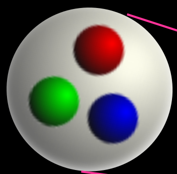
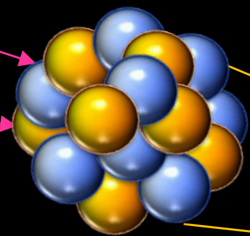
From Quarks to Neutron Stars

Tetsuo Hatsuda (RIKEN iTHEMS)

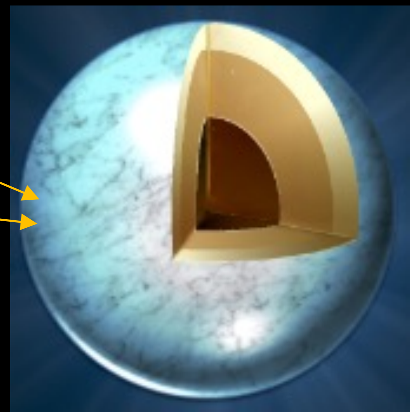
nucleon ~10^{-13} [cm]



nucleus ~10^{-12} [cm]



Neutron star ~10 [km]

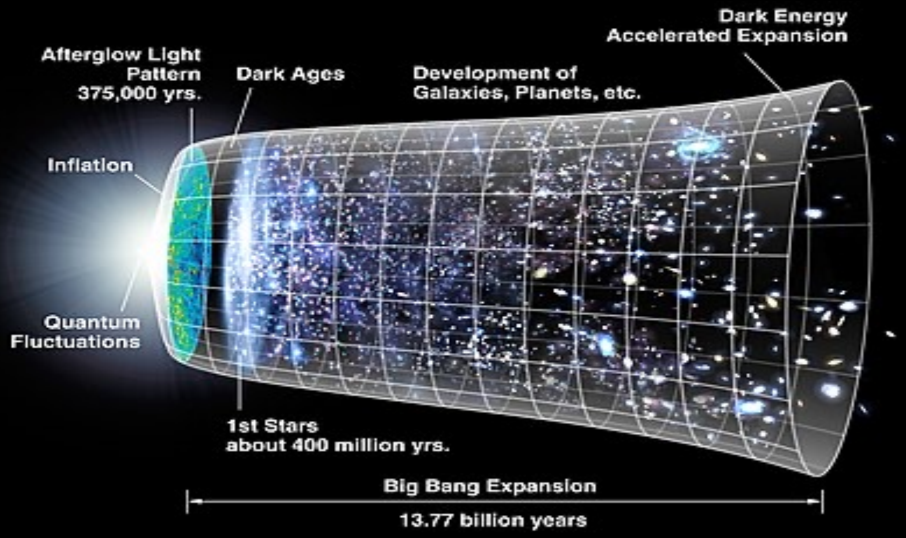


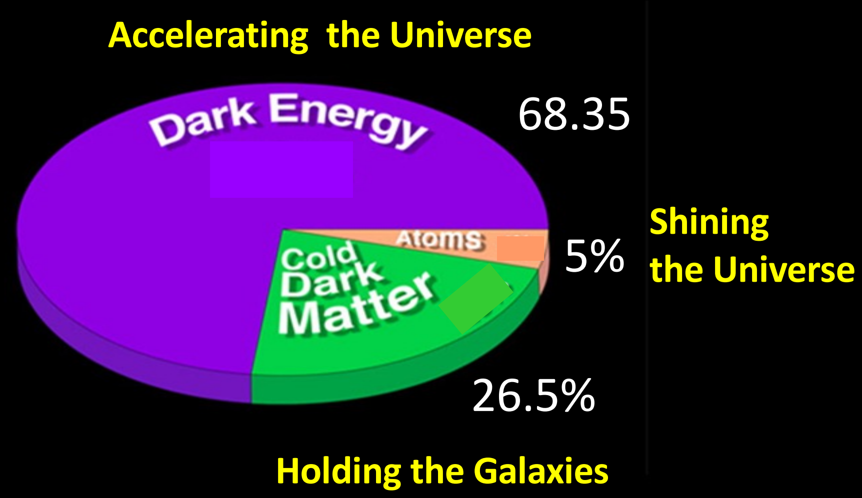
1. From quarks to the nucleon
2. From quarks to the nuclear force
3. From quarks to neutron stars ?
4. Summary

References

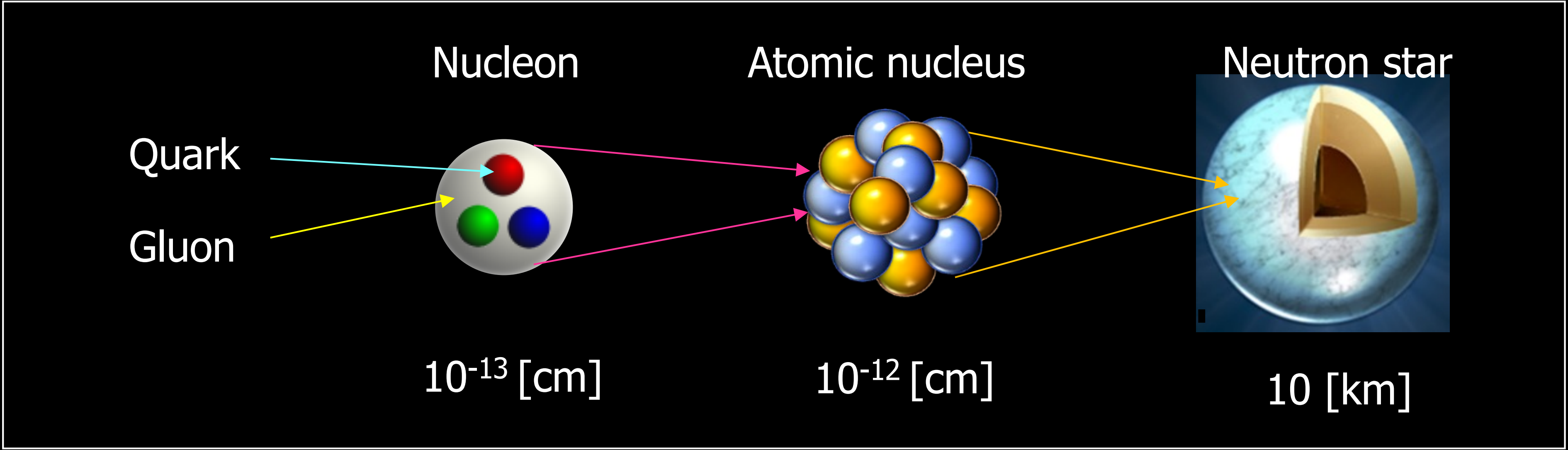
- Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902
- Kojo, Baym, Hatsuda, Astrophys. J. 936 (2022) 46
- Huang, Baiotti, Takami, Sotani, Togashi, Hatsuda, Nagataki, Fan, Phys, Rev. Lett. 129 (2022) 181101

Visible Matter





Visible Matter



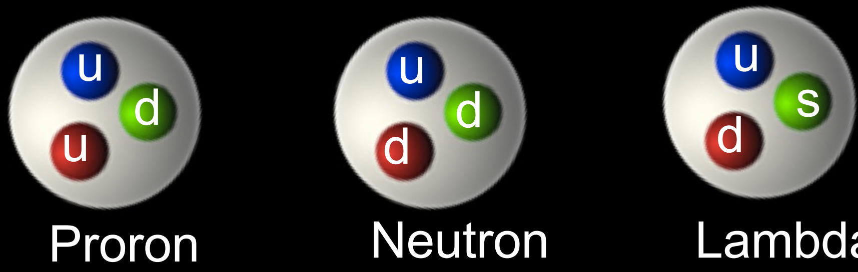
QCD (Quantum Chromo Dynamics) = SU(3) gauge theory for color charges (**B**, **R**, **G**)

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

Symmetry:

$SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_B$

color flavor

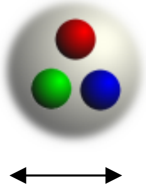


Asymptotic Freedom and Color Confinement
-- two sides of the same coin --

K. Wilson (1974)

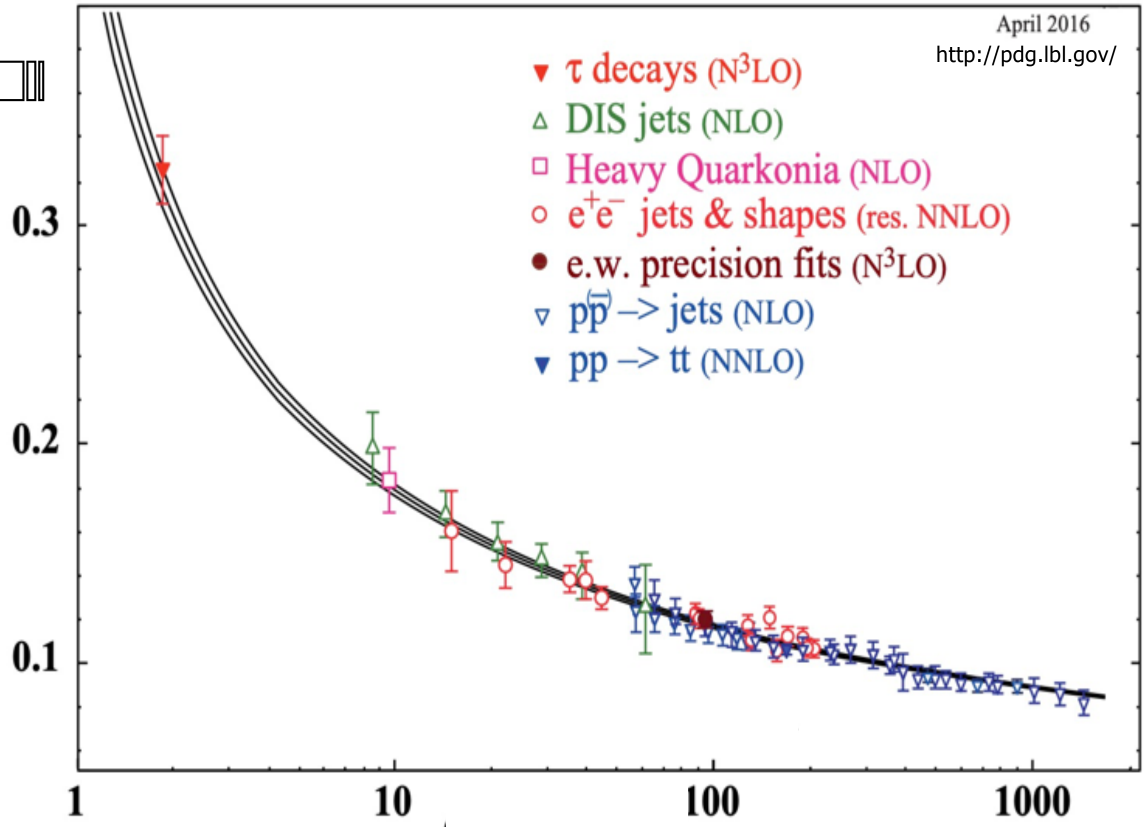
Gross, Wilczek, Politzer (1973)

Color Confinement



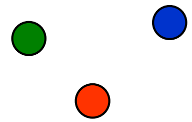
~ 10^{-13} cm
= 1 fm

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



κ [GeV]

Asymptotic Freedom



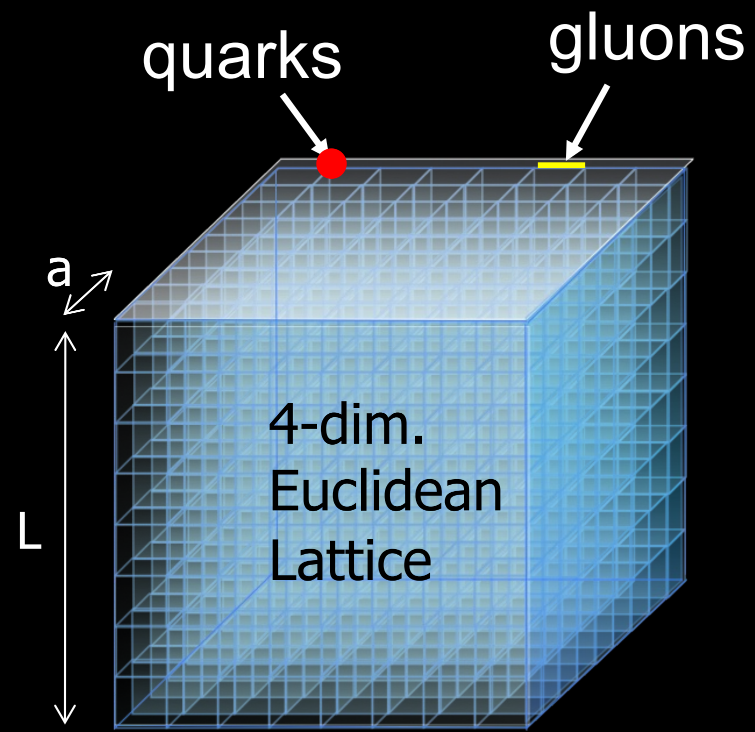
Matter under normal conditions

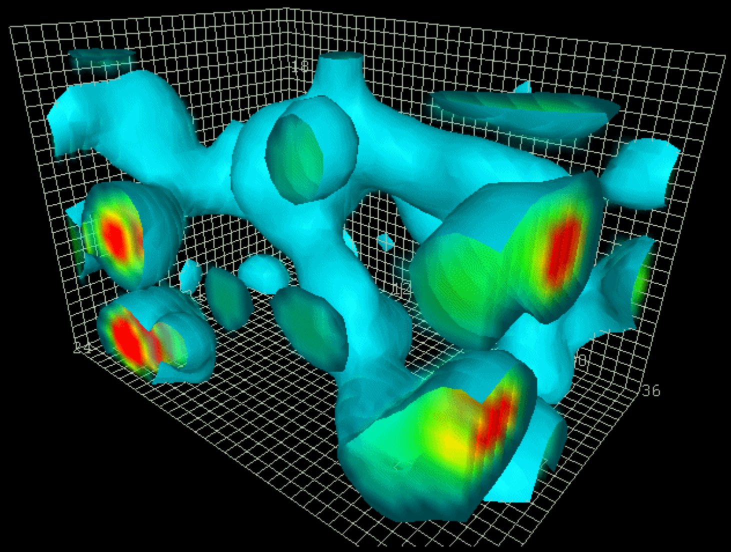
Matter under extreme conditions

- Early Universe
- Neutron Star Core

Lattice QCD : Numerical Approach

K. Wilson (1974)





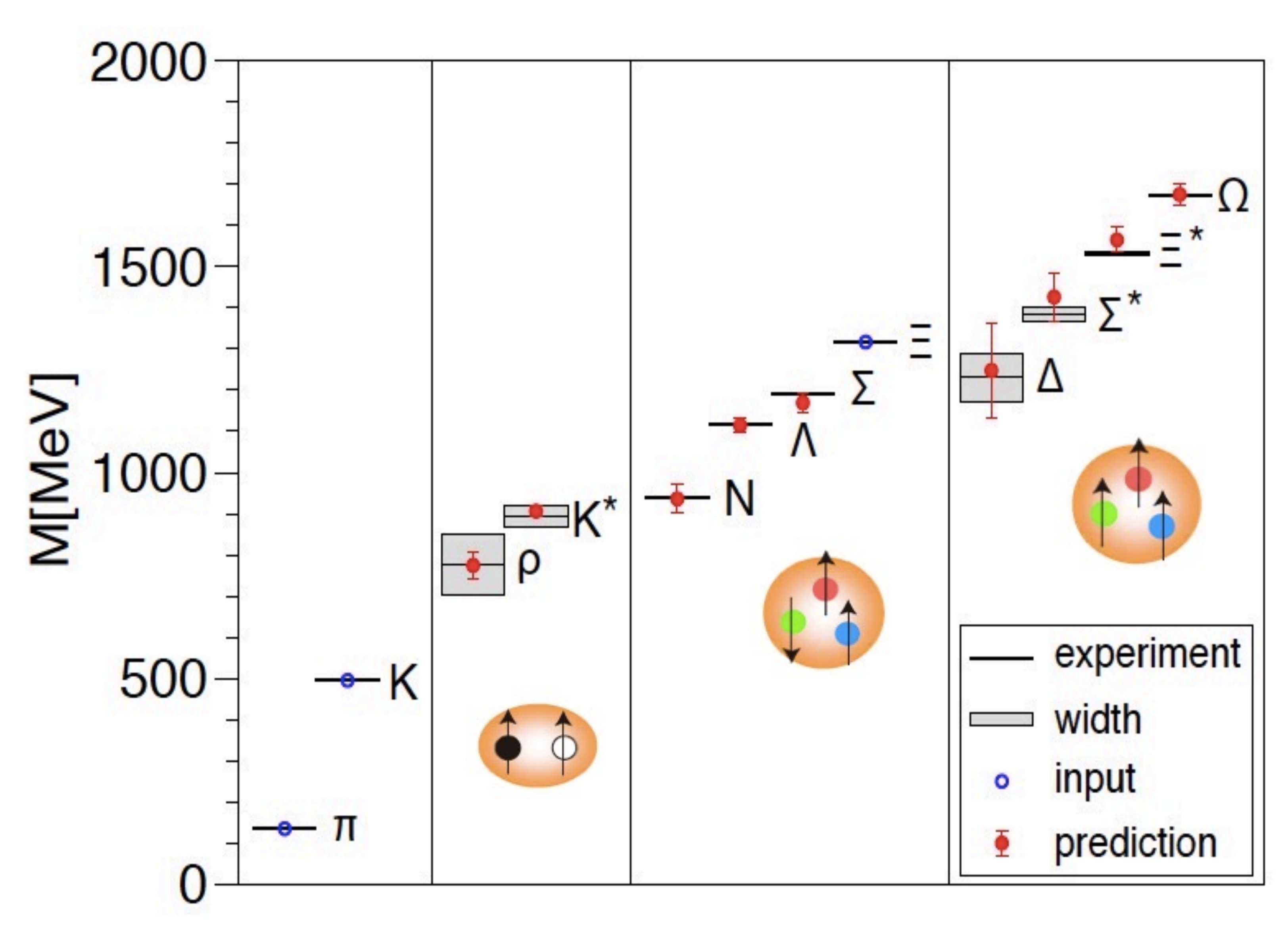
http://www.physics.adelaide.edu.au/theory/staff/leinweber
/VisualQCD/Nobel/index.html

