NEUTRON STAR PHYSICS IN THE MULTI-MESSENGER ERA

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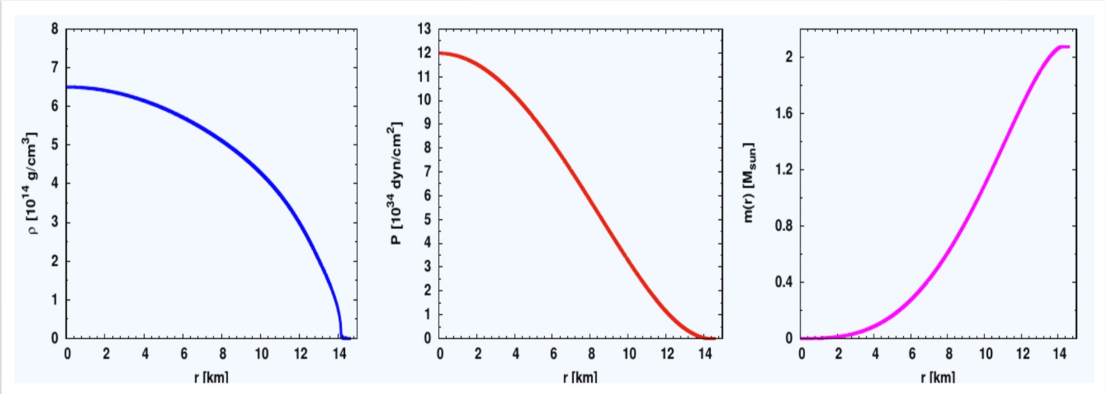
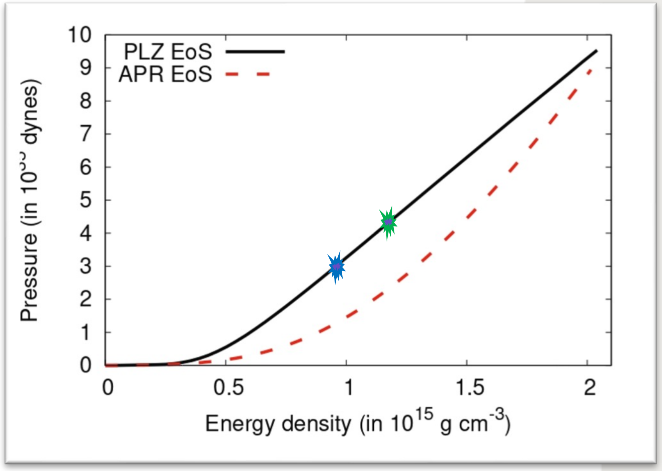
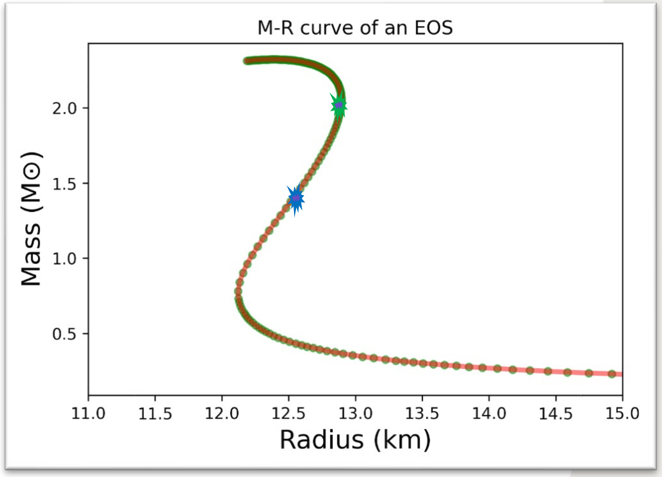
NEUTRON STAR

TOV Equation

$$\frac{dP}{dr} = -G\frac{M(r)\rho(r)}{r^2}\frac{\left[1+\frac{P(r)}{\rho(r)c^2}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)c^2}\right]}{\left[1-\frac{2GM(r)}{rc^2}\right]}, \qquad M(r) = 4\pi\int_0^r \rho(r) r^2 dr$$







NEUTRON STAR

Given an EoS (relationship between thermodynamic variables)

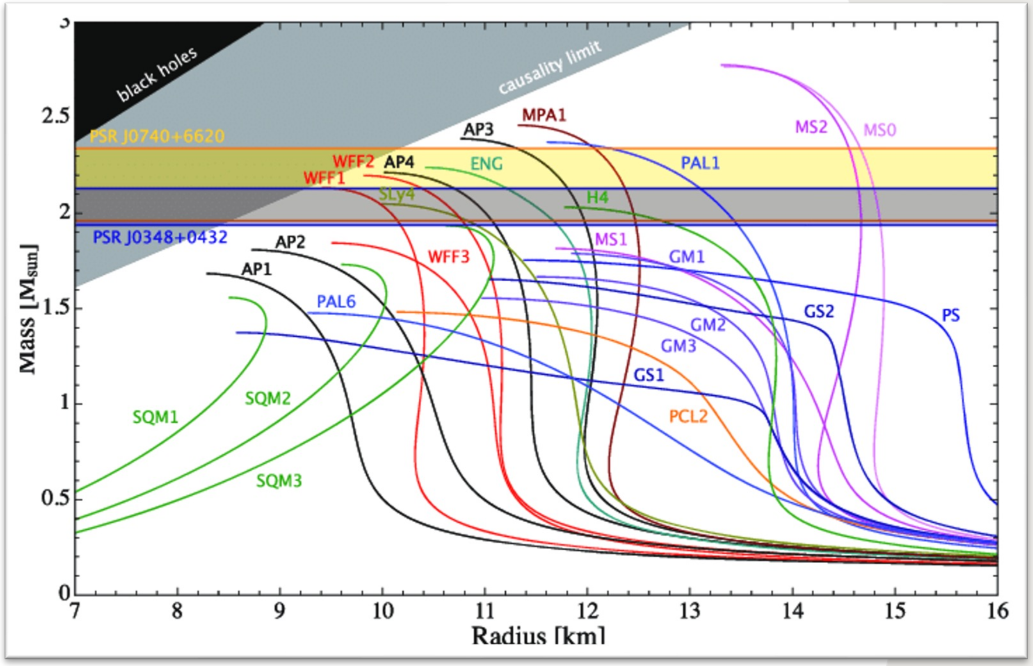
⬇

Unique Mass-Radius curve

Different curve for different EoS

What is the actual EoS?
The form of matter at the core of NS?

