Gravitational wave signatures of phase transition from hadronic to quark matter in isolated neutron stars and binaries

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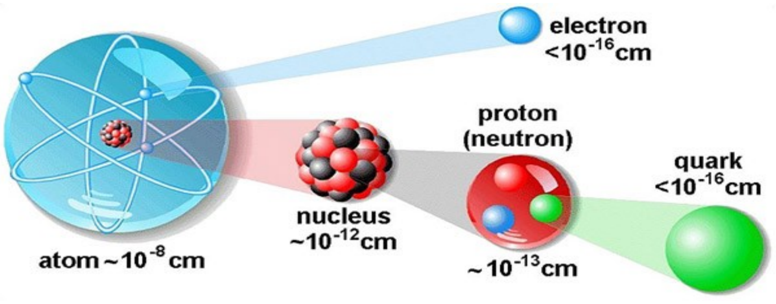
Astrophysical Phase Transition

Importance of Astrophysical PT:

Quark-gluon plasma is confirmed at high temperature (collider experiments).
What about high density?
Still No earth-based experiments.



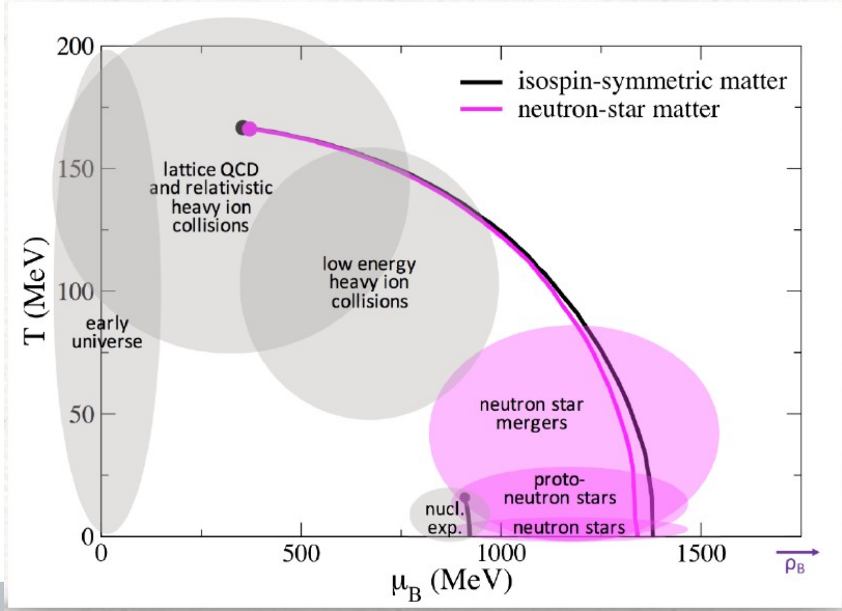
Natural laboratory are Neutron stars.
Renewed interest after detection of NS-NS mergers.

What about phase transition in neutron stars.
Neutron stars $\longrightarrow$ **Quark stars**

A two-step process

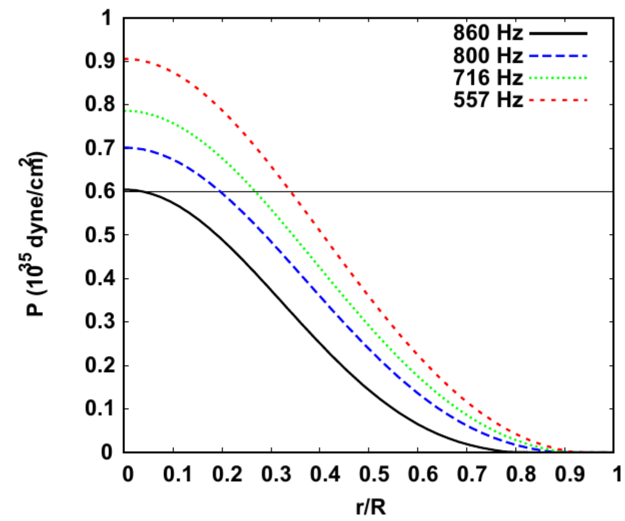
P $\longrightarrow$ **uud**
N **udd**

u + d $\longrightarrow$ **u + s**



Figs: Dexheimer et al., Universe (2019)

Phase transition in isolated stars

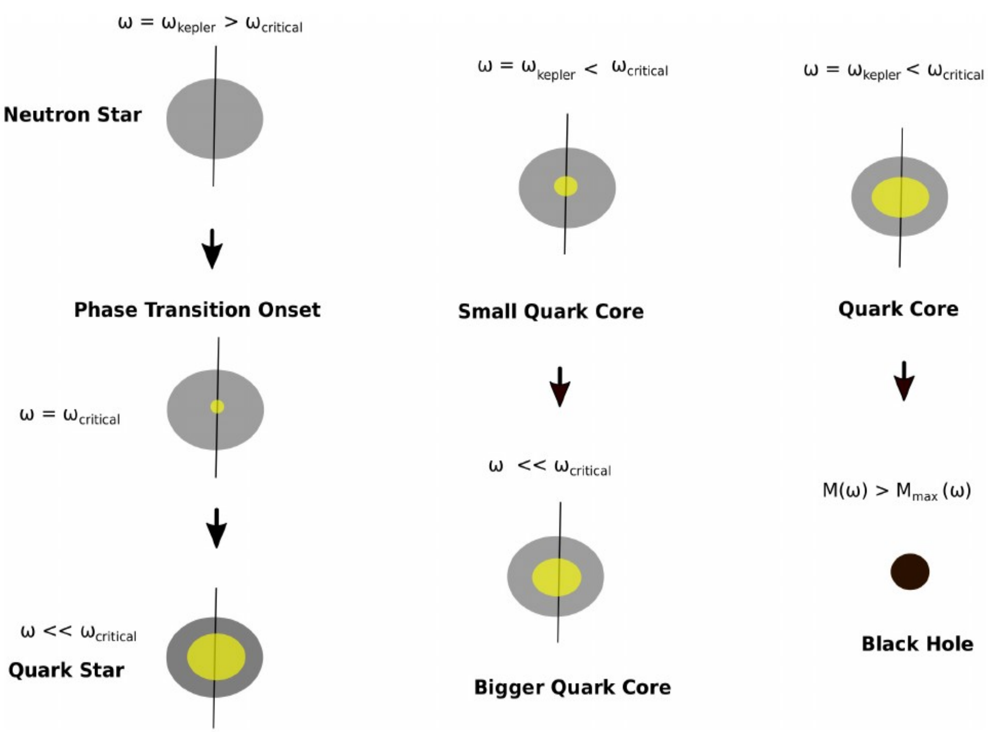


Seeding of the quark core:

The seeding happens as the star slows down.

