Gravitational wave signal for quark matter with realistic phase transition

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References:

Y. Fujimoto, K. Fukushima, K. Hotokezaka, K. Kyutoku, arXiv:2205.03882
Y. Fujimoto, K. Fukushima, L. McLerran, M. Praszalowicz, arXiv:2207.06753

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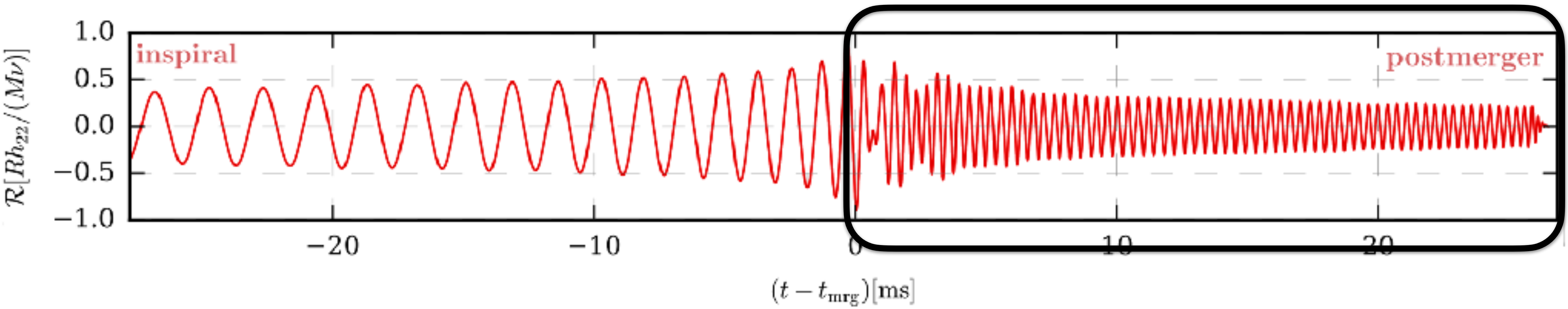
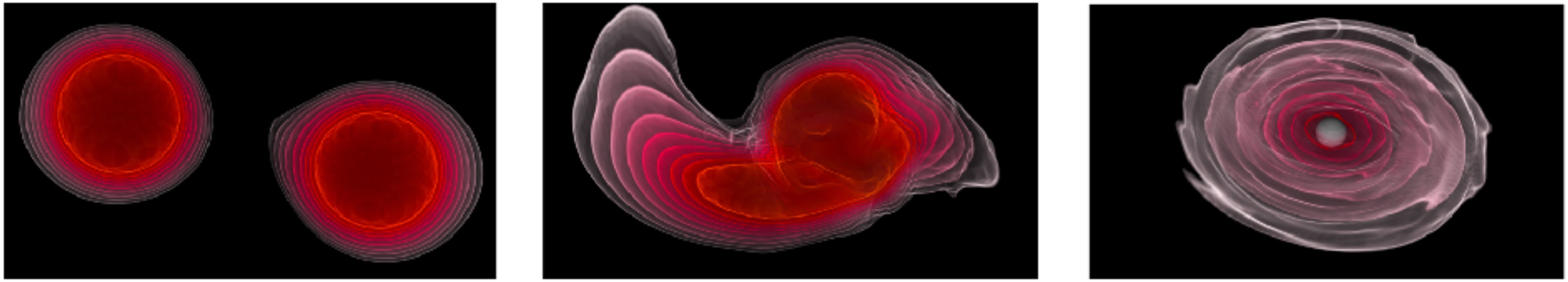
Prelude

Dense quark matter in neutron stars (NSs)?

Detectability in the future gravitational wave observation?

Postmerger phase contains more information on the EoS





From: Dietrich,Hinderer,Samajdar (2020)

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)

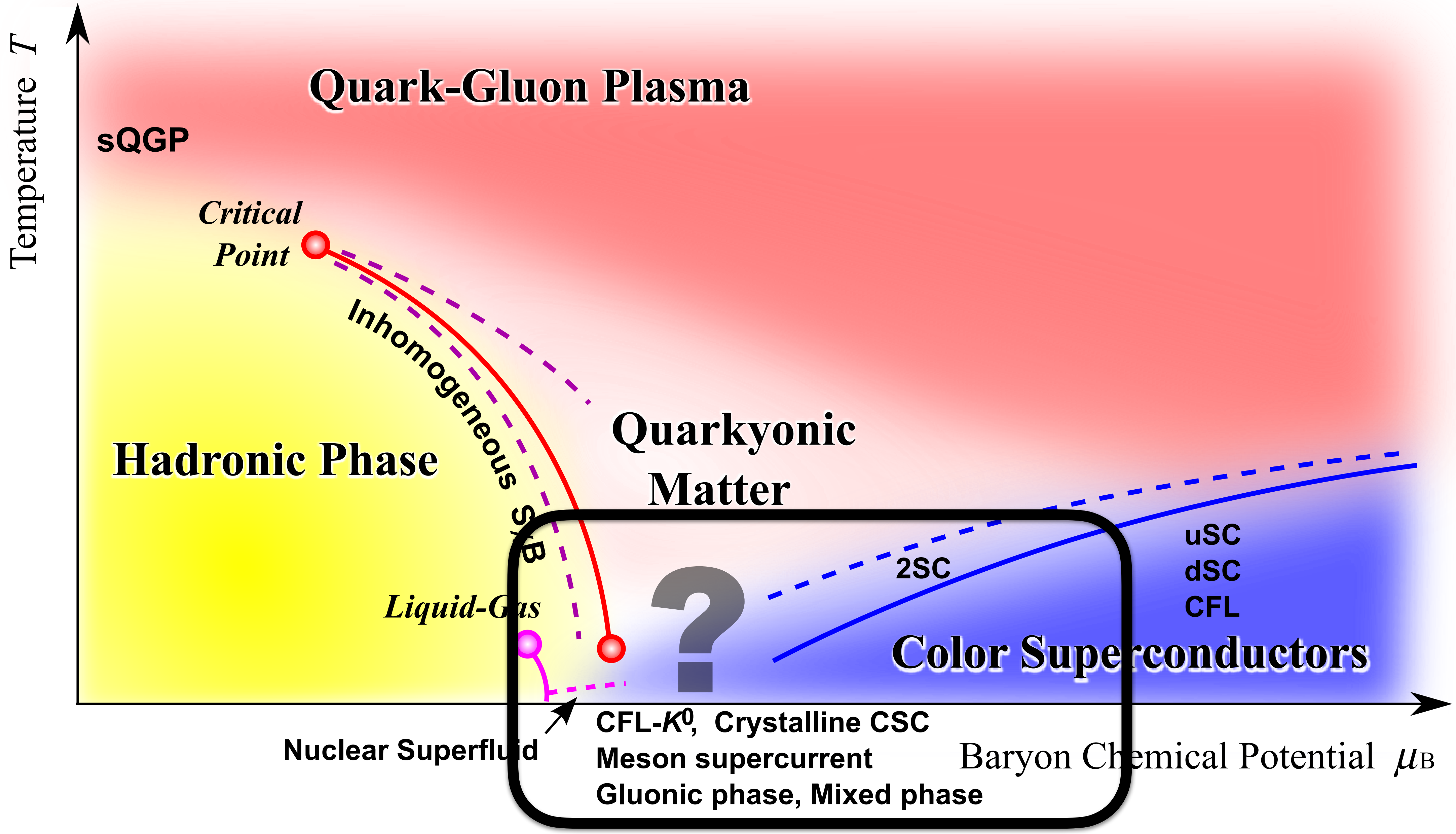
- Prerequisite for the QCD-based EoS
- Modeling the PT: crossover case

2) Detecting quark matter by GWs

- GW signals and detectability
- Useful check: electromagnetic counterpart

Quark liberation at high densities

Fukushima,Hatsuda (2010)

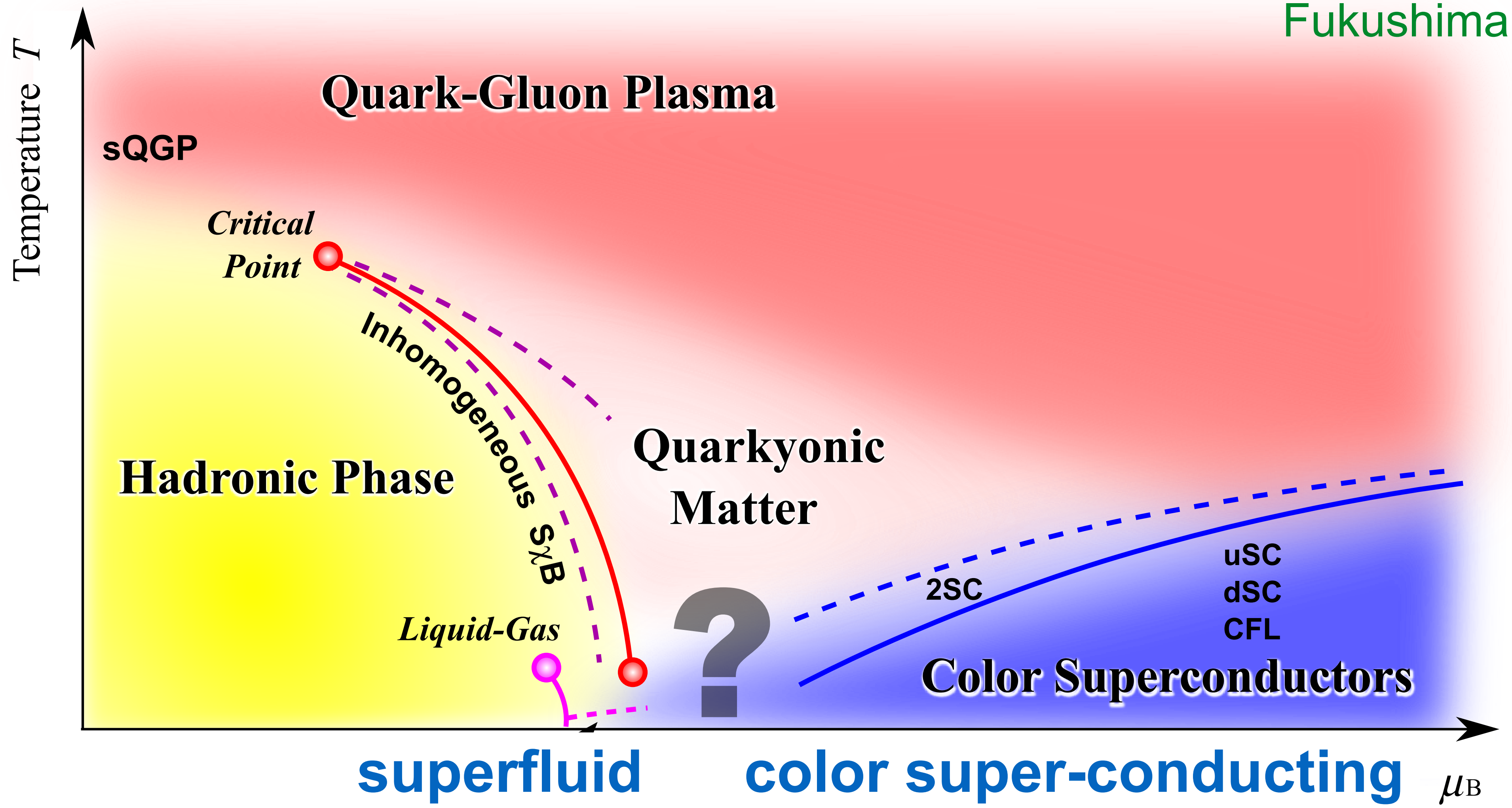


Quark deconfinement transition: 1st-order or crossover?

