Gravitational wave signal for quark matter with realistic phase transition

Yuki Fujimoto

(INT, U Washington)

Reference:

Y. Fujimoto, K. Fukushima, K. Hotokezaka, K. Kyutoku, arXiv:2205.03882

May 24, 2022

INT workshop “The r-process and the nuclear EOS after LIGO-Virgo’s third observing run”

Motivation & Outline of this talk

Dense quark matter in neutron stars (NSs)?

Detectability in the future postmerger GWs?

1) QCD-based equation of state (EoS) with a crossover-type hadron-to-quark phase transition (PT)

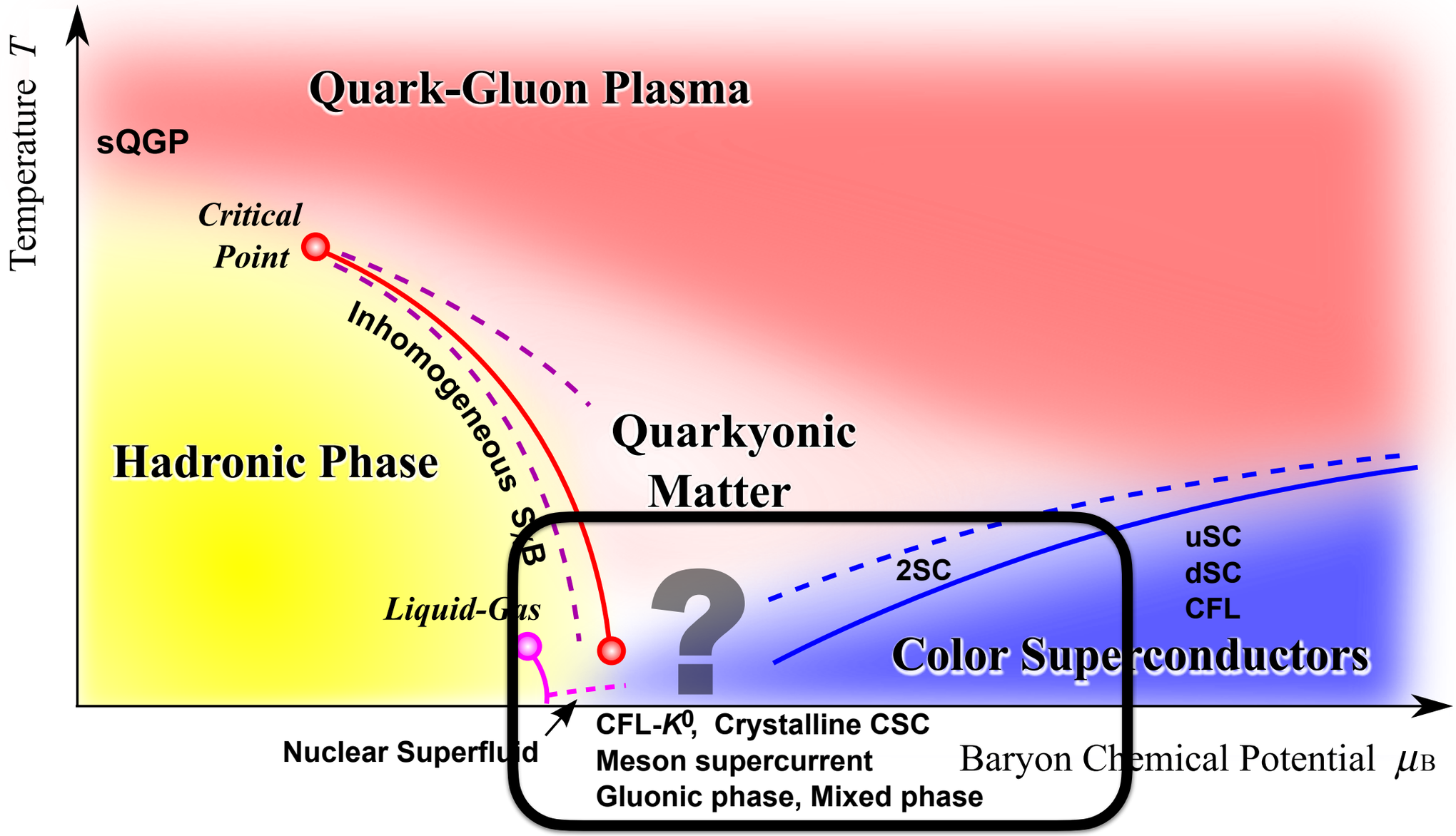
- Prerequisite for the QCD-based EoS
- Parametrization & possible scenarios for PTs

2) Detecting quark matter by GWs

- GW signals and detectability
- Useful check: electromagnetic counterpart

Quark liberation at high densities

Fukushima,Hatsuda (2010)

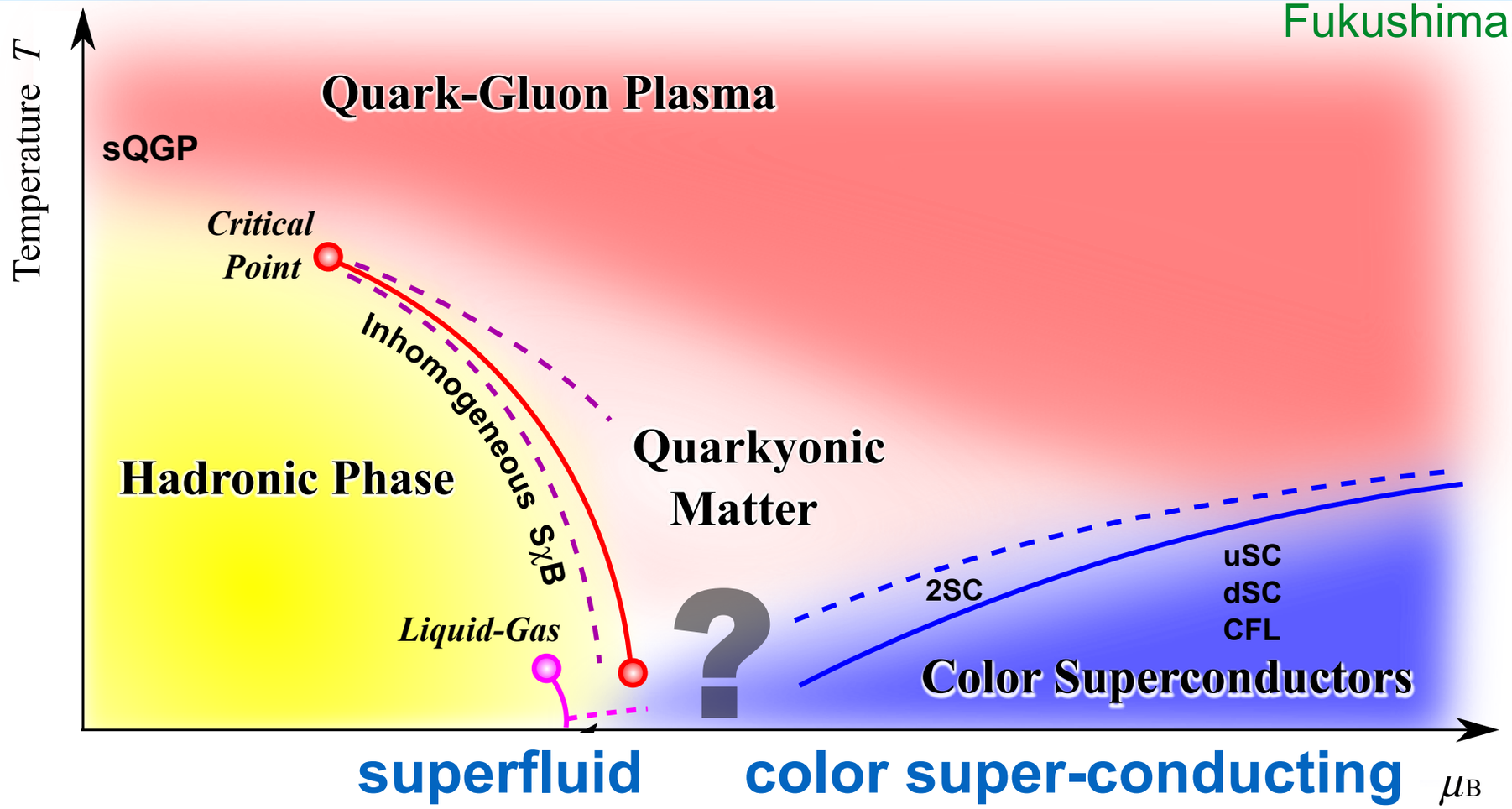


Quark deconfinement transition: 1st-order or crossover?

Colins,Perry (1974); Baym,Chin (1975); McLerran,Pisarski (2008)…

Underlying physics of crossover

Fukushima,Hatsuda (2010)



superfluid hadronic matter — **color super-conducting quark matter**

Global symmetry breaking patterns are identical:

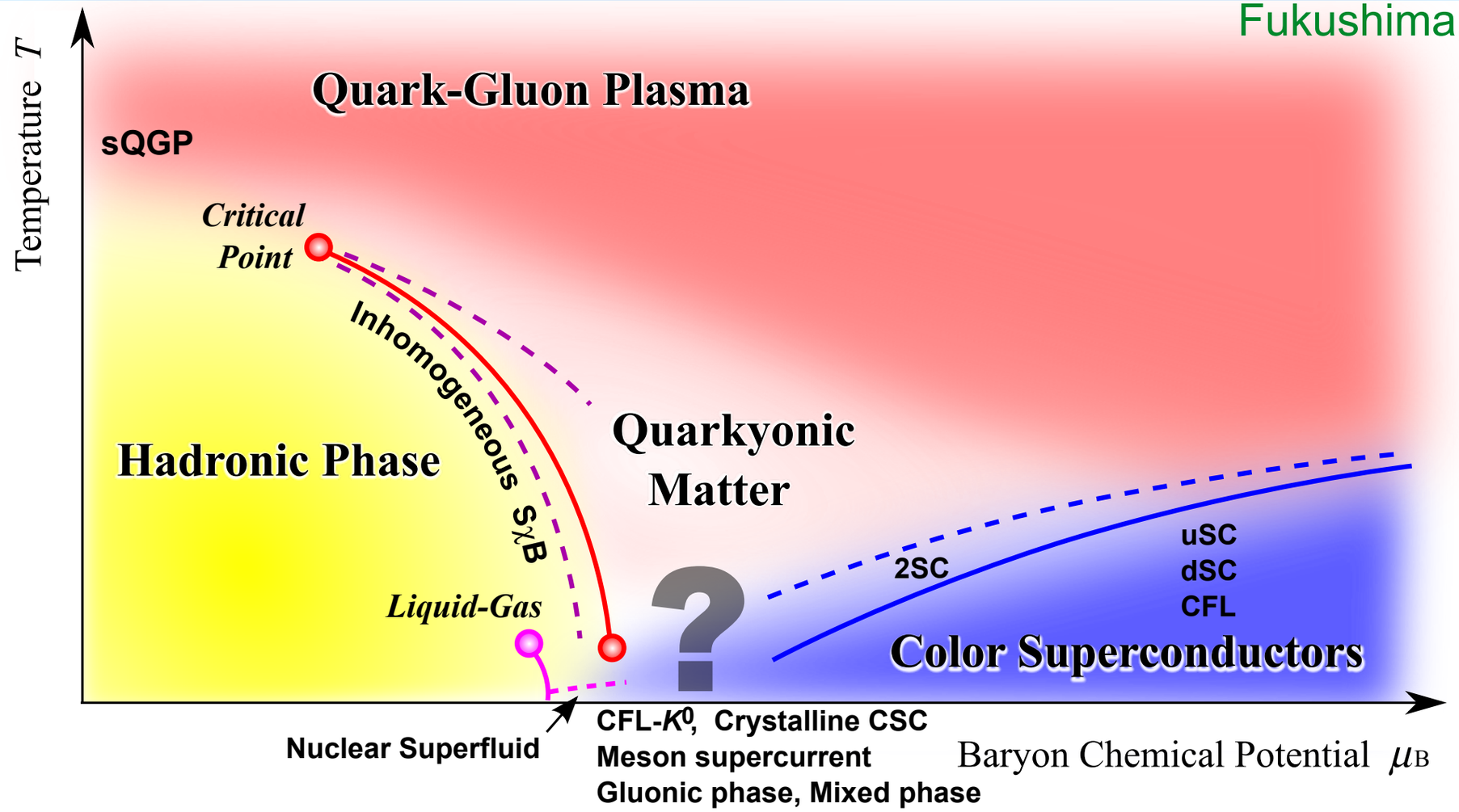
$$G = SU(3)_L \times SU(3)_R \times U(1)_B \to SU(3)_{L+R}$$