Test the theory of high-density matter with NS observation



Huanchen Hu et al, MNRAS 497, 3118 (2020)

NEUTRON STAR: EOS

Current Knowledge

Two extremes

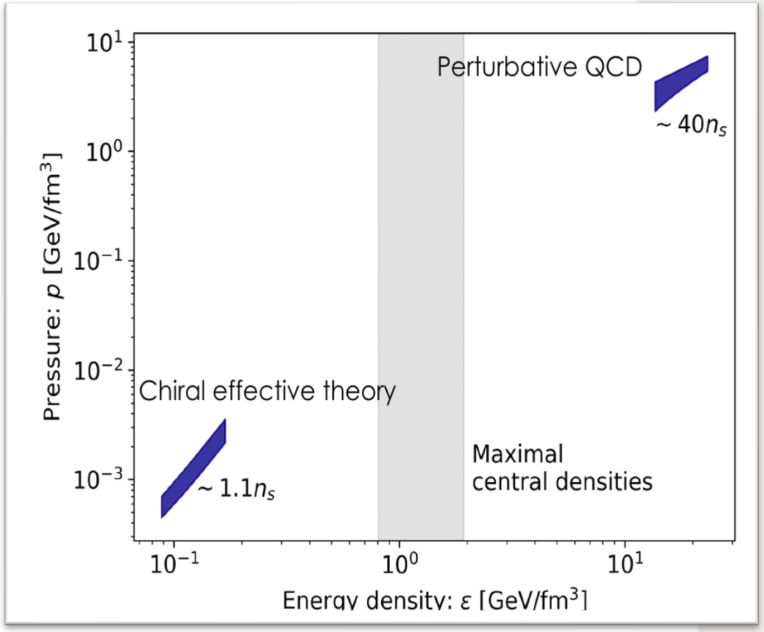
We are confident about the matter properties at the two extremes

Low density: Chiral effective field theory

High density: perturbative QCD

Filling the unknown region with all thermodynamically consistent EoS

- Speed-of-of sound interpolation
- Piecewise-polytrope



A Kurkela, Quark Confinement Conf, Stavanger

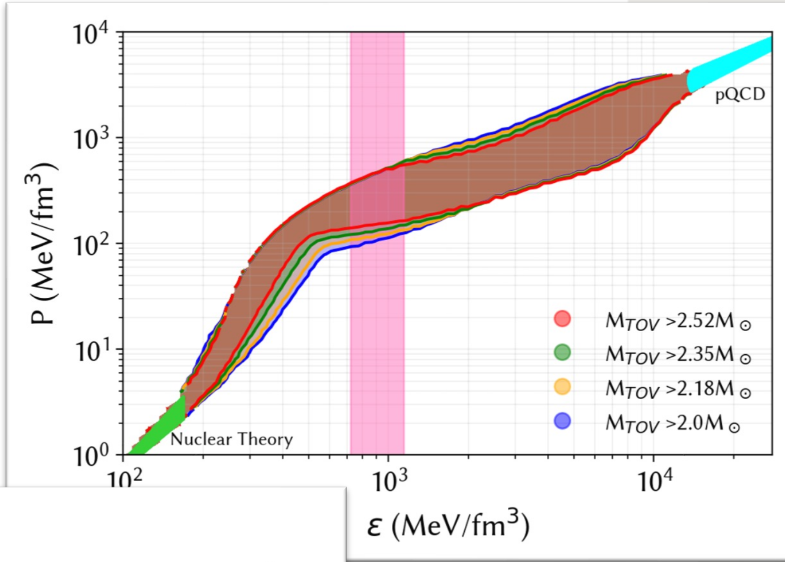
NEUTRON STAR: EOS

Astrophysical Constraints

Mass constraints

PSR J0348+0432 (~ ***2.0***)

PSR J0740+6620 (~ ***2.0***)

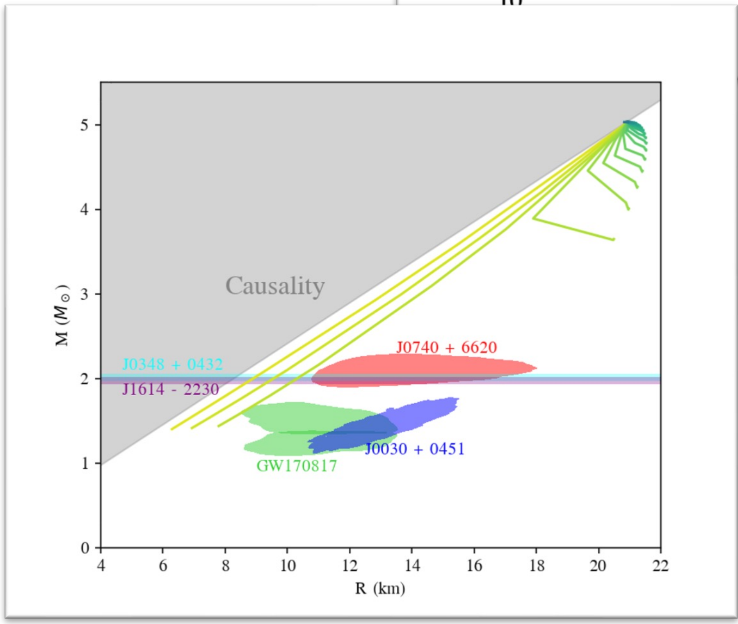


NICER & Astrophysical constraints

$R_{1.1} >$ ***10.75 km***

$R_{2.0} <$ ***14.8 km***

11.5 km $< R_{1.4} <$ ***13.85 km***



GW170817 constraints

$\bar{\lambda}_{1.4} < 800$

Saha & Mallick, Arxiv:2407.13149

NEUTRON STAR: EOS

Different EoS types

Can be smooth

Can have Phase transition

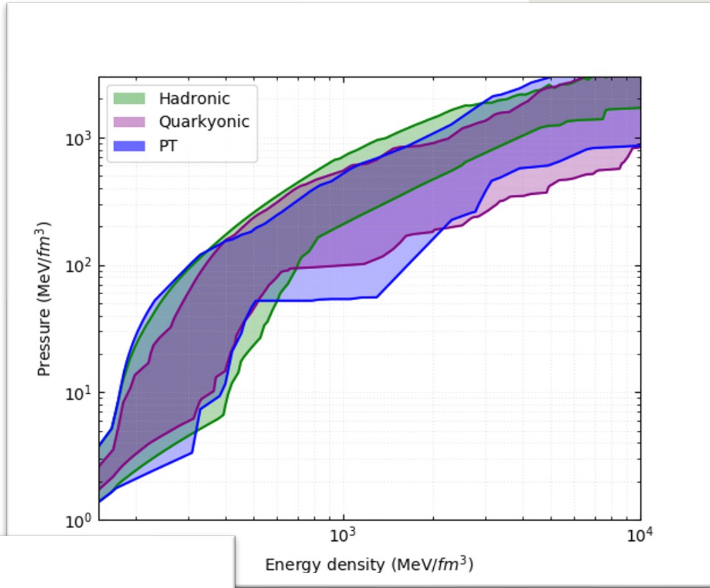
Smooth, 1st-order, Quarkyonic ….