Once the critical density is crossed the quark seed forms.

The seed grows as the star slows down further.



4 scenarios:

1. Low-mass star never attains quark core
2. Core develops during lifetime
3. Core grows during lifetime
4. Core grows and ultimately star collapse to BH

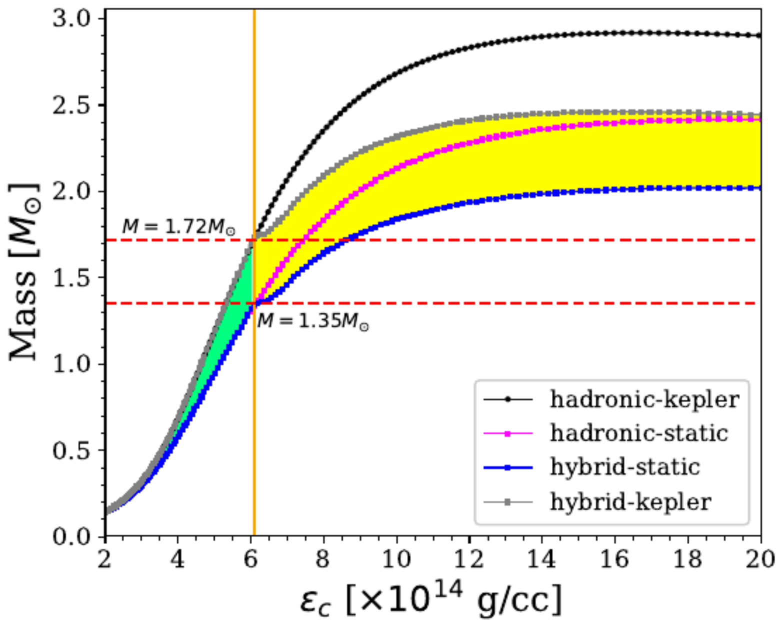
Prasad & mallick, arXiv:2207.03234

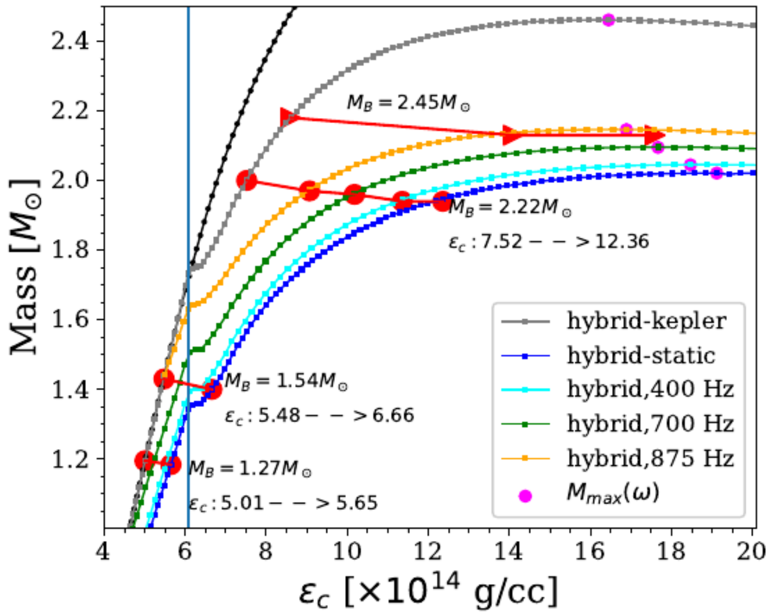
Phase transition in isolated stars

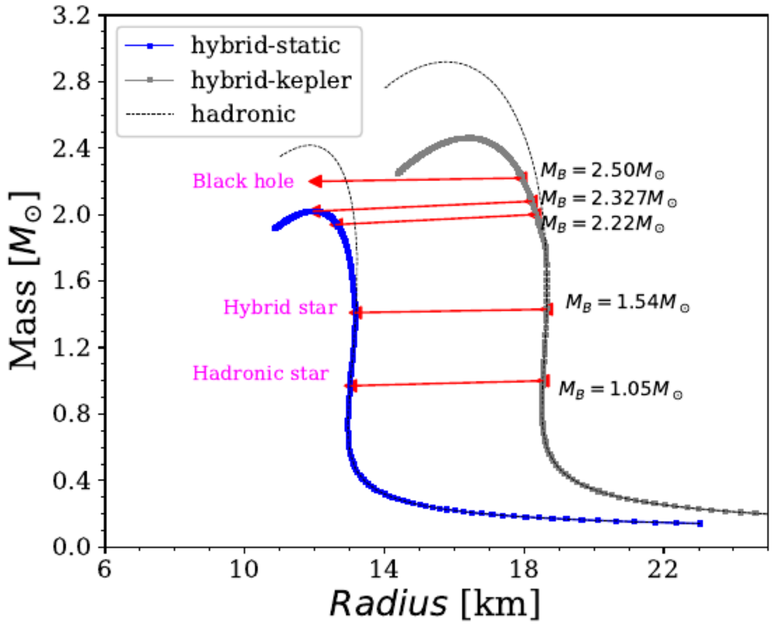
A handful of stars:

The range of stars which attains a quark core depends on the EoS.

Changing the EoS the quantitative nature changes but qualitatively they remain same.





