Gravitational Waves Probing Quark Matter Crossover

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— Baryon rich matter, neutron stars, and gravitational waves —

Multi-Messenger Astrophysics

GW170817 **Phys. Rev. Lett. 119, 161101 (2017)**

Advanced LIGO/Virgo reported the gravitational waves from the binary NS merger on August 17, 2017.

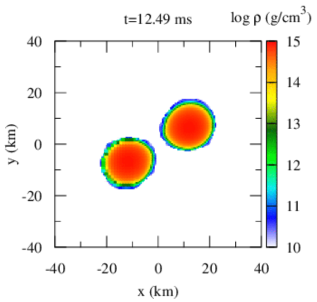
Distance was only **40Mpc** (many theory calculations were around 100Mpc but thought to be too optimistic…)

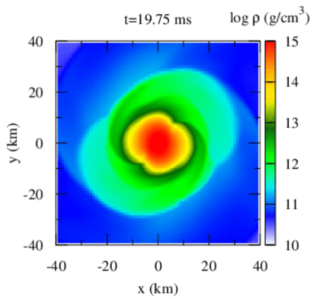
Total mass ~ 2.75$M_\odot$

Kilonova (AT 2017gfo) was confirmed: thermal radiation of light — an important hint for the *r*-process
Ejecta mass ~ 0.05$M_\odot$

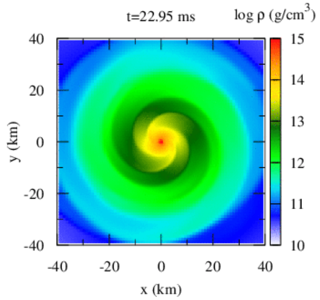
Gravitational Waves

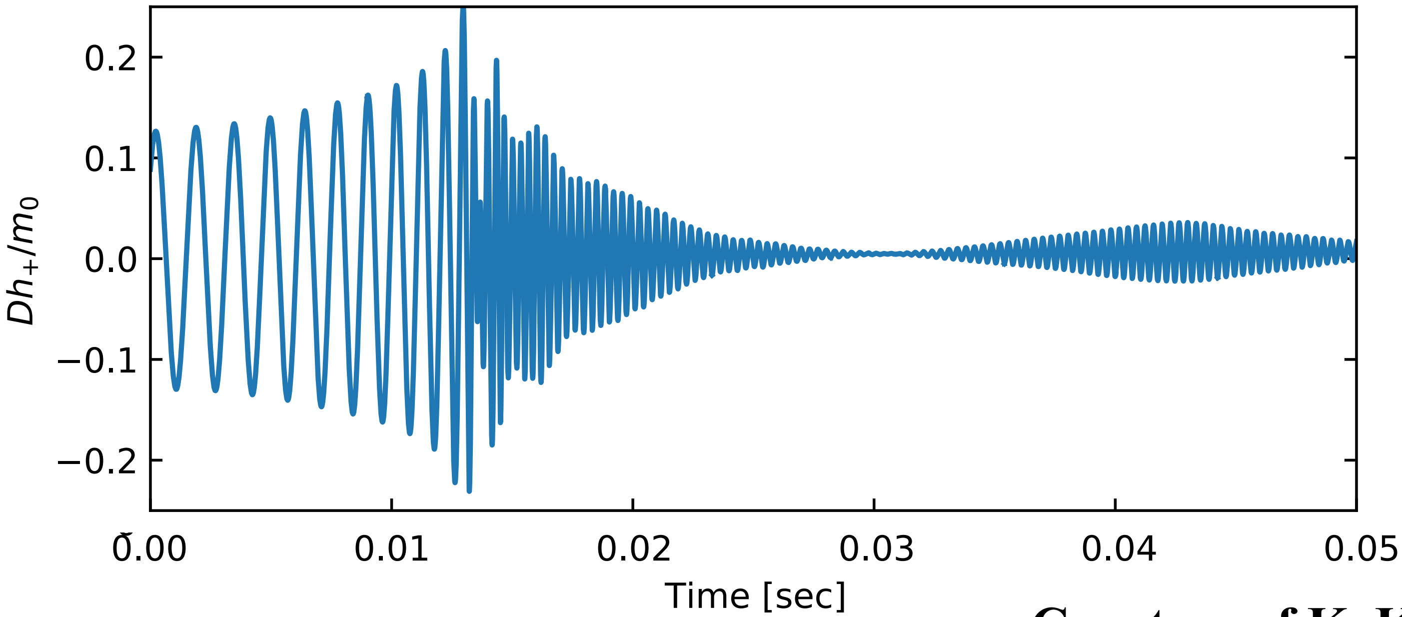
[Inspiral] **[Post-Merger]** **[Blackhole]**





