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### From Quarks to Neutron Stars

nucleon  $\sim 10^{-13}$  [cm]  
nucleus  $\sim 10^{-12}$  [cm]  
Neutron star  $\sim 10$  [km]

- From quarks to the nucleon
- From quarks to the nuclear force
- From quarks to neutron stars?
- Summary

References:  
- Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 83 (2018) 056902  
- Kojo, Baym, Hatsuda, Astrophys. J. 936 (2022) 46  
- Huang, Baiotti, Takami, Sotani, Togashi, Hatsuda, Nagataki, Fan, Phys. Rev. Lett. 122 (2022) 181101

### Structure of Neutron Star (NS)

Mass  $M \sim (1-2) M_{\odot}$   
Radius  $R \sim 10$  km  
Mass density  $\sim 10^{12}$  kg/cm<sup>3</sup>  $\sim$  several times atomic nuclei

### Color superconductivity

$(d_L)_{ia} \sim \epsilon_{ijk} \epsilon_{abc} (q_L)_b^j C(q_L)_c^k$   
 $(d_R)_{ia} \sim \epsilon_{ijk} \epsilon_{abc} (q_R)_b^j C(q_R)_c^k$

flavor color

2SC, uSC, dSC, CFL

2. Color-flavor entanglement  $d_{ia}$   $\rightarrow$  Various phases (c.f. Ice,  $^3\text{He}$ )  
2SC, uSC, dSC, CFL etc

### Visible Matter

Quark, Gluon, Nucleon, Atomic nucleus, Neutron star

10<sup>-13</sup> [cm], 10<sup>-12</sup> [cm], 10 [km]

QCD (Quantum Chromo Dynamics) = SU(3) gauge theory for color charges (B, R, G)

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

Symmetry:  
SU(3)<sub>c</sub> x SU(3)<sub>f</sub> x SU(3)<sub>c</sub> x U(1)<sub>b</sub>  
color, flavor

Proton, Neutron, Lambda

### Neutron Star (NS) observations

- 1932 Discovery of the neutron [J. Chadwick]
- 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. Demorest et al.]
- 2017 Discovery of GW from NS merger [LIGO/Virgo]
- 2019 Light bending around pulsar [NICER]

### CSC stiffens EOS

$$\epsilon = An^{4/3} + B - Cn^{2/3} + Dn^2 \quad (A \propto 1+2a/3\pi, C \propto a^2)$$

$$P = n^2 \frac{\partial(\epsilon/n)}{\partial n} = \frac{1}{3} An^{4/3} - B + \frac{1}{3} Cn^{2/3} + Dn^2$$

stiffer, softer

Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 83 (2018)

### Asymptotic Freedom and Color Confinement

two sides of a same coin

K. Wilson (1974) Gross, Wilczek, Politzer (1973)

$\alpha_s = g^2/4\pi t$

Color Confinement  $\sim 10^{-13}$  cm = 1 fm

Asymptotic Freedom

Matter under normal conditions, Matter under extreme conditions

Early Universe, Neutron Star Core

### Neutron Star (NS) observations

Özel and Freire, Annu. Rev. Astrophys. 54 (2016) 401  
Enoto, Kizuka, and Shibata, Rept. Prog. Phys. 82 (2019) 106901

### QHC21 EOS (Chiral EFT+NJL) vs. Observation (SD+GW+NICER)

Kojo, Baym, Hatsuda, Astrophys. J. 936 (2022) 46

$M/M_{\odot}$  vs  $R$  [km]

QHC21, M<sub>max</sub> + 6σ, A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub>, D<sub>1</sub>, Driscoll

### QCD phase diagram (realistic (2+1)-flavor)

T [MeV  $\sim 10^{10}$  K],  $\mu_Q$  [MeV]

LHC @ CERN, RHIC @ BNL

156 ± 1.5 MeV Critical Point

Quark-Gluon Plasma, Hadronic Phase, Quarkyonic Matter, Color Superconductors

Nuclear Superfluid  $\sim 400$  MeV?

### Structure of Neutron Stars

Observables:  $M \sim (1-2) M_{\odot}$ ,  $R \sim 10$  km,  $T \sim 10^6-10^9$  K,  $B \sim 10^6-10^{15}$  G,  $P \sim 1$  ms-10 s

Matter under extreme condition: Nuclear pasta, Nuclear superfluid, Meson condensate, Hyperon liquid, Quark liquid & CSC

Astrophysics, Nuclear physics, Particle physics, Cond. Matt. physics

### Transition from baryonic matter to color-superconducting quark matter

$\leftrightarrow$  post-merger GW frequency

Next-generation GW detectors in kHz band with  $\sim 50$ Hz resolution

- upgrade of Advanced LIGO and advanced Virgo
- Einstein Telescope
- Cosmic Explorer
- NEMO

### From Quarks to Neutron Stars

Quantum Chromodynamics

Lattice QCD, Sign problem, Baryon Interactions, Many-body Theory

Hot Equation of State, Cold Equation of State

Relativistic Hydrodynamics, Heavy Ion Collisions, General Relativity, Neutron Stars

### From Hadronic Matter to Quark Matter

$T$  vs  $\mu_B$

Strongly interacting baryonic matter, Strongly interacting quark matter

Hadron-Quark Crossover?

Same SSB pattern  $(G = \text{SU}(3)_c \times \text{SU}(3)_f \times \text{U}(1)_b \rightarrow \text{SU}(3)_{c+f})$ : Schuler and Wilczek, PRL 82 (1999)  
Hatsuda, Tachibana, Yamamoto, Baym, PRL 82 (2006)  
Mouhalla, Hatsuda, Takatsuka, Astrophysical J. 681 (2013)

### Summary

Theory: Quantum Chromodynamics + many body theory

Cosmic Observation: Gravitational wave, Electromagnetic wave, Neutrino

Condensed Matter: Liquid helium, Unitary fermi gas, Bose-Fermi mixture

Nuclear Physics: Nuclear collisions, RIBF, J-PARC, FAIR, HIAF