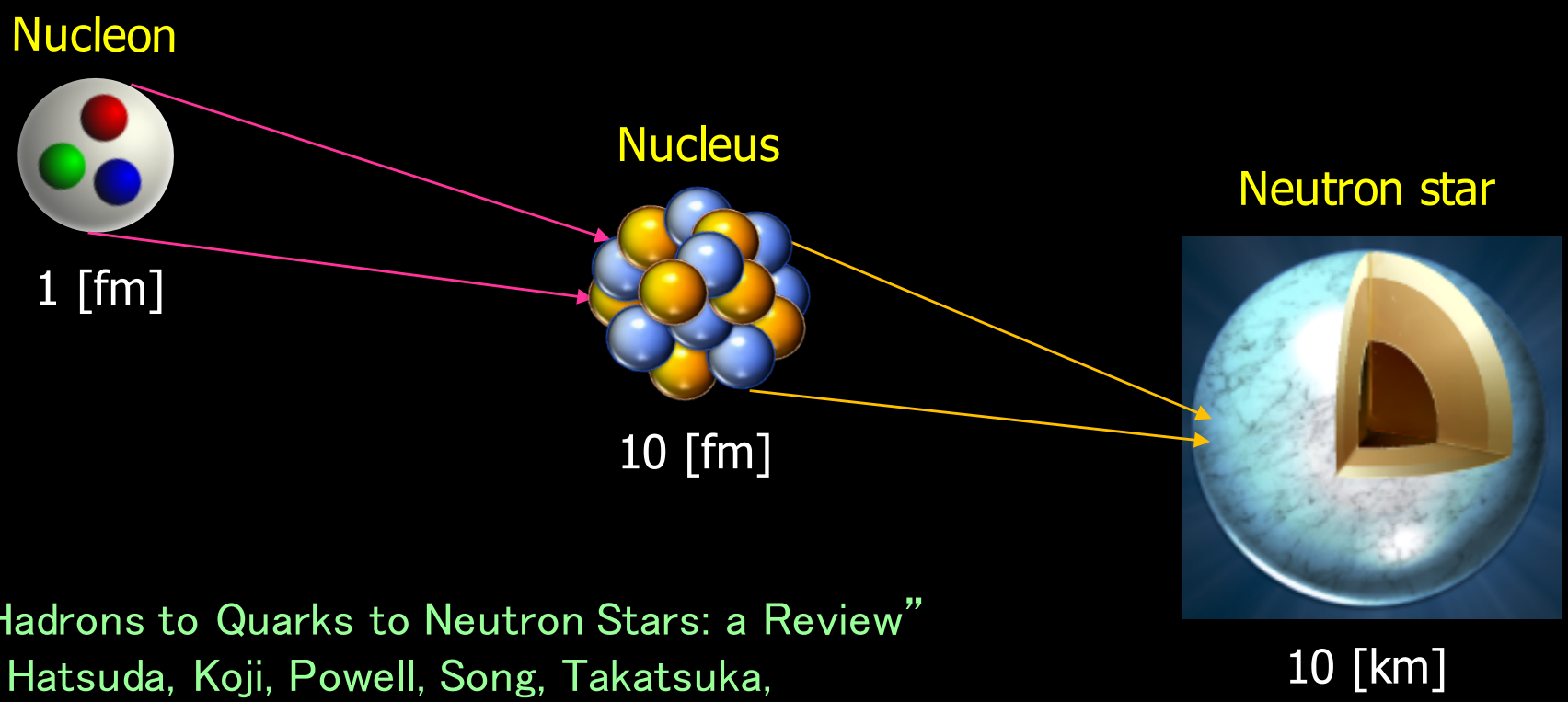
From Quarks to Neutron Stars

Tetsuo Hatsuda
interdisciplinary Theoretical and Mathematical Sciences Program
(iTHEMS), RIKEN

PACIFIC 2018 (Feb. 13, 2018)

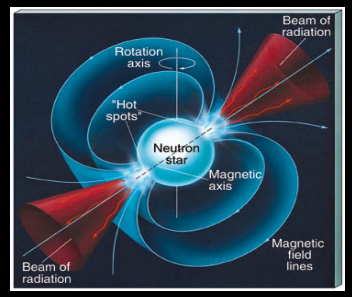


"From Hadrons to Quarks to Neutron Stars: a Review"
Baym, Hatsuda, Koji, Powell, Song, Takatsuka,
1707.04966 [astro-ph.HE] (ROPP in press)

Brief history of NS obs.

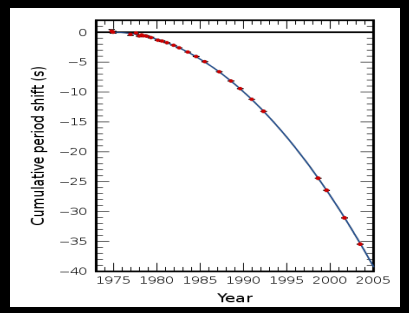
1932 Discovery of the neutron [J. Chardwick]

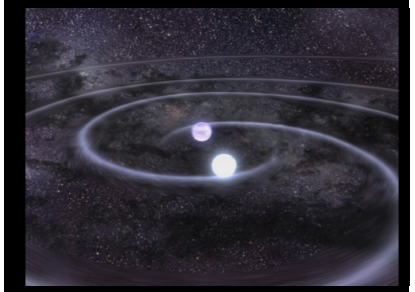
1934 Prediction of neutron star [W. Baade and F. Zwicky]



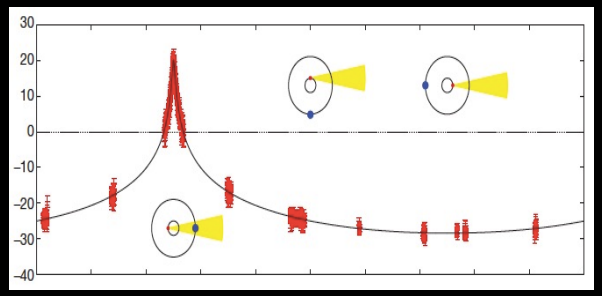
1968 Discovery of pulsar [S. J. Bell and A. Hewish]

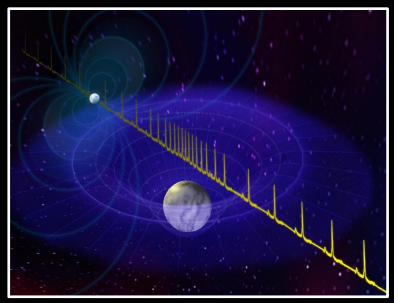
1974 Discovery of binary neutron star
[R. A. Hulse and J.H. Taylor]



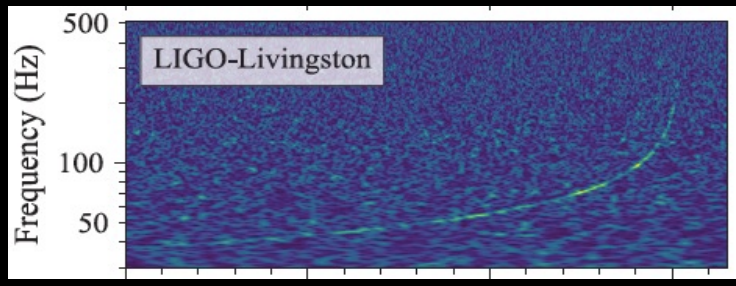


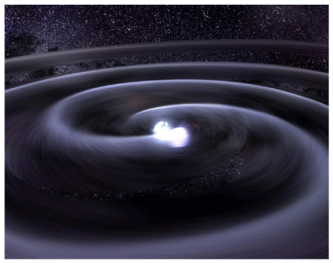
2010 Discovery of massive neutron star
[P. Detmorest et al.]

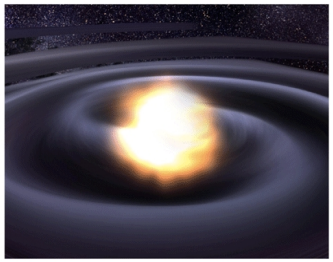




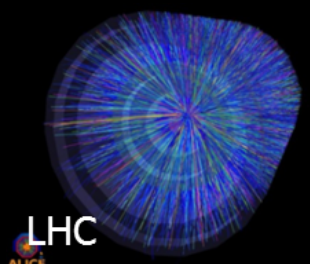
2017 Discovery of GW from NS merger
[LIGO/Virgo]