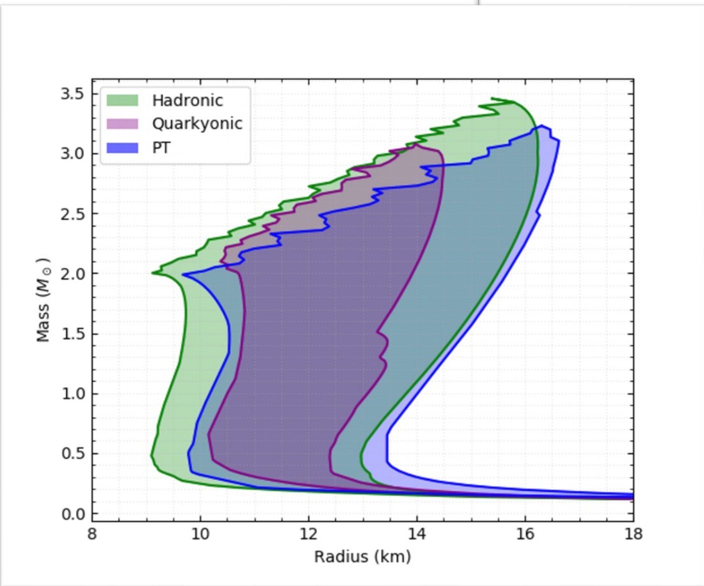
Is it possible to differentiate them?

Astrophysical observation

Very difficult

Significant Overlap



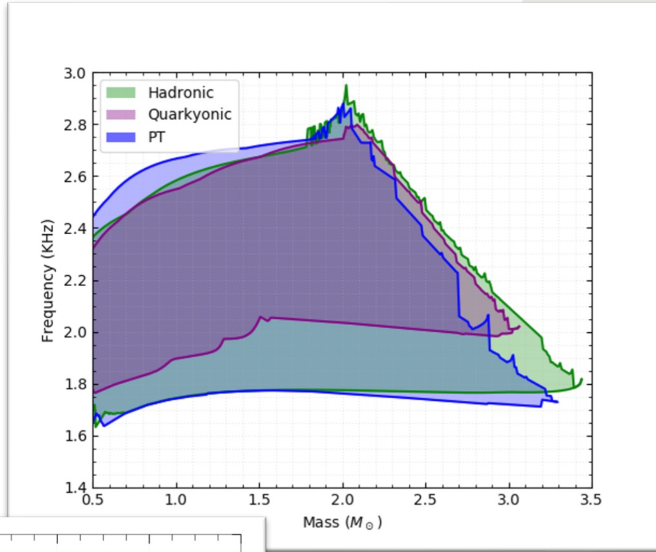


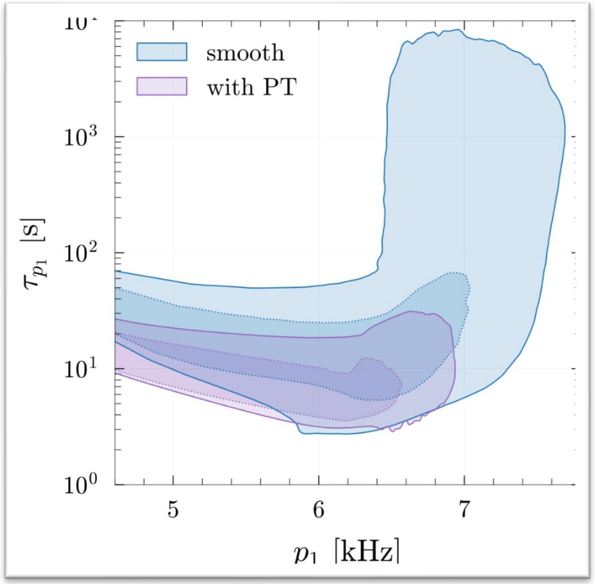
NEUTRON STAR: EOS

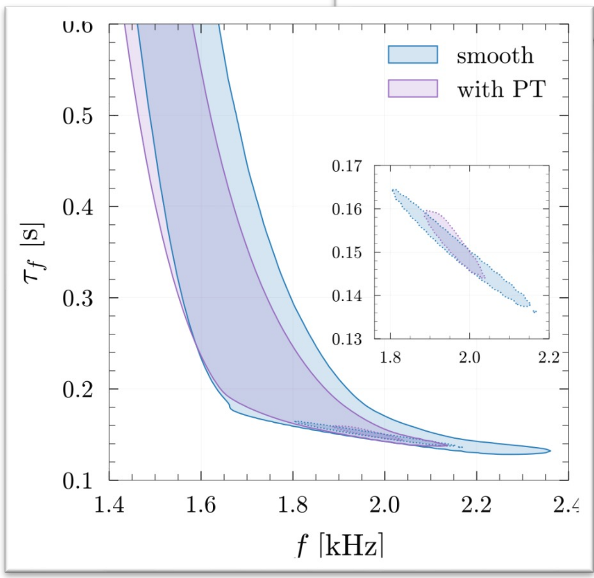
Asteroseismology:

Non-radial oscillations modes: f-mode, p-mode, g-mode

Still difficult as there is significant overlap





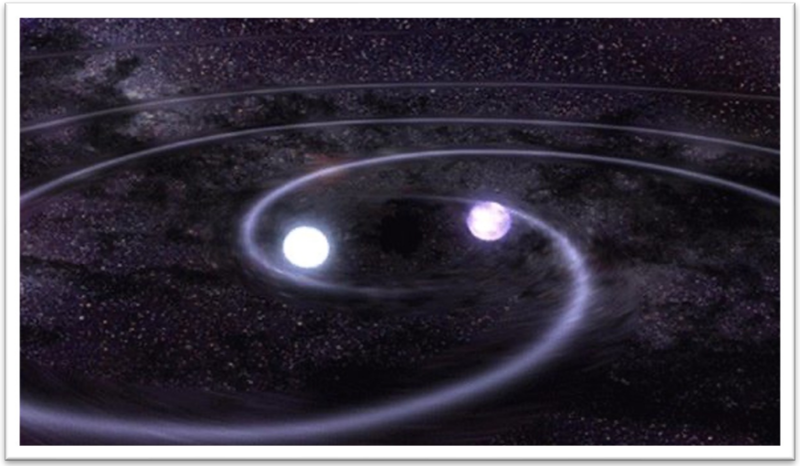


Thakur et al., PRD 110, 103045, 2024

NEUTRON STAR BINARIES

GRAVITATIONAL

BINARIES

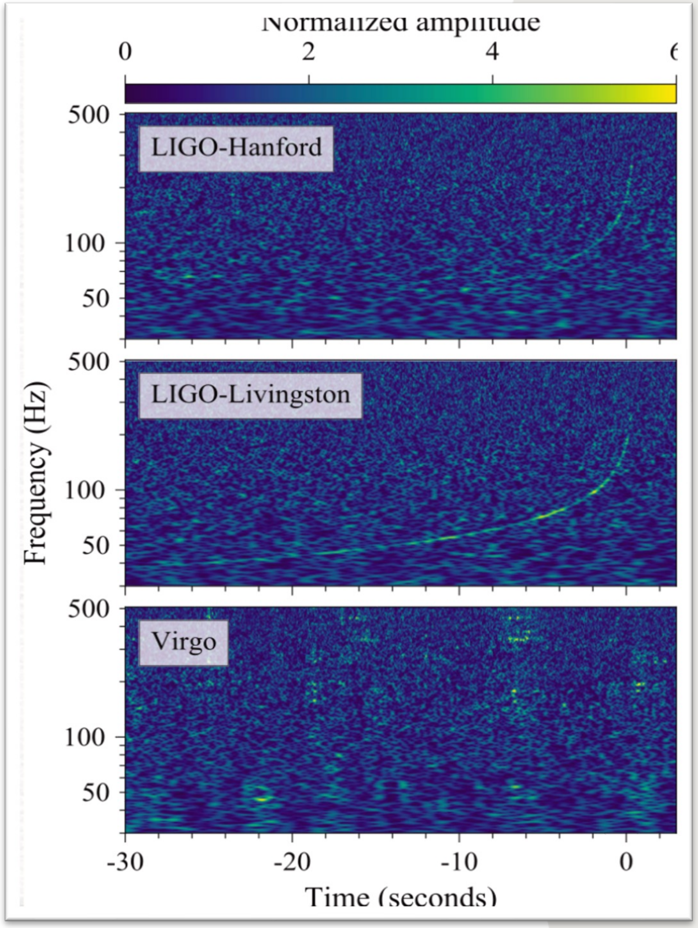


NASA/Dana Berry, Sky Works Digital

Binary Neutron star merger

GW170817

NS + NS —GW→ HMNS —GW→ BH



Abbott et al., PRL119, 161101 (2017)

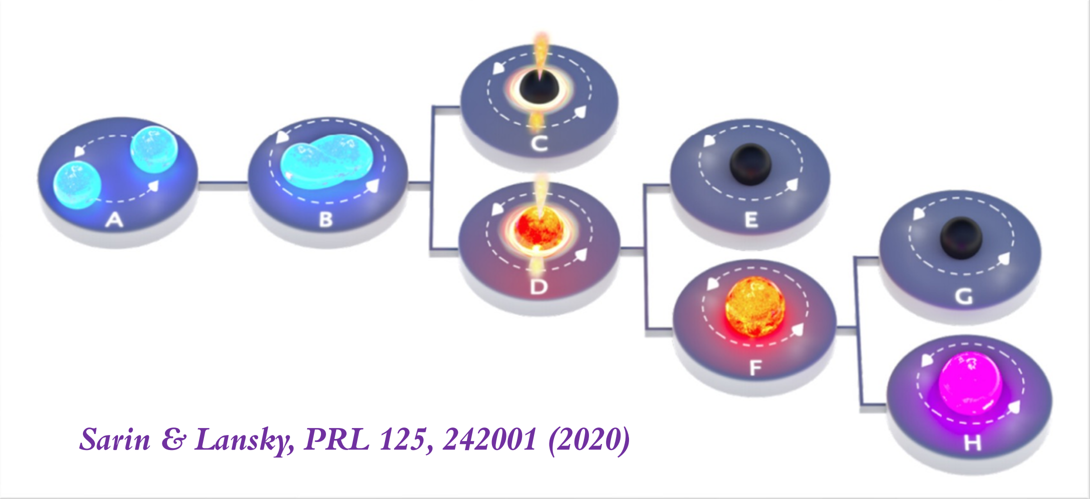
BINARIES

Detection of the inspiral part, before the merger

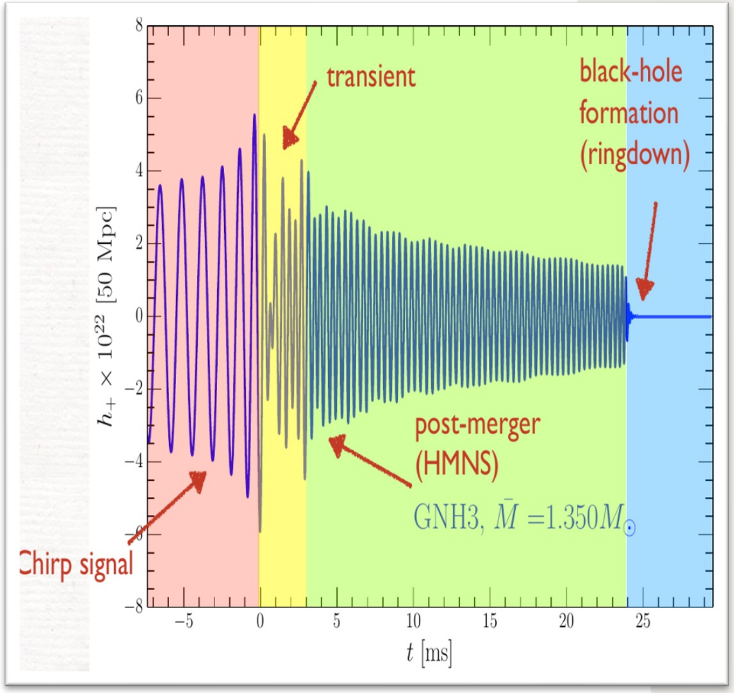
Not only GW but also sGRB and Electromagnetic Signal

Multi-messenger signal

Post-merger signal not detected, expected to have more rich physics



Sarin & Lansky, PRL 125, 242001 (2020)



Takami et al., PRL 113, 091104 (2014)

BINARIES

Equation of State

Hadronic: DD-ME2 Quark: MIT bag model

Mixed phase, Polytropic Fit

3-different onset point (where mixed phase starts)