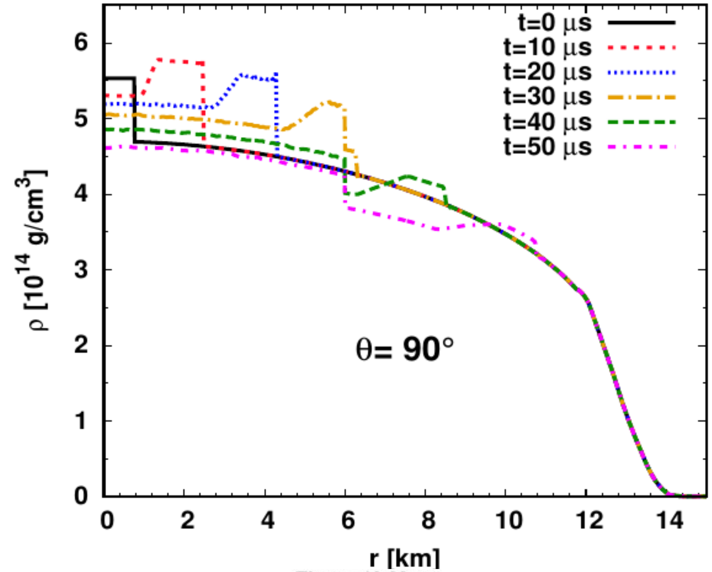


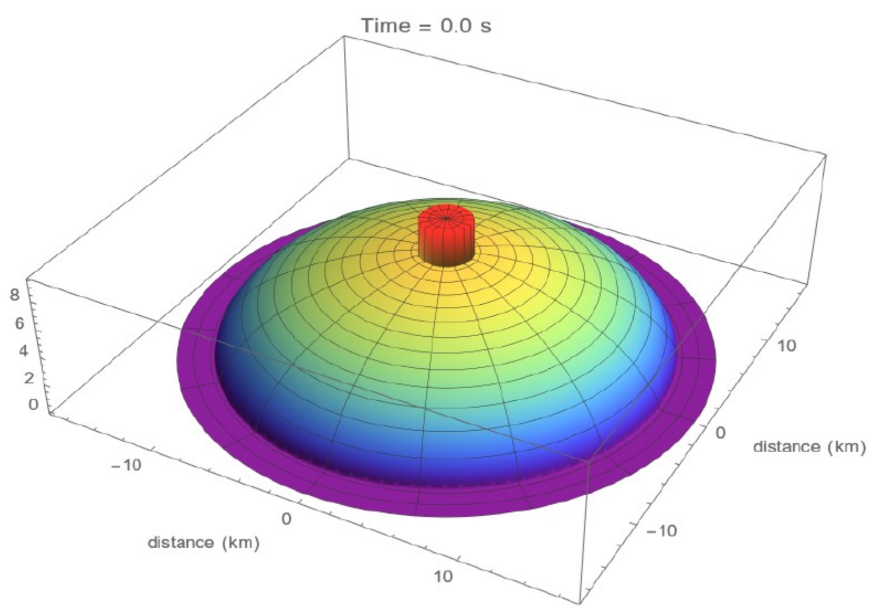
Phase transition in isolated stars

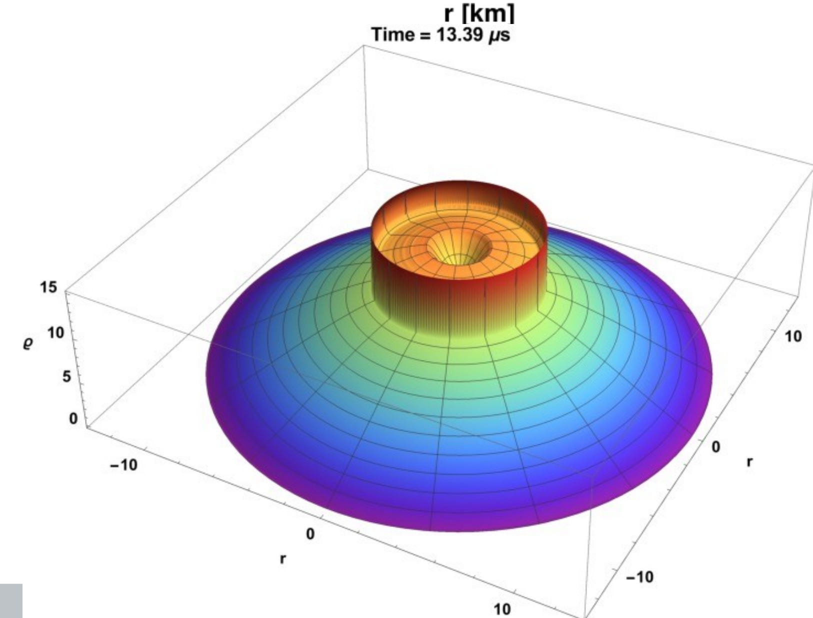
Evolution of the shock leading to deconfinement

The shock velocity is some fraction of velocity of light

The deconfinement takes about 50 microseconds







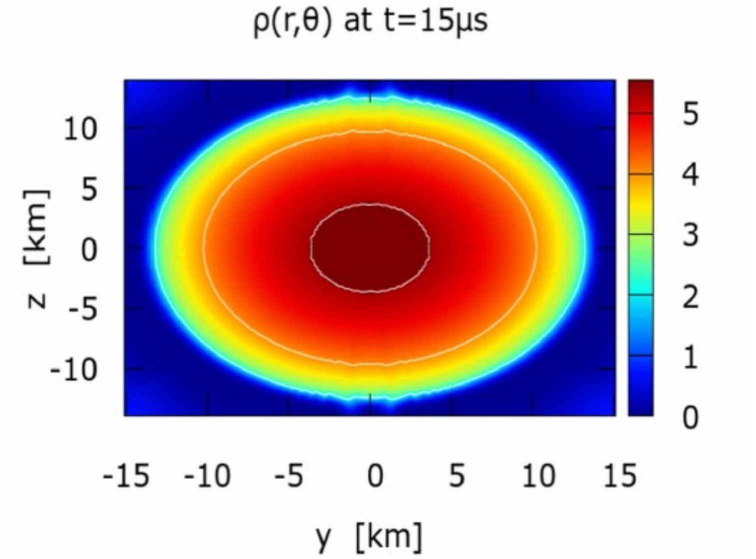
Prasad & Mallick, ApJ, 859, 57 (2018)