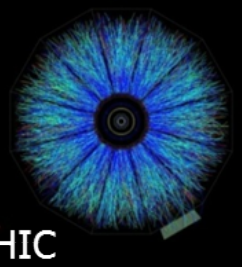


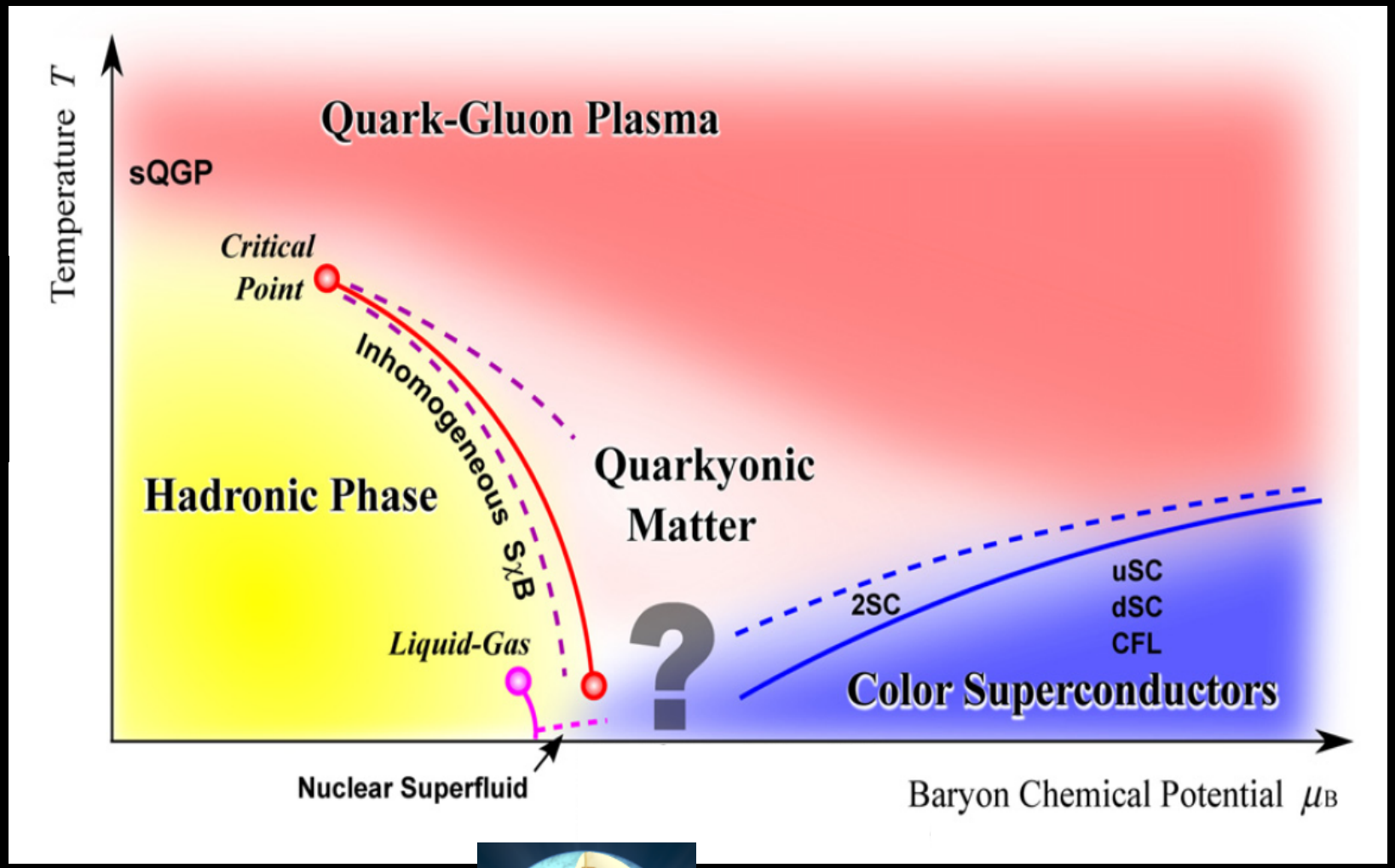


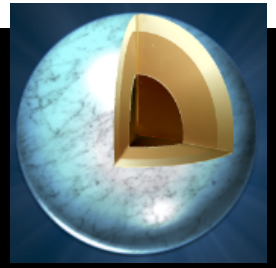


QCD phase diagram and hot/dense matter







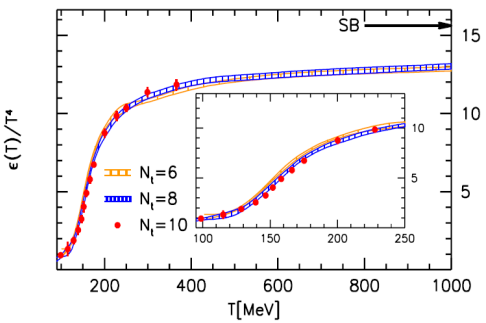


K. Fukushima and T. Hatsuda,
Rep. Prog. Phys. 74 (2011) 014001

From QCD to Hot/Dense Matter (Theory Status)

Quantum Chromo Dynamics

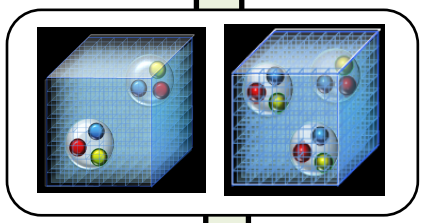
LQCD at finite T



LQCD at finite μ

Sign problem

LQCD at fixed N



Many-body methods

Equation of State for Hot Matter

Equation of State for Dense Matter

Relativistic Hydrodynamics

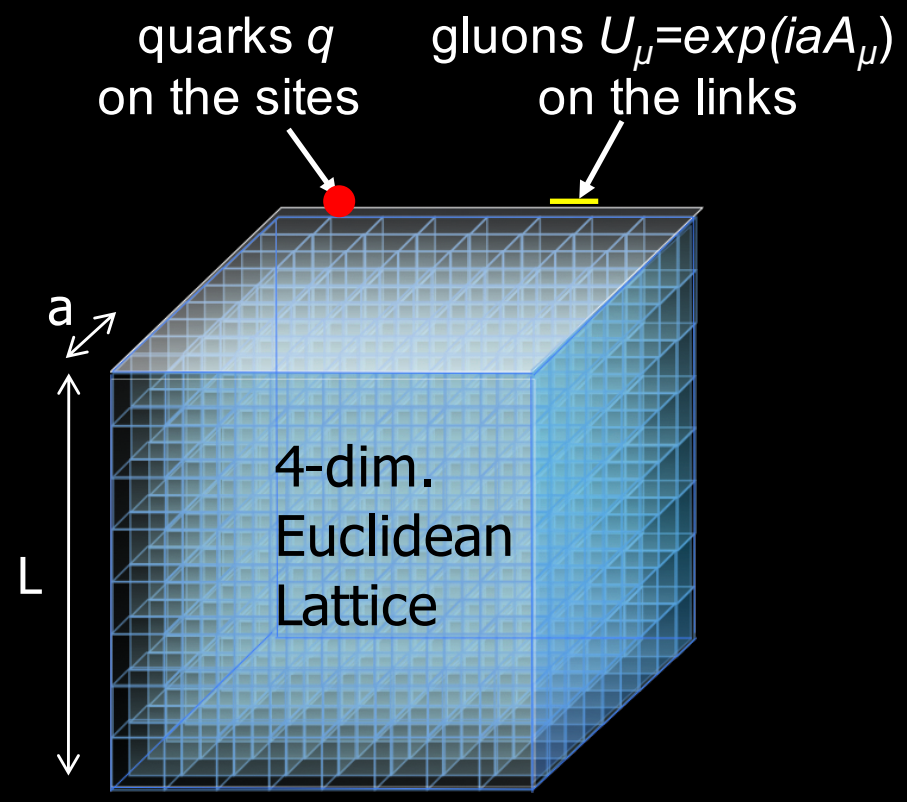
General Relativity

QGP in heavy-Ion collisions

Quark Matter in neutron stars

Lattice QCD (LQCD) Simulations

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



Importance Sampling

(In practice; Hybrid MC = MD + Metropolis)

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int [d\phi] \ \mathcal{O}(\phi) e^{-S(\phi)}$$

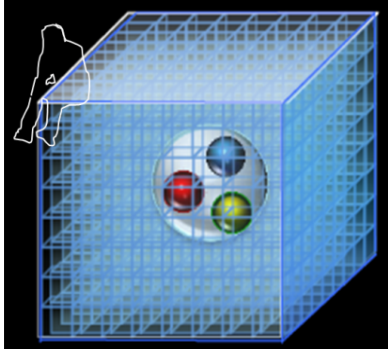
$$= \frac{1}{N} \sum_{n=1}^{N} \mathcal{O}^{(n)} \pm \sqrt{\frac{\sigma^2}{N}}$$

Signal Noise

Continuum & Thermodynamic Limits

($a \rightarrow 0$ & $L \rightarrow \infty$)

