Signature of hadron-quark crossover in binary neutron star mergers

Yuki Fujimoto
(University of Washington)

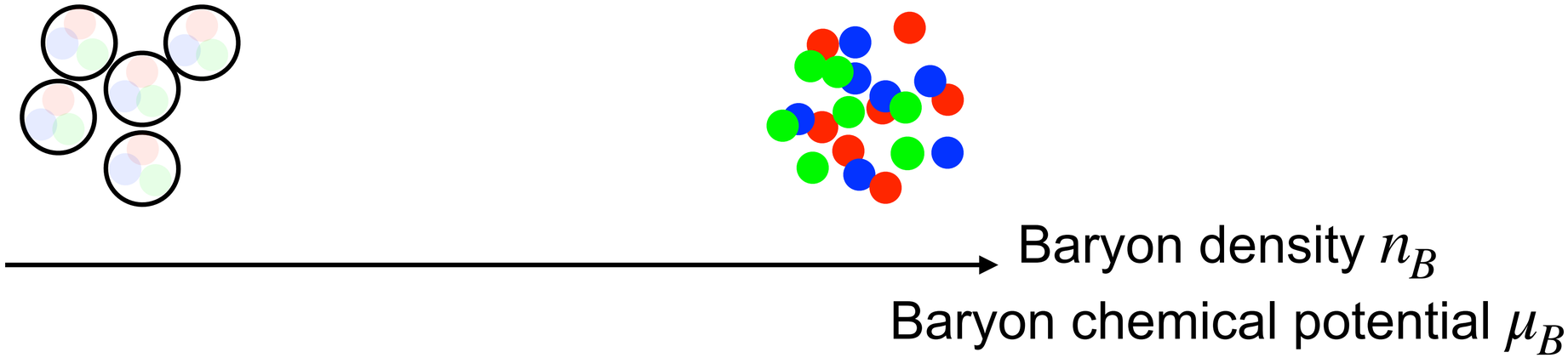
References:
[1] Y. Fujimoto, K. Fukushima, K. Hotokezaka, K. Kyutoku, PRL130 (2023) [2205.03882]; [2408.10298]
[2] Y. Fujimoto, T. Kojo, L. McLerran, PRL132 (2024) [2306.04304]

September 5, 2024 - INT Workshop: EOS Measurements with Next-Generation Gravitational-Wave Detectors

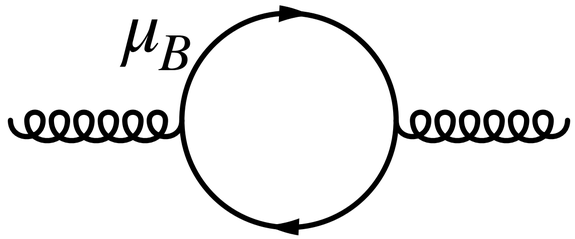
Quark deconfinement at high density

Collins & Perry (1974): **Naive picture of deconfinement**

In weak-coupling regime at high density, quarks liberate



This is led by screening of the confinement potential



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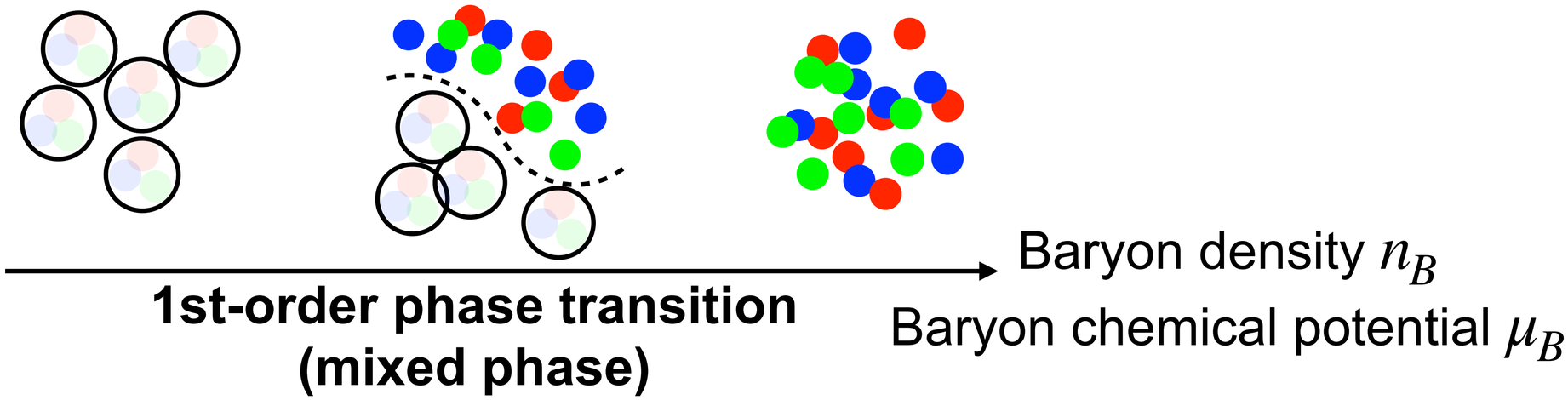