Density grows

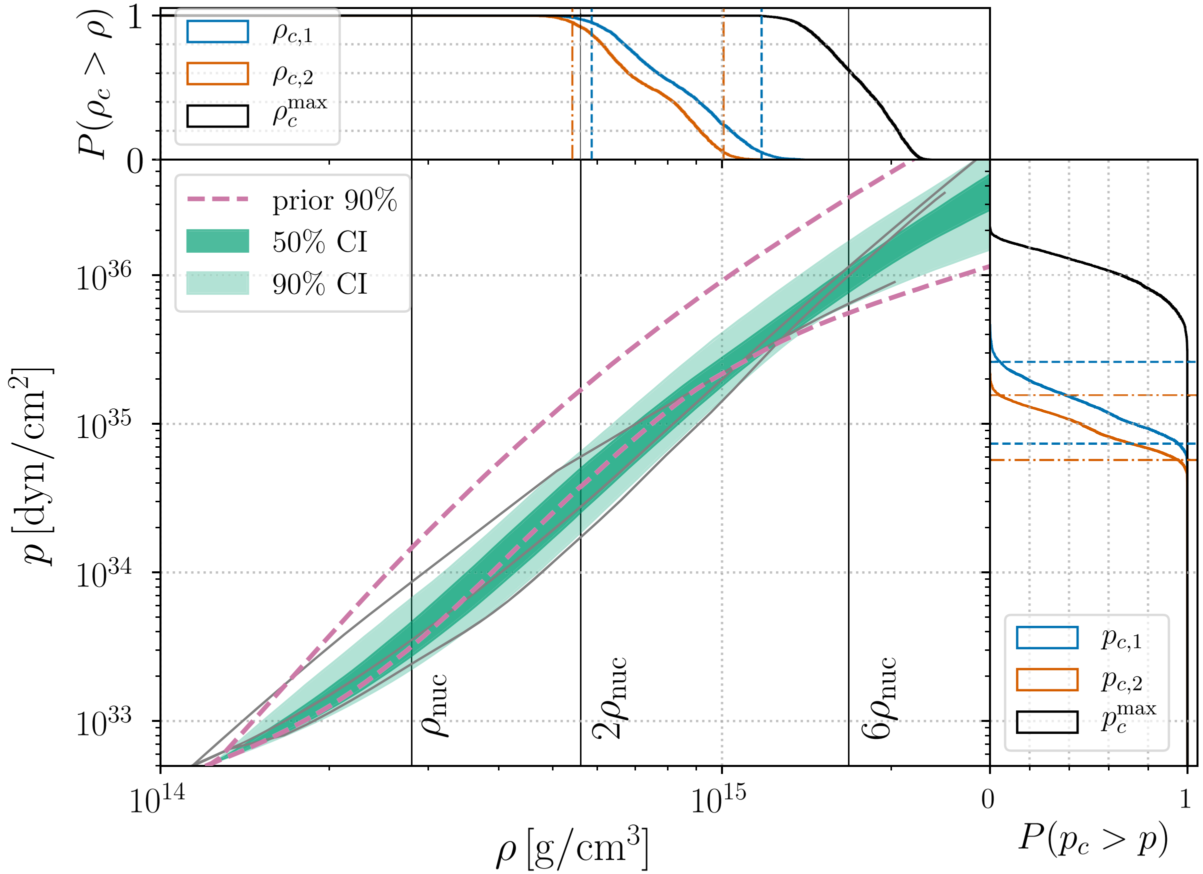




Courtesy of K. Kyutoku

Constraints from inspiral on EOS

LIGO/Virgo: Phys. Rev. Lett. 121, 161101 (2018)



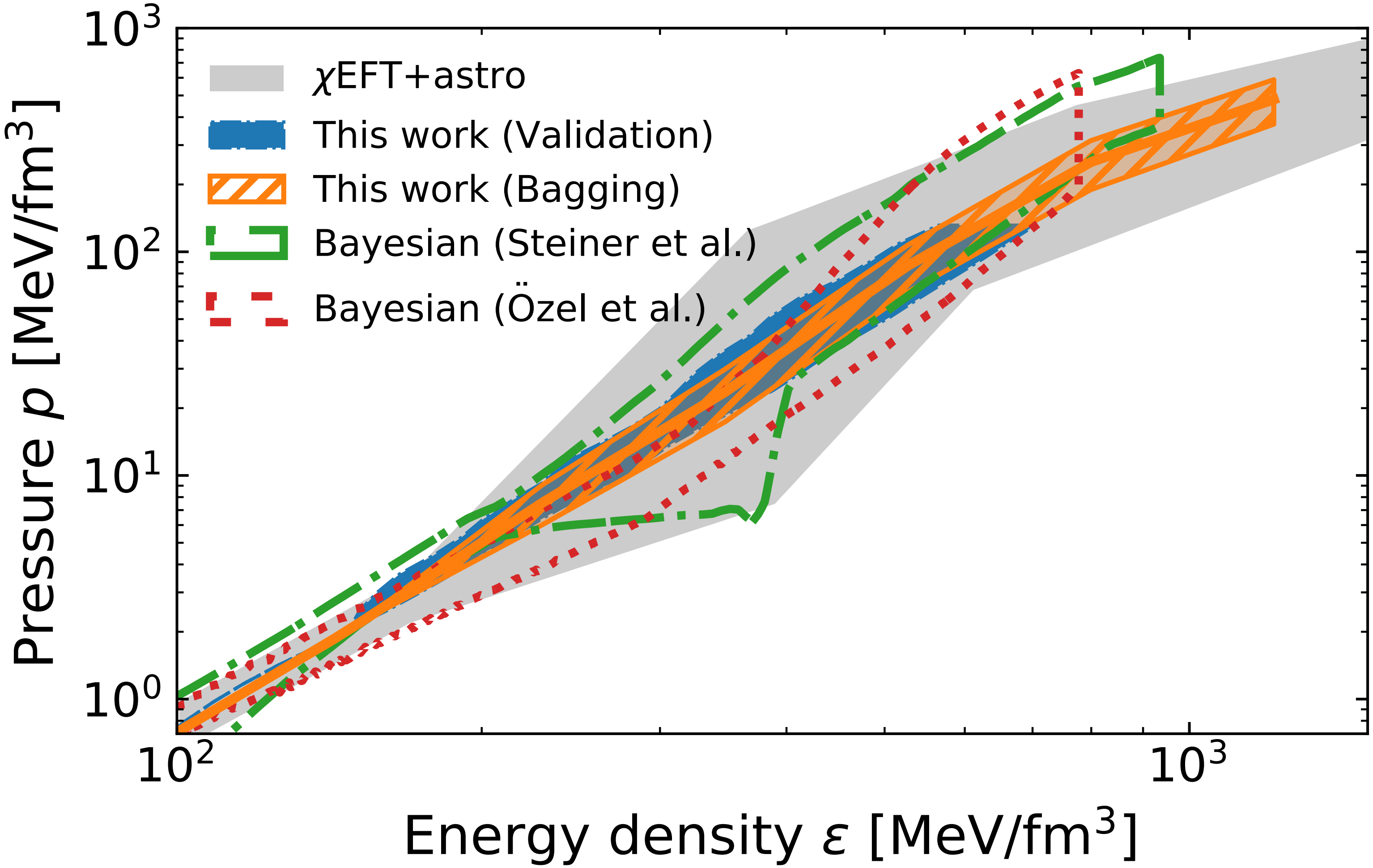
Softer than H4?
WFF1 okay?
APR4 preferred?

Favors soft EOS at low density
(high density regions really constrained?)

More stringent constraints should be coming in the future!

