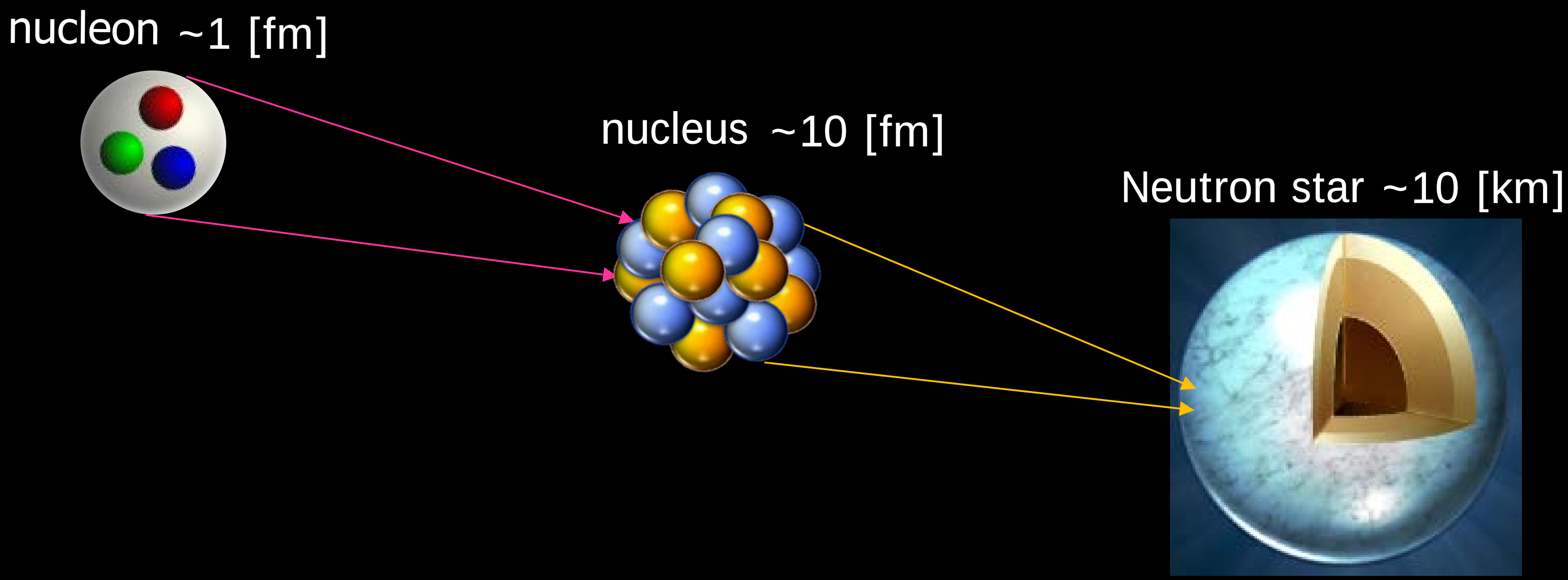
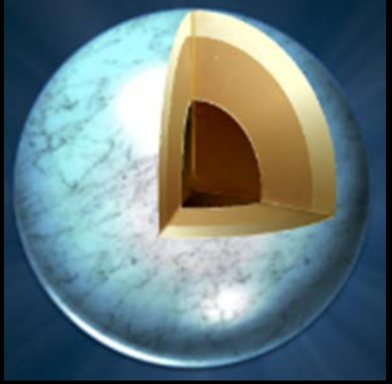
Dense QCD and Compact Stars



KEK Workshop (Jan. 21, 2014)

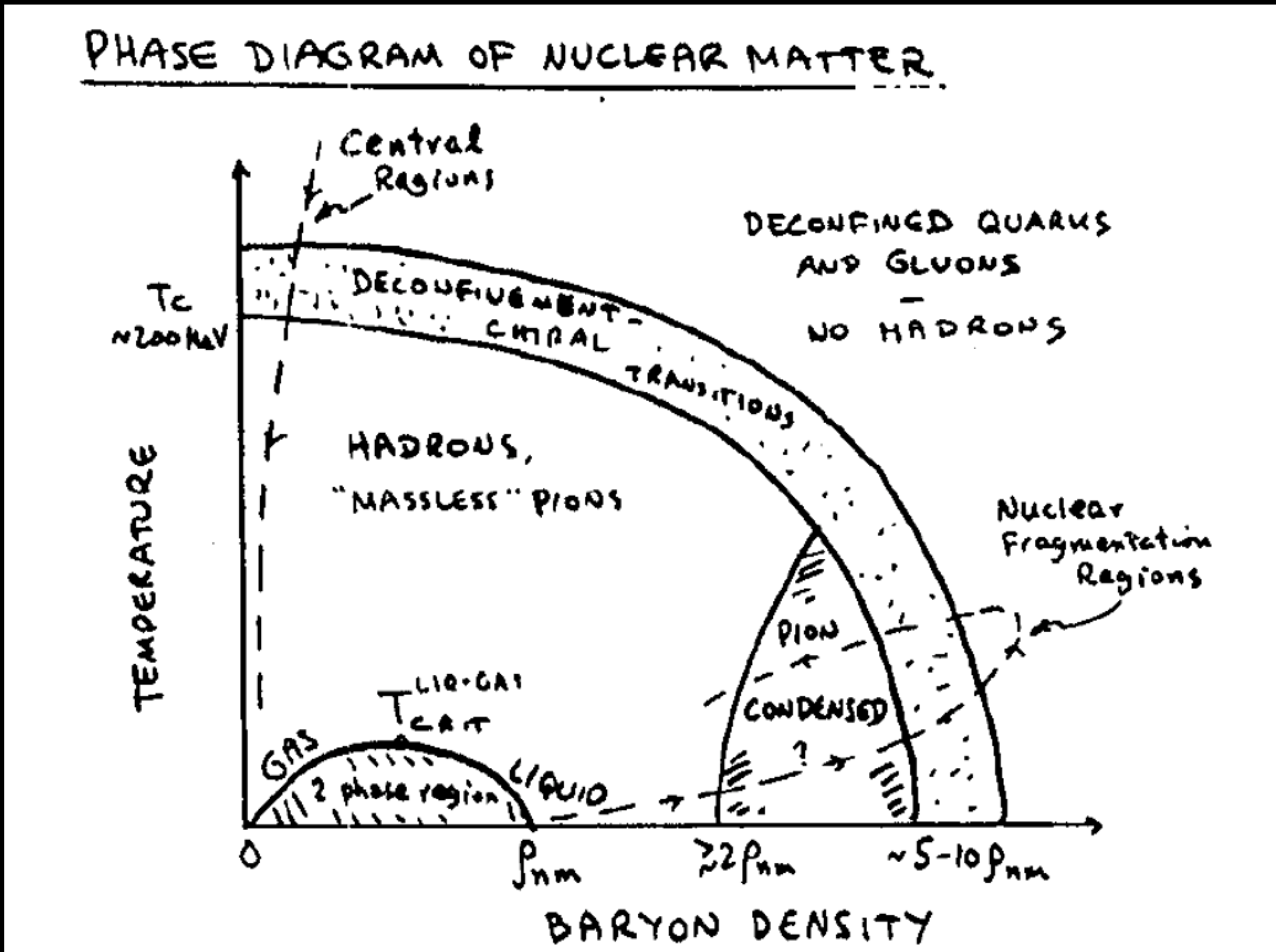
Tetsuo Hatsuda (RIKEN)

Plan of this Talk



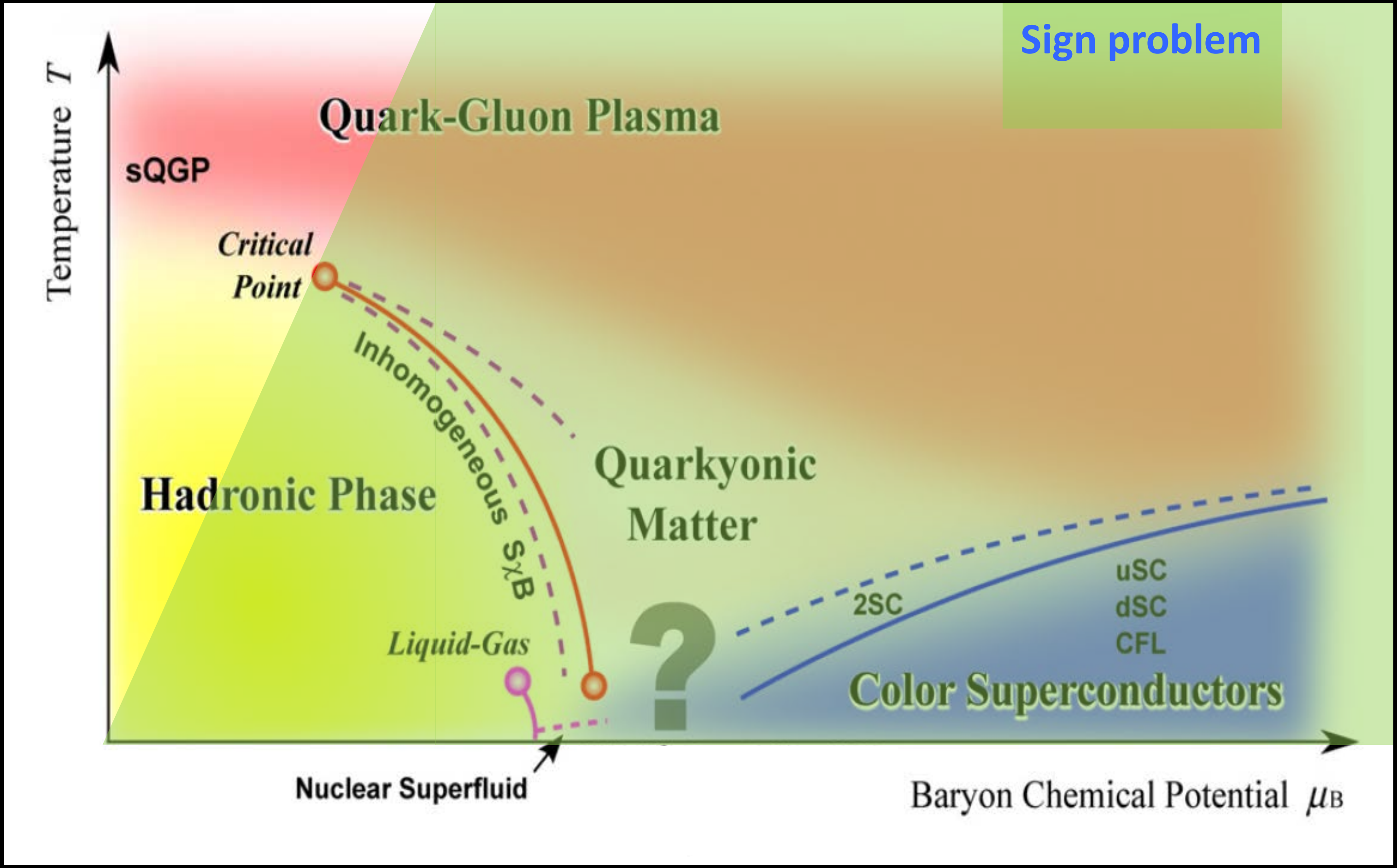
1. QCD Phase Structure
2. Neutron Star and Dense EOS
3. Dense EOS and Lattice QCD
4. Neutron Star and Hadron-Quark Crossover
5. Summary

QCD Phase Diagram (30 years ago)



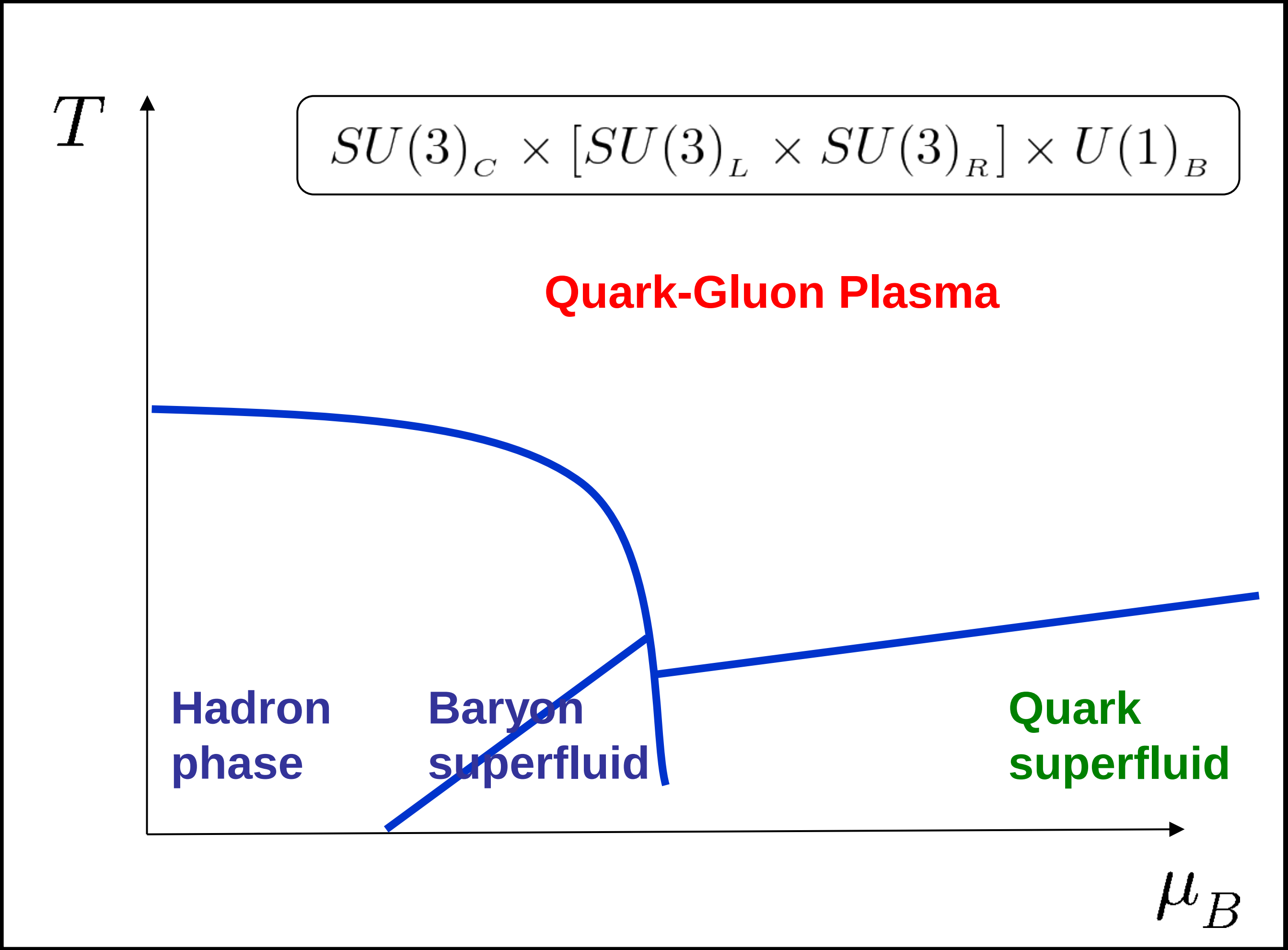
E. Fermi (1953) → G. Baym (1983)

QCD Phase Diagram (now)