Initial Setup

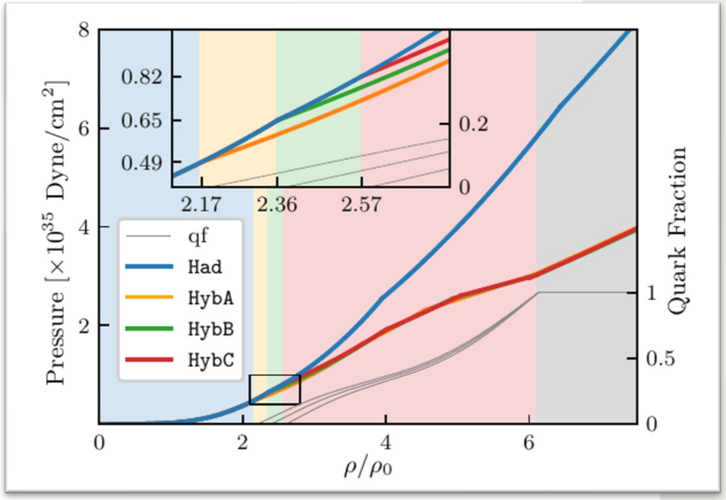
LORENE code: Binary star code

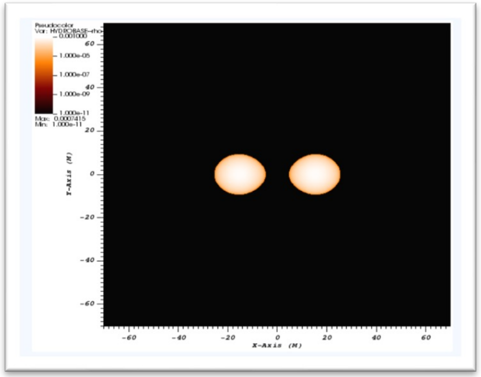
Solves the constraints equation

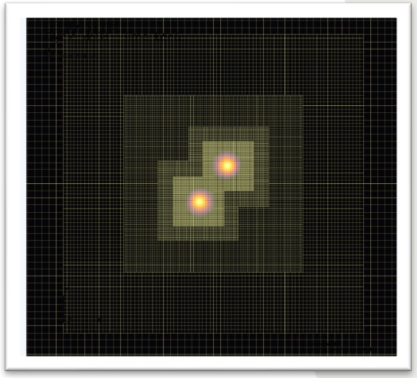
Evolution

Einstein Toolkit: solves the evolution equations

GW extraction

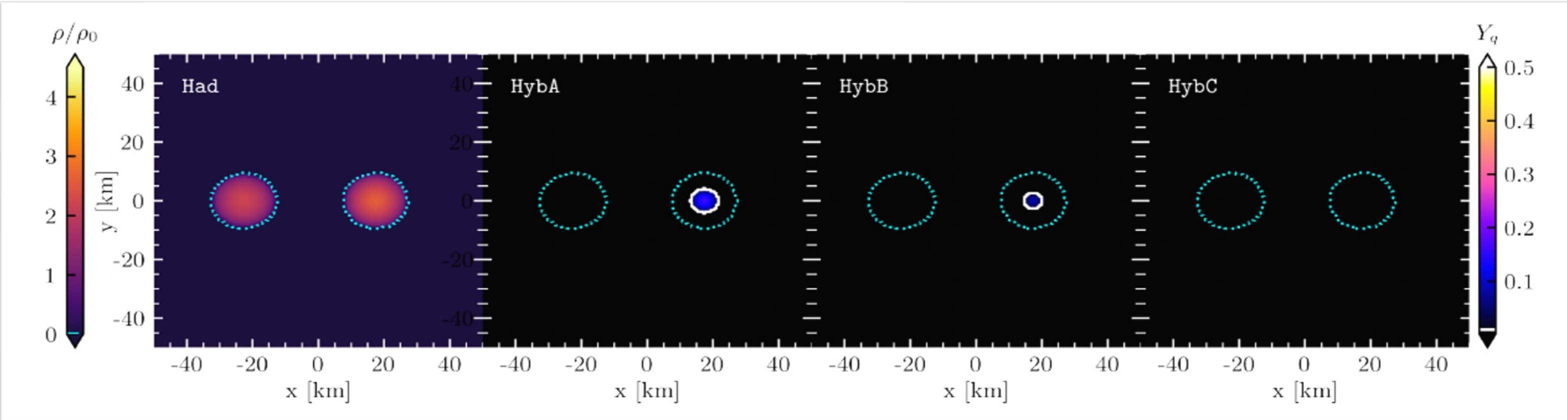




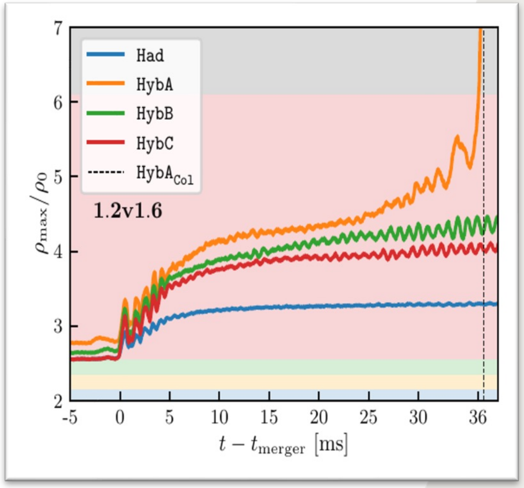


S. Haque, R. Mallick … MNRAS, 527, 11575 (2024)

BINARIES



Unequal Mass binaries: 1.2 + 1.6



Initial configuration: Appearance of mixed phase region even before merging

The HMHS where mixed phase appears collapses early

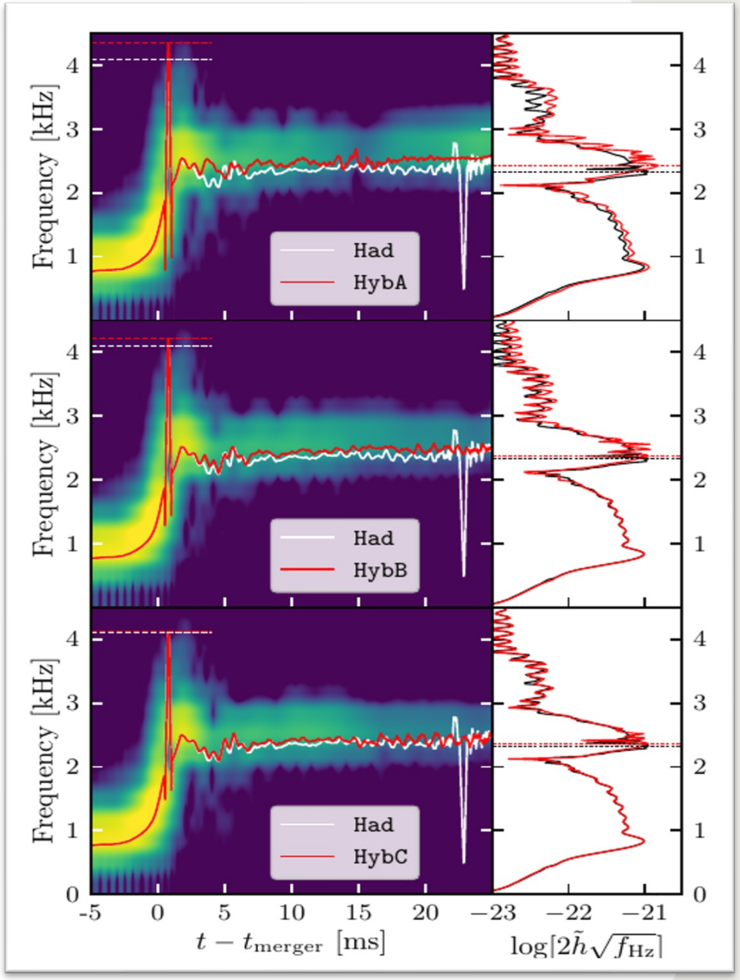
The HMNS remains stable for the longest time