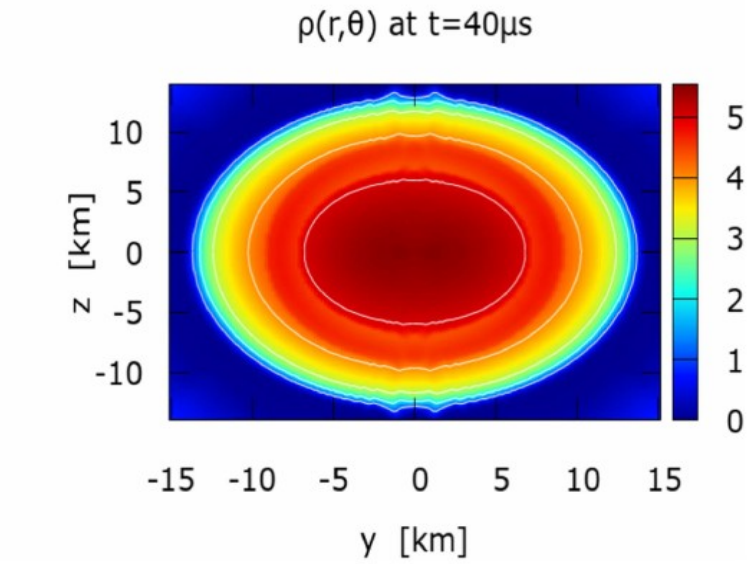
Phase transition in isolated stars

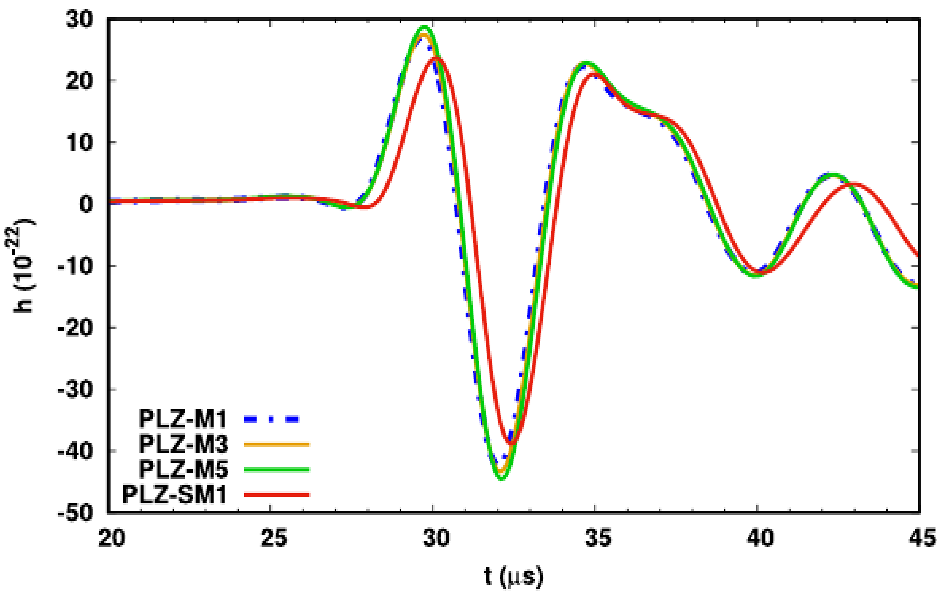
Gravitational wave generation

The change in the density profile brings about a change in the mass quadrupole moment

Results in the emission of GW







Prasad & Mallick, ApJ, 893, 151 (2020)

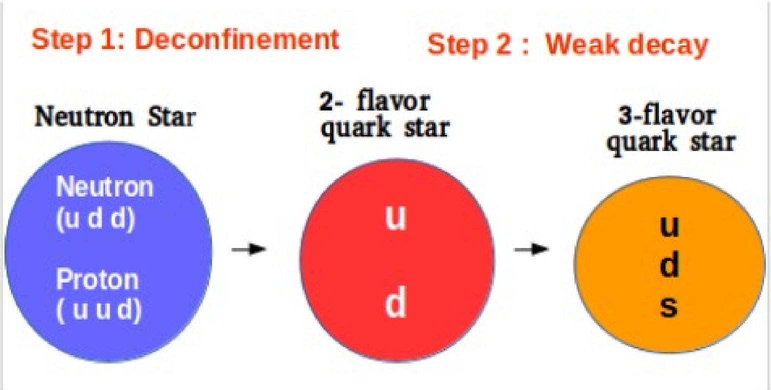
Phase transition in isolated stars

Weak decay and Stability

$$d \to u + e^- + \nu_{e^-},$$

$$s \to u + e^- + \nu_{e^-},$$

$$d + u \quad \to \quad s + u.$$



$$\boxed{\frac{d^2a}{dr^2} + \left[\frac{1}{\sqrt{|g|}}\frac{d}{dr}(\sqrt{|g|}) + \frac{1}{g^{rr}}\frac{d}{dr}(g^{rr}) - \gamma_g \frac{1}{(g^{rr})^2}\frac{v}{D}\right]\frac{da}{dr} - \frac{R(a)}{Dg^{rr}} = 0}$$

$D \propto \left(\frac{\mu_b}{T}\right)^2$ and $R(a) = \frac{a^3}{\tau}$

$$a(r) = \frac{n_k^{2f}(r) - n_k^{3f}(r)}{2n_b(r)}$$

$$n_k = \frac{1}{2}(n_d - n_s)$$

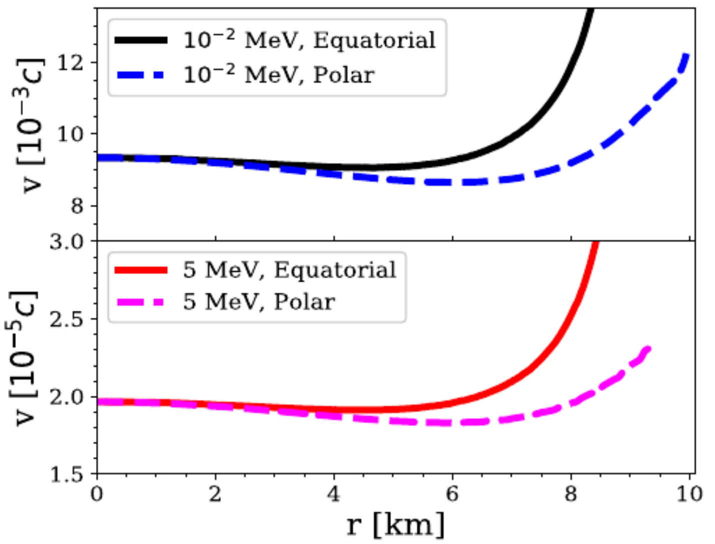
Mallick, Singh & Prasad, MNRAS, 507, 1318-1328 (2021)

