Lessons from hot QCD matter and unknowns from the nuclear physics point of view

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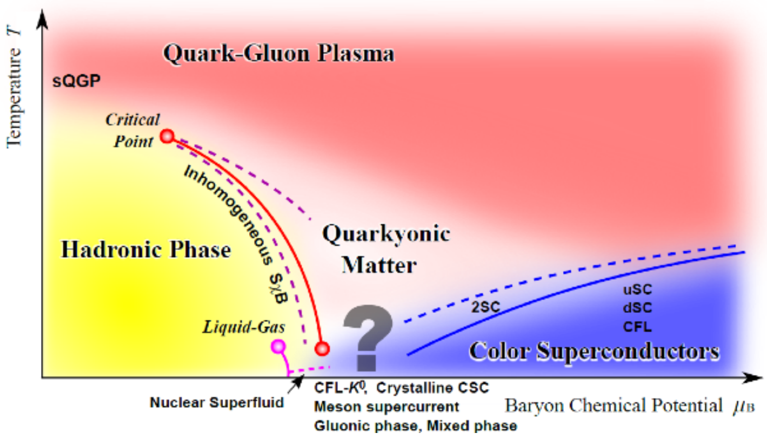
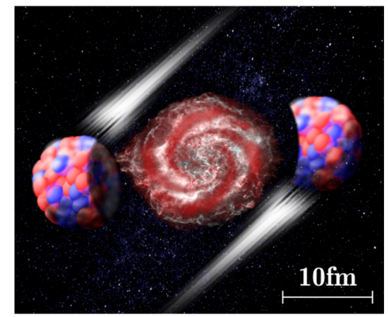
— From Quarks to Neutron Stars: Insights from kHz Gravitational Waves —

I am talking about…

Degrees of Freedom Change
→ Exotic Scenarios



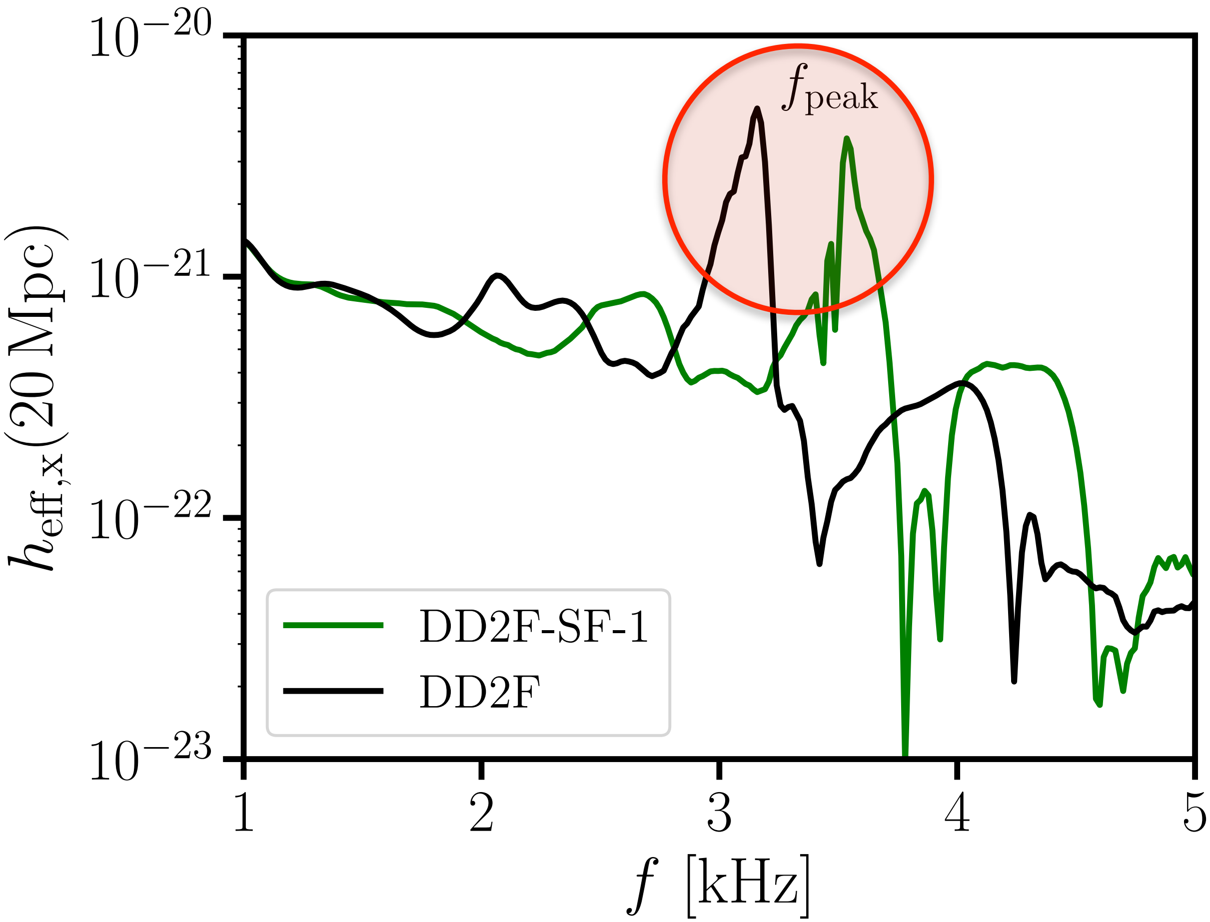
Chirality + External Fields
→ Transport



Criticality / Phases
→ Crossover vs. First-Order

Why kHz?

Bauswein-Bastian-Blaschke-Chatziioannou-Clark-Fischer-Oertel (2018)

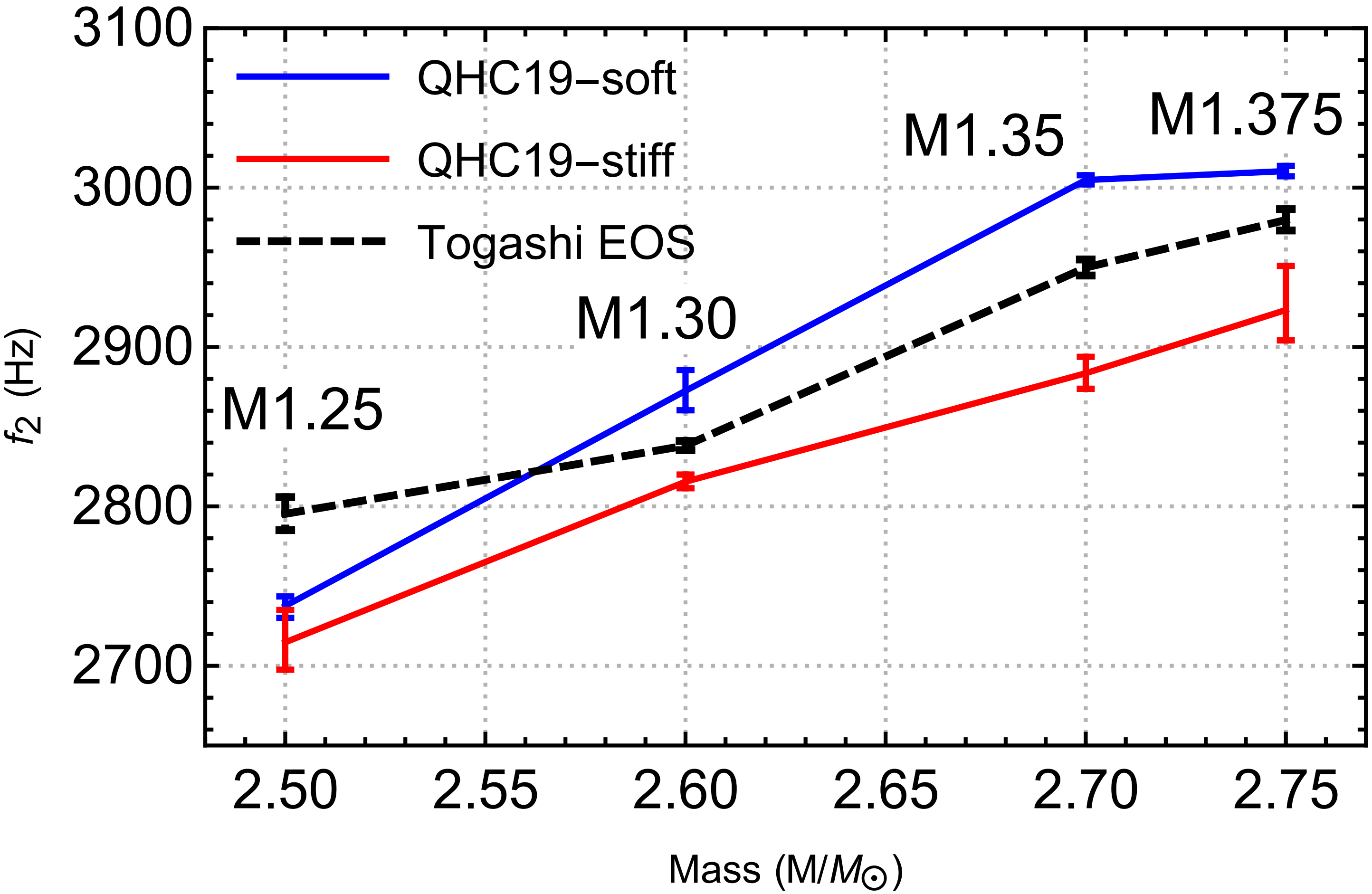


Evidence of First-Order?

Shift from what?

Why kHz?

