Investigation of the EoS with multi-messenger signals from compact-star binaries

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September 24, 2023

Compact stars and equation of state

- Stars are supported by strong interaction
- Equation of state is determined by the interaction
- Components of compact star
  - Neutron star (n, p, e)
  - Hadronic star (hyperon, Δ...)
  - Hybrid star (quark core)
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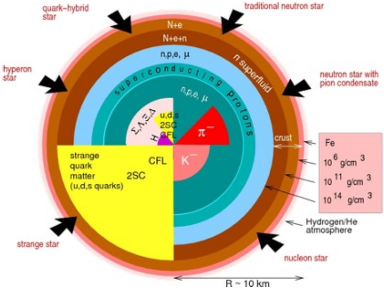

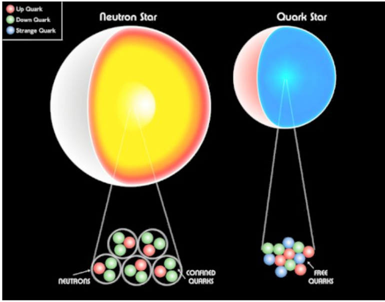

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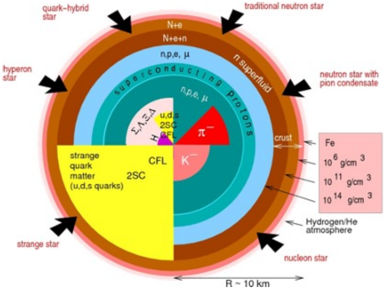

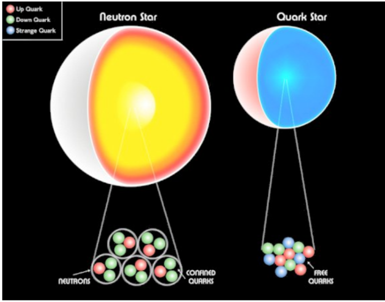

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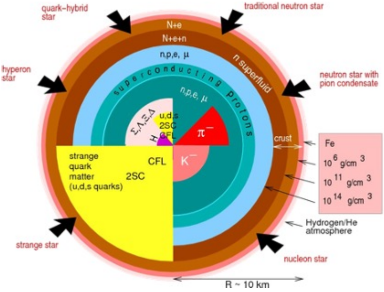

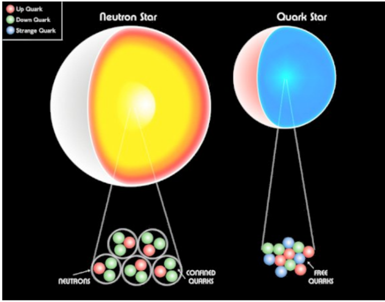

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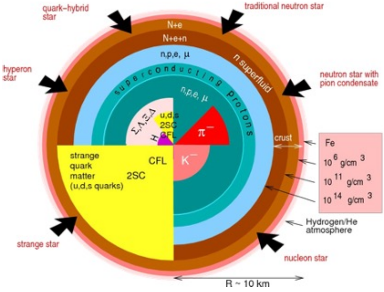

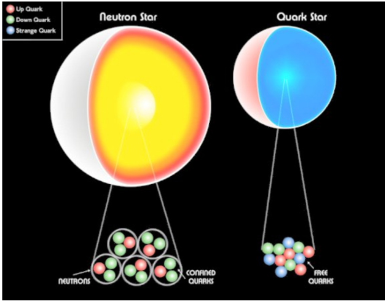

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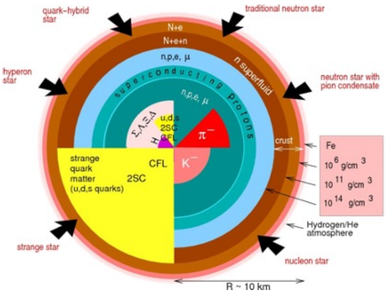

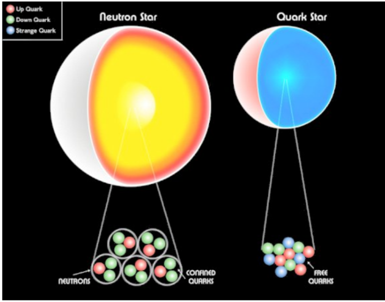

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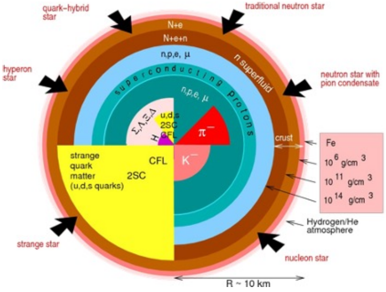