Quark-hadron continuity

Schafer,Wilczek (1998); Hatsuda,Tachibana,Yamamoto,Baym (2006);
see, however, Cherman,Jacobson,Sen,Yaffe (2020)

Underlying physics of crossover

Fukushima,Hatsuda (2010)



Alternative possibility: **Quarkyonic matter**

McLerran,Pisarski (2008); McLerran,Reddy (2018)

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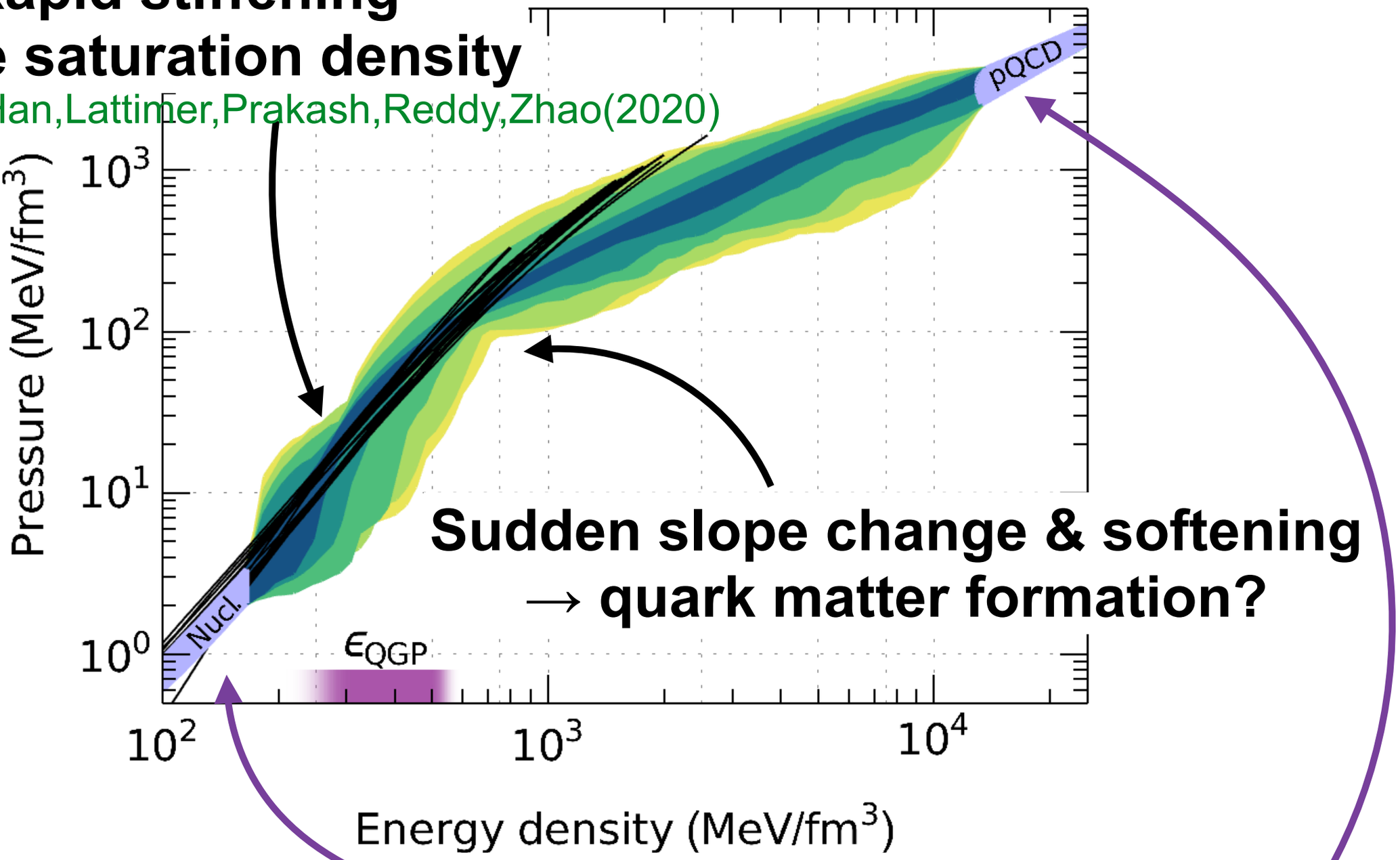
QCD-based view on the EoS

Annala,Gorda,Kurkela,Nättilä,Vuorinen (2019)

Rapid stiffening above saturation density

e.g., Drischler,Han,Lattimer,Prakash,Reddy,Zhao(2020)

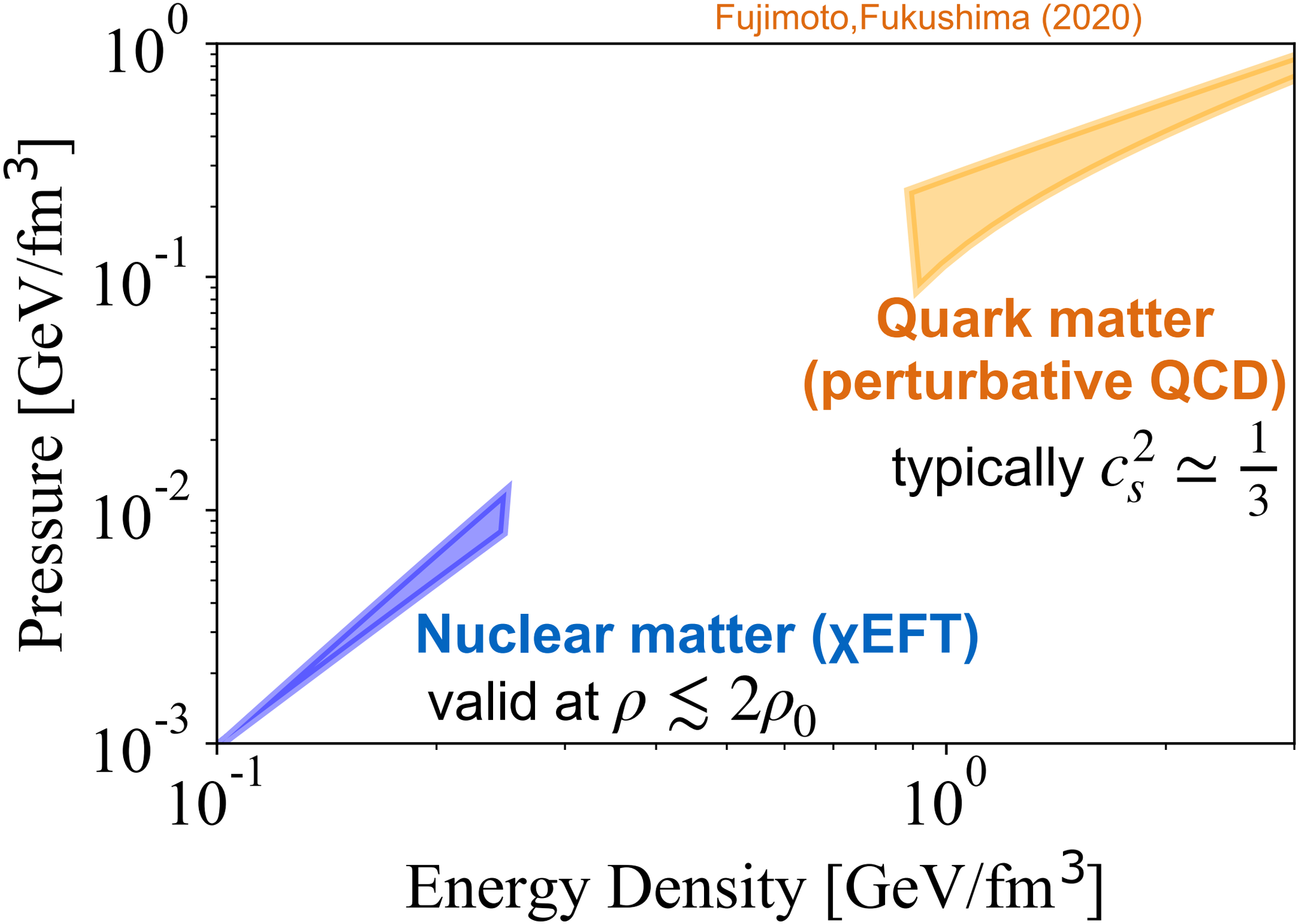


Sudden slope change & softening
→ quark matter formation?