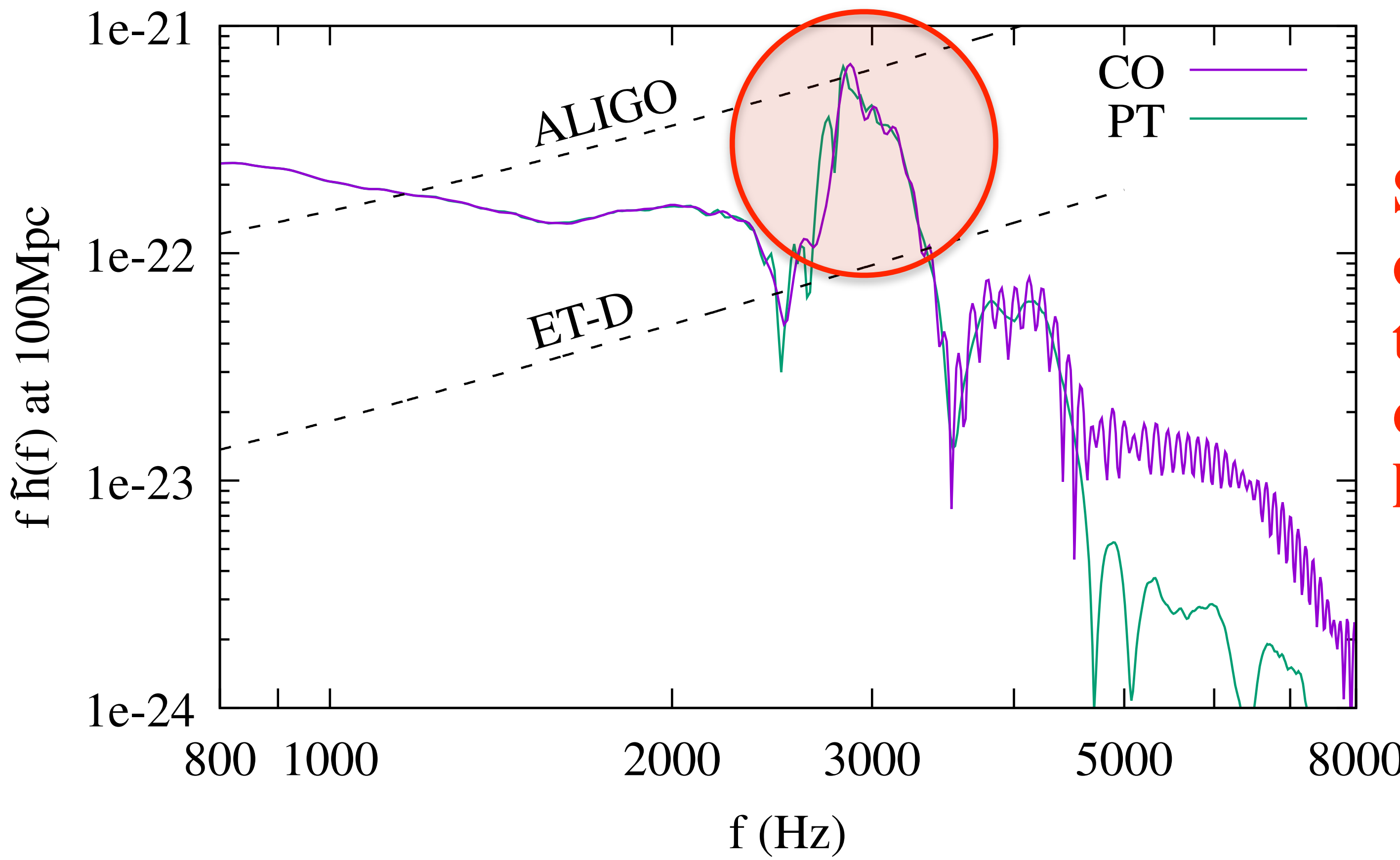
Huang-Baiotti-Kojo-Takami-Sotani-Togashi-Hatsuda-Nagataki-Fan (2022)



Why kHz?

Fujimoto-Fukushima-Hotokezaka-Kyutoku (2023/2025)

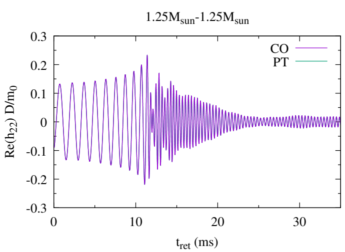
$1.4M_{sun}$-$1.35M_{sun}$

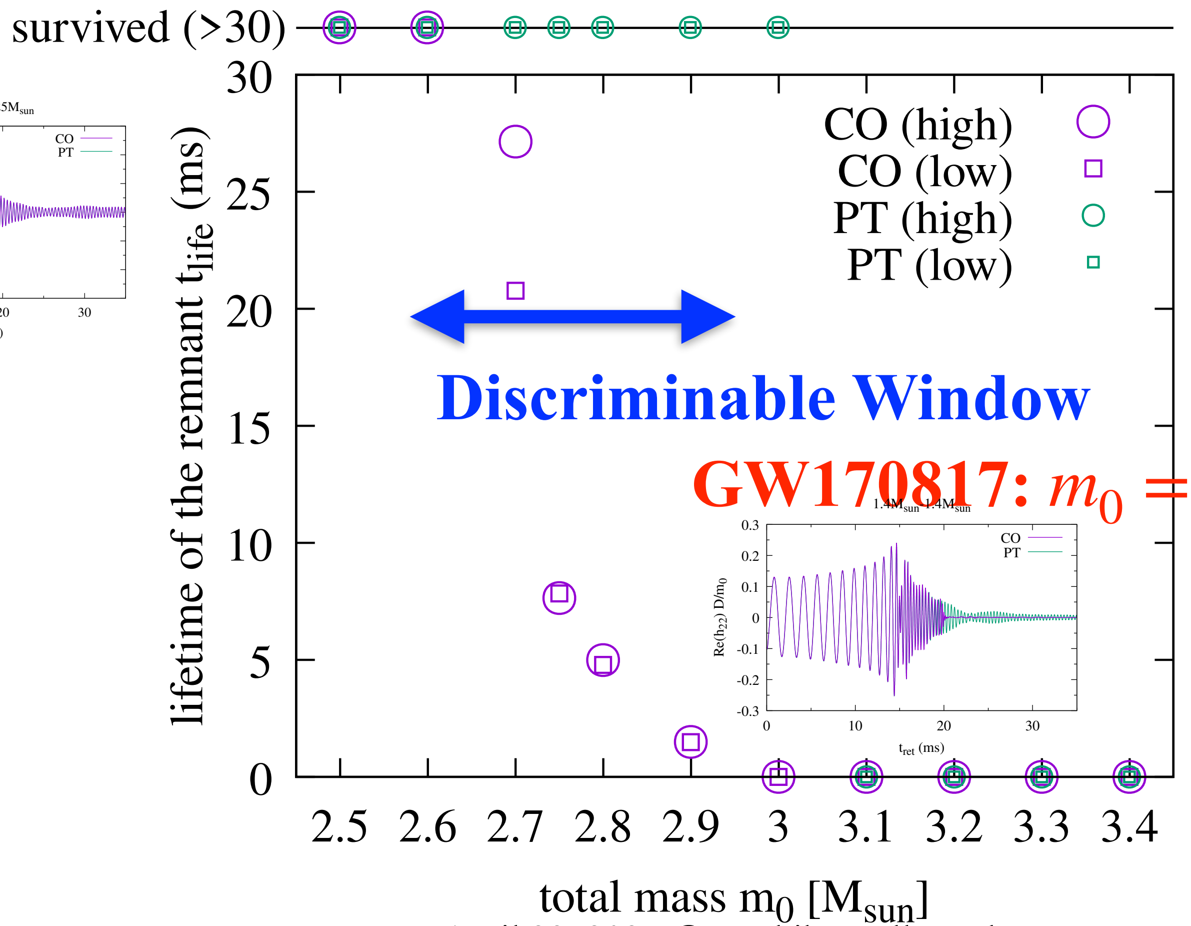


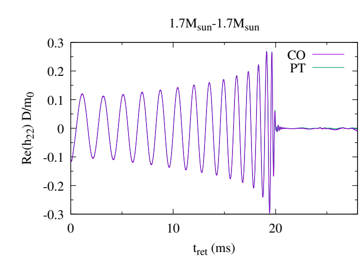
Shift seen only when the EOS changes at low density.

Multi-Messenger

Fujimoto-Fukushima-Kyutoku-Hotokezaka (2022-2024)

