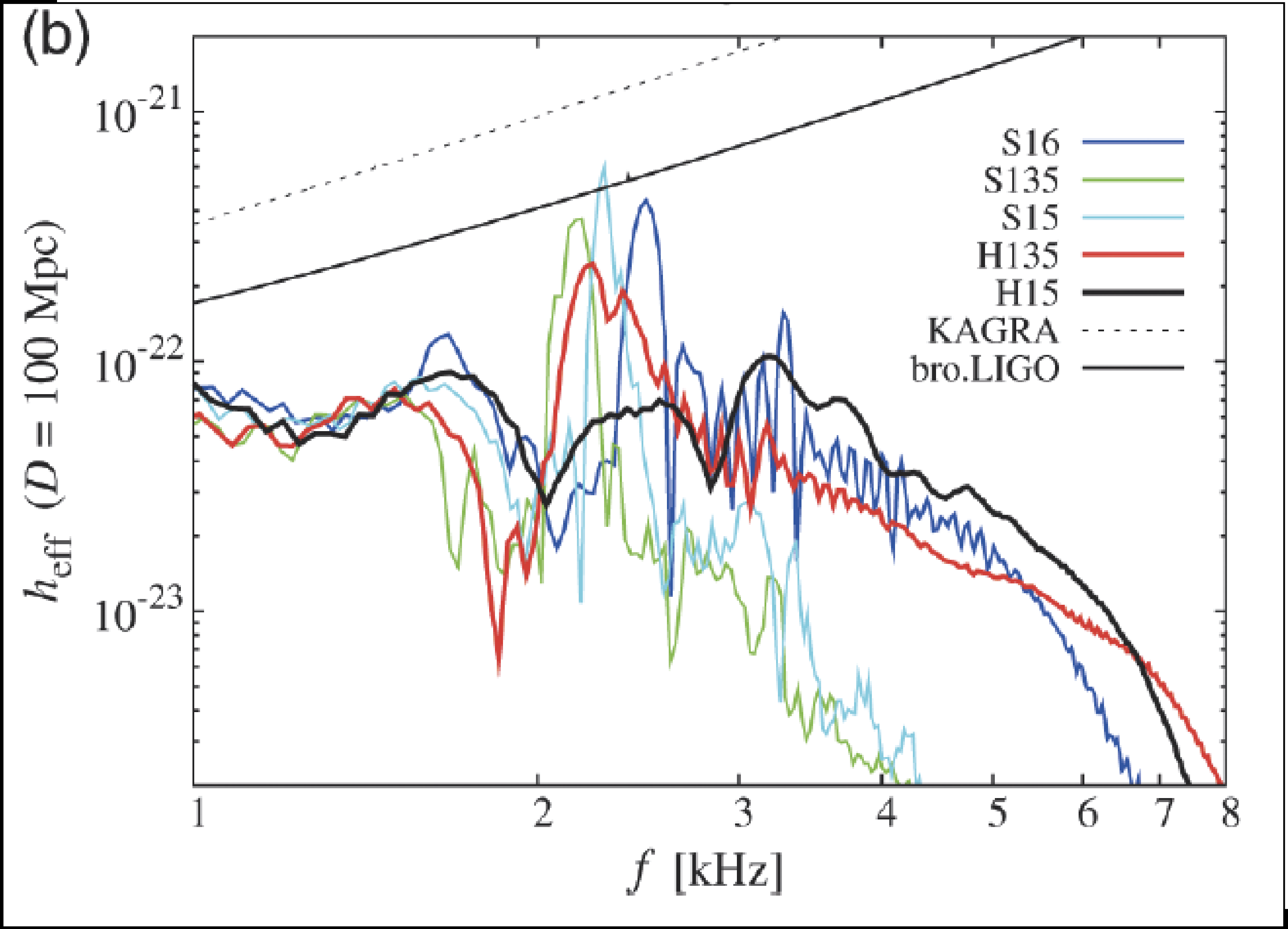




Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

Gravitational wave from N$_\star$ merger
-- Expected signal --





Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

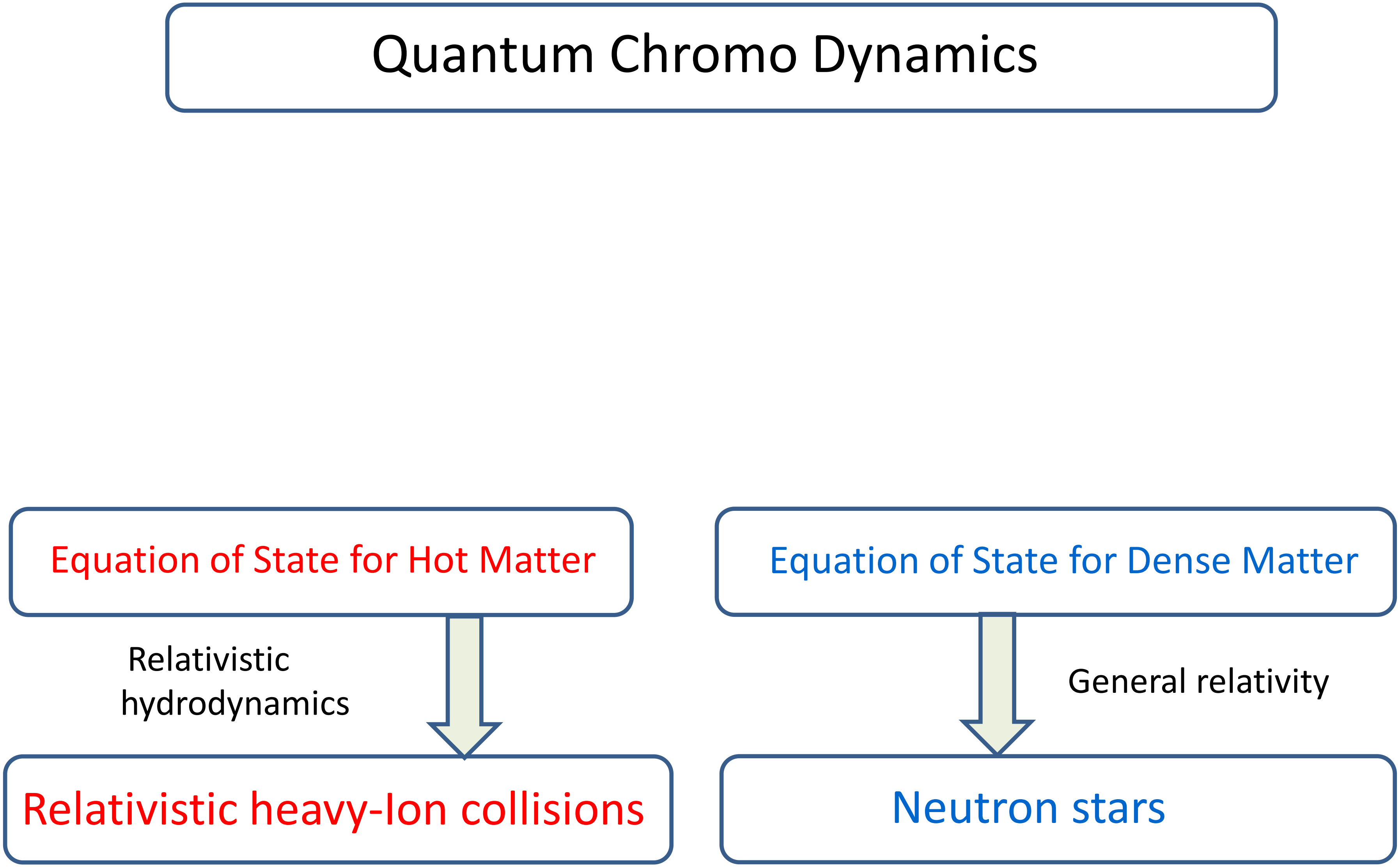
From QCD to Hot/Dense Matter

Quantum Chromo Dynamics

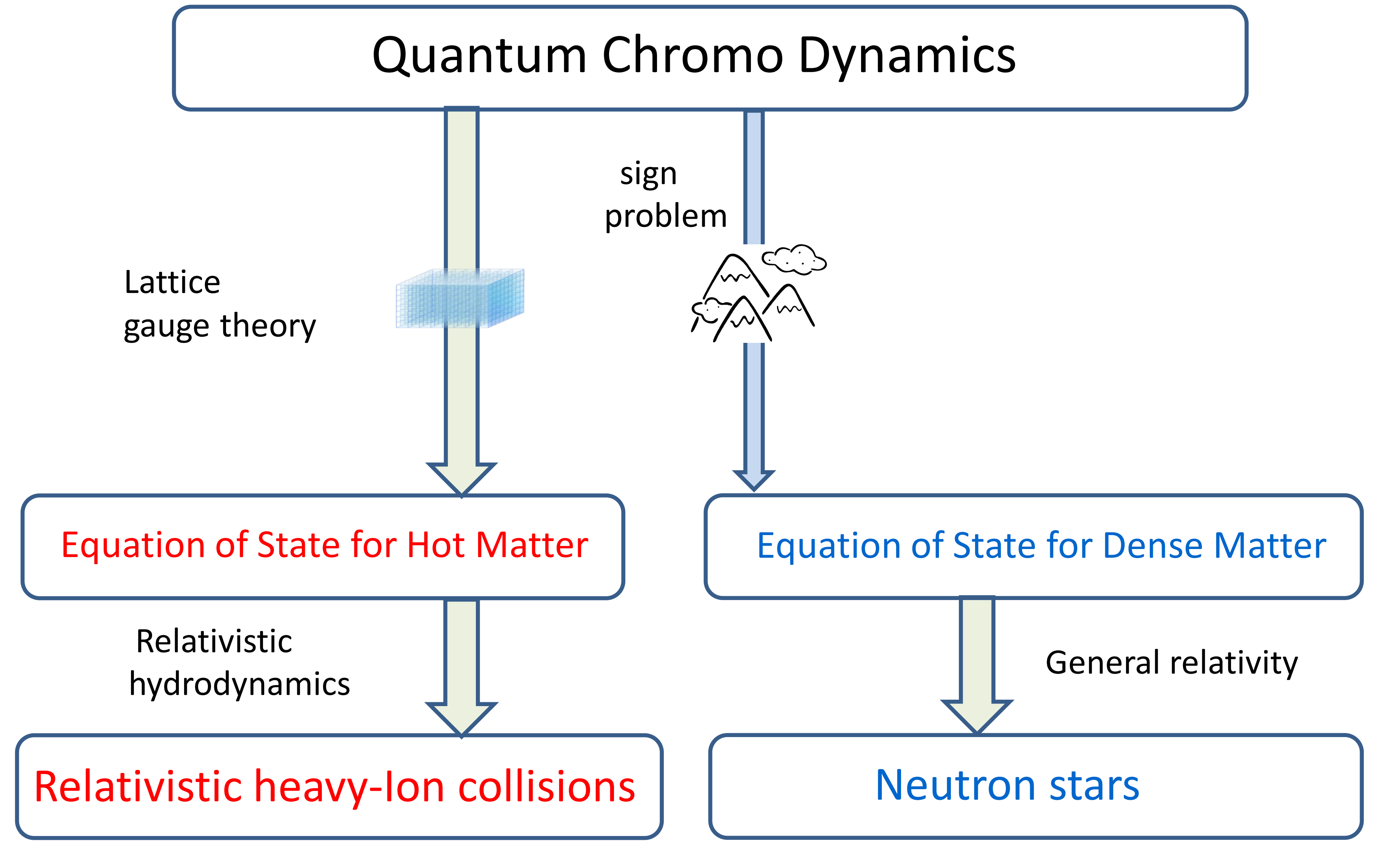
Relativistic heavy-Ion collisions

Neutron stars

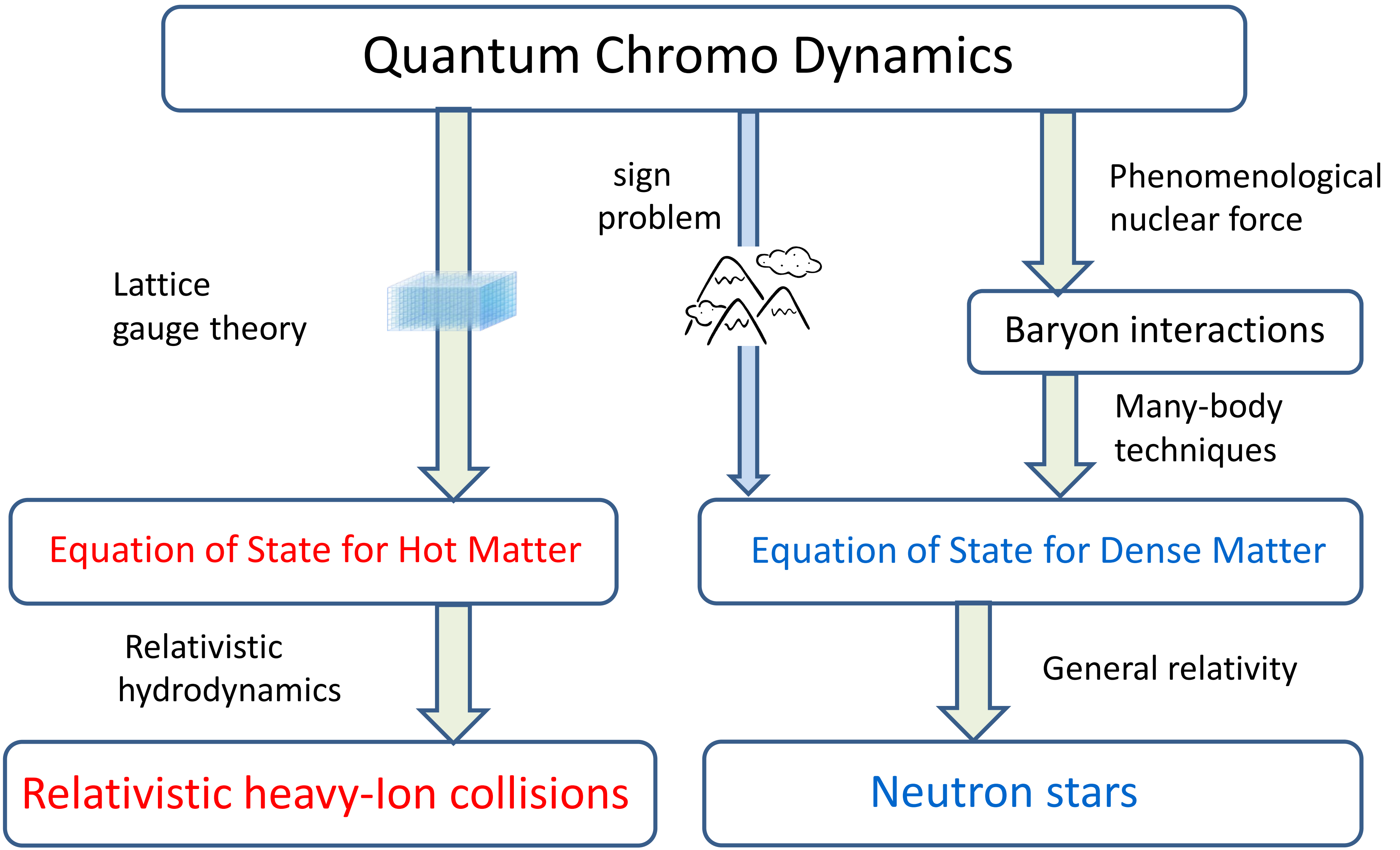
From QCD to Hot/Dense Matter



