QCD, Dense EOS and Quark Matter in Neutron Stars

Tetsuo Hatsuda (RIKEN iTHEMS)

1. QCD
2. Hot Matter EOS
3. Dense Matter EOS
3. Implication to Neutron Stars
4. Summary

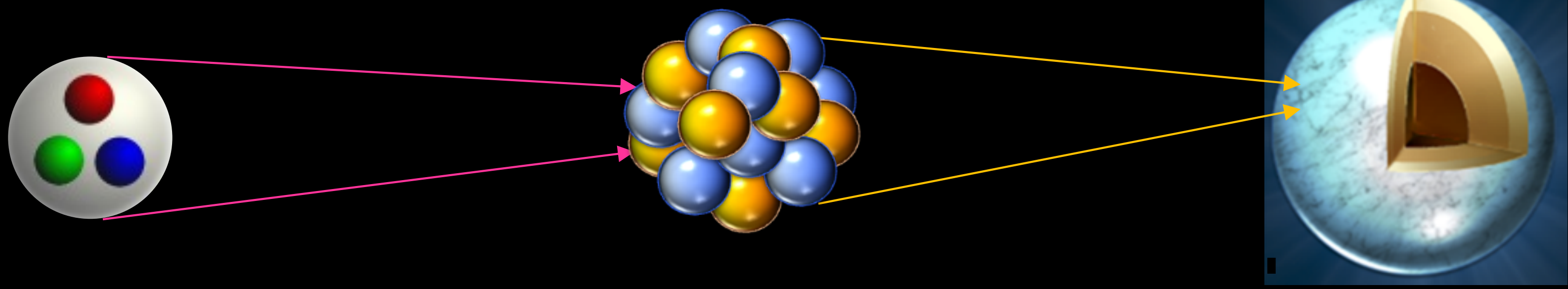
References

- Masuda, Hatsuda, Takatsuka, Astrophys. Journal 762, 12 (2013); PTEP 2013, 073 (2013)
- Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902
- Baym, Furusawa, Hatsuda, Kojo, Togashi, Astrophys. Journal 885, 42 (2019)
- Kojo, AAPPS Bulletin, (2021) 31:11

Neutron Star WS (Aug. 12, 2021)

QCD and Visible Matter

nucleon | nucleus | Neutron star

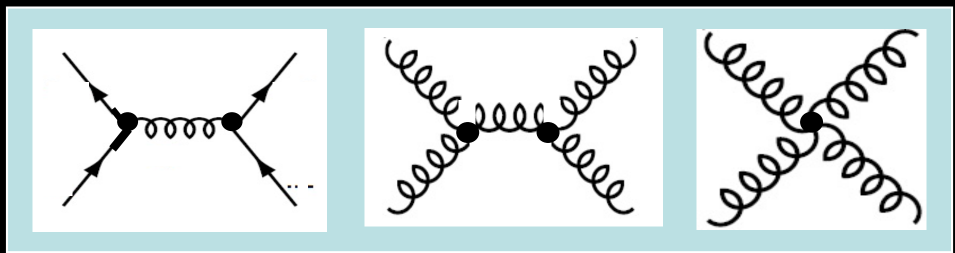


$r \sim 1$ [fm] $= 10^{-13}$ [cm] | $r \sim 10$ [fm] | $r \sim 10$ [km]

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

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

Y. Nambu (1966)

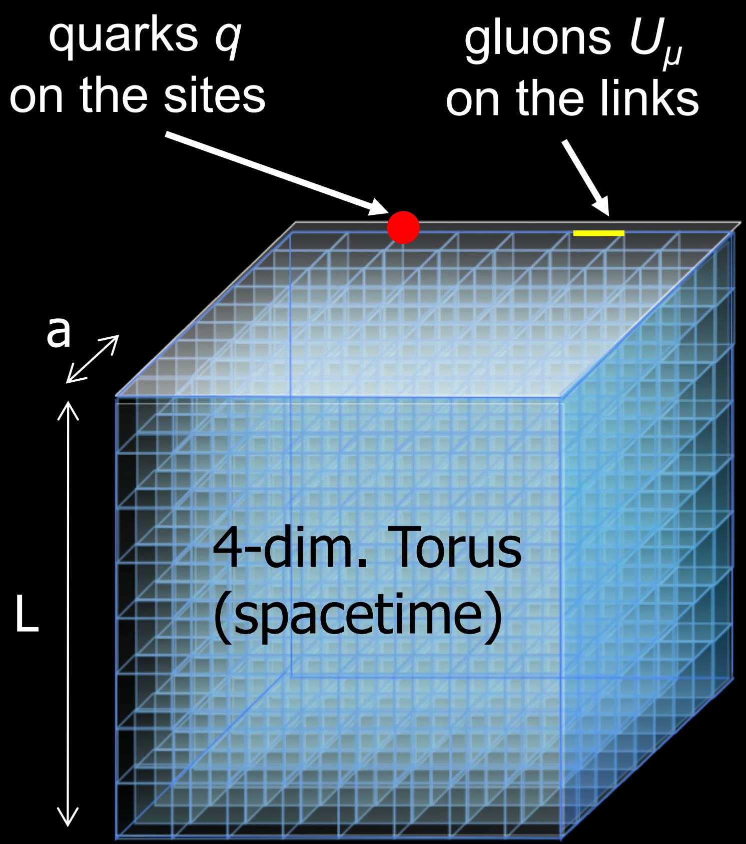


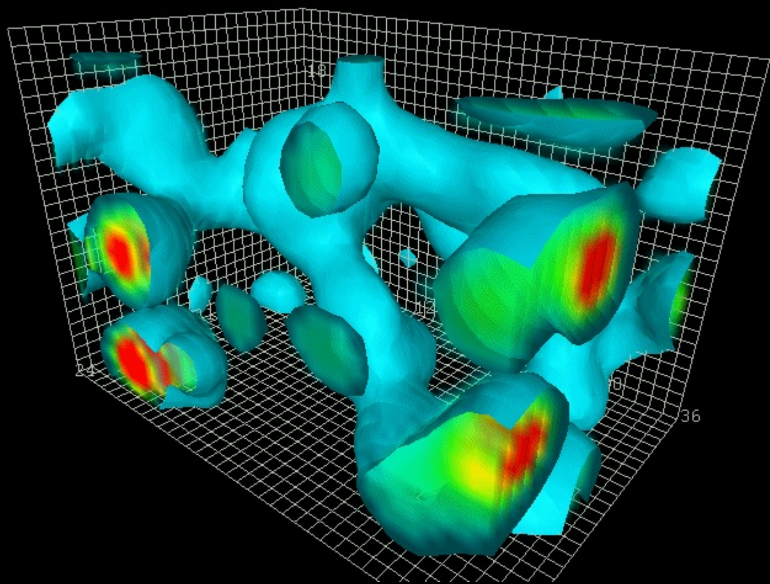
Lattice QCD

K. Wilson (1974)

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

$$= \int [dU] \det F(U) e^{-S_{\rm glue}(U)} = \int [dU] e^{-S_{\rm eff}(U)} = \int [dU dP] e^{-\mathcal{H}_{\rm eff}(U,P)}$$