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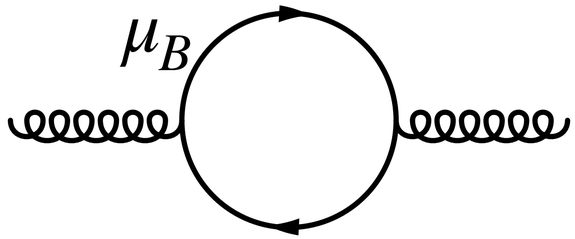
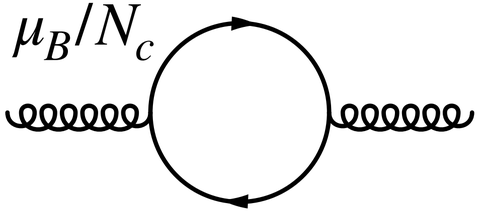


Quark deconfinement at high density

Deconfinement at high density may not be that simple…

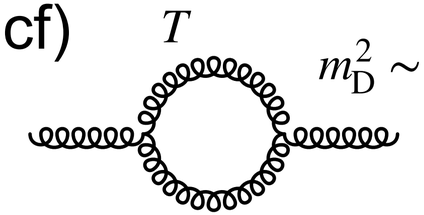
McLerran & Pisarski (2007): Quarks never deconfine in large-N_c QCD

$\mu = \mu_B / N_c$



$$m_{\mathrm{D}}^2 \sim \frac{\lambda_{\text{'t Hooft}}\, \mu^2}{N_c} \to 0$$

cf)



$m_{\mathrm{D}}^2 \sim g^2 N_c T^2$

$\sim \lambda_{\text{'t Hooft}}\, T^2$

… (de)confinement is never affected by quark medium!

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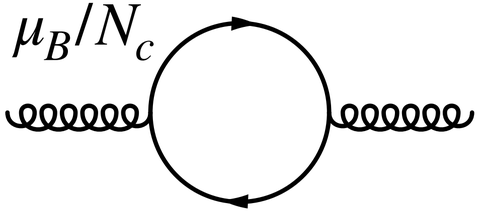

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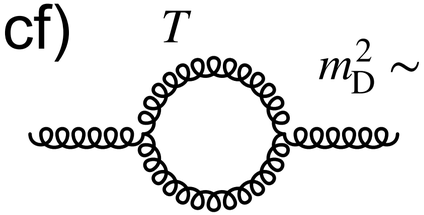

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Dense large-Nc QCD matter can be described either as

- **Confined baryons** (because confining interaction is never screened)
- **Quarks** (at densities where weak-coupling QCD is valid)

→ implies duality between quark and confined baryonic matter

Quark yonic

Quark deconfinement at high density

Another famous examples

Son & Stephanov (2000): QCD at finite isospin density and zero baryon density

- Quarks are gapped by Δ
- At energy scale below the gap Δ, no Debye screening for gluons
  $\rightarrow$ only pure $SU(3)$ gluodynamics, which is confining!

Cf. Srimoyee Sen's talk last week

Rischke, Son & Stephanov (2001): Two-flavor color superconductor

- Color superconductor "breaks" the gauge redundancy: $SU(3)_c \rightarrow SU(2)_c$
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These examples also points to the duality between confined hadrons and quarks

Hadron-quark crossover

- These are examples for confinement-deconfinement duality

- Such duality leads to **hadron-quark crossover** in the EoS
  Not 1st-order phase transition

- This was confirmed by model analysis in
  Fujimoto, Kojo, McLerran, PRL132 (2024)
  See also: McLerran,Reddy (2018); Lattimer,Zhao (2020); …

Can crossover be detectable from the postmerger signal in binary neutron star megers?