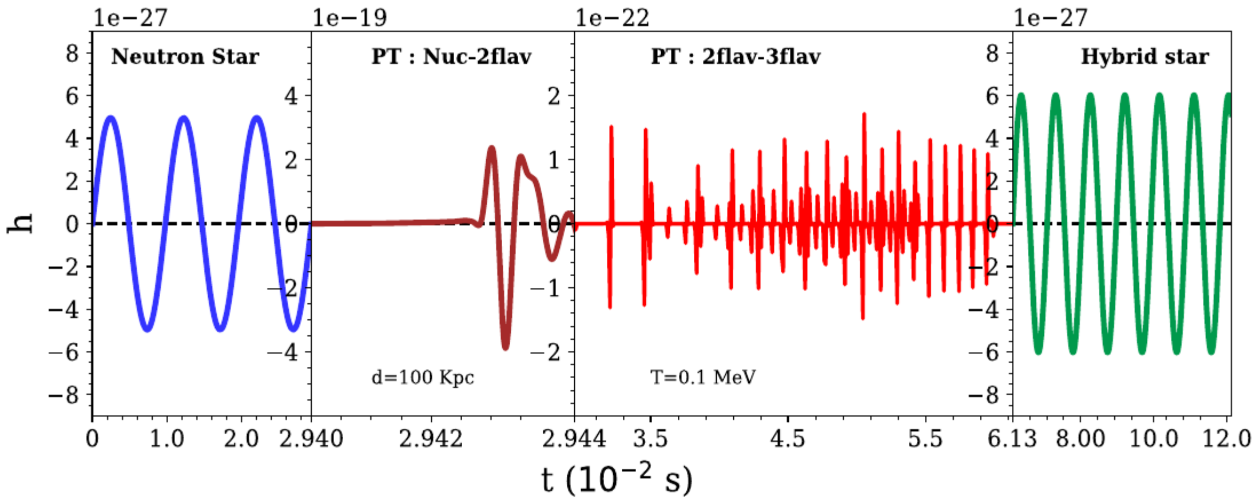
Phase transition in isolated stars

Weak decay and GW

For a NS: Mass = 2.0 solar mass
Frequency = 50 Hz
Distance = 100 Kpc
Temp = 0.1 MeV

Decay timescale 50-60 ms
Bursts type signal

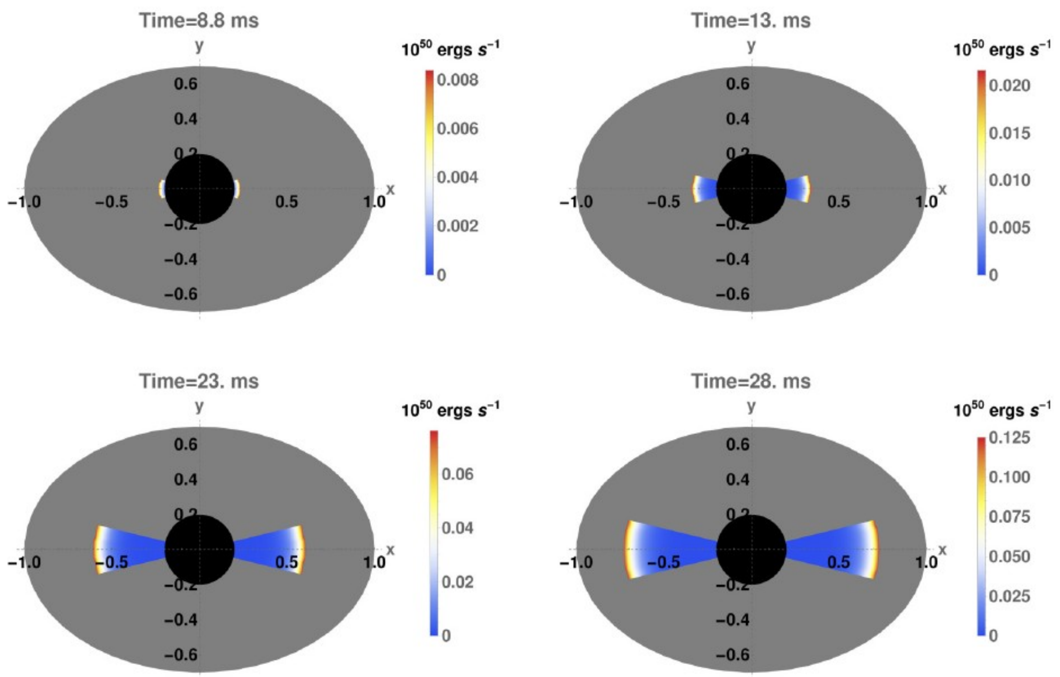


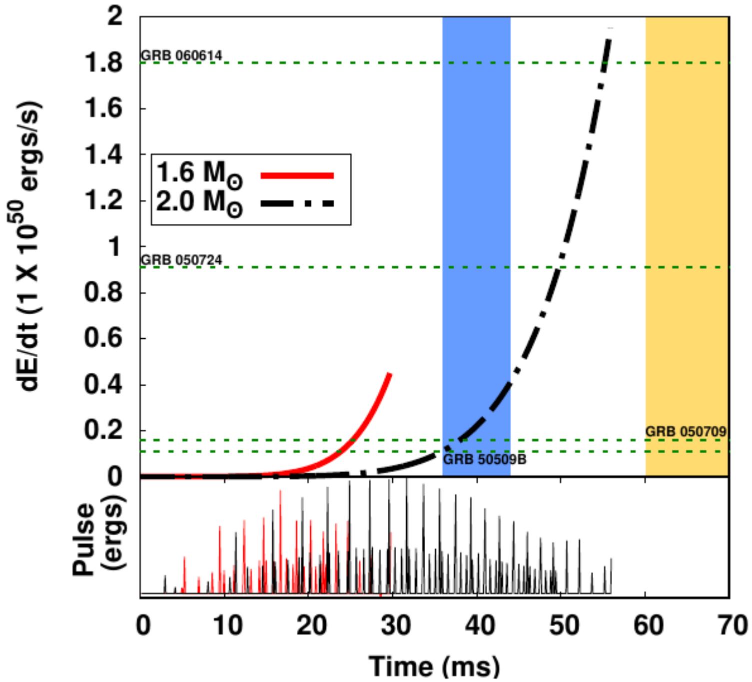


Phase transition in isolated stars

Multitude signal from Phase transition

1. Neutrino generation: energy deposided at the surface $10^{49} – 10^{50}$
   Energy budget same as **Gamma Ray Bursts**