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:

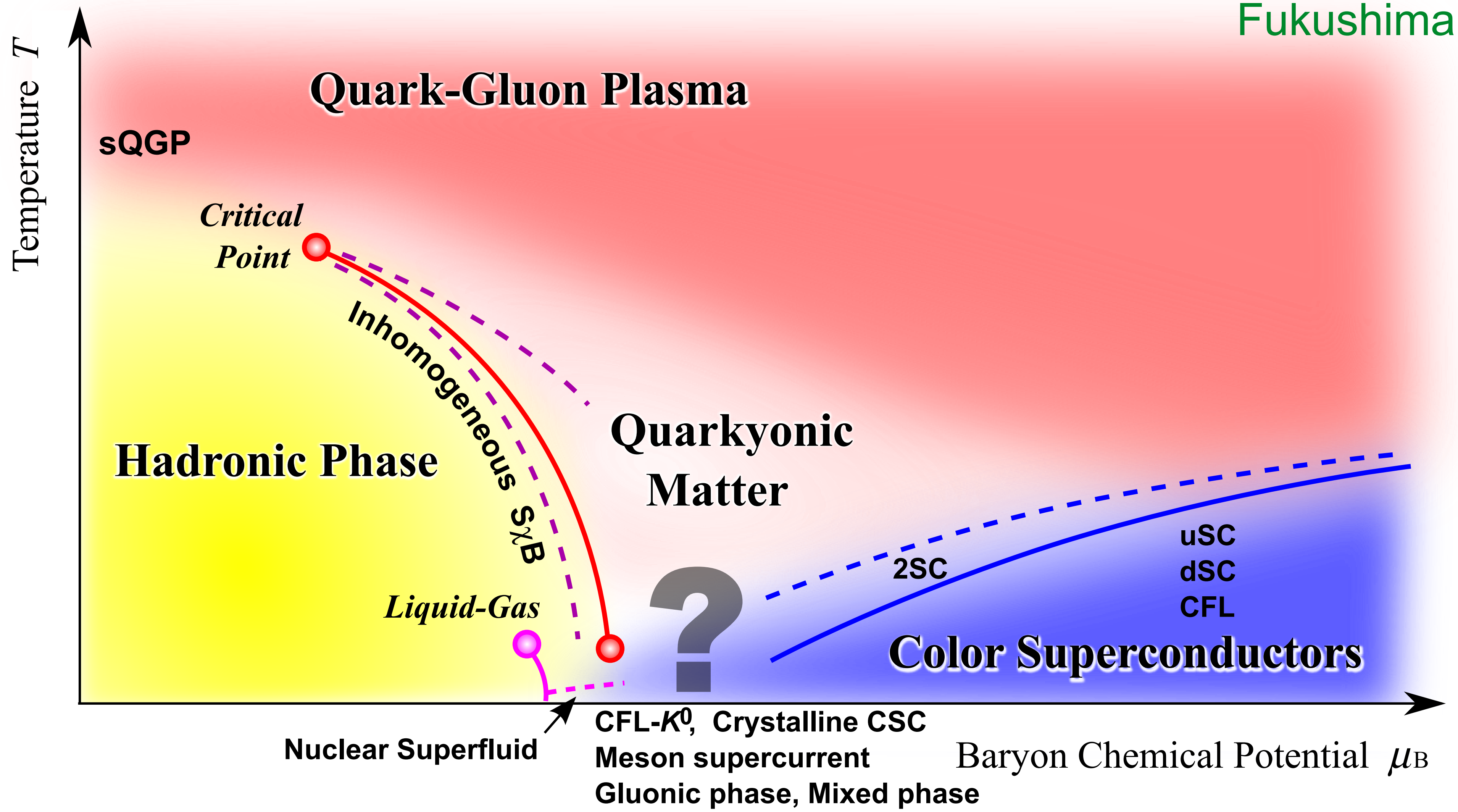
$$G = SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{L+R}$$

Quark-hadron continuity

Schafer,Wilczek (1998); Hatsuda,Tachibana,Yamamoto,Baym (2006); Fujimoto,Fukushima,Weise (2019)
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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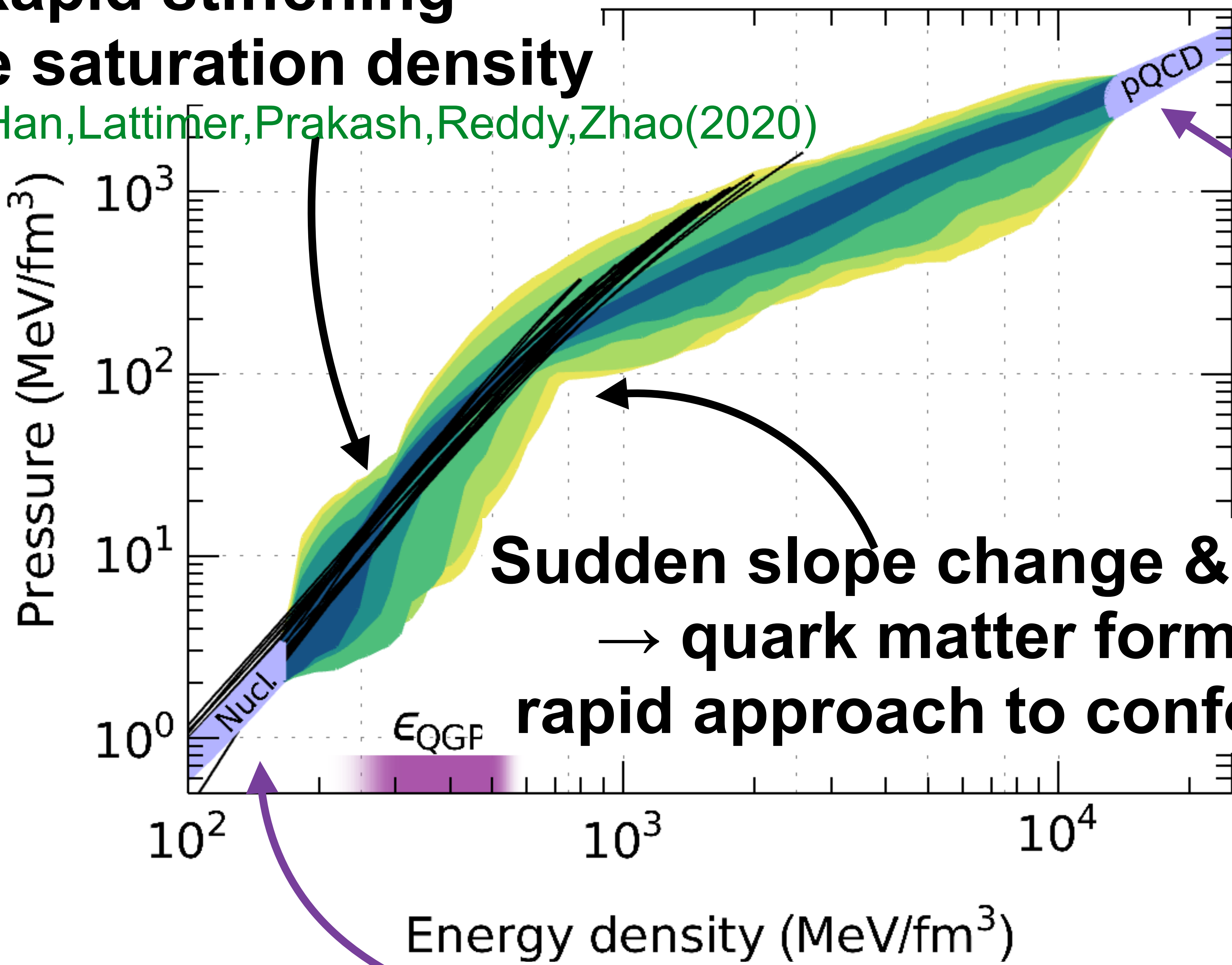
QCD-based view

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? rapid approach to conformality?