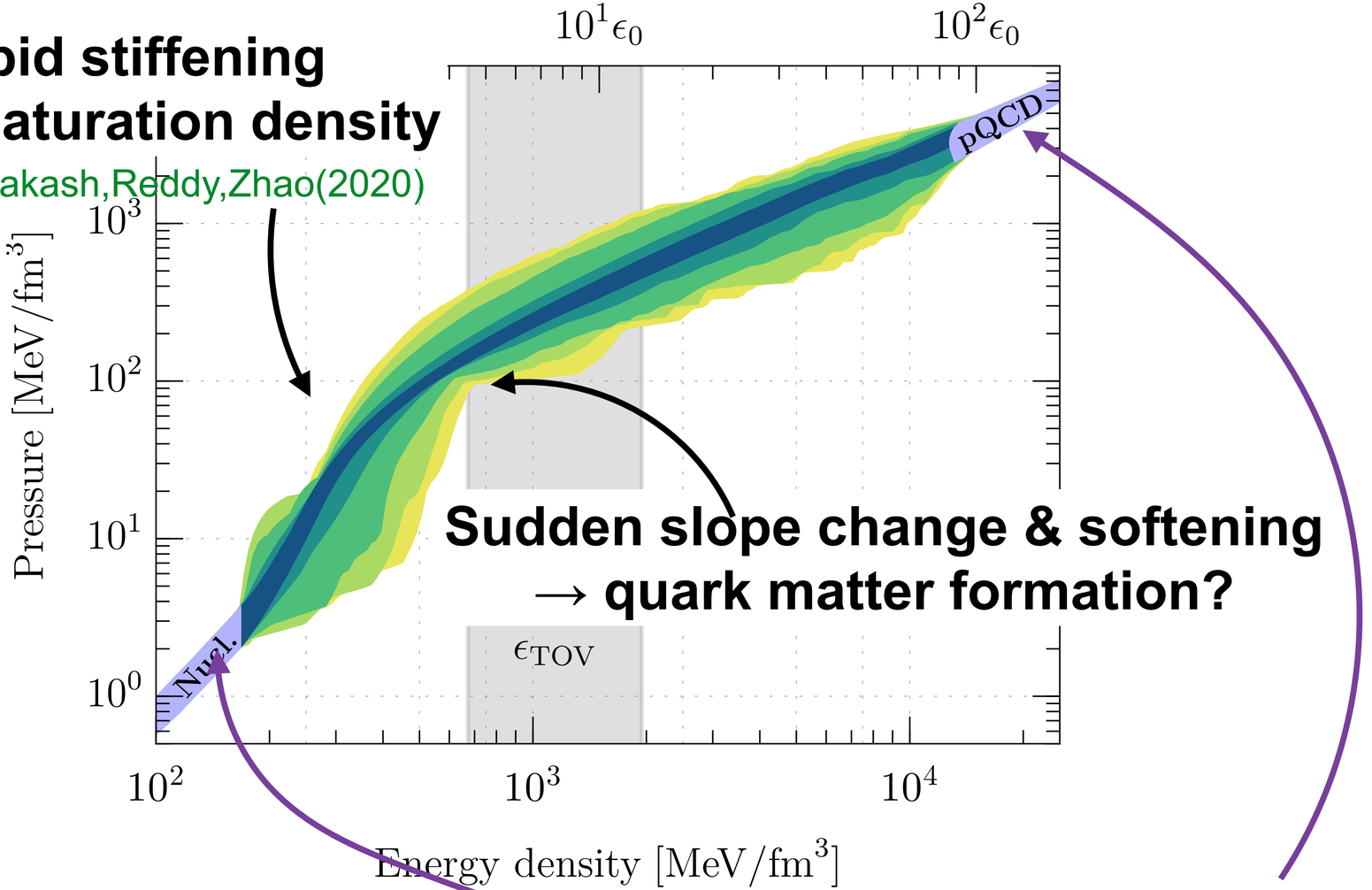
Modeling the crossover EoS

Annala,Gorda,Katerini,Kurkela,Nättilä,Paschalidis,Vuorinen (2021)

QCD-based view:

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

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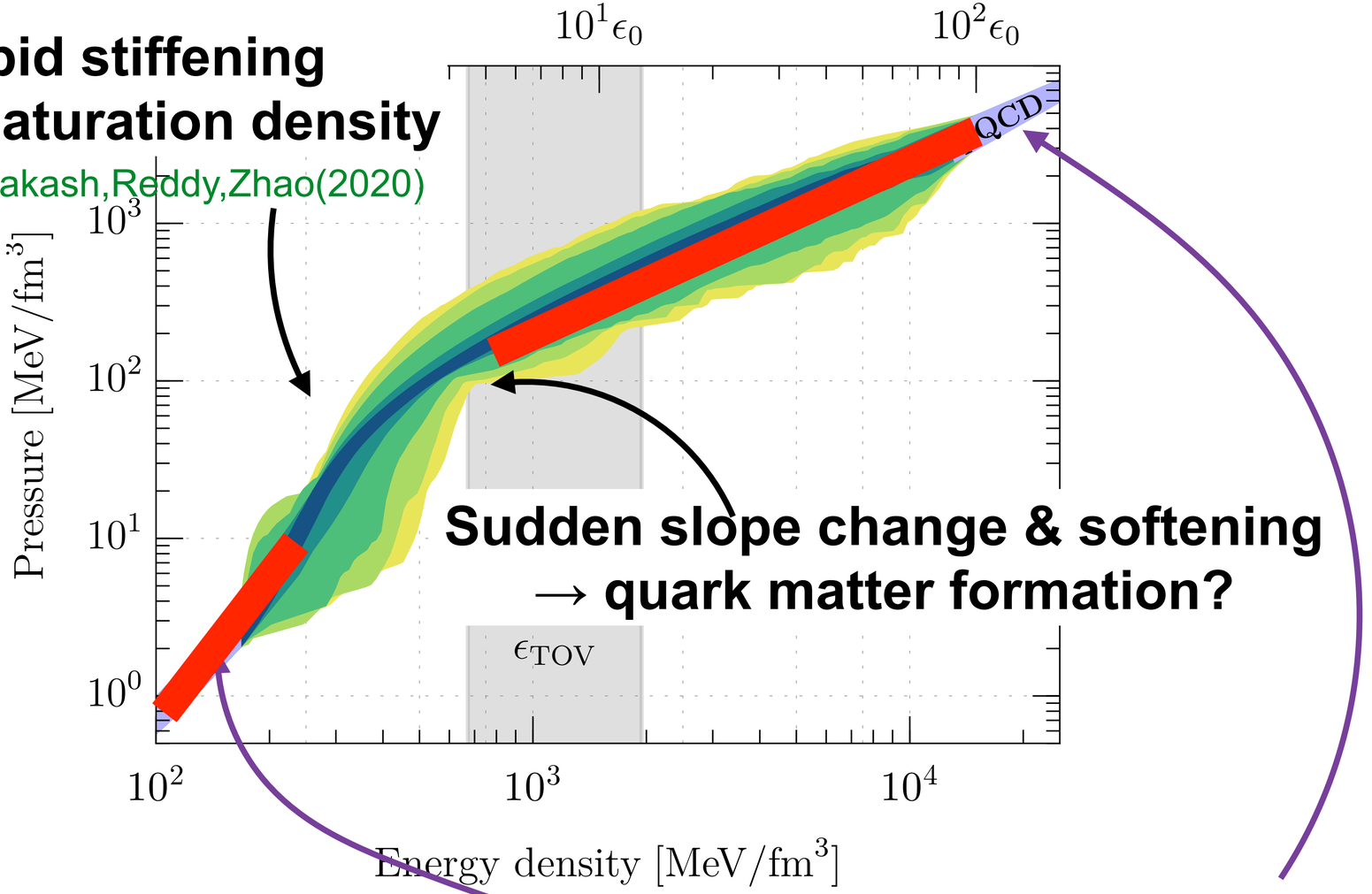