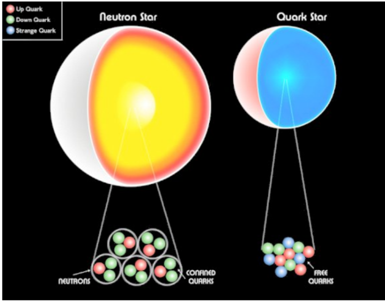

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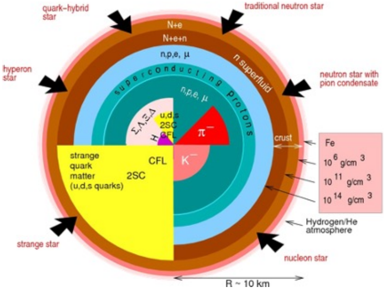

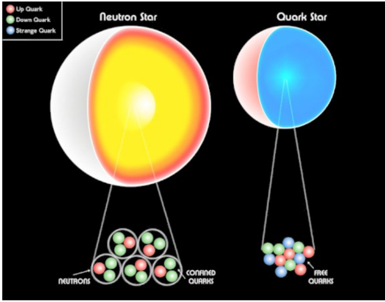

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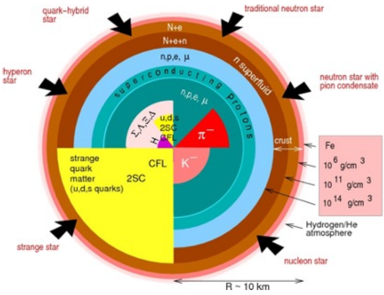

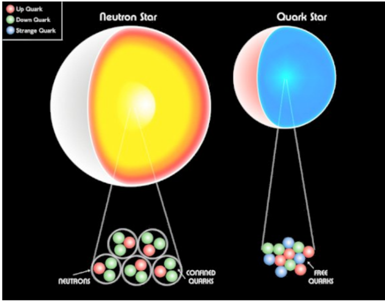

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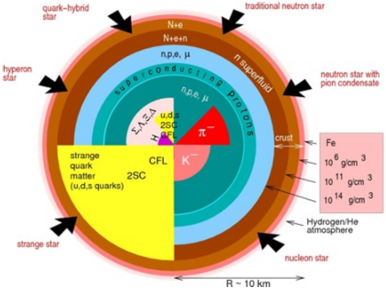
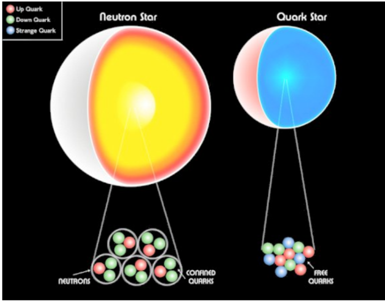
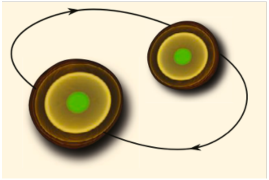
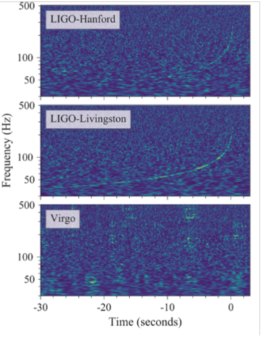




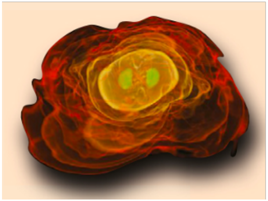
Binary compact star merger

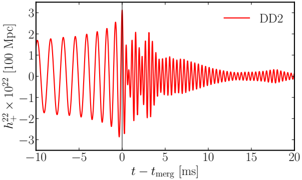
Inspiral Phase





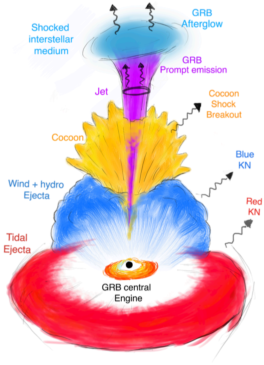
Postmerger





By Einstein Telescope
or Cosmic Explorer

GRB and kilonova



Adapted from S. Ascenzi+ (2010)

and L. Baiotti+ (2018)

