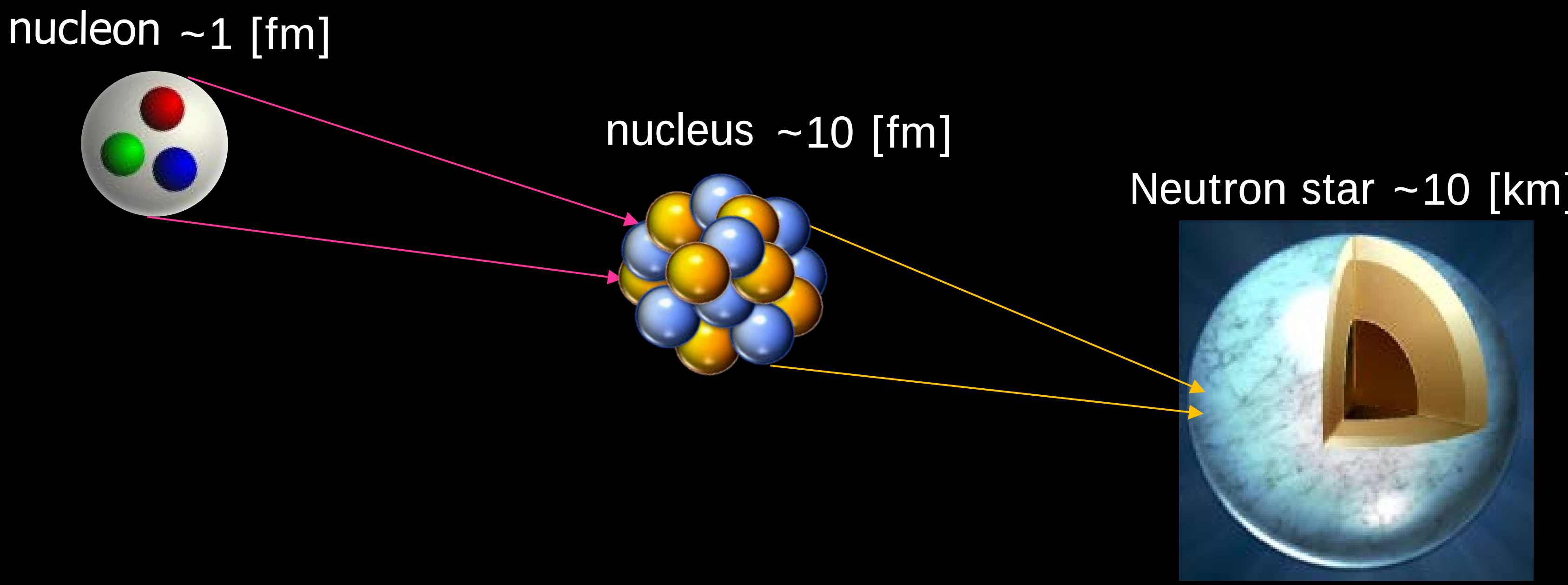
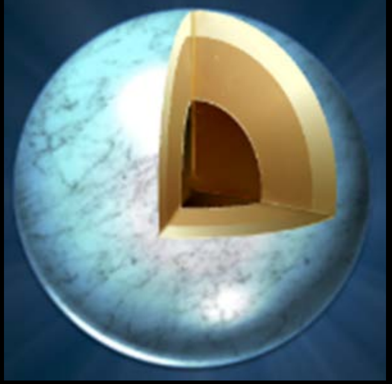
Dense QCD and Compact Stars



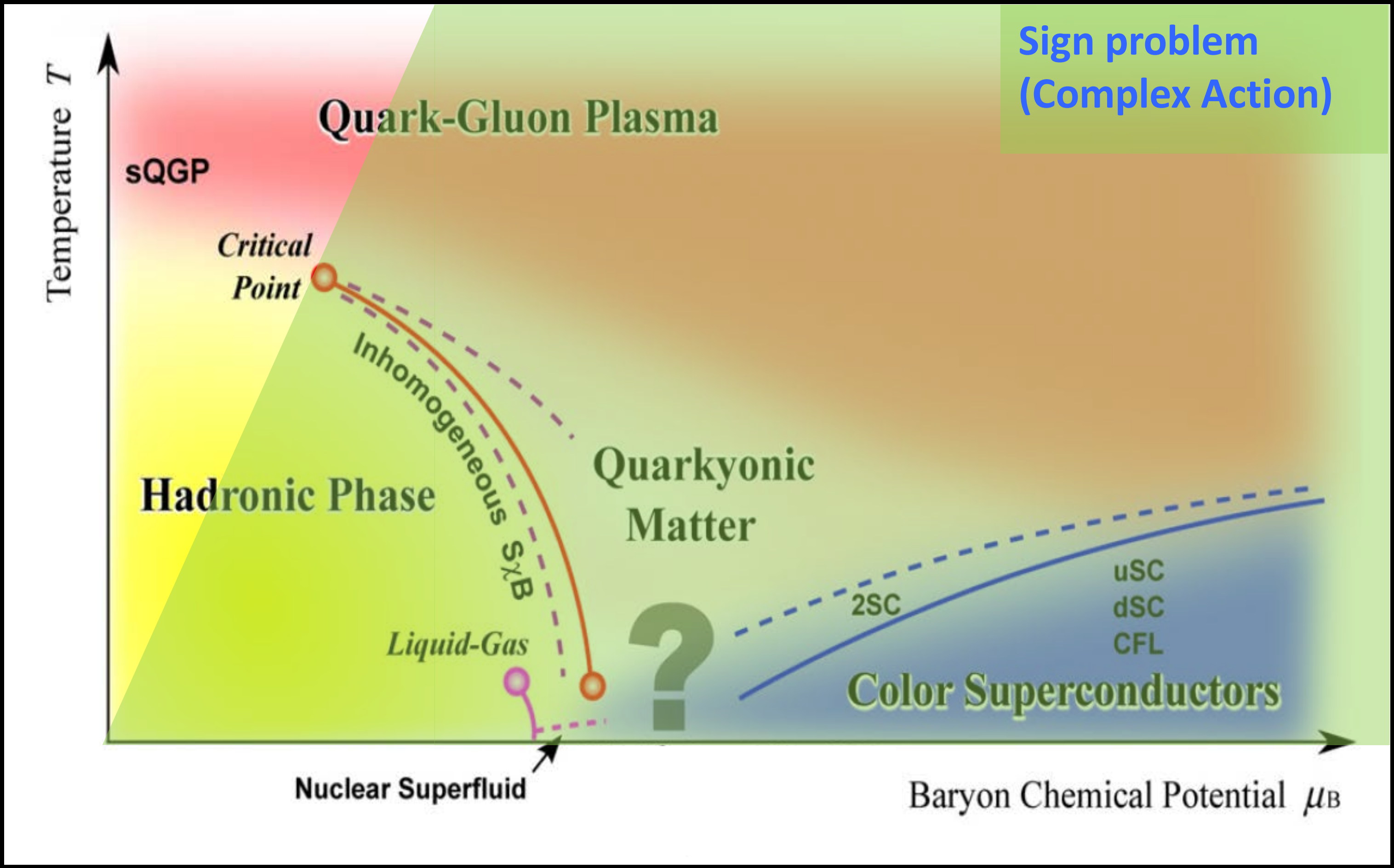
NFQCD Symposium (Dec. 1, 2013)
Tetsuo Hatsuda (RIKEN)

Plan of this Talk



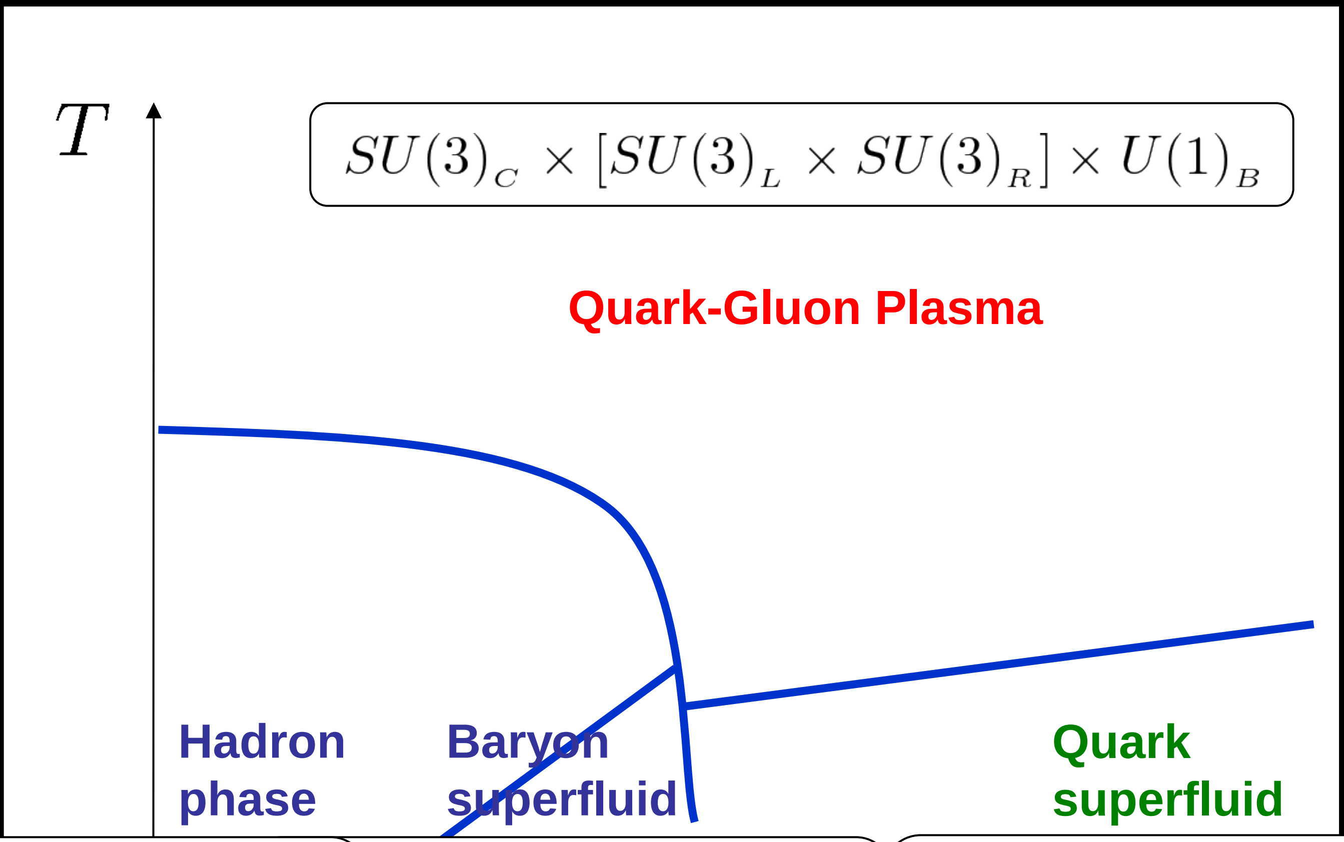
1. QCD Phase Structure
2. Dense Matter and Neutron Star
3. Lattice QCD and Neutron Star
4. Hadron-Quark Crossover and Neutron Star
5. Summary

QCD Phase Structure



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

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



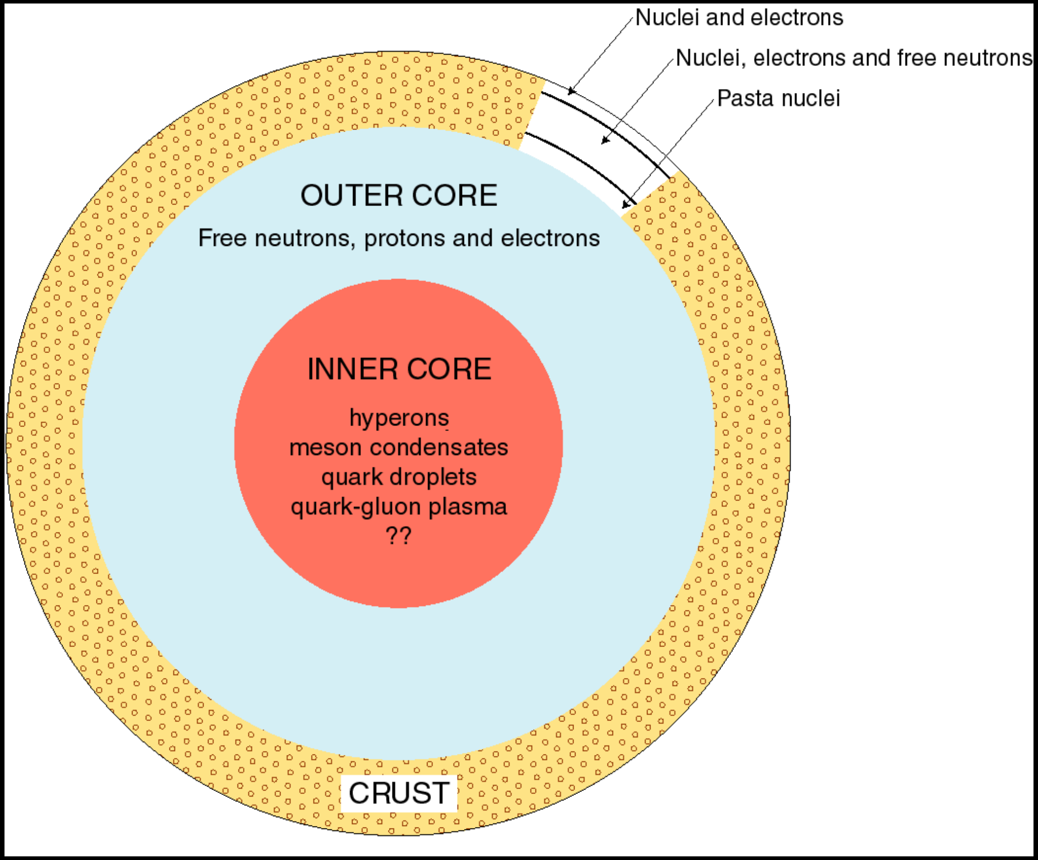
$$\langle \bar{q}_L q_R \rangle \neq 0$$
$$SU(3)_C \times SU(3)_{L+R} \times U(1)_B$$

$$\langle BB \rangle \neq 0$$
$$SU(3)_C \times SU(3)_{L+R}$$

$$\langle (q_L q_L)(\bar{q}_R \bar{q}_R) \rangle \neq 0$$
$$SU(3)_C \times SU(3)_{L+R}$$

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:

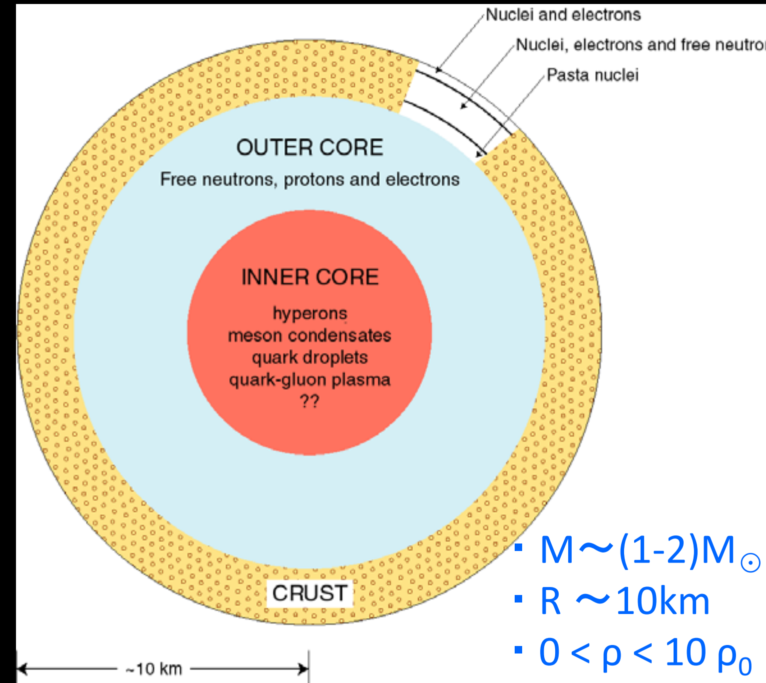
$M=(1.97\pm0.04)M_{\odot}$ (Nature 2010)
$M=(2.01\pm0.04)M_{\odot}$ (Science 2013)
⇔ cold EOS

X-ray bursts ⇔ cold EOS

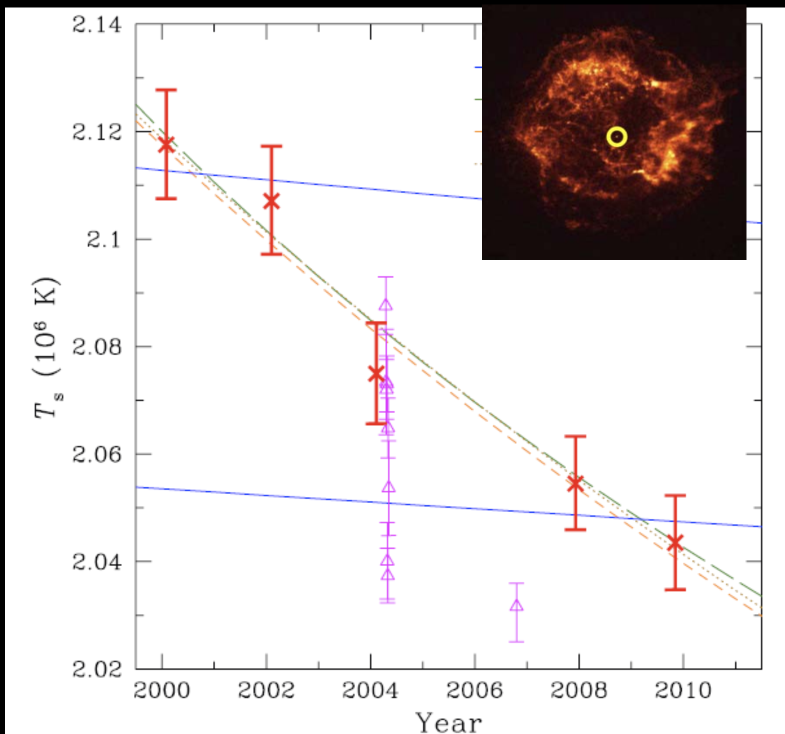
Cooling of CAS-A ⇔ $^3P_2$ superfluid?
Magnetars ⇔ ferromagnetic core?