ab initio QCD calculations: Chiral EFT & perturbative QCD

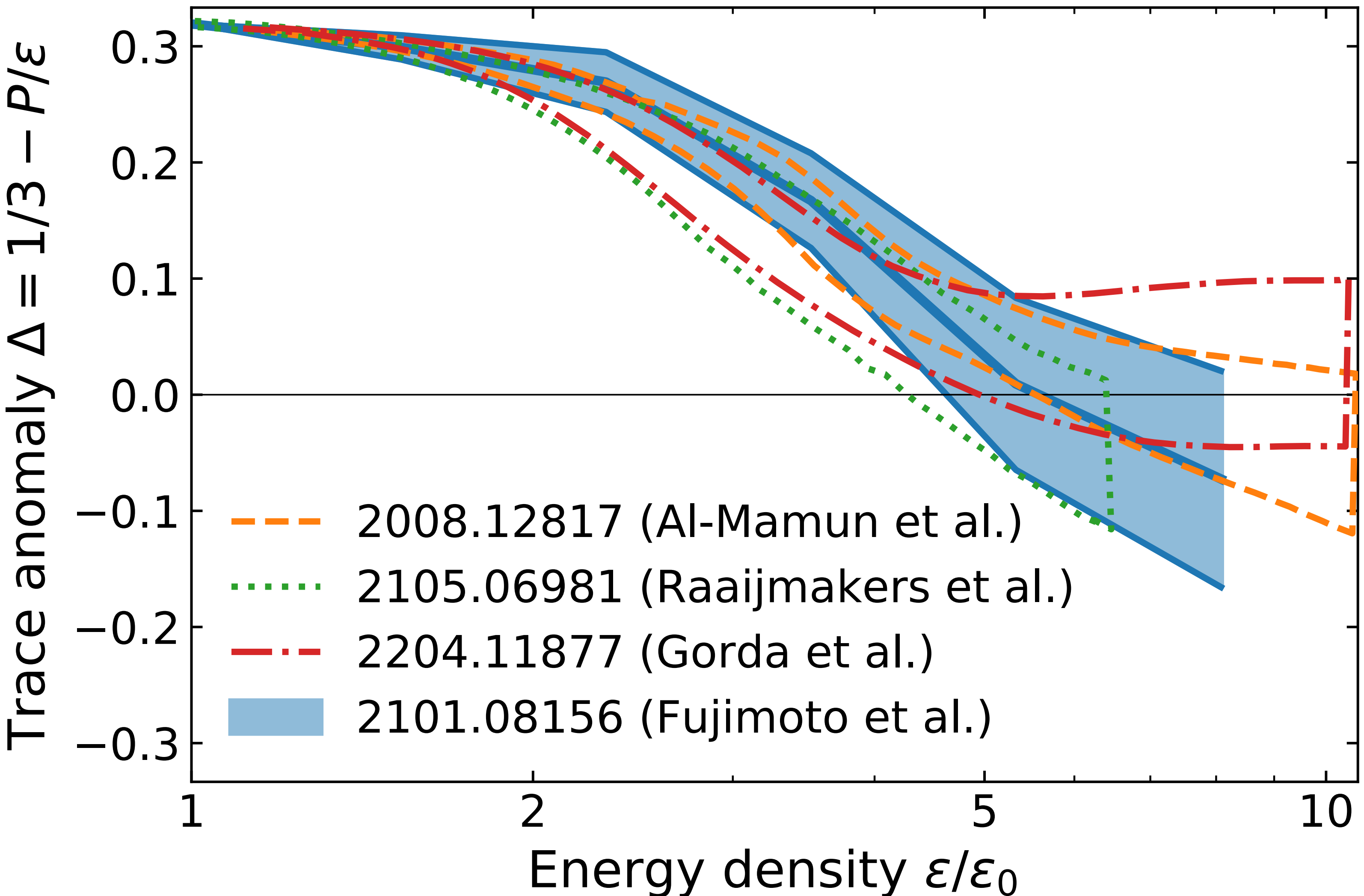
Trace anomaly in neutron stars

Fujimoto,Fukushima,McLerran,Praszalowicz (2022)

- Consider the normalized trace anomaly:

$$\Delta \equiv \frac{\langle T^{\mu}_{\ \mu} \rangle_{\mu_B}}{3\varepsilon} = \frac{1}{3} - \frac{P}{\varepsilon}$$

- Inferred from neutron star data:



$\Delta \sim 0$ already at $\sim 5\varepsilon_0$
$\rightarrow$ rapid approach to conformality.

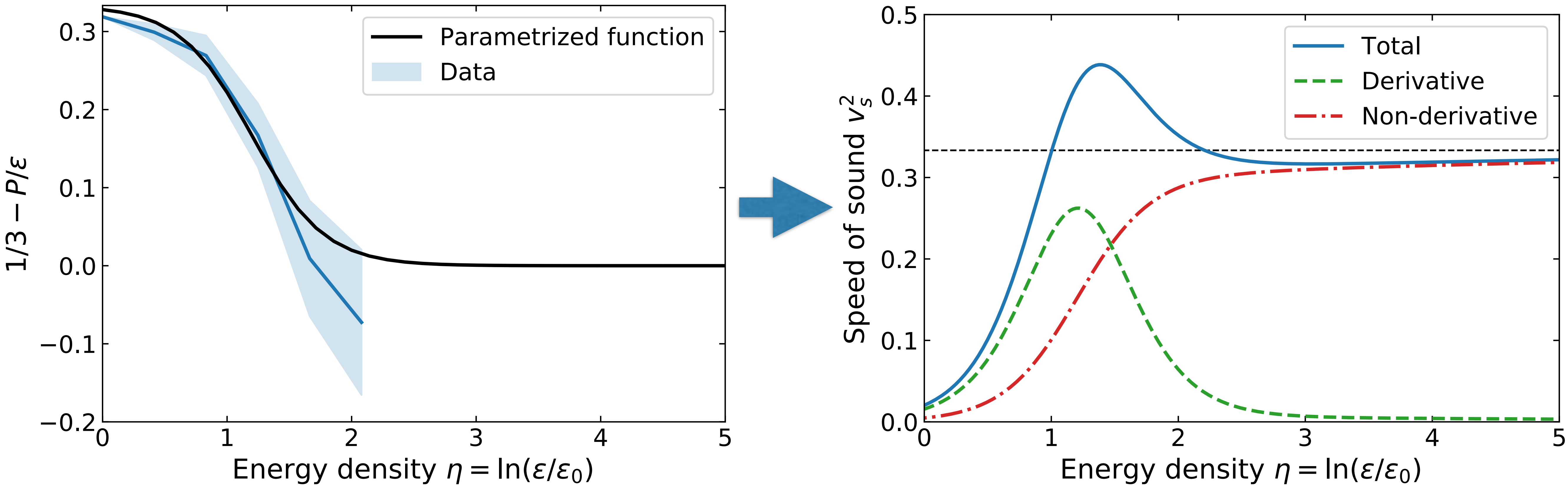
Suggests strongly-coupled conformal matter with
$P \approx \varepsilon/3$

Trace anomaly in neutron stars

Fujimoto,Fukushima,McLerran,Praszalowicz (2022)

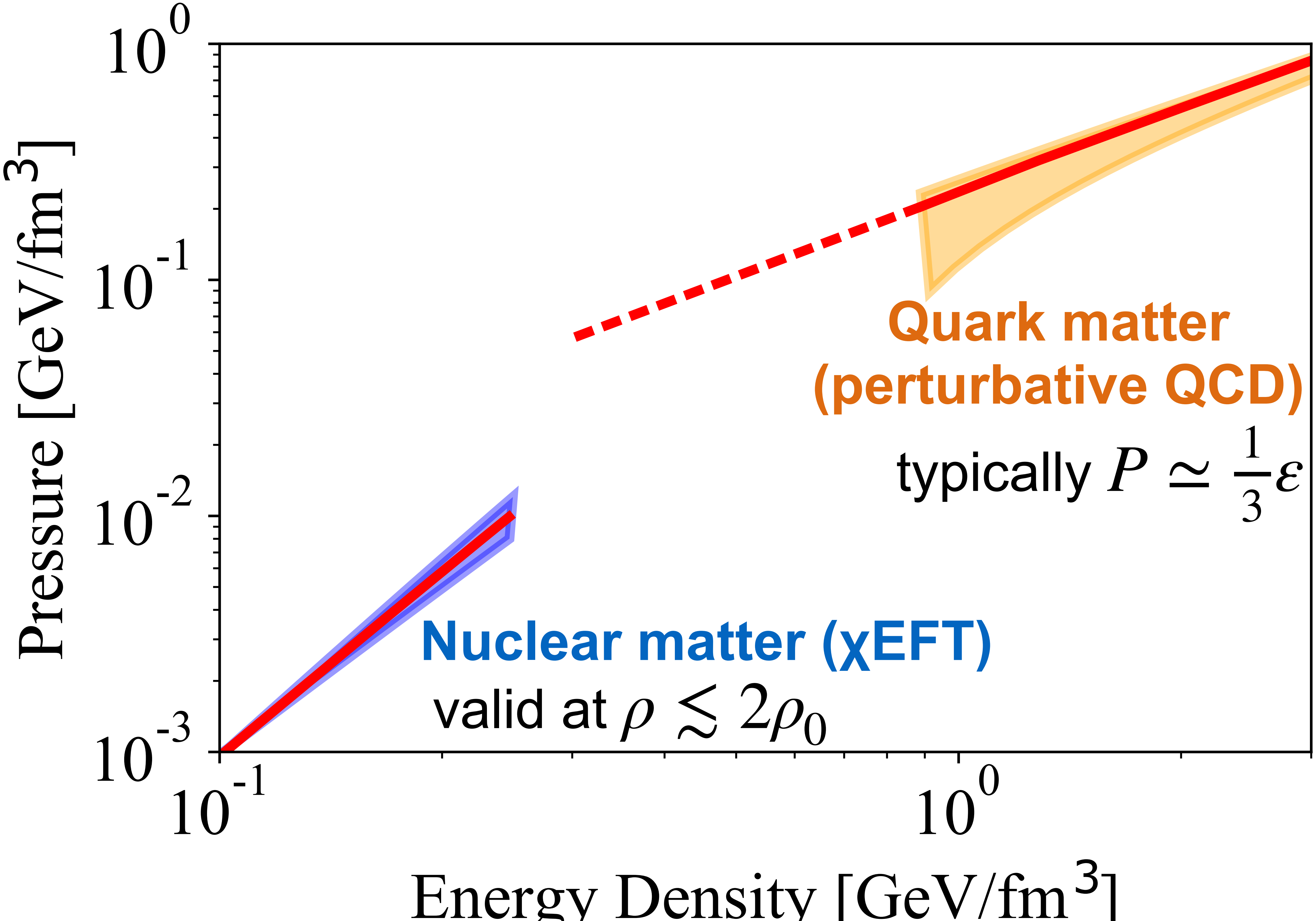
- Side remark: rapid approach to conformality naturally spike the sound velocity $v_s^2 = \partial P / \partial \varepsilon$

Trace anomaly $\Delta = \frac{1}{3} - \frac{P}{\varepsilon}$ Sound velocity $v_s^2 = \frac{P'}{\varepsilon'}$