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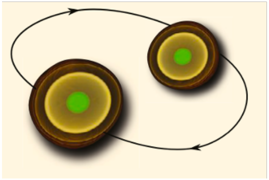

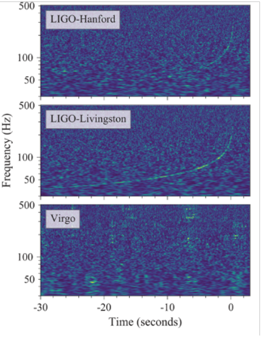

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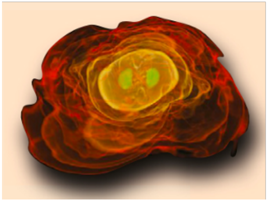

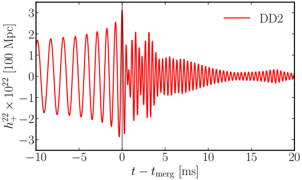

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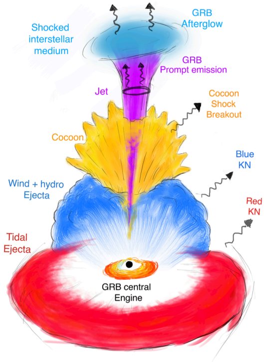

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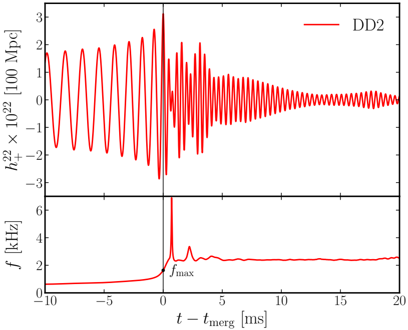
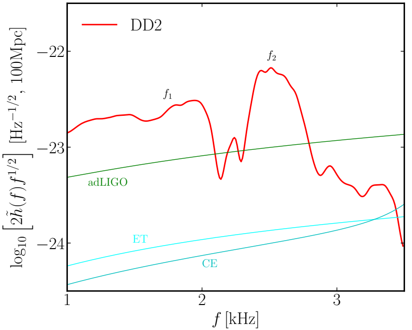
Post-merger gravitational wave



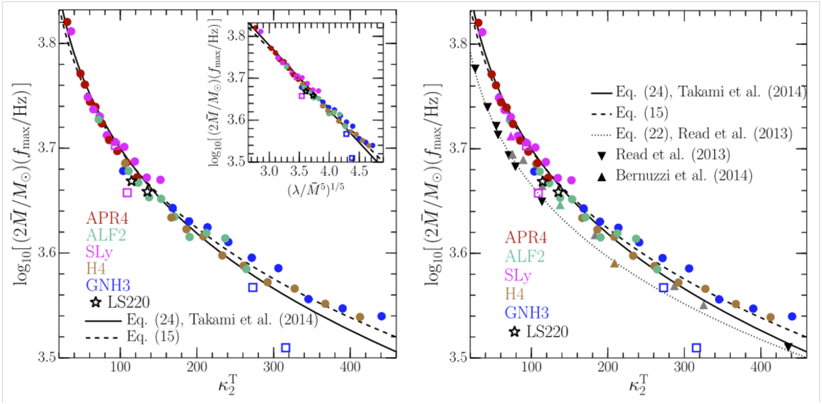
Strain and instantaneous frequency



Power spectral density

- Three characteristic frequency for post-merger
- Instantaneous frequency of merger $f_{\max}$
- Two peak frequency of PSD f_1, and f_2