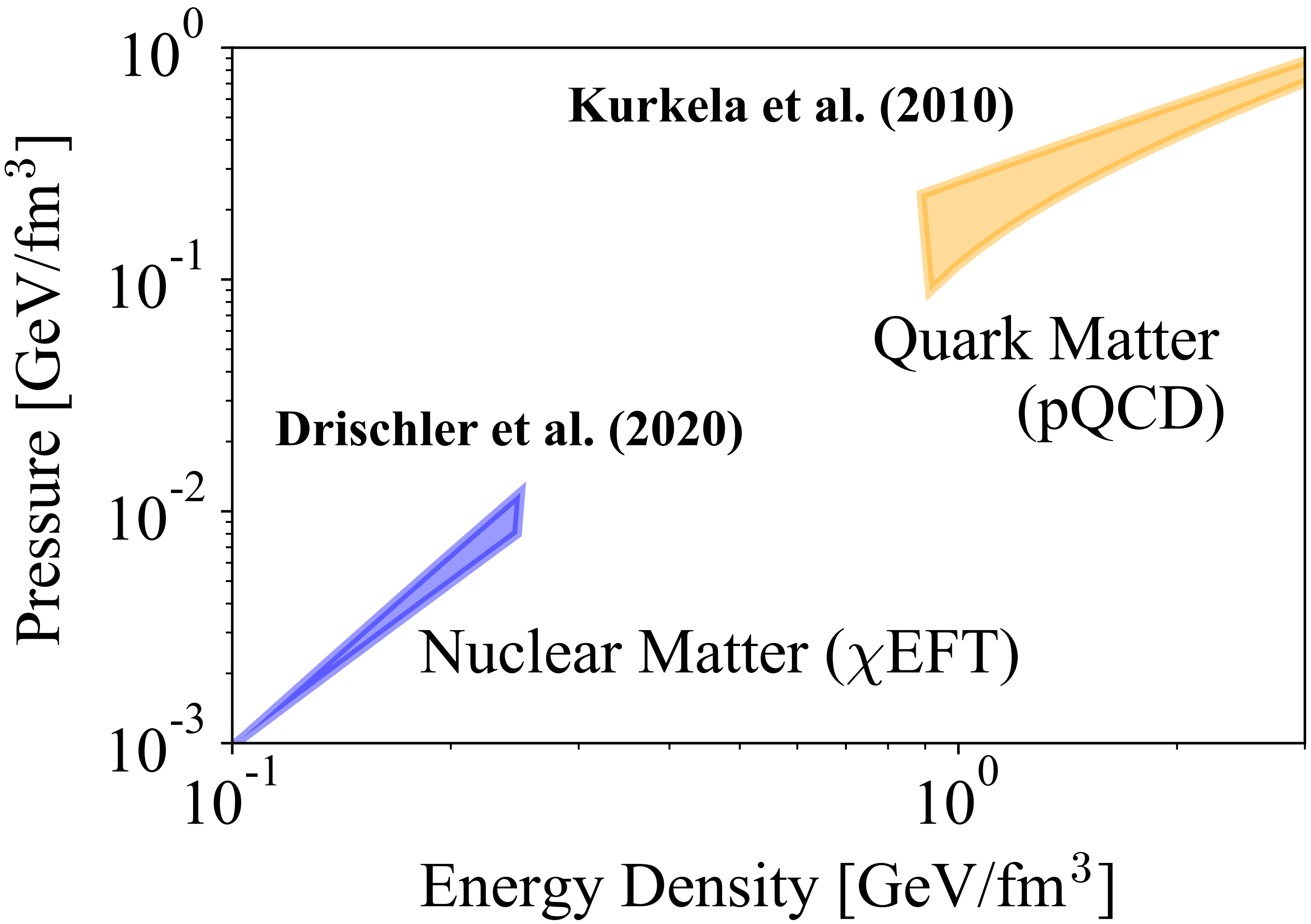
Various Inferences of EOS

Fujimoto-Fukushima-Murase (2018,19,21)



Unbiased View of EOS

Ab Initio Constraints



$\bar{\Lambda}/\mu_q = 2 \sim 4$

Upper edge is favored by resummed pQCD; see, Fujimoto-Fukushima (2020)

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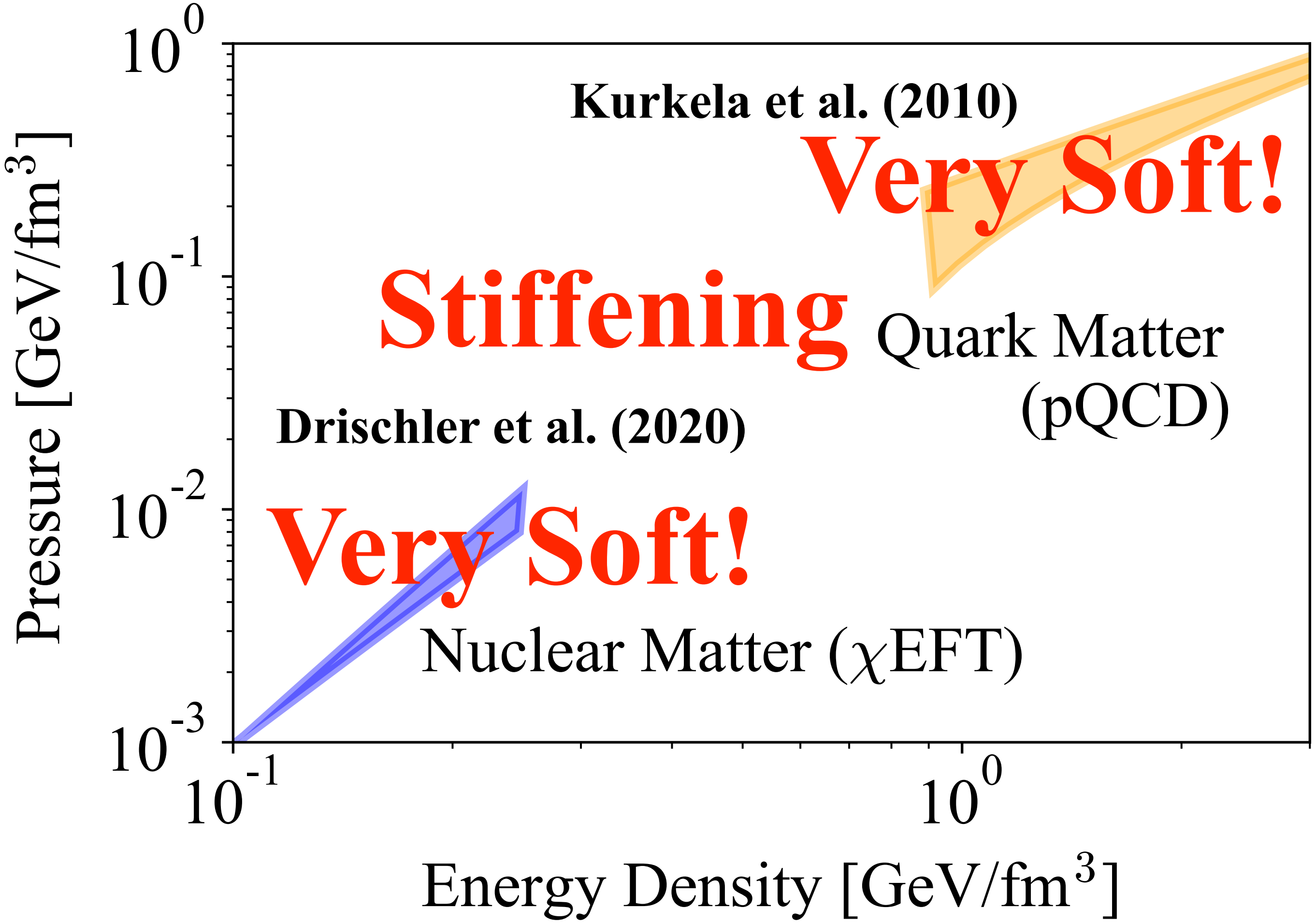