From QCD to Hot/Dense Matter

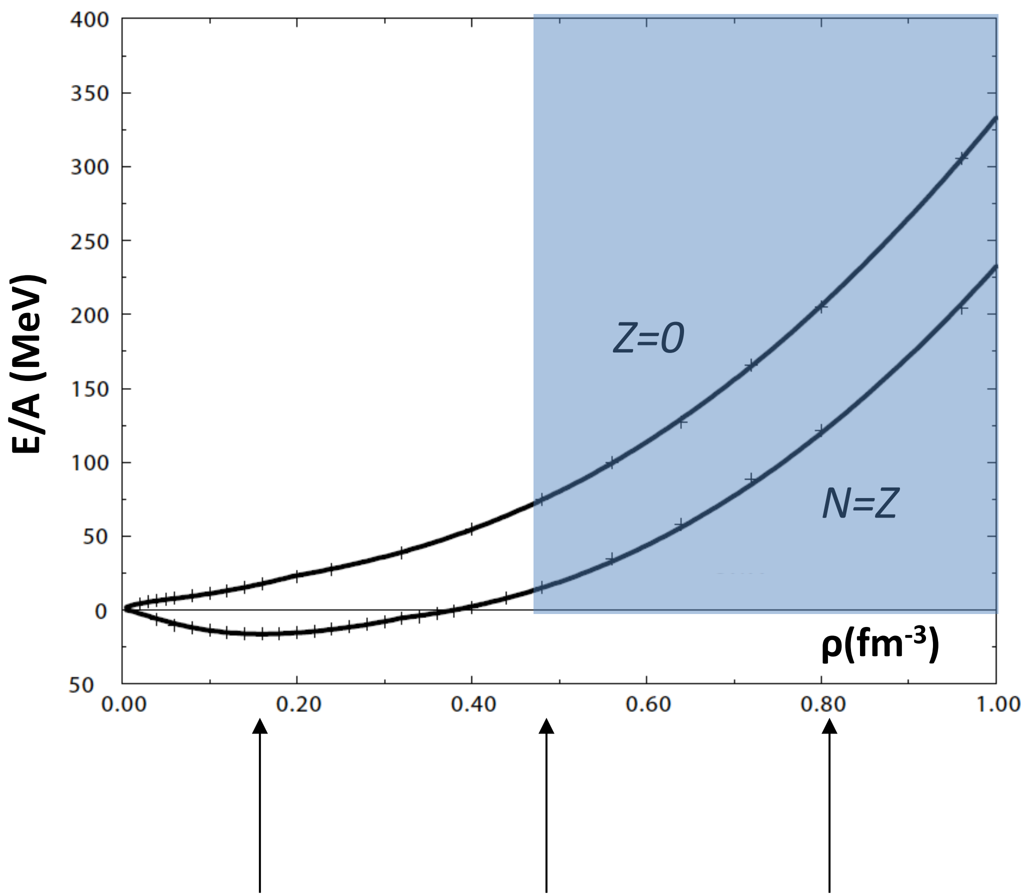


From QCD to Hot/Dense Matter



Nuclear Force and dense EOS（nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

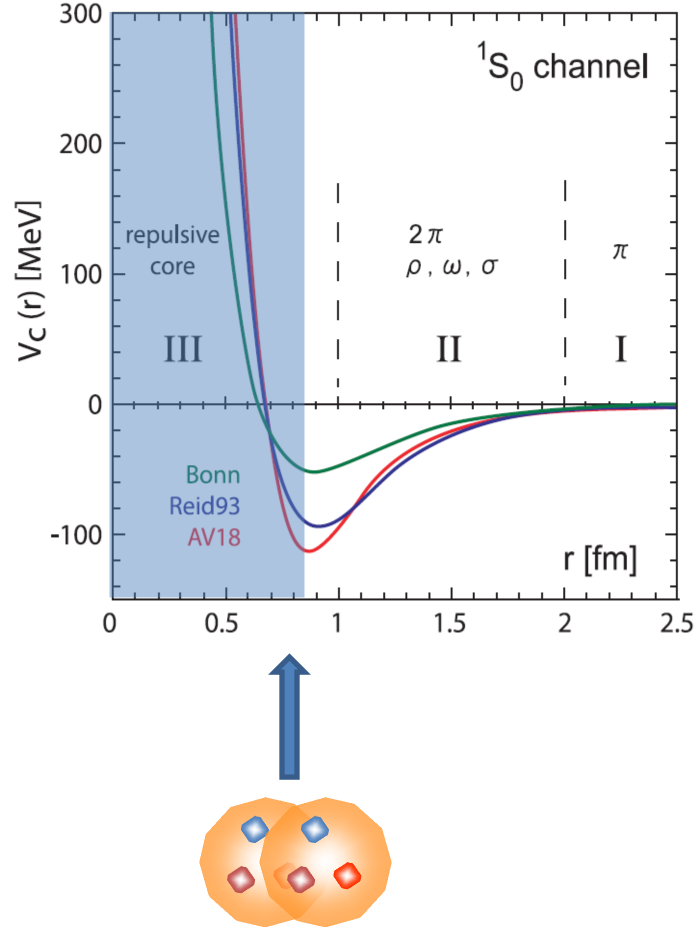


ρ_0
$= 0.16\ \mathrm{fm}^{-3}$

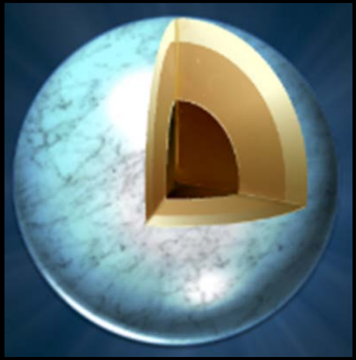
$3\rho_0$

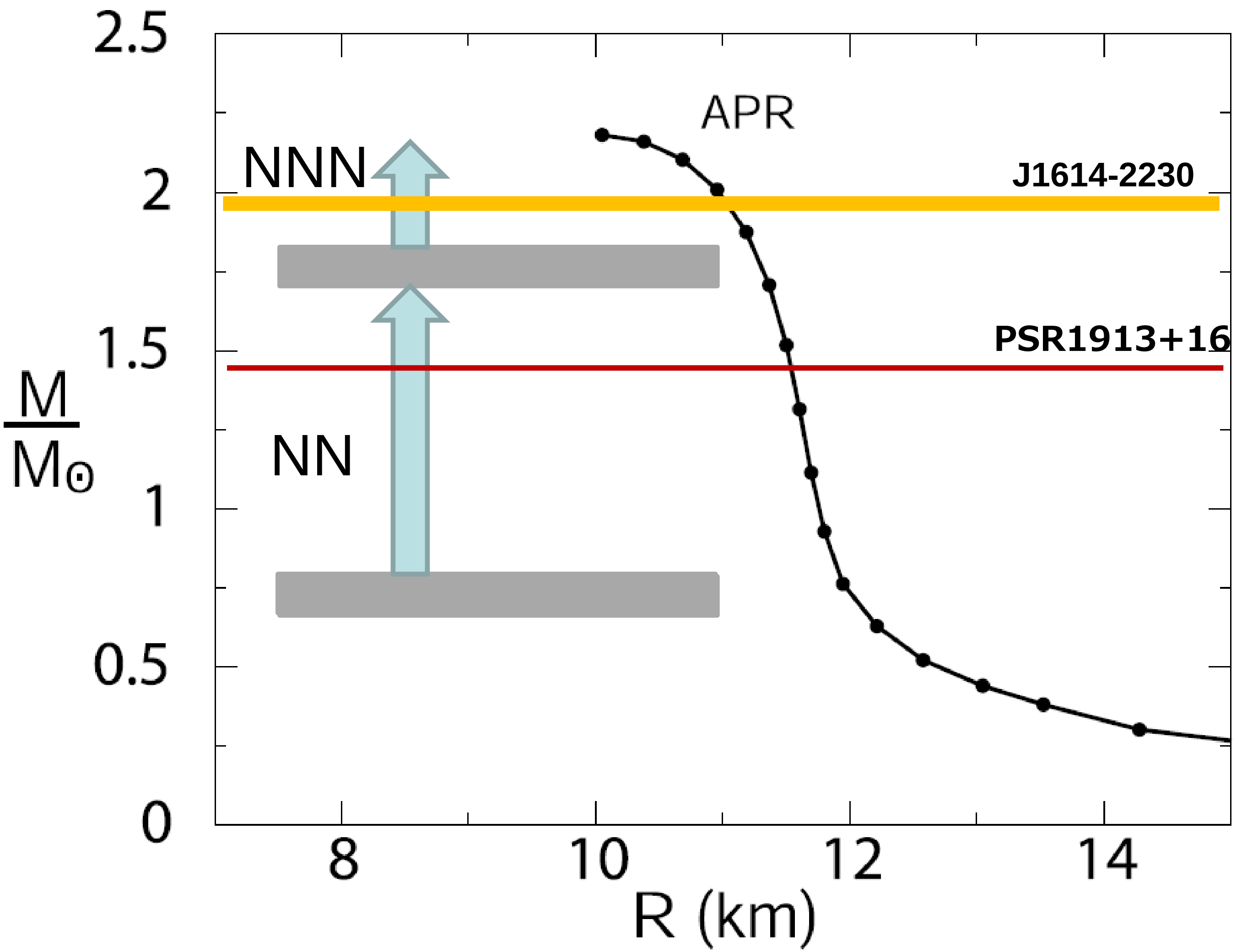
$5\rho_0$

Phenomenological nuclear force

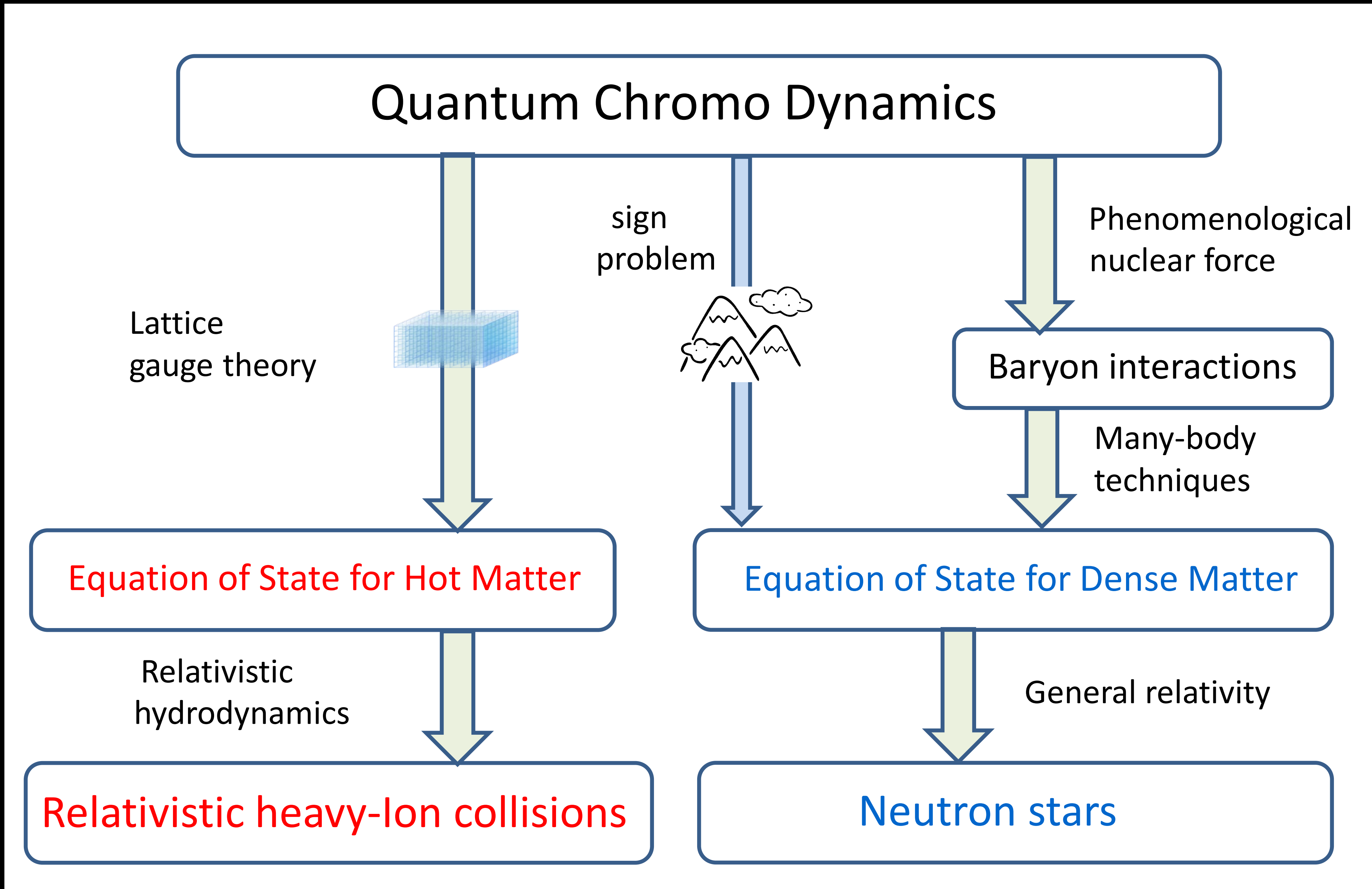


Mass-Radius relation of $N_{☆}$ (nucleons only)