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Modeling the crossover EoS

Fujimoto,Fukushima,Hotokezaka,Kyutoku, PRL130 (2023)

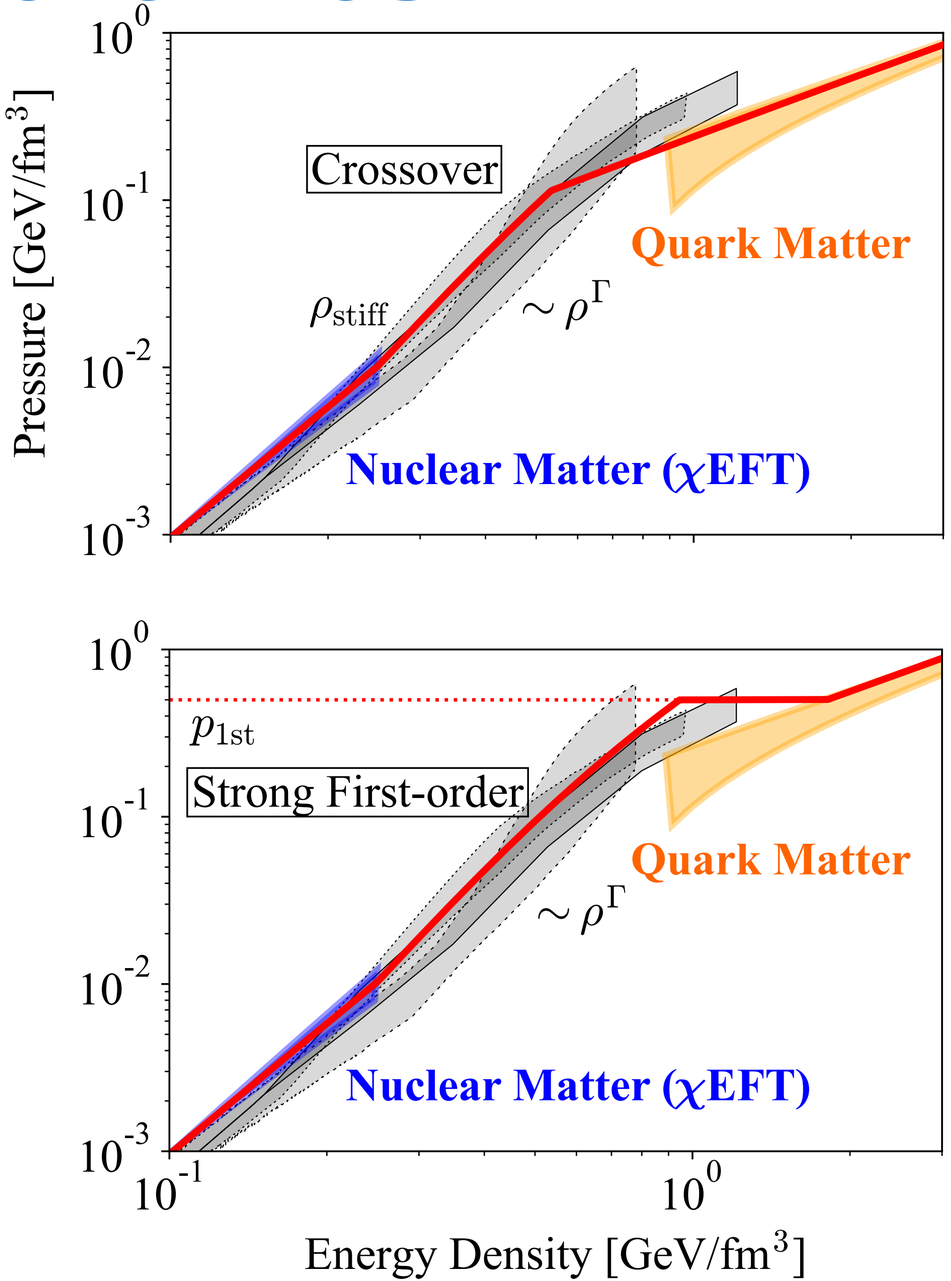
Crossover (CO):