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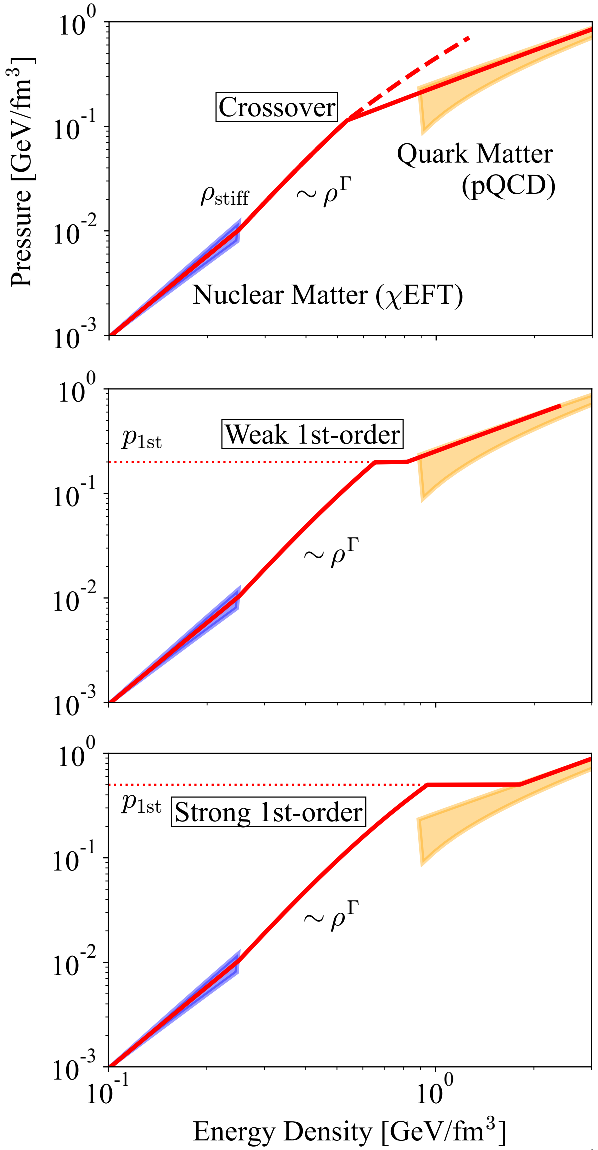
Possible EOS Scenarios



Stiffening is absolutely necessary to support the two-solar-mass NS.

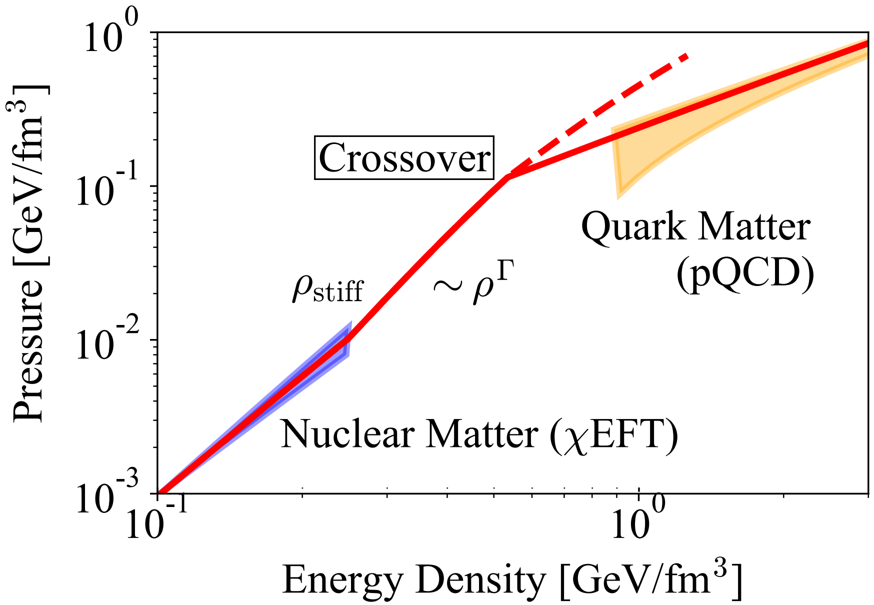
Too much stiffening would violate the causality (speed of sound limit).

