

Binary neutron star mergers: Numerical modeling, gravitational waves and the equation of state

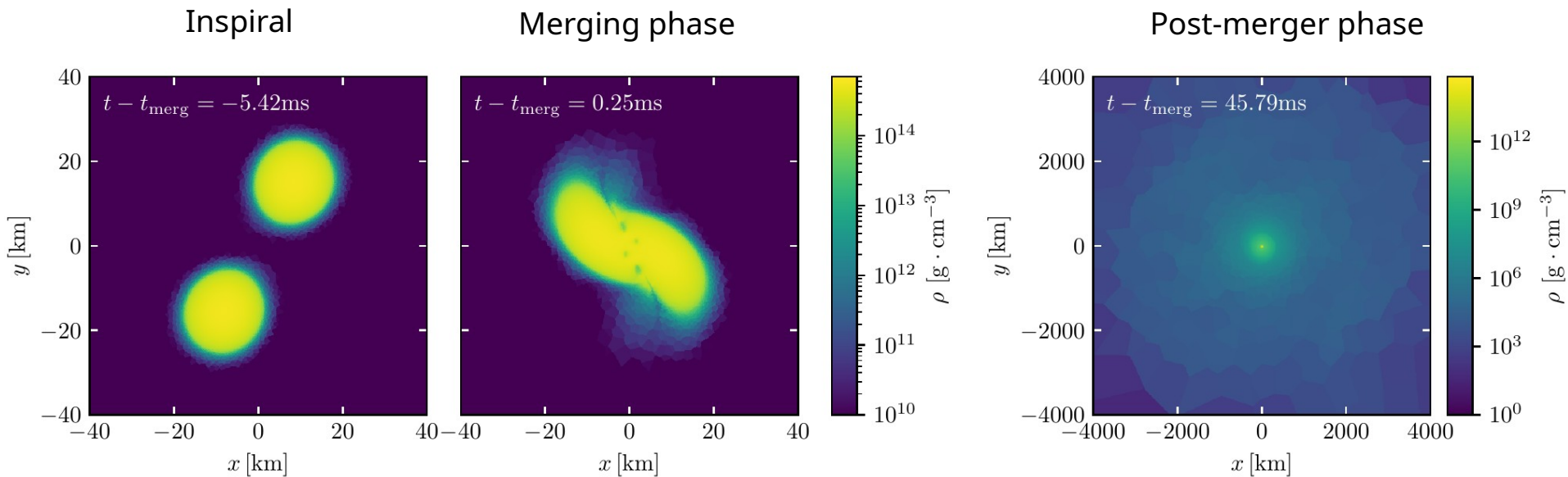
Georgios Lioutas
Heidelberg Institute for Theoretical Studies

Nuclear lunch
NKUA 05/2026



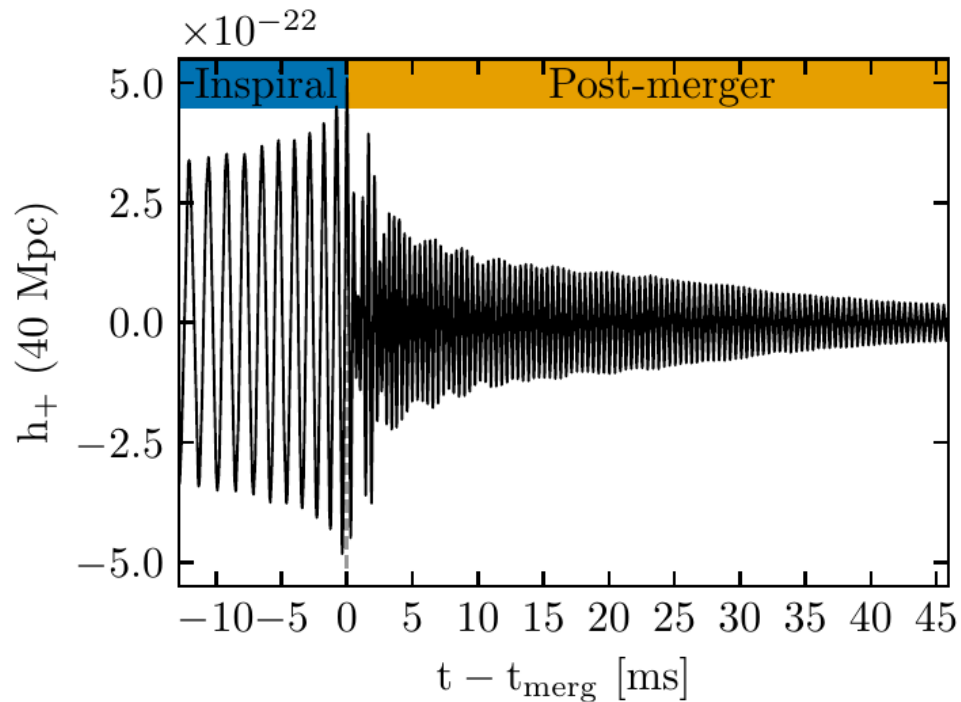
Motivation

Basic physical picture: Binary neutron star (BNS) mergers



- Inspiral driven by gravitational wave (GW) emission
- Post-merger:
 - Compact object with roughly total mass forms; neutron star (NS) or black-hole (BH)
 - Disk formation
 - Some matter becomes gravitationally unbound
- Broad range of densities, length-scales, time-scales relevant

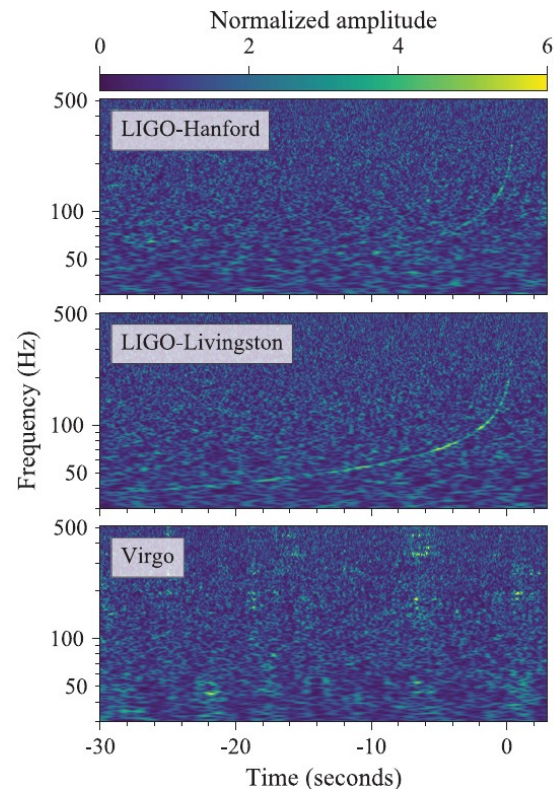
Why are BNS mergers interesting I: Gravitational waves



