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 6, 2022, Seminar @ Academica Sinica

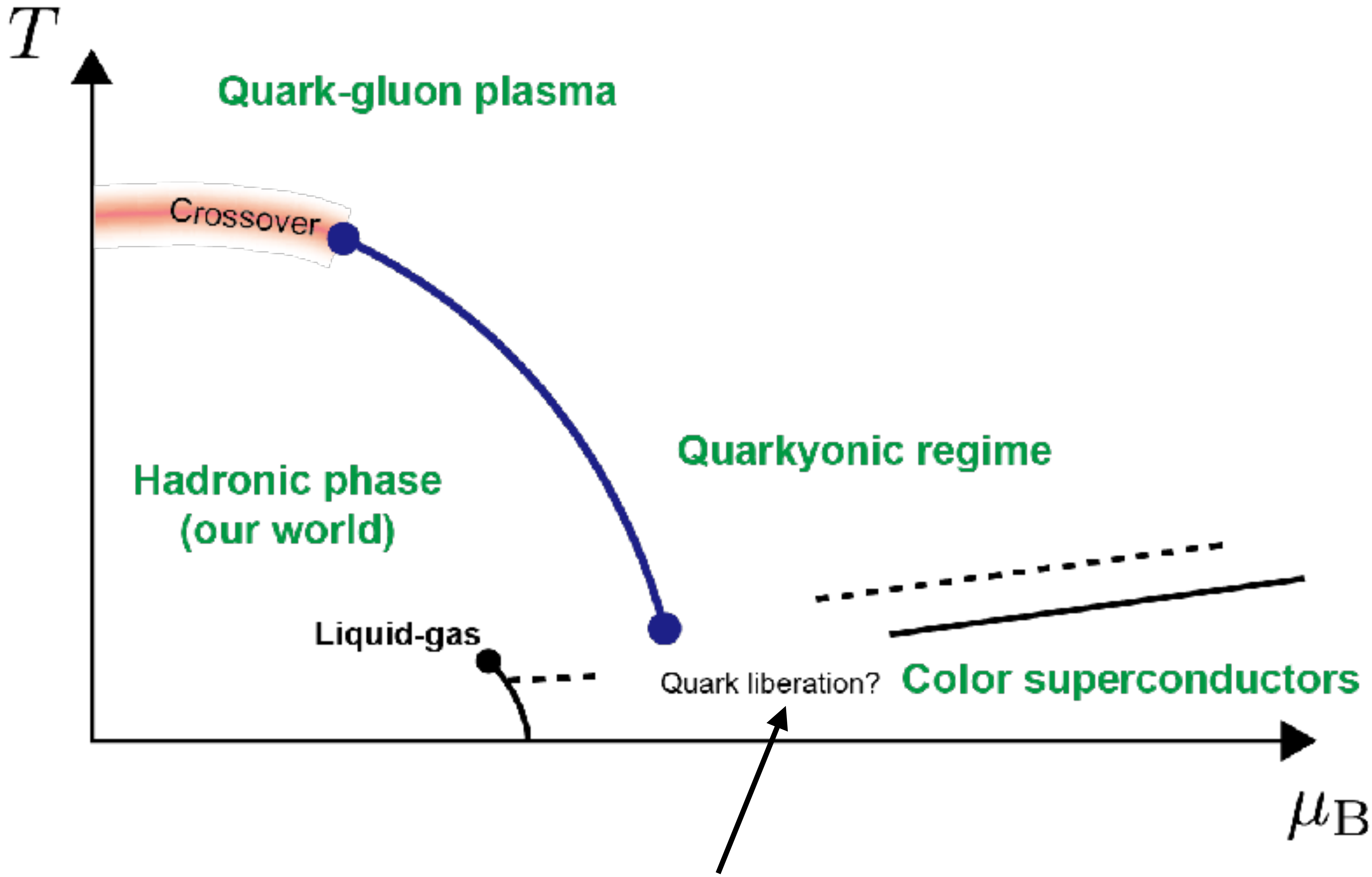
Motivation & Outline of this talk

- **0) Introduction: Dense quark matter in neutron stars (NSs)? How to detect it?**

- **1) QCD-based equation of state (EoS) with a realistic hadron-to-quark phase transition (PT)**
  - Prerequisite for the QCD-based EoS
  - Parametrization & possible scenarios for PTs

- **2) Detecting quark matter by gravitational waves (GWs)**
  - GW signals and detectability
  - Some issues: thermal index, electromagnetic counterpart

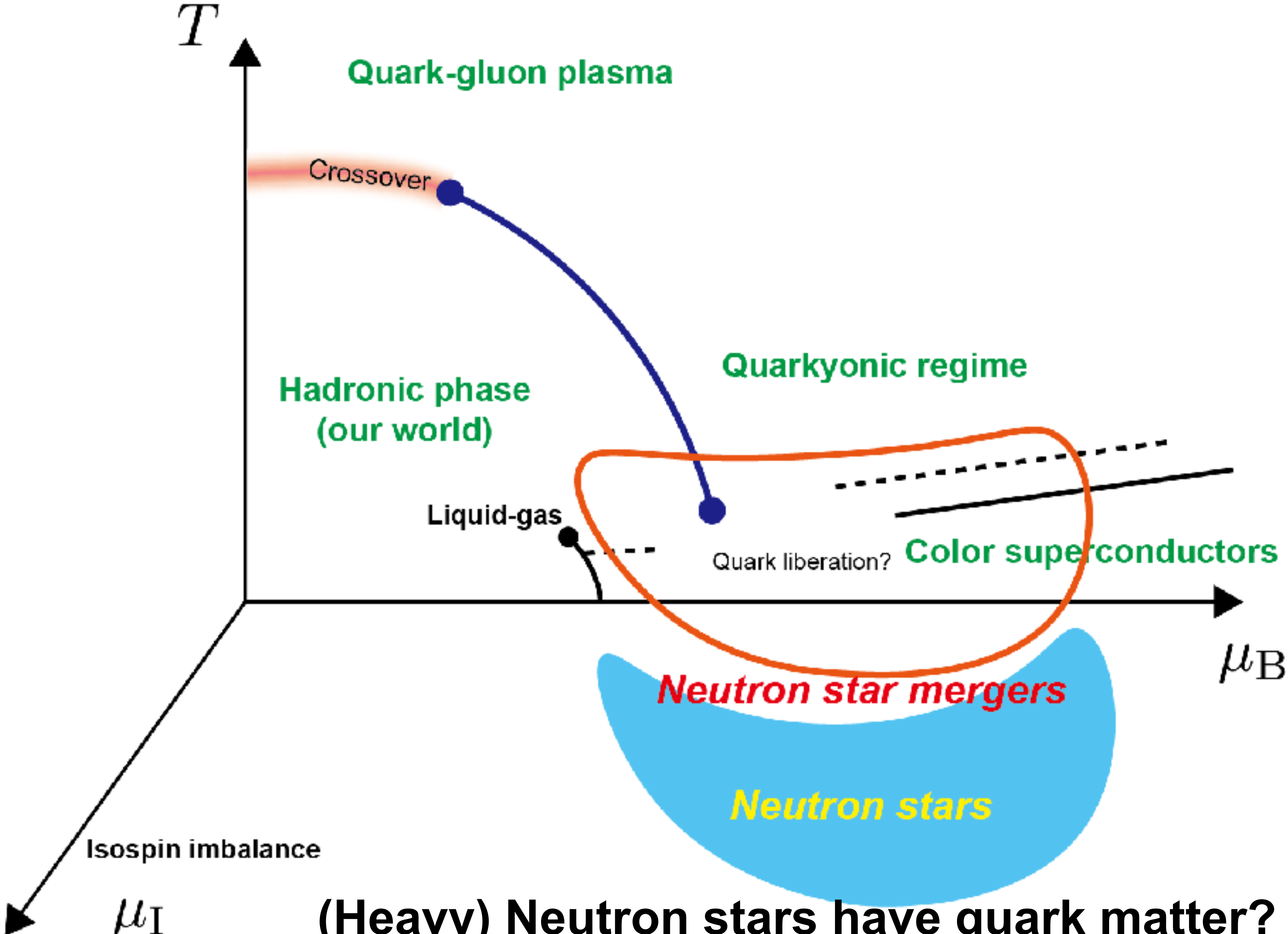
Quark liberation at high densities



Quark liberation at high densities?

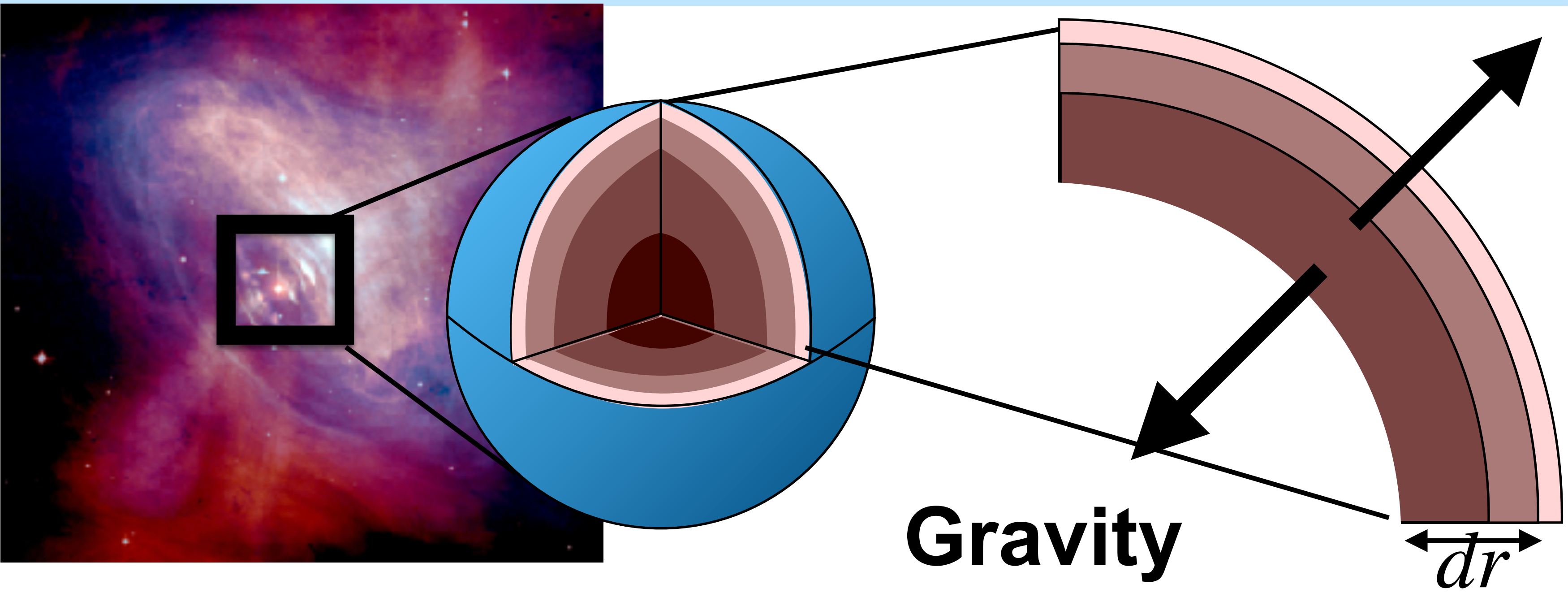
Colins,Perry (1974); McLerran,Pisarski (2008);
Quark-hadron continuity: Schafer,Wilczek (1998); Fujimoto,Fukushima,Weise (2019)

Quark liberation at high densities



(Heavy) Neutron stars have quark matter?

Structure of static NSs



Hydrostatic equilibrium (pressure = gravity)

Tolman (1939)
Oppenheimer, Volkoff (1939)

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2} \times \underbrace{\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}}_{\text{General relativistic correction}}$$

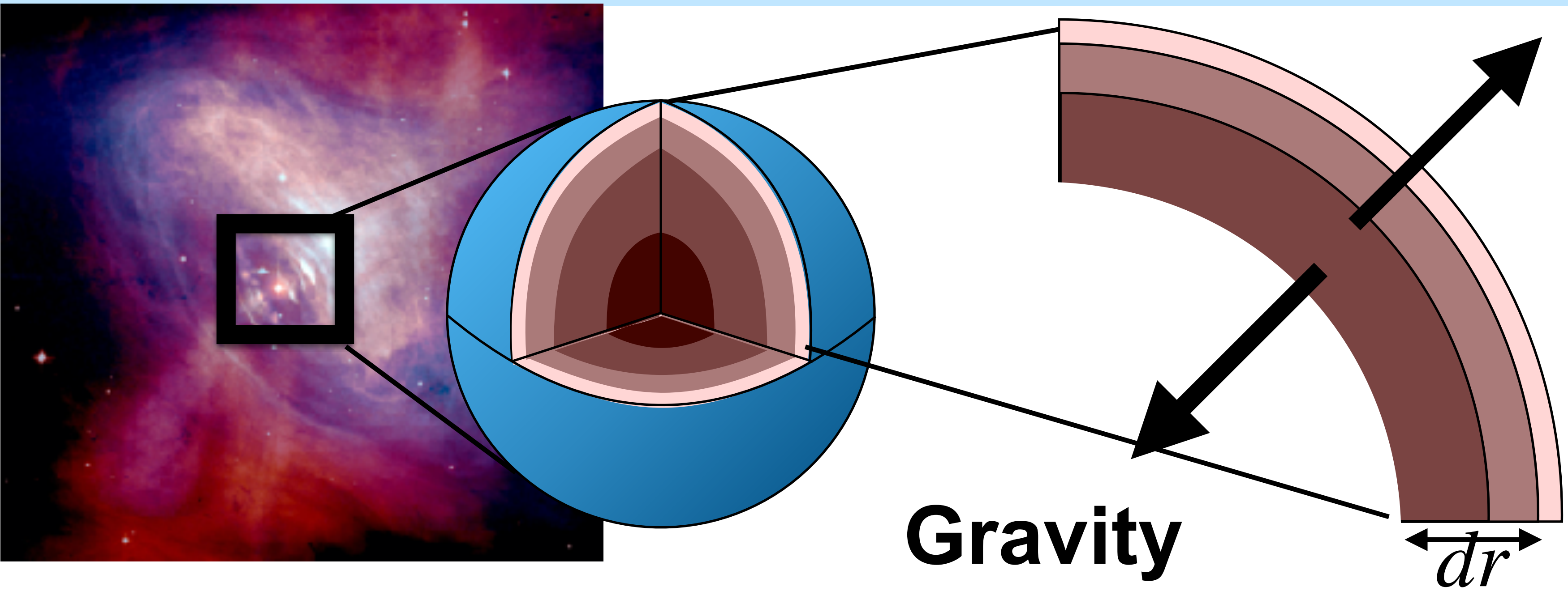
← **TOV equation**

$$m(r) = \int_0^r dr 4\pi r^2 \varepsilon(r)$$

Unknown variables:
$P(r)$, $m(r)$ and $\varepsilon(r)$

One condition missing!