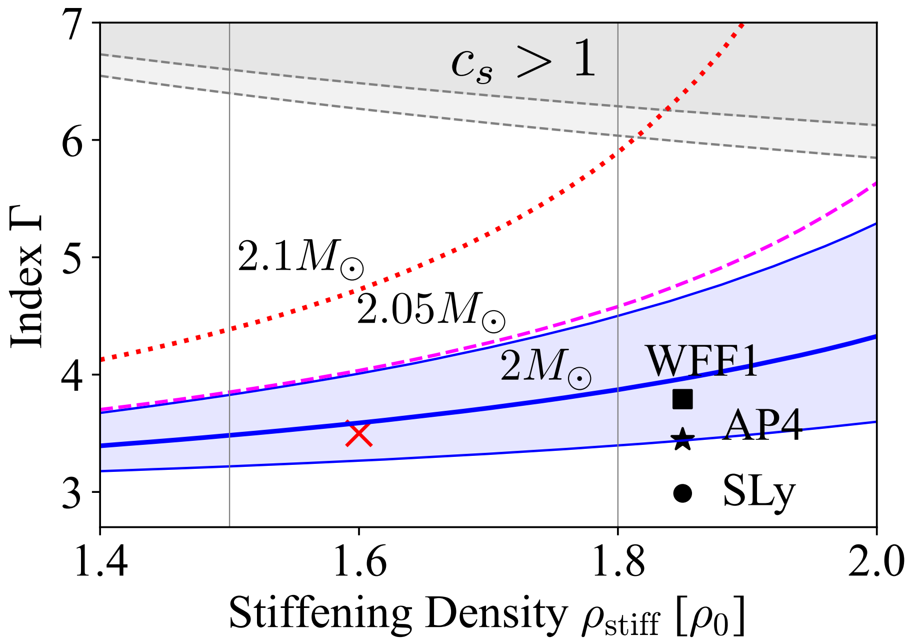
Weak 1st-order transition is not distinguished from crossover within the resolution of observation.

We make a comparison with crossover (or weak 1st-order PT) and without crossover (or strong 1st-order PT).

Possible EOS Scenarios

Allowed region of parameters:





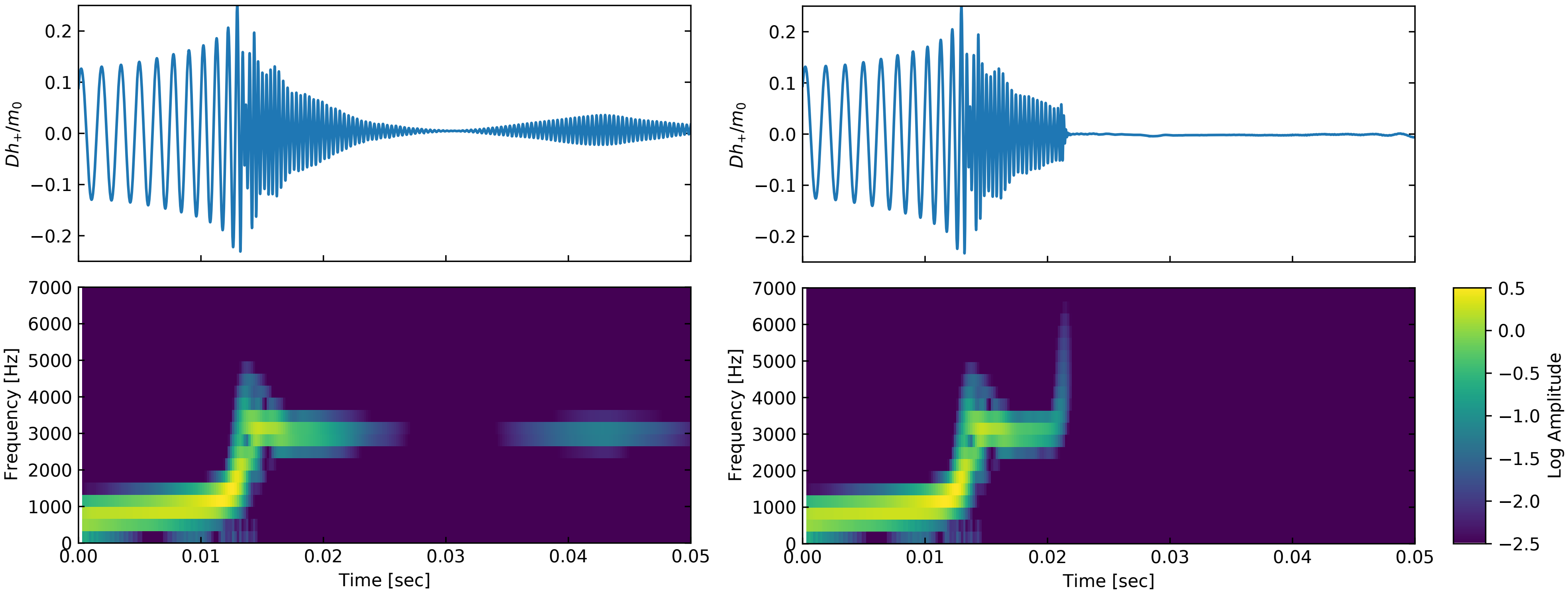
Fujimoto-Fukushima-Hotokezaka-Kyutoku (appearing)

We can perform a similar analysis for the 1st-order PT.