Smoothly connects two limits
by fulfilling the two-solar-mass condition

vs

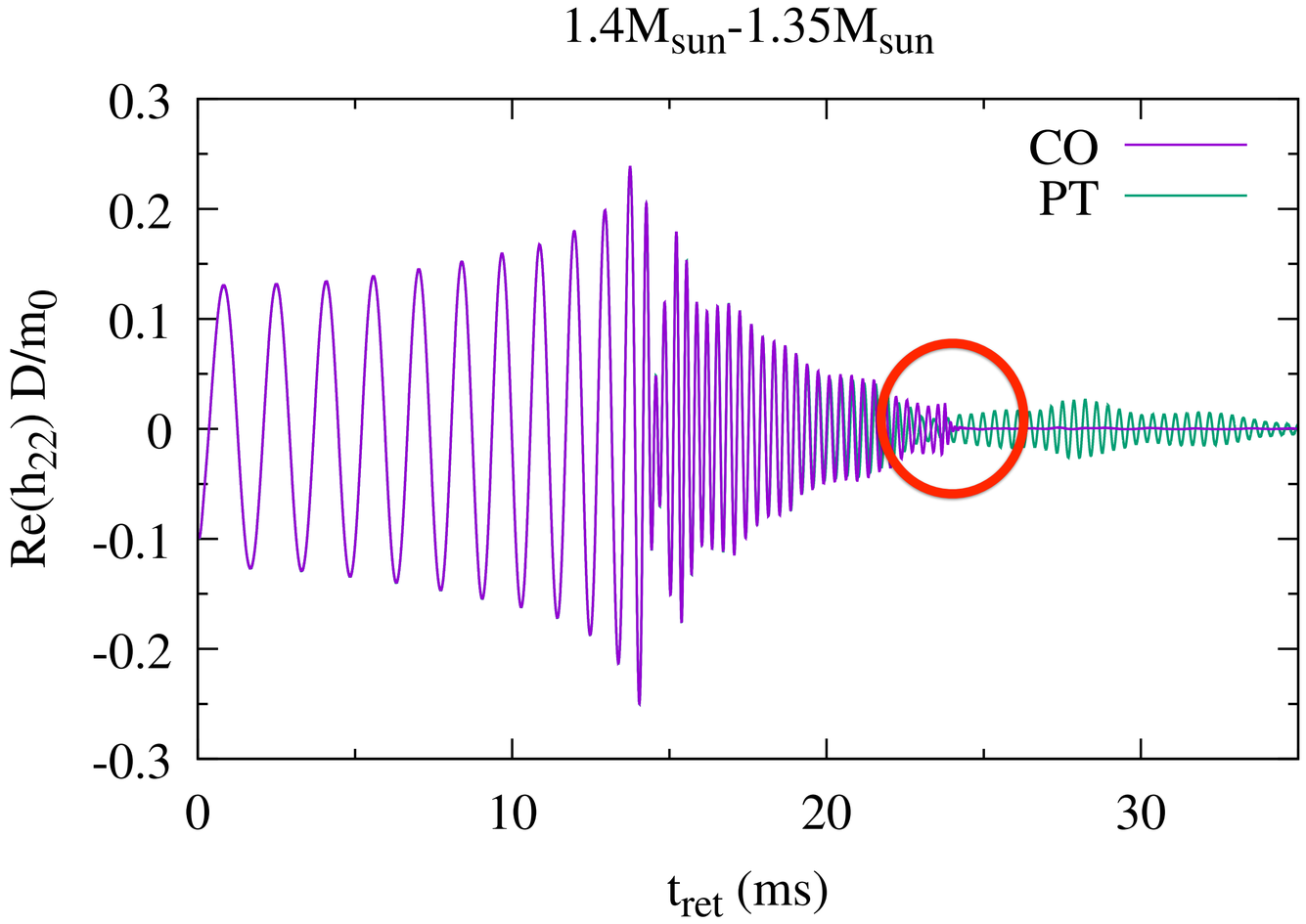
1st-order Phase Transition (PT):