Structure of static NSs



Pressure
(nuclear force
= strong interaction)

Hydrostatic equilibrium (pressure = gravity)

Tolman (1939)
Oppenheimer, Volkoff (1939)

$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2} \times \underbrace{\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}}_{\text{General relativistic correction}}$$

← **TOV equation**

$$m(r) = \int_0^r dr 4\pi r^2 \varepsilon(r)$$

Unknown variables:
$P(r)$, $m(r)$ and $\varepsilon(r)$

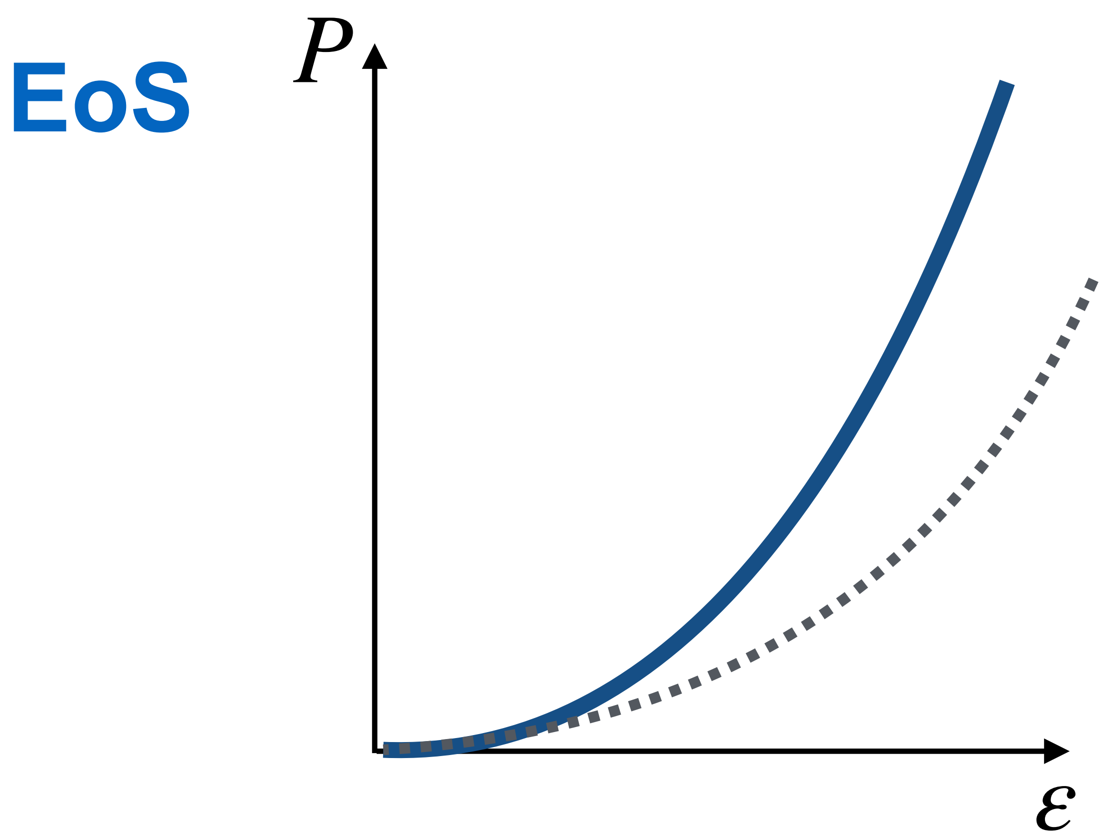
One condition missing! →

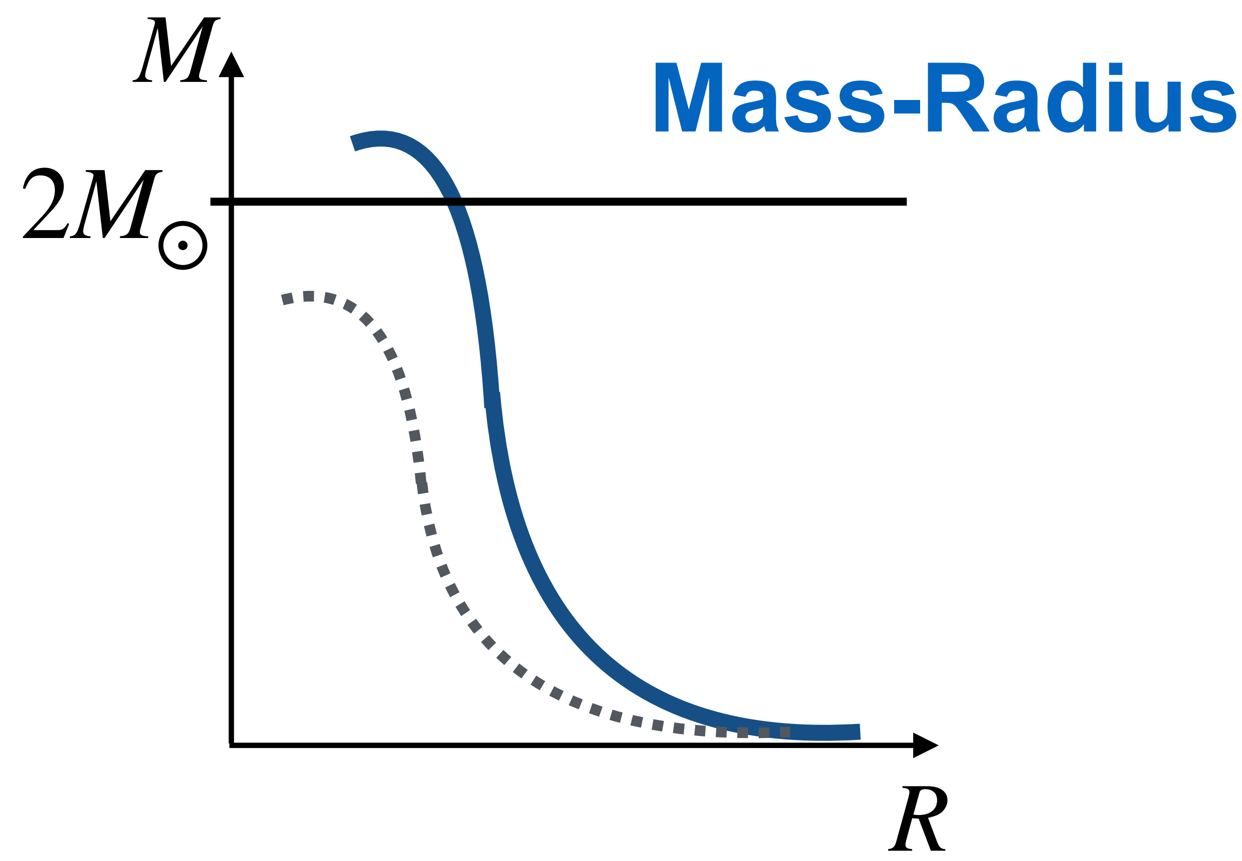
Equation of State (EoS)

$$P = P(\varepsilon)$$

Structure of static NSs

Two solar mass pulsar: Demorest et al. (2010); Antoniadis et al. (2013); Cromartie et al. (2019)



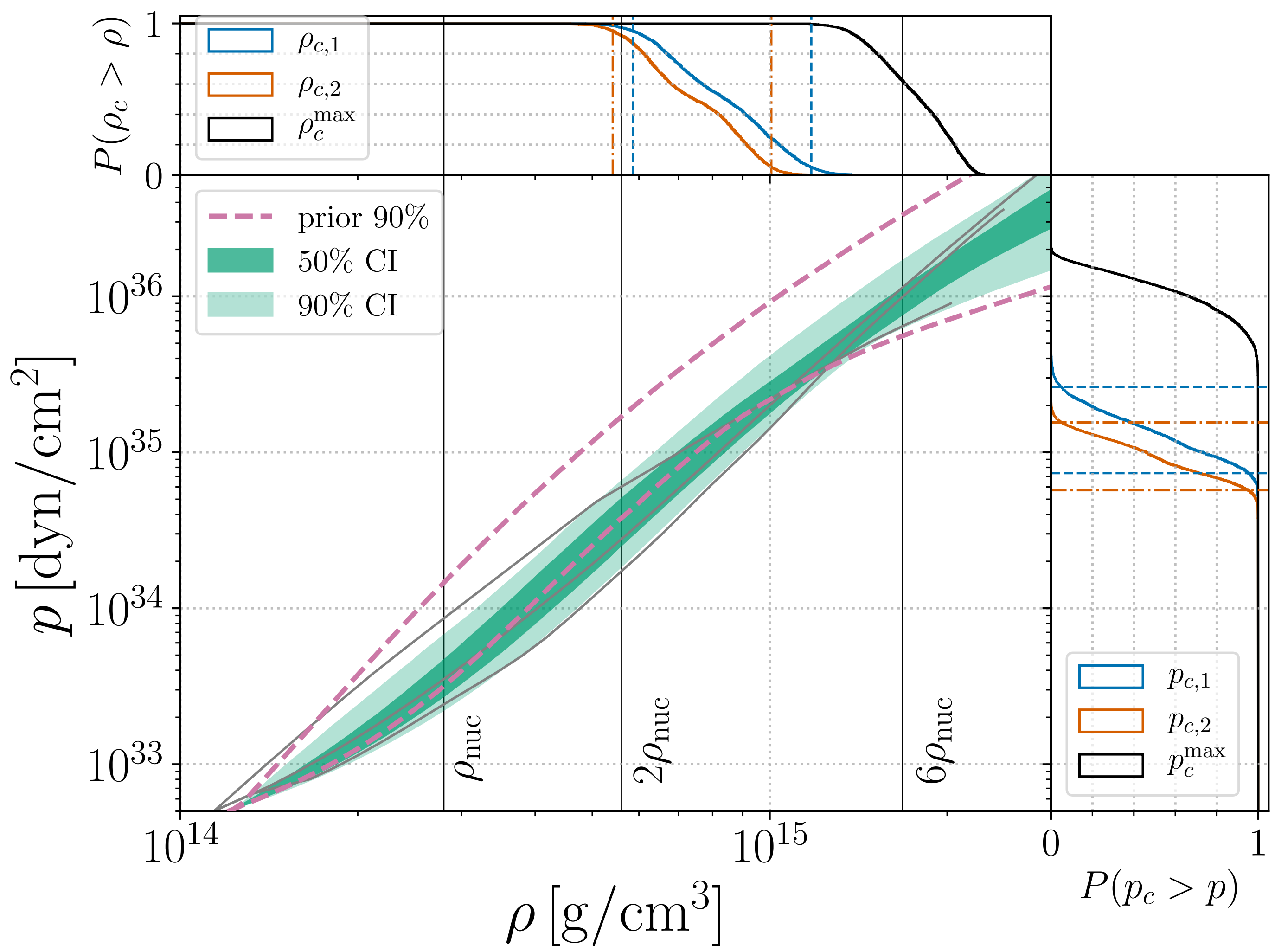


Maximum mass corresponding to any EoS should exceed $2M_\odot$
If maximum-mass condition is not fulfilled, then EoS is rejected

Gravitational waves (GWs) from binary NSs

Ligo-Virgo Collaboration (2018)

More information obtained from NSs in dynamical event
Constraints on the EoS by GWs from binary NS mergers:

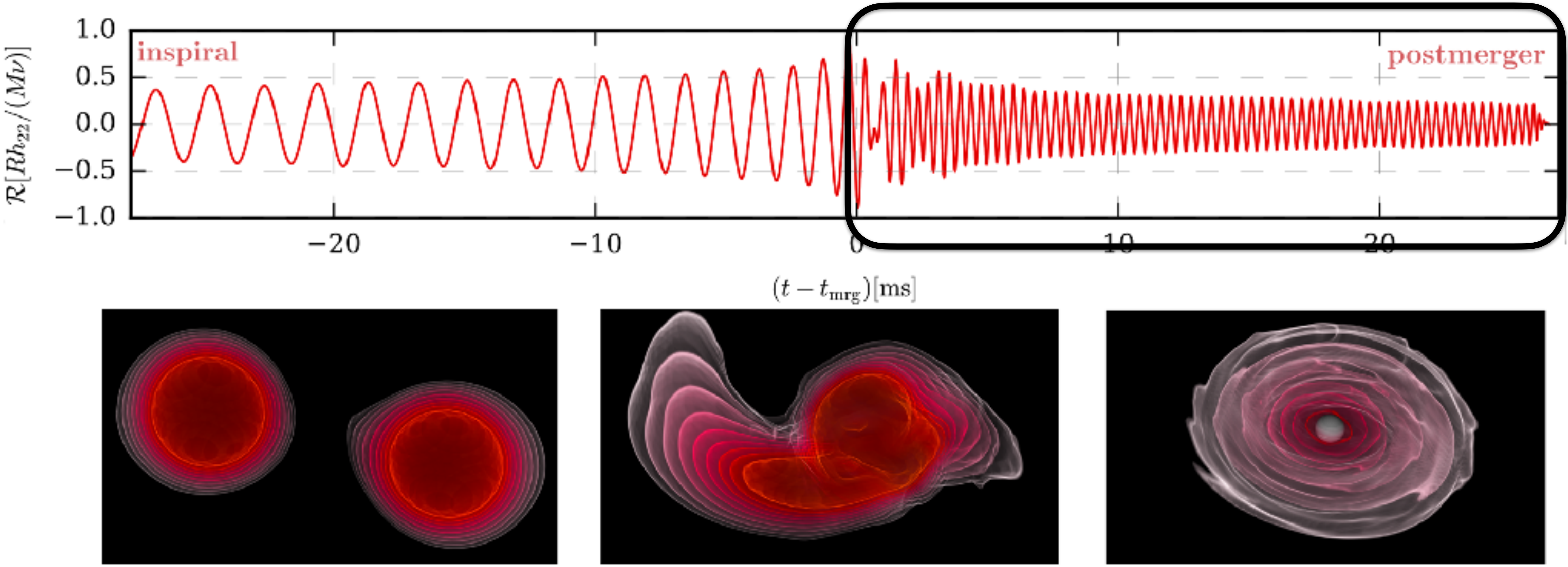


If there is quark matter inside NS, there should be imprints in the EoS → Probe it with GWs

Gravitational waves from binary NSs

GW signals in numerical relativity simulations:

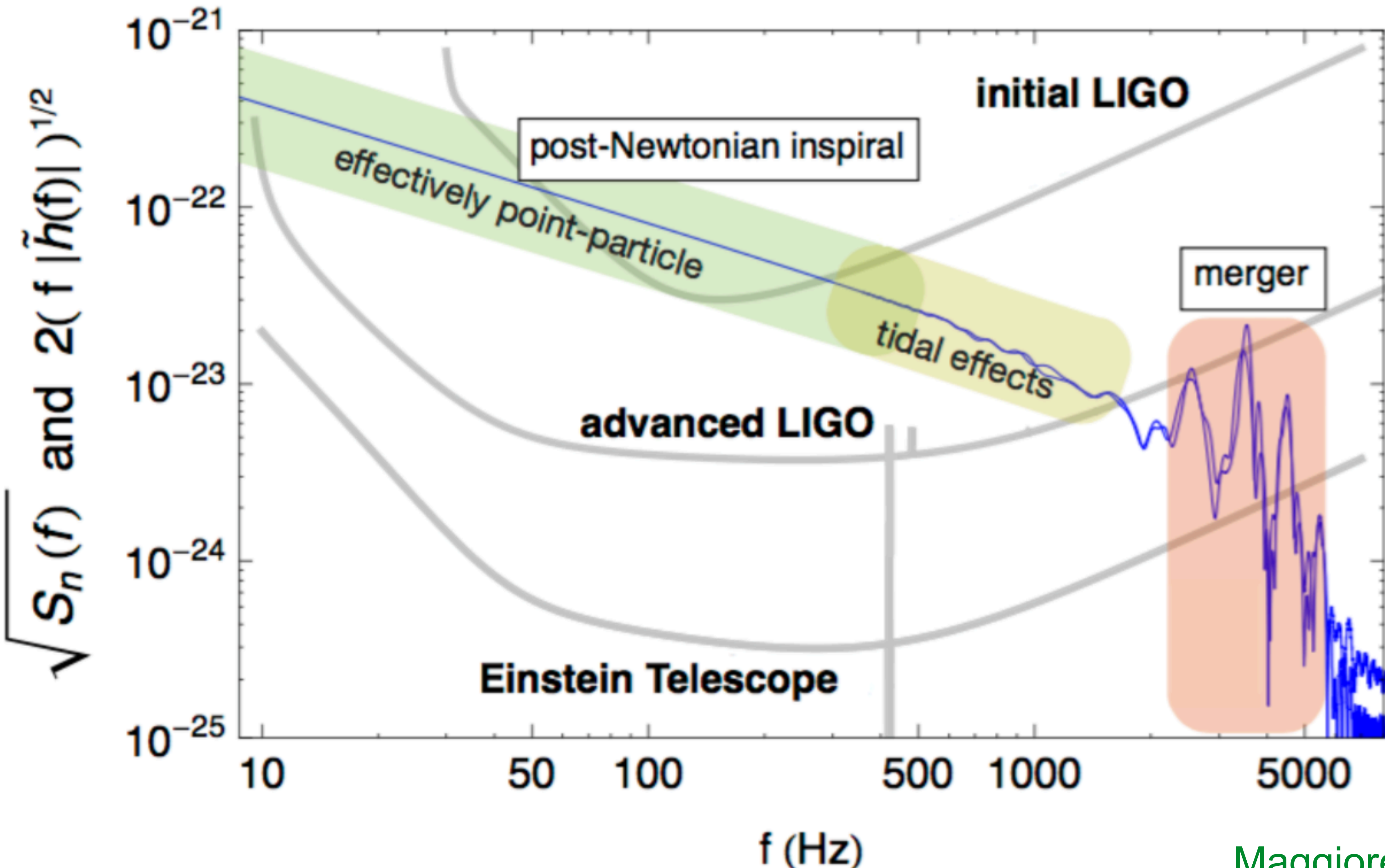
postmerger phase contains more information on the EoS



