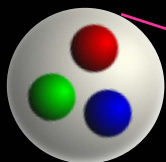
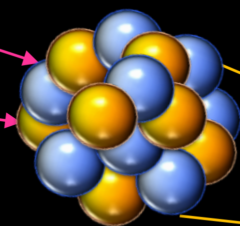
From Quarks to Neutron Stars

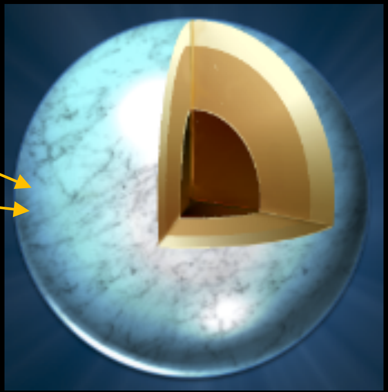
nucleon ~1 [fm]



nucleus ~10 [fm]



Neutron star ~10 [km]



G. Baym

"Compact stars and gravitational waves"
at YITP (Nov. 2, 2016)
Tetsuo Hatsuda (RIKEN iTHEMS)

iTHEMS

Outline

1. Nuclear phase diagram

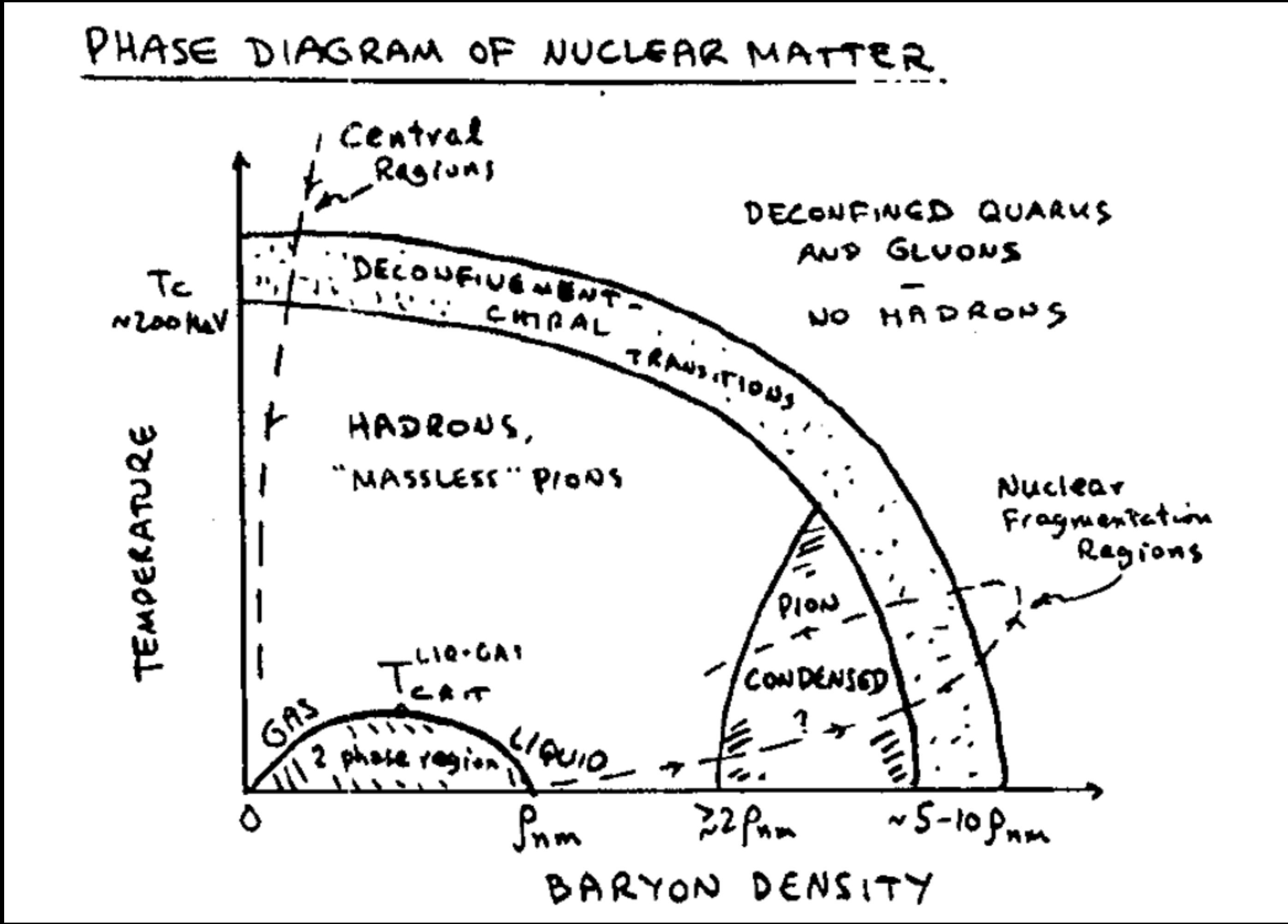
2. Hyperon puzzle

3. Baryon interactions from lattice QCD

4. Quark matter inside neutron stars ?

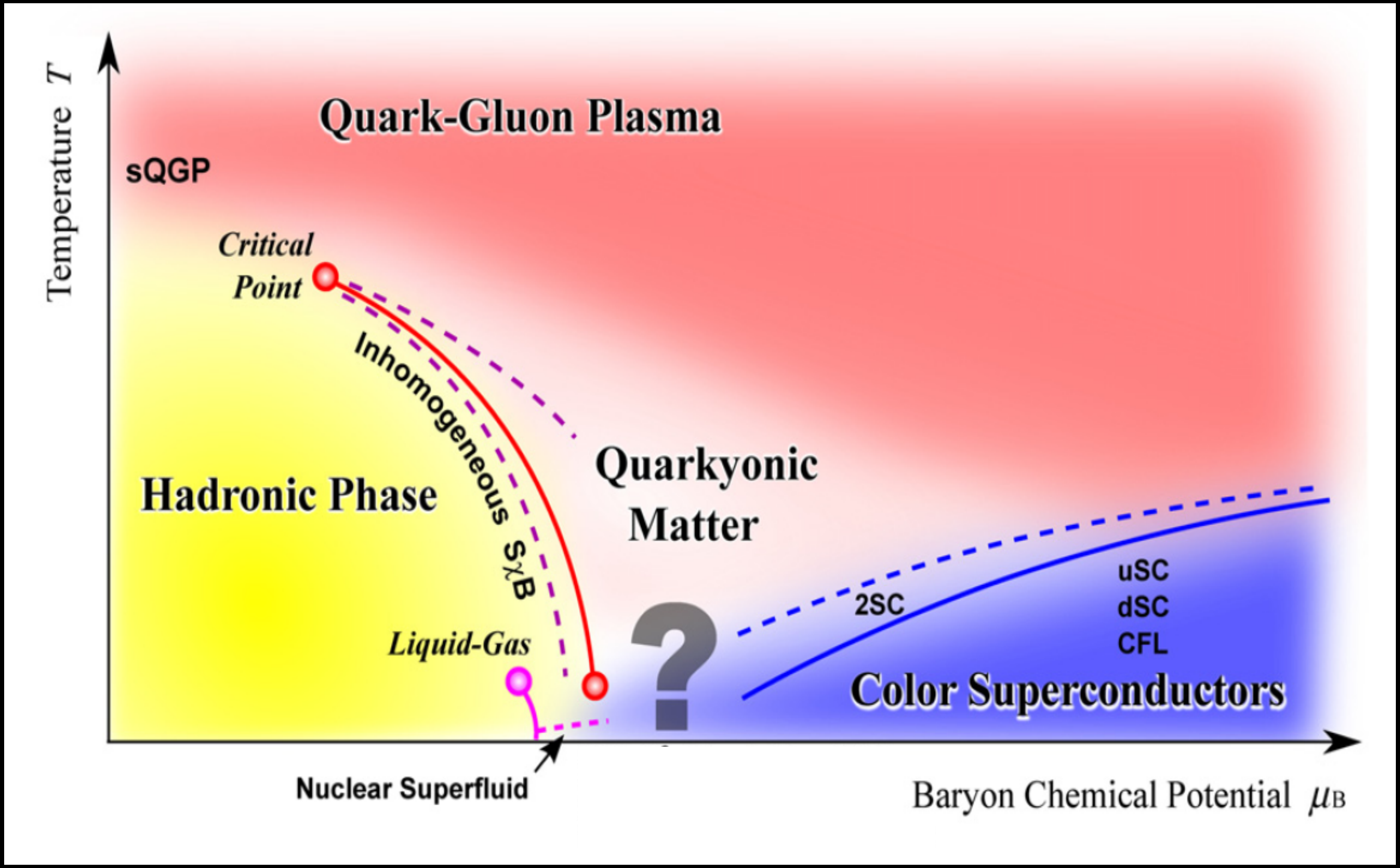
5. Summary

Nuclear Phase Diagram *(1983)*



G. Baym (1983)

Nuclear Phase Diagram (2016)



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

Quantum Chromo Dynamics

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

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

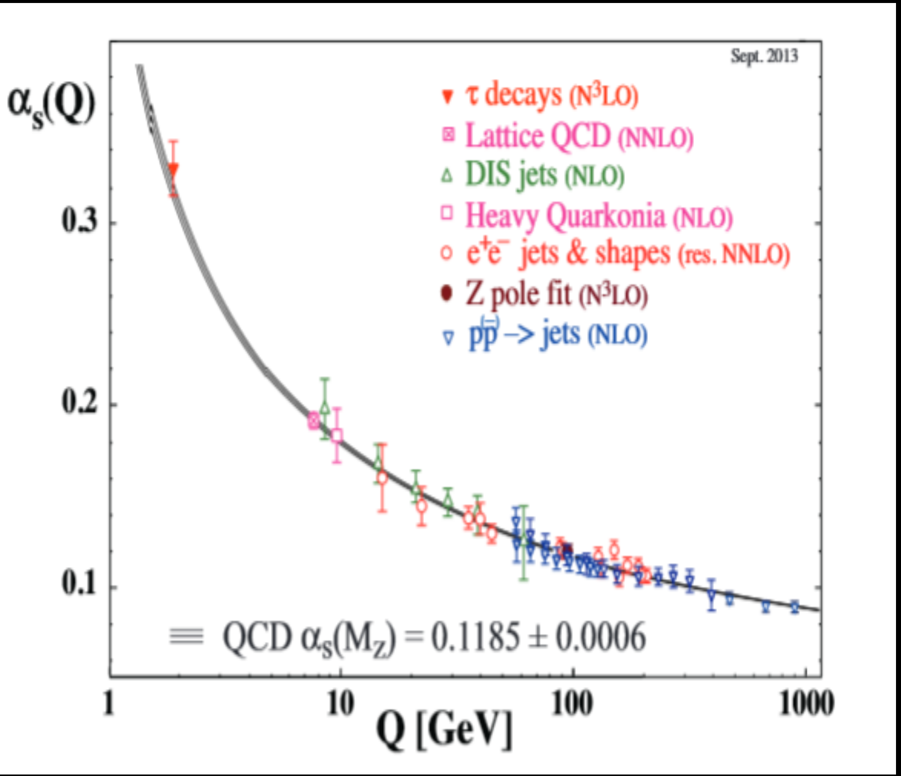
ALL the QCD parameters are fixed in "high" precision

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 (1.5)(1.9)

FLAG Coll.(2015) http://itpwiki.unibe.ch/flag/

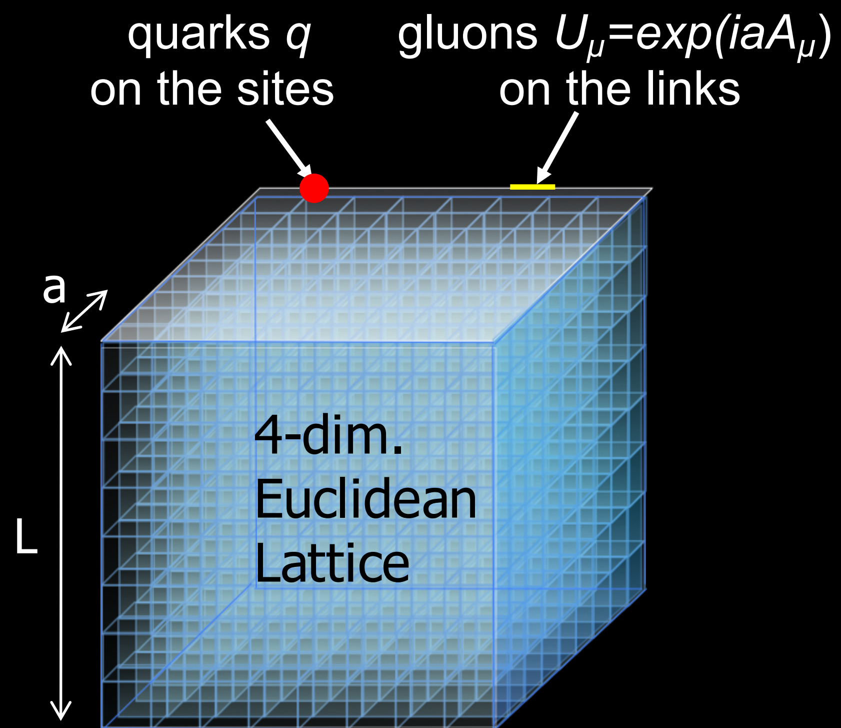
Running coupling: $\alpha_s(Q)=g^2/4\pi$

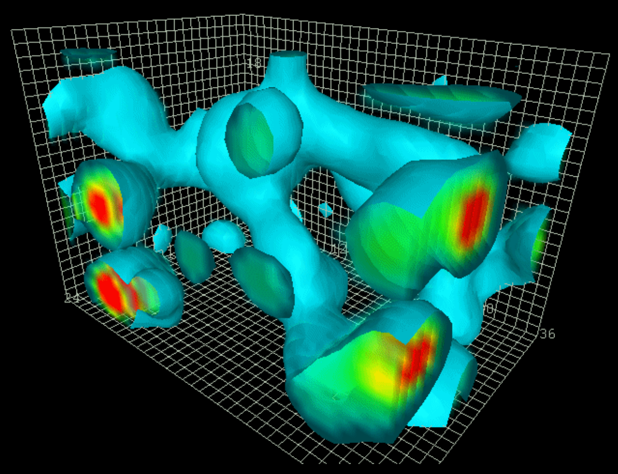


PDG (2014) http://pdg.lbl.gov/

Lattice QCD

$$Z = \int [dU][dqd\bar{q}] \;\; \exp\left[-\int d\tau d^3x \mathcal{L}_\mathrm{E}\right]$$

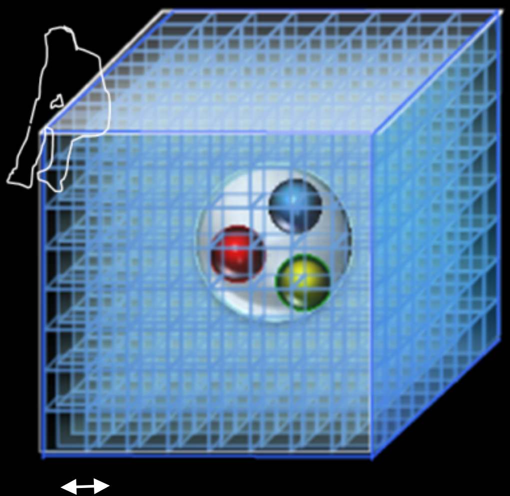




10^7 - 10^9 dimensional integral
→ Monte Carlo integration

LQCD for single hadron without QED (2010)