Prerequisite for the QCD-based EoS

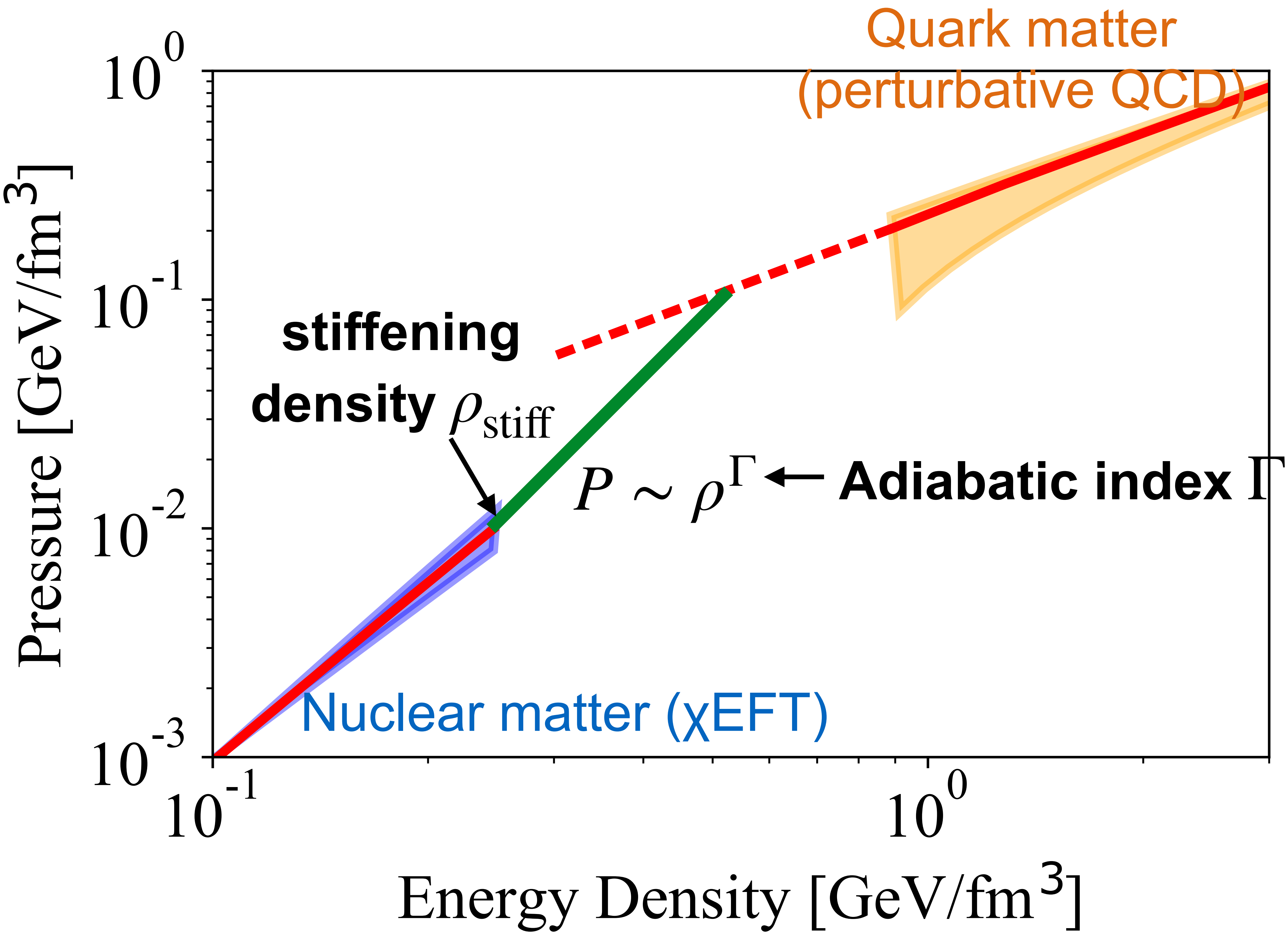
pQCD: Freedman,McLerran (1976); Baluni (1977); Kurkela,Romatschke,Vuorinen,Gorda,Sappi,… (2009-)



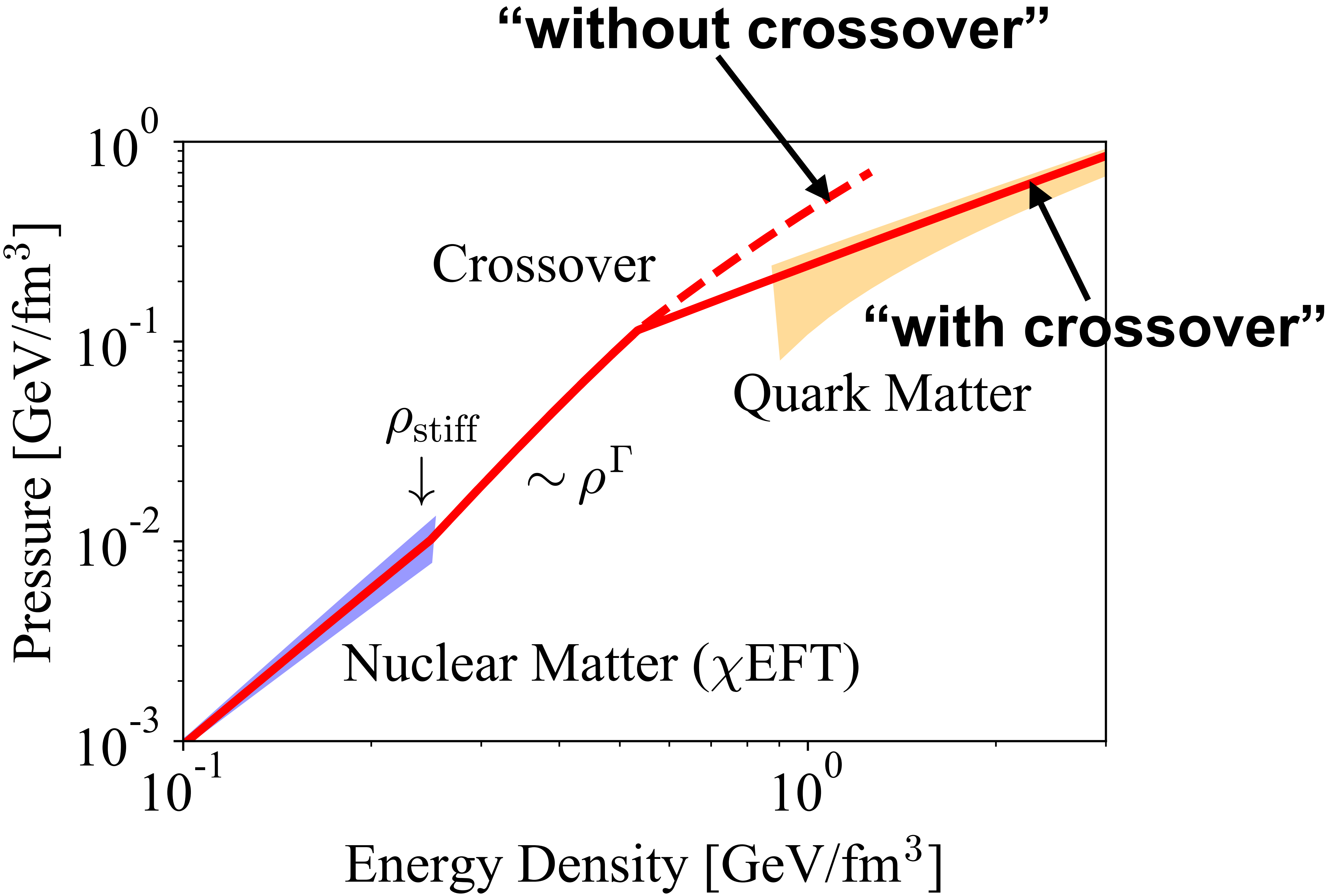
χEFT: Drischler,Han,Lattimer,Prakash,Reddy,Zhao (2021)

Modeling the intermediate region

Crossover parametrization for piecewise polytropes:



Crossover



"without crossover"
"with crossover"
Crossover
Quark Matter
ρ_{stiff}
$\sim \rho^{\Gamma}$
Nuclear Matter (χEFT)
Pressure [GeV/fm^3]
Energy Density [GeV/fm^3]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0

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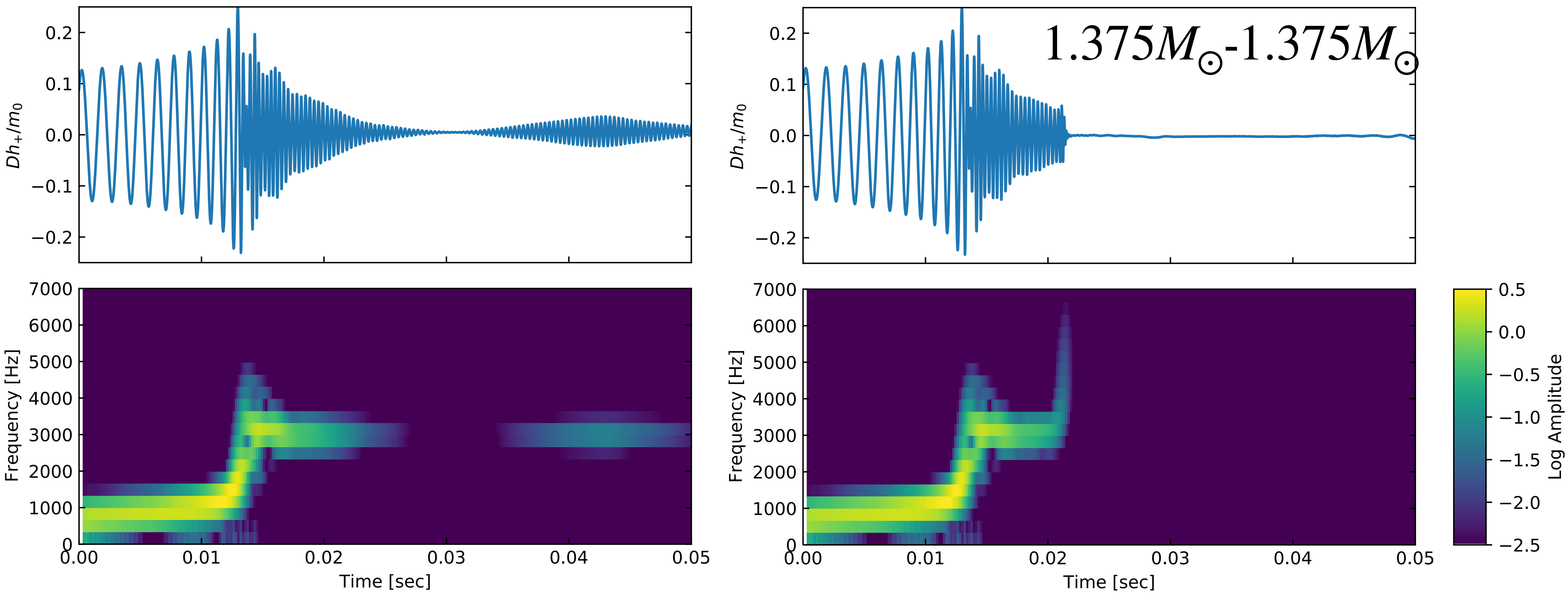
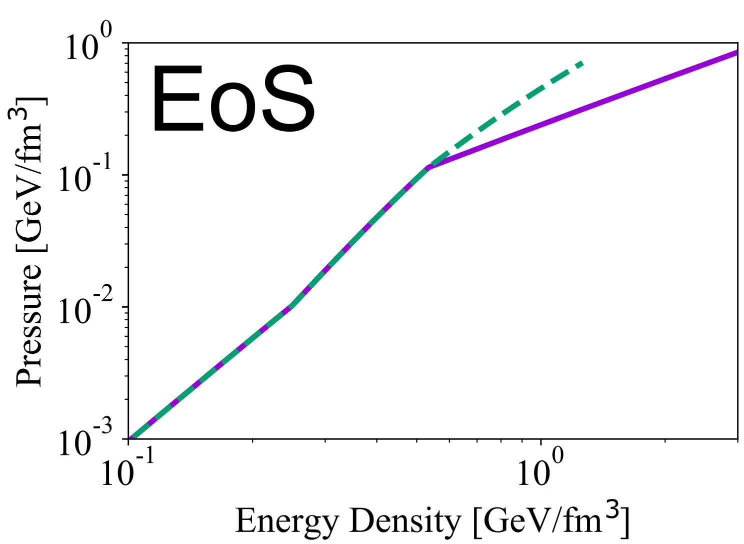
GW signals from quark matter