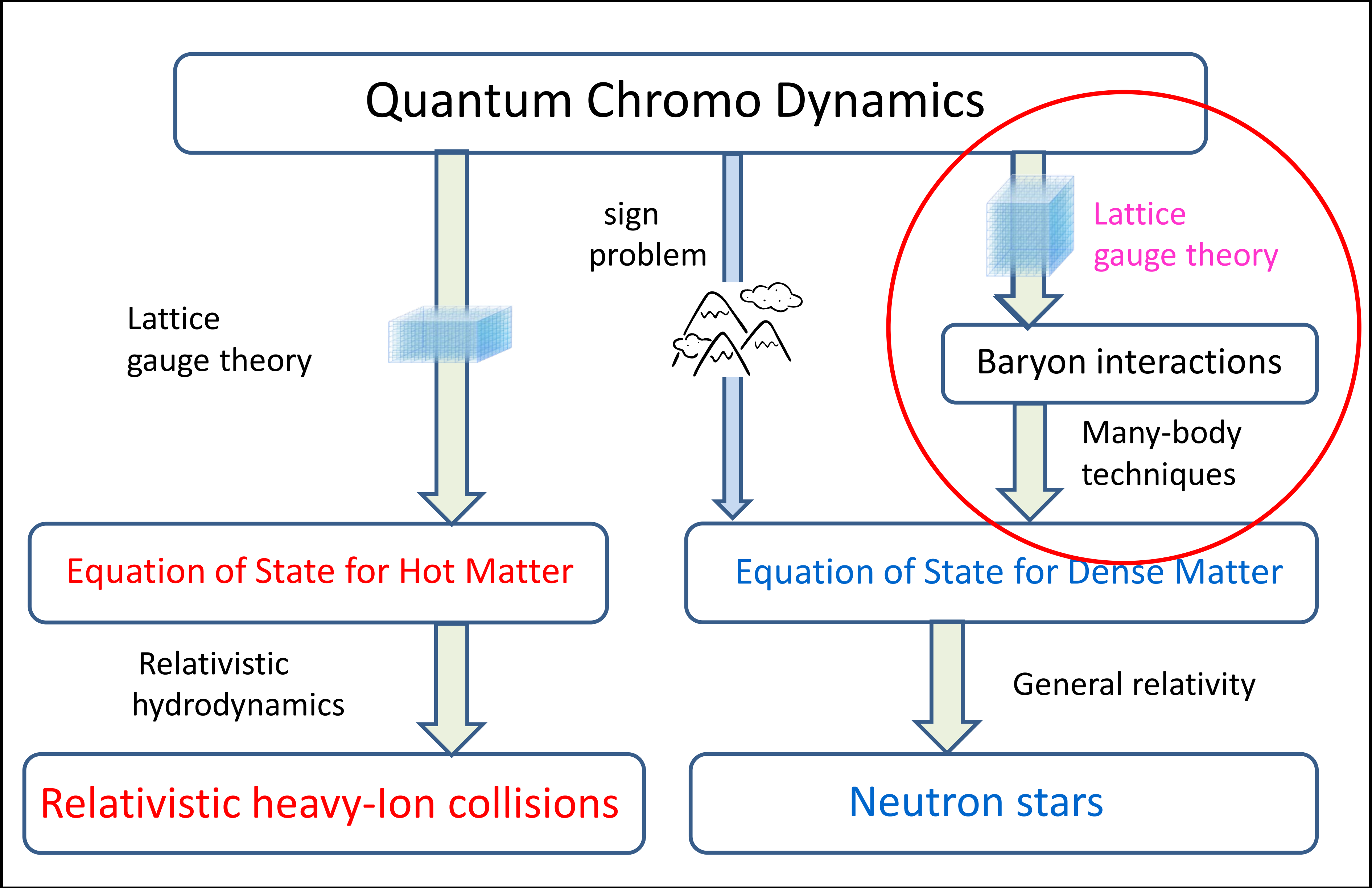




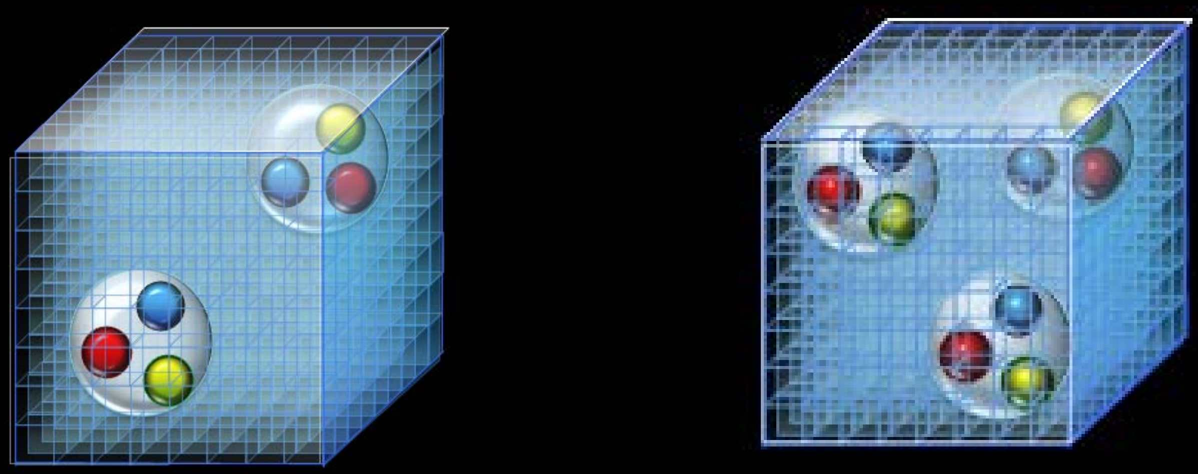
From QCD to Hot/Dense Matter



From QCD to Hot/Dense Matter



Multi-baryons on the Lattice



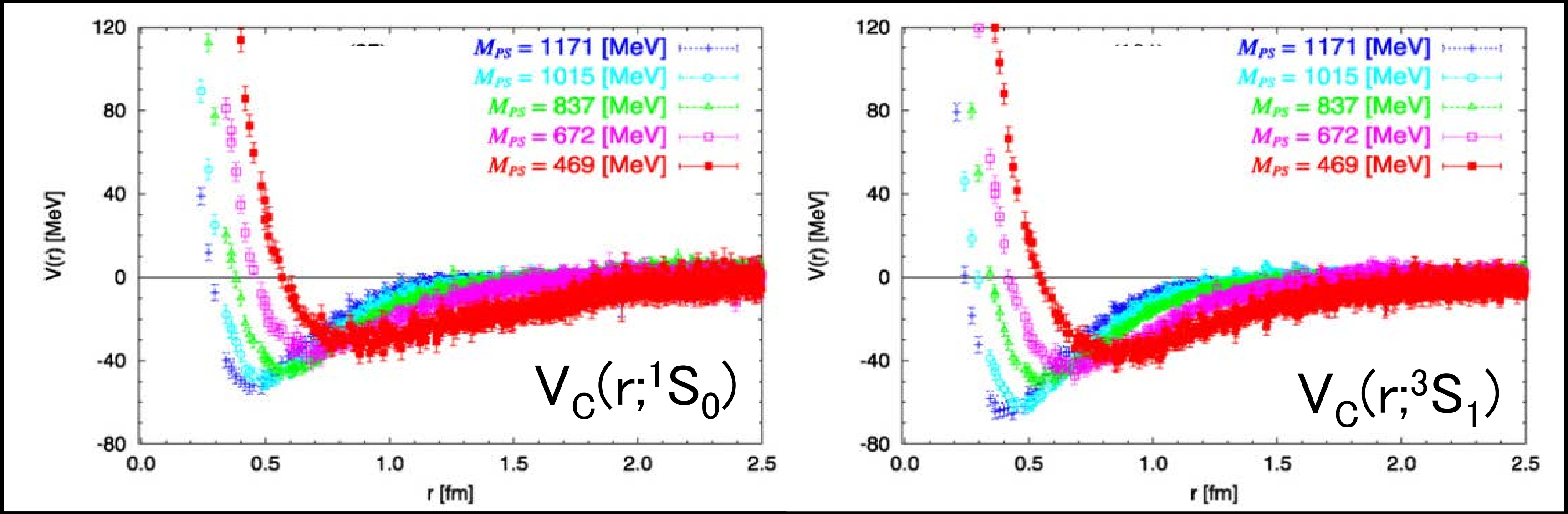
Hadrons to Atomic nuclei HAL from Lattice QCD

Univ. Tsukuba	N. Ishii, H. Nemura, K. Sasaki
RIKEN	T. Doi, T. Hatsuda, Y. Ikeda
Nihon Univ.	T. Inoue
Kyoto Univ.	S. Aoki, K. Murano
Univ. Tokyo	B. Charron

Review: "Lattice QCD Approach to Nuclear Physics"
HAL QCD Collaboration, Prog. Theor. Exp. Phys. 2012 (2012) 01A105

NN Force in 3-flavor QCD

HAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002,
Nucl. Phys. A881 (2012) 28