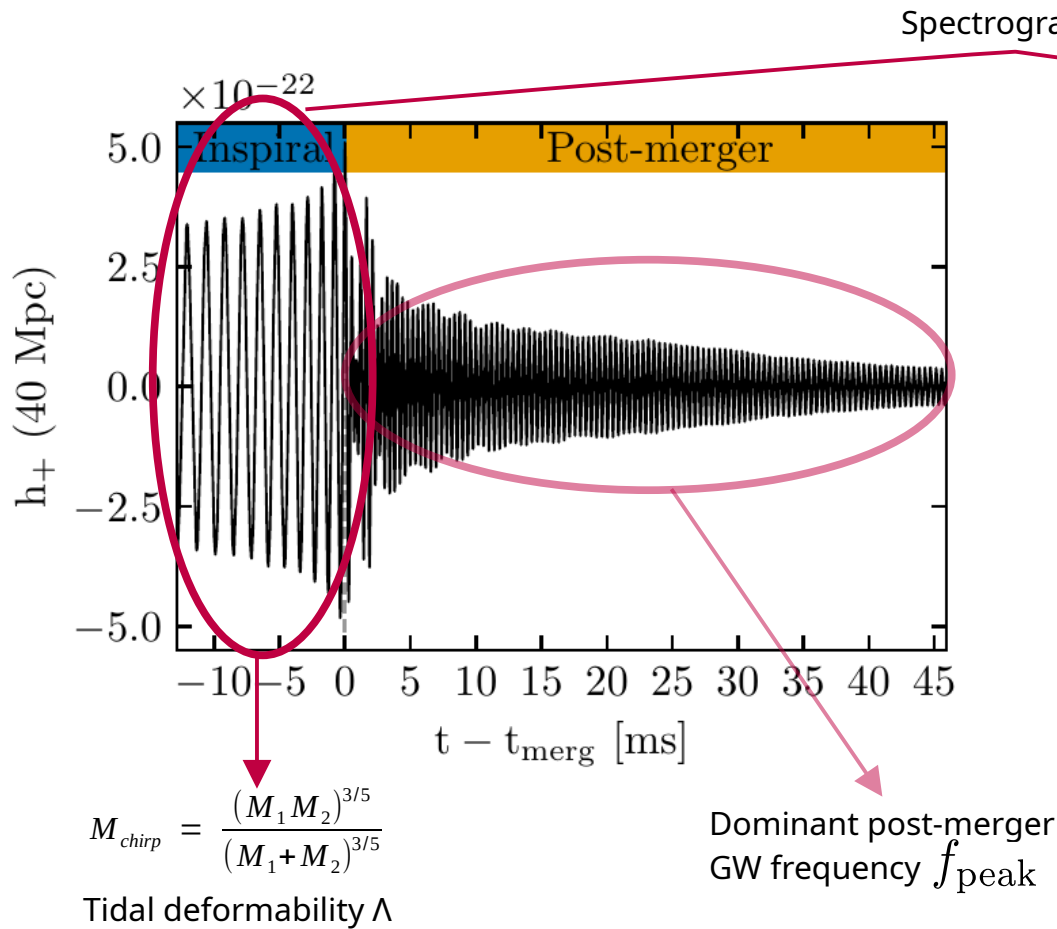
(From simulation)

GW170817

Abbott et al 2017 (PRL)

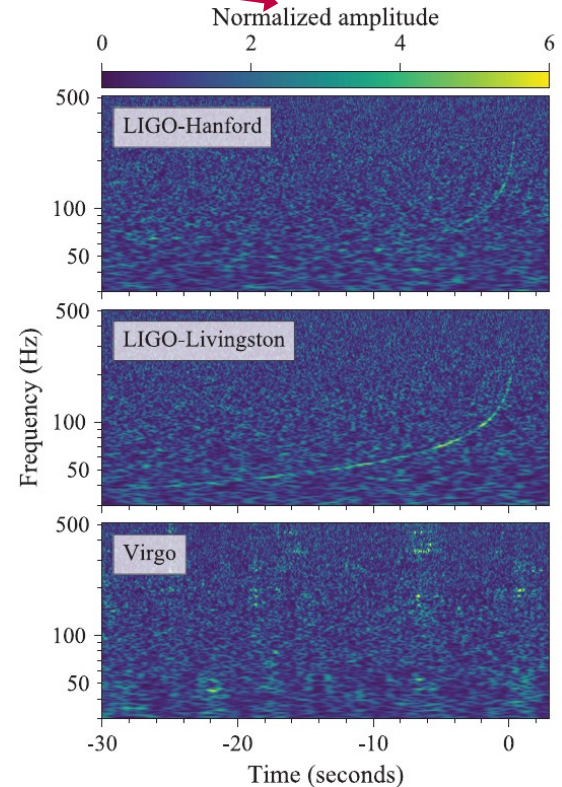


Why are BNS mergers interesting I: Gravitational waves



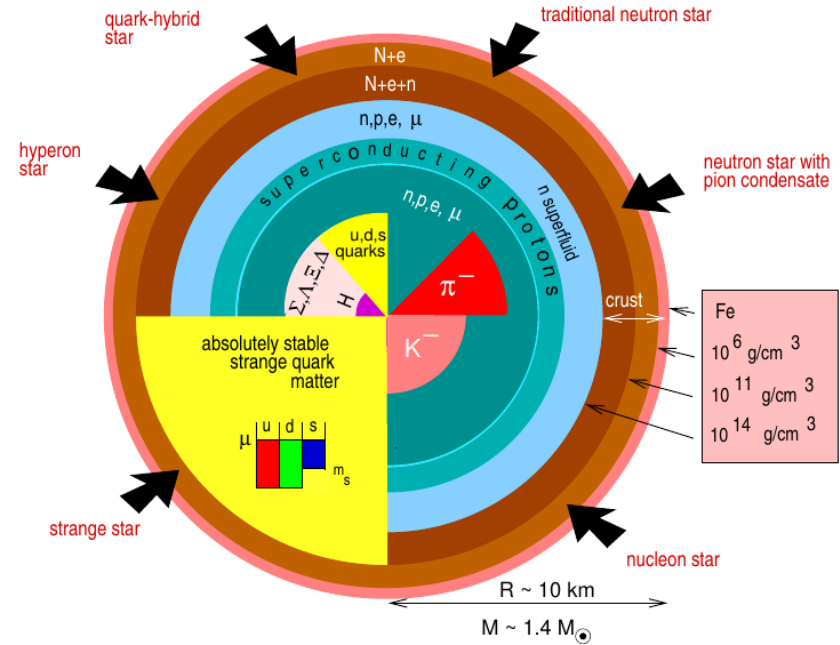
GW170817

Abbott et al 2017 (PRL)



Why are BNS mergers interesting II: Equation of state (EOS)

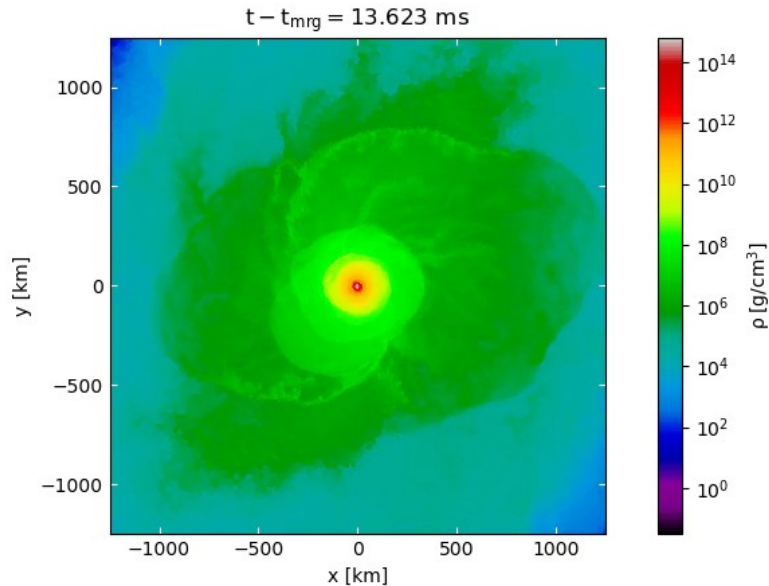
- Masses: $\sim 1-3 M_{\odot}$
- Radii: $\sim 10-15$ km
- Central density a few times nuclear saturation density $\rho_{\text{sat}} = 2.7 \times 10^{14} \text{ g cm}^{-3}$
→ high density equation of state (EoS) partially unknown hence we rely on different models for the EoS
- Very compact: General relativity needed