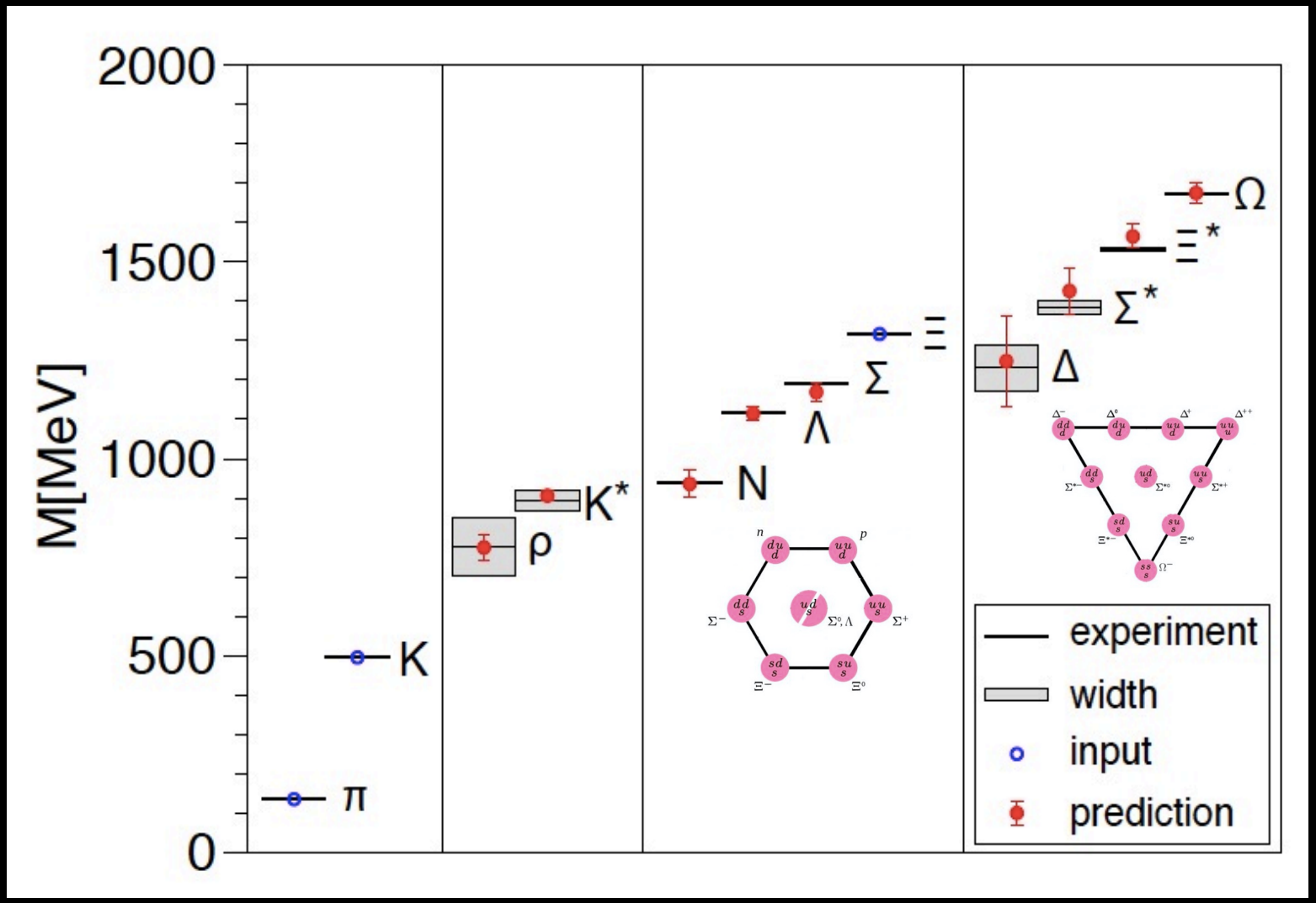
Precision LQCD
-- light hadron masses --