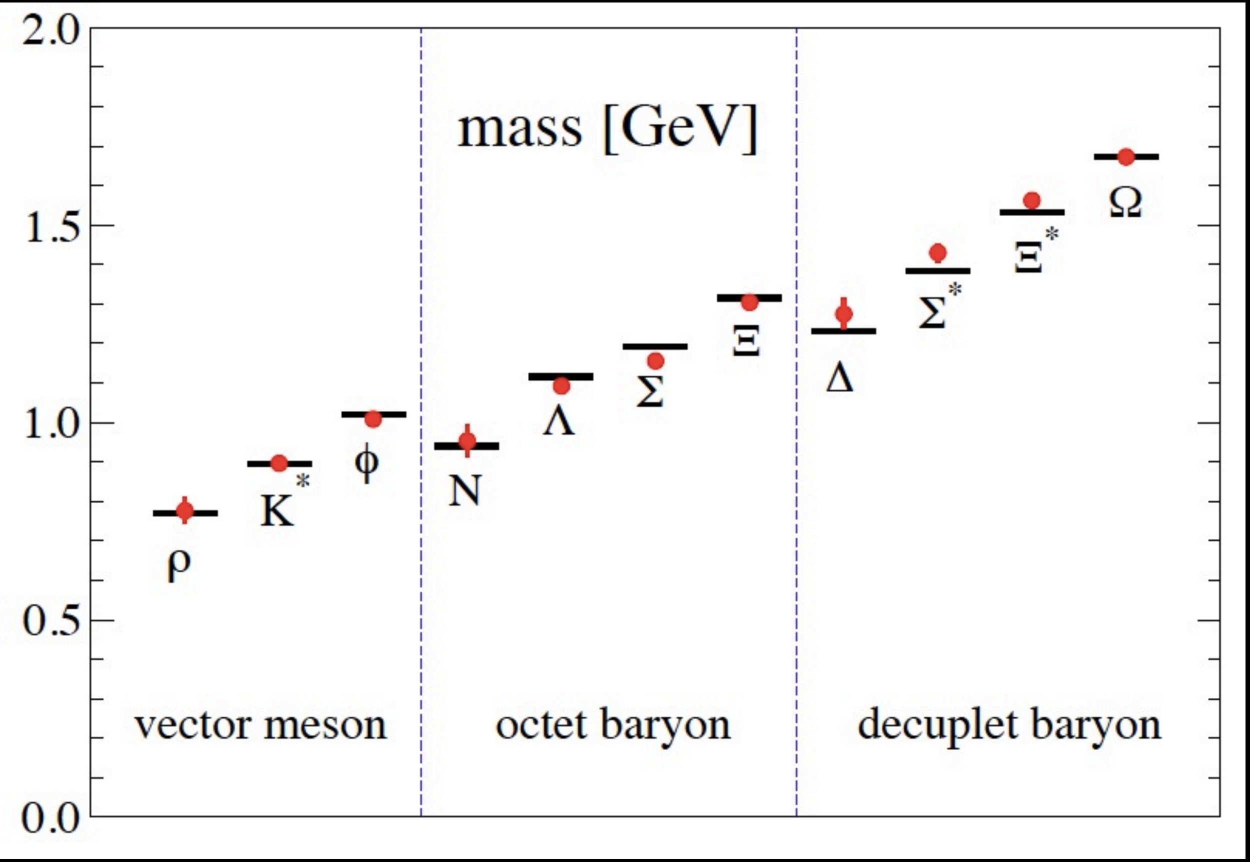
PACS-CS Coll. Phys.Rev. D81 (2010) 074503



a_{min} = 0.09 fm

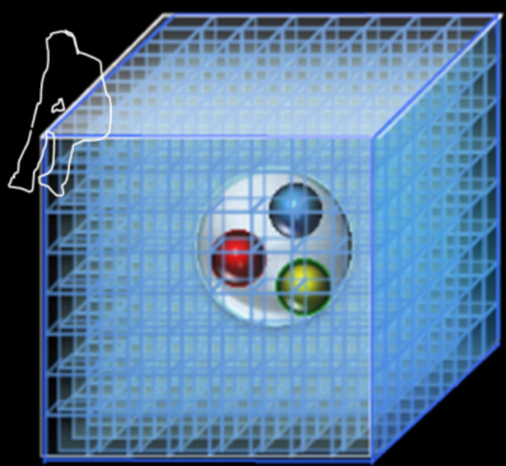
L_{max} = 2.9 fm

M_π > 150 MeV



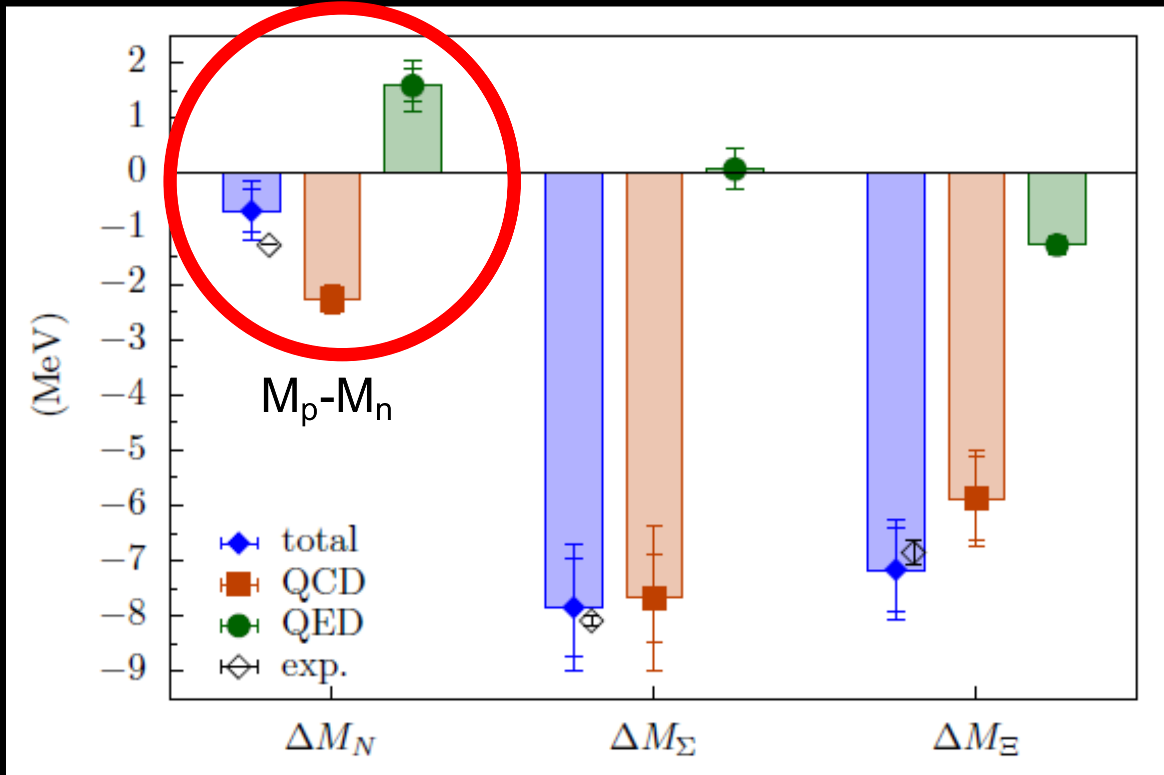
LQCD for single hadron with QED (2013)

BMW Coll.: Phys.Rev.Lett. 111 (2013) 252001



a_{min} = 0.054 fm

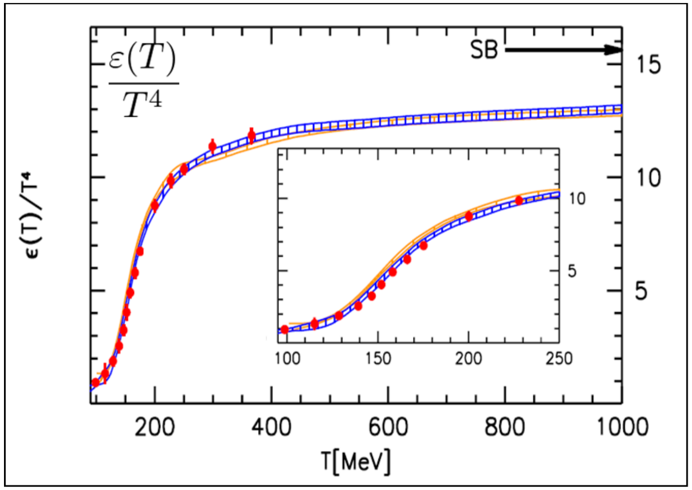
L_{max} = 6 fm



From QCD to Hot Matter

Quantum Chromo Dynamics

Lattice QCD
Z(T)

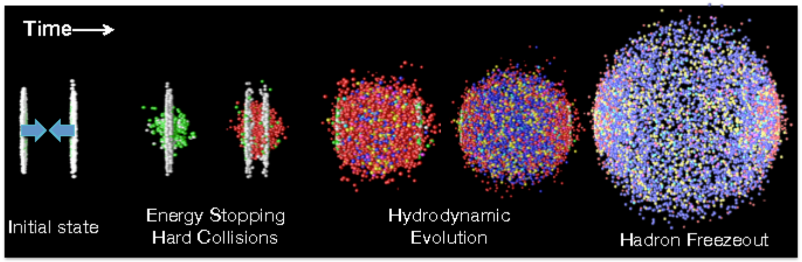


Wuppertal-Budapest Coll. JHEP 1011 (2010) 77

Equation of State for Hot Matter

Relativistic
hydrodynamics

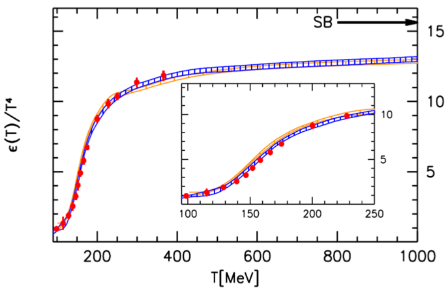
Relativistic heavy-Ion collisions

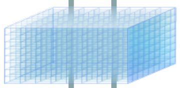


From QCD to Dense Matter

Quantum Chromo Dynamics

Lattice QCD





Lattice QCD ?

Equation of State for Hot Matter

Equation of State for Dense Matter

Relativistic hydrodynamics

General relativity

Relativistic heavy-Ion collisions

Neutron stars

sign problem

Toy model:

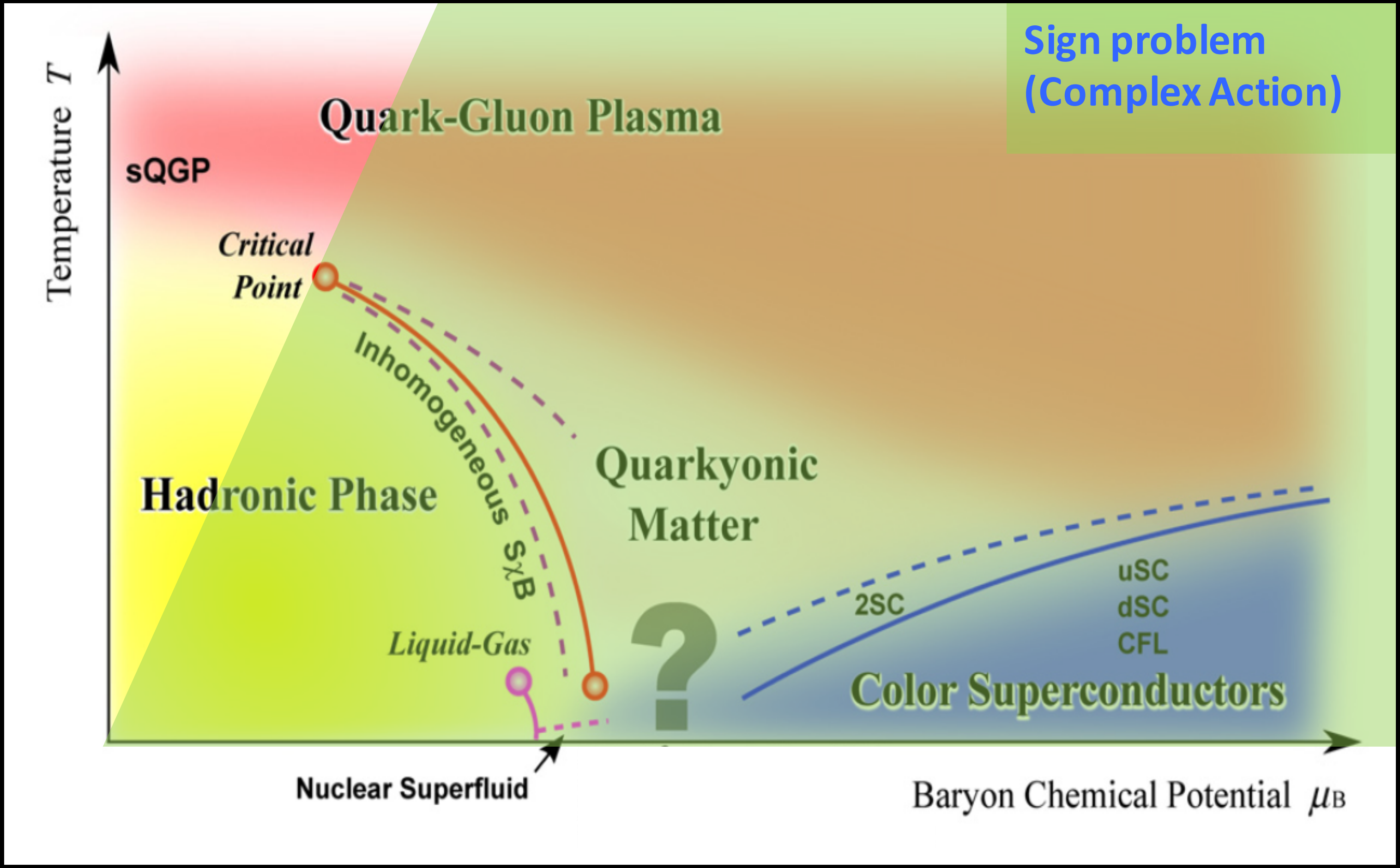
$$Z = \sum_{\{\phi(\mathbf{x})=\pm 1\}} \mathrm{sgn}(\phi)\ e^{-S(\phi)} \quad \Longleftrightarrow \quad \left(Z_0 = \sum_{\{\phi(\mathbf{x})=\pm 1\}} e^{-S(\phi)} \right)$$

QCD:

$$Z = \mathrm{Tr}\left[e^{-(H-\mu N)/T}\right] = \int [dA]\ \mathrm{Det}[\hat{D} + m + i\mu\gamma_4]\ e^{-S(A)}$$

Complex

Nuclear Phase Diagram (2016)

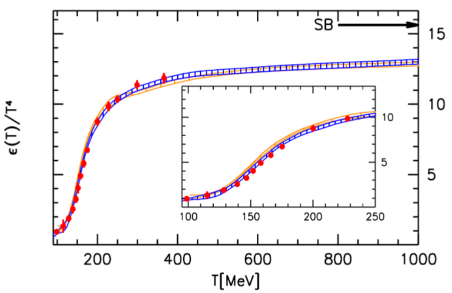


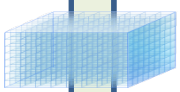
K. Fukushima and T. Hatsuda,
Rep. Prog. Phys. 74 (2011) 014001

From QCD to Dense Matter

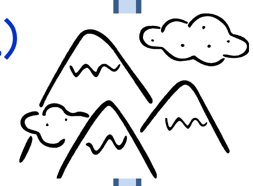
Quantum Chromo Dynamics

Lattice gauge simulations





sign problem
$Z(T,\mu)$



Phenomenological nuclear force

Baryon interactions

Many-body techniques

Equation of State for Hot Matter

Equation of State for Dense Matter

Relativistic hydrodynamics

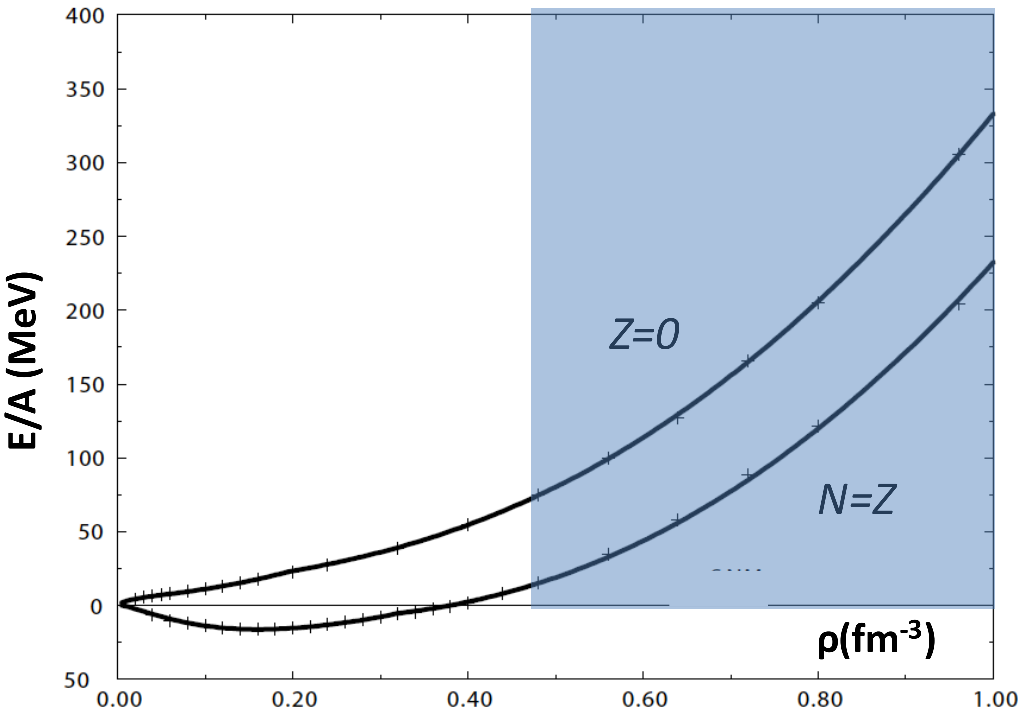
General relativity

Relativistic heavy-Ion collisions

Neutron stars

Phenomenological NN Force and dense EOS（nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)