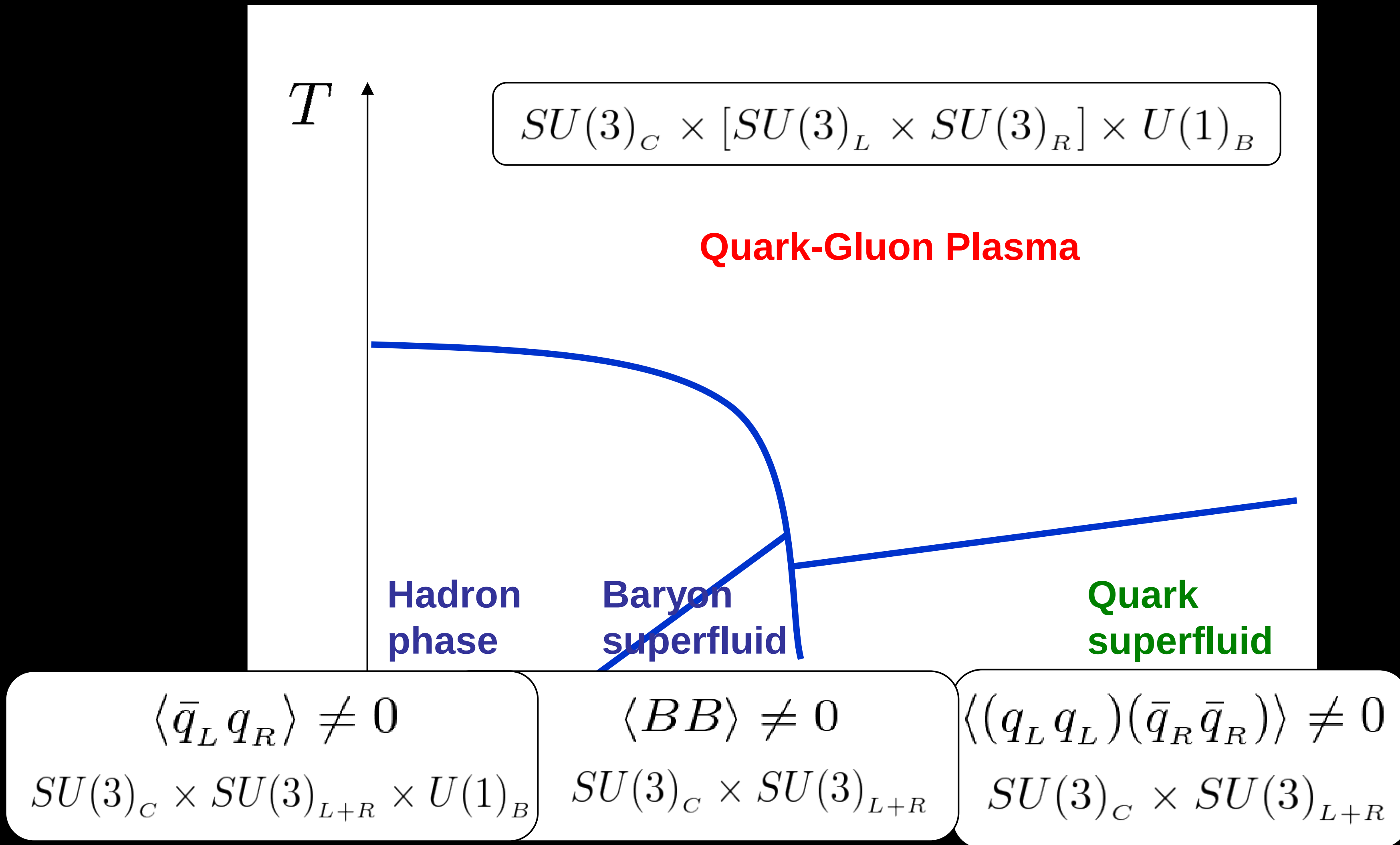


K. Fukushima and T. Hatsuda,
"The Phase Diagram of Dense QCD"
Rep. Prog. Phys. 74 (2011) 014001

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

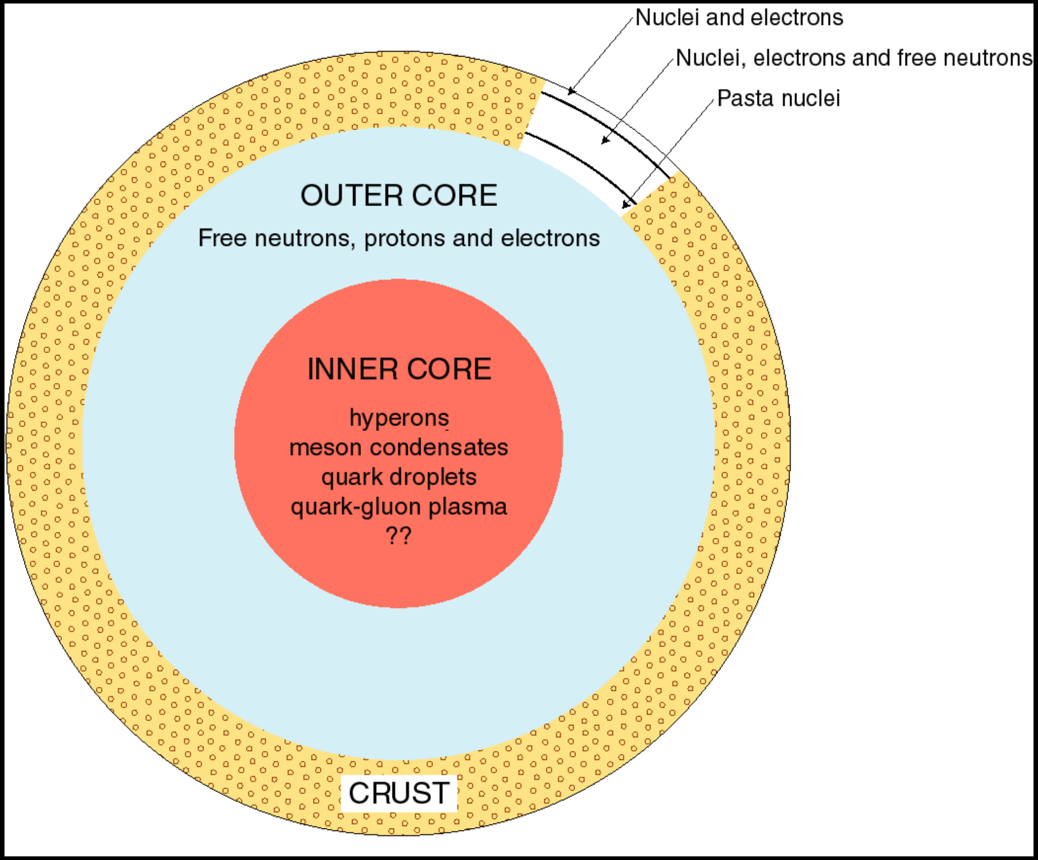


Symmetry Realization in dense QCD (N_c=3, N_f=3)



Chiral symmetry is always broken at finite density

Dense Matter and Neutron Star



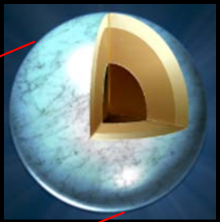
- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\, \rho_0$

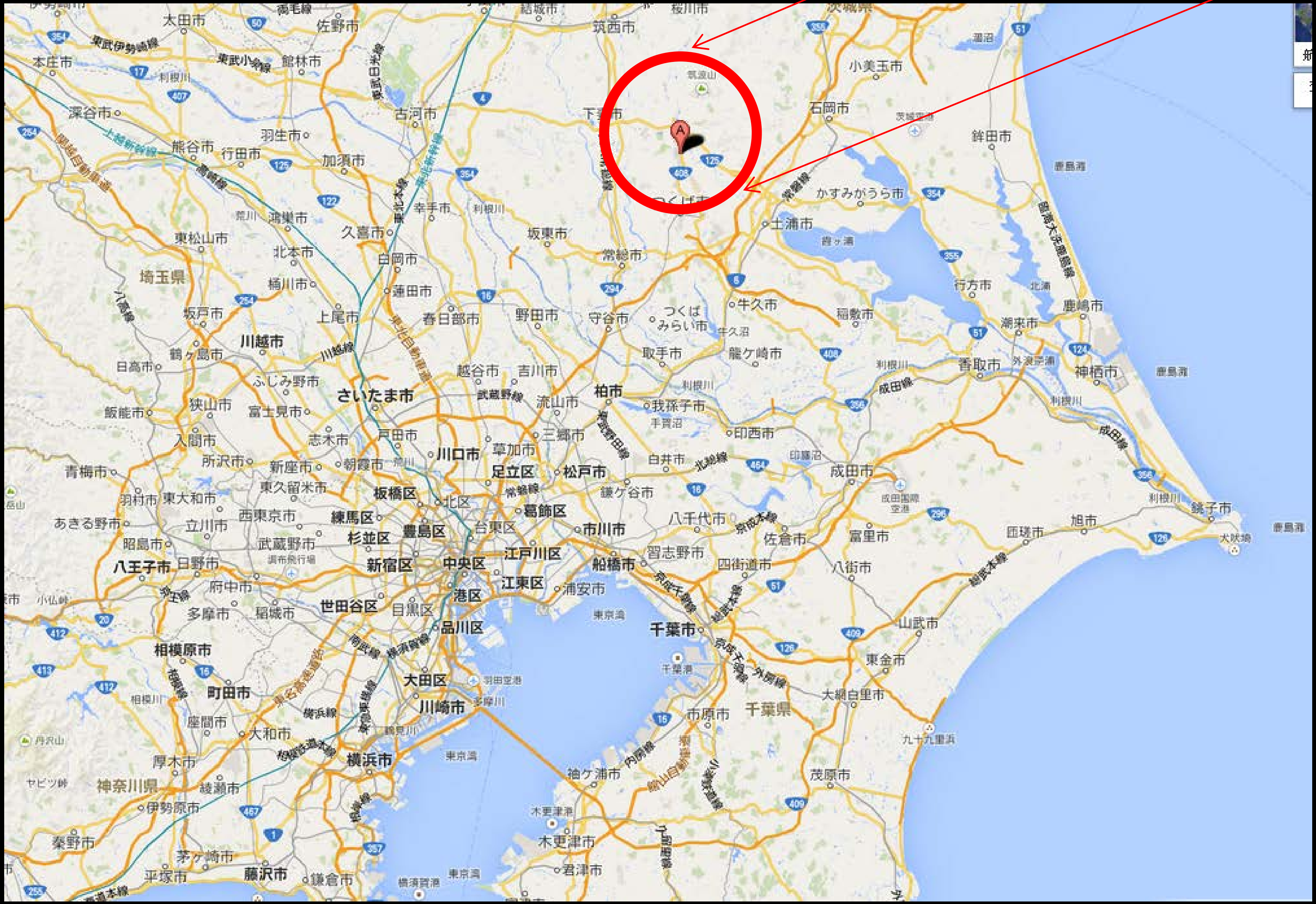
composition

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

\+ leptons (e, μ)

Neutron Star on top of KEK





Basic equations for compact star

1. Tolman–Oppenheimer–Volkoff equation ← GR

(TOV)

$$\frac{d\mathcal{M}(r)}{dr} = 4\pi r^2 \varepsilon(r),$$

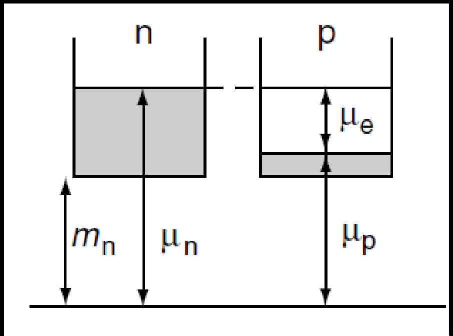
$$-\frac{dP(r)}{dr} = \frac{G\varepsilon\mathcal{M}}{r^2}\left(1-\frac{2G\mathcal{M}}{r}\right)^{-1}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{\mathcal{M}}\right),$$

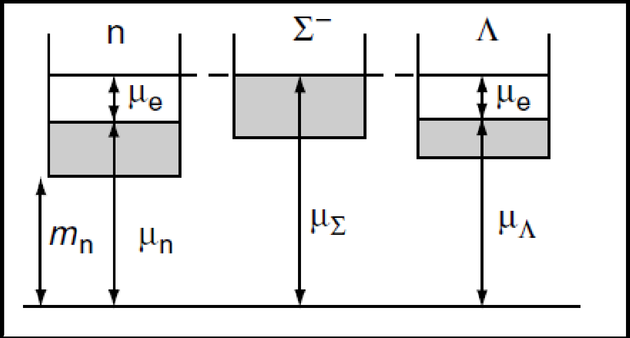
2. Equation of state P=P(ε) ← Strong int.

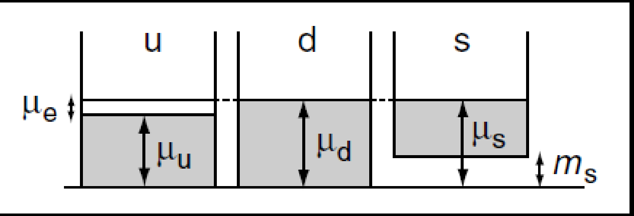
(EOS)

EM int. （charge neutrality）

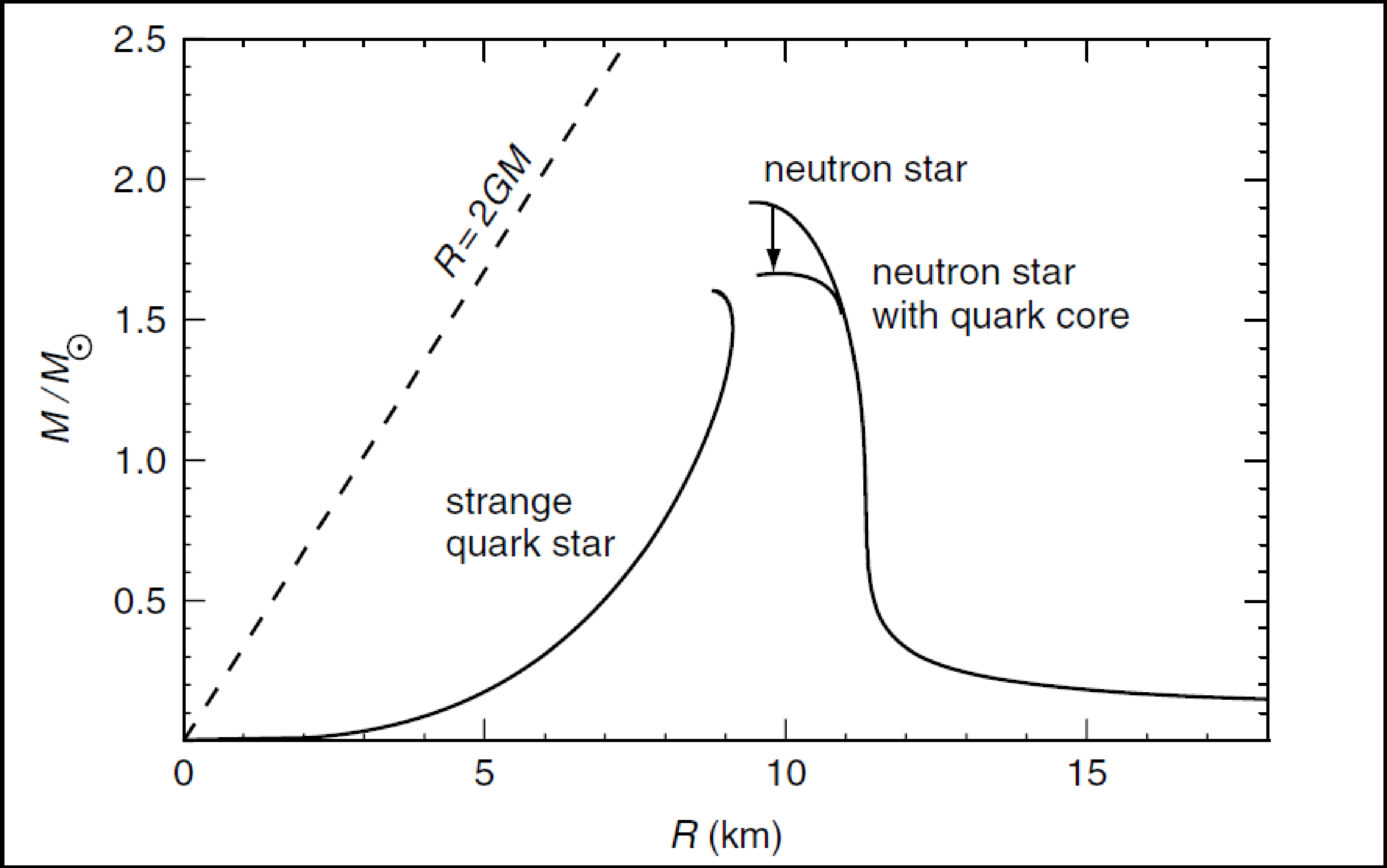
Weak int. (β equilibrium)







Schematic Mass-Radius relation



From Yagi, Miake and Hatsuda,
"Quark-Gluon Plasma", Cambridge Univ. Press (2008)

$N_{\star}$ observations

Current:

$M=(1.97\pm0.04)M_{\odot}$ (Nature 2010)

$M=(2.01\pm0.04)M_{\odot}$ (Science 2013)

⇔ cold EOS

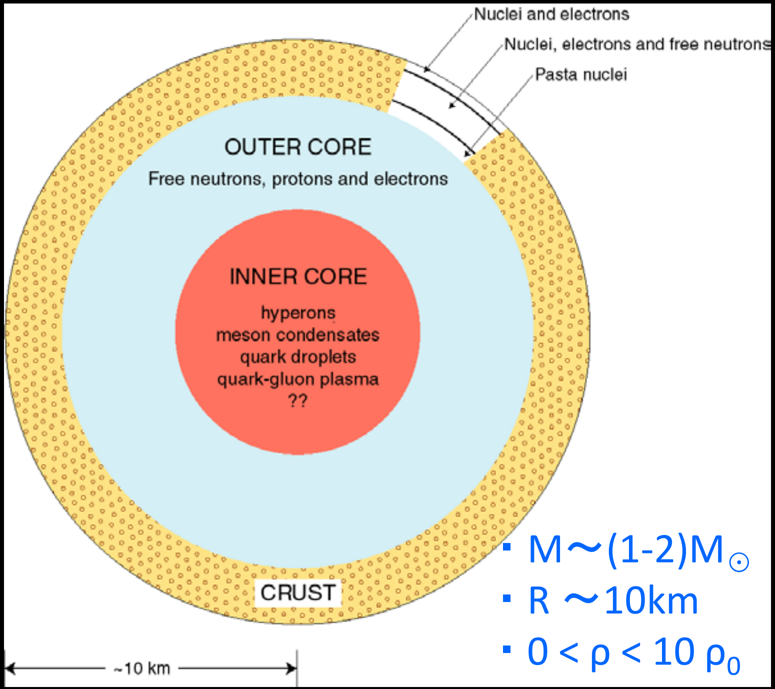
X-ray bursts ⇔ cold EOS

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

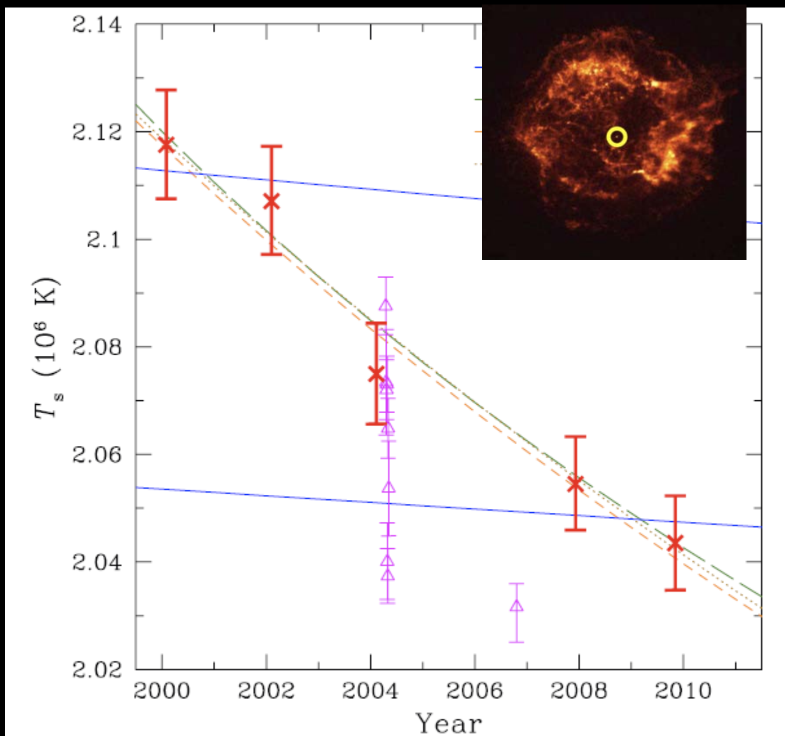
Magnetars ⇔ ferromagnetic core?