Fujimoto,Fukushima,Hotokezaka,Kyutoku (2022)

without crossover | with crossover



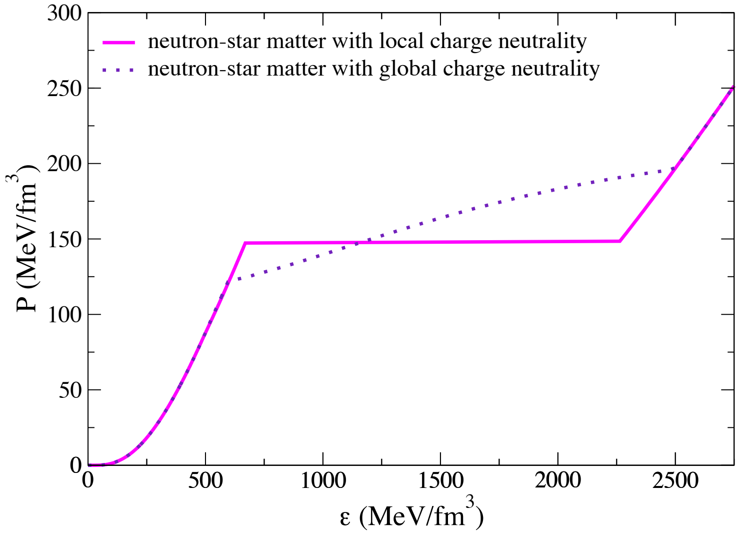


Crossover to quark matter (softening) drives the collapse to black holes

Comparing the results with related works

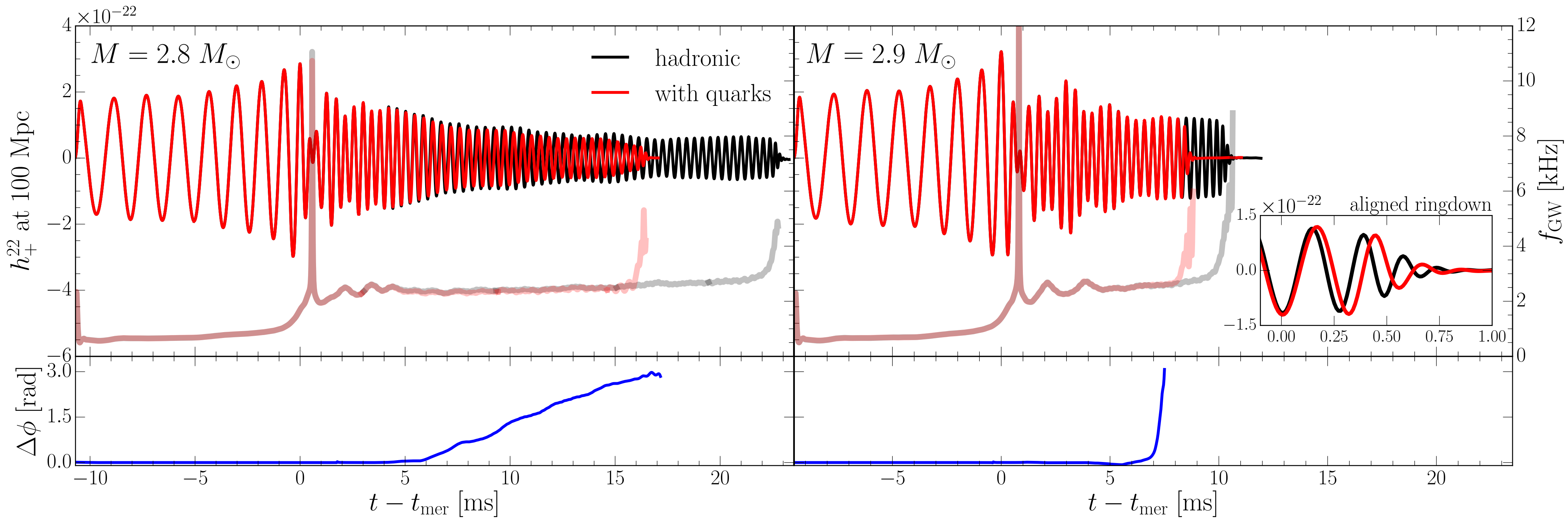
Most,Papenfort,Dexheimer,Hanauske,Schramm,Stoecker,Rezzolla (2018)

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

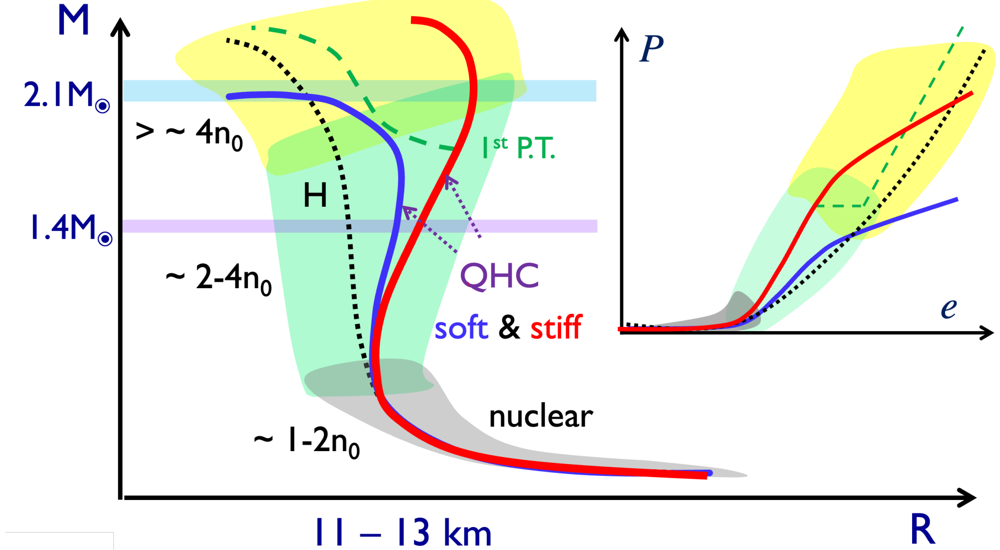


see also: Bauswein et al. (2018)

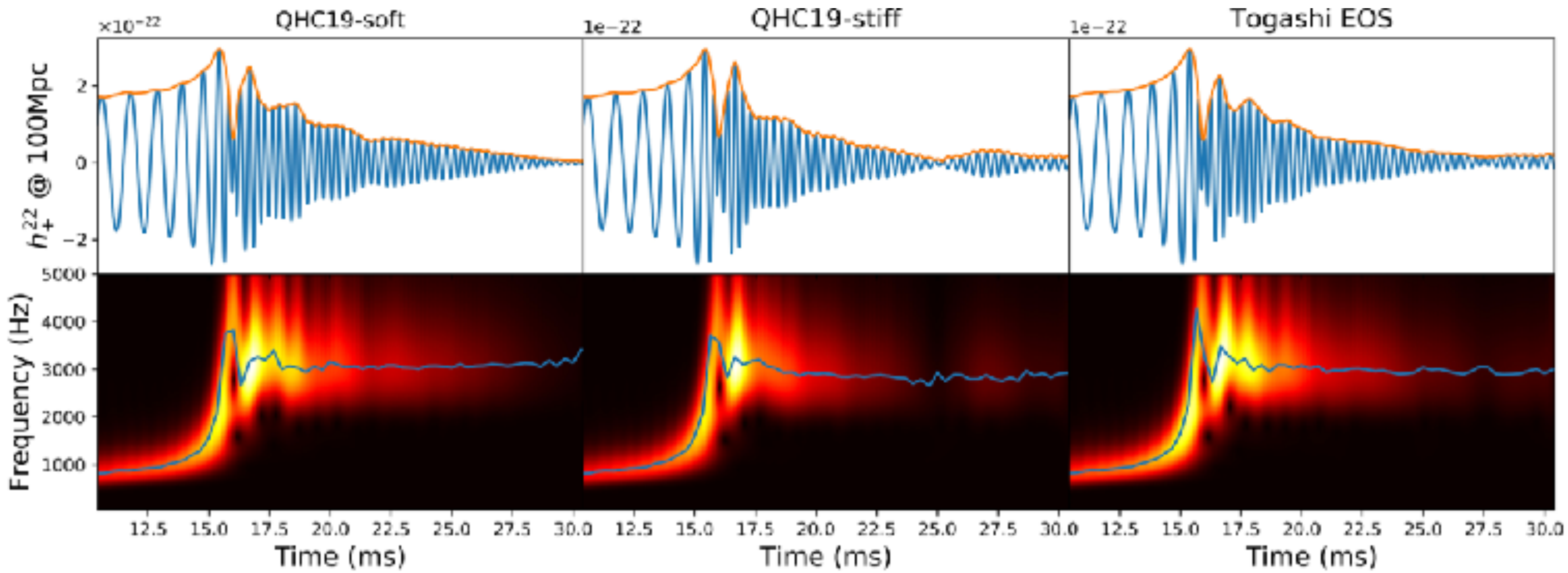
Comparing the results with related works

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

Crossover-type NJL model EoSs (QHC19),
with **stiff quark matter** (does not respect pQCD constraint)