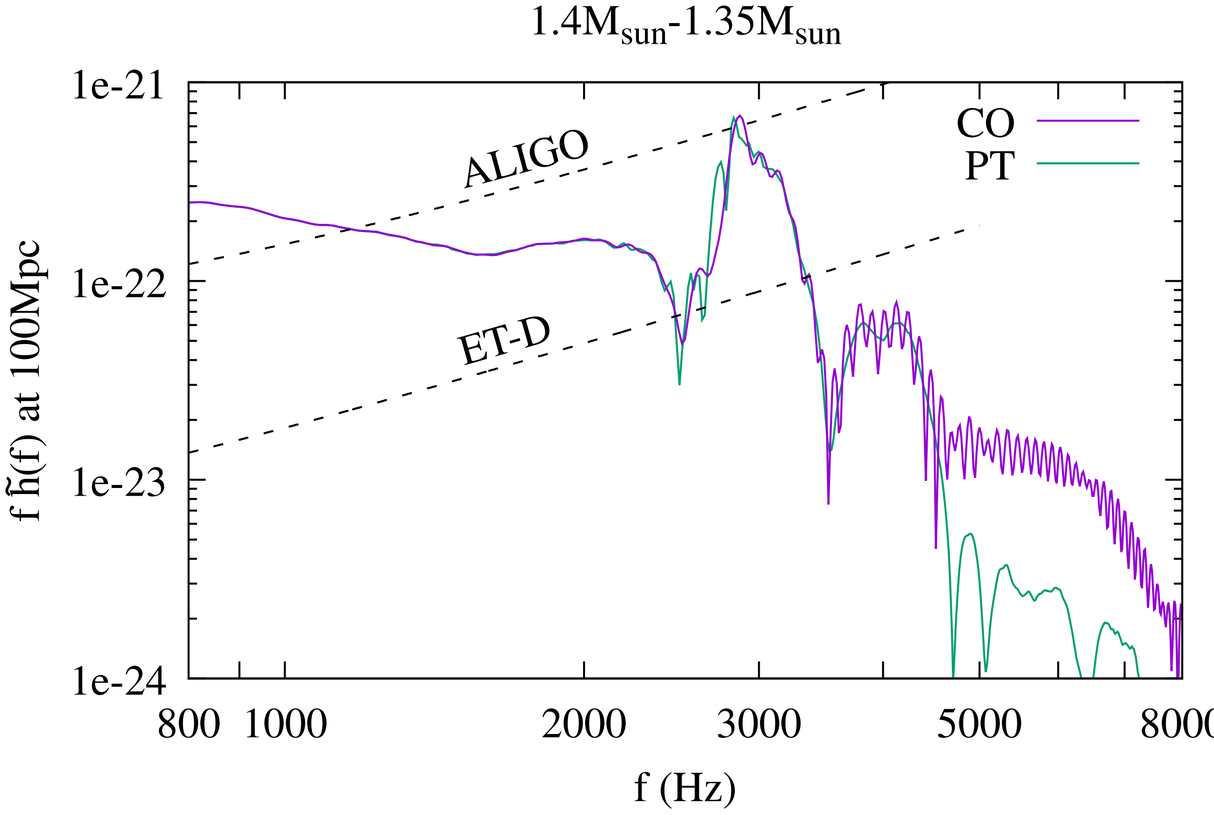
Within this setup, strong density jump
is feasible only at high density
Virtually hadronic EoS because the onset of PT
is beyond the reach of the maximum density



