From Quarks to Neutron Stars

Tetsuo Hatsuda
(RIKEN iTHEMS)

通識演講 (Colloquium), 中央研究院 物理研究所, July 15, 2025

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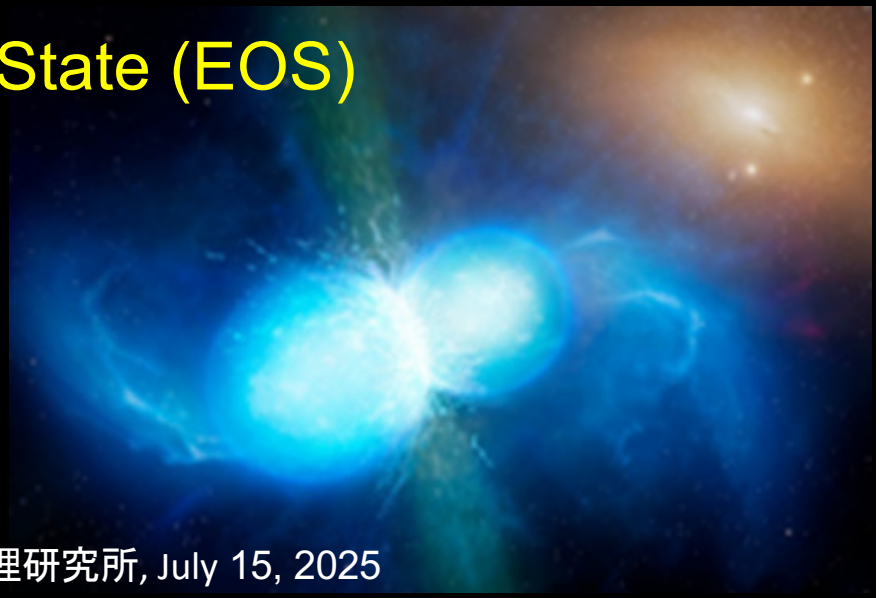
1. Phase Diagram of QCD
2. Dense QCD and Neutron Stars
3. Neutron Star Merger and Gravitational Wave (GW)
4. GW and Dense Equations of State (EOS)
5. Summary



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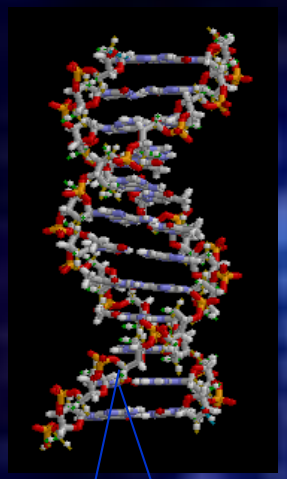
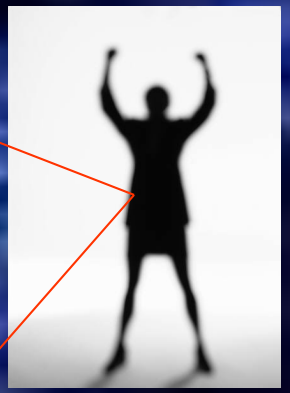
DNA



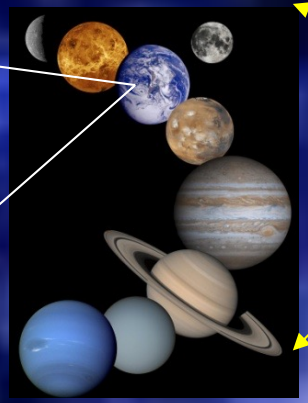
10^{-7} [cm]

Human



10^{2}[cm]

Solar system



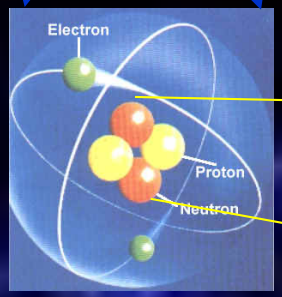
10^{12}[cm]

Galaxy

10^{23}[cm]

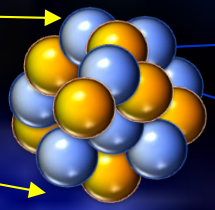
What are we made of ?

10^{-8} [cm]



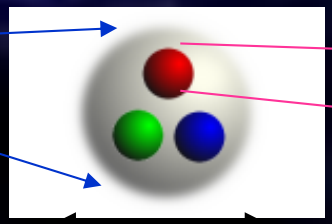
Atom

10^{-12} [cm]



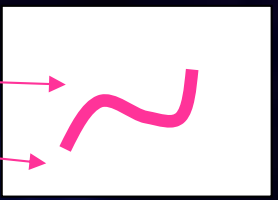
Nucleus

10^{-13} [cm]

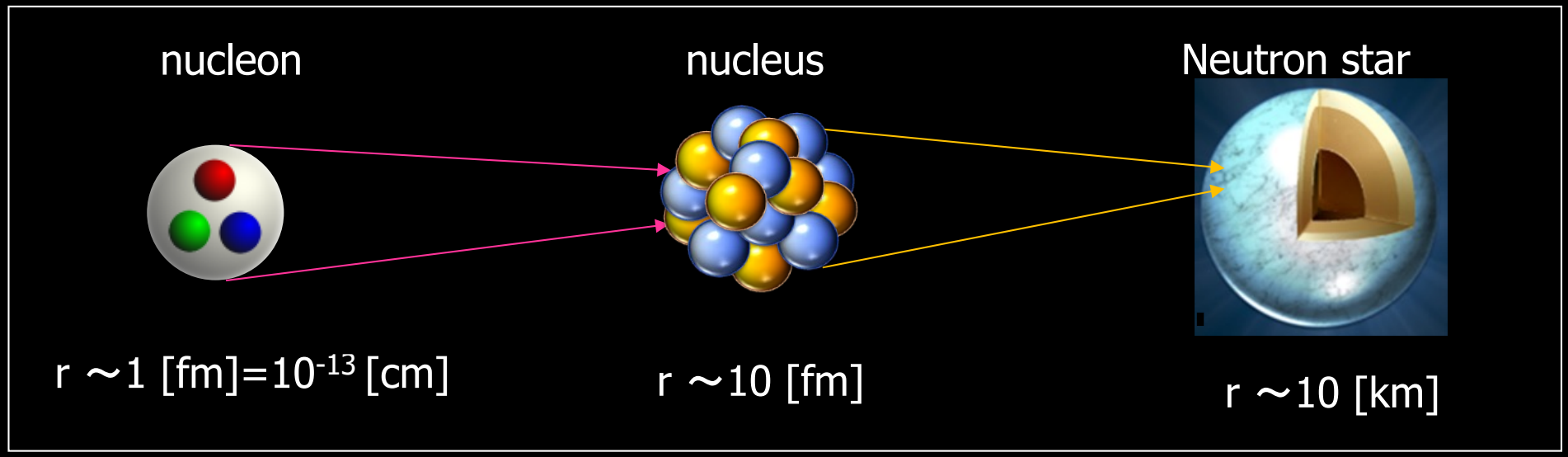


Proton/Neutron

$< 10^{-17}$ [cm]



QCD (Quantum Chromo Dynamics)



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

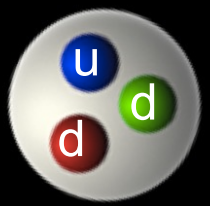
Y. Nambu (1966)

Continuous symmetry for 3-flavor QCD (m=0)

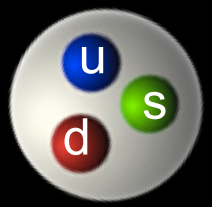
$SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_B$

color flavor

Proron



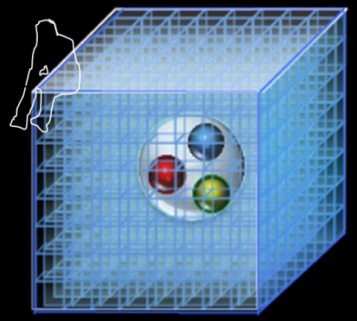
Neutron

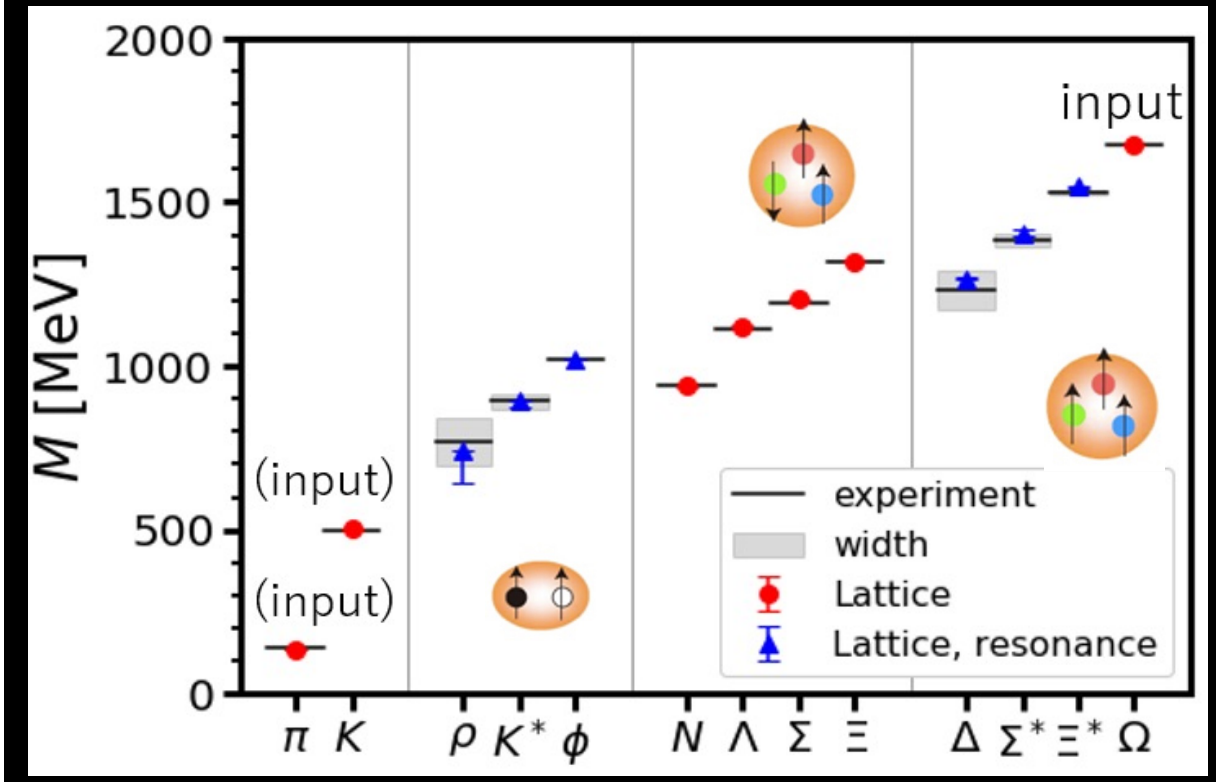


Lambda

Hadrons from ab initio Lattice QCD simulations

$$Z_{\rm QCD} = \int [dU][dqd\bar{q}] e^{-[S_{\rm glue}(U) + \bar{q}F(U)q]} = \int [dU] e^{-S_{\rm eff}(U)}$$