ab initio QCD calculations: Chiral EFT & perturbative QCD

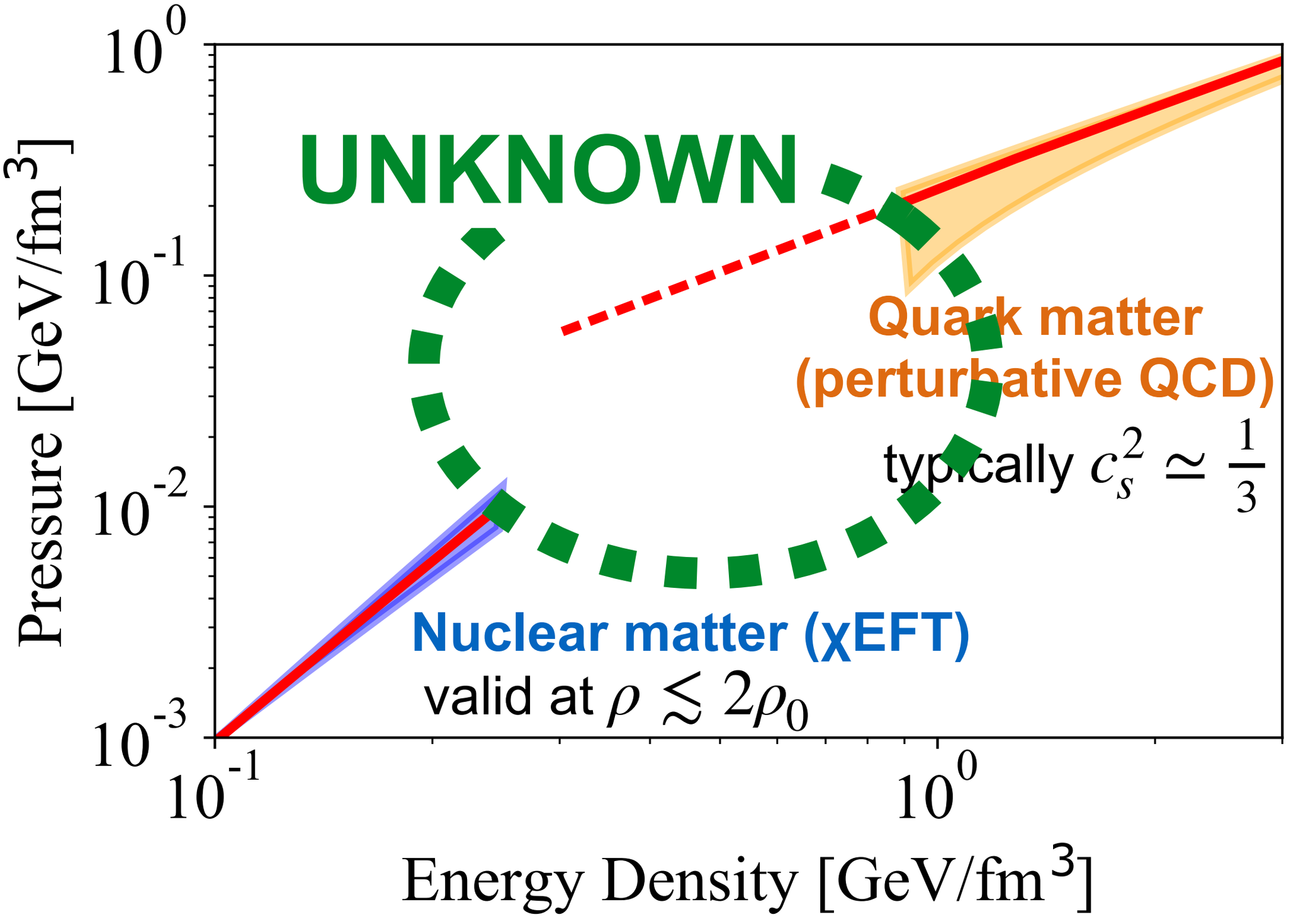
Prerequisite for the QCD-based EoS

pQCD: Freedman,McLerran (1976); Baluni (1977);
Kurkela,Romatschke,Vuorinen,Fraga,… (2009-);
Fujimoto,Fukushima (2020)



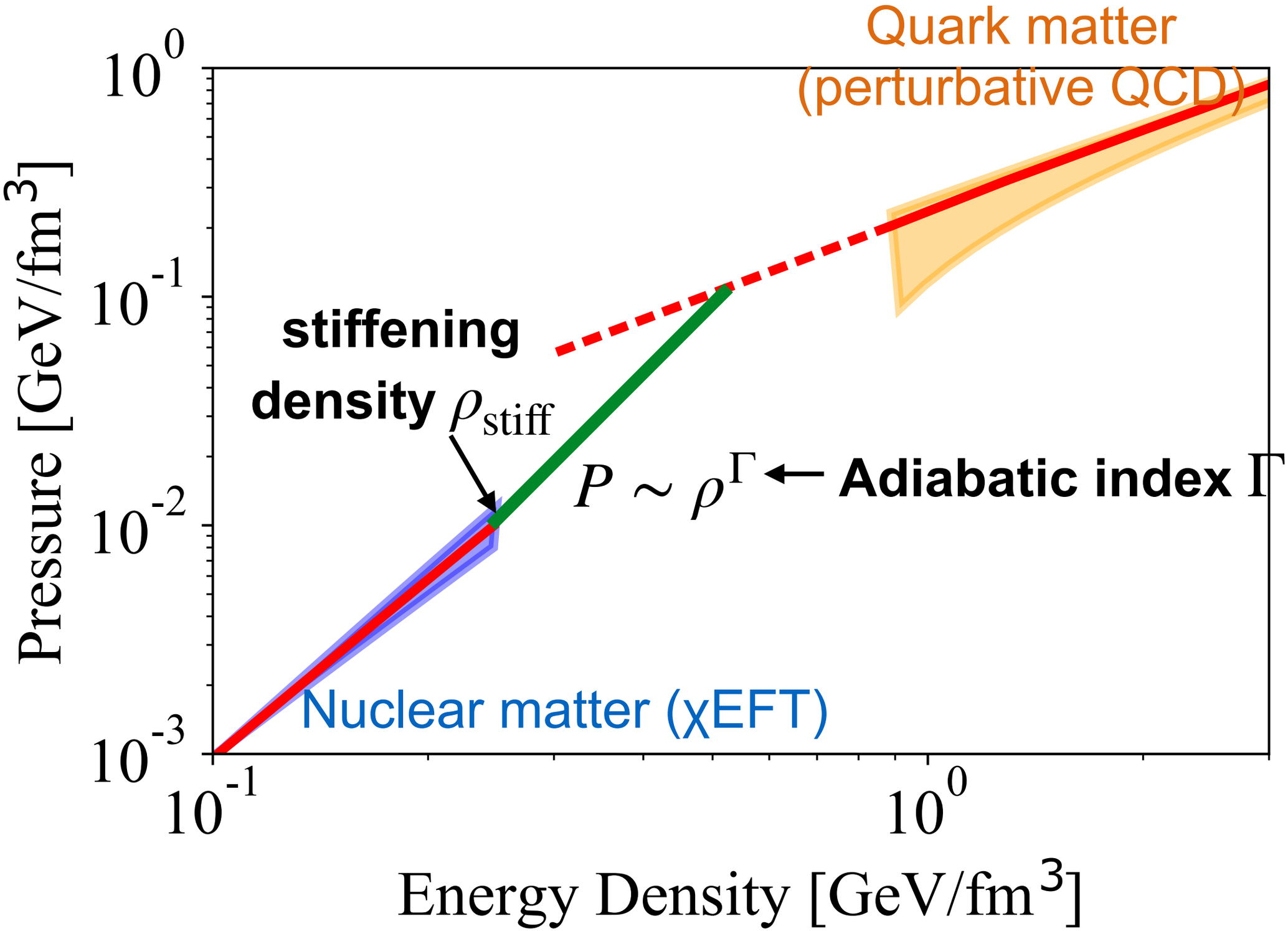
χEFT:
Drischler,Han,Lattimer,Prakash,Reddy,Zhao (2021)

Prerequisite for the QCD-based EoS

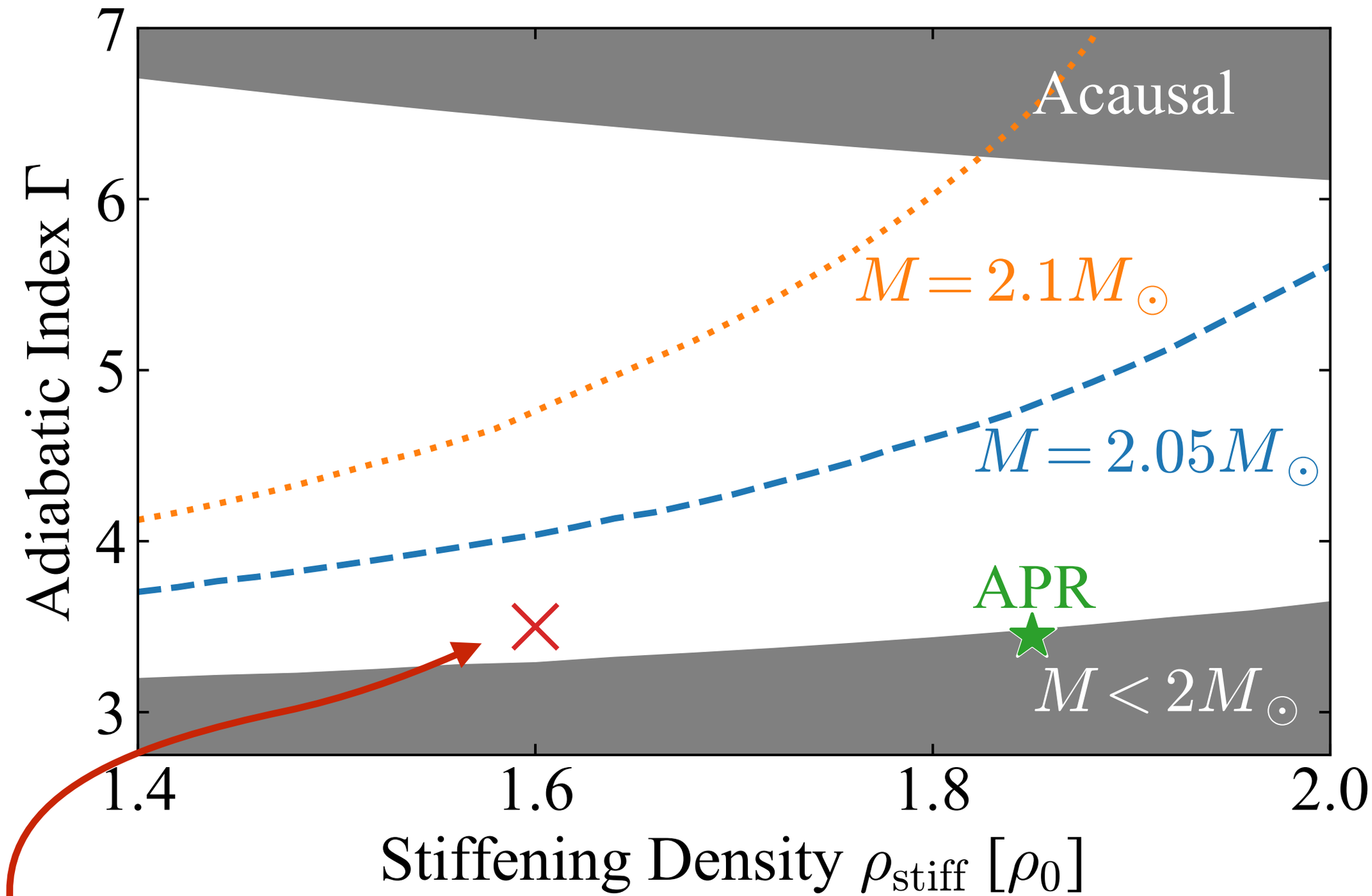


Parametrizing the intermediate region

Crossover parametrization for piecewise polytropes:



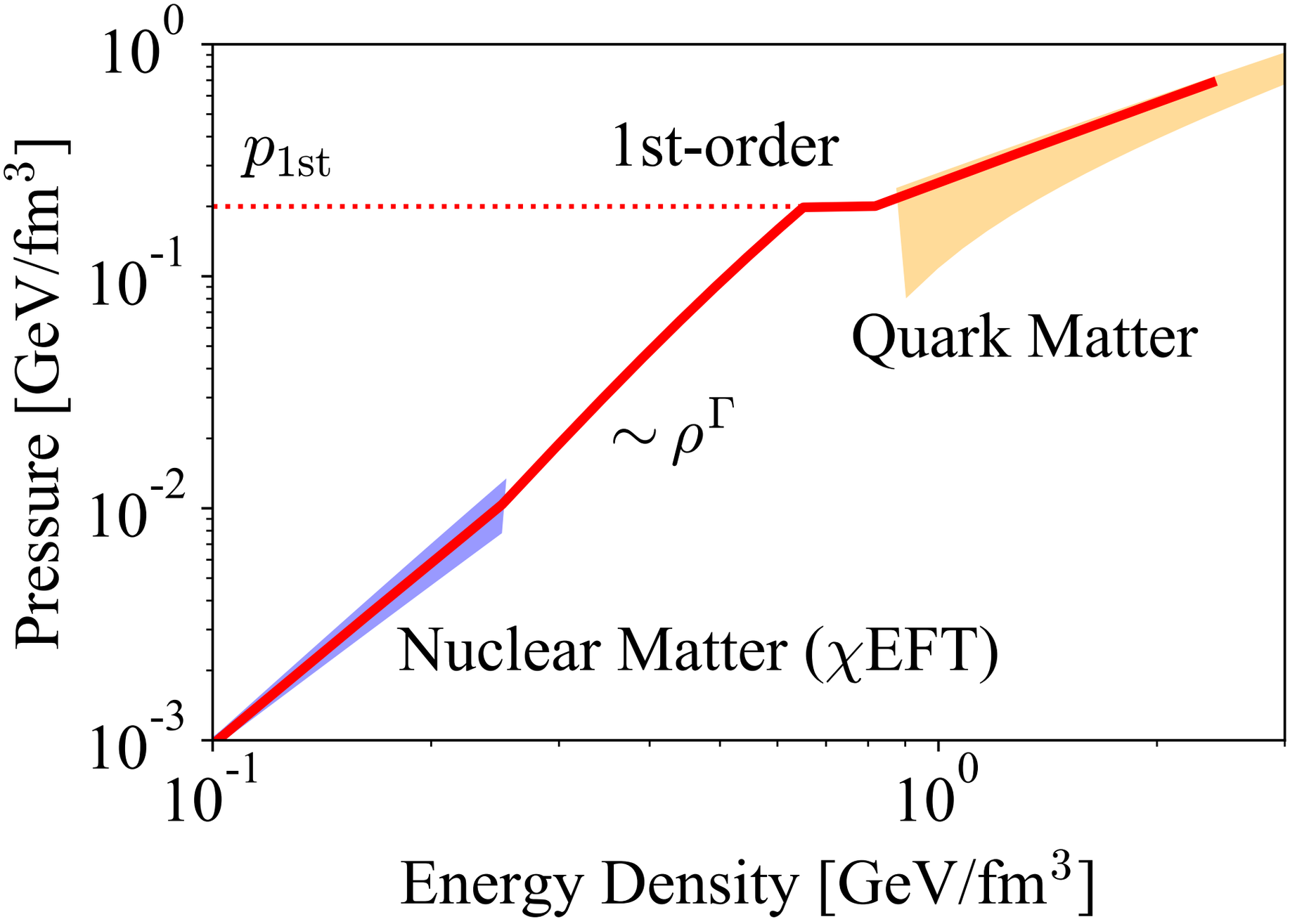
Allowed region of parameters



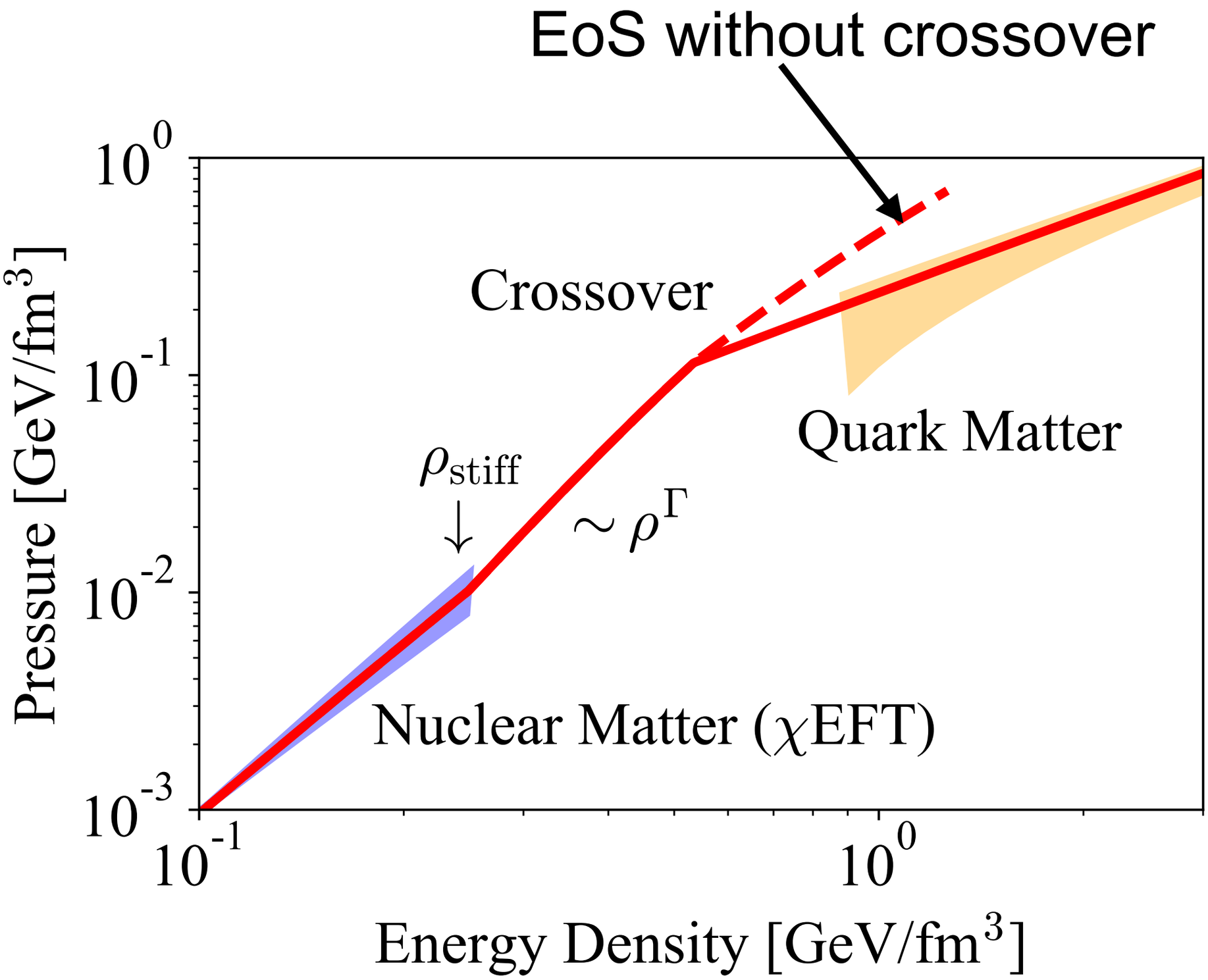
In later calculations, we take $(\rho_{\rm stiff},\ \Gamma) = (1.6\rho_0,\ 3.5)$

Parametrizing the intermediate region

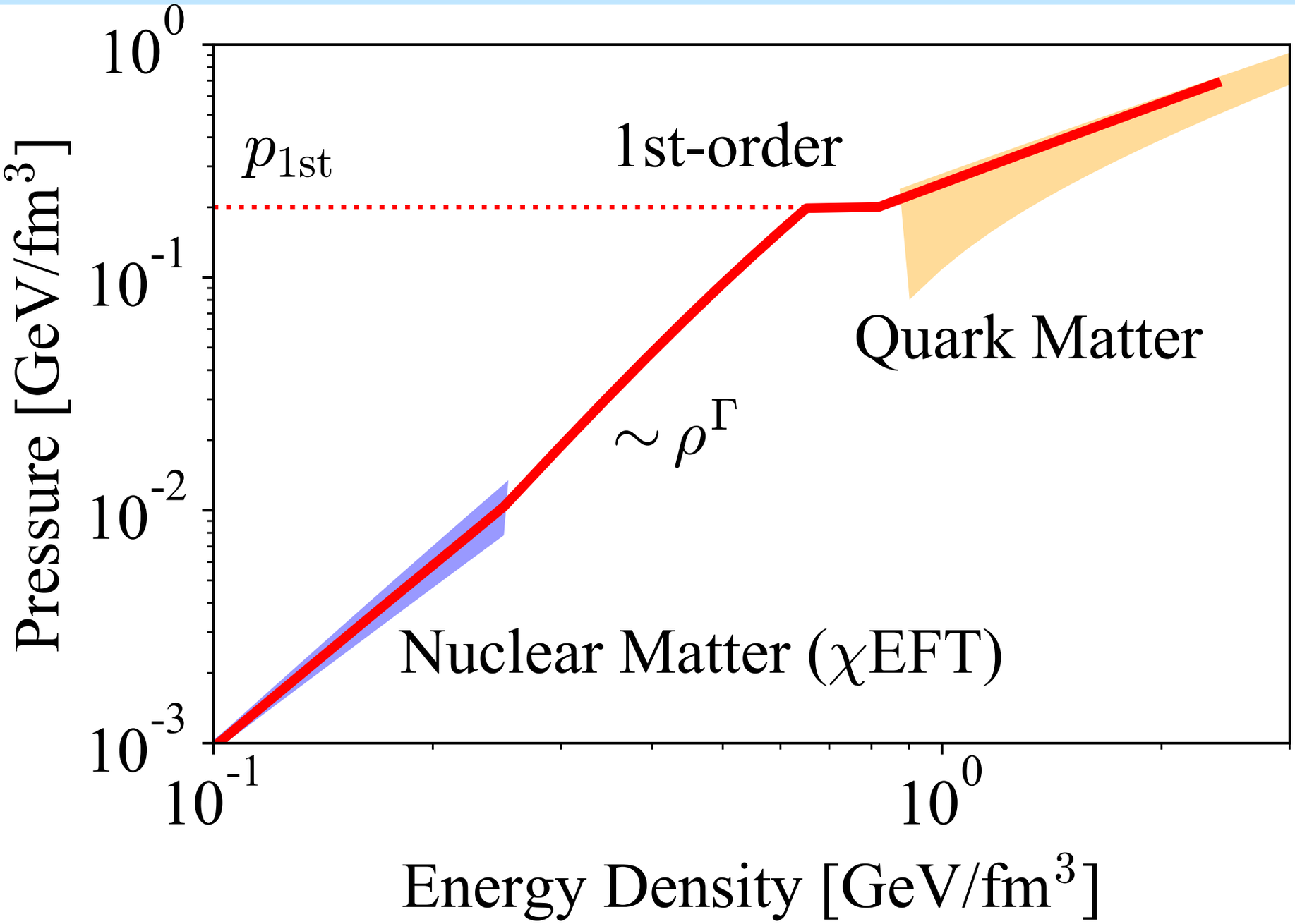
1st-order PT can be treated likewise:



Three possibilities: (1) Crossover

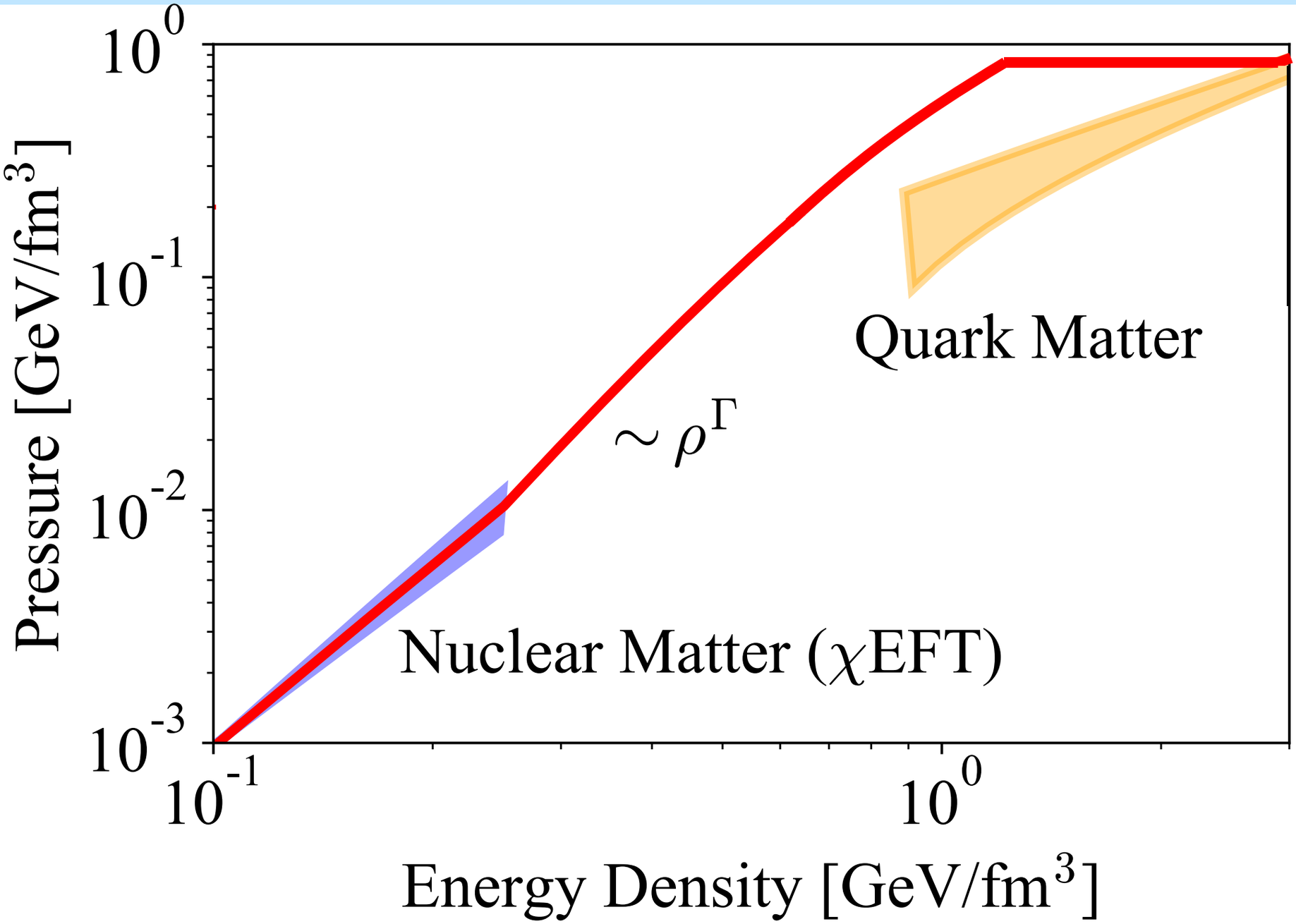


(2) Weak 1st-order PT



1st-order PT effect is small; similar to the crossover case

(3) 1st-order PT at very high densities



Quark matter undetectable!

1st-order PT is at too high densities, so no contribution from quark matter within the realistic neutron-star densities

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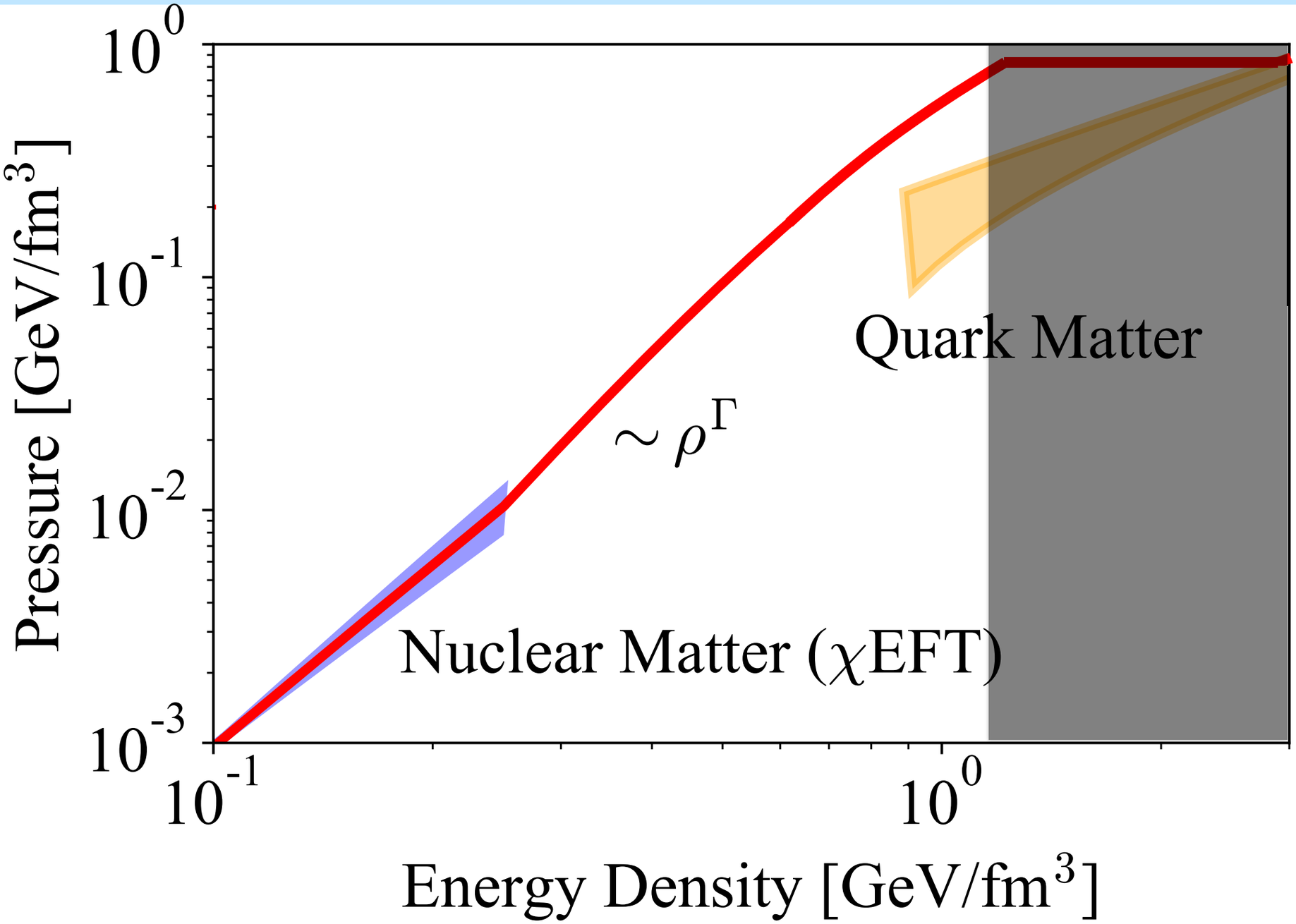