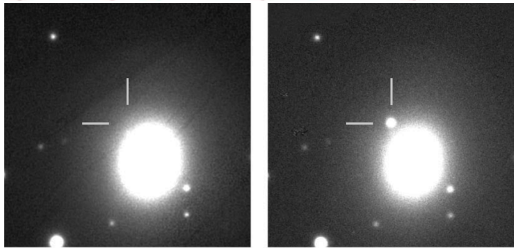




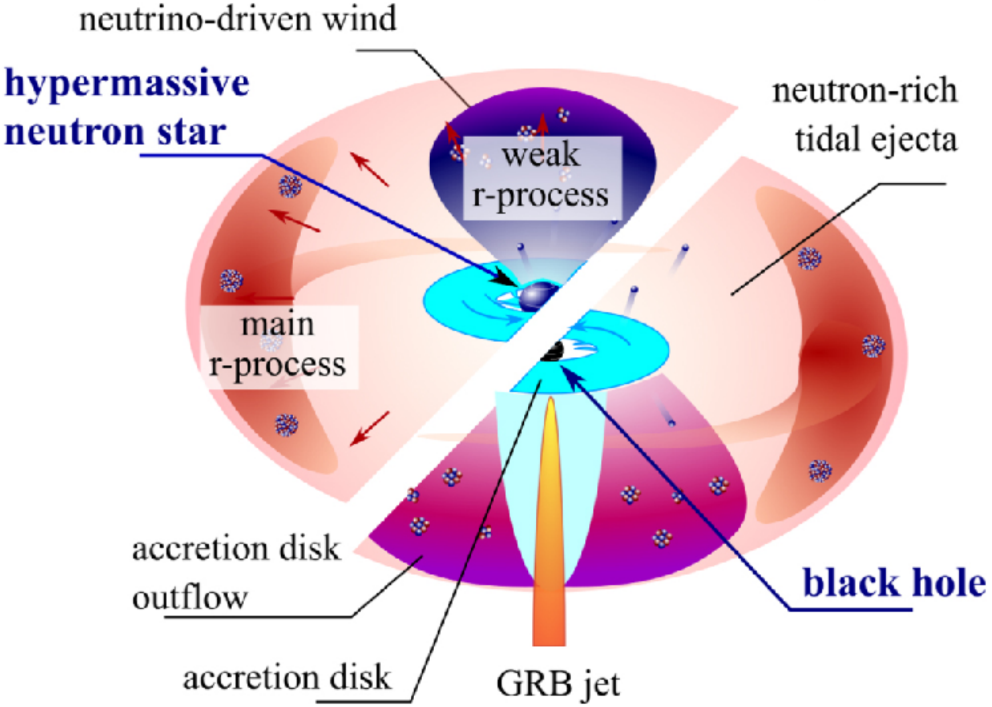


Multi-Messenger

Kilonova brightness:
ejected mass $> 0.05 M_\odot$



AT 2017 gfo

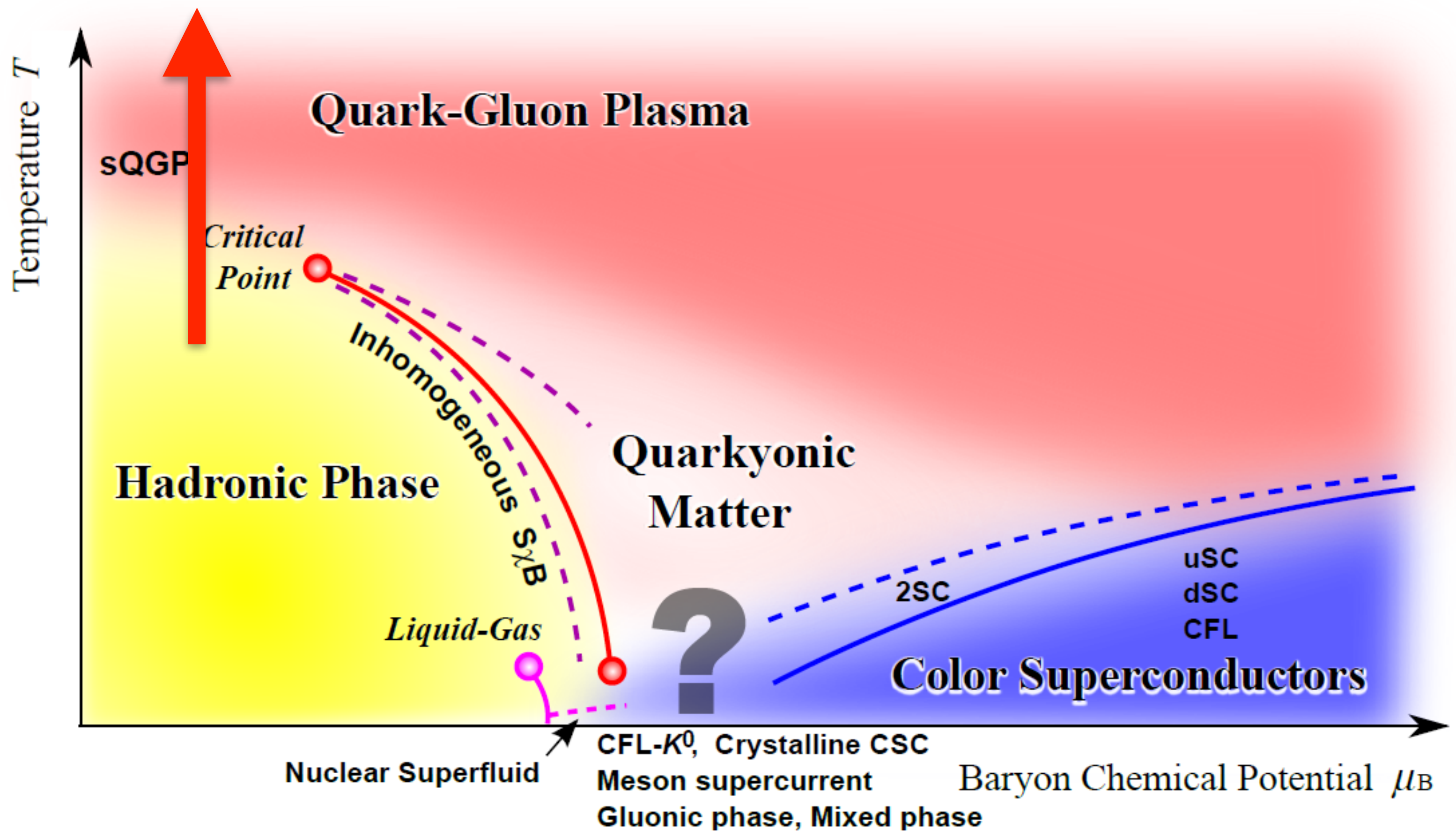


Even if the BH collapse cannot be seen, the correlation to Kilonova tells us a lot!

Illustration from Korobkin+ (2021)

Lessons from hot QCD matter

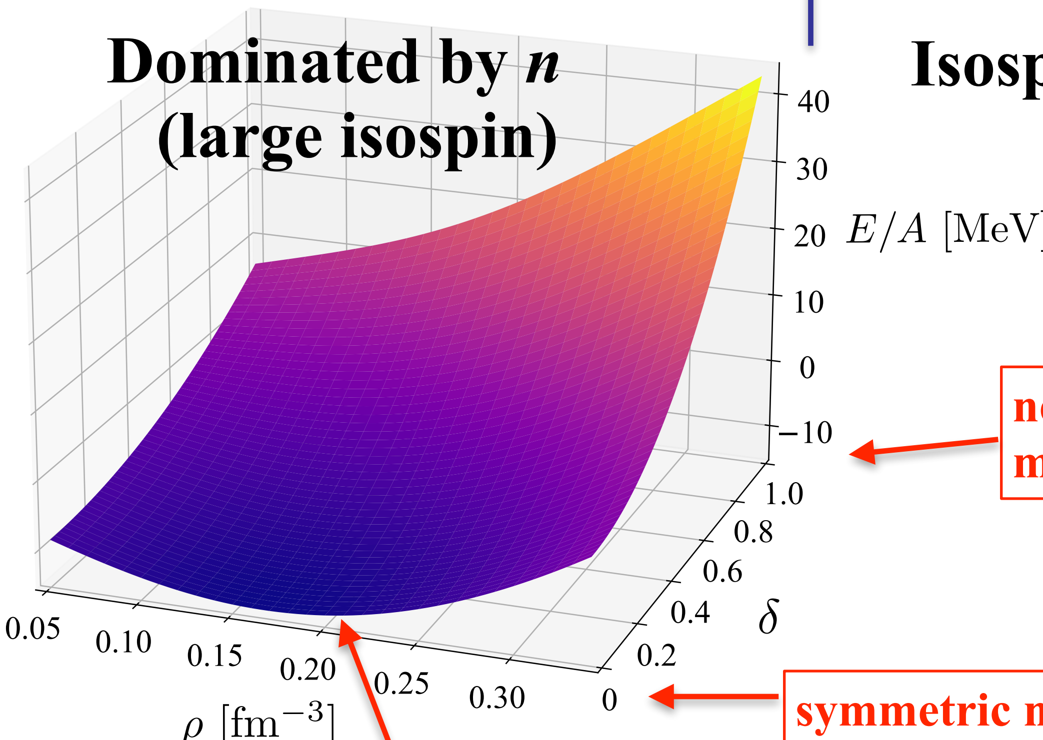
No sharp phase transition called "crossover"



Lessons from hot QCD matter

Neutron Star

Dominated by *n*
(large isospin)



saturation density
(1st-order transition)

Heavy-Ion Collision

Isospin fixed by *p*/*n* ratio
(small isospin)

neutron matter

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$\rho = \rho_n + \rho_p$$

symmetric nuclear matter (HIC)

DISCLAIMER!

Lessons from hot QCD matter

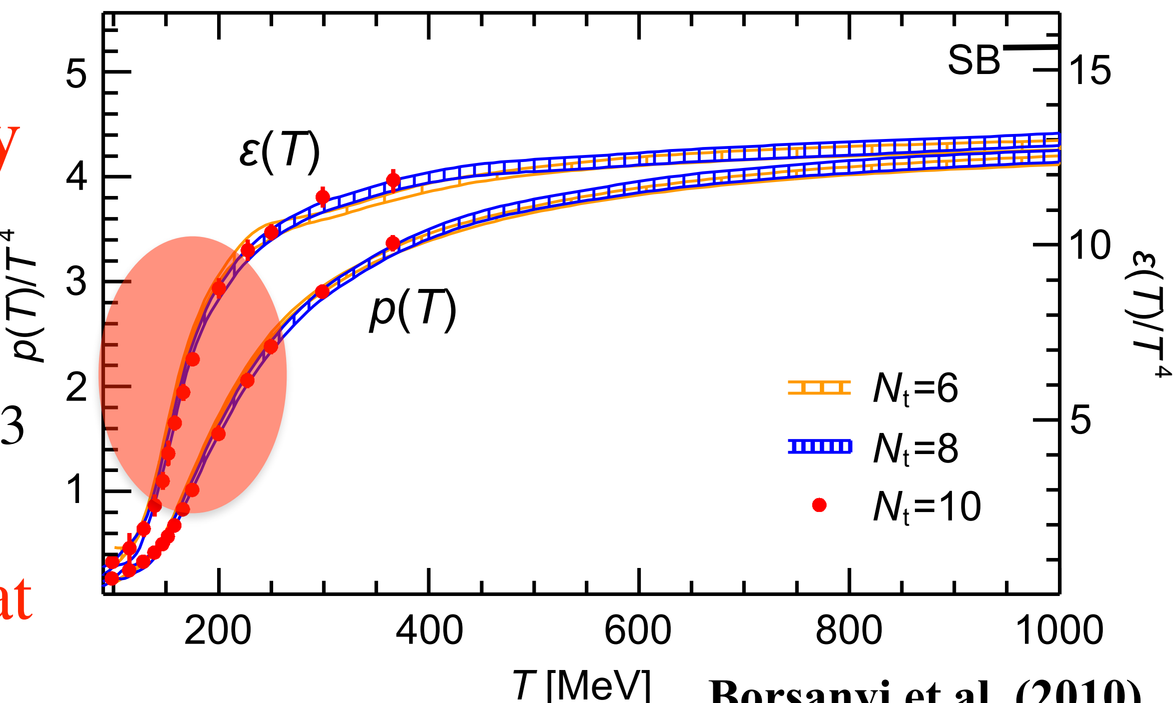
Neutron rest-energy $E_N = M_n c^2 \simeq 939\,\mathrm{MeV}$

Saturation energy $\varepsilon_{\mathrm{sat}} \simeq 150\,\mathrm{MeV\,fm^{-3}}$

Transition energy to a QGP

$200\text{-}500\,\mathrm{MeV\,fm^{-3}}$

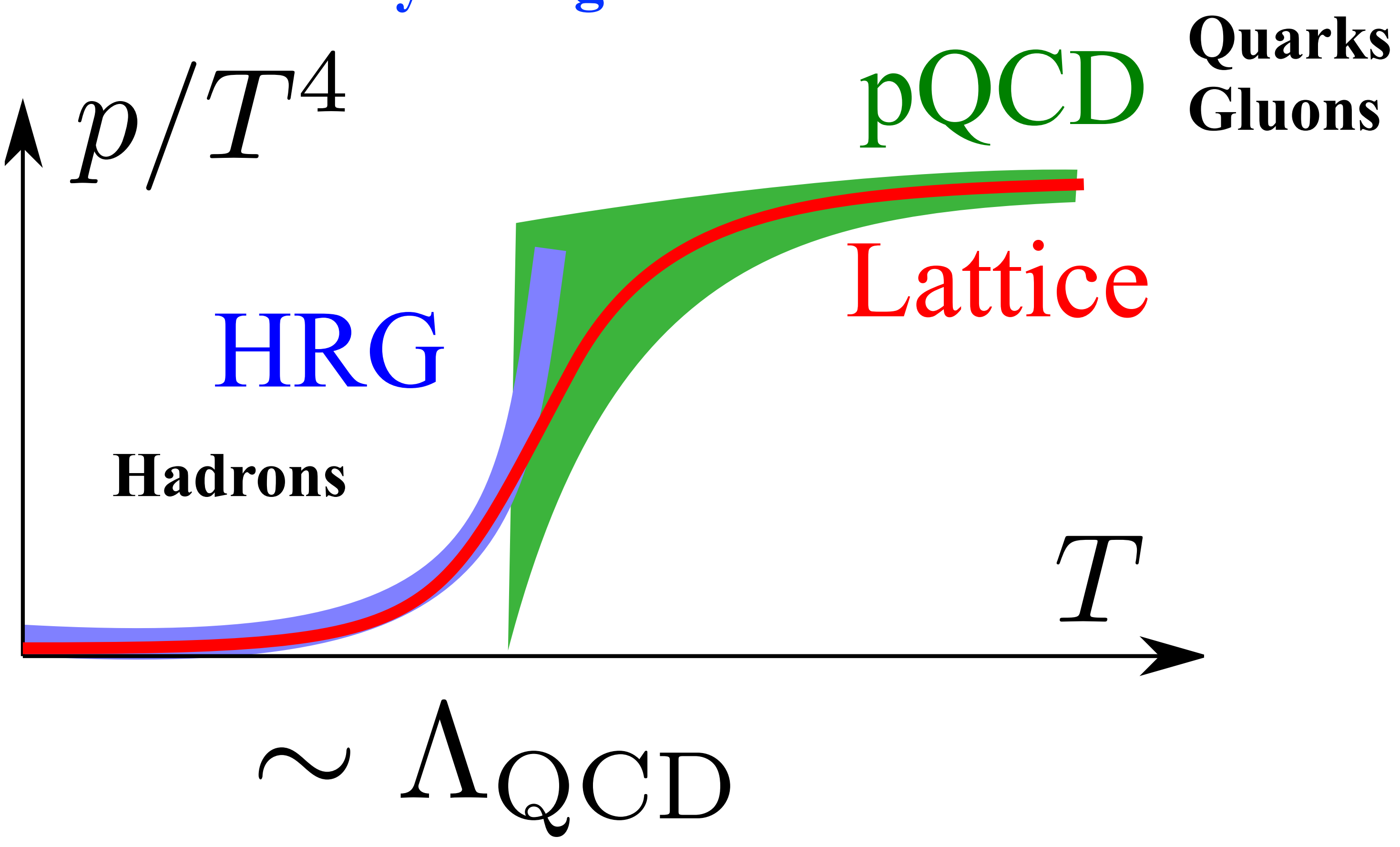
$\sim (1.5 - 4) \times \varepsilon_{\mathrm{sat}}$



Borsanyi et al. (2010)

Lessons from hot QCD matter

Crossover is the point where the physical degrees of freedom continuously change.