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

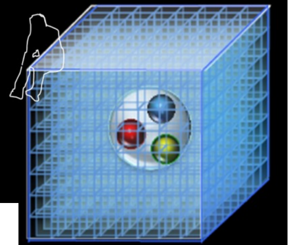
10^9 dimensional integral (for a=0.01 fm, L=10 fm)

→ Monte Carlo integration on supercomputers

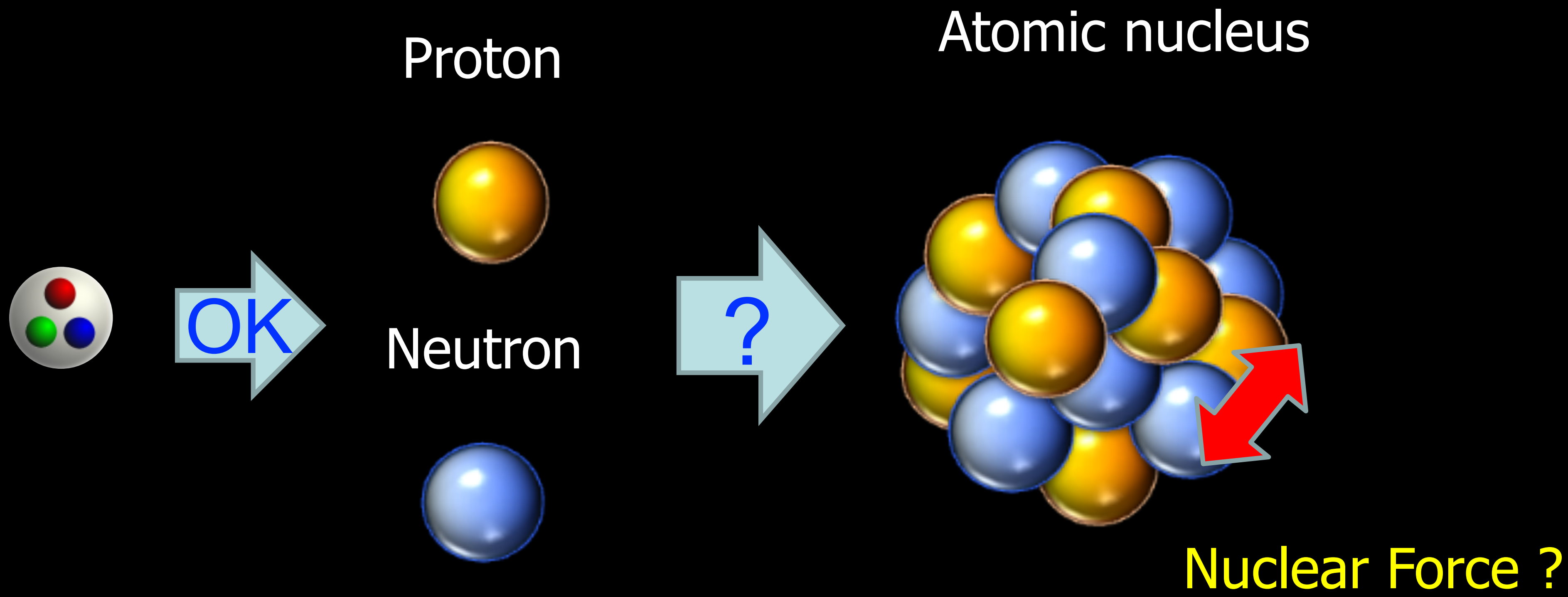
Hadron masses from LQCD



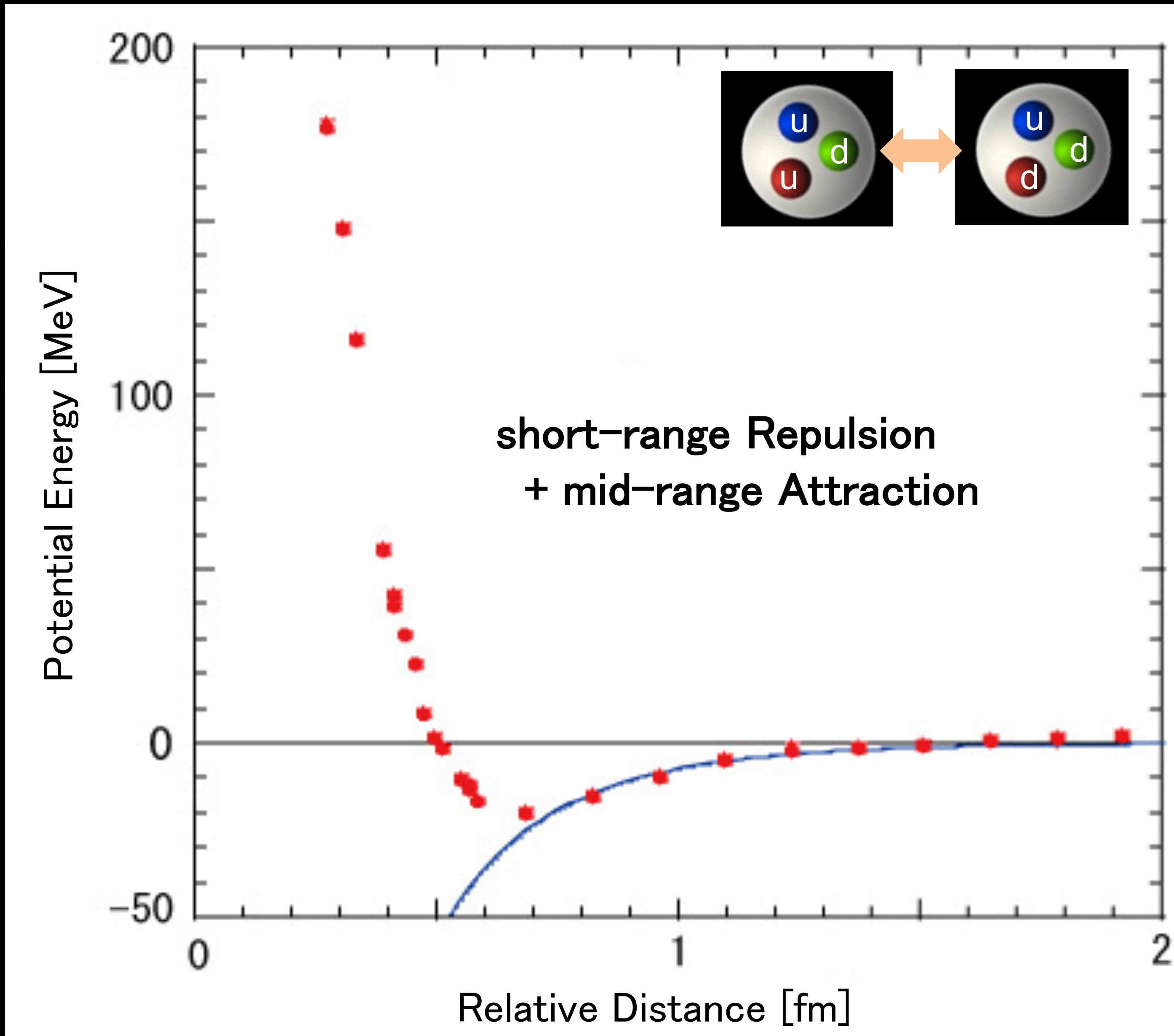
Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

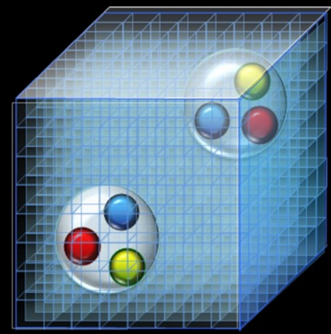


From Nucleons to Atomic Nuclei



Nuclear Force from lattice QCD

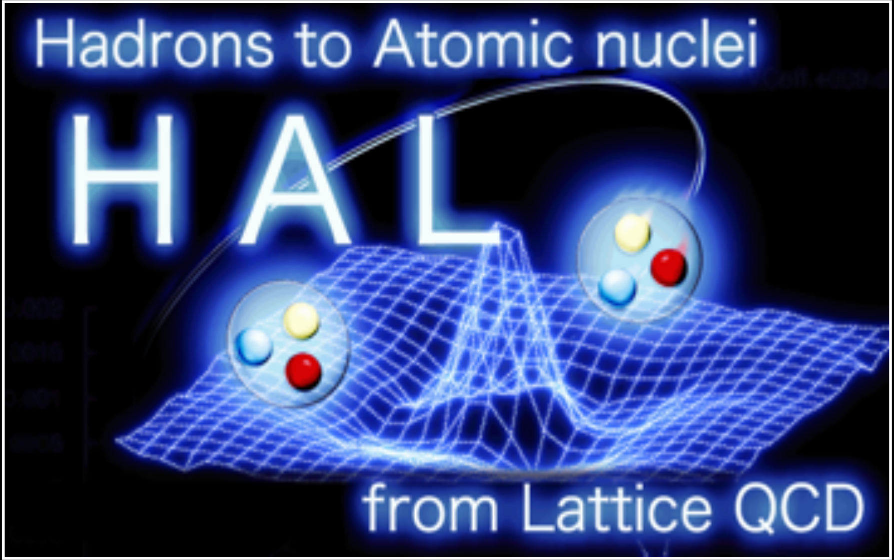




m_π=530 MeV

Ishii, Aoki, Hatsuda, PRL 99 (2007) 022001

Realistic force between hadrons from LQCD



(KEK) T. Aoyama

(RIKEN) T. Doi, T. Hatsuda, T. Sugiura

(Nihon) T. Inoue

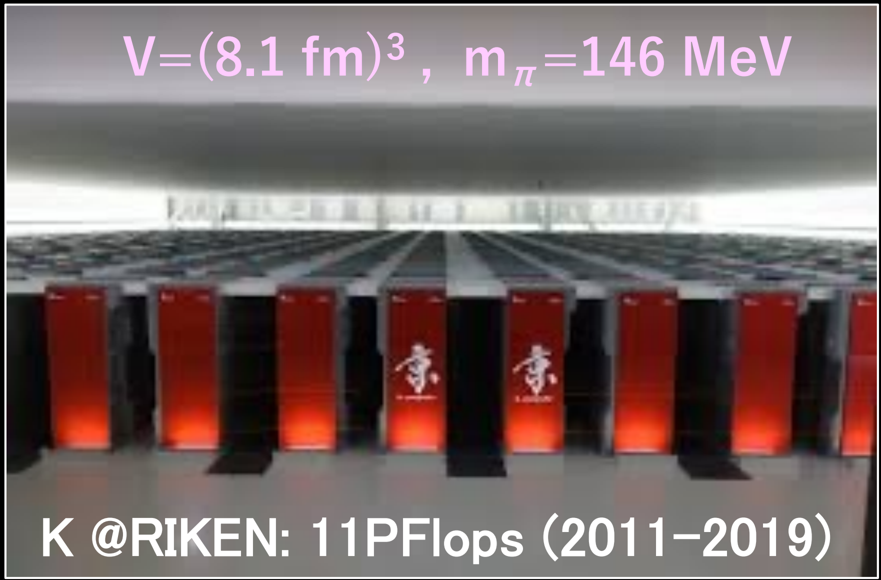
(YITP) Y. Akahoshi, S. Aoki, K. Murakami

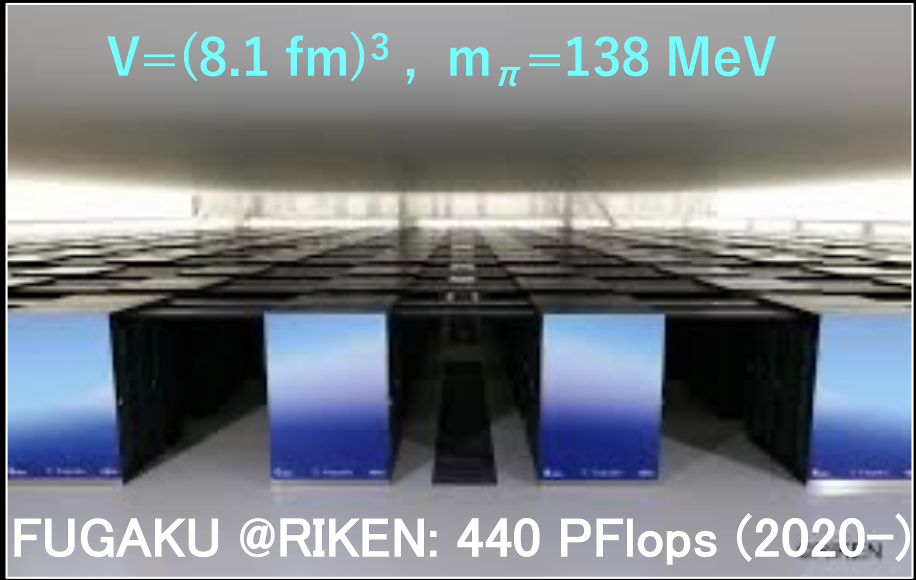
(RCNP) T. M. Doi, N. Ishii, K. Murano, H. Nemura

(Osaka) Y. Ikeda, K.Sasaki

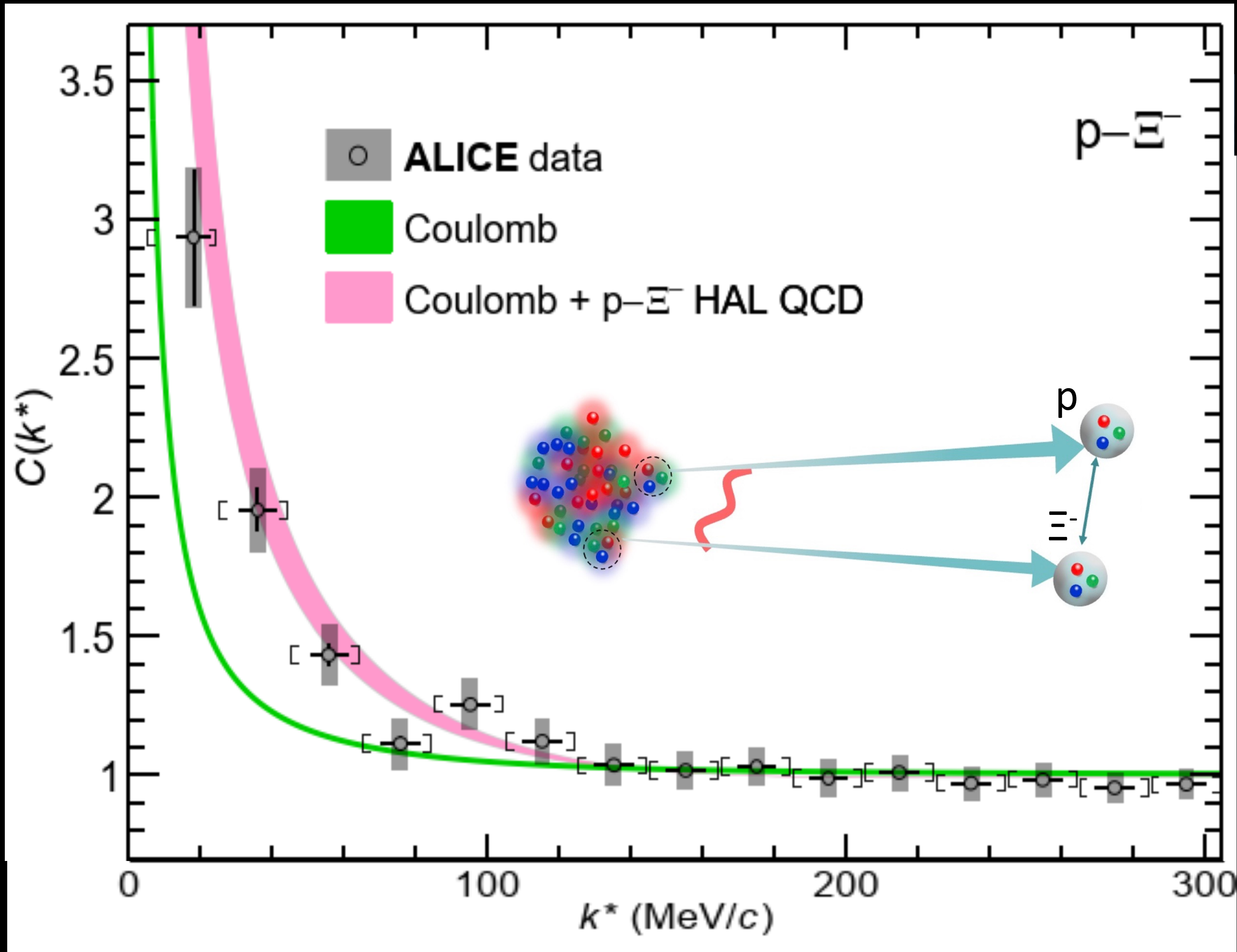
(Birjand) F. Etminan

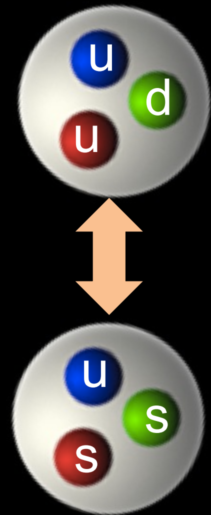
(Beijing) Yan Liu, Hui Tong





Femtoscopy: momentum correlation in high-energy collisions





Sasaki+ [HAL QCD Coll.] Nucl. Phys. A998 (2020) 121737
LHC ALICE Coll., Nature 588 (2020) 232