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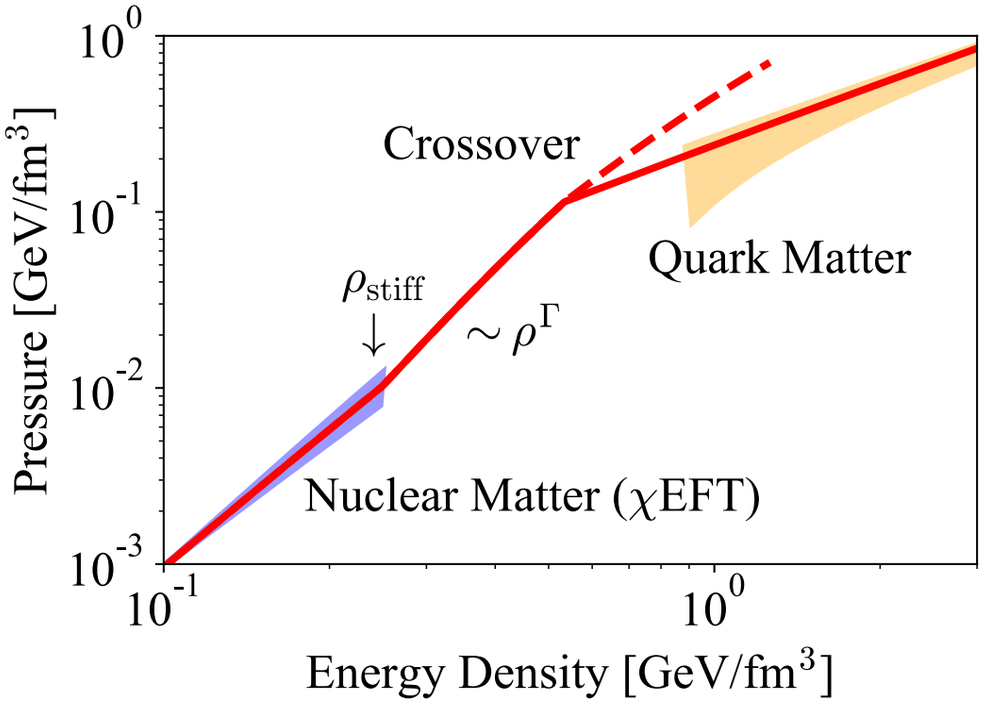
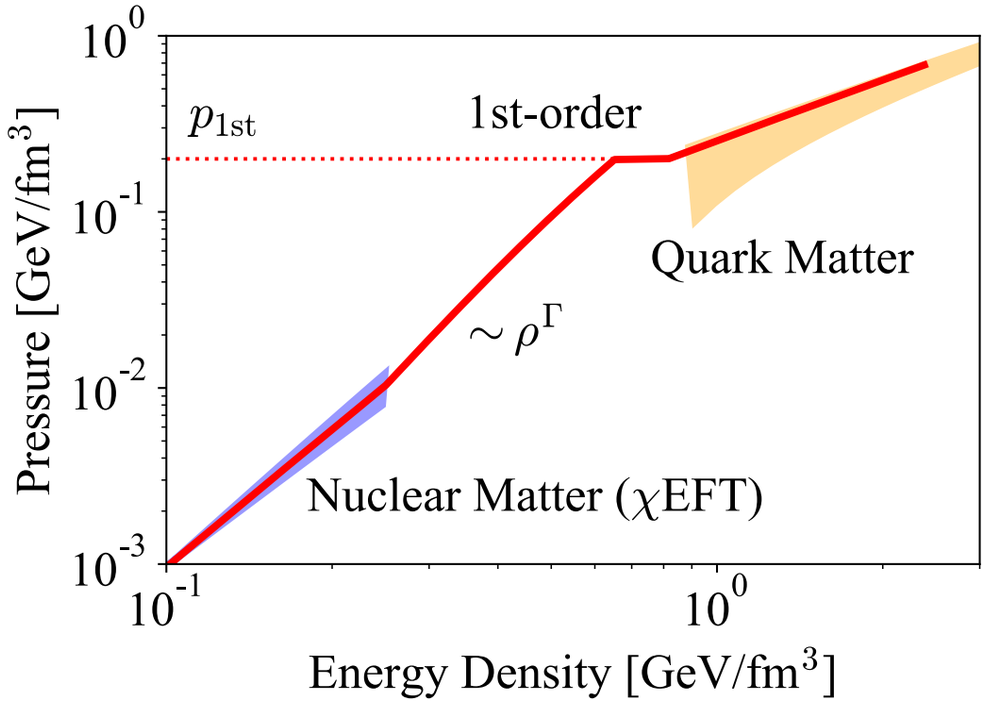
Categories of realistic PT pattern

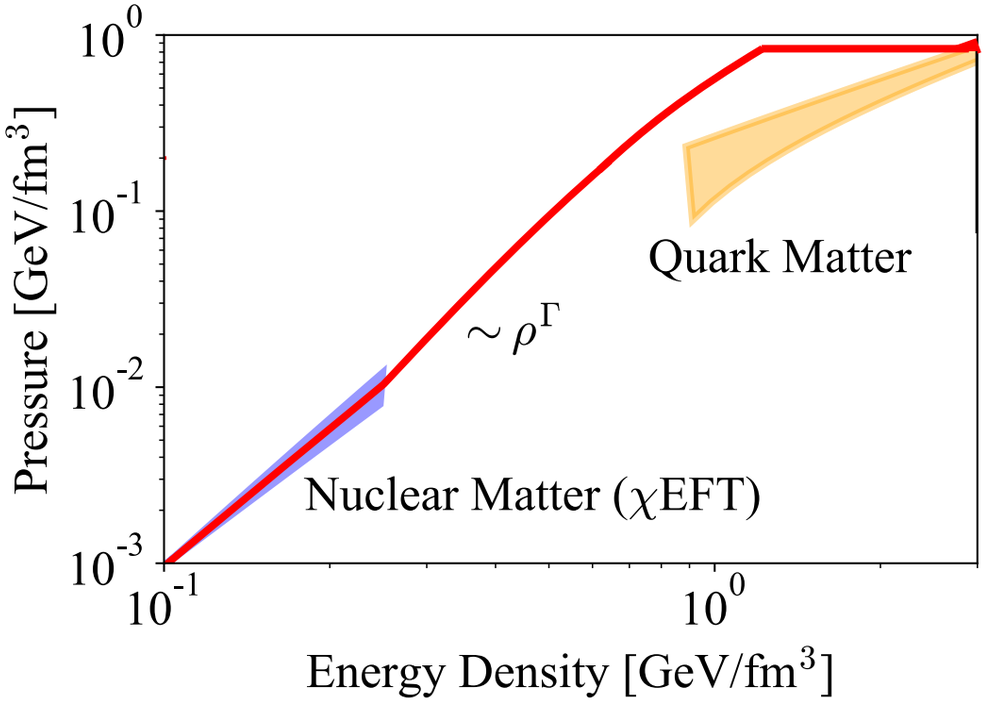
(1) Crossover



(2) Weak 1st-order



(3) Strong 1st-order @ high ρ



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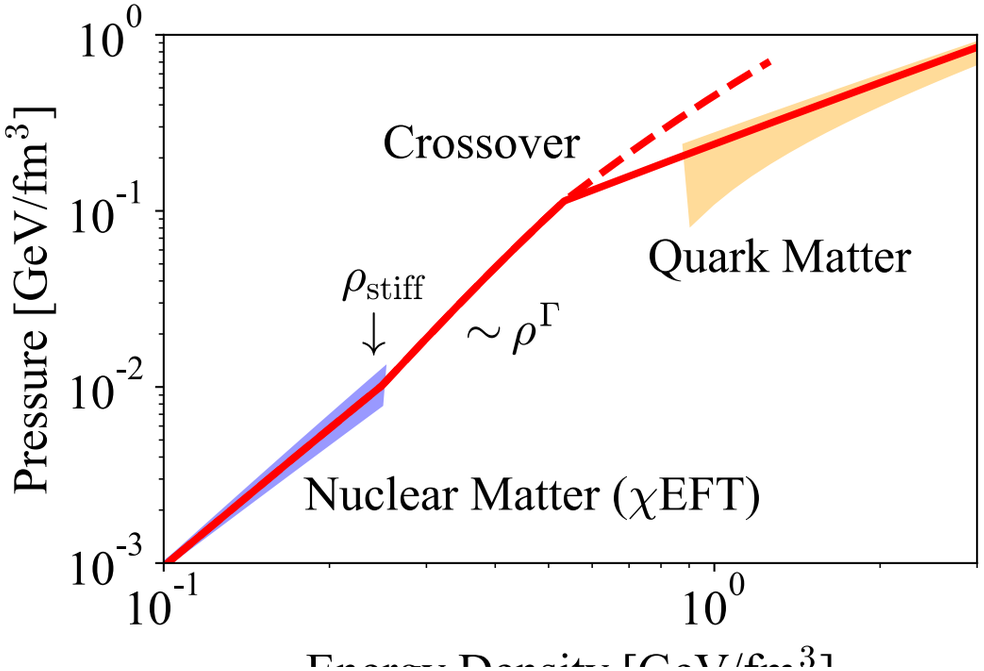

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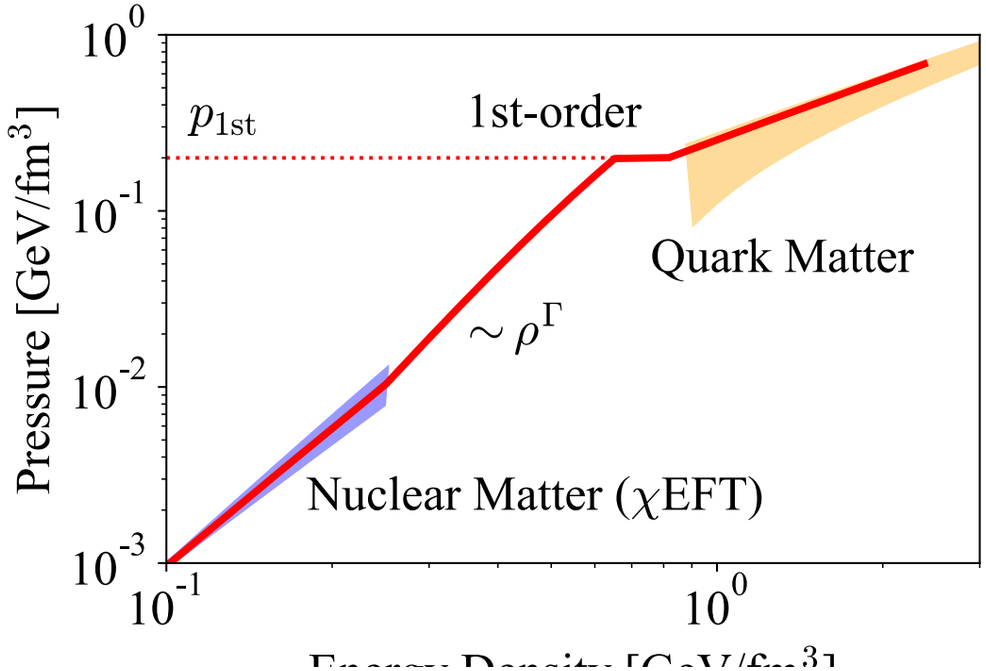
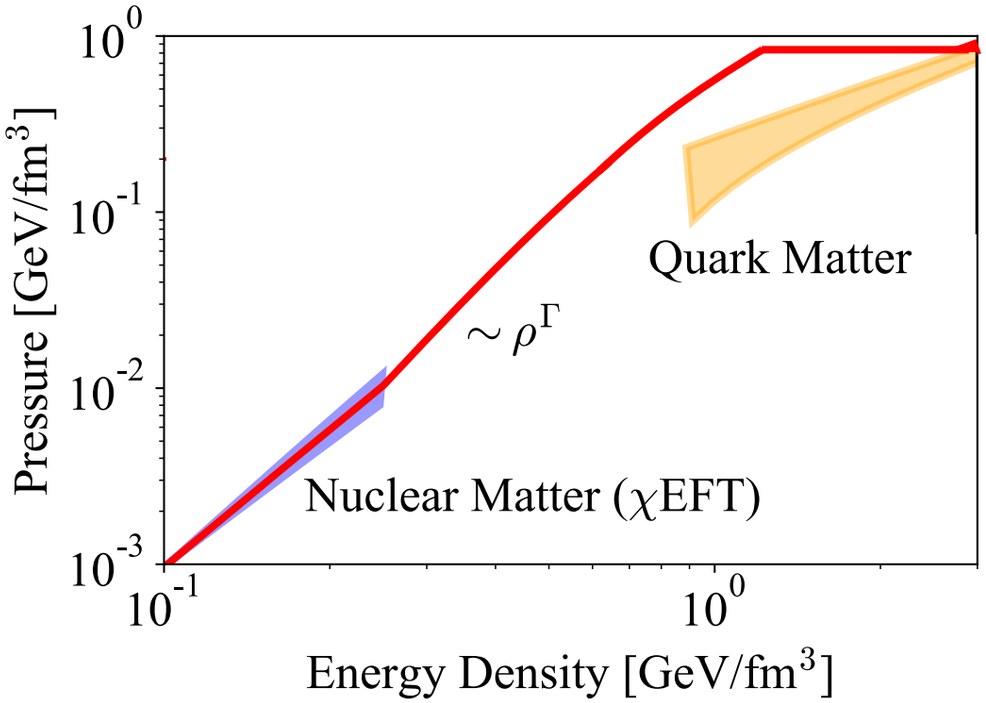