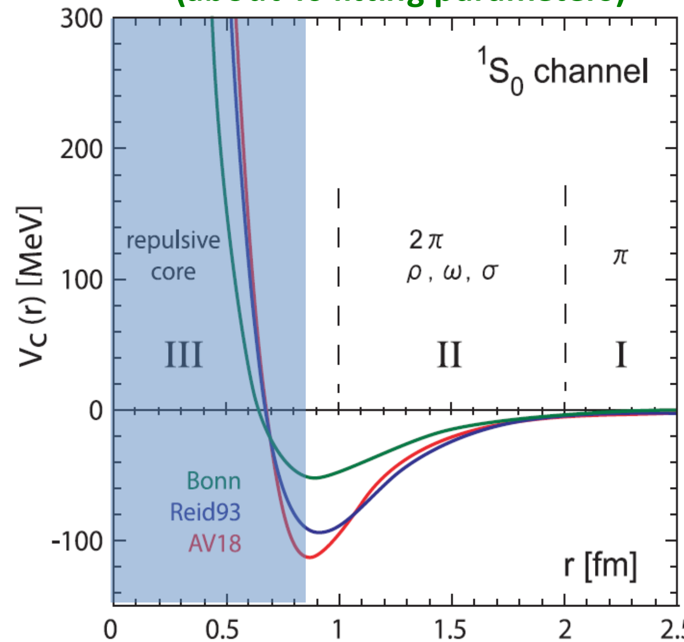
ρ_0

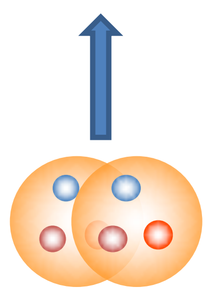
$= 0.16\ \mathrm{fm}^{-3}$

$3\rho_0$

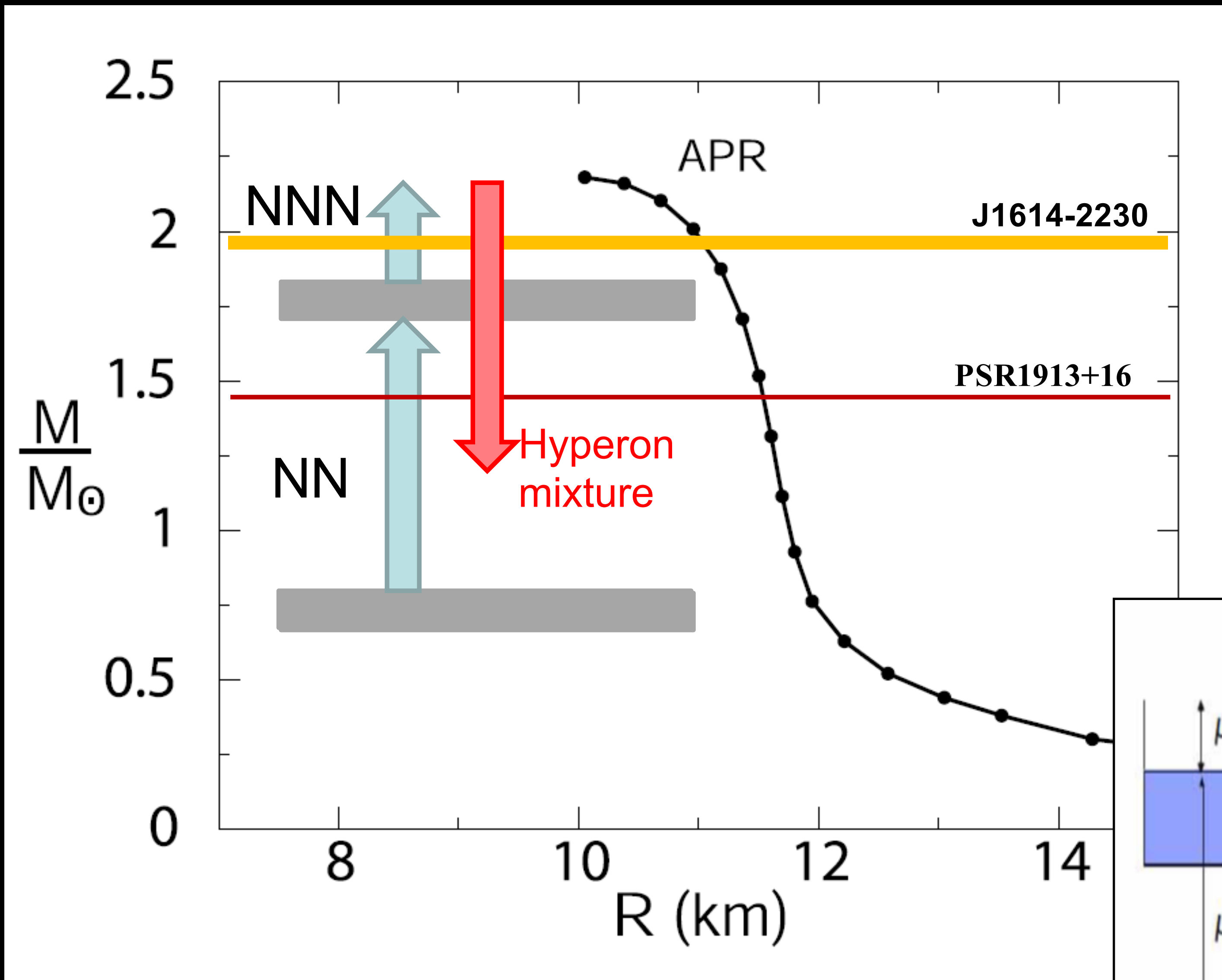
$5\rho_0$

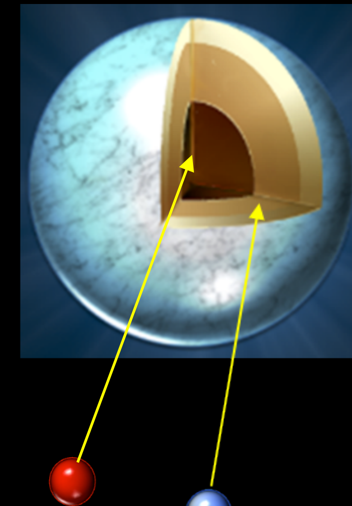
Phenomenological nuclear force (about 40 fitting parameters)

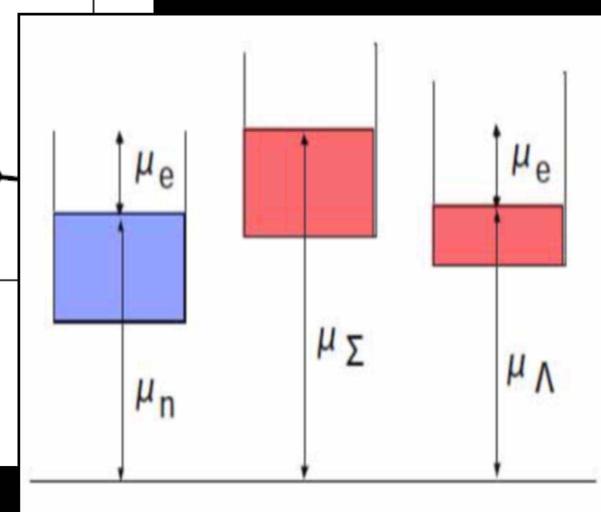




Hyperon Puzzle

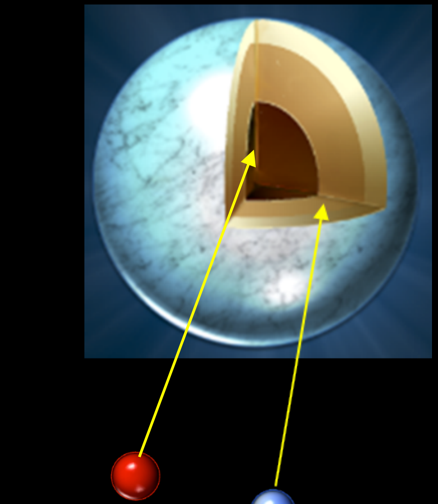


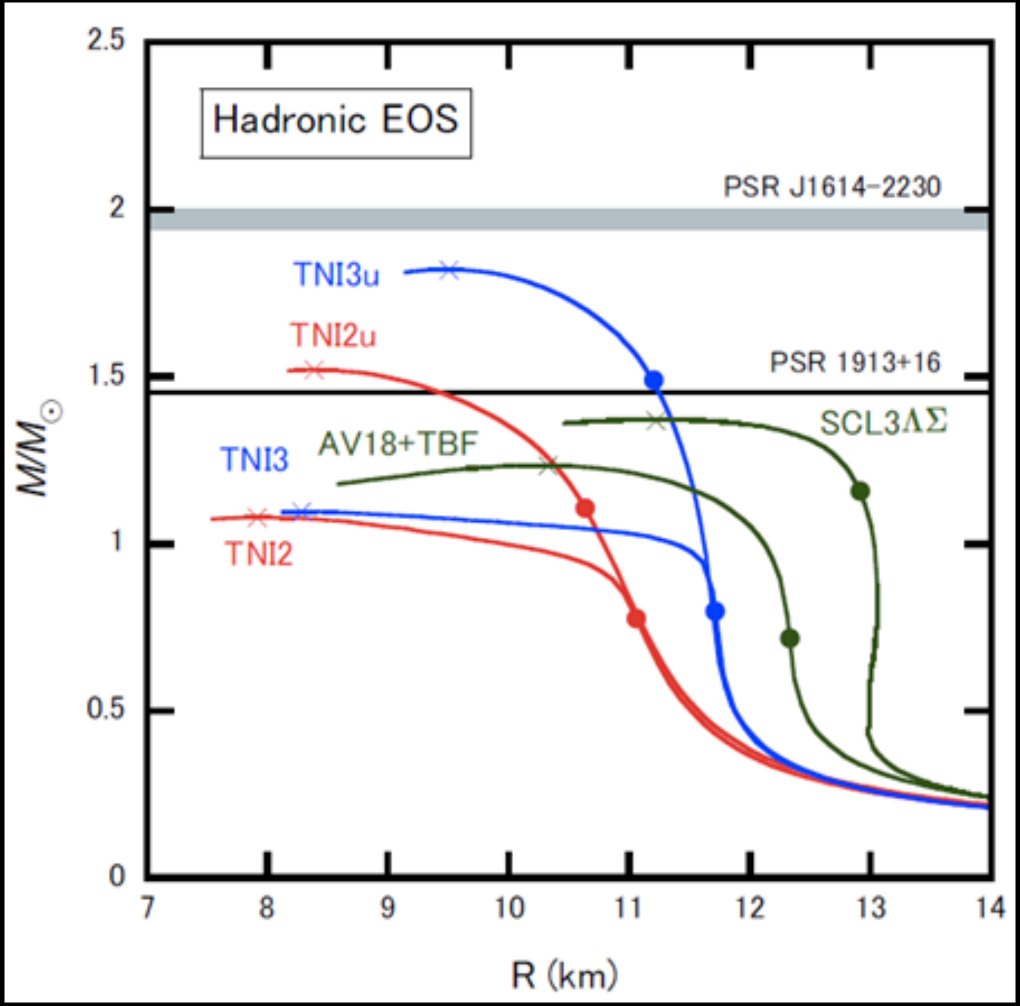




Hyperon Puzzle and YNN force

Nishizaki, Yamamoto & Takatsuka, PTP 105 (2001), PTP 108 (2002)





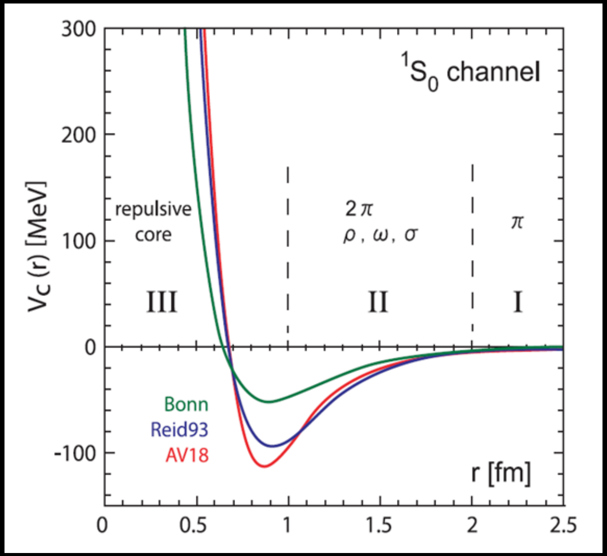
Masuda, Hatsuda & Takatsuka, ApJ Lett. 764 (2013) 12

Baryon interactions from QCD ?

- Phenomenological NN Force

  4500 np and pp scattering data (T_{lab} < 300 MeV)

  ⇔ 40 fitting parameters (AV18)



- Phenomenological YN and YY Forces

  Limited data from hyper nuclei

  ⇔ More than 100 fitting parameters

- Phenomenological NNN, YNN, YYN, YYY Forces

  Limited data from light nuclei

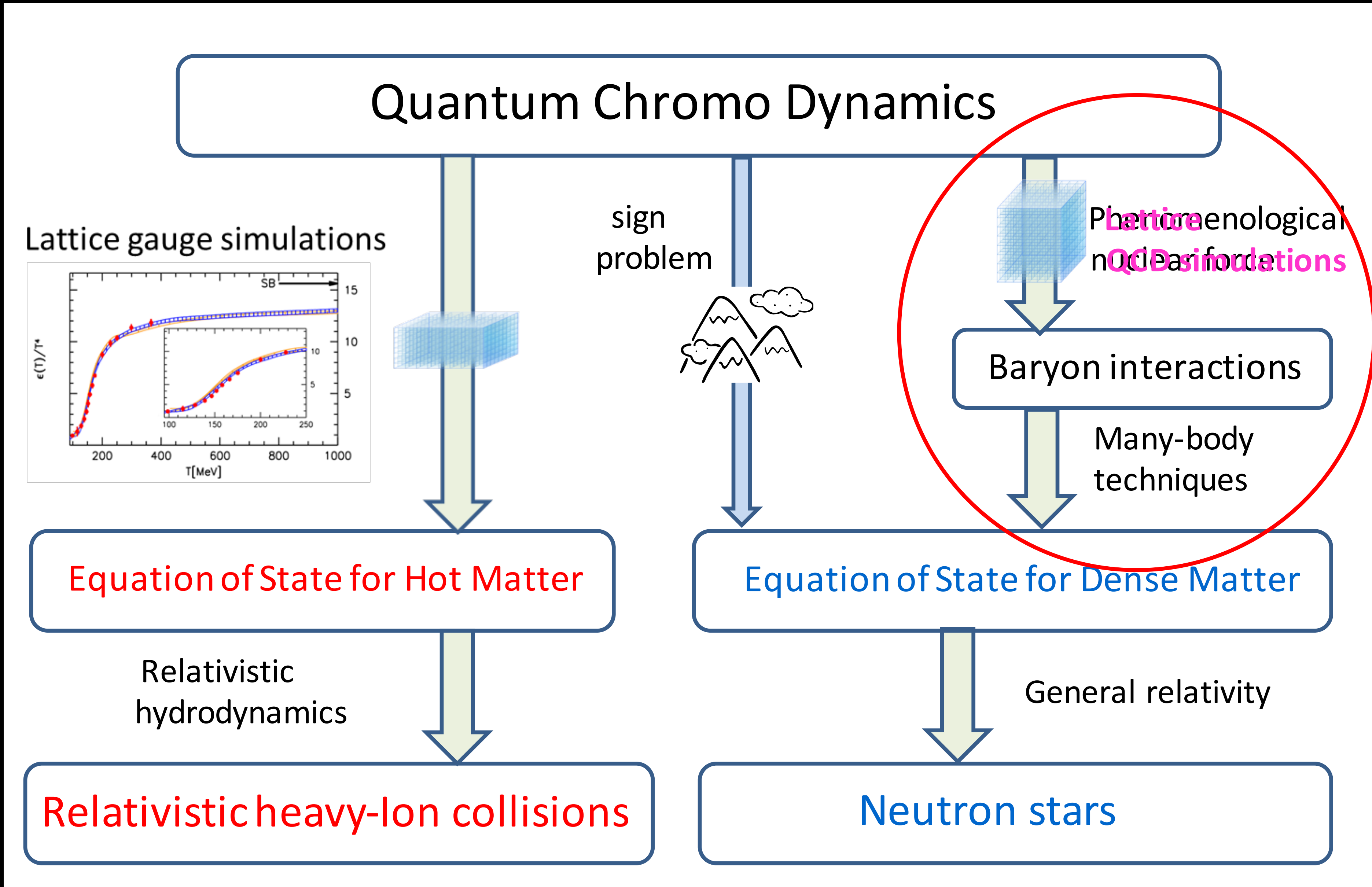
  ⇔ Many fitting parameters

QCD has only 4 parameters: g , $m_{u,d,s}$

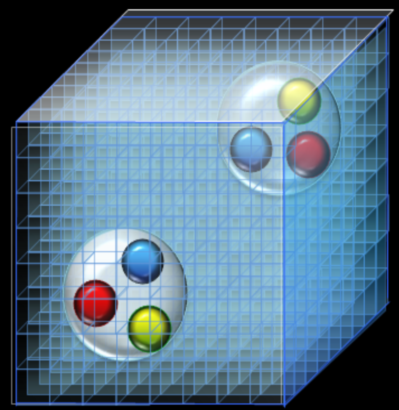
- Derivation of the nucleon and hyperon forces from QCD ?