BINARIES

Unequal Mass Binary : 1.2 + 1.6

The peak frequency is different for HMNS and HMHS

The power spectral density also shows difference for HMNS and HMHS



TWINS

The speciality about twins

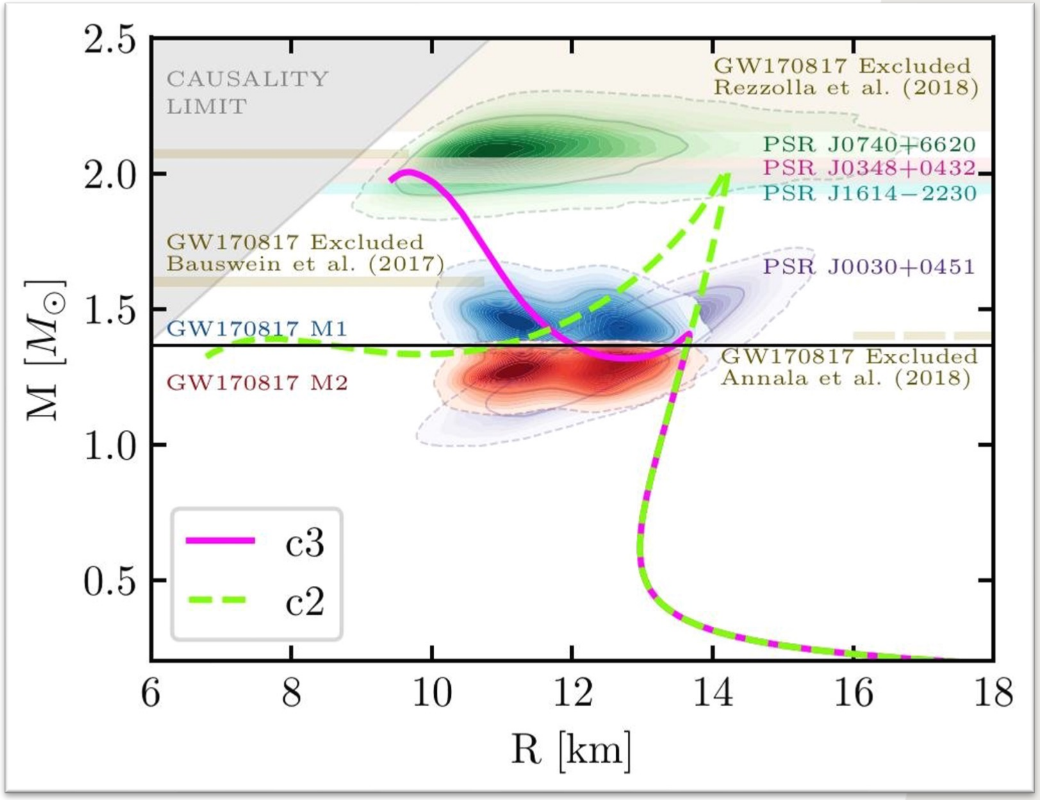
In some cases, the second branch can be unstable for some radius and then again becomes stable