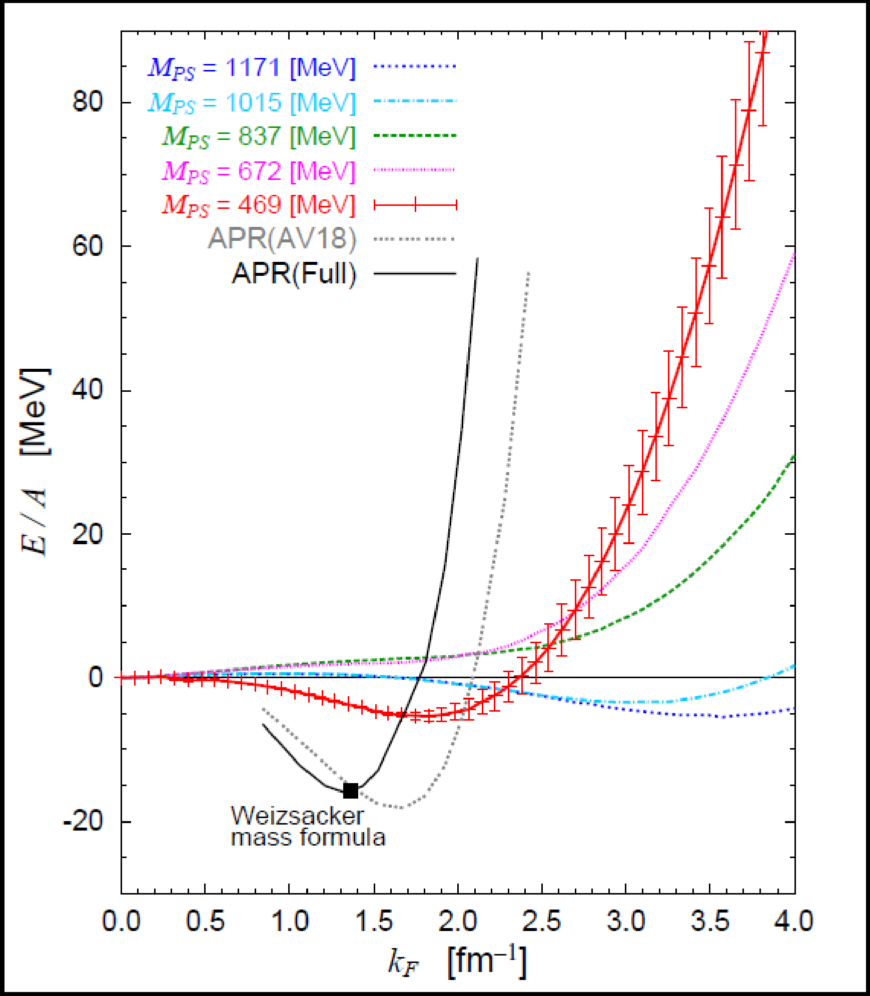


Nuclear EOS from Lattice NN force + BHF calculation

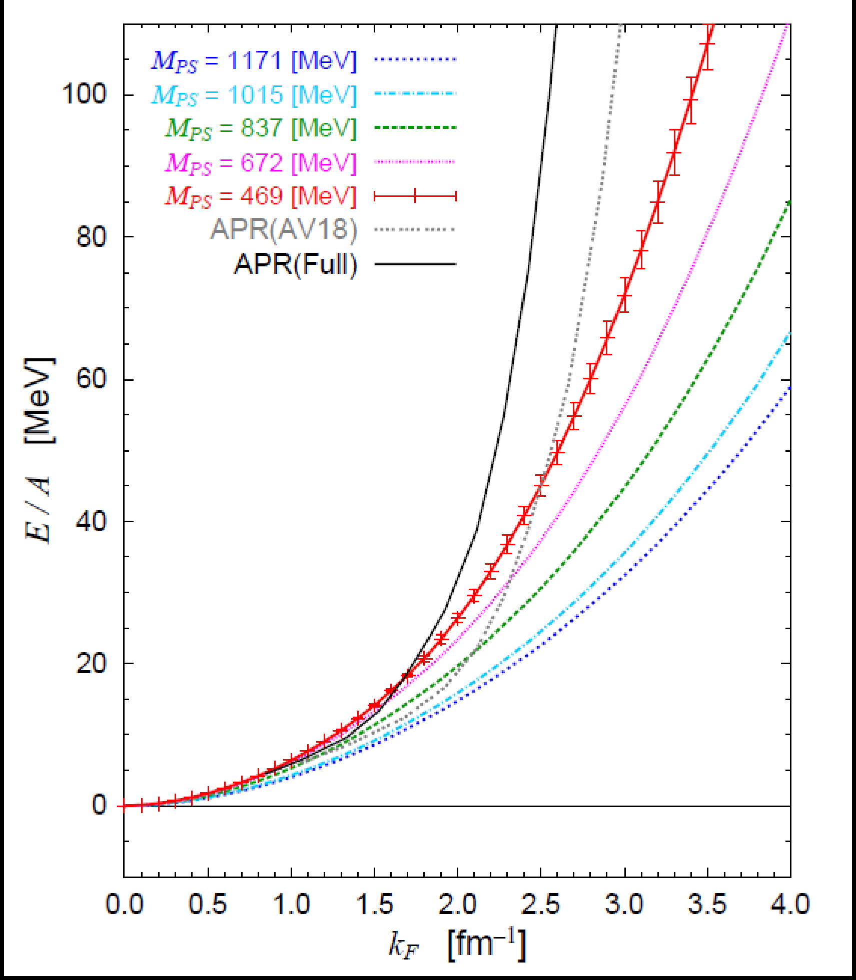
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

HAL QCD Coll., Phys. Rev. Lett. 111 (2013) 112503

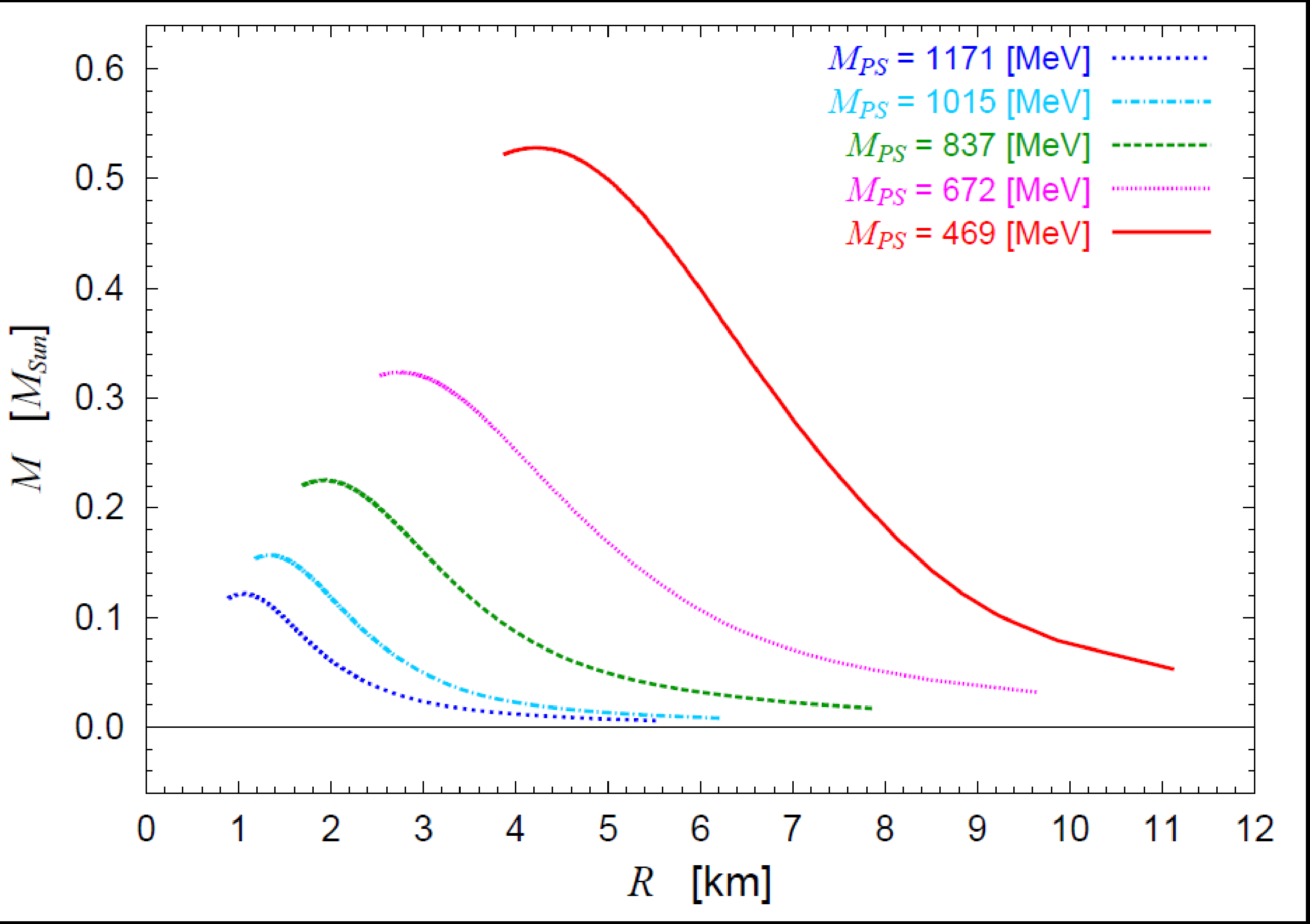
Nuclear Matter



Neutron Matter

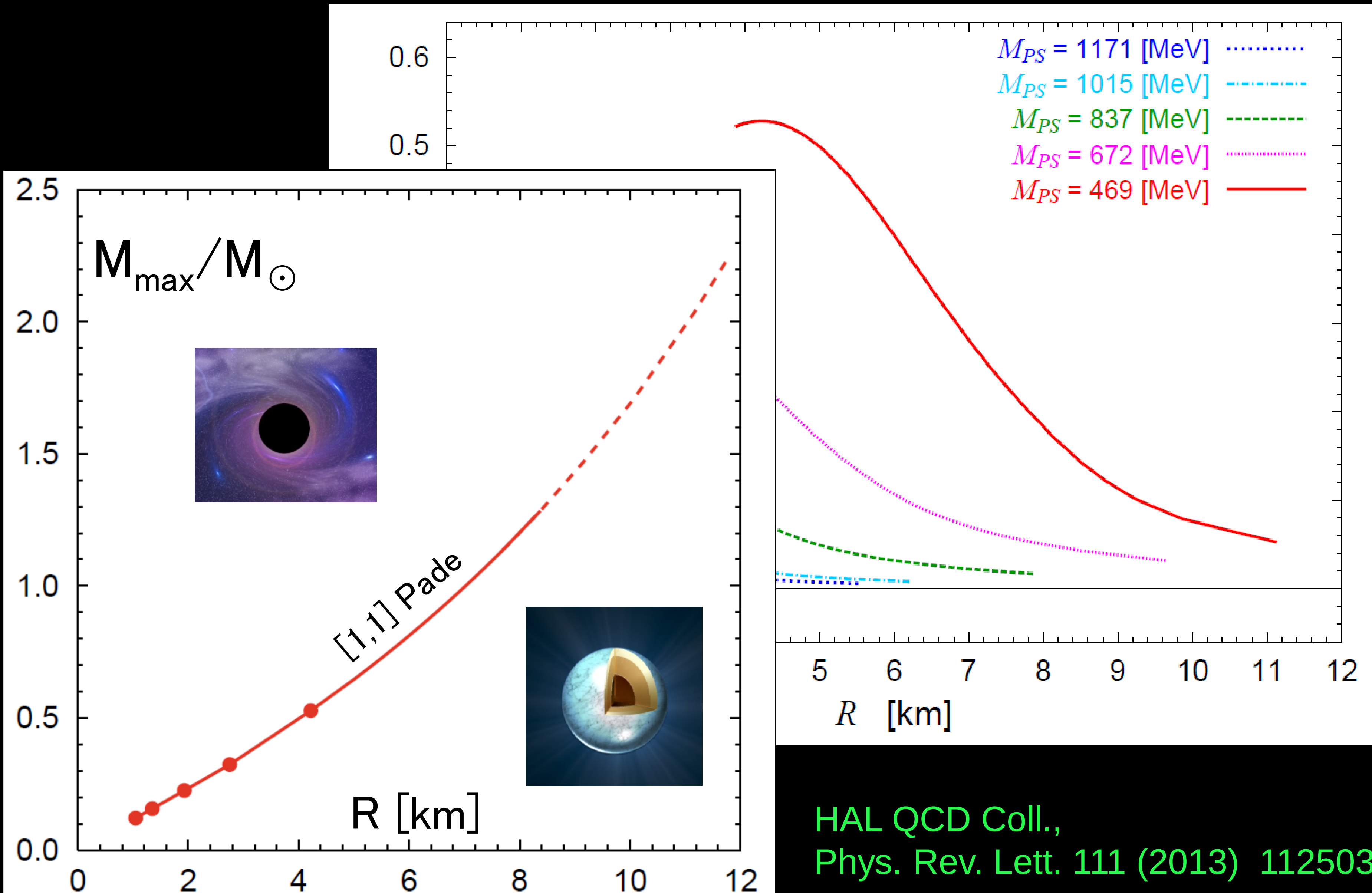


Neutron Star from "Lattice EOS"



HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

Neutron Star from "Lattice EOS"