Lessons from hot QCD matter

Hagedorn Picture

Hagedorn Spectrum (String Excitations)

$$Z = \int dm\, \rho(m)\, e^{-m/T} \qquad \rho(m) \sim e^{m/T_H}$$

$$Z = \int dm\, \underbrace{e^{m/T_H}}_{\text{Entropy}} \cdot \underbrace{e^{-(m-\mu_B)/T}}_{\text{Energy}} \to \infty$$

Excited states, Strangeness (Hyperons), etc.

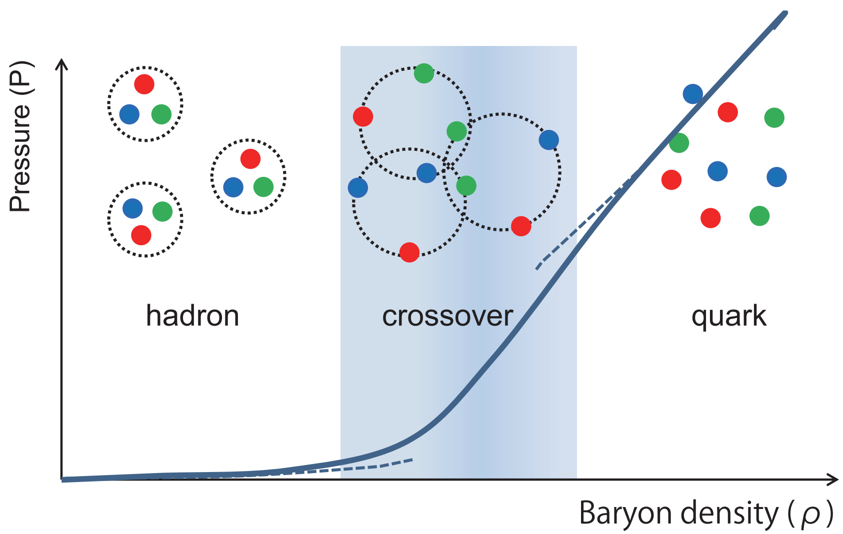
Entropy > Energy for Deconfinement

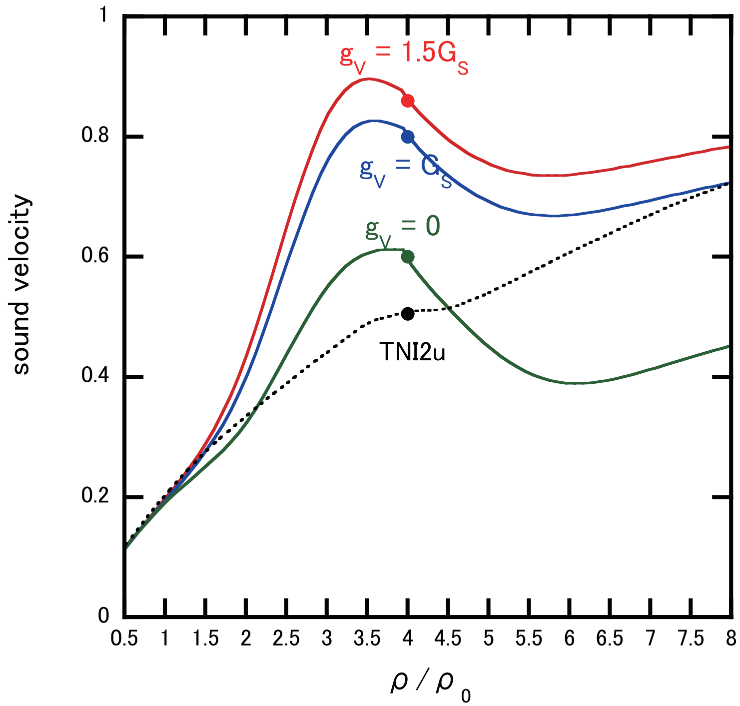
Hyperon puzzle is not a puzzle: EOS is softened as a precursory toward deconfined quark matter

Scenarios at High Density

Crossover Scenario

Hatsuda-Masuda-Takatsuka (2013)



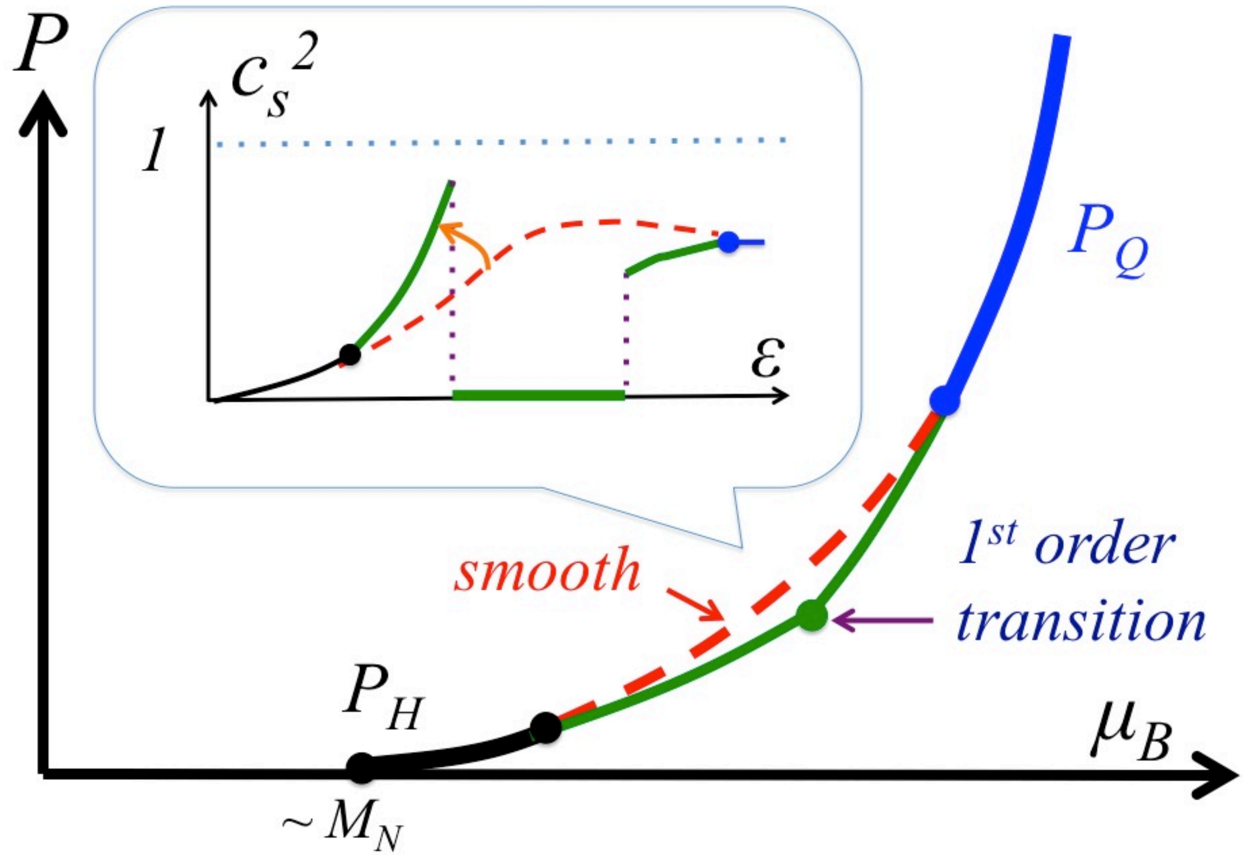


Sound velocity exceeds the conformal limit?

Scenarios at High Density

Crossover Scenario

Baym-Hatsuda-Kojo-Powell-Song-Takatsuka (2017)



Scenarios at High Density

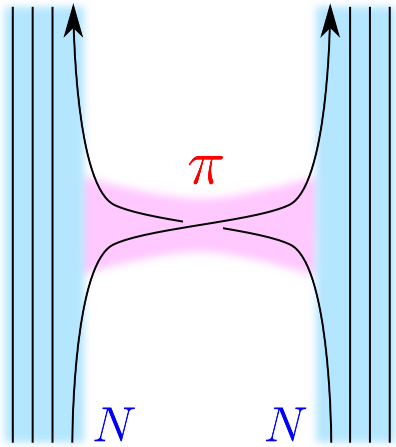
Duality Picture

If we have strongly interacting baryonic matter and weakly interacting quark matter, how can we distinguish them?