Postmerger signal: Black hole formation as a key

Fujimoto,Fukushima,Hotokezaka,Kyutoku, PRL130 (2023): 2408.10298



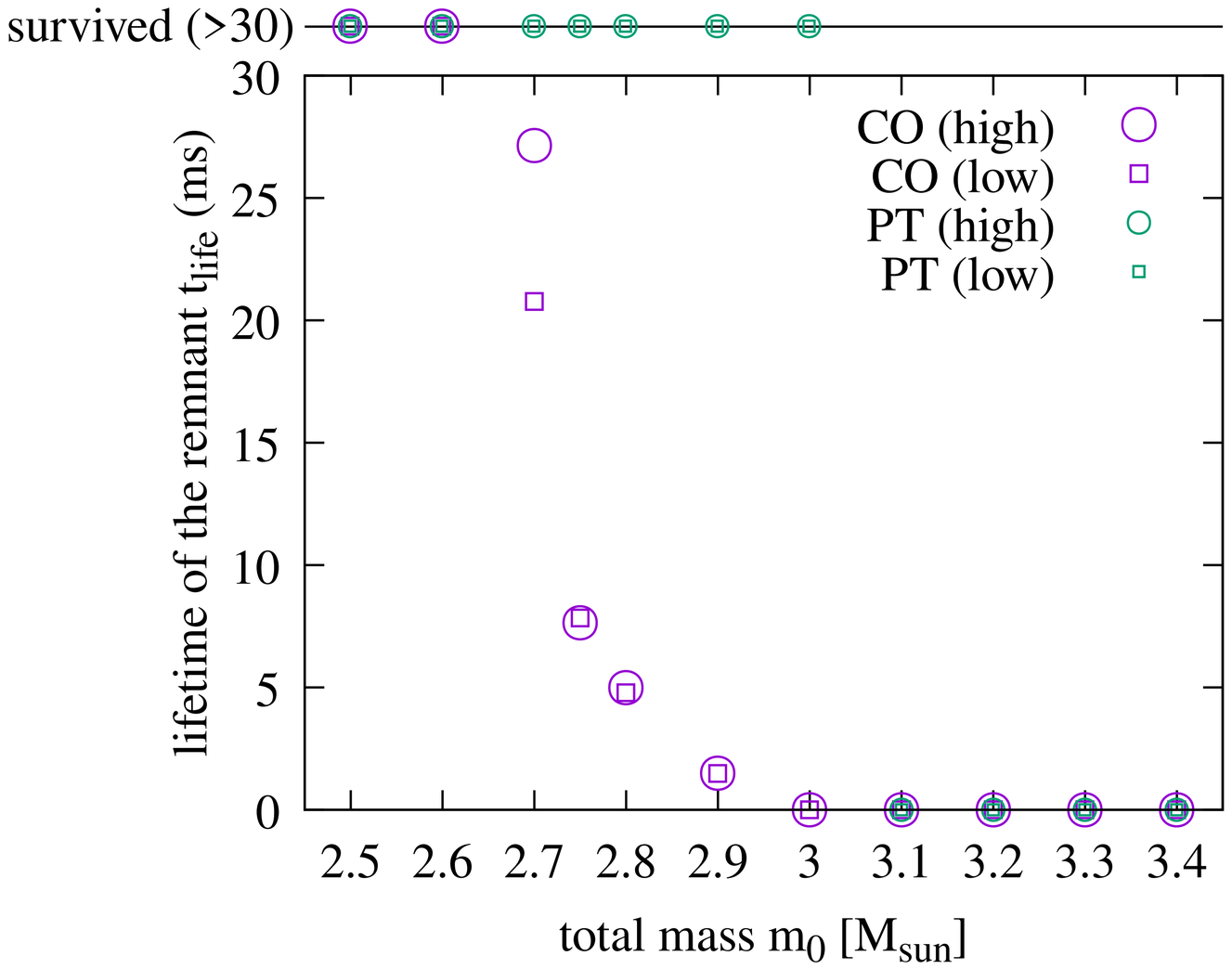


Crossover (softening) drives the collapse to black holes

Lifetime of the merger remnant

Fujimoto,Fukushima,Hotokezaka,Kyutoku, 2408.10298

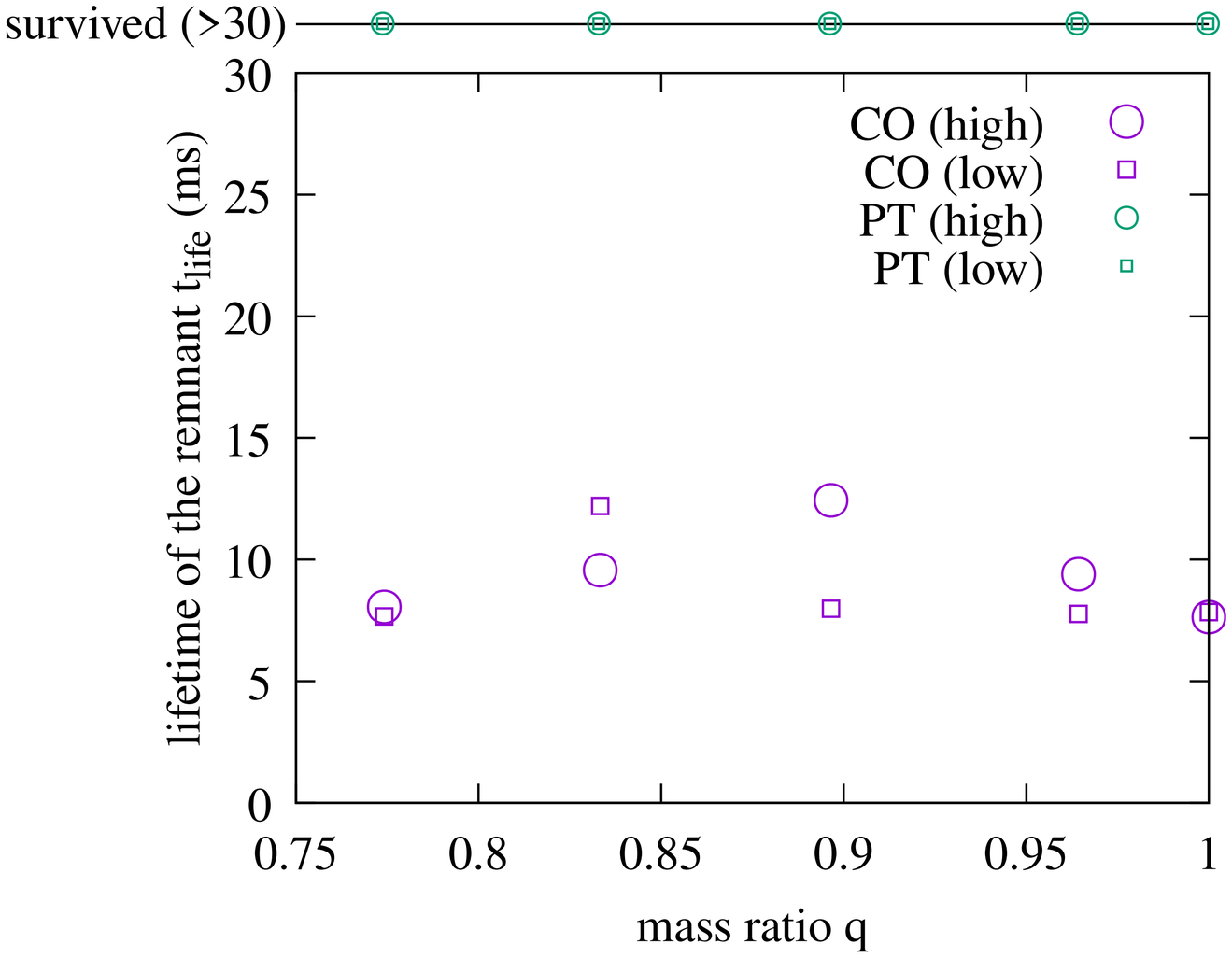
Lifetime is determined primarily by the total mass of binary