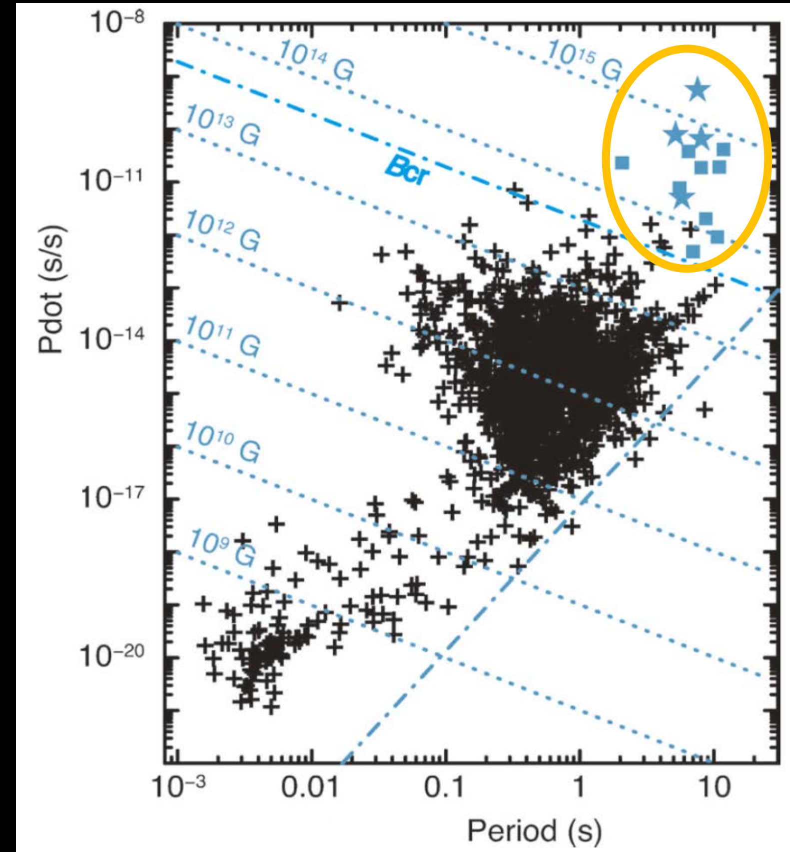
Near Future:

GW from $N_{\star}$ merger ⇔ hot EOS



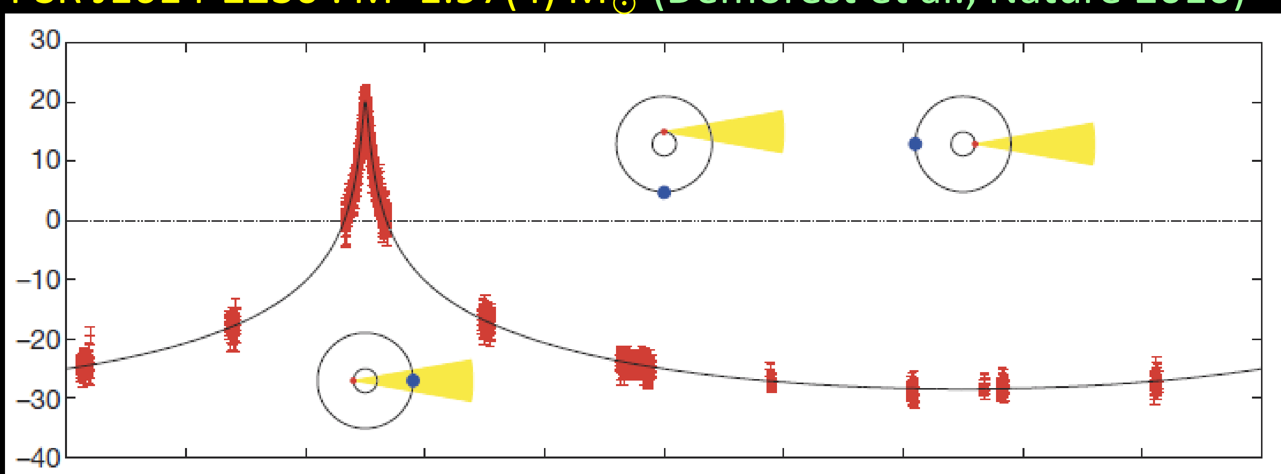
Cassiopeia A cooling: T decreases by 4% in 9 years
(Heinke & Ho, ApJ 2010)





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

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

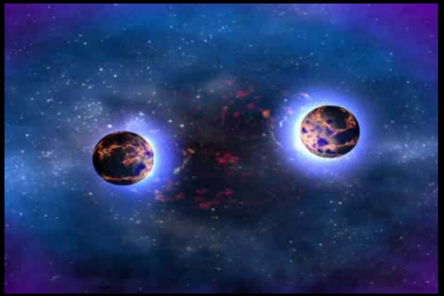


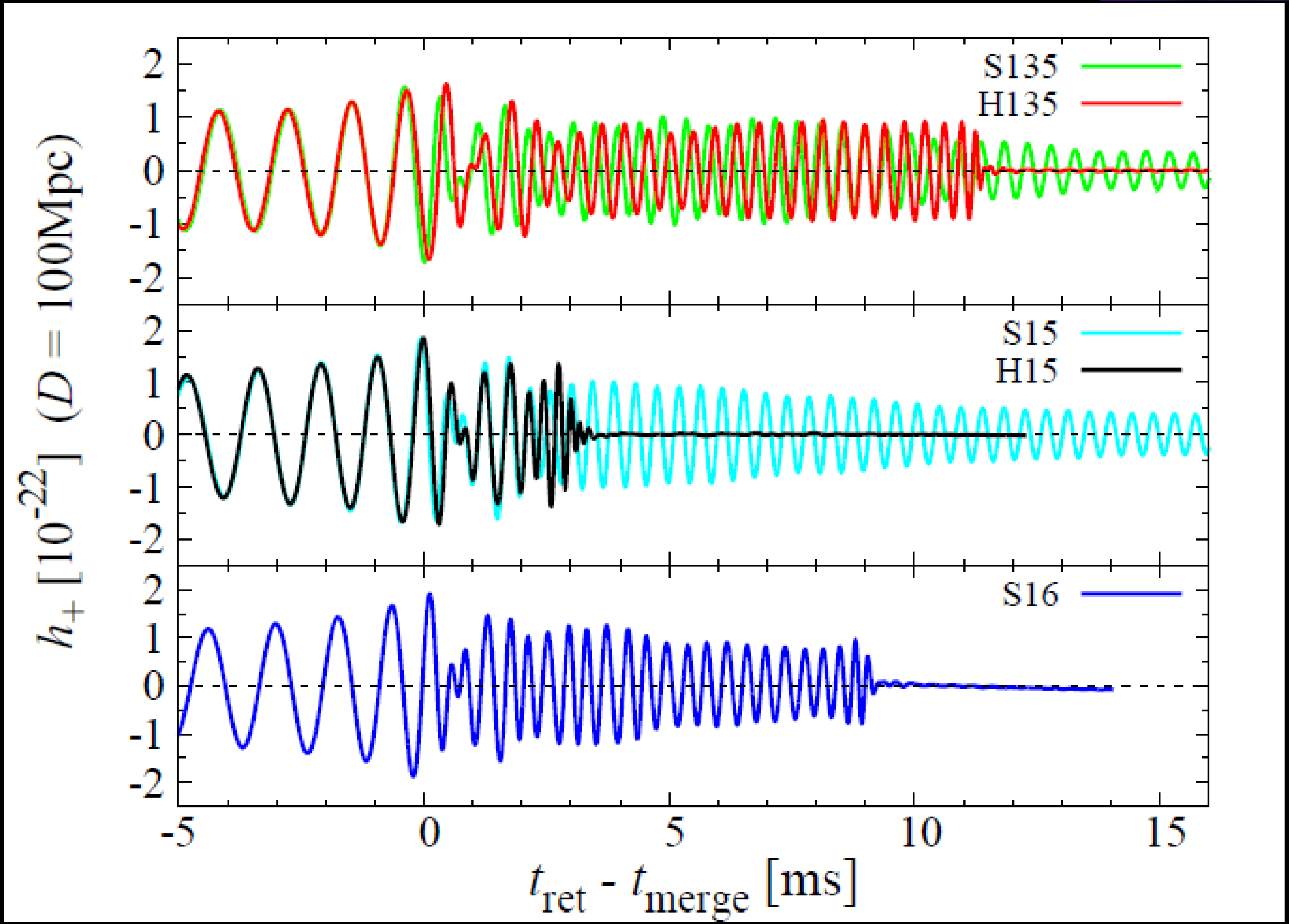
T, B, M

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

M. Shibata (YITP)

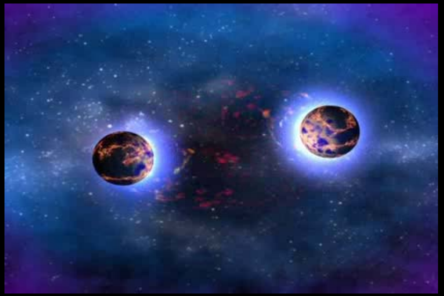
Gravitational wave from $N_{\star}$ merger
-- Expected signal --

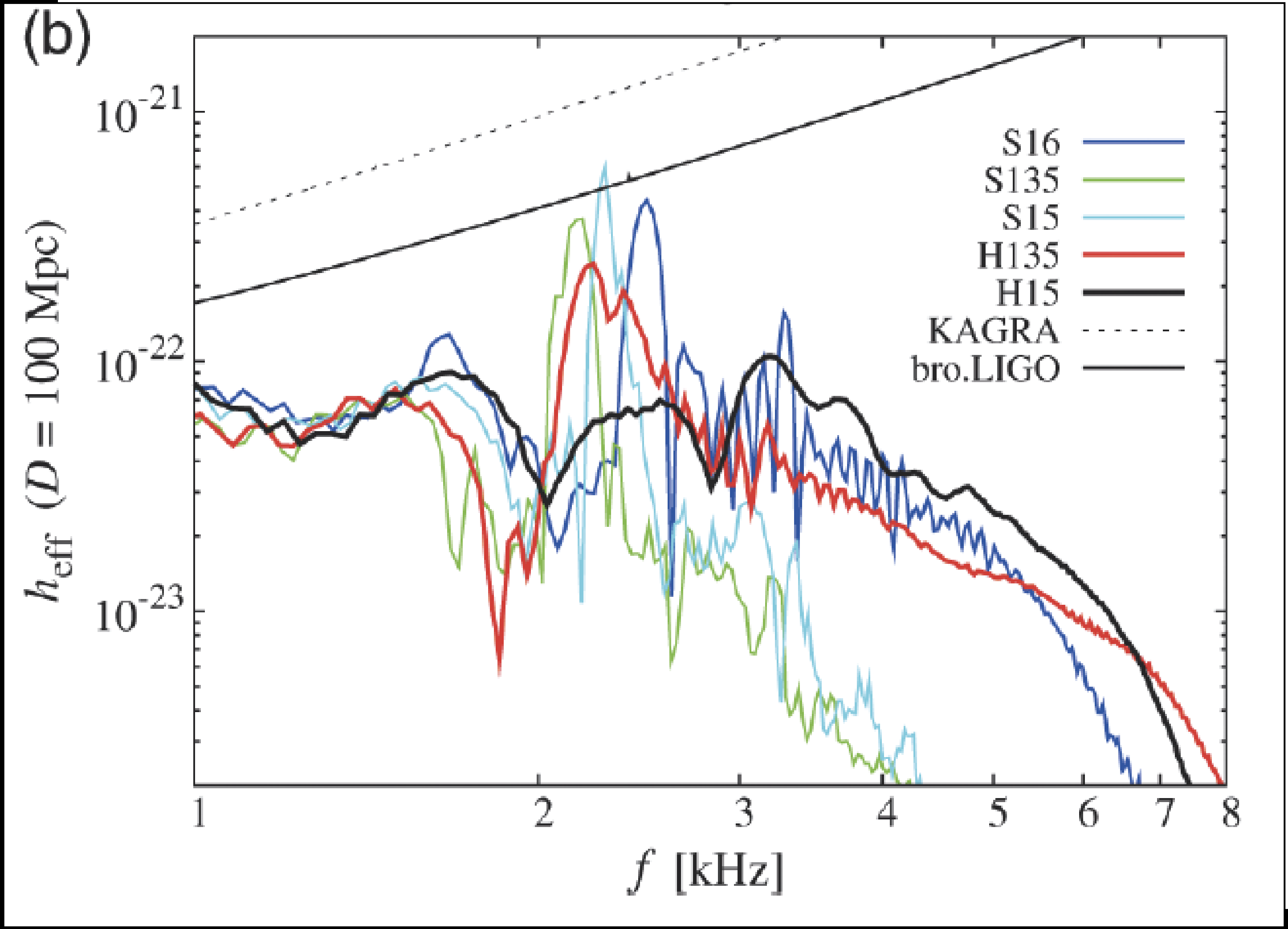




Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

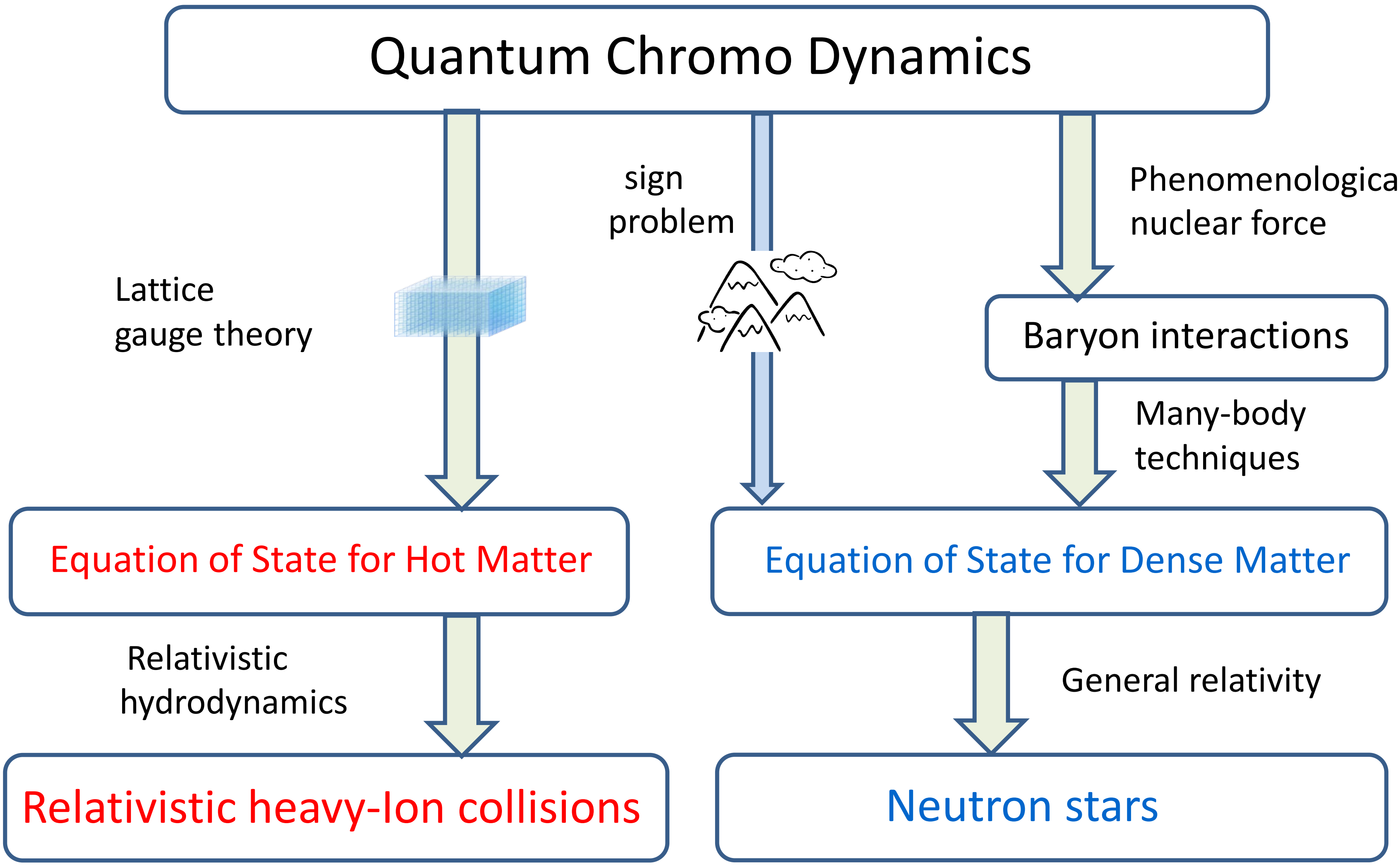
Gravitational wave from N$_\star$ merger
-- Expected signal --