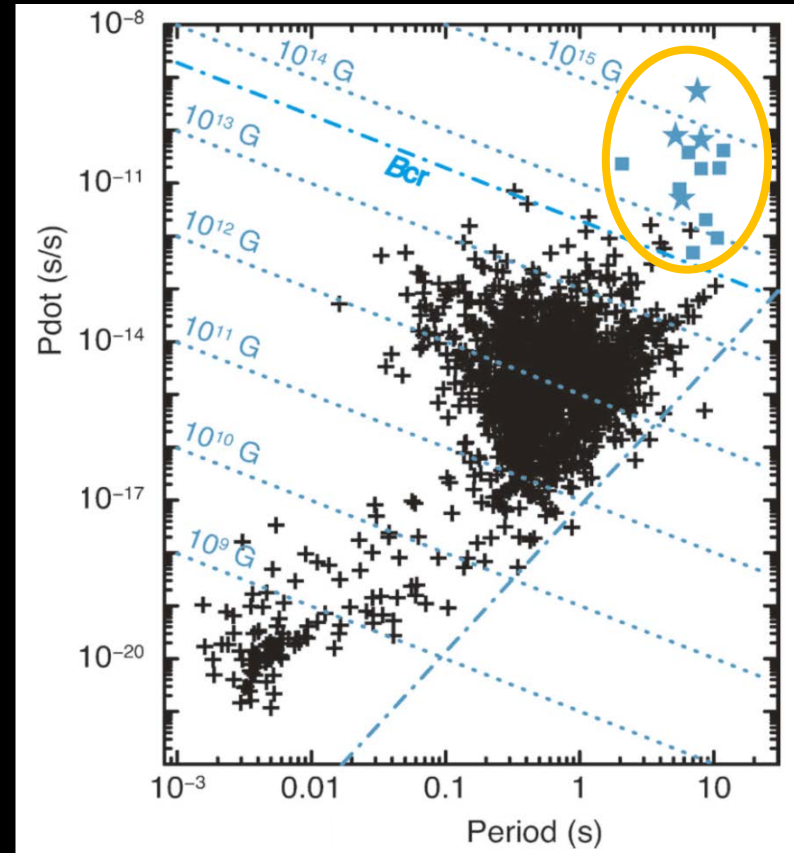
Near Future:

GW from $N_{\star}$ merger ⇔ hot EOS

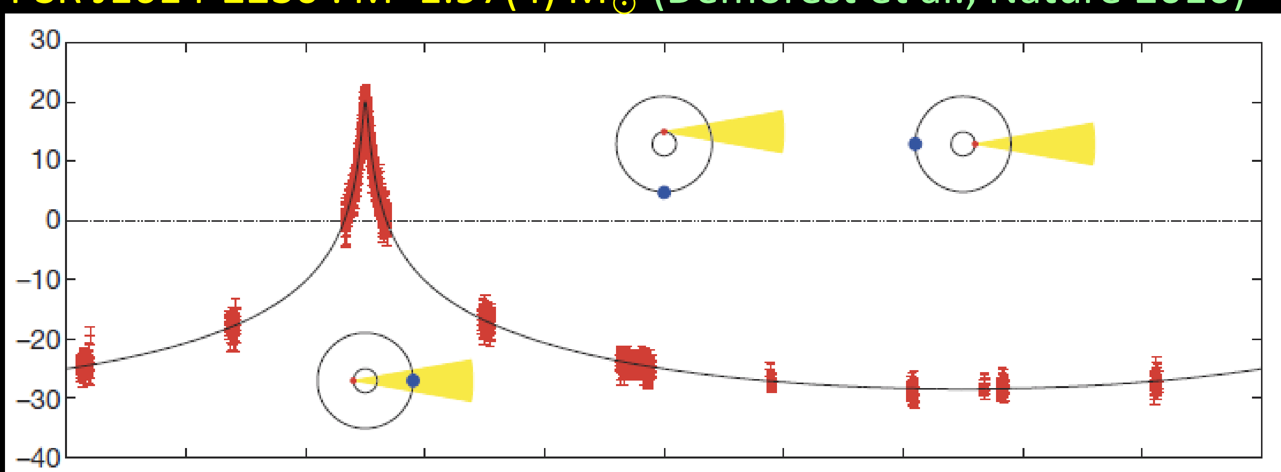


Cassiopeia A cooling: T decreases by 4% in 9 years
(Heinke & Ho, ApJ 2010)





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



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

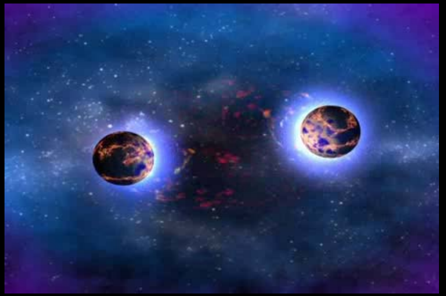
T, B, M

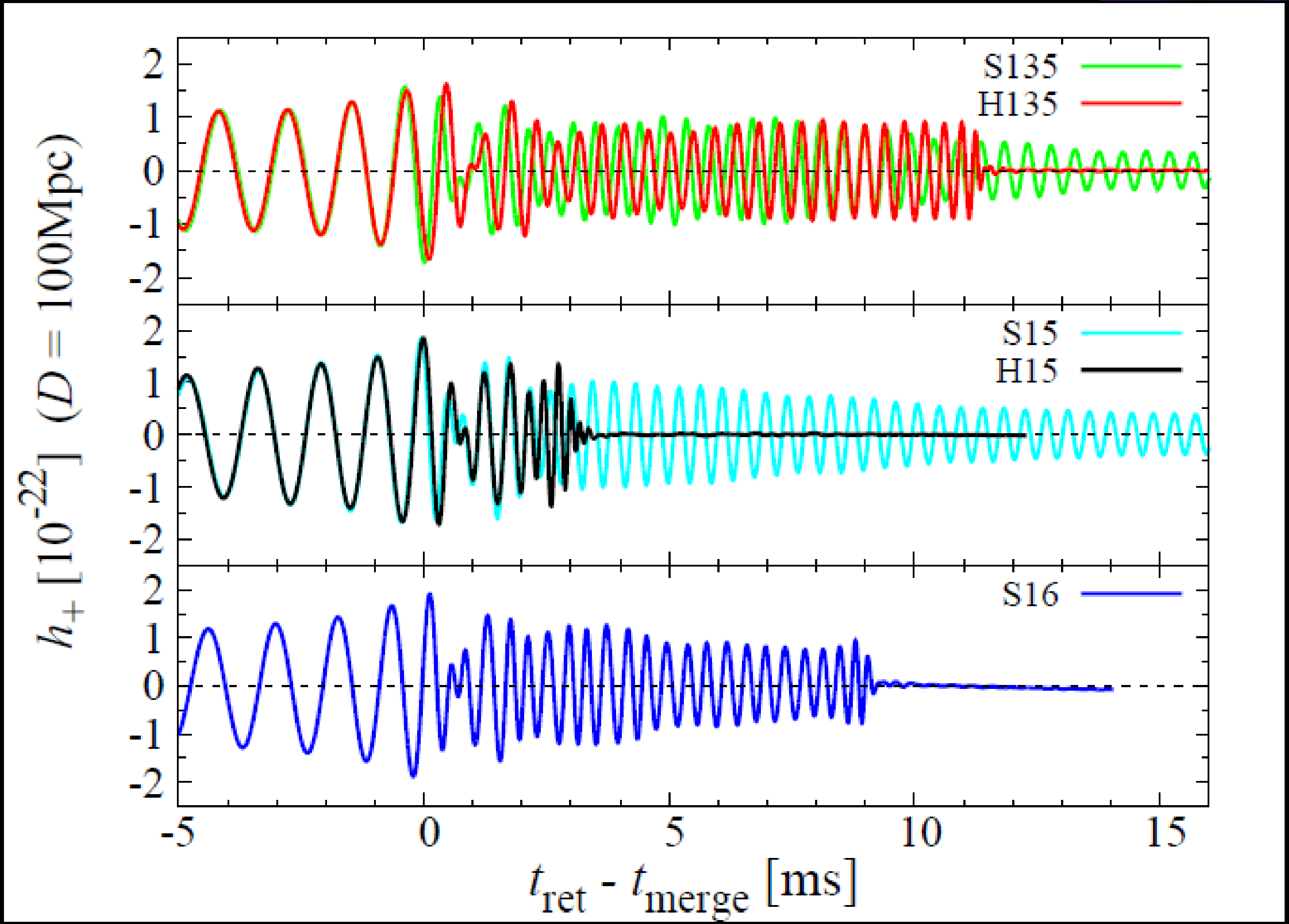
Gravitational wave from $N_{\star}$ merger
-- Detectors --

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

M. Shibata (YITP)

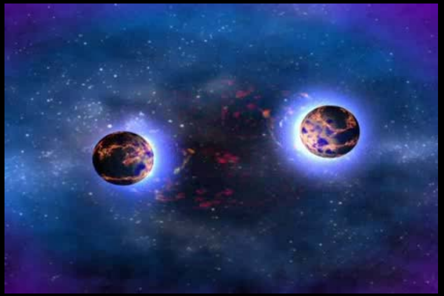
Gravitational wave from $N_{\star}$ merger
-- Expected signal --

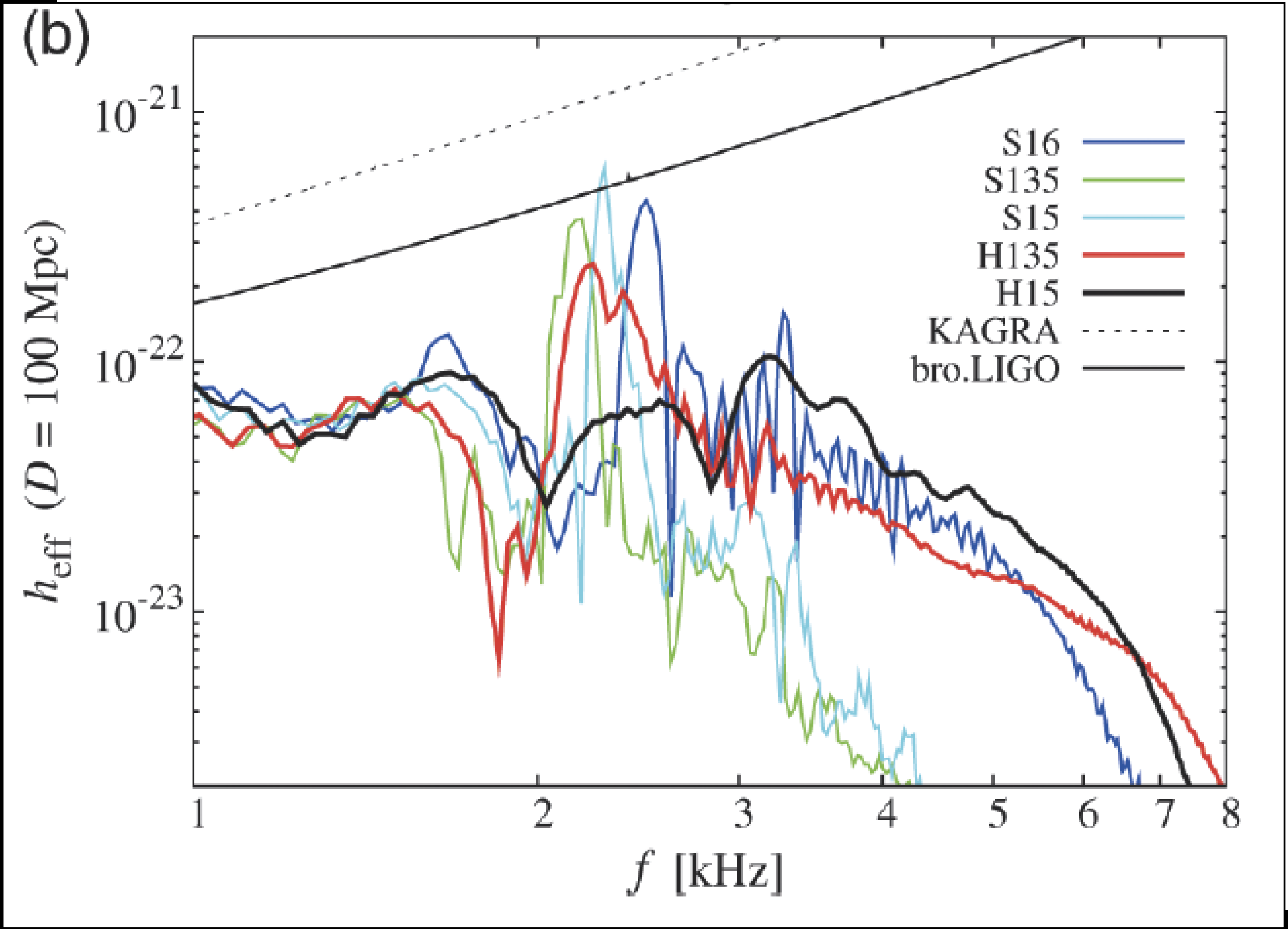




Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

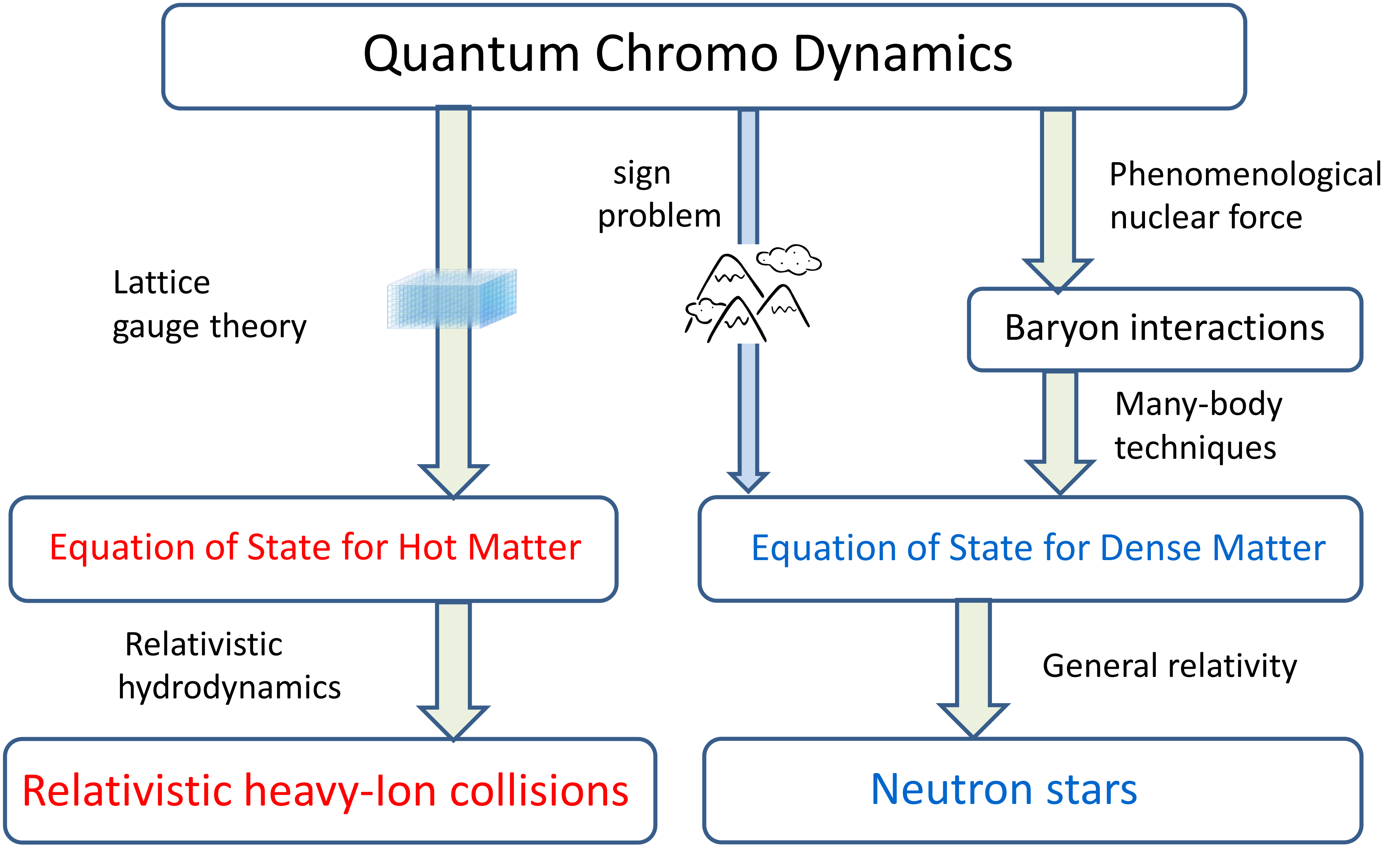
Gravitational wave from N$_\star$ merger
-- Expected signal --