Assume that baryons are bound-states of N_c quarks.

$$P_{\text{baryon}} \sim V_{\text{baryon}} \sim O(N_c)$$

$$P_{\text{quark}} \sim K_{\text{quark}} \sim O(N_c)$$

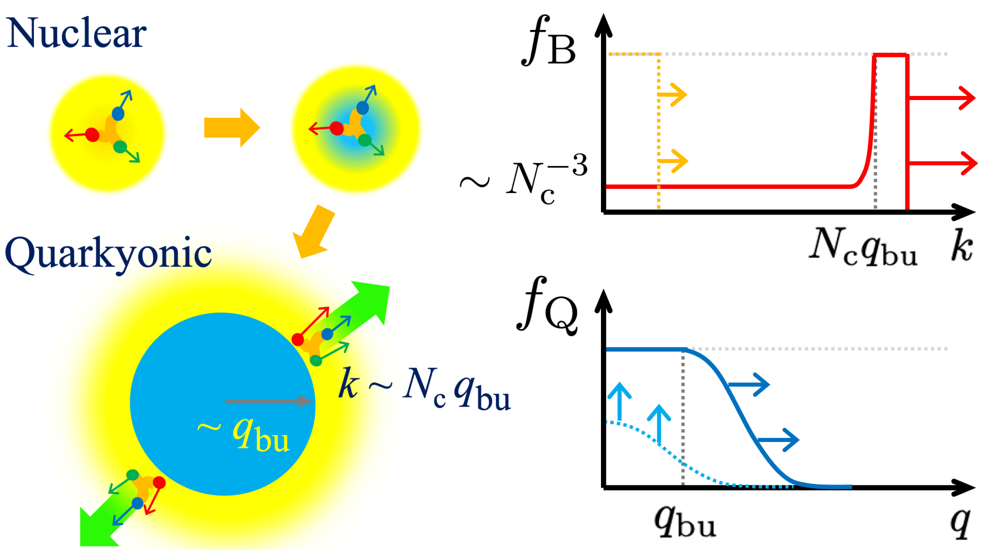


Pressure knows quarks even in baryonic matter → Quarkyonic

Pisarski-McLerran (2008)

Scenarios at High Density

Idyllic **Fujimoto-Kojo-McLerran (2024)**

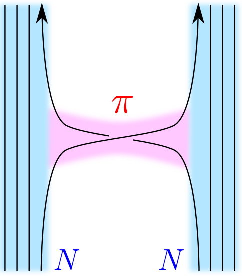


$$n_B \sim \mu_B^3 \sim N_c^3 \mu_q^3$$

$\wr\wr$ **Dual**

$$n_q \sim \mu_q^3$$

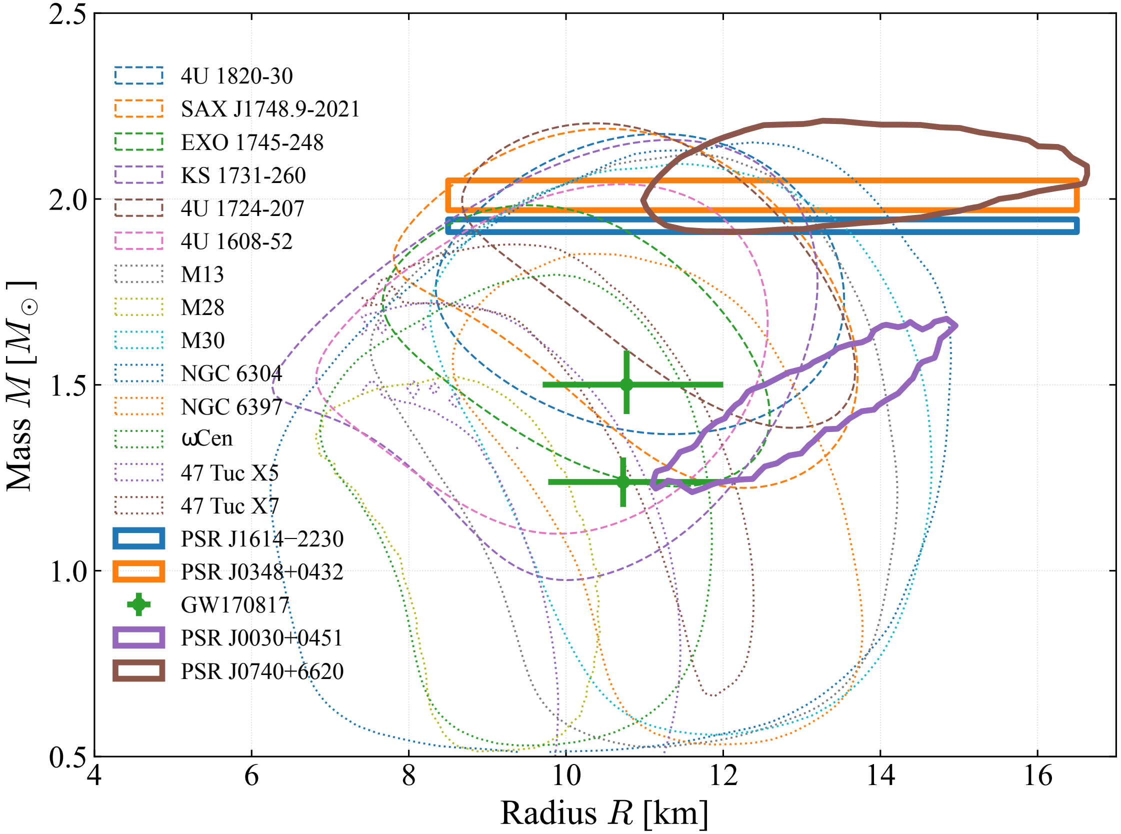
Suppression of baryonic distribution should be caused by repulsive core interaction due to quark exchanges.



Data Never Lie

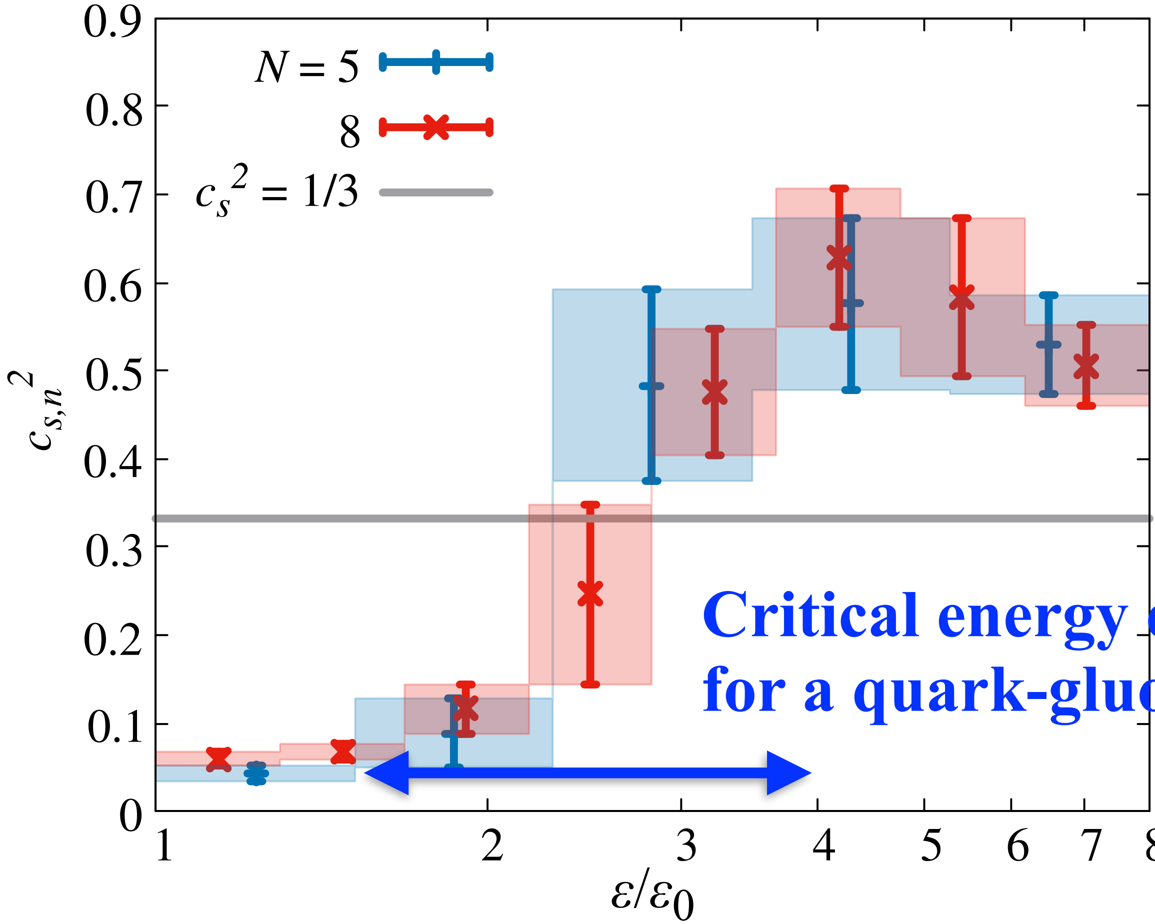
Compilation of the observed data (68% Credible)

Fujimoto-Fukushima-Kamata-Murase (2024)



Data Never Lie

Fujimoto-Fukushima-Kamata-Murase (2018-2024)



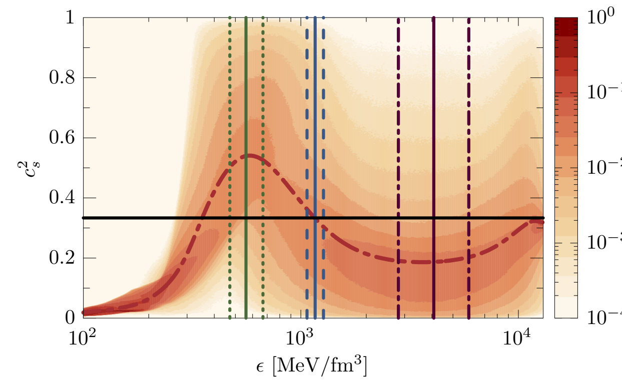
Conformal limit violated!

Not minimum, but maximum!?

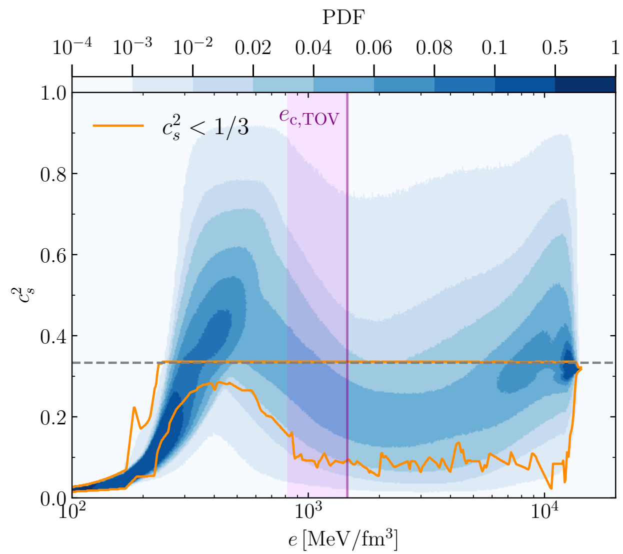
$\varepsilon_0 = 150\,\mathrm{MeV\ fm^{-3}}$

Data Never Lie

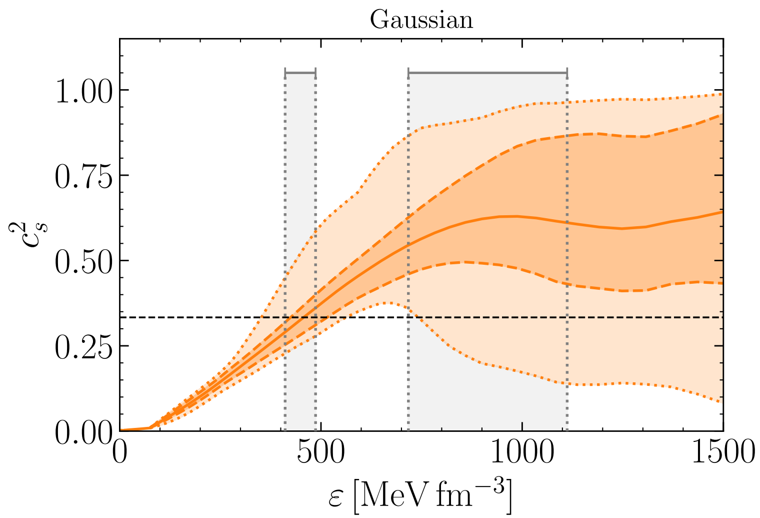
Marczenko-McLerran-Redlich-Sasaki (2022)