Gravitational Wave Signals

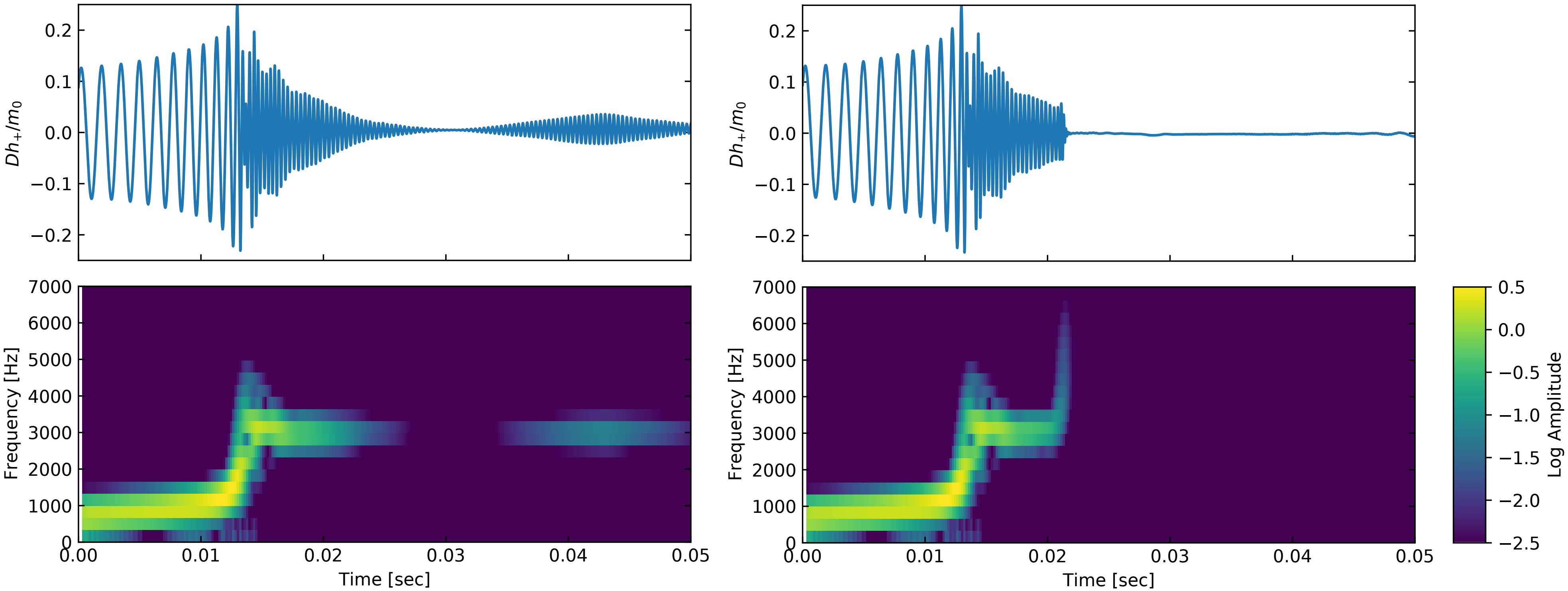
Life-time before the BH formation

Without Crossover **With Crossover**



Fujimoto-Fukushima-Hotokezaka-Kyutoku (appearing)

Gravitational Wave Signals

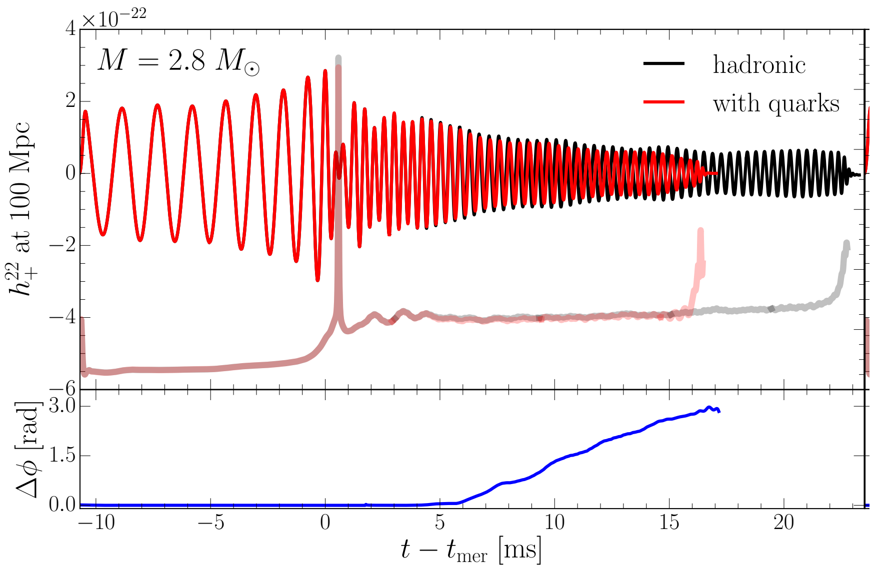


The pQCD branch of EOS is very soft and, once the density reaches the crossover point, the transient NS collapses. This behavior reflects the spectrogram (lower panels).

Preceding Works

Most-Papenfort-Dexheimer-Hanauske-Schramm-Stocker-Rezzolla (2018)

$\mathrm{CMF_Q}$: EOS with a strong-1st PT to Quark Matter (3~4 times n_0)
$\mathrm{CMF_H}$: EOS without quarks



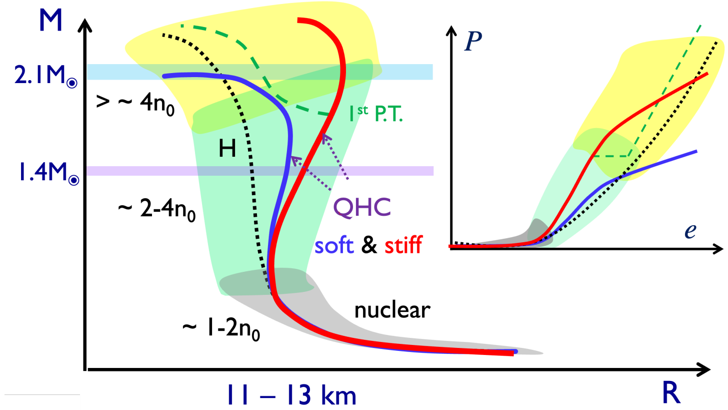
Quark matter shortens the lifetime of post-merger hypermassive neutron star.

Similar behavior to ours…

Essentially, underlying physics is the same (EOS softening is seen), but the ab initio constraints are not fully taken into account.