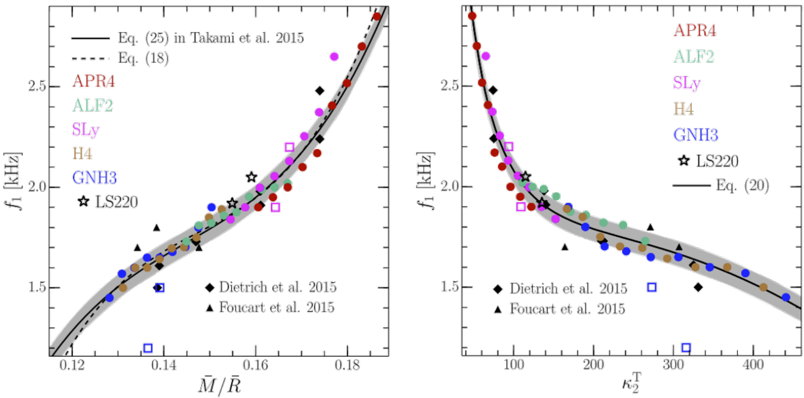
Quasi-universal relations



$f_{\max}$ v.s. tidal deformability

L. Rezzolla+ (2016)

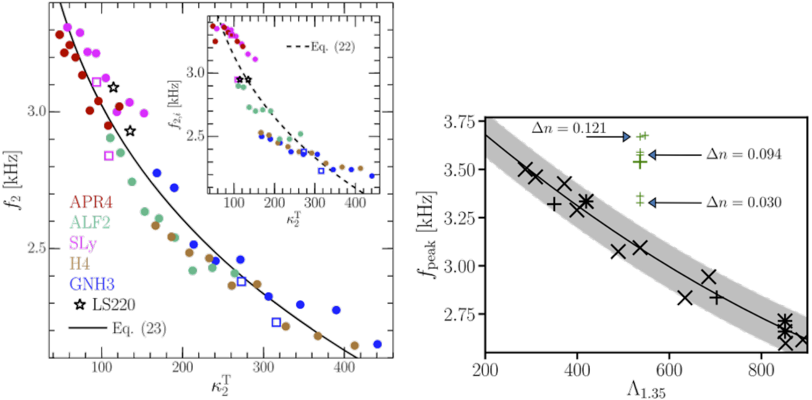
Quasi-universal relations



f_1 v.s. tidal deformability and compactness

L. Rezzolla+ (2016)

Quasi-universal relations

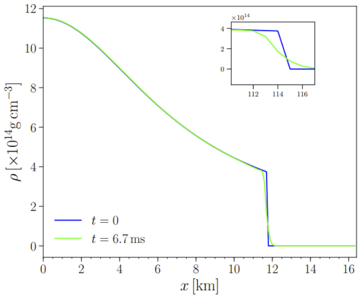


f_2 v.s. tidal deformability

A. Bauswein+ (2016) L. Rezzolla+ (2016)

Post-merger GW of binary quark star?

- Simulations of binary quark star are necessary
- Density discontinuous
- The only successful quark star simulation previously:
  - CFC + SPH A. Bauswein+ (2010)
- How to simulate it in full GR + Eulerian hydrodynamic?
  - Solution: contact discontinuity and continuous enthalpy
  - Additional treatment of EoS with $\rho < \rho_{\mathrm{surface}}$



The density profile of quark star

E. Zhou+ (2021)

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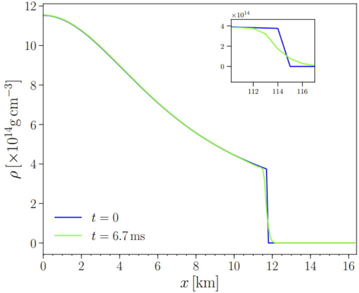

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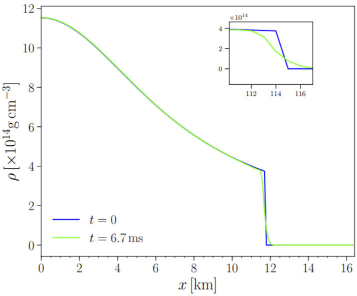

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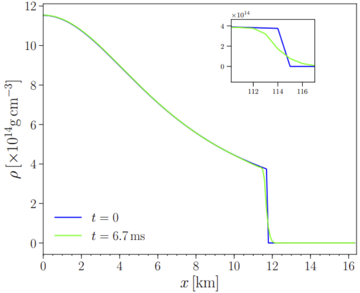

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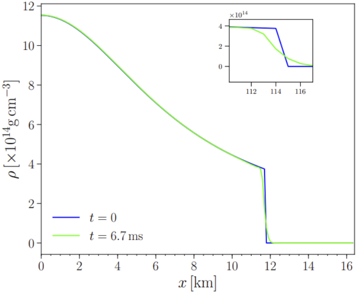