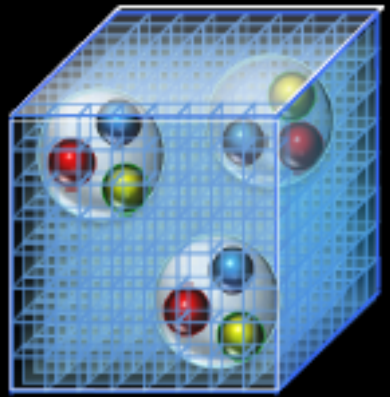
- Prediction of 3-body forces from QCD?

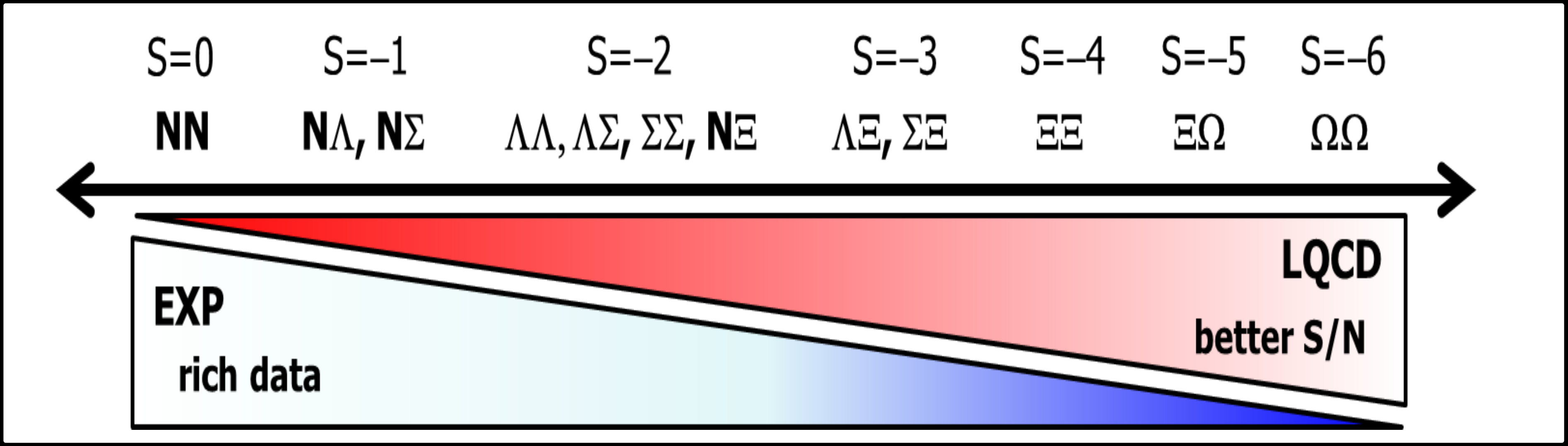
From QCD to Dense Matter



Baryon Forces from LQCD



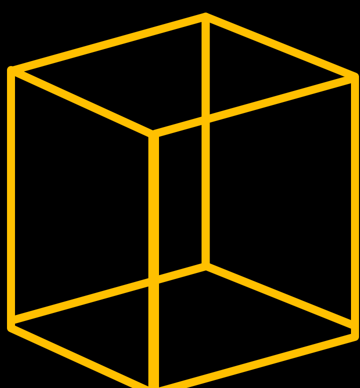




→ More by S. Aoki (Fri.)

-2014

T2K Tsukuba (0.1 PFlops)

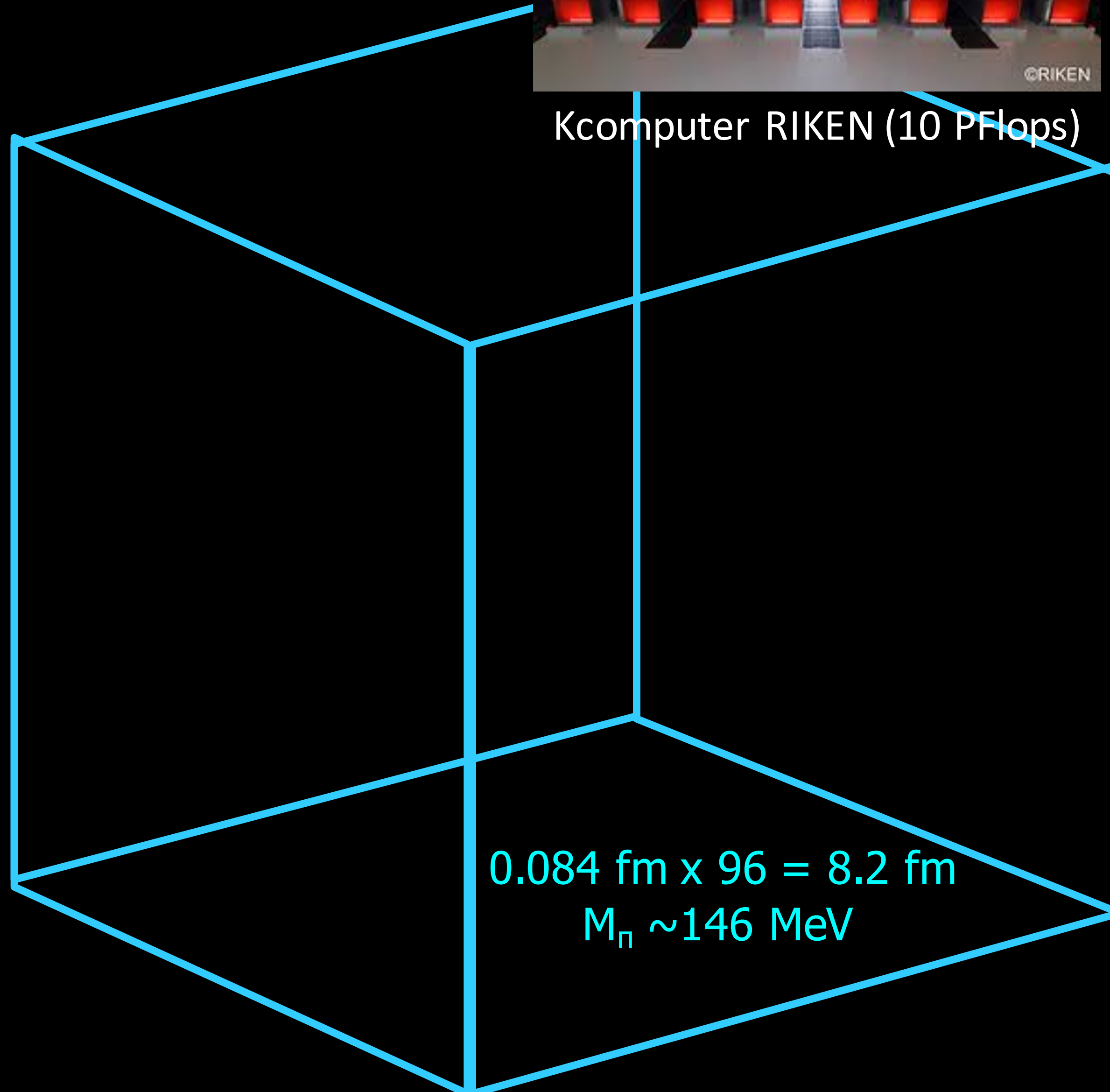


0.121 fm x 32 = 3.9 fm

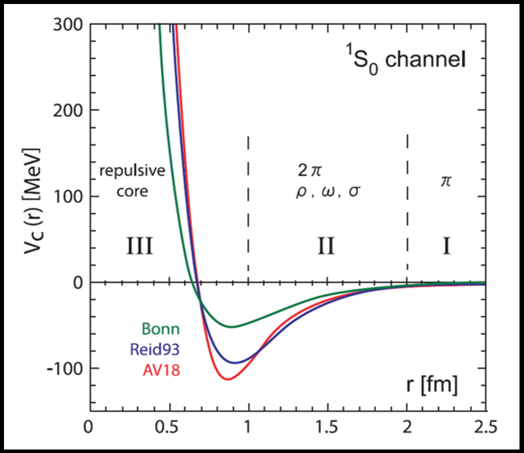
m_π=350-1200 MeV

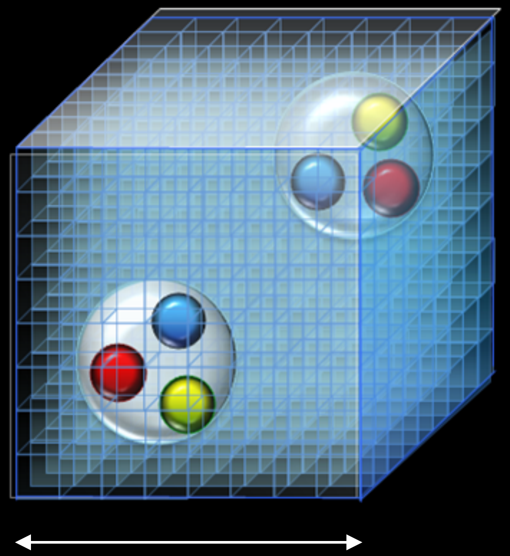
2015-

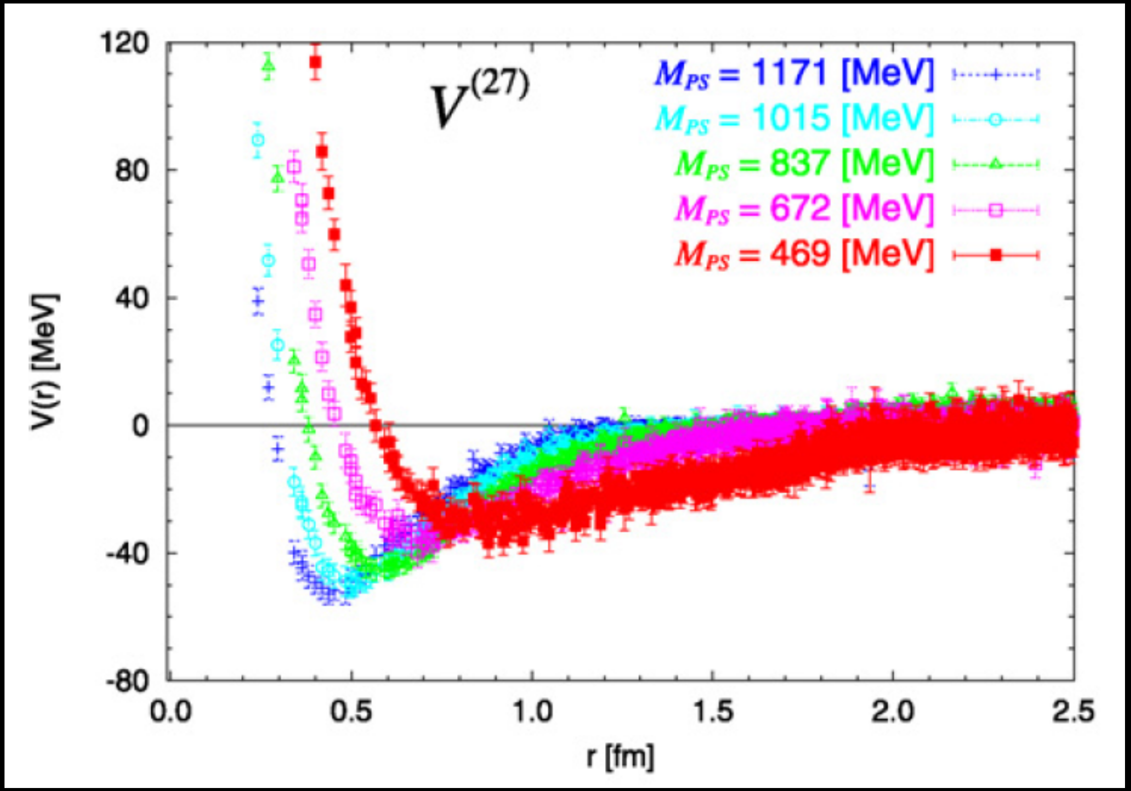
Kcomputer RIKEN (10 PFlops)



Qualitative studies (2010-2014)
LQCD simulations of BB force
with 3 degenerate flavors (m_u=m_d=m_s)







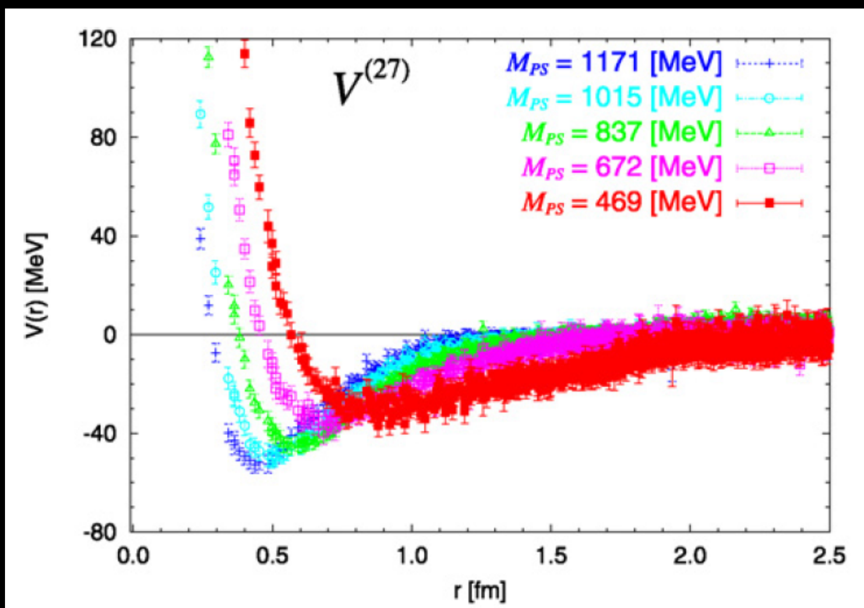
HAL QCD Coll., Phys. Rev. Lett. 106(2011) 162002
Nucl. Phys. A881 (2012) 28

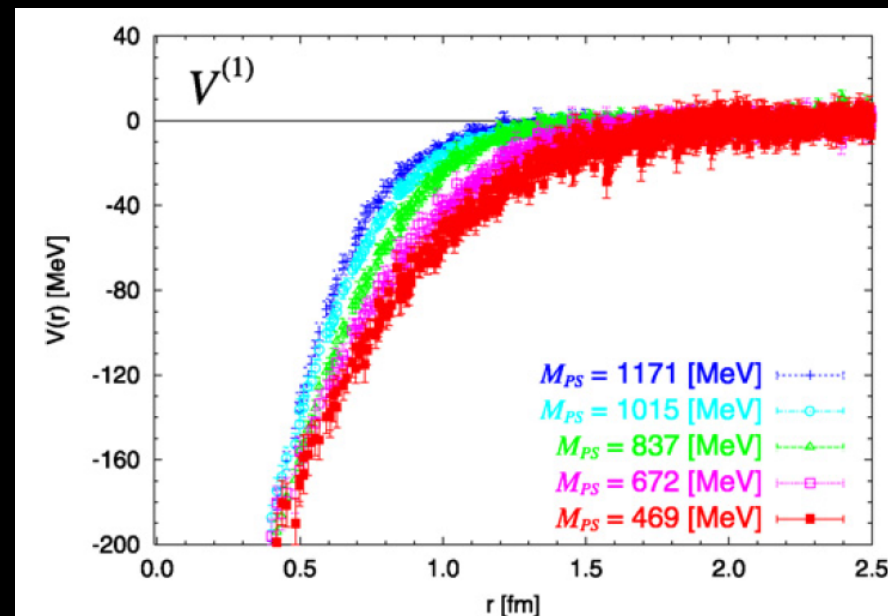
Channel dependence !