HAL QCD Coll., Phys. Rev. D110 (2024) 094502

m_π=137.1 MeV, L=8.1 fm

FUGAKU Supercomputer (440PFlops) at RIKEN

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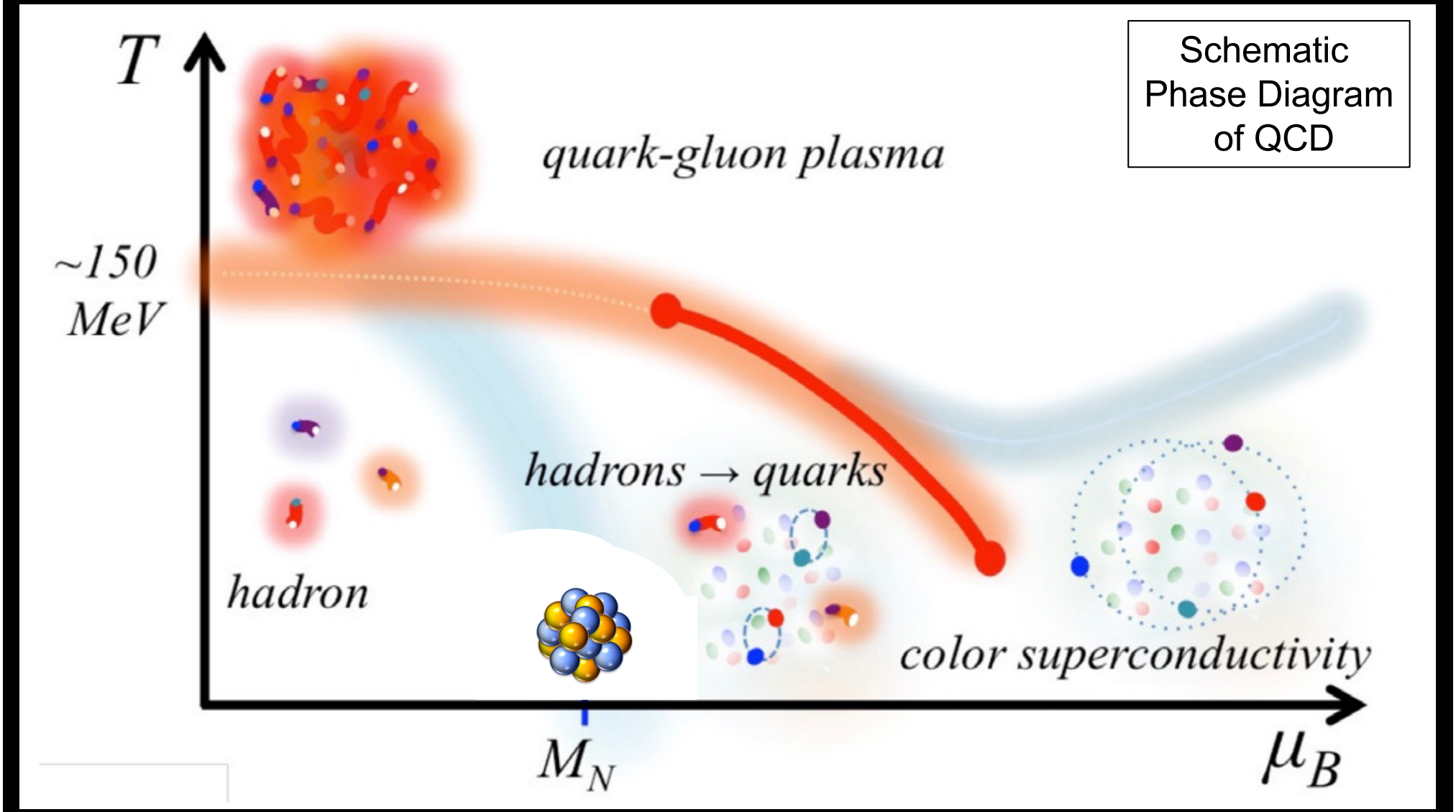
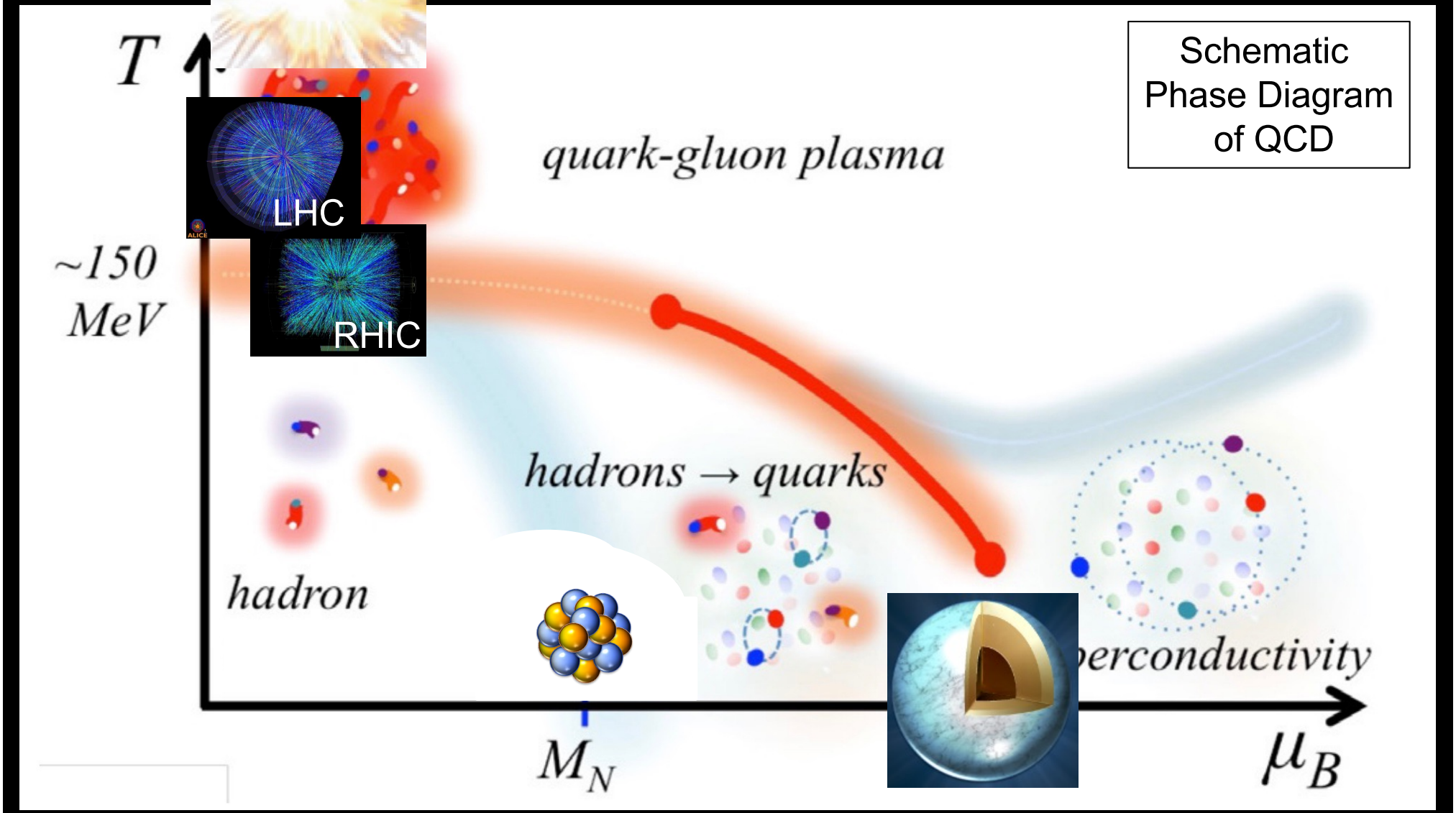
Many-body problems in QCD (uncharted territory)



Baym, Hatsuda, Kojo, Powell, Song, Takatsuka,
Rept. Prog. Phys. 81 (2018) 056902

Many-[Big bang]oblems in QCD (uncharted territory)



Baym, Hatsuda, Kojo, Powell, Song, Takatsuka,
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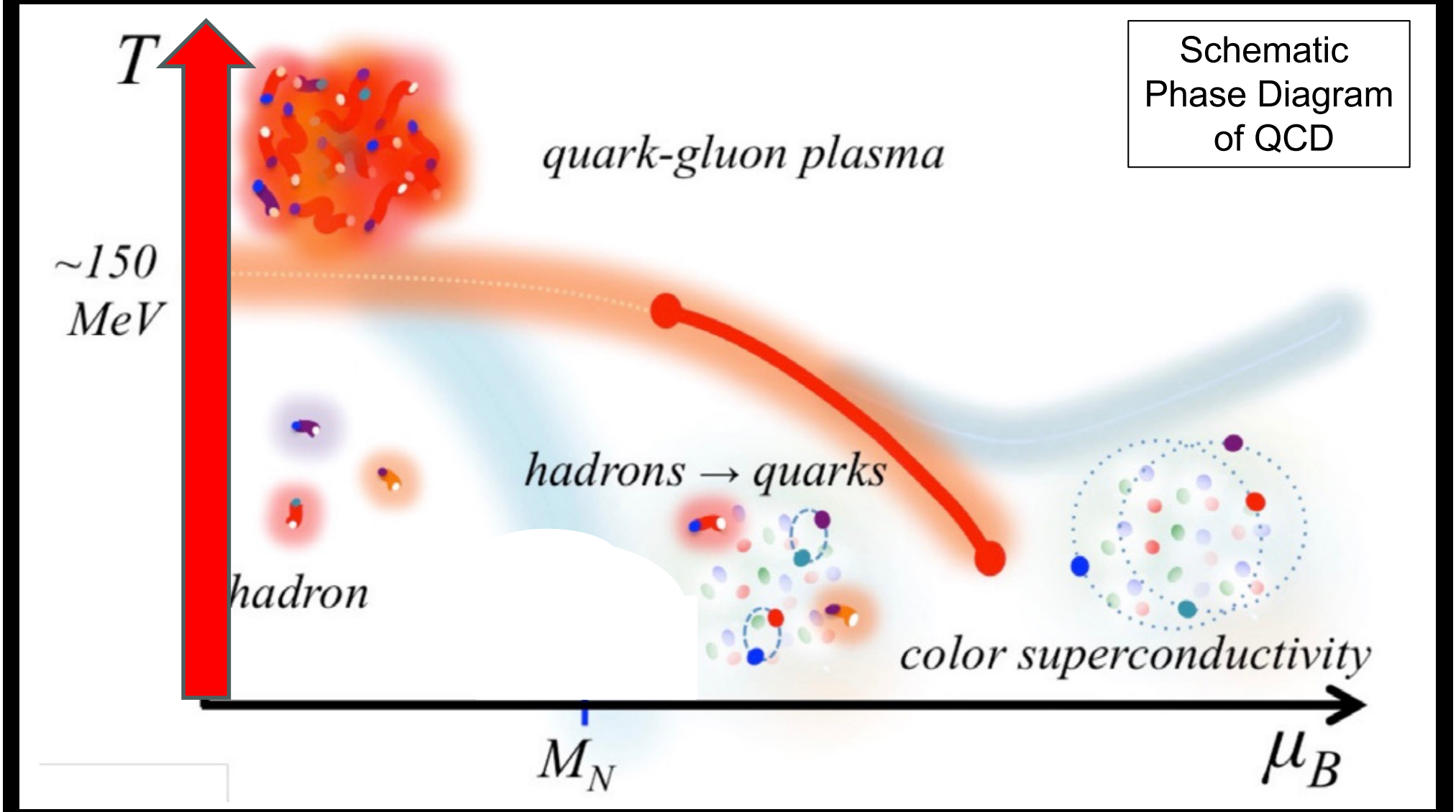
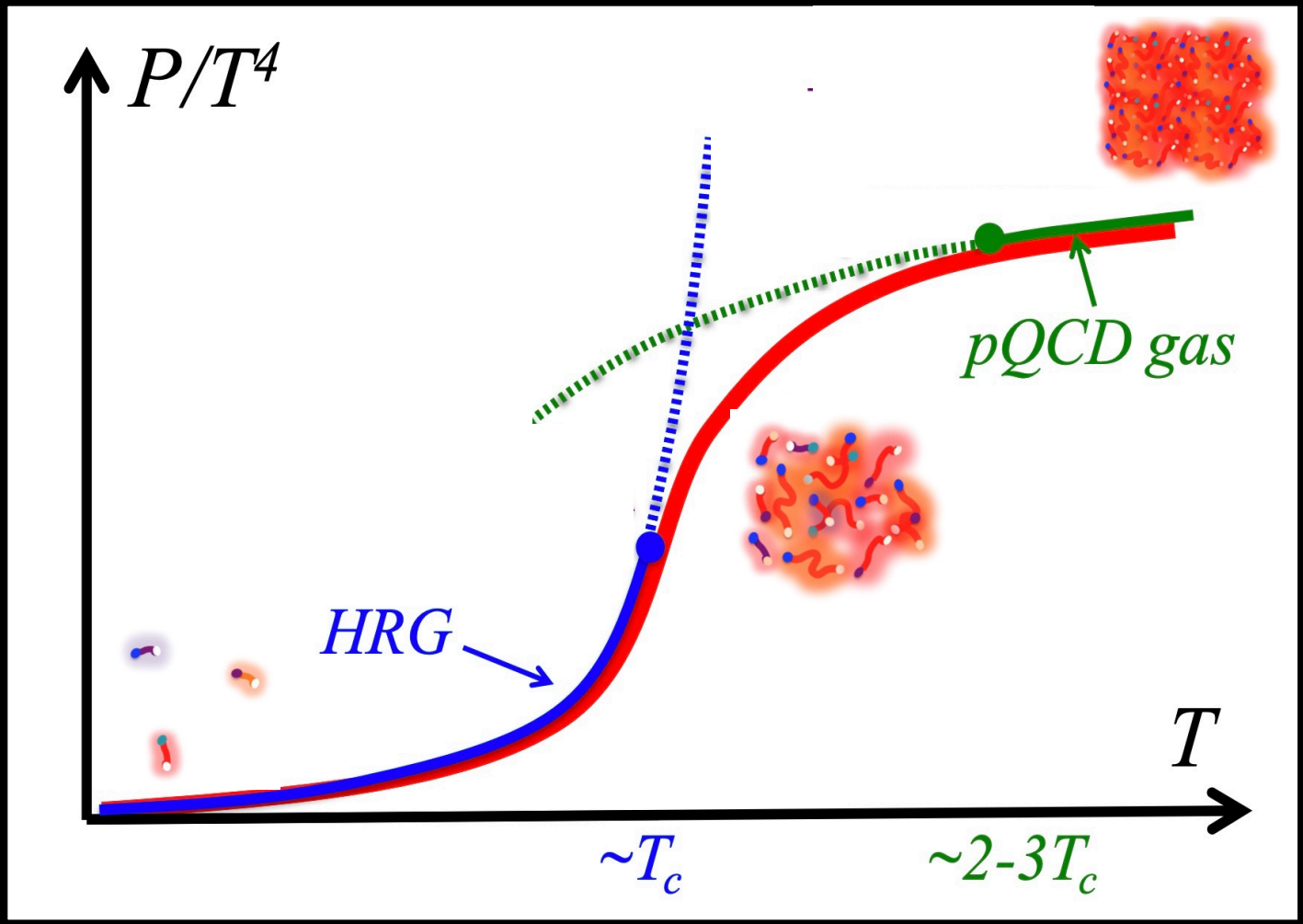


Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

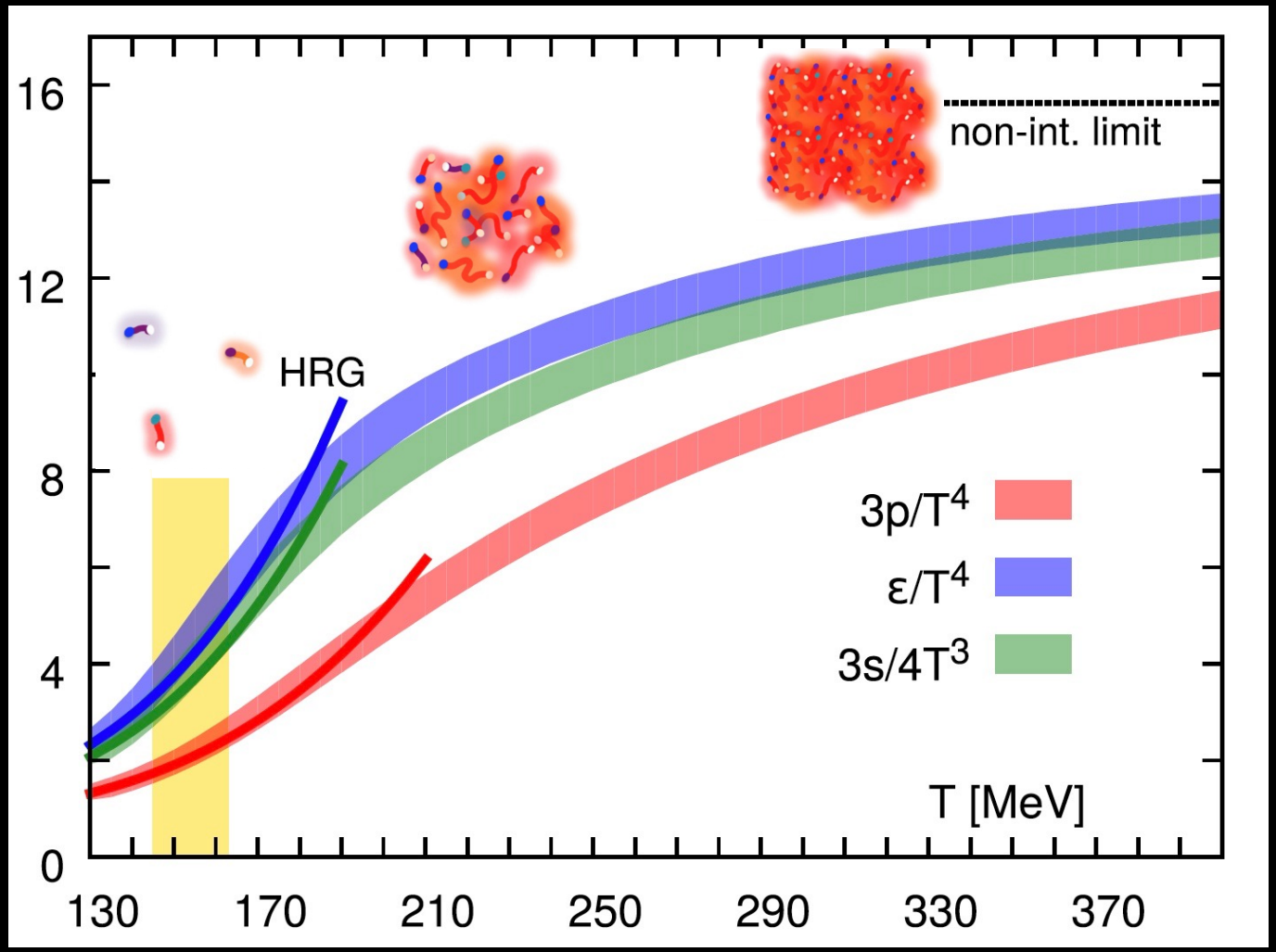
Hot Equation of State ((EOS)
(schematic picture)



Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

Asakawa and Hatsuda, Phys. Rev. D 55 (1997) 4488

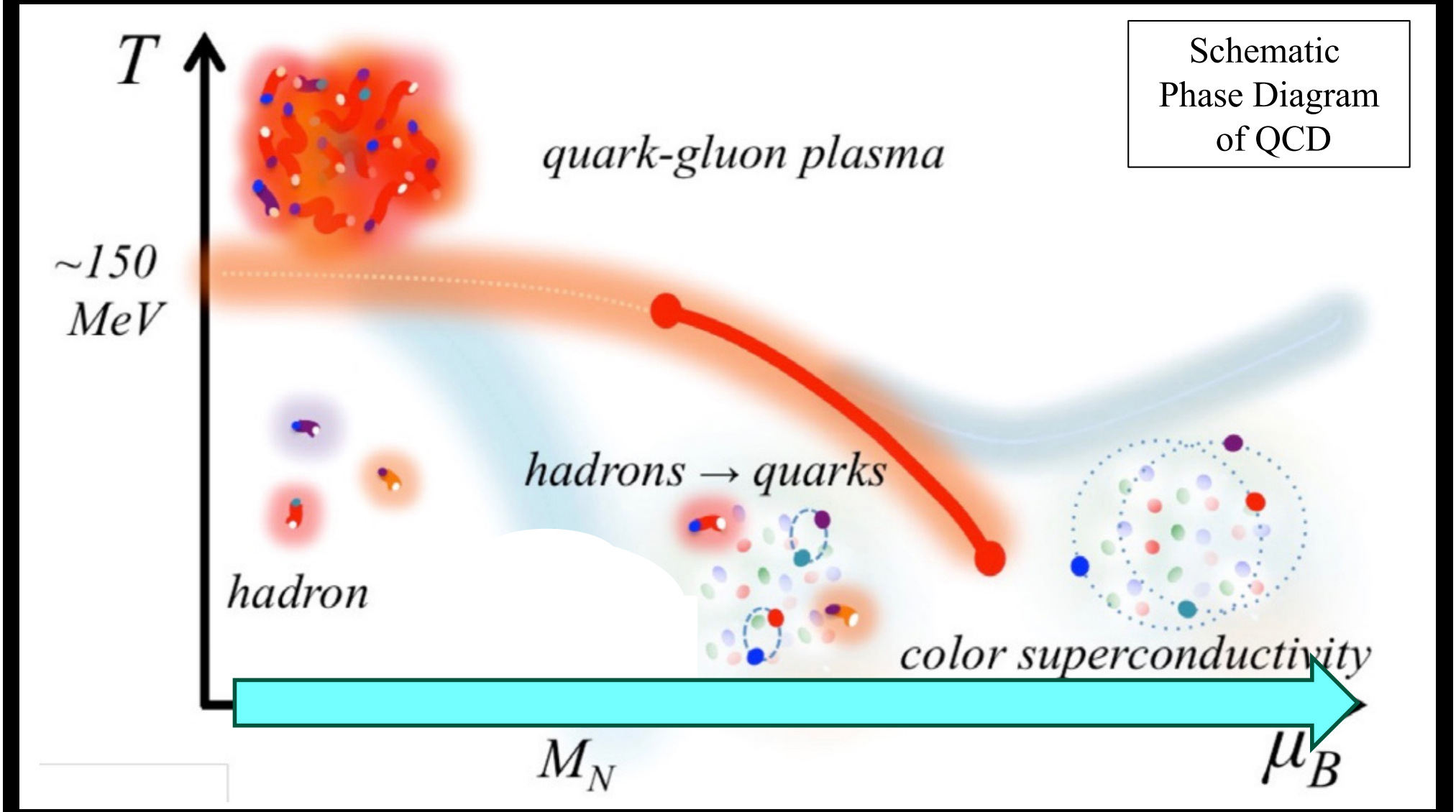
Hot Equation of State ((EOS)
(lattice QCD)



T_{pc} = 156±1.5 MeV

HotQCD Coll., Phys. Rev. D90 (2014) 094503

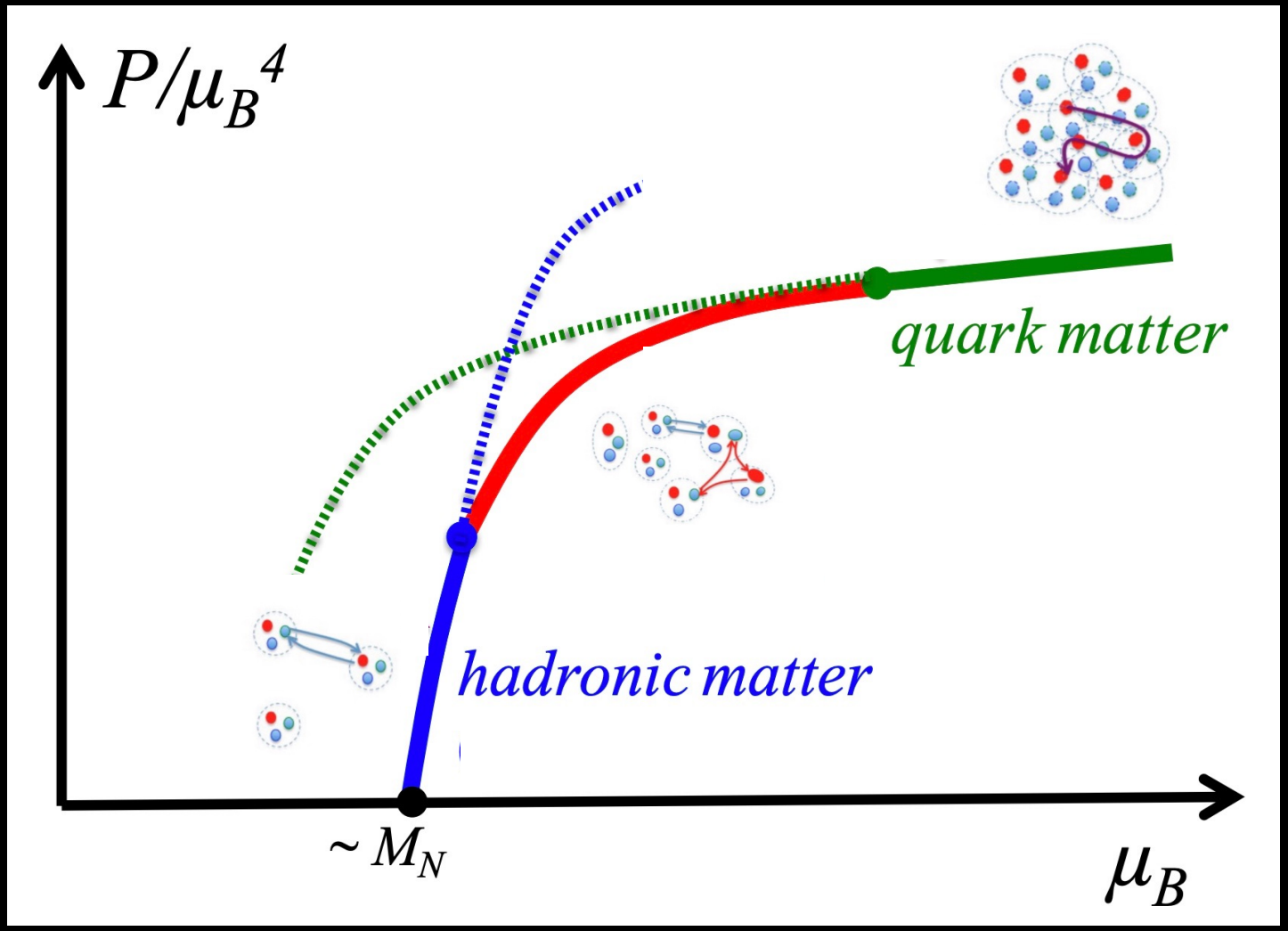
Many-body problems in QCD (uncharted territory)



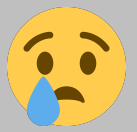
Baym, Hatsuda, Kojo, Powell, Song, Takatsuka,
Rept. Prog. Phys. 81 (2018) 056902

Dense Equation of State ((EOS)

(schematic picture)



No LQCD due to sign problem



Ask neutron Stars!

Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

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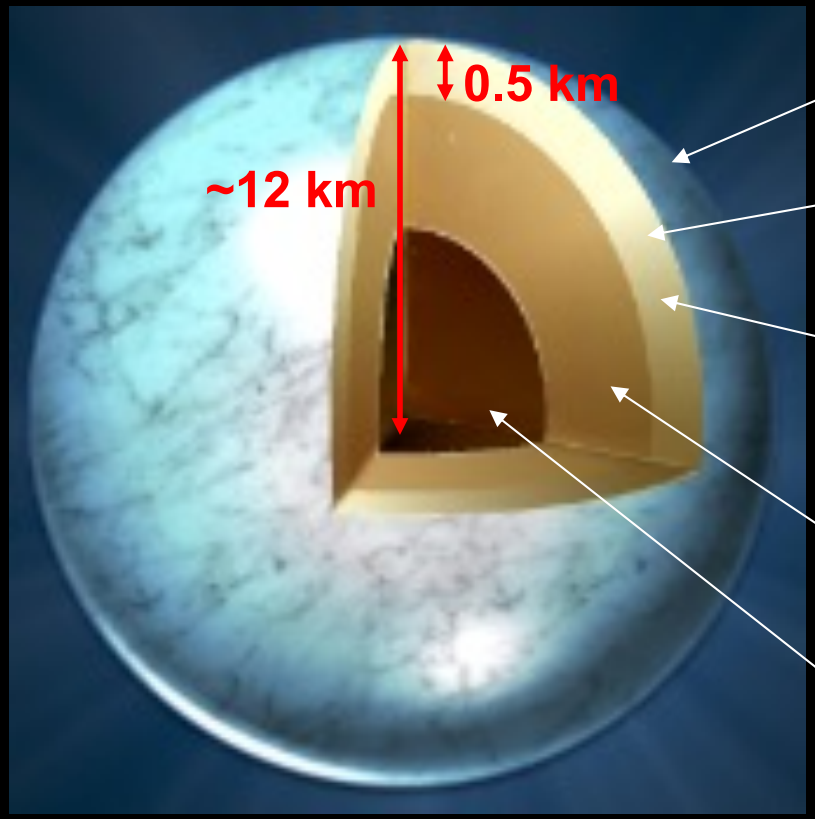
Structure of Neutron Star

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



Atmosphere
H, He, C, etc

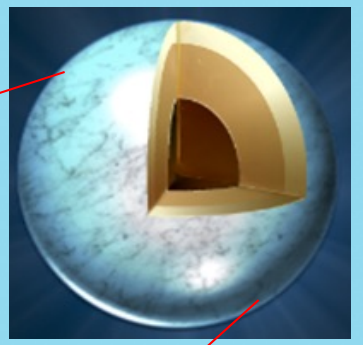
Surface
Atomic nuclei (solid)

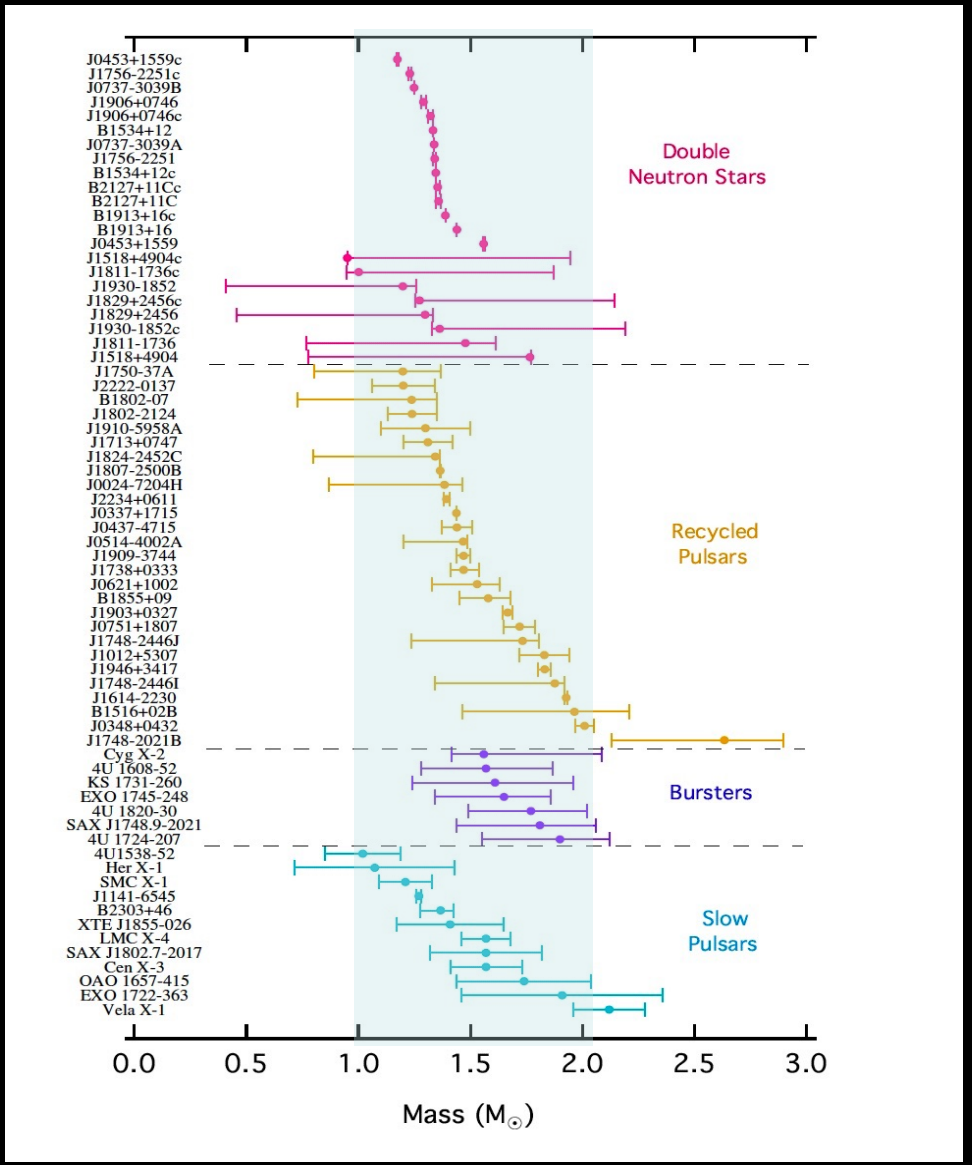
Crust
Atomic nuclei（solid）
+Neutrons ($^1S_0$ superfluid)