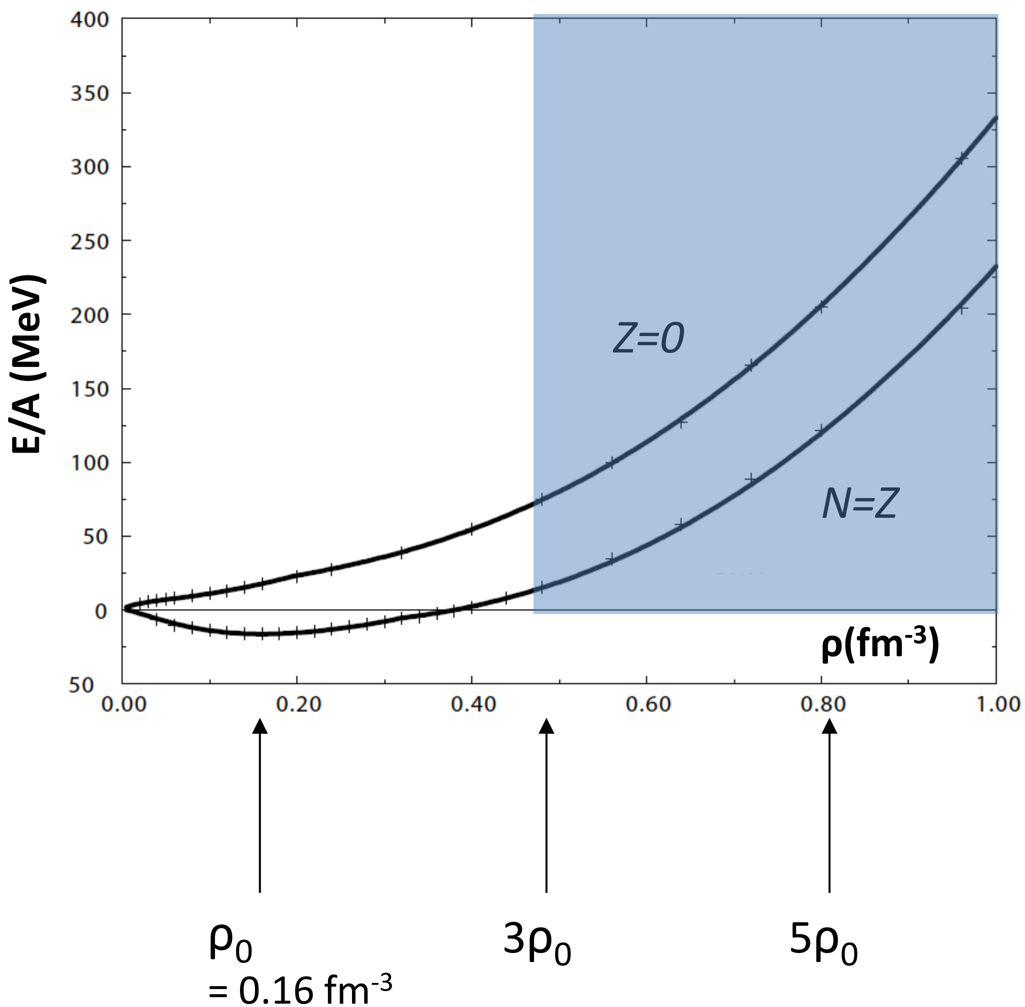
Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL 107 (2011); PTEP (2013)

From QCD to Hot/Dense Matter

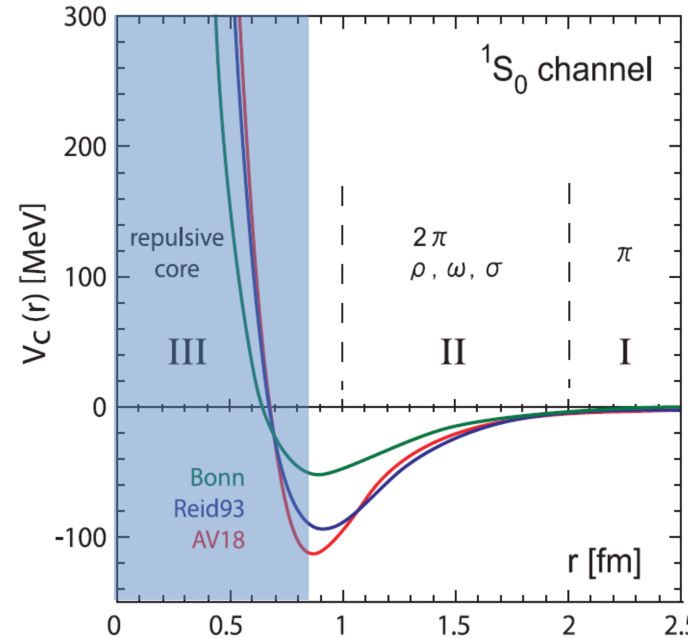


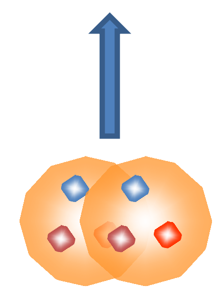
Nuclear Force and dense EOS（nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

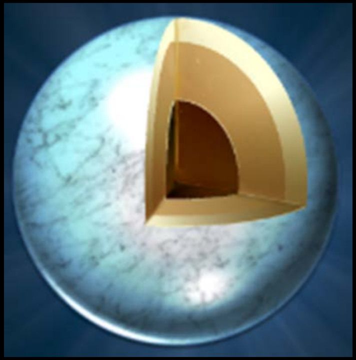


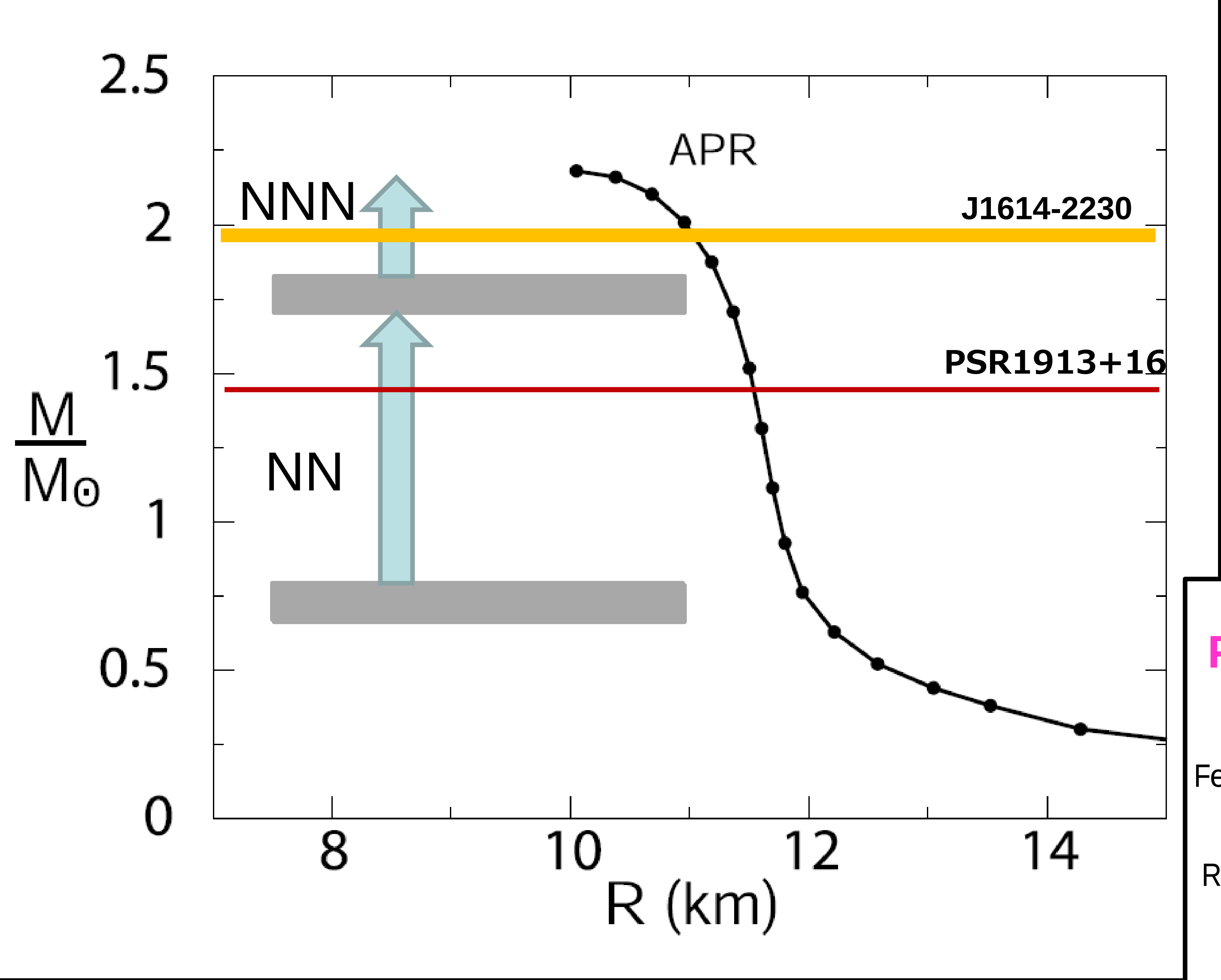
Phenomenological nuclear force

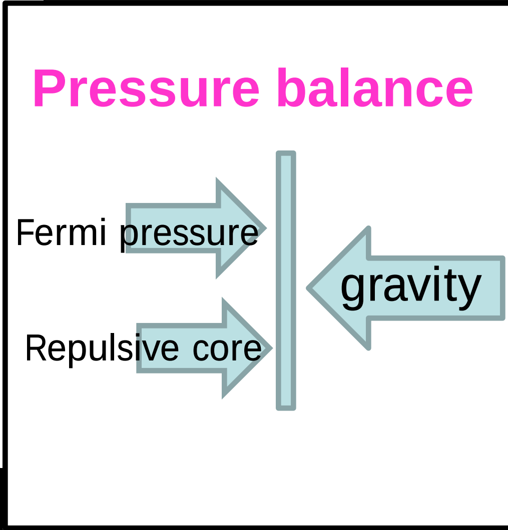




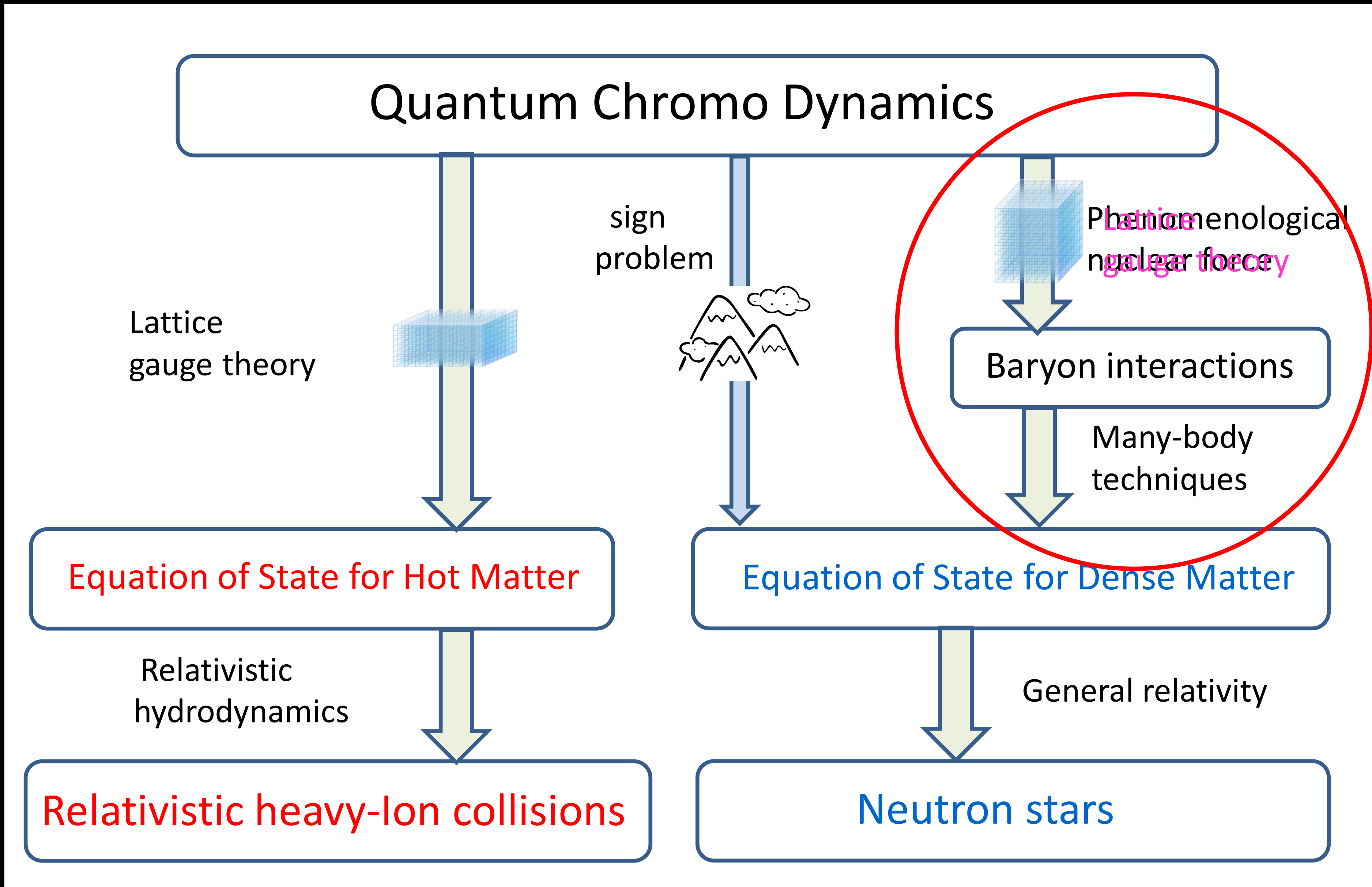
Mass-Radius relation of $N_{☆}$ (nucleons only)