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

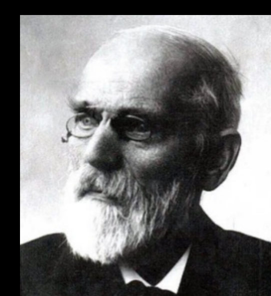
PP (uud-uud) channel
(partial) Pauli blocking

H (uds-uds) channel
No Pauli blocking



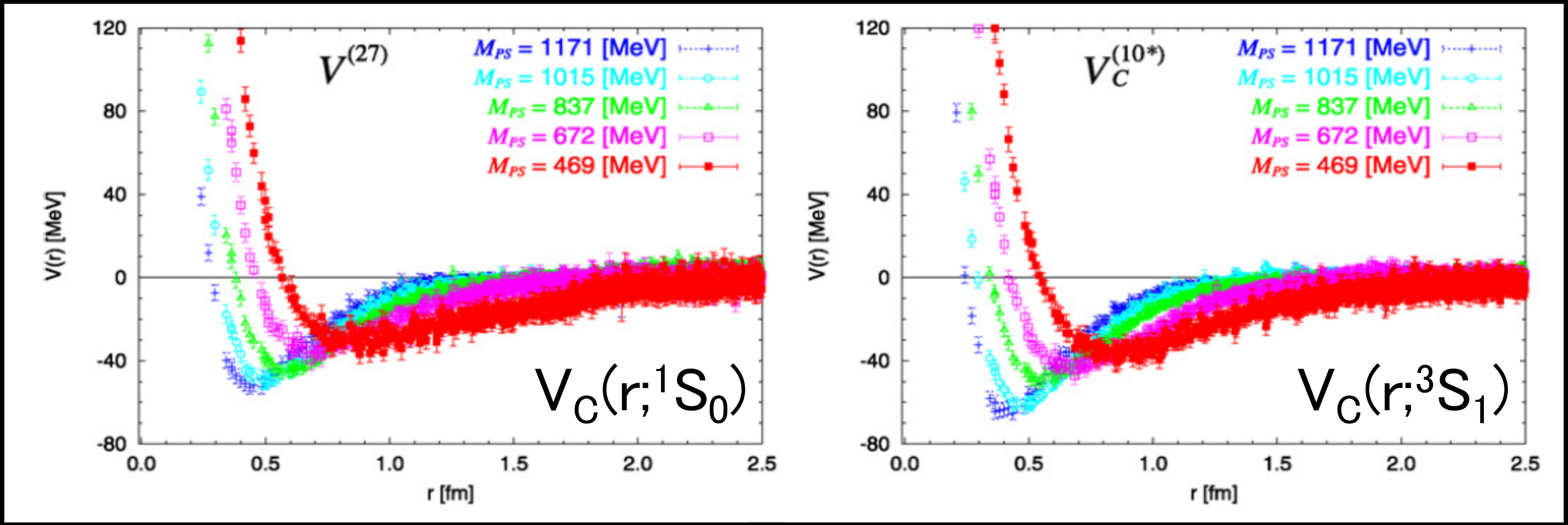


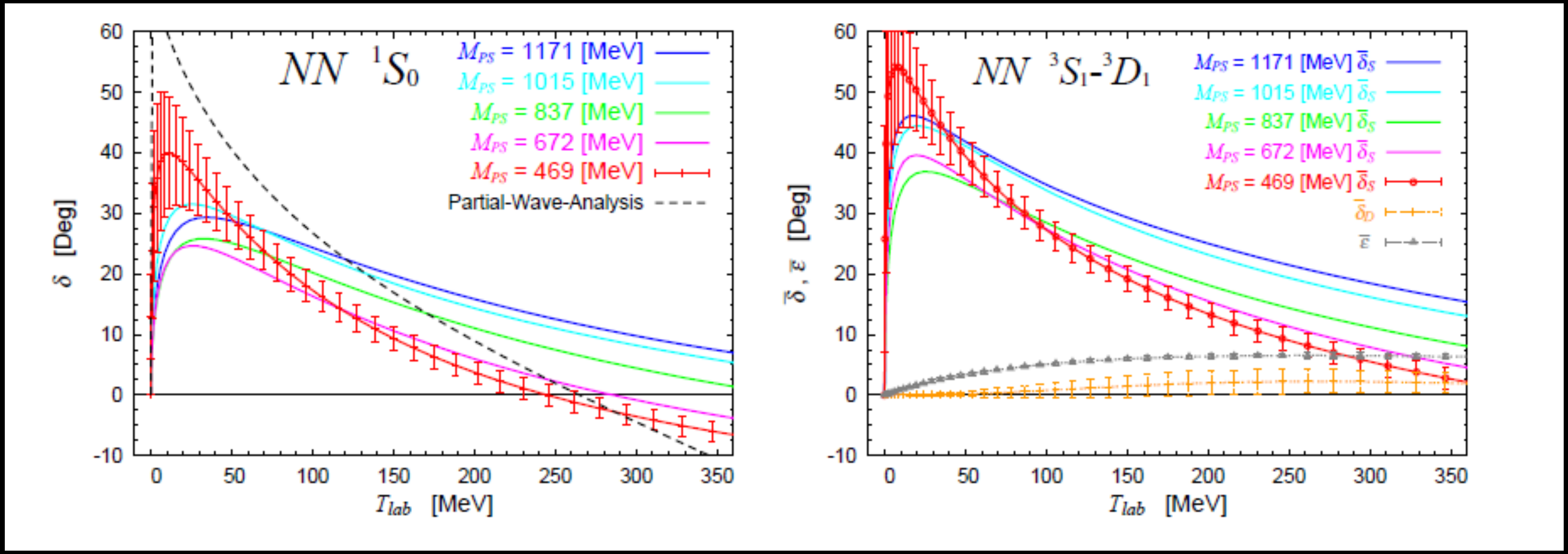
Pauli and van der Waarls
at work !



NN Force in 3-flavor QCD

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





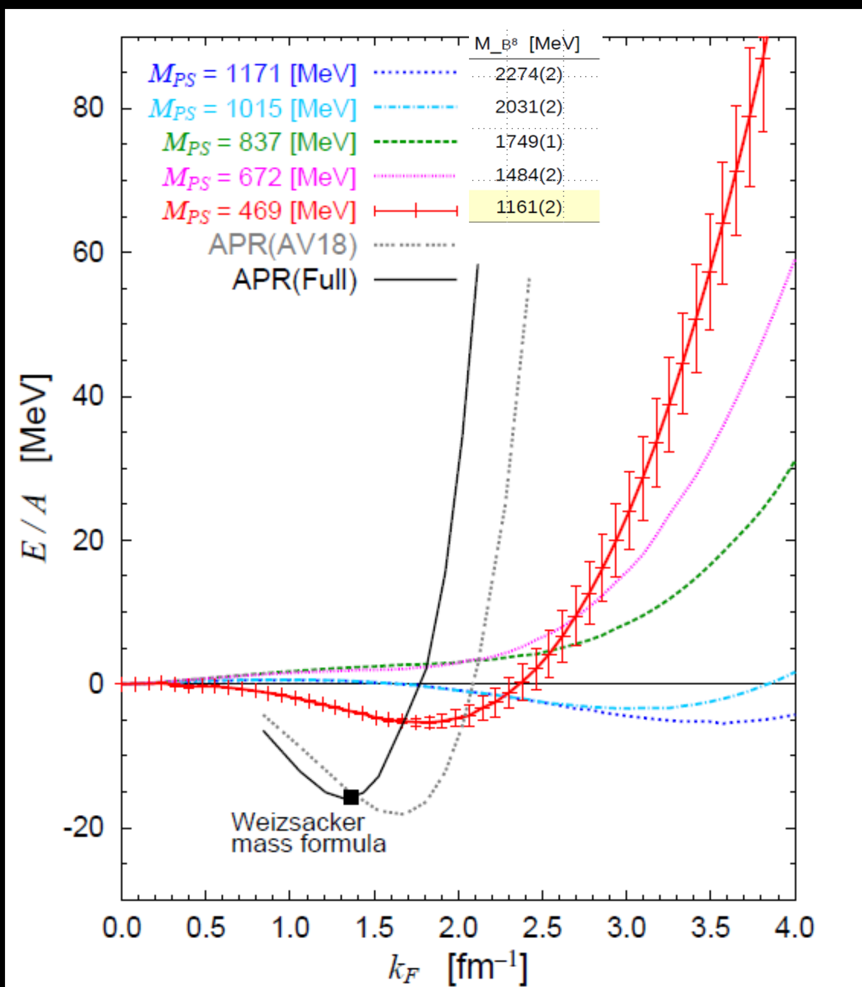
- Stronger attraction in the deuteron channel
- Physical point is close to the unitary region

Nuclear EOS from Lattice NN force + BHF calculation

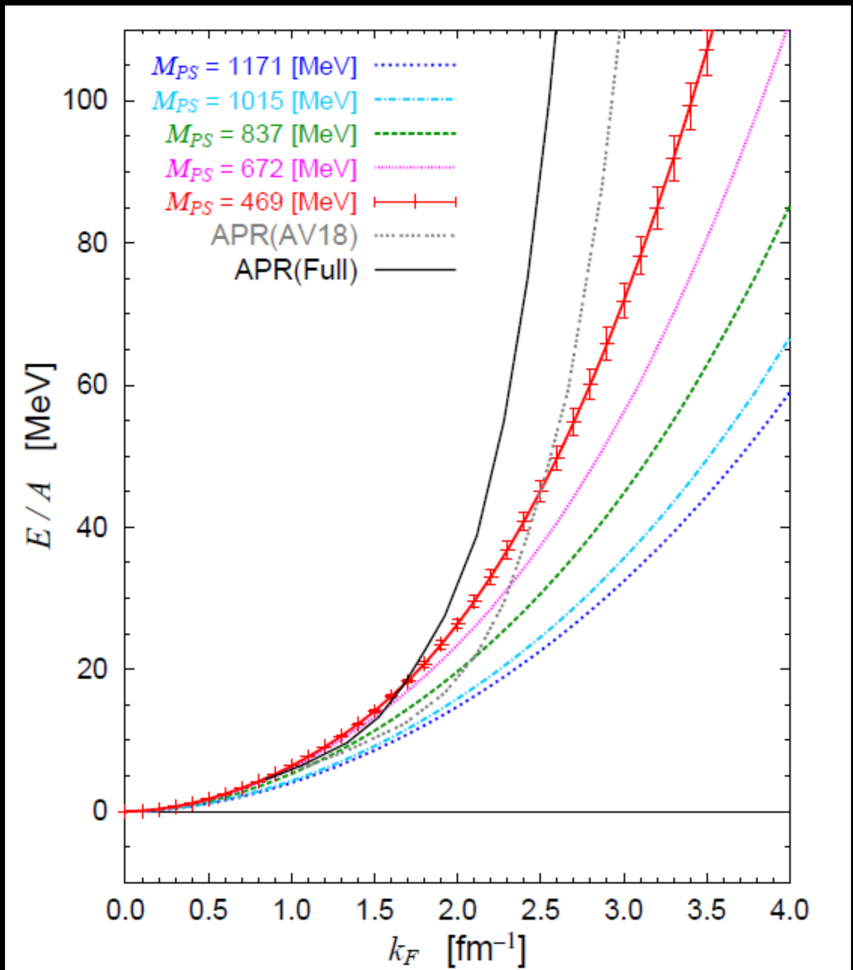
(NN force: $^1S_0$, $^3S_1$, $^3D_1$ channels only)

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

Nuclear Matter

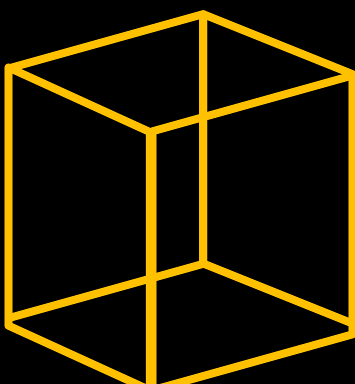


Neutron Matter



-2014

T2K Tsukuba (0.1 PFlops)

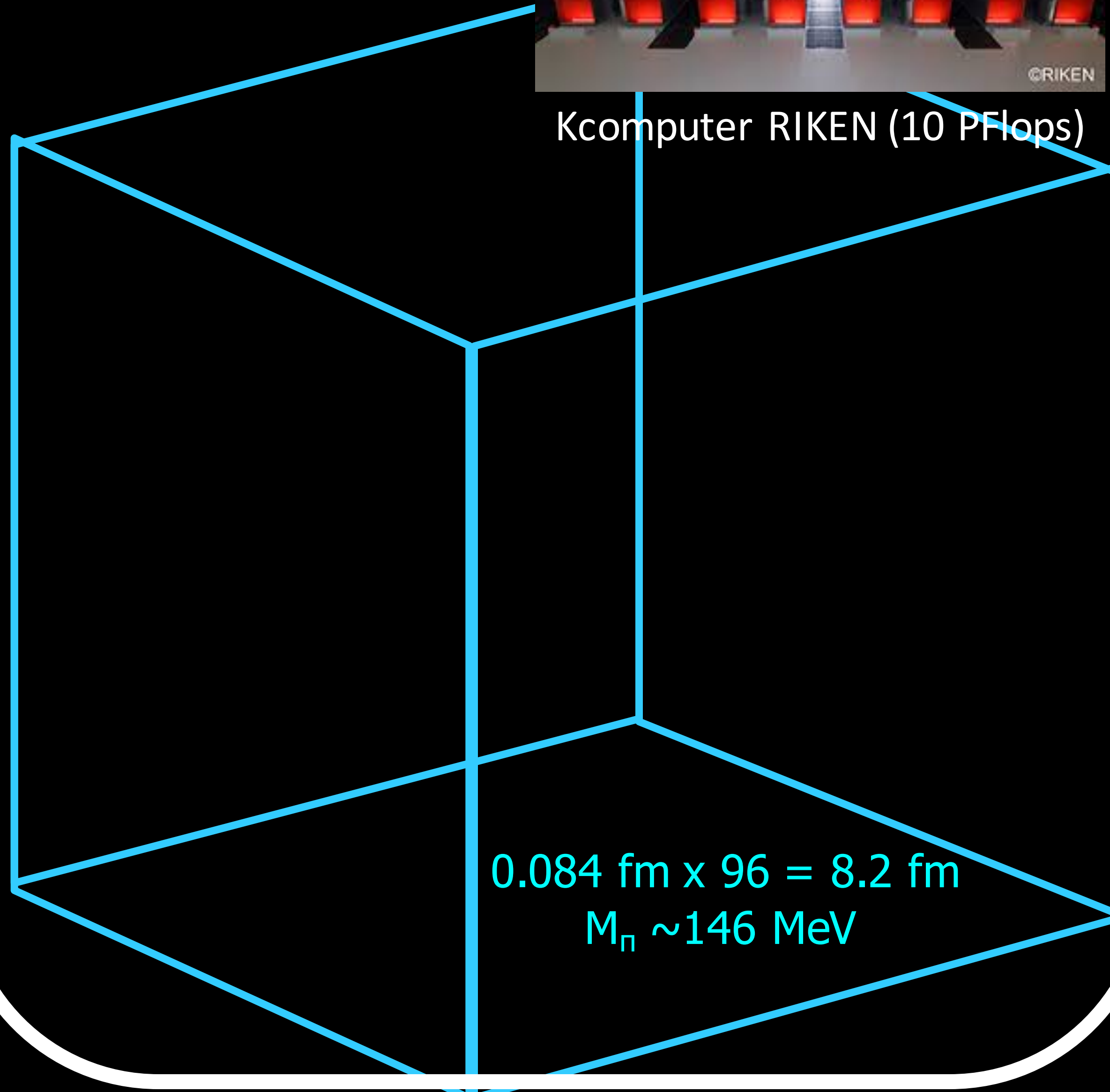


0.121 fm x 32 = 3.9 fm

m_{π}=350-1200 MeV

2015-

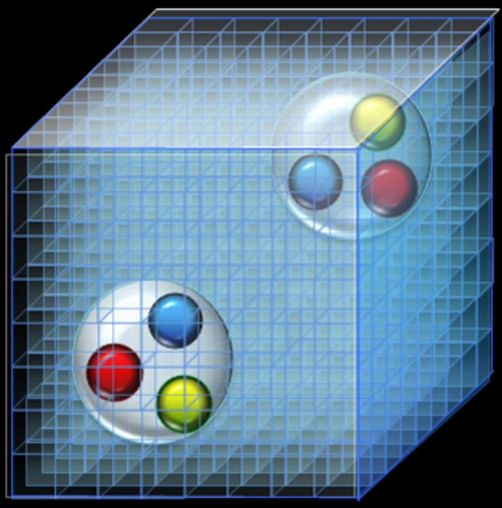
Kcomputer RIKEN (10 PFlops)