Mass of the star of stable and unstable branch same, but different Radius

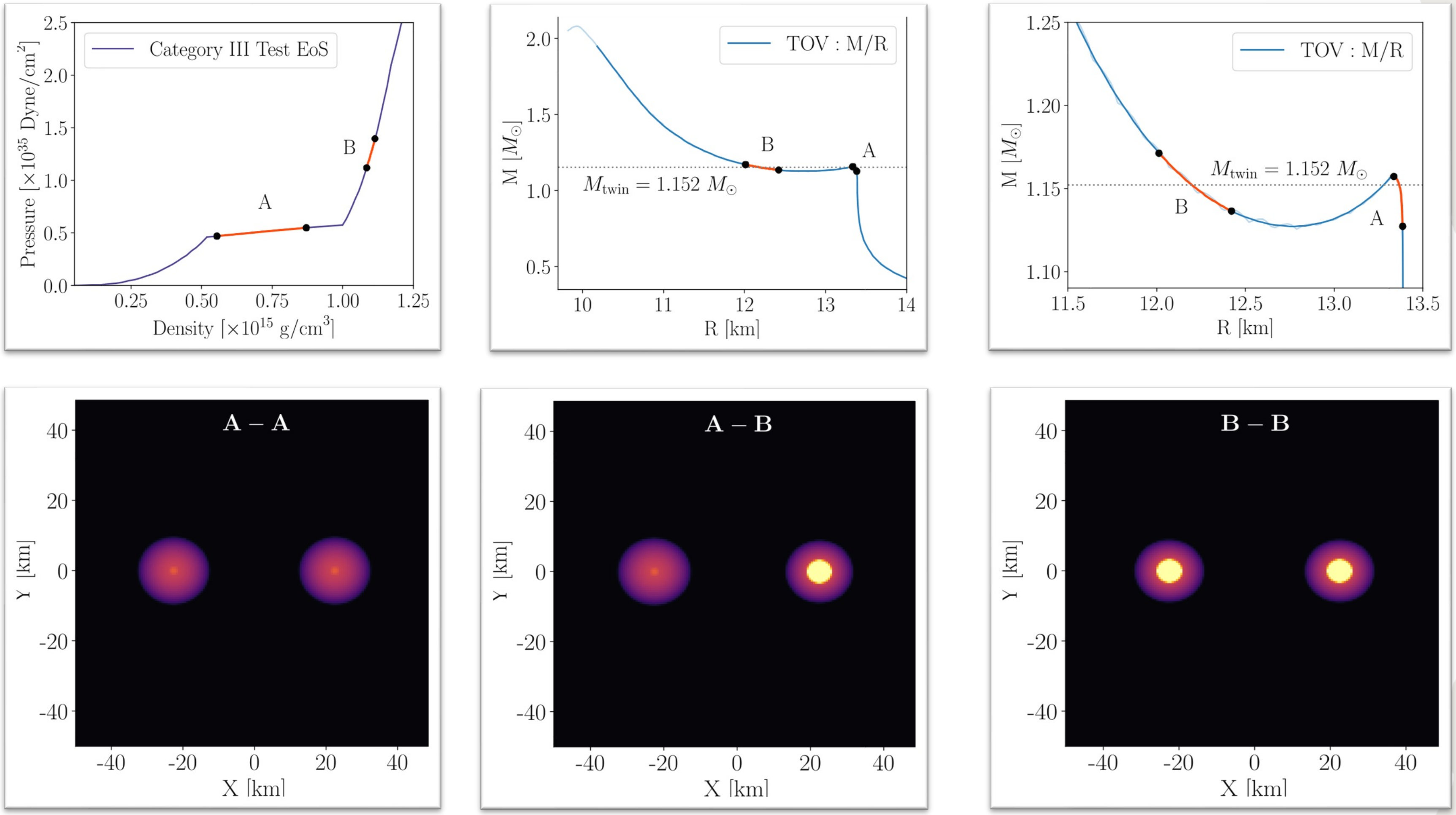
Twins

Same mass → Different Radius →

Can be of various types

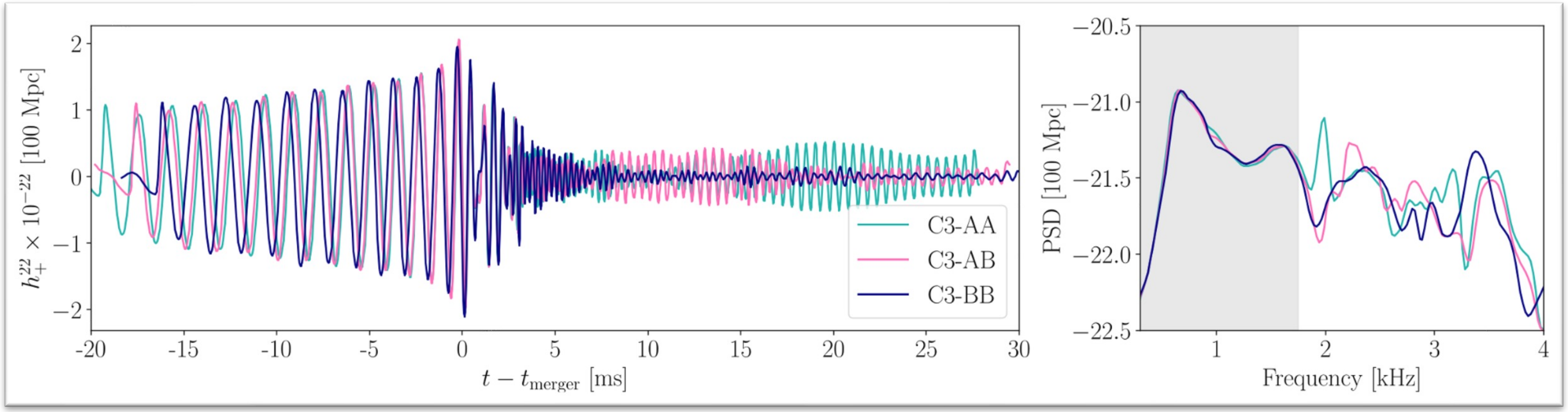


TWINS

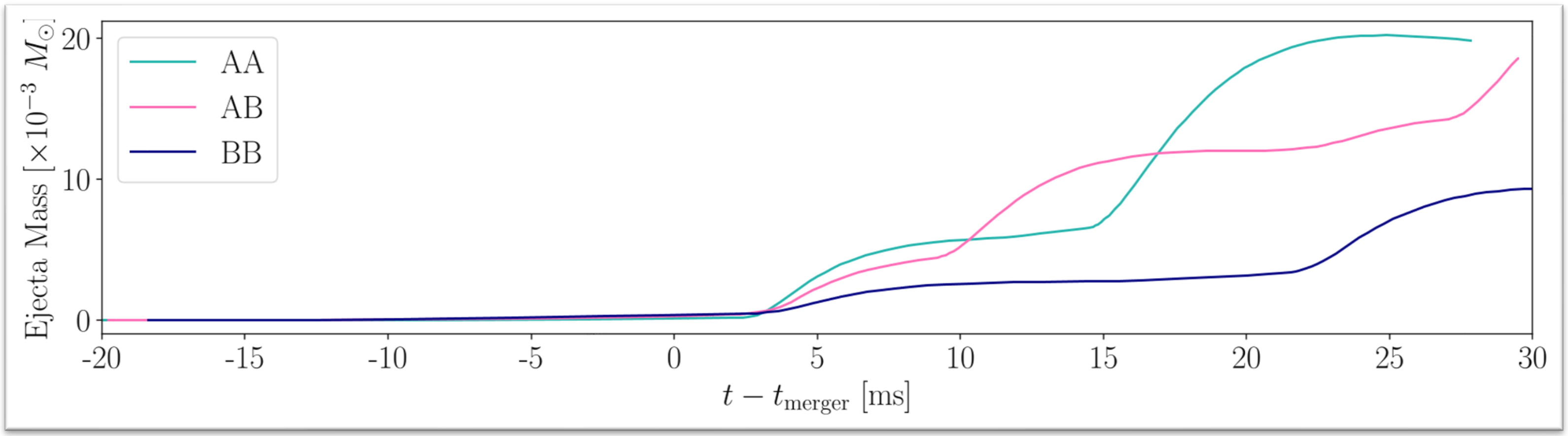


Category III Test EoS
Pressure [×10^35 Dyne/cm^2]
Density [×10^15 g/cm^3]
A
B
TOV : M/R
M [M⊙]
R [km]
M_twin = 1.152 M⊙
A
B
TOV : M/R
M [M⊙]
R [km]
M_twin = 1.152 M⊙
A
B
A – A
A – B
B – B
Y [km]
X [km]

TWINS



$h_+^{22} \times 10^{-22}$ [100 Mpc]
$t - t_{\mathrm{merger}}$ [ms]
C3-AA
C3-AB
C3-BB
PSD [100 Mpc]
Frequency [kHz]



Ejecta Mass [$\times 10^{-3}\ M_\odot$]
$t - t_{\mathrm{merger}}$ [ms]
AA
AB
BB

NEUTRON STAR BINARIES

ELECTROMAGNETIC

KILONOVA

Electromagnetic signals from the binary merger ⟶ KiloNova

Signal AT2017gfo (from GW170817)