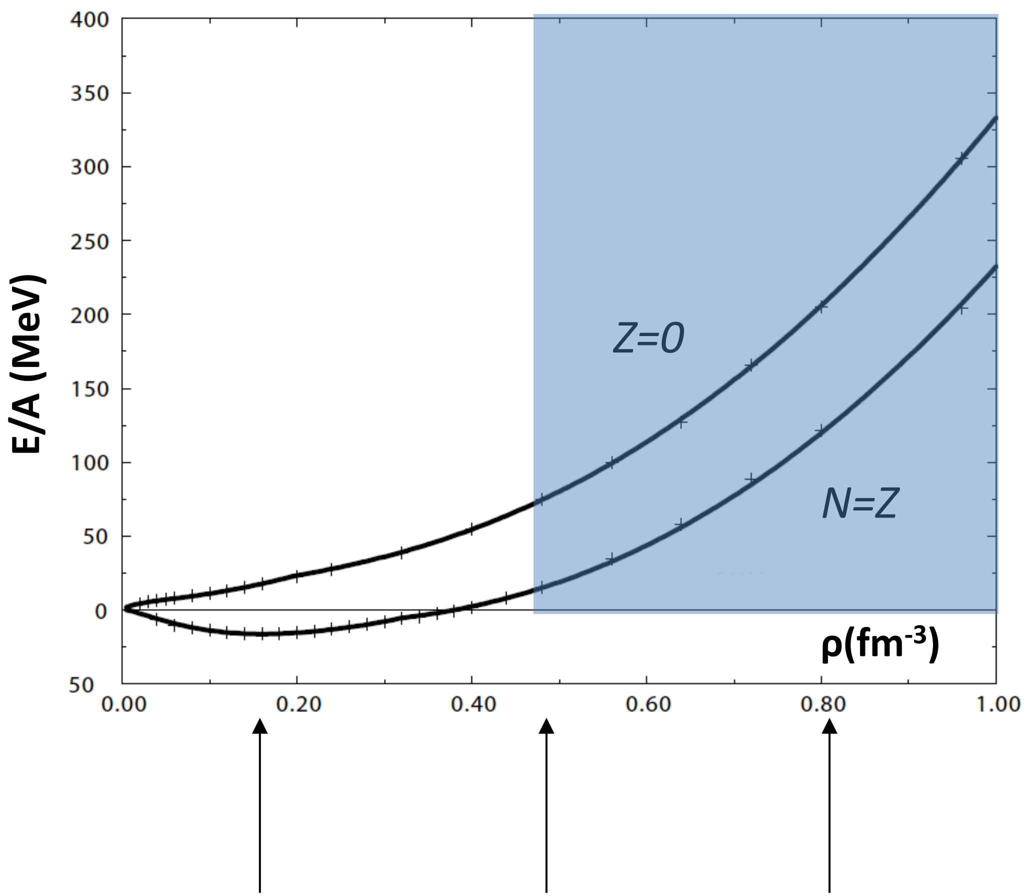
Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

From QCD to Hot/Dense Matter



Nuclear Force and dense EOS（nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

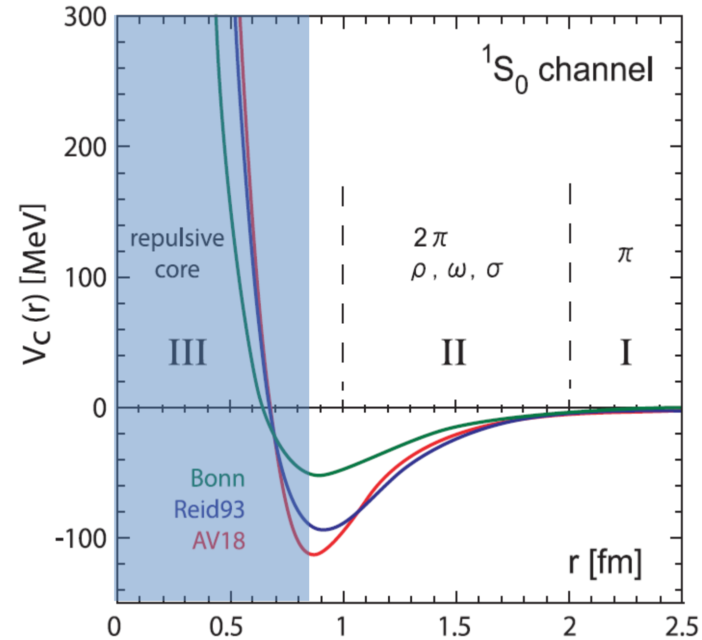


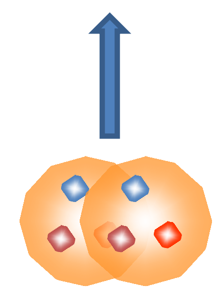
ρ_0
$= 0.16\ fm^{-3}$

$3\rho_0$

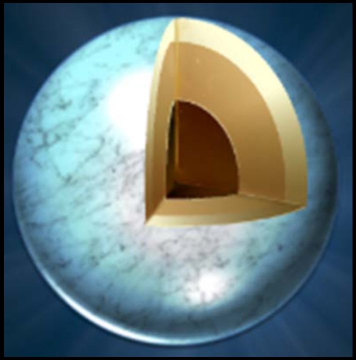
$5\rho_0$

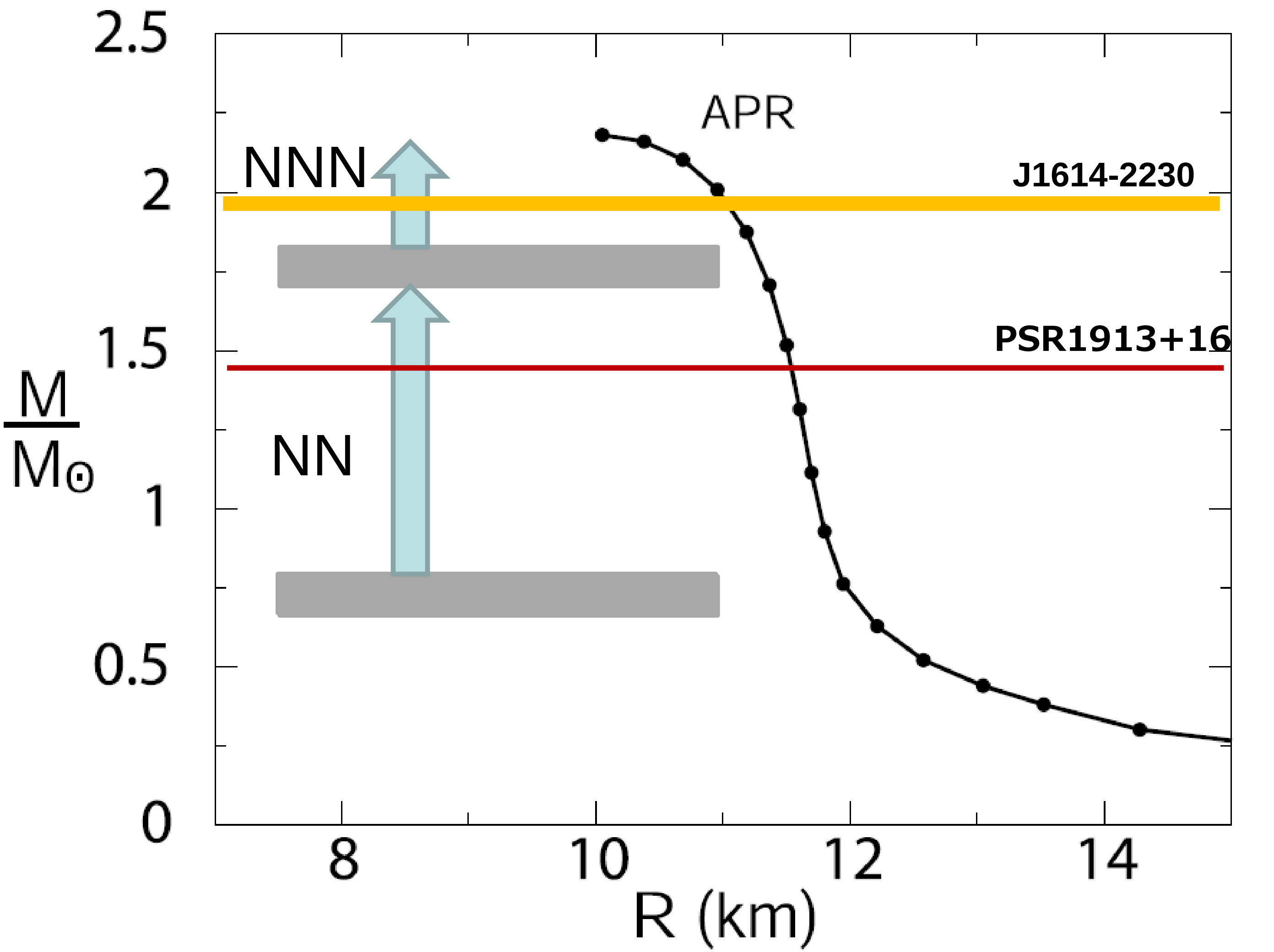
Phenomenological nuclear force



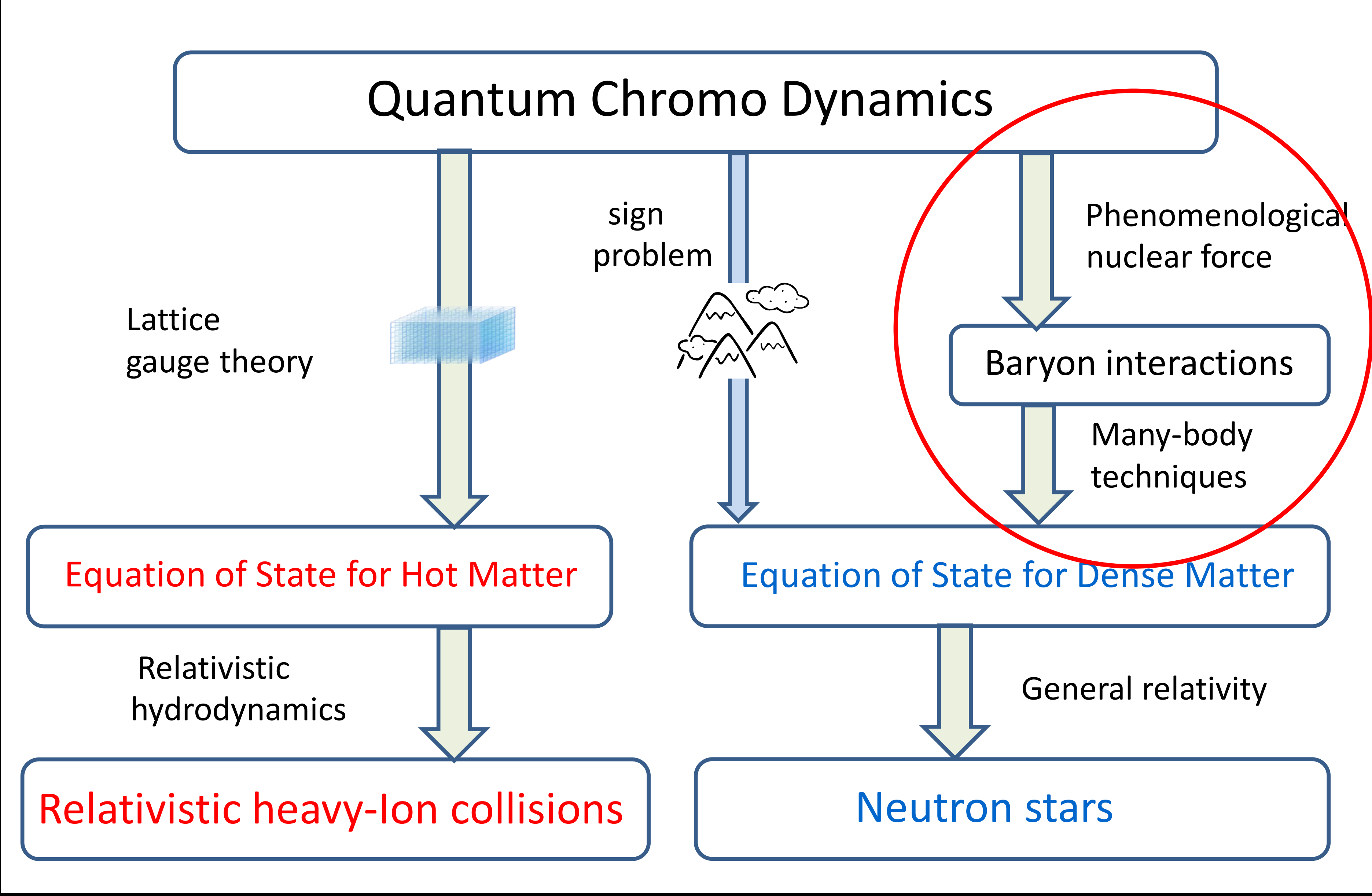


Mass-Radius relation of $N_{☆}$ (nucleons only)