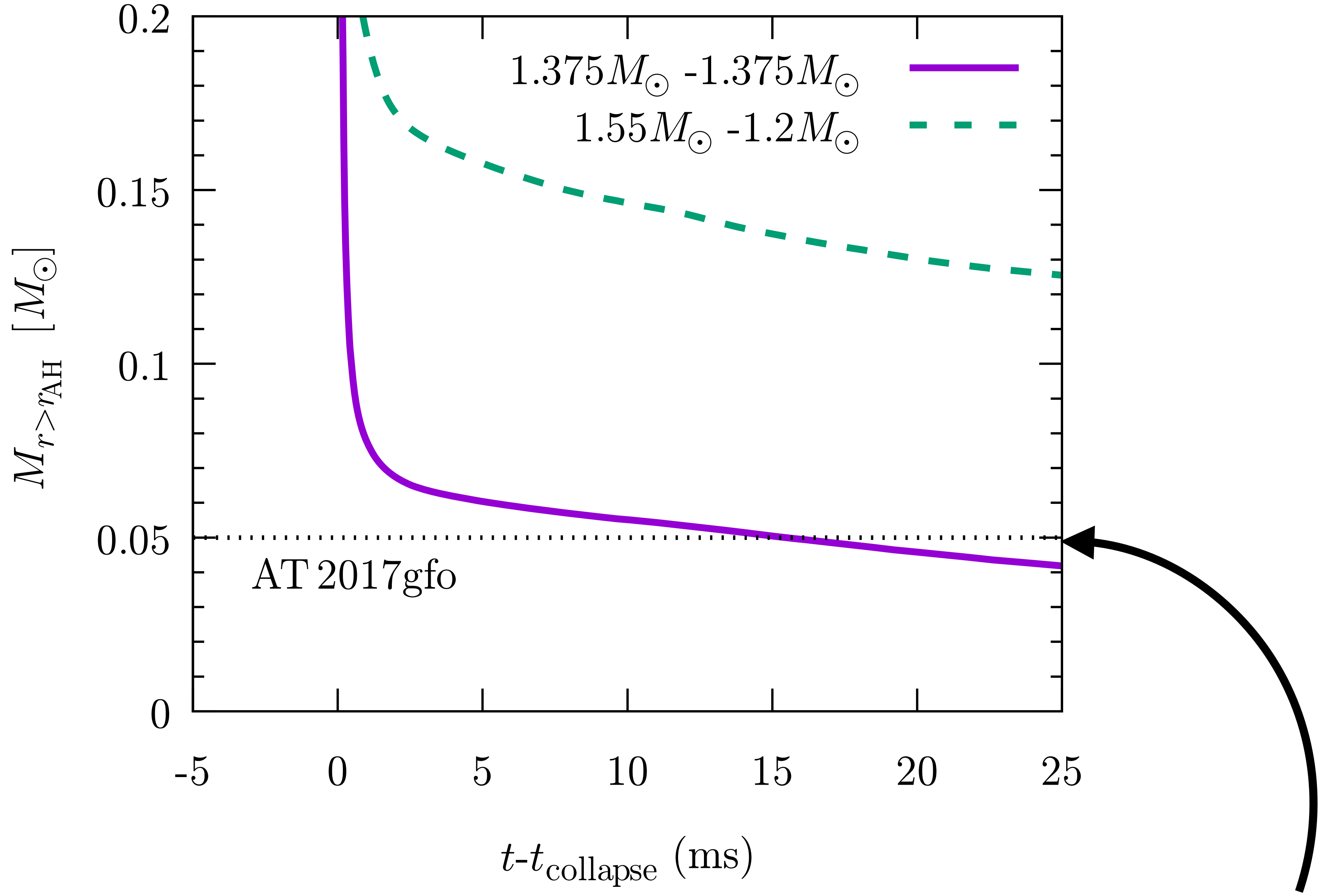
Results are consistent with our "without crossover" EoS



see also: Kedia,Kim,Suh,Mathews (2022)

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

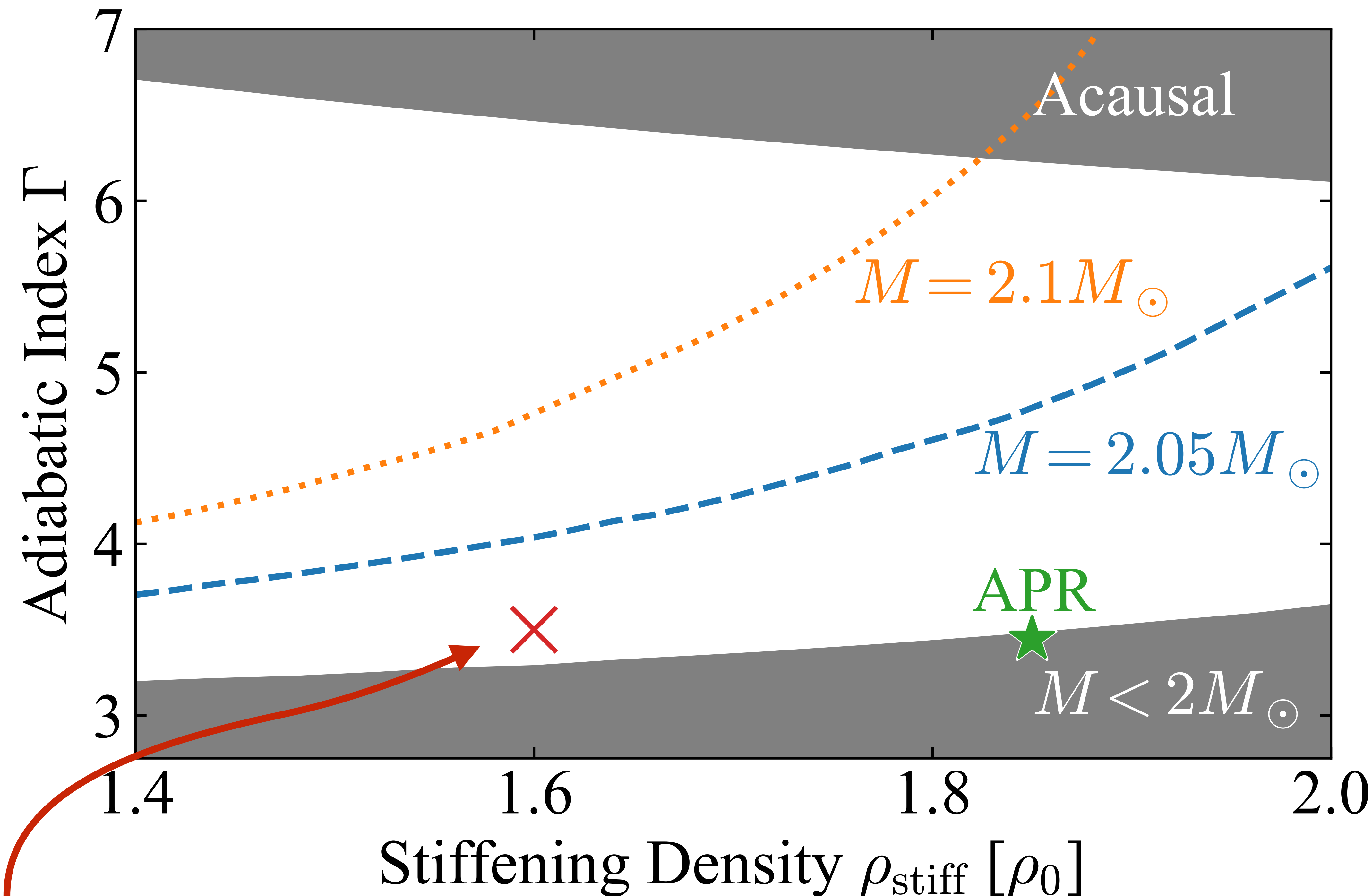
- Detectability of quark matter by gravitational waves from binary neutron star mergers is discussed