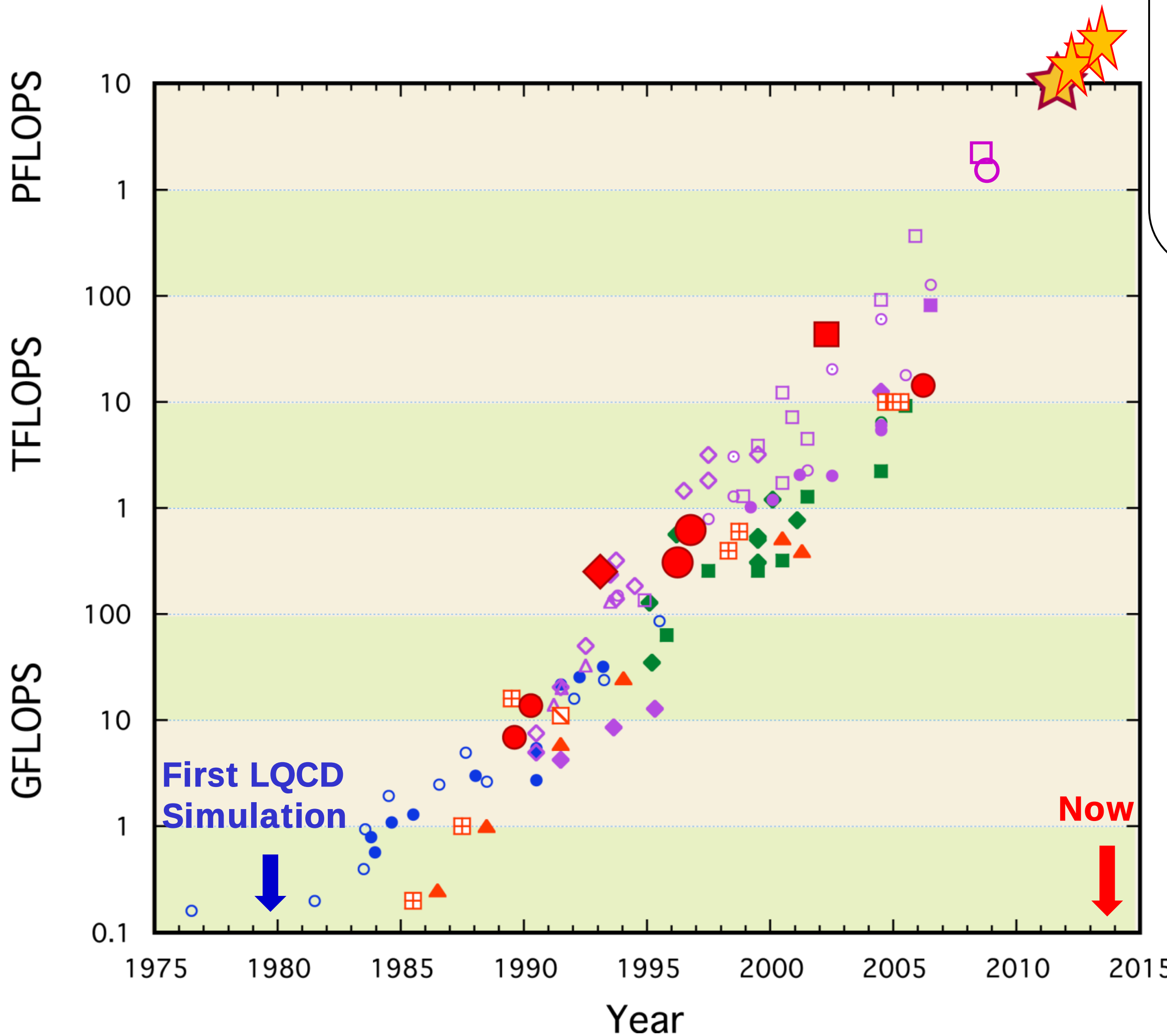


HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

High Performance Computers

2013 June top5

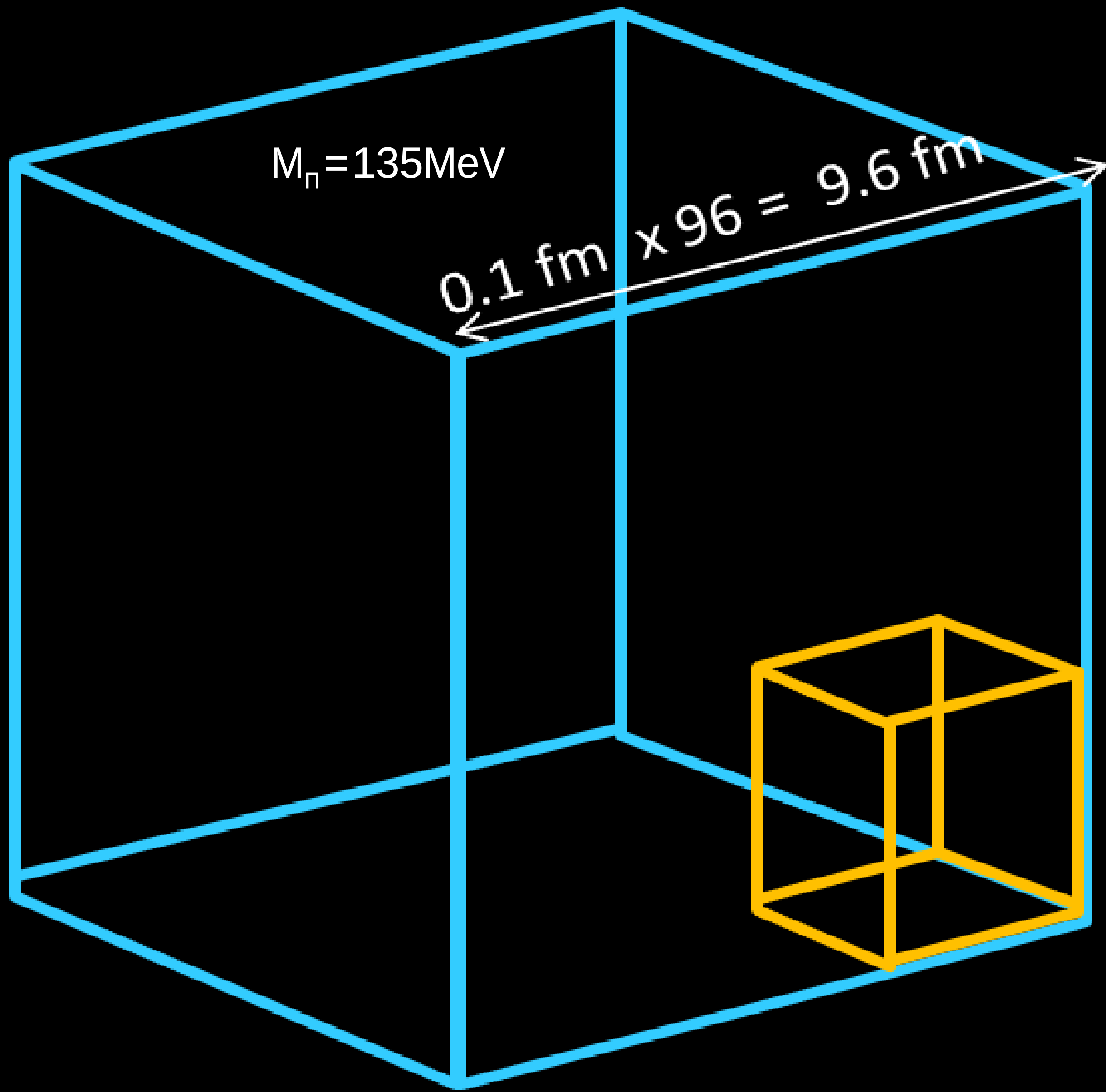
Tianhe-2	(34 PFlops)
Titan	(18 PFlops)
Sequoia	(17 PFlops)
K	(11 PFlops)
Mira	(9 PFlops)

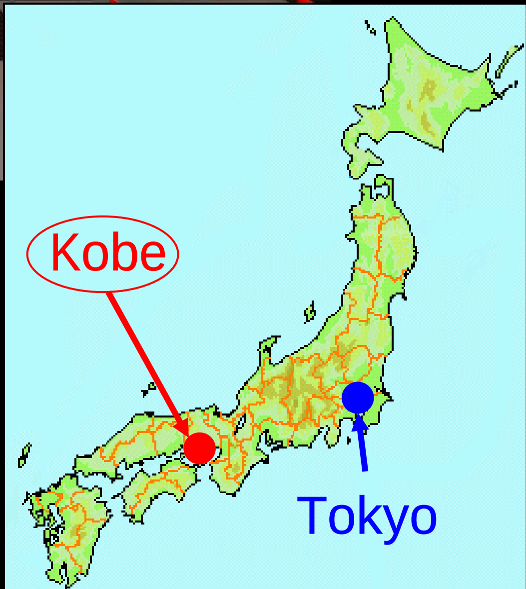


original plot by A. Ukawa

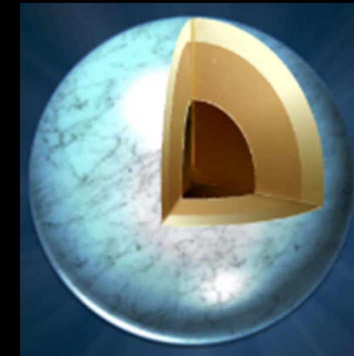
K computer @ RIKEN

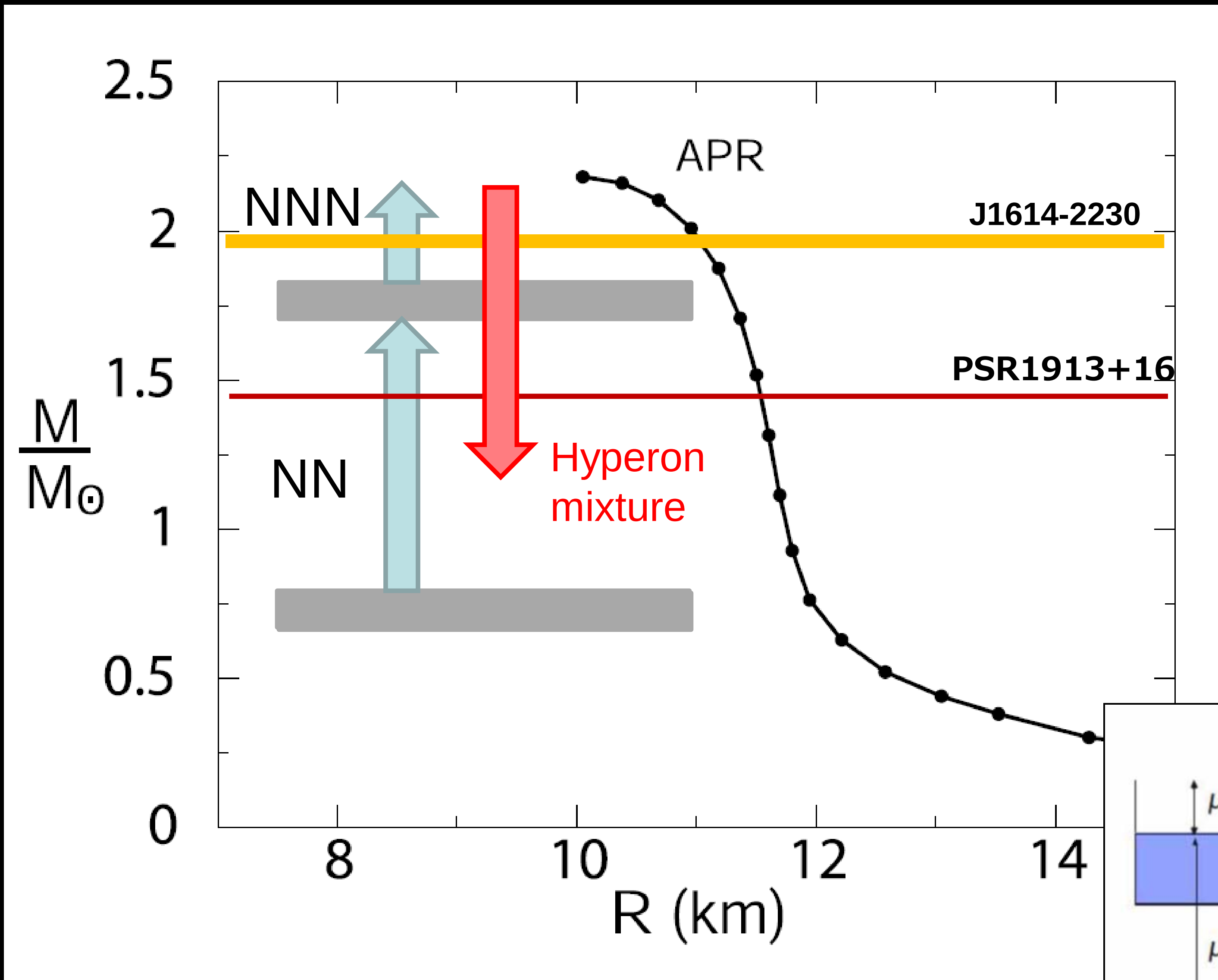
(11.28 PFlops, 80,000 CPUs x 8 = 640,000 cores)