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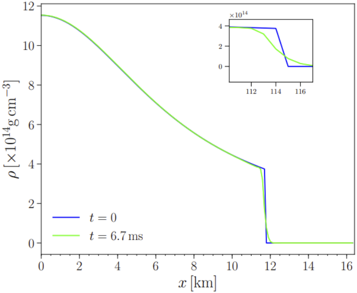

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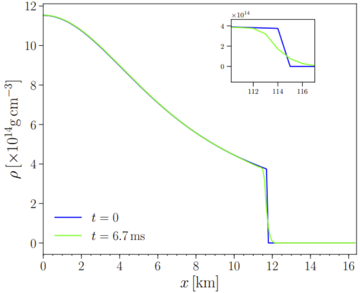
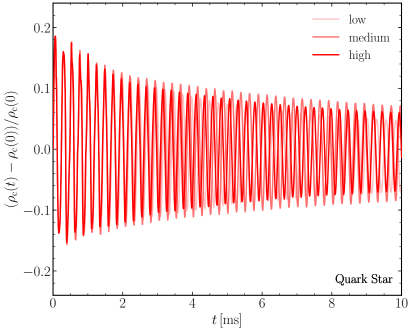
  see Z. Zhu+ (2021) E. Zhou+ (2021) E. Zhou+ (2022) K. Chen+(2023)

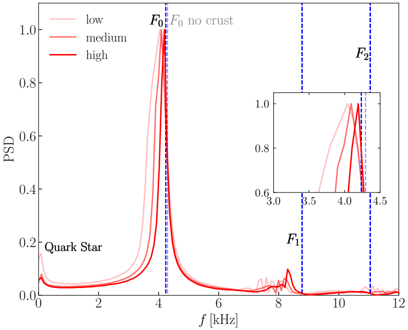


The density profile of quark star

E. Zhou+ (2021)

Test for isolated quark star





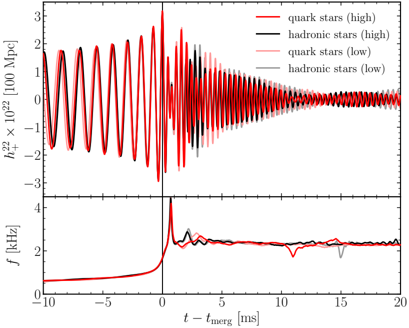
Density oscillations as a function of time

power spectral density of the oscillations

- Oscillations of quark star in GRHD simulations
- Simulations perfectly match with perturbative calculations

Z. Zhu+ (2021)

Post-merger GW of binary quark star



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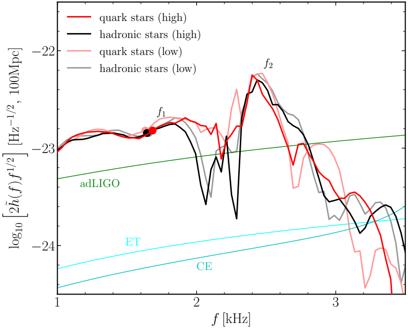
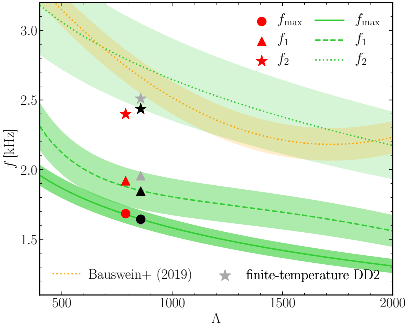


PSD of postmerger GW

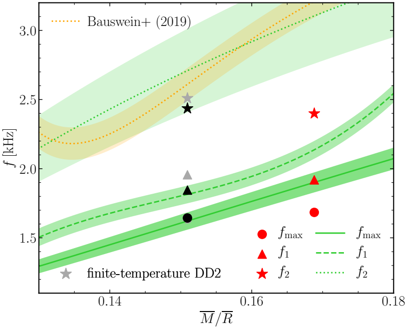
- Simulations of binary quark star merger
- quark stars v.s. hadronic stars
  - Similar tidal deformability but different radius