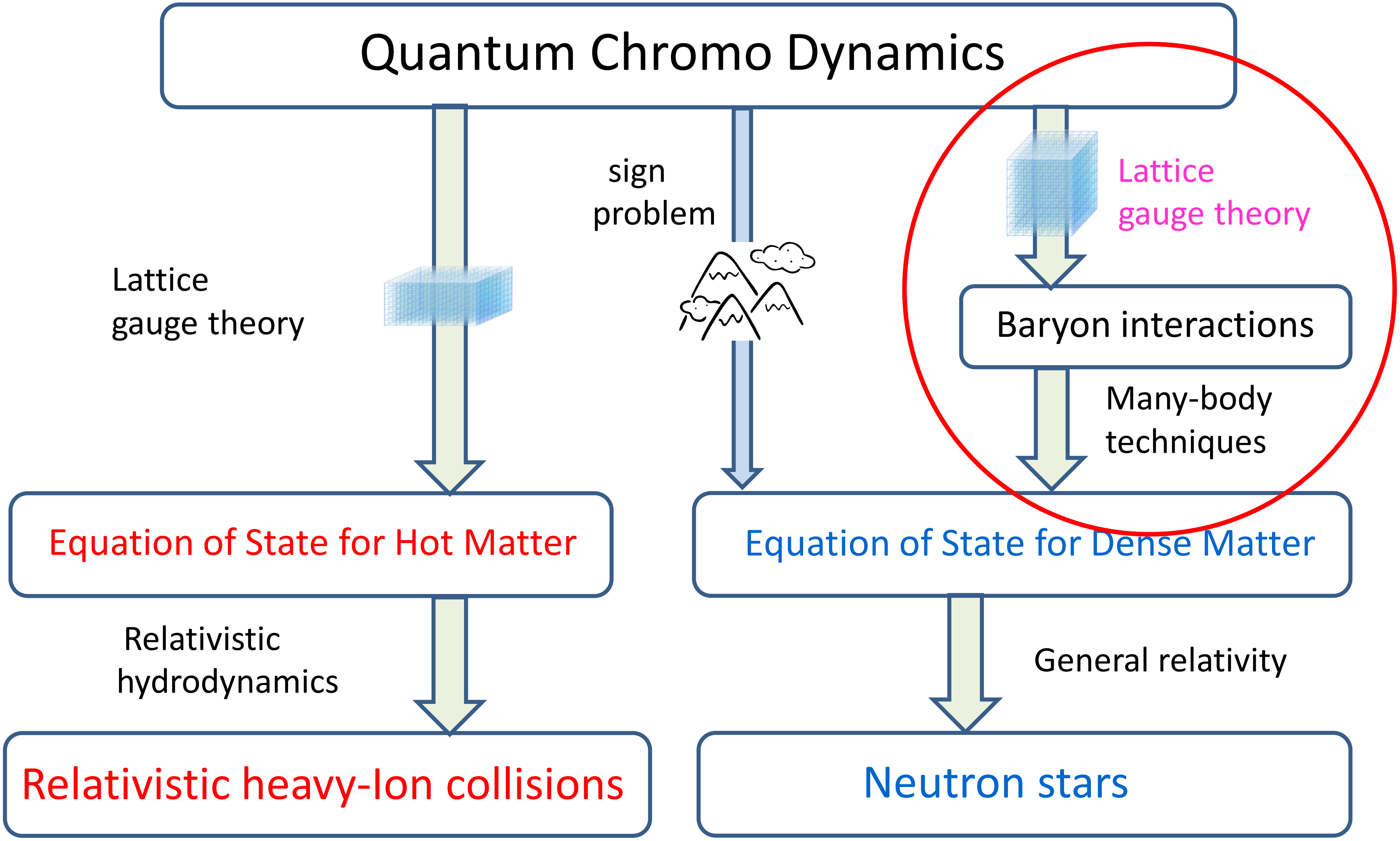




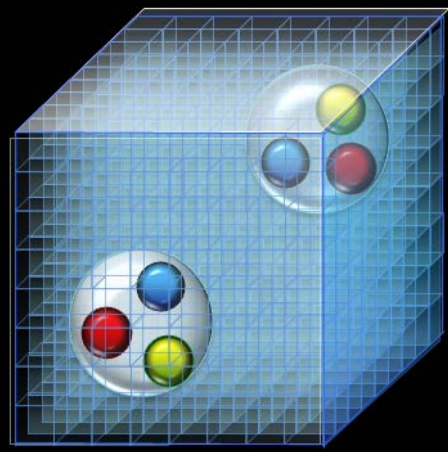
From QCD to Hot/Dense Matter

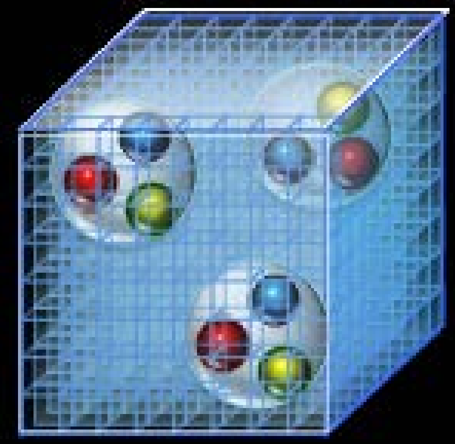


From QCD to Hot/Dense Matter



Multi-baryons on the Lattice

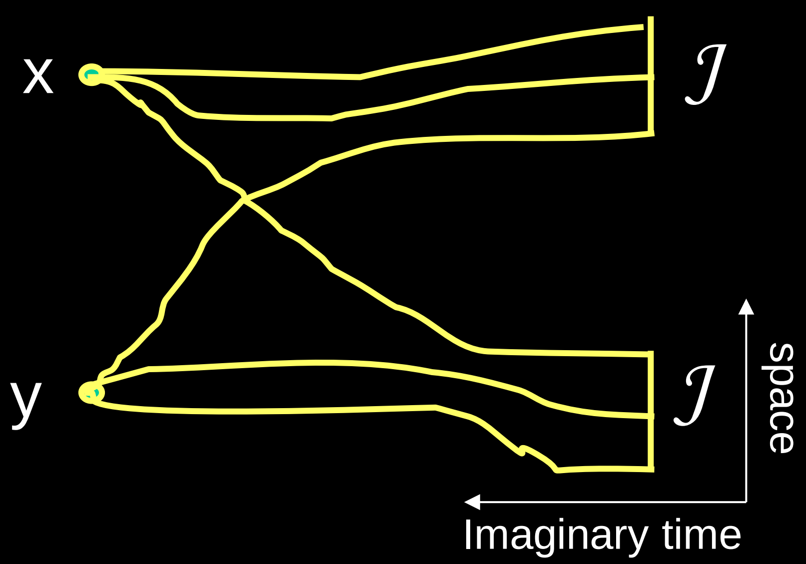




Univ. Tsukuba	N. Ishii, H. Nemura, K. Sasaki
RIKEN	T. Doi, T. Hatsuda, Y. Ikeda
Nihon Univ.	T. Inoue
Kyoto Univ.	S. Aoki, K. Murano
Univ. Tokyo	B. Charron

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

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

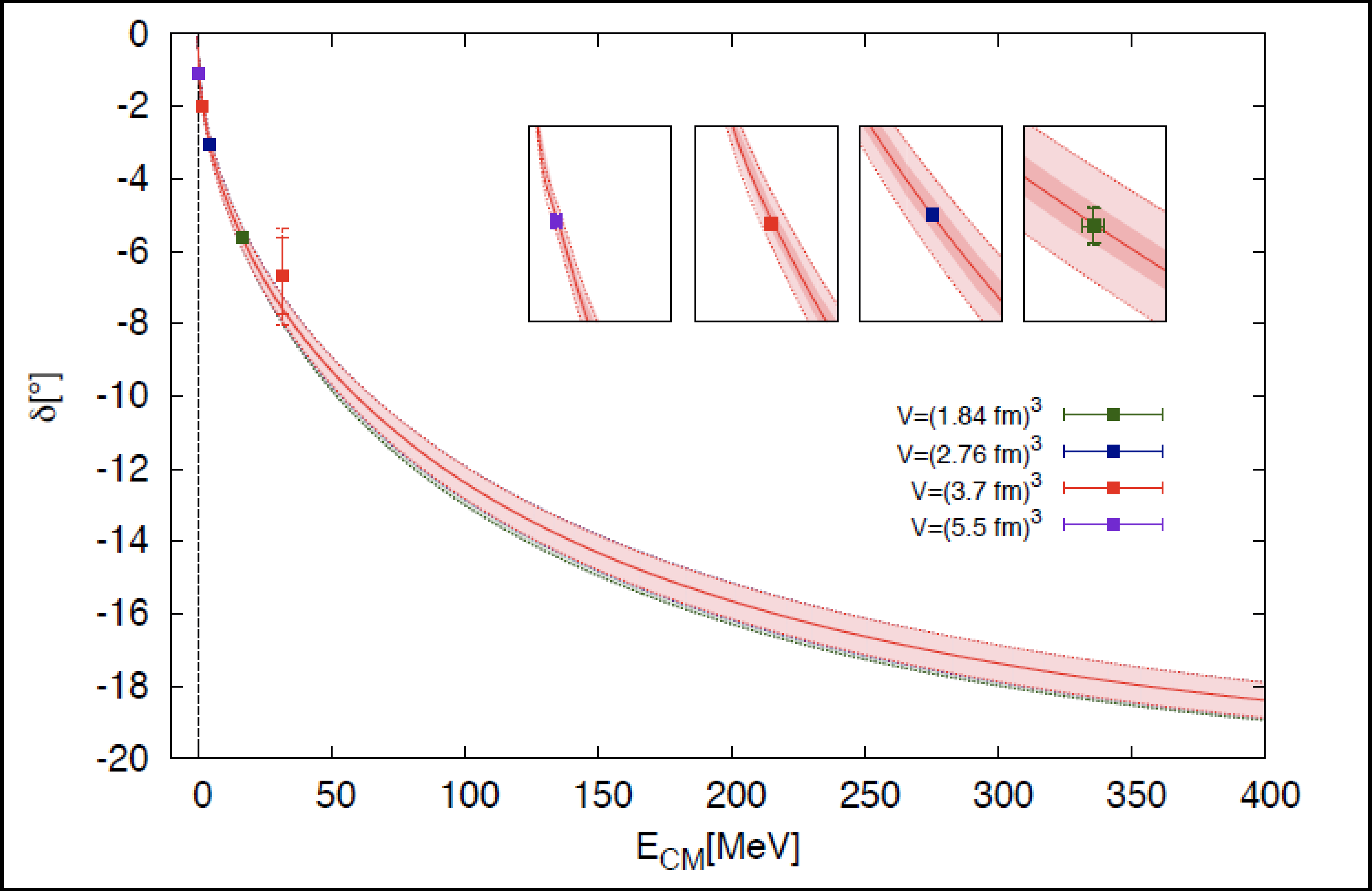
HAL QCD Method

$\phi(r,t)$ → kernel → phase shift

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

FV Method vs. HAL QCD Method : do they agree ?

$\pi\pi$ scattering in I=2 channel

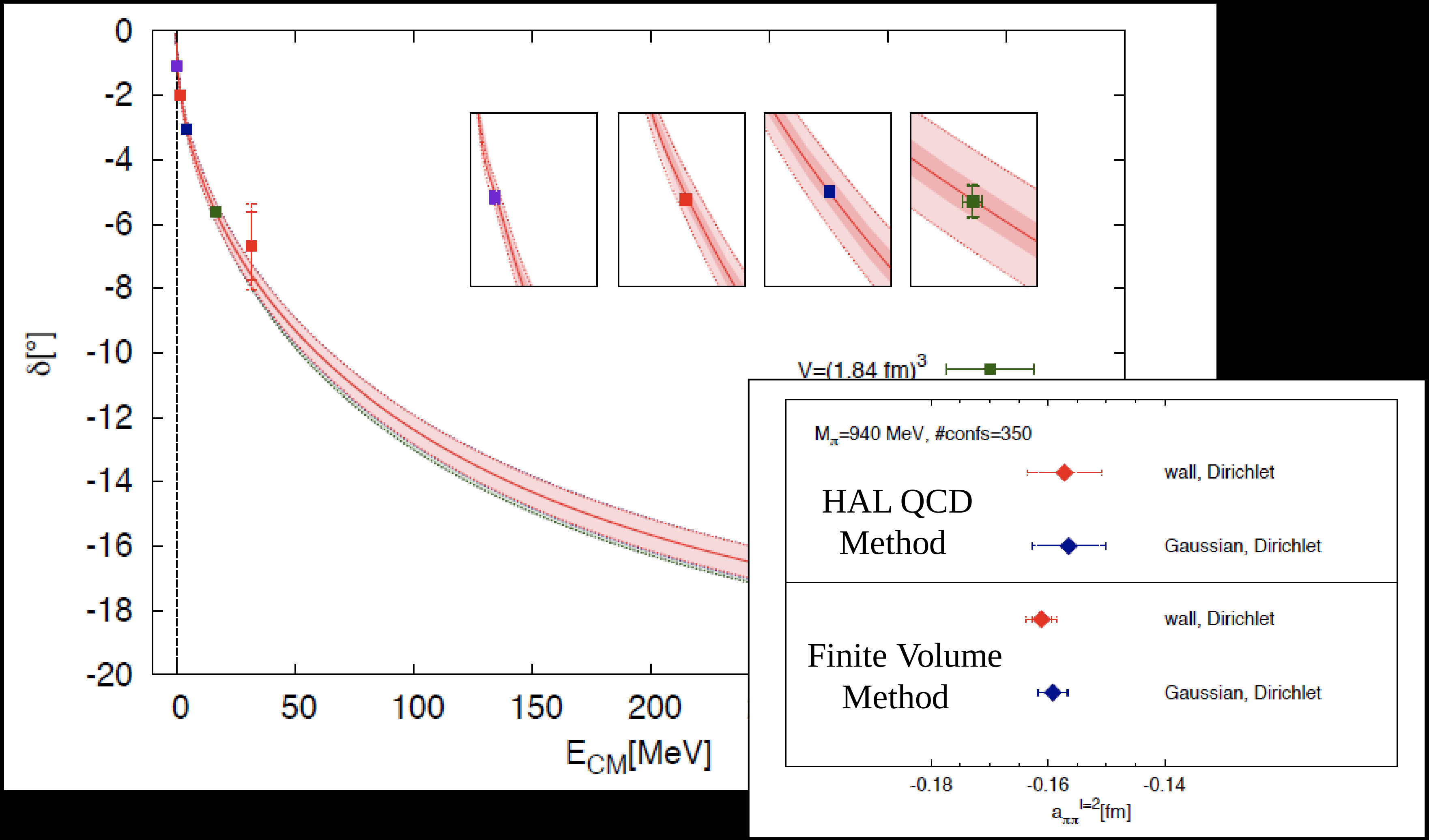


N_s=16,24,32,48, N_t=128 a=0.115 fm, (quenched QCD, m_π=940 MeV)

Kurth, Ishii, Doi, Aoki & Hatsuda, arXiv: 1305.4462 [hep-lat]

FV Method vs. HAL QCD Method : do they agree ?

$\pi\,\pi$ scattering in I=2 channel



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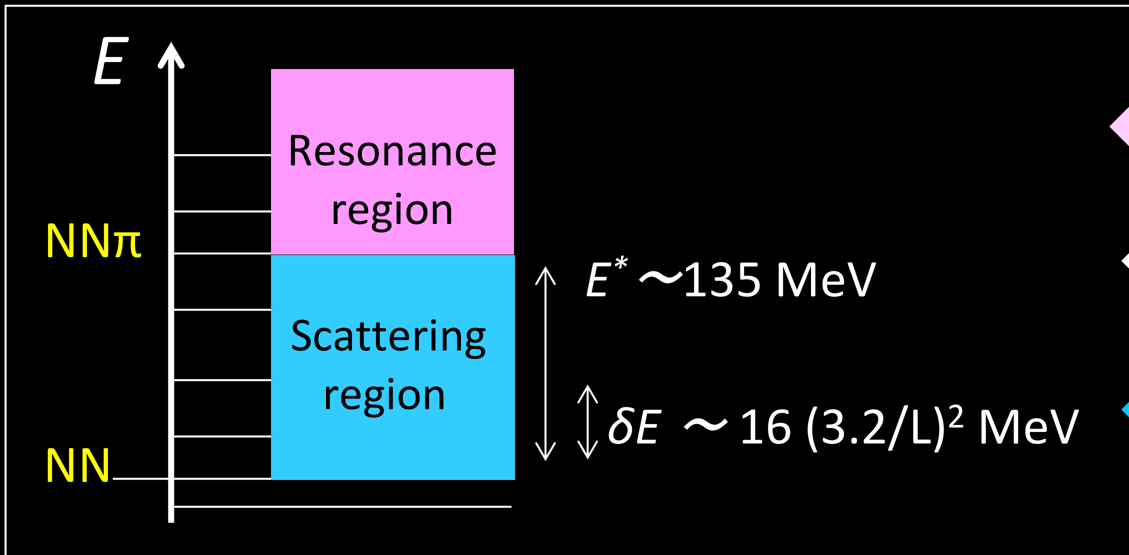
What about NN ?