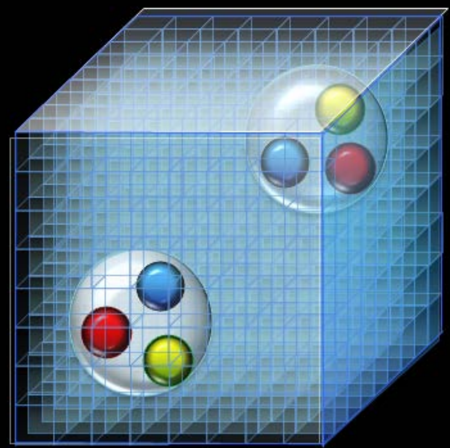


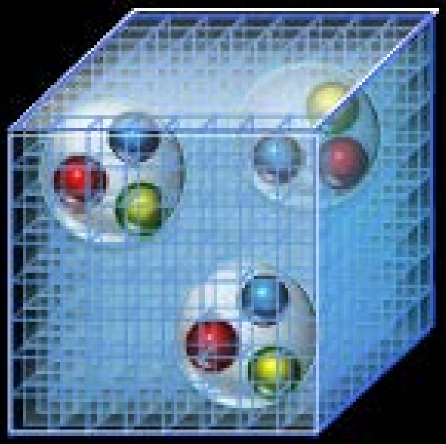


From QCD to Hot/Dense Matter



Lattice QCD and Multi-baryon

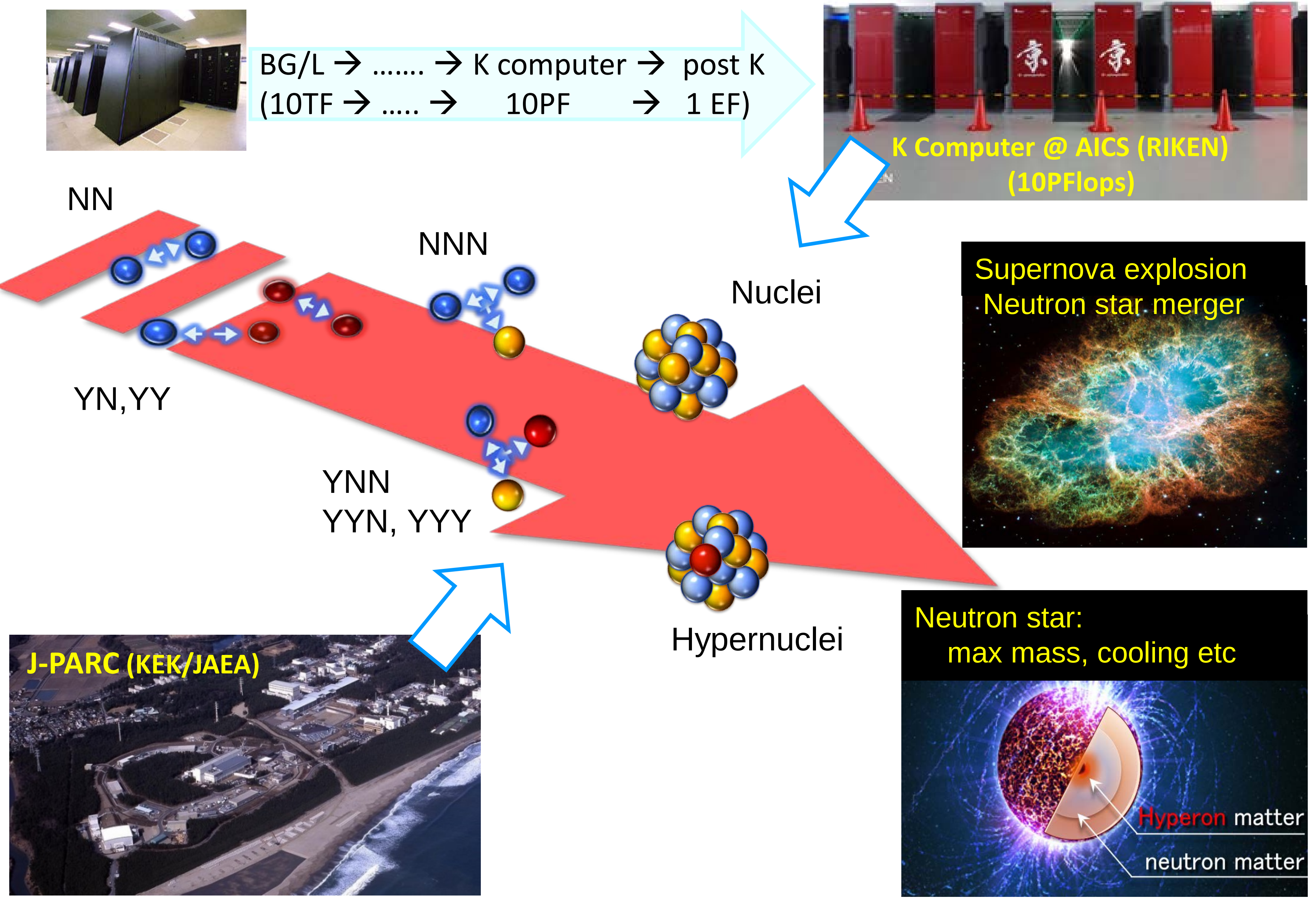




Univ. Tsukuba	N. Ishii, H. Nemura, K. Sasaki
RIKEN	T. Doi, T. Hatsuda, Y. Ikeda
Nihon Univ.	T. Inoue
Kyoto Univ.	S. Aoki, K. Murano
Univ. Tokyo	B. Charron

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

HAL QCD Strategy : From QCD to Compact stars

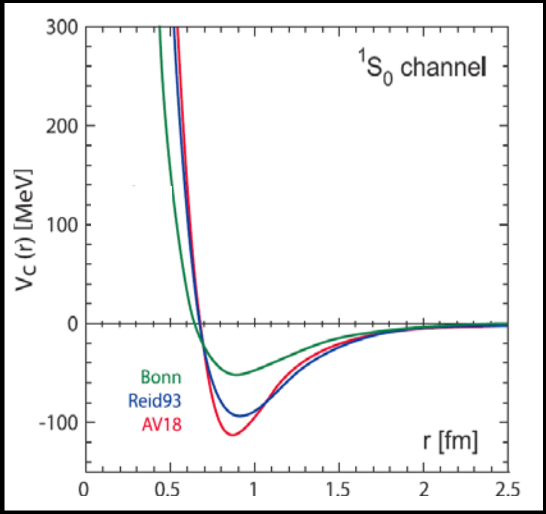


Baryon force: From phenomenology to 1st principle

- NN int.: about 4500 np and pp scatt. data

"high precision" NN interactions		# of parameters
CD Bonn	(p space)	38
AV18	(r space)	40
EFT in N^3LO	($n\pi$+contact)	24

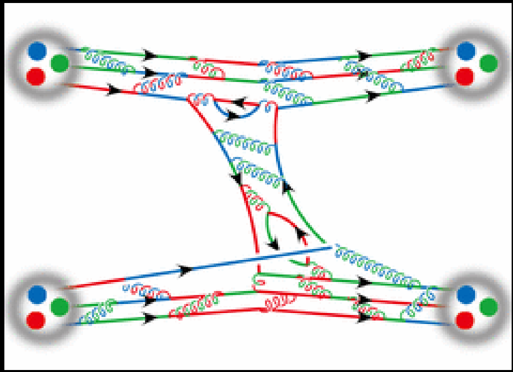
R. Machleidt, arXiv:0704.0807 [nucl-th]



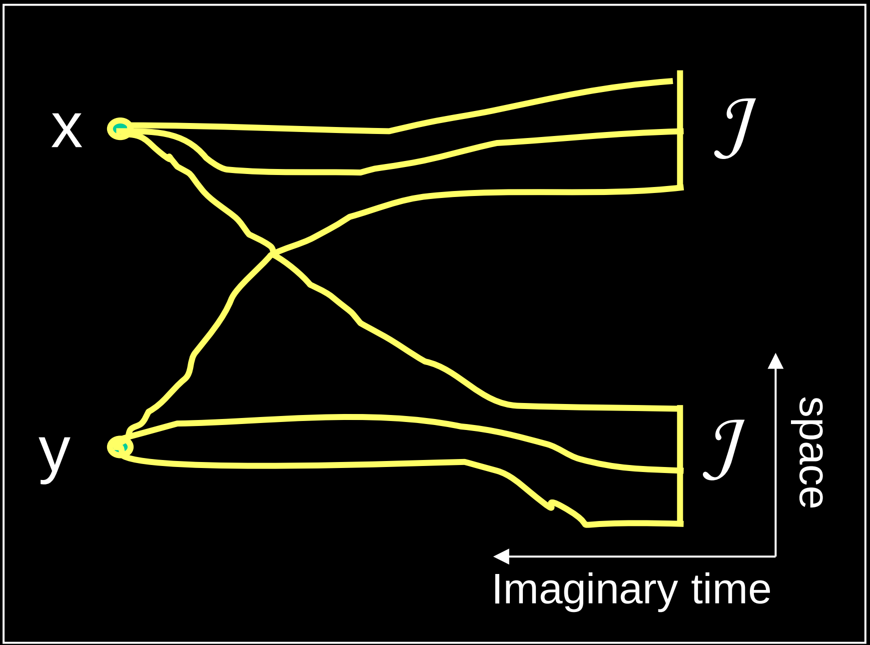
- NNN, YN, YY : data very limited
- YNN, YYN, YYY : none

QCD has only four parameters :

m_u, m_d, m_s, Λ_{QCD}



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

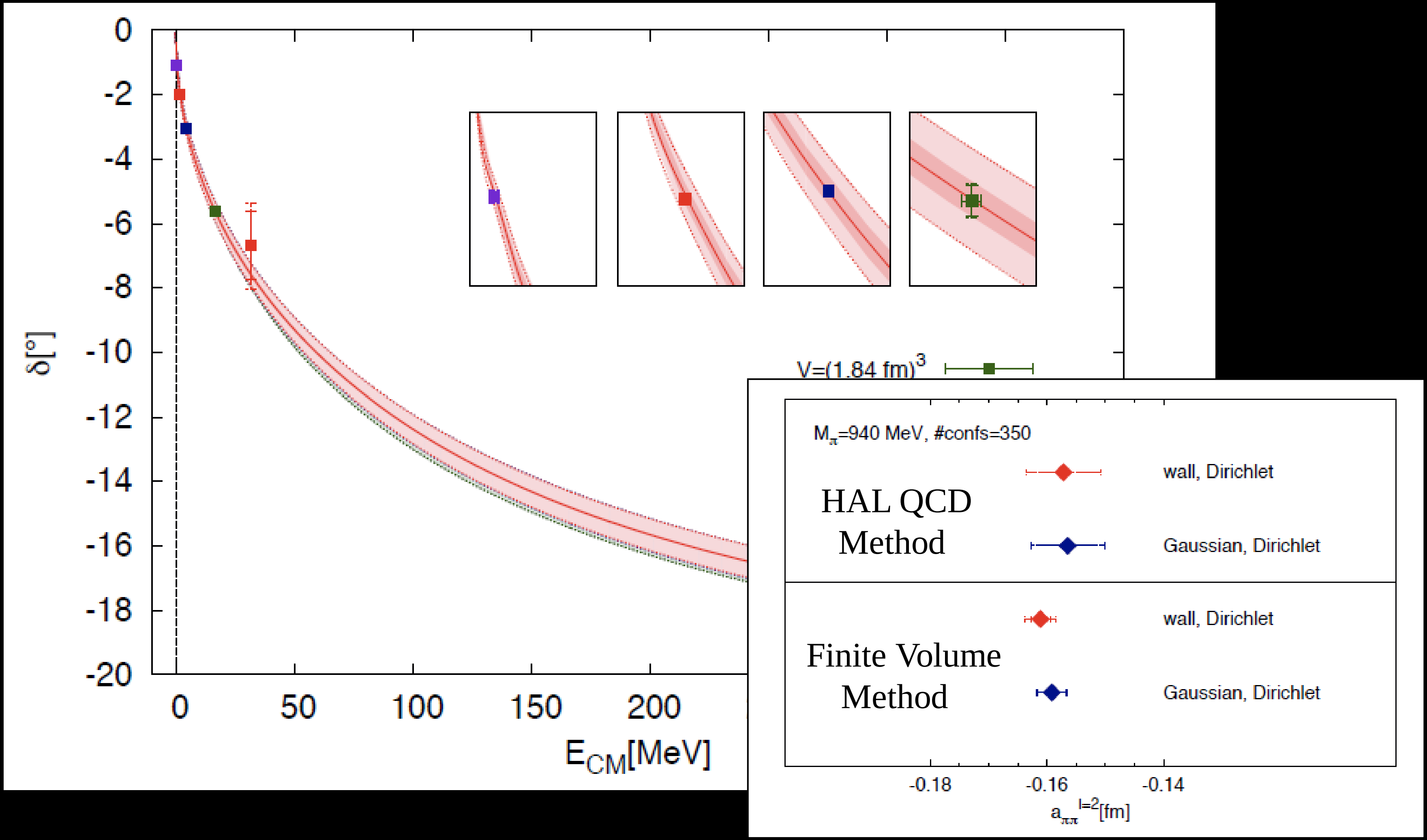
HAL QCD Method

ϕ (r,t) → kernel → phase shift

Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001
Comp. Sci. Dis. 1 (2009) 015009
HAL QCD Coll., PLB 712 (2012) 437

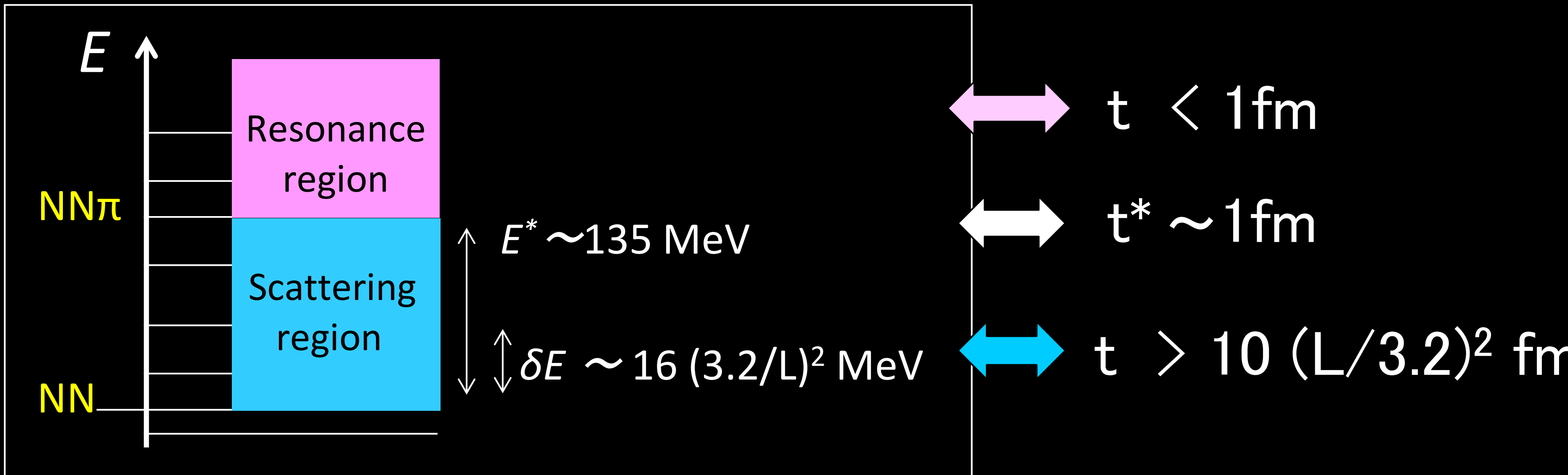
FV Method vs. HAL QCD Method : do they agree ?

π π 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: JHEP 1312 (2013) 015

What about NN ?



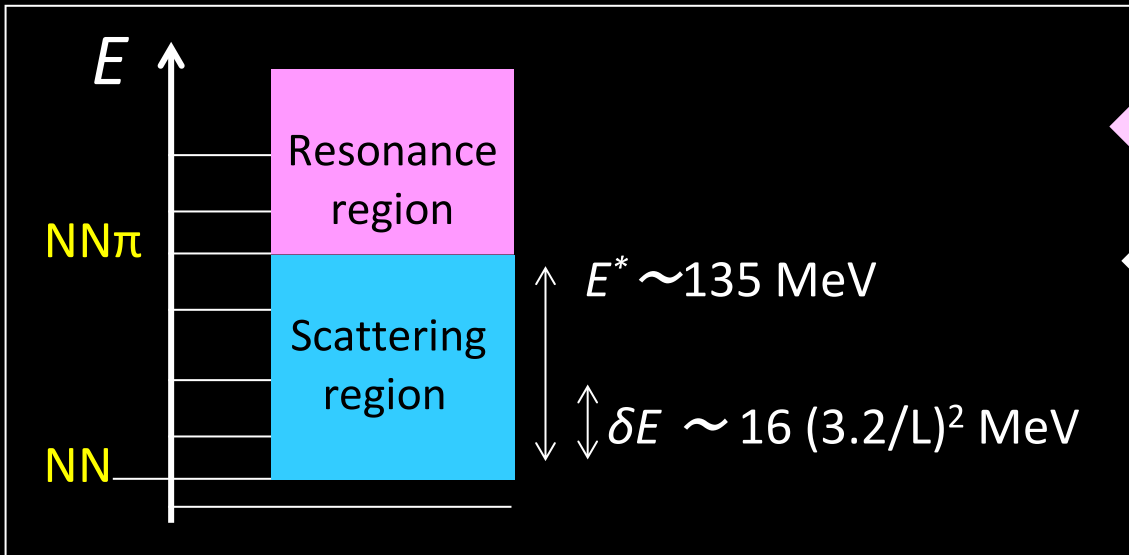
$$\left(\frac{\mathcal{S}}{\mathcal{N}}\right)_{NN} \sim \sqrt{N_{\rm gc}}\; e^{-2(m_N - 3m_\pi/2)t}$$