Altiparmak-Ecker-Rezzolla (2022)



Brandes-Weise-Kaiser (2022)

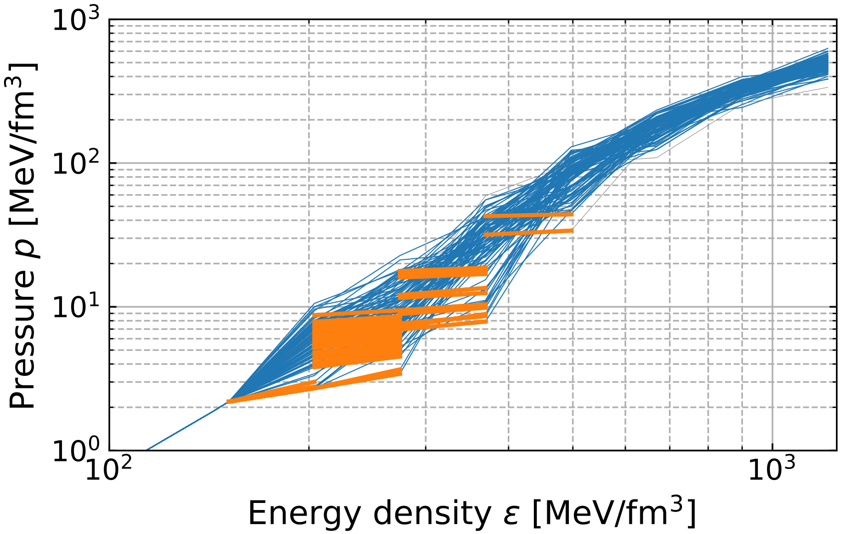


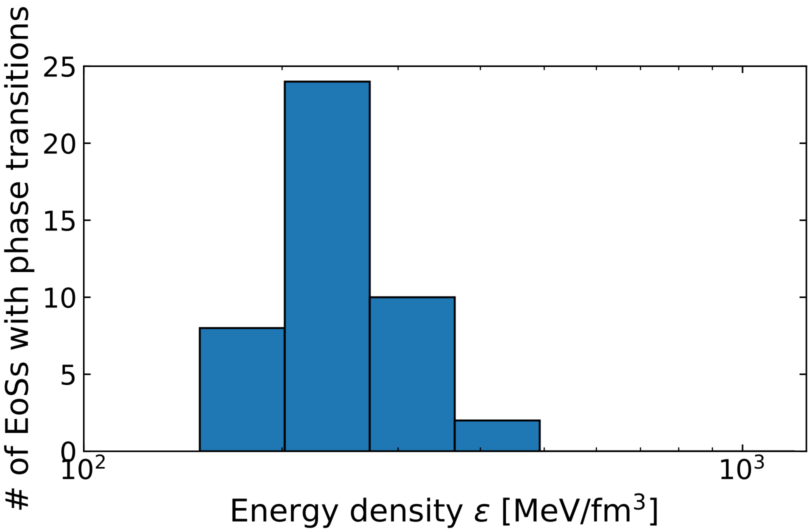
Supporting the peak!

Data Never Lie

First-Order can never be destroyed… force be with you…

ML inferred EoSs: Fujimoto-Fukushima-Murase (2021)





On average, the inferred EOS looks smooth, but weak First-Order at intermediate density is favored…?

First-Order

What could be the underlying physics?

- **Deconfinment phase transition is of first order?**
  This is the case in the holographic model (V-QCD) but the Sakai-Sugimoto can still have a second order.

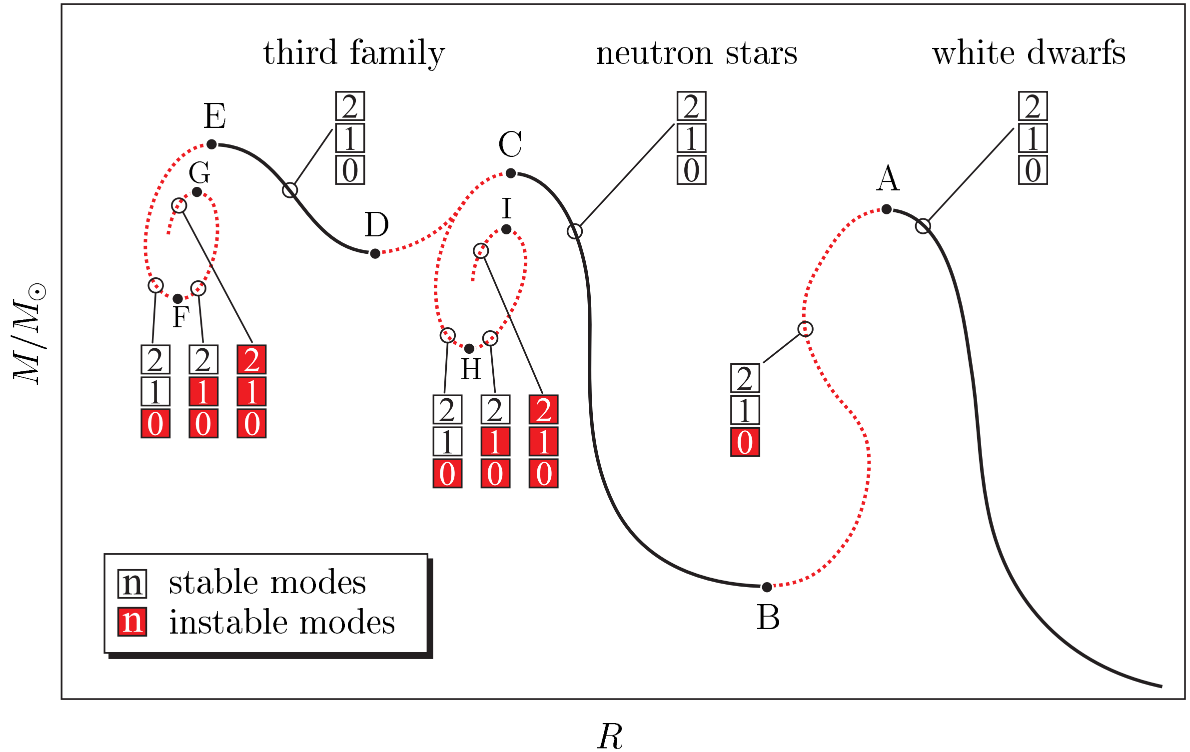
- **Chiral phase transition is of first order?**
  This is the case in many chiral models unless the repulsive vector interaction is not introduced.

- **Bosonic condensation (mesons/diquarks) is of first order?**
  This is the case in some chiral models unless the local color gauge is not introduced.

Inspiral GWs from BNS-merger would resolve the issues!

First-Order

Schertler-Greiner-Schaffner-Bielich-Thoma (2000)



It may trigger the third family… intriguing…

Conformal Measure

Fujimoto-Fukushima-McLerran-Praszalowicz (2022)

Measure of conformality: $\boxed{\Delta = \frac{1}{3} - \frac{p}{\varepsilon}}$

Gavai-Gupta-Mukherjee (2004)

$$c_s^2 = \frac{dp}{d\varepsilon} = c^2_{s,\,\mathrm{deriv}} + c^2_{s,\,\mathrm{non-deriv}}$$

$$c^2_{s,\,\mathrm{deriv}} = -\,\varepsilon\frac{d\Delta}{d\varepsilon} \qquad c^2_{s,\,\mathrm{non-deriv}} = \frac{1}{3} - \Delta$$

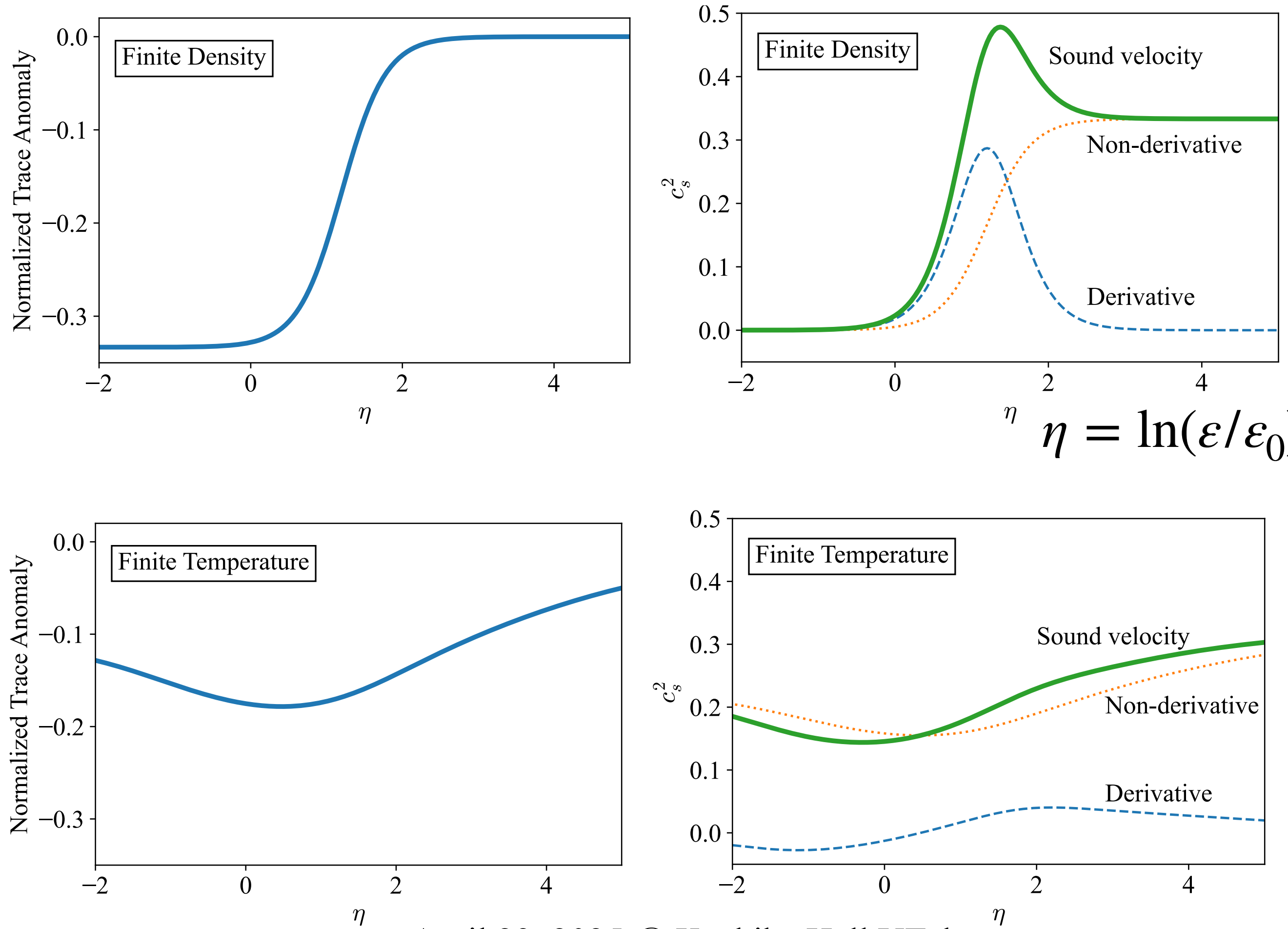
Derivative **Non-Derivative**

Dominant at high density making a peak!