Outer core
Neutrons ($^3P_2$ superfluid）
+ Protons ($^1S_0$ superconductor)

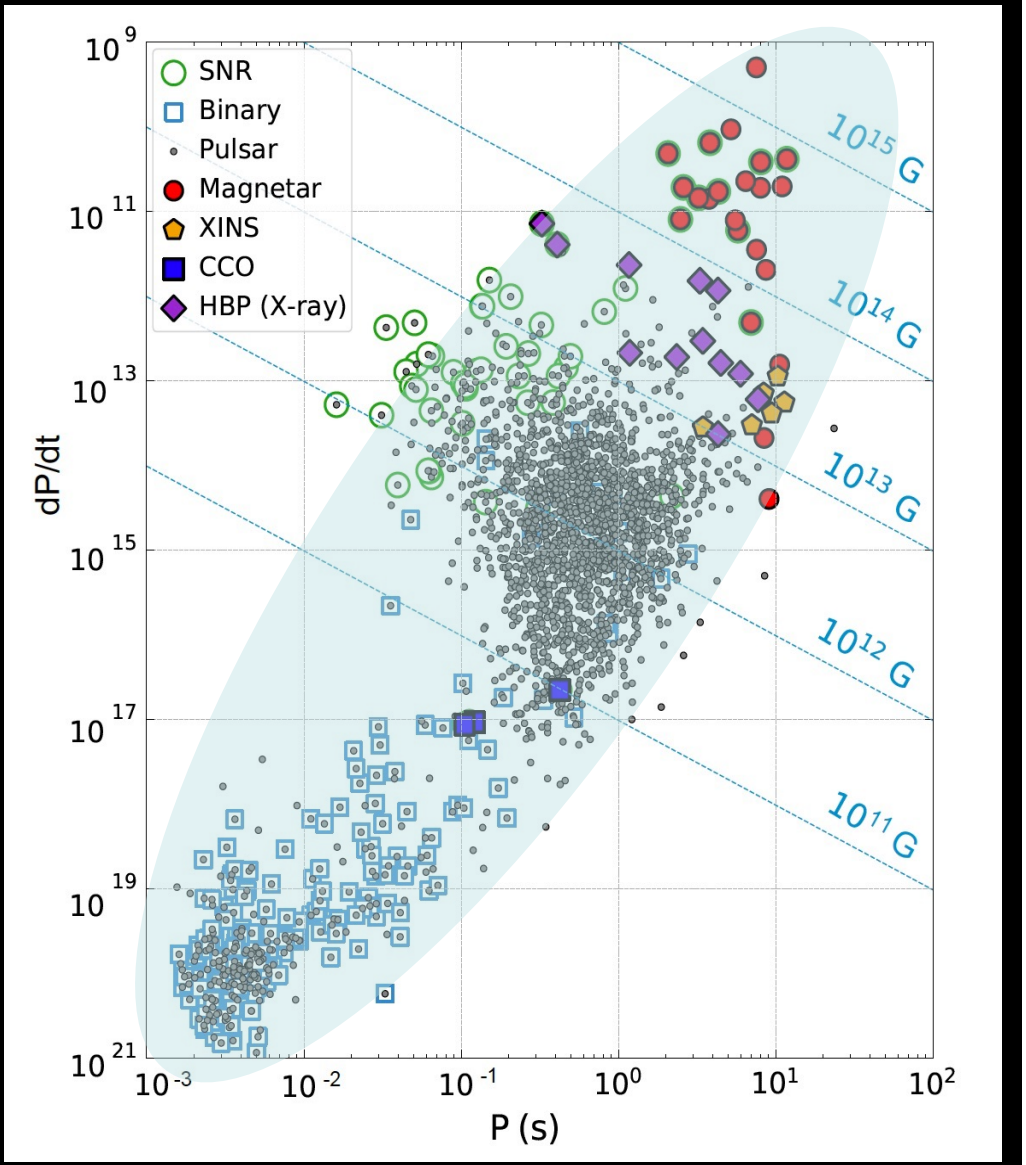
Inner core
Quarks（color superconductor）?

Neutron Star in Taipei





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



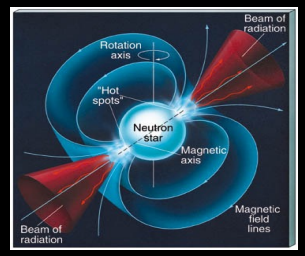
Enoto, Kisaka, and Shibata,
Rep. Prog. Phys. 82 (2019) 106901.

Neutron Star (NS) observations

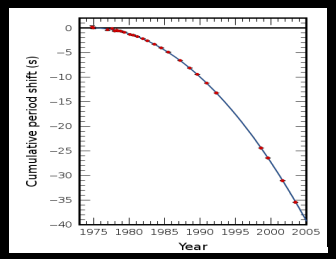
1932 Discovery of the neutron [J. Chardwick]

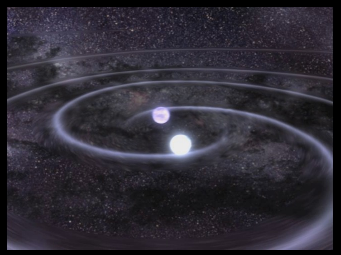
1934 Prediction of neutron star [W. Baade and F. Zwicky]

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

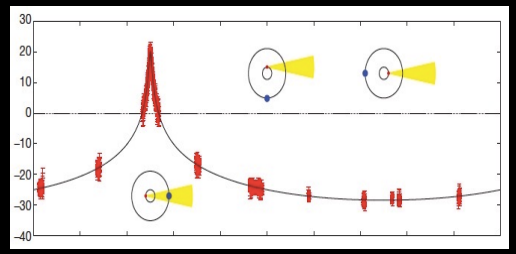


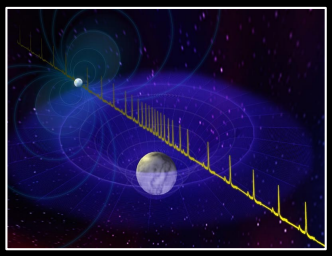
1974 Discovery of binary neutron star
[R. A. Hulse and J.H. Taylor]



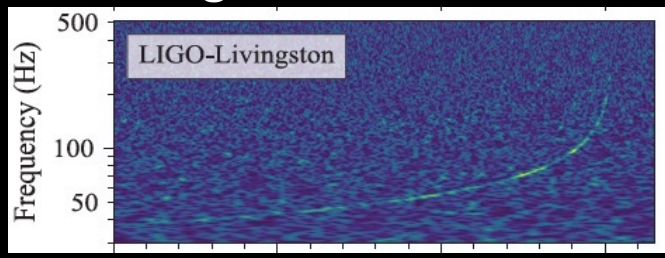


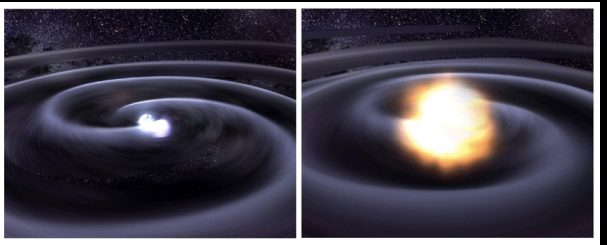
2010 Discovery of massive neutron star
[P. Detmorest et al.]



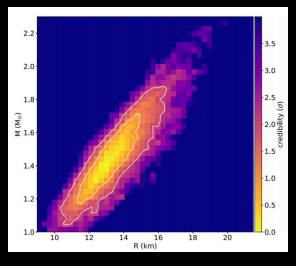


2017 Discovery of GW from NS merger
[LIGO/Virgo]





2019 Light bending around pulsar
[NICER]



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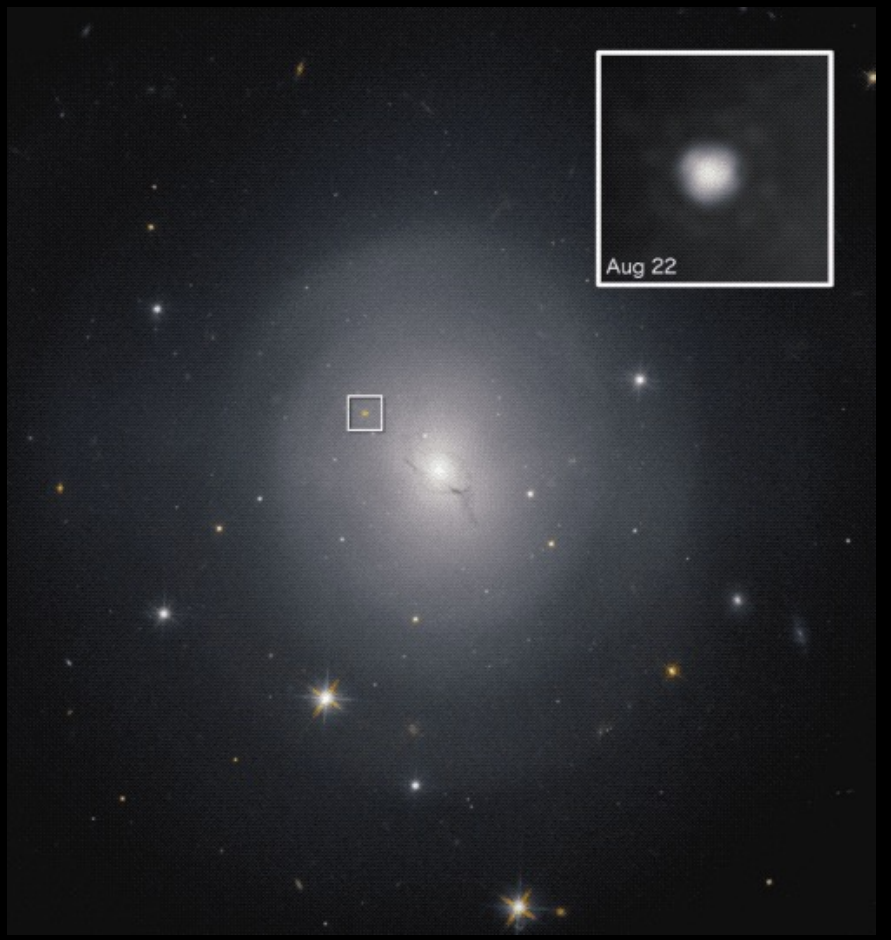
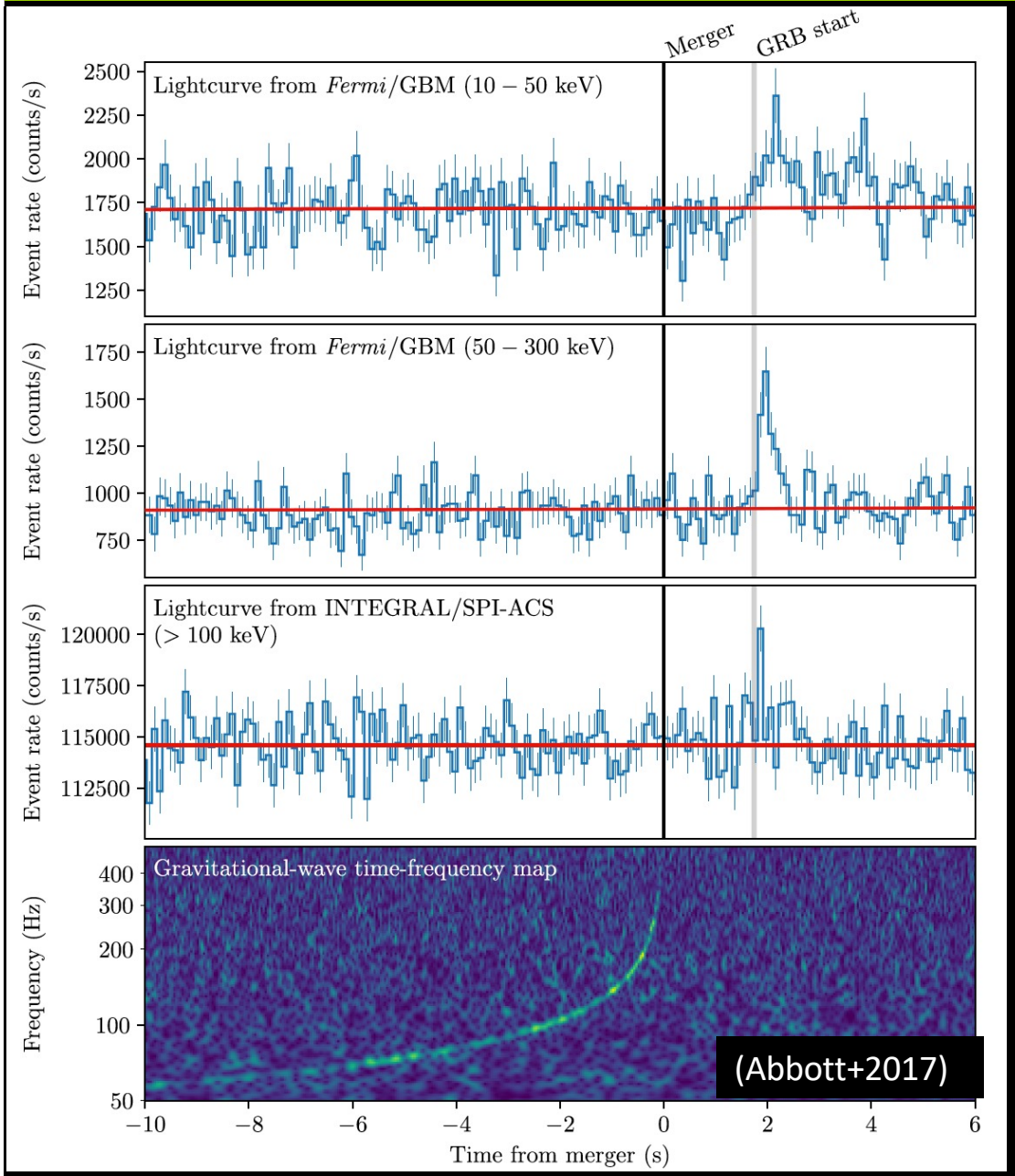
Neutron Star Merger GW170817

in NGC4993 (44.1 Mpc=144 Mly away)