0.084 fm x 96 = 8.2 fm

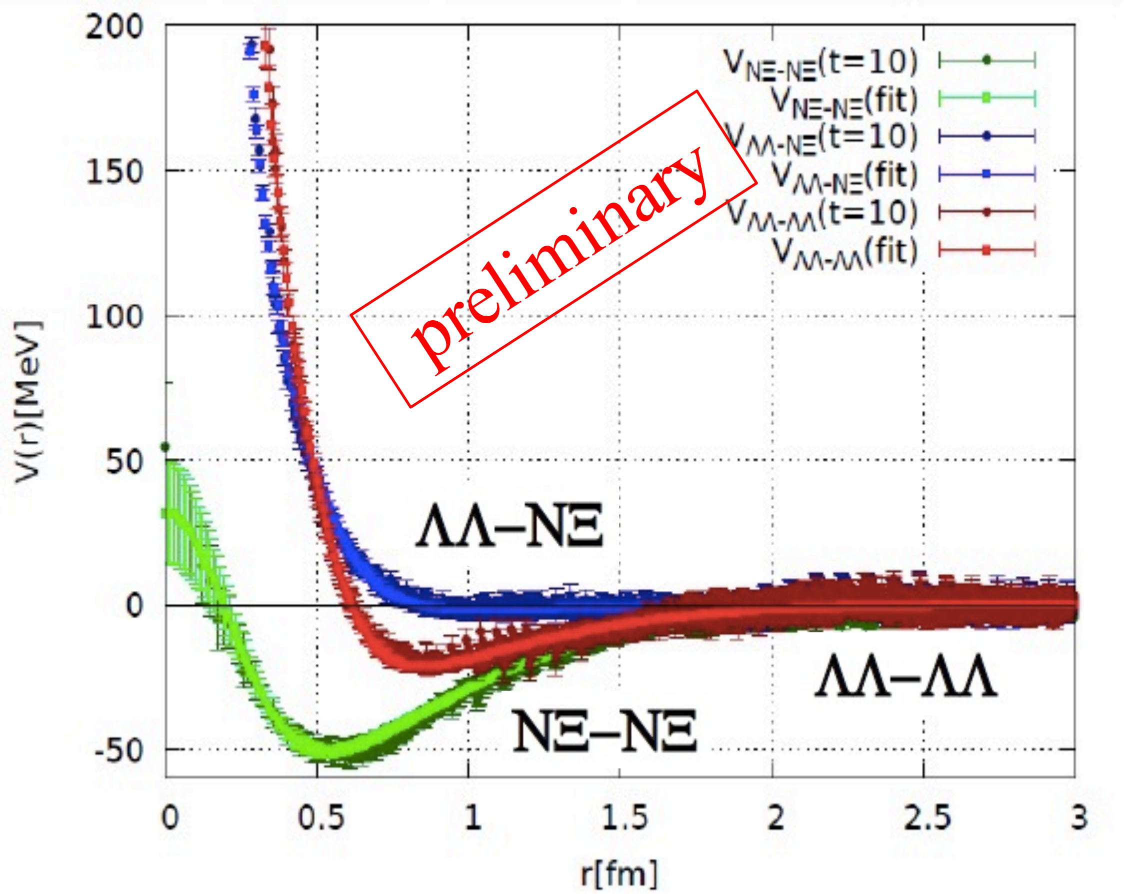
M_{π} ~146 MeV

Quantitative studies (2015-)
LQCD simulations of BB force
at physical point ($m_u = m_d \neq m_s$)

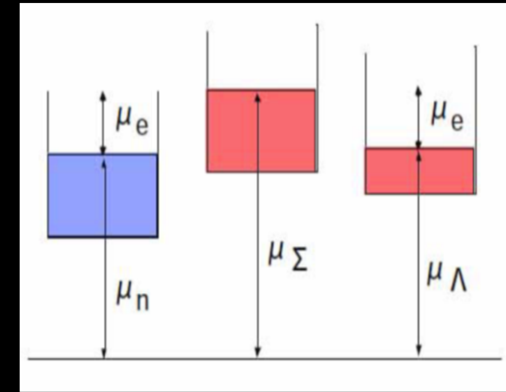


8.2 fm

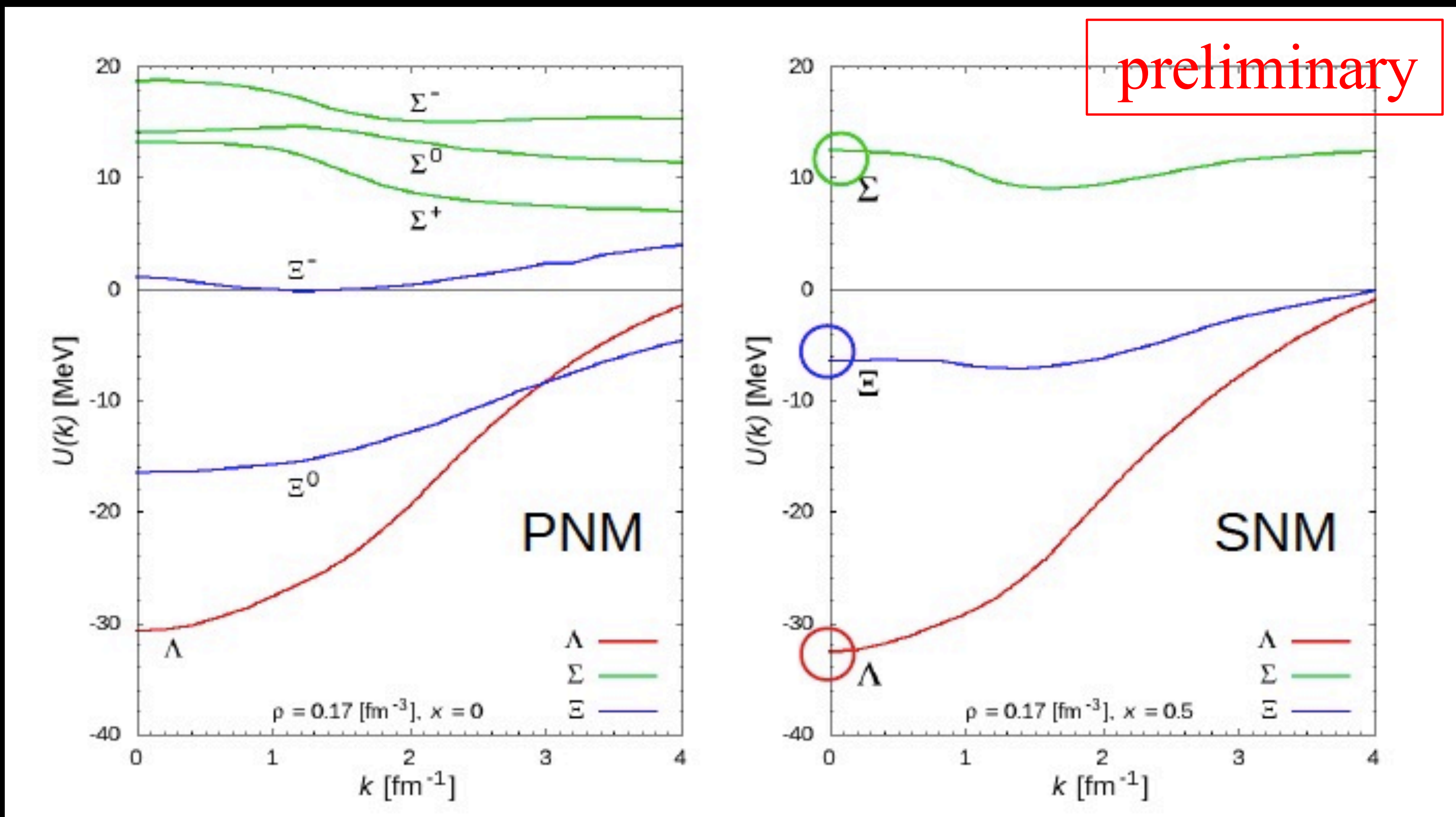
M_π ~146 MeV



Hyperon self-energy with physical point LQCD results of YN potentials

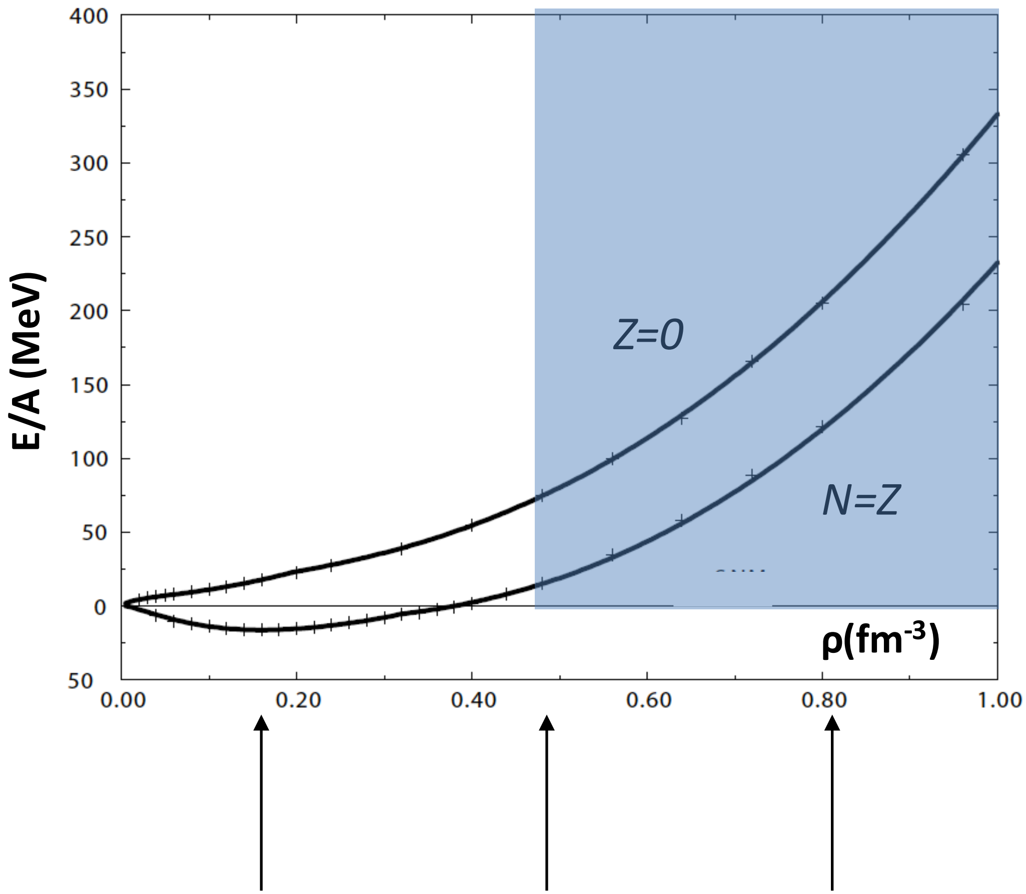


Inoue et al. [HAL QCD Coll.] (2016)



EOS based on baryonic degrees of freedoms meaningful ?

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

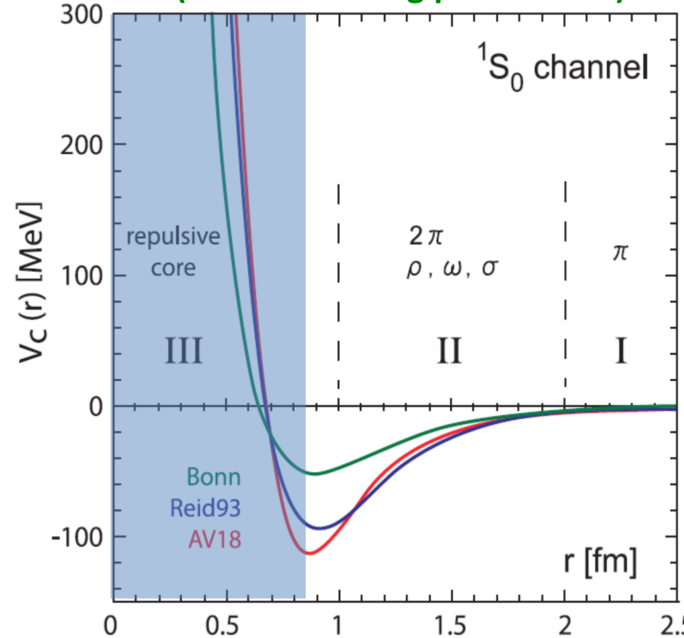


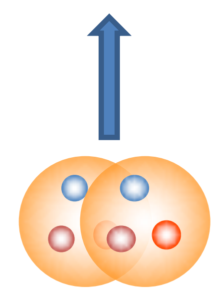
ρ_0
$= 0.16\ fm^{-3}$

$3\rho_0$

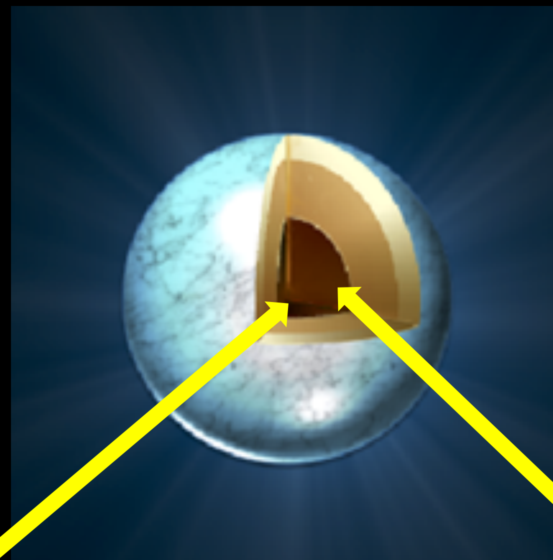
$5\rho_0$

Phenomenological nuclear force (about 40 fitting parameters)



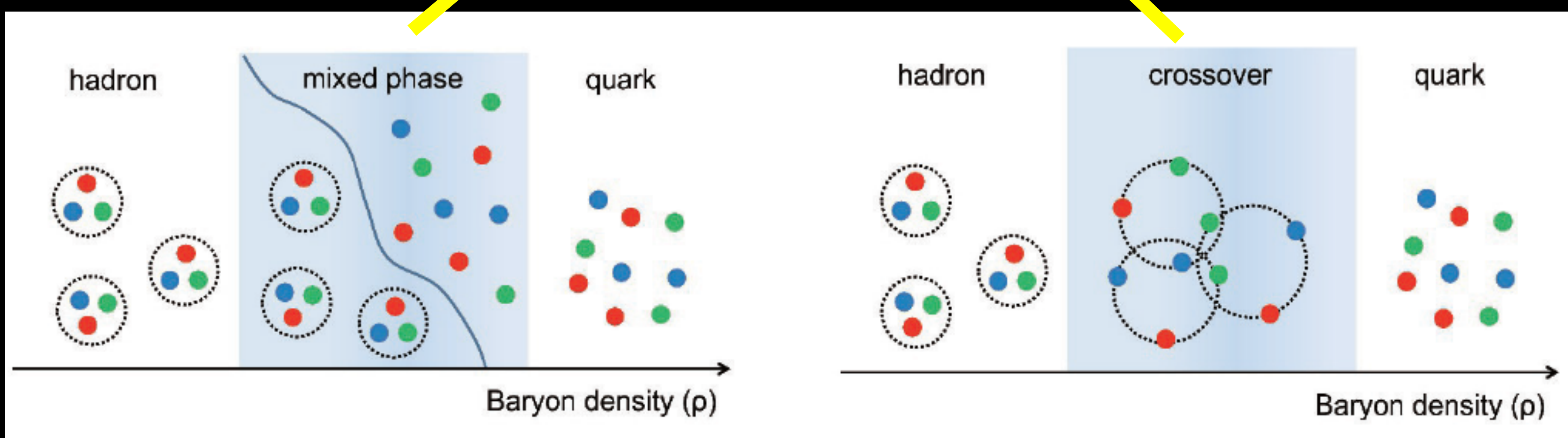


First order or crossover in dense matter ?



