# Further probing the neutron star equation of state via frequency deviations in universal relations

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FAIRness 2022
Katerini, 23-27 May 2022

Supported by
ERC through
Starting Grant
no. 759253

European Research Council
Established by the European Commission

UNIVERSITÄT
HEIDELBERG
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SEIT 1386

# Neutron stars

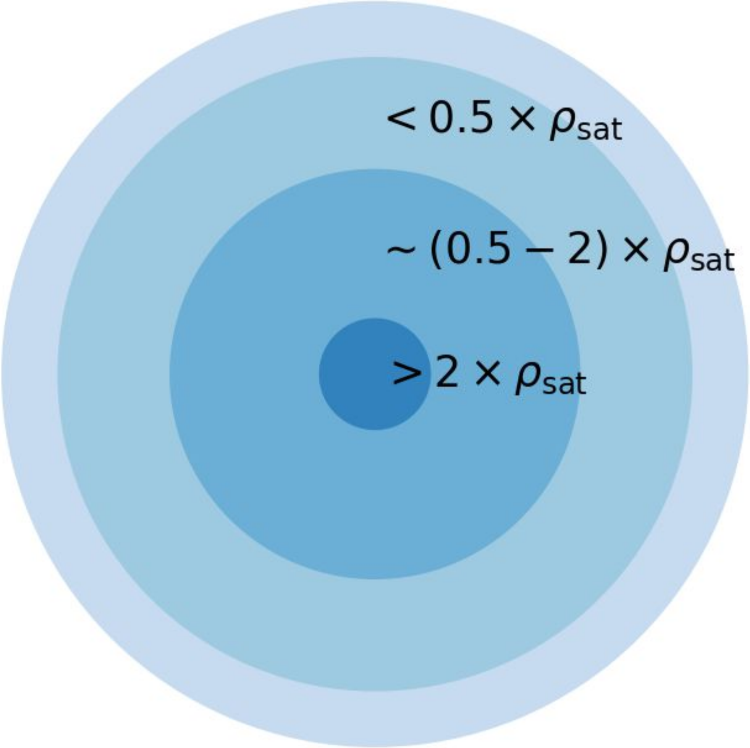
- Masses: ~1-3 $M_\odot$
- Radii: ~10-15 km
- Central density a few times nuclear saturation density $\rho_{sat}$ → high density equation of state (EoS) partially unknown hence we rely on different models for the EoS

Very compact so General Relativity needed!

⇓

Fluid oscillations can produce gravitational waves (GWs).

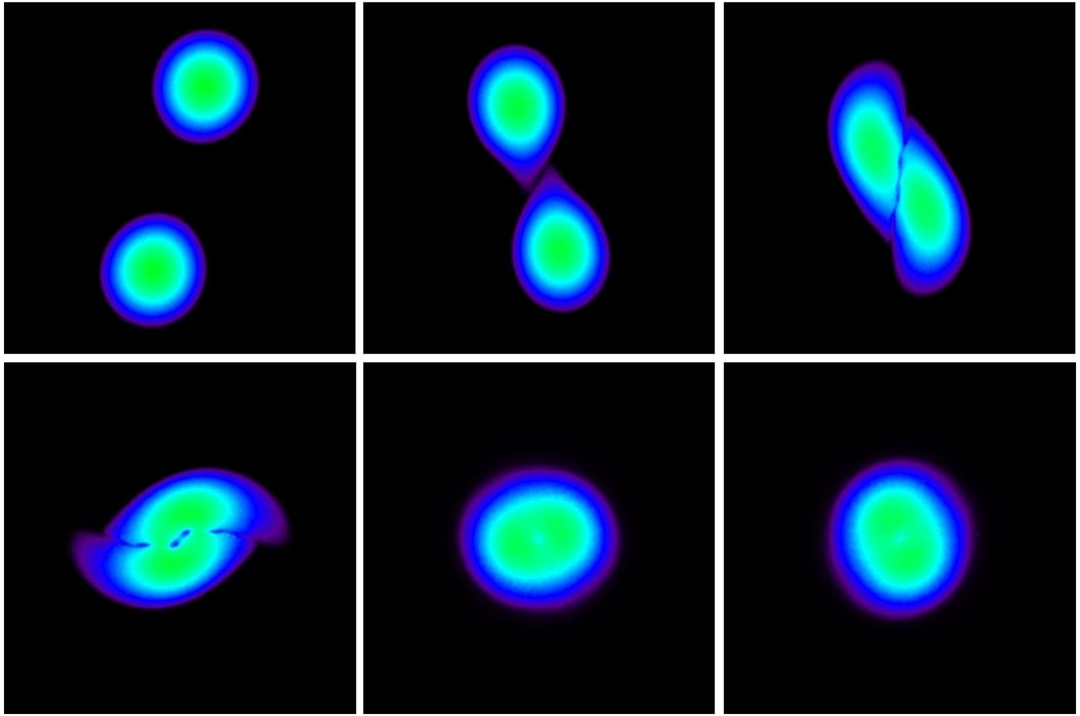
Aim: Observe these GWs to obtain information about the EoS!




$\rho_{sat} \simeq 2.7 \times 10^{14}$ gr cm$^{-3}$

# Binary neutron star mergers

Inspiral: Tidal effects →Tidal deformability $\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{GM} \right)^5$



Observations:
GW170817
GW190425

Remnant: Dominant oscillation $f_{peak}$

Bauswein & Blacker

# Binary neutron star mergers

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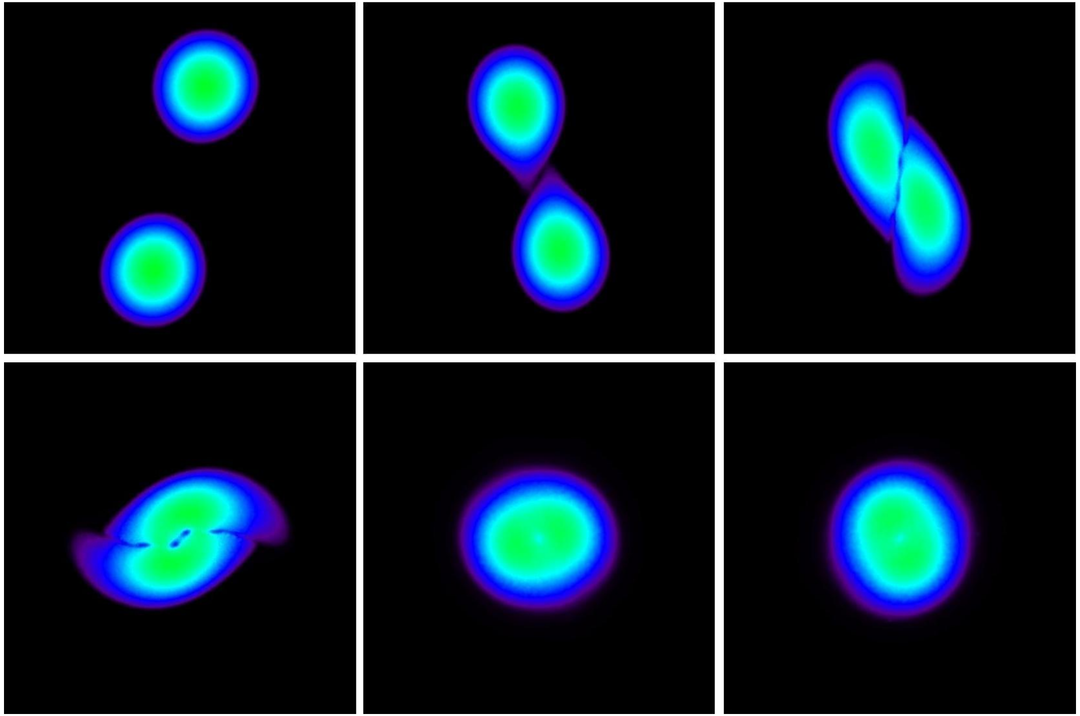
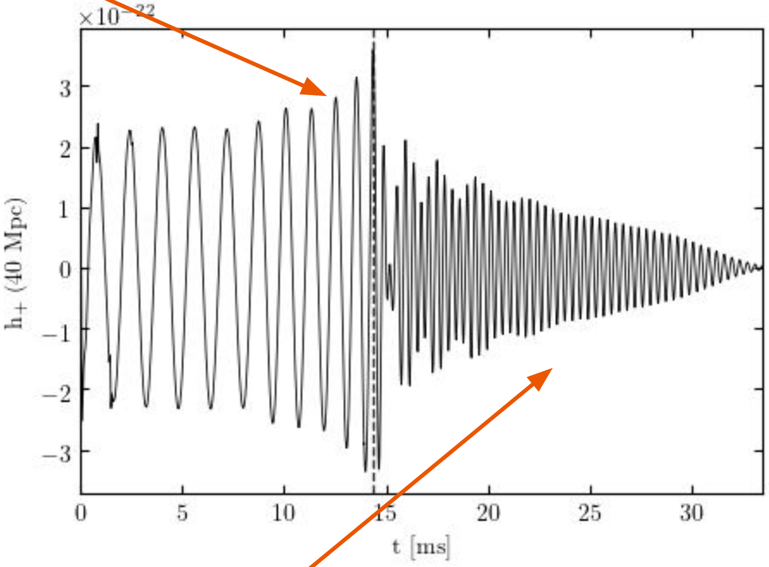
$$\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{G M} \right)^5$$






Remnant: Dominant oscillation $f_{peak}$

Bauswein & Blacker

# Setup and data

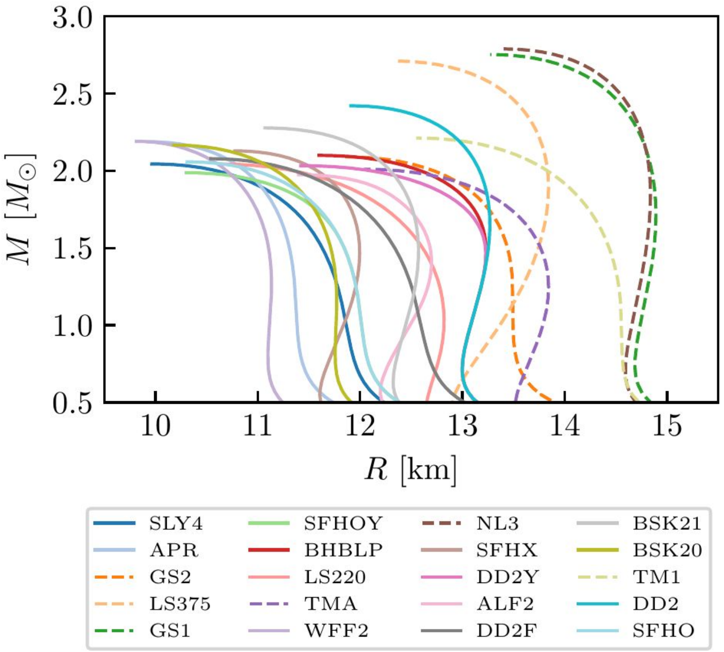
2 very different systems

Isolated, cold, non-rotating neutron stars:

- ➢ Perturbative calculation for l=m=2 (f-)mode with linear eigenvalue code
- ➢ GW frequencies $f_{pert}$ for 1.1-1.9 $M_\odot$ NSs for each EoS

Binary neutron star (BNS) merger remnants:

- ➢ 3D smoothed particle hydrodynamics code with dynamical spacetime (conformal flatness)
- ➢ Total of 57 equal-mass binary systems with total mass of 2.4, 2.7, 2.8, 3 $M_\odot$
- ➢ Dominant postmerger GW frequency $f_{peak}$ extracted




A set of 20 hadronic EoSs considered
(16 with full temperature dependence)

PRD 104, 043011

# Setup and data

2 very different systems

1st part: All masses

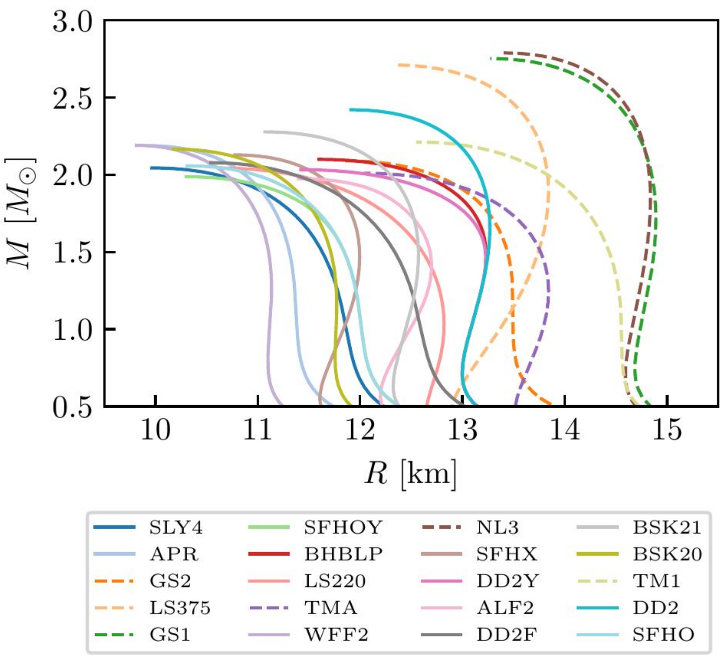
<u>Isolated, cold, non-rotating neutron stars</u>:

- Perturbative calculation for l=m=2 (f-)mode with linear eigenvalue code
- GW frequencies $f_{pert}$ for 1.1-1.9 $M_\odot$ NSs for each EoS

<u>Binary neutron star (BNS) merger remnants</u>:

- 3D smoothed particle hydrodynamics code with dynamical spacetime (conformal flatness)
- Total of 57 equal-mass binary systems with total mass of 2.4, 2.7, 2.8, 3 $M_\odot$
- Dominant postmerger GW frequency $f_{peak}$ extracted

2nd part: Fixed mass

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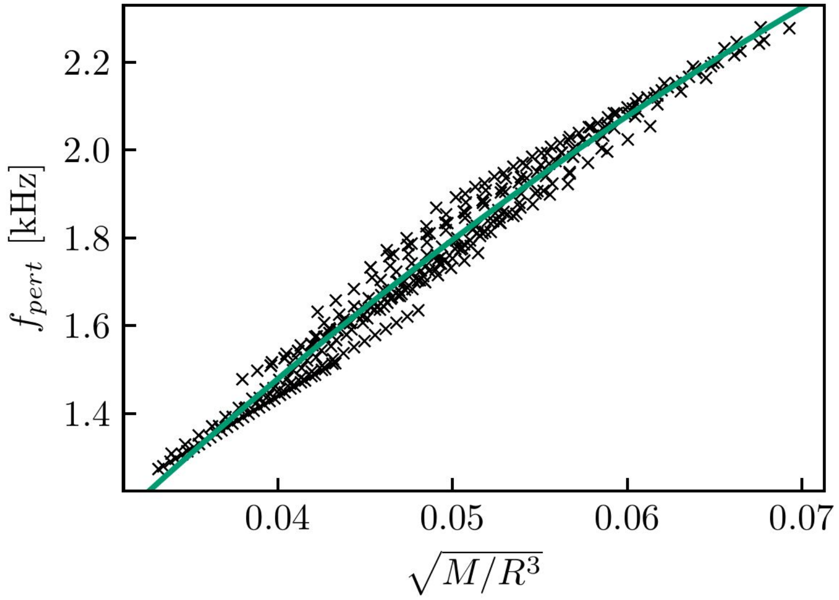
# Part I

## Empirical relations for isolated neutron stars

# Empirical relations

Relations between GW frequencies and macroscopic quantities (e.g. radius R, moment of inertia I, tidal deformability Λ) which hold for a wide range of EoSs.




Relation proposed by Andersson & Kokkotas (1998), plot from Phys. Rev. D 104, 043011

Different relations proposed:

- $f_{\rm pert}(\sqrt{M/R^3})$
- $M f_{\rm pert}(\sqrt{M/R})$
- $M f_{\rm pert}(I)$
- $M f_{\rm pert}(\ln \Lambda)$
- $M f_{\rm pert}(\Lambda^{-1/5})$ (NEW)

# Empirical relations

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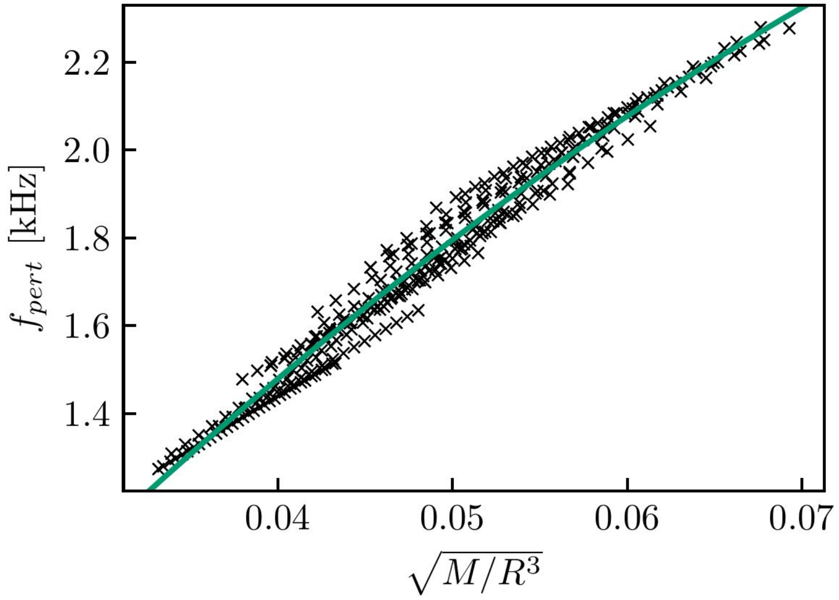
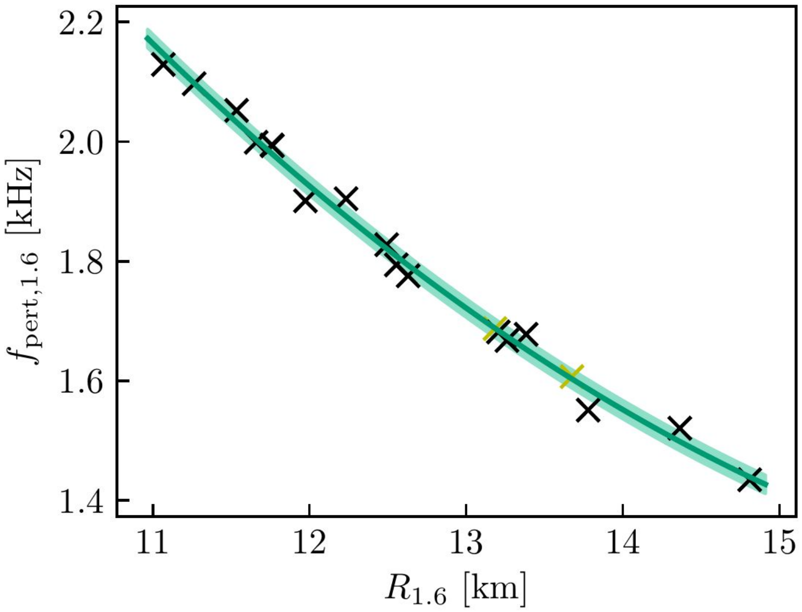



Relation proposed by Andersson & Kokkotas (1998), plot from Phys. Rev. D 104, 043011

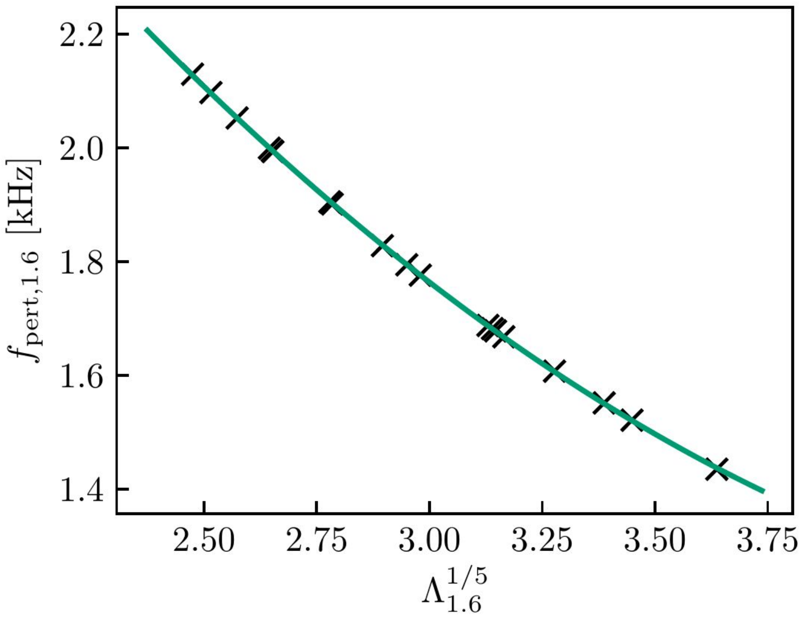
| Different relations proposed: | (Mean, Max) deviations [Hz] |
|---|---|
| • $f_{\rm pert}(\sqrt{M/R^3})$ | ~(30, 100) |
| • $M f_{\rm pert}(\sqrt{M/R})$ | ~(20, 50) |
| • $M f_{\rm pert}(I)$ | ~(1, 5) |
| • $M f_{\rm pert}(\ln \Lambda)$ | ~(0.1, 1) |
| • $M f_{\rm pert}(\Lambda^{-1/5})$ (NEW) | ~(0.1, 1) |

# Relation to tidal Love number $k_2$

Focus on a single mass M=1.6 $M_\odot$.




Scatter




No scatter

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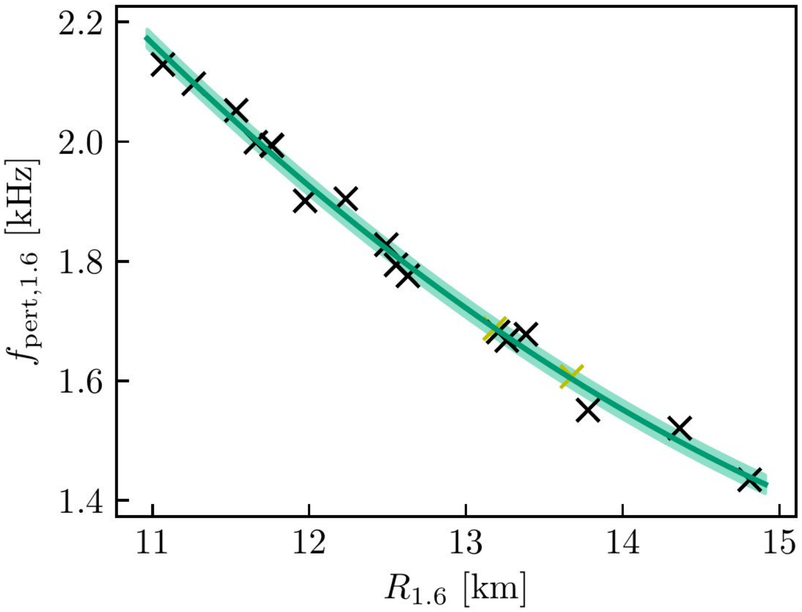
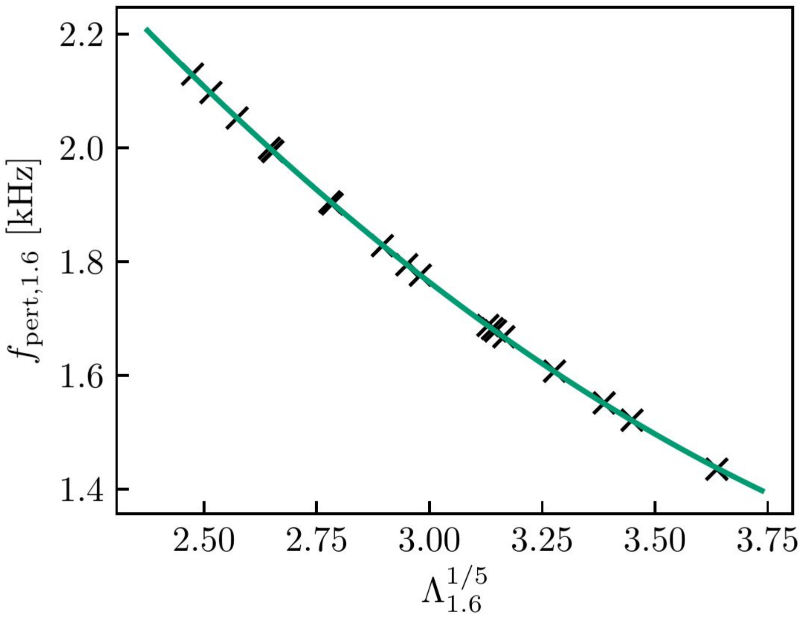
# Relation to tidal Love number $k_2$

Focus on a single mass M=1.6 $M_\odot$.

➔ Deviations influenced by (high) density EoS!
➔ $k_2$ informative about EoS!




Deviations related to Λ(R)

Scatter ⟷ No scatter

$$\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{GM} \right)^5$$

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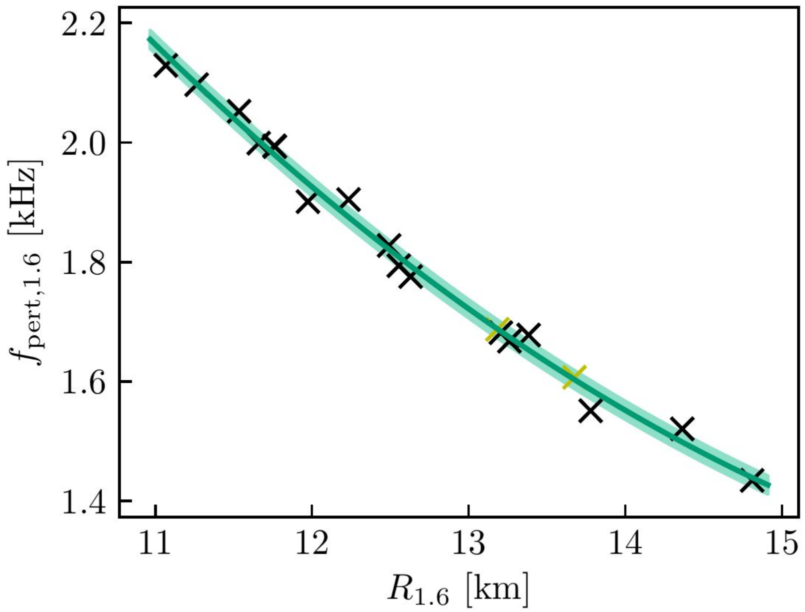
# Part II

## Frequency deviations in isolated NSs and BNS merger remnants

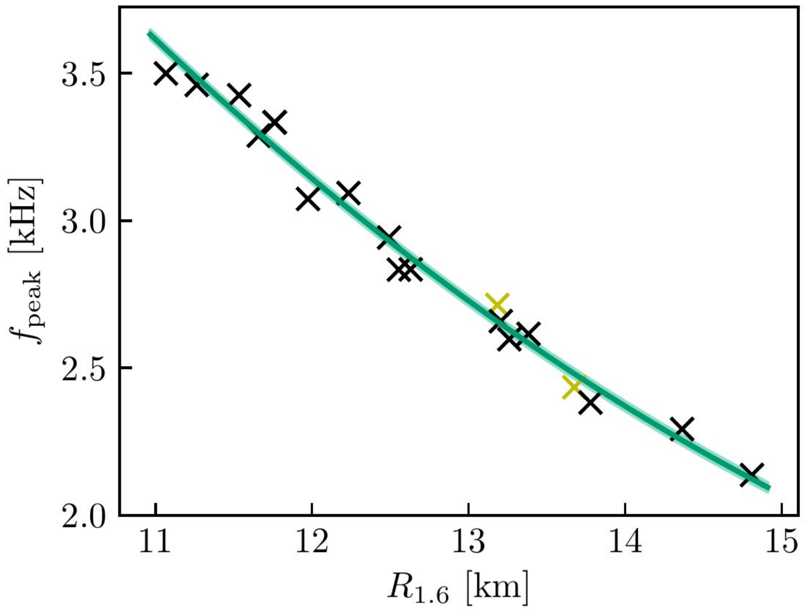
# Correspondence in frequency deviations

1.6 $M_\odot$




Isolated, cold, non-rotating NS
(perturbation theory for frequencies)

1.35+1.35 $M_\odot$ BNS




Hot, rapidly rotating, higher mass BNS merger remnant
(full dynamical evolution)

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# Correspondence in frequency deviations

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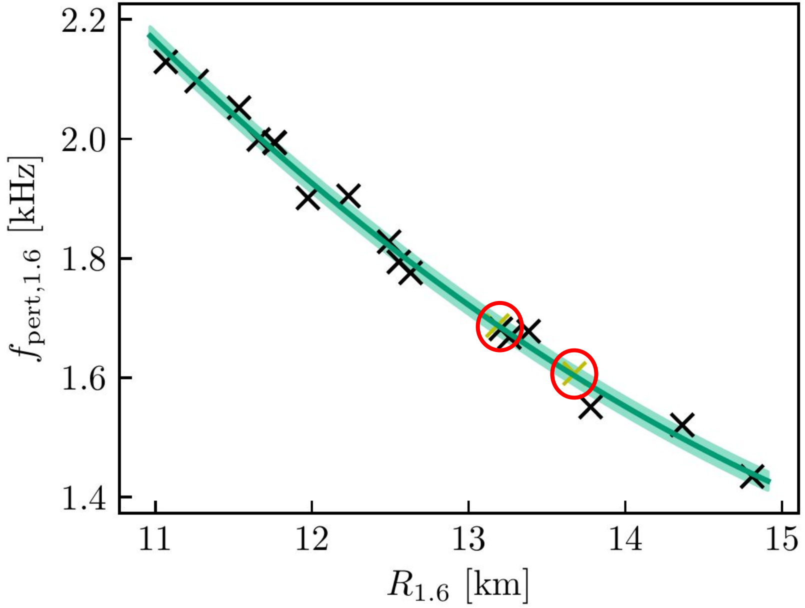


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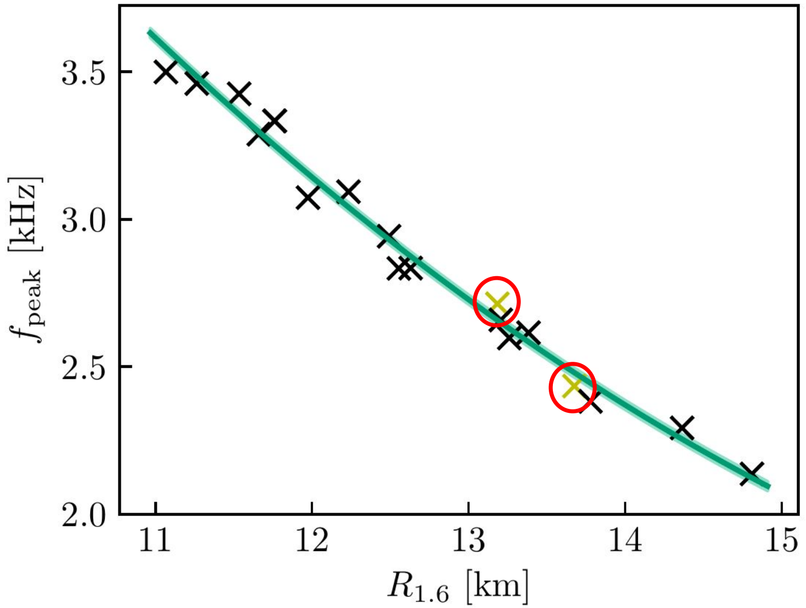


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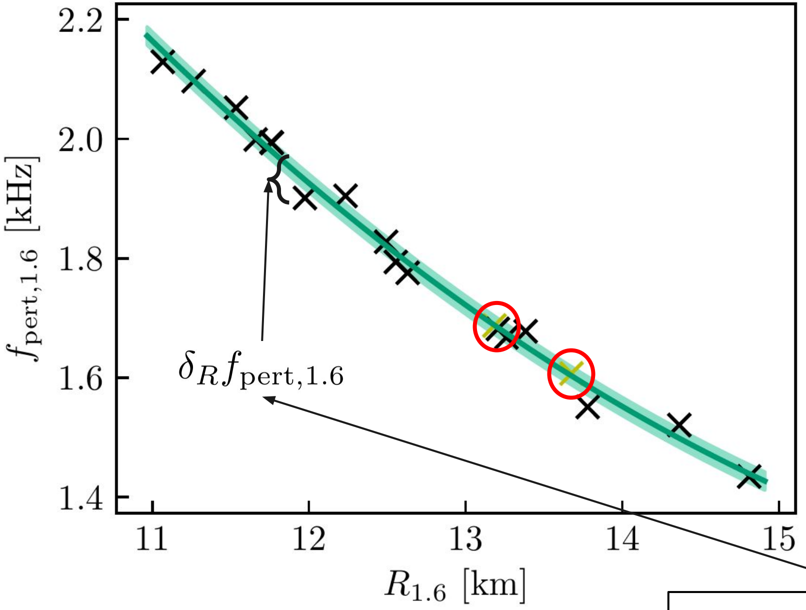


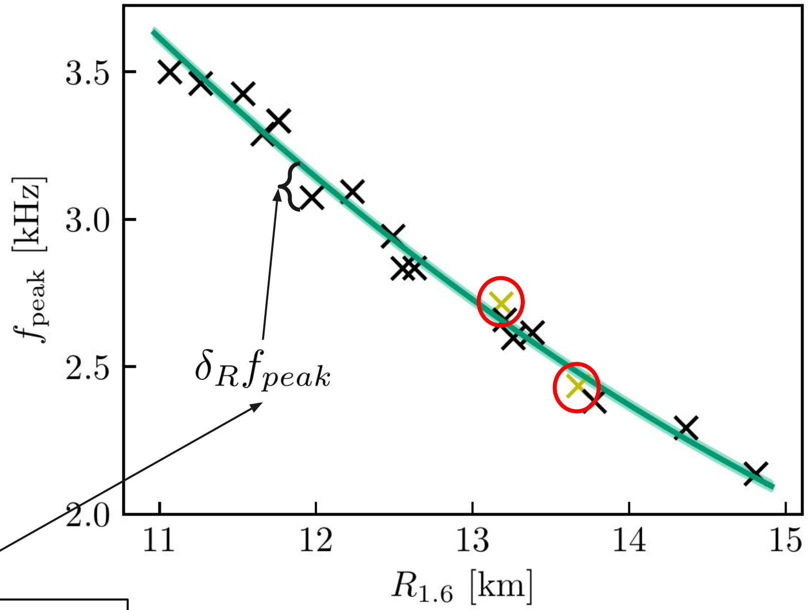


Mapping between the 2!

Isolated, cold, non-rotating NS
(perturbation theory for frequencies)

Hot, rapidly rotating, higher mass BNS merger remnant
(full dynamical evolution)

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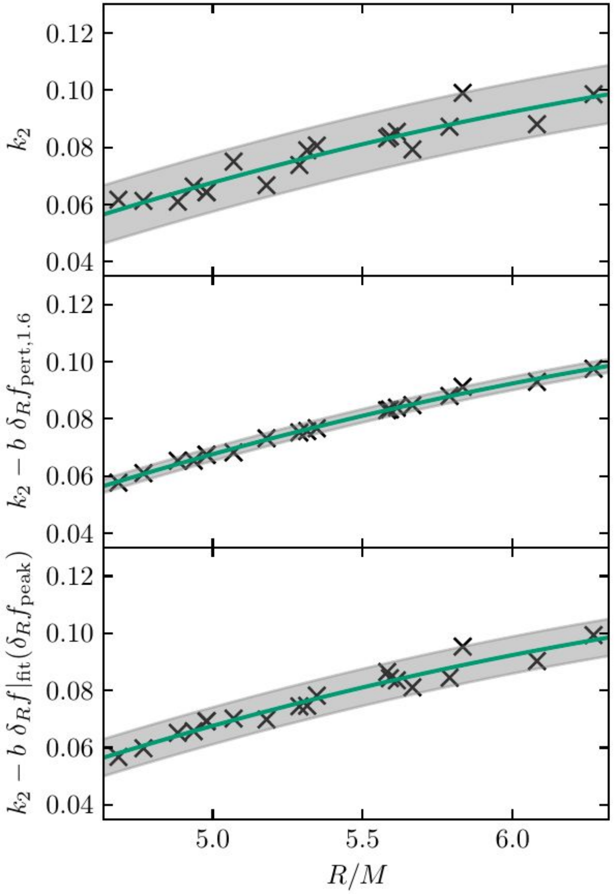
# Relation to tidal Love number $k_2$ (II)




For fixed mass $k_2(R)$

Corrected via deviations for isolated systems

Corrected via deviations for BNS systems

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Reminder: $\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{GM} \right)^5$

So frequency deviations help break degeneracy between R, Λ and $k_2$!

- Sign of deviations ⇨ reduce error by 50%
- Similar results for different masses and f(Λ) plots
- Deviations in f(Λ) plots constrain dΛ/dM derivative

# Conclusions

- We compared the accuracy of different empirical relations based on a consistent data set and identified one relation which is extremely tight and makes $f_{pert}$ and $\Lambda^{-1/5}$ practically equivalent.
- We showed that the scatter on such relations contains information about the (high) density EoS.
- We found an striking similarity in frequency deviations between isolated, cold, non-rotating stars and hot, rapidly rotating, BNS merger remnants.
- We discussed how these deviations can be employed to help break the degeneracy between R, $\Lambda$ and $k_2$.

Thank you for the attention!