$t < 1\text{fm}$

$t^* \sim 1\text{fm}$

$t > 10\,(L/3.2)^2\ \text{fm}$

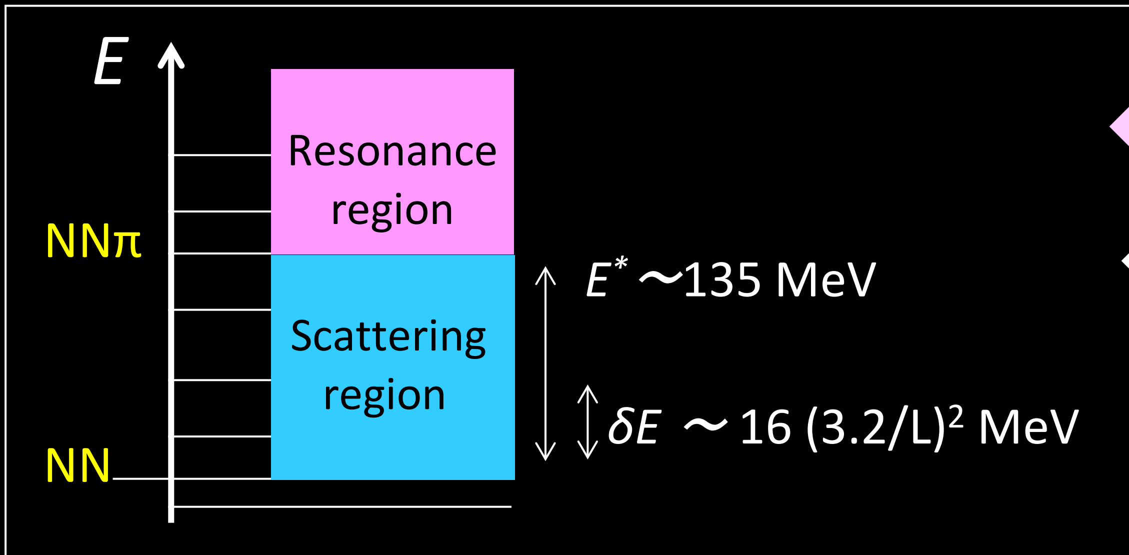
$$\left(\frac{\mathcal{S}}{\mathcal{N}}\right)_{NN} \sim \sqrt{N_{\rm gc}}\; e^{-2(m_N - 3m_\pi/2)t}$$

$$\left(\frac{\mathcal{S}}{\mathcal{N}}\right)_{\pi\pi} \sim \sqrt{N_{\rm gc}}$$

Finite Volume Method
guaranteed to fail
for NN system
with small m_π and large L

Lepage, TASI 1989 Lecture

What about NN (cont'd) ?



$t < 1\text{fm}$

$t^* \sim 1\text{fm}$

$$\phi(\mathbf{r}, t > t^*) = \sum_{n<n^*} b_n \phi_n(\mathbf{r}) e^{-E_n t} \equiv \varphi(\mathbf{r}, t) e^{-2m_N t}$$

$$\left[\frac{1}{4m_N}\frac{\partial^2}{\partial t^2} - \frac{\partial}{\partial t} + \frac{\nabla^2}{m_N}\right]\varphi(\mathbf{r}, \mathrm{t}) = \int U(\mathbf{r}, \mathbf{r}')\varphi(\mathbf{r}')d^3r'$$

HAL QCD Coll., PLB 712 (2012) 437

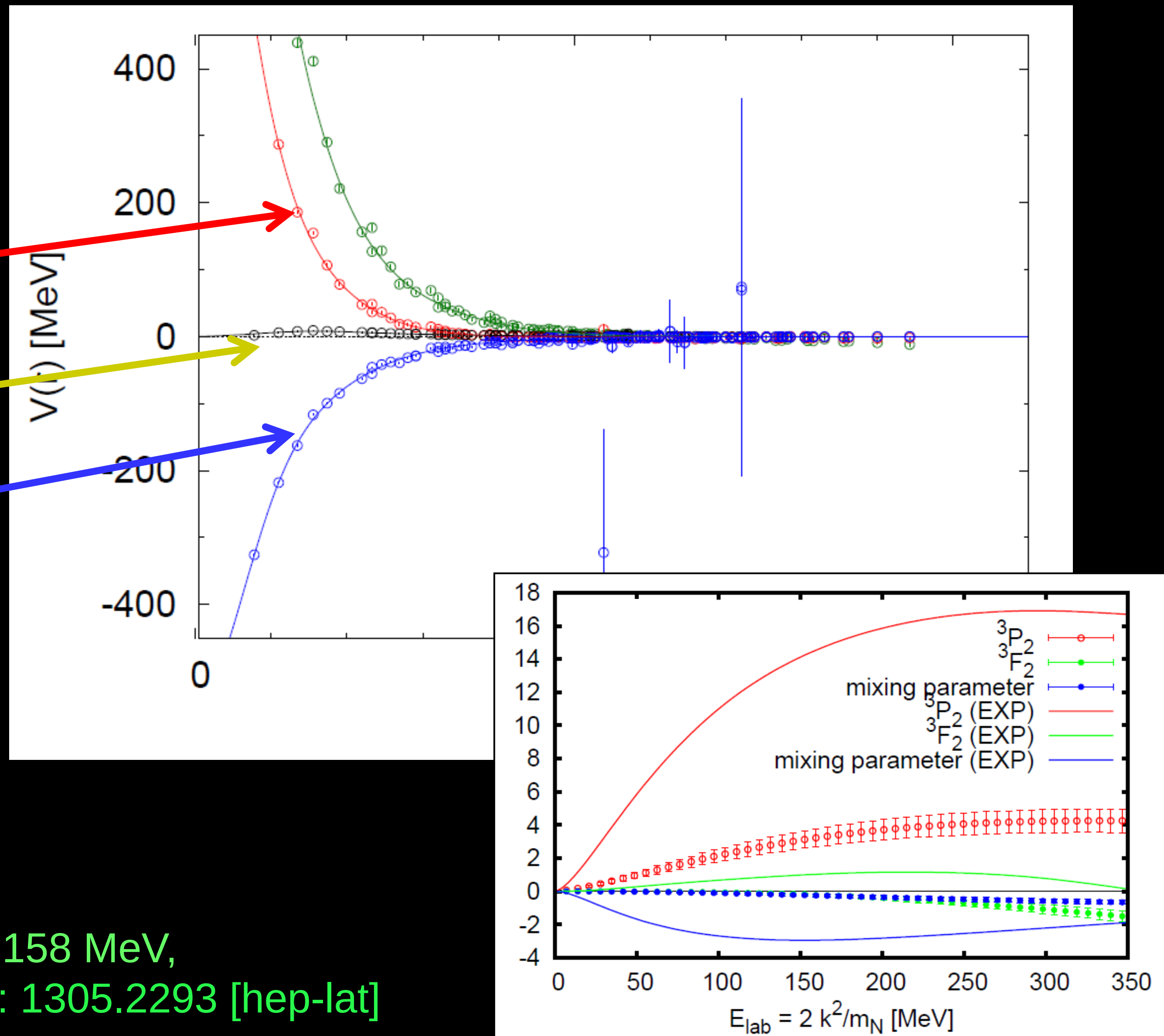
$t > t^*$ is only necessary

Non-local kernel U(r,r')

- energy independent
- L-insensitive
- consistent 3-body force
- not an observable

First Result on the Spin-Orbit Force in 2-flavor QCD

$$V(r;\ {}^3P_2) = V_{\mathrm{C},S=1}^{I=1}(r) - \frac{2}{5}V_{\mathrm{T}}^{I=1}(r) + V_{\mathrm{LS}}^{I=1}(r)$$



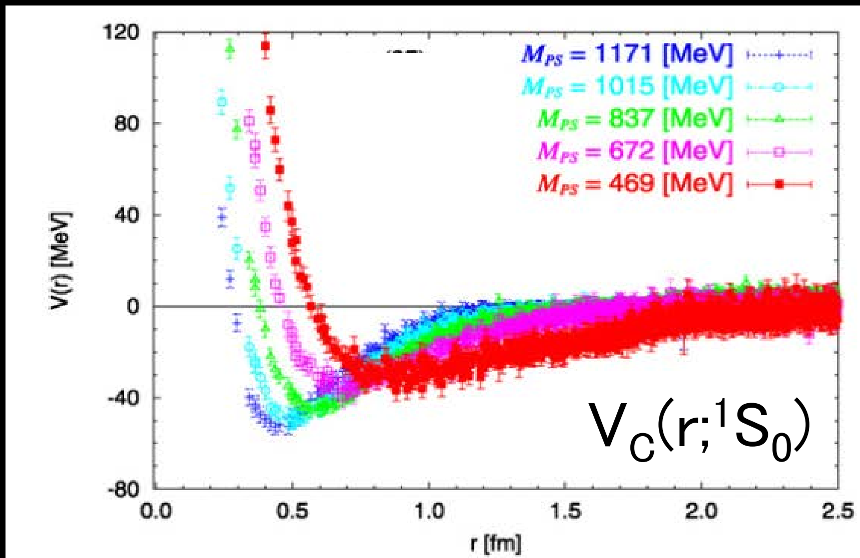
L = 2.5 fm

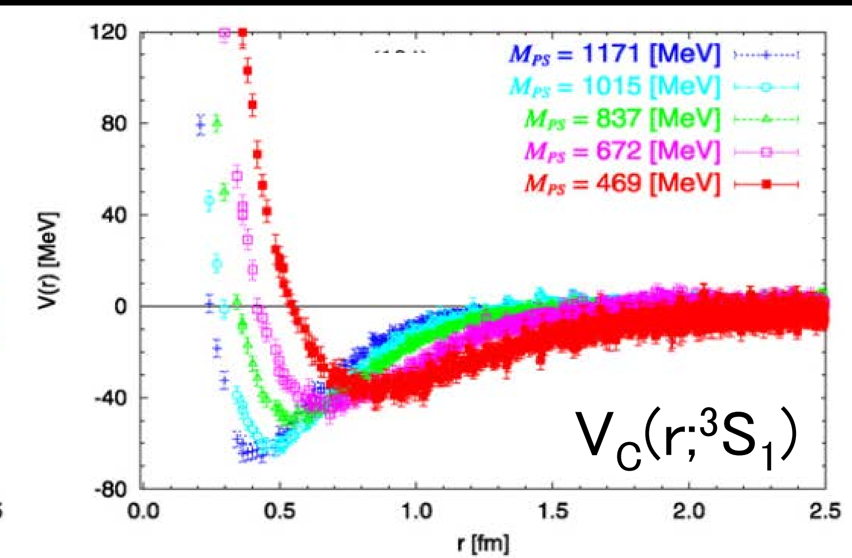
m_π = 1133MeV, m_N = 2158 MeV,

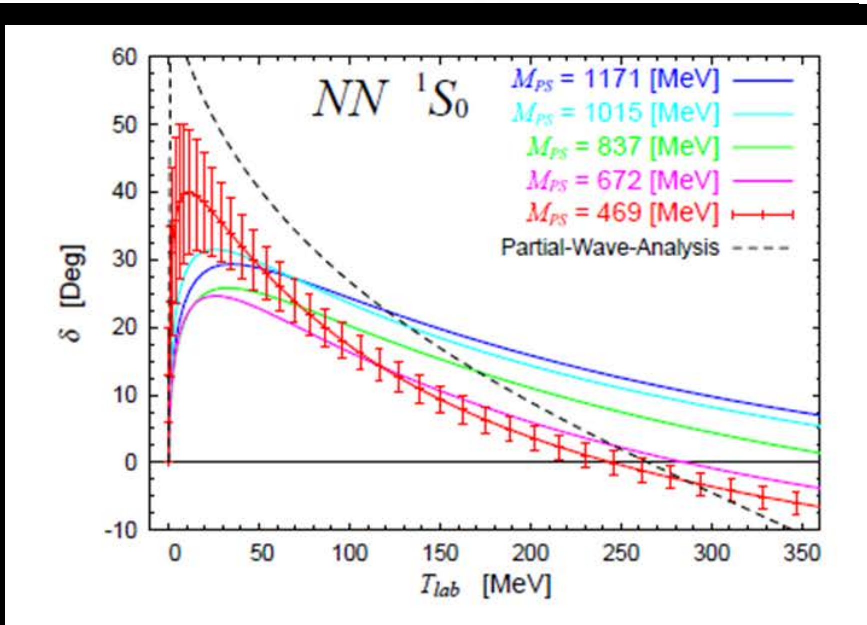
HAL QCD Coll., arXiv: 1305.2293 [hep-lat]

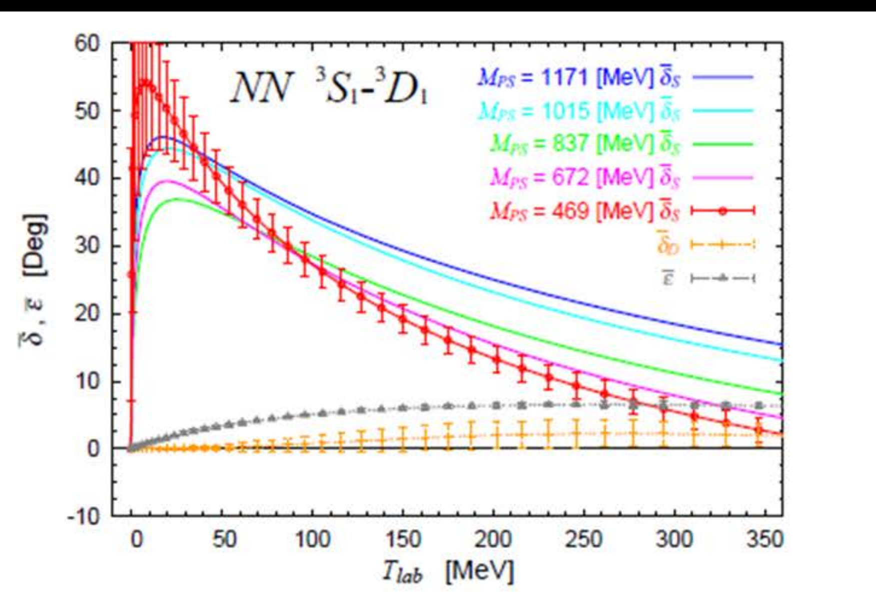
NN Force in 3-flavor QCD

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







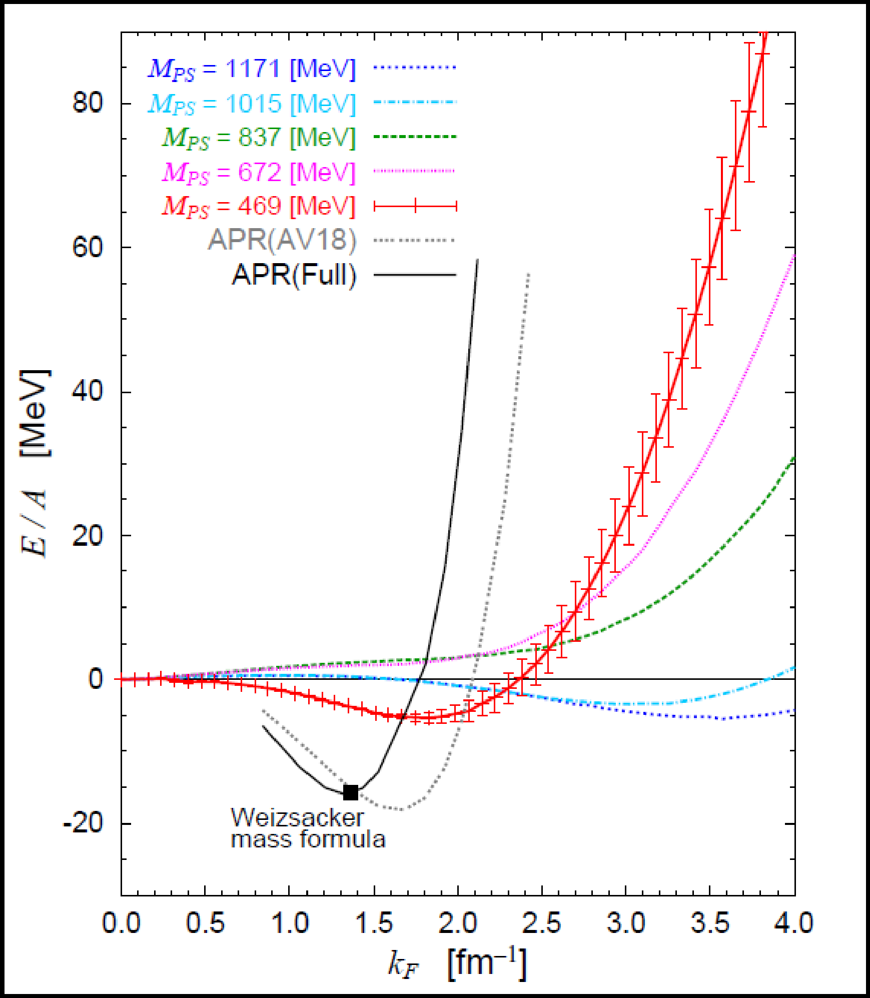


Nuclear EOS from Lattice NN force + BHF calculation

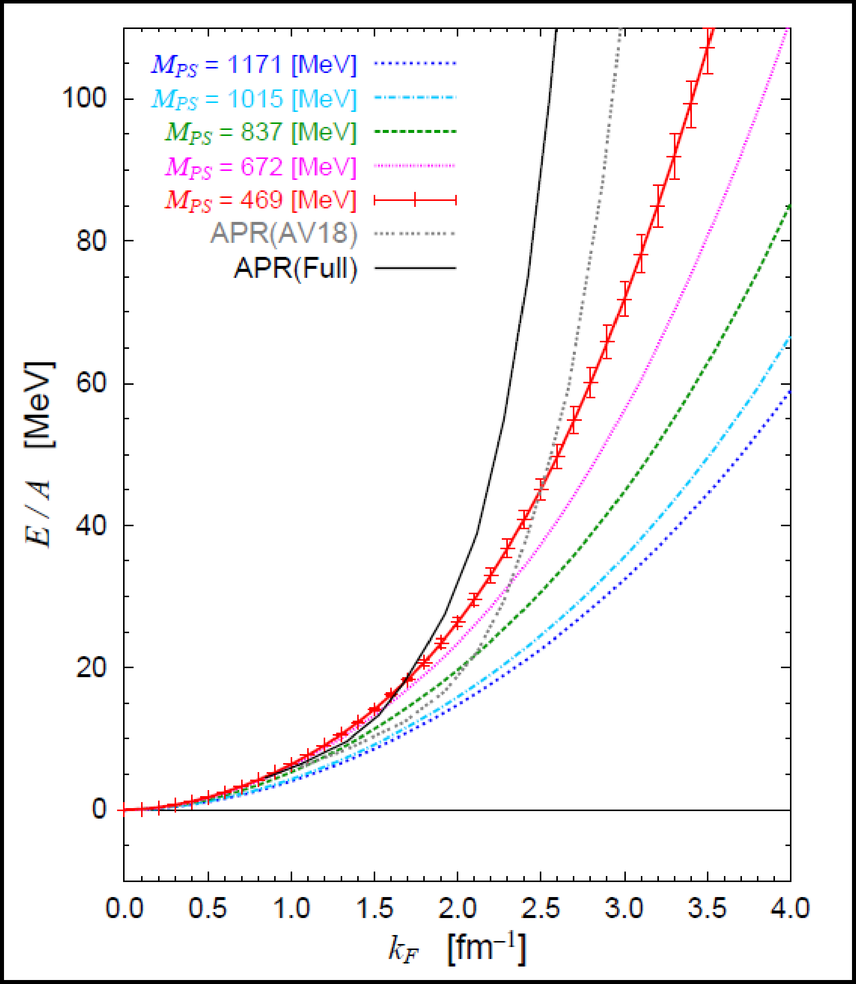
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