Preceding Works

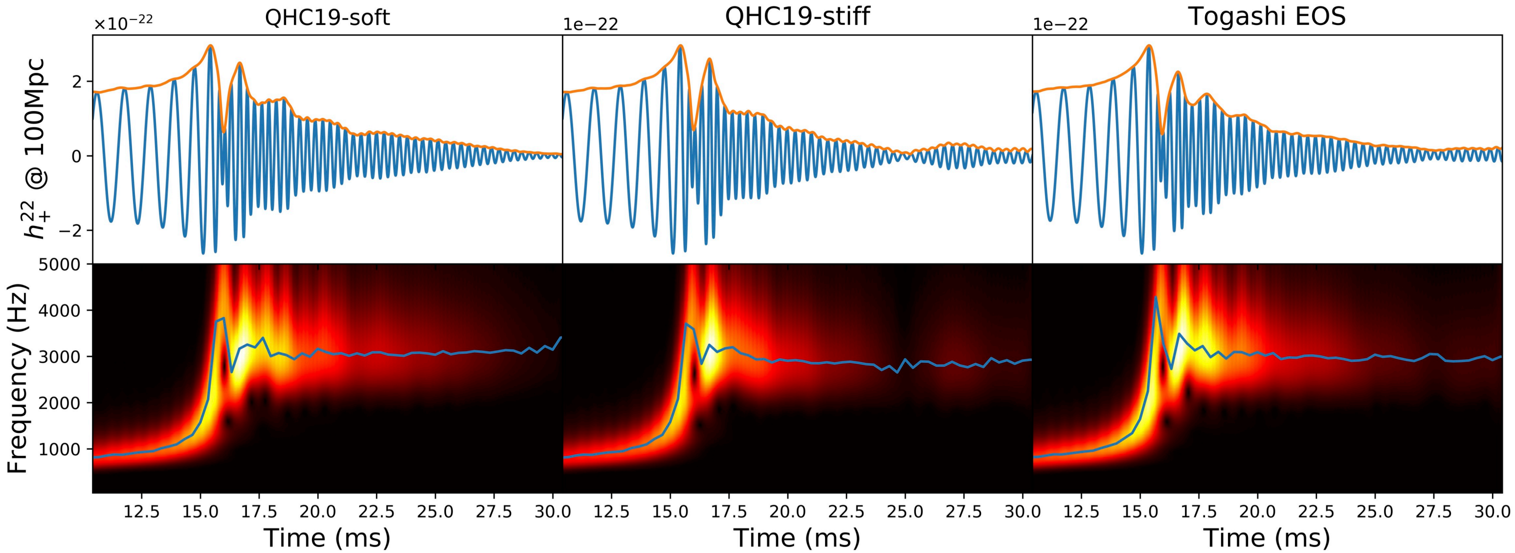
Huang et al. 2203.04528 [astro-ph.HE]



[QHC19 / Togashi EoS]

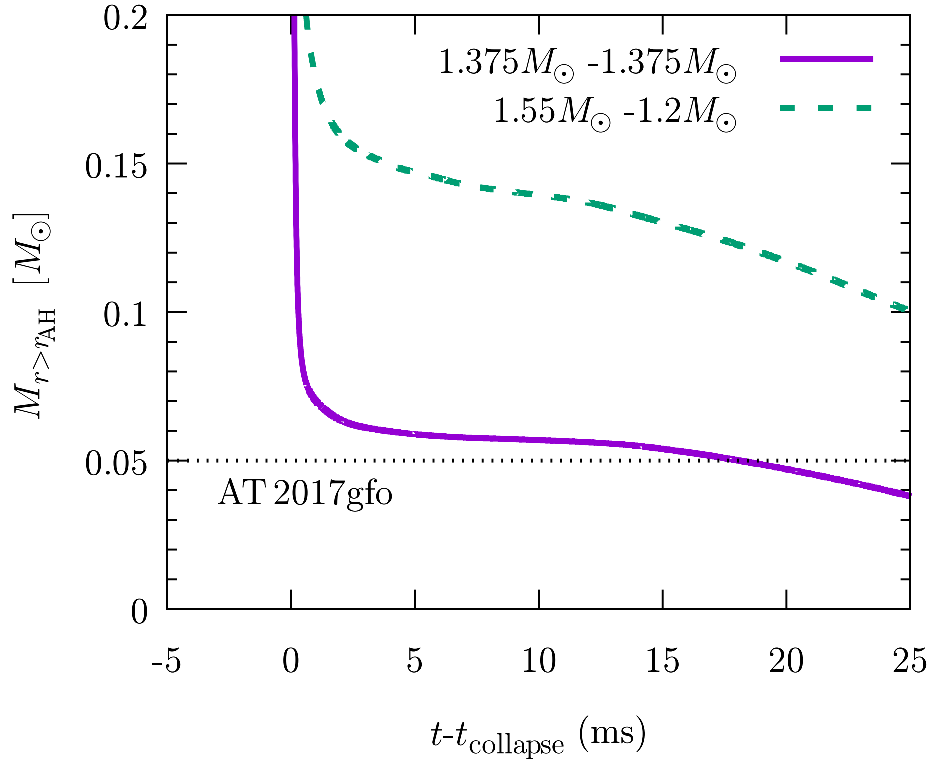
Does not approach the conformal limit (not connected to pQCD)

Consistent with our "Without Crossover Scenario"



Important Check

Fujimoto-Fukushima-Hotokezaka-Kyutoku (appearing)



From the kilonova data the ejecta mass is known to be $0.05M_\odot$

The remaining mass outside the apparent horizon after the BH formation should be larger than this mass.

Equal mass case is disfavored, but unequal mass is possible. If the mass ratio is determined independently, the ejecta mass imposes a very useful constraint on EOS.

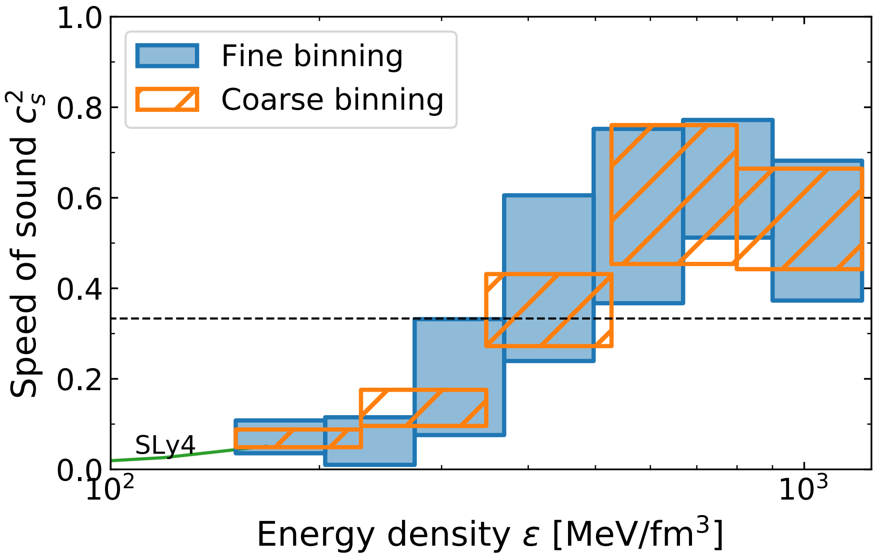
Summary

- **Gravitational waves from the post-merger stage should be sensitive to EOS at high density.**
  - Needs further upgrade but should be coming if the (reliable) theoretical prediction is made.
- **Crossover (or weak 1st-order PT at low density) vs. strong 1st-order PT at high density**
  - Life-time till the BH collapse signifies the sudden softening of EOS associated with quark matter.
- **Kilonova and ejecta mass give another constraint.**
  - Some discussions on the maximum NS mass could be changed with realistic EOS.