Weak dependence on mass ratio

Fujimoto,Fukushima,Hotokezaka,Kyutoku, 2408.10298

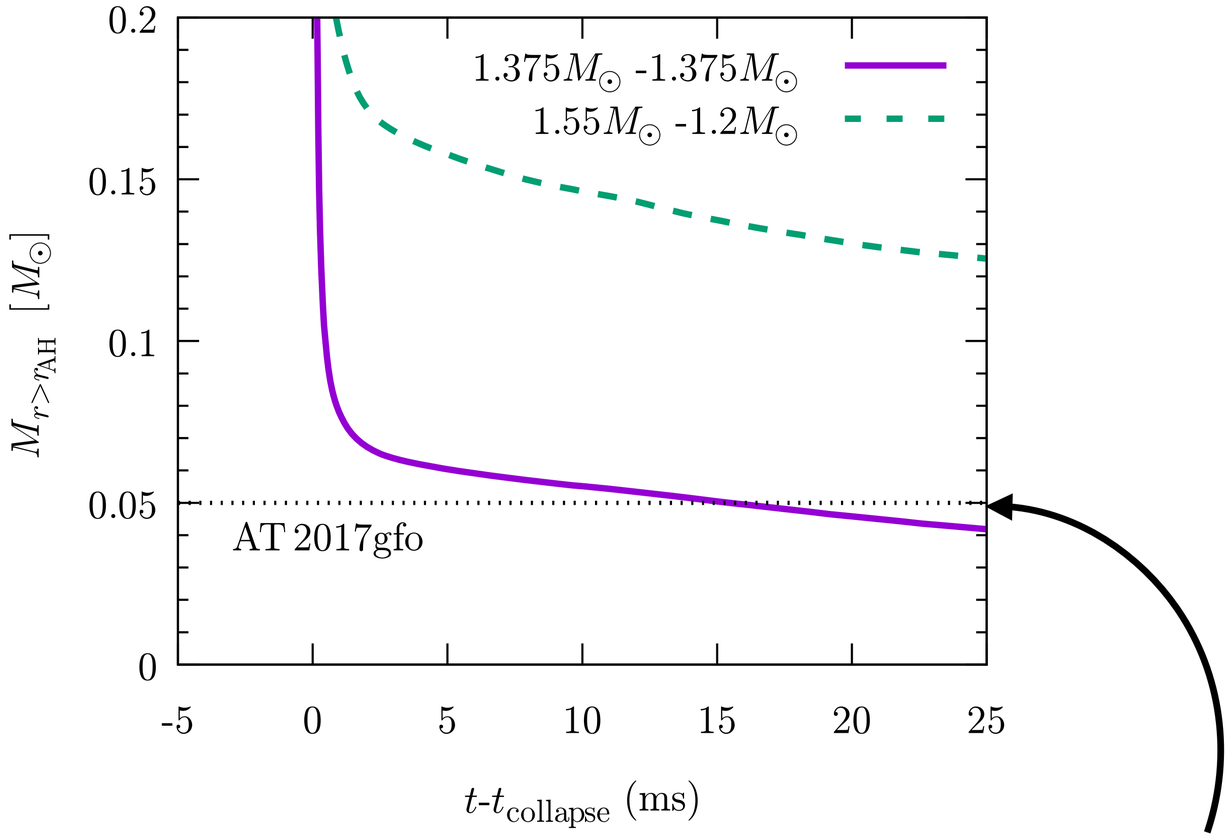
For total mass $m_0 = 2.75\,M_\odot$, mass ratio dependence is weak



Consistency with kilonova AT2017gfo

Fujimoto,Fukushima,Hotokezaka,Kyutoku, PRL130 (2023): 2408.10298

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

- **Deconfinement transition:** may not just be a simple transition to deconfined matter. Involves intricate screening and confinement. There may be a duality between confined d.o.f. and bare quarks.

- **Hadron-Quark crossover (CO):** maybe a realistic scenario. We contrasted with the strong 1st-order phase transition (PT) scenario.

- **Postmerger signals:** Blackhole formation may be regarded as a signature of the crossover within this model.
  Although strong PT is hard to accomodate within the current constraints, how can we disentangle the crossover with PT?
  Also, weak PT is still possible. Indistinguishable from CO?