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

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 < 1fm

t* ~ 1fm

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

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

t > t* is only necessary

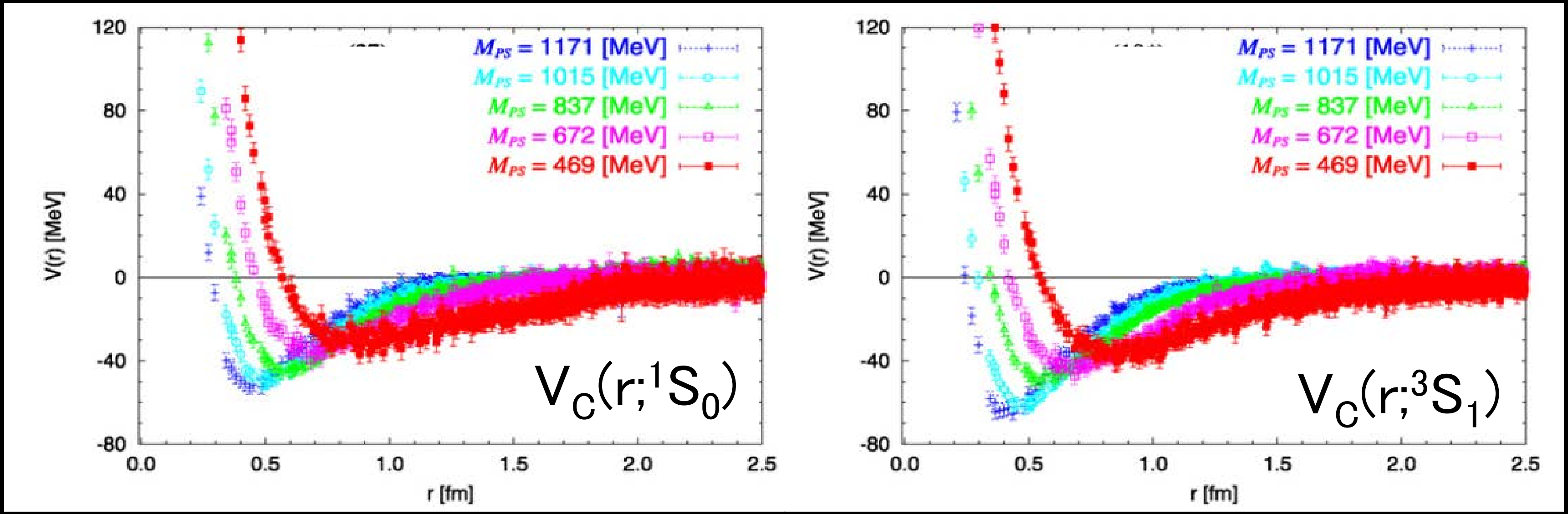
Non-local kernel U(r,r')

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

HAL QCD Coll., PLB 712 (2012) 437

$$V(\vec{r}, \nabla) = V_{\rm C}(r) + S_{12}V_{\rm T}(r) + \vec{\rm L}\cdot\vec{\rm S}\; V_{\rm LS}(r) + \{V_{\rm D}(r), \nabla^2\} + \cdots$$

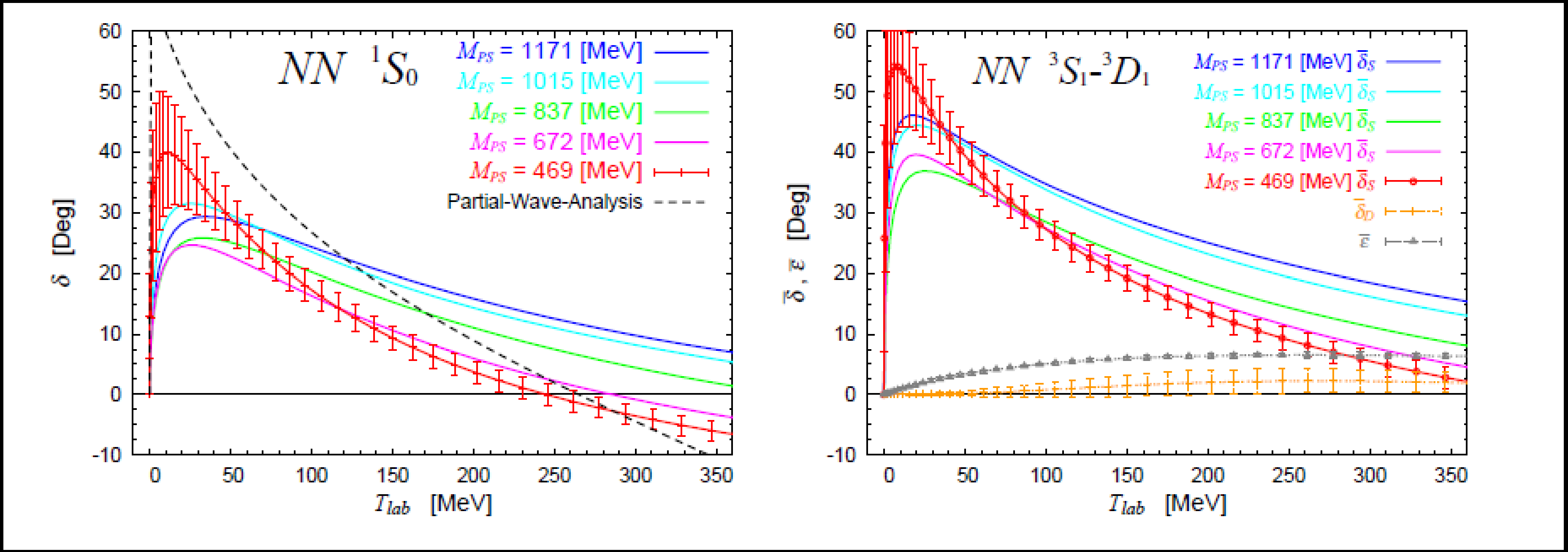
LO LO NLO NNLO



NN
Central & Tensor Forces
in 3-flavor QCD

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

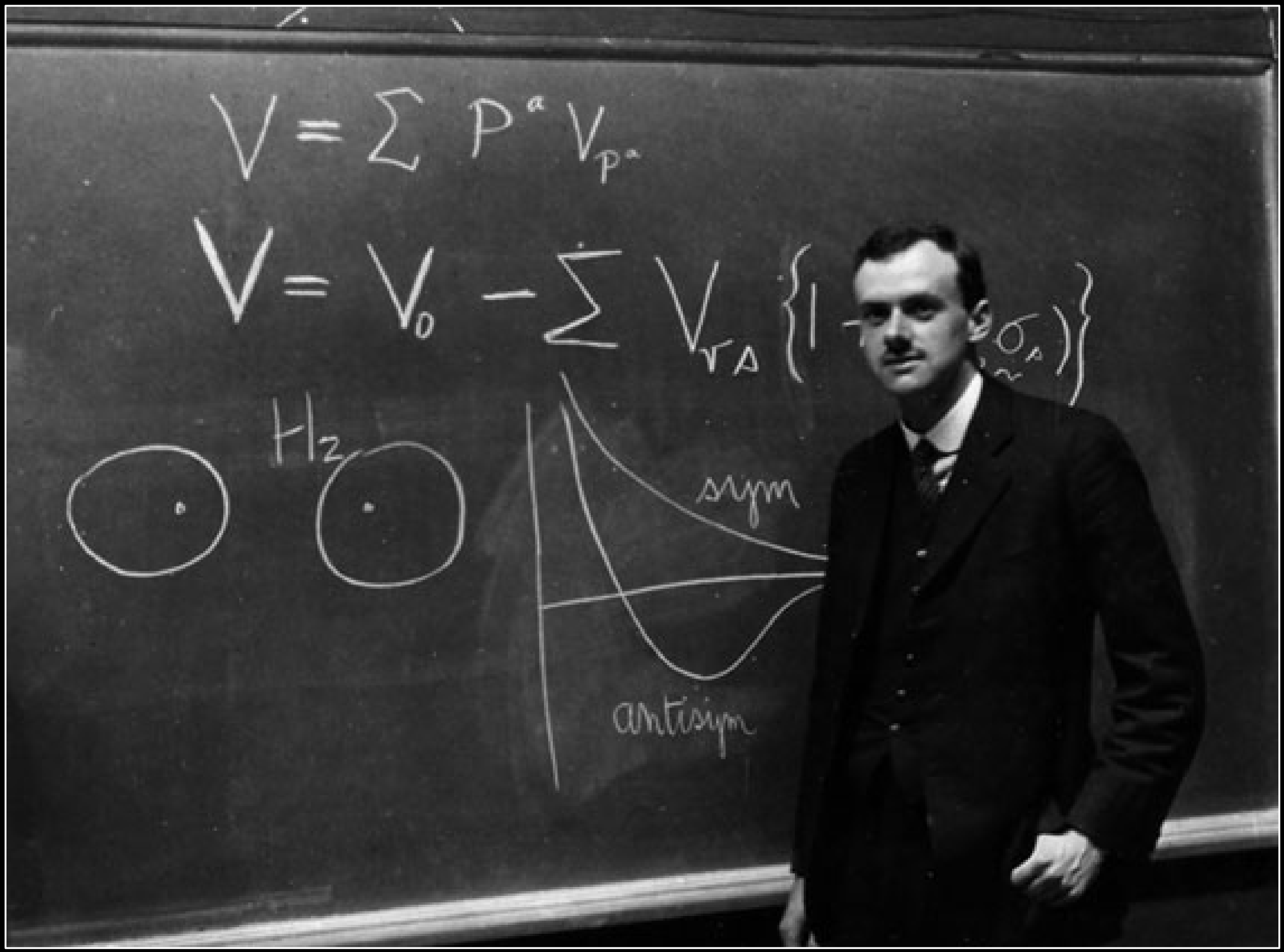
NN phase shifts in 3-flavor QCD



Stronger attraction in the deuteron channel

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

Symmetry Matters

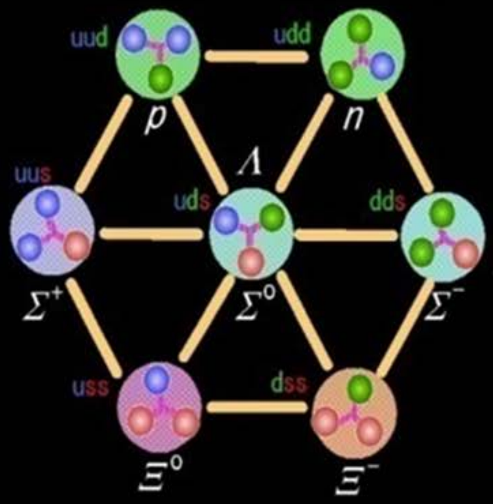


Heisenberg (1926), Dirac (1926)
Heitler-London (1927)

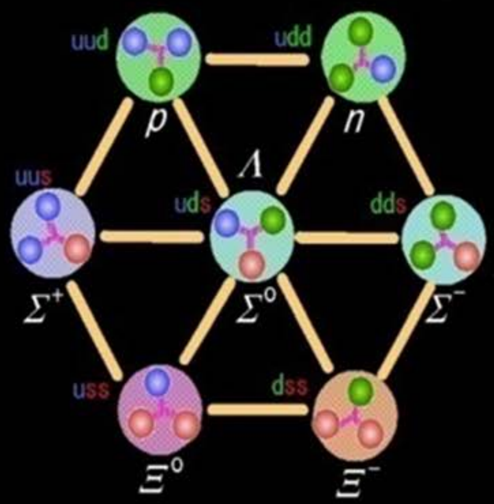
BB potentials in 3-flavor QCD

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

⇒ Baryon-baryon force in flavor SU(3)



X



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

Six independent potentials in the flavor-basis

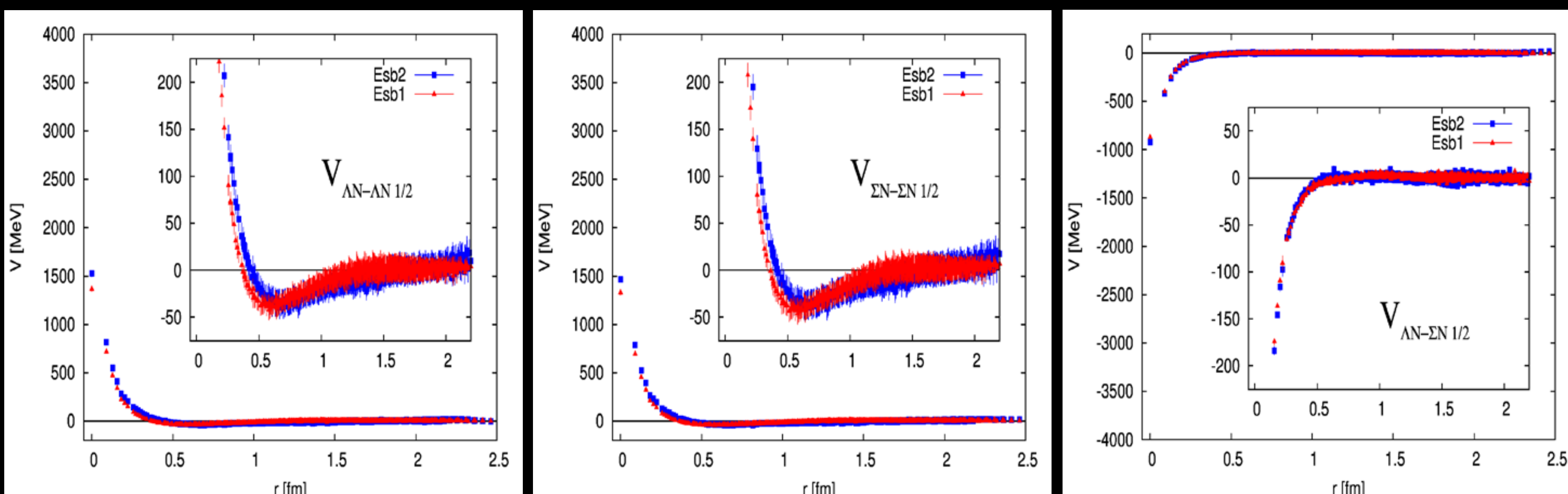
SU(3) breaking: coupled channel LQCD

Sasaki et al.
[HAL QCD Coll.] (2012)

$$\left(k_n^2 + \nabla^2\right) \phi_n^{\alpha}(\vec{r}, t) = \int U(\vec{r}, \vec{r}')^{\alpha\beta} \phi_n^{\beta}(\vec{r}', t) d^3 r'$$

Example: S=-1, $^3S_1$, I=1/2 (m_π/m_K=0.89, 0.8)