From LIGO HP

Neutron Star Merger GW170817



Gamma-ray from Fermi Satellite

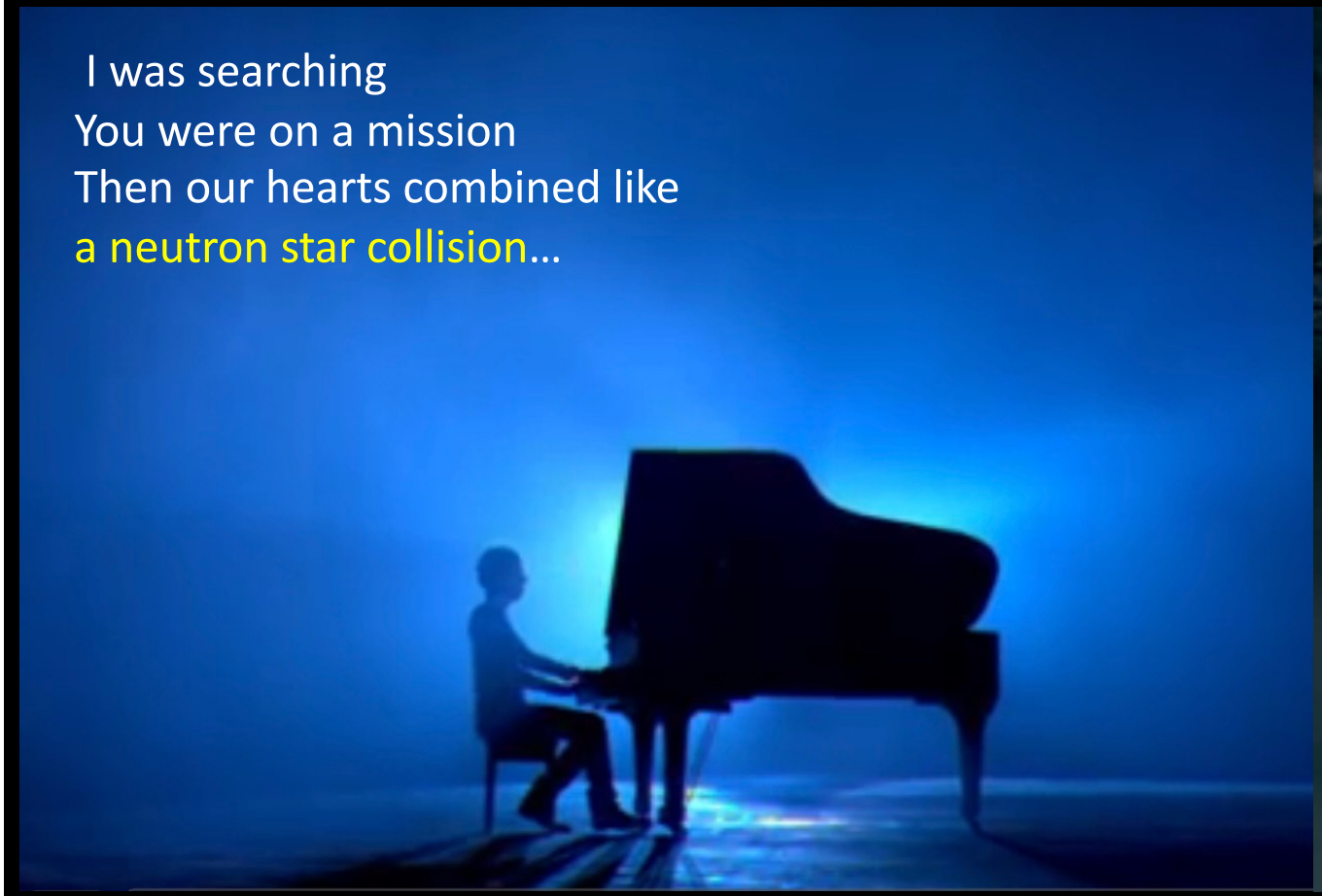
Gravitational Wave from LIGO

Neutron Star Collision (2017)

GW170817 in NGC4993
(44.1 Mpc=144 Mly away from us)

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

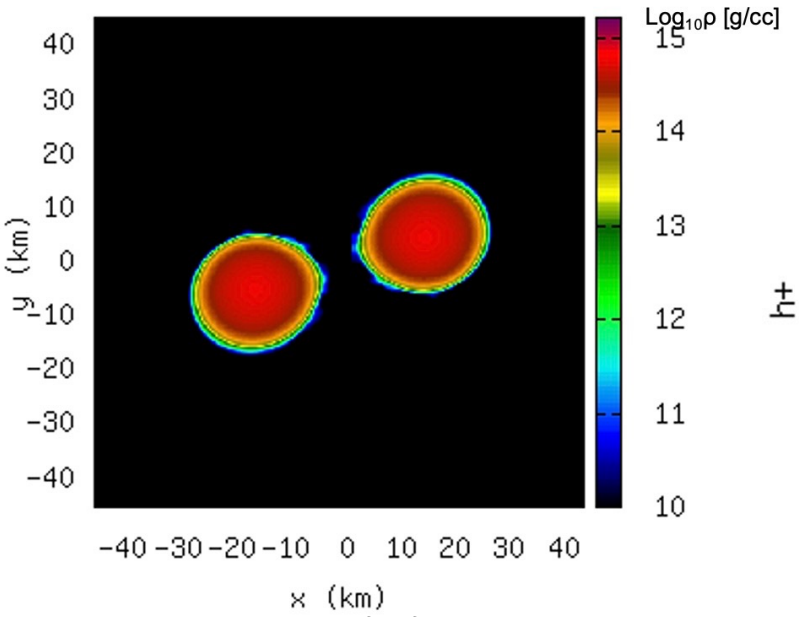
Neutron Star Collision (film/music, 2010)



Neutron Star Collision (Love is Forever) by Muse
https://www.youtube.com/watch?v=MTvgnYGu9bg

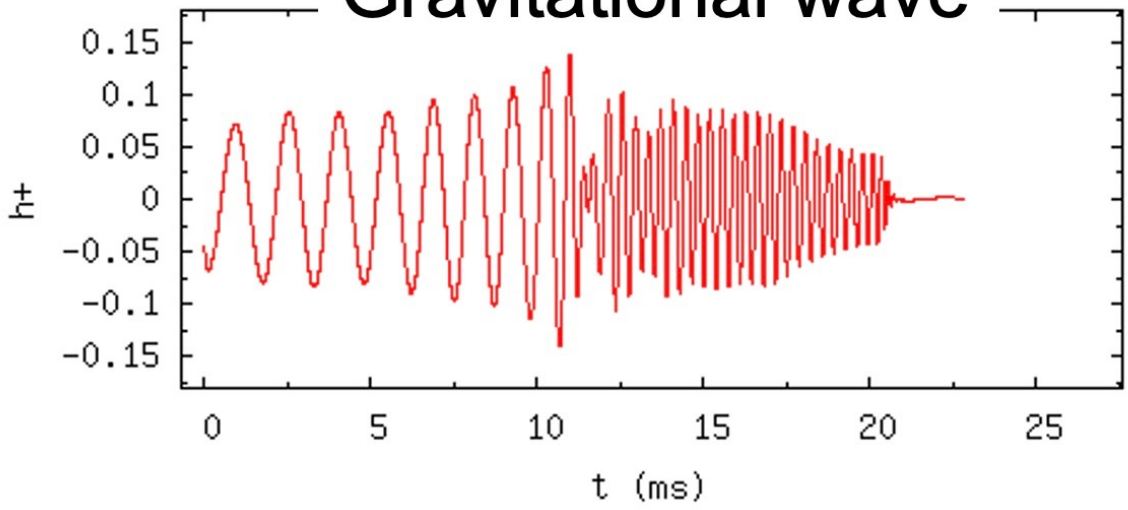
NS merger and gravitational wave by numerical relativity

Matter density



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \; T_{\mu\nu}$$

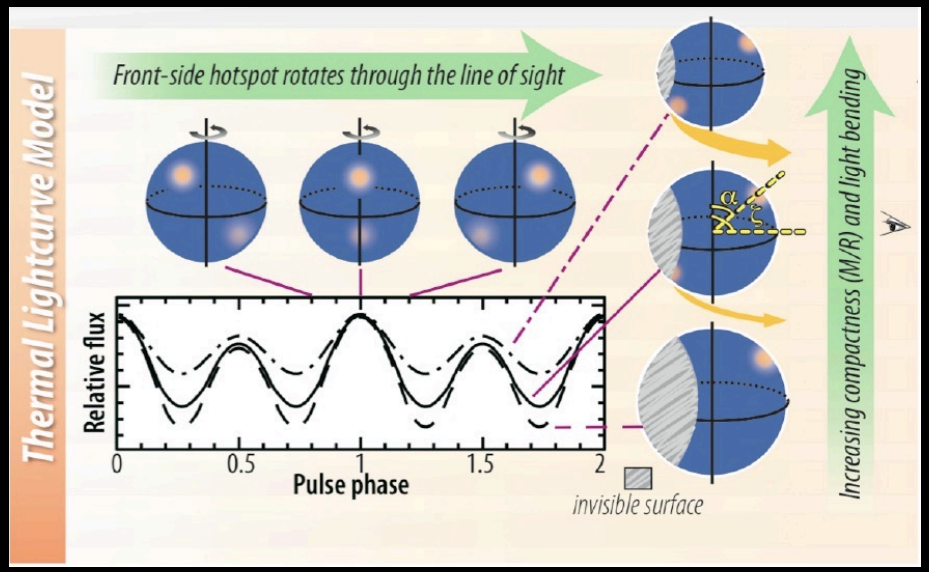
Gravitational wave

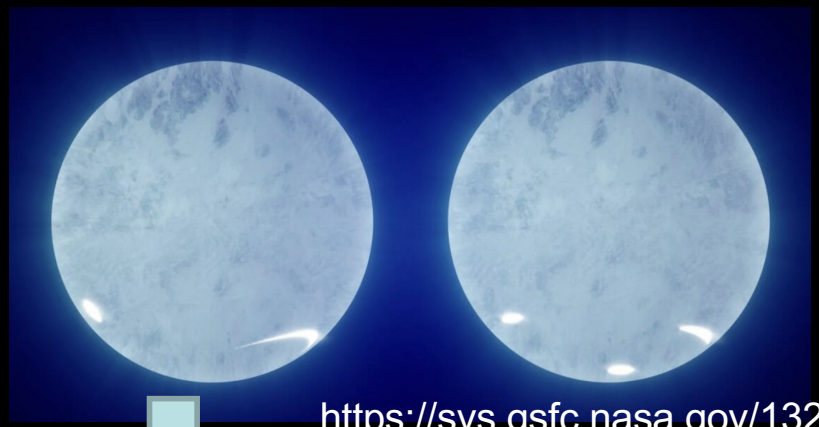


Merger of 1.4M_s + 1.4 M_s neutron stars into a blackhole

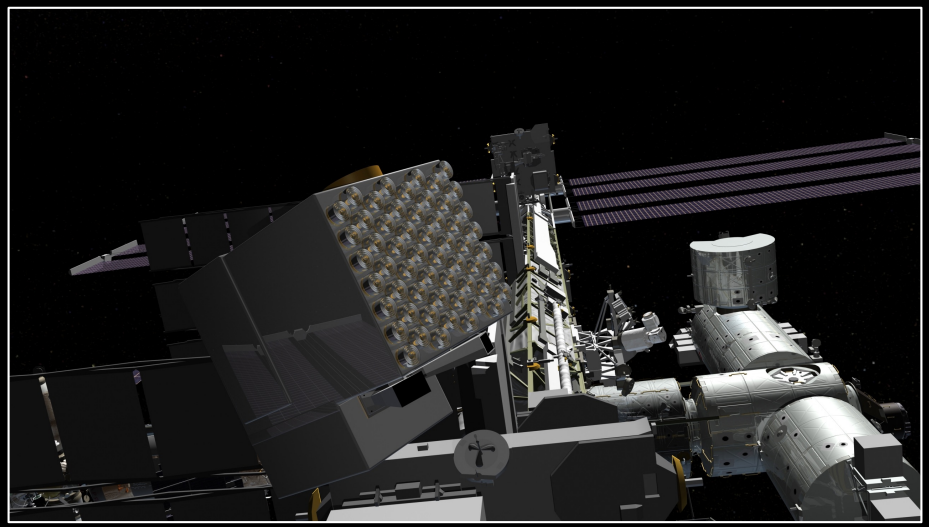
K. Hotokezaka, K. Kiuchi, K. Kyutoku, H. Okawa, Y. Sekiguchi, M. Shibata, and K. Taniguchi, "The mass ejection from the merger of binary neutron stars", Phys. Rev. D 87, 024001 (2013).
http://www2-tap.scphys.kyoto-u.ac.jp/~hotoke/anime/index.html

Light bending around NS

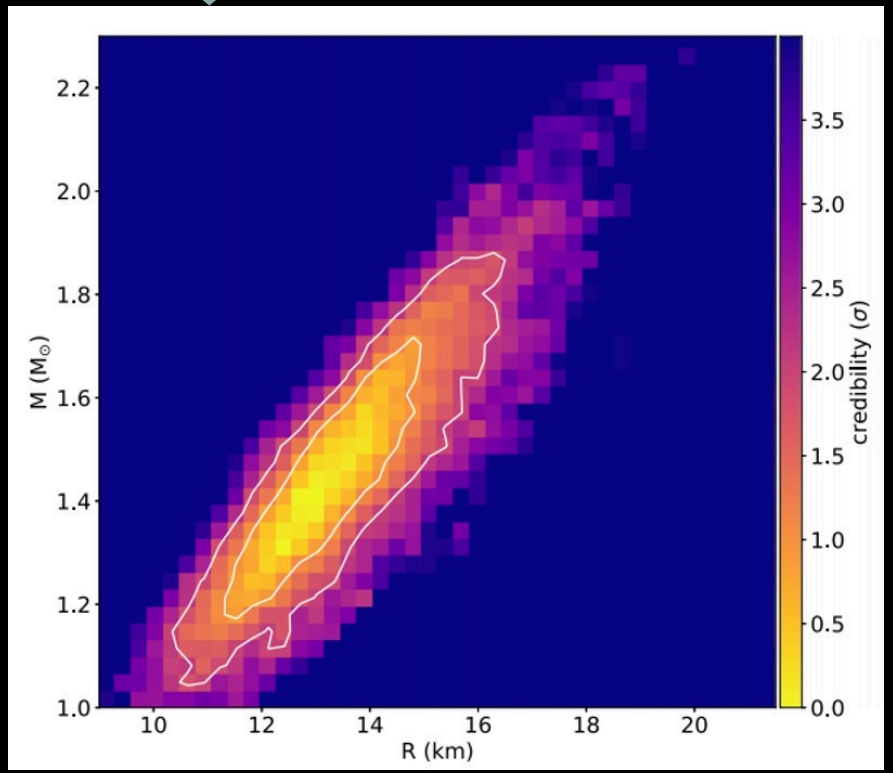




https://svs.gsfc.nasa.gov/13240



Neutron Star Interior Composition Explorer (NICER) on ISS



NICER: ApJ 887 (2019)

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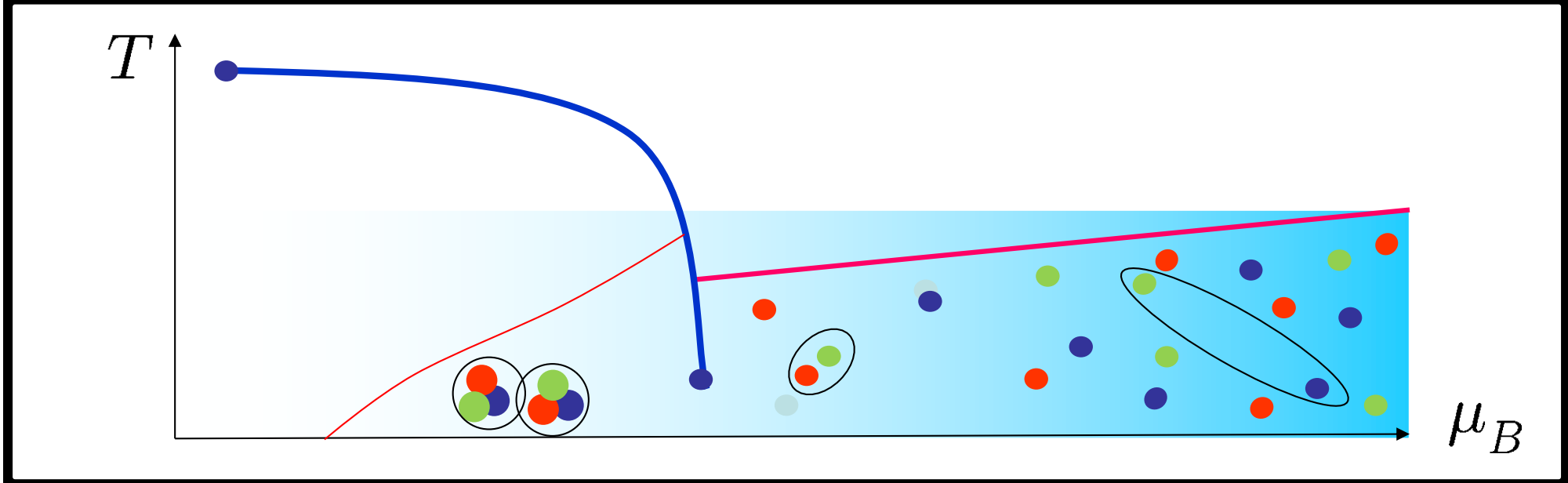
Quark-Hadron Crossover ?