a_{min} = 0.065 fm

L_{max} = 4.1 fm

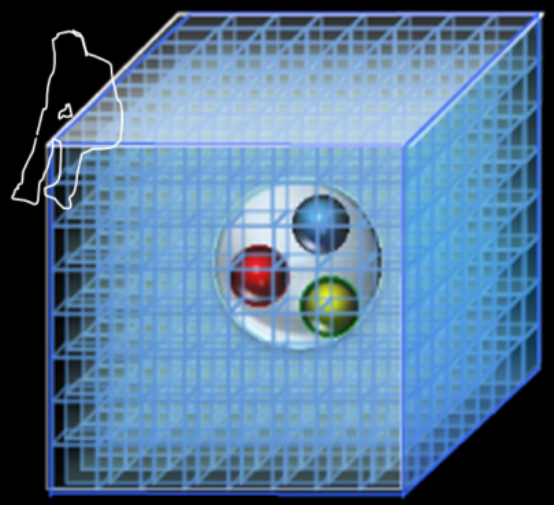
$m_{\pi,min}$ =190 MeV



taken from Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

Precision LQCD
-- neutron-proton mass difference --

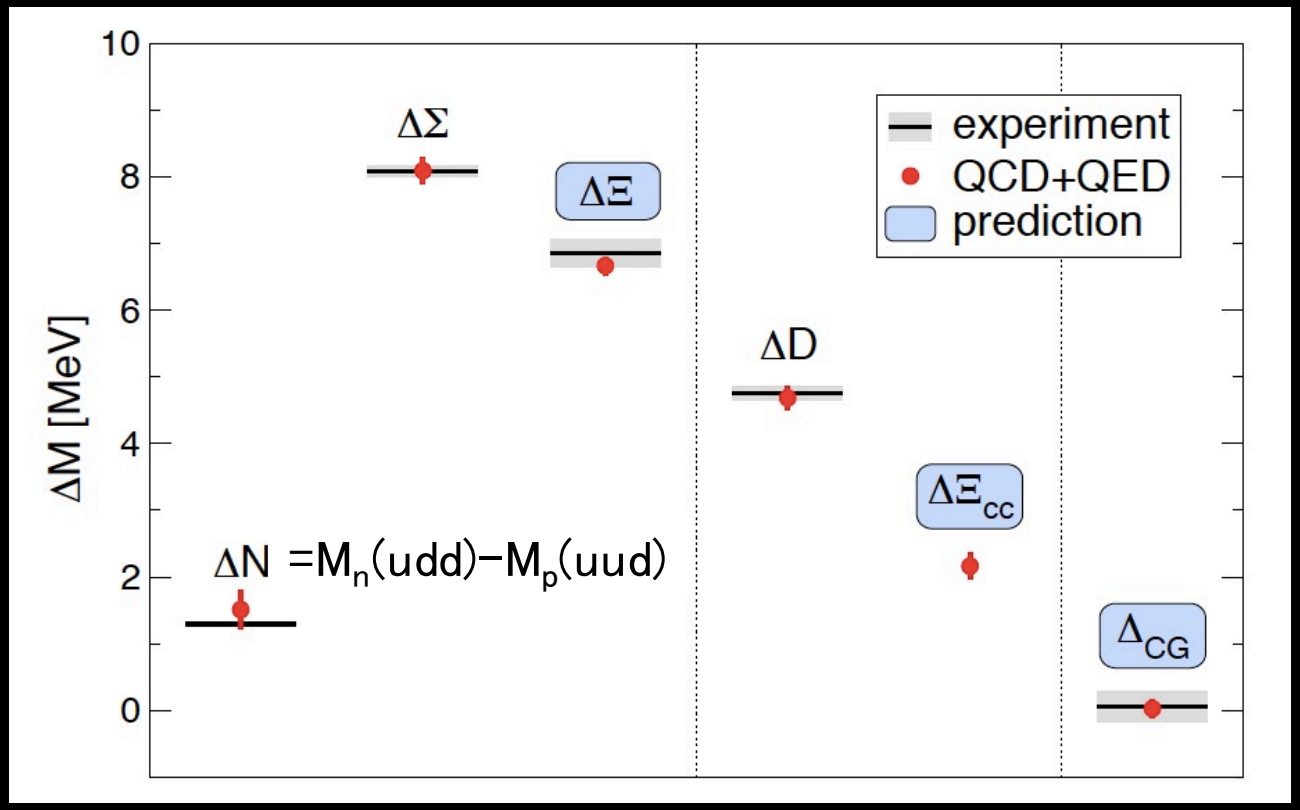
BMW Coll., Science 347 (2015) 1452



a_{min} = 0.054 fm

L_{max} = 8 fm

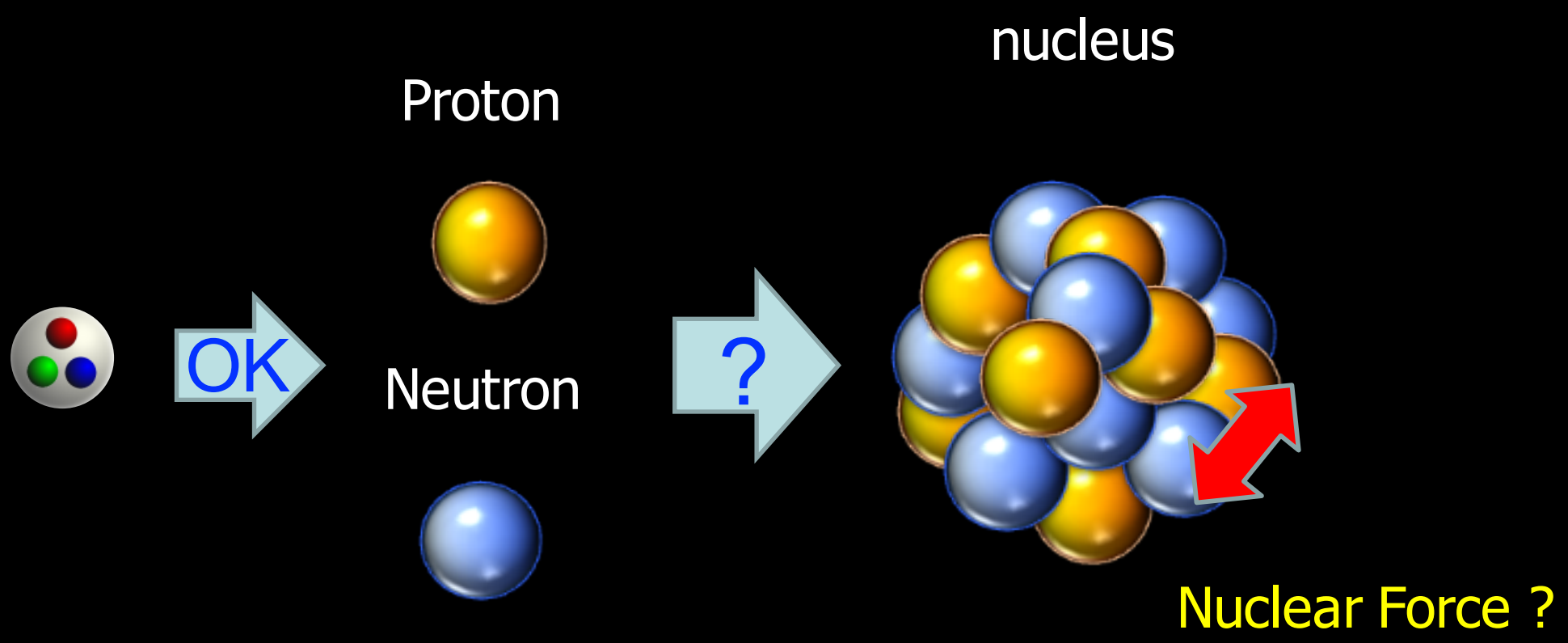
$m_{\pi,min}$ =190 MeV



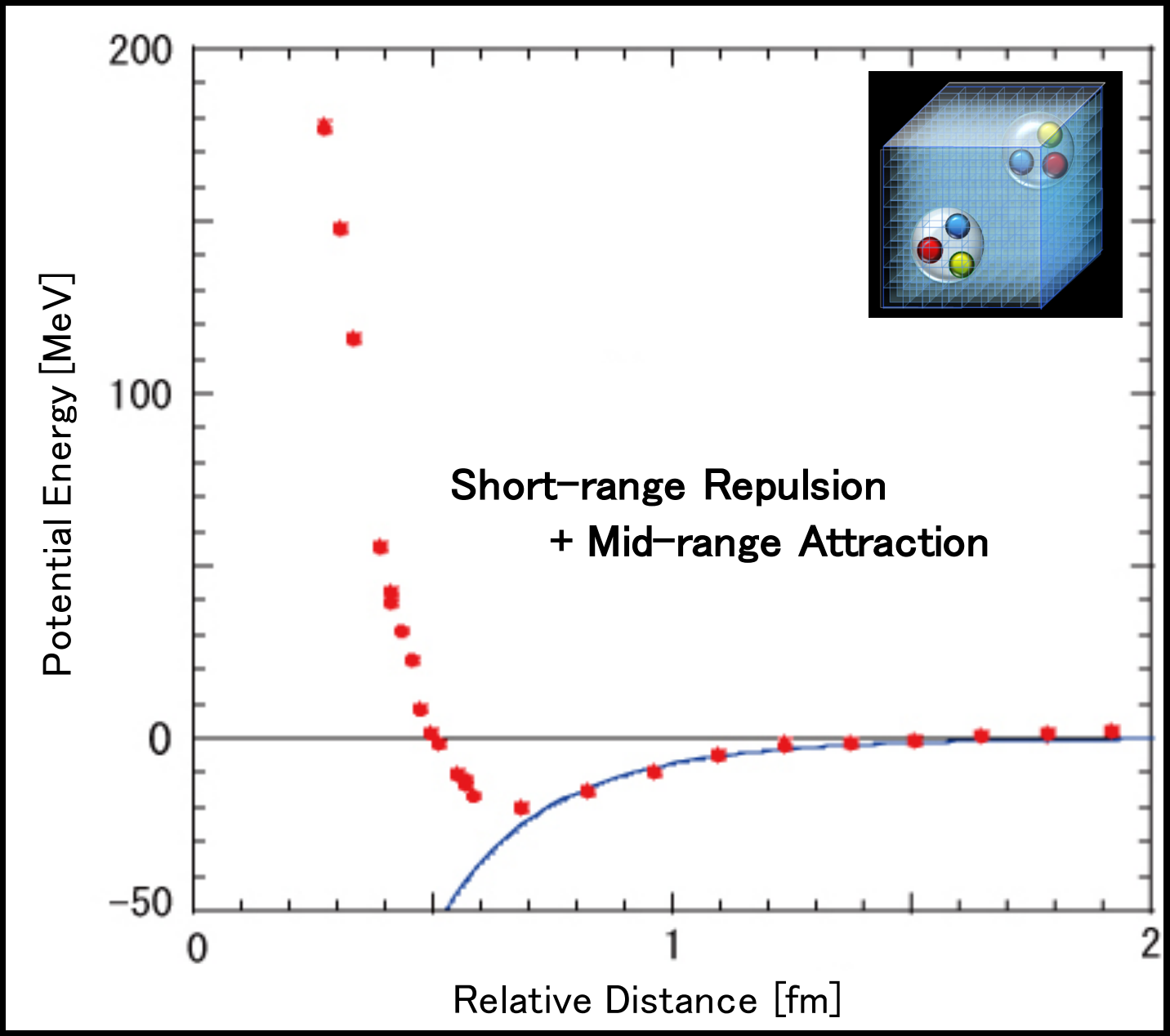
$(M_n - M_p)_{lat}$ = 1.51(16)(23) MeV

$(M_n - M_p)_{exp}$ = 1.29 MeV

From Nucleons to Nucleus

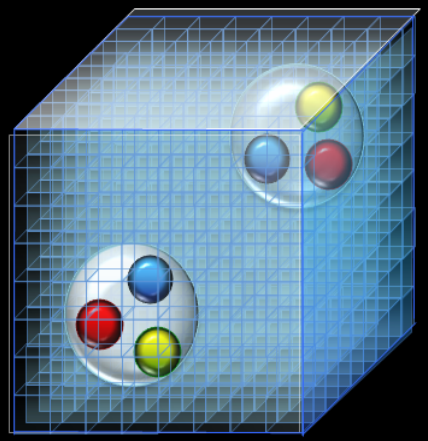


Nuclear Force from LQCD



Ishii, Aoki, Hatsuda, PRL (2007)

Large scale BB simulations with (2+1)-flavor LQCD



$a = 0.085$ fm

$L = 8.1$ fm

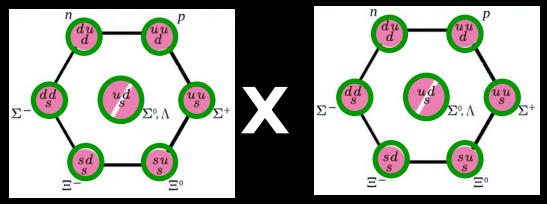
$m_\pi = 146$ MeV
$M_K = 525$ MeV

Hadrons to Atomic nuclei
HAL
from Lattice QCD

YITP:	S. Aoki, K. Sasaki, D. Kawai, T. Miyamato
RIKEN:	T. Doi, T.Hatsuda, T. Iritani, S. Gongyo, T.T. Doi
Nihon U.:	T. Inoue
RCNP:	Y. Ikeda, N. Ishii, K. Murano
U. Tsukuba:	H. Nemura
Birjand U.:	F. Etminan

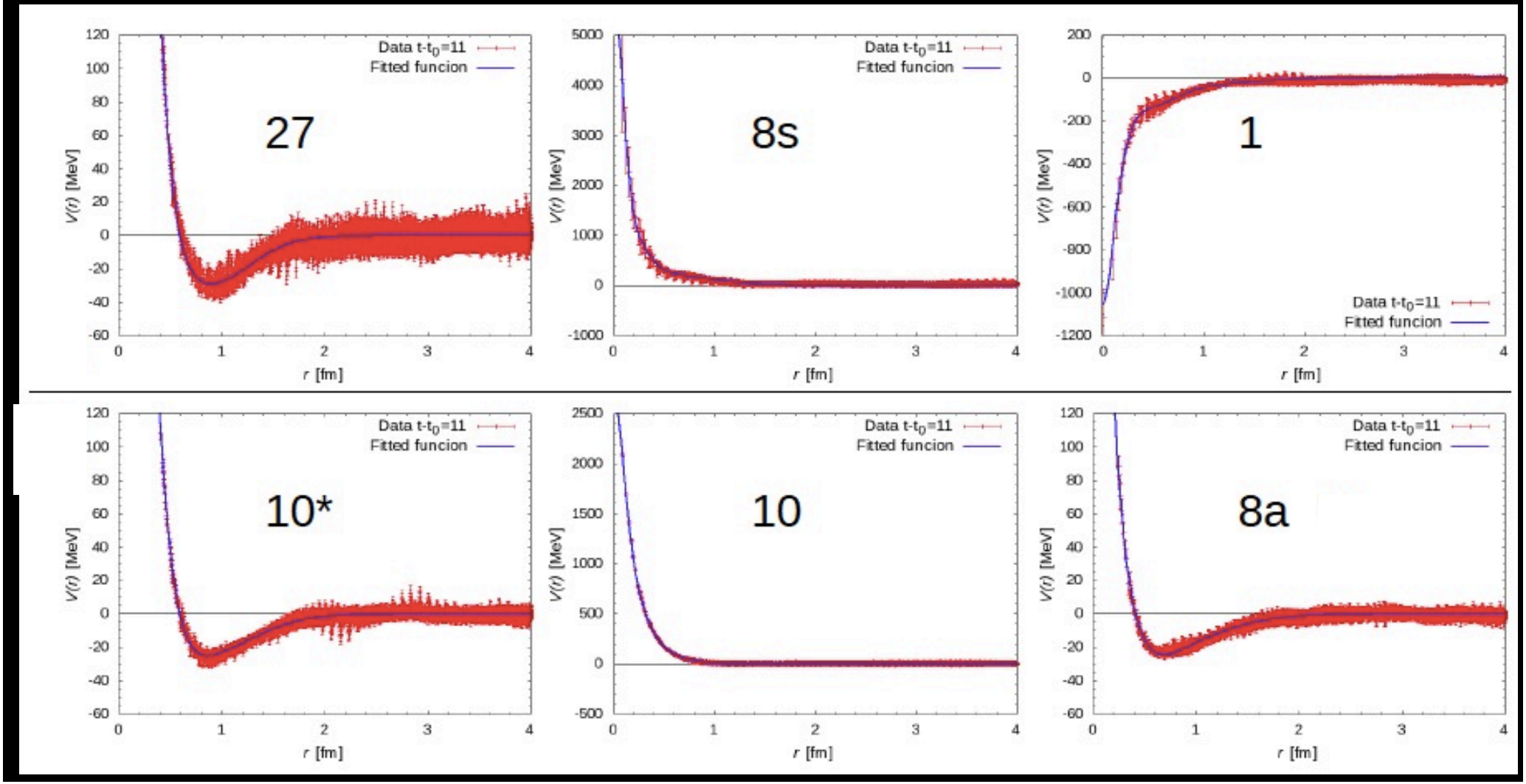
BB interactions in the flavor basis: $V_C(r)$