Dietrich,Hinderer,Samajdar ('20)

Gravitational waves from binary NSs

Expected sensitivity in future detectors



Maggiore (2018)

Motivation & Outline of this talk

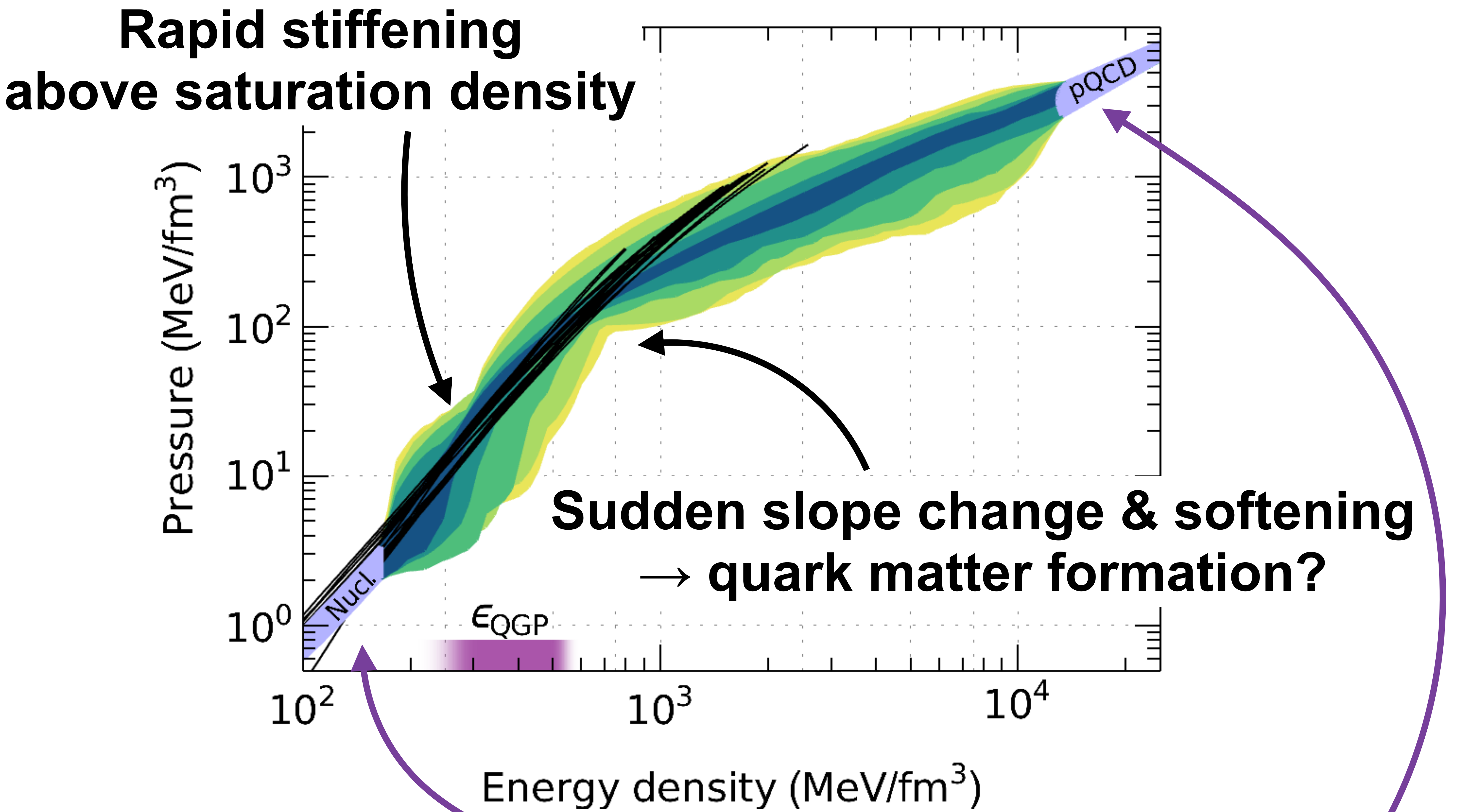
- 0) Introduction: Dense quark matter in neutron stars (NSs)? How to detect it?

- 1) QCD-based equation of state (EoS) with a realistic hadron-to-quark phase transition (PT)
  - ○ Prerequisite for the QCD-based EoS
  - ○ Parametrization & possible scenarios for PTs

- 2) Detecting quark matter by gravitational waves (GWs)
  - ○ GW signals and detectability
  - ○ Some issues: thermal index, electromagnetic counterpart

Modern view on the EoS

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

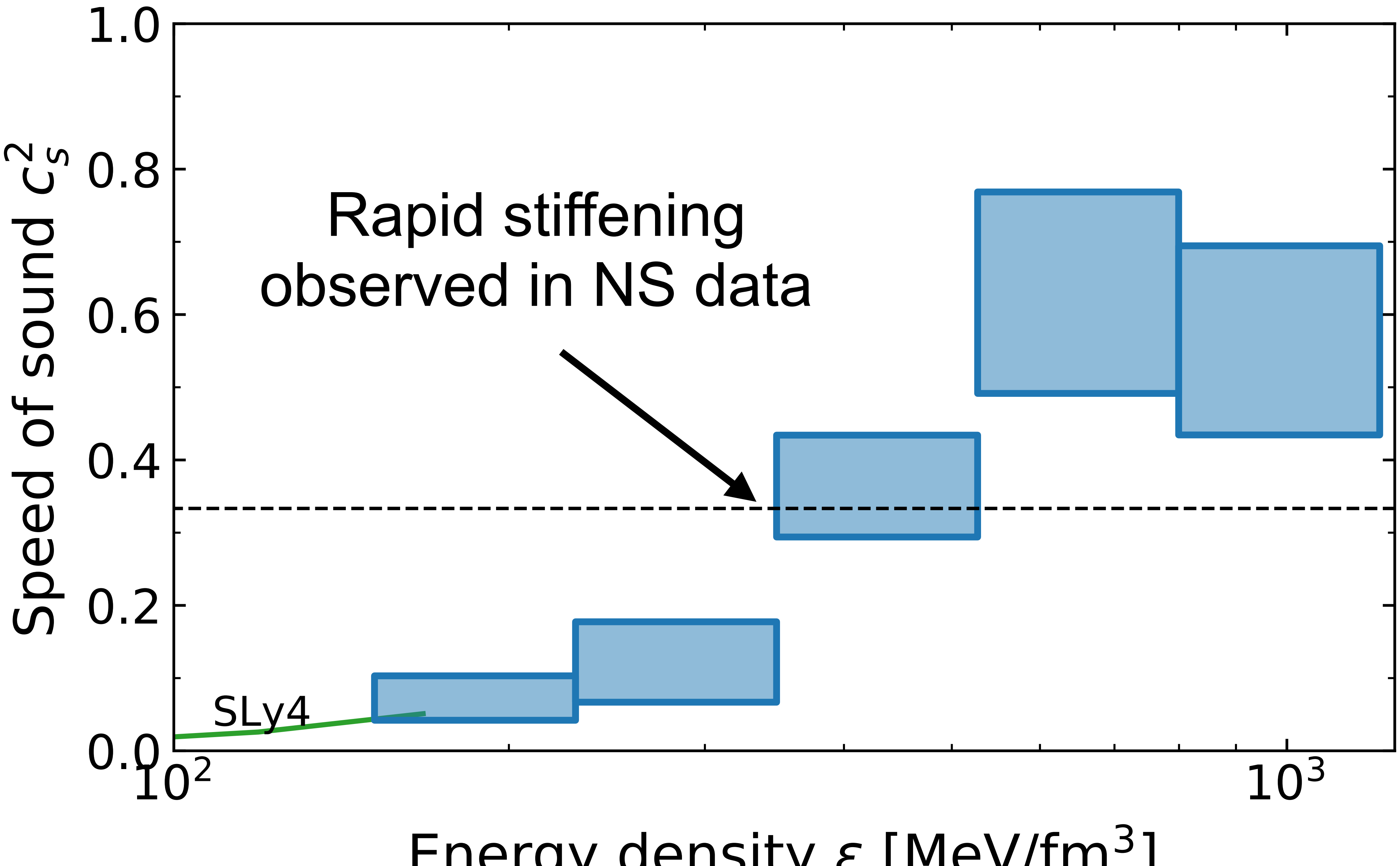


ab initio QCD calculations: Chiral EFT & perturbative QCD

Support from NS observation

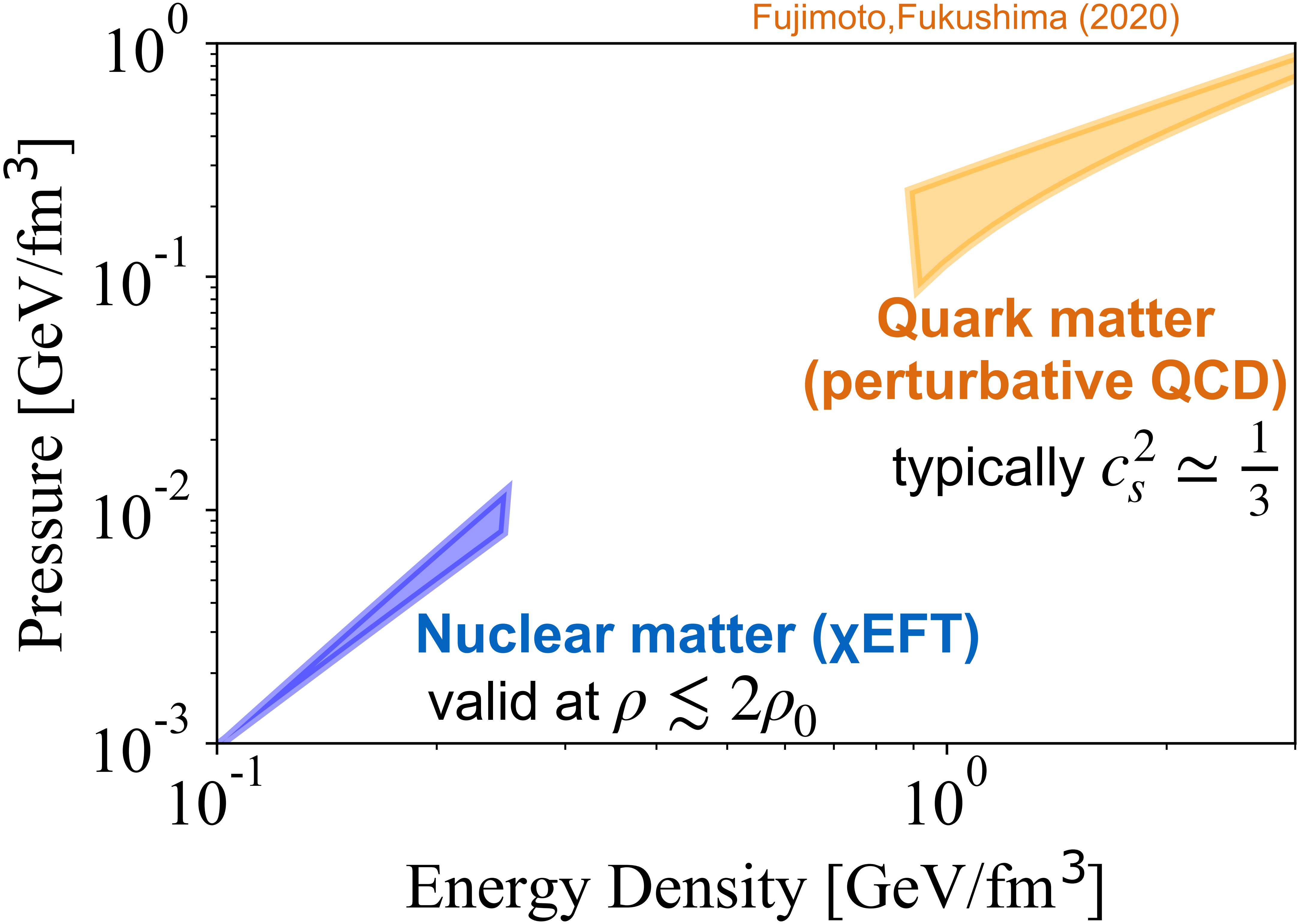
Fujimoto,Fukushima,Murase (2019, 2021)

Speed of sound $c_s^2 = \partial P / \partial \varepsilon$ (slope of the EoS) from deep learning analysis of NS data



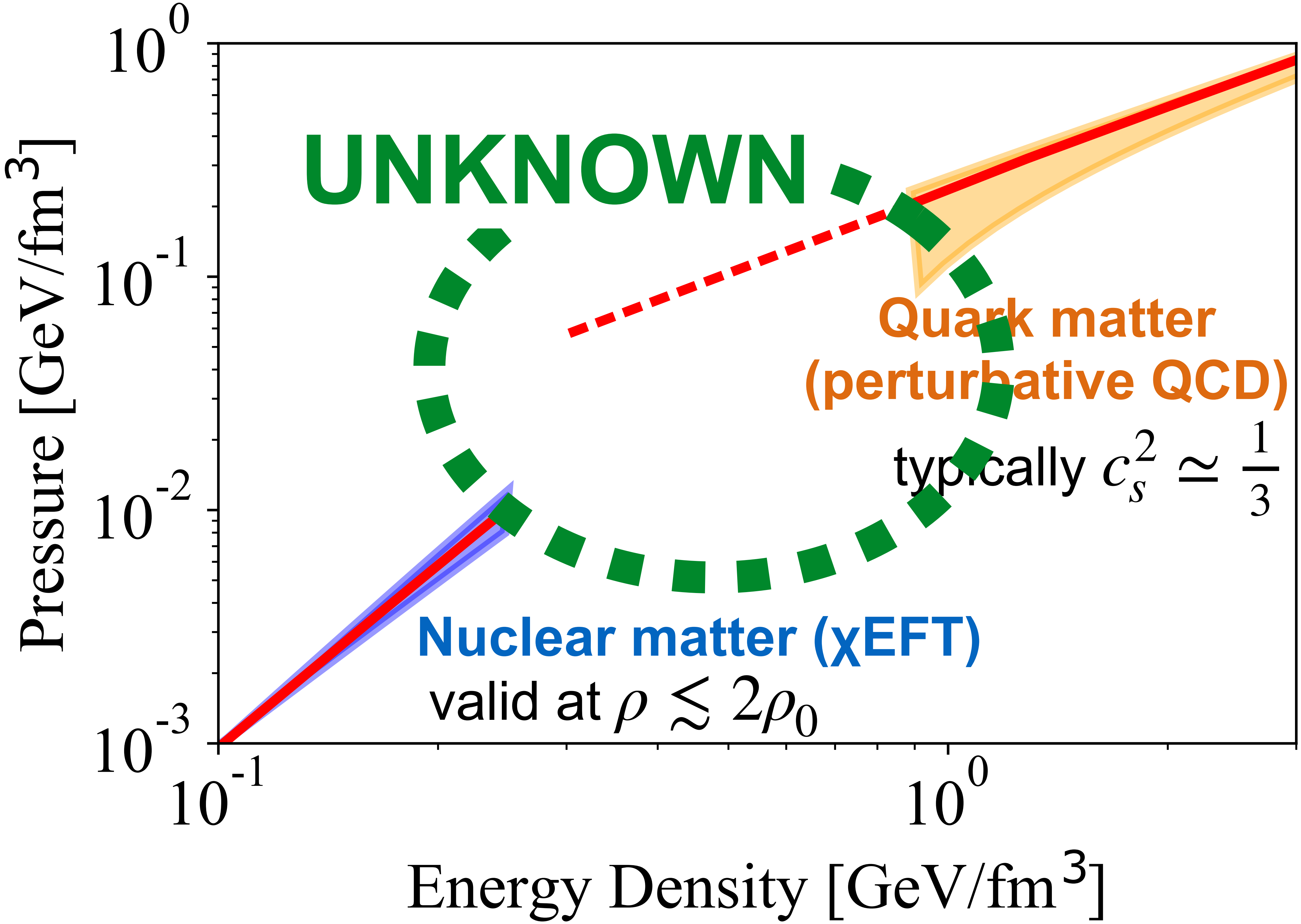
Prerequisite for the QCD-based EoS

pQCD: Freedman,McLerran (1976); Baluni (197
Kurkela,Romatschke,Vuorinen,Fraga,… (2009-)
Fujimoto,Fukushima (2020)



