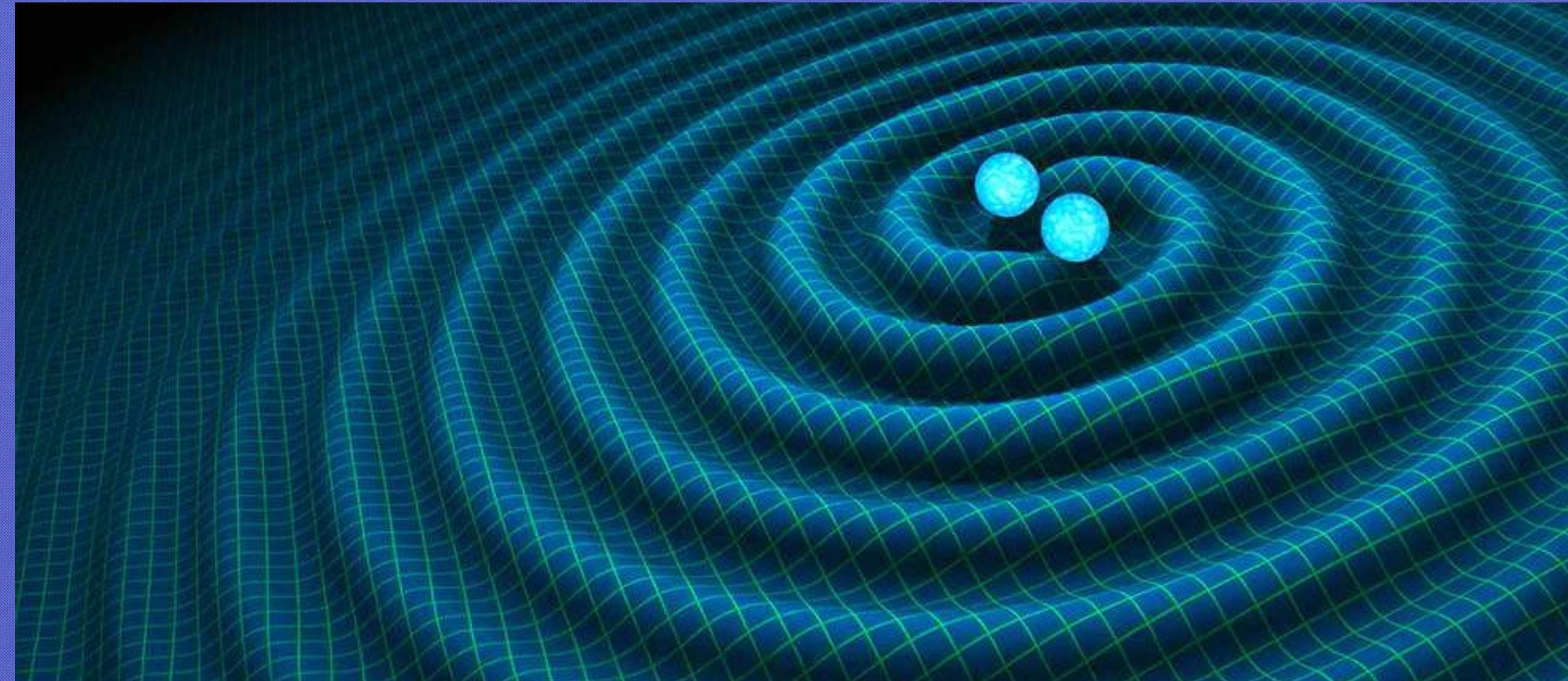


# Constraining the equation of state of neutron stars using multi-messenger observations



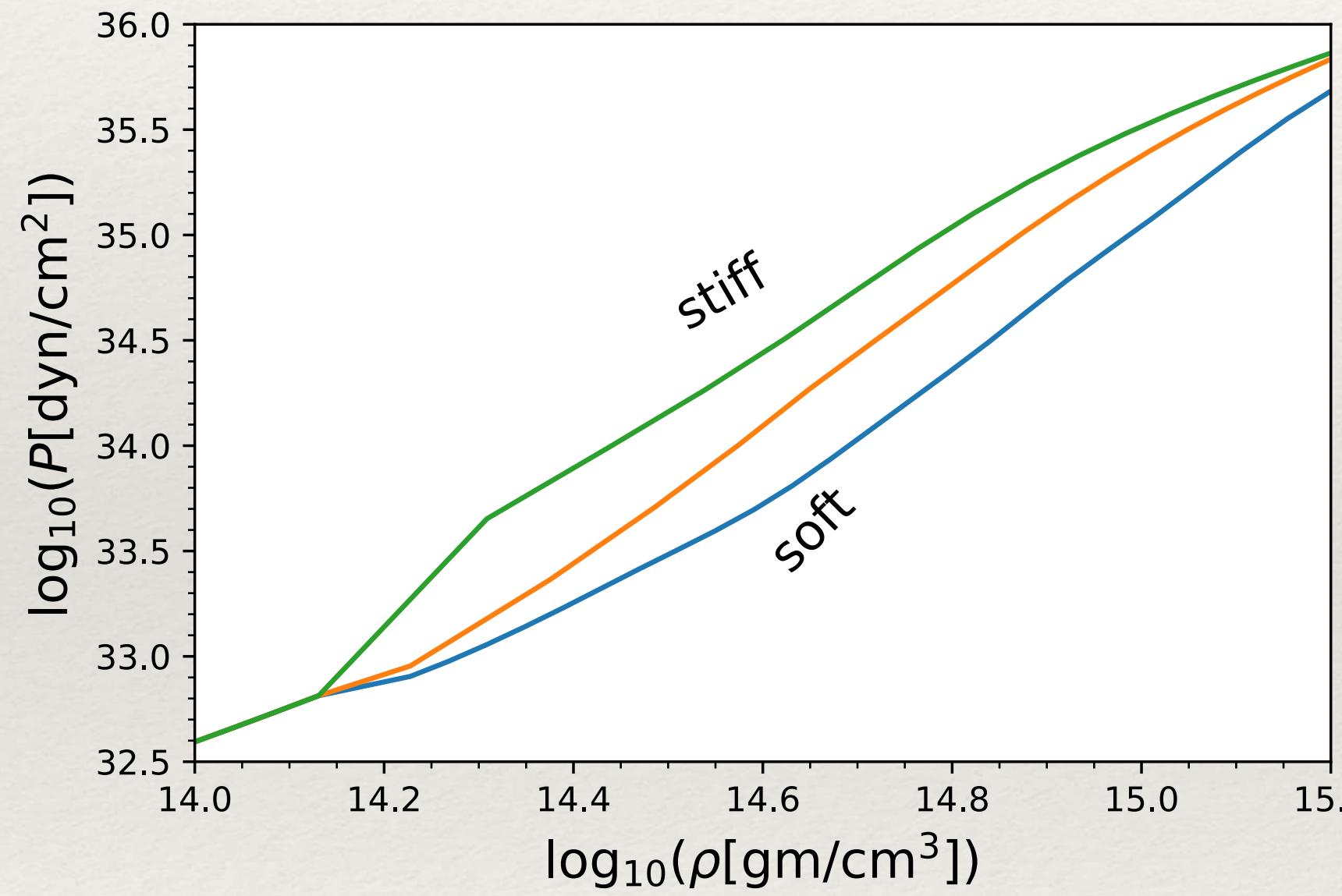