Z. Zhu+ (2021)

Peak frequencies of binary quark star



f v.s. tidal deformability

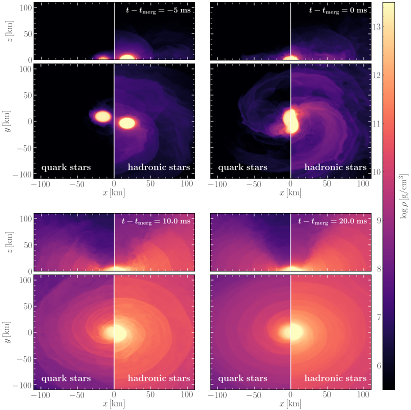


f v.s. compactness

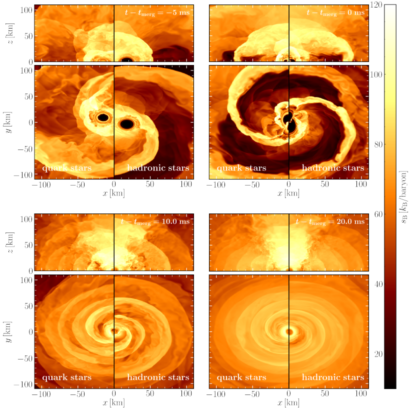
- QS obey the same relations?
  - rare samples of BQS (Z. Zhu+ (2021) E. Zhou+ (2022))
- Merger frequencies are independent on the R?
  - Similar tidal deformability but different radius

Z. Zhu+ (2021)

Matter ejection of binary merger



f v.s. tidal deformability



f v.s. compactness

- Ejecta: Tidal force driven and shock-heating driven
- Determined the kilonova emission

Z. Zhu+ (2021)

Equation of state and kilonova

- How we connect the equation of state with the kilonova light curve

- Mapping from binary parameters to properties of ejecta
  - Rare BQS simulations, no self-consistent simulations (ν, 3D EoS)
  - One example from our simulation
  - Ejected mass is suppressed

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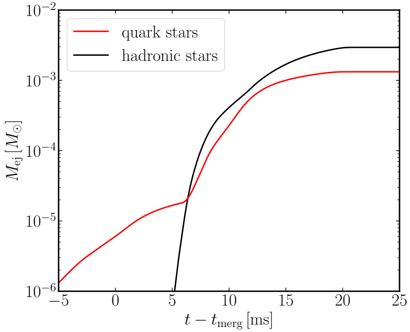

ejected mass v.s. time

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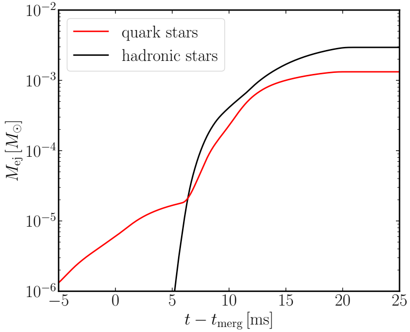

ejected mass v.s. time

Constraining NS EoS by kilonova

- Bayesian inference of equation of state with kilonova light curve (AT2017gfo)

EoS → $\Lambda,\ (q,\ \mathcal{M})$ → Properties of ejecta → Kilonova

- EoS are described by relativistic mean field model and quark mean field model
- The saturation properties $(K_0,\ J_0,\ L_0,\ M_N^*)$ are inputted as prior
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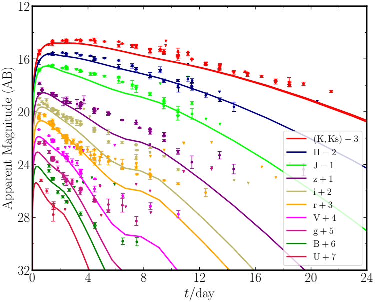
Kilonova (AT2017gfo) light curve

- First step: Infer the ejecta properties (ejected mass, velocity, electron fraction) with kilonova light curve
- Only the dynamical ejecta included
- Data after 4 day can not be fitted very well
- Additional mechanism of ejecta components

Best-fitted model



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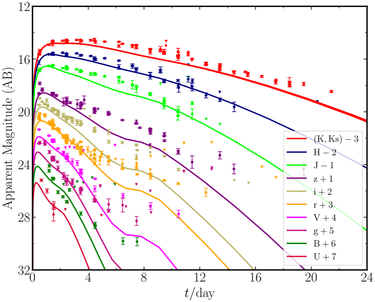

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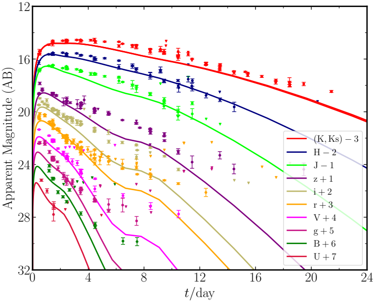