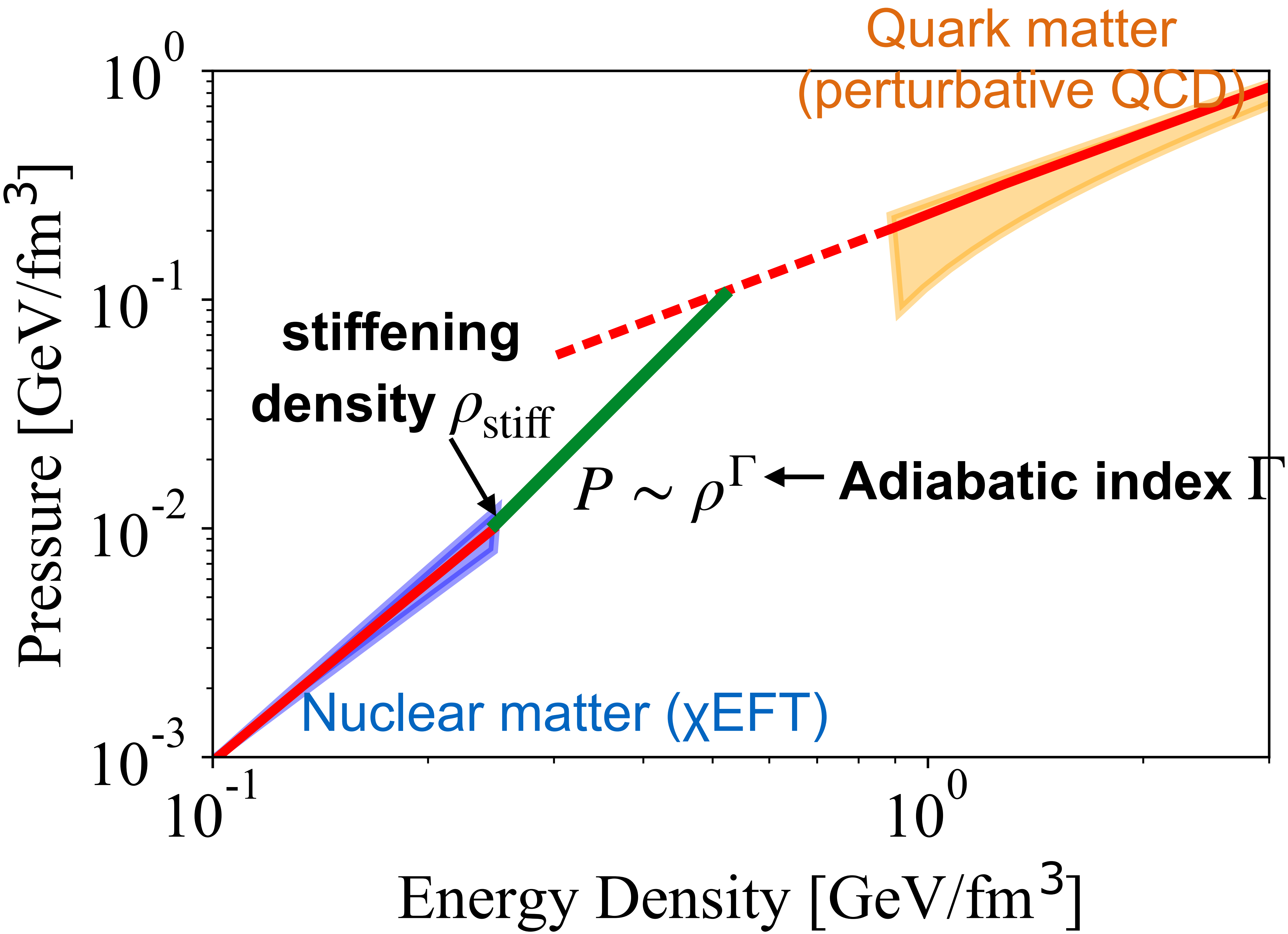
χEFT:
Drischler,Han,Lattimer,Prakash,Reddy,Zhao (2021)

Prerequisite for the QCD-based EoS

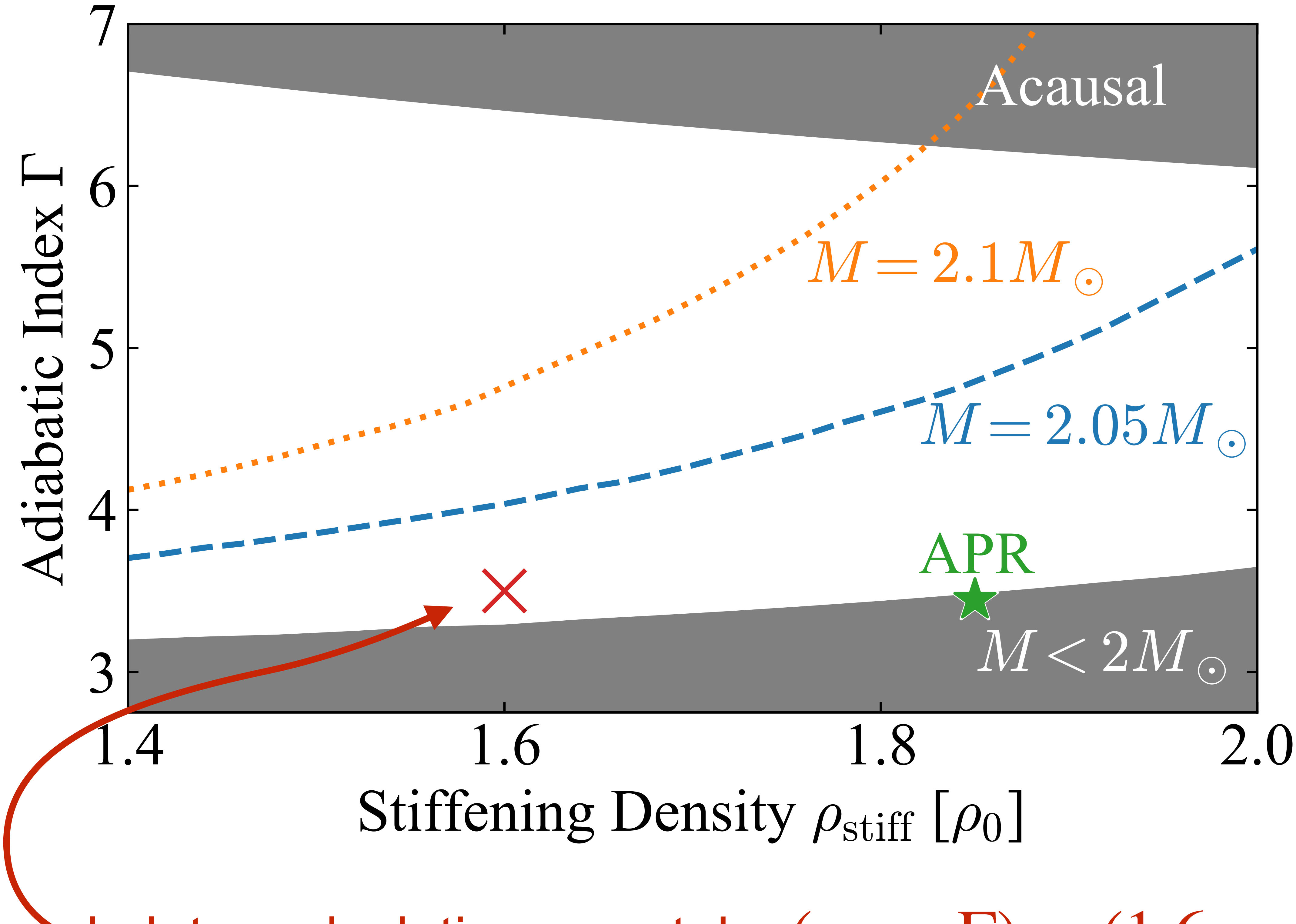


Parametrizing the intermediate region

Crossover-type parametrization:



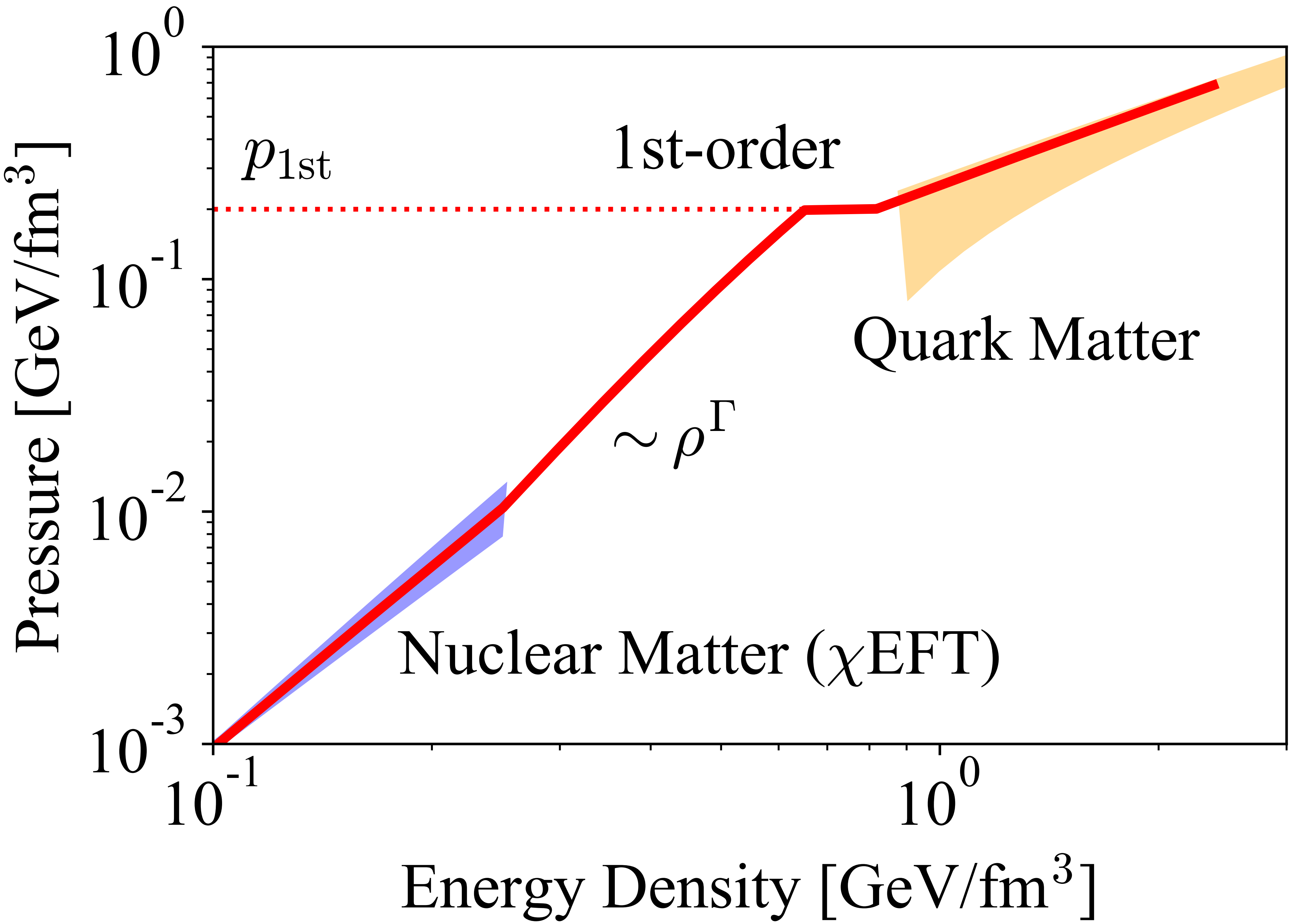
Allowed region of parameters



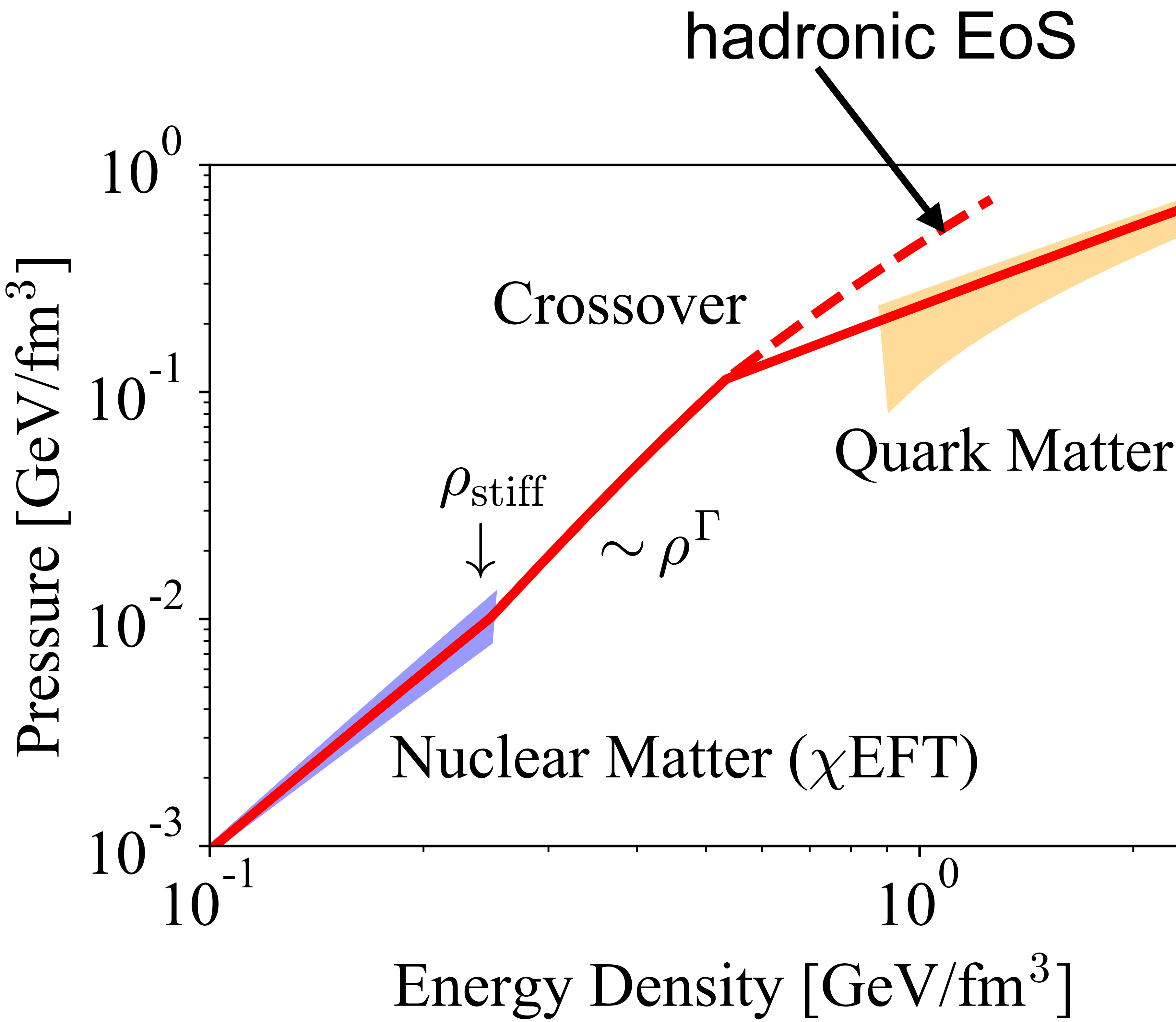
In later calculations, we take $(\rho_{\rm stiff}, \Gamma) = (1.6\rho_0, 3.5)$