Backup: Speed of Sound

Machine Learning Inference

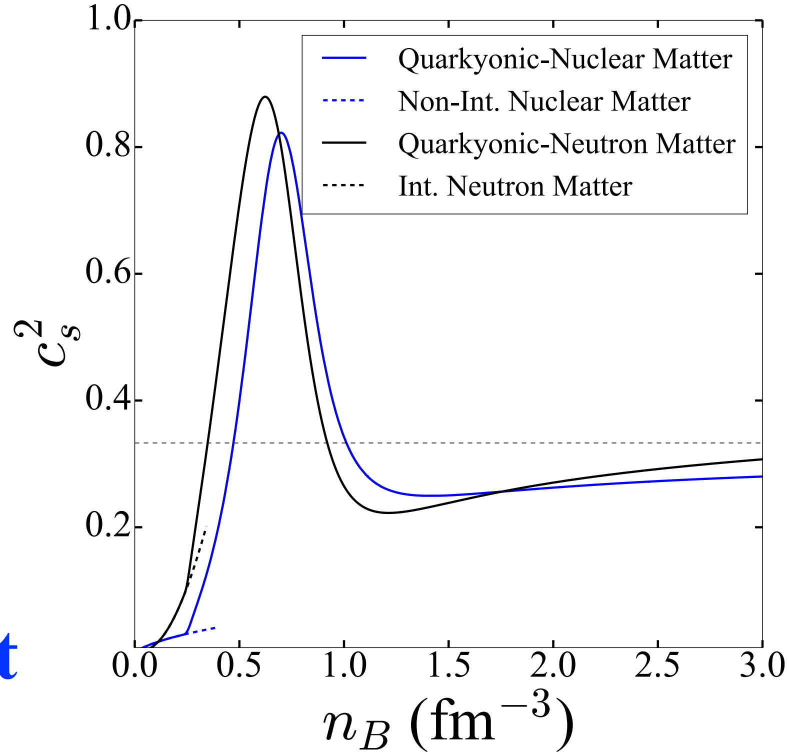
Fujimoto-Fukushima-Murase (2020)



Consistent with Soft-Stiff-Soft turning of EOS

Quarkyonic Matter

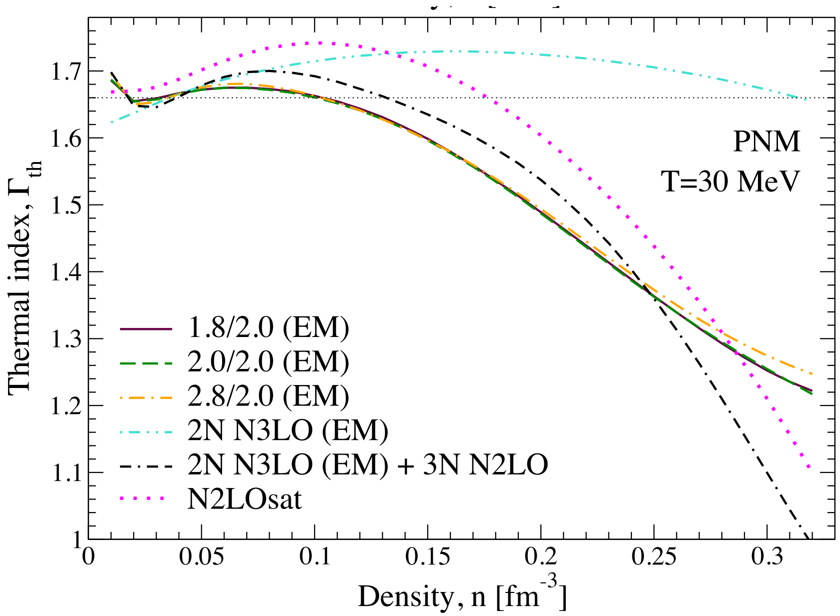
McLerran-Reddy (2018)



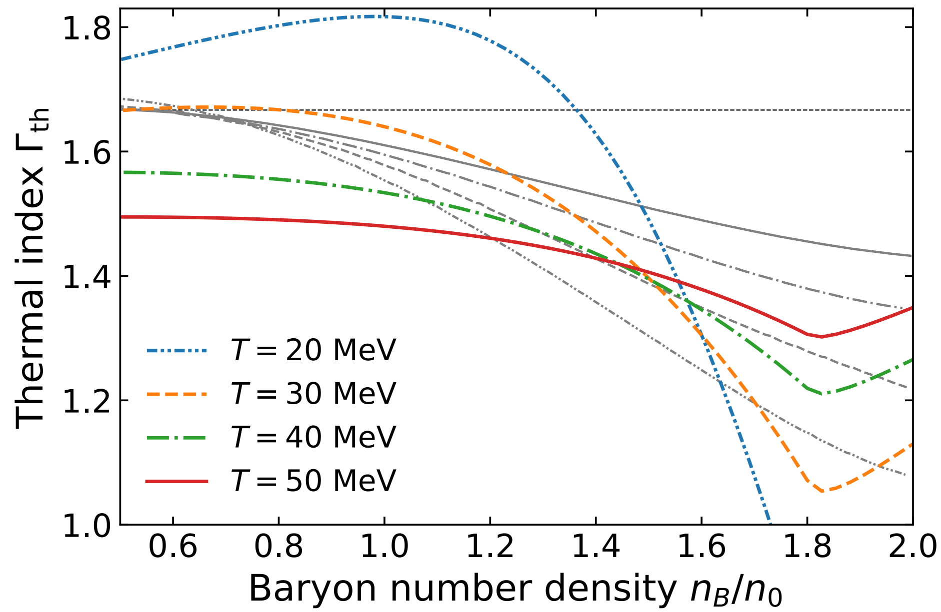
Backup: Thermal Index

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

Fujimoto-Fukushima-Hidaka-Hiraguchi-Iida (2021)



Carbone-Schwenk (2019)



Thermal index is not larger than 1.8 and could be ~1.5 at high density.