Bhaskar Biswas | Hamburg observatory

GWsNS School

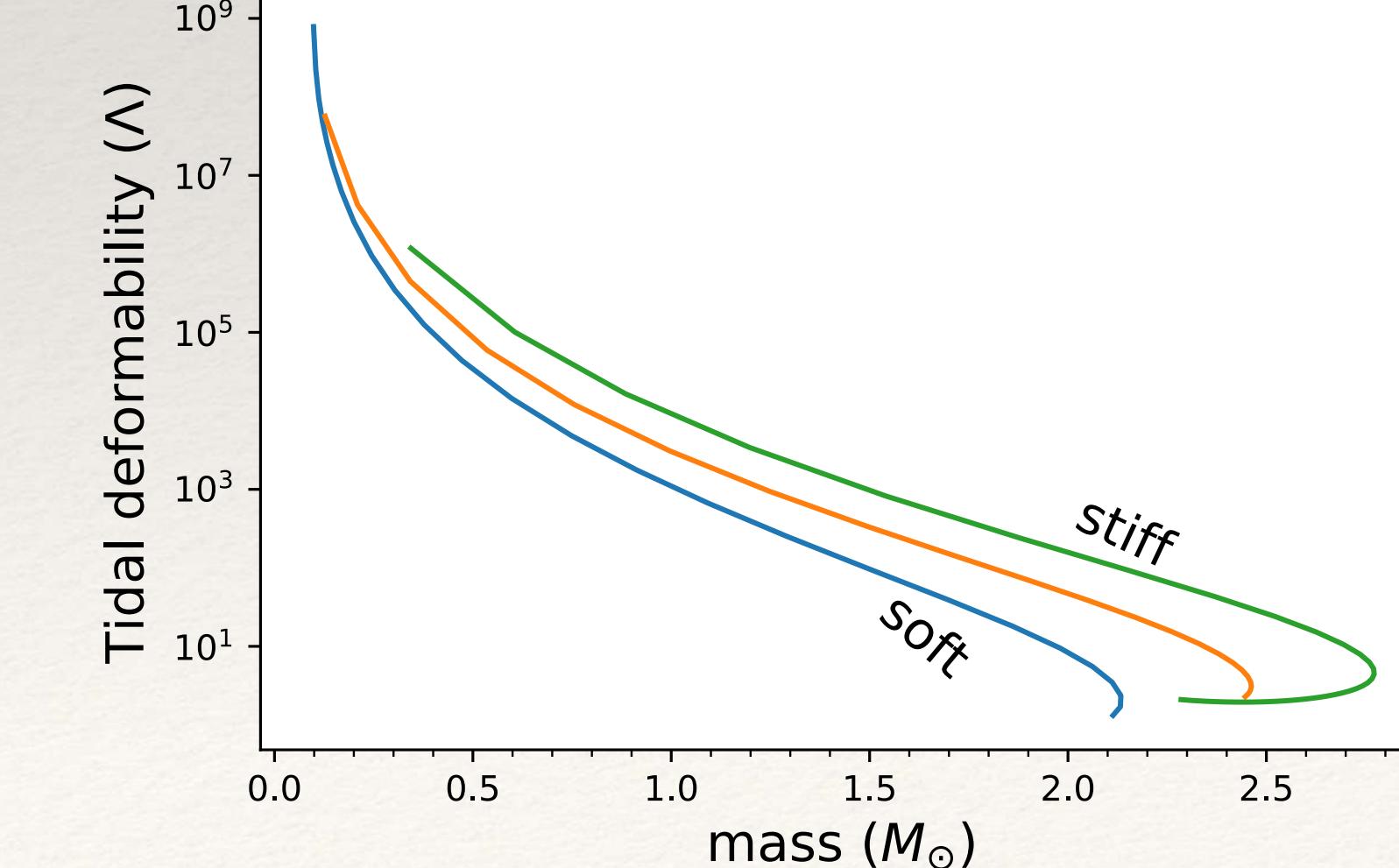
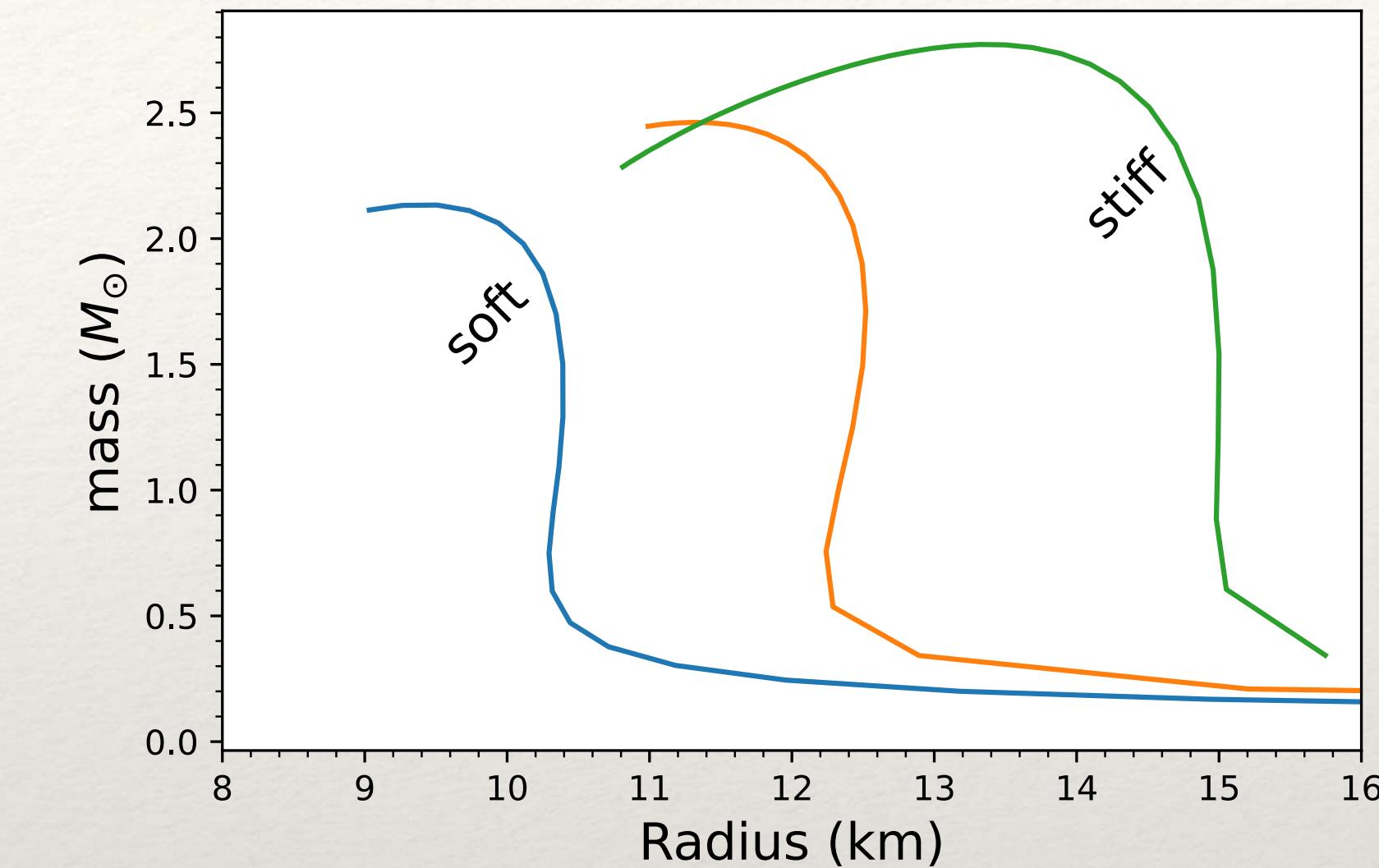
June 5-9, 2023

# EOS & observables

EOS,  $P = P(\rho)$

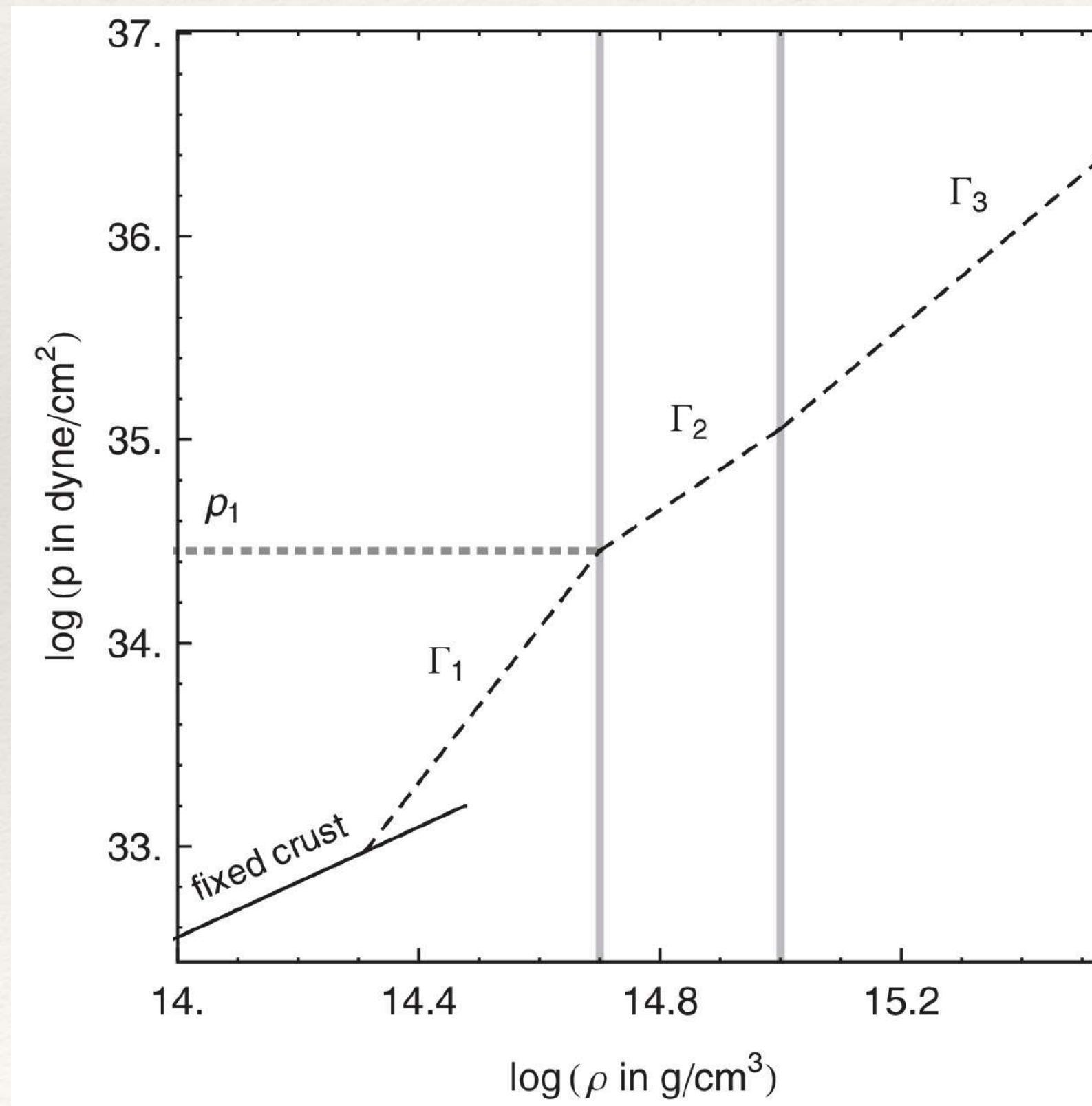


- ❖ Radio observables —  $M$
- ❖ X-ray observables —  $M, R$
- ❖ GW observables —  $M, \Lambda$



# Traditional approach to constrain NS EOS

Piecewise polytope,  
Read+ PRD 2008

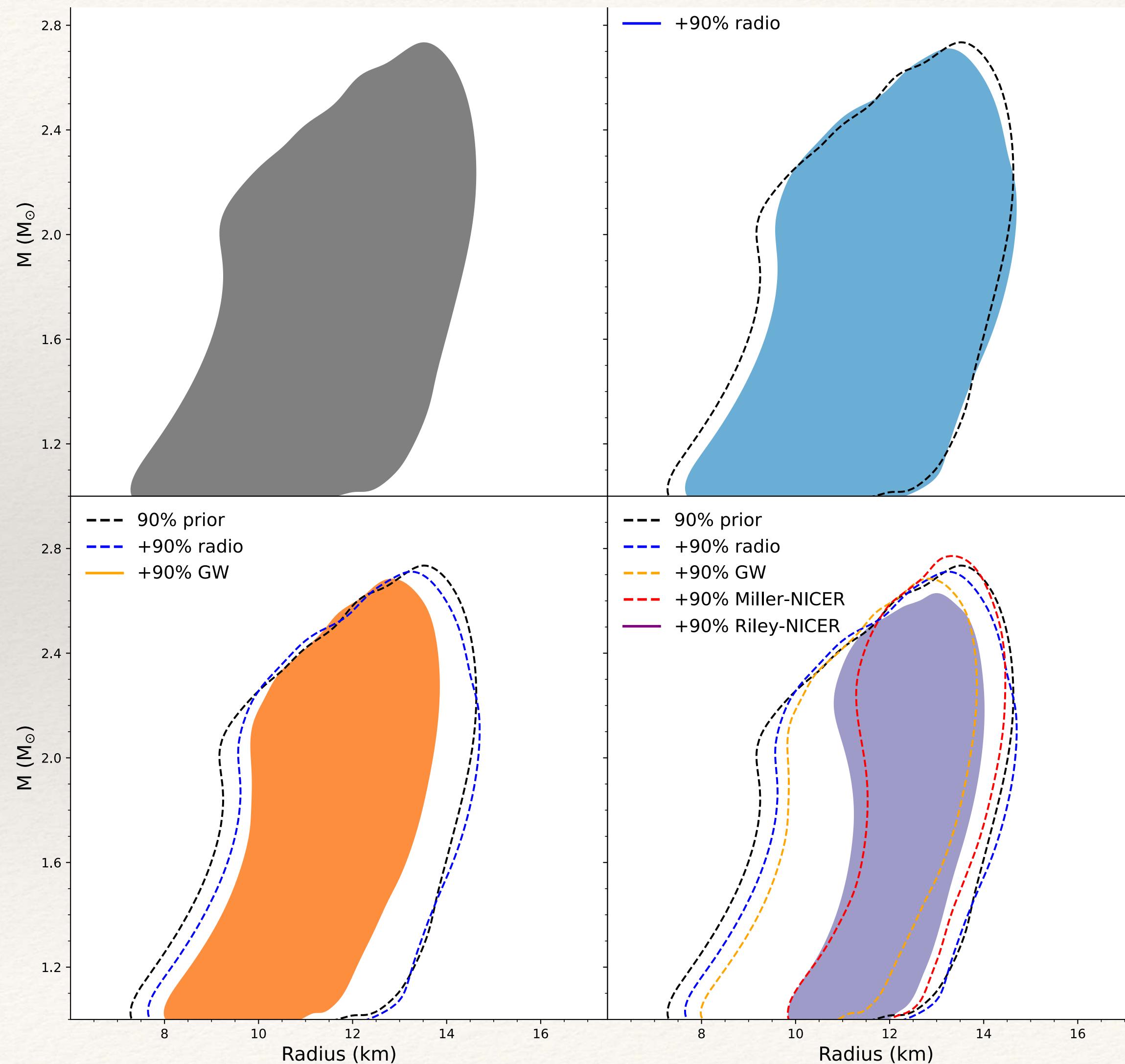


Hierarchical Bayesian statistics to infer NS EOS  
(My PhD thesis, arXiv: 2204.08555)

$$P(\Gamma_k | d) \propto P(\Gamma_k) \prod_i P(d_i | \Gamma_k),$$

Posterior      Prior      Likelihood

# Current mass-radius constraints





Thank you for your attention!

# Effect of Spin in Binary Neutron Star Mergers

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Beyhan Karakaş

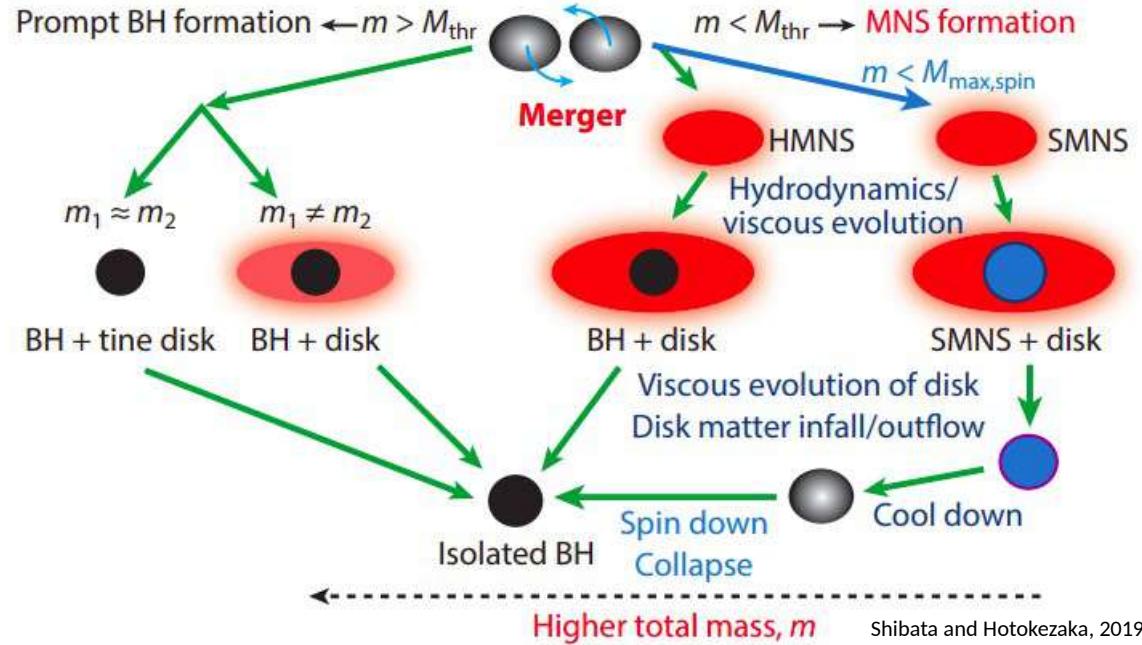
In collaboration with: Rahime Matur (UoS), Maximilian Ruffert (UoE)



This work has been supported by HPC-Europa3, under the H2020 Programme at EPCC. The numerical calculations reported in this work were partially performed at TUBITAK ULAKBIM, High Performance and Grid Computing Center (TRUBA resources).



# Introduction



- $M_{\text{thr}} > 2.8 M_{\odot}$
- $M_{\text{max,spin}} > 2.4 M_{\odot}$
- $M_{\text{max,spin}} < m < M_{\text{thr}}$ , HMNS
- $m < M_{\text{max,spin}}$ , SMNS
- Masses  $1.3 - 1.4 M_{\odot}$  (Thorsett and Chakrabarty, 1998, valentim et al., 2011)
- PSR J0453+1559 (Martinez et al., 2015): most asymmetric having  $q = 0.75$
- PSR J1748-2446ad: fastest  $f_{\text{spin}} = 716 \text{ Hz}$  (Hessels et al., 2006)
- PSR J092-067 fastest (MW) and the most massive (Bassa et al., 2017; Wynn C., Ho, 2019, Romani et al., 2022)  $f_{\text{spin}} = 707 \text{ Hz}$ ,  $M_{\text{NS}} = 2.35 \pm 0.17 M_{\odot}$

# IDs and Tools

Total Mass	Spin
2.5456	$q=1; (0,0), (+04,+04), (-04,0) , (+04,0), (-04,+04), (-065,+065), (-0.65, -0.65), (+0.67, +0.67)$
3.05	For $q=1; (0,0), (+0.4, +0.4)$ - For $q=2.05; (0, 0), (0, +0.6)$
4.1	$q=1; (0,0), (-0.65, -0.65), (-0.65, +0.65), (+0.67, +0.67)$

(+,+): aligned-aligned

(-,-) : anti aligned-anti aligned

(+,-) : aligned-anti aligned

(0, +): irrotational-aligned

(0,-) : irrotational-anti aligned

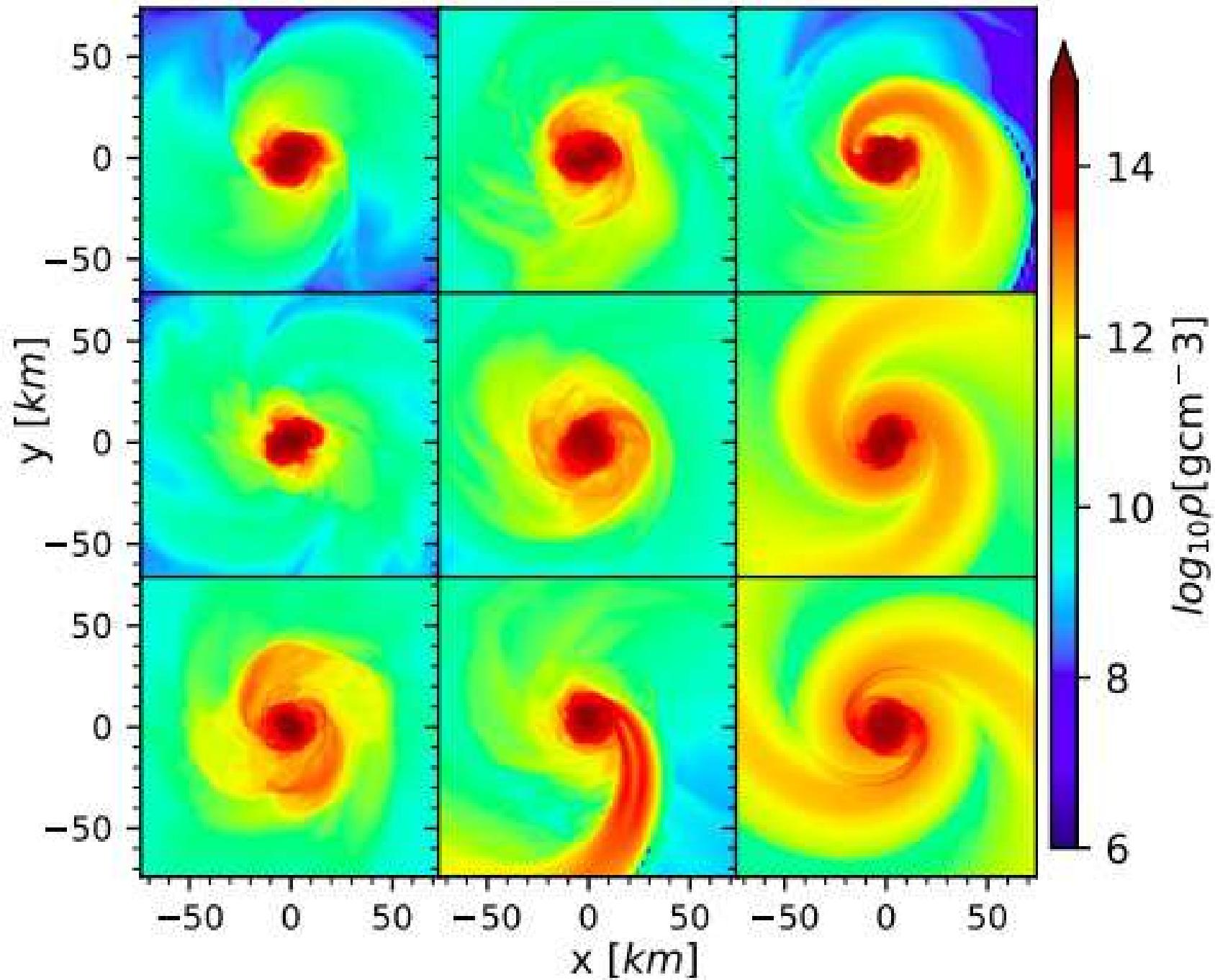
(0,0) : irrotational

	$R_{1.35}$ (km)	$C_{NS}$	$M_{Max}$
SFHo (Steiner et al., 2013, stellarcollapse.org)	11.9	0.167	2.06  Kyutoku et al., 2021

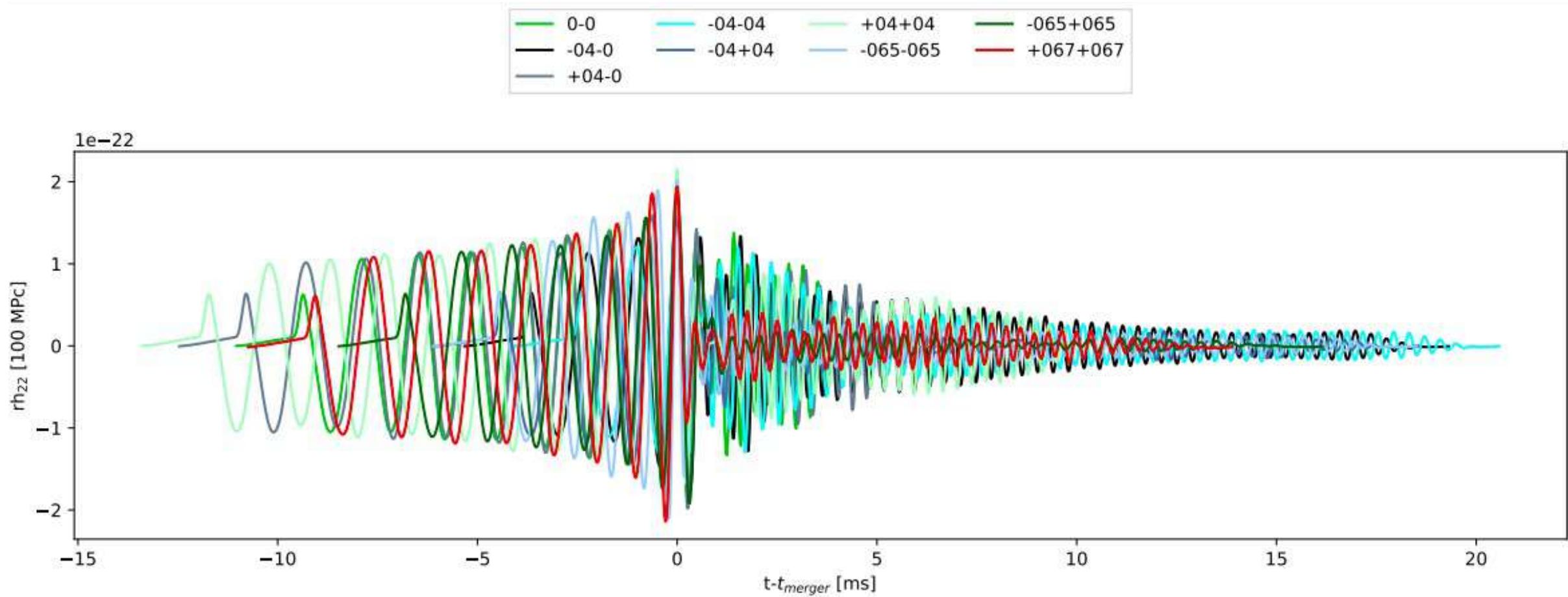


FUKA

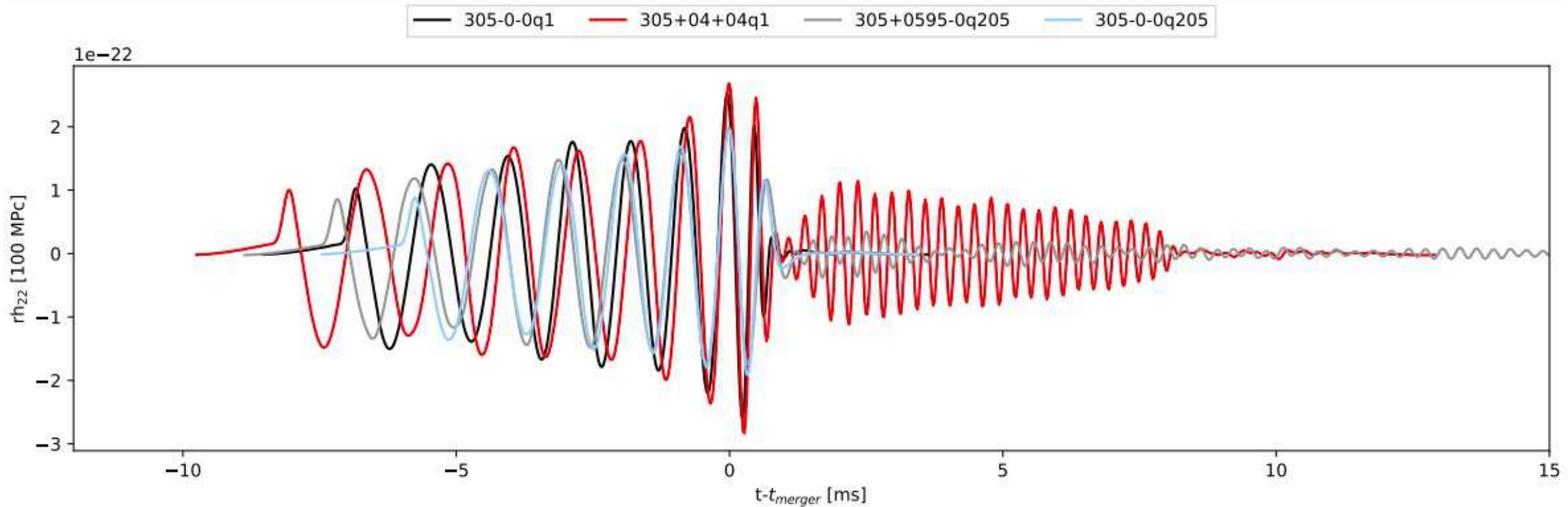
PostCactus



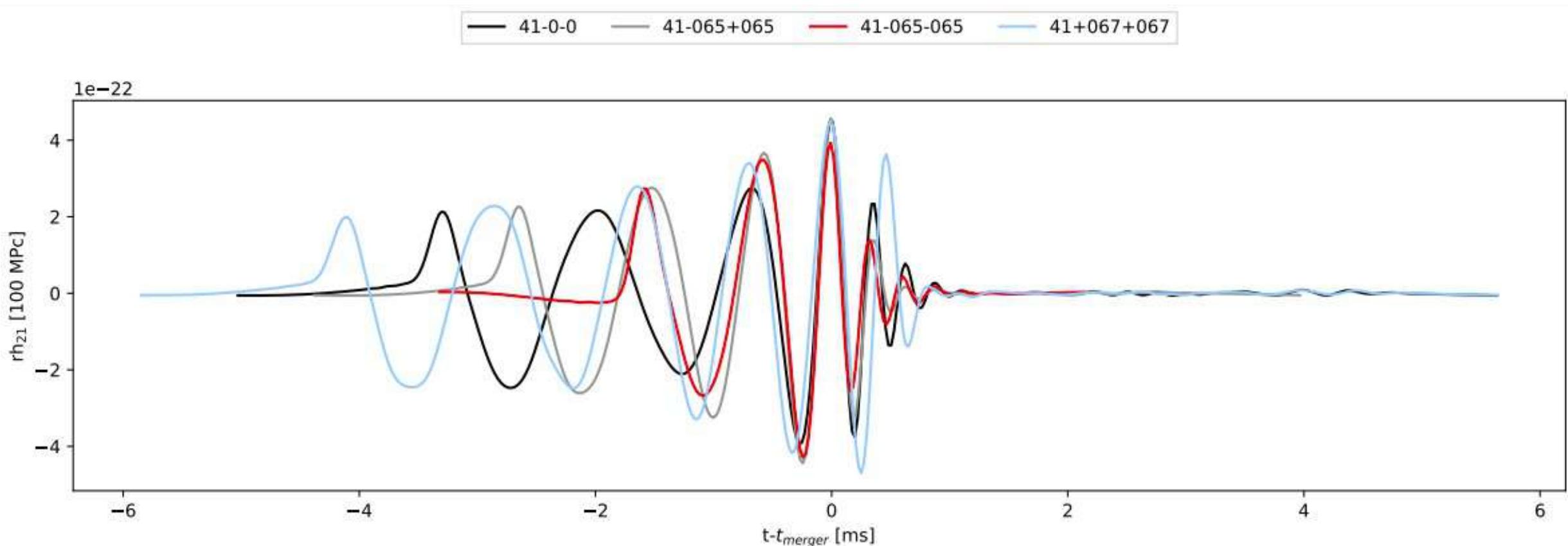
**M<sub>T</sub> = 2.5456, q=1**



**M<sub>T</sub> = 3.05, q=1 & q=2.05**



**M<sub>T</sub> = 4.1, q=1**



# References

- Einstein Toolkit, <https://www.einsteintoolkit.org/> (Zlochower et al., 2022)
- WhiskyTHC, <http://personal.psu.edu/dur566/whiskythc.html> (Radice, D., Rezzolla, L., 2012; 2014a; 2014b)
- Fuka, <https://kadath.obspm.fr/fuka/> (Papenfort et al., 2021)
- Lorene, <https://lorene.obspm.fr/> (Bonazzola et al., 1998)
- PostCactus, <https://github.com/wokast/PyCactus>



THANK YOU!

# Impact of pions on binary neutron star mergers

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V. Vijayan,<sup>1,2</sup> N. Rahman,<sup>1</sup>, A. Bauswein,<sup>1,3</sup>, G. Martinez-Pinedo<sup>1,3,4</sup>, I. L. Arbina<sup>1,4</sup>

<sup>1</sup> *GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*

<sup>2</sup> *Universität Heidelberg, Heidelberg, Germany*

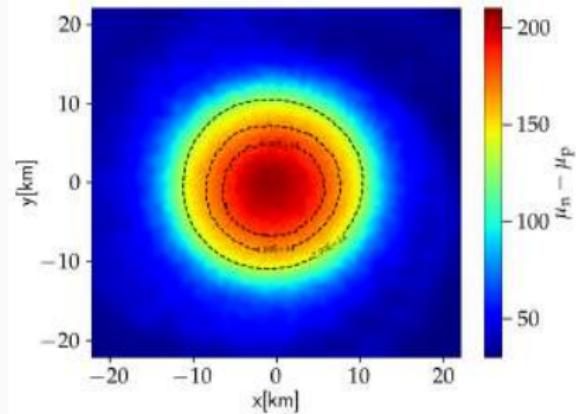
<sup>3</sup> *Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*

<sup>4</sup> *TU Darmstadt , Darmstadt, Germany*



# BNS mergers

- To probe physics of matter at extreme densities.
- Neutron star (NS) interior : n, p,  $^A_Z X$ ,  $e^-$ ,  $e^+$ ,  $\gamma$ , Quarks, Hyperons, **Pions**, etc. Incompletely known equation of state (EoS).



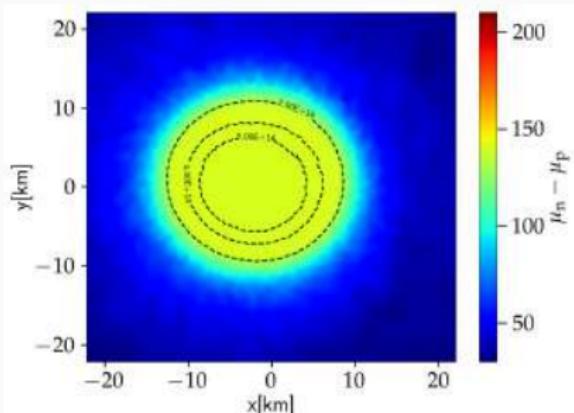
(a) Base DD2

- Neutron-proton chemical potential difference is large enough for the presence of pions,  $\pi^-$ ,  $\pi^+$  and  $\pi^0$ , since  $m_{\pi^\pm} = 139.6$  MeV and  $m_{\pi^0} = 134.9$  MeV.
- Pions can exist as condensate and thermal pions, i.e.

$$Y_\pi = Y_{\pi^{\text{condensate}}} + Y_{\pi^{\text{thermal}}}.$$

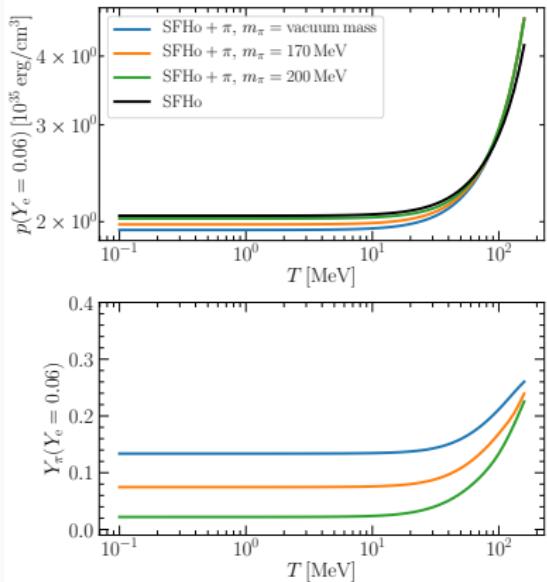
# BNS mergers

- Considered two base EoSs: SFHo and DD2 (includes n, p,  $\frac{A}{Z}X$ ,  $e^-$ ,  $e^+$ ,  $\gamma$ )
- Pions included as non-interacting boson gas. In thermal and chemical equilibrium with nucleons through the strong interaction.
- $\mu_{\pi^\pm} = \mp(\mu_n - \mu_p)$  and  $\mu_{\pi^0} = 0$
- Charge neutrality :  
$$Y_p = Y_e + Y_\pi = Y_e + Y_{\pi^-} - Y_{\pi^+}$$
- Chosen effective mass of the pions: Vacuum mass, 170MeV and 200MeV.

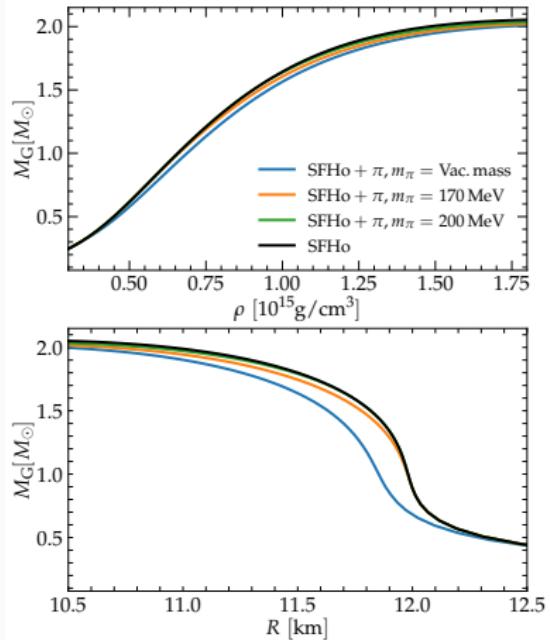


(b) DD2 +  $\pi$ ,  $m_\pi$  = Vac. mass

# NS EoS + Pions



Pressure and  $Y_\pi$



TOV properties

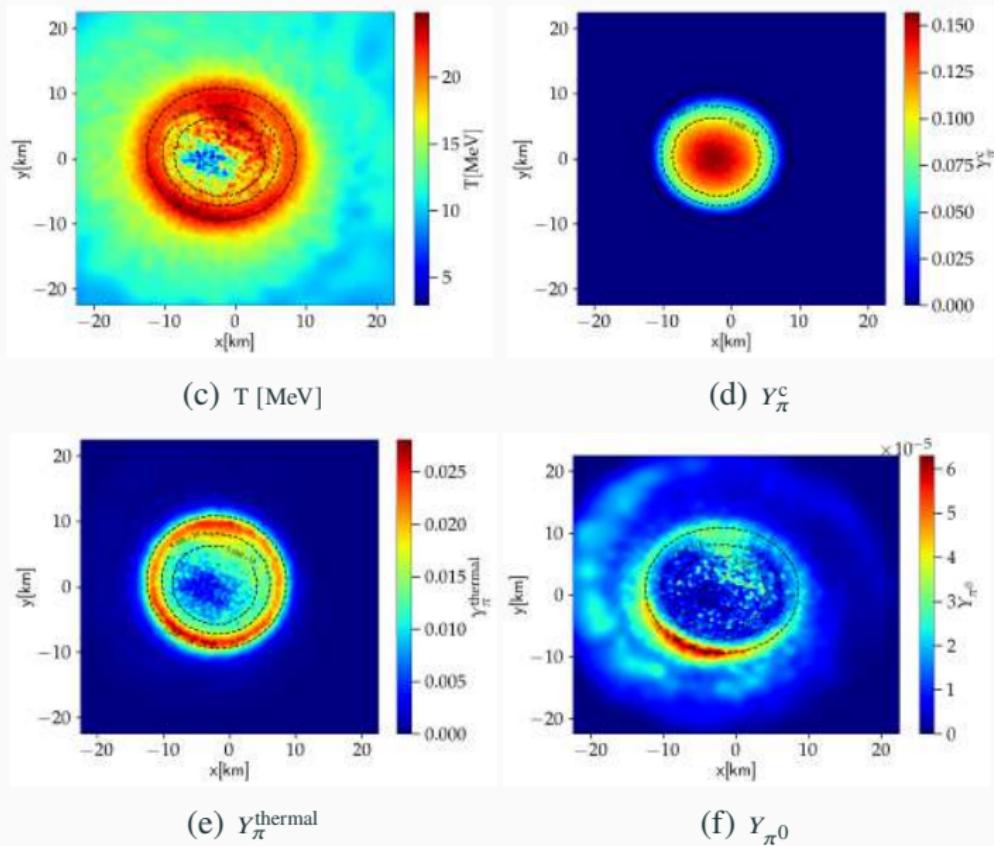
- Overall reduction of the pressure and the softening of the EoS.

# BNS merger

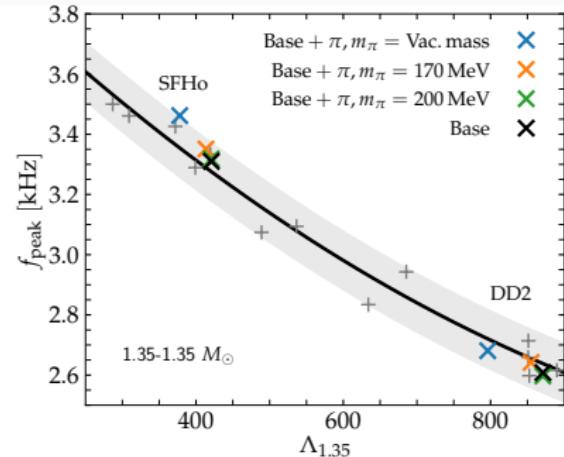
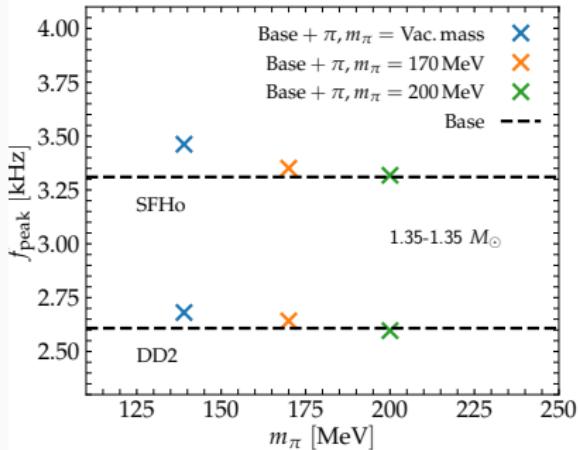
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Temperature Profile

# Pion

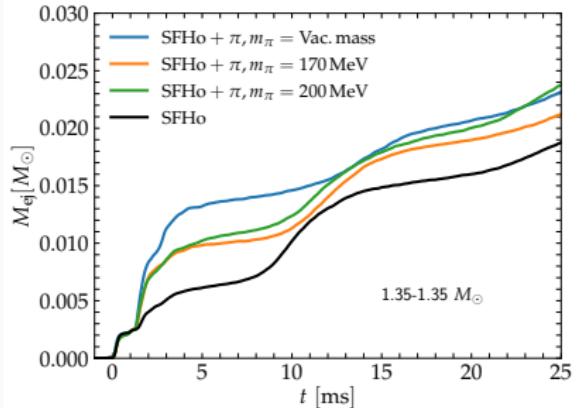
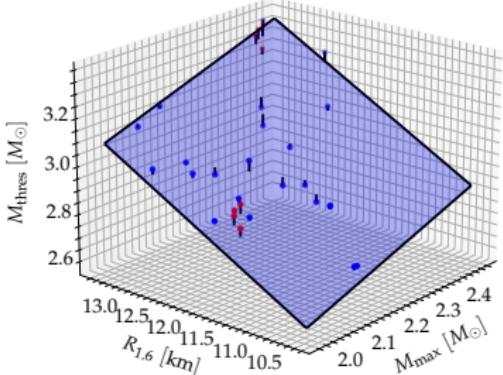


# Results



- Shift of the dominant postmerger gravitational-wave frequency by up to 150Hz to higher frequencies (stronger for smaller effective pion masses).
- Evaluated empirical relations between the threshold mass or the  $f_{\text{peak}}$  and stellar parameters of nonrotating neutron stars remain valid to good accuracy.

# Results

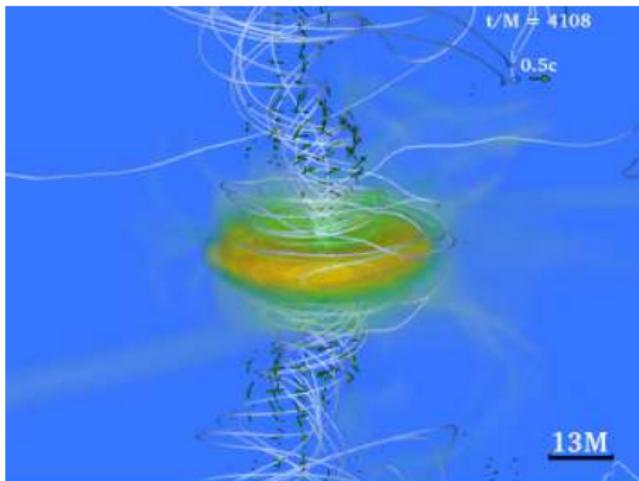


- Reduction of the threshold binary mass for prompt black-hole formation by up to  $0.07 M_\odot$  (stronger for smaller effective pion masses).
- Pronounced changes in the ejecta mass.

## Merger of Black Hole-Neutron Star Binaries in General Relativity

João de Jesus

- Under certain conditions of mass ratio and black hole spin, black hole-neutron star binaries can emit jets of short-hard gamma ray bursts.
- We intend to study the ejection of jets in high mass ratio systems ( $M_{\text{BH}}/M_{\text{NS}} \gtrsim 7$ ) with rapidly spinning BHs ( $a/m > 0.9$ ).





# Muons in the aftermath of Neutron Star mergers and their impact on Trapped Neutrinos

Eleonora Loffredo\*, Albino Perego, Domenico Logoteta, Marica Branchesi

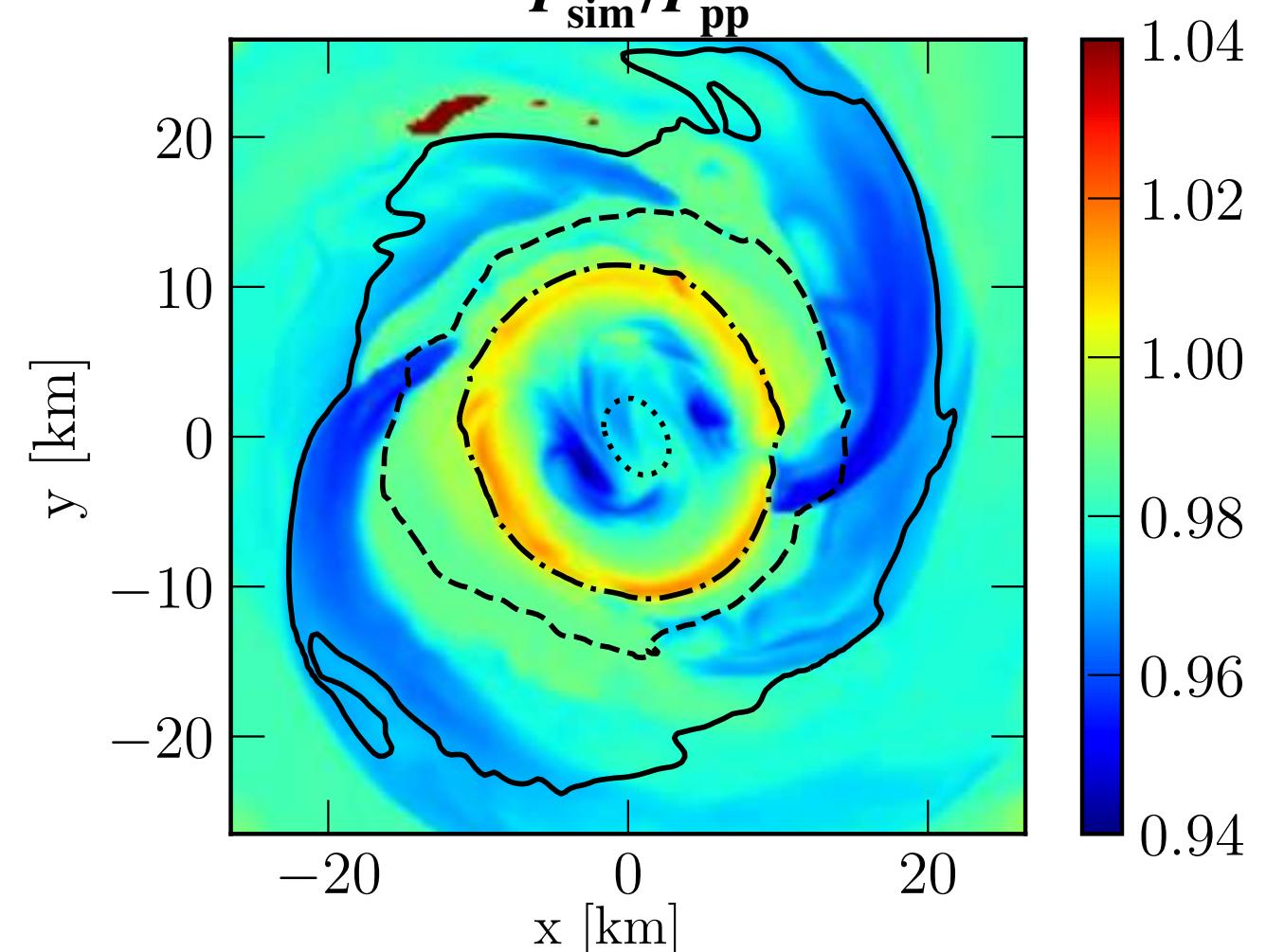
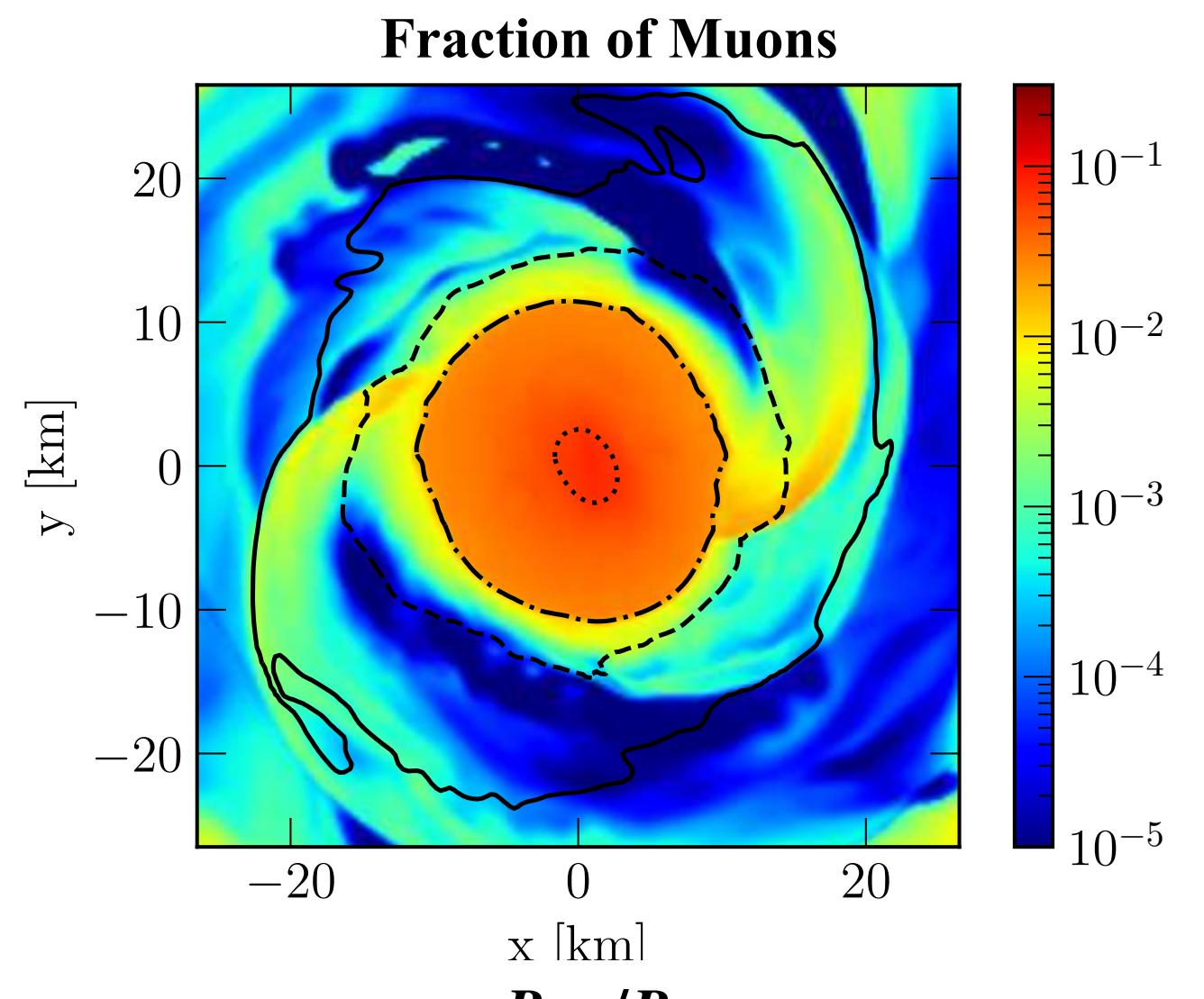
\*[eleonora.loffredo@gssi.it](mailto:eleonora.loffredo@gssi.it)



- Muons relevant in microphysics of Cold NSs and SNe.
- State-of-the-art simulations of BNS mergers don't include muons!
- **Our aim:** estimating impact of muons on the merger remnant and on the trapped neutrino component in post-processing.
- Published on **A&A**

## Results:

1. Muon fraction  
 $\sim 30\% \div 70\%$  of net electron fraction → muons needed for accurate modelling of merger
2. Muons modify the neutrino hierarchy in the aftermath
3. Remnant pressure modified by muons!  
→ Possibly implications for collapse time, ejecta, and **Kilonova**!



# Taming systematics in redshift measurements with current and future gravitational-wave detectors

Adriano Frattale Mascioli, Sapienza University of Rome & INFN Roma1

In collaboration with Francesco Pannarale, Paolo Pani & Costantino Pacilio

## Some goals with GW astronomy

- Constrain **NS EoS**;
- Solving **Hubble Tension**;
- **Population** inference;
- And many **others...**



## A limiting problem

- Accurate **distance (redshift)** measurements needed;
- Distance **degenerate** with inclination.



## How to solve it

- Secondary effects may help;
- Consider **higher modes** in the inference analysis.



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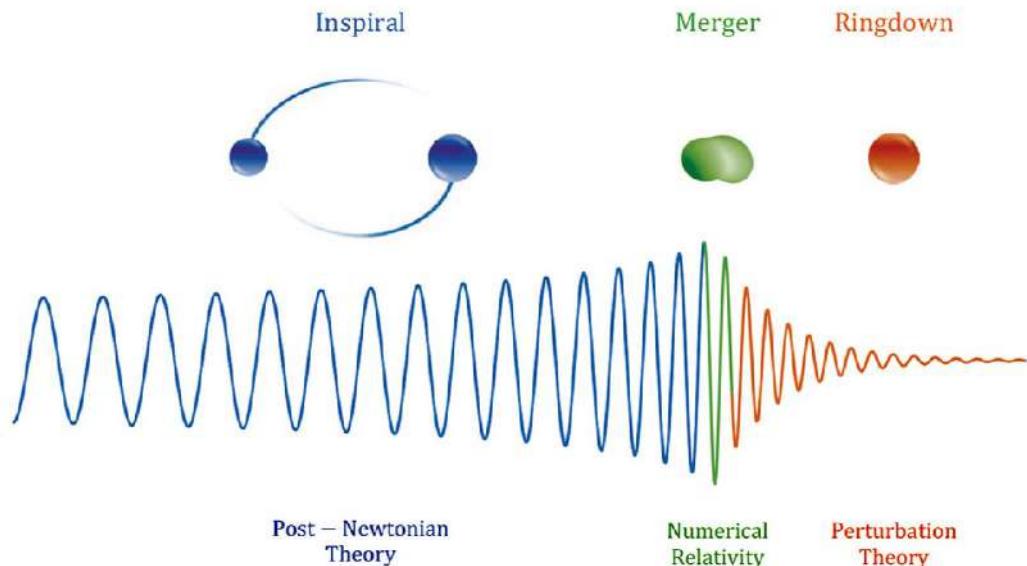