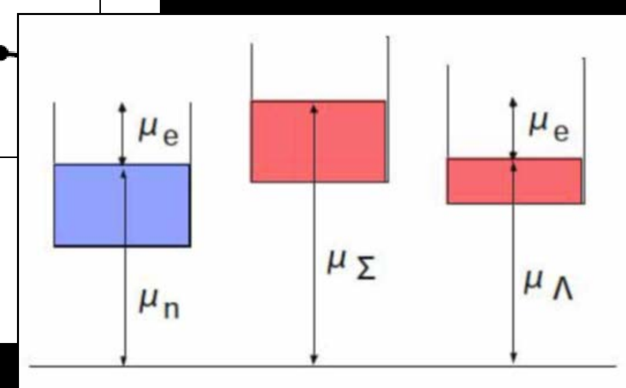




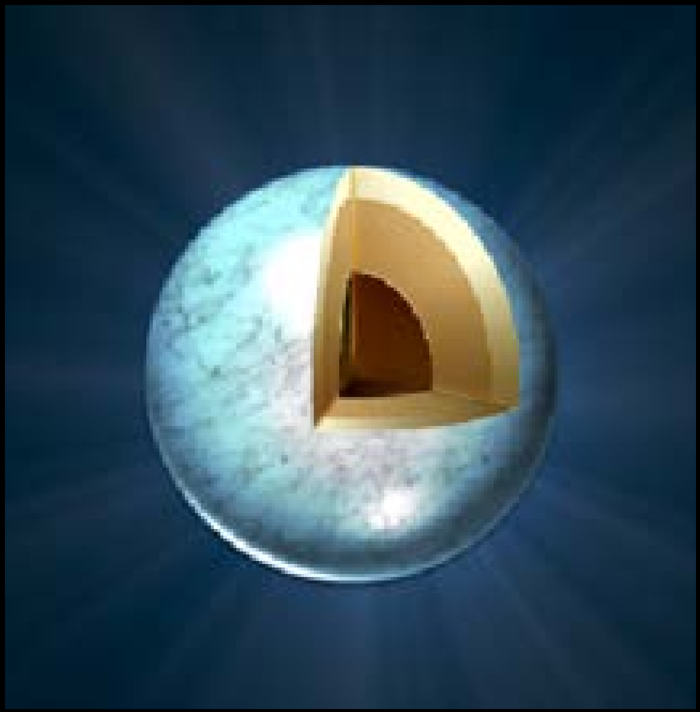
Hyperon Crisis

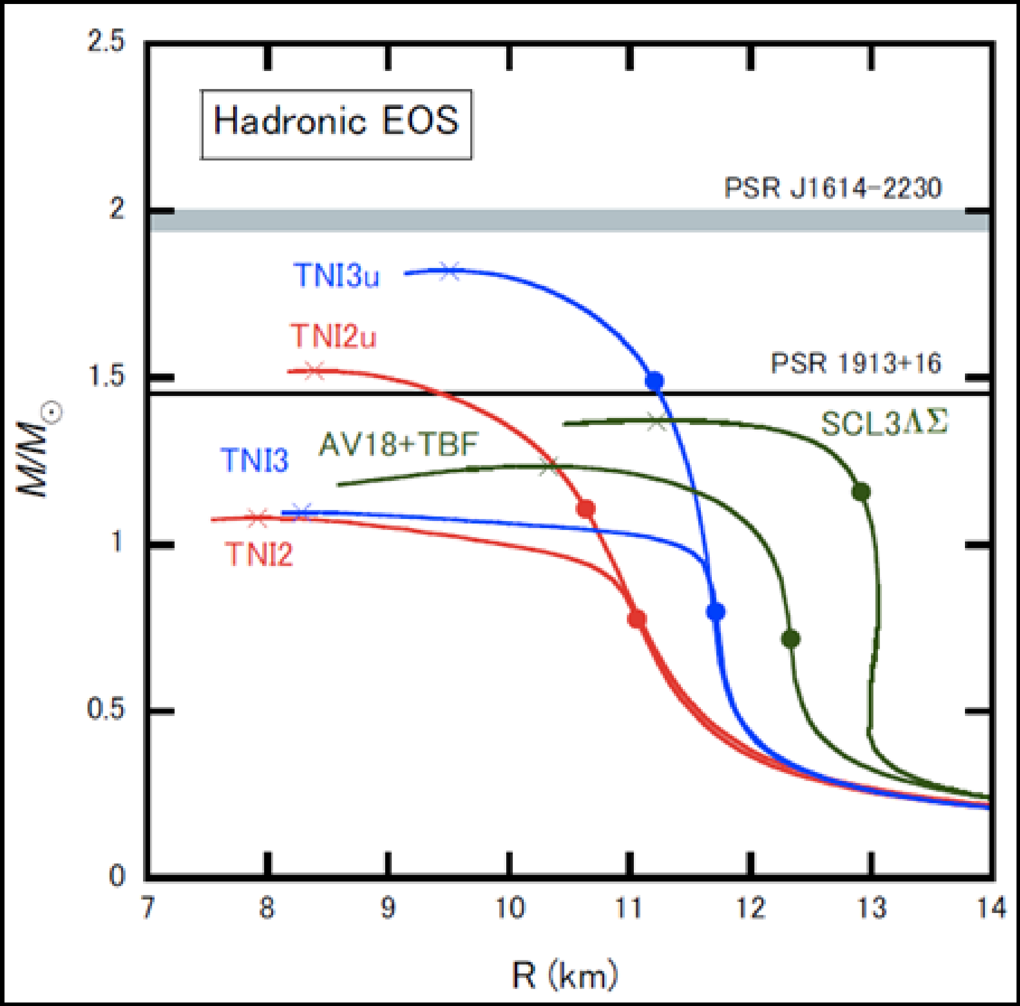






Hyperon Crisis



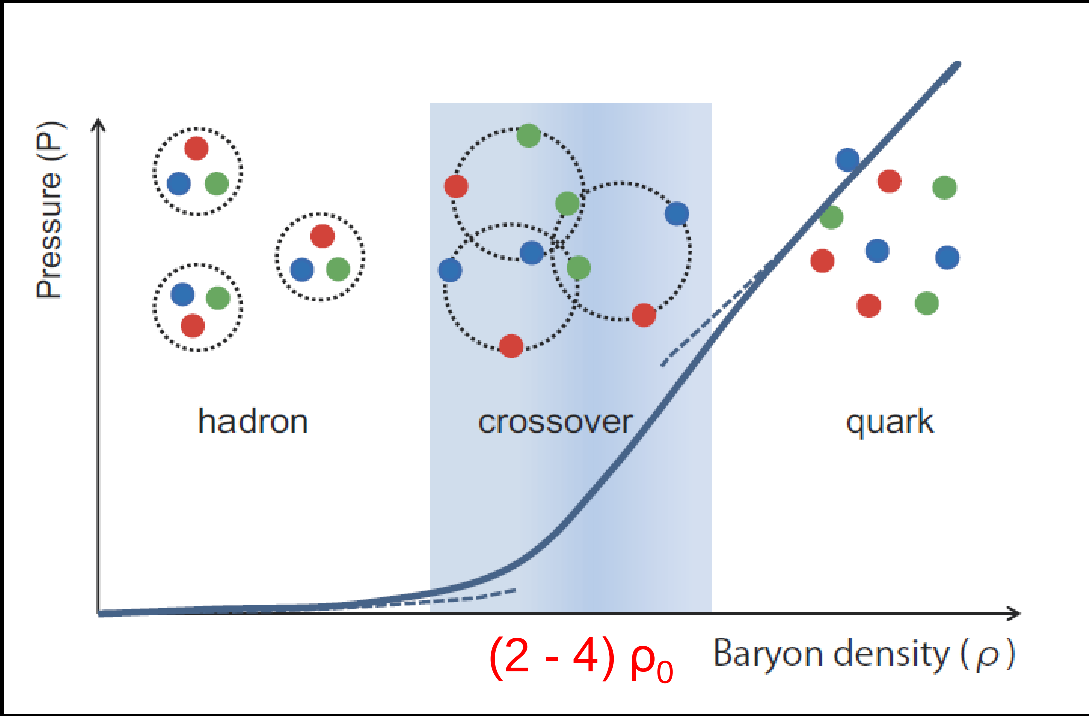


Masuda, Hatsuda & Takatsuka,
Astrophysical Journal Letters 764 (2013) 12

A Possible Resolution of Hyperon Crisis

Crossover to quark matter ?

Hatsuda, Tachibana, Yamamoto & Baym, PRL 97 (2006) 122001
Bratovic, Hatsuda and Weise, Phys.Lett. B719 (2013) 131

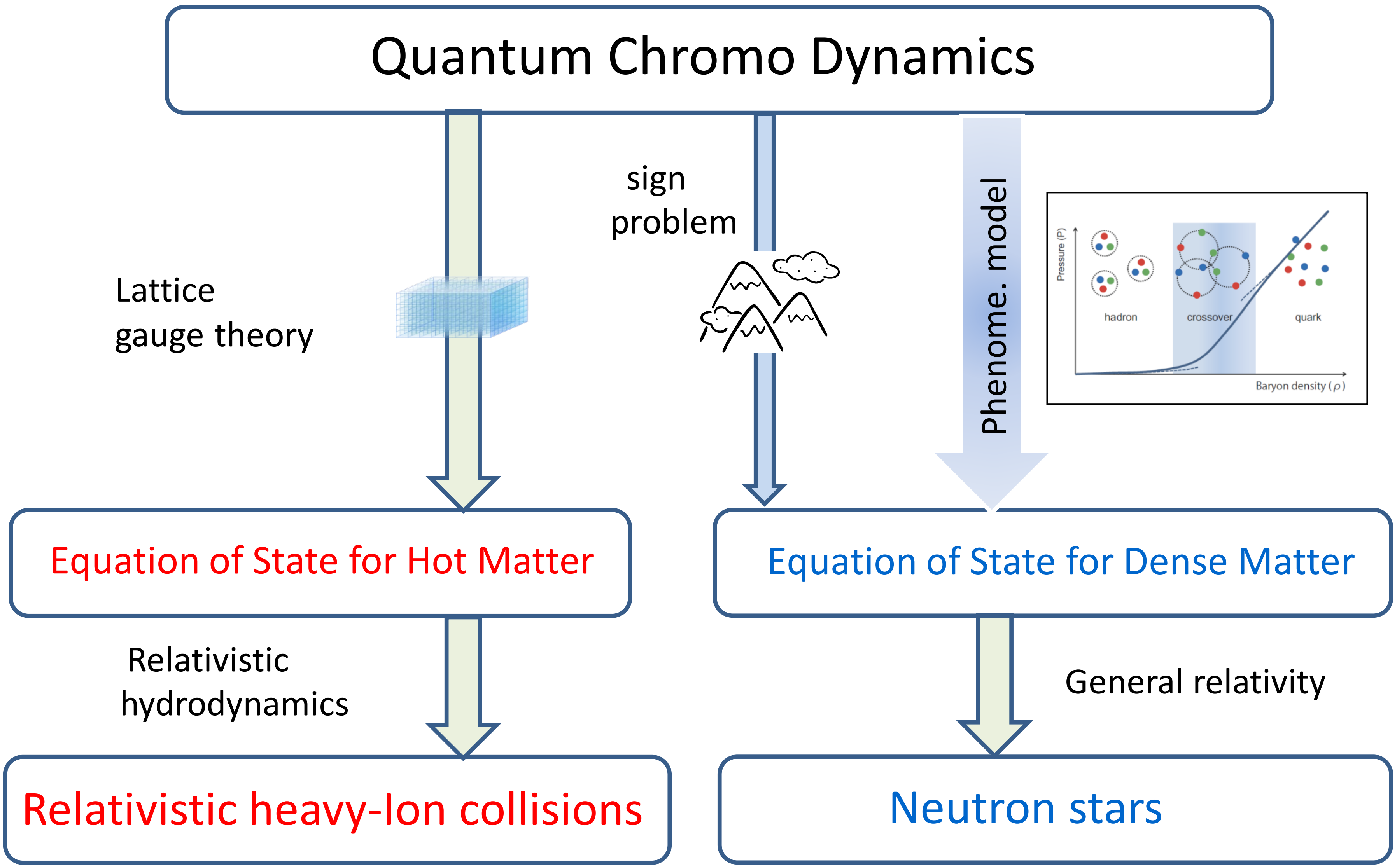


2$M_\odot$ neutrons stars require,

(i) STIFF quark-matter EOS (ii) Crossover at ρ=(2-4) ρ_0

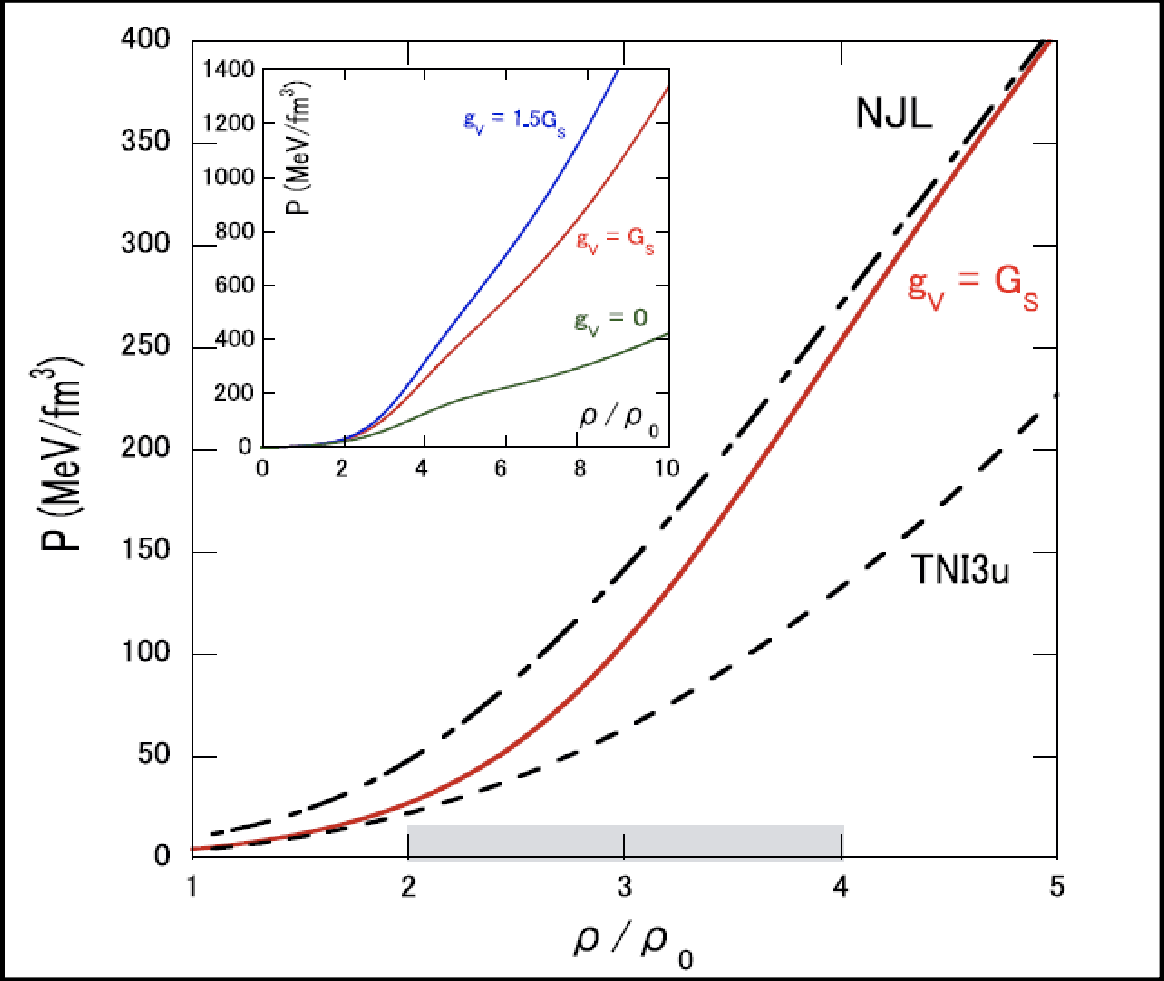
Masuda, Hatsuda & Takatsuka, Astrophysical Journal Letters 764 (2013) 12