Weber 2001 (JPG)

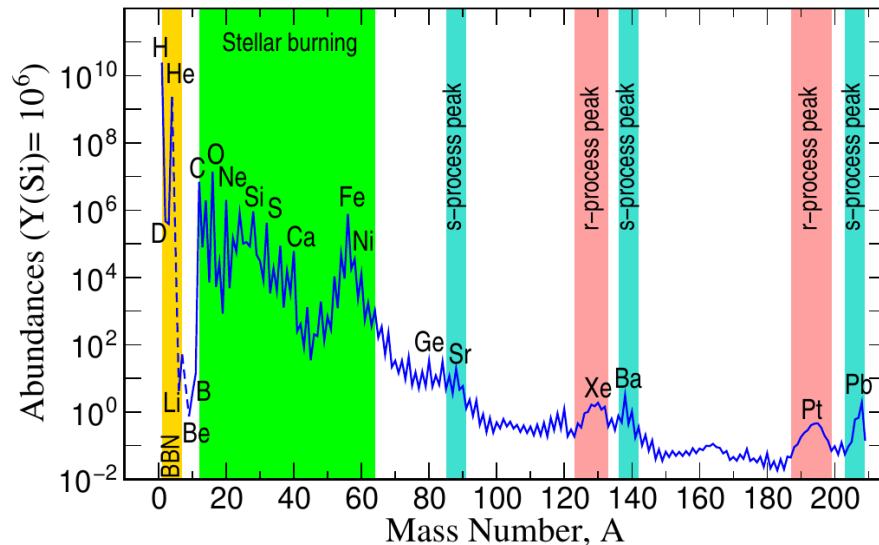
Why are BNS mergers interesting III: Heavy element nucleosynthesis

- Matter becomes gravitationally unbound (collision, tidal effects, angular momentum redistribution, disk ejecta, ...)



(From simulation)

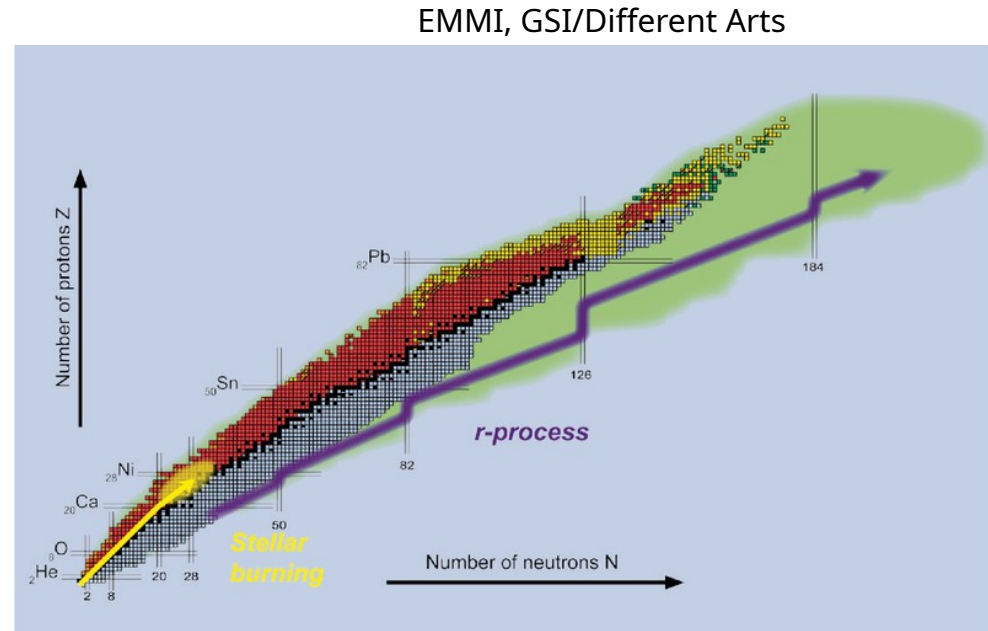
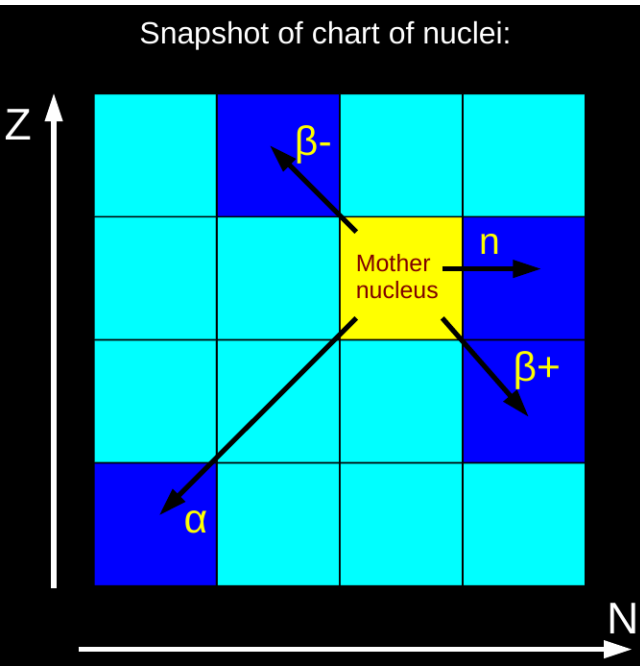
Cowan et al 2021 (RMP)



- Elements up to Fe form in stellar cores via nuclear burning
- What about elements beyond Fe?