HAL QCD Coll.
preliminary



x

$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1\,,\ ^3D_1}$$



Structure of Neutron Stars

Observables

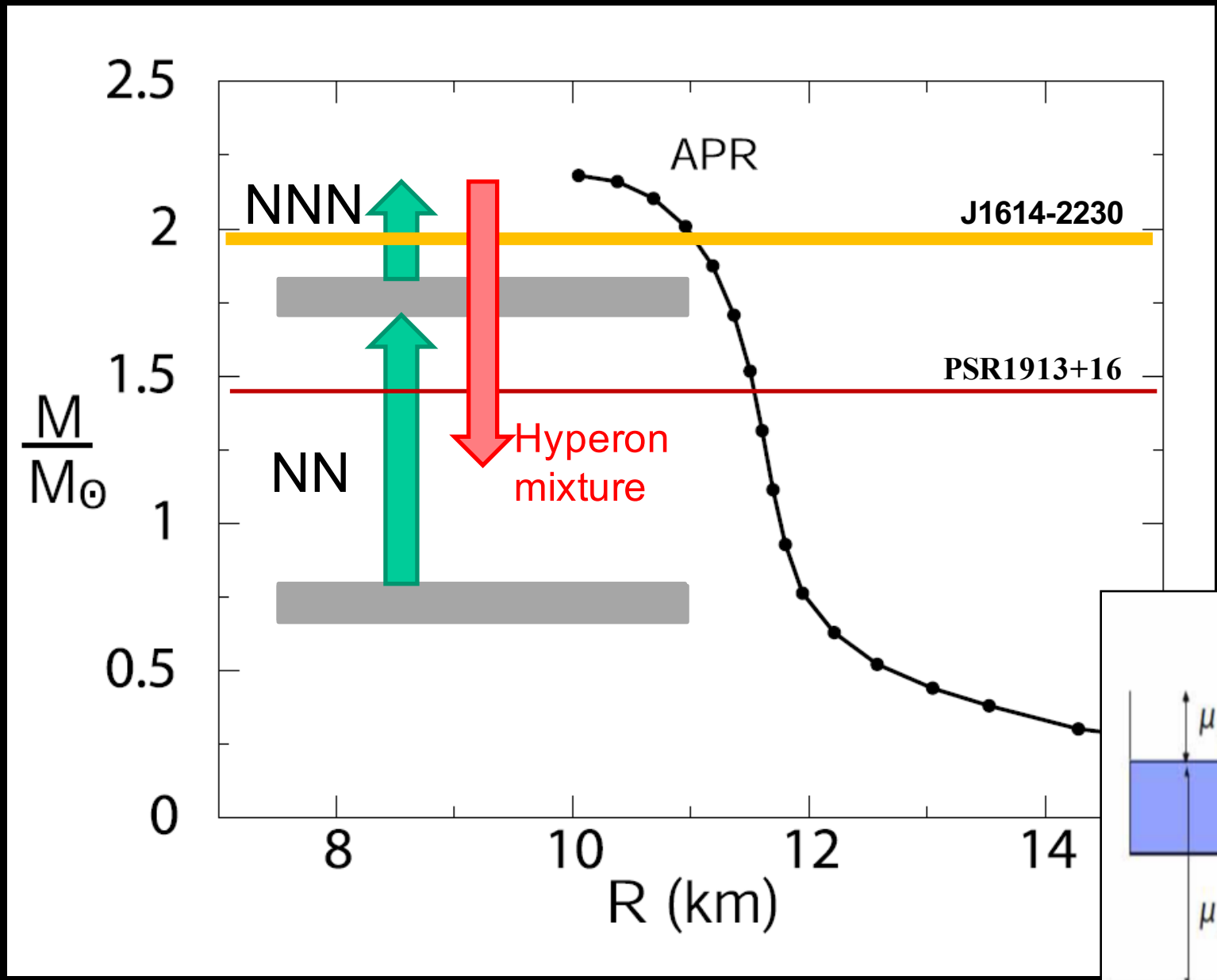
- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10$ km
- $T \sim 10^6\text{-}10^9$ K
- $B \sim 10^6\text{-}10^{15}$ G
- $P \sim 1$ ms-30 s
- $\Lambda < 800$
-

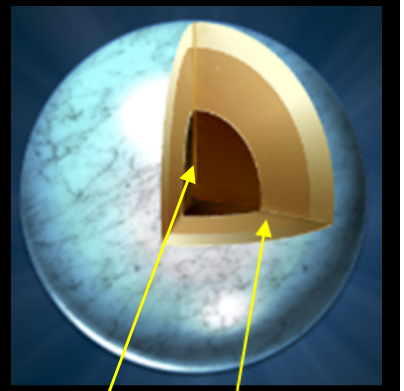
Astrophysics
Nuclear physics
Particle physics
Cond. Matt. physics

Matter under extreme condition

- Nuclear pasta
- Nuclear superfluid
- Meson condensate
- Hyperon liquid
- Quark liquid & CSC
-

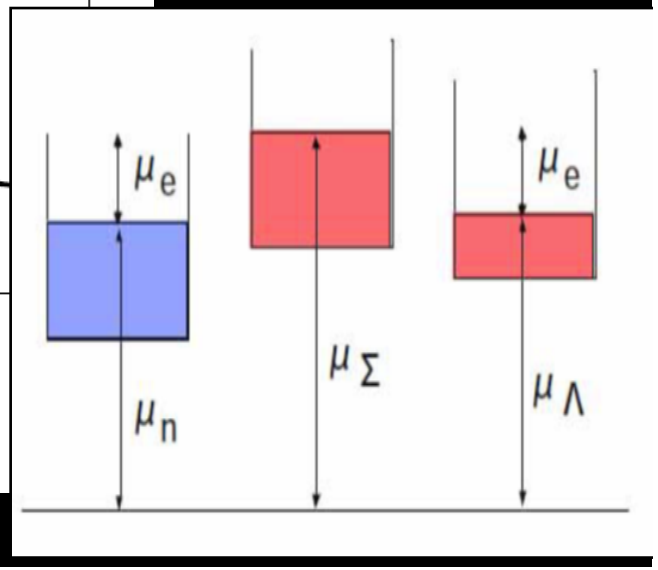
Hyperon Puzzle



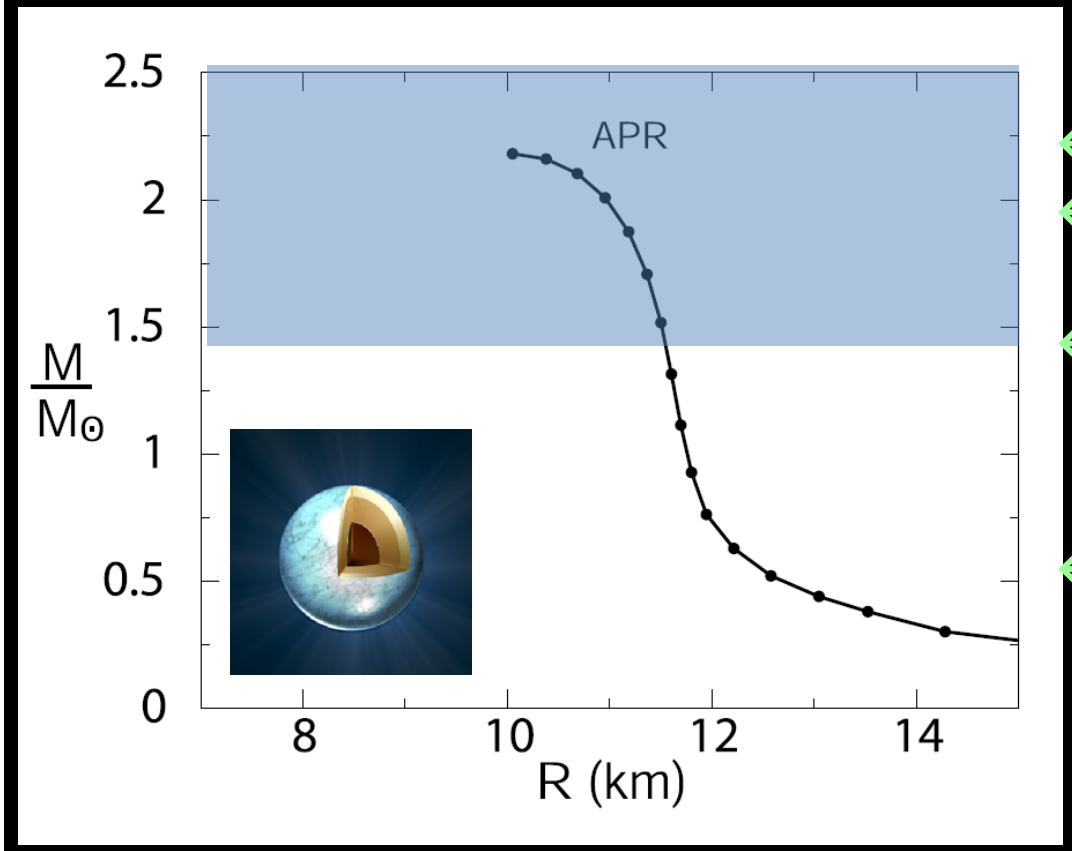


hyperons

neutrons



Nuclear EOS meaningful at high density ?