Matched well with the light powered by radioactive decay of heavy nuclei

Synthesized by r-neutron capture of neutron rich ejected matter

Is being detected still now

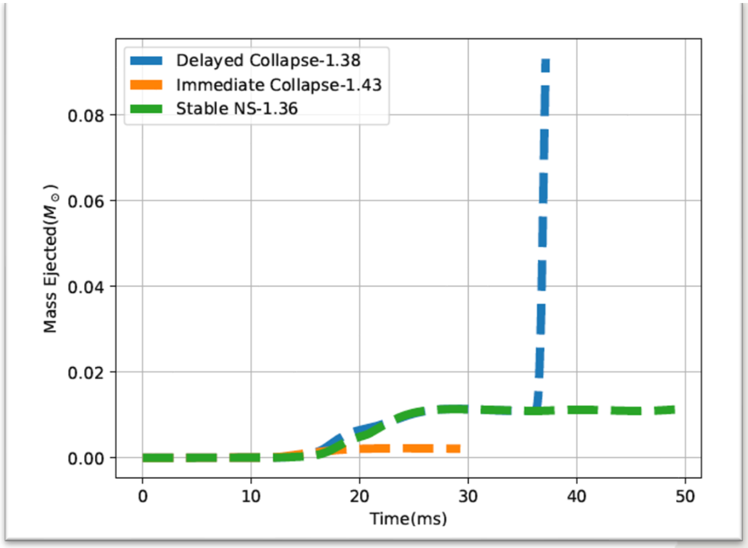
KILONOVA

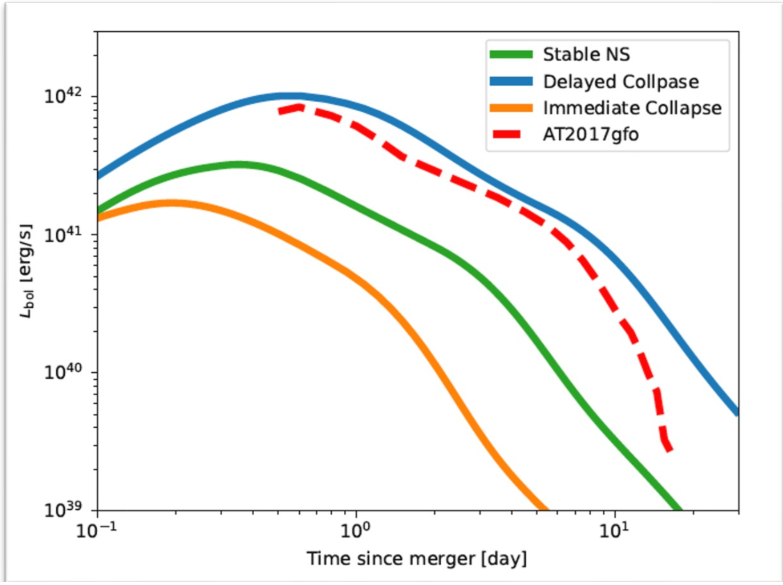
Energy provided by the radioactive decay of heavy elements

Depends on the ejected mass

Ejected mass depends on the type of collapse
Prompt collapse
Delayed collapse
Stable configuration

$$\frac{dE}{dt} = \dot{Q}(t) - L(t) - \frac{E}{t}$$





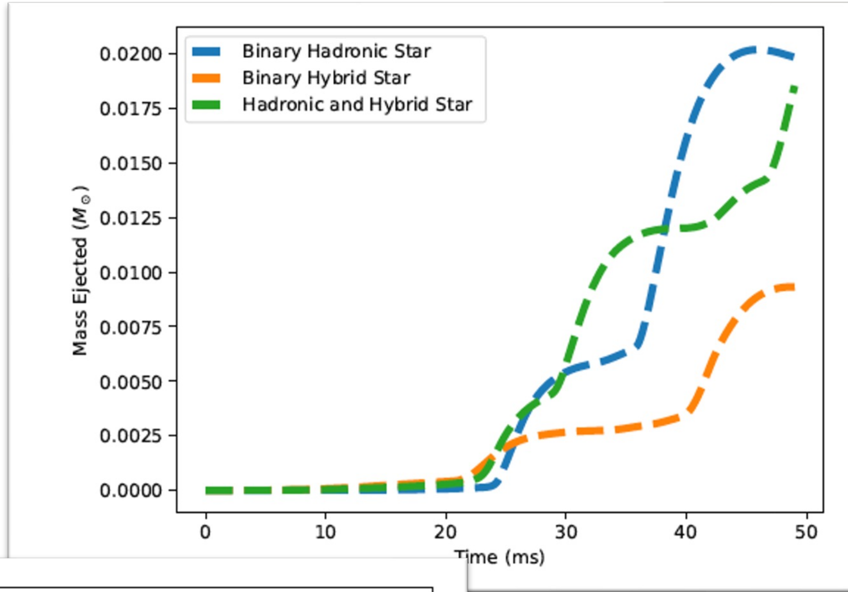
KILONOVA

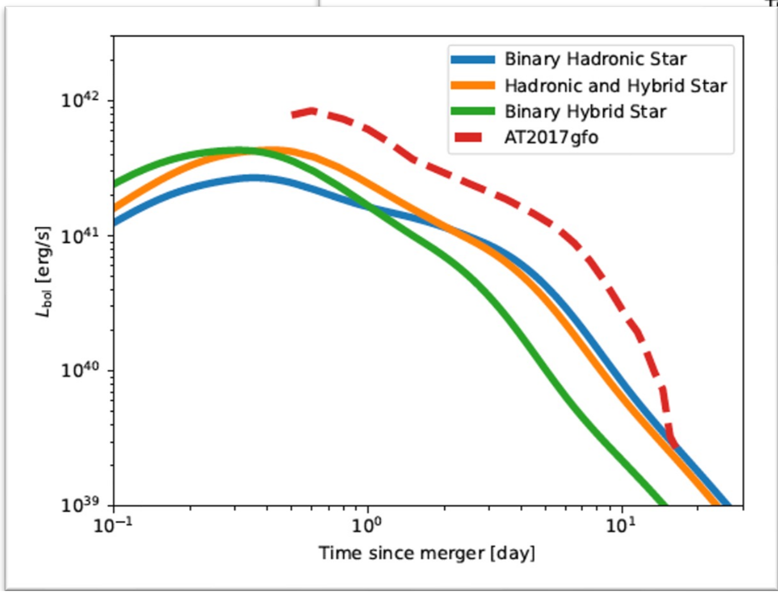
Depends on the type of EoS (N/Q)
Binary neutron star
Binary quark star
Neutron-quark binary

This match is done with
given mass ratio of GW170817

Still a lot of unknown goes in the
Calculation

Velocity of ejecta
Model of the mass contribution
Elements for the radioactive decay





THANK YOU