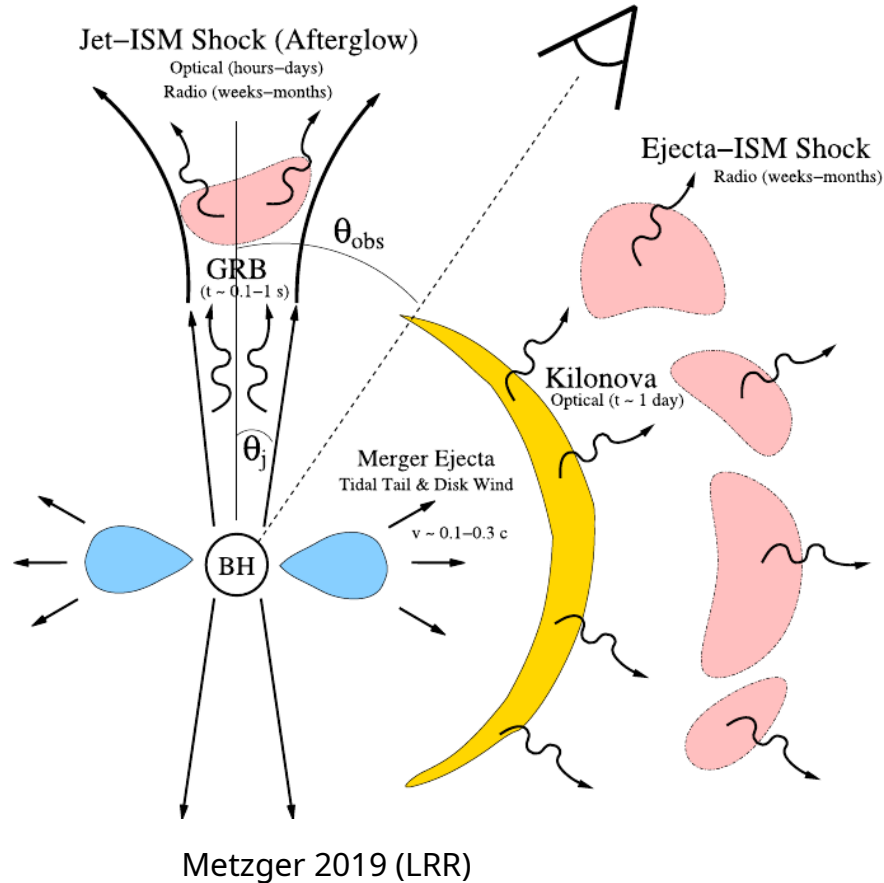
Why are BNS mergers interesting III: r-process

- Neutron capture: $(Z,A) + n \rightarrow (Z,A+1)$
- β^+ decay: $(Z,A) \rightarrow (Z-1,A) + e^+ + \nu_e$
- β^- decay: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$
- α decay: $(Z,A) \rightarrow (Z-2, A-4) + \text{He}$
- ...



- Neutron rich environment \rightarrow Neutron captures \gg β -decays
- Heavy elements (beyond Fe) can form
- Role of neutrinos important for composition
- BNS mergers participate in heavy element enrichment of the Universe

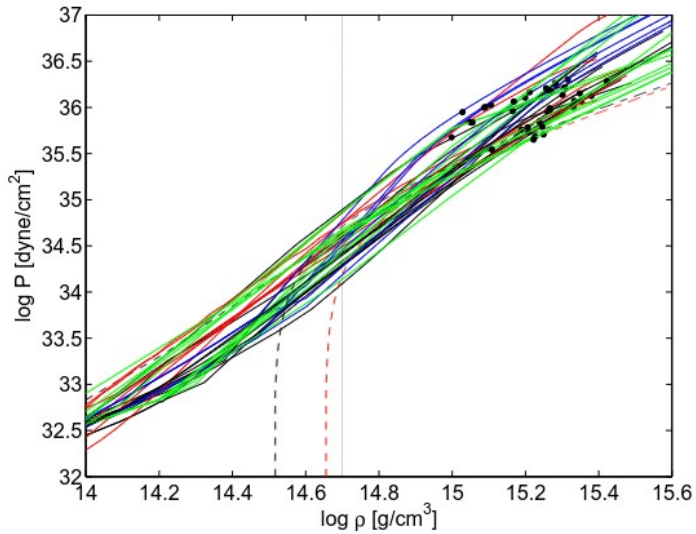
Why are BNS mergers interesting IV: short gamma ray bursts



- Short gamma ray bursts (< 2 secs) are an open problem
- Massive compact remnant (NS or BH) + accretion disk forms
- Strong magnetic fields
- Narrow ultra-relativistic jet formation
- Mechanisms (?): Particle acceleration due to internal shocks, magnetic field reconnection, ...
- Does jet points towards us? Does the jet get "choked"? Does it always form?

**Equation of state signatures on the post-merger
gravitational wave signal**

Macroscopic characteristics of NSs and the Equation of state



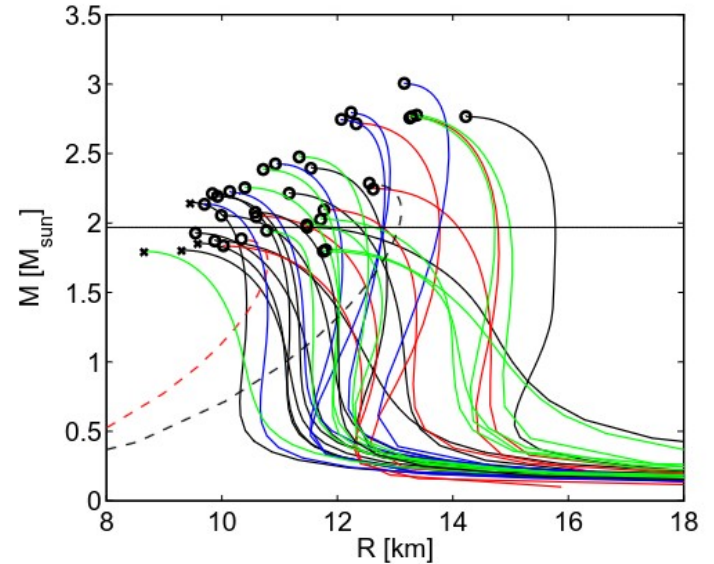
Partially unknown nuclear
EoS (many candidates) at
- fixed $T=0.1$ MeV and
- neutrino-less beta equilibrium

1-1 relation



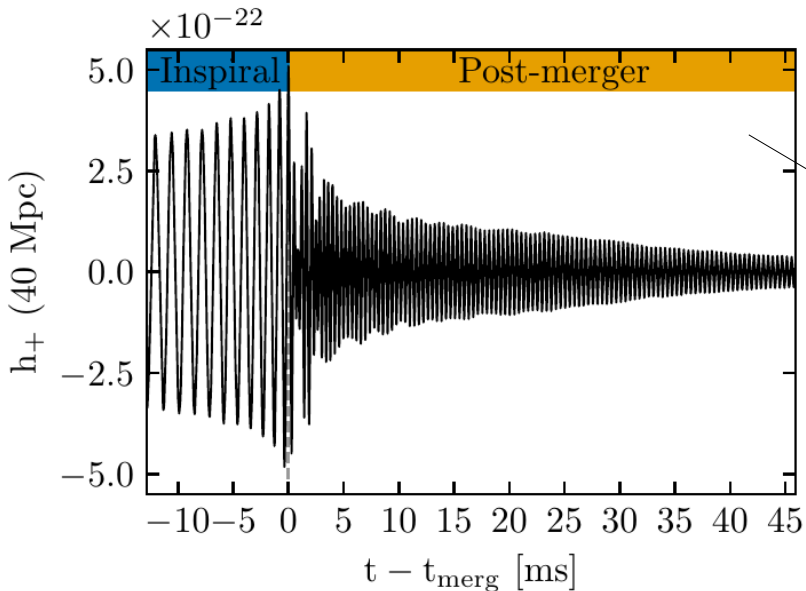
Hydrostatic equilibrium
TOV system

Bauswein et al 2012 (PRD 2012)