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-- two sides of a same coin --

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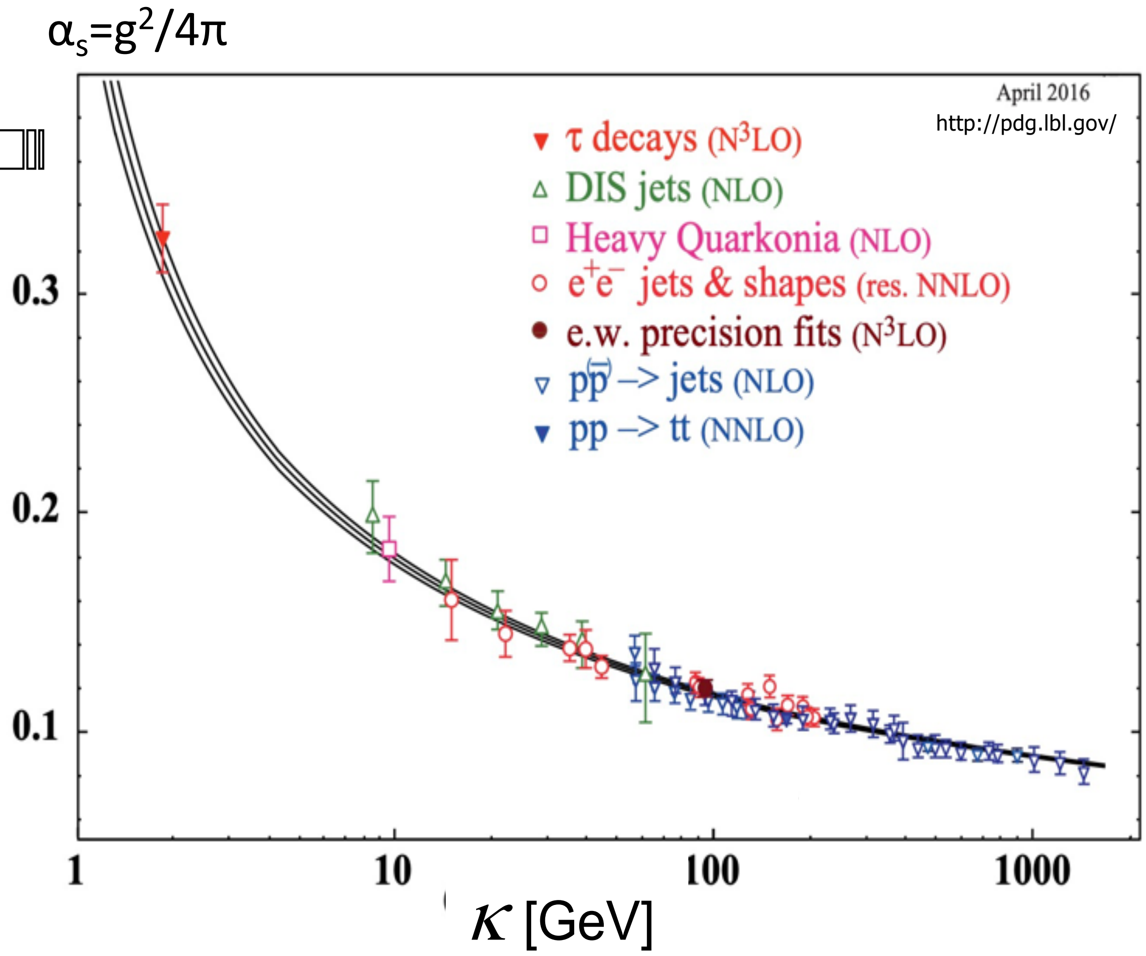
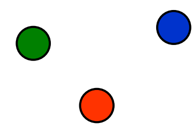
Color Confinement

~ 10^{-13} cm
= 1 fm



Asymptotic Freedom



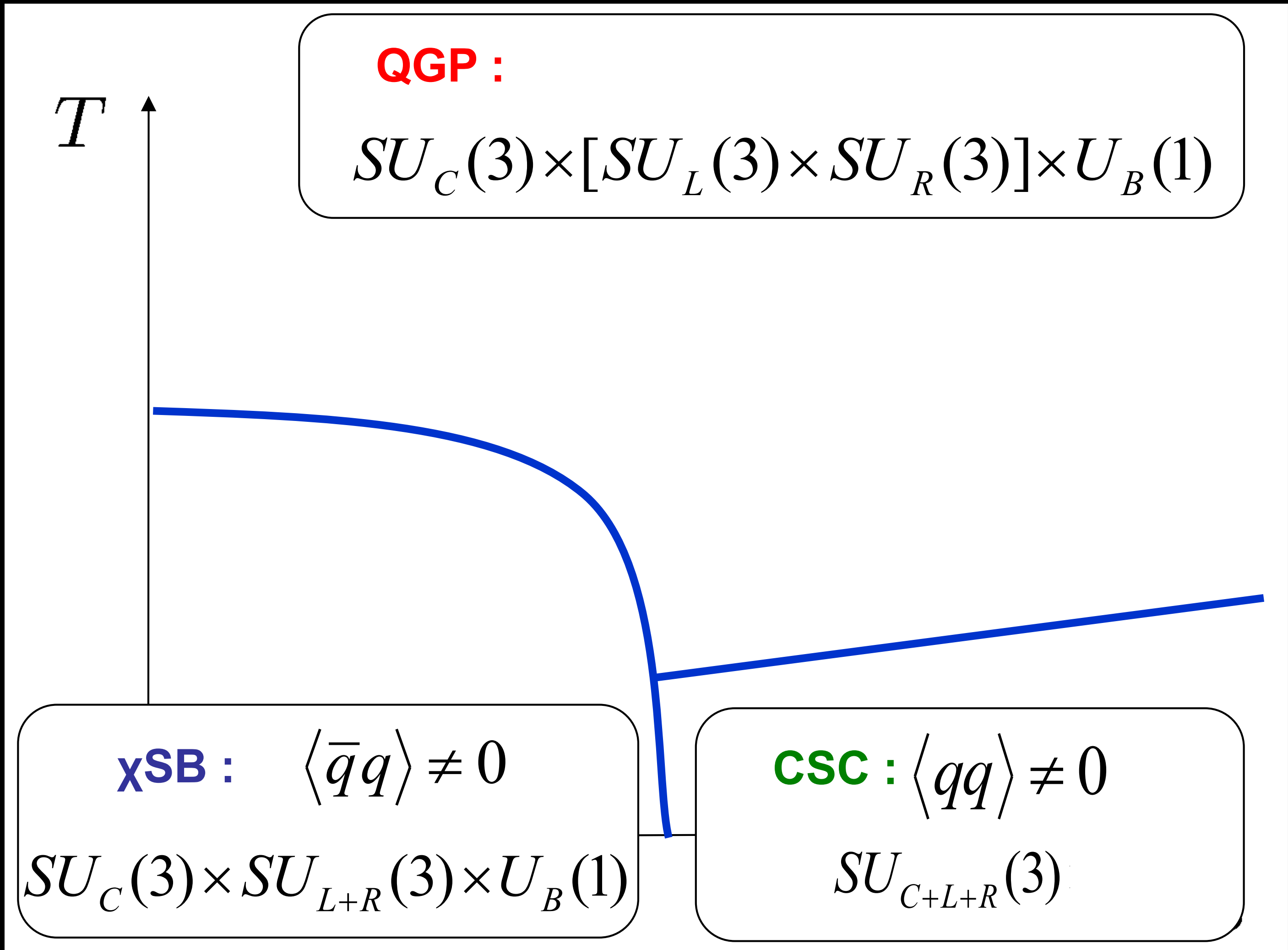
Matter under normal conditions

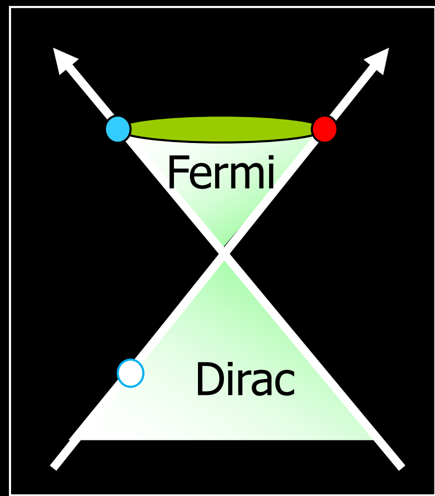
Matter under extreme conditions

- **Early Universe**
- **Neutron Star Core**

Schematic QCD phase diagram（massless 3-flavor）

Cabibbo and Parisi, PLB 59 (1975), Collins & Perry, PRL 34 (1975)





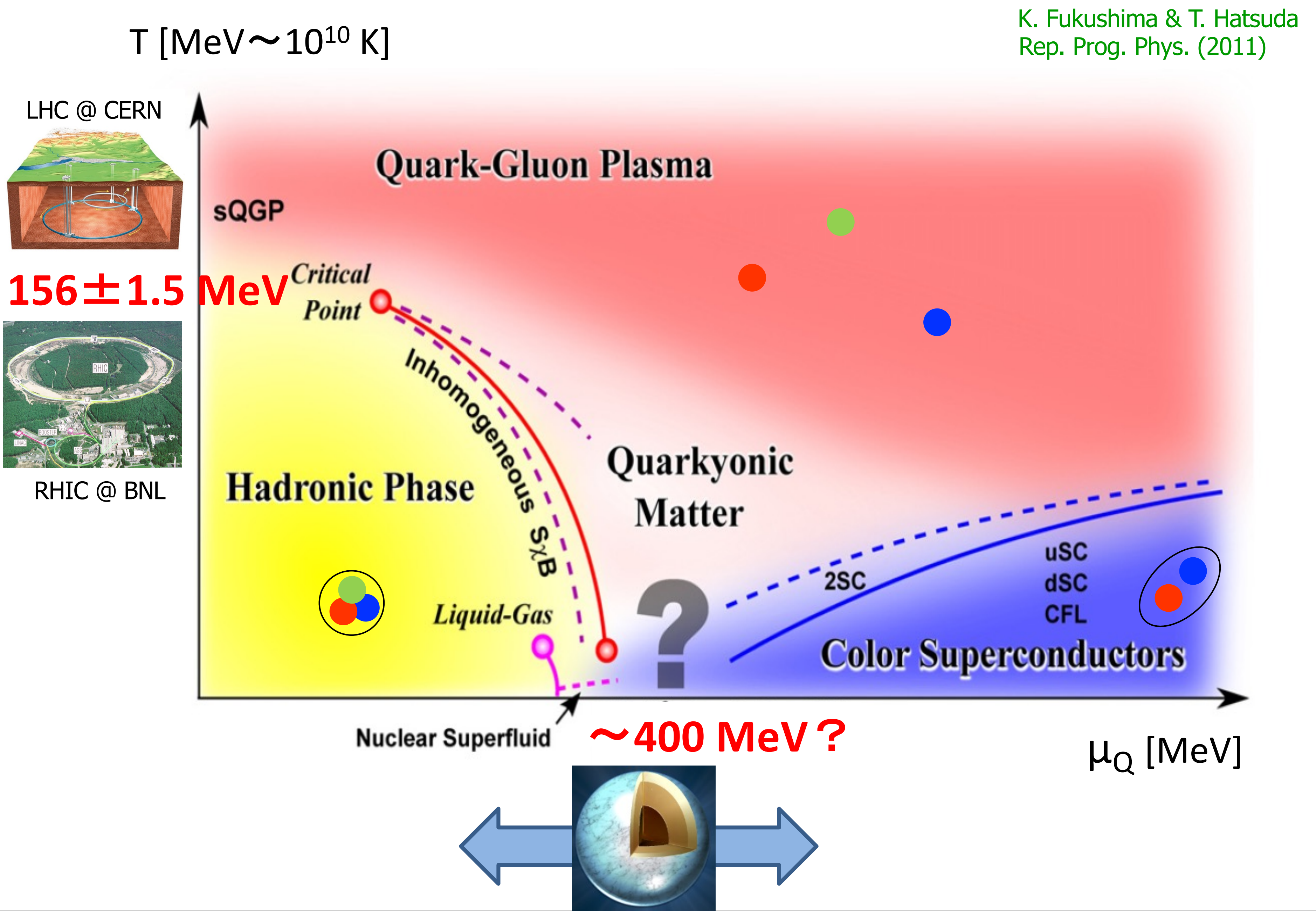
Nambu, PRL 4 (1960)

Alford, Rajagopal & Wilczek, NP B537 (1999)

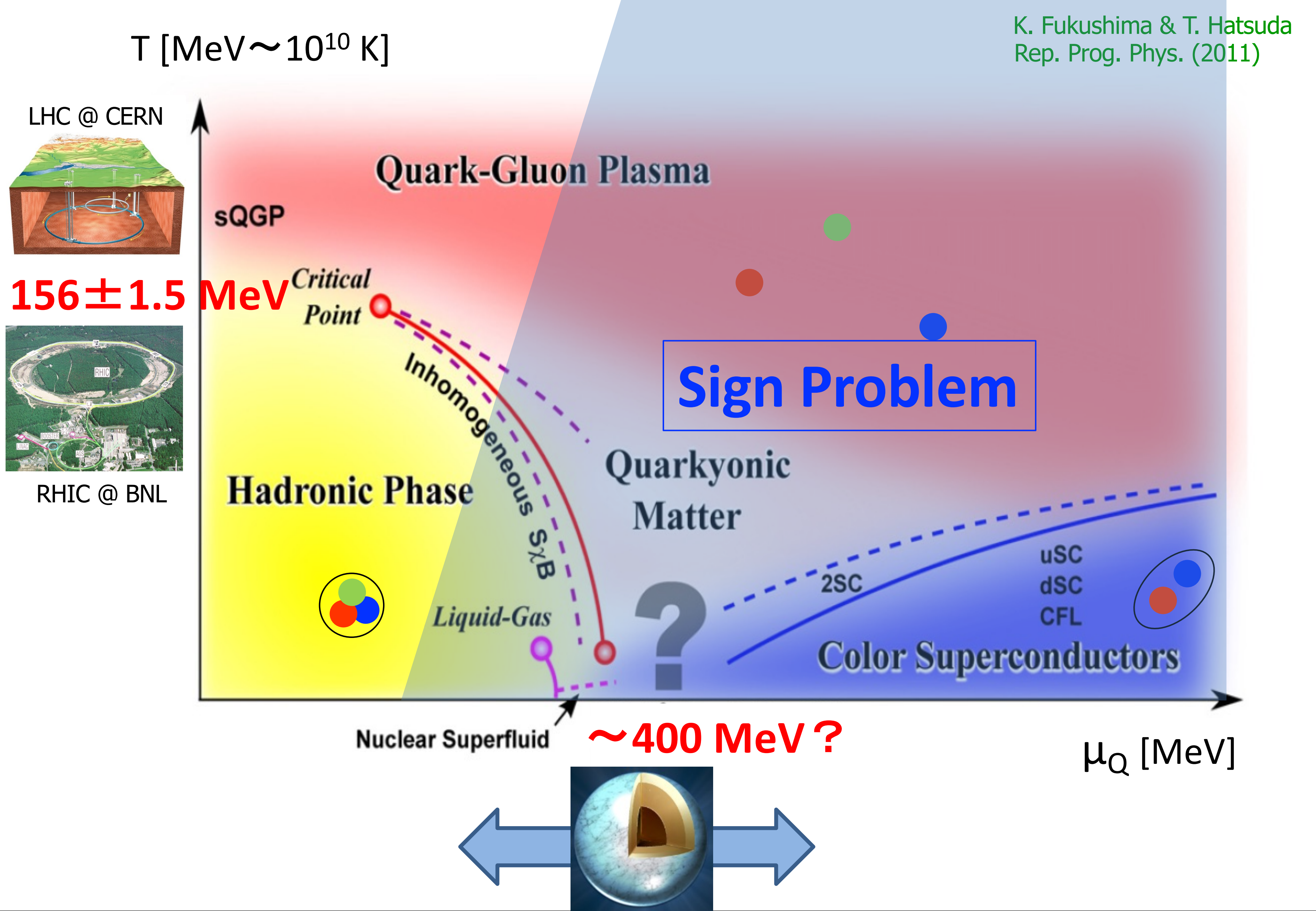
Dirac mass

Majorana mass

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



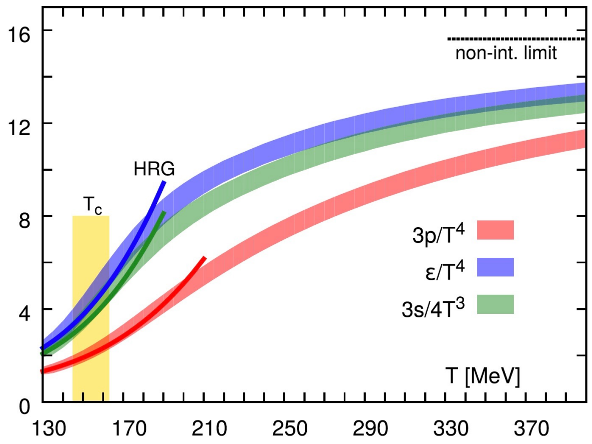
QCD phase diagram ((2+1)-flavor)