- **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

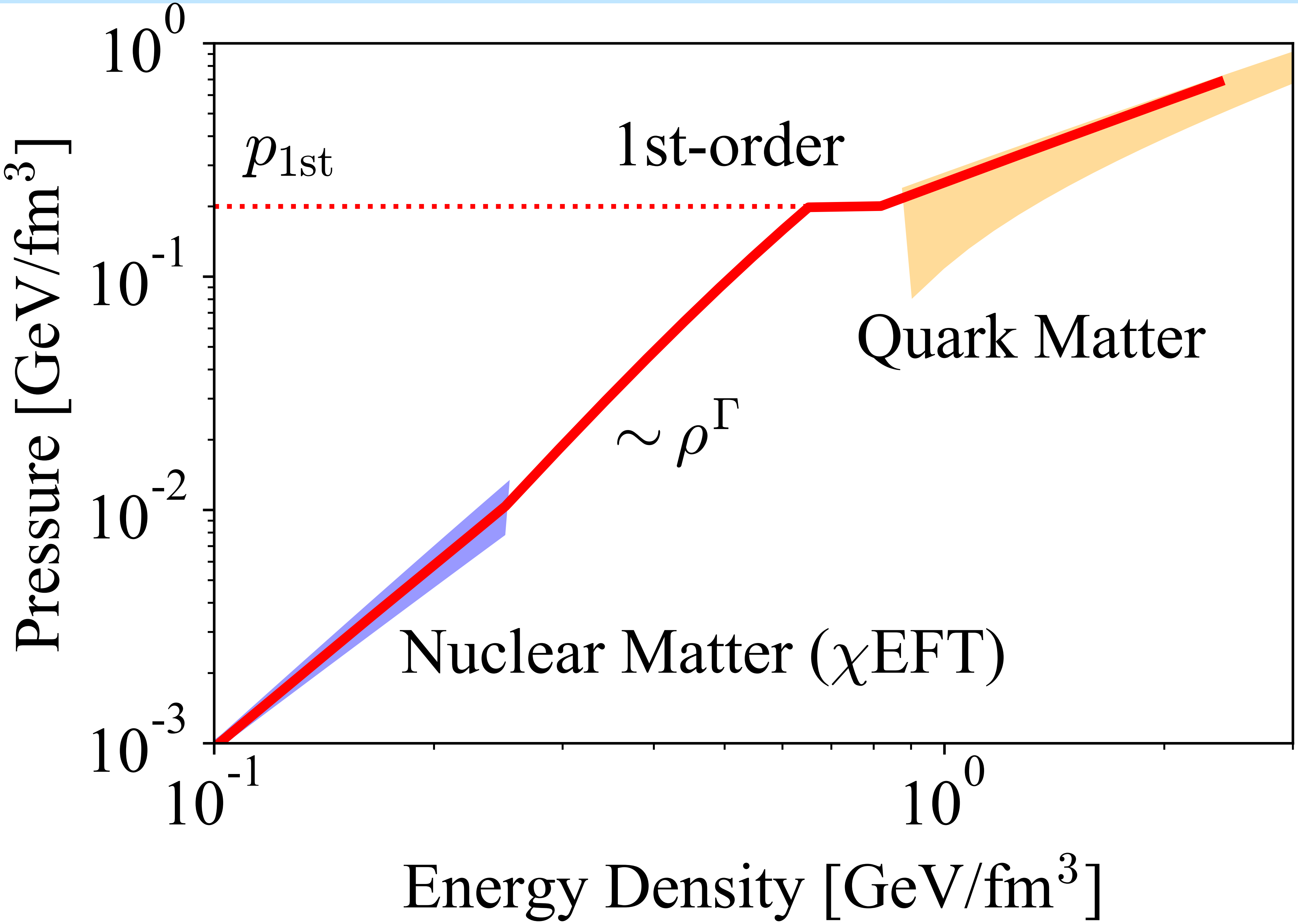
Backup slides

Allowed region of parameters



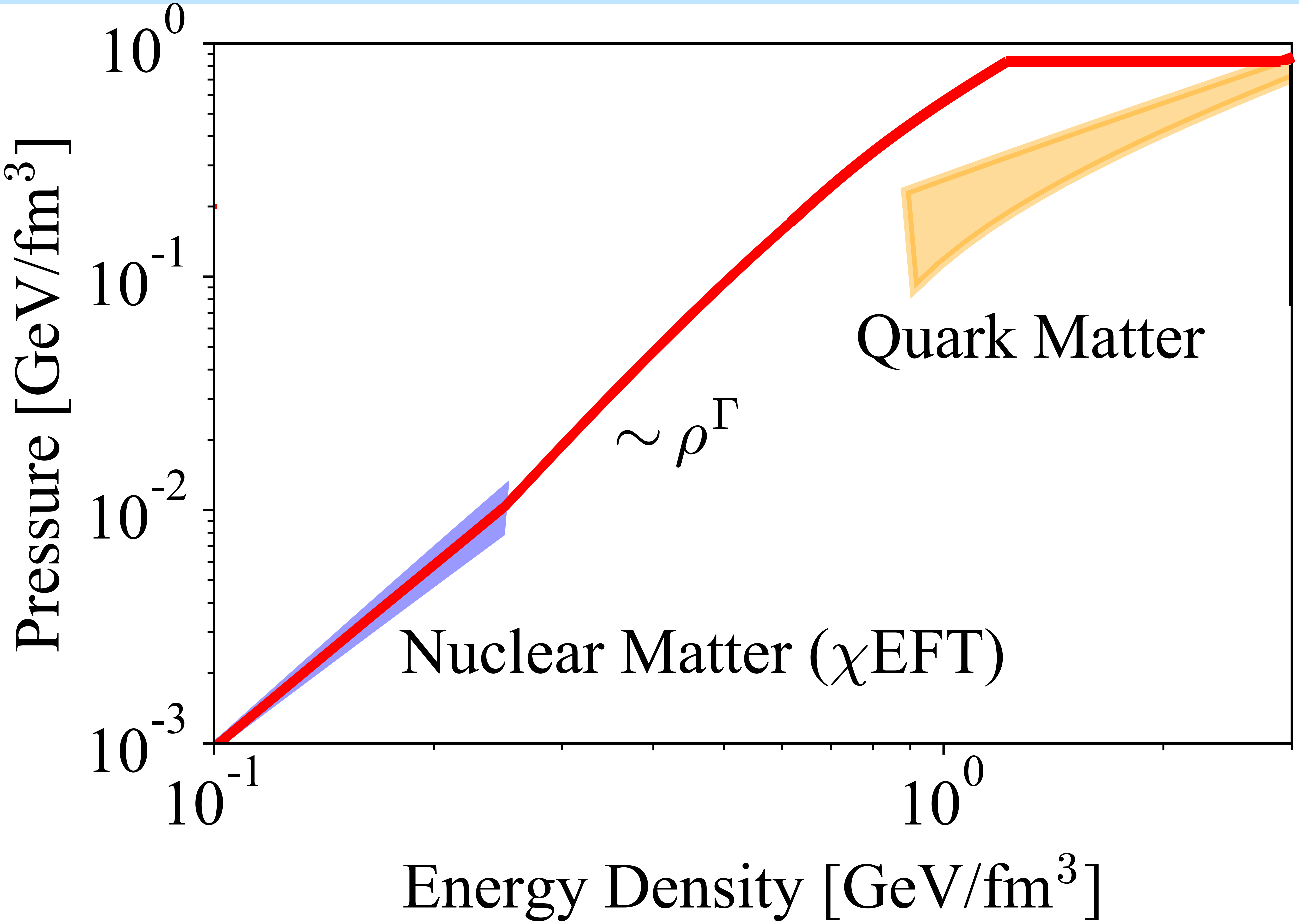
In later calculations, we take $(\rho_{\rm stiff}, \Gamma) = (1.6\rho_0, 3.5)$

Alternative scenario: Weak 1st-order PT



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

Alternative: 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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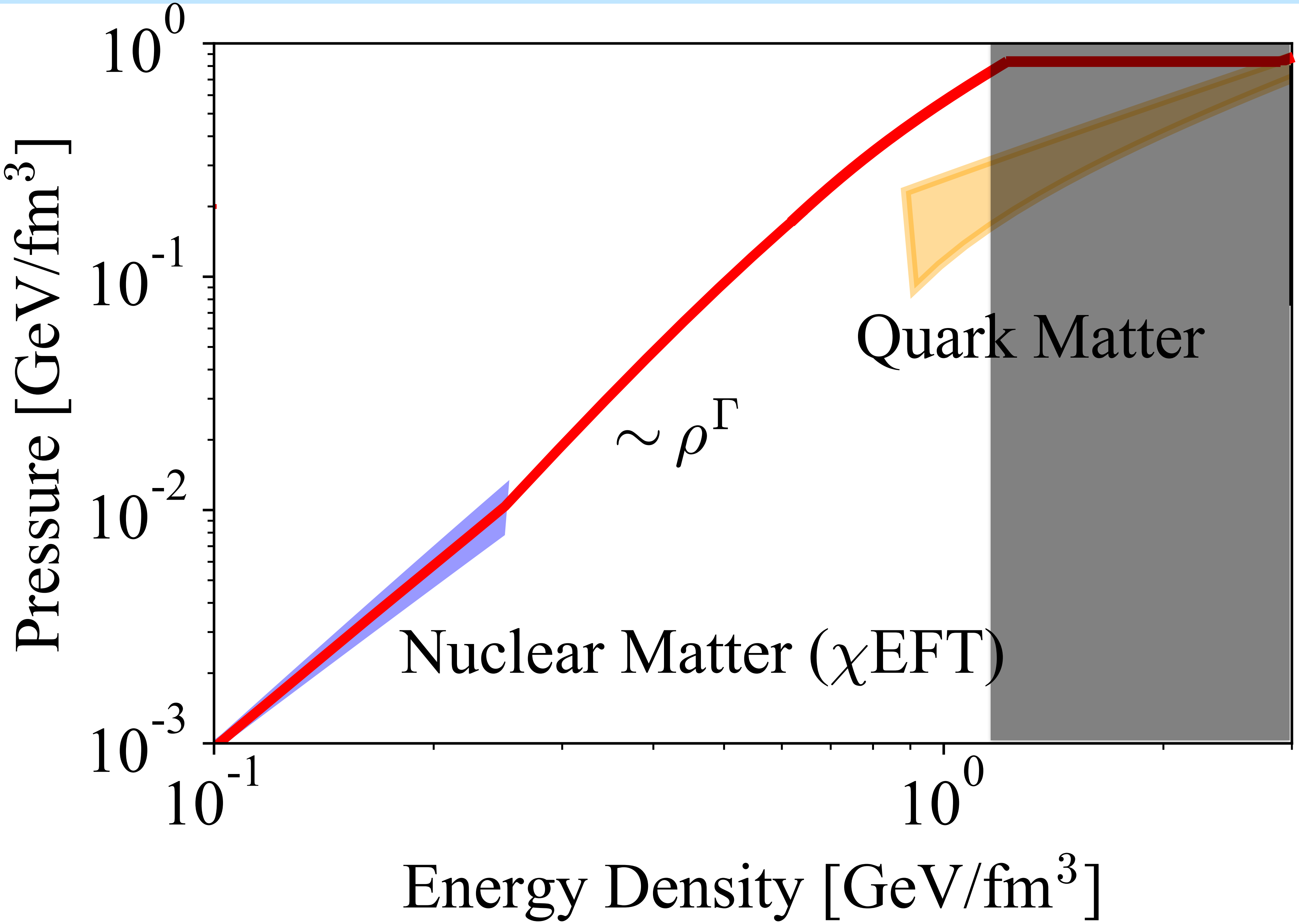