Parametrizing the intermediate region

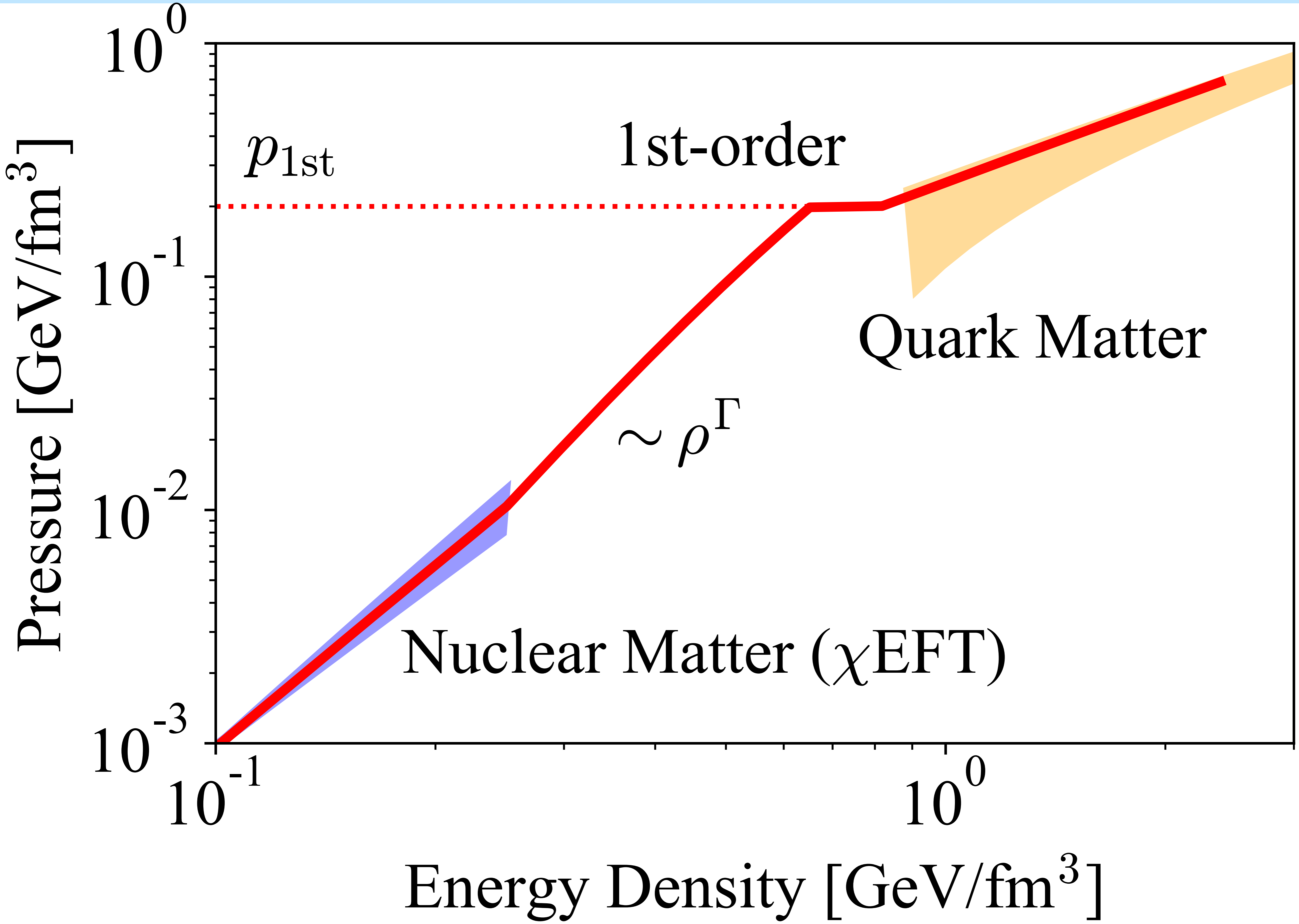
1st-order PT can be treated likewise:



Four possibilities: (1) Crossover

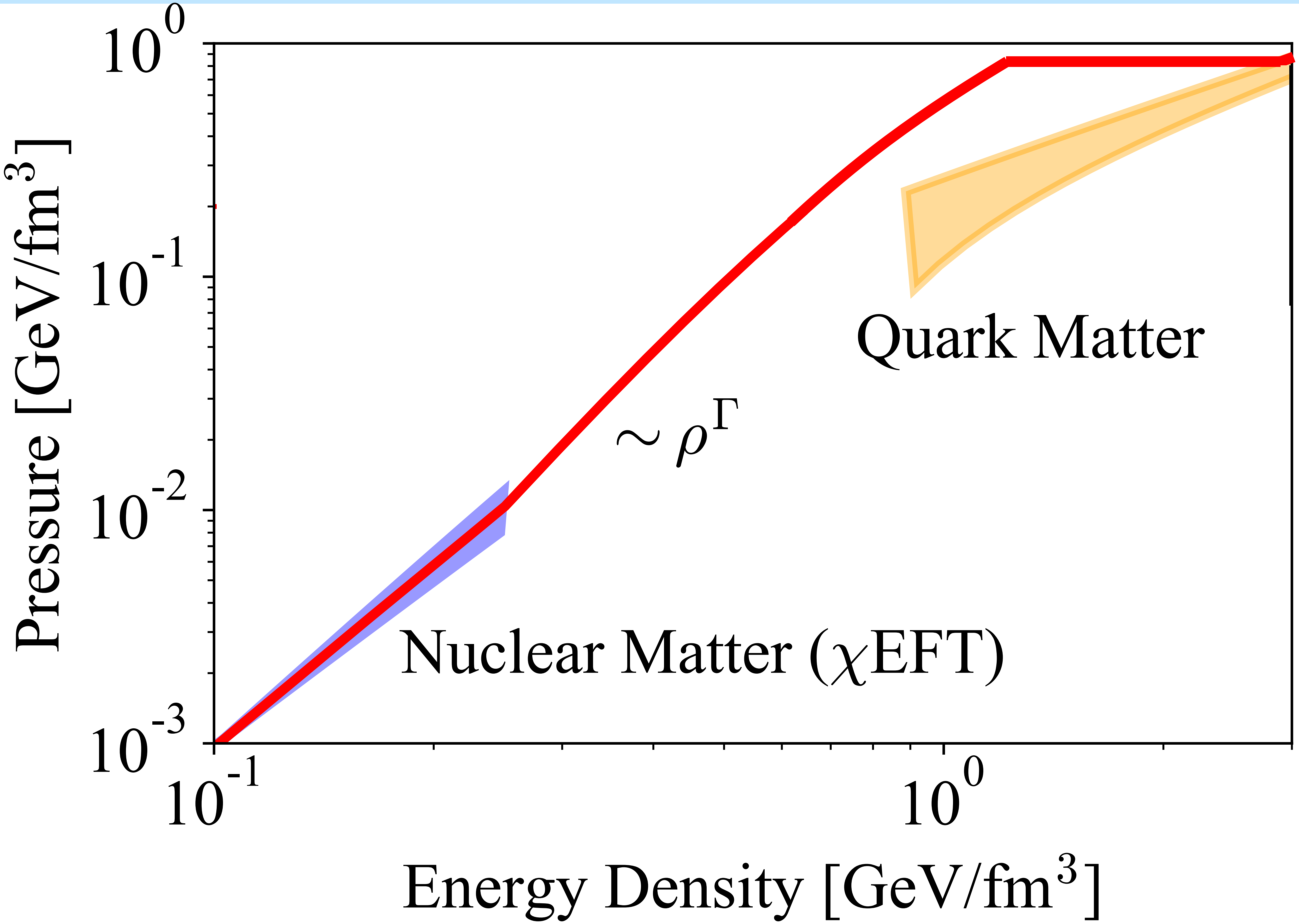


(2) Weak 1st-order PT



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

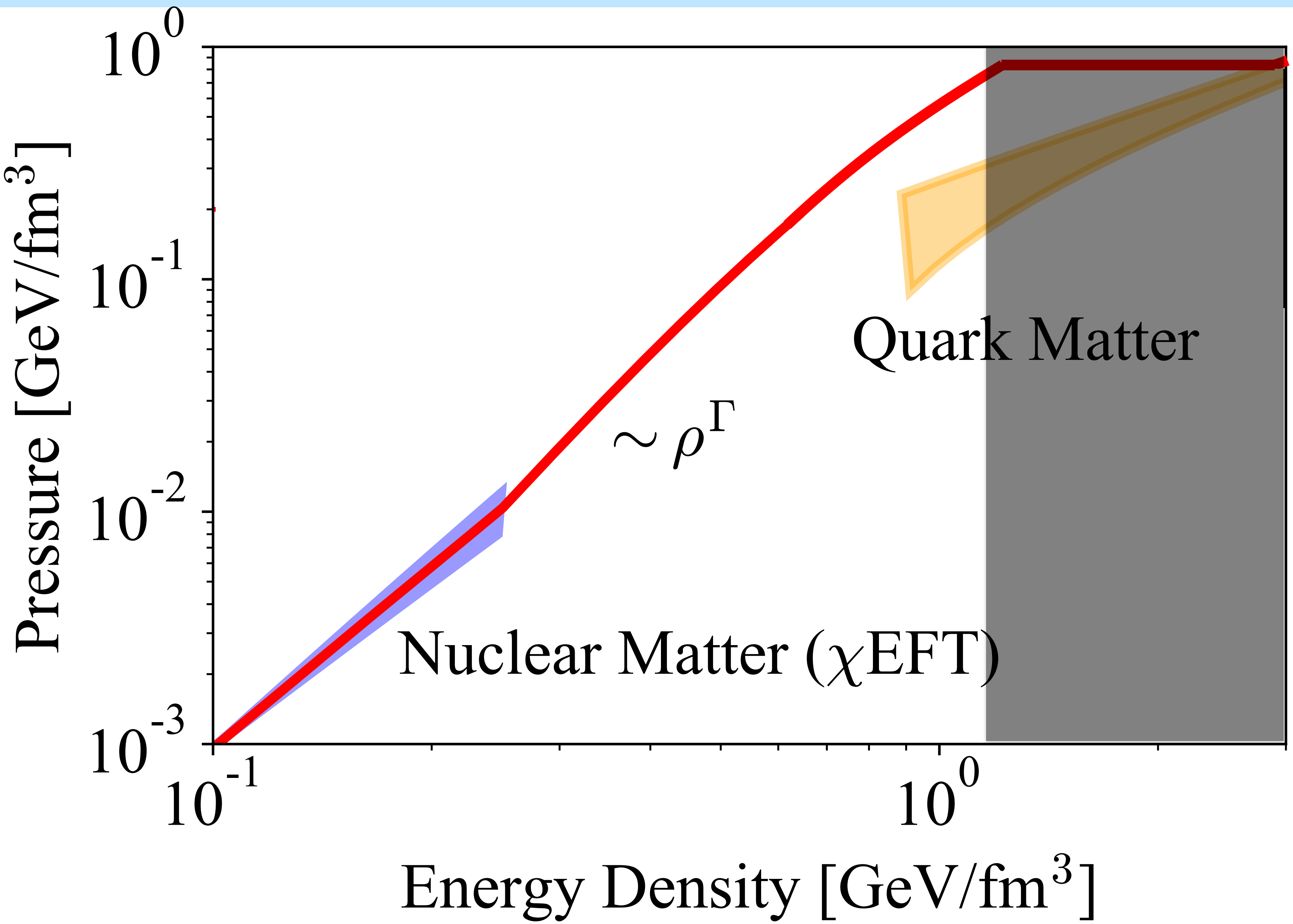
(3) 1st-order PT at very high densities



Quark matter undetectable!

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

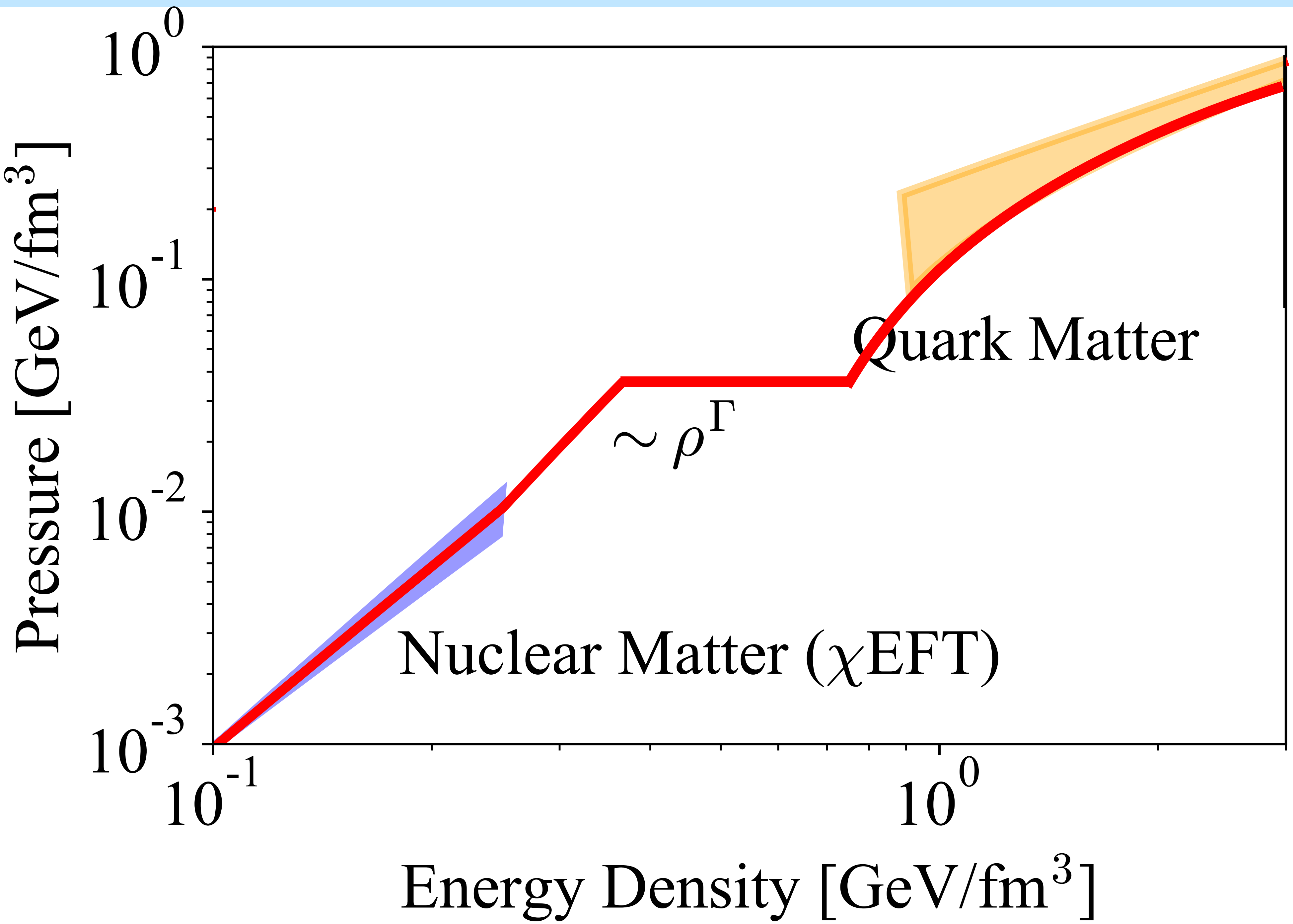
(3) 1st-order PT at very high densities



Quark matter undetectable!