Neutron Superfluid
Tamagaki, Hoffberg+ (1970)

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

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

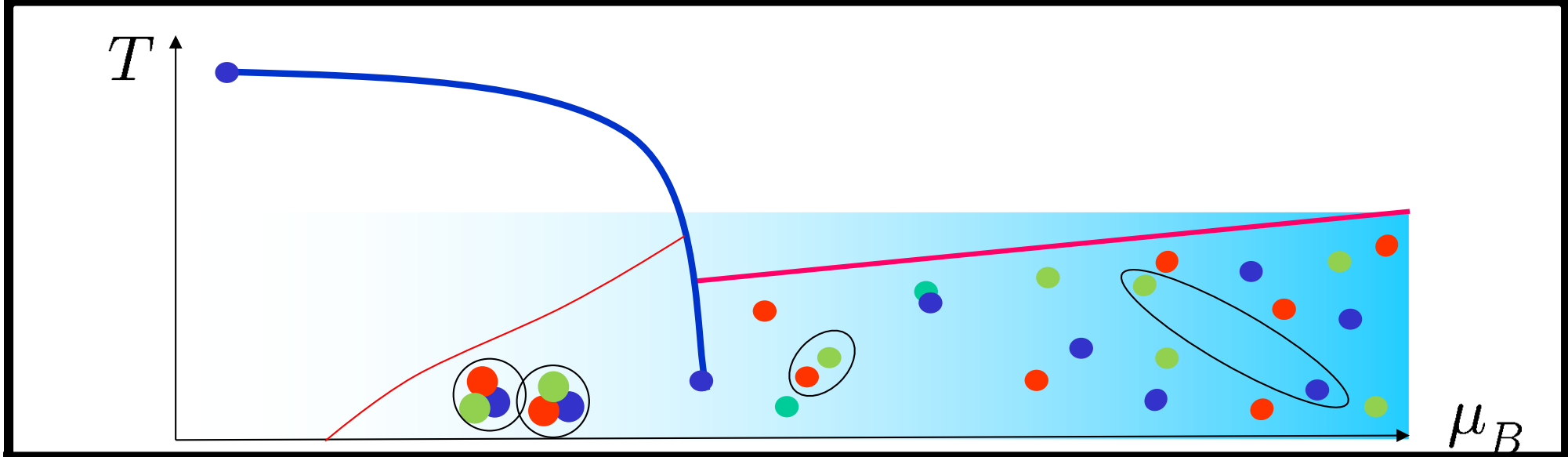
Quark-Hadron Crossover ?

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: Kitazawa, Koide, Kunihiro, Nemoto, PTP 108 (2002)
Hatsuda, Tachibana, Yamamoto, Baym, PRL 97 (2006)

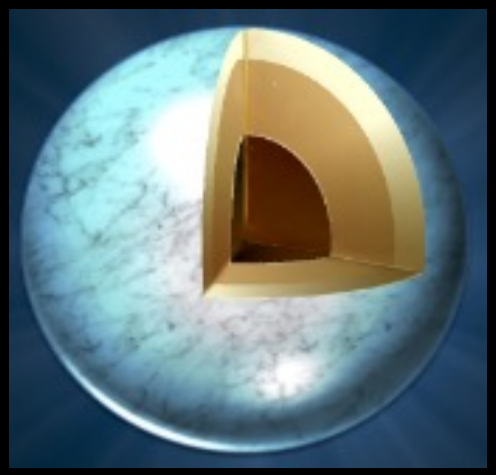
Implication to neutron star phenomenology: Masuda, Hatsuda, Takatsuka, Astrophysical J. 764 (2013)

Quark-Hadron Crossover ?



$2\rho_0$ $5\rho_0$

Strongly interacting baryonic matter



Strongly interacting quark matter

Solving Neutron Star

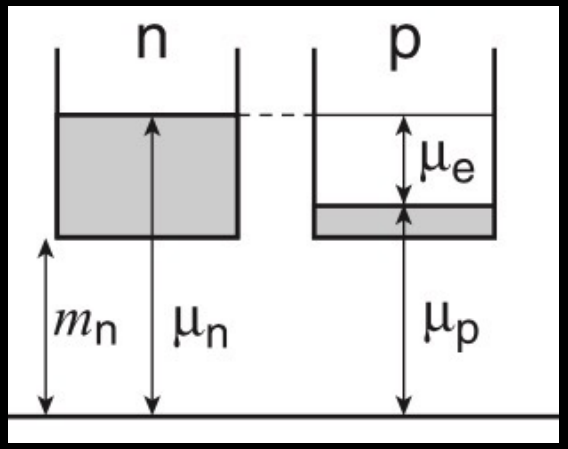
1. Tolman–Oppenheimer–Volkoff equation ← General Relativity (TOV)

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

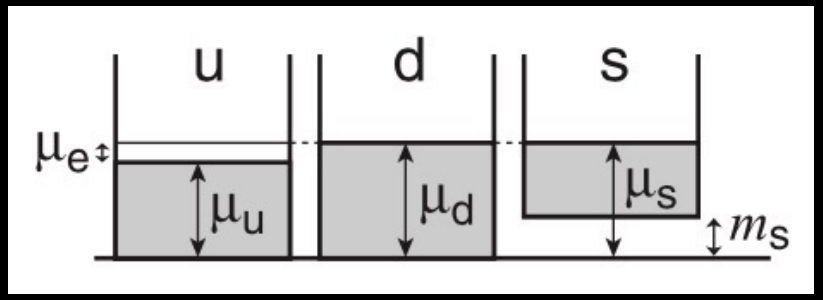
$$-\frac{dP(r)}{dr} = \frac{G\varepsilon\mathcal{M}}{r^2}\left(1-\frac{2G\mathcal{M}}{r}\right)^{-1}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{\mathcal{M}}\right),$$

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

EOS with Quark-Hadron Crossover (QHC)

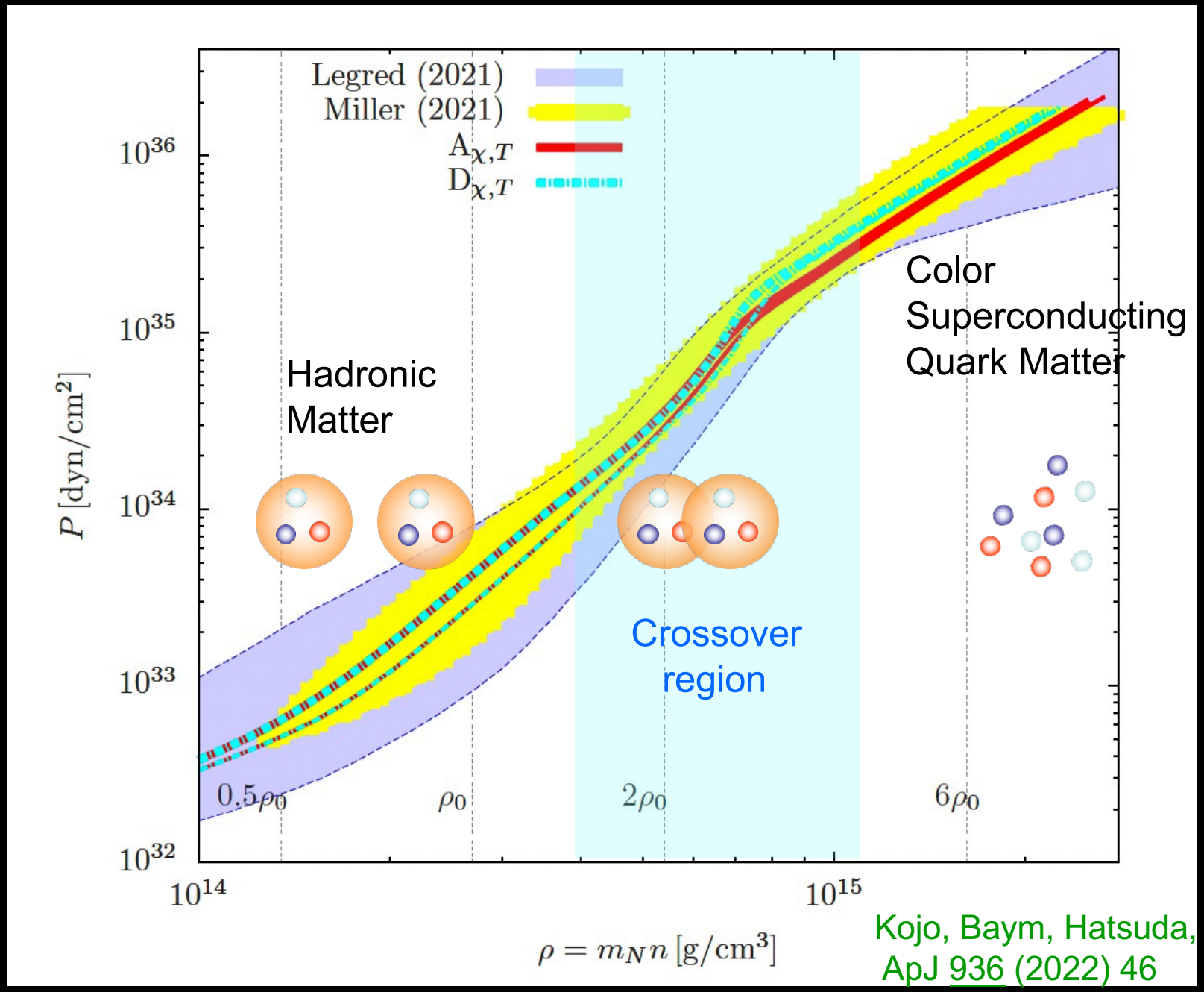
- Original idea of QHC (2013)
  Masuda, Hatsuda, Takatsuka, ApJ 762 (2013) 12

- Detailed construction (2016-2021)
  QHC21: Kojo, Baym, Hatsuda, ApJ 936 (2022) 46

- Low density ($n < 1.5\ n_0$): Hadronic matter (N^3LO chiral EFT)
- High density ($N > 3.5\ n_0$): Quark matter with color superconductivity (NJL)
- Smooth interpolation with two constraints:
  Thermodynamic consistency and $M_{max} > 2\ M_\odot$

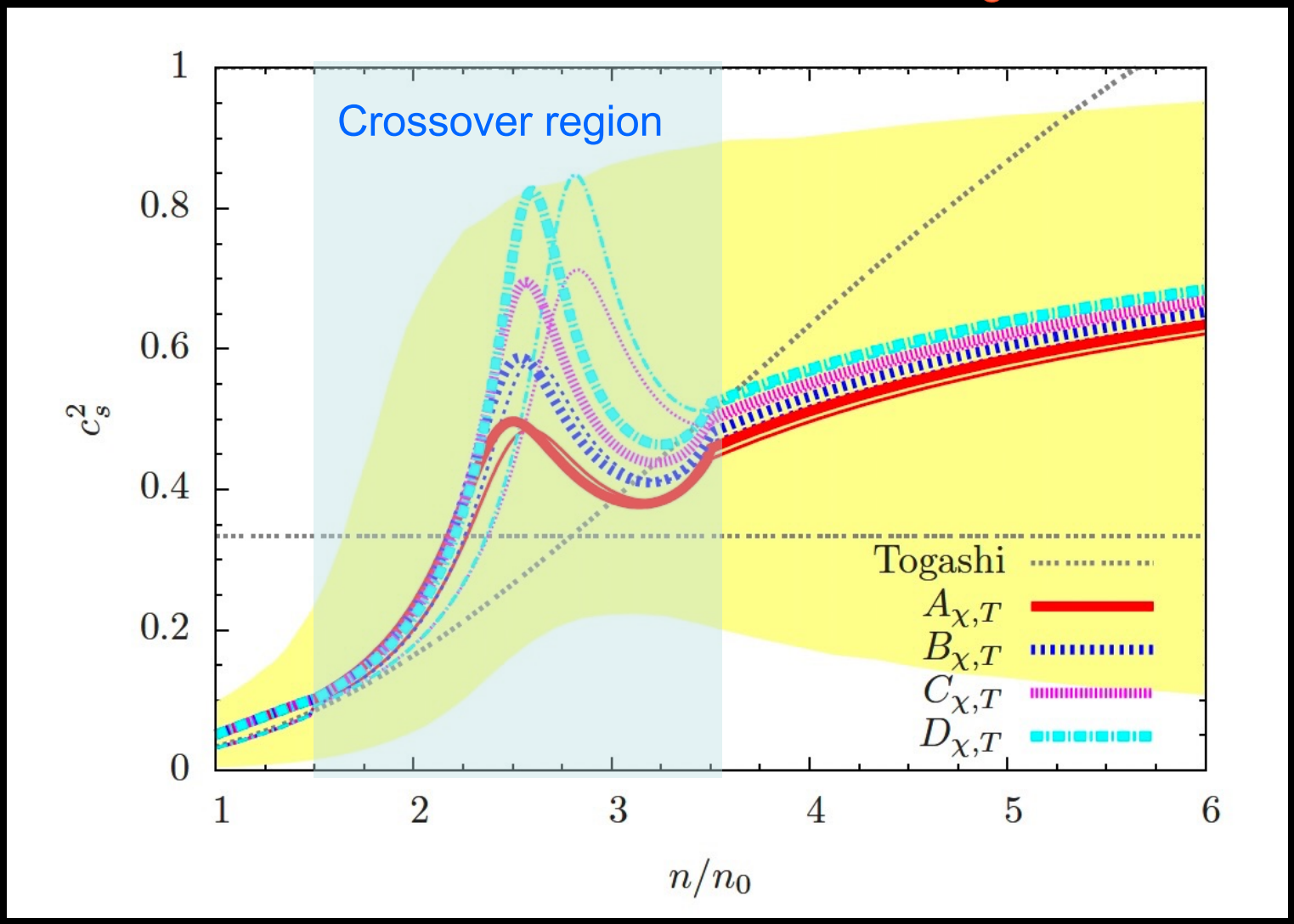
- NS Merger simulation with QHC (2022-)
  Huang, Baiotti, Kojo, Takami, Sotani, Togashi, Hatsuda, Nagataki, Fan,
  PRL 129 (2022) 181101
  Hensh, Huang, Kojo, Baiotti, Takami, Nagataki, Sotani,
  arXiv:2407.09446 [astro-ph.HE]