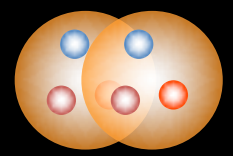
ρ_{center}

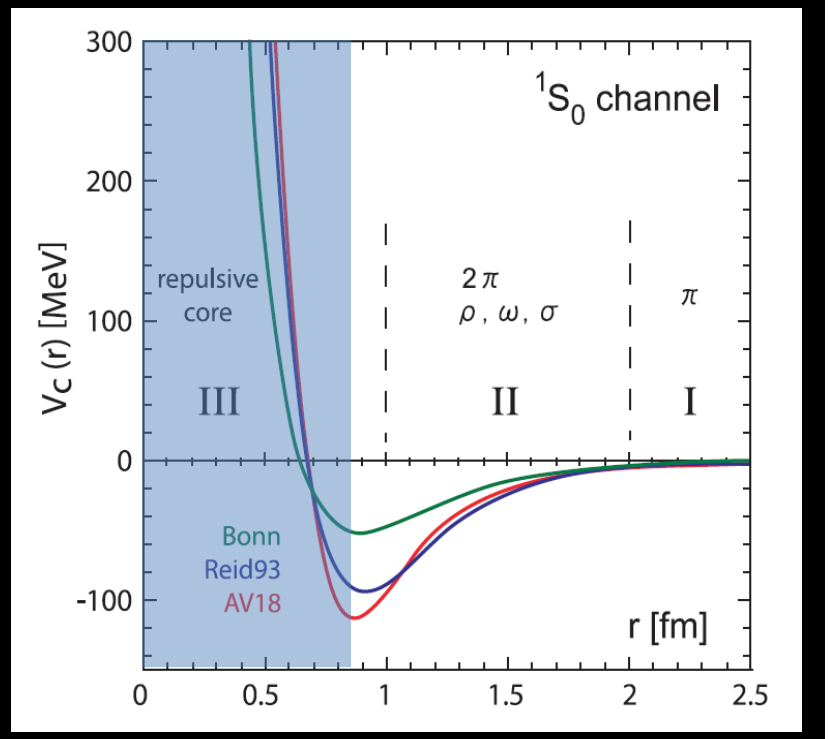
$\leftarrow 6\rho_0$

$\leftarrow 5\rho_0$

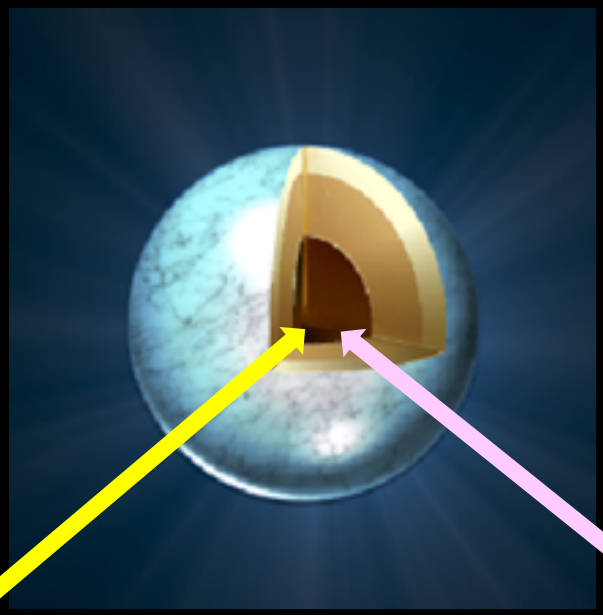
$\leftarrow 3.4\rho_0$

$\leftarrow 2\rho_0$

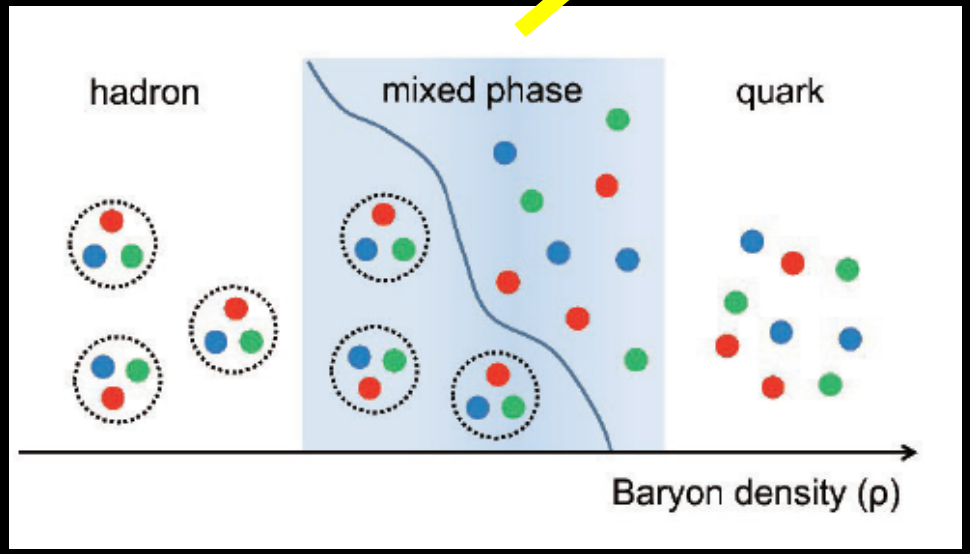


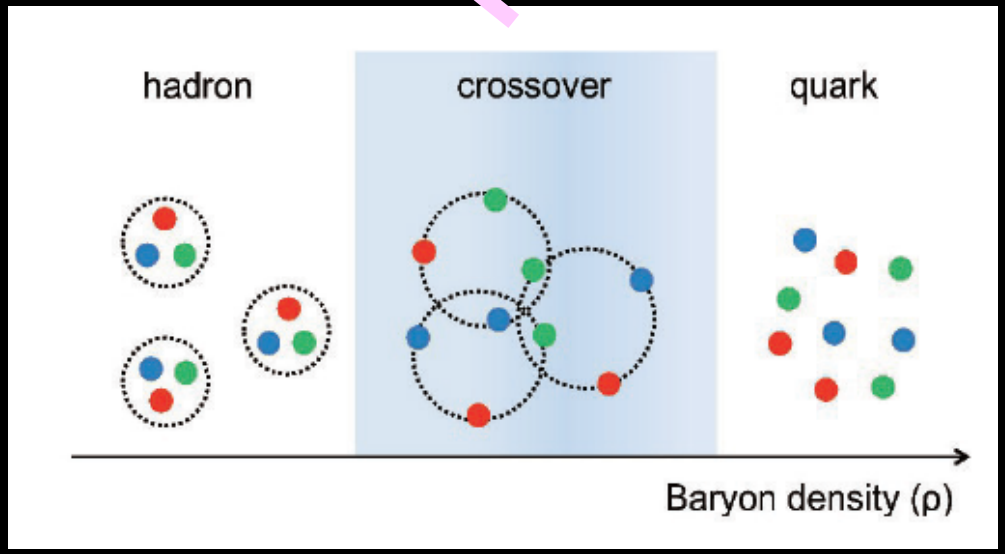


First order or crossover in dense matter ?

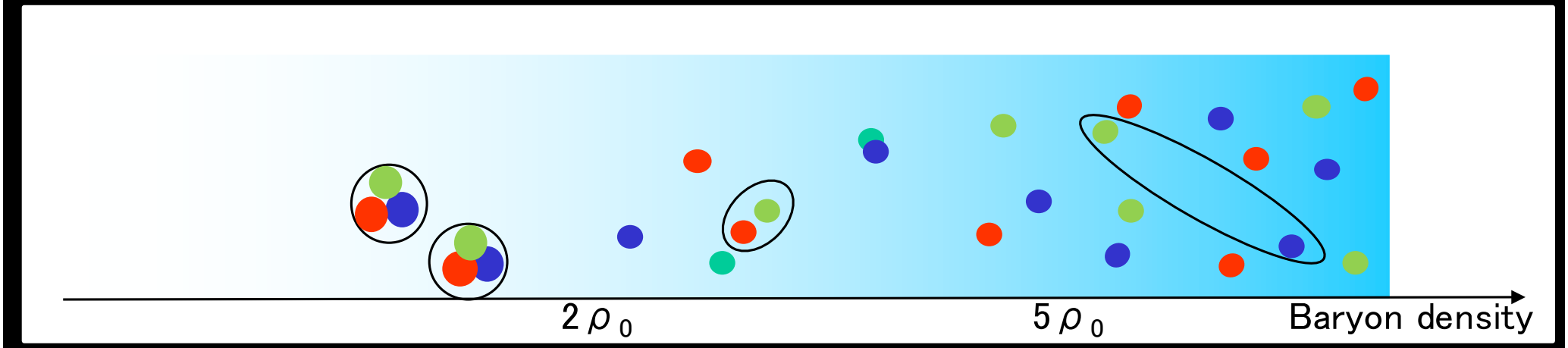


Baym & Chin (1976)





From Hadronic Matter to Quark Matter



Neutron Superfluid
Tamagaki (1970)
Hoffberg+ (1970)

Bose-Fermi mixture
Maeda, Baym & Hatsuda (2009)

Color Superconductivity
Alford, Rajagopal & Wilczek (1999)

Hadron-Quark Continuity

Schafer & Wilczek (1999), Fukushima (2004)
Hatsuda, Tachibana, Yamamoto & Baym (2006)