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

(4) Other possibility of 1st-order PT



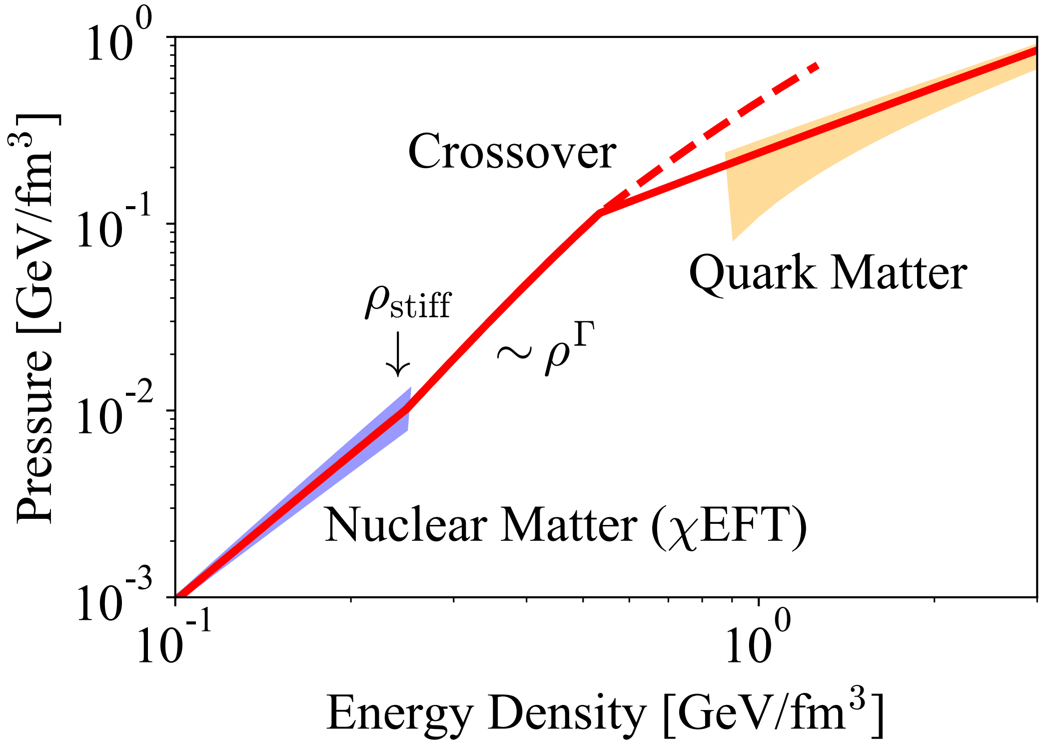
Cannot be treated within our framework,

but already considered in the preceding studies

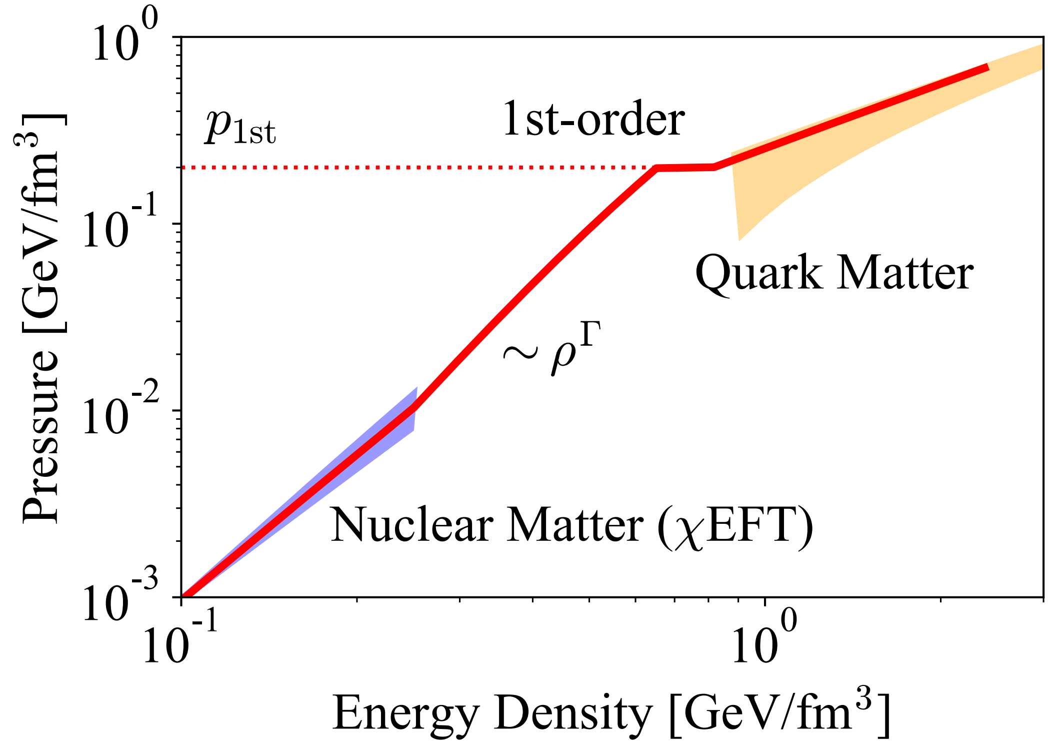
Most,Papenfort,Dexheimer,Hanauske,Schramm,Stoecker,Rezzolla (2018)