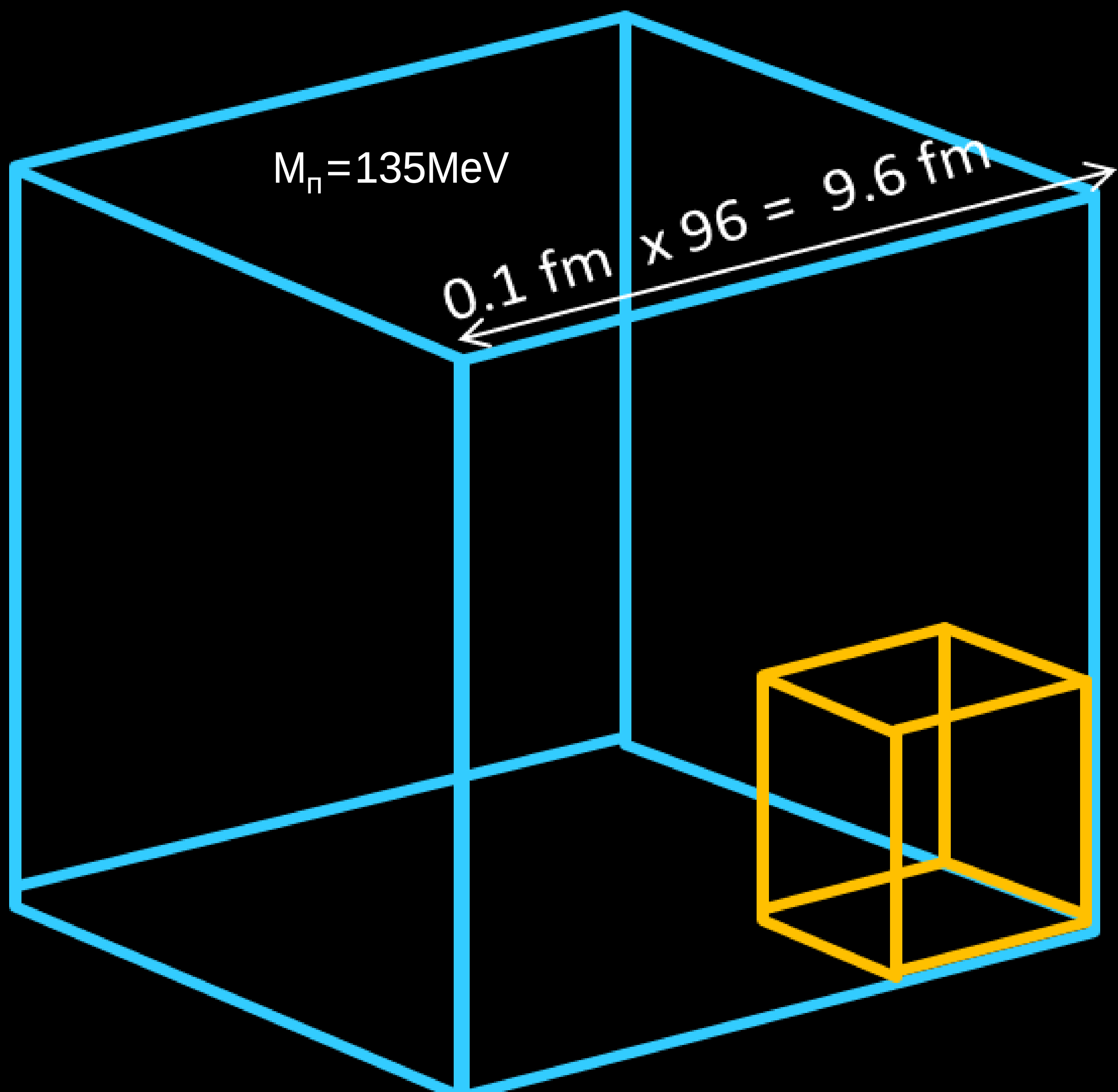
ΛN-ΛN ΣN-ΣN ΛN-ΣN

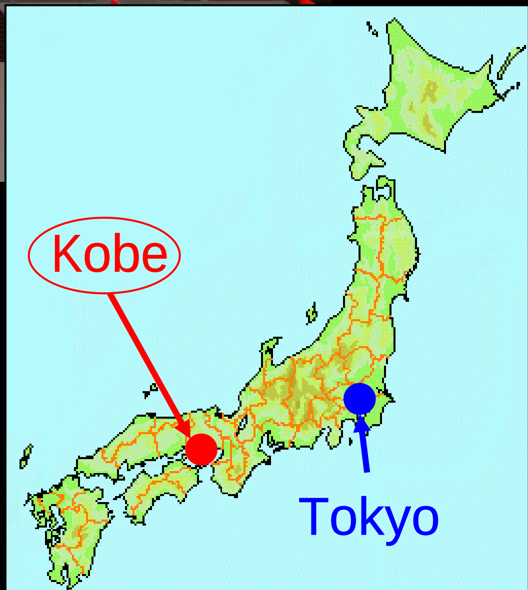


PACS-CS (2+1)-flavor config.
L=2.9 fm

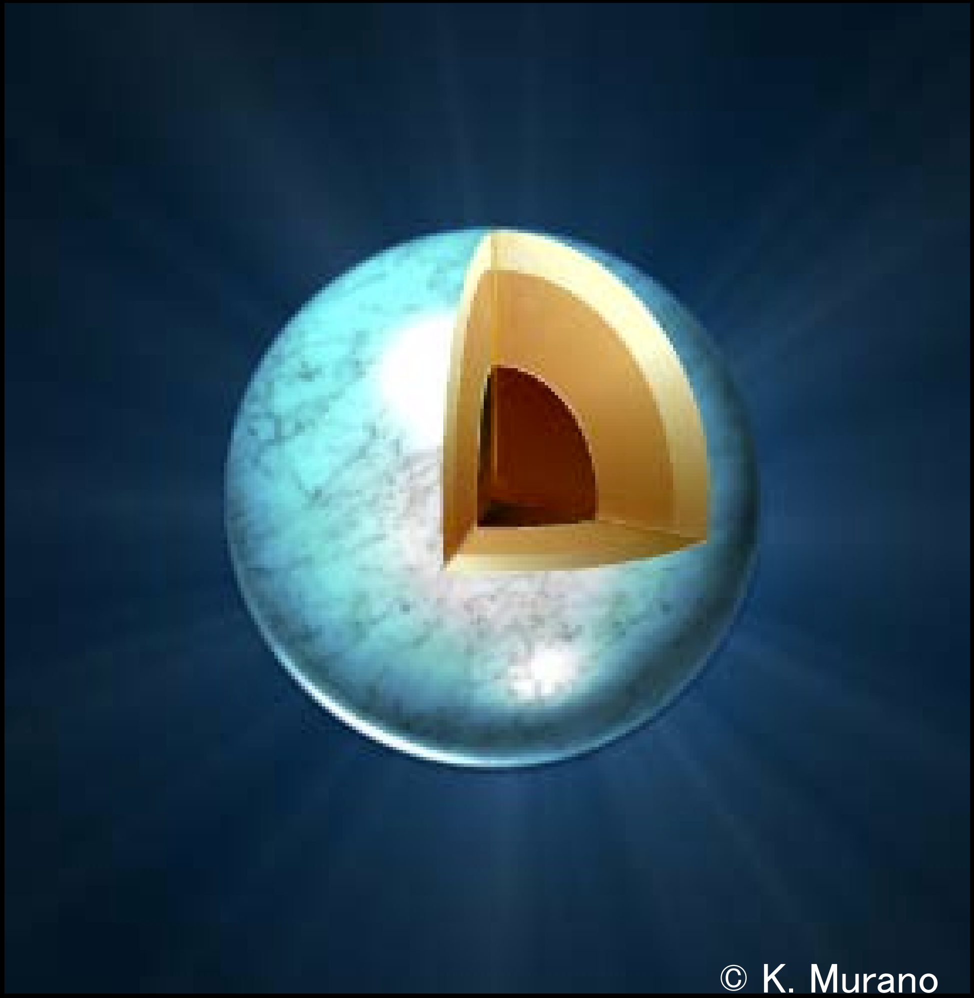
K computer @ RIKEN

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





From Quarks to Cosmos

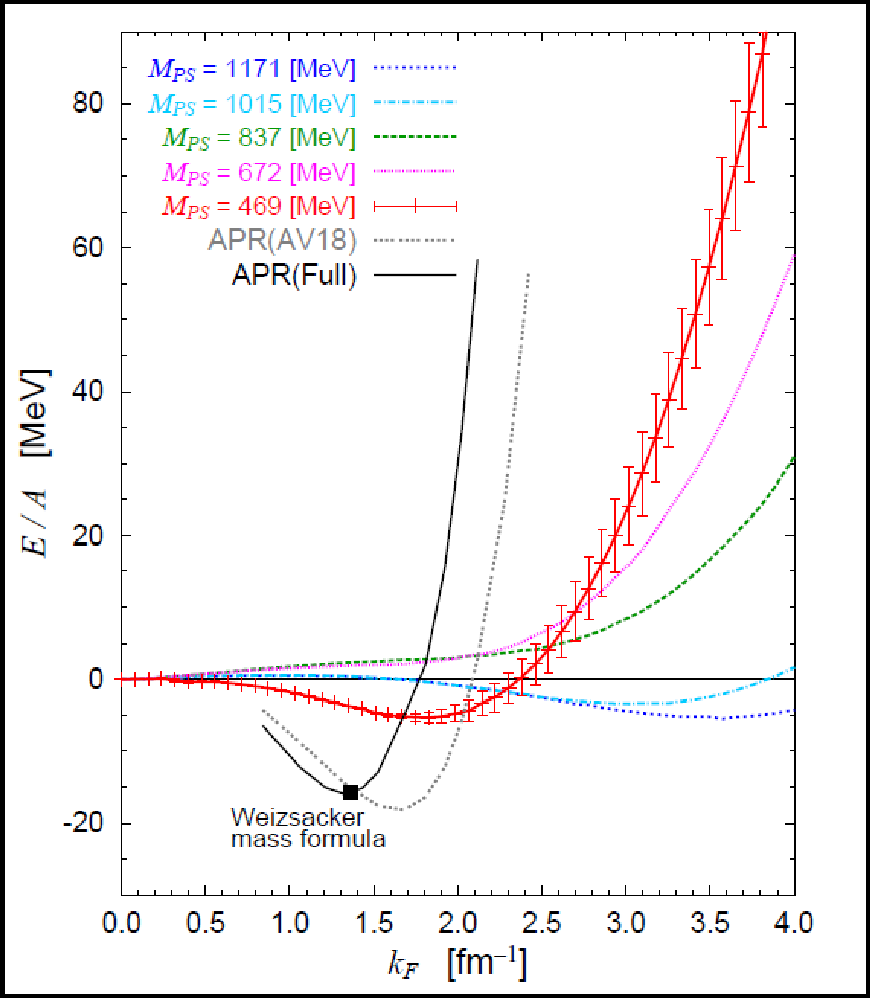


Nuclear EOS from Lattice NN force + BHF calculation

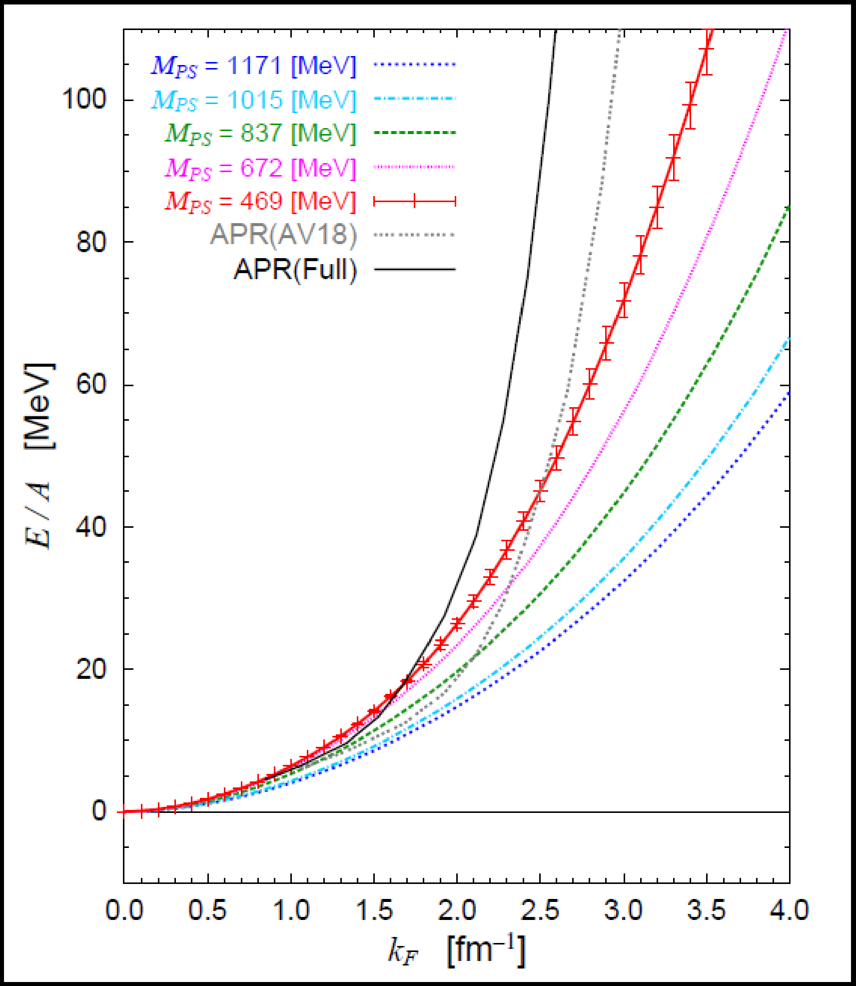
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

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

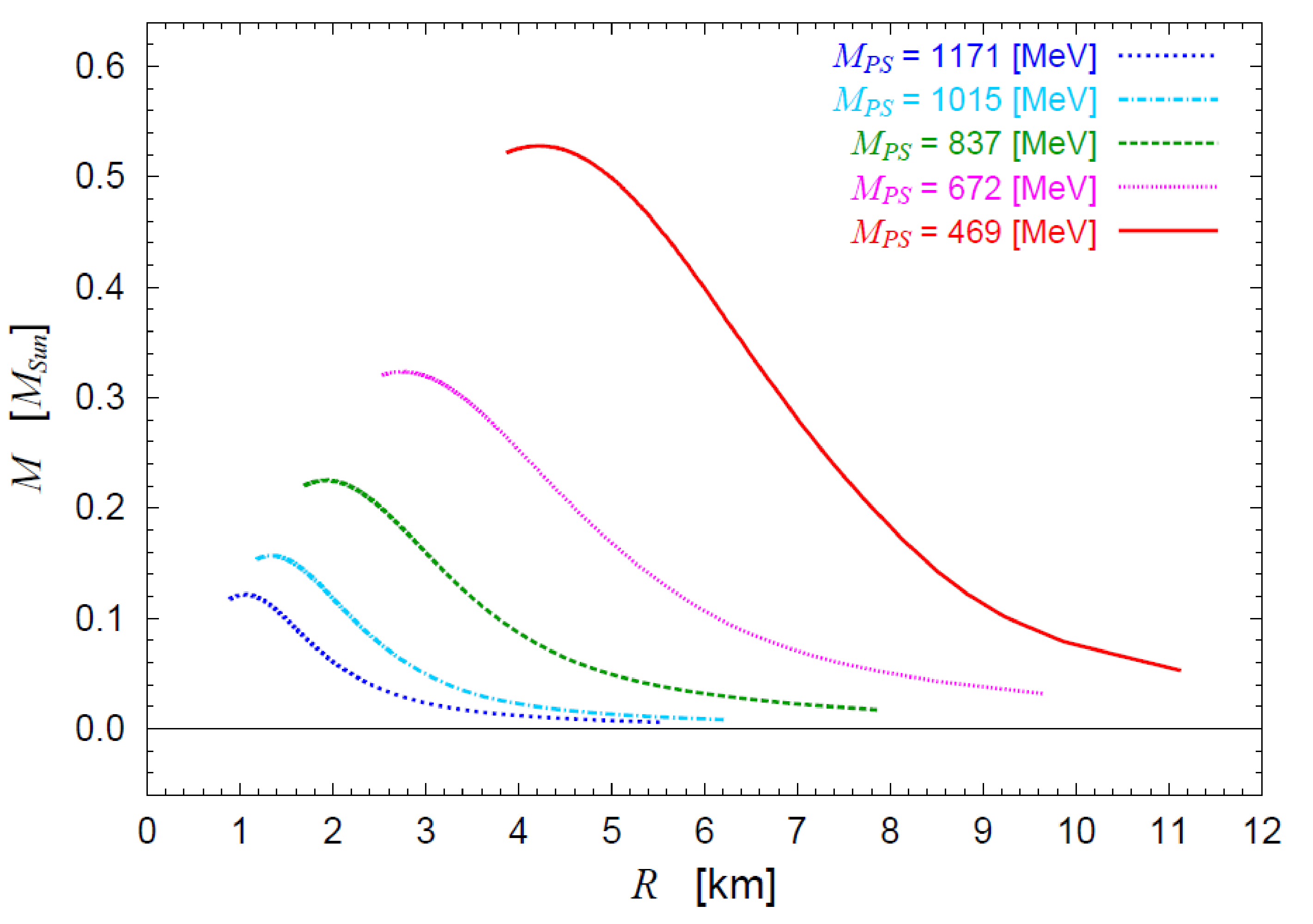
Nuclear Matter



Neutron Matter

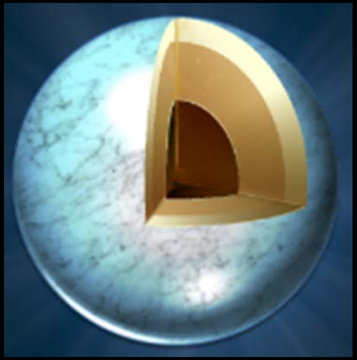


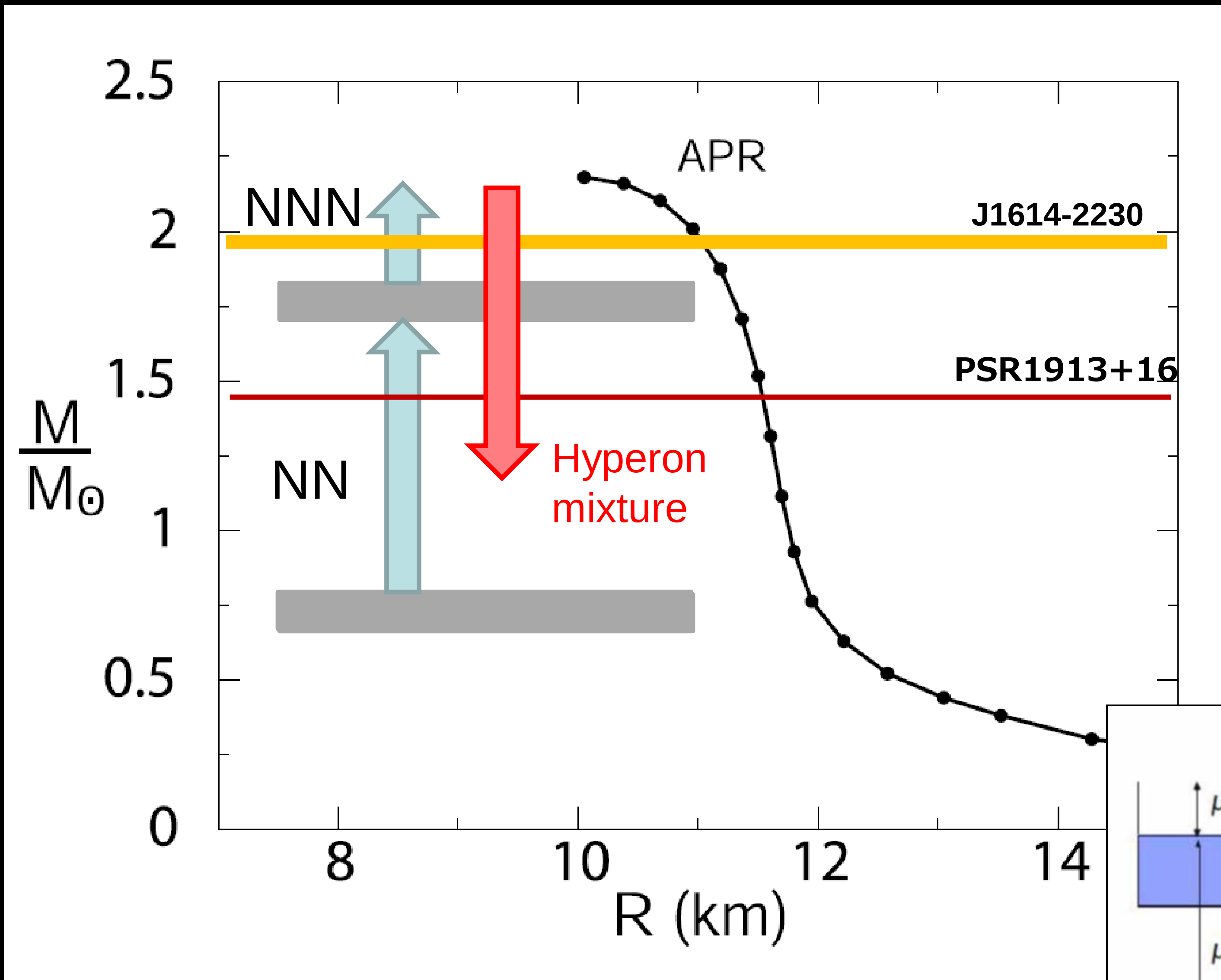
Neutron Star from “Lattice EOS”

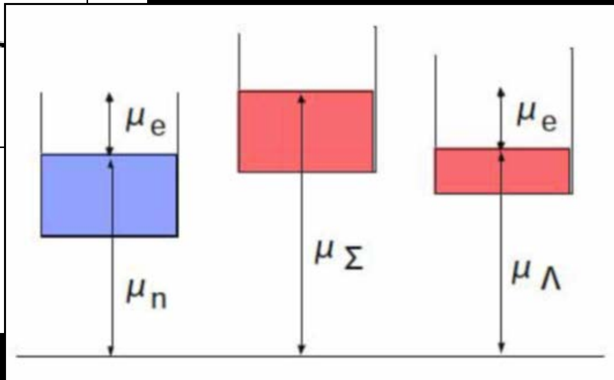


HAL QCD Coll.,
Phys. Rev. Lett. 111 (2013) 112503

Hyperon Crisis







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 ?