Quark-hadron Crossover EOS vs. GW+NICER constraint



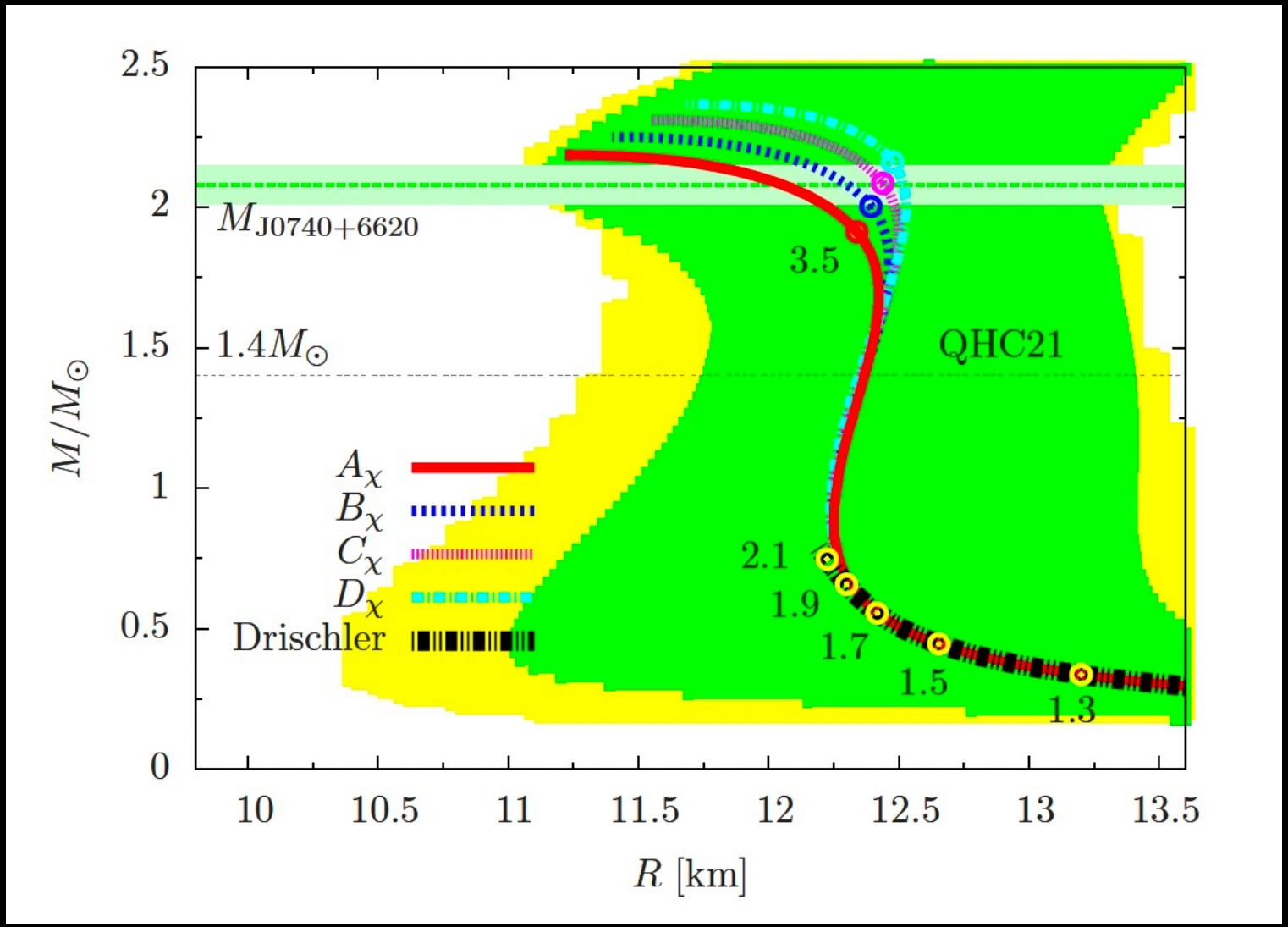
Kojo, Baym, Hatsuda, ApJ 936 (2022) 46

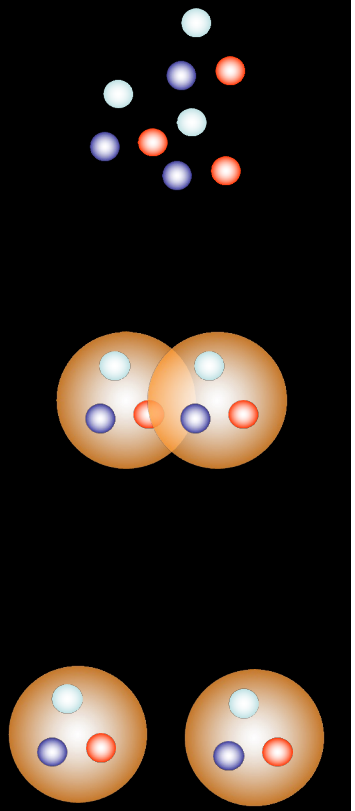
Quark-Hadron Crossover: sound velocity



Kojo, Baym, Hatsuda, ApJ 936 (2022) 46

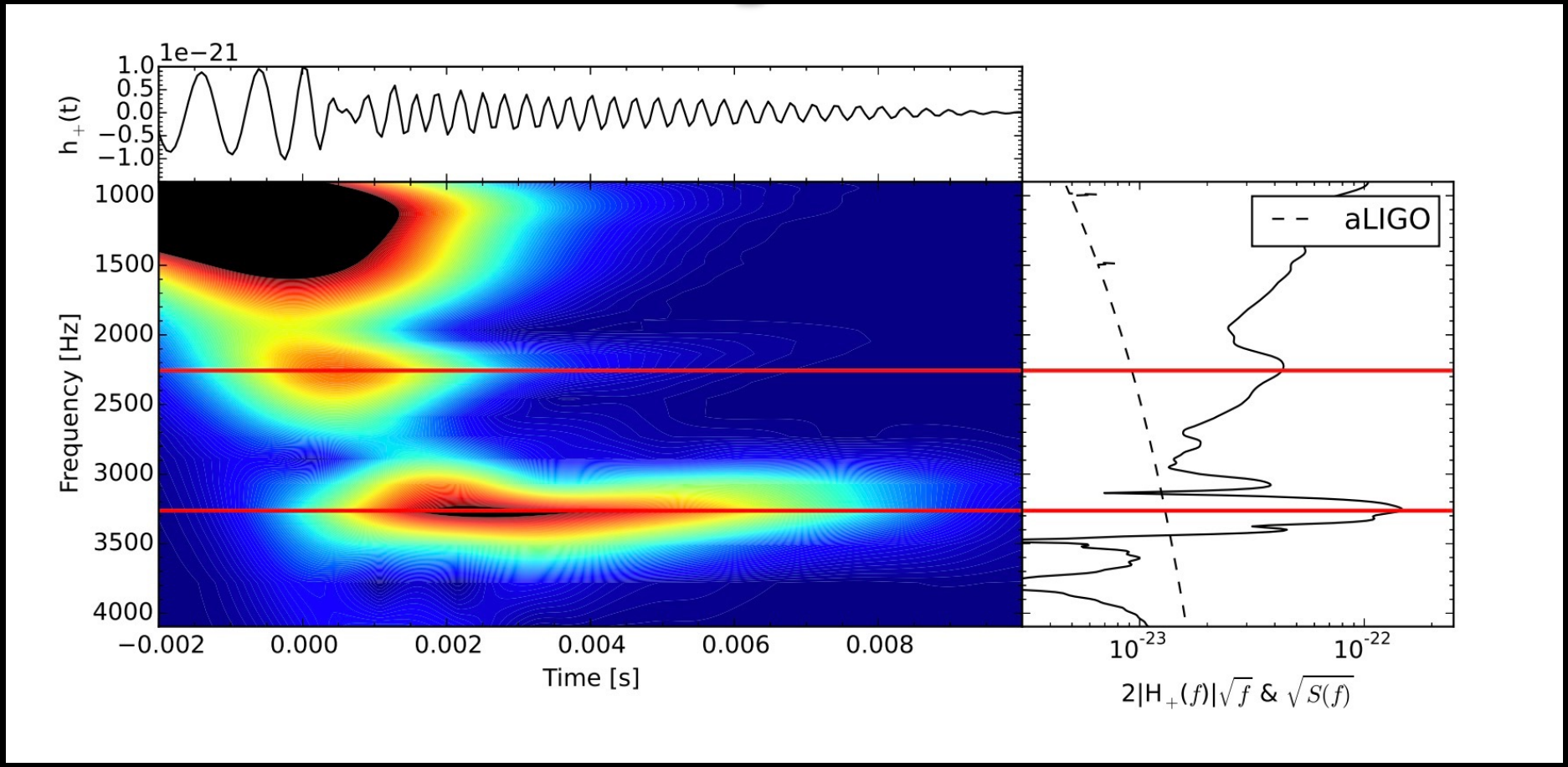
QHC21 EOS: M-R relation





Kojo, Baym, Hatsuda, ApJ 936 (2022) 46

Binary neutron star: Post merger GW

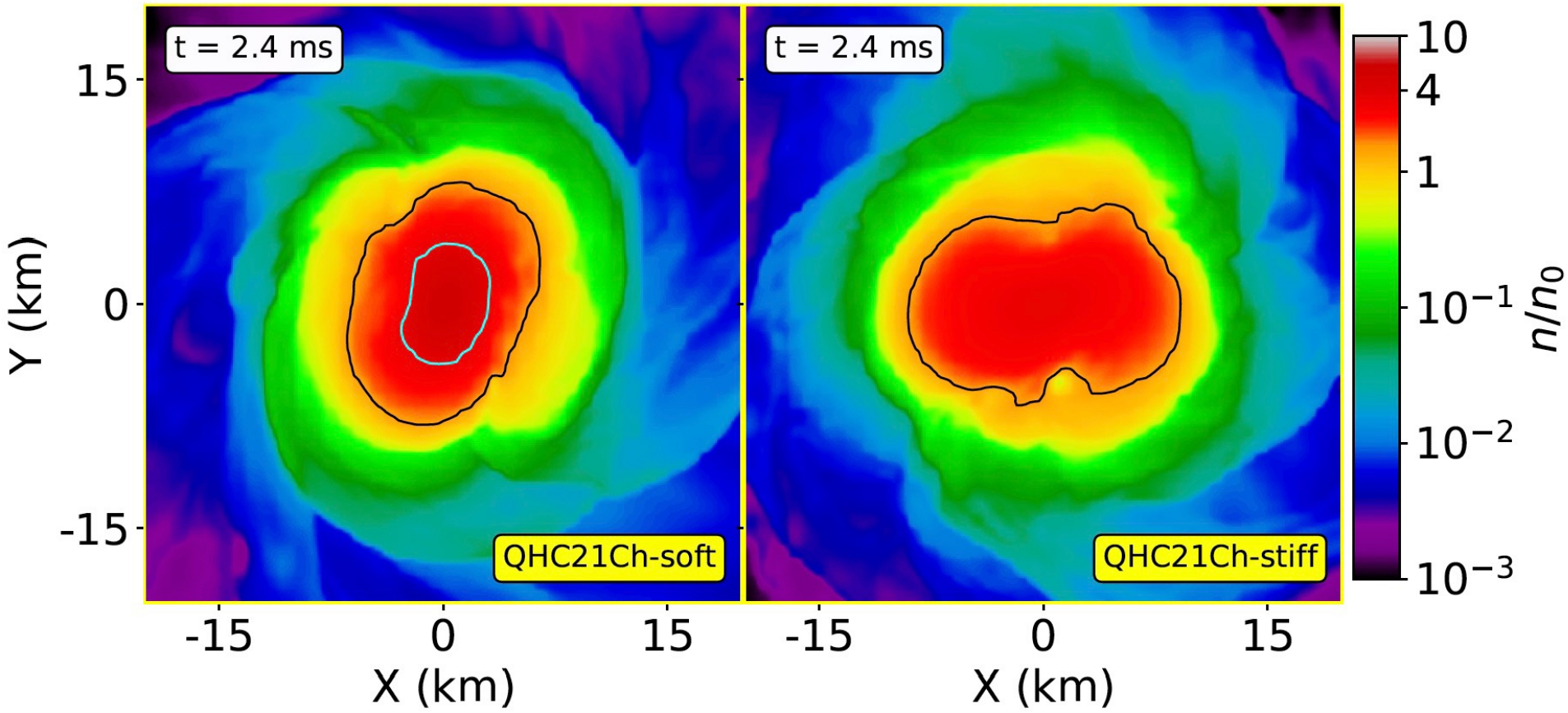


Time-frequency analysis for the TM1 1.35+1.35 M_s waveform from a source at 50 Mpc