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

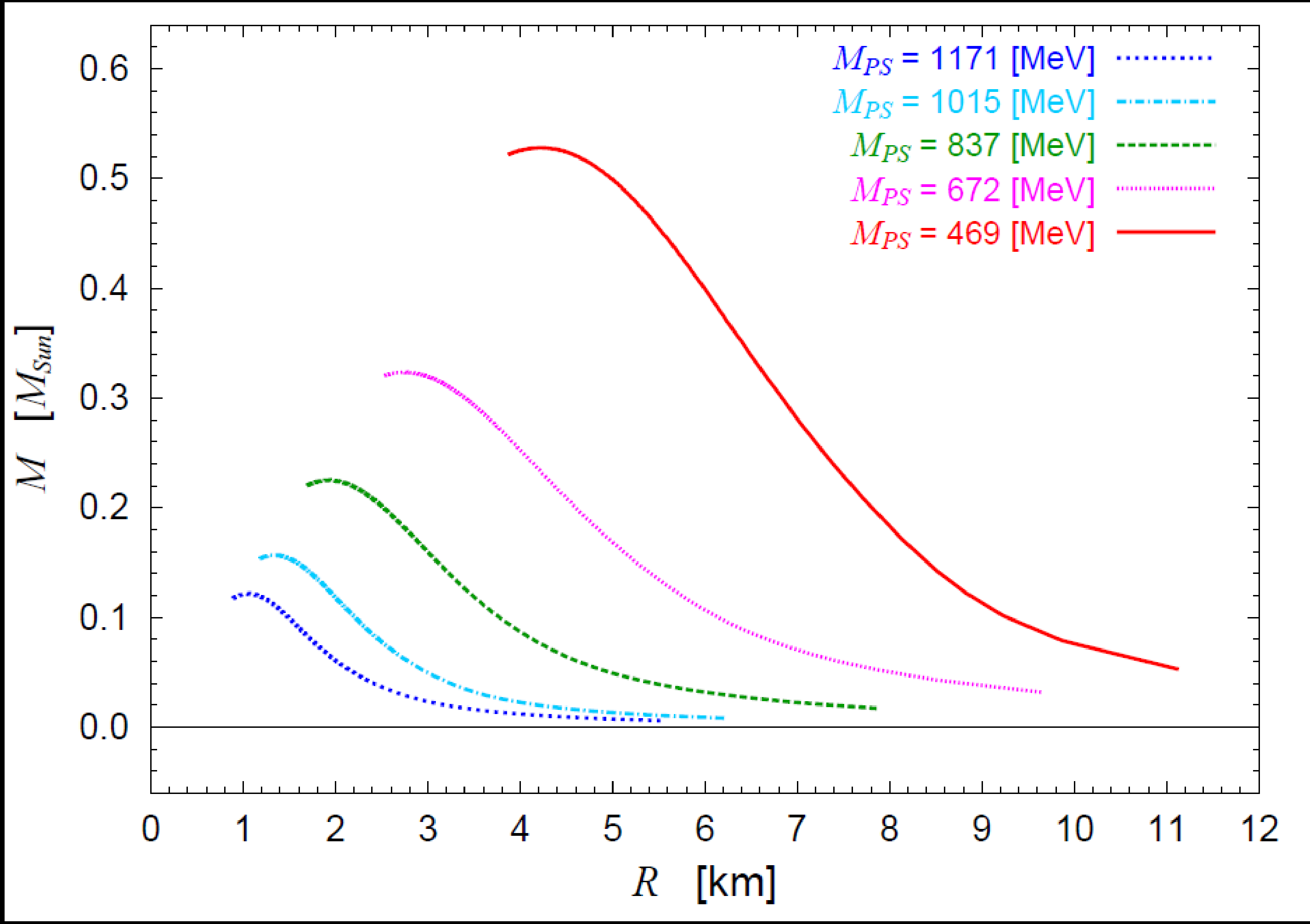
Nuclear Matter



Neutron Matter

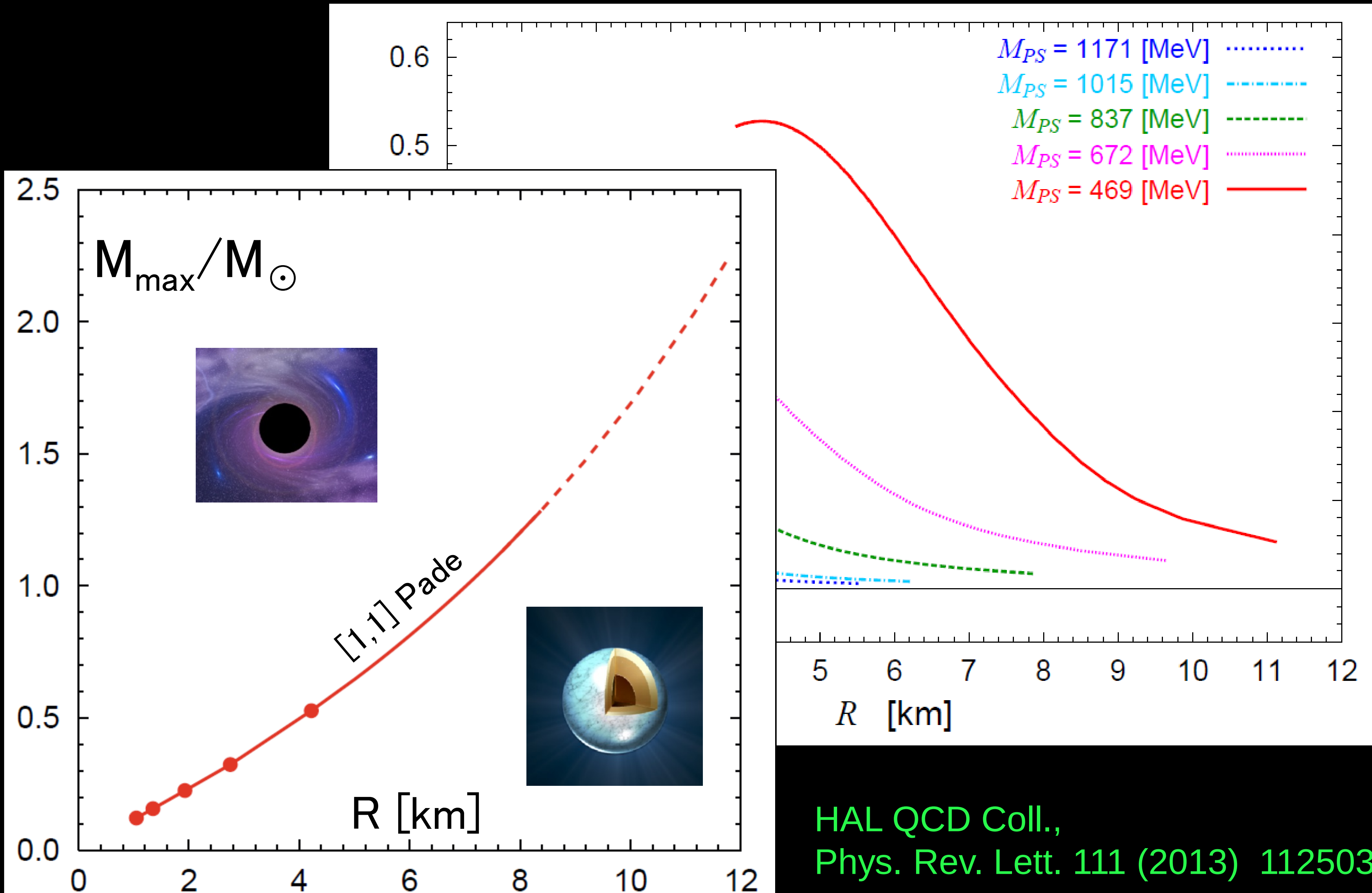


Neutron Star from “Lattice EOS”



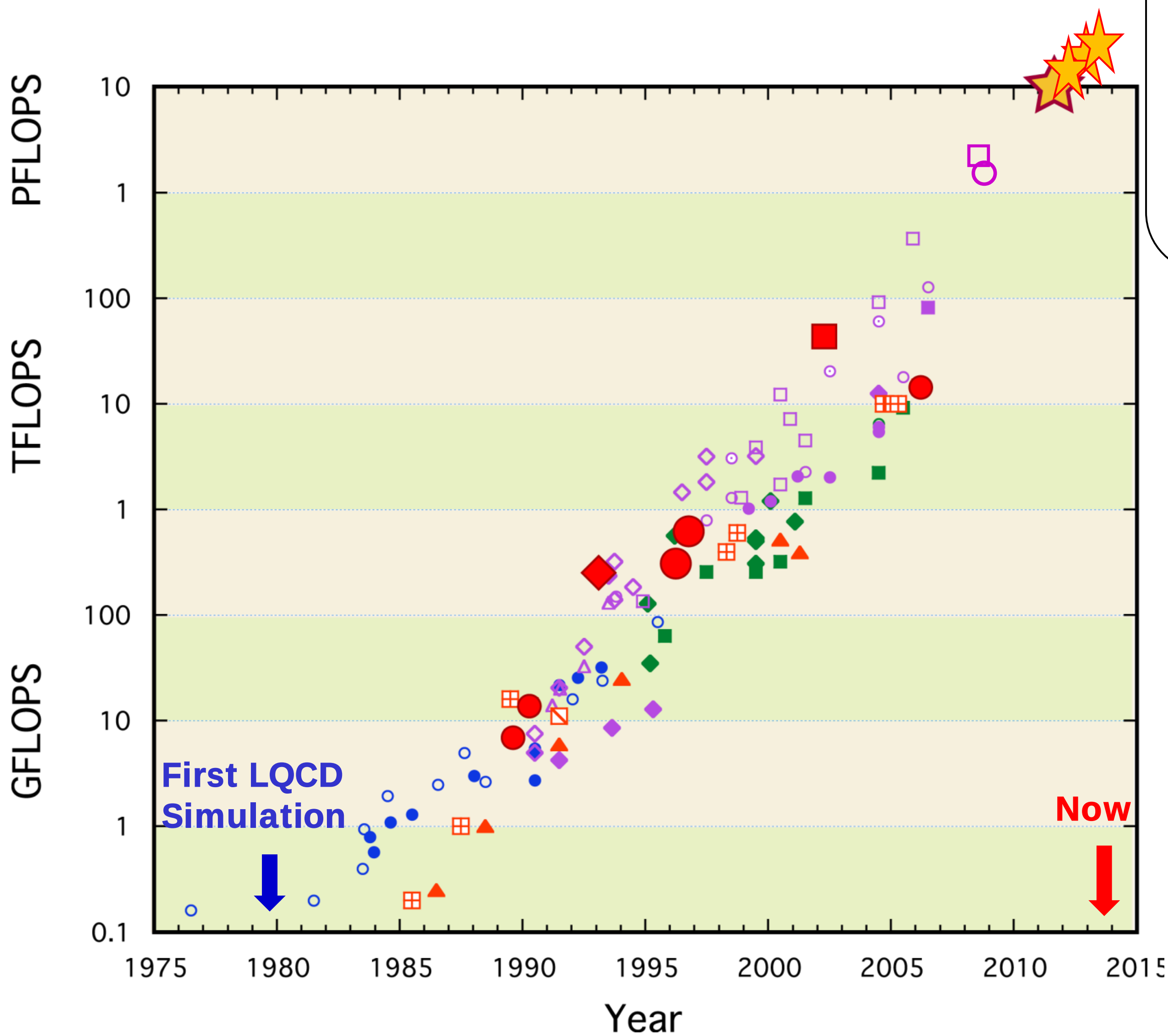
HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

Neutron Star from “Lattice EOS”



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

High Performance Computers



2013 June top5

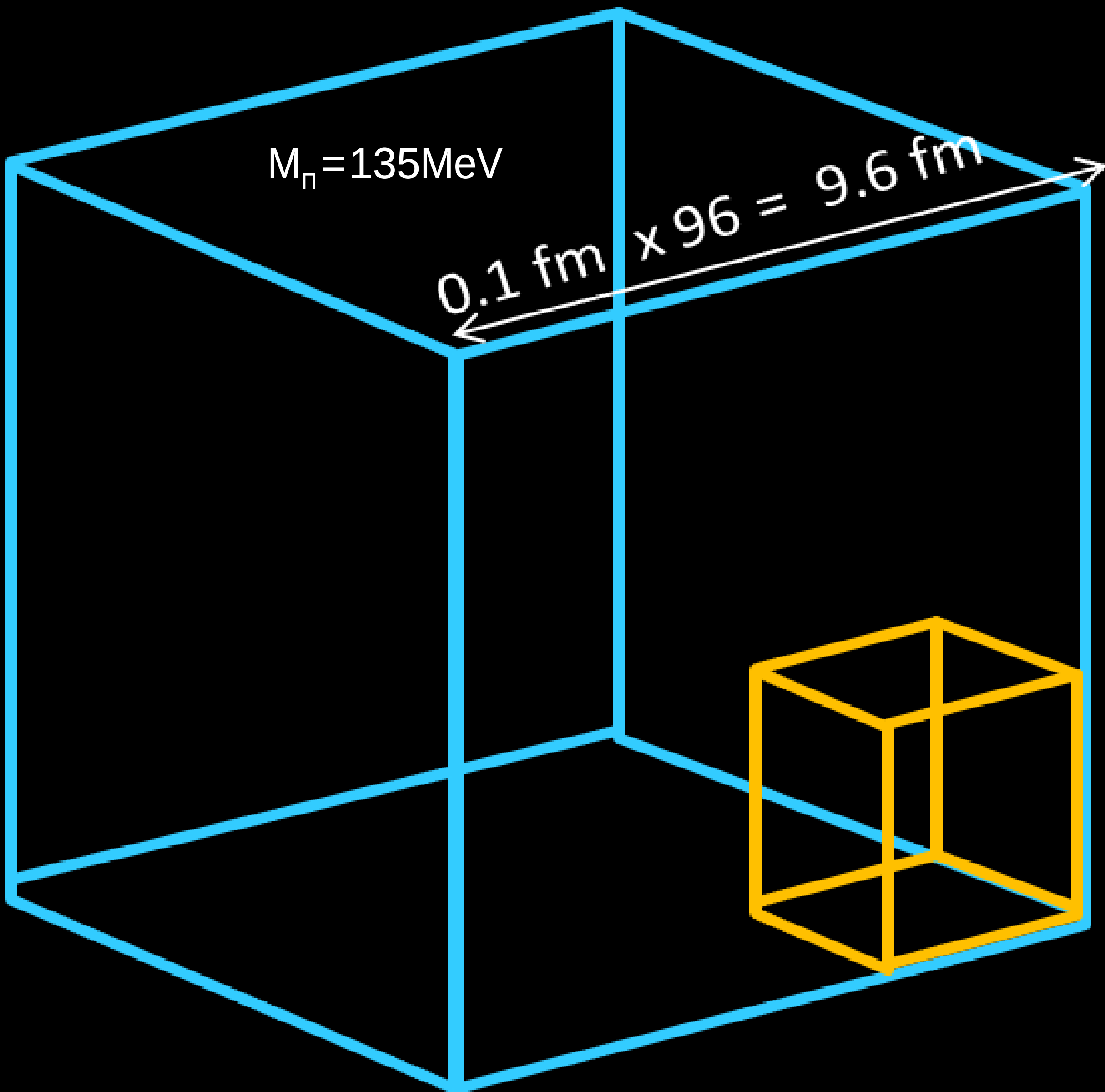
Tianhe-2	(34 PFlops)
Titan	(18 PFlops)
Sequoia	(17 PFlops)
K	(11 PFlops)
Mira	(9 PFlops)