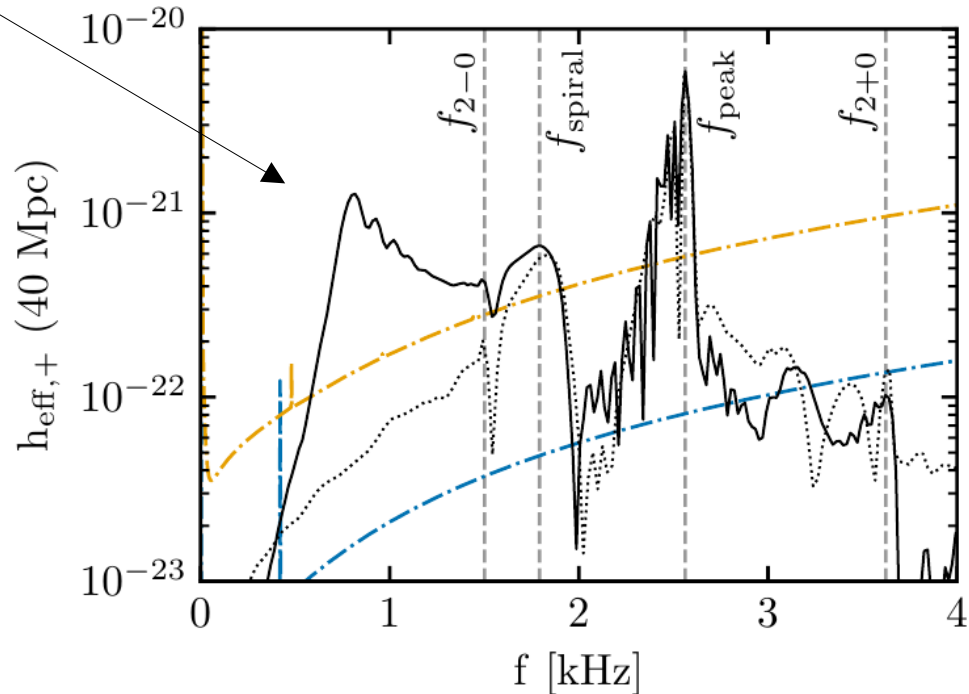
Mass-Radius diagram
(i.e. astrophysics)

GW spectrum from BNS mergers

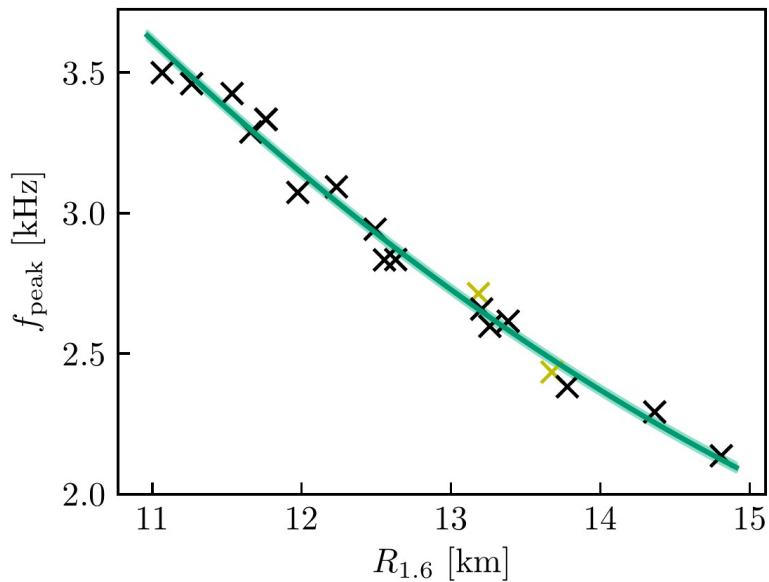


- Spectrum peaks are connected to dynamics of remnant (see Stergioulas et al 2011, Bauswein+Stergioulas 2019)
- Dominant peak connects to the quadrupole oscillation
- Above detector sensitivity curves!

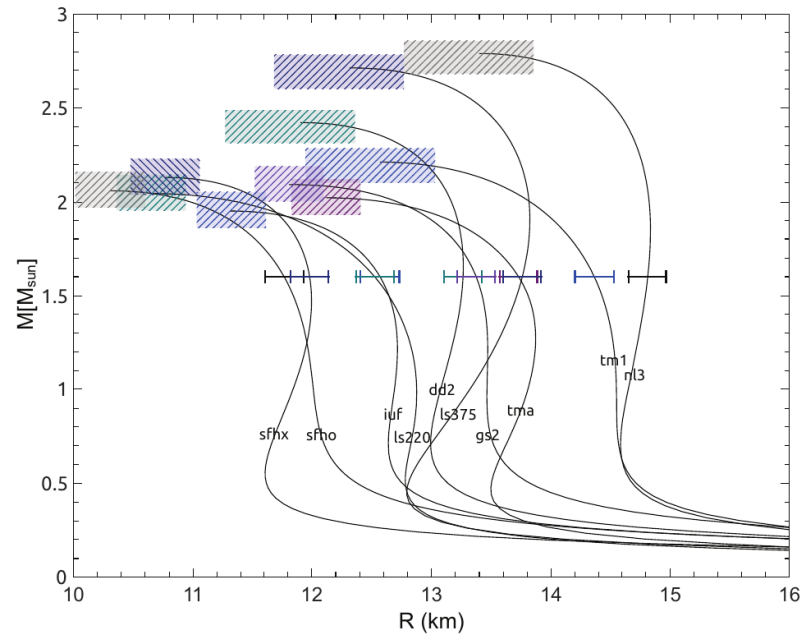
Fourier transformation



Radius measurements via GWs



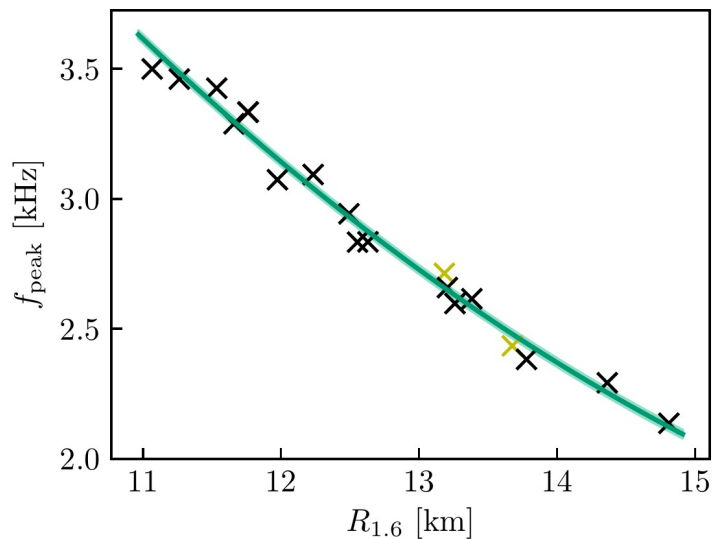
Bauswein et 2014 (PRD 2014)



- f_{peak} Correlates with radius of fixed mass NSs
- f_{peak} measurement gives constraint on NS radius
- Ability of certain EOS to replicate such radius \rightarrow viable EOS model