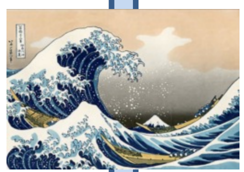
From Quarks to Neutron Stars

Quantum Chromodynamics

Lattice QCD



Sign problem



Lattice QCD

Baryon Interactions

Many-body Theory

Hot Equation of State

Cold Equation of State

Relativistic Hydrodynamics

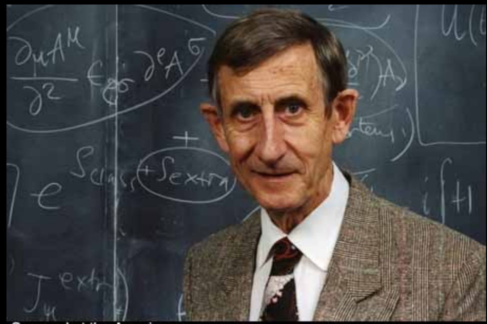
General Relativity

Heavy Ion Collisions

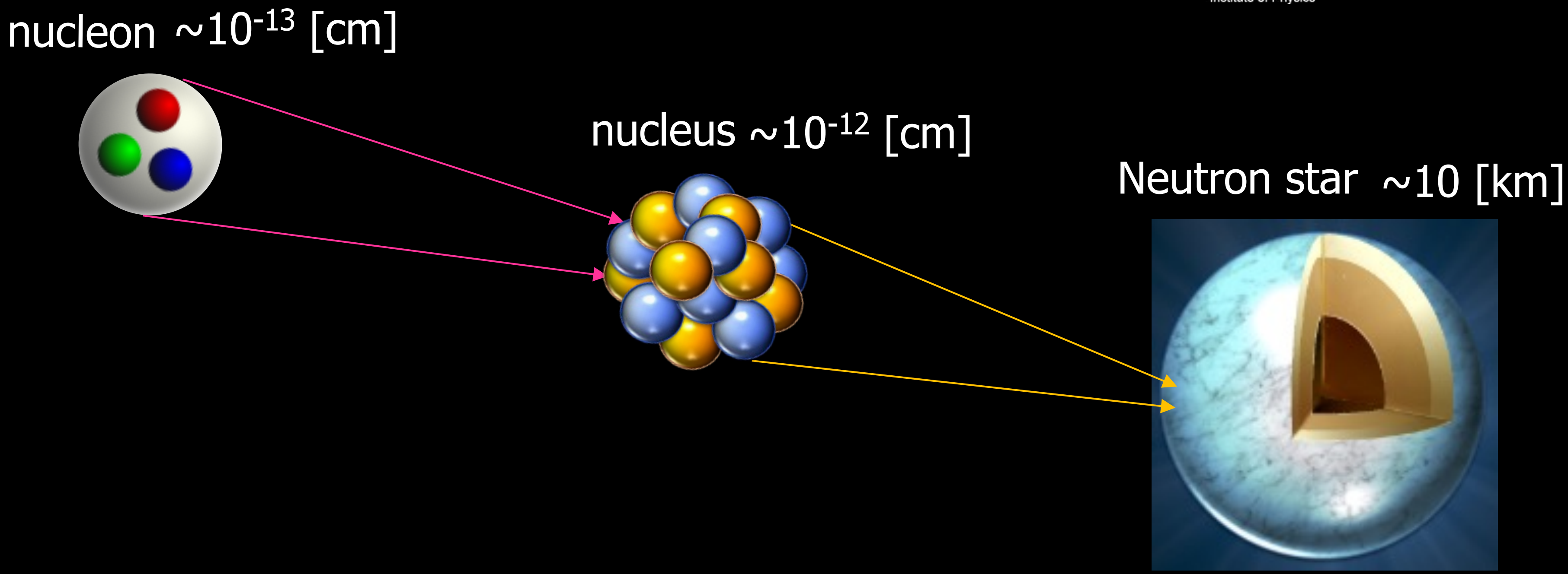
Neutron Stars

The progress of science requires the growth of understanding in both directions, downward from the whole to the parts and upward from the parts to the whole.

From “The Scientist as Rebel” by Freeman J. Dyson
https://en.wikipedia.org/wiki/Freeman_Dyson

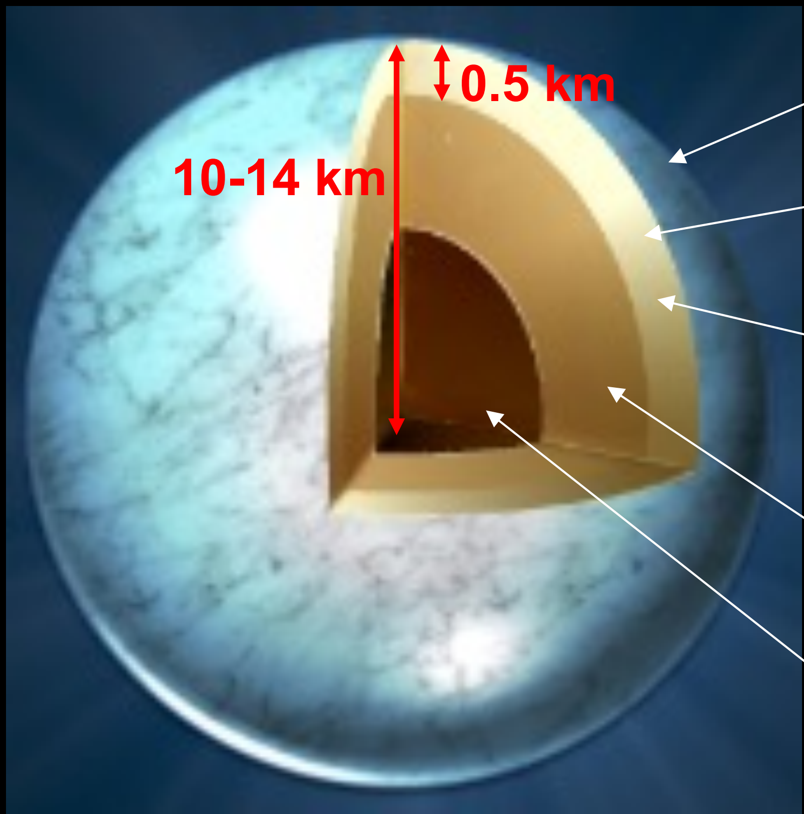


Scanned at the American Institute of Physics



Structure of Neutron Star (NS)

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



Atmosphere
H, He, C, etc

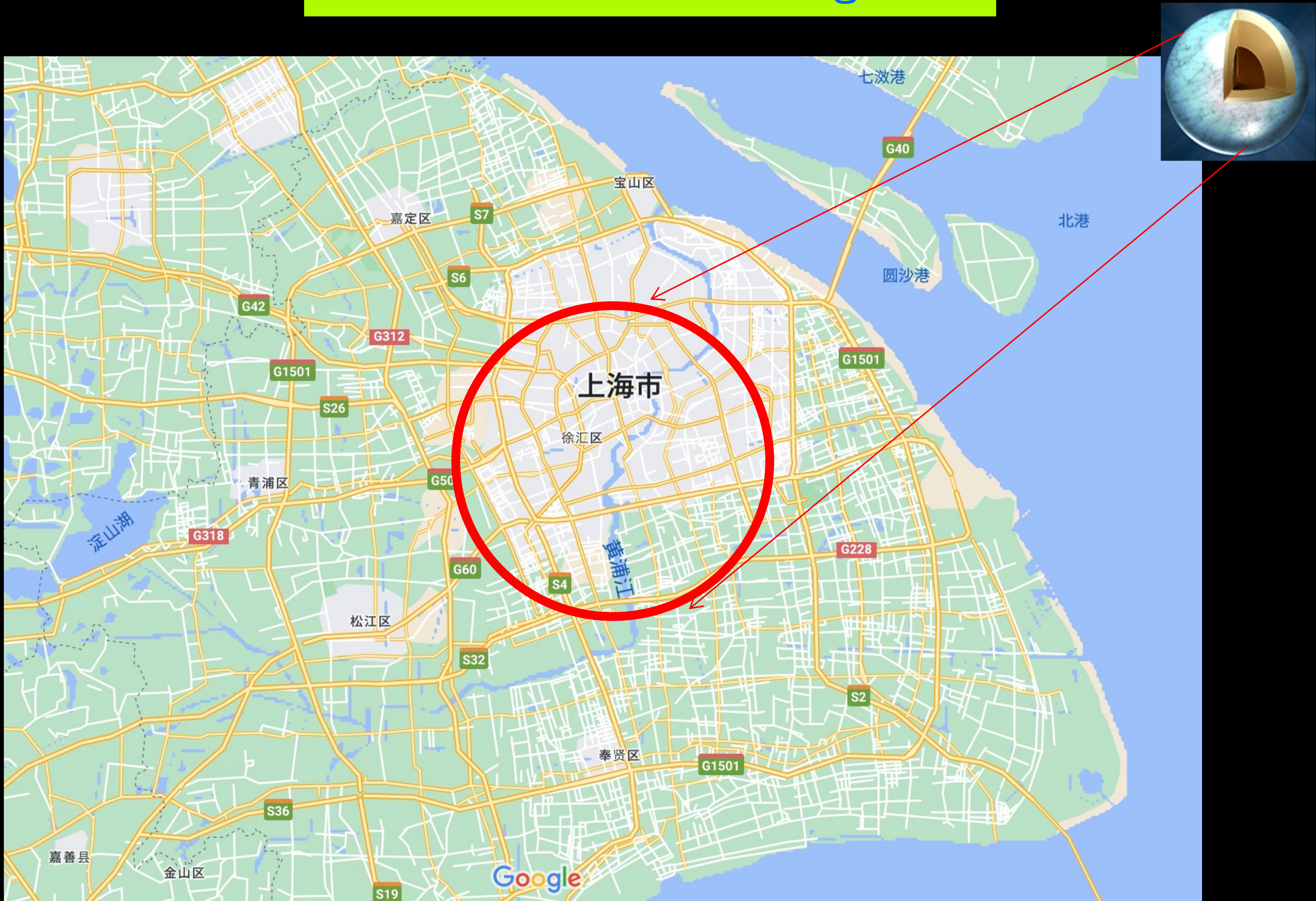
Outer crust
Atomic nuclei (solid)

Inner crust
Atomic nuclei（solid）
+Neutron ($^1S_0$ superfluid)

Outer core
Neutron ($^3P_2$ superfluid）
+ Proton ($^1S_0$ superconductor)

Inner core
Quark（color superconductor）?

Neutron Star in Shanghai

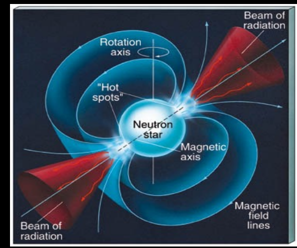


Neutron Star (NS) observations

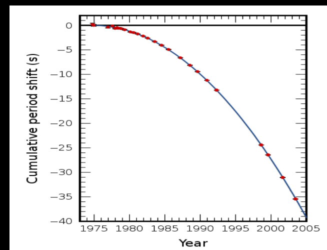
1932 Discovery of the neutron [J. Chardwick]

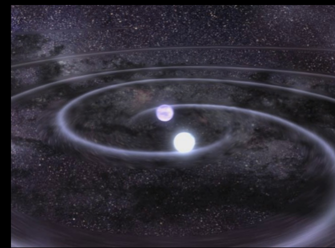
1934 Prediction of neutron star [W. Baade and F. Zwicky]

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

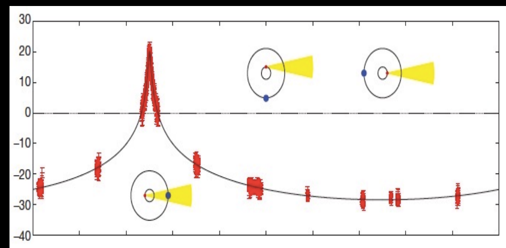


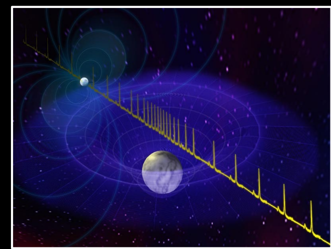
1974 Discovery of binary neutron star
[R. A. Hulse and J.H. Taylor]



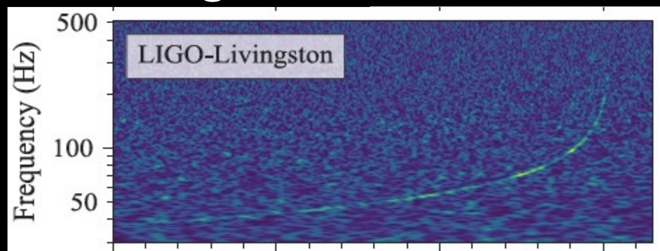


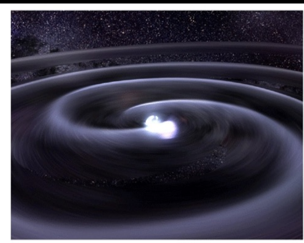
2010 Discovery of massive neutron star
[P. Detmorest et al.]

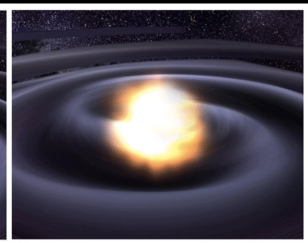




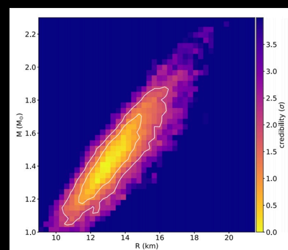
2017 Discovery of GW from NS merger
[LIGO/Virgo]





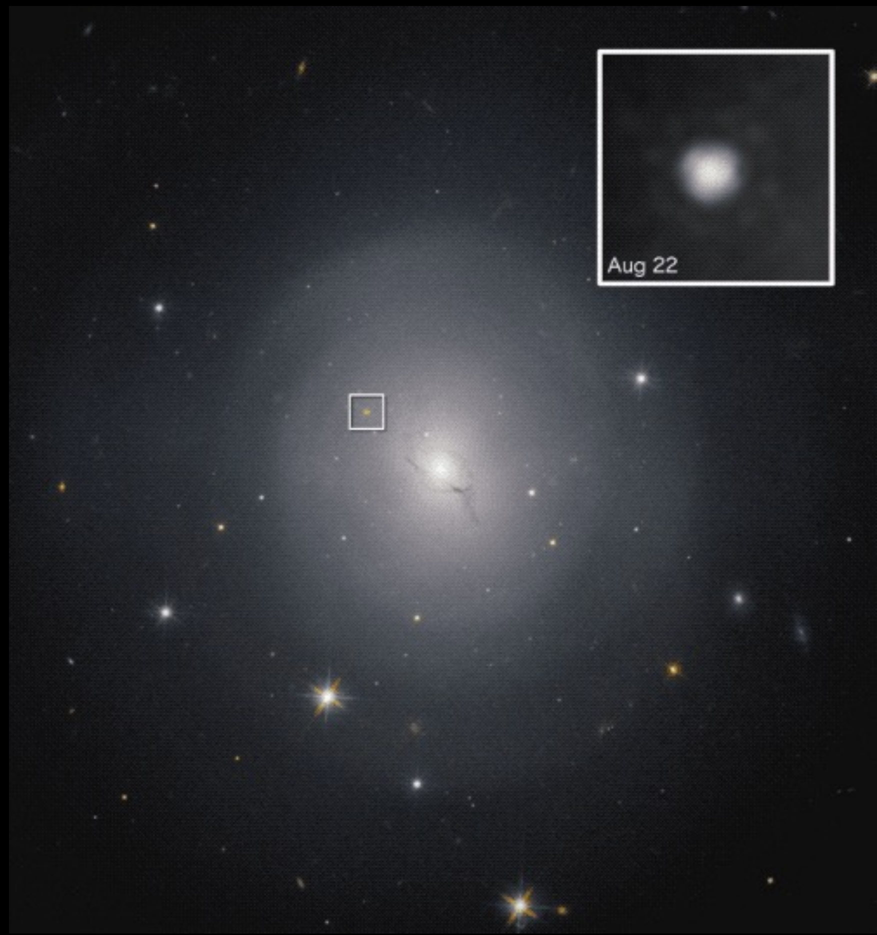


2019 Light bending around pulser
[NICER]



Neutron Star Merger GW170817

in NGC4993 (44.1 Mpc=144 Mly away)