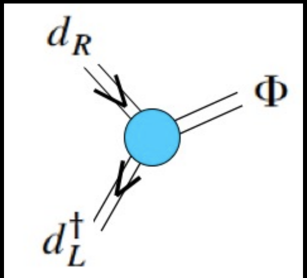
Baym & Chin
Phys.Lett. 62B (1976)241

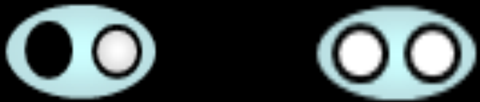
Baym
Physica 96A (1979) 131



Hadron-quark crossover – theory --

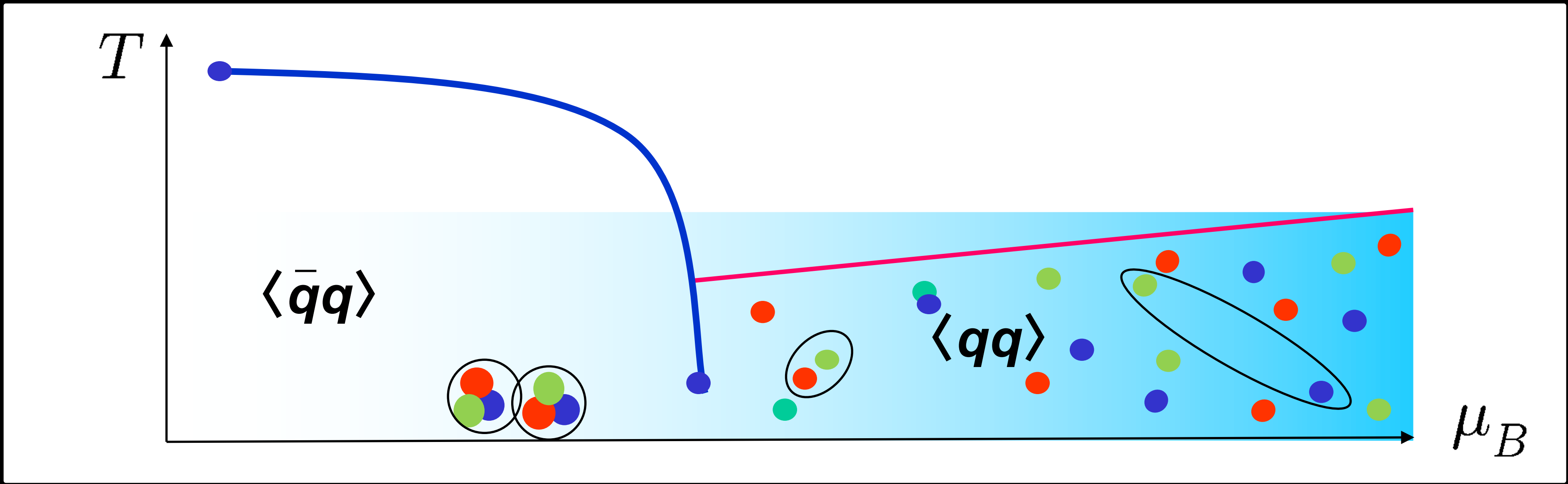
Hatsuda, Yamamoto, Tachibana & Baym, PRL97 ('06)





QCD axial anomaly

$$\mathcal{V}(\Phi, d) = \mathcal{V}_\chi(\Phi) + \mathcal{V}_d(d_L, d_R) + \mathcal{V}_{\chi d}(\Phi, d_L, d_R)$$



Strongly interaction baryonic matter → Strongly interacting quark matter

PRL 97, 122001 (2006) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2006

New Critical Point Induced By the Axial Anomaly in Dense QCD

Tetsuo Hatsuda,[1] Motoi Tachibana,[2] Naoki Yamamoto,[1] and Gordon Baym[3]

[1]*Department of Physics, University of Tokyo, Japan*

[2]*Department of Physics, Saga University, Saga 840-8502, Japan*

[3]*Department of Physics, University of Illinois, 1110 W. Green St., Urbana, Illinois 61801, USA*

(Received 10 May 2006; published 18 September 2006)

We study the interplay between chiral and diquark condensates within the framework of the Ginzburg-Landau free energy, and classify possible phase structures of two and three-flavor massless QCD. The QCD axial anomaly acts as an external field applied to the chiral condensate in a color superconductor and leads to a crossover between the broken chiral symmetry and the color superconducting phase, and, in particular, to a new critical point in the QCD phase diagram.

DOI: 10.1103/PhysRevLett.97.122001 PACS numbers: 12.38.−t, 26.60.+c

PRL 99, 130406 (2007) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

Superfluidity and Magnetism in Multicomponent Ultracold Fermions

R. W. Cherng,[1] G. Refael,[2] and E. Demler[1]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

[2]*Department of Physics, California Institute of Technology, Pasadena, California 91125, USA*

(Received 2 May 2007; published 28 September 2007)

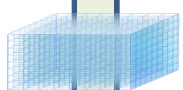
We study the interplay between superfluidity and magnetism in a multicomponent gas of ultracold fermions. Ward-Takahashi identities constrain possible mean-field states describing order parameters for both pairing and magnetization. The structure of global phase diagrams arises from competition among these states as functions of anisotropies in chemical potential, density, or interactions. They exhibit first and second order phase transition as well as multicritical points, metastability regions, and phase separation. We comment on experimental signatures in ultracold atoms.

DOI: 10.1103/PhysRevLett.99.130406 PACS numbers: 05.30.Jp, 03.75.Mn, 03.75.Ss

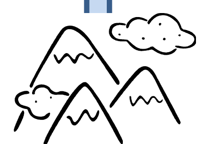
From QCD to Dense Matter

Quantum Chromo Dynamics

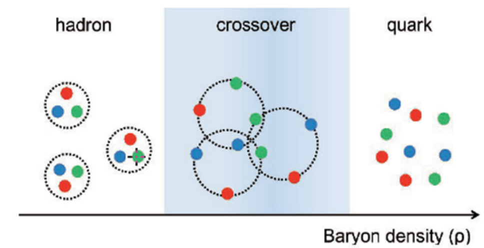
Lattice gauge theory



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

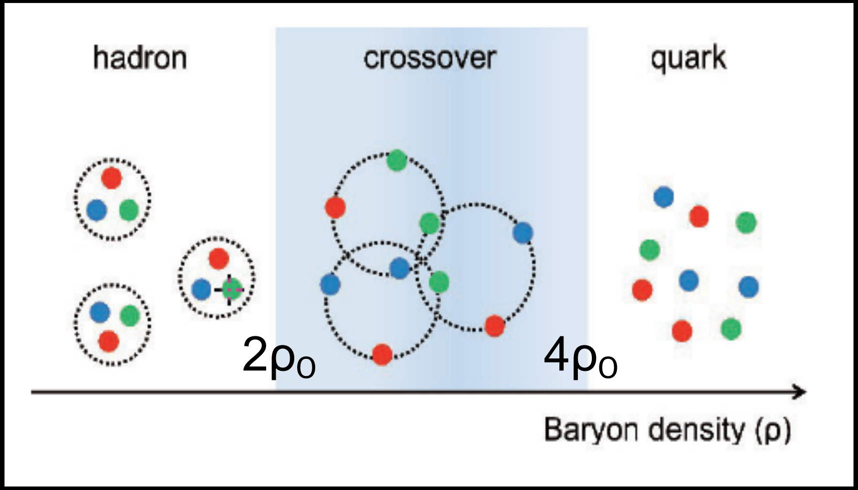
Hadron-Quark Crossover – phenom. EOS at T=0 -

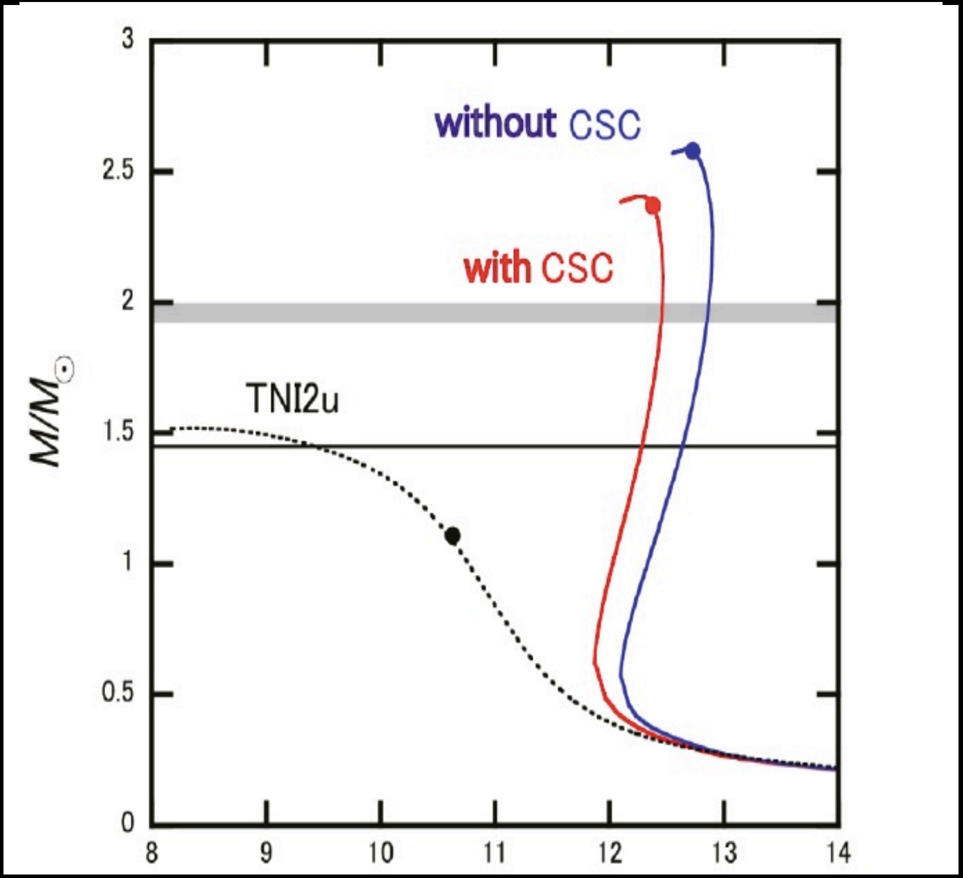
Masuda, Hatsuda, Takatsuka,
ApJ Lett. 764 (2013) ; PTEP 2013 (2013); Eur. Phys. J. A52 (2016)

See also, Koji, Powell, Song, Baym, PRD91 (2015)

$$\hat{E}(\rho) = \hat{E}_{\mathrm{H}}(\rho) w_{-}(\rho) + \hat{E}_{\mathrm{Q}}(\rho) w_{+}(\rho),$$

EOS: CRover_cold



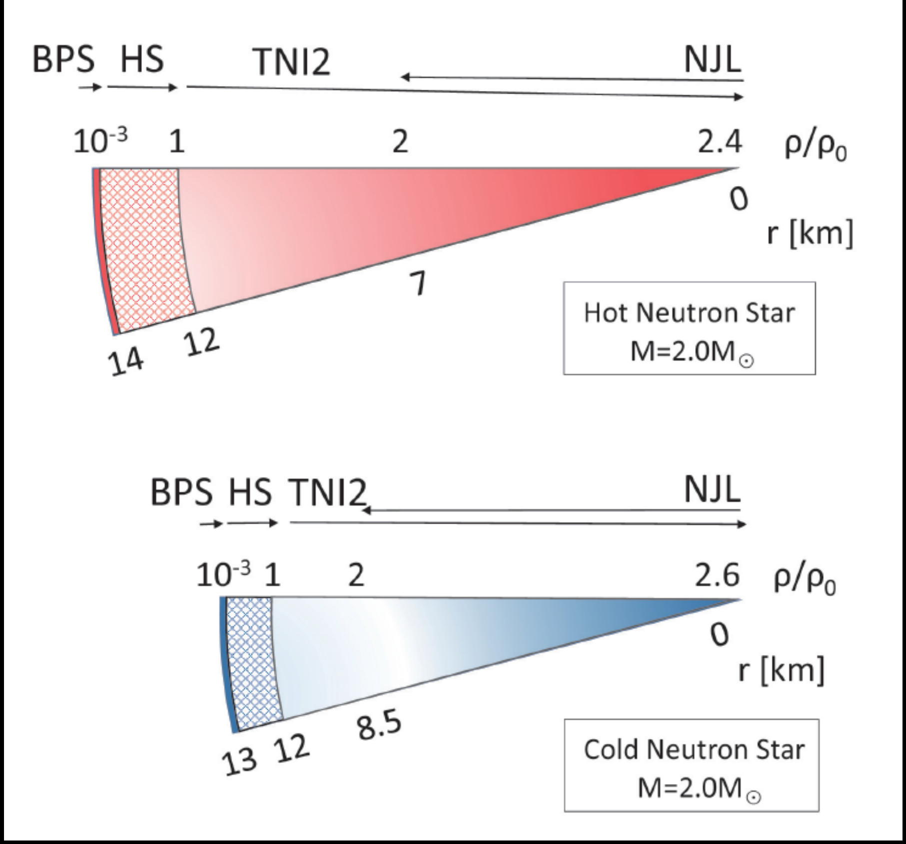


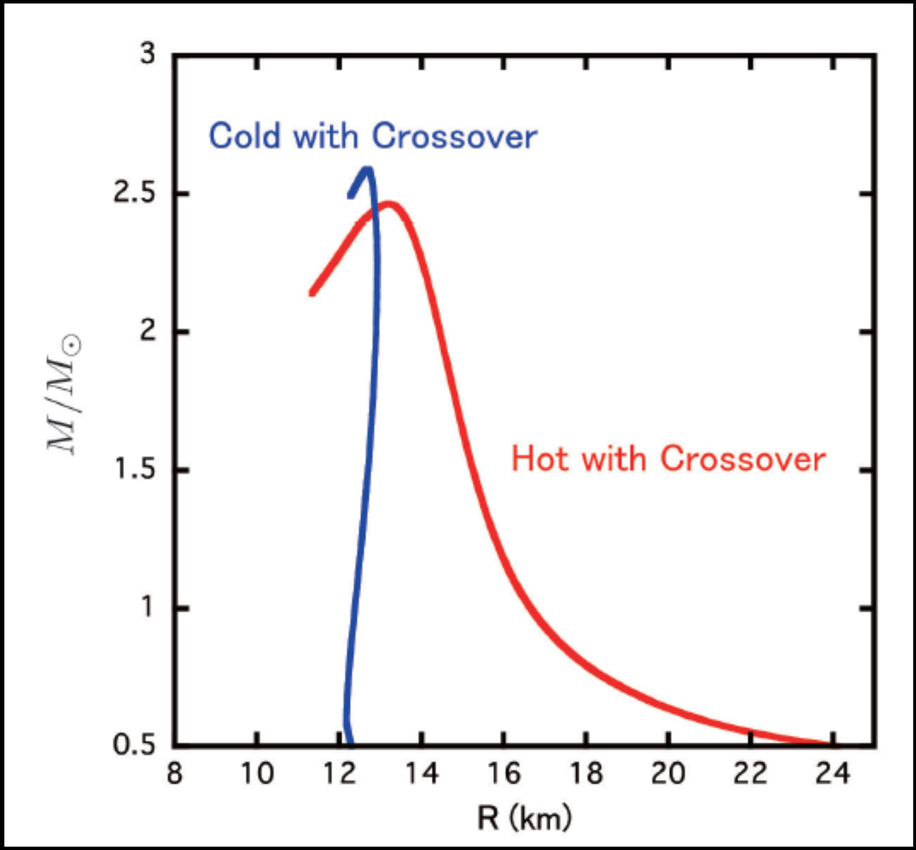
Hadron-Quark Crossover – phenom. EOS at finite T --

$$\hat{F}(\rho,T;Y_l) = \hat{F}_{\mathrm{HL}}(\rho,T;Y_l)w_-(\rho,T) + \hat{F}_{\mathrm{QL}}(\rho,T;Y_l)w_+(\rho,T).$$

Masuda, Hatsuda and Takatsuka, PTEP 2016 (2016) 7, 021D01; Eur. Phys. J. A52 (2016) 65.