Clark+, Class. Quantum Grav. **33** (2016) 085003

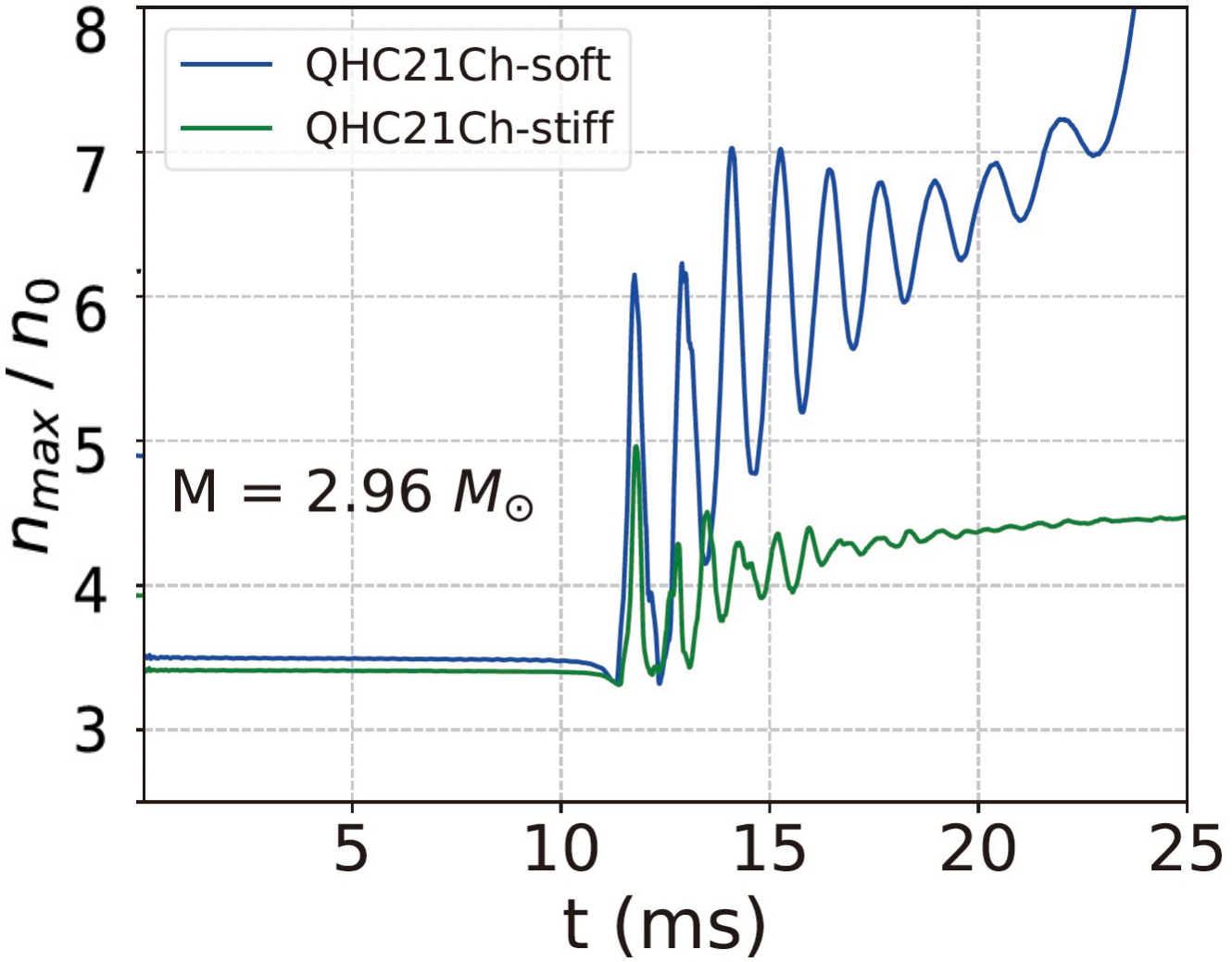
Density contour of the NS merger with QHC21

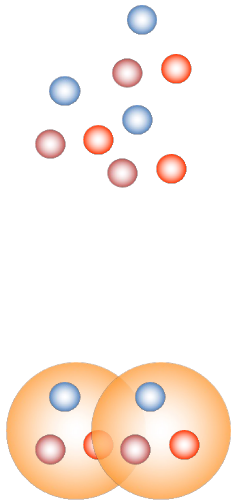
(total mass M=2.96 $M_\odot$ at t = 2.4 ms)



Hensh, Huang, Kojo, Baiotti, Takami, Nagataki, Sotani, arXiv:2407.09446 [astro-ph.HE]

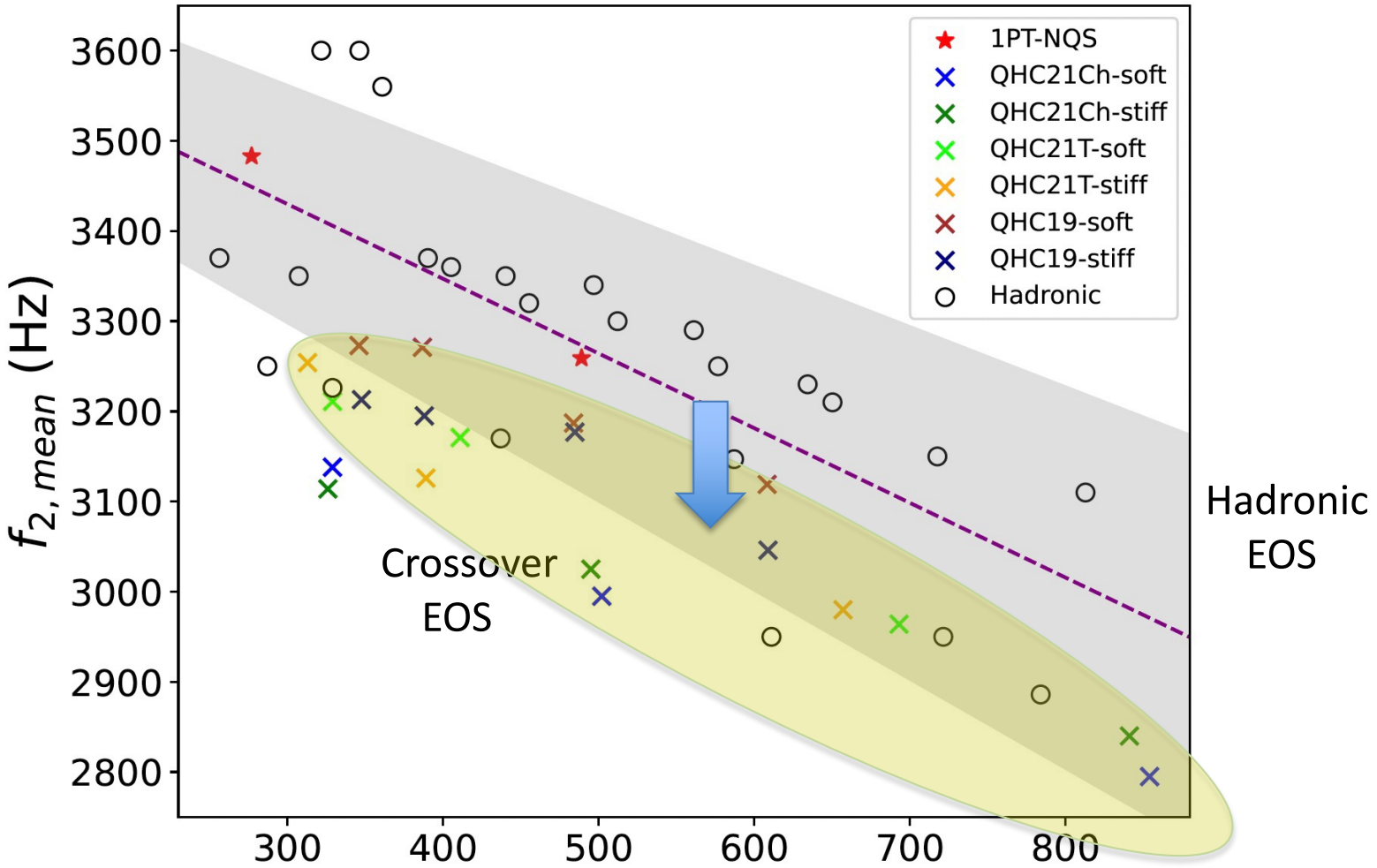
Max. density of the NS merger with QHC21
(total mass M=2.96 $M_\odot$)

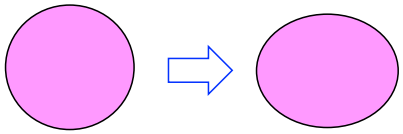




Hensh, Huang, Kojo, Baiotti, Takami, Nagataki, Sotani,
arXiv:2407.09446 [astro-ph.HE]

GW frequency f_2 after the merger vs. tidal deformability

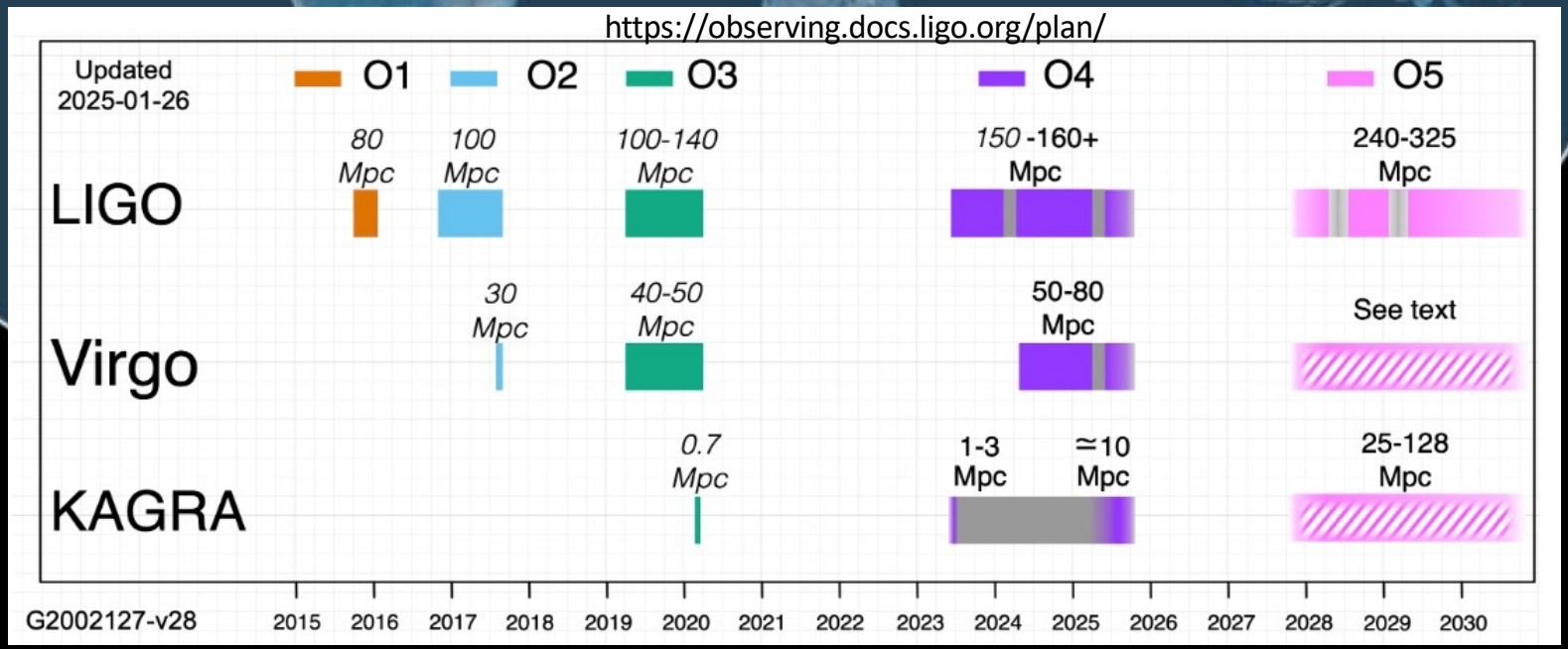




Hensh, Huang, Kojo, Baiotti, Takami, Nagataki, Sotani, arXiv:2407.09446 [astro-ph.HE]

全球重力波觀測站

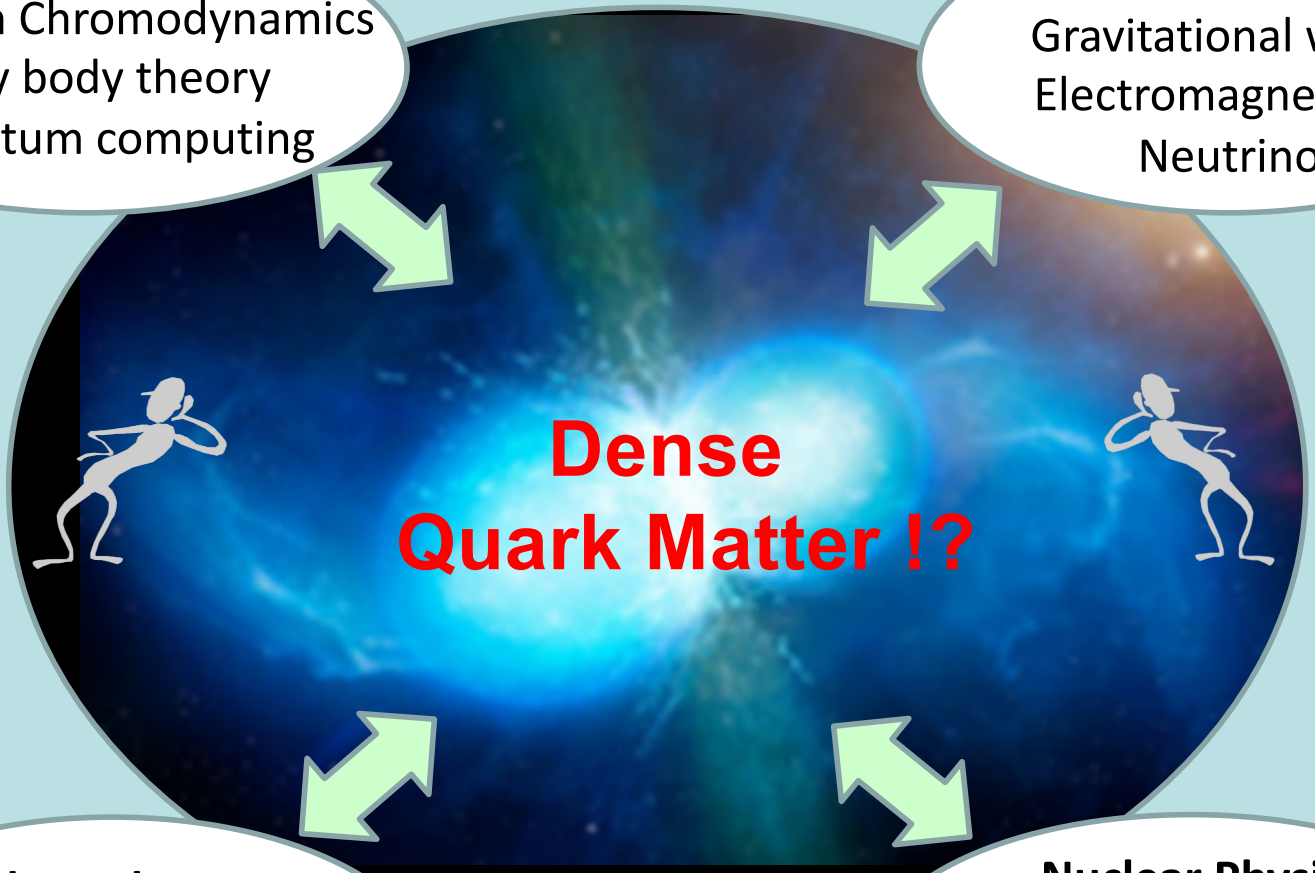
https://observing.docs.ligo.org/plan/



Summary

Theory
Quantum Chromodynamics
- many body theory
- quantum computing

Cosmic Observation
Gravitational wave
Electromagnetic wave
Neutrino



Condensed Matter
Liquid helium
Unitary fermi gas
Bose-Fermi mixture

Nuclear Physics
Nuclear collisions
RHIC, LHC, J-PARC
FAIR, RIBF, HIAF

感謝各位的聆聽，謝謝！