From QCD to Hot/Dense Matter



Phenomenological crossover between soft hyperon-matter to stiff quark-matter

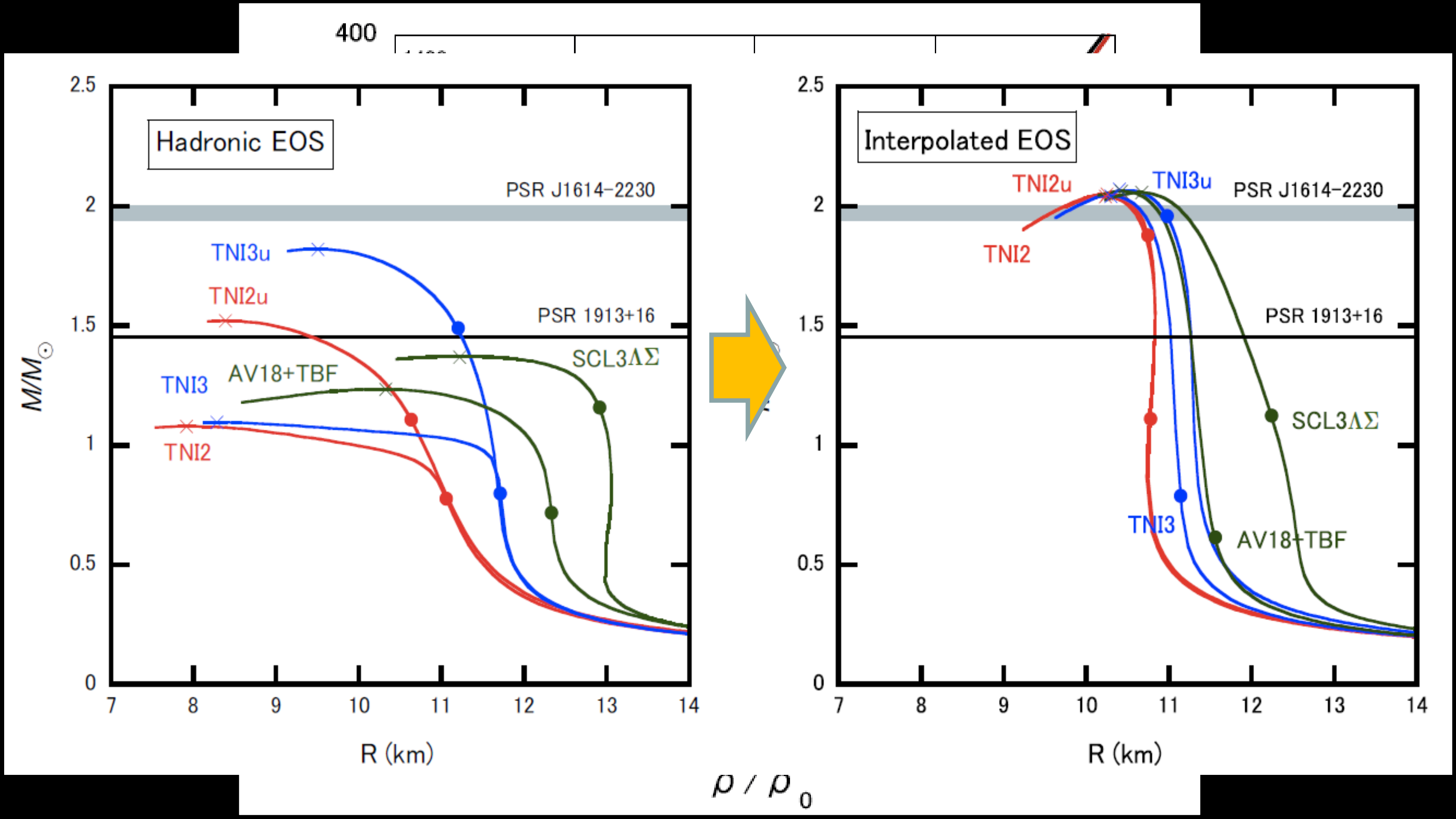
(NJL model with vector mean-field)



Masuda, Hatsuda & Takatsuka, ApJ. Lett. 764 (2013) 12

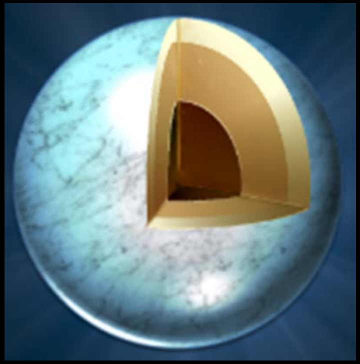
Phenomenological crossover between soft hyperon-matter to stiff quark-matter

(NJL model with vector mean-field)



Masuda, Hatsuda & Takatsuka, ApJ. Lett. 764 (2013) 12

Summary



1. Dense QCD is a real challenge

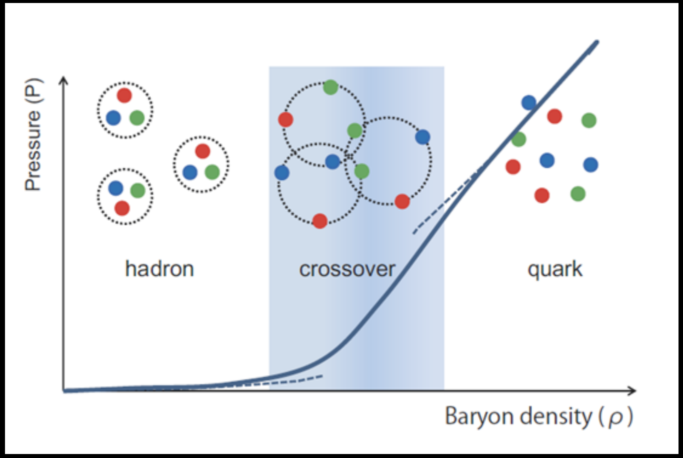
theory:

- BB and BBB forces from lattice QCD (HAL QCD Coll.)
  - -- physical point results with L~10 fm in a few years
- sign problem unsolved

obs.:

- progresses in M, R, T, B measurements
  - -- $2M_\odot$ NStars, Magnetars, CAS-A cooling, X-ray bursts
- Gravitational wave detections will be ready soon

2. Hyperon Crisis



- no convincing resolution yet
  - -- n-body hyperon force ?
  - -- crossover to stiff quark matter
    - → may be studied by HIC ?
    - (Xu, Song, Ko & Li, PRL 2014)

Elliptic flow splitting as a probe of the QCD phase structure at finite baryon chemical potential

Jun Xu,[1,*] Taesoo Song,[2] Che Ming Ko,[2] and Feng Li[2]

[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[2]*Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*

(Dated: November 15, 2013)

Using a partonic transport model based on the 3-flavor Nambu-Jona-Lasinio model and a relativistic hadronic transport model to describe, respectively, the evolution of the initial partonic and the final hadronic phase of heavy-ion collisions at energies carried out in the Beam-Energy Scan program of the Relativistic Heavy Ion Collider, we have studied the effects of both the partonic and hadronic mean-field potentials on the elliptic flow of particles relative to that of their antiparticles. We find that to reproduce the measured relative elliptic flow differences between nucleons and antinucleons as well as between kaons and antikaons requires a vector coupling constant as large as 0.5 to 1.1 times the scalar coupling constant in the Nambu-Jona-Lasinio model. Implications of our results in understanding the QCD phase structure at finite baryon chemical potential are discussed.

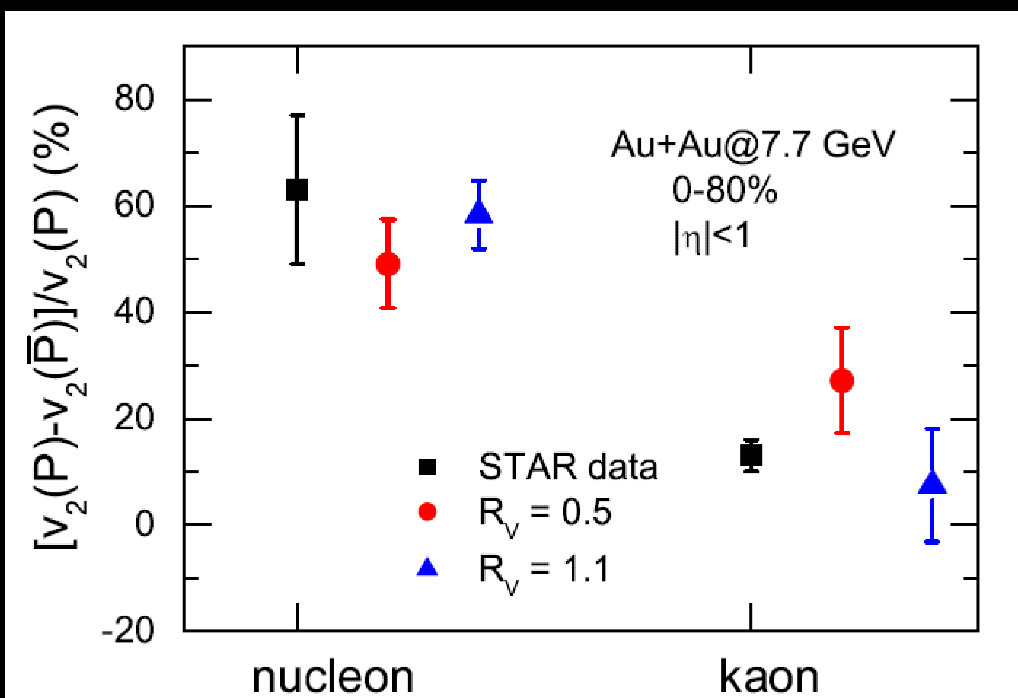


FIG. 4: (Color online) Relative elliptic flow difference between nucleons and antinucleons as well as kaons and antikaons for different values of $R_V = G_V/G$ in the NJL model compared with the STAR data [8].

(Xu, Song, Ko & Li, PRL 2014)

END

Precision QCD

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

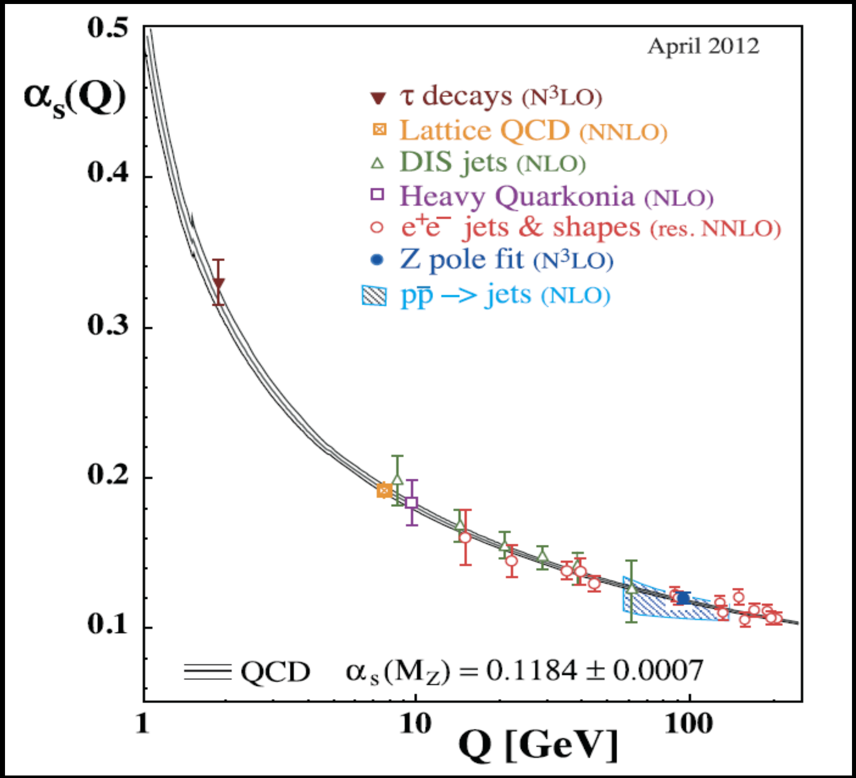
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Running masses: $m_q(Q)$

quark masses (from lattice QCD)	**[MeV]** (MS-bar @ 2GeV)
m_u	2.16 (9)(7)
m_d	4.68 (14)(7)
m_s	93.8 (2.4)

FLAG Collaboration update(July 26, 2013)
http://itpwiki.unibe.ch/flag/

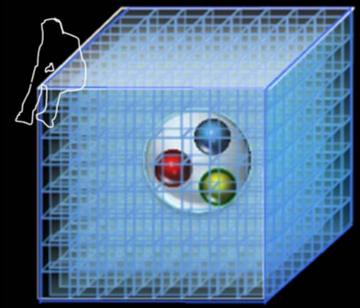
Running coupling: $\alpha_s(Q)=g^2/4\pi$