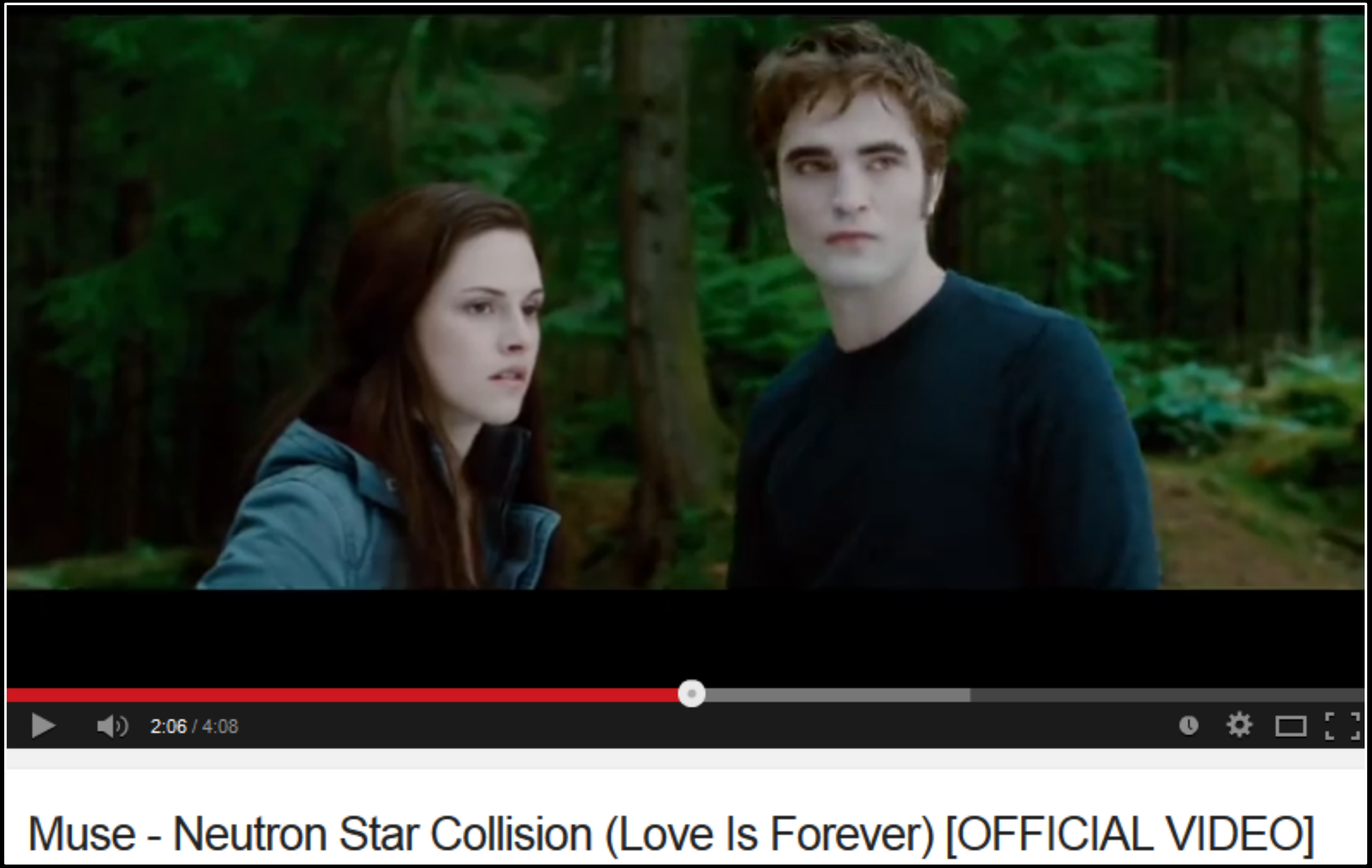
EOS: CRover_hot





Y_l=0.3, S/N=1.0

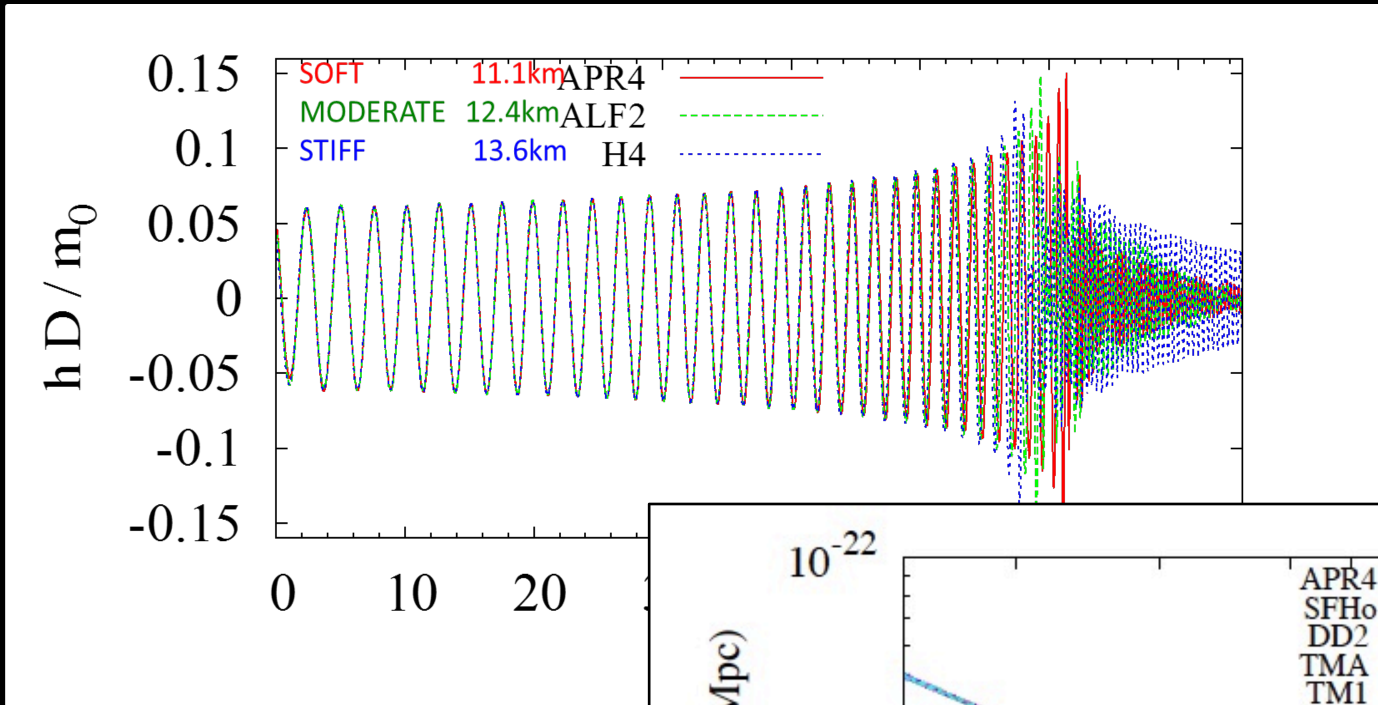
Neutron Star Collision

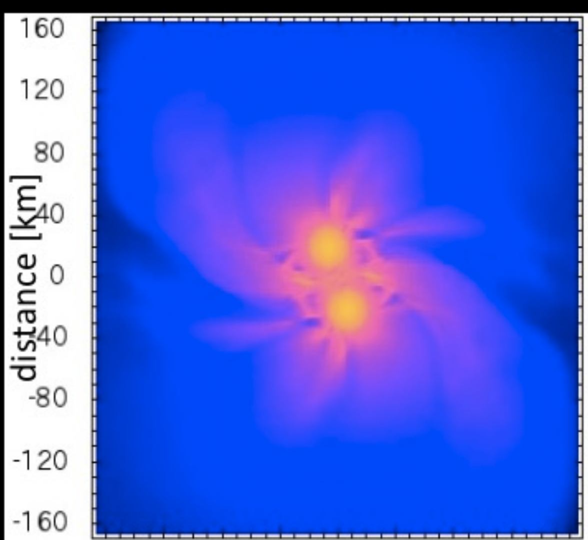


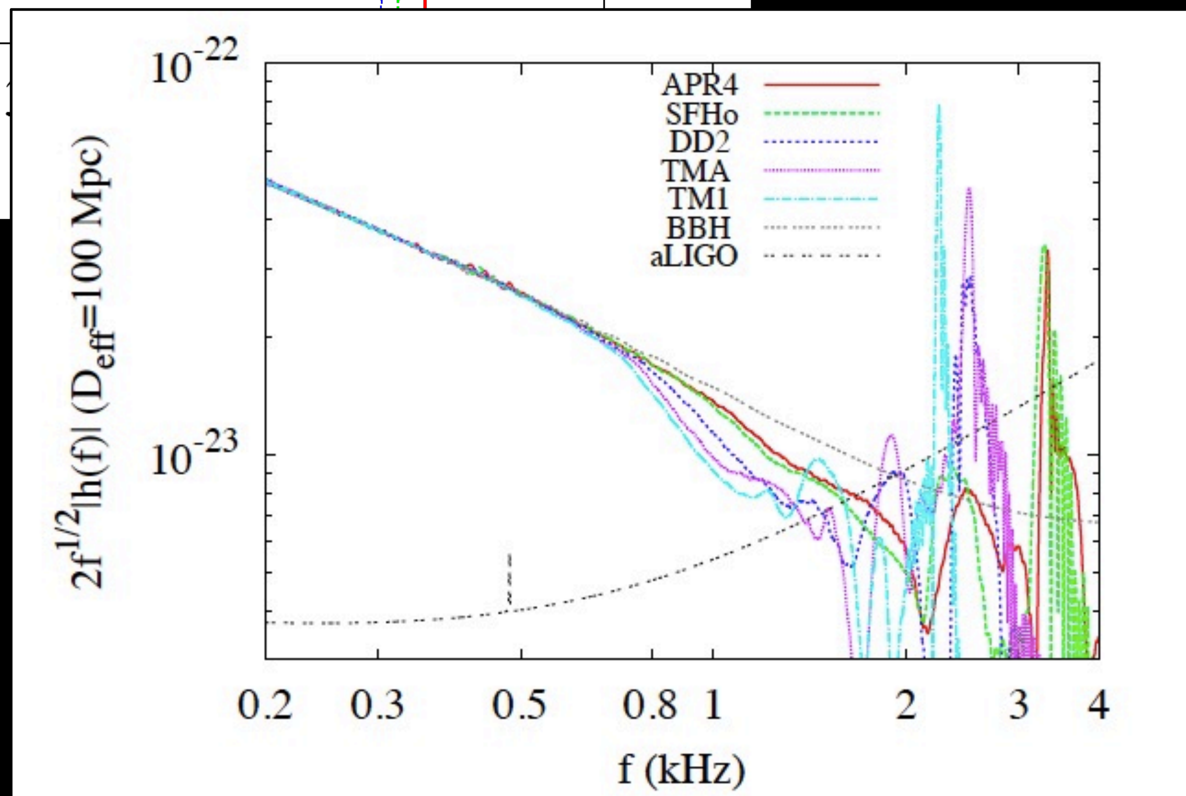
https://www.youtube.com/watch?v=MTvgnYGu9bg

Expected GW signal

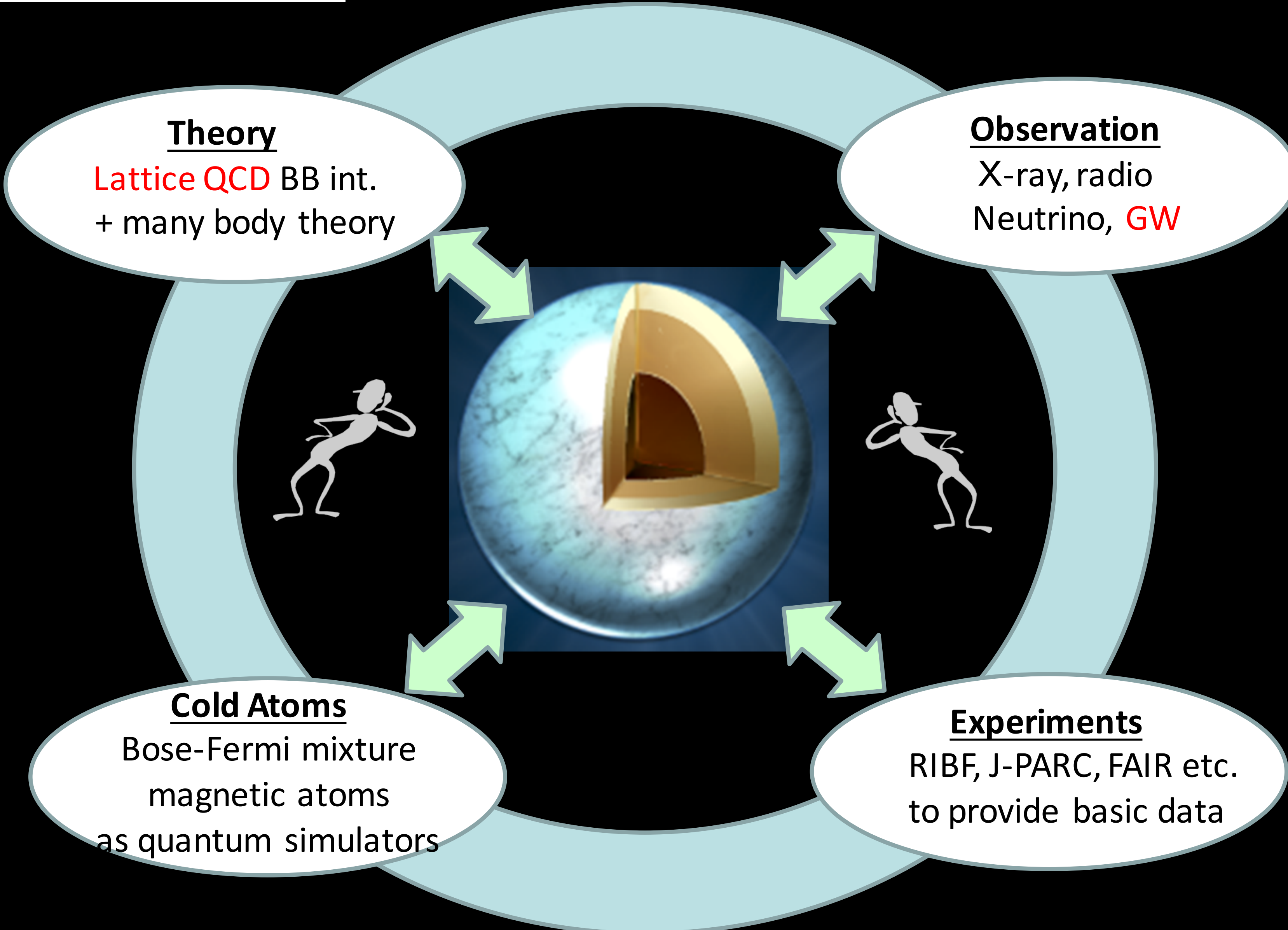
Hotokezaka, Kyutoku, Shibata & Sekiguchi, PRD 93 (2016)







Summary


Theory
Lattice QCD BB int.
+ many body theory
Observation
X-ray, radio
Neutrino, GW
Cold Atoms
Bose-Fermi mixture
magnetic atoms
as quantum simulators
Experiments
RIBF, J-PARC, FAIR etc.
to provide basic data