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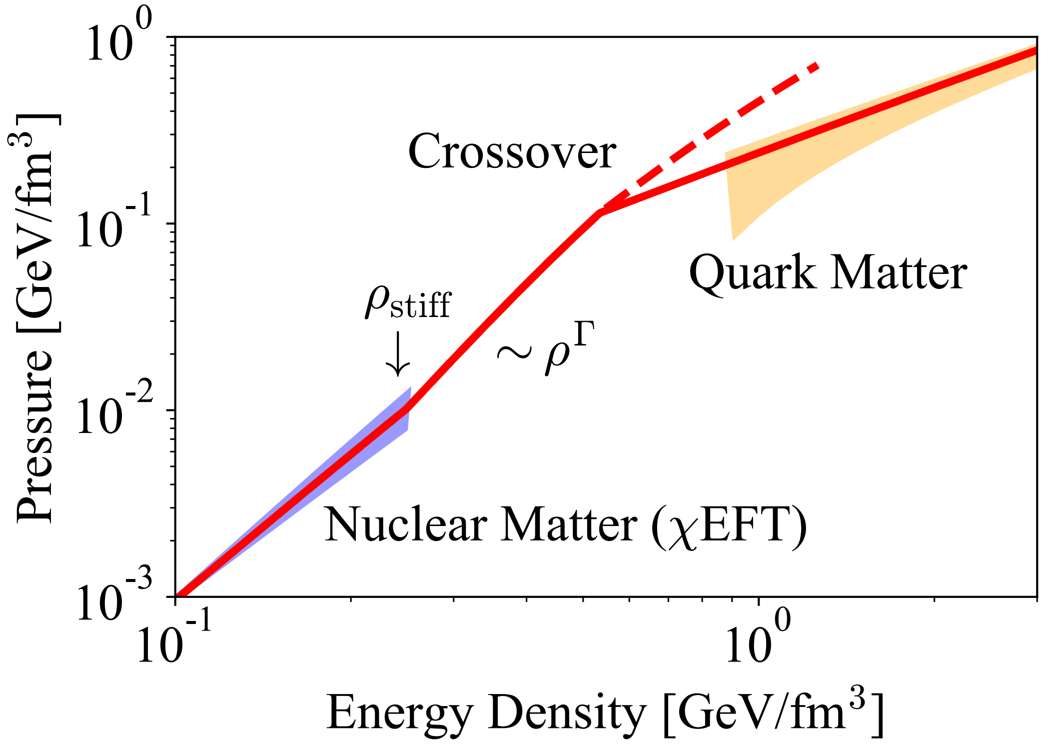
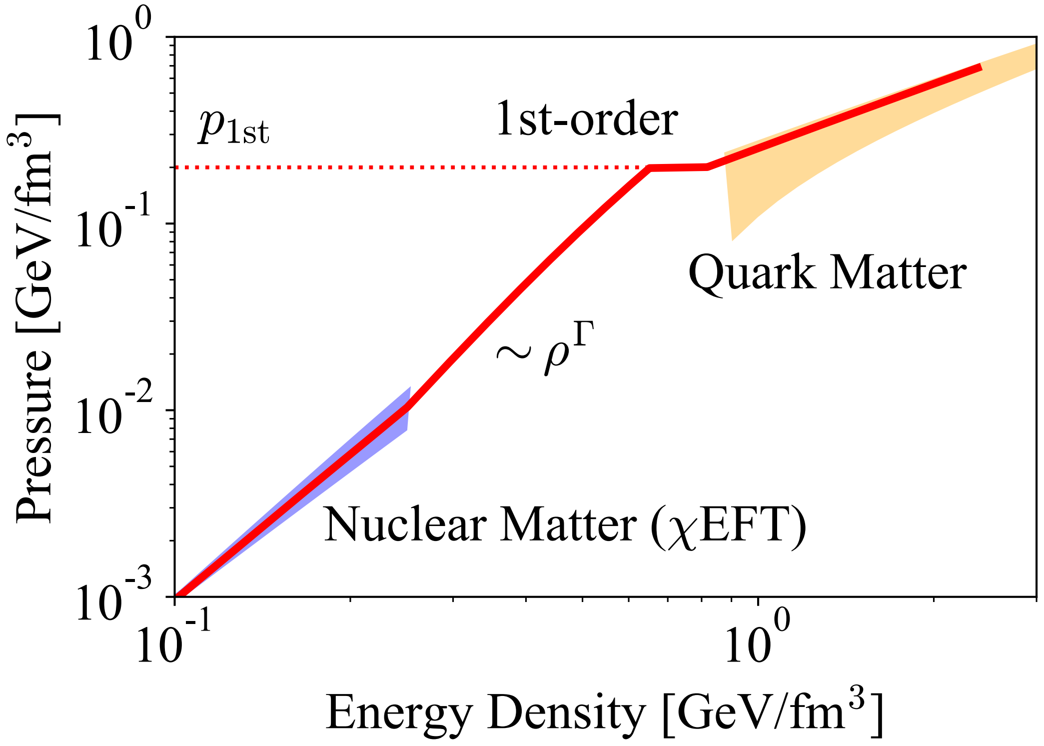
Categories of realistic PT pattern

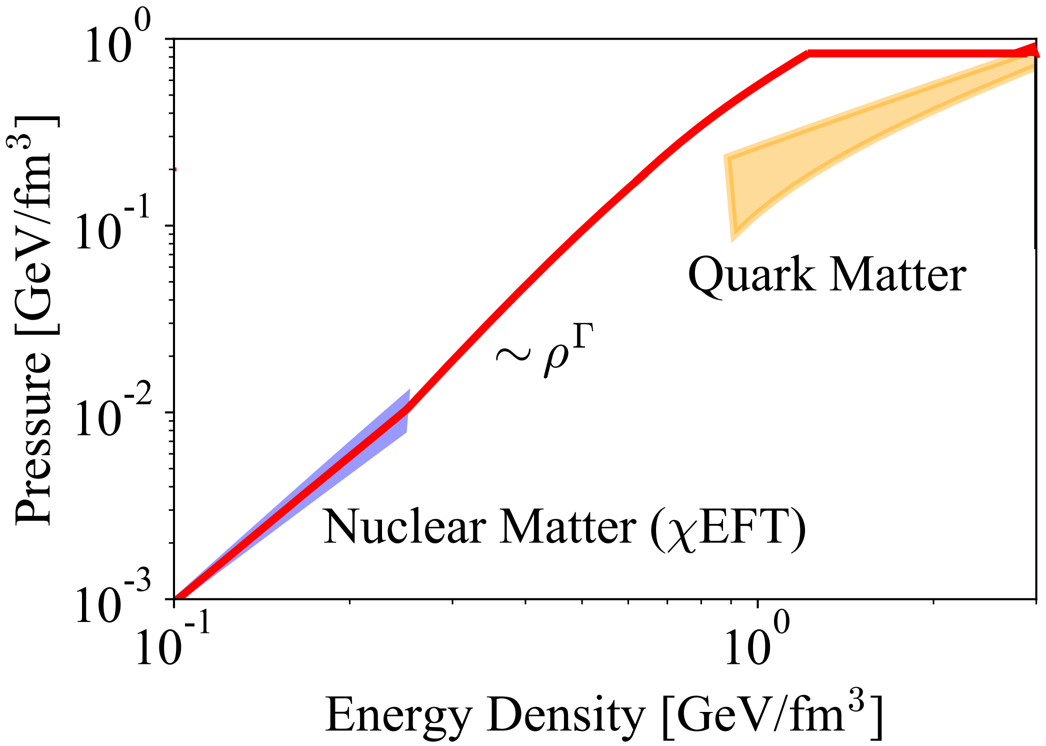
(1) Crossover



(2) Weak 1st-order



(3) Strong 1st-order @ high ρ



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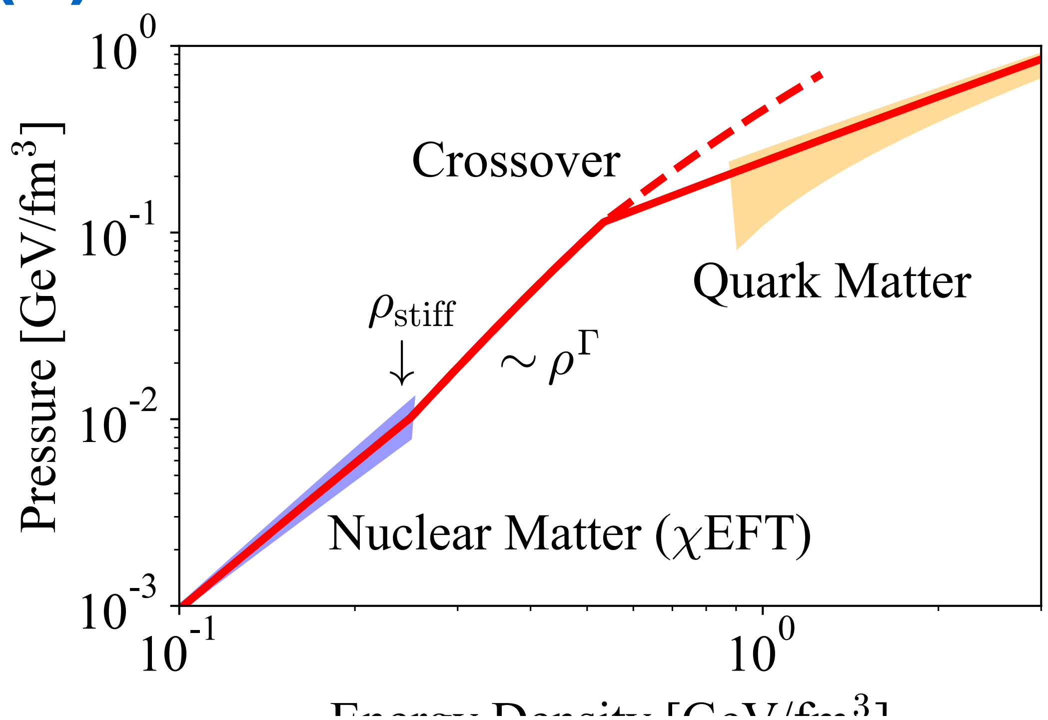

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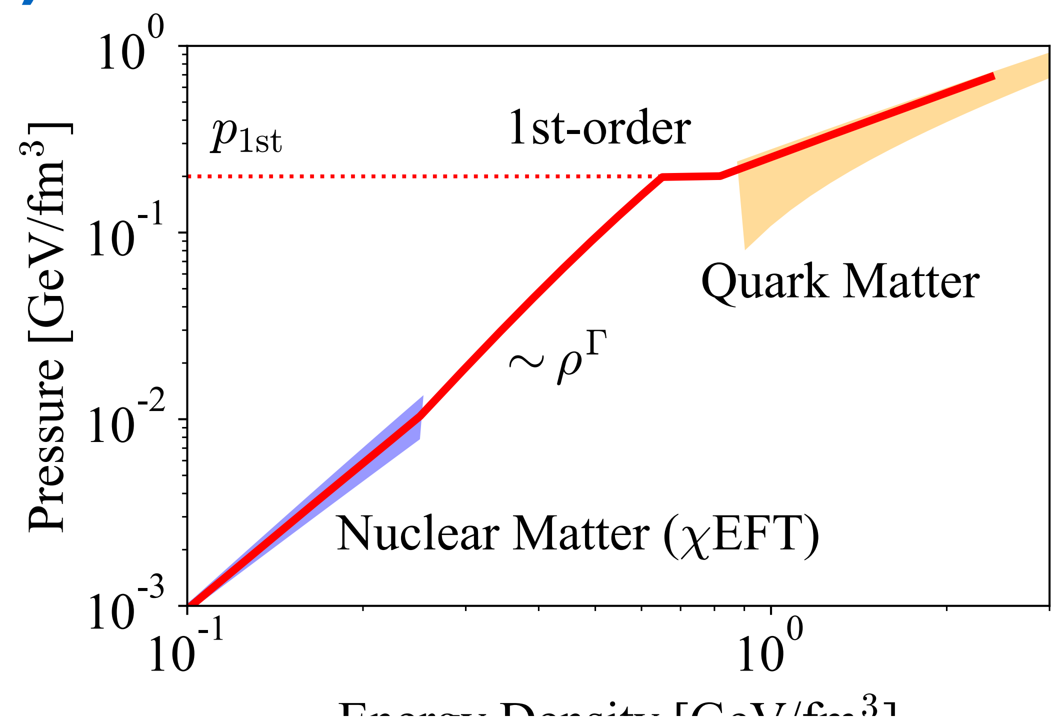

Simulating this case is enough for the current purpose

(3) Strong 1st-order @ high ρ