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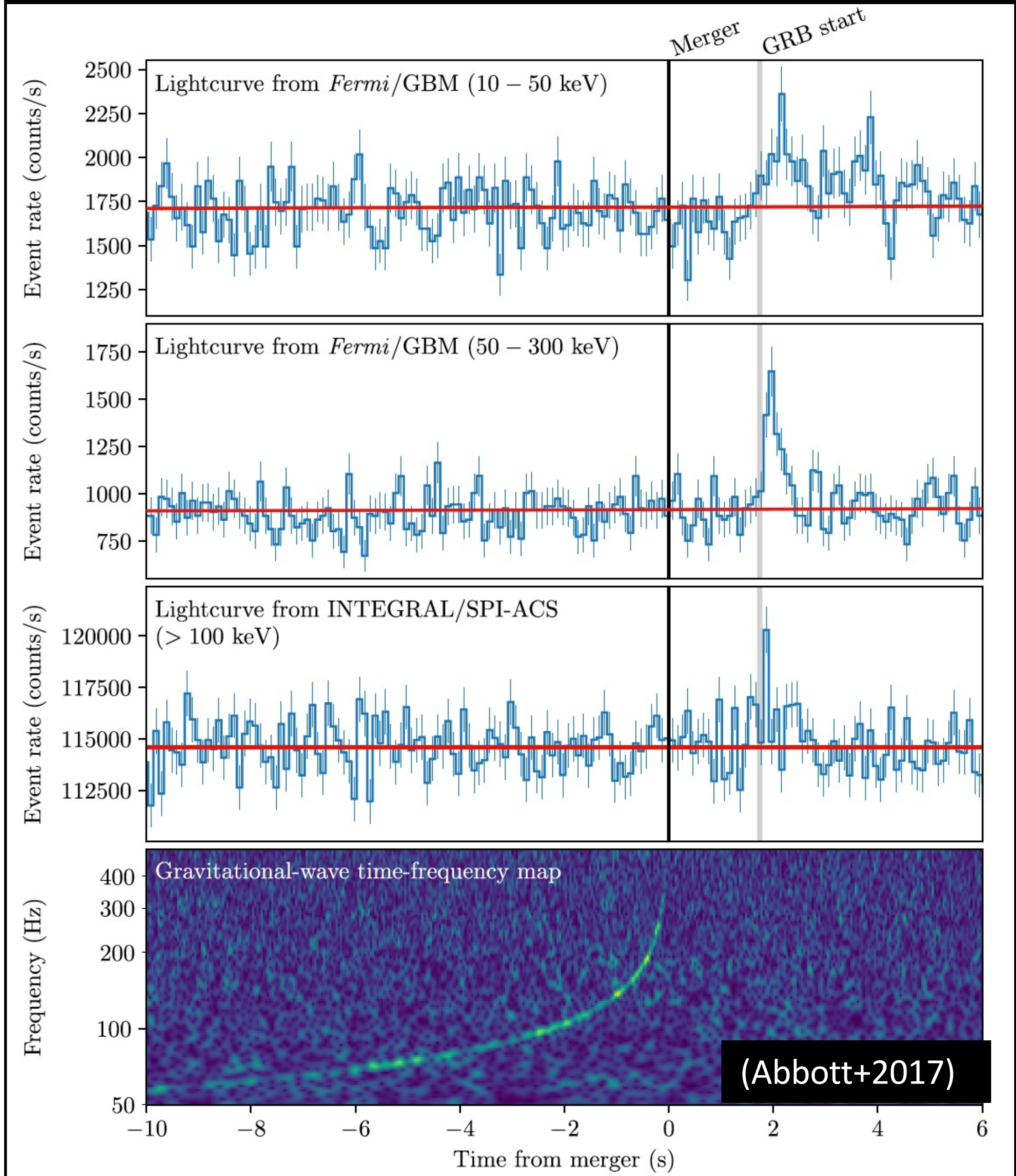
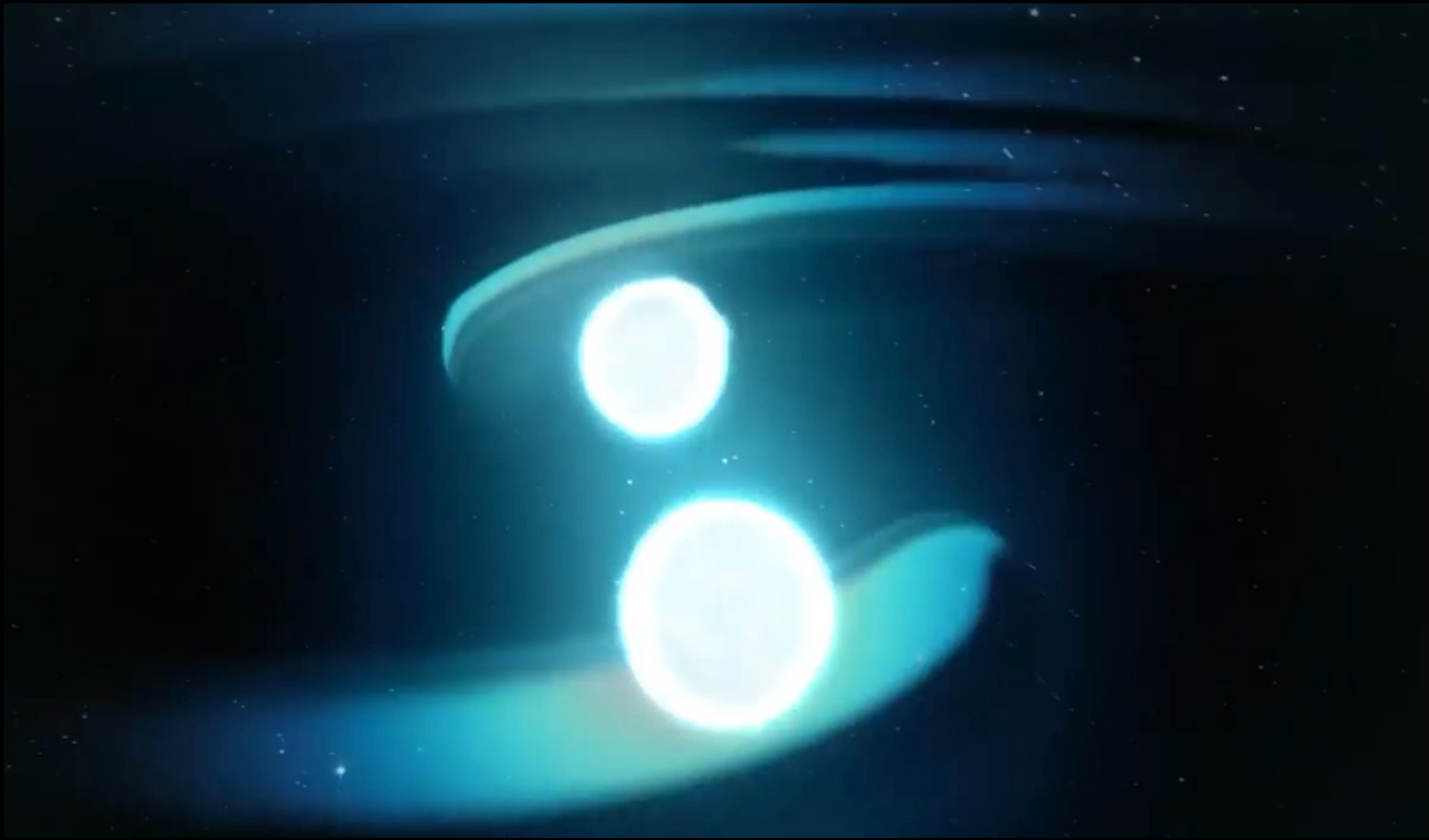


Gamma-ray from Fermi Satellite

Gravitational Wave from LIGO

Neutron Star Merger GW170817

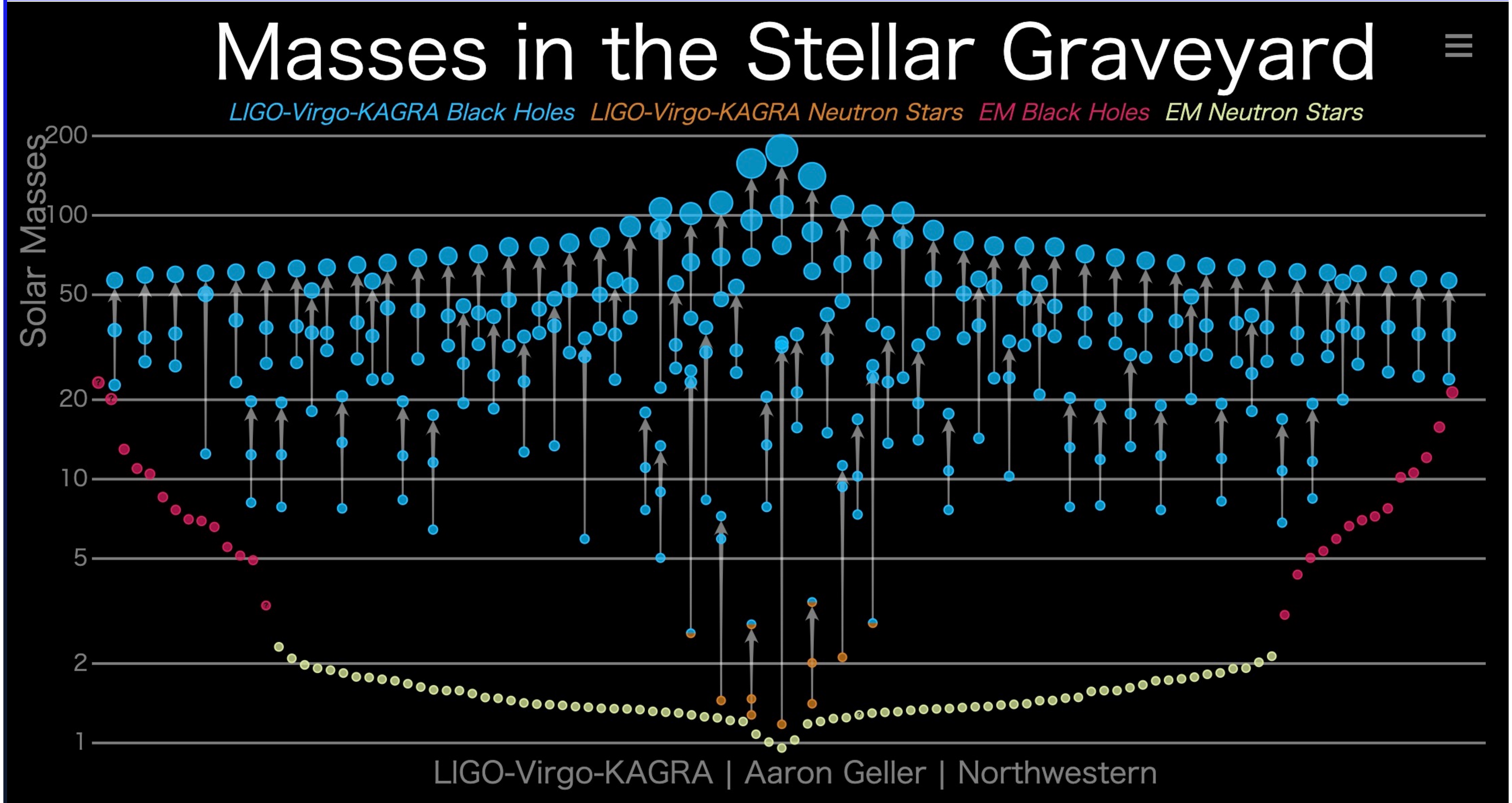
in NGC4993 (44.1 Mpc=144 Mly away) https://www.youtube.com/watch?v=x_Akn8fUBeQ



photons (gamma ray, X ray, UV light, visible light, IR light, radio wave) were observed simultaneously with GW.

Neutron Star Collision (film/music, 2010)

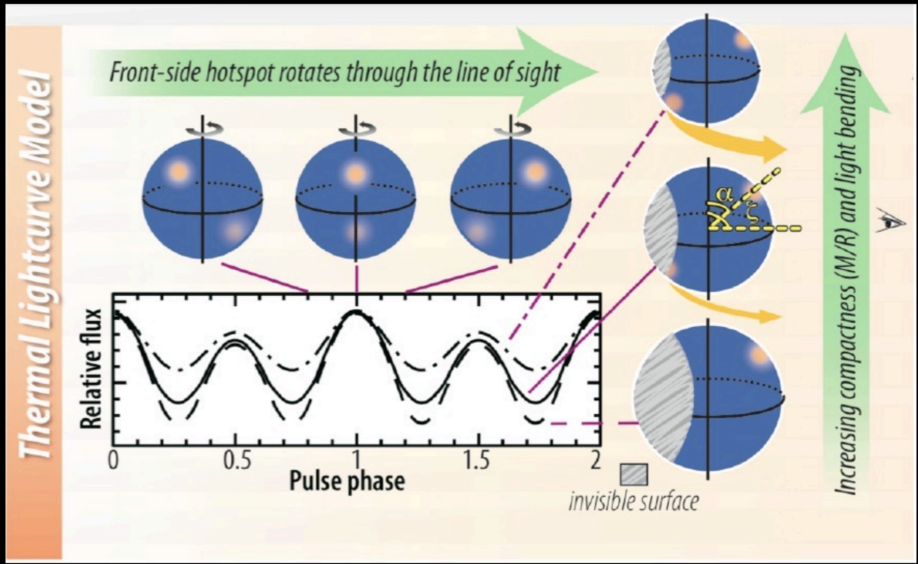
https://en.wikipedia.org/wiki/The_Twilight_Saga:_Eclipse
https://www.youtube.com/watch?v=MTvgnYGu9bg

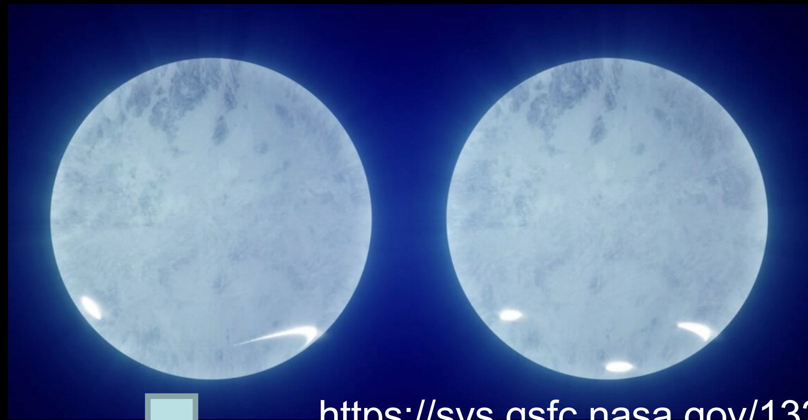


https://media.ligo.northwestern.edu/gallery/mass-plot

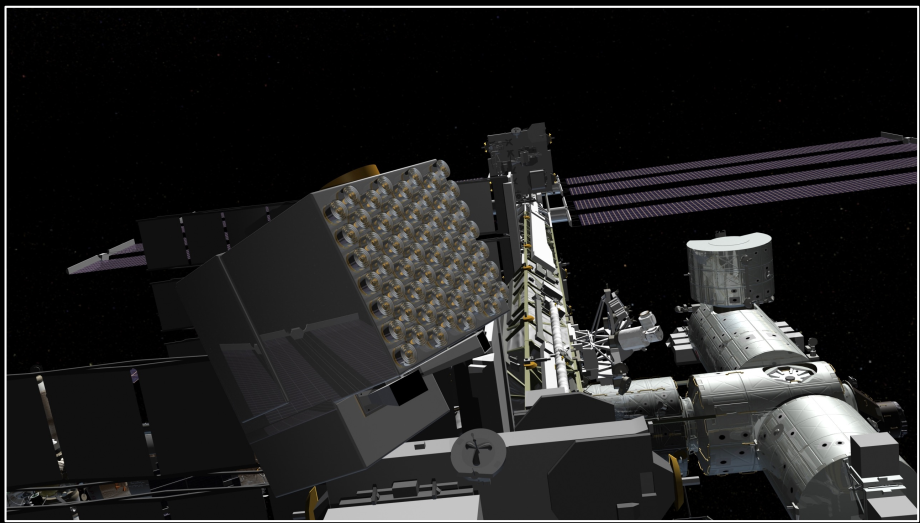
~100M NS
in our galaxy
~2000 observed
~ 5% binary