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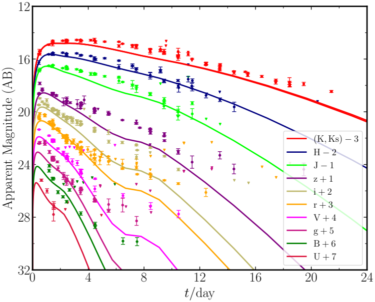

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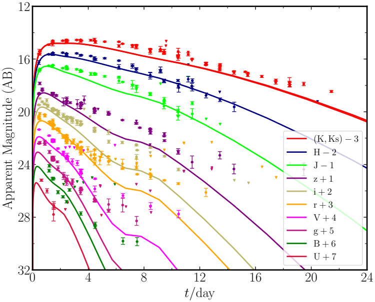

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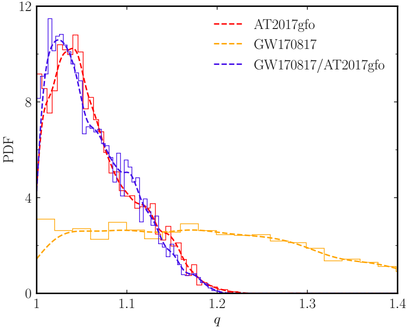
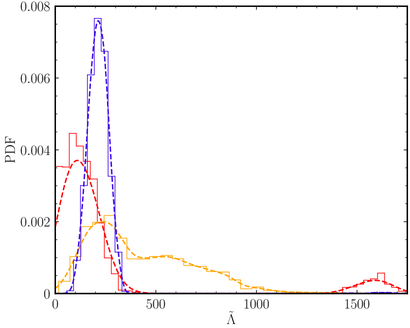
Mass ratio and tidal deformability



Posteriors of mass ratio



Posteriors of tidal deformability

- Mass ratio and tidal deformability posterior
- AT2017gfo display a bimodal structure on TD
- AT2017gfo favor a smaller TD

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Mass, radius and TD posteriors

- AT2017gfo favors a smaller radii, TD and soft EoS
- GW170817 and AT2017gfo are consistent with each other
- NICER data favors to stiff EoS because of the maximum mass constraints

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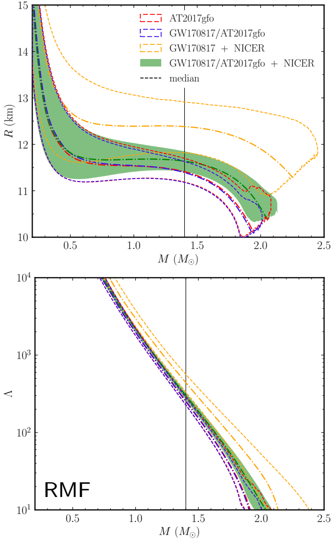
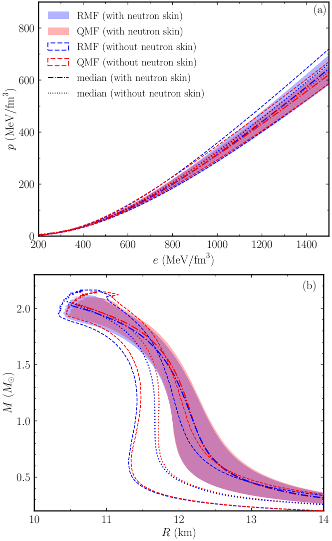


90% contour of M-R and M-Λ

Comparison of QMF and RMF

- Relativistic mean field (RMF) and quark mean field (QMF) results are consistent
- Neutron skin data strongly favors to a larger symmetry energy slope (L_0), and lareger radius

PREX-II $L = (106 \pm 37)$MeV



90% contour of EoS and M-R

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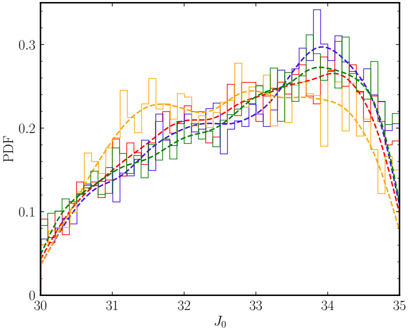
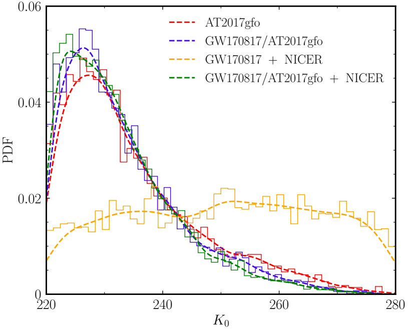
Saturation properties posteriors