Frequency deviations

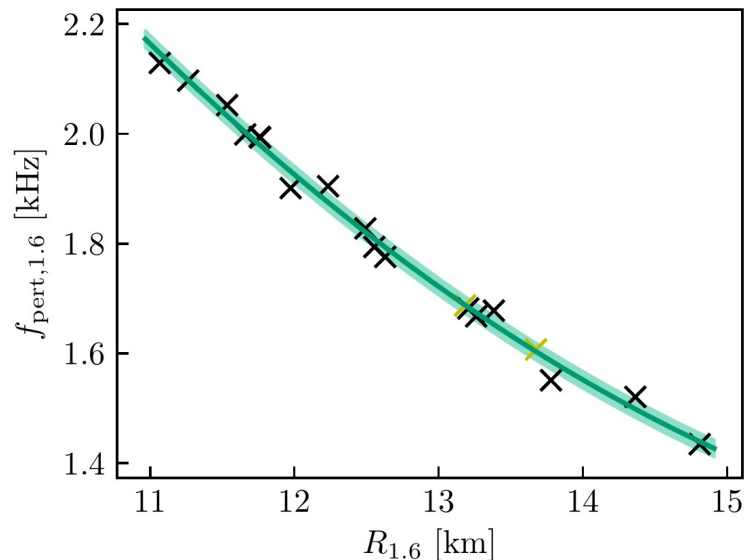
1.35 M_{\odot} + 1.35 M_{\odot} BNS system



Each marker is a different EoS

Hot, rapidly rotating, higher mass
BNS merger remnant
(Frequency from 3D hydro simulation)

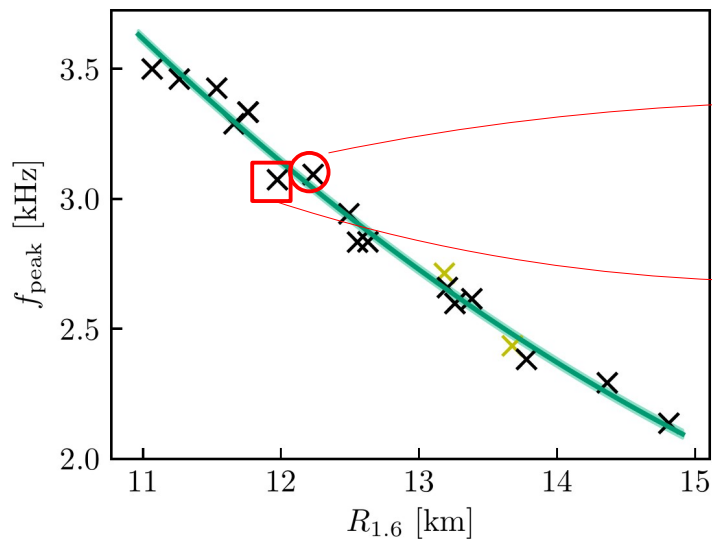
1.6 M_{\odot} single NS



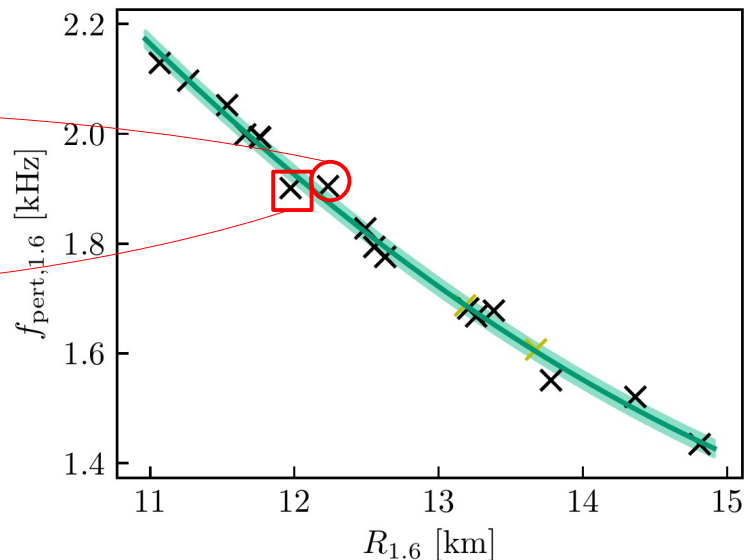
Single, cold, non-rotating NS
(frequencies via perturbation theory)

Frequency deviations

1.35 M_{\odot} + 1.35 M_{\odot} BNS system



1.6 M_{\odot} single NS

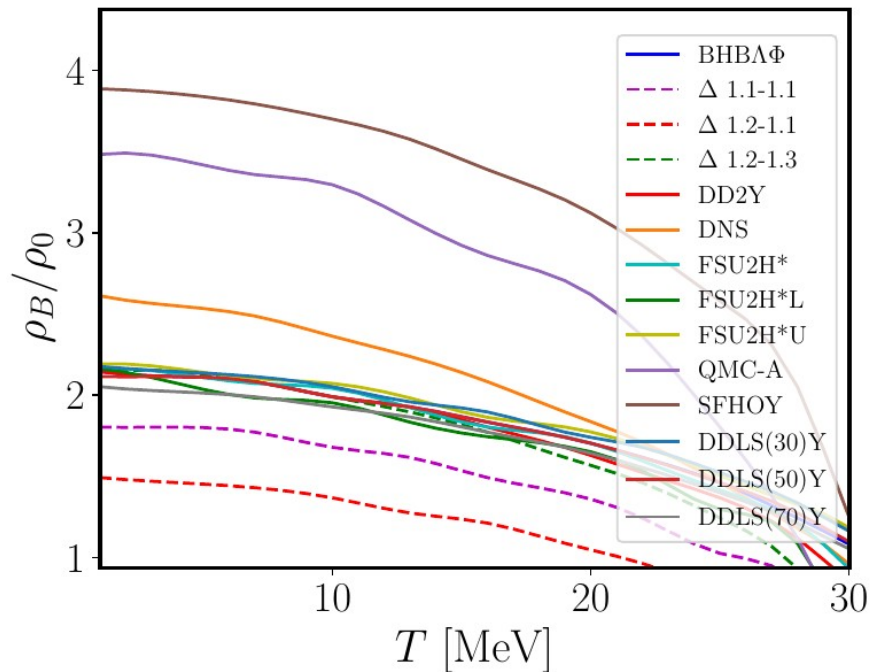


- Vastly different systems, yet almost perfect agreement in distribution wrt the fit
- Fit can be seen as a “statistically mean” behavior of different EOS models
- The deviations contain additional information for the cold EOS that seems to “survive” in a BNS merger

**Exotic/Non-nucleonic degrees of freedom in the equation
of state: Focus on hyperons**

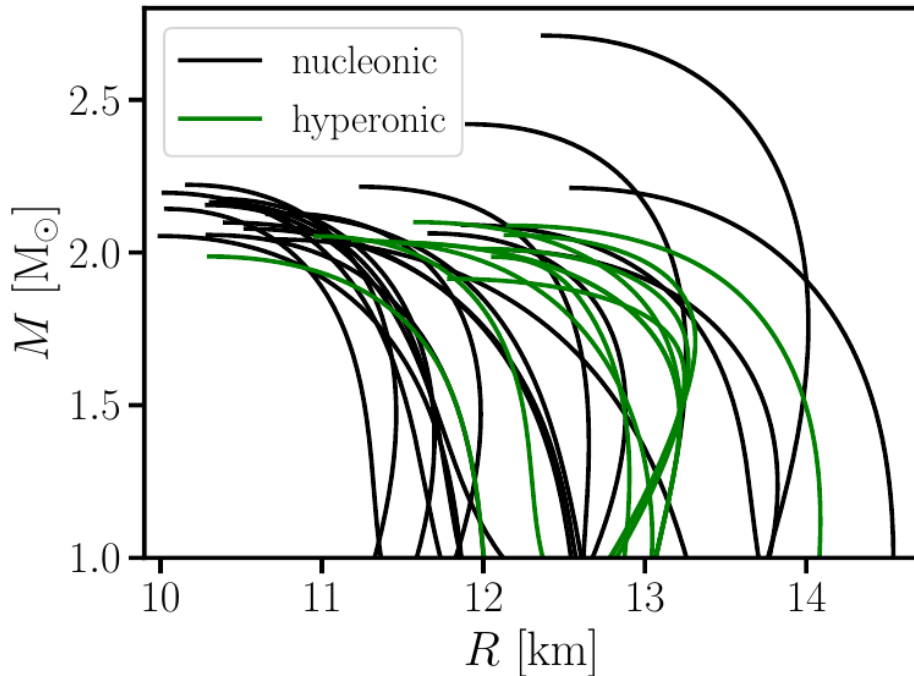
The hyperon problem

Hyperon onset density



Kochankovski et al 2025 (PRD)