Light bending around NS

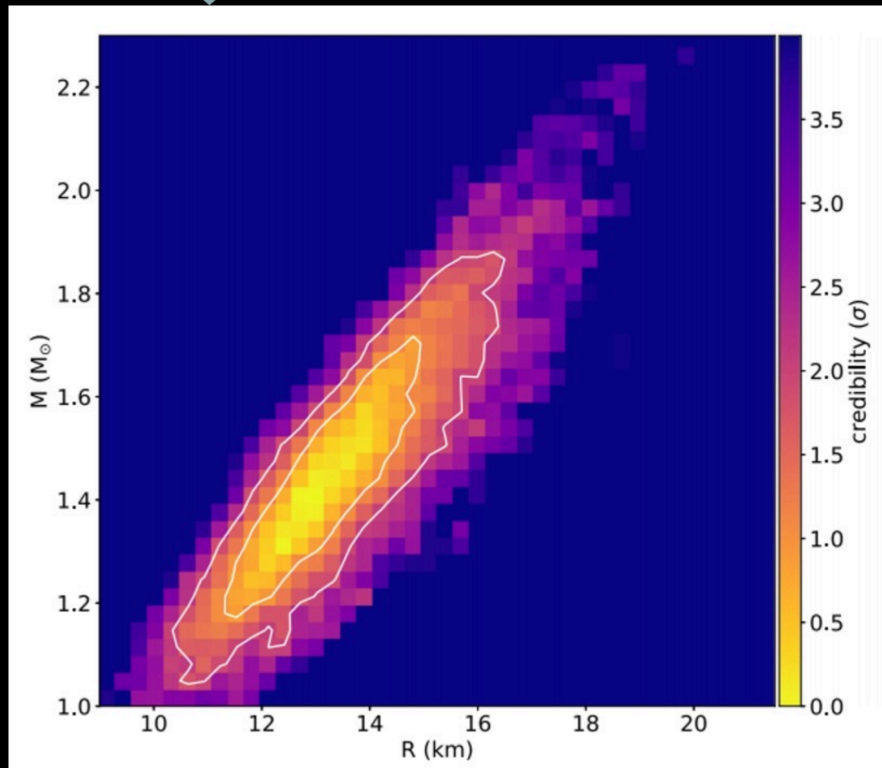




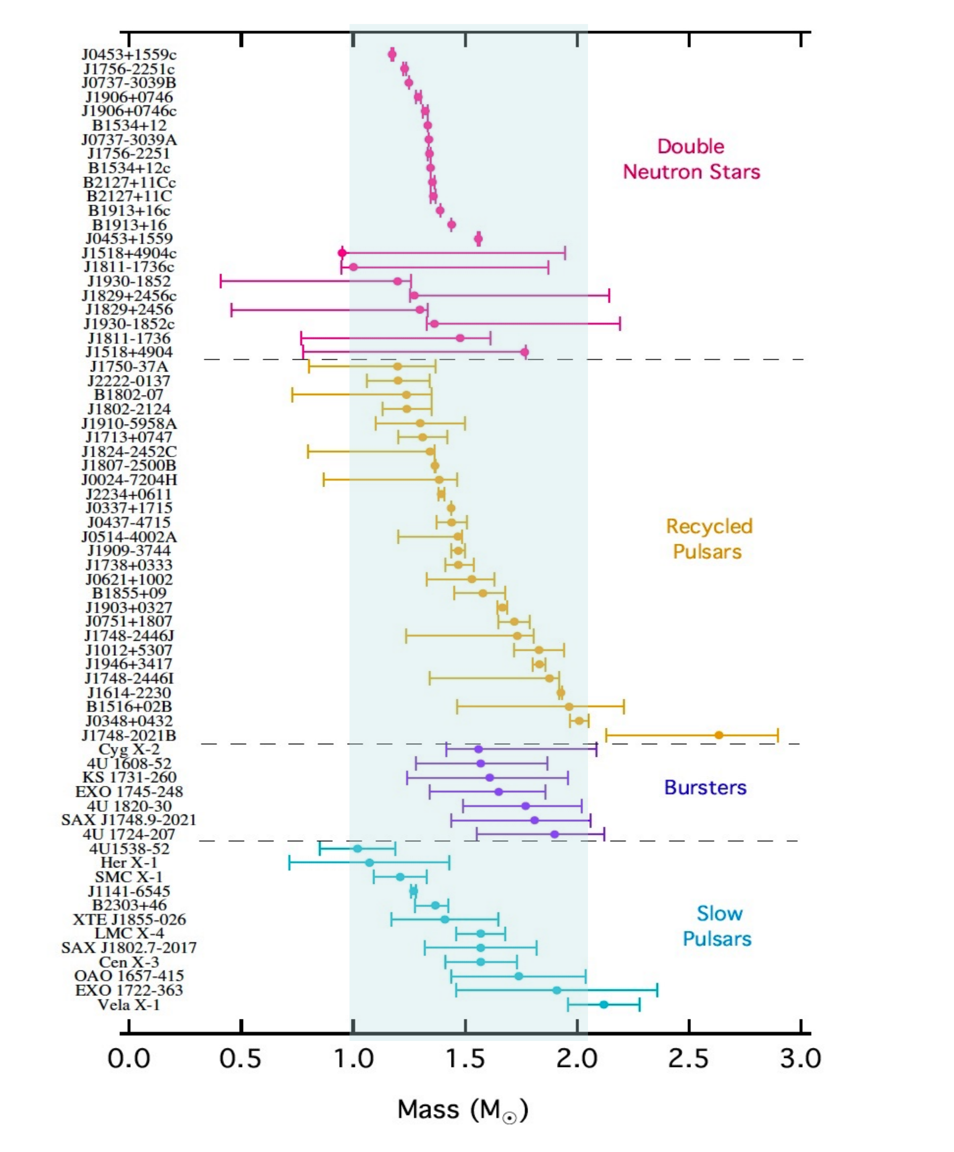
https://svs.gsfc.nasa.gov/13240

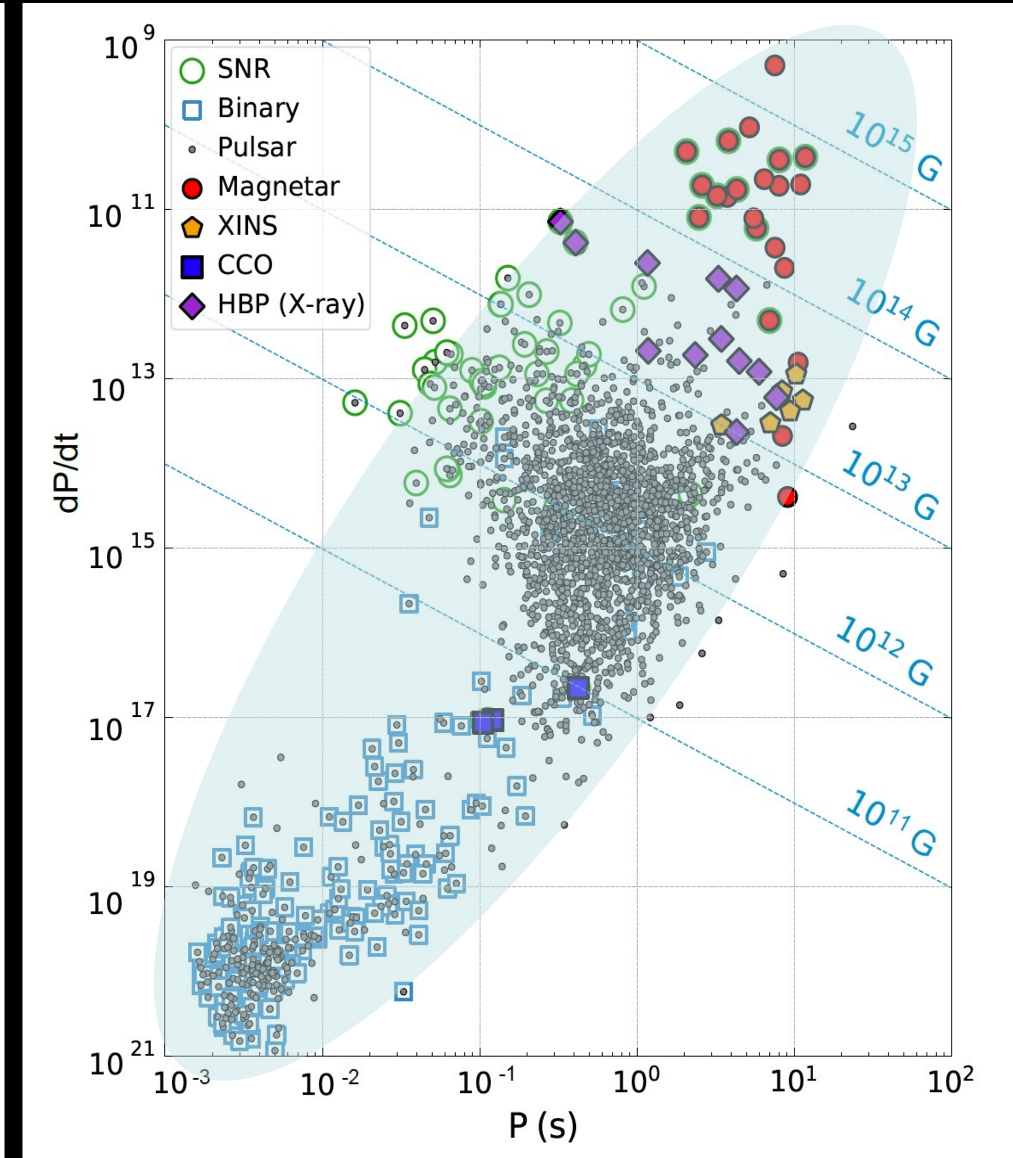


Neutron Star Interior Composition Explorer (NICER) on ISS



NICER: ApJ 887 (2019)





Özel and Freire,
Annu. Rev. Astrophys. 54 (2016) 401.

Enoto, Kisaka, and Shibata,
Rep. Prog. Phys. 82 (2019) 106901.

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-10 s
- .....

Astrophysics
Nuclear physics
Particle physics
Cond. Matt. physics

Matter under extreme condition

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

Solving Neutron Star

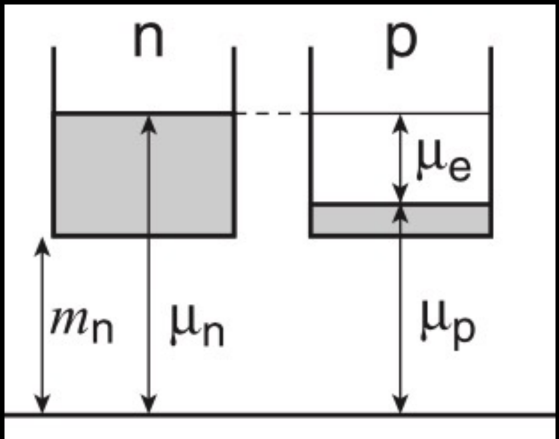
1. Tolman–Oppenheimer–Volkoff equation ← General Relativity
   (TOV)

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

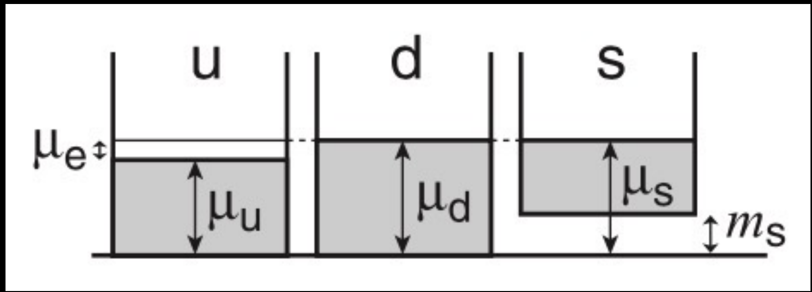
$$-\frac{dP(r)}{dr} = \frac{G\varepsilon\mathcal{M}}{r^2}\left(1-\frac{2G\mathcal{M}}{r}\right)^{-1}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{\mathcal{M}}\right),$$

2. Equation of state P=P(ε) ← Stong/EM/Weak Interactions
   (EOS)

Low density
(nucleon superfluid)

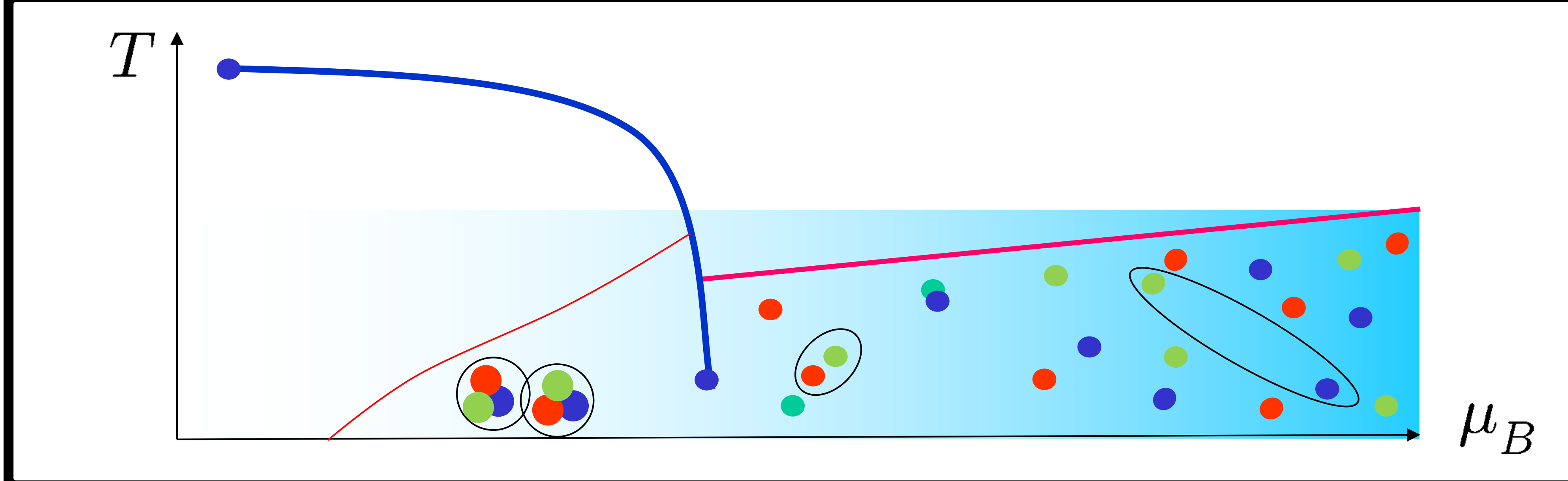


high density
(quark superfluidity)



TOV + EOS → Mass-Radius Relation of Neutron Stars

From Hadronic Matter to Quark Matter



Neutron Superfluid
Tamagaki, Hoffberg+ (1970)

Bose–Fermi mixture
Maeda, Baym, Hatsuda, PRL (2009)

Color Superconductivity
Alford, Rajagopal, Wilczek, NPB (1999)

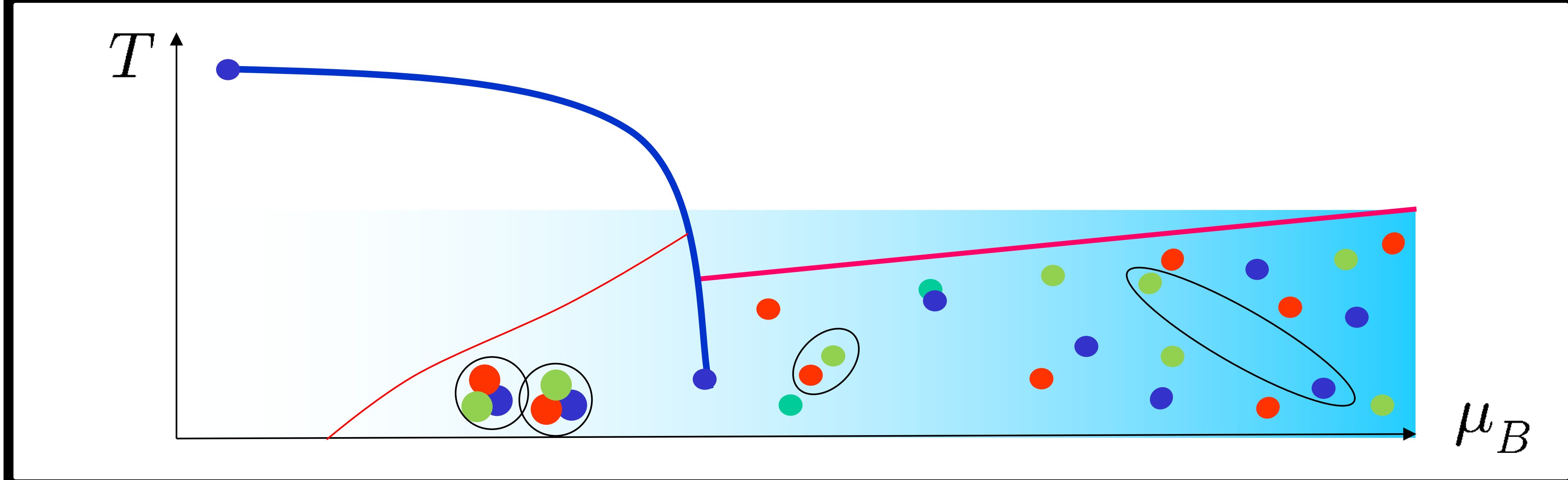
Hadron–Quark Crossover ?