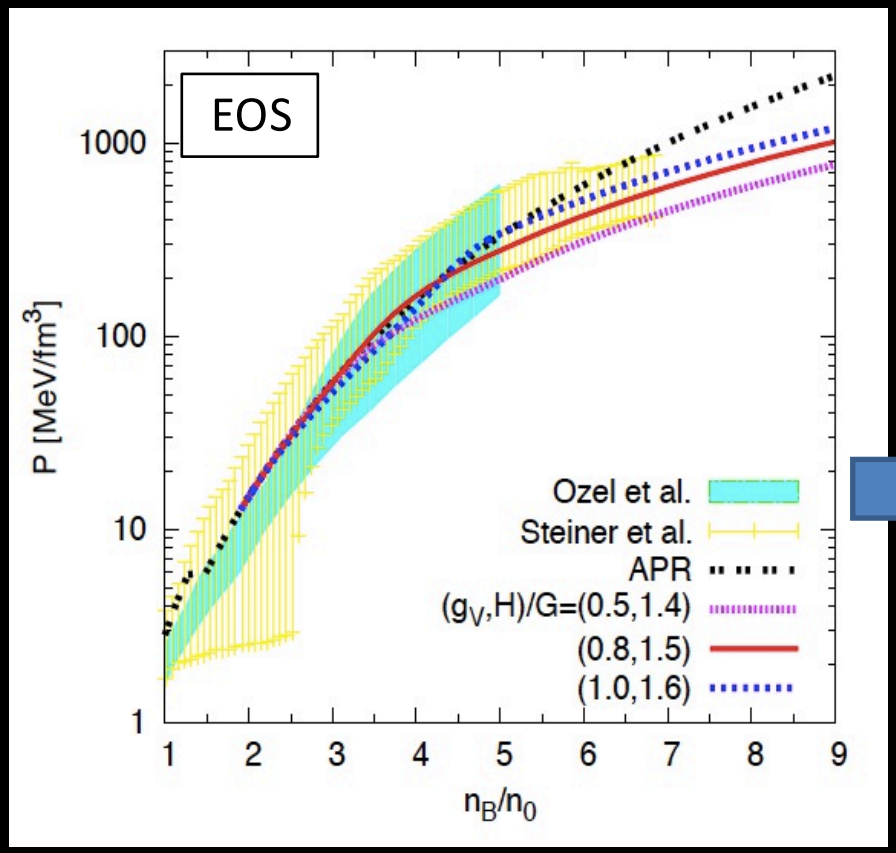
$$\mathcal{V}(\Phi, d) = \mathcal{V}_\chi(\Phi) + \mathcal{V}_d(d_L, d_R) + \mathcal{V}_{\chi d}(\Phi, d_L, d_R)$$

$$\Phi_{ij} \sim (\bar{q}_R)^j_a (q_L)^i_a$$

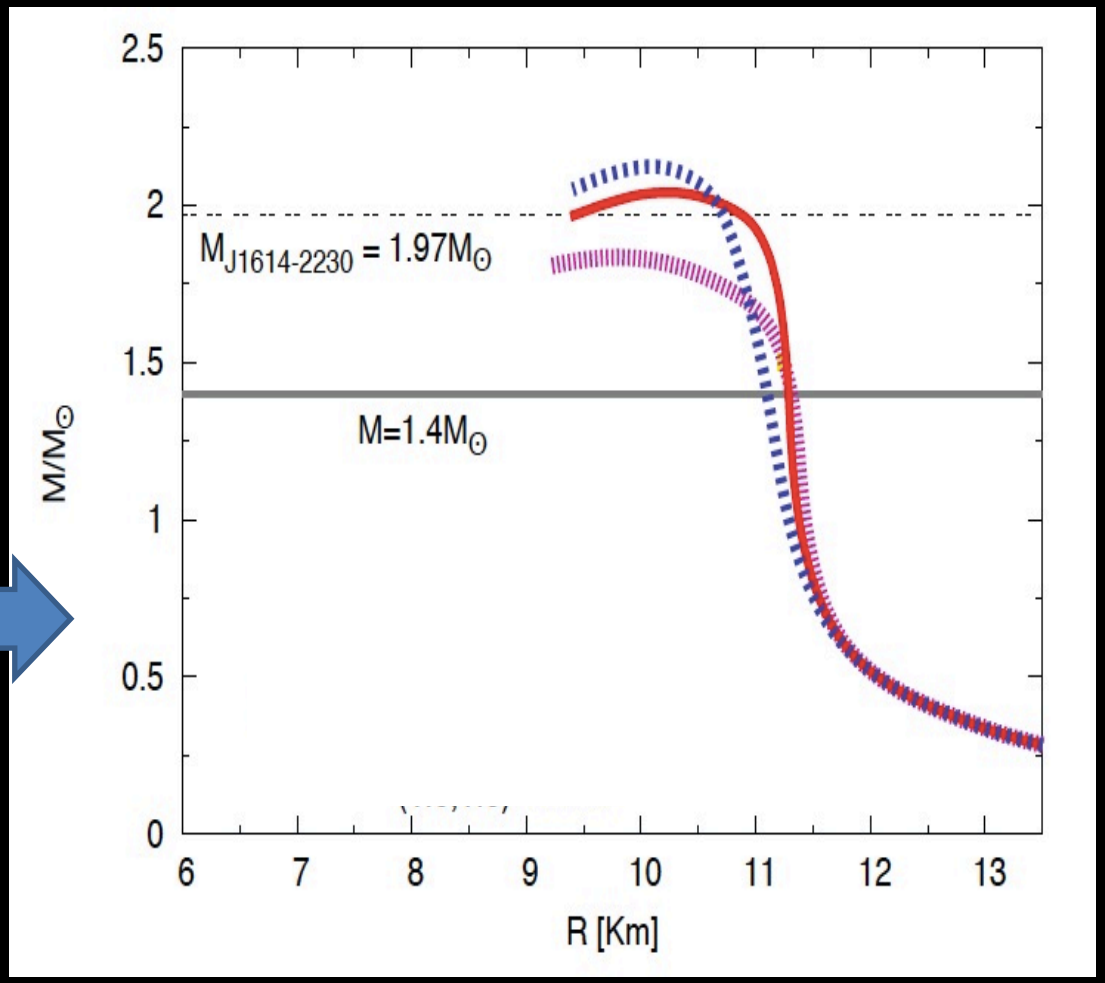
$$(d_L)_{ia} \sim \epsilon_{ijk}\epsilon_{abc}(q_L)^j_b C (q_L)^k_c$$

A Neutron star EOS with hadron-quark crossover: HQC18

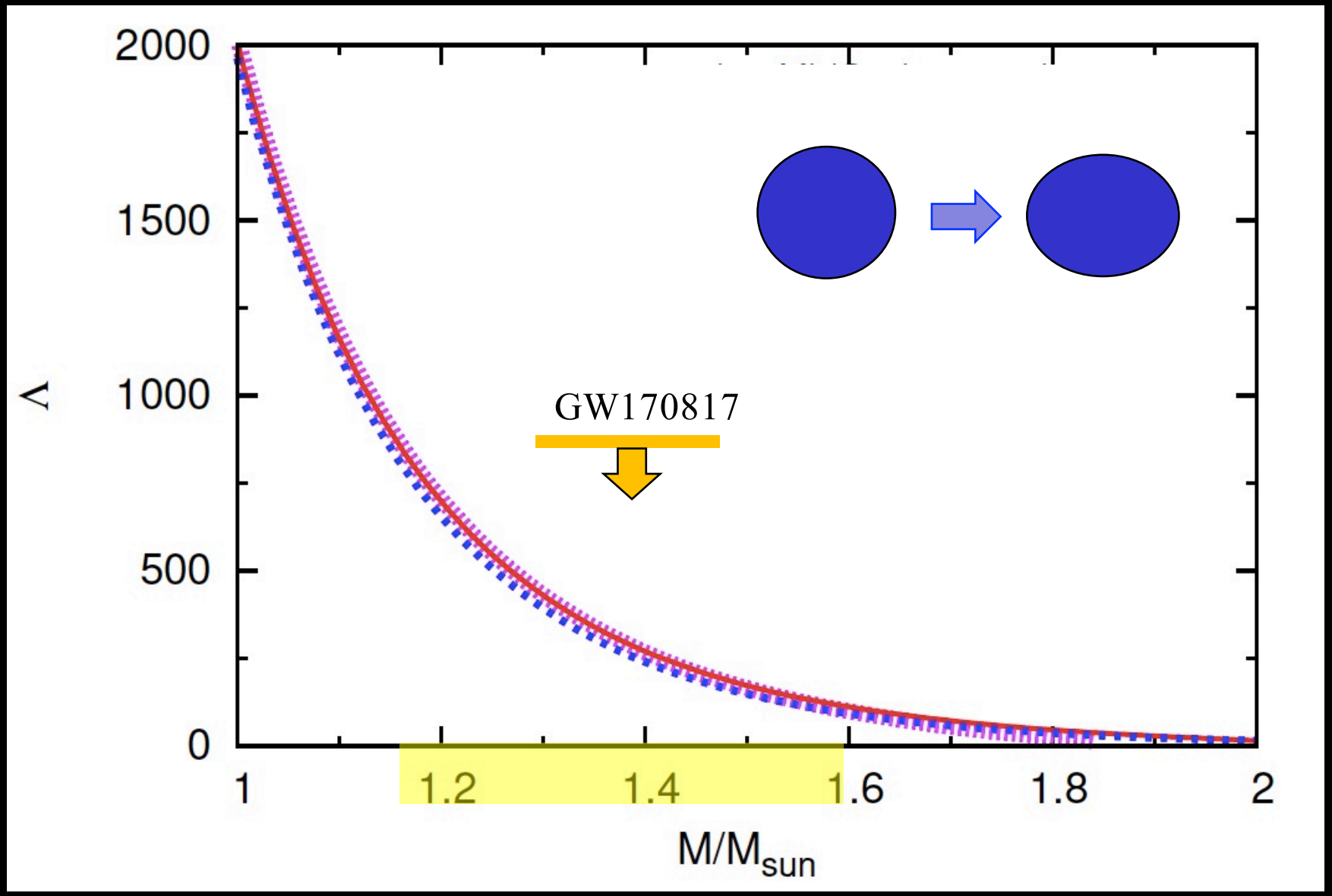
Baym, Hatsuda, Koji, Powell, Song, Takatsuka, 1707.04966 [astro-ph.HE]