Posteriors of symmetry energy (J_0)



Posteriors of incompressibility (K_0)

- GW170817 and NICER have a weak constraints on incompressibility (K_0)
- AT2017gfo favors to soft EoS, therefore smaller K_0 and larger effective mass

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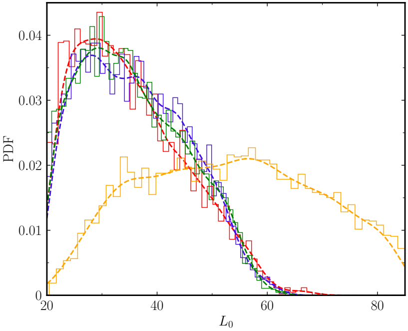
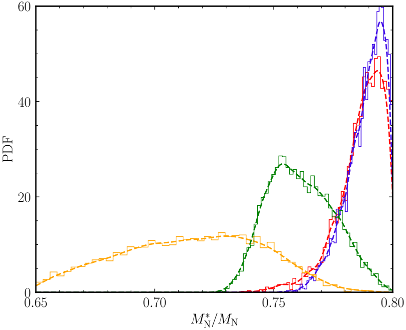


Posteriors of symmetry energy slope (L_0)



Posteriors of effective mass (M_N^*)

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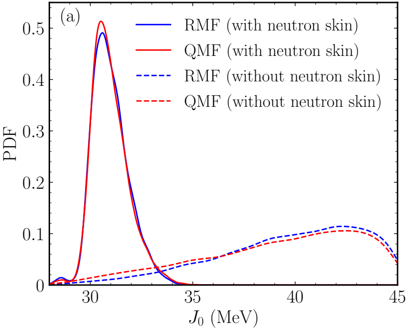
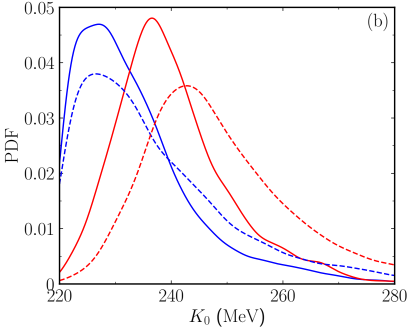
Saturation properties: RMF v.s. QMF



Posteriors of symmetry energy (J_0)



Posteriors of incompressibility (K_0)

- From the model level, QMF favors to larger M_N^*. high M_N^* (=>soft EoS) is compensated by larger K_0 (stiff EoS) N.Hornick+ (2018)

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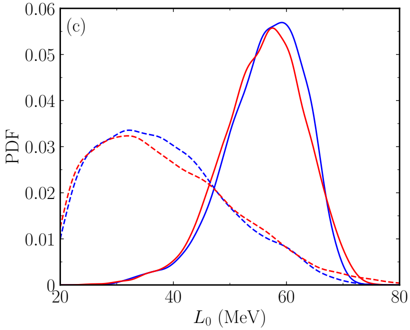
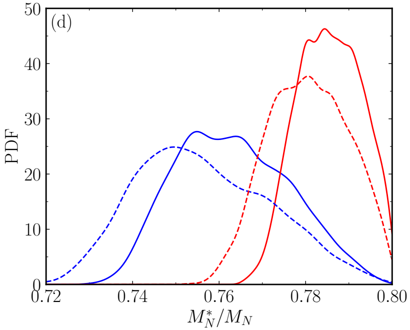
Saturation properties: RMF v.s. QMF





Posteriors of symmetry energy slope (L_0)

Posteriors of effective mass (M_N^*)

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Conclusions

- We performed the fully GR simulation of binary quark stars merger after solving the problems of discontinuity of stellar surface
- The peak frequencies of binary quark star merger do not deviate from the quasi-universal relations in our example simulation, it needs more investigations
- Kilonova light curve (AT2017gfo) is used to constrain the EoS, and the results are consistent with GW170817
- AT2017gfo favors soft EoS compare to the NICER data
- QMF and RMF shows consistent predictions on M-R relation, but the saturation properties are different