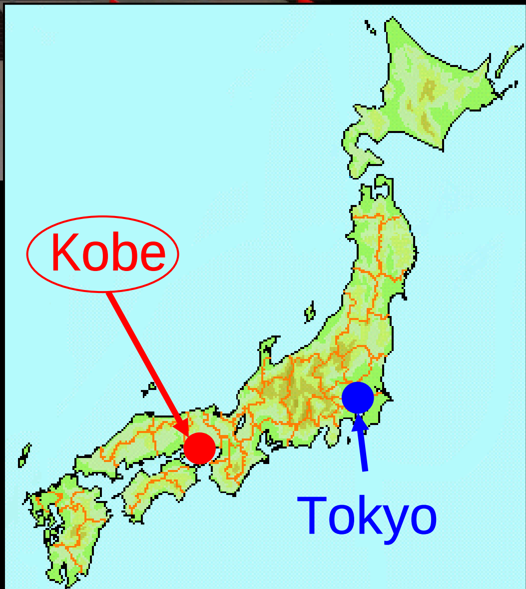
original plot by A. Ukawa

K computer @ RIKEN
(11.28 PFlops, 80,000 CPUs x 8 = 640,000 cores)

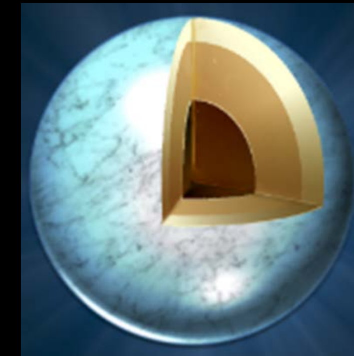
K computer @ RIKEN

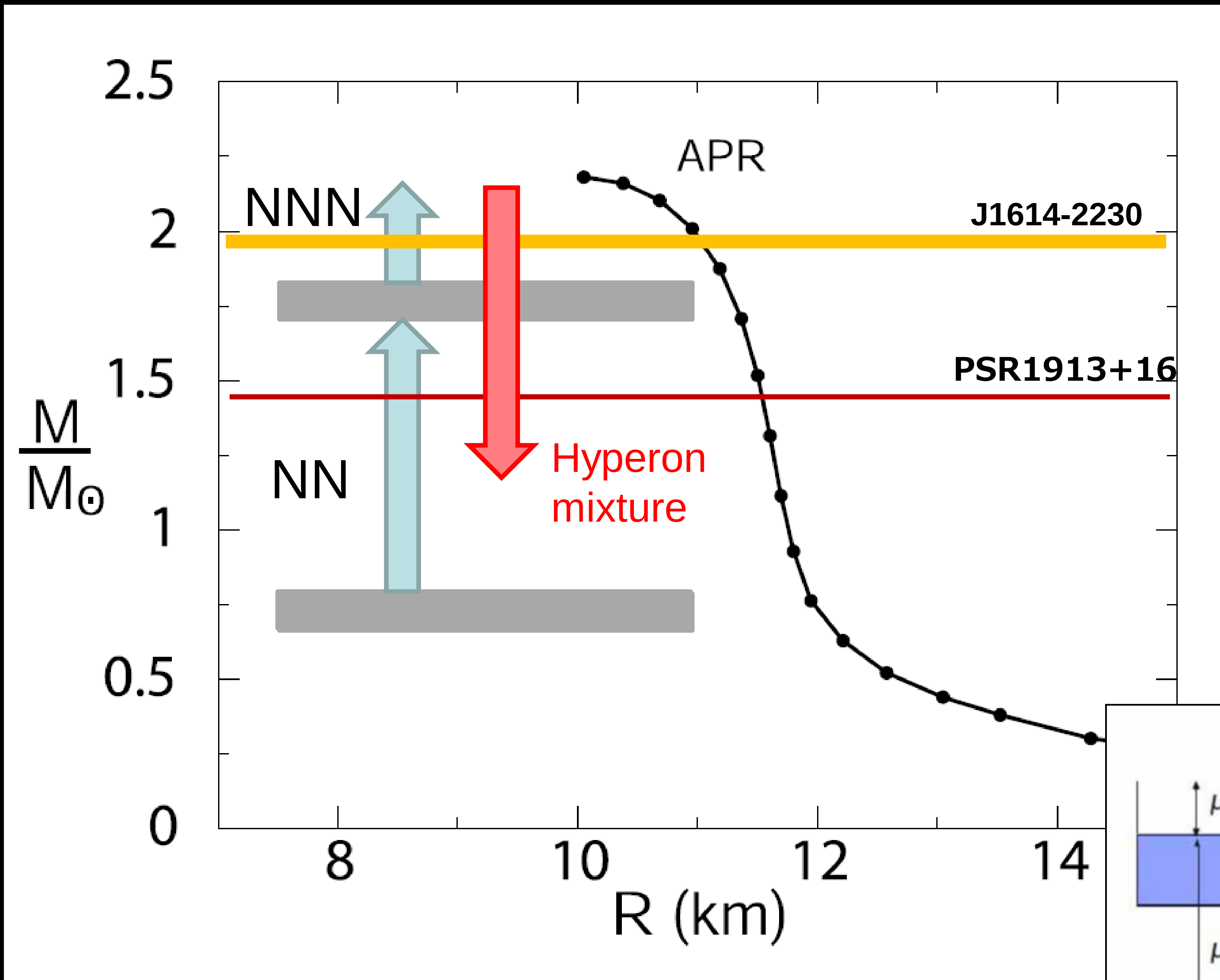
(11.28 PFlops, 80,000 CPUs x 8 = 640,000 cores)

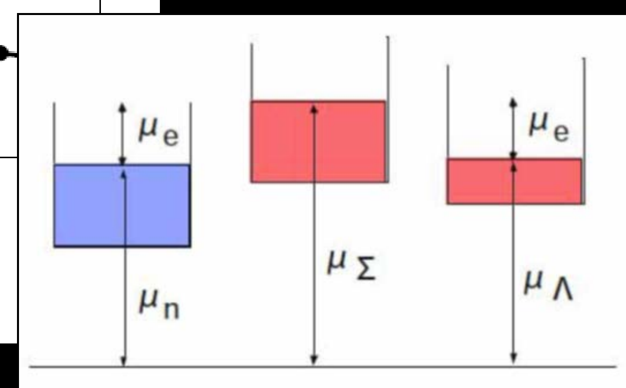




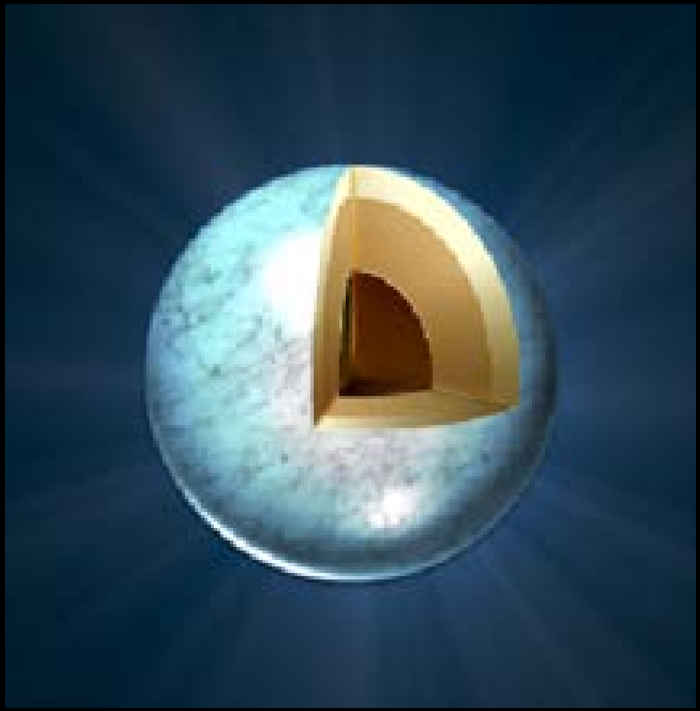
Hyperon Crisis

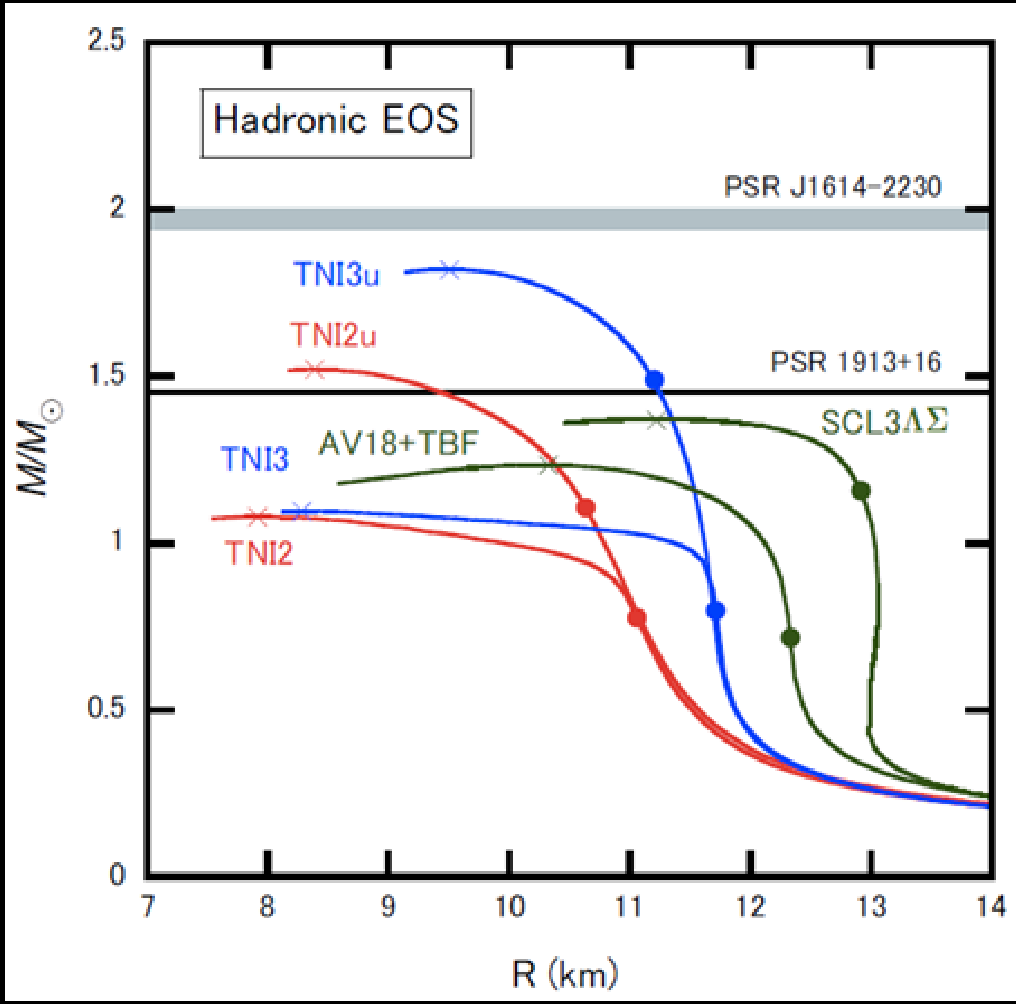






Hyperon Crisis





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

Possible Resolution(s) of Hyperon Crisis

1. 2-body YN forces completely different from NN?

   unlikely from lattice QCD studies — HAL QCD Coll., Nucl.Phys.A881 (2012) 28

2. Repulsive 3-body forces in YN too?

   not enough even with $V_{YNN} = V_{YYN} = V_{YYY} = V_{NNN}$

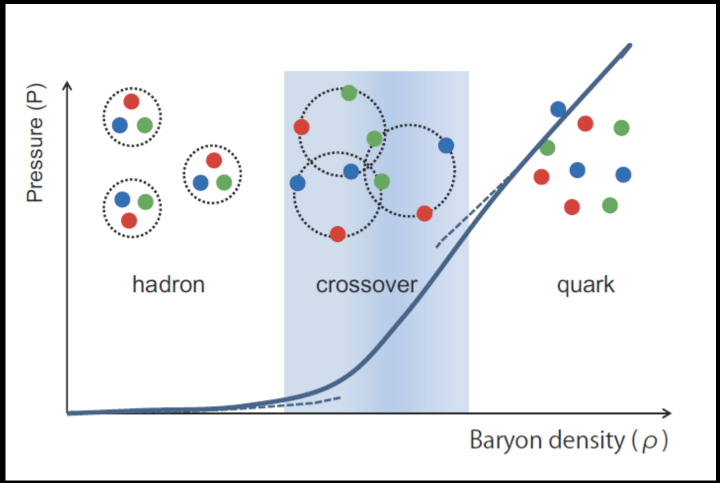
3. n(>3) -body forces ?

   no information so far. convergence ?

4. Crossover to quark matter ?

   Hatsuda, Tachibana, Yamamoto & Baym, PRL 97 (2006) 122001
   Maeda, Baym & Hatsuda, PRL 103, (2009) 085301

$(2\text{-}4)\rho_0$



$2M_\odot$ neutrons stars require,

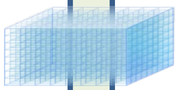
- STIFF quark-matter EOS
- Smooth crossover (no 1st order transition)
- Crossover at $\rho=(2\text{-}4)\,\rho_0$