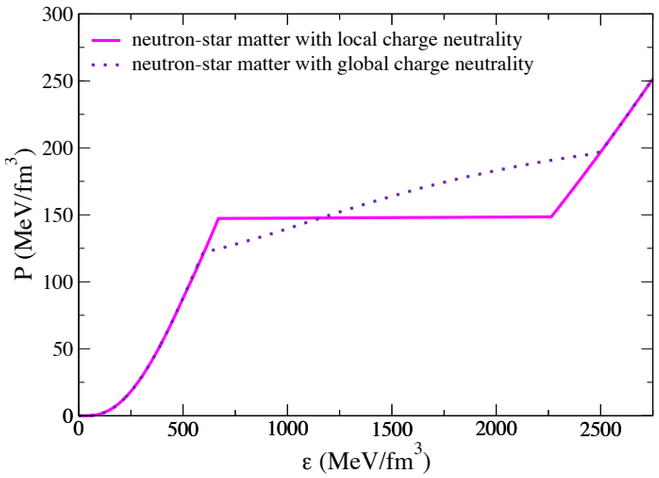
Simulating this case is enough for the current purpose

(3) Strong 1st-order @ high ρ



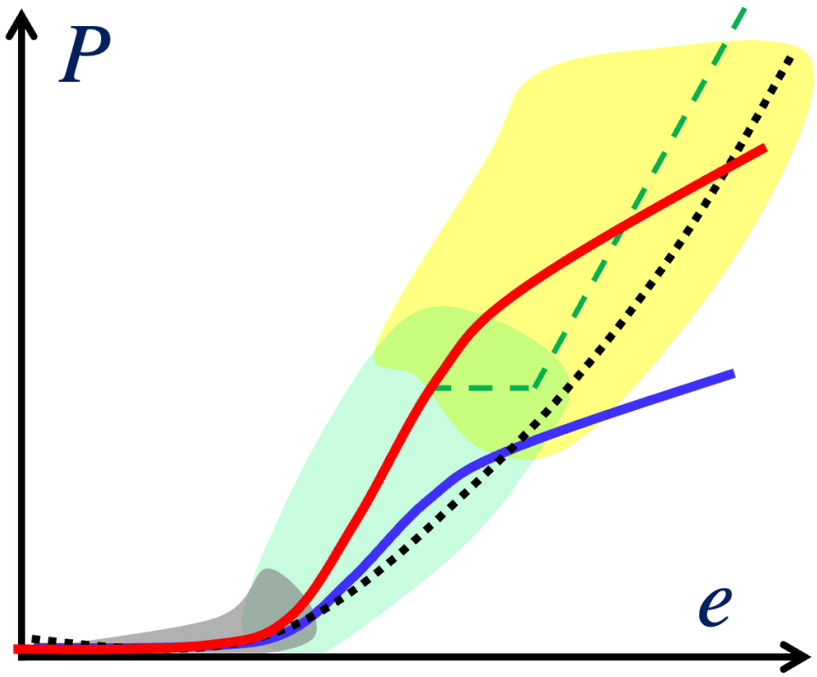
Related preceding works

Most,Papenfort,Dexheimer,Hanauske,Schramm,Stoecker,Rezzolla (2018);
Bauswein,Bastian,Blaschke,Chatziioannou,Clark,Fischer,Oertel (2018)



1st-order PT model EoSs,
Most *et al.*: soft quark matter
Bauswein *et al.*: stiffer quark matter

Huang,Baiotti,Kojo,Takami,Sotani,Togashi,Hatsuda,Nagataki,Fan (2022);
Kedia,Kim,Suh,Mathews (2022)



Crossover-type NJL model EoSs (QHC19),
not based on ab-initio QCD calculation,
and predicts stiff EoS at high densities
→ can be categorized into
“without crossover" EoS of case (1)

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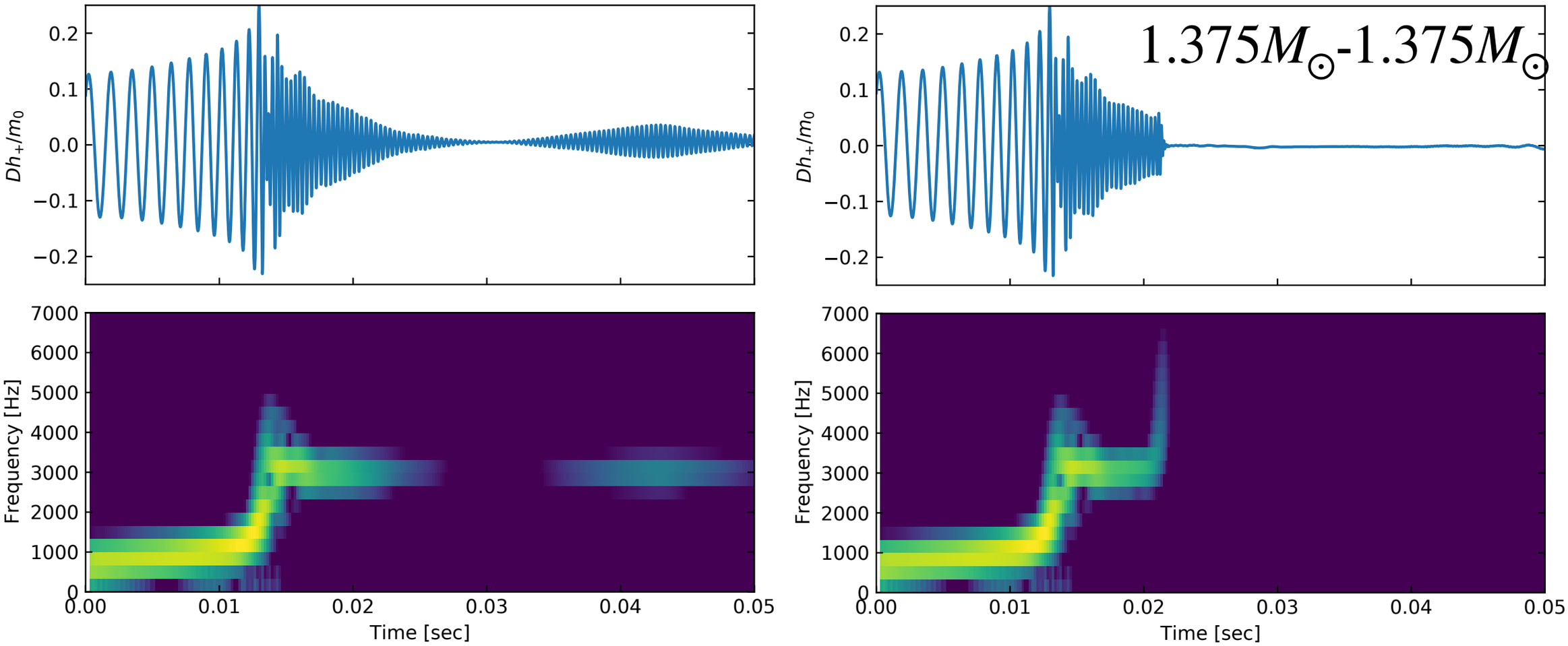
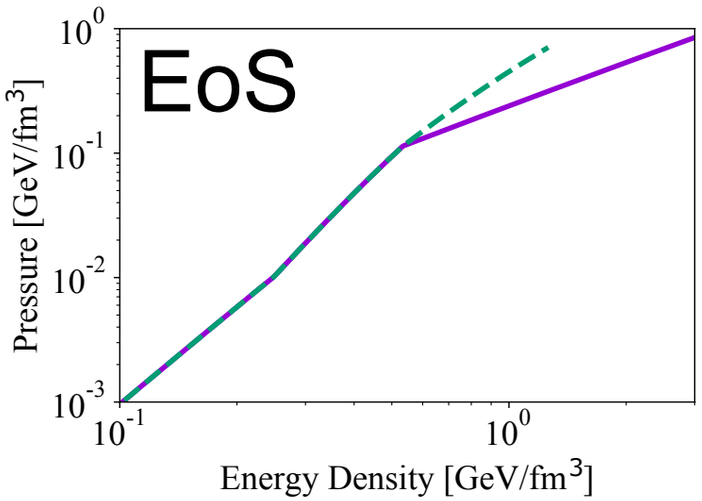
GW signals from quark matter

Fujimoto,Fukushima,Hotokezaka,Kyutoku (2022)

without crossover

with crossover



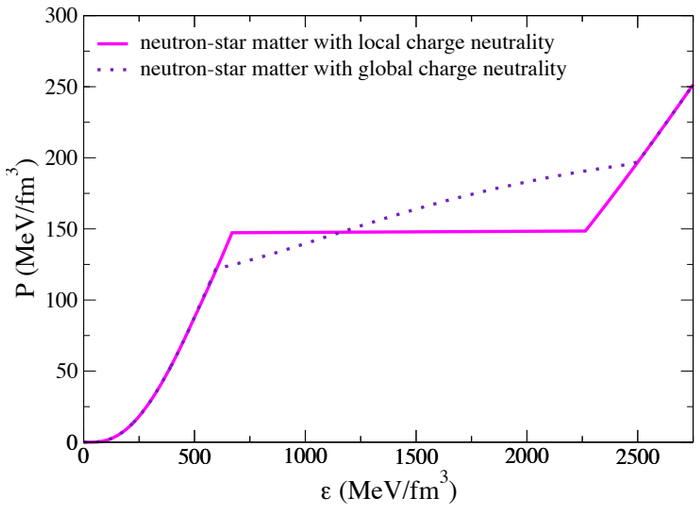


Crossover to quark matter (softening) drives the collapse to black holes

Comparing the results with related works

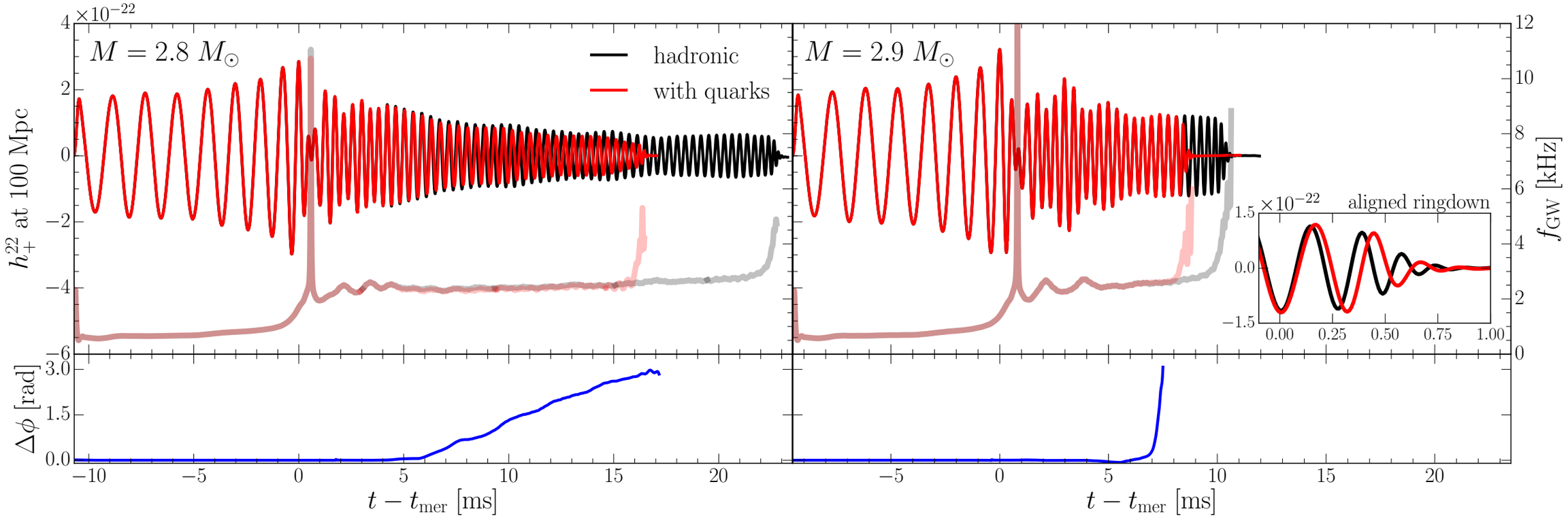
Most,Papenfort,Dexheimer,Hanauske,Schramm,Stoecker,Rezzolla (2018)