Conformal Measure

Derivative contribution makes a peak structure!

Sign Flipped $-\Delta$

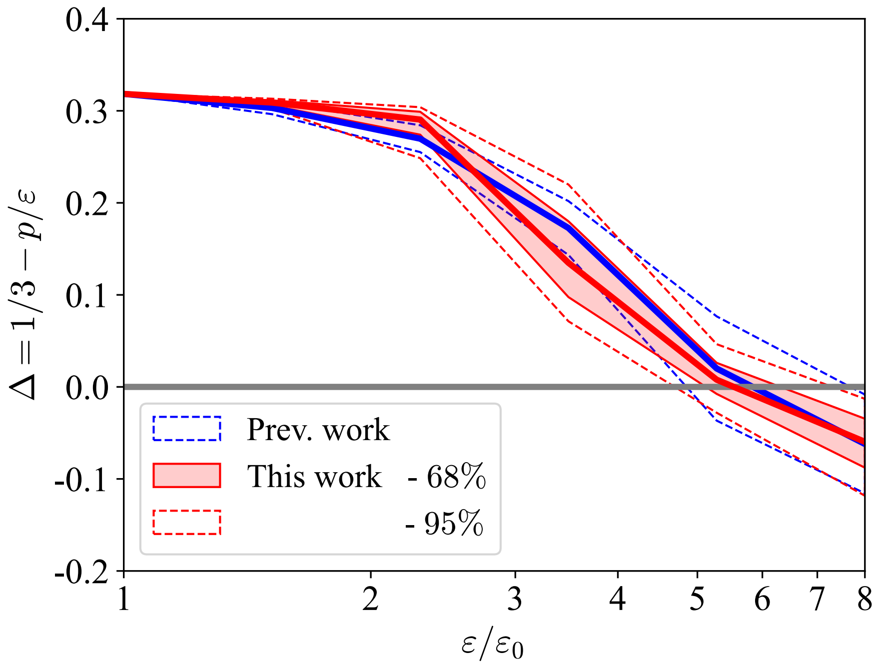


$\eta = \ln(\varepsilon/\varepsilon_0)$

Speed of Sound

Conformal Measure

Physical interpretation of $\Delta < 0$???



$$\Delta \propto \varepsilon - 3p$$

$$\propto \frac{d}{d\mu}\left(\underline{\frac{p}{\mu^4}}\right)$$

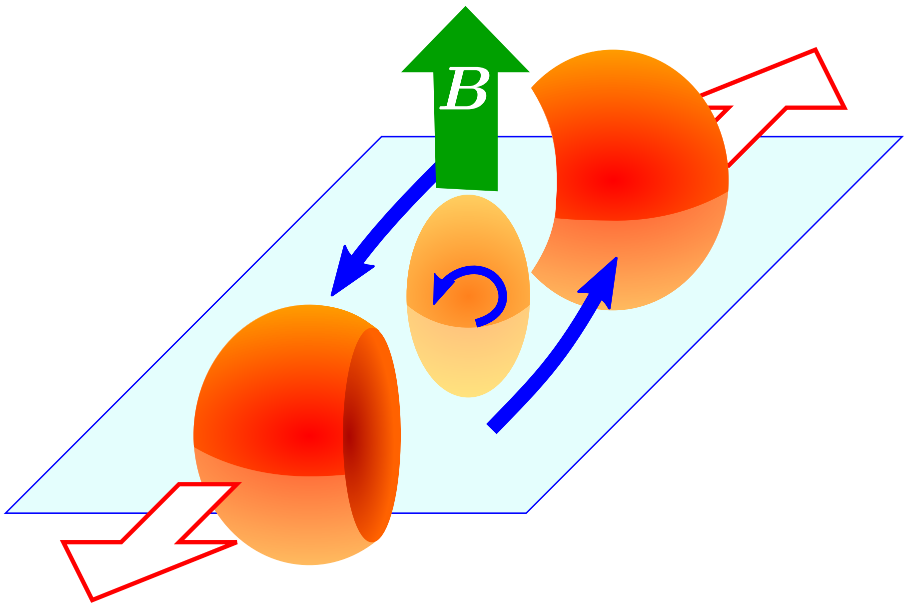
Thermodynamic degrees of freedom

Negative trace anomaly implies the presence of "condensates"!?

Lattice!

External Fields

In the heavy-ion collision:



Large B

~1000 times stronger than the magnetar surface

Large J

$\sim 10^7 \hbar \; (\omega \sim 10^{22}\,\mathrm{s}^{-1})$

Chiral Fermions

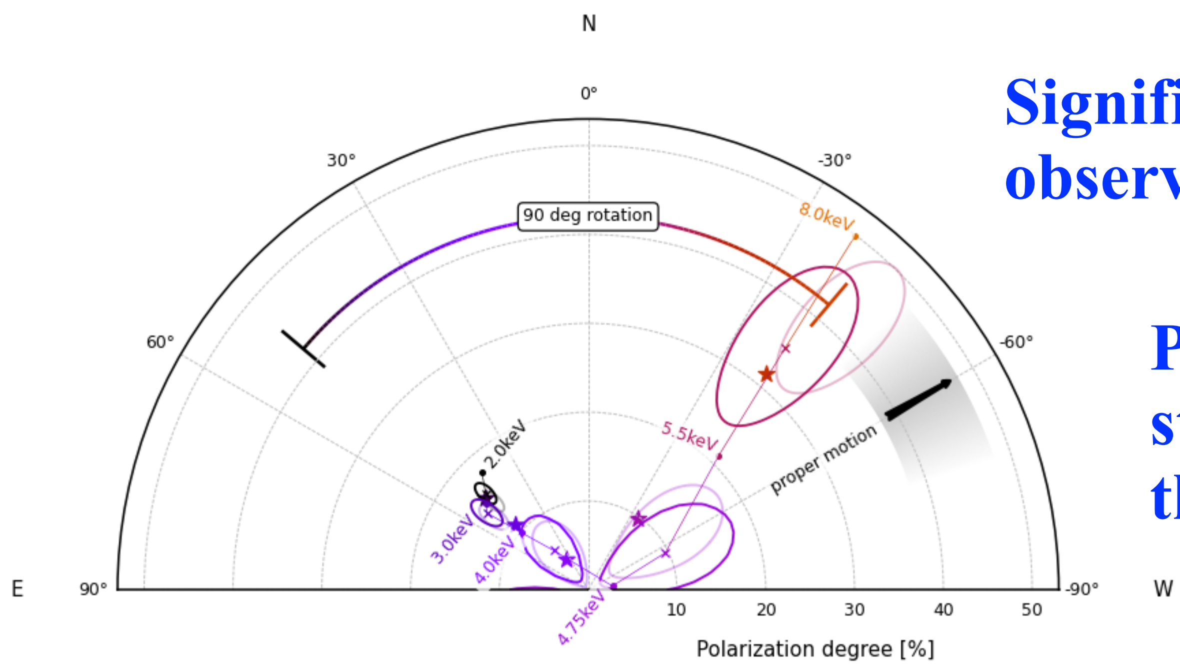
If chiral symmetry is restored…

External Fields

Polarized X-ray from the magnetar:

Science 378, 646-650 (2022)

Imaging-X-ray Polarimetry Explorer (IXPE)

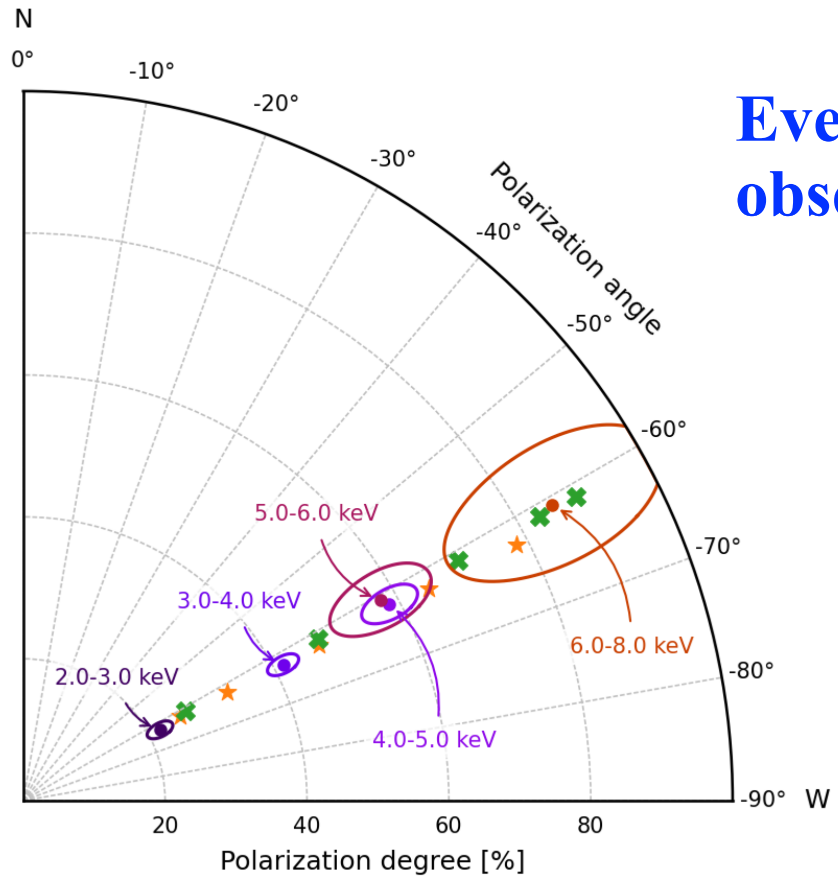


Significant polarization was observed — how!?

Polarization angle has strong dependence on the photon energy.

External Fields

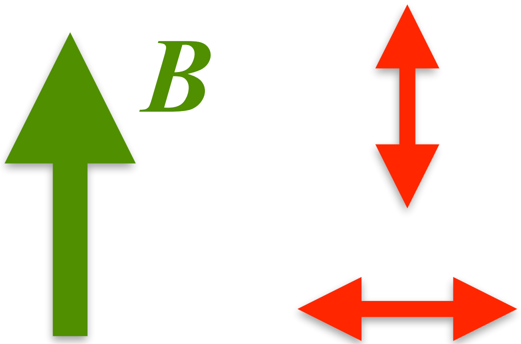
Astrophys.J.Lett.944, L27 (2023)



Even 80% polarization was observed — surprise!