M/M_s=2.9: Upper limit (Kalogera-Baym 1996)



Tidal deformability: $\Lambda = (2/3)\, k_2\, (R/M)^5$

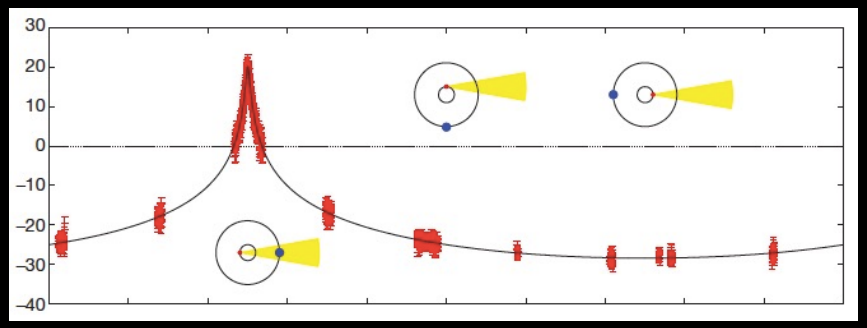


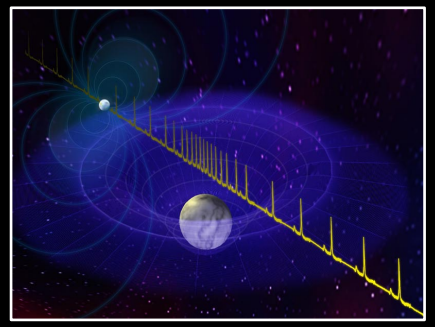
Baym, Hatsuda, Koji, (2018)

GR tools to measure M & R of neutron stars

- Shapiro delay from binary systems → M

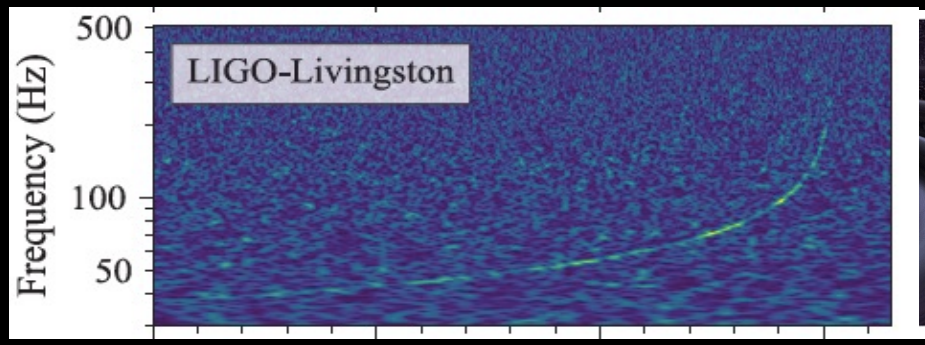
PSR J1614-2230
GBT-GUPPI
Nature (2010)

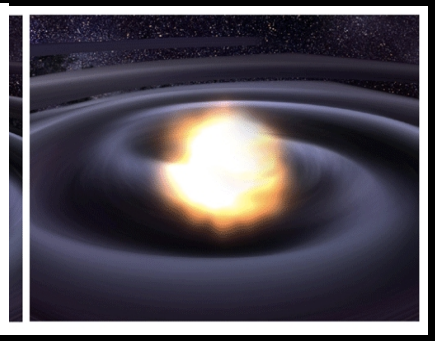




- Gravitational wave from NS mergers → M and R

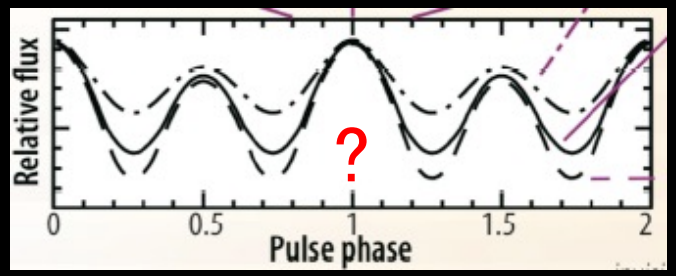
GW17817
LIGO-Virgo
Phys .Rev. Lett. (2017)

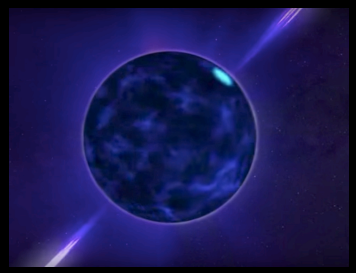




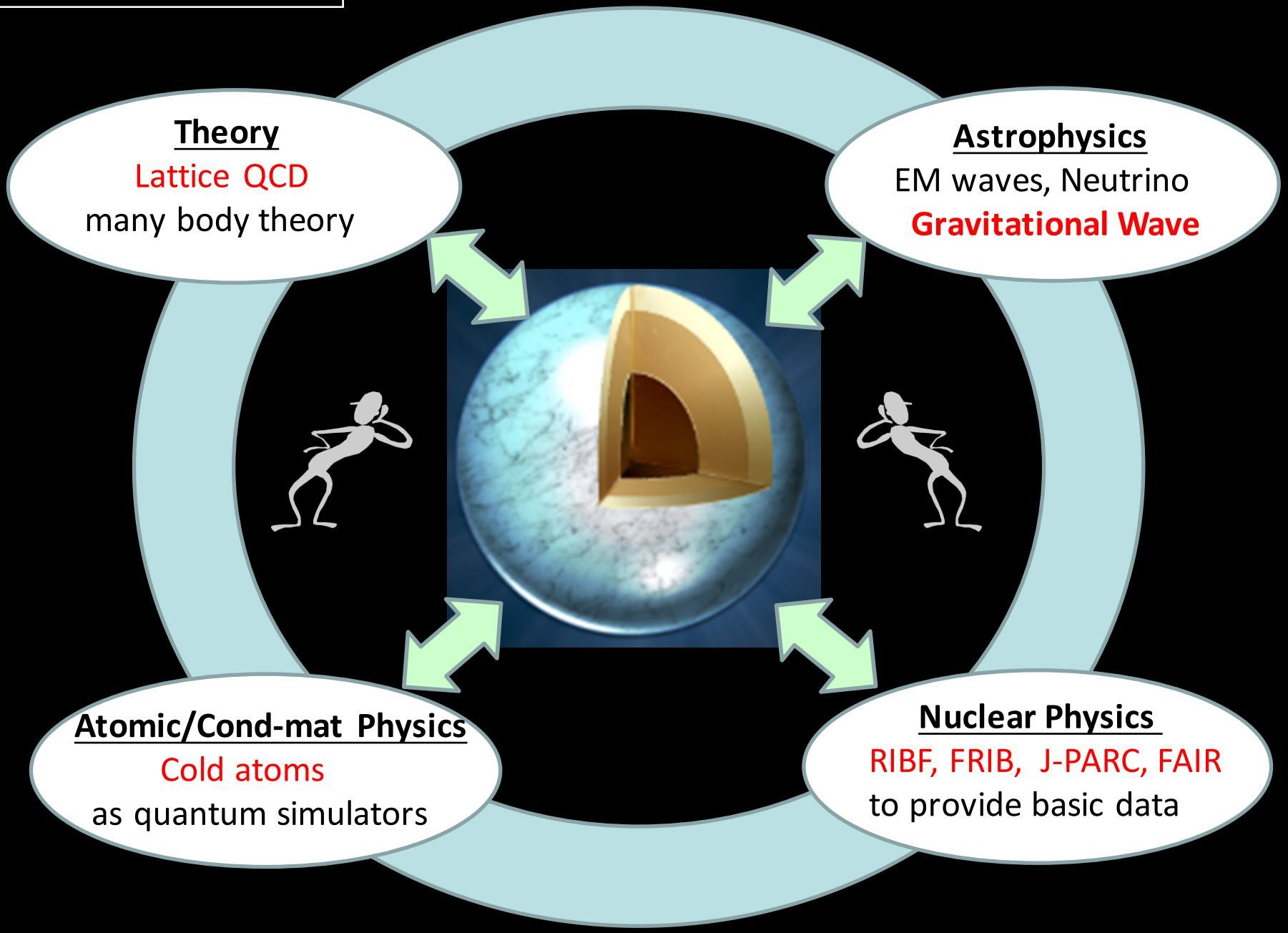
- Gravitational lensing from pulsars → M/R

NICER
(2018 ?)





Summary


Theory
Lattice QCD
many body theory
Astrophysics
EM waves, Neutrino
Gravitational Wave
Atomic/Cond-mat Physics
Cold atoms
as quantum simulators
Nuclear Physics
RIBF, FRIB, J-PARC, FAIR
to provide basic data