Chiral mean field model EoSs with 1st-order PT to **soft quark matter**



Results are consistent with our crossover EoS

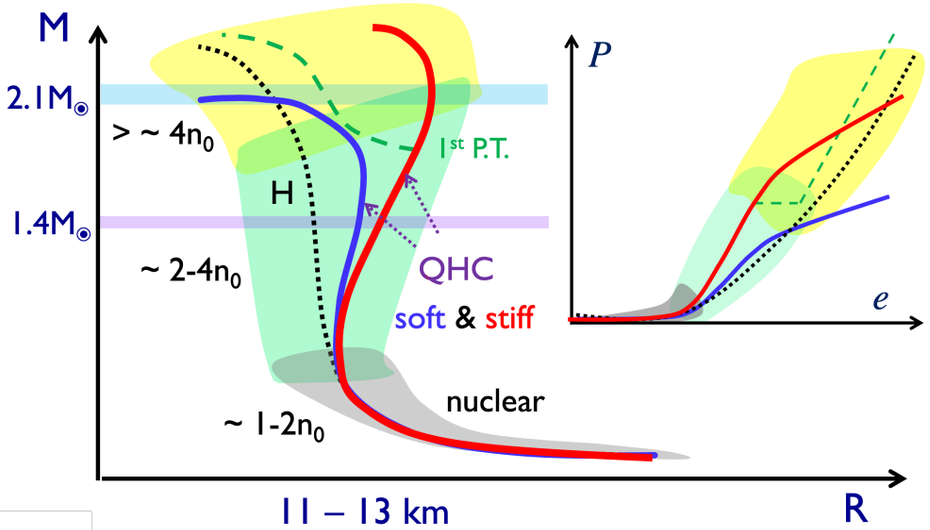
EoS softening is essential for quark matter detection



Comparing the results with related works

Huang,Baiotti,Kojo,Takami,Sotani,Togashi,Hatsuda,Nagataki,Fan (2022)

Crossover-type NJL model EoSs (QHC19),
with **stiff quark matter**



Results are consistent with our
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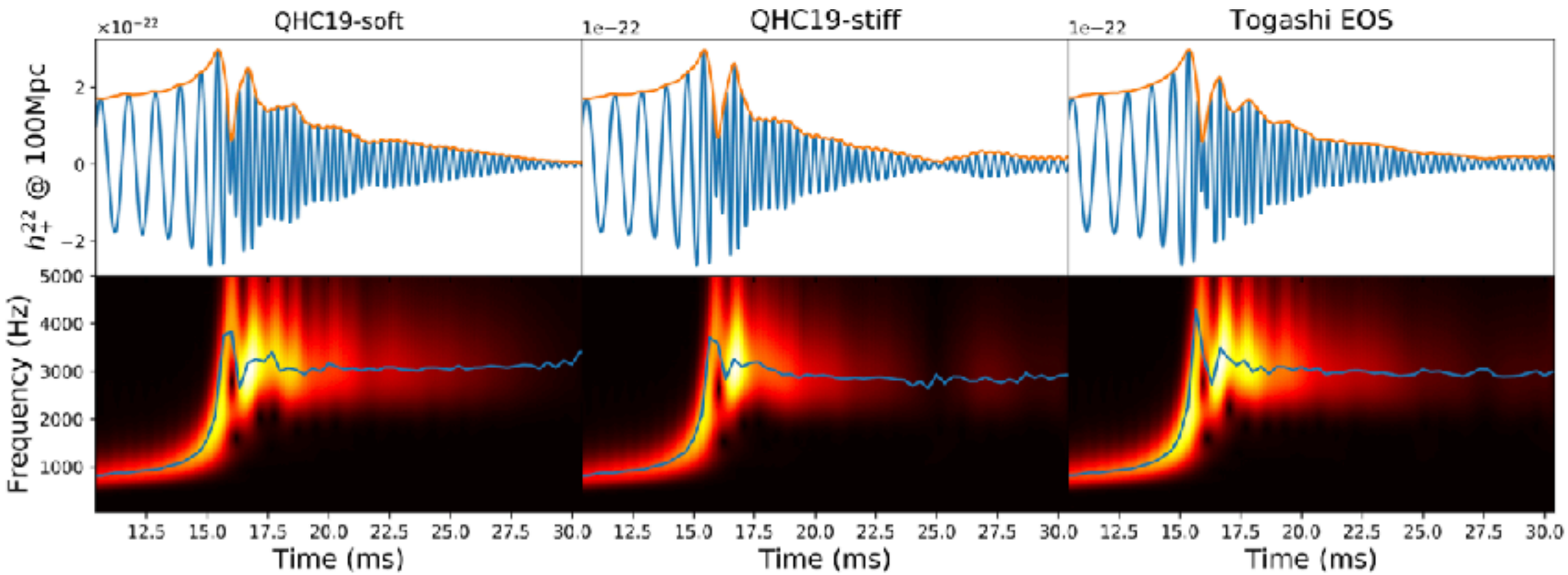
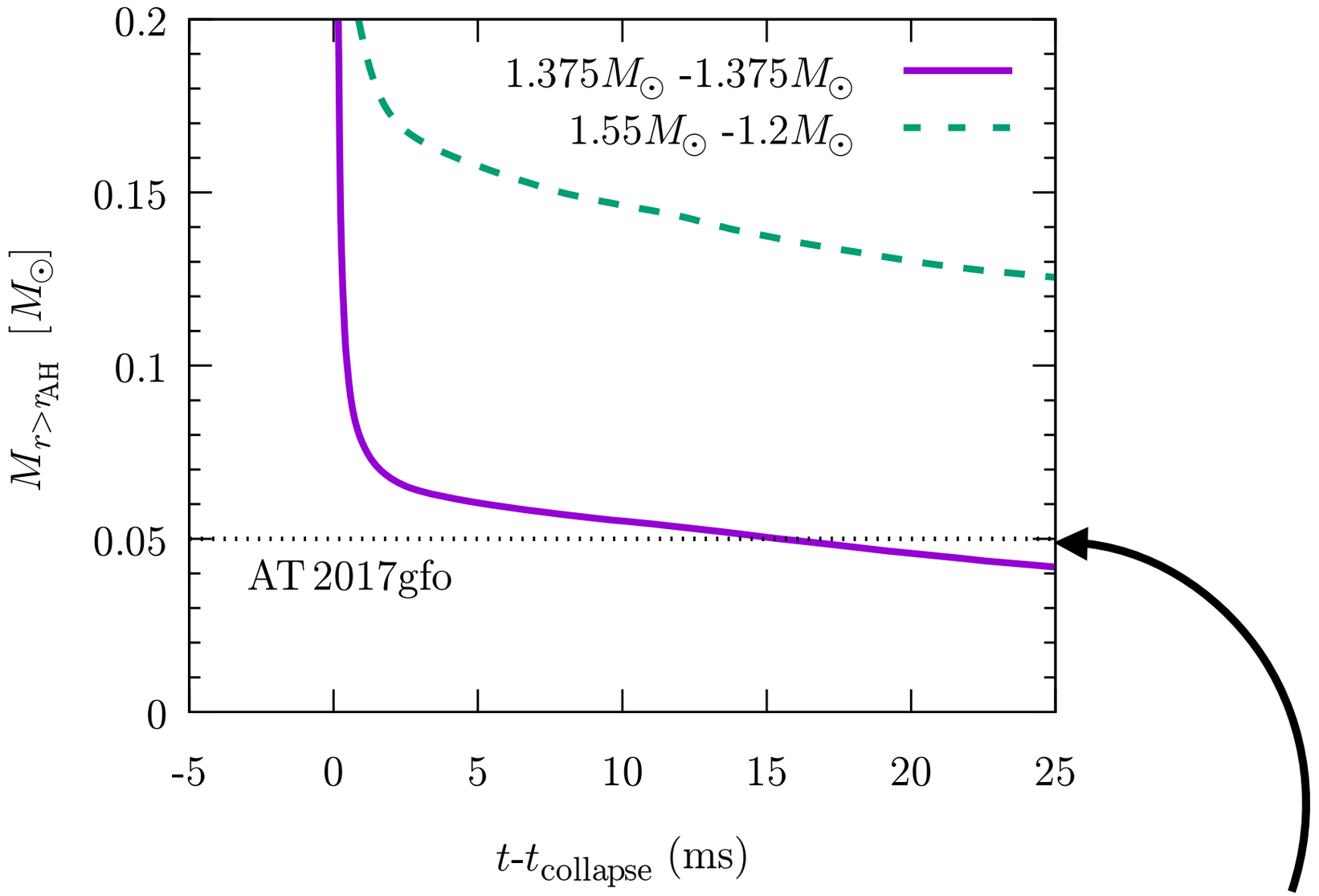


Consistency with kilonova AT2017gfo

Remnant mass outside the apparent horizon of the BH



AT2017gfo, electromagnetic counterpart of GW170817,
requires ejection of $\approx 0.05M_\odot$ for its observed luminosity

Summary

- Detectability of quark matter by gravitational waves from binary neutron star mergers is discussed

- **The QCD-based EoS:**
  - Based on the ab initio QCD calculations, PTs can be categorized into a few possibilities (Crossover or 1st-order)

- **Central results:**
  - Crossover and hadronic EoSs show qualitative difference; Crossover to quark matter drives the collapse to black holes, while the hadronic EoS does not.
  - Electromagnetic counterparts (kilonova) can be useful check