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

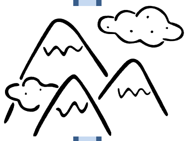
From QCD to Hot/Dense Matter

Quantum Chromo Dynamics

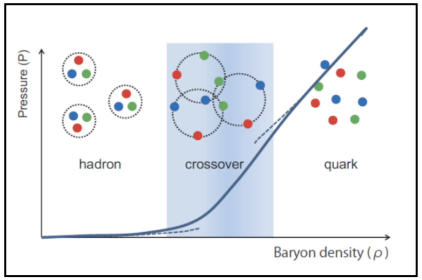
Lattice gauge theory



sign problem



Phenome. model



Equation of State for Hot Matter

Equation of State for Dense Matter

Relativistic hydrodynamics

General relativity

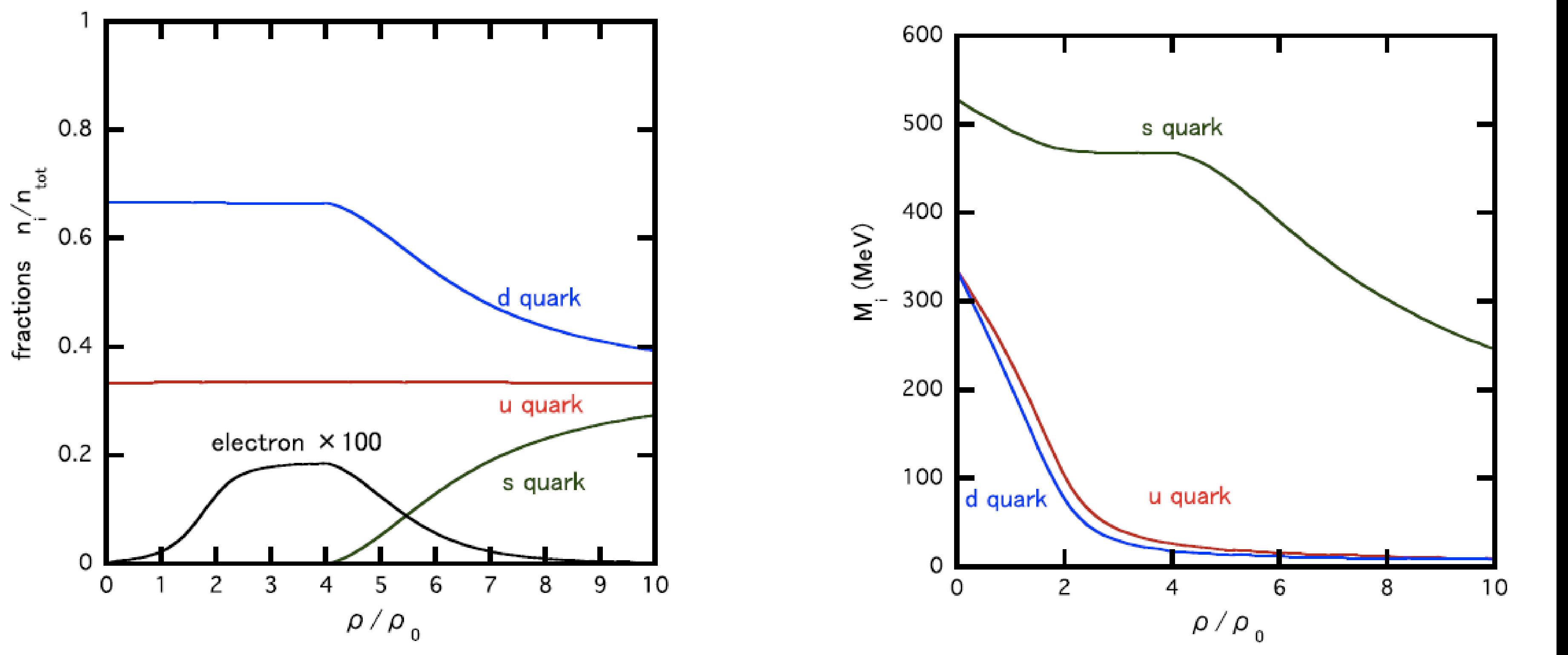
Relativistic heavy-Ion collisions

Neutron stars

A phenomenological model of strongly interacting Quark Matter

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

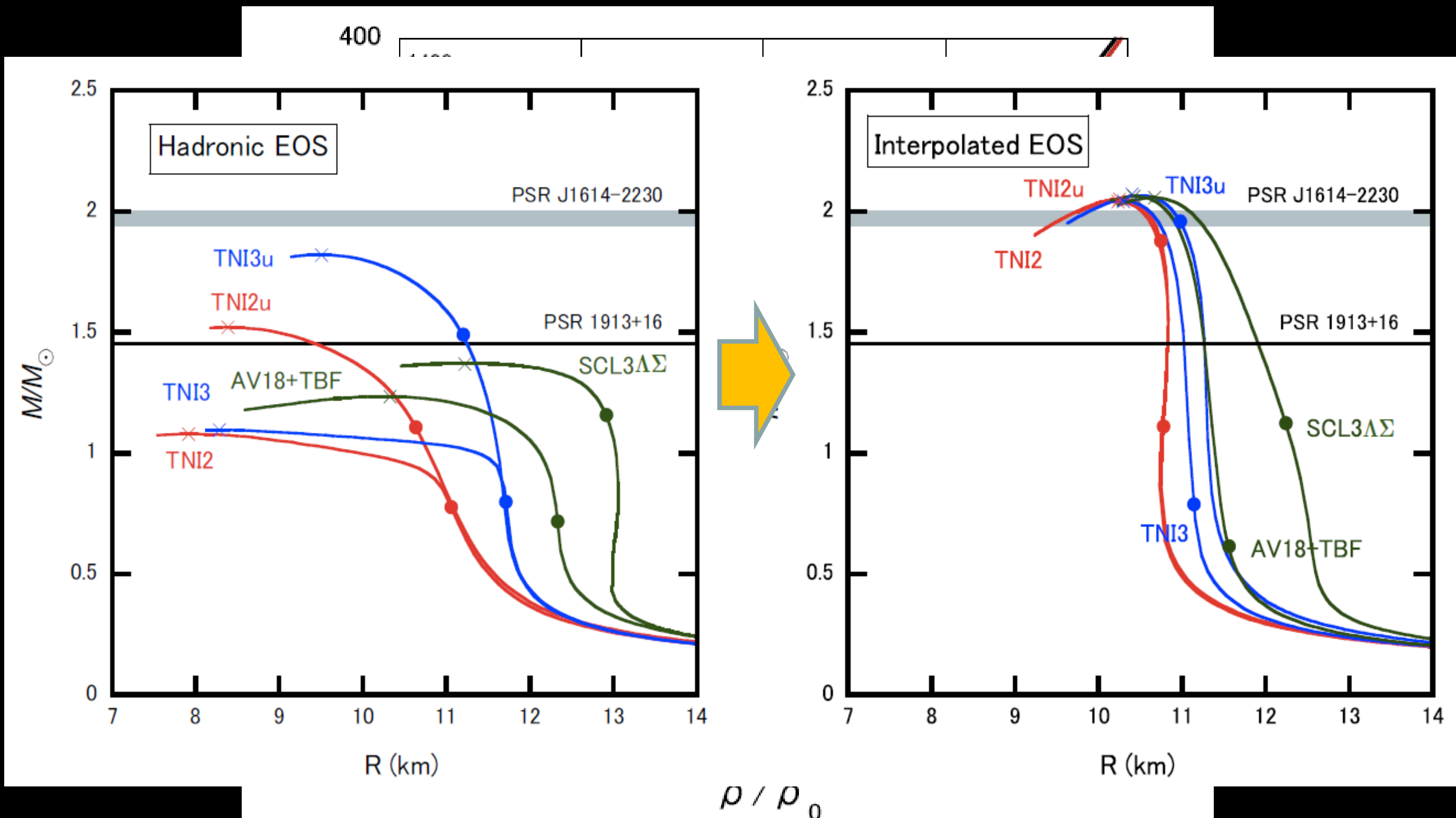
$$- \begin{cases} \frac{1}{2}g_V\,(\bar{q}\gamma^\mu q)^2 \\ \frac{1}{2}G_V\,\sum_{a=0}^{8}\left[(\bar{q}\gamma^\mu\lambda^a q)^2 + (\bar{q}i\gamma^\mu\gamma_5\lambda^a q)^2\right] \end{cases}$$



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

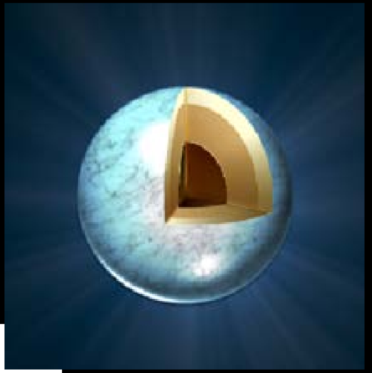
Phenomenological crossover between soft hyperon-matter to stiff quark-matter

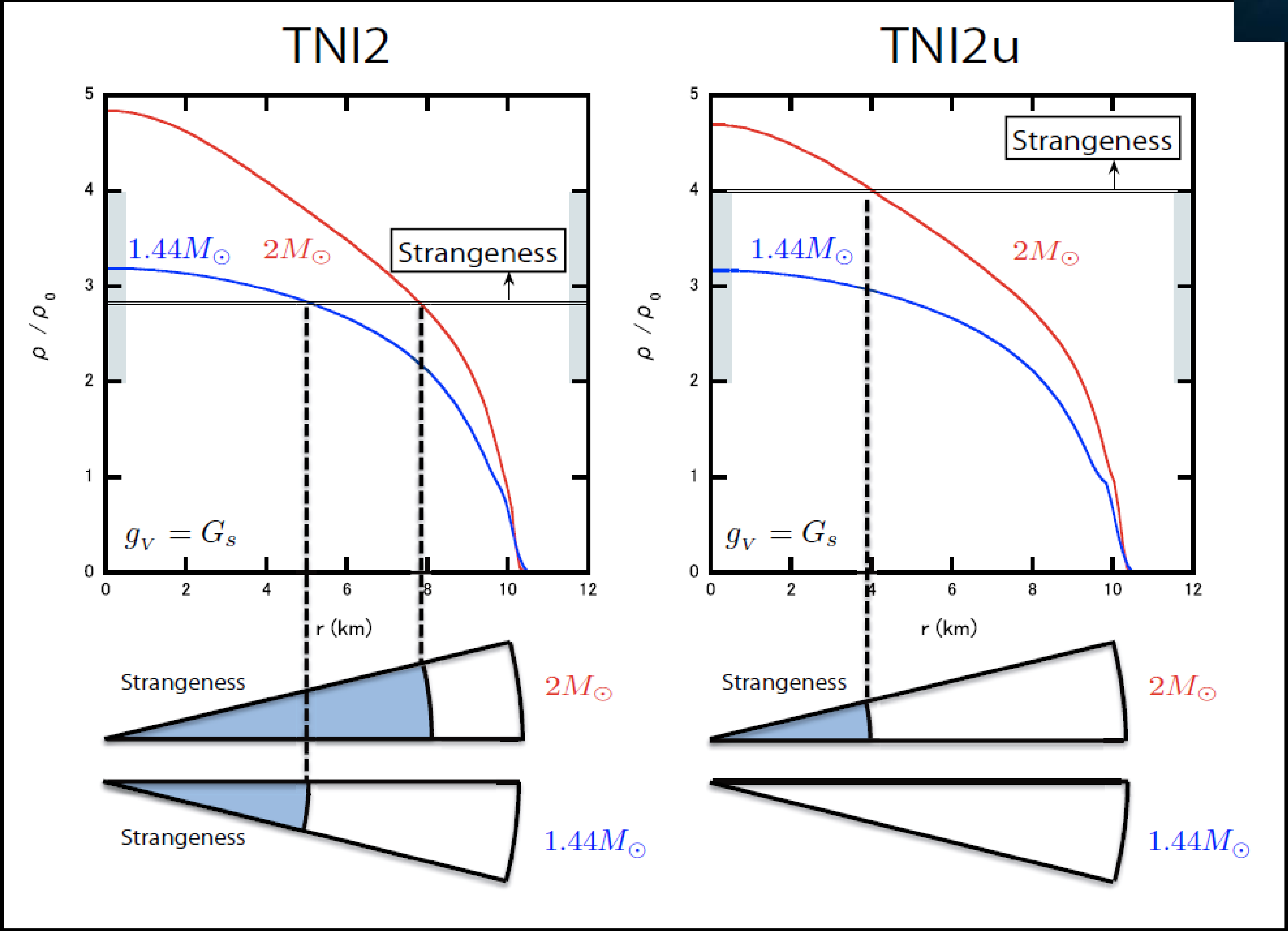
(NJL model with vector mean-field)



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

Hyperon 3-body force and onset of strangeness

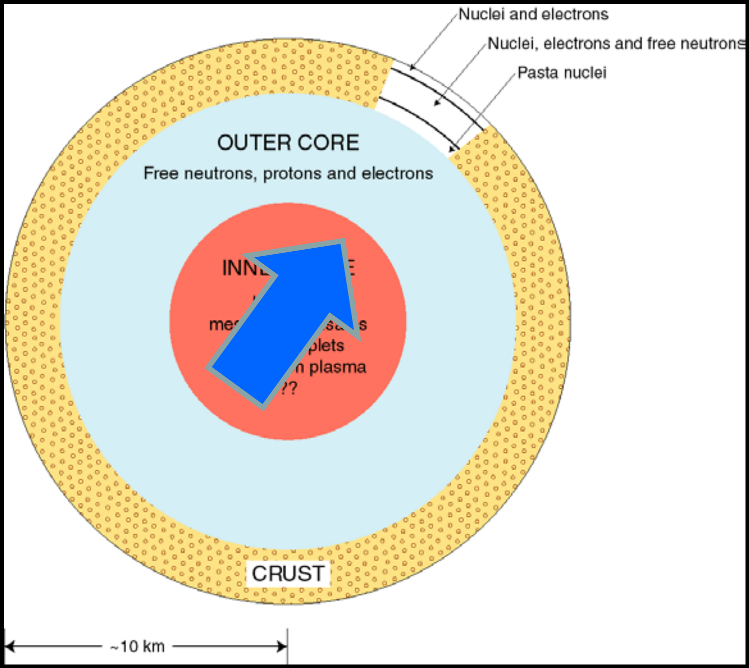


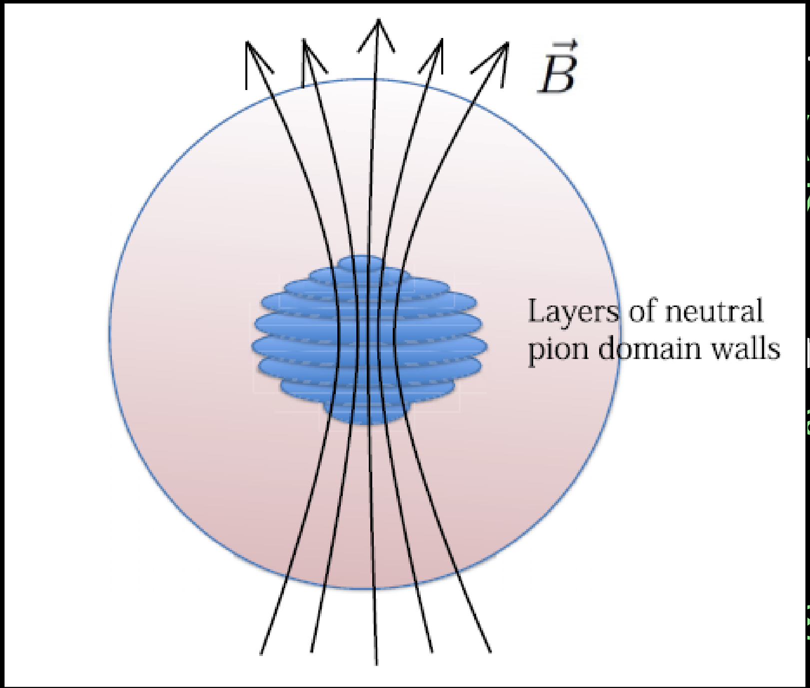


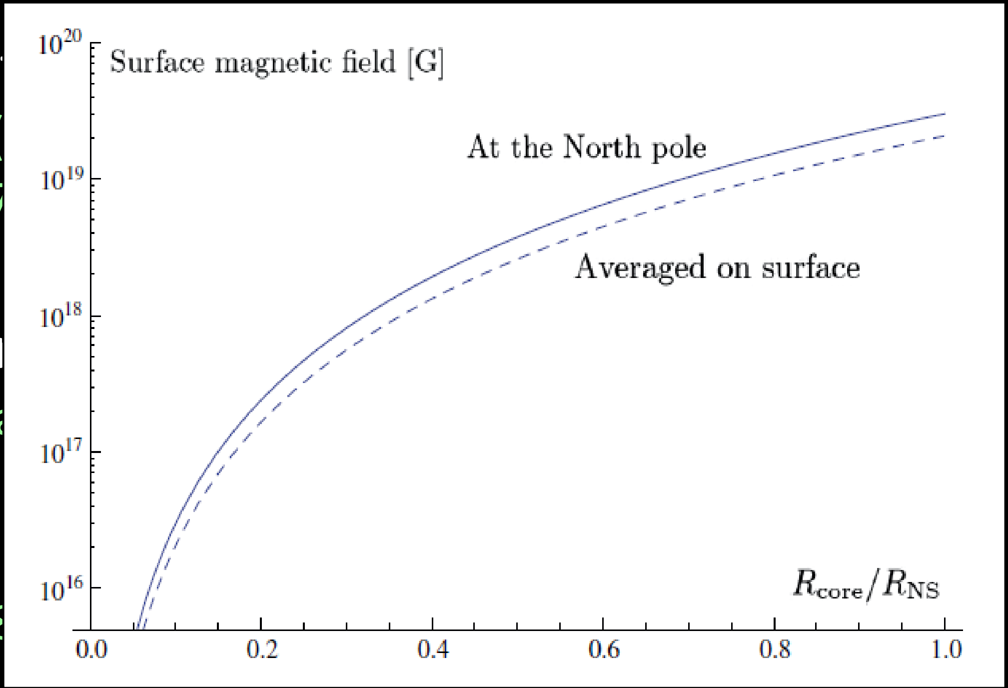
Highly magnetized neutron stars (Magnetars)

Surface $\sim 10^{14\text{-}15}$ G
Interior $\sim 10^{18\text{-}19}$ G ?

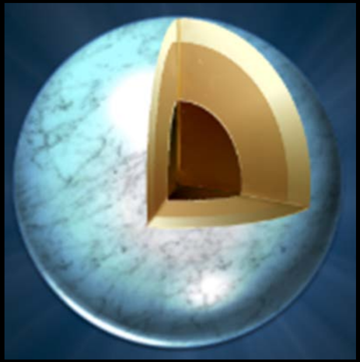
Physics of strong interaction?







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
  -- higher body hyperon force ?
  -- crossover to stiff quark matter
  → may be studied by HIC ?