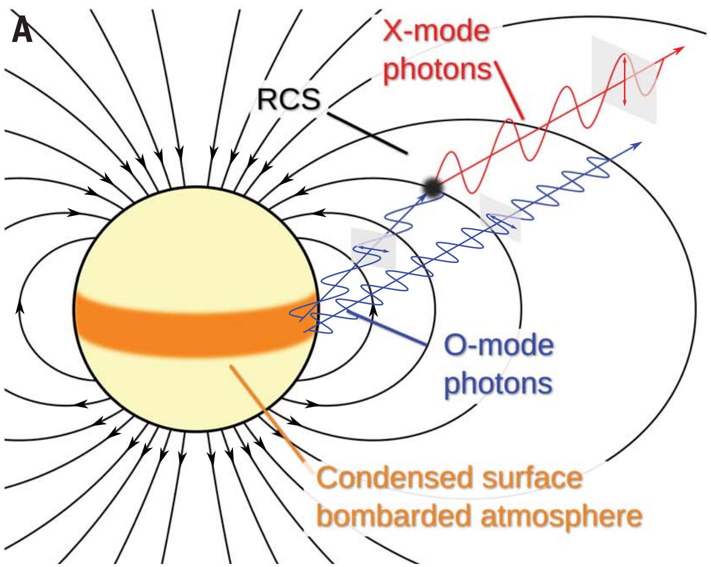
Polarization angle has no dependence on the photon energy???

External Fields



O-mode (ordinary mode)
Parallel to the magnetic field

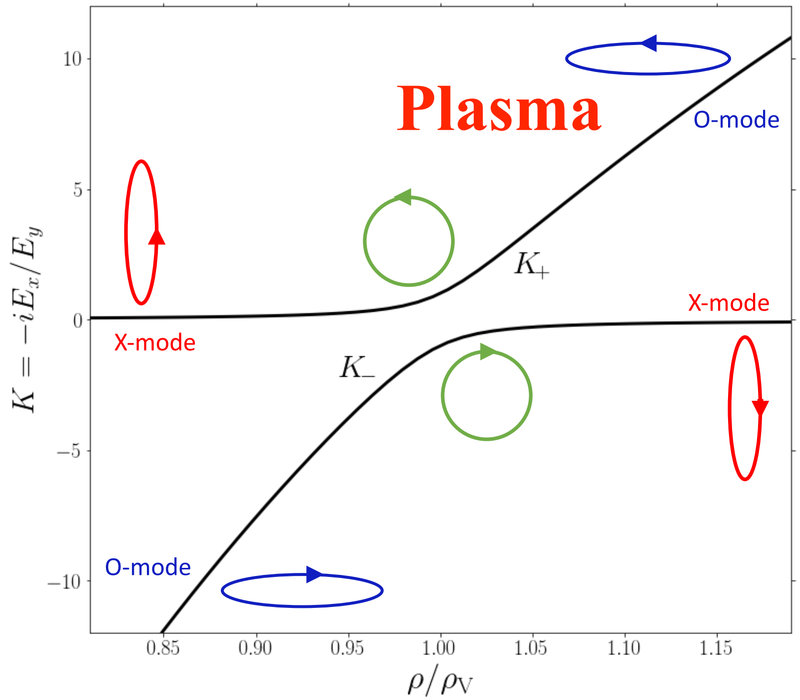
X-mode (extraordinary mode)
Perpendicular to the magnetic field



Science 378, 646-650 (2022)

External Fields

Don Lai (2022)



Vacuum

Assume:

No mode conversion for $E < E_{\rm ad}$

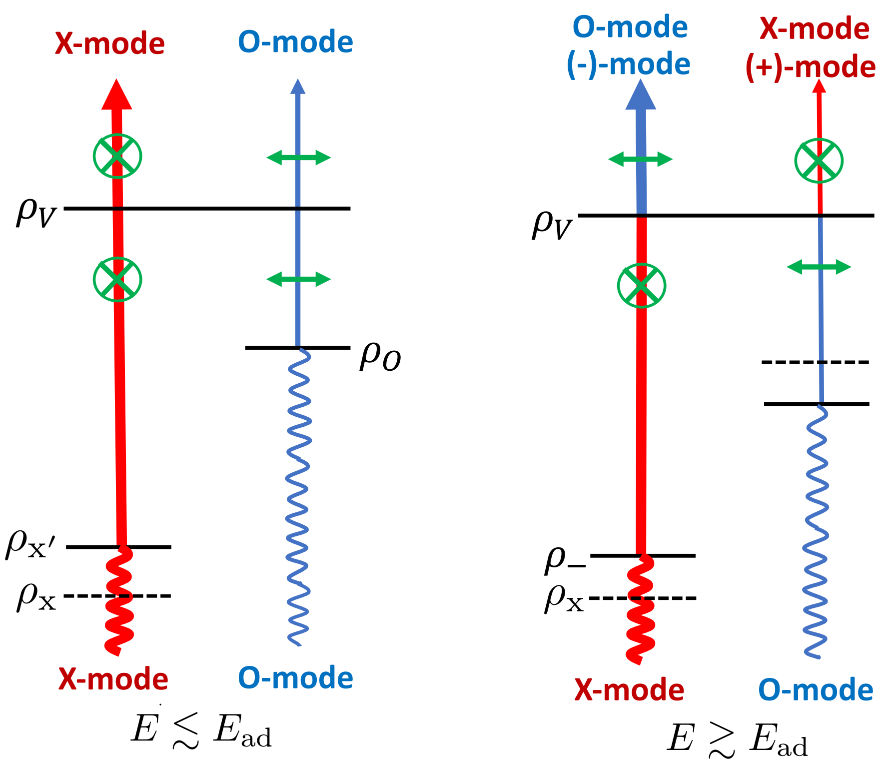
Mode conversion for $E > E_{\rm ad}$

Density of atmosphere (*e* + ions)

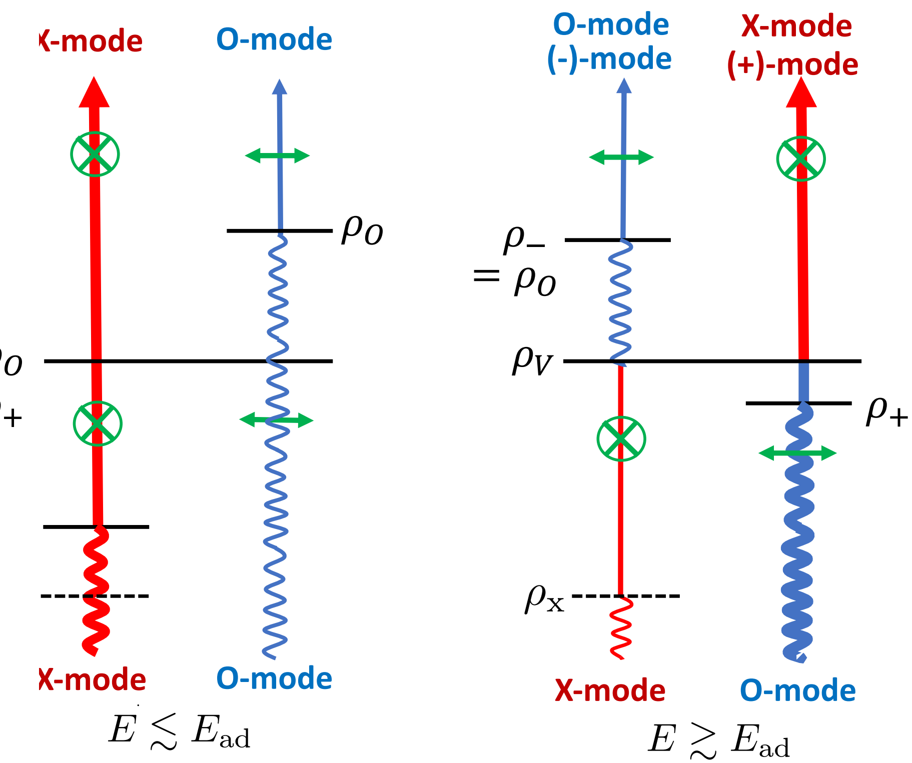
External Fields

Don Lai (2022)

Small magnetic field case



Strong magnetic field case



Chirality

Various Chiral Effects

Chiral Magnetic Effect $j \propto \mu_5 B$ **Electric Current**

Chiral Separation Effect $j_A \propto \mu B$ **Spin Polarization**

Chiral Vortical Effect $j \propto \mu^2 \omega \quad j_A \propto \mu\mu_5 \omega$

Many discussions for the supernovae (Yamamoto), the proto-neutron star (neutrino emission), etc.

No experimental evidence in the nuclear physics…
Even the magnetic field has not been detected…

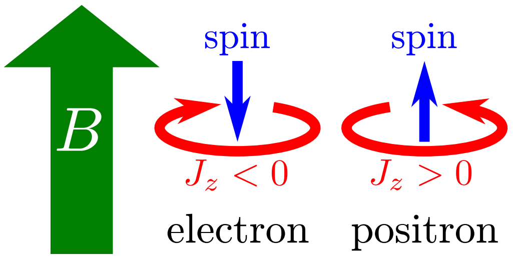
Chirality

Various Chiral Effects

What if B and ω coexist?

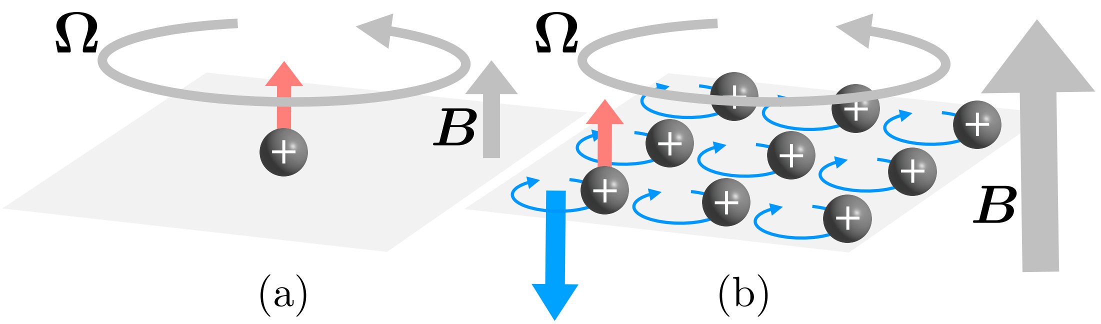
Hattori-Yin (2016)

$$\Delta q = C\boldsymbol{B}\cdot\boldsymbol{\omega}$$



If B is sufficiently strong:

Fukushima-Hattori-Mameda (2025)



$$\Delta J \sim -C\mu\boldsymbol{B}$$

$$\Delta M \sim -C\mu\boldsymbol{\omega}$$

Opposite!?

$$\Delta q = -C\boldsymbol{B}\cdot\boldsymbol{\omega} \;\rightarrow\; \Delta p = -C\mu\boldsymbol{B}\cdot\boldsymbol{\omega}$$

Summary

- **Neutron Star is the astro-nuclear laboratory for dense QCD matter.**

- **Difficult to combine the heavy-ion collision data, but we can still learn the lessons.**

- **Unknowns — Peak or monotonic rise in the speed velocity? Condensate from the trace anomaly more quantified? HIC unseen chiral effects detectable? Definition of quark matter? (How to define deconfined matter is more nontrivial than confinement…)**