Categories of realistic PT pattern

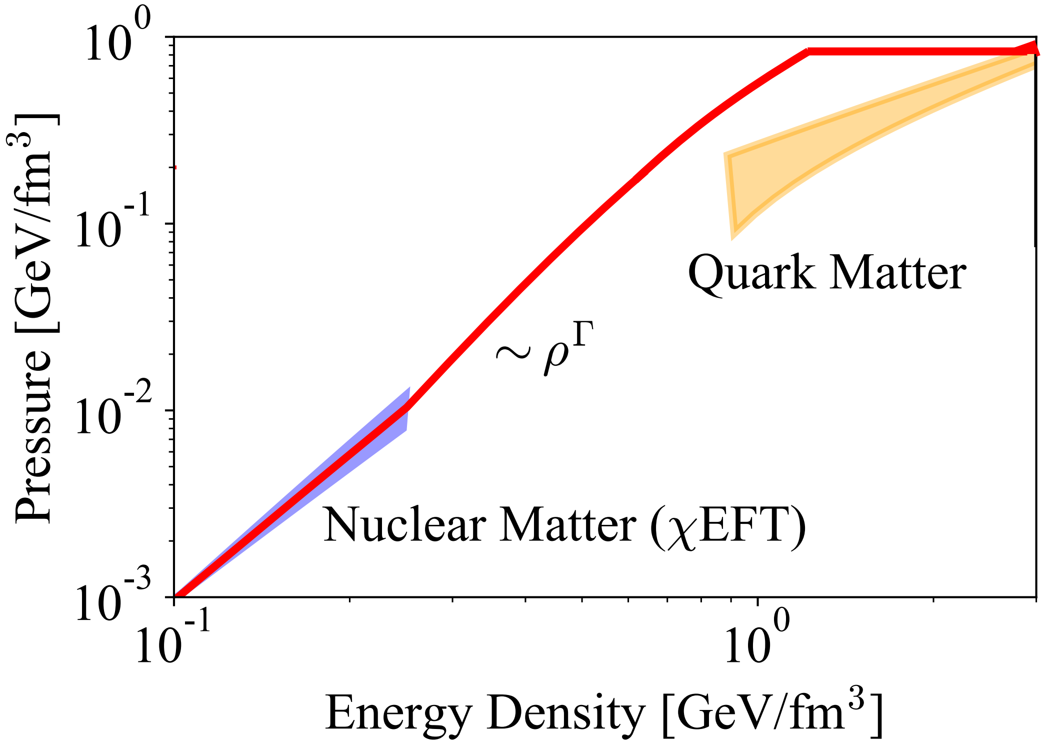
(1) Crossover



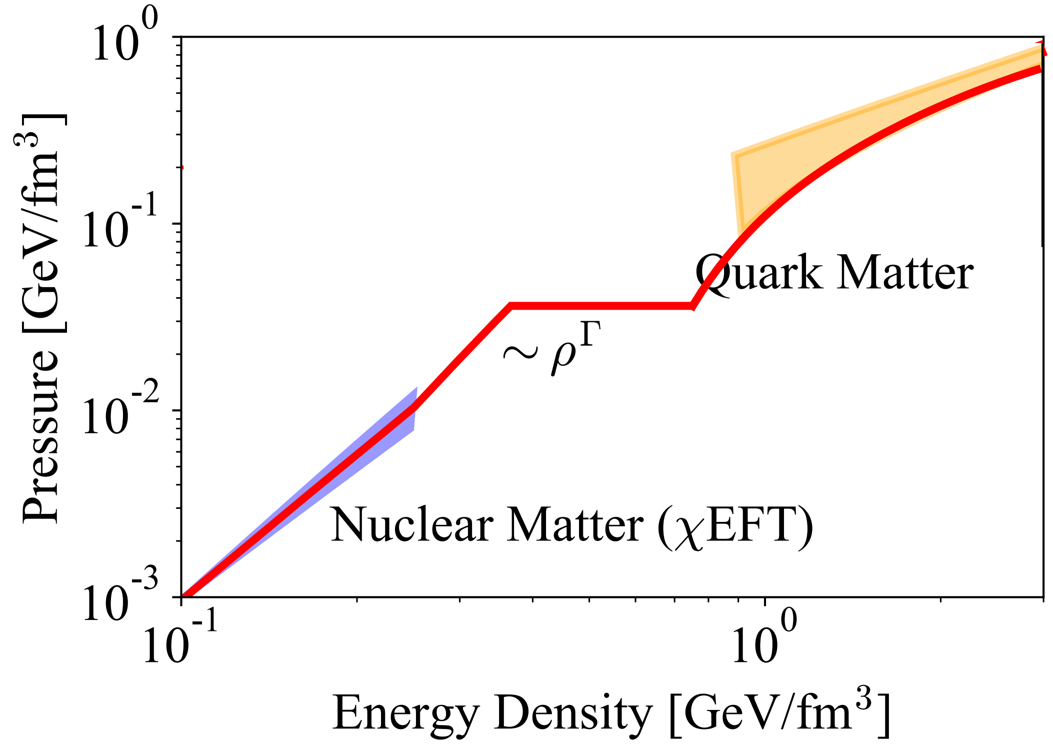
(2) Weak 1st-order



(3) Strong 1st-order @ high ρ

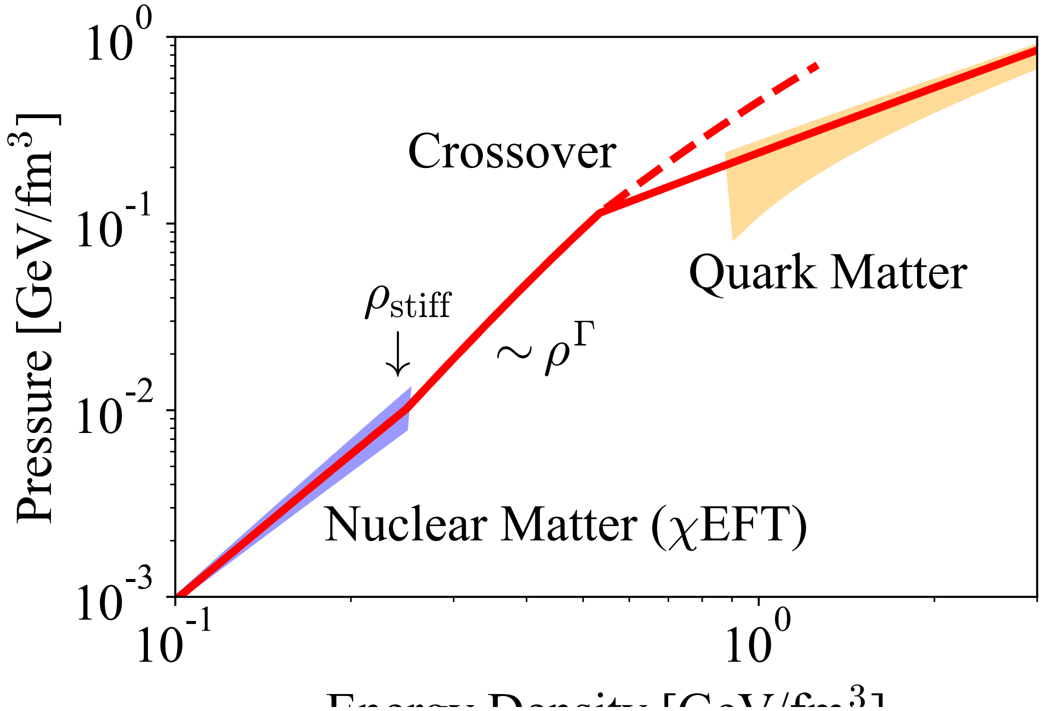


(4) Strong 1st-order @ low ρ

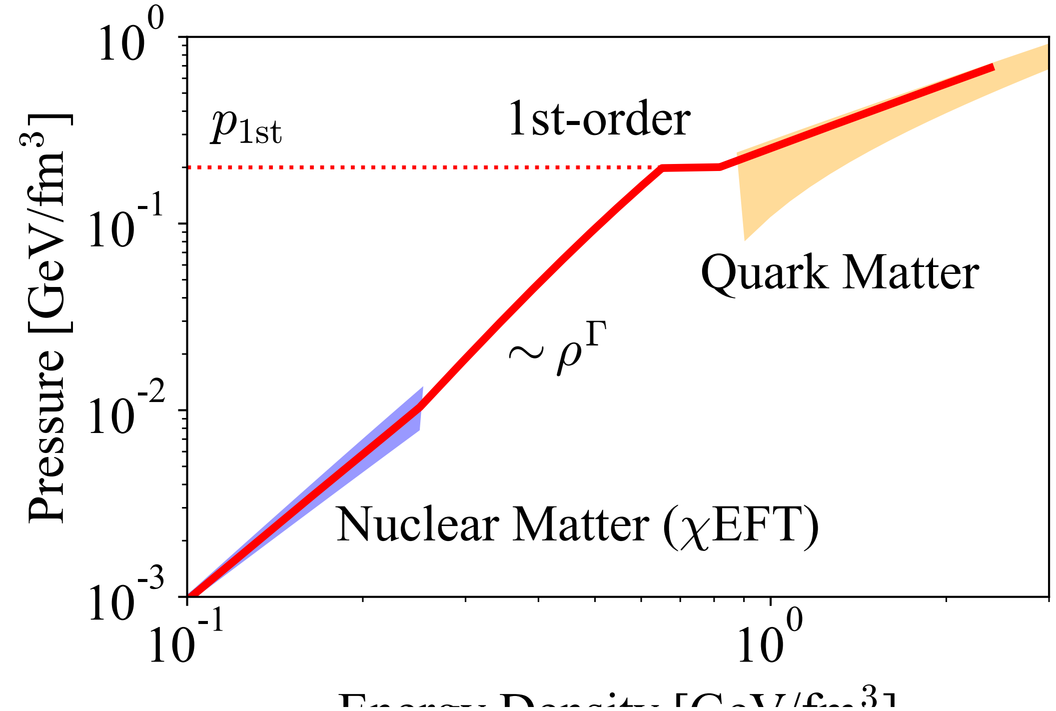


Categories of realistic PT pattern

(1) Crossover

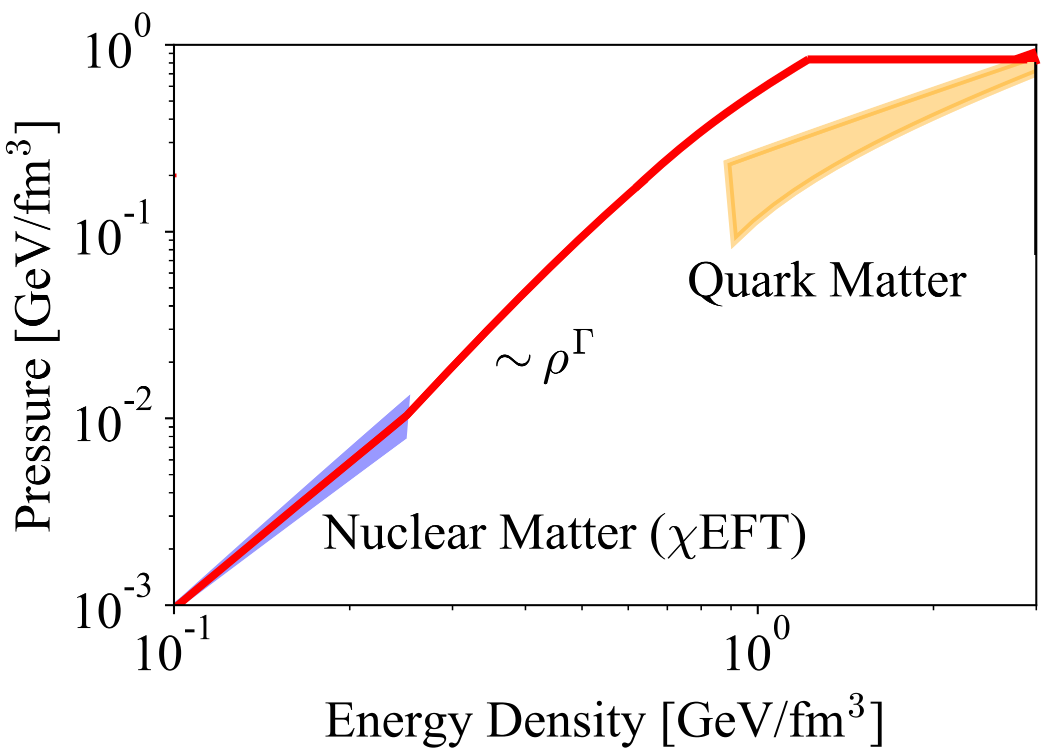


(2) Weak 1st-order

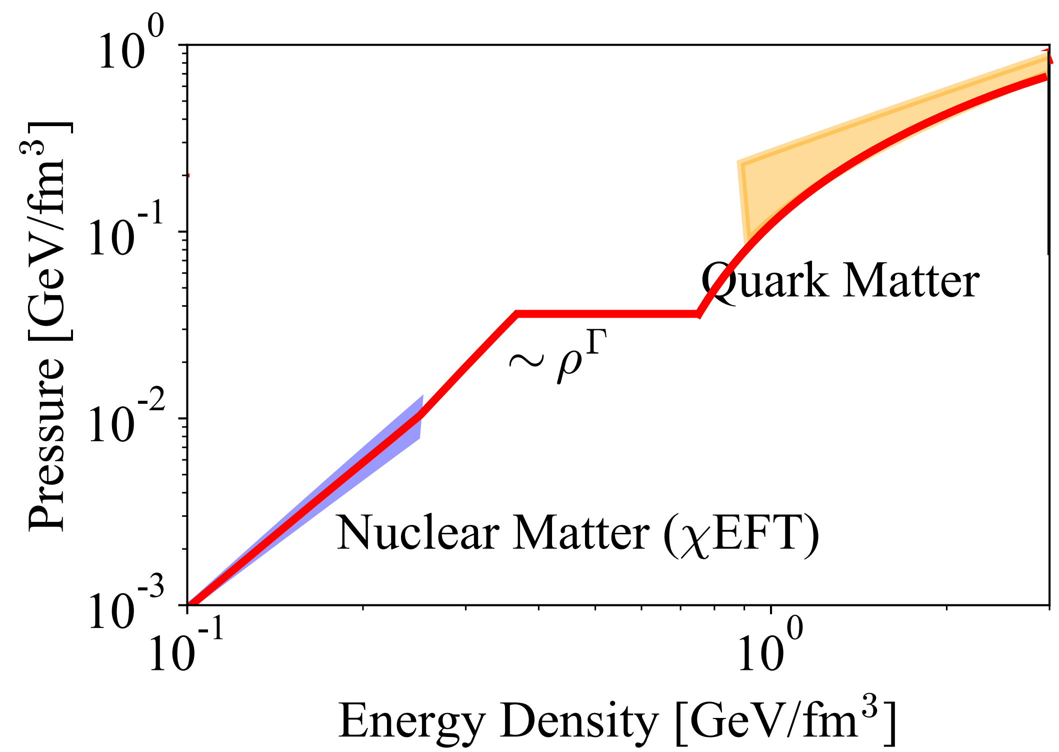


Simulating this case is enough for the current purpose

(3) Strong 1st-order @ high ρ

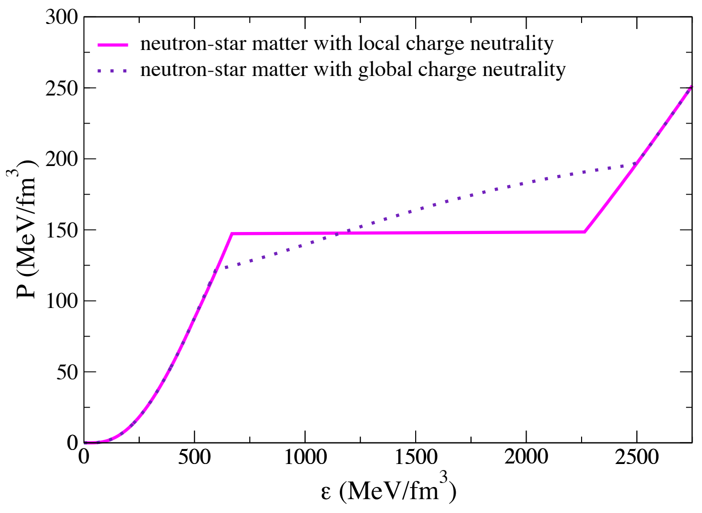


(4) Strong 1st-order @ low ρ



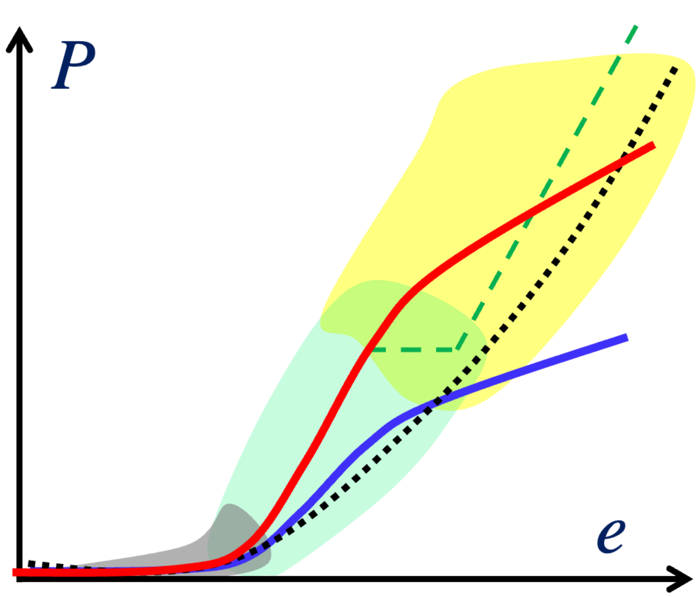
Related preceding works

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



1st-order PT model EoSs,
not based on pQCD,
but predicts soft EoS at high densities
→ can be categorized into (4)

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

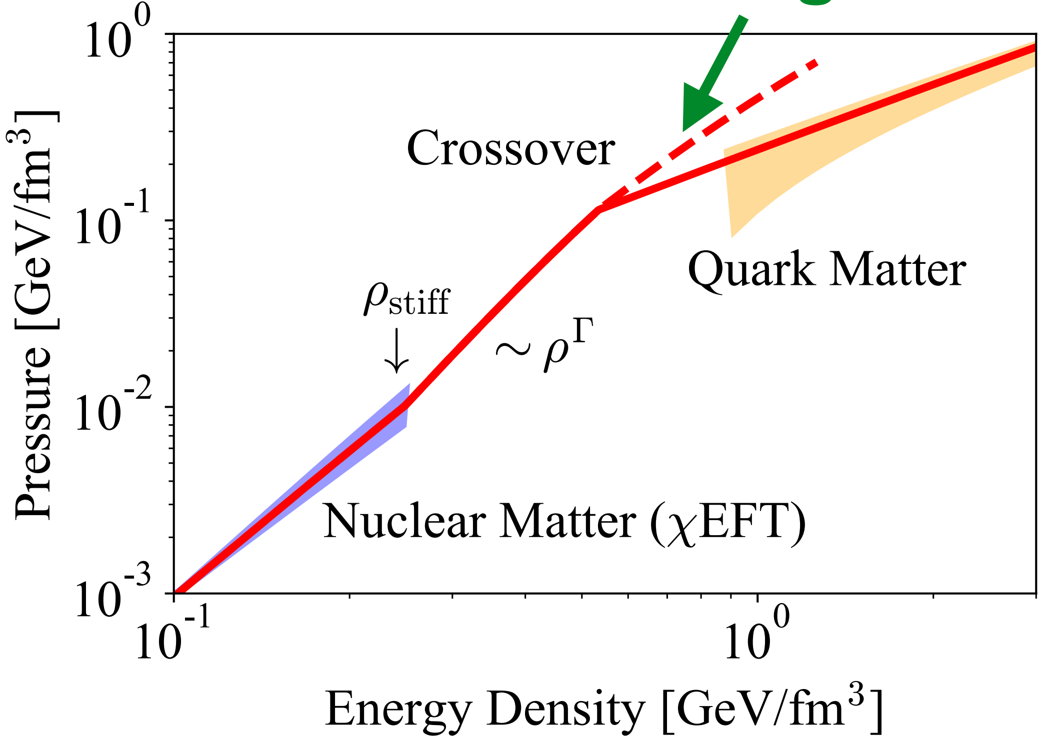


Crossover-type NJL model EoSs (QHC19),
not based on pQCD either,
and predicts stiff EoS at high densities
→ can be categorized into (1)

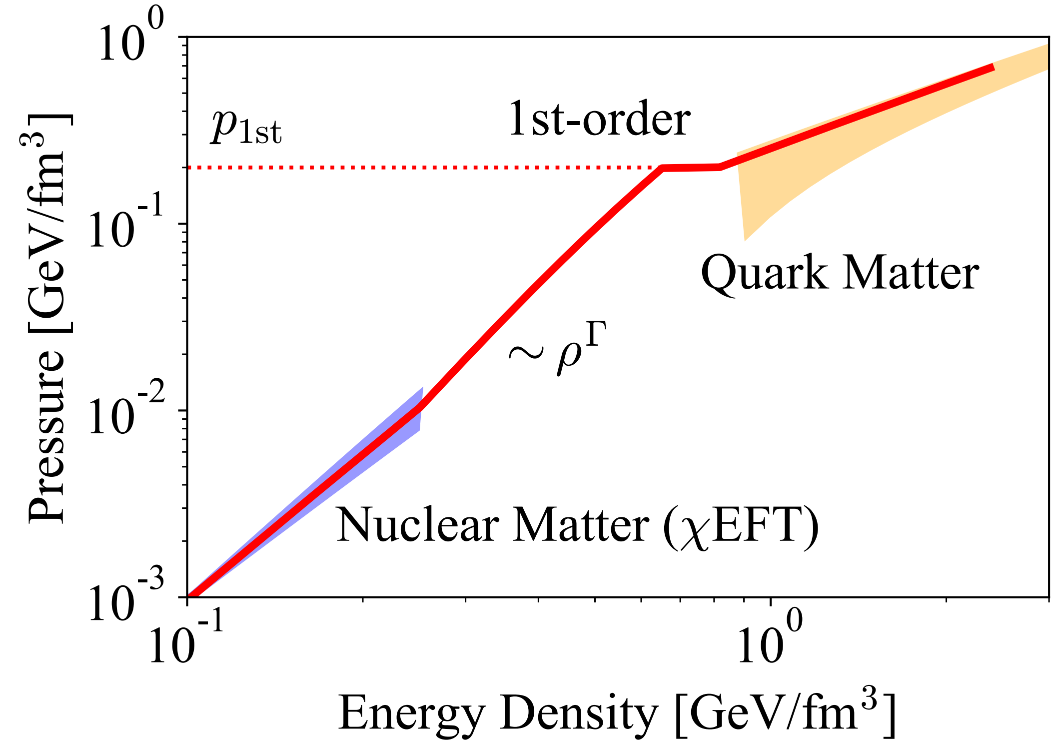
Related preceding works

(1) Crossover

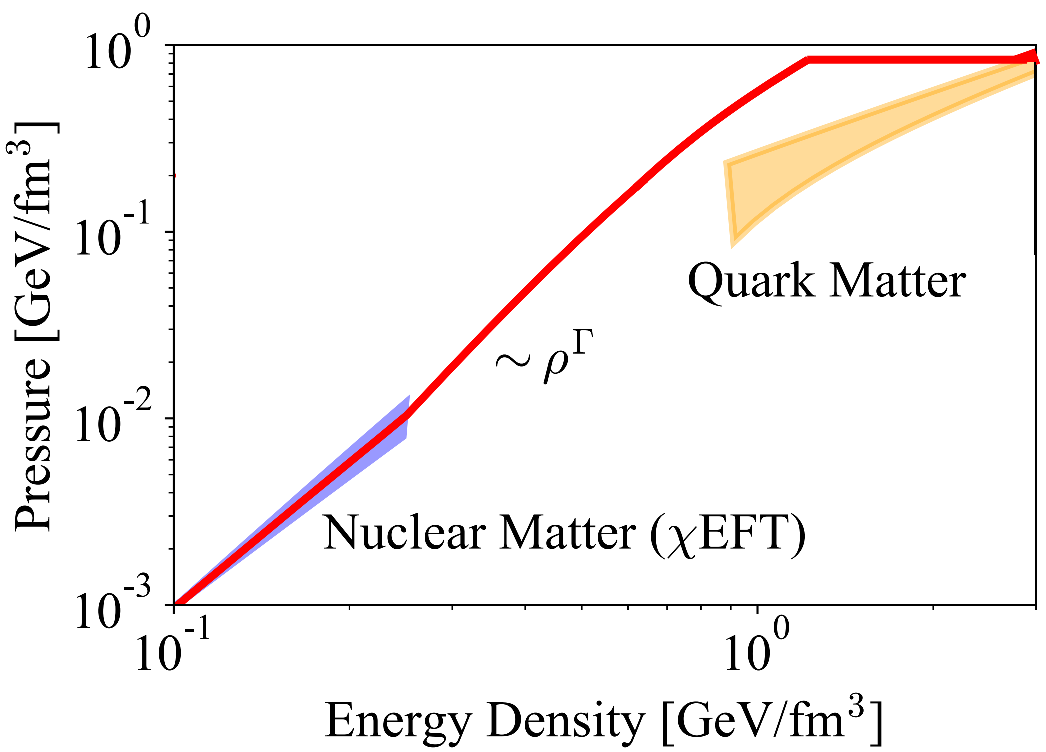
Huang et al. ('22)



(2) Weak 1st-order

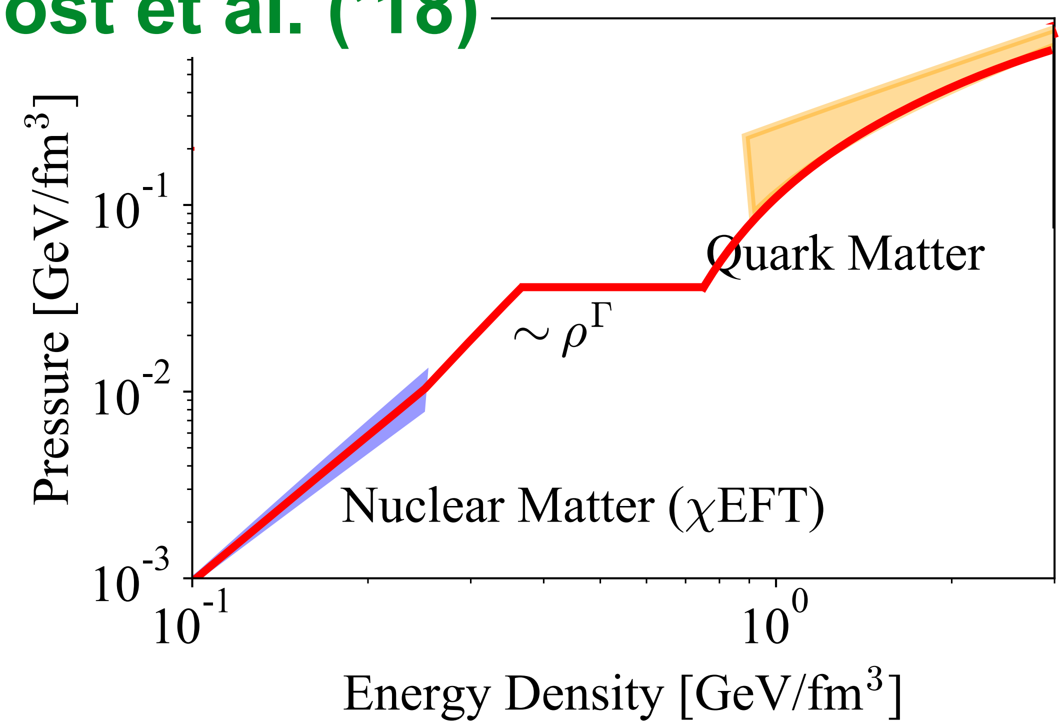


(3) Strong 1st-order @ high ρ



(4) Strong 1st-order @ low ρ

Most et al. ('18)



Motivation & Outline of this talk

- **0) Introduction: Dense quark matter in neutron stars (NSs)? How to detect it?**