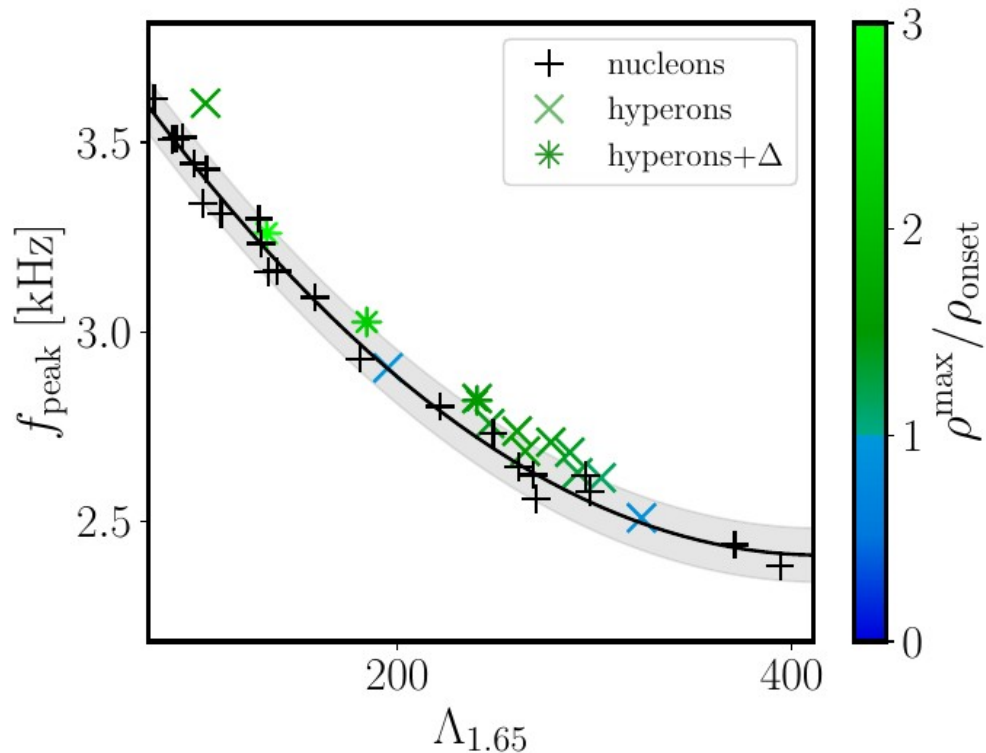
Hyperonic and nucleonic EOSs produce similar cold static stars!



Blacker et al 2024 (PRD)

How to find hyperons through GWs: Equal-mass systems

1.4-1.4 M_{\odot} BNS systems



Hyperons from above an onset density ρ_{onset}

- X-axis: A quantity that probes stars that do not reach ρ_{onset}
- Y-axis: A quantity that probes stars that do reach ρ_{onset}

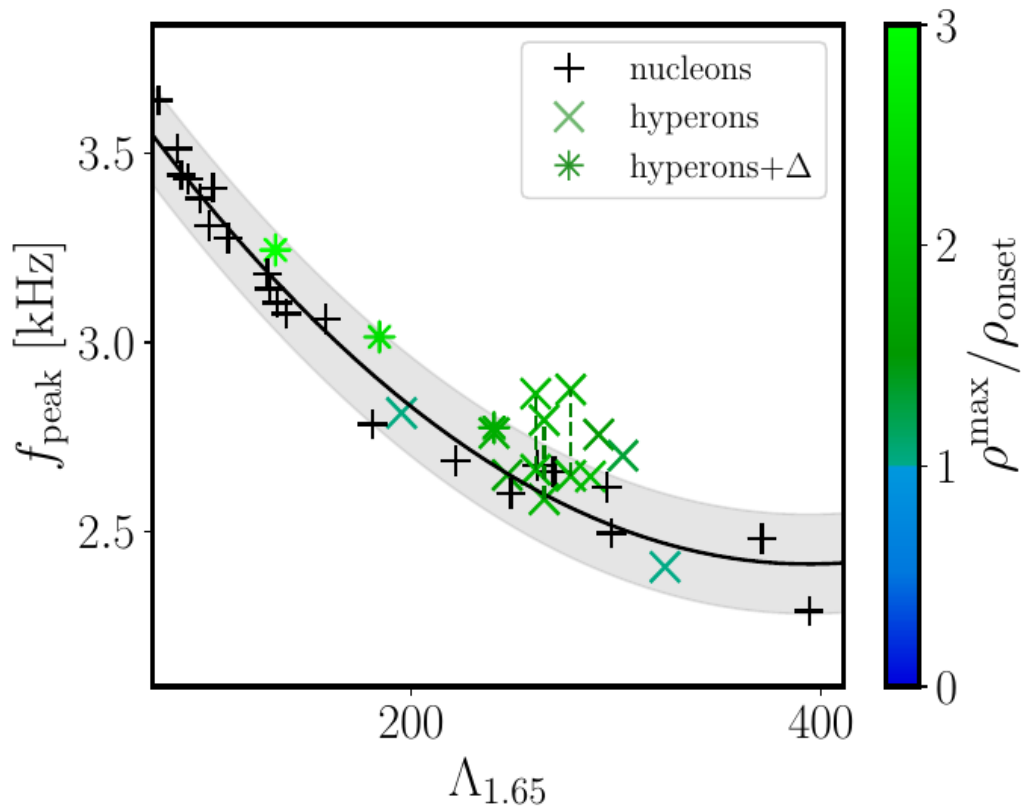
$f_{\text{peak}}(\Lambda_M)$ relation based on nucleonic models, but different sensitivity to hyperons

Observation outside of band as indication of hyperons

Note: Potentially difficult to measure, not necessarily unique hyperon signature

(deconfined quarks have similar/more pronounced effect)