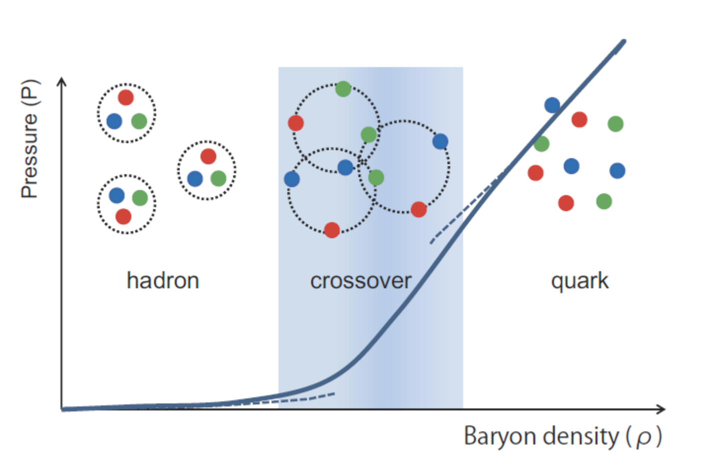
4. Crossover to quark matter ?

Hatsuda, Tachibana, Yamamoto & Baym, PRL 97 (2006) 122001

$2M_\odot$ neutrons stars require,

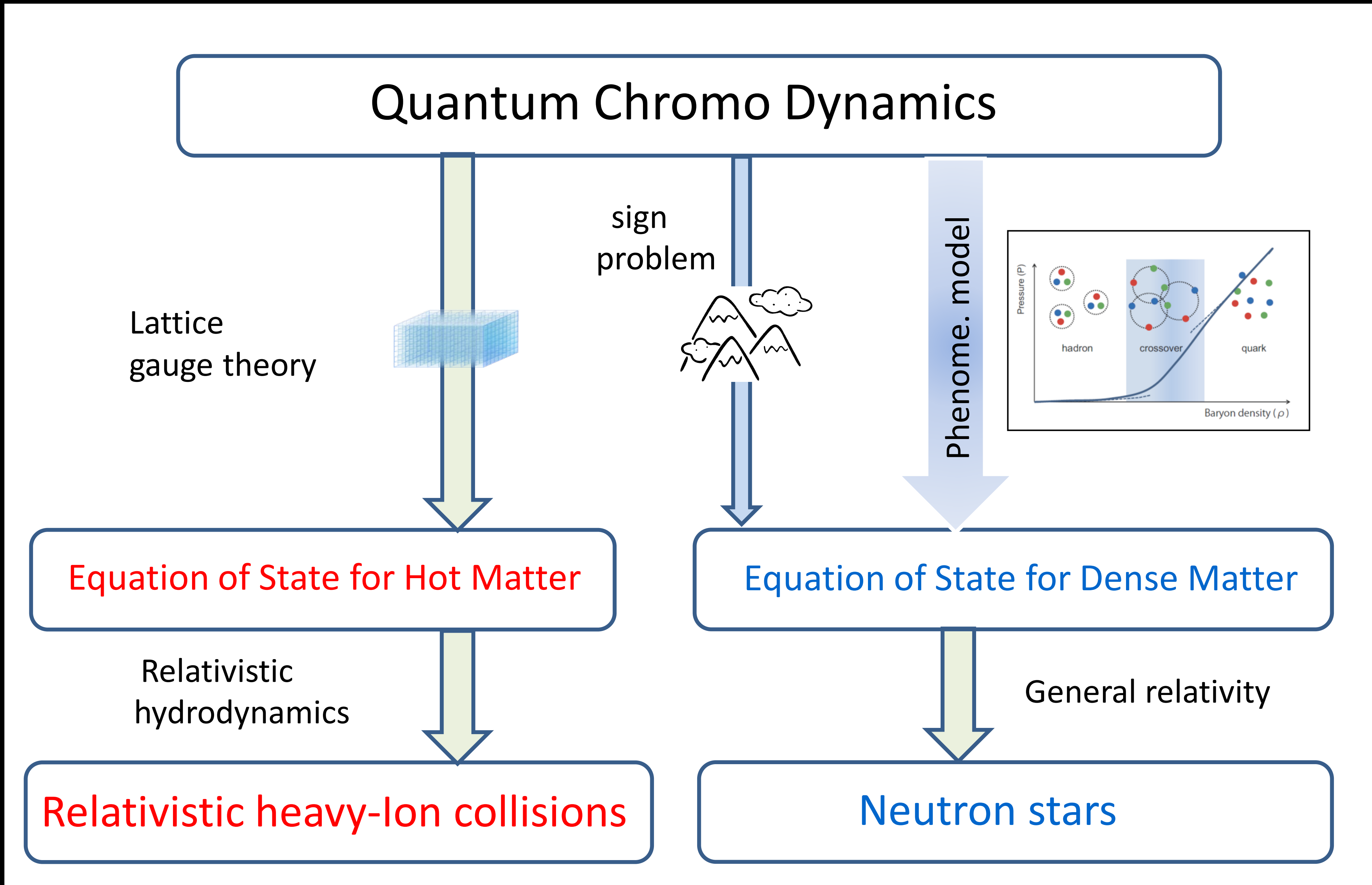
- STIFF quark-matter EOS
- Smooth crossover (no 1st order transition)
- Crossover at $\rho=(2\text{-}4)\,\rho_0$

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

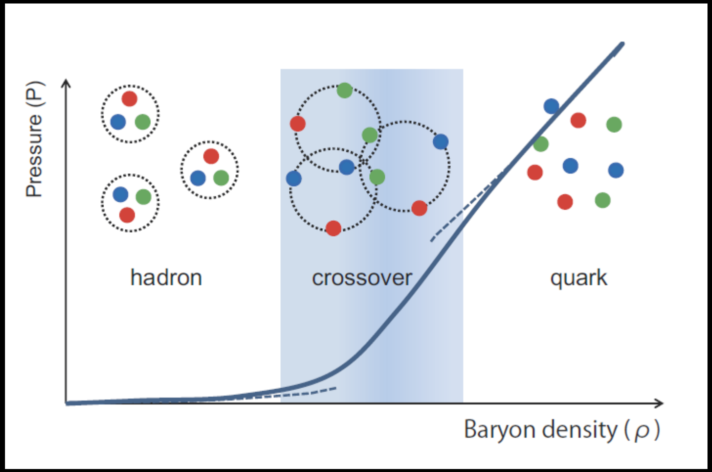


Masuda, Hatsuda & Takatsuka, Astrophysical Journal Letters 764 (2013) 12

From QCD to Hot/Dense Matter

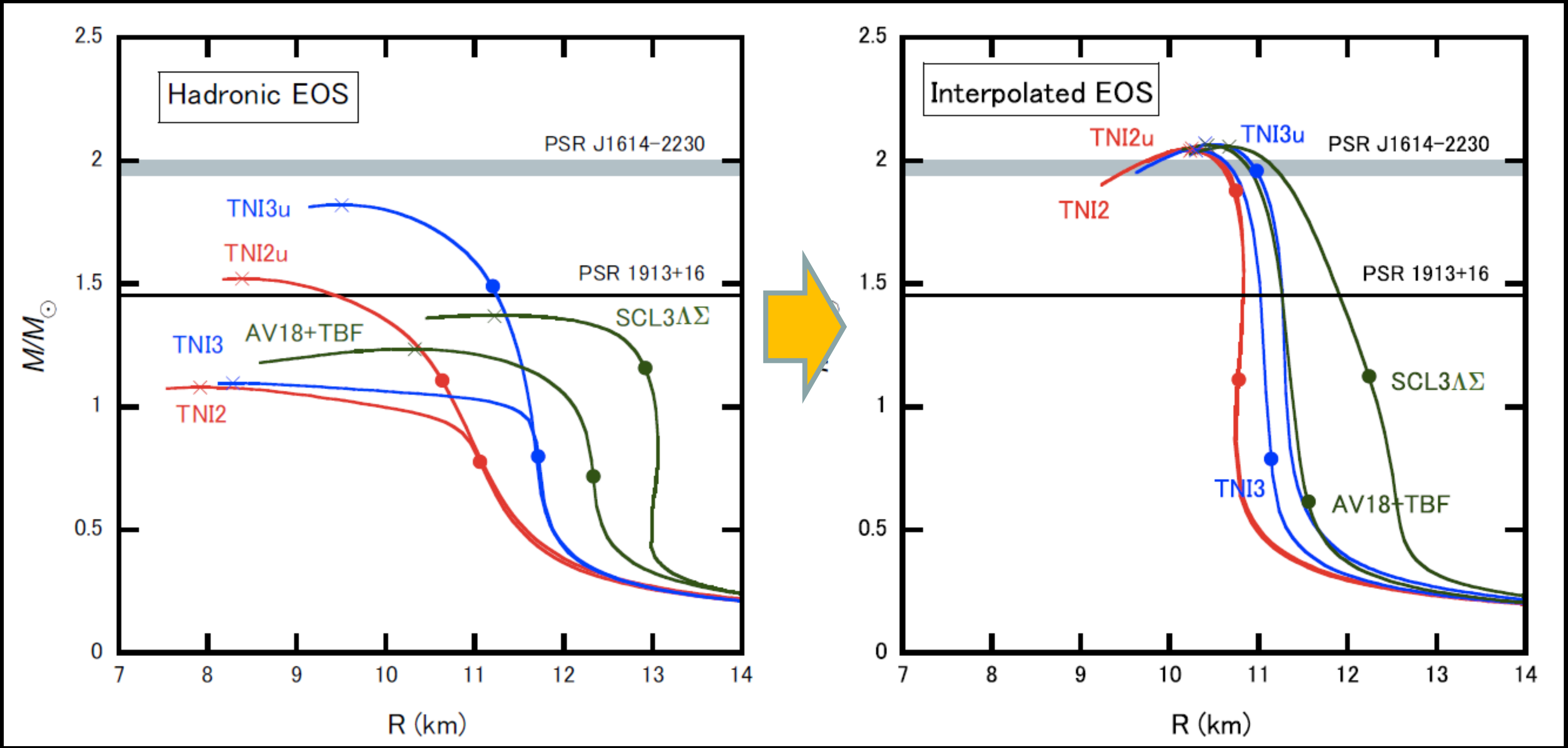


Crossover from Soft Hyperon Core to Stiff Quark Core



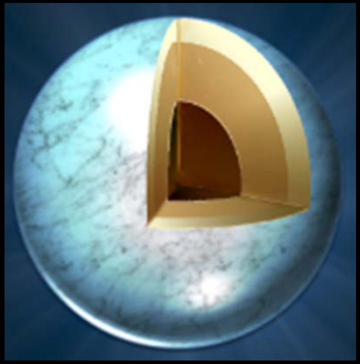
Hatsuda, Tachibana, Yamamoto & Baym, Phys. Rev. Lett. 97, 122001 (2006)

Bratovic, Hatsuda & Weise, PLB 719, 131 (2013)



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

Summary



1. Dense QCD is a real challenge

theory:

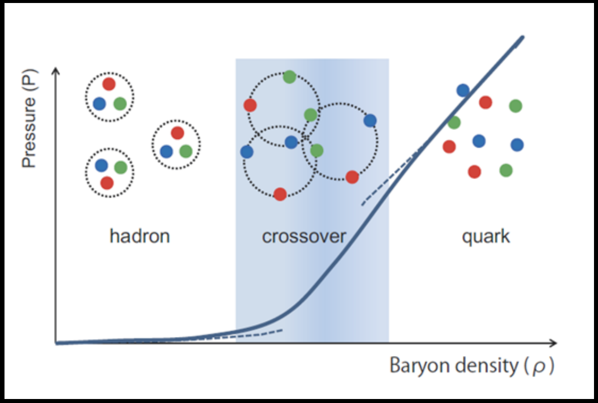
- BB and BBB forces from lattice QCD (HAL QCD Coll.)
  -- physical point results with L~10 fm will come soon.
- sign problem unsolved

obs.:

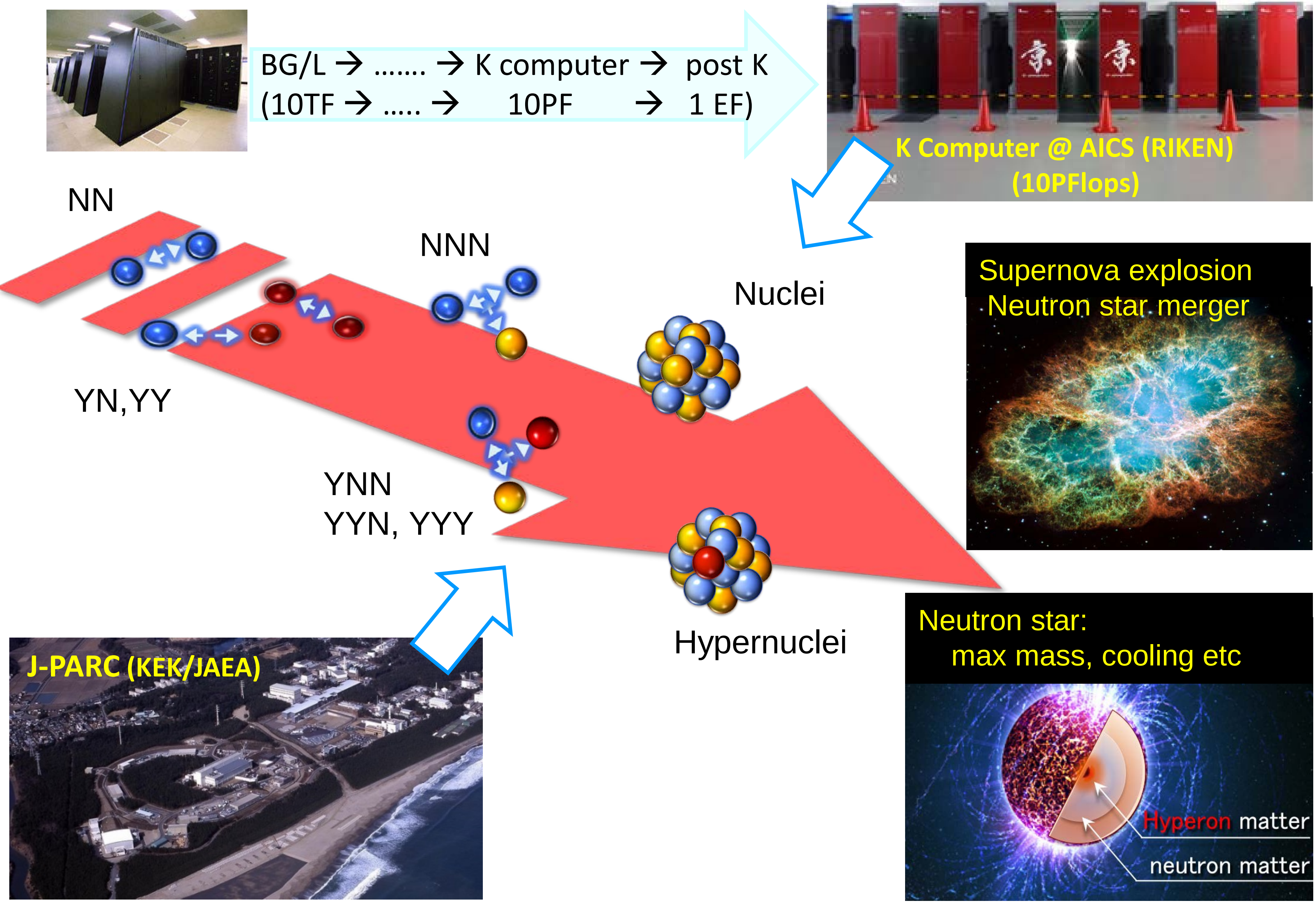
- progresses in M, R, T, B measurements
  -- $2M_\odot$ NStars, Magnetars, CAS-A cooling, X-ray bursts
- Gravitational wave detections will be ready soon

2. Hyperon Crisis

- no convincing resolution yet
  -- higher body hyperon force ?
  -- crossover to stiff quark matter
  → may be studied by HIC ?



HAL QCD Strategy : From QCD to Compact stars



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