Same SSB pattern ($G = SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{L+R}$) : Schafer and Wilczek, PRL 82 (1999)

Possible new critical point: Hatsuda, Tachibana, Yamamoto, Baym, PRL 97 (2006)

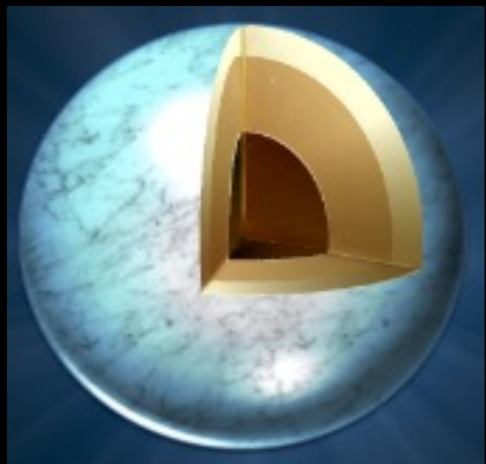
Implication to neutron star phenomenology: Masuda, Hatsuda, Takatsuka, Astrophysical J. 764 (2013)

From Hadronic Matter to Quark Matter



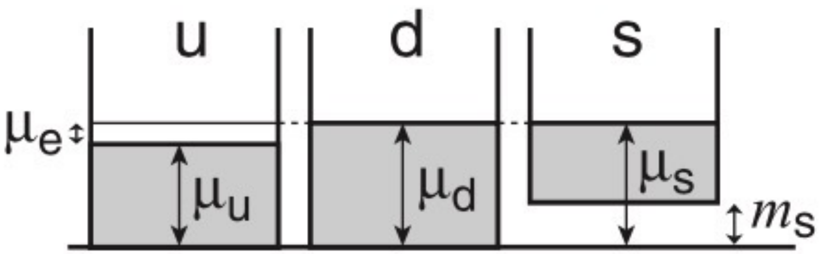
$2\rho_0$ Crossover ? $5\rho_0$

Strongly interacting baryonic matter



Strongly interacting quark matter

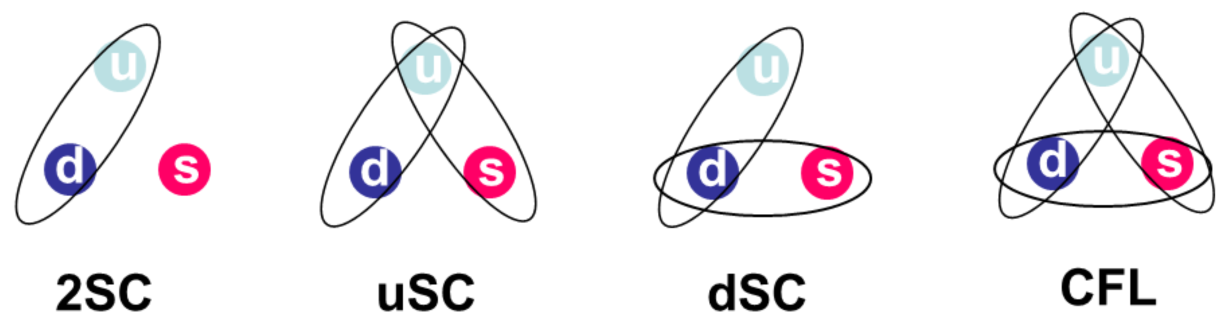
Color superconductivity



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

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

flavor color



2. Color-flavor entanglement

$$d_{ia}$$

Various phases (c.f. Ice, ^{3}He)
2SC, uSC, dSC, CFL etc

Ginzburg-Landau free energy for chiral-super interplay in 3-flavor QCD (m_{uds}=0)

Symmetry: $SU(3)_C \times [SU(3)_L \times SU(3)_R] \times U(1)_B \times \cancel{U(1)}_A$

Chiral field:

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

$$\varphi \to e^{-2i\alpha_A} V_L \varphi V_R^\dagger$$

Diquark field:

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

$$d_L \to e^{2i\alpha_A} e^{2i\alpha_B} V_L d_L V_C^{\mathrm{T}}$$

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

Pisarski & Wilczek, PRD29 ('84)

- Iida & Baym, PRD63 ('01)
- Iida, Matsuura, Tachibana & Hatsuda, PRD71 ('05)

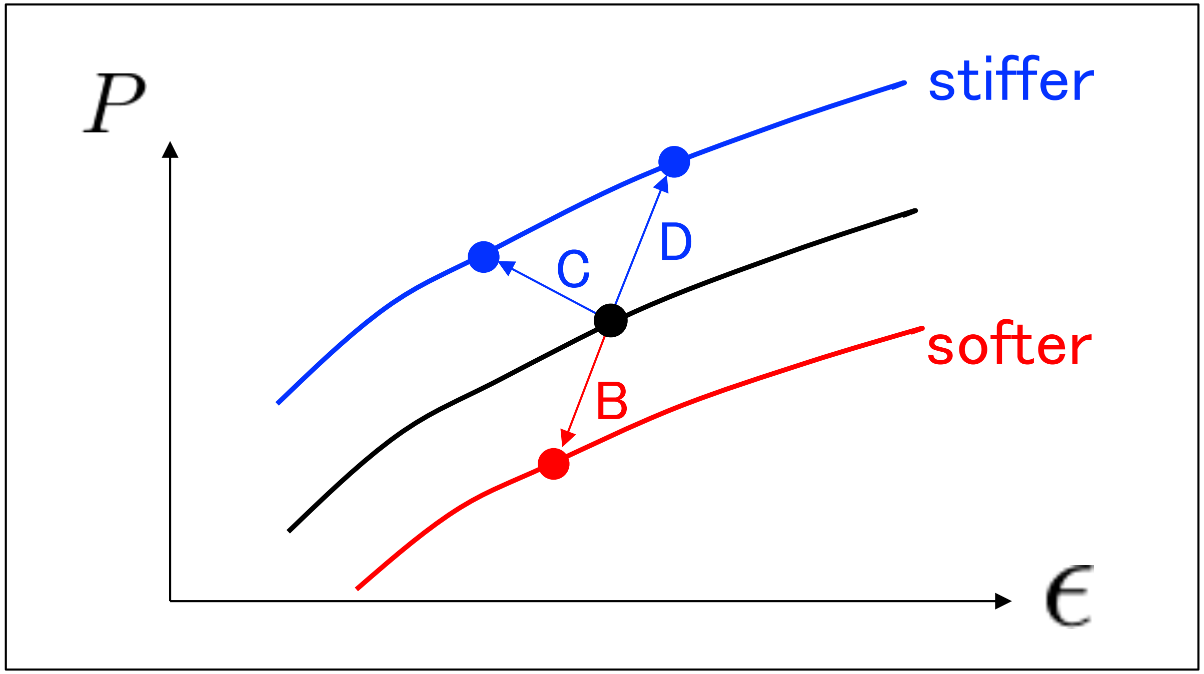
Hatsuda, Yamamoto, Tachibana & Baym, PRL97 ('06)

CSC stiffens EOS

$$\boxed{\epsilon = An^{4/3} + B - Cn^{2/3} + Dn^2}$$

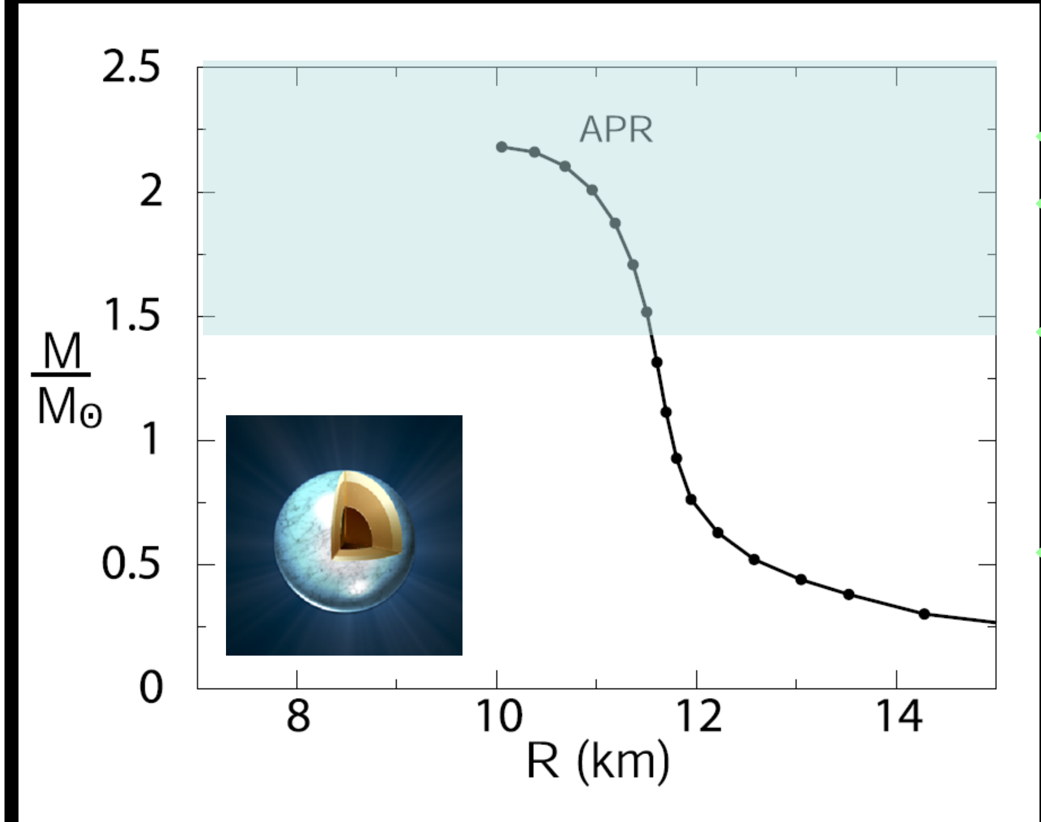
$(A \propto 1+2\alpha_s/3\pi)$
$(C \propto \Delta^2)$

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



Baym, Hatsuda, Kojo,
Powell, Song, Takatsuka,
Rept. Prog. Phys. 81 (2018)

Nuclear EOS meaningful at high density ?



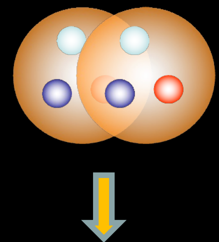
ρ_{center}

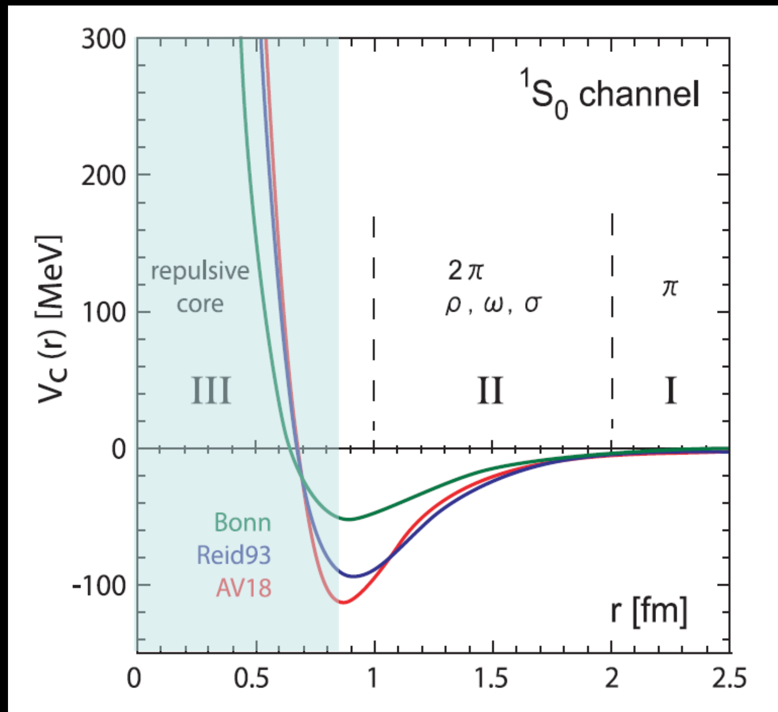
← $6\rho_0$

← $5\rho_0$

← $3.4\rho_0$

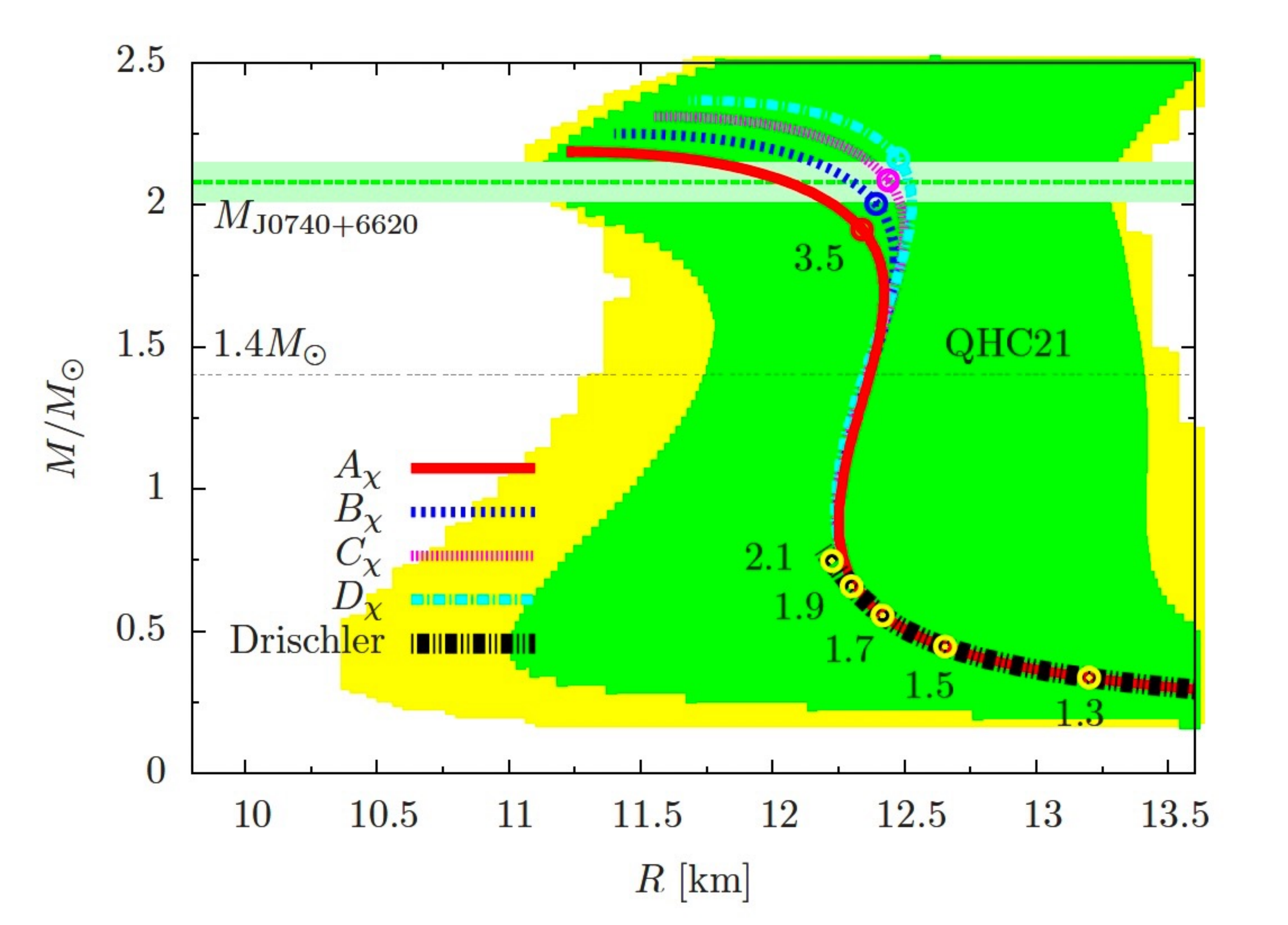
← $2\rho_0$

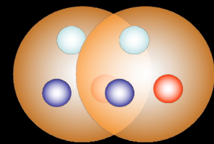


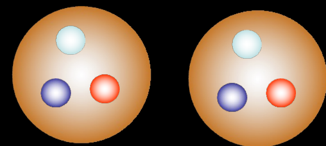


QHC21 EOS (Chiral EFT+ NJL) vs. Observation (SD+GW+NICER)

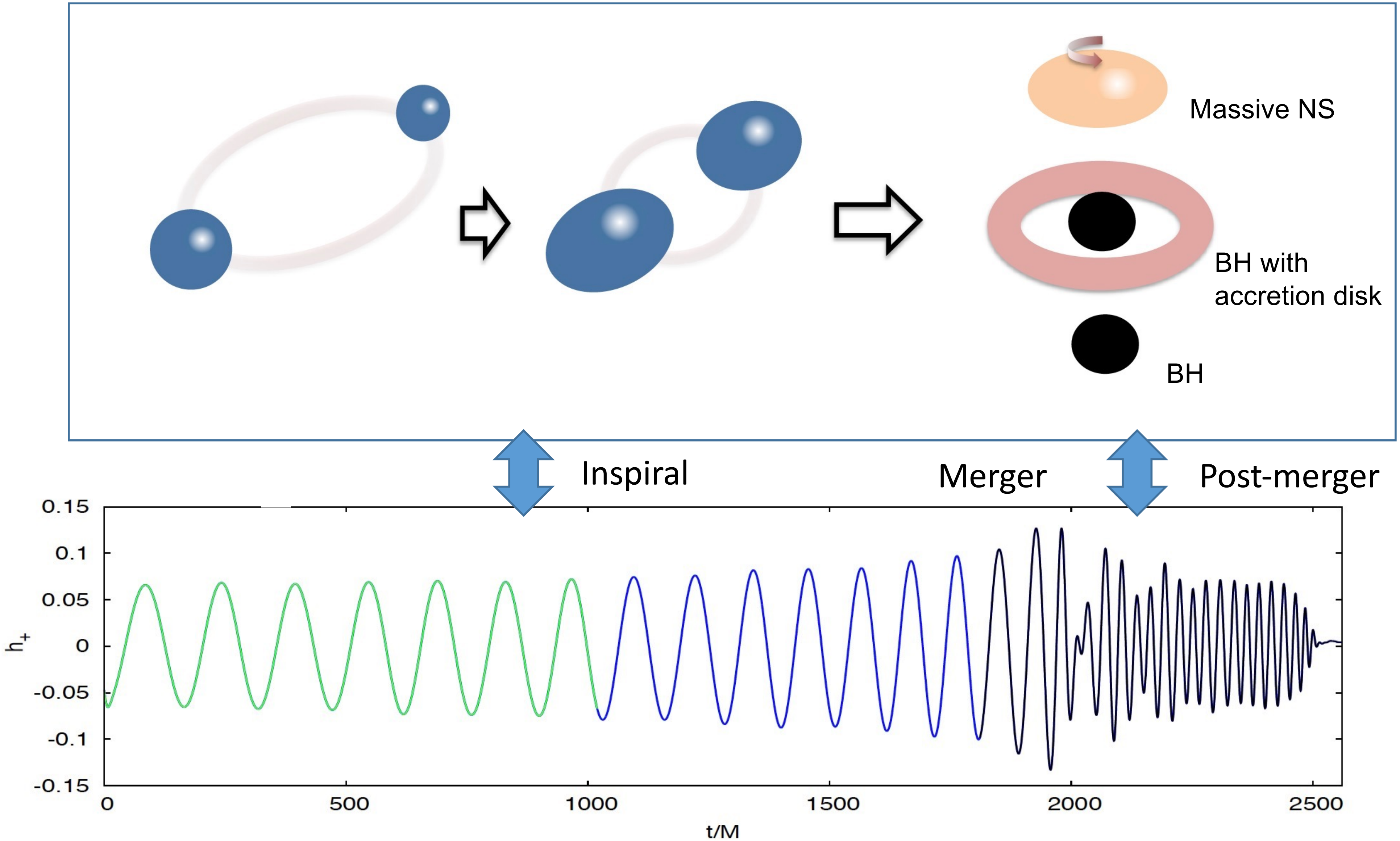
Kojo, Baym, Hatsuda, Astrophys. J. 936 (2022) 46