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

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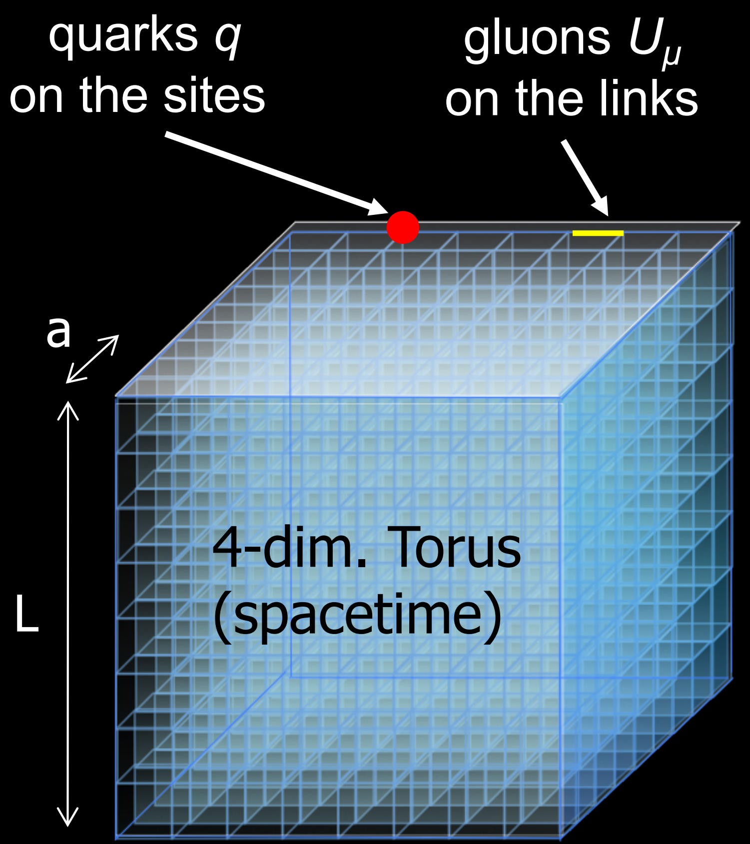
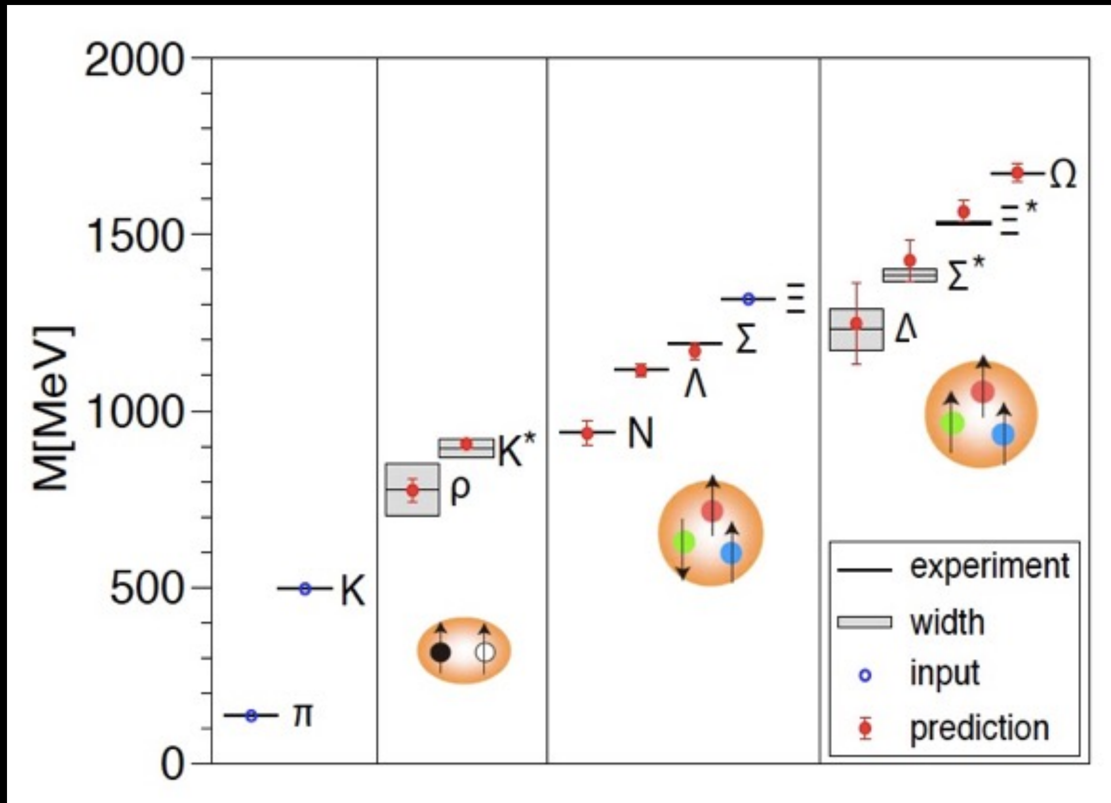
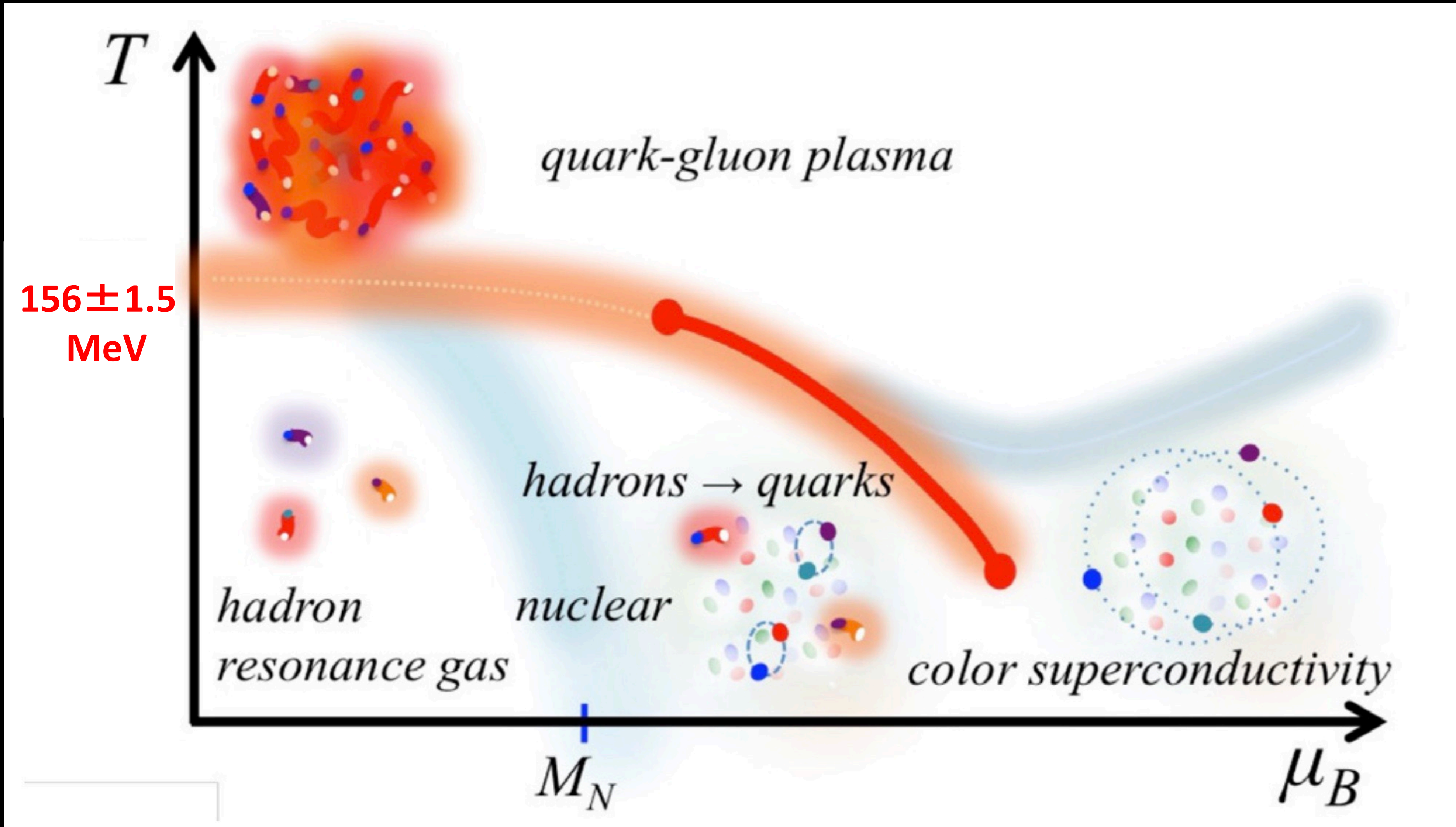




Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

QCD Phases



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

Early Universe

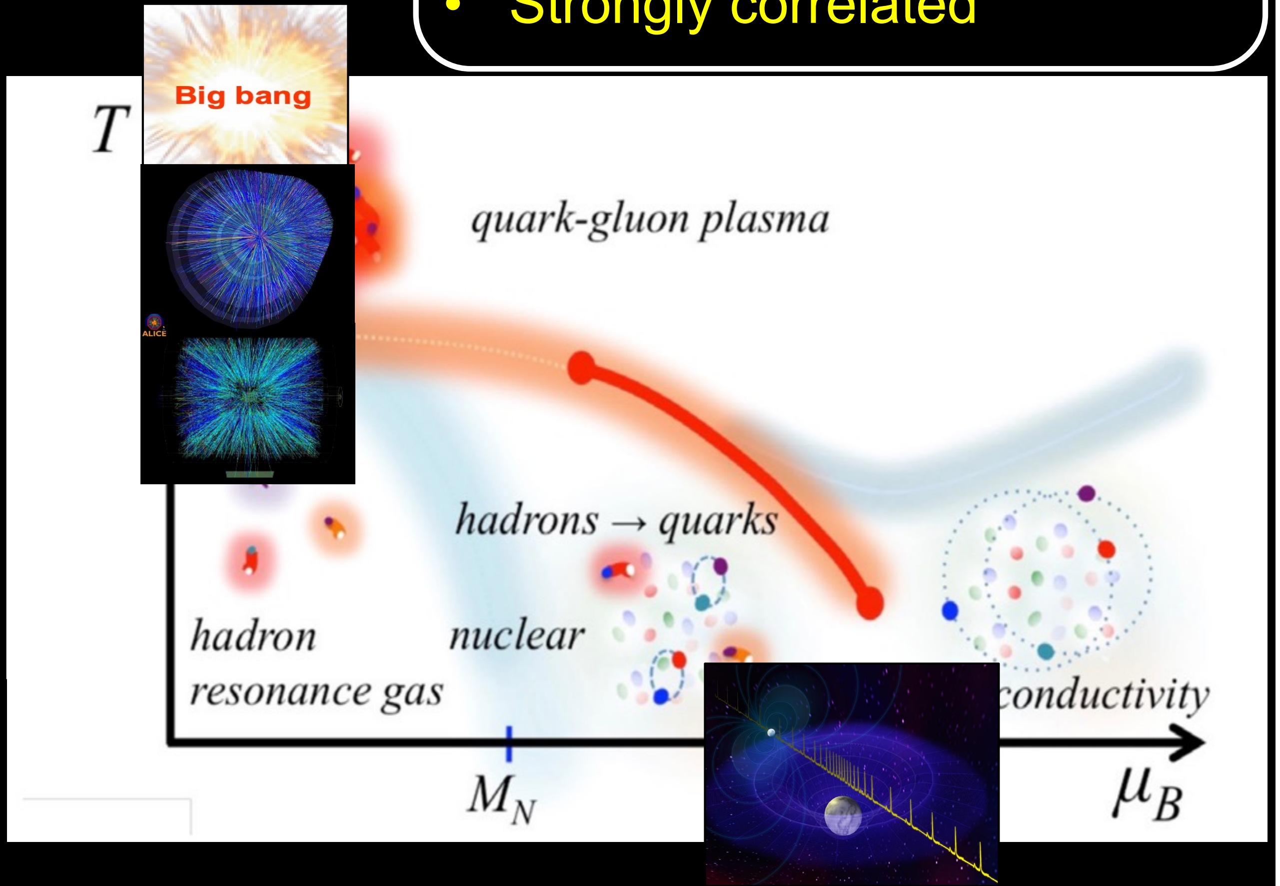
time : t ~ 10^{-4} sec

temperature: T > 10^{12} K

baryon density : ρ ~ 0

Quark-gluon plasma

- Deconfined, Chiral symmetric
- Relativistic
- Strongly correlated

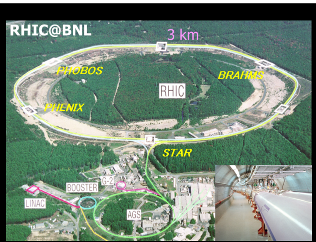


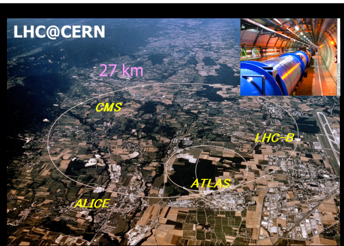
Relativistic heavy-ion collisions

time : t ~ 10^{-22} sec

temperature : T > 10^{12} K

baryon density : ρ ~ 0

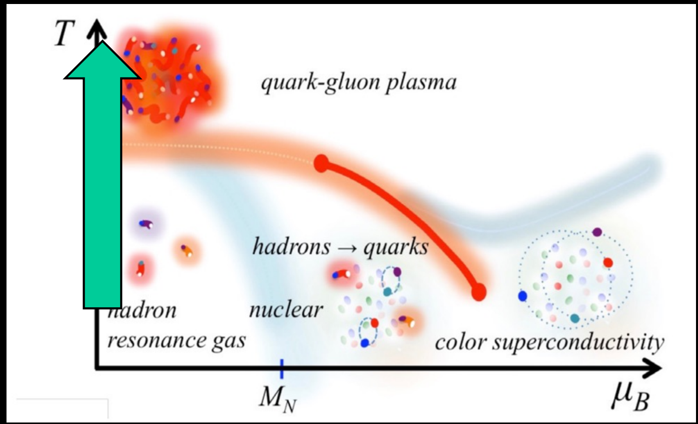


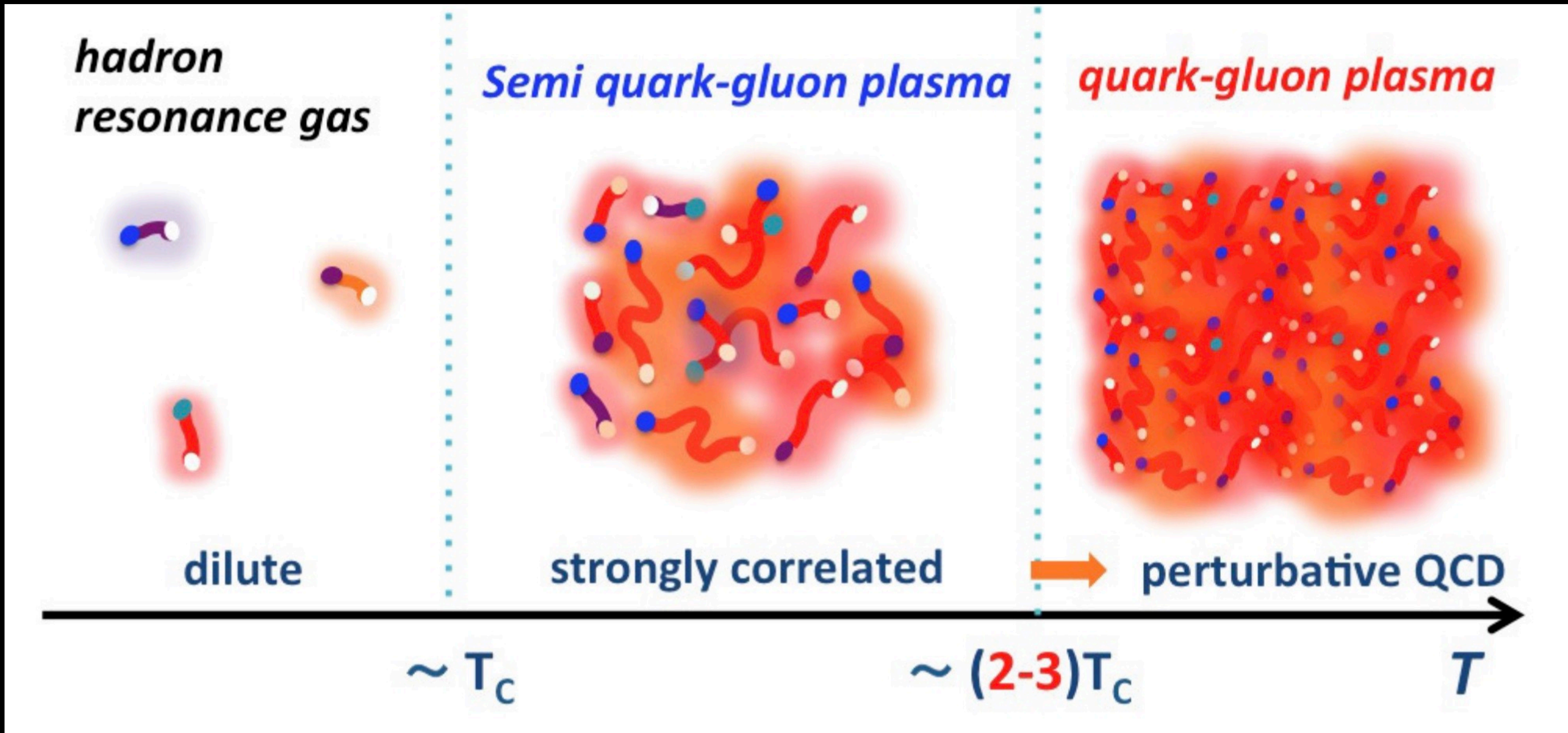


Central core of neutron stars

temperature : T < 10^{10} K

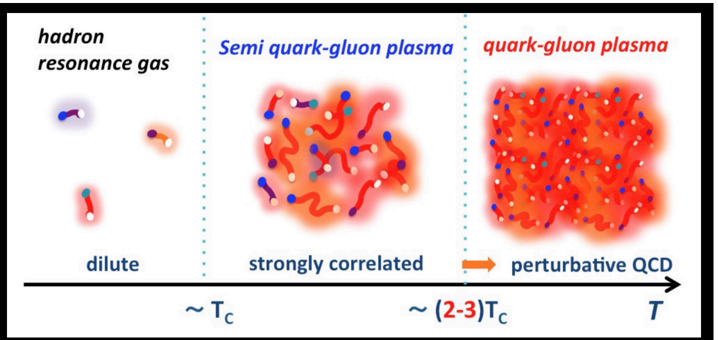
baryon density : ρ > 10^{12} kg/cm^3

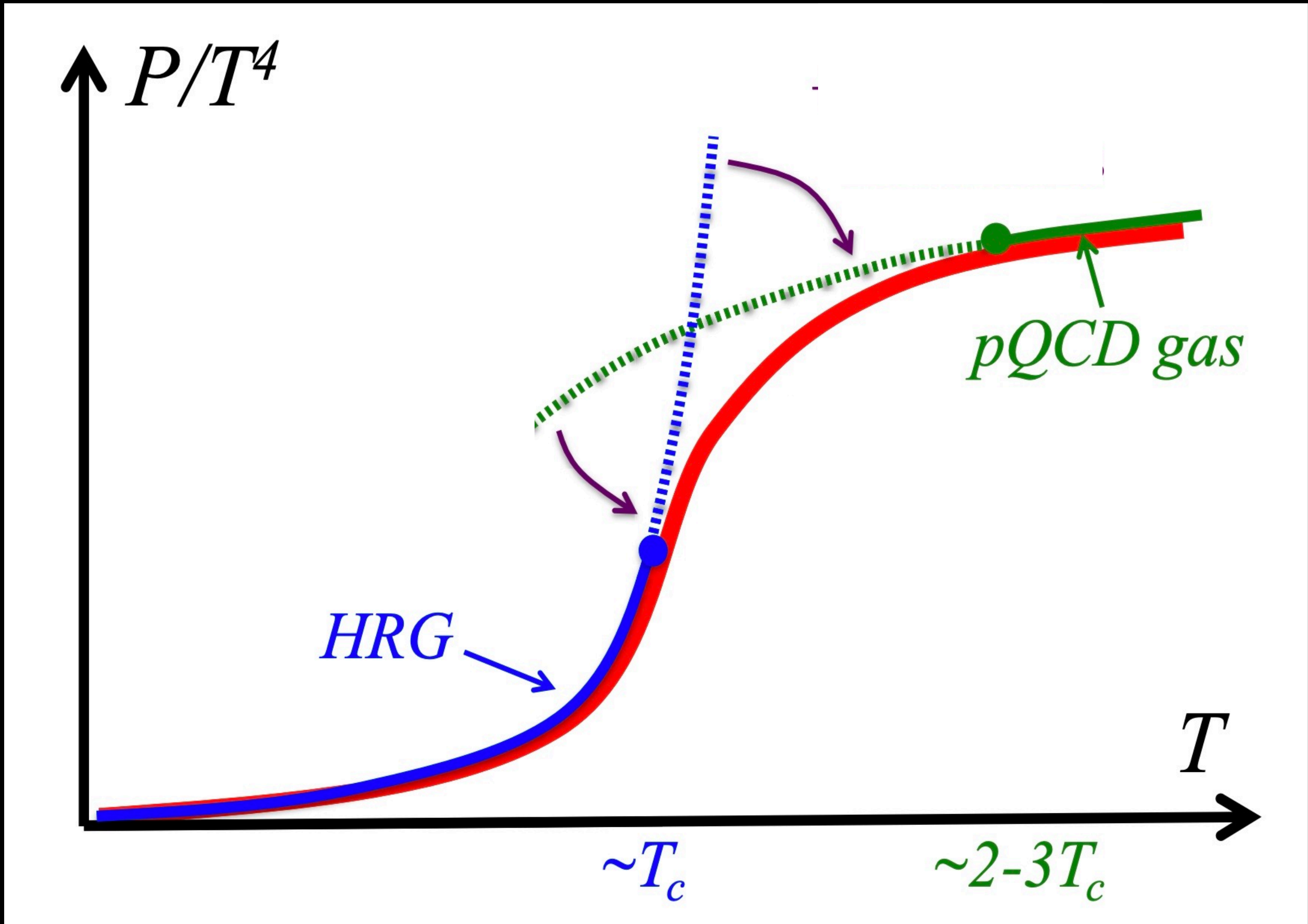




Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

Schematic picture of hot EOS

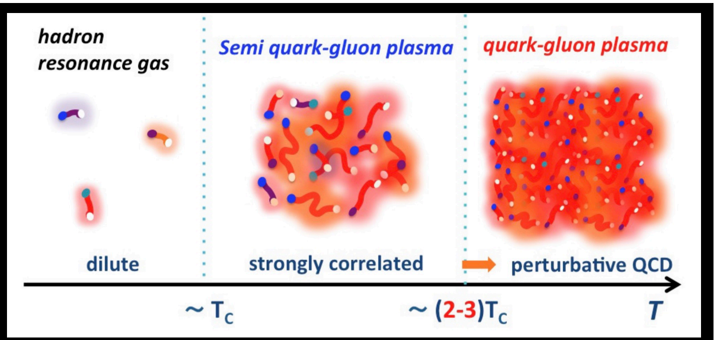


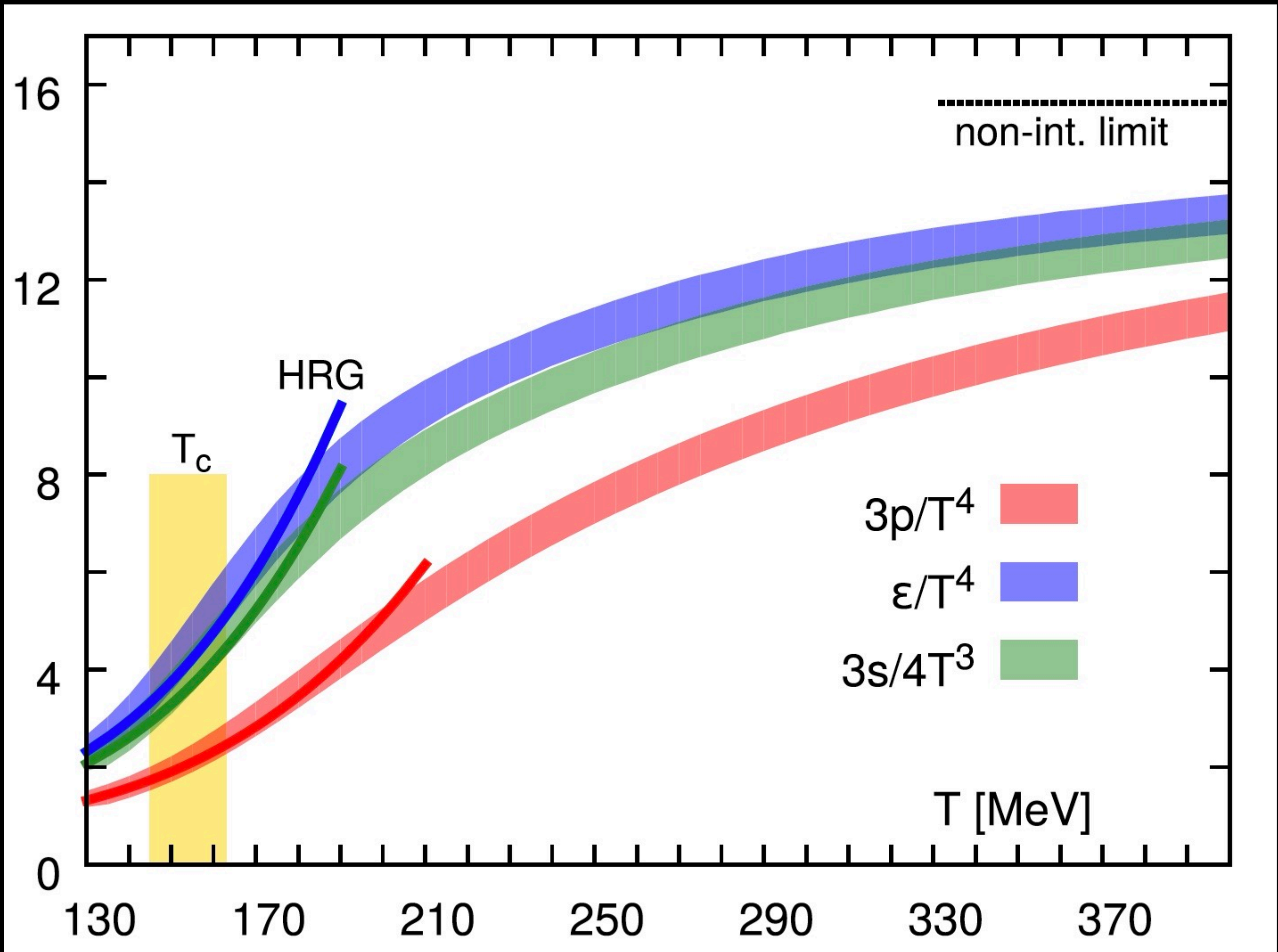


Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

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

Real picture of hot EOS from lattice QCD

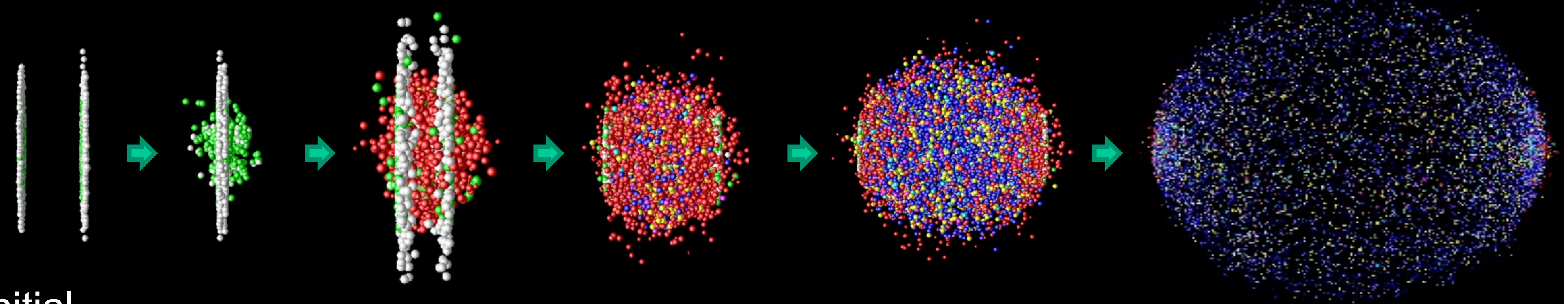




HotQCD Coll., Phys. Rev. D90 (2014) 094503

Application of hot EOS to heavy ion collisions

particle production — **thermalization** — **QGP** — **hydrodynamic expansion** — **Freezeout**



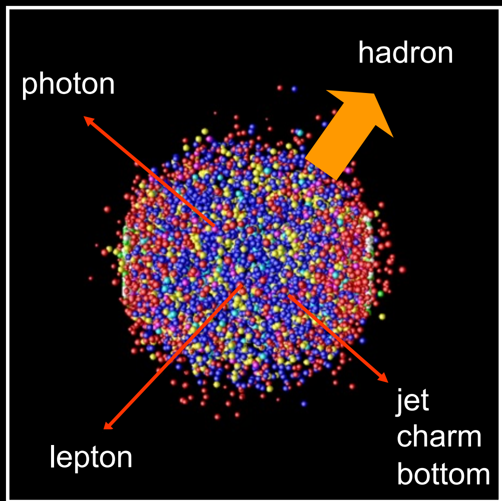
Initial parton distribution

Non-equilibrium process

Relativistic hydrodynamics
+ LQCD equation of state

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n_i^\mu = 0$$

Relativistic kinetic theory

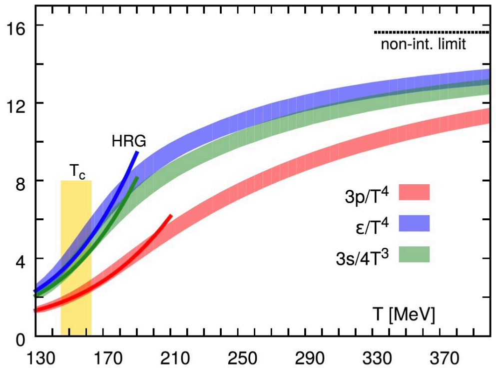


$(10^{-12}\ \mathrm{cm})^3$
$\times\ 10^{-22}$ sec

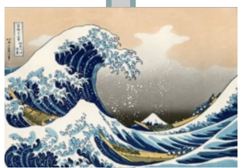
From QCD to Neutron Stars

Quantum Chromodynamics (QCD)

Lattice QCD



Sign problem



Lattice QCD

Baryon Interactions

Many-body Theories

Hot Equation of State

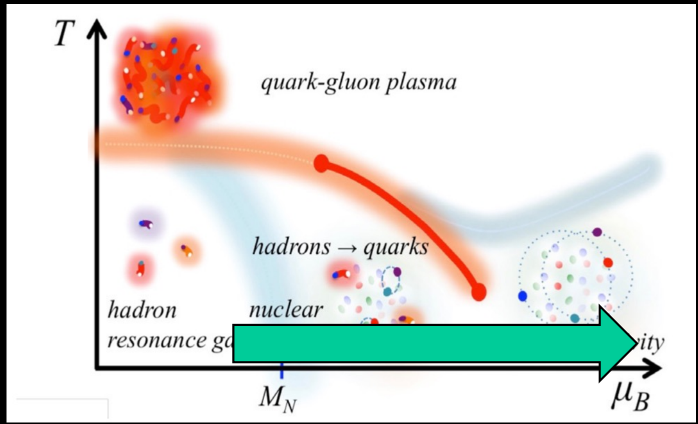
Relativistic Hydrodynamics

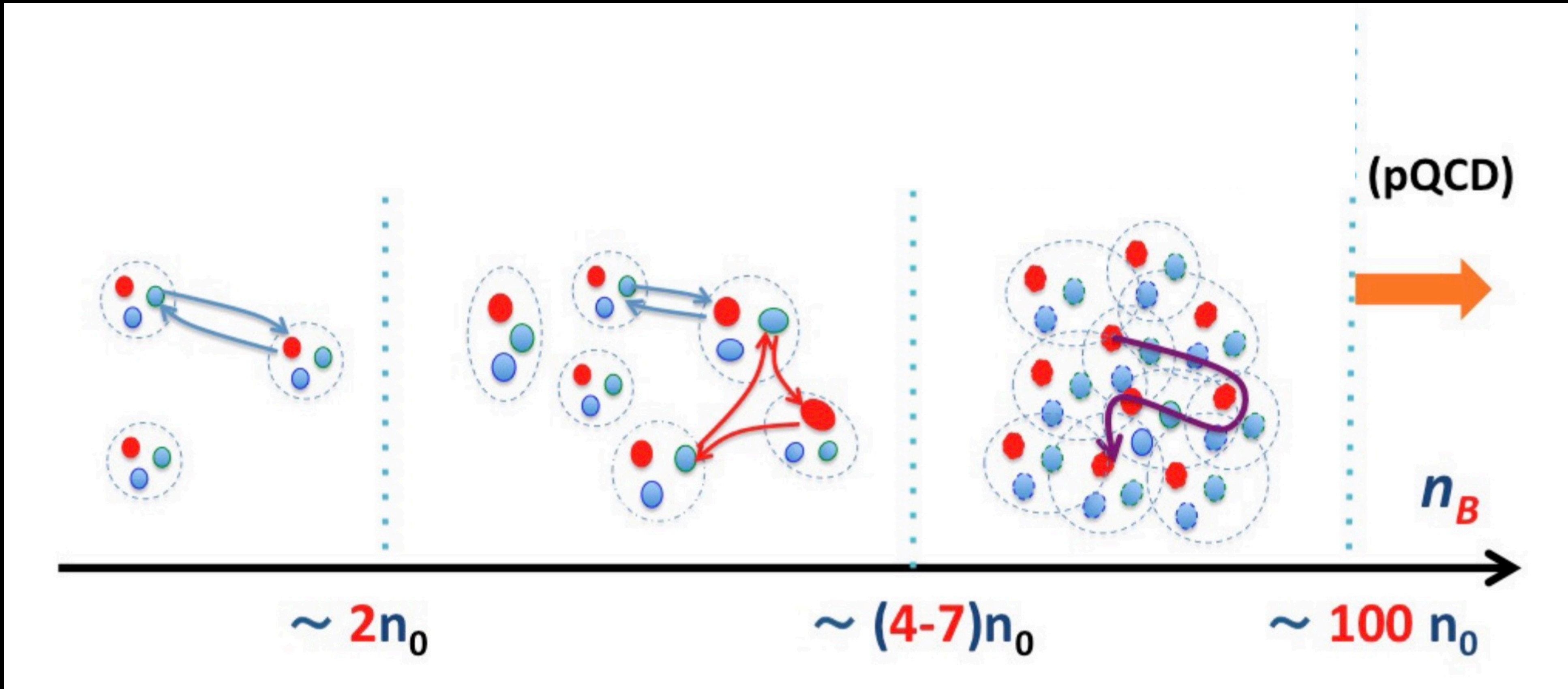
Heavy Ion Collisions

Cold Equation of State

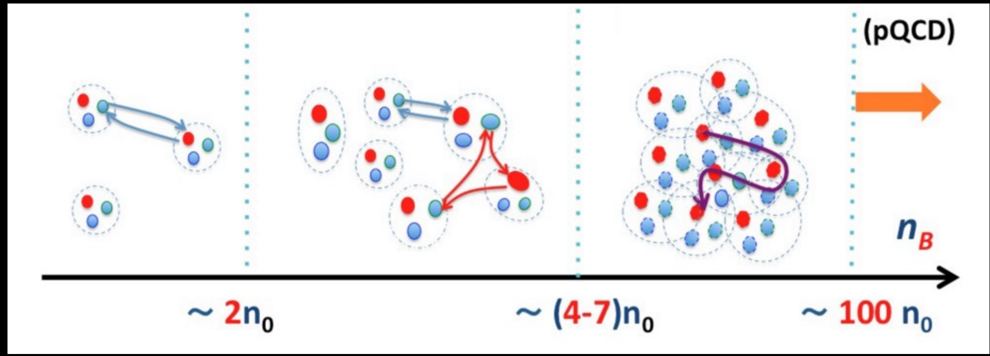
General Relativity

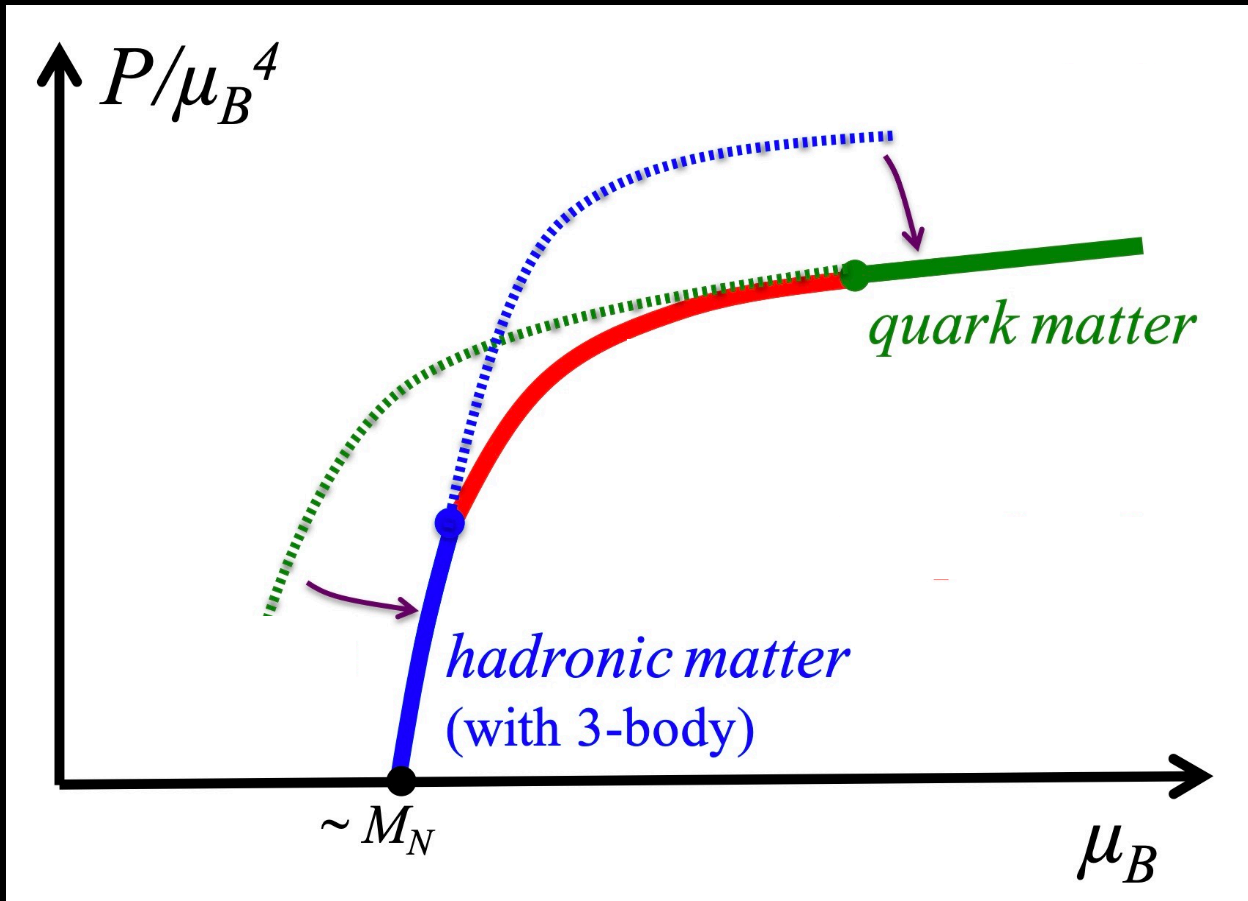
Neutron Stars





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

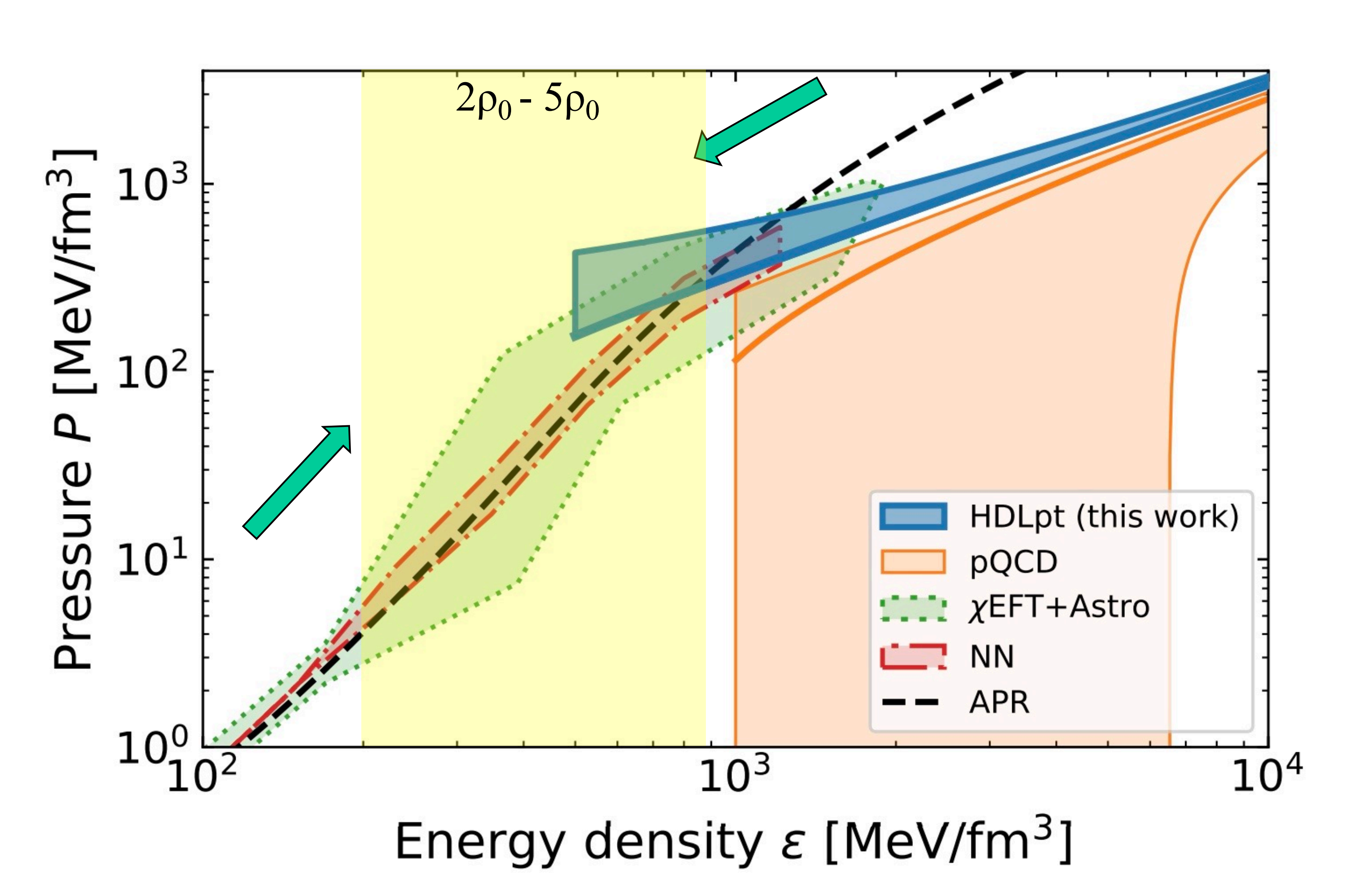




Baym and Chin, Phys. Lett. B62 (1976) 241
Masuda, Hatsuda, Takatsuka, Astrophys. Journal 762, 12 (2013); PTEP 2013, 073 (2013).
Baym, Hatsuda, Kojo, Powell, Song, Takatsuka, Rept. Prog. Phys. 81 (2018) 056902

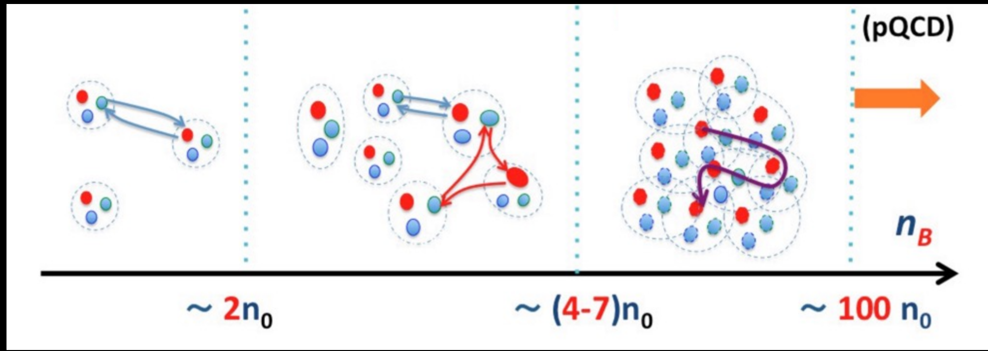
Extrapolations from both ends

Fujimoto & Fukushima, arXiv:2011.1089 [hep-ph]

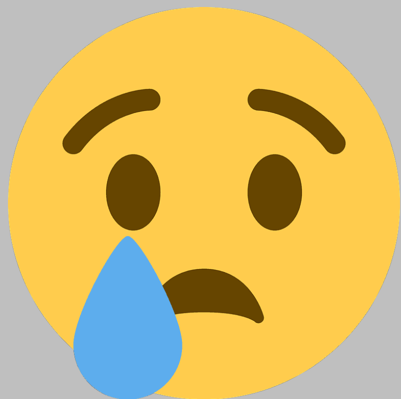


➡ Isobe's talk

➡ Fujimoto's talk



No lattice QCD data
due to sign problem



sign problem:

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

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

$$\langle \mathrm{sgn}(\phi) \rangle_0 = \frac{Z}{Z_0} = e^{-(f-f_0)V/T} \ll 1$$

$$\frac{\Delta \mathrm{sgn}}{\langle \mathrm{sgn} \rangle_0} = \frac{\sqrt{\langle \mathrm{sgn}^2 \rangle_0 - \langle \mathrm{sgn} \rangle_0^2}}{\sqrt{N} \langle \mathrm{sgn} \rangle_0} \simeq \frac{e^{(f-f_0)V/T}}{\sqrt{N}} \ll 1$$

⇨

$$N \gg \mathrm{e}^{2(f-f_0)V/T}$$

*Dense QCD (T~0, **μ** large)*

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

Complex

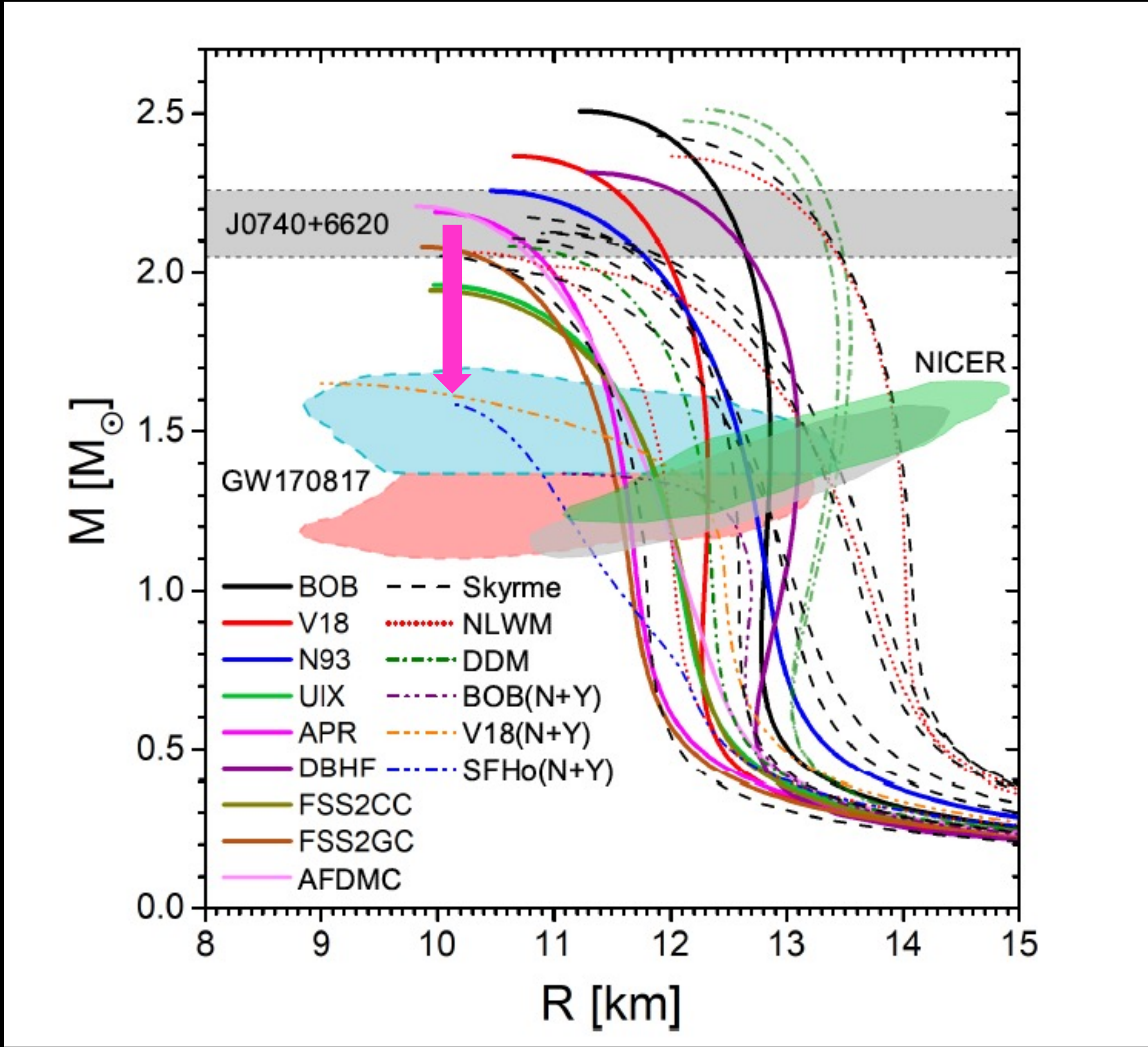
Complete new idea necessary

Hadronic EOS → M-R reltion

Hyperon puzzle
by Nishizaki,
Yamamoto,
Takatsuka
PTP (2002)

↓

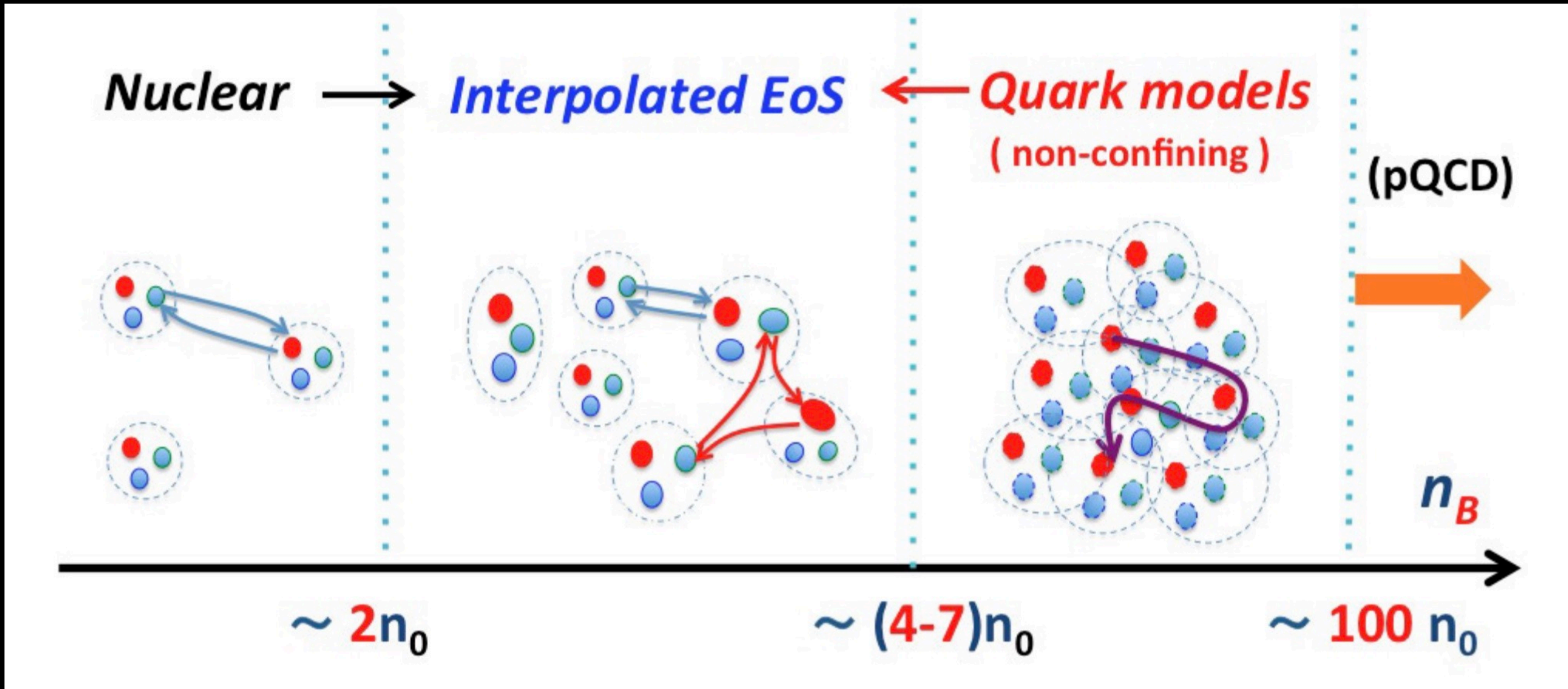
Muto's talk



Burgio+, arXiv:2105.03747 [nucl-th]

Hybrid EOS (Hadron-quark crossover)

QHC19 : Baym, Furusawa, Hatsuda, Kojo, Togashi, Astrophysical Journal 885 (2019)



Cf. Masuda, Hatsuda, Takatsuka,
Ap.J. 762, 12 (2013);); PTEP 2013, 073 (2013)

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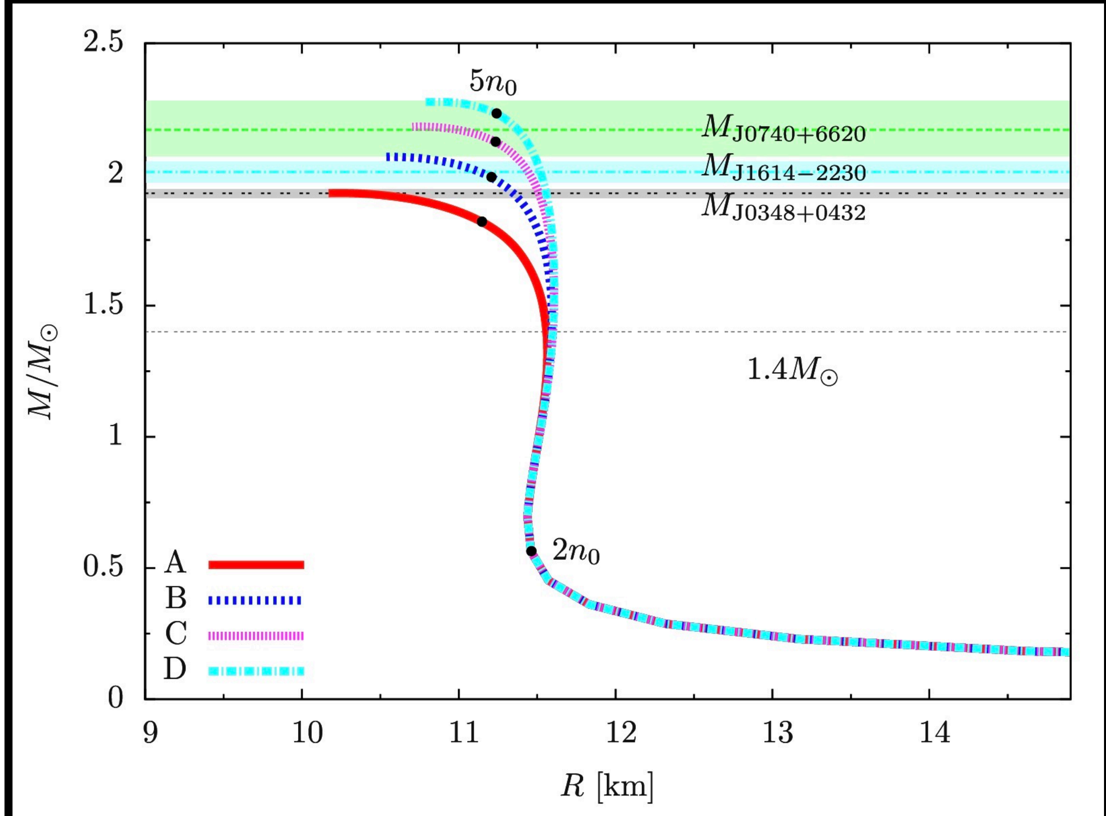
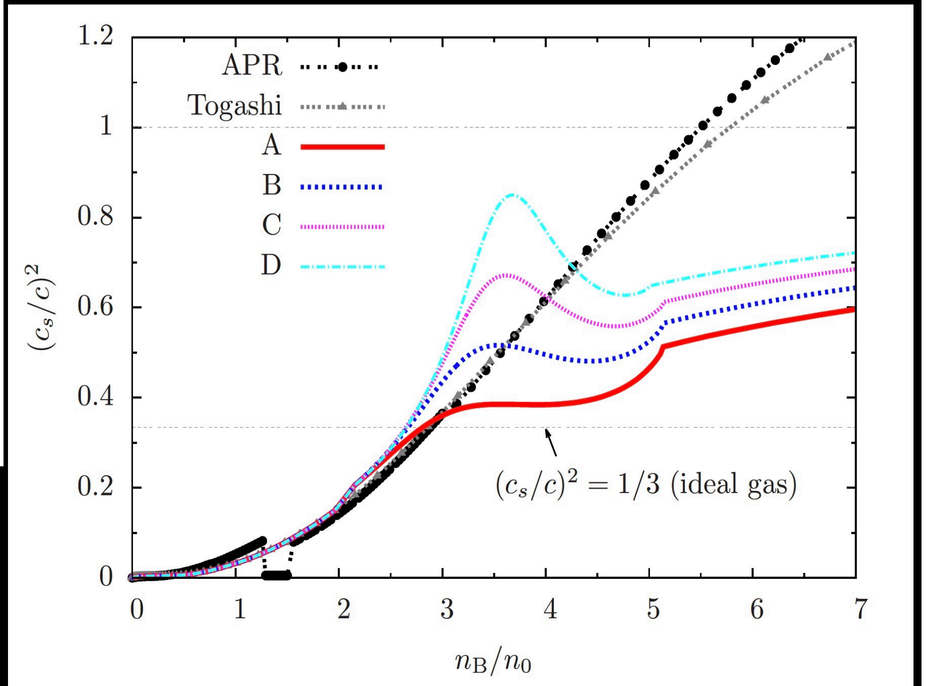


Sound Velocity



Cf. Masuda, Hatsuda, Takatsuka,
Ap.J. 762, 12 (2013);); PTEP 2013, 073 (2013)

Equation of State with Quark-Hadron Crossover

QHC series : Baym, Furusawa, Hatsuda, Kojo, Togashi, Astrophysical Journal 885 (2019)

CompOSE

CompStar Online Supernovæ Equations of State

comp star

Nparam	Name	Subgroup	Family	Particles	nb min fm^{-3}	nb max fm^{-3}	nb pts	
1	QHC18	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNq	8.7e-11	1.7	400	details
1	DD2_FRG (2+1 flavors)	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNqqs	6.9e-10	2.7	230	details
1	DD2_FRG (2 flavors)	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeN q	6.9e-10	2.7	235	details
1	QHC19-A	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNq	7.9e-11	1.8	183	details
1	QHC19-C	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNq	7.9e-11	1.4	180	details
1	QHC19-D	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNq	7.9e-11	1.3	179	details
1	QHC19-B	Hybrid (quark-hadron) EoS	Cold Neutron Star EoS	npeNq	7.9e-11	1.6	181	details

Kojo *AAPPS Bulletin* (2021) 31:11
https://doi.org/10.1007/s43673-021-00011-6

REVIEW ARTICLE

QCD equations of state and speed of sound in neutron stars

Toru Kojo

→ Kojo's talk

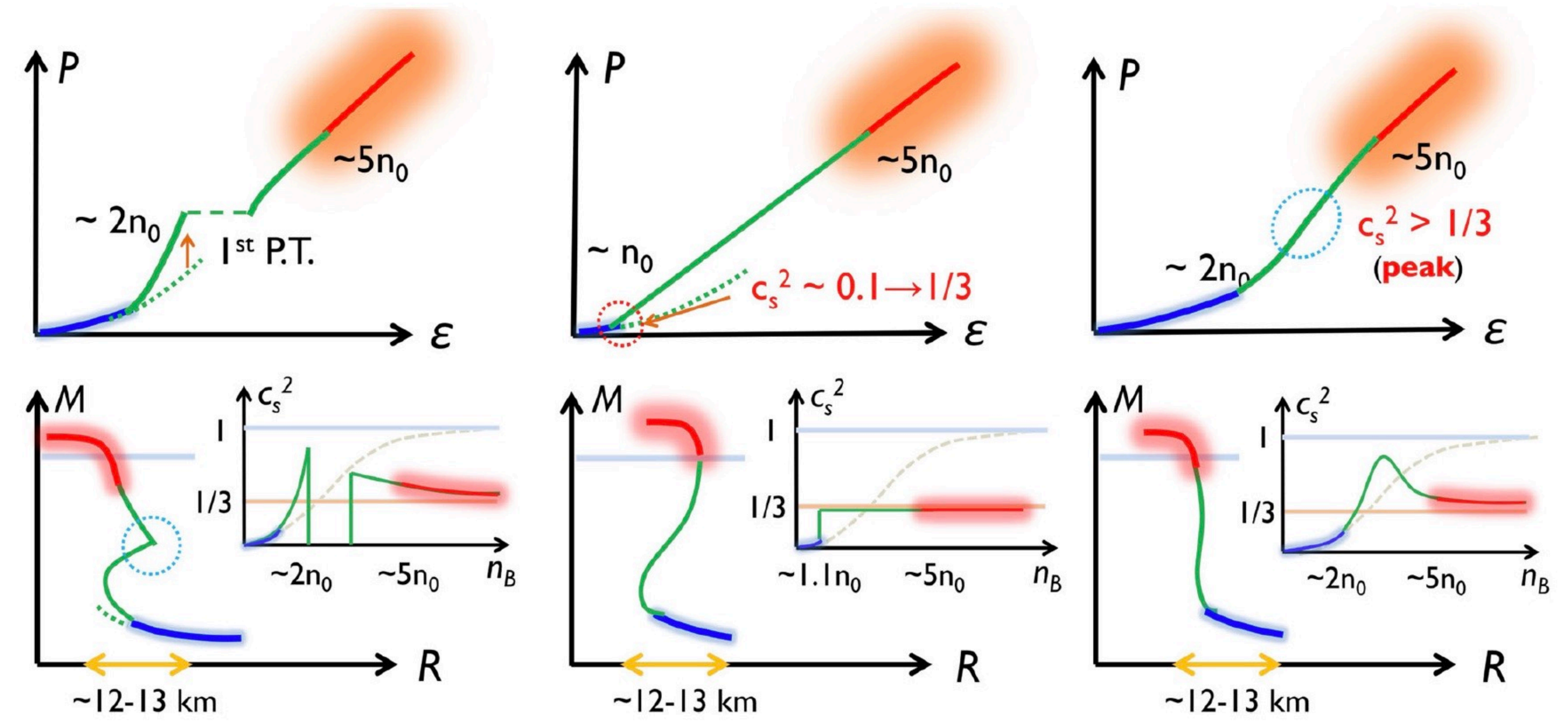
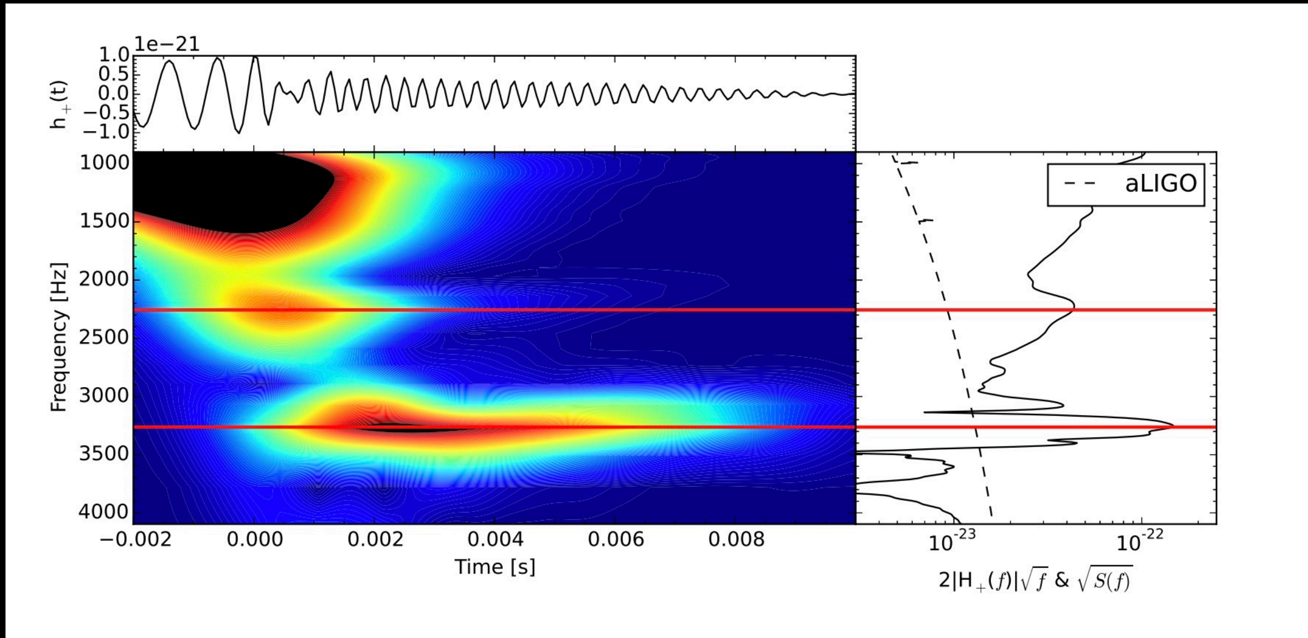


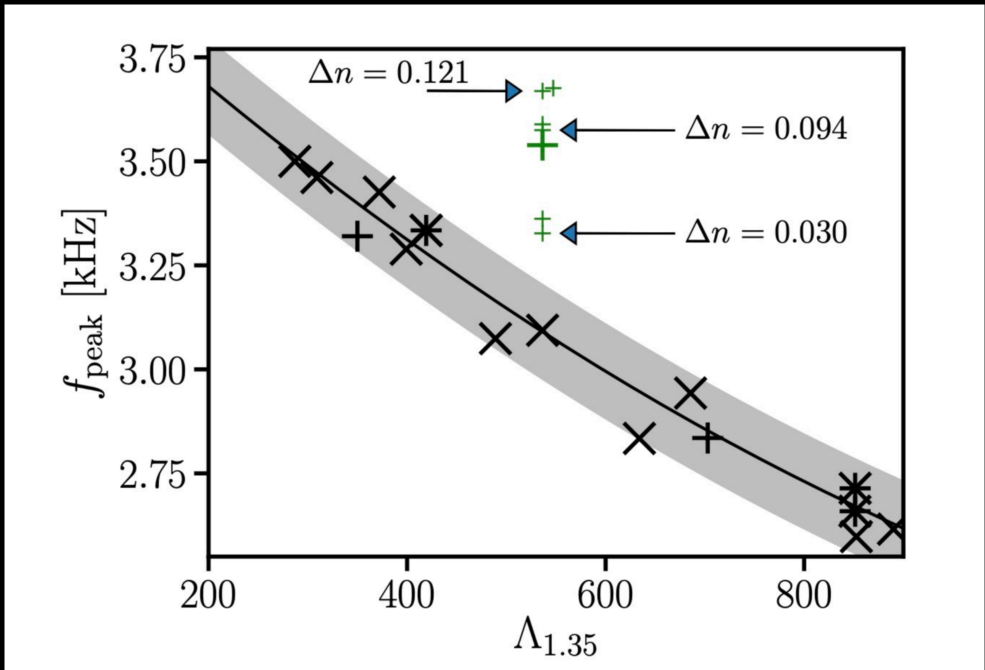
Fig. 2 Rough sketches of P-ε, M-R, and c_s^2-n_B relations for three characteristic EoS; see the main text for details. For c_s^2, we also show the typical behavior of nucleonic EoS with dashed lines

Binary neutron star: Post merger GW signal

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

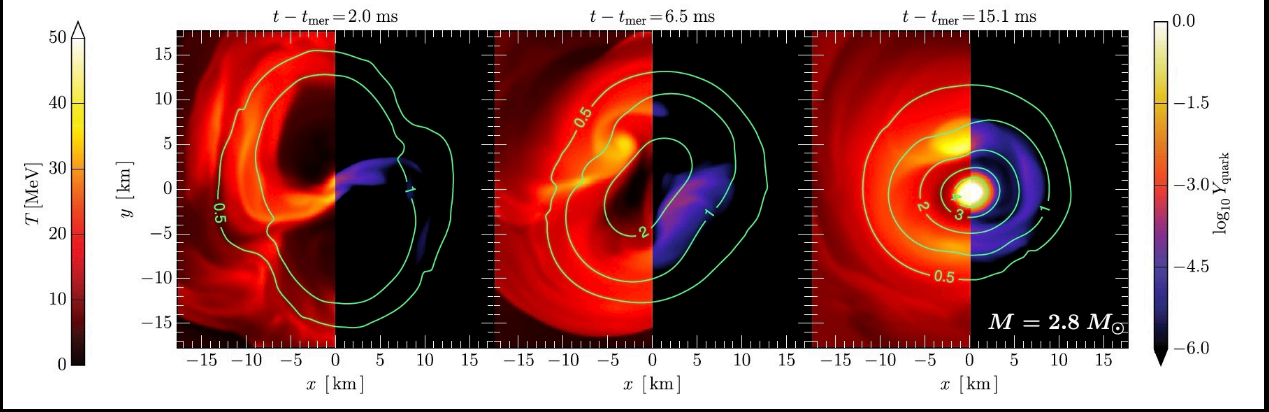




Dominant post merger GW frequency f_{peak} as function of tidal deformability Λ for 1.35-1.35 M_s mergers

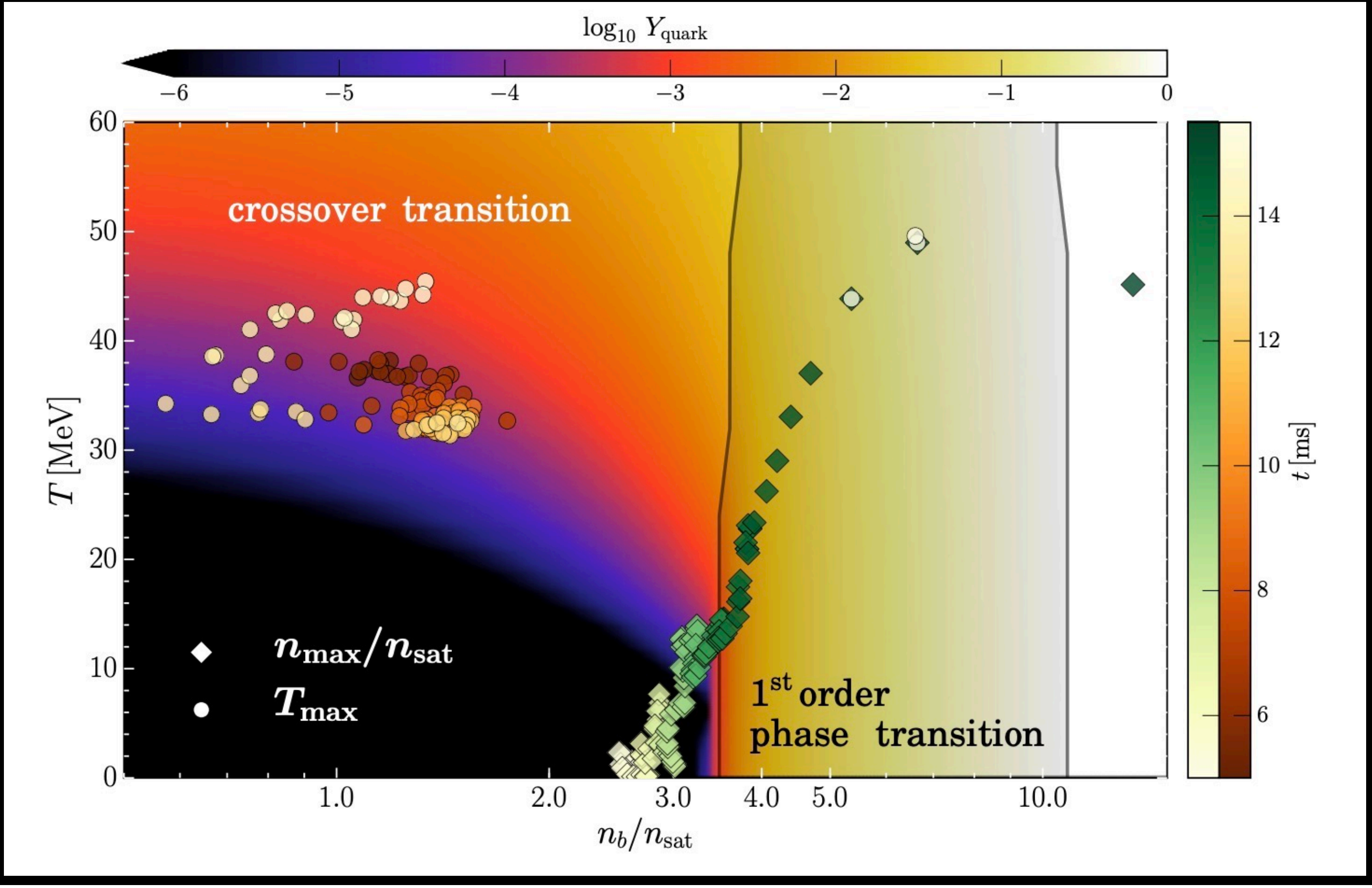
Bauswein +,
PRL**122** (2019) 061102

Binary neutron star: Post merger trajectory



$M=2.8M_s$

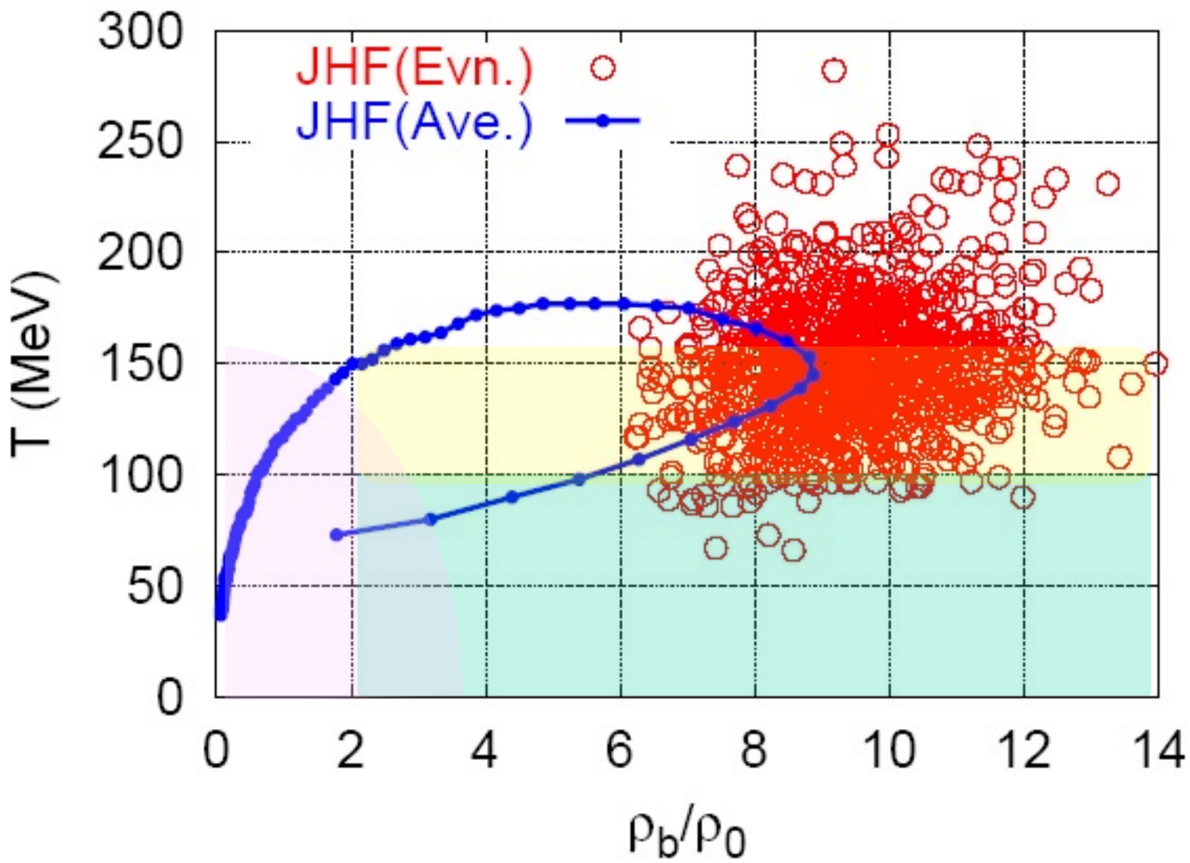
1st order transition to quark matter



Most+, PRL**122** (2019) 061102

Heavy Ion Collisions: Trajectory at J-PARC

[25A GeV Au] +Au



JAM

(Hadronic cascade model)

Y. Nara et al, PRC61 (2000)

$\rho_B > 6\ \rho_0$

for about 3 fm/c

Figure taken from JHF report (2002) by A.Ohnishi

Summary

1. Global QCD phase structure has been studied extensively by using various theoretical methods.

   Quantitative understanding above $2\rho_0$ is far from satisfactory.
   - -- What kind of phases exit ?
   - -- What is the order of the hadron-quark transition ?
   - -- New theoretical tools are called for.

2. Neutron star, neutron star mergers and HIC will continue to provide valuable information on high density matter.

3. It is time that experimentalists and theorists work more closely together to unravel the physics of dense QCD.
   - -- as it happened in the case of QGP search.