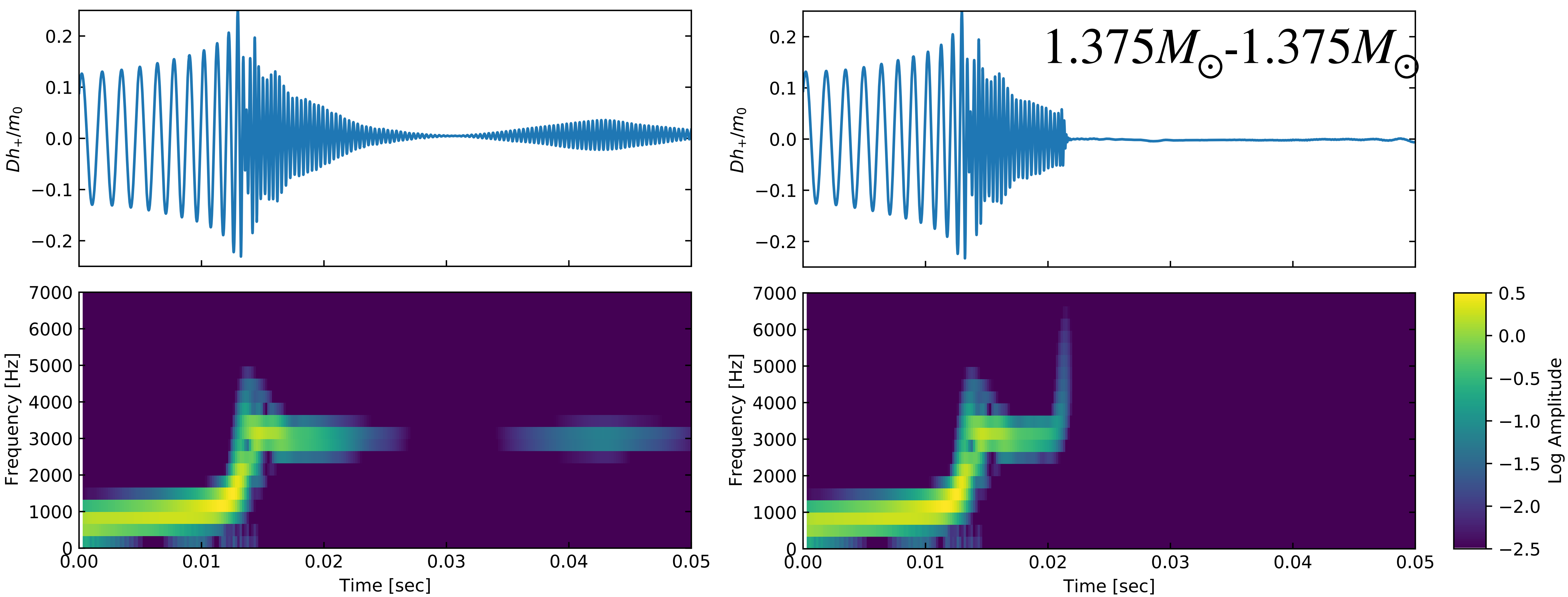
- **1) QCD-based equation of state (EoS) with a realistic hadron-to-quark phase transition (PT)**
  - Prerequisite for the QCD-based EoS
  - Parametrization & possible scenarios for PTs

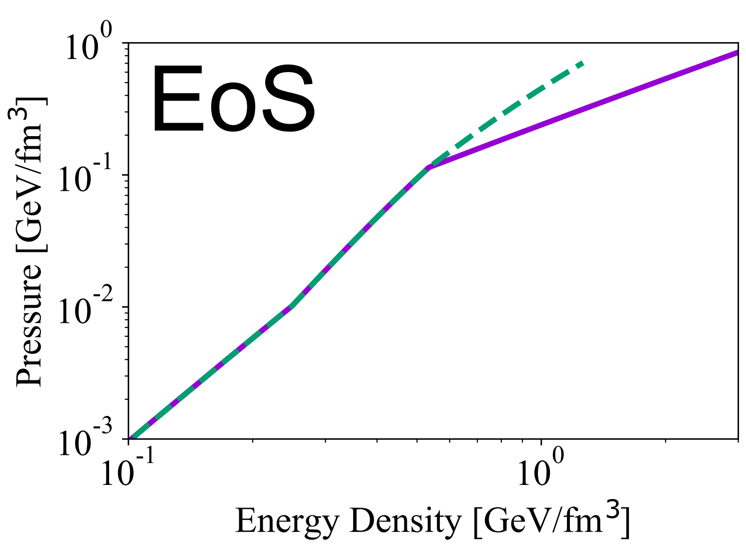
- **2) Detecting quark matter by gravitational waves (GWs)**
  - GW signals and detectability
  - Some issues: thermal index, electromagnetic counterpart

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

Thermal effect

In the simulation, thermal part of EoS is parametrized as free gas

$$P = P_{\rm cold} + P_{\rm thermal}$$

$$\varepsilon = \varepsilon_{\rm cold} + \varepsilon_{\rm thermal}$$

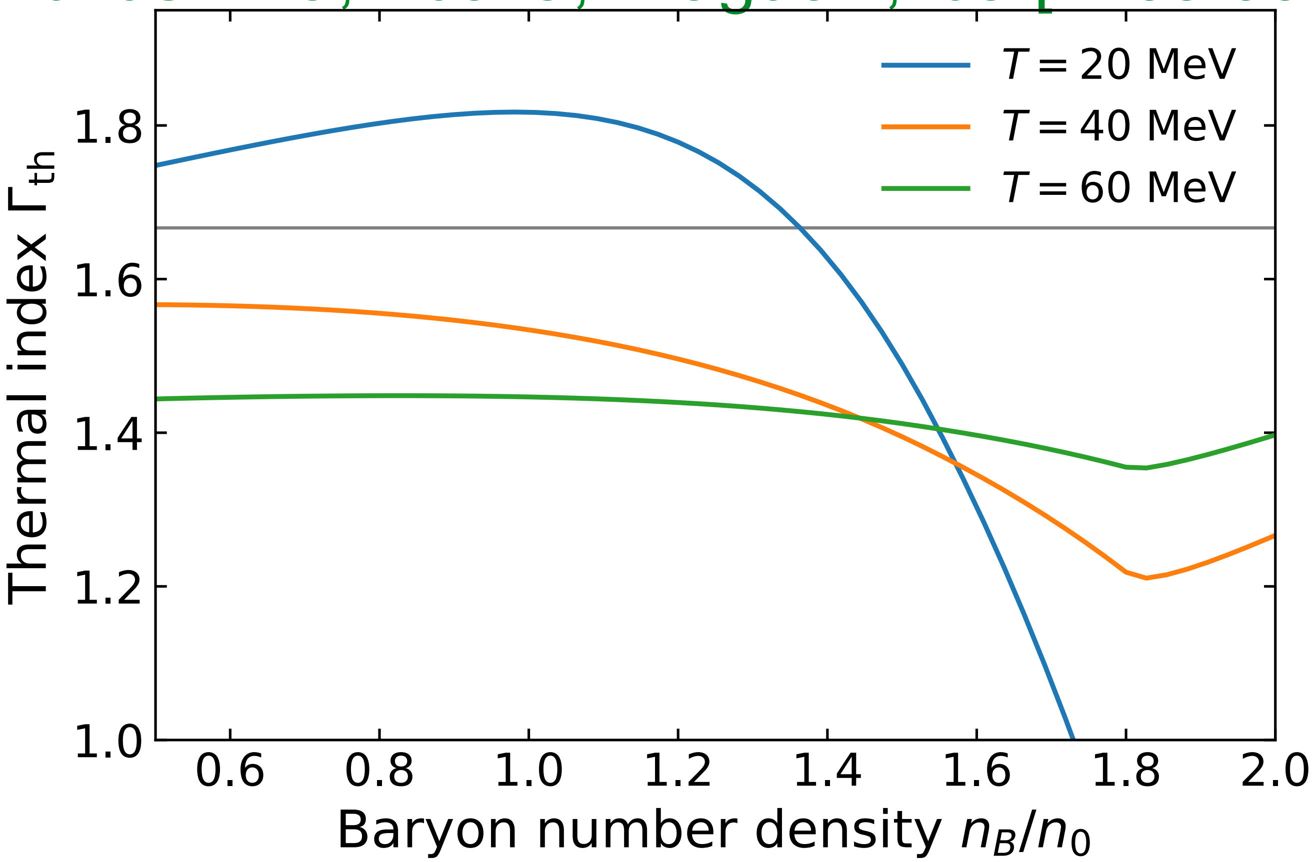
$$P_{\rm thermal} \approx \rho\varepsilon_{\rm thermal}(\Gamma_{\rm th} - 1)$$

thermal index

Our choice: $\Gamma_{\rm th} = 1.75$

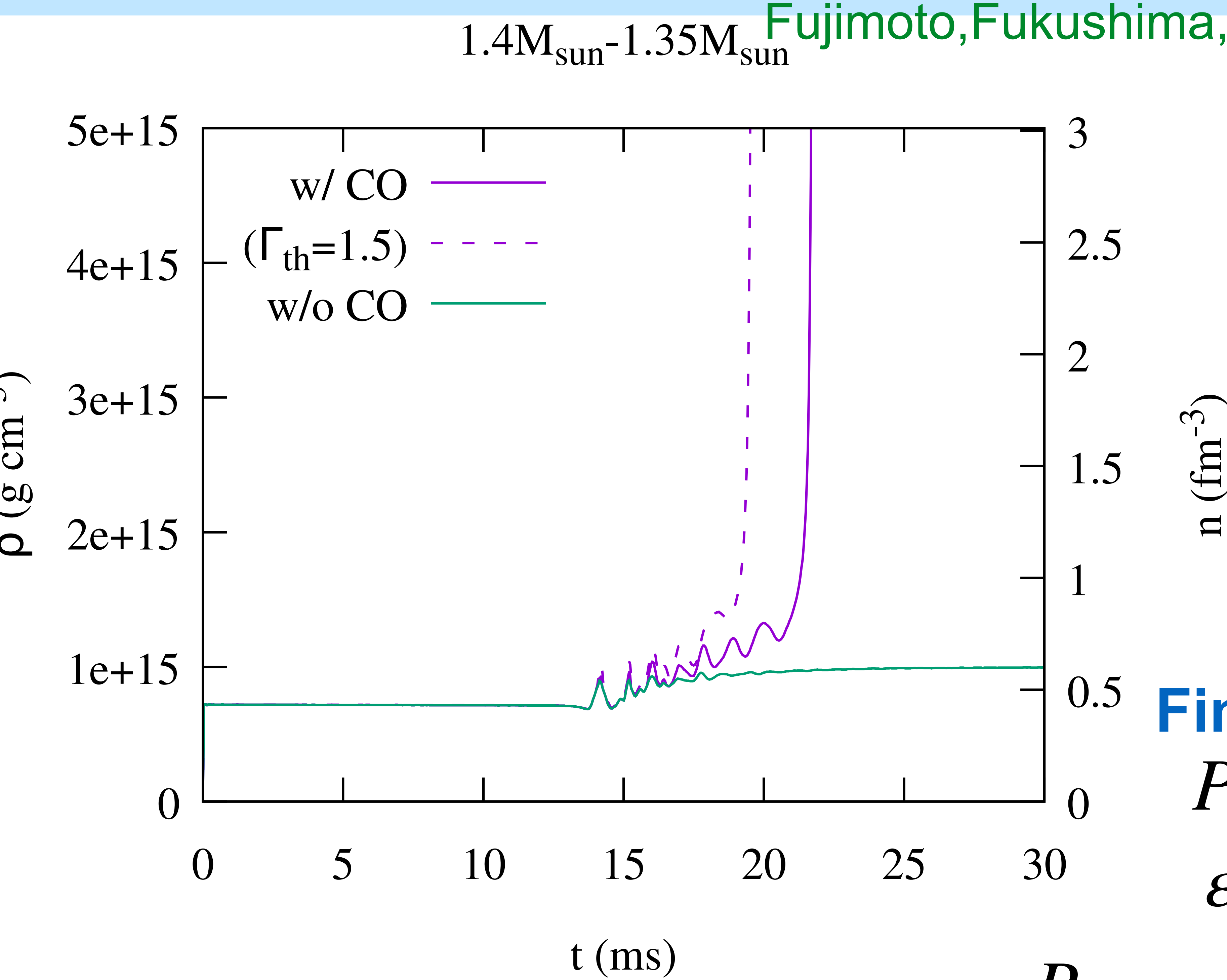
Bauswein et al. (2018),…

Fujimoto,Fukushima,Hidaka,Hiraguchi,Iida [2109.06799]



Thermal effect & maximum density

Fujimoto,Fukushima,Hotokezaka,Kyutoku (2022



Finite-T treatment:

$$P = P_{\rm cold} + P_{\rm thermal}$$

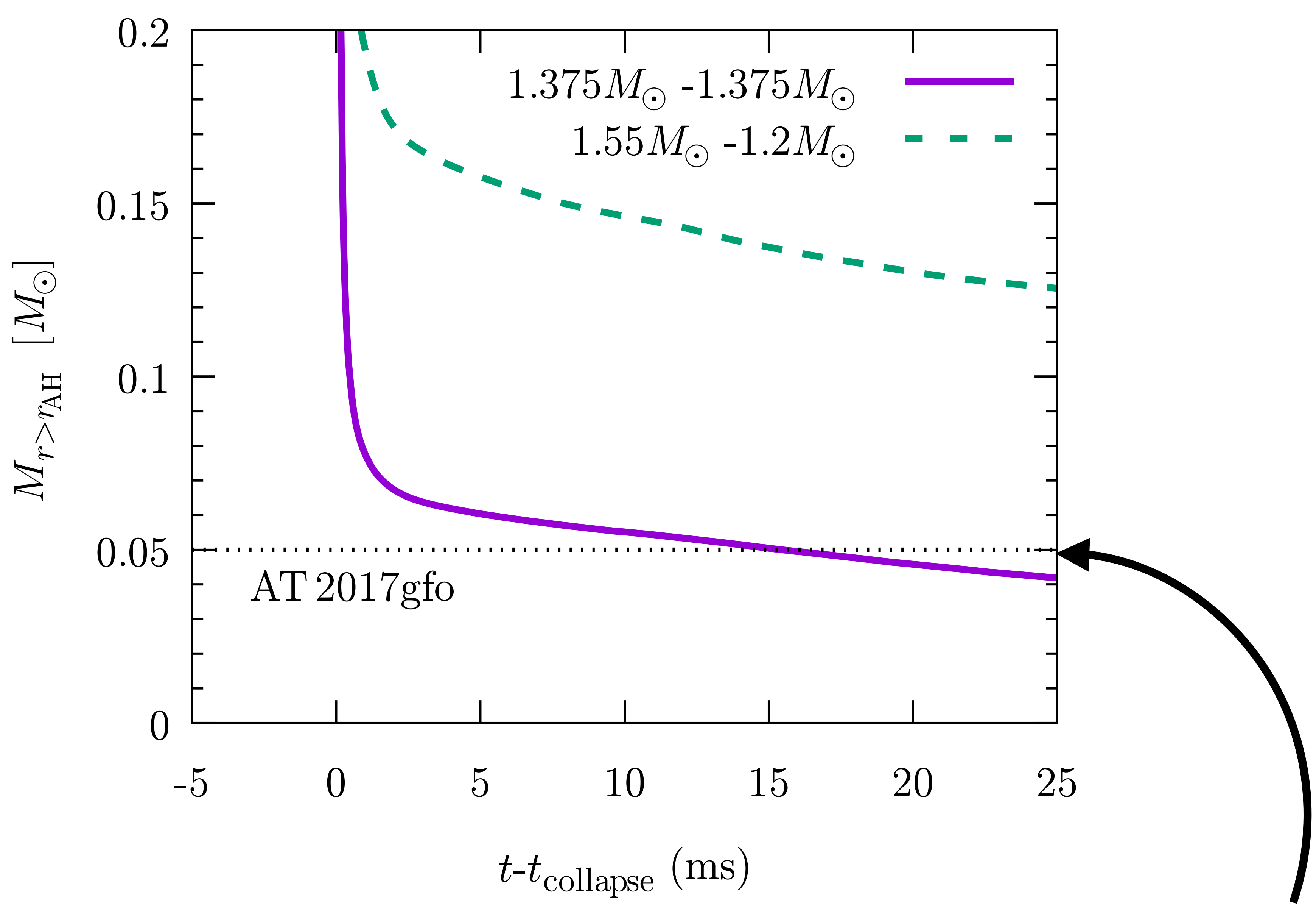
$$\varepsilon = \varepsilon_{\rm cold} + \varepsilon_{\rm thermal}$$

$$P_{\rm thermal} \approx \rho \varepsilon_{\rm thermal} (\Gamma_{\rm th} - 1)$$

$$\Gamma_{\rm th} = 1.75$$

Consistency with kilonova AT2017gfo

Remnant mass outside the apparent horizon of the BH



AT2017gfo, electromagnetic counterpart of GW170817, requires ejection of $\approx 0.05 M_\odot$ 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 QCD calculations, PTs can be categorized into four possibilities (Crossover or 1st-order)
    - Related preceding works also fit into these categories

- **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.
    - Uncertainty in thermal effect is to be explored more.
    - Electromagnetic counterparts (kilonova) can be useful check