NS merger and gravitational wave

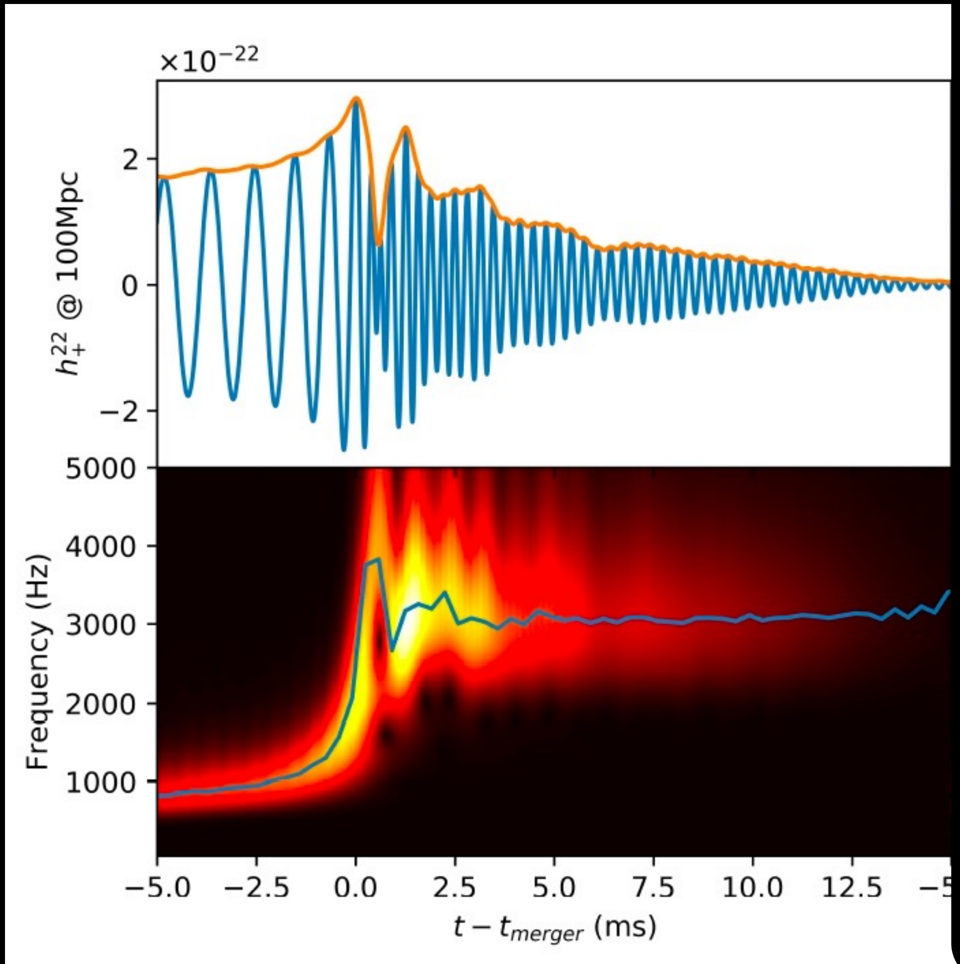


http://member.ipmu.jp/masamune.oguri/rironkon2013/talks/06_Shibata.pdf

Merger and post-merger of binary neutron stars with a quark-hadron crossover equation of state

Physical Review Letters 129 (2022) 181101

Yong-Jia Huang[1,2,3], Luca Baiotti[4], Toru Kojo[5,6], Kentaro Takami[7,3], Hajime Sotani[8,3], Hajime Togashi[6], Tetsuo Hatsuda[3], Shigehiro Nagataki[3,8] and Yi-Zhong Fan[1,2]



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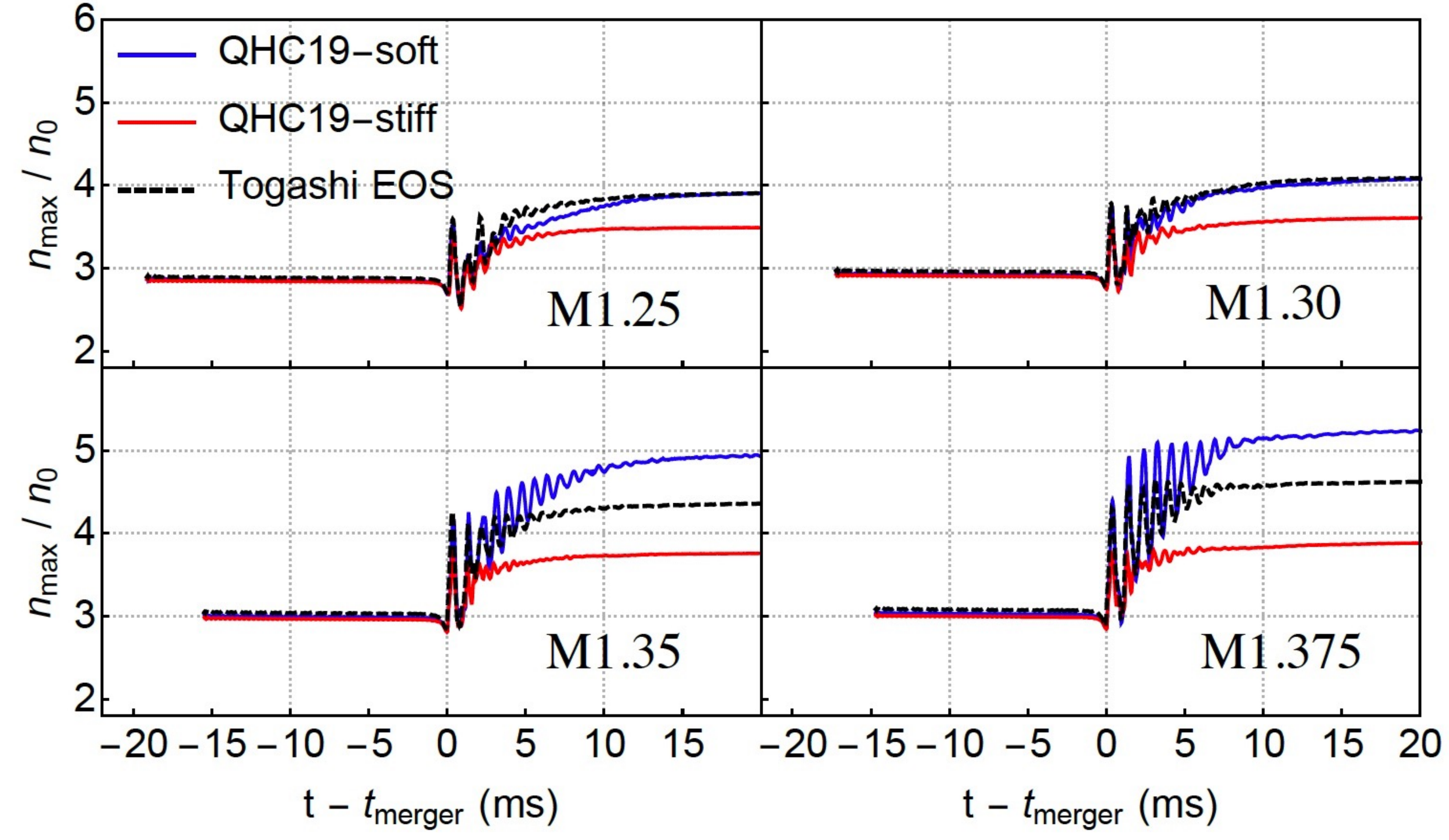
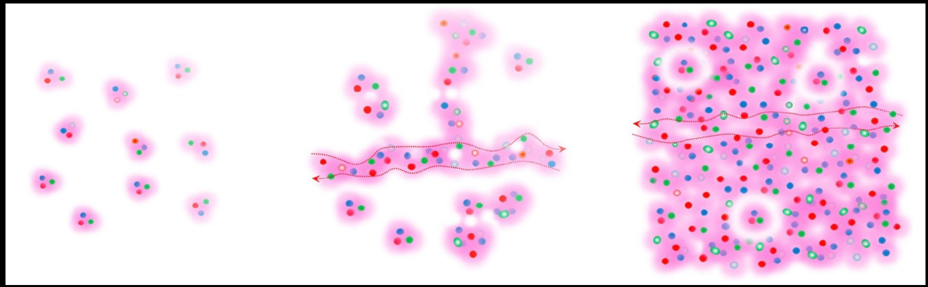
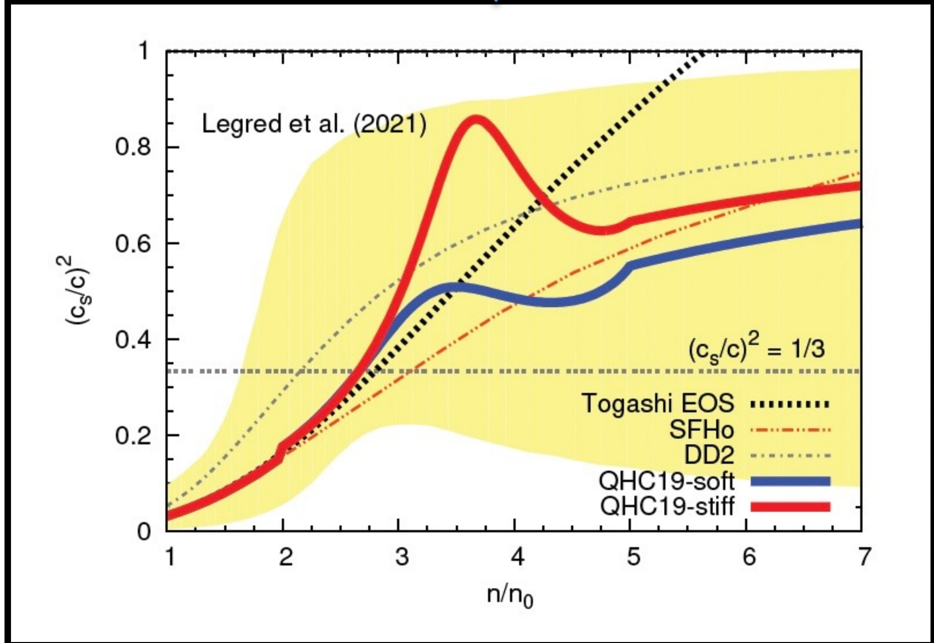
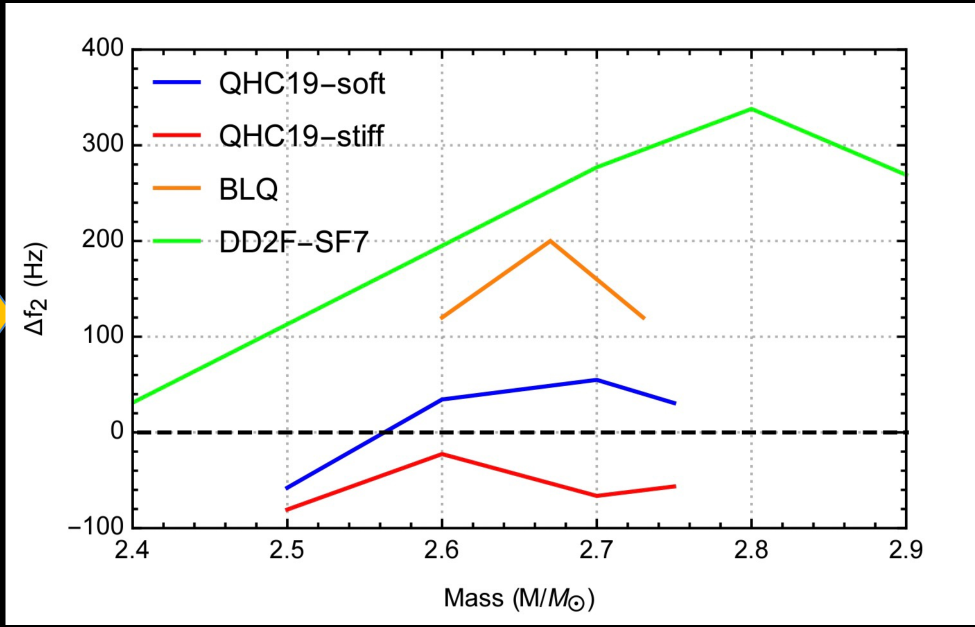




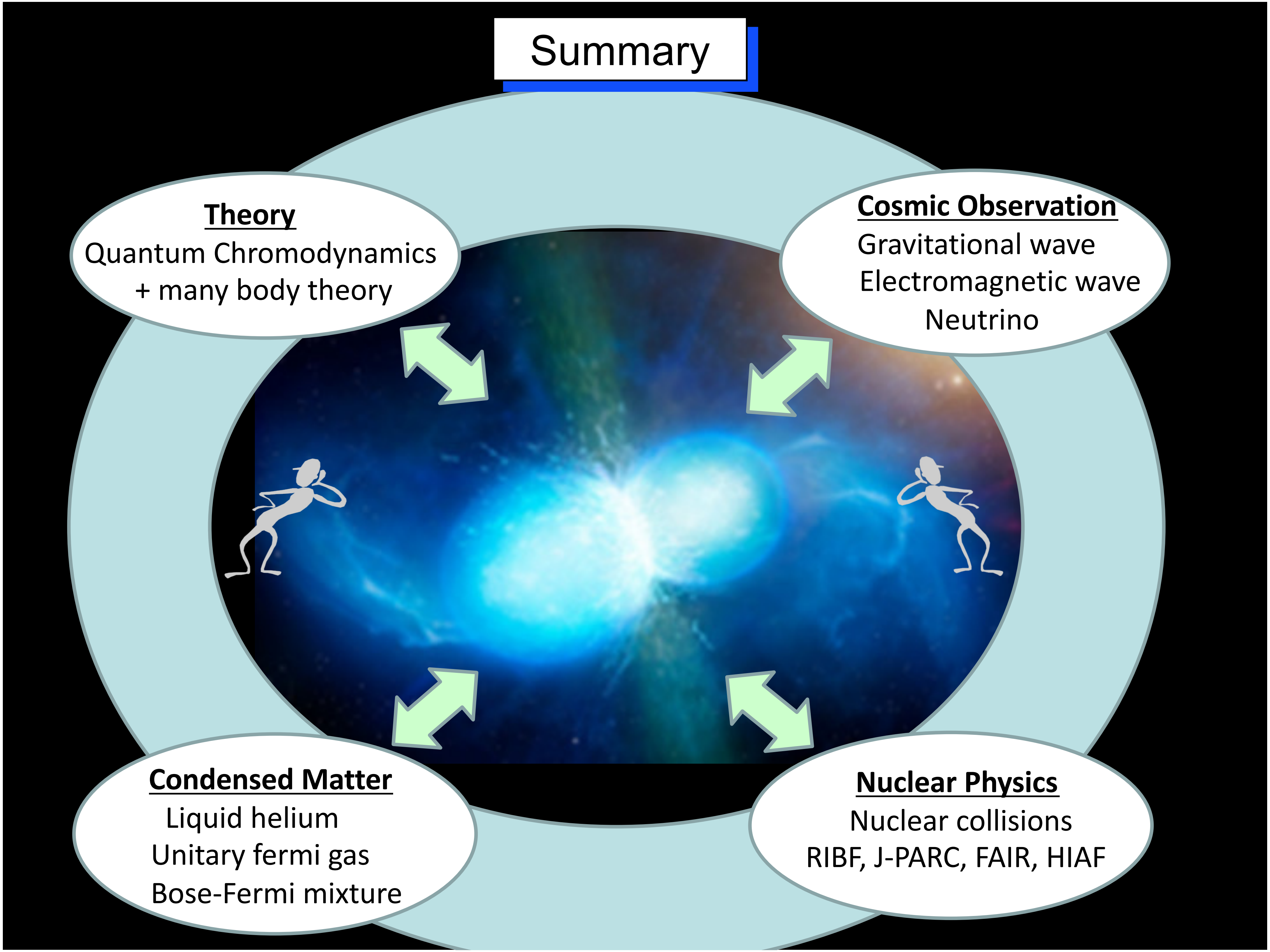
Transition from baryonic matter to color-superconducting quark matter
←→ post-merger GW frequency



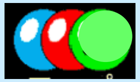
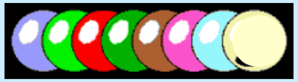


Next-generation GW detectors in kHz band with ~ 50Hz resolution

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


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

QCD as quantum many-body problem

 quarks  gluons

QCD	Condensed Matter
Chiral symmetry breaking	BCS superconductivity
Renormalization group & asymptotic freedom	Renormalization group & Kondo problem
Lattice gauge theory & confinement	Quantum Monte Carlo simulations
Axial anomaly & topology	Topological insulators
Baryonic Skyrmion	Magnetic Skyrmions
Color superconductivity	High T_c superconductors
Hadron-quark crossover	BEC-BCS crossover
Massless quarks	Dirac fermions
…………………	………………..