How to find hyperons through Gws: Unequal-mass systems



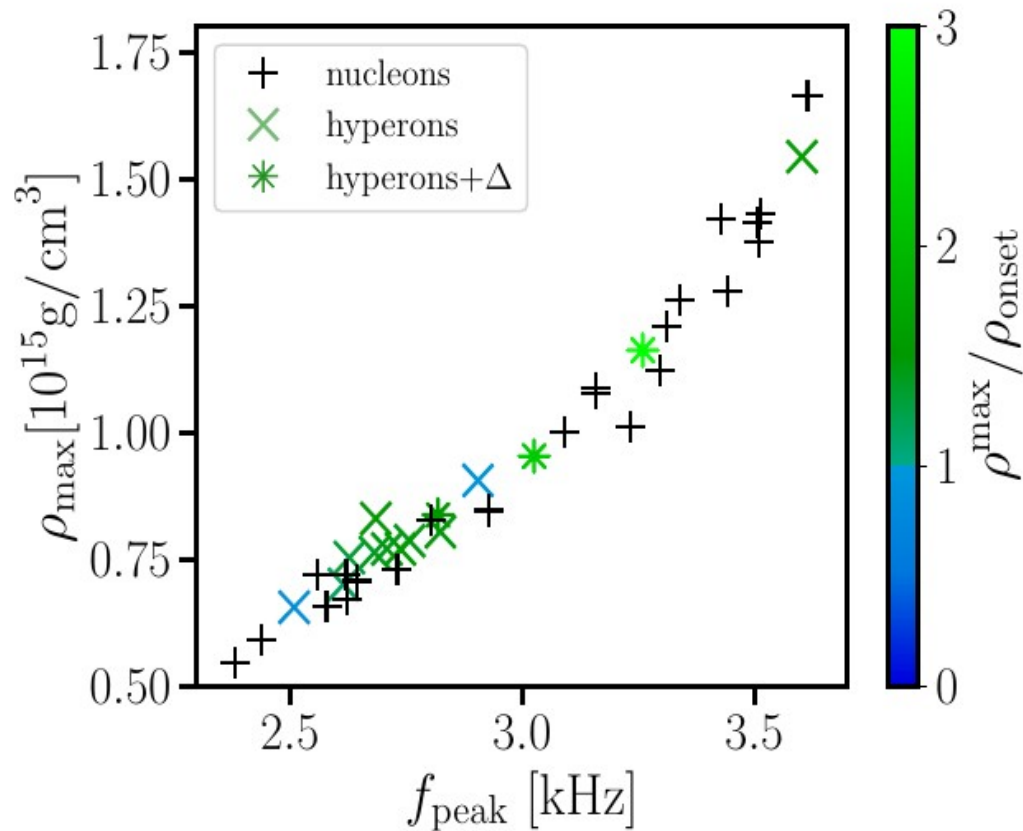
Binary systems with unequal mass companion stars:

- $q = M_1/M_2 = 0.8$
- $M_{\text{tot}} = M_1 + M_2 = 2.8 M_{\odot}$

More pronounced effect due to higher hyperonic content

Similar effect for more massive binary systems

How to find hyperons through Gws: Unequal-mass systems



$\rho_{\max}(f_{\text{peak}})$ relation based on simulations

Use:

Observational indication of hyperons

ρ_{\max} upper limit on ρ_{onset}

Note:

Shown 1.4-1.4 M_{\odot} systems, but the relation is insensitive to total mass

Neutron star merger numerical modeling
(EXTREMELY superficial view)

Necessary ingredients for simulations

- Three-dimensional general relativistic hydrodynamics codes:
 - Gravity: Evolve Einstein equations (general relativity): $G_{\mu\nu} = 8\pi T_{\mu\nu}$
 - Hydrodynamics: Solve conservations laws
 - Baryon conservation: $\nabla_{\mu}(\rho u^{\mu}) = 0$
 - Stress-energy conservation: $\nabla_{\mu} T^{\mu\nu} = 0$
- Additional physics:
 - Magnetic fields
 - Neutrino transport
 - ...
- Input:
 - Initial spacetime and fluid data, e.g. initial data for a binary neutron star system (metric + hydro fields)
 - Equation of state: $P=P(\text{density, temperature, composition})$

Here:

$$T^{\mu\nu} = \rho h u^{\mu} u^{\nu} + P g^{\mu\nu}$$

the energy momentum tensor,

$G_{\mu\nu}$ the Einstein tensor,

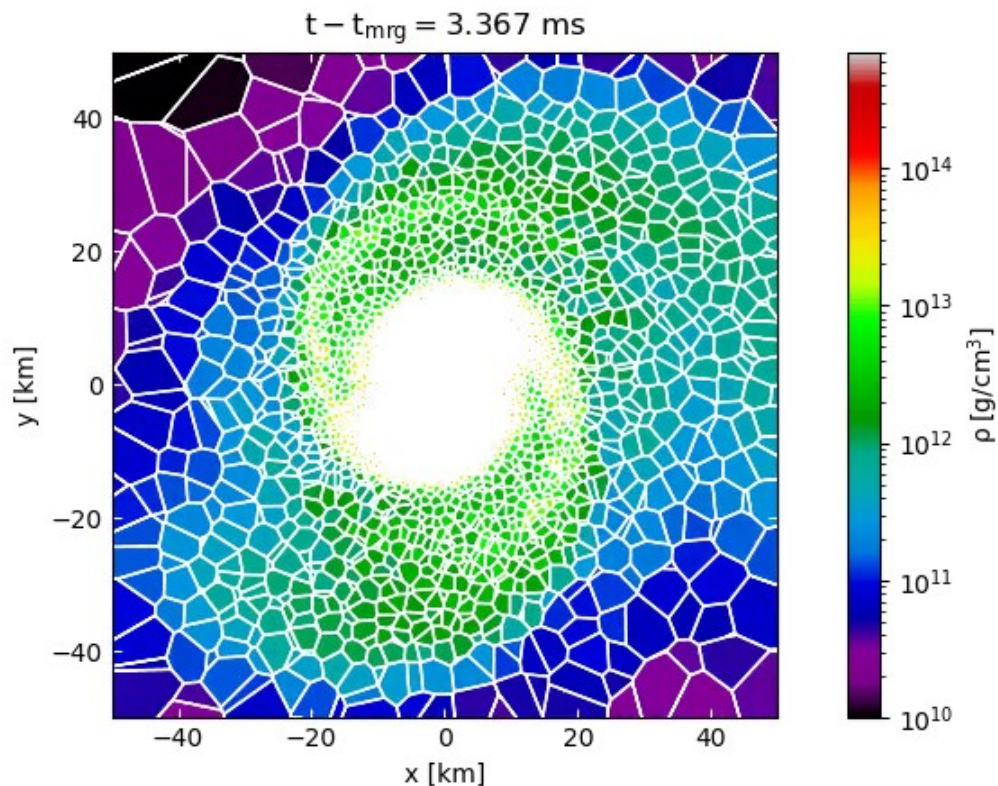
ρ the rest-mass density,

h the enthalpy,

P the pressure,

u^{μ} the 4-velocity

Moving mesh simulations



- Solve hydrodynamical equations on a mesh that comoves with the fluid → reduces advection errors
- Extend Newtonian moving-mesh AREPO code to be general relativistic
- Widely used in astrophysics (e.g. cosmology, white-dwarfs, ...)
- First ever relativistic moving-mesh simulations of binary neutron star mergers

Summary

- The aim of the presentation was to introduce binary neutron star mergers as a system and motivate why it is interesting
- Special focus was placed on the information that gravitational waves carry about the high-density equation of state
- Part of my research was briefly discussed:
 - Study of isolated neutron stars within perturbation theory
 - Signatures of the cold ($T=0.1\text{MeV}$) equation of state in the post-merger GW signal
 - Occurrence of hyperons in neutron stars and observational indications of their presence
 - Moving-mesh technique in modeling neutron star mergers

Thank you for your attention