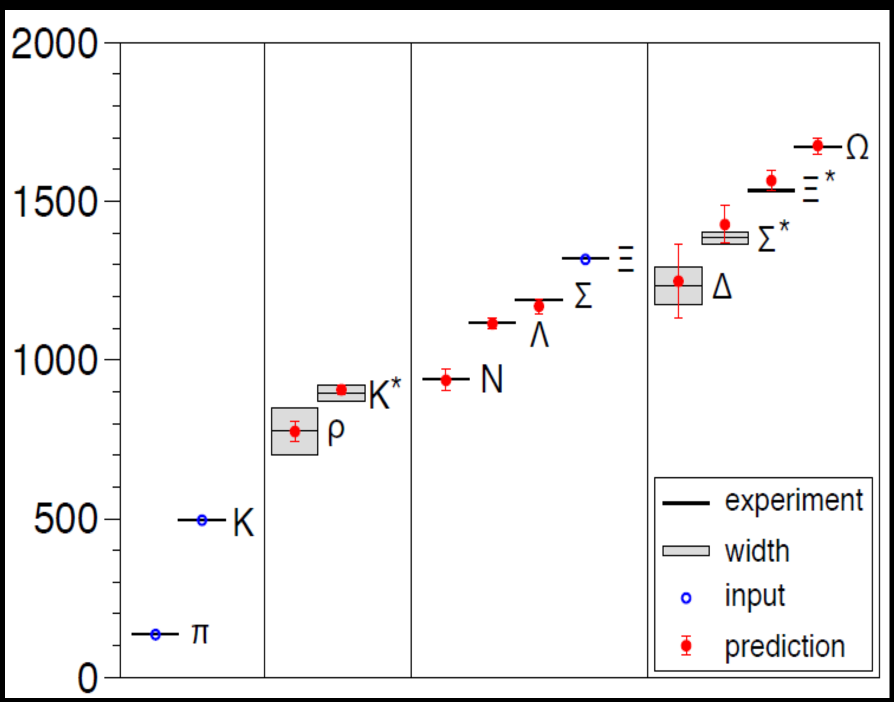


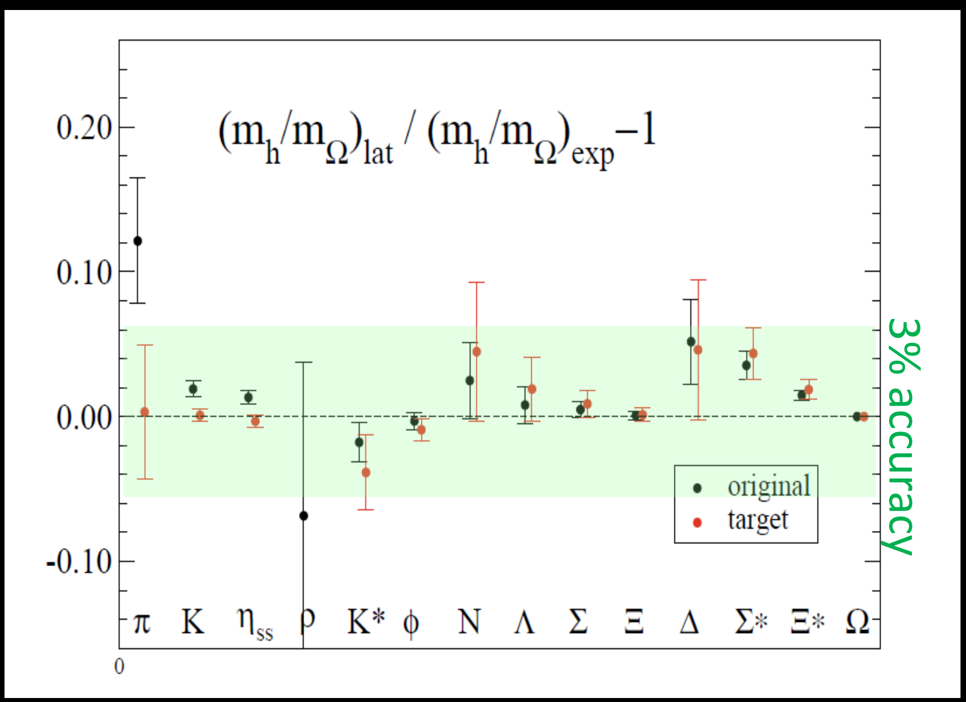
PDG (2012) http://pdg.lbl.gov/

Hadron masses (2008)
$m_\pi > 190$ MeV

Hadron masses (2010)
$m_\pi = 135$ MeV



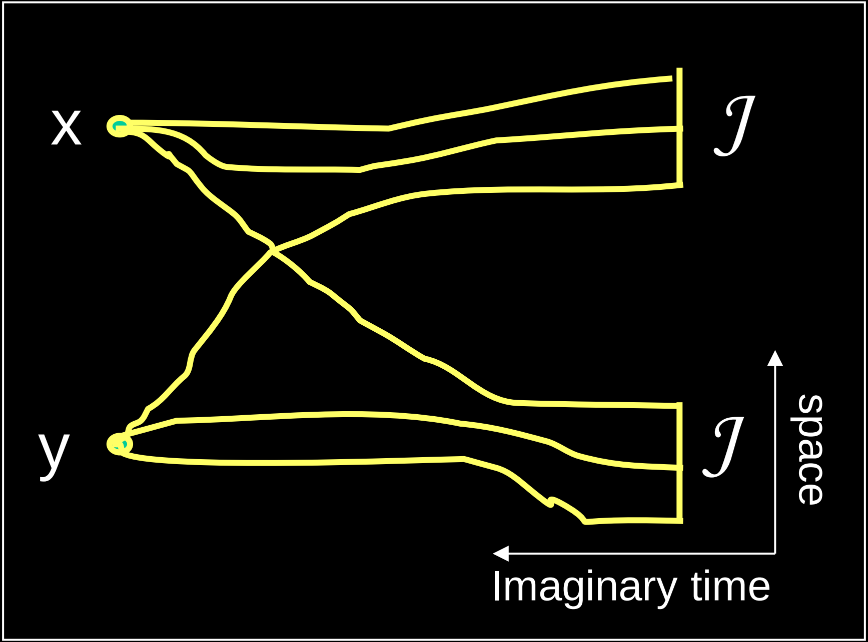




BMW Collaboration, Science 322 (2008) 1224

PACS-CS Coll.: Phys. Rev.D81 (2010) 074503

Hadronic correlations in LQCD



$$\langle N_1(\mathbf{x},t)N_2(\mathbf{y},t)\mathcal{J}_1^\dagger(0)\mathcal{J}_2^\dagger(0)\rangle$$
$$= \sum_n \langle 0|N_1(\mathbf{x})N_2(\mathbf{y})|n\rangle a_n e^{-E_n t}$$
$$\xrightarrow{t>t^*} \phi(\mathbf{r},t) = \sum_{n<n^*} b_n \phi_n(\mathbf{r}) e^{-E_n t}$$

Finite Volume Method

$E_0(L)$ → phase shift

Luescher, Nucl. Phys. B354 (1991) 531

HAL QCD Method

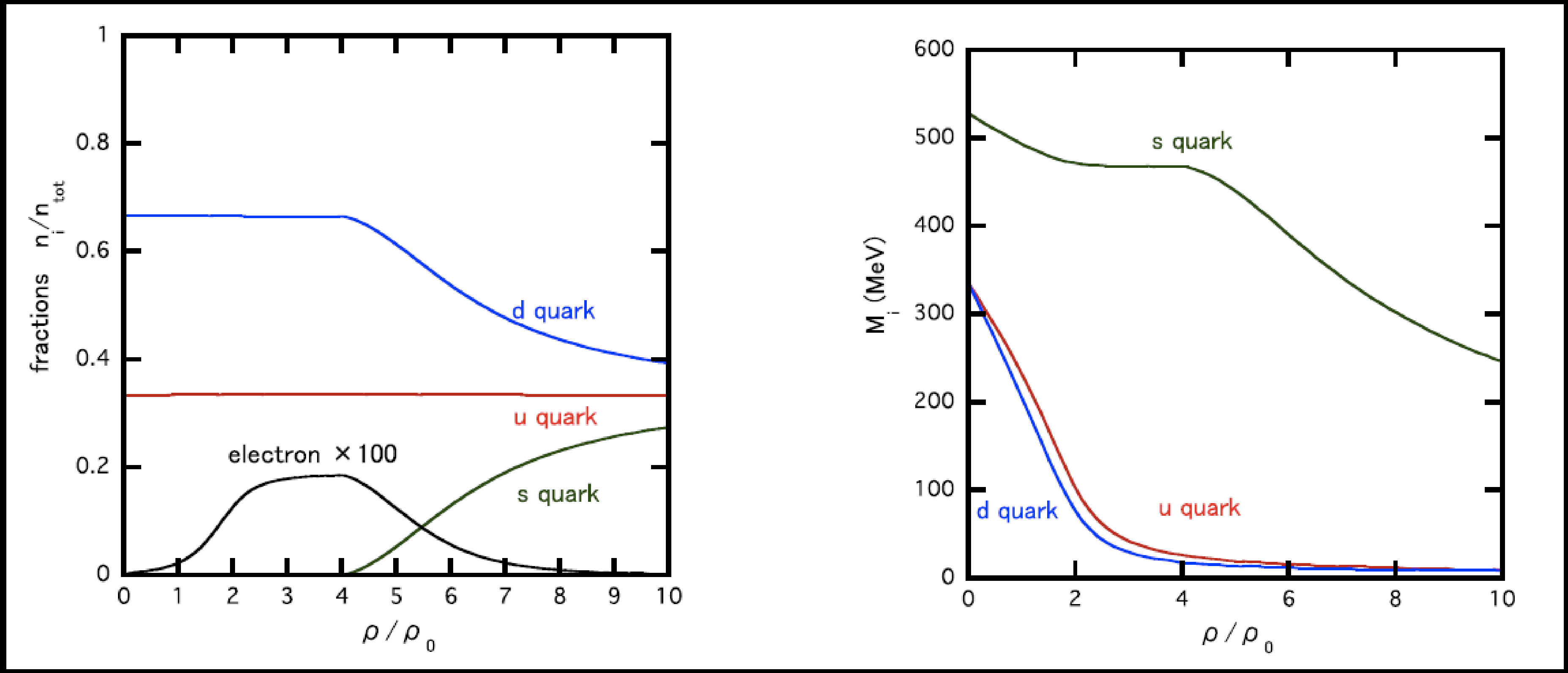
$\phi(r,t)$ → kernel → phase shift

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001
HAL QCD Coll., PLB 712 (2012) 437

A phenomenological model of strongly interacting Quark Matter

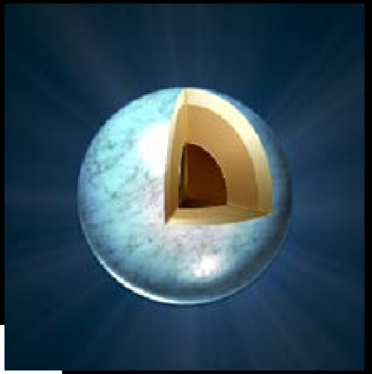
$$\mathcal{L}_{\rm NJL} = \overline{q}(i\partial\!\!\!/ - m)q + \frac{1}{2}G_S \sum_{a=0}^{8}[(\overline{q}\lambda^a q)^2 + (\overline{q}i\gamma_5\lambda^a q)^2] + G_D[\det\overline{q}(1+\gamma_5)q + \text{h.c.}]$$

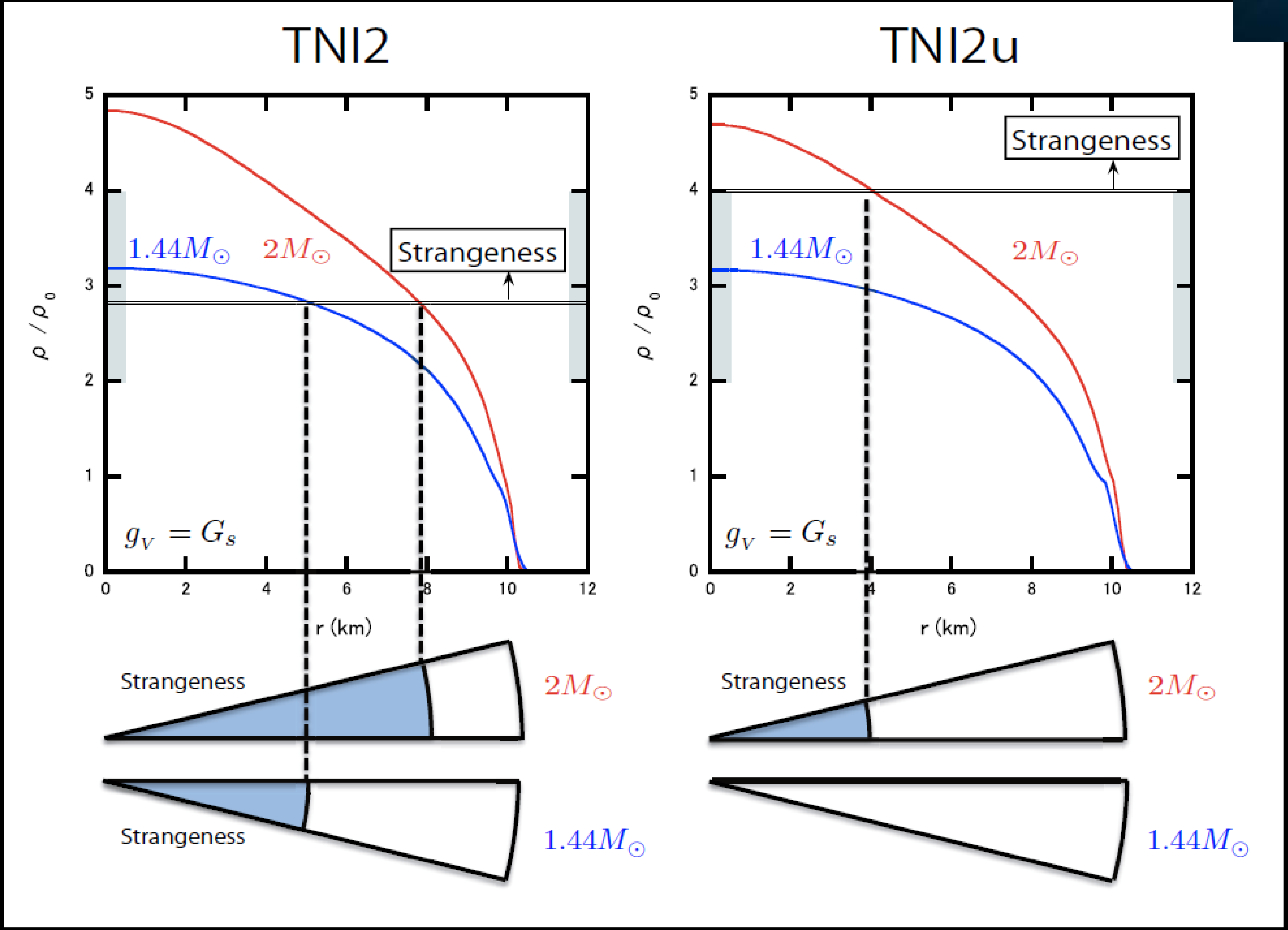
$$- \begin{cases} \frac{1}{2}g_V\,(\overline{q}\gamma^\mu q)^2 \\ \frac{1}{2}G_V\,\sum_{a=0}^{8}\left[(\overline{q}\gamma^\mu\lambda^a q)^2 + (\overline{q}i\gamma^\mu\gamma_5\lambda^a q)^2\right] \end{cases}$$



Masuda, Hatsuda & Takatsuka, Ap. J. Lett. 764 (2013) 12

Hyperon 3-body force and onset of strangeness





Highly magnetized neutron stars (Magnetars)

Surface ~$10^{14\text{-}15}$ G

Interior ~$10^{18\text{-}19}$ G ?

Physics of strong interaction?