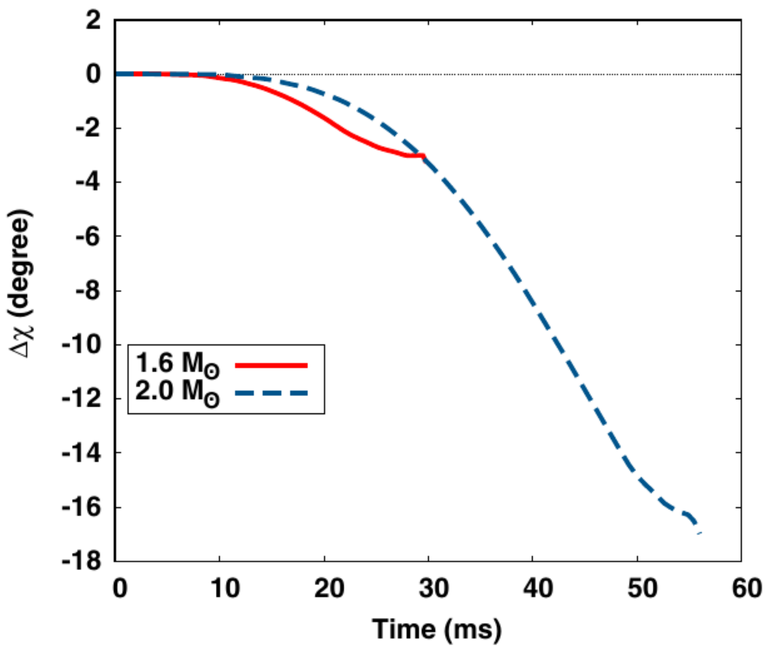
Phase transition in isolated stars

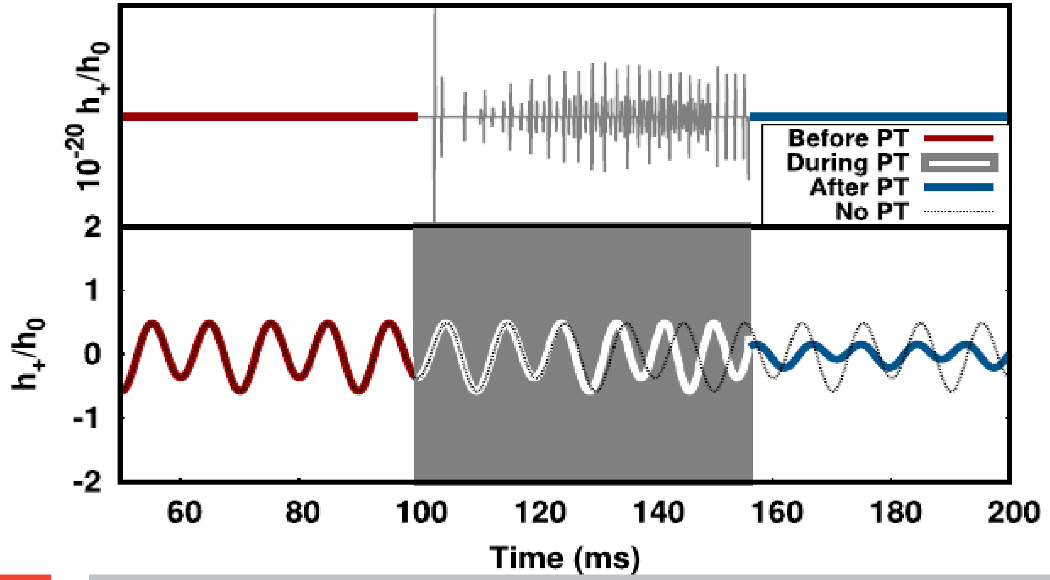
Multitude signal from Phase transition

2. Tilt angle evolution: Can evolve upto 20 degrees
   A sudden evolution (not slow)

Pulsar can suddently go out of line of sight
Some may also suddently emerge

3. Change in the continious GW signal





Phase transition in isolated stars

Summary and Conclusion:

1. Slow down of a neutron star can induce a quark core seed at the centre of the star

2. A shock discontinuity develops at the core and propagates outwards.

3. A two-step conversion process: Deconfinement of nuecleons to 2-f quark. Weak decay of 2-f quark matter to 3-f quark matter.

4. Deconfinement transition happens in microseconds and have bursts type strong GW Signal. Frequency of the signal on the higher side.

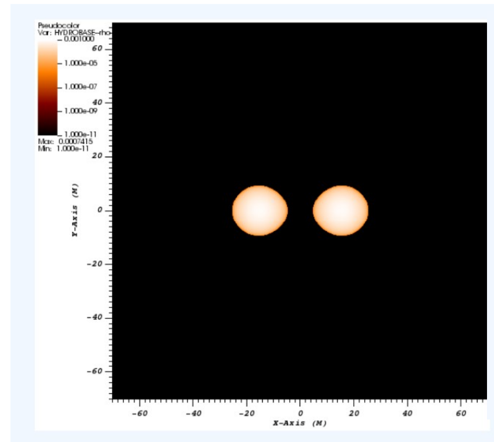
5. Weak decay transition takes few 10s of miliiseconds, also bursts type GW signal. Frequency on the signal in the present detector capacity range.

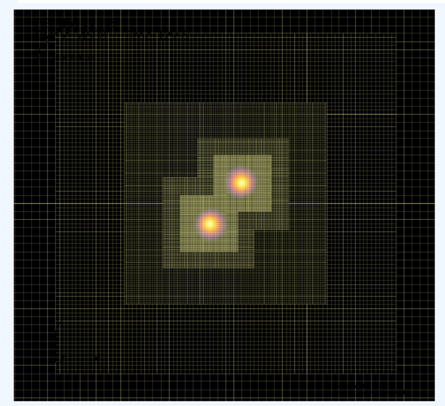
6. PT can also have other type of signals: Neutrino generation, tilt angle evolution.

Phase transition in Binary NS

Initial Setup

LORENE code: Binary star code





Evolution

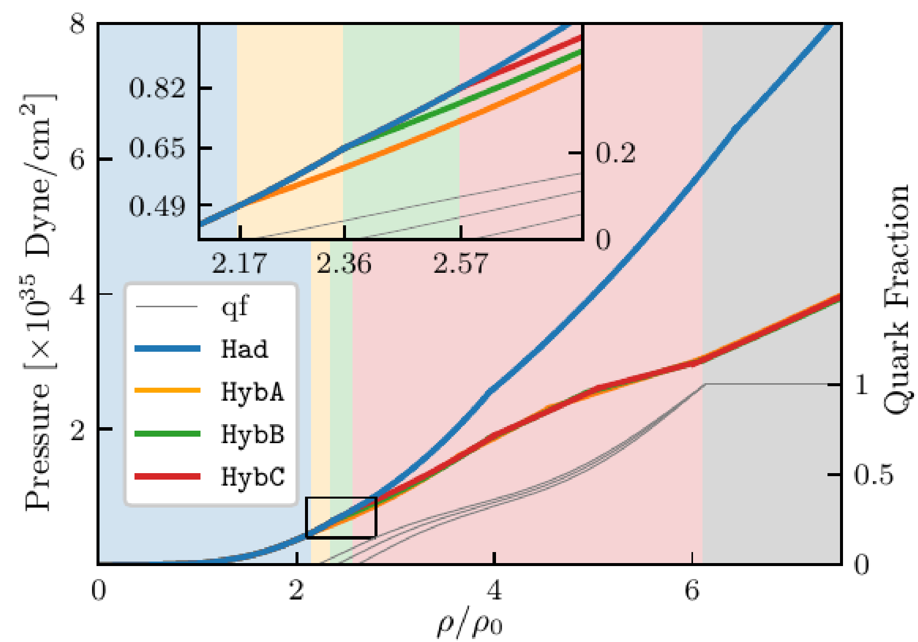
Einstein Toolkit: solves the evolution equations
GW extraction

Equation of State

Hadronic: DD-ME2 Quark: MIT bag model

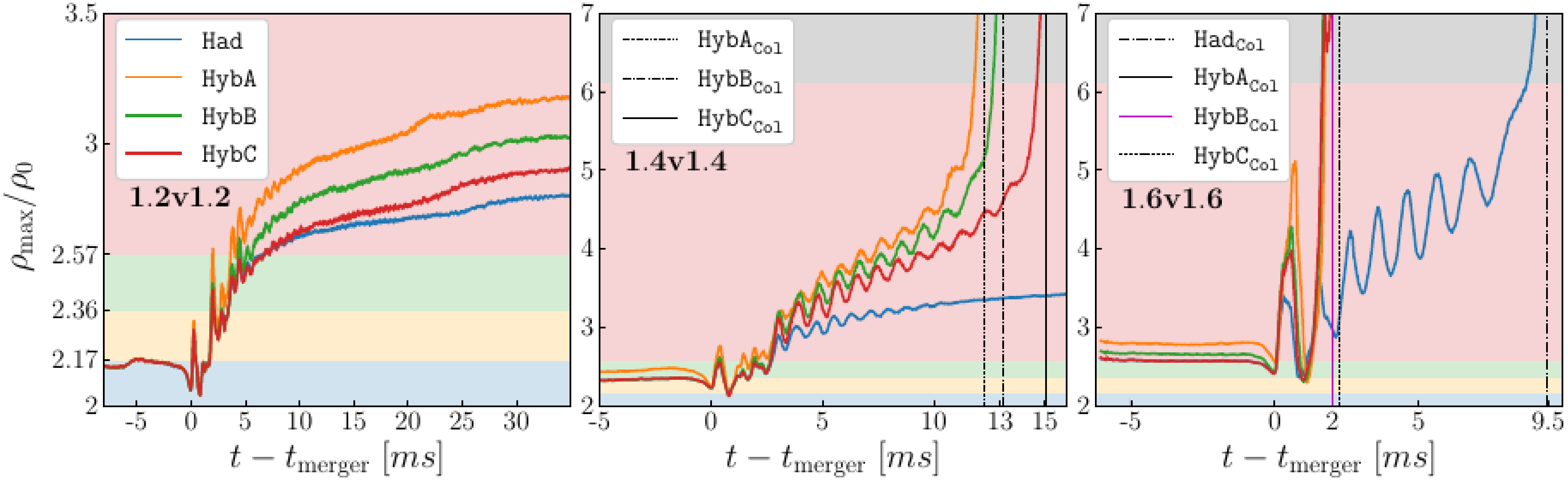
Mixed phase, Polytropic Fit

3-different onset point
(point where mixed phase starts)



Phase transition in Binary NS

Equal Mass binaries



Small binary stars made entirely of hadrons: after merging gives stable configuration

Intermediate mass binaries: hadronic star stable
hybrid HMHS ultimately collapses

Heavy mass binaries: Ultimately HMNS/HMHS every star collapses

Haque, Mallick & Thakur, arXiv: 2207.14485

Phase transition in Binary NS

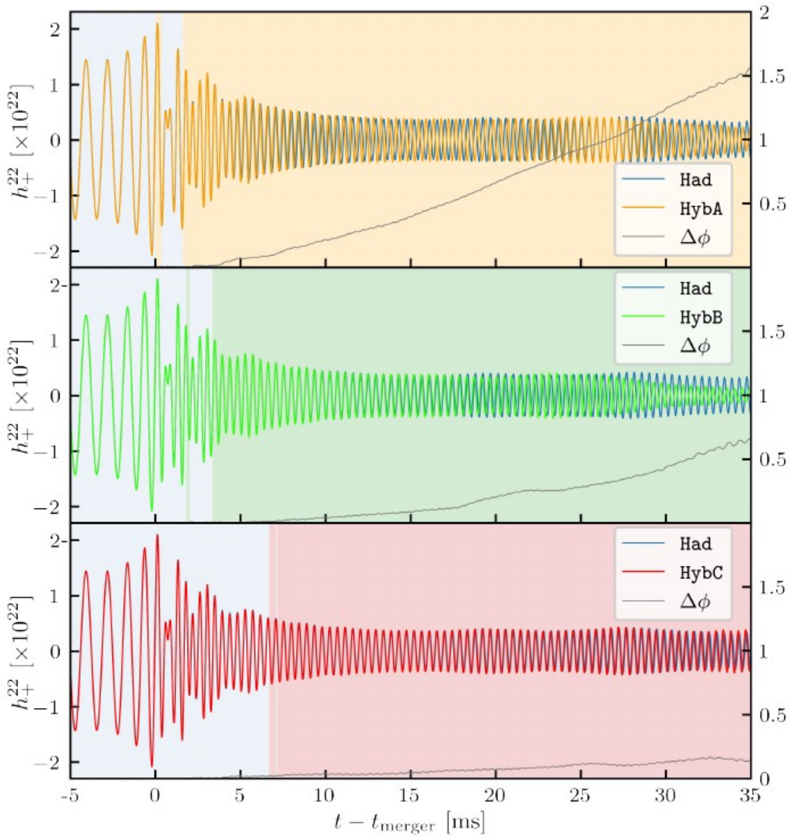
Equal Mass binaries: 1.2 +1.2

Difference in the GW signal depending on whether the merger product is HMNS or HMHS

Difference is maximum for stars where mixed phase appears earlier

If mixed phase appears at higher density, GW signal of HMNS and HMHS is almost same

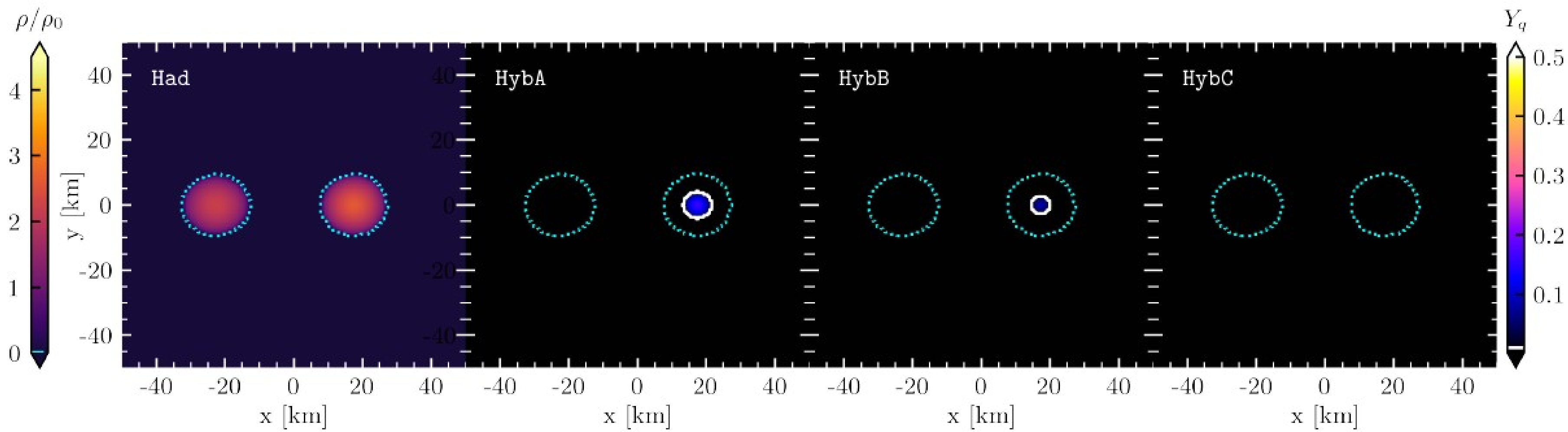
The 2nd peak frequency for all configuration appears at almost same frequency



Phase transition in Binary NS

Unequal Mass binaries: 1.2 + 1.6

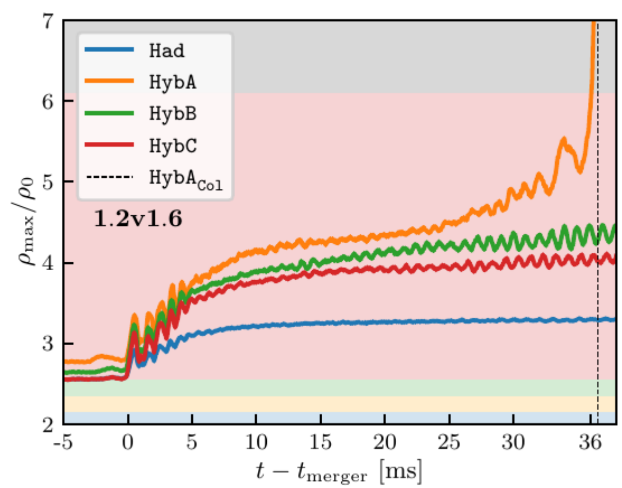
Initial configuration: Appearance of mixed phase region even before merging



With hybrid EoS one star has quark core for at least two Hyb EoS

The HMHS where mixed phase appears collapses early

The HMNS reamins stable for the longest time



Phase transition in Binary NS

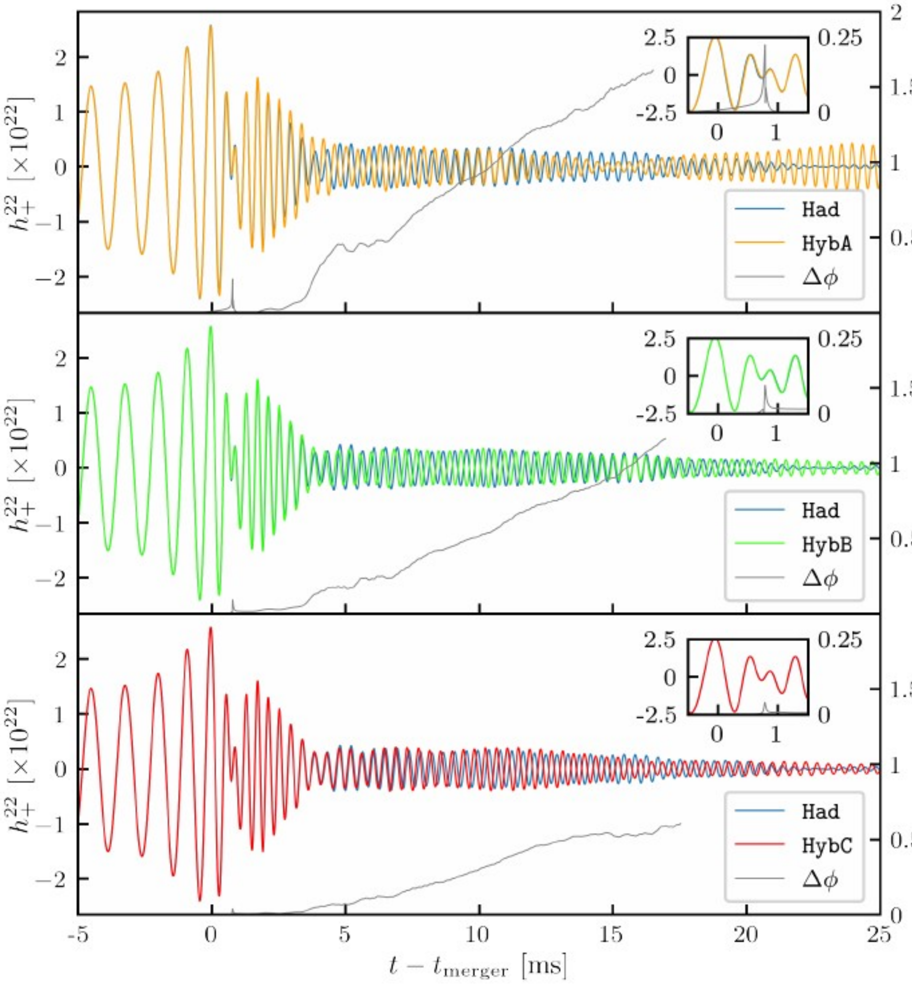
Unequal Mass binaries: 1.2 + 1.6

Have same baryonic mass as that of 1.4+1.4 equal mass binary merger

Difference in the GW signal depending on whether the merger product is HMNS or HMHS

Difference is maximum for stars where mixed phase appears earlier

At the moment of first contact the phase difference spikes momentarily



Phase transition in Binary NS

Summary and Conclusion:

1. Difference in the GW signature depending on whether merging stars are NS or HS

2. After the merger the GW differs between HMNS and HMHS

3. Difference is prominent if the quark appearance is at low density

4. The onset point (of mixed phase) and the stiffness of the EoS can be gauged by having several observation of the post-merger phase of BNSM for different binaries.

Thank You all