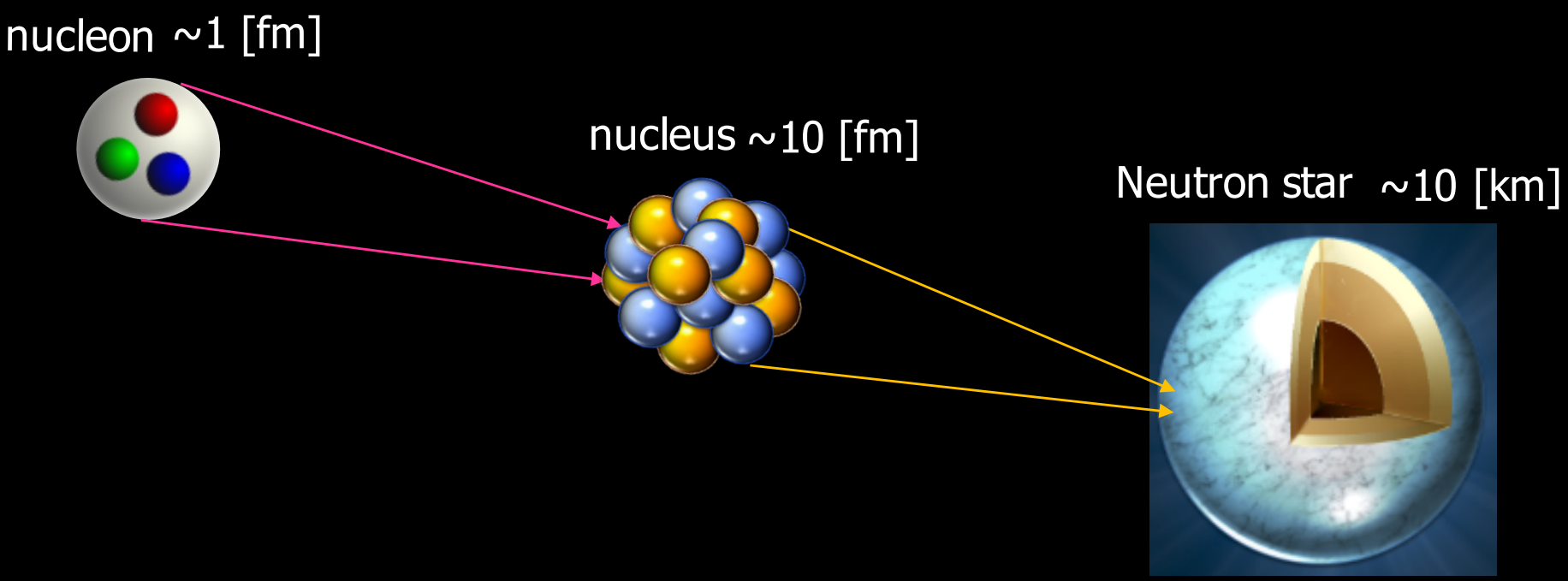
From Quarks to Neutron Stars



"From Hadrons to Quarks in Neutron Stars: A Review"
Baym, Hatsuda, Koji, Powell, Song, Takatsuka,
1707.04966 [astro-ph.HE]
(Reports on Progress in Physics)

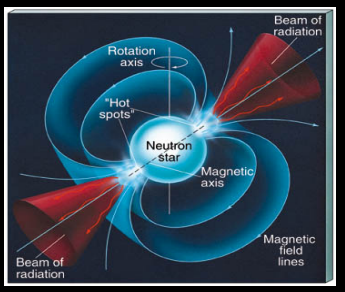
Tetsuo Hatsuda (RIKEN)
WS on Recent Developments in QCD and QFT (Nov. 11, 2017)

iTHEMS
RIKEN interdisciplinary Theoretical & Mathematical Sciences

Brief history of NS obs.

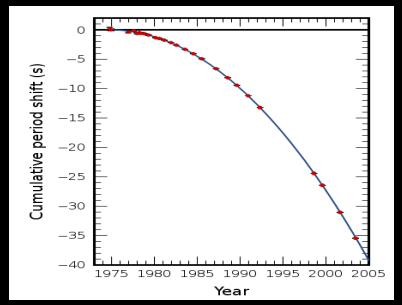
1932 Discovery of the neutron [J. Chardwick]

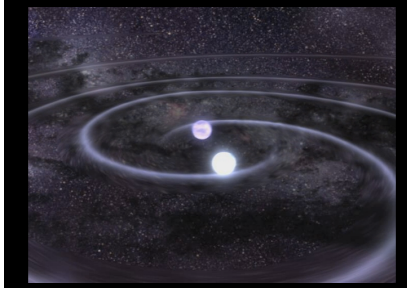
1934 Prediction of neutron star [W. Baade and F. Zwicky]



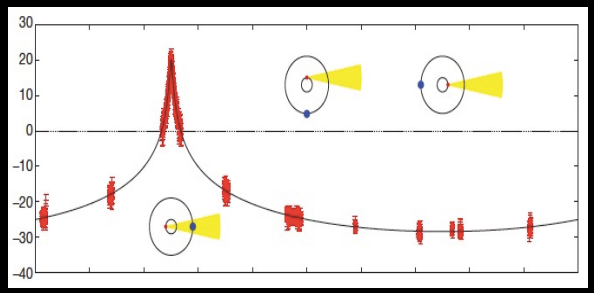
1968 Discovery of pulsar [S. J. Bell and A. Hewish]

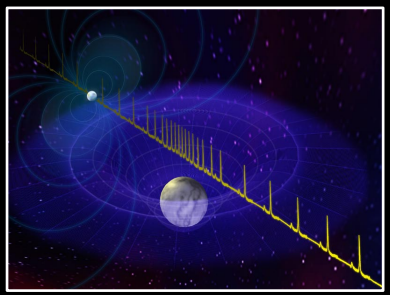
1974 Discovery of binary neutron star
[R. A. Hulse and J.H. Taylor]



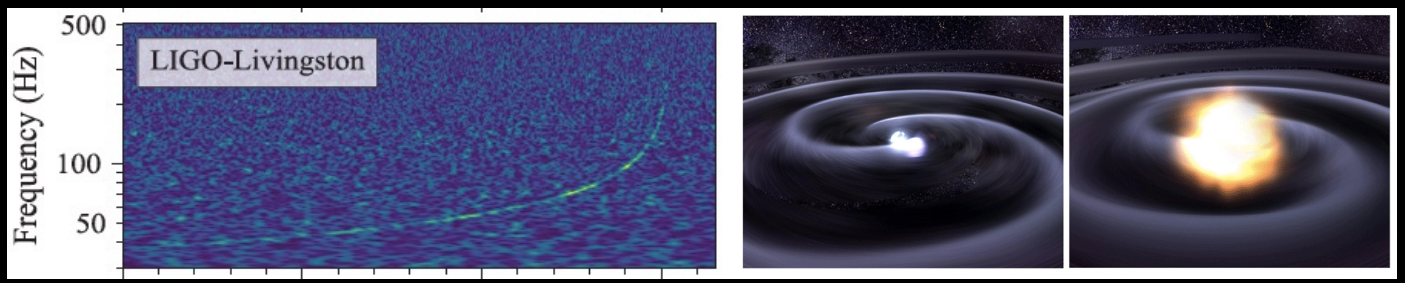


2010 Discovery of massive neutron star
[P. Detmorest et al.]





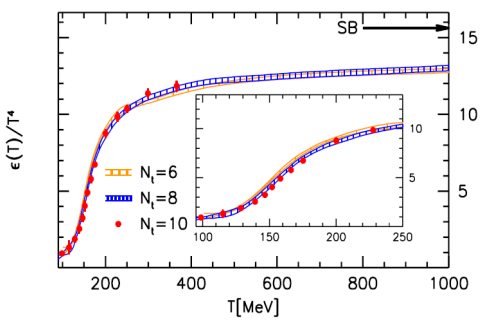
2017 Discovery of GW from NS merger
[LIGO/Virgo]



From LQCD to Hot/Dense Matter (Theory Status)

Lattice Quantum Chromo Dynamics

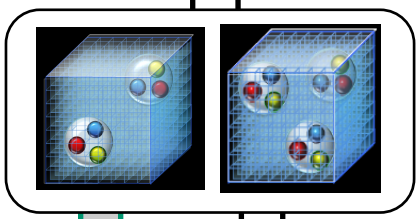
LQCD at finite T



LQCD at finite μ

S/N = 0

LQCD at fixed N



Direct cal.

S/N = 0

HAL QCD

Many-body methods

Equation of State for Hot Matter

Equation of State for Dense Matter

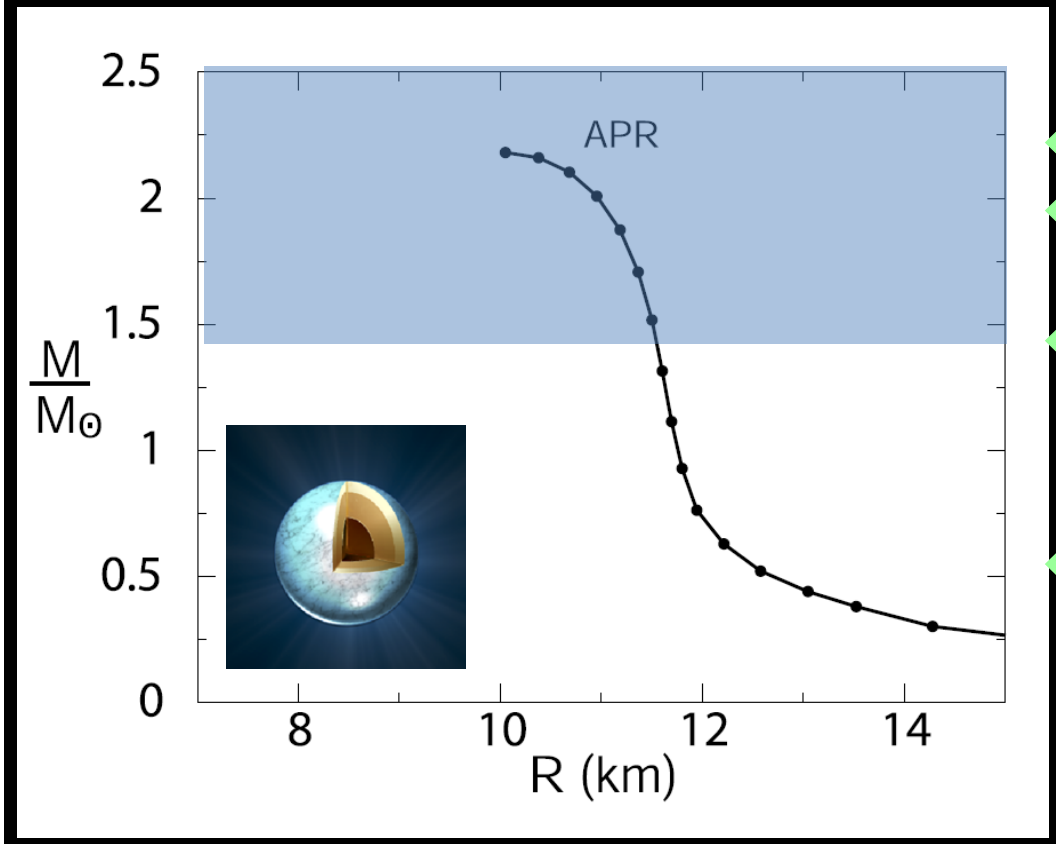
Relativistic Hydrodynamics

General Relativity

Rel. heavy-Ion collisions

Neutron stars

Nuclear EOS meaningful at high density ?



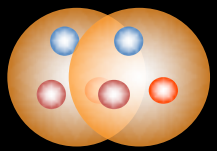
ρ_{center}

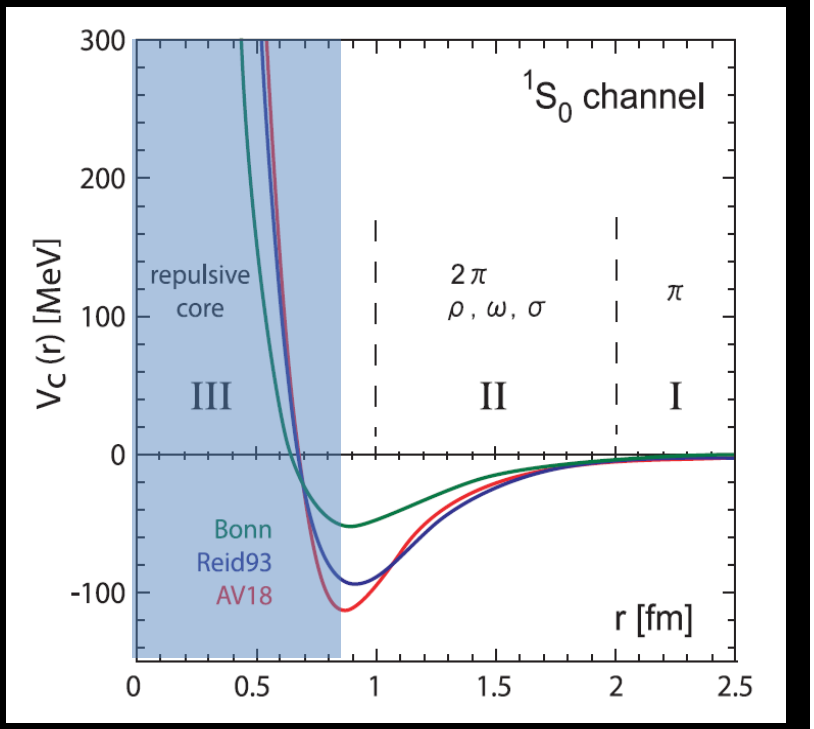
$\leftarrow 6\rho_0$

$\leftarrow 5\rho_0$

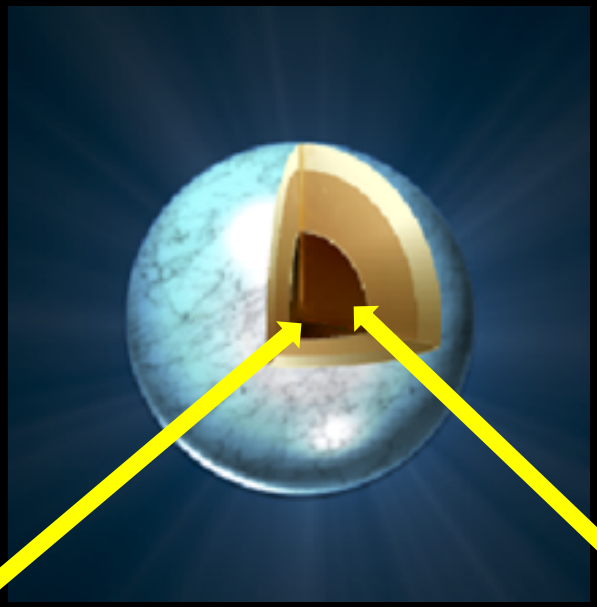
$\leftarrow 3.4\rho_0$

$\leftarrow 2\rho_0$



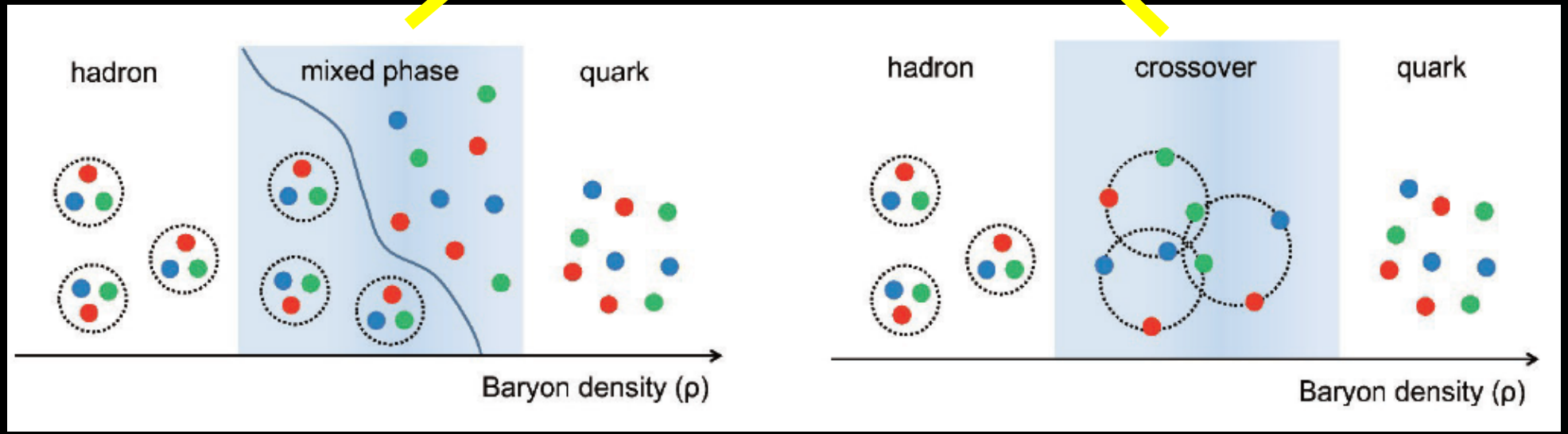


Quark Matter inside Neutron Stars ?



Baym & Chin,
Phys.Lett. 62B (1976)241

Baym,
Physica 96A (1979) 131

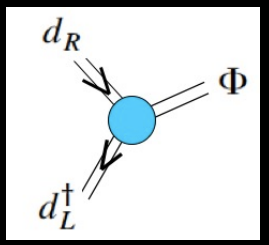


Hadron-Quark Continuity ?

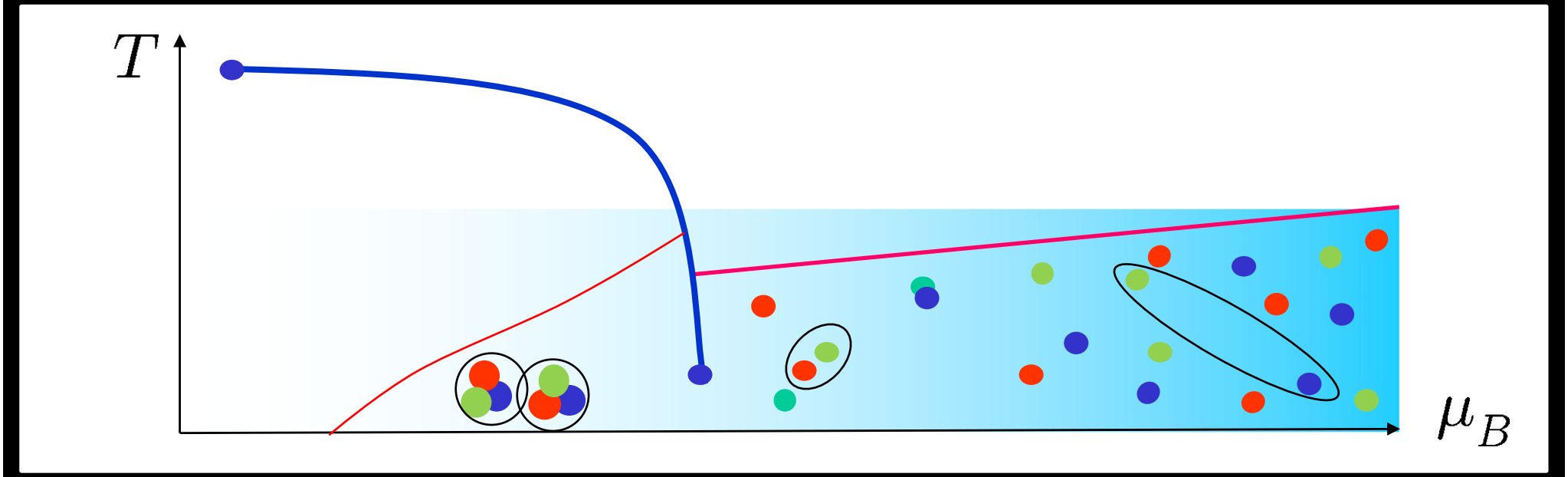
Schafer & Wilczek (1999), Fukushima (2004)
Hatsuda, Yamamoto, Tachibana & Baym ('06)

$$\Phi_{ij} \sim (\bar{q}_R)^j_a (q_L)^i_a \qquad (d_L)_{ia} \sim \epsilon_{ijk}\epsilon_{abc}(q_L)^j_b C (q_L)^k_c$$

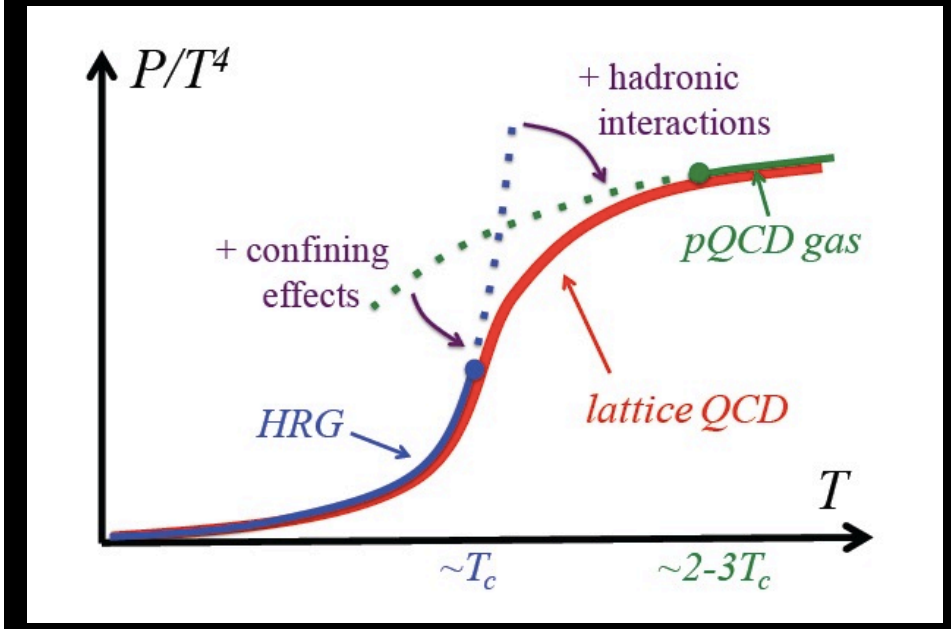
QCD axial anomaly



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

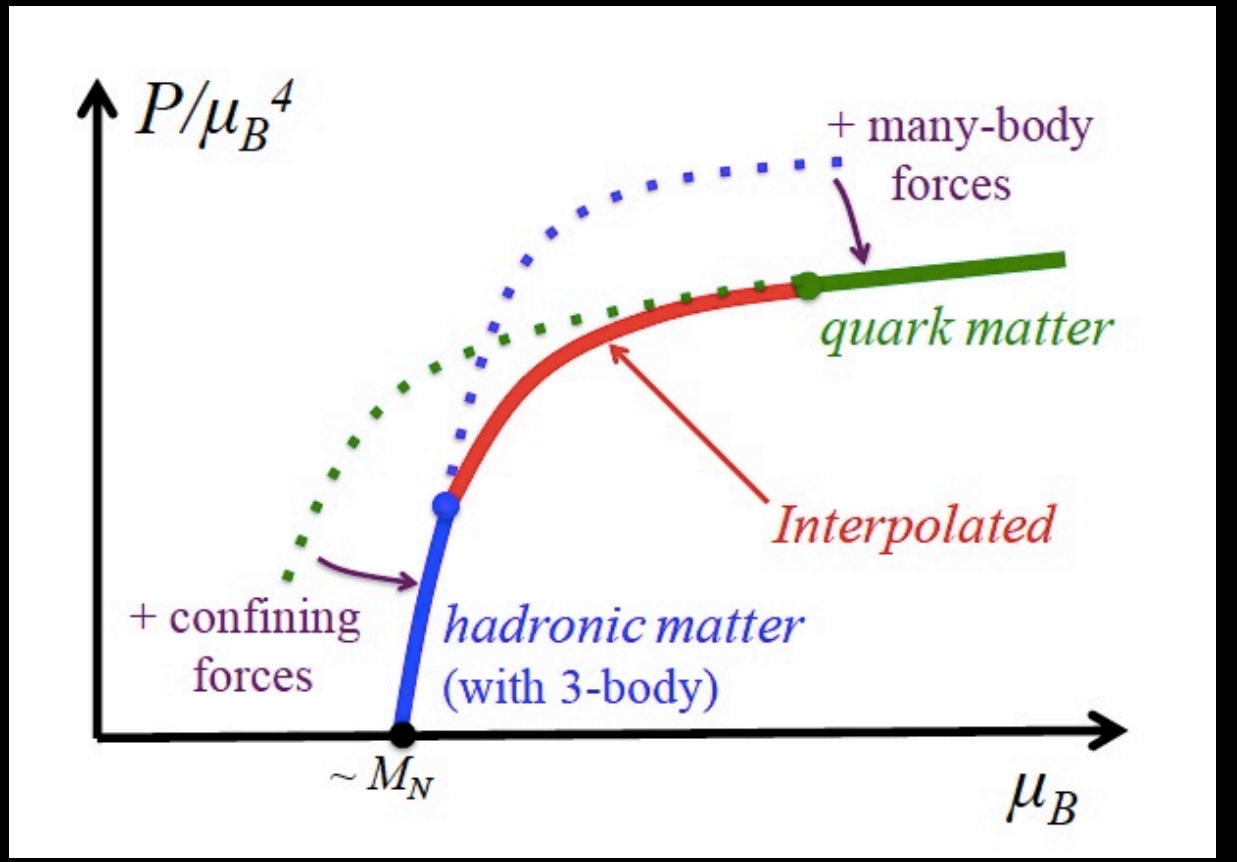


Strongly interaction hadronic matter → Strongly interacting quark matter



Asakawa, Hatsuda,
Phys. Rev. D55 (1997)

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

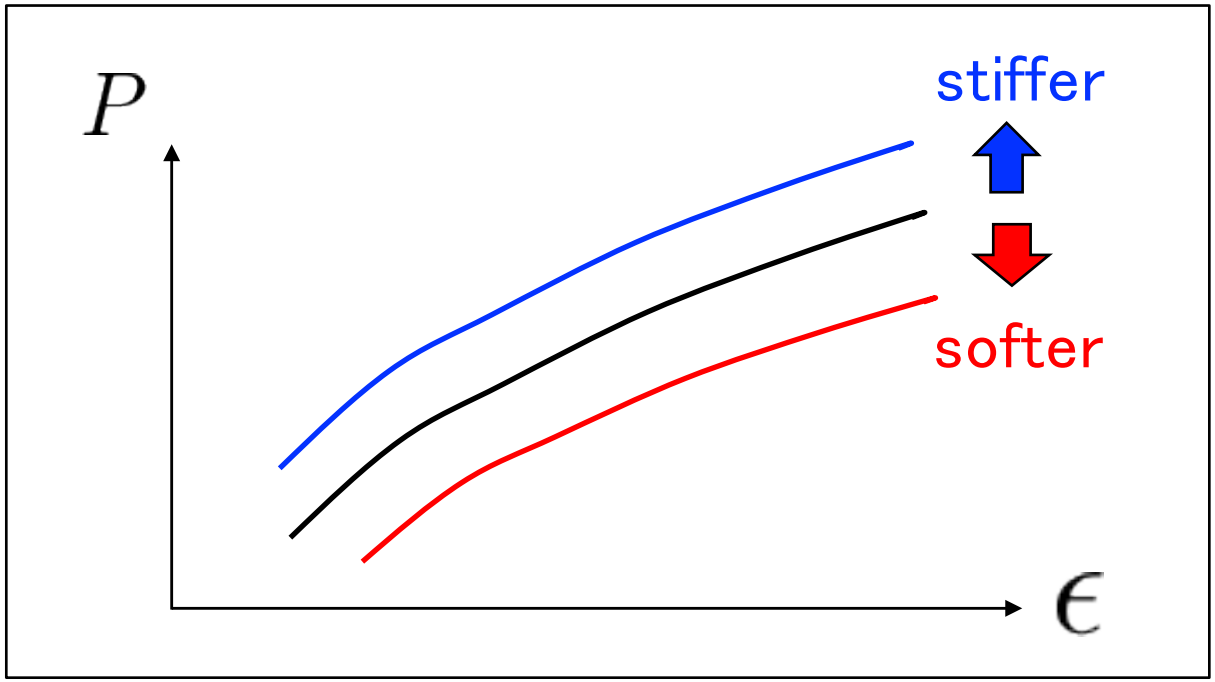


“Toy EOS” for quark matter

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

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

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



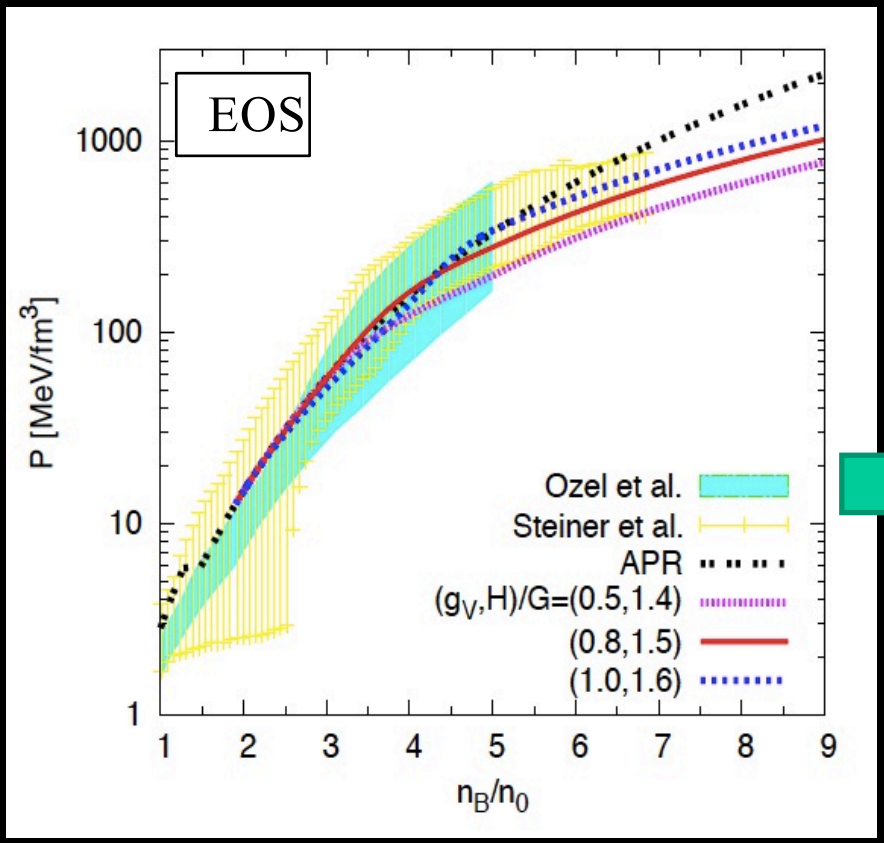
C, D → large

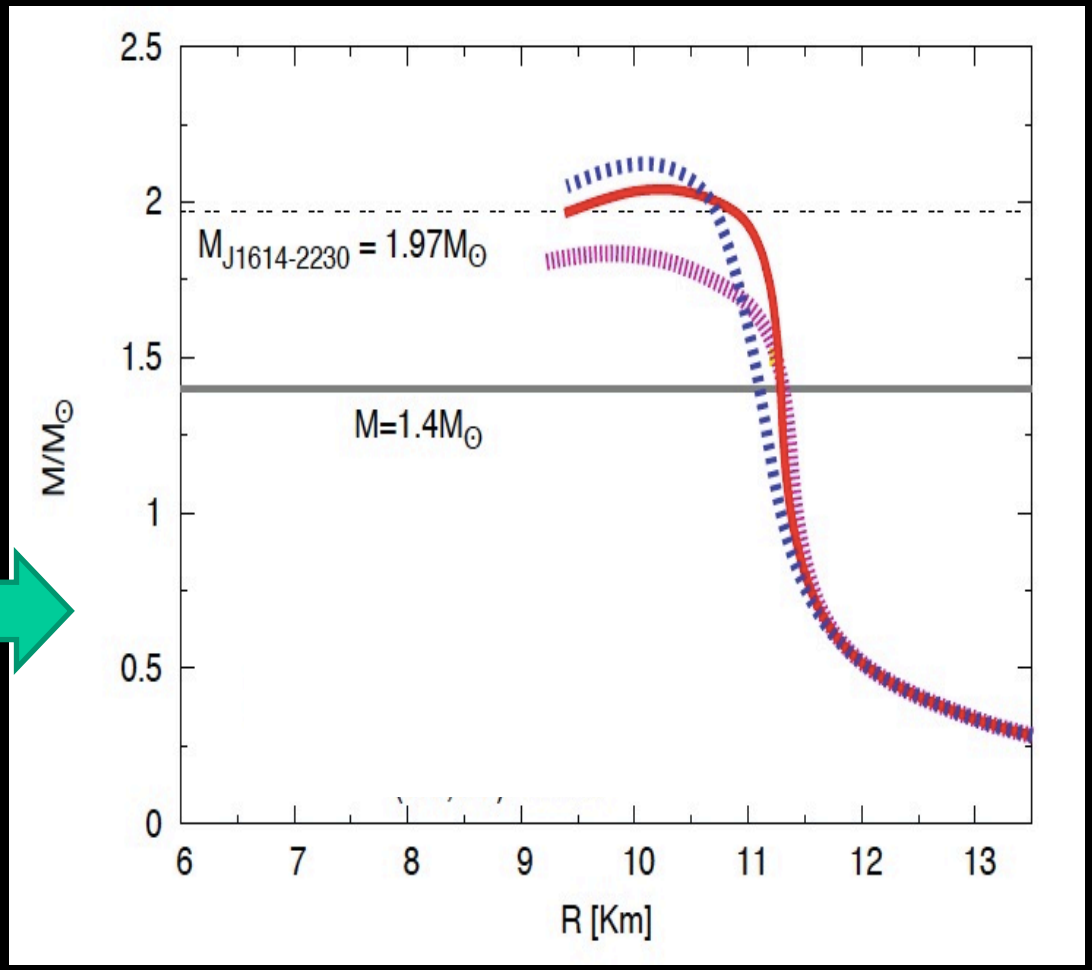
B → large

A Neutron star EOS with hadron-quark crossover : APR – NJL (HQC17)

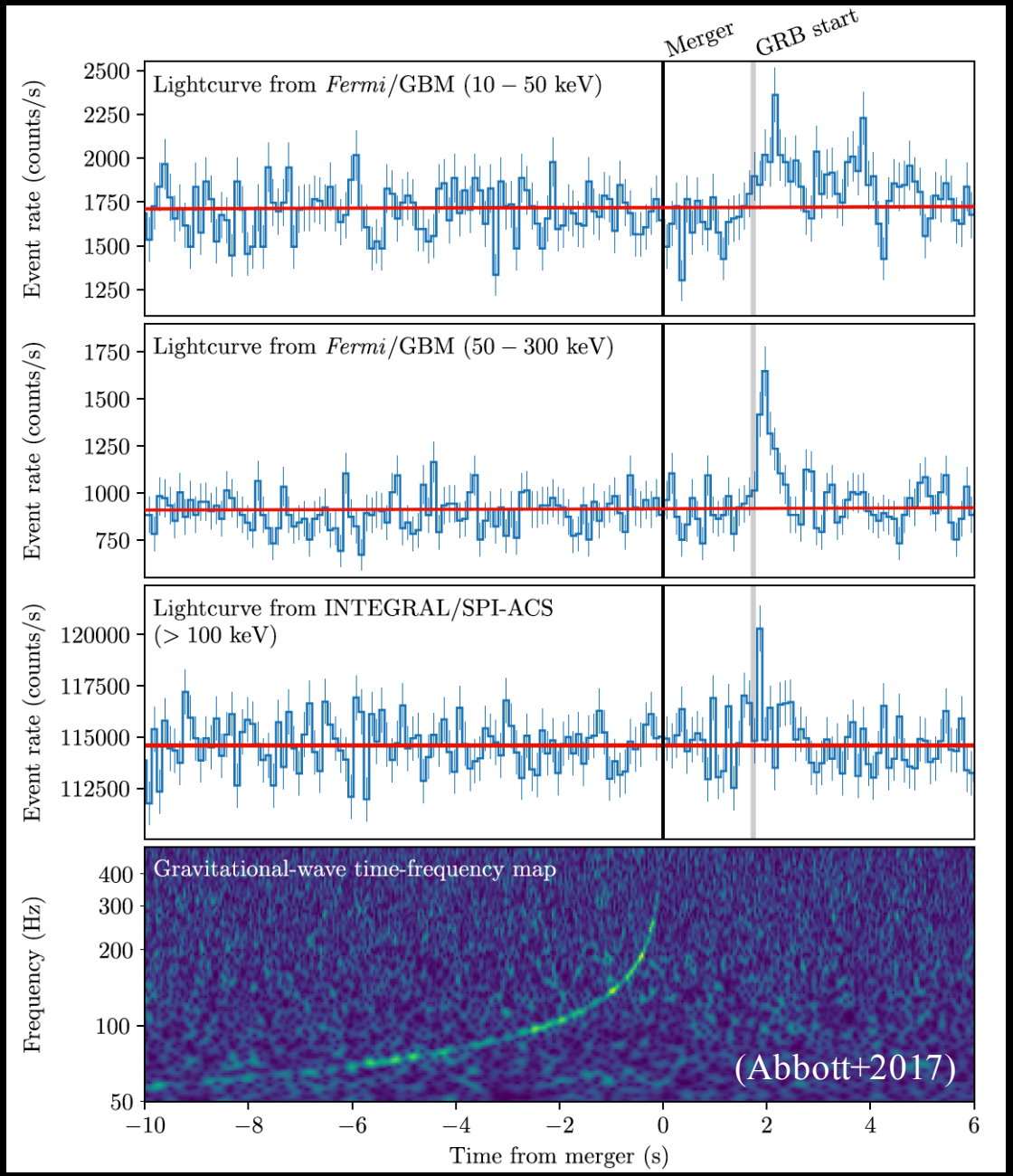
Baym, Hatsuda, Koji, Powell, Song, Takatsuka, 1707.04966 [astro-ph.HE]

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





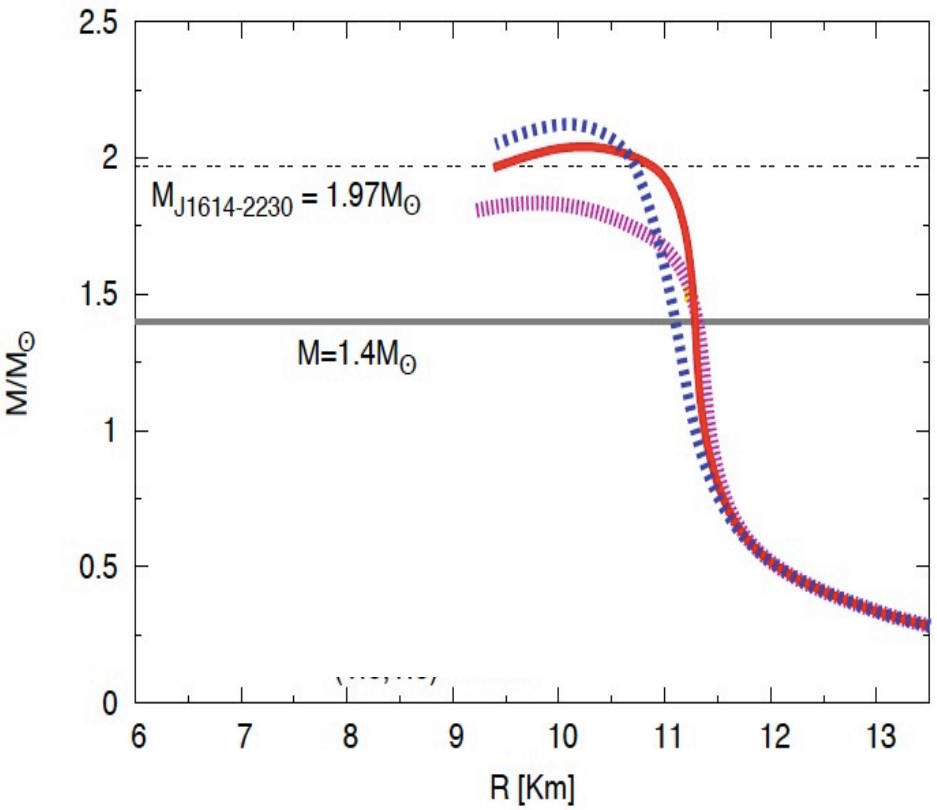
Neutron Star Merger GW170817



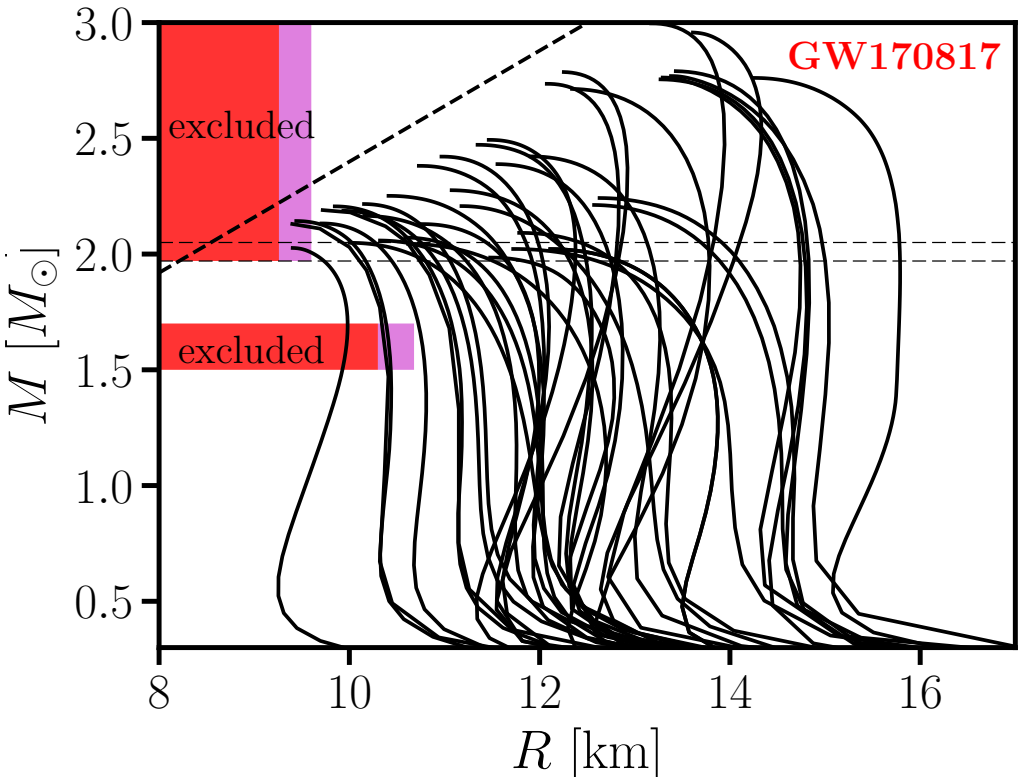
Gamma-ray from fermi Satellite

Gravitational Wave from LIGO

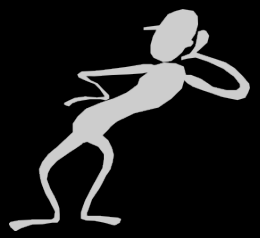
Baym, Hatsuda, Koji, Powell, Song, Takatsuka,
1707.04966 [astro-ph.HE]



Bauswein, Just, Janka, Stergioulas,
arXiv:1710.06843v2



Structure of Neutron Stars



Observables

- M～(1-2)$M_\odot$
- R ～10 km
- T ～10^6-10^9 K
- B ～10^6-10^{15} G
- P ～1 ms-30 s
- .....

Astrophysics
Nuclear physics
Particle physics
Cond. Matt. physics

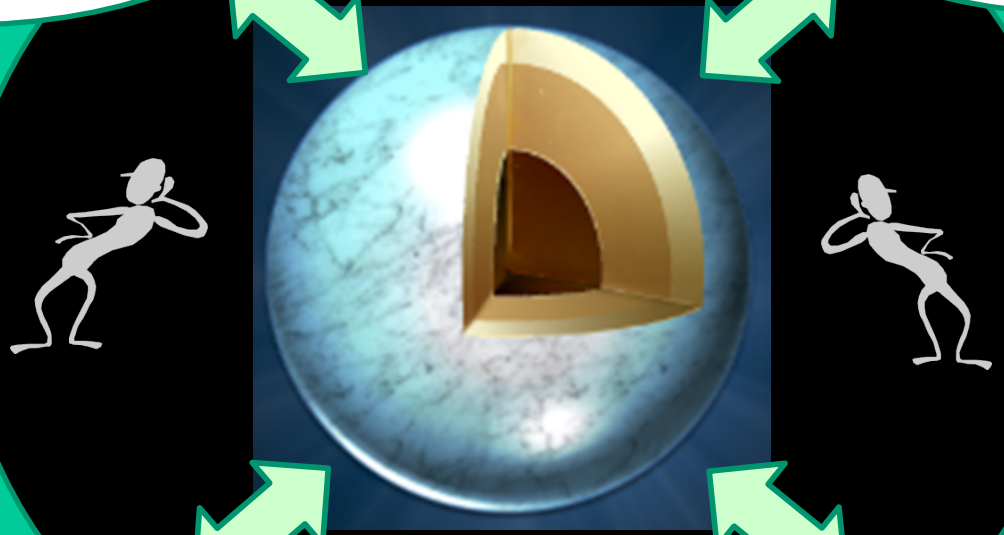
Matter under extreme condition

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

Summary

Theory
Lattice QCD / EFT
+ many body theory

Observation
EM waves, Neutrino
Gravitational Wave



THANKS

Cold Atoms
multi-component fermions
as quantum simulators

Experiments
RIBF, FRIB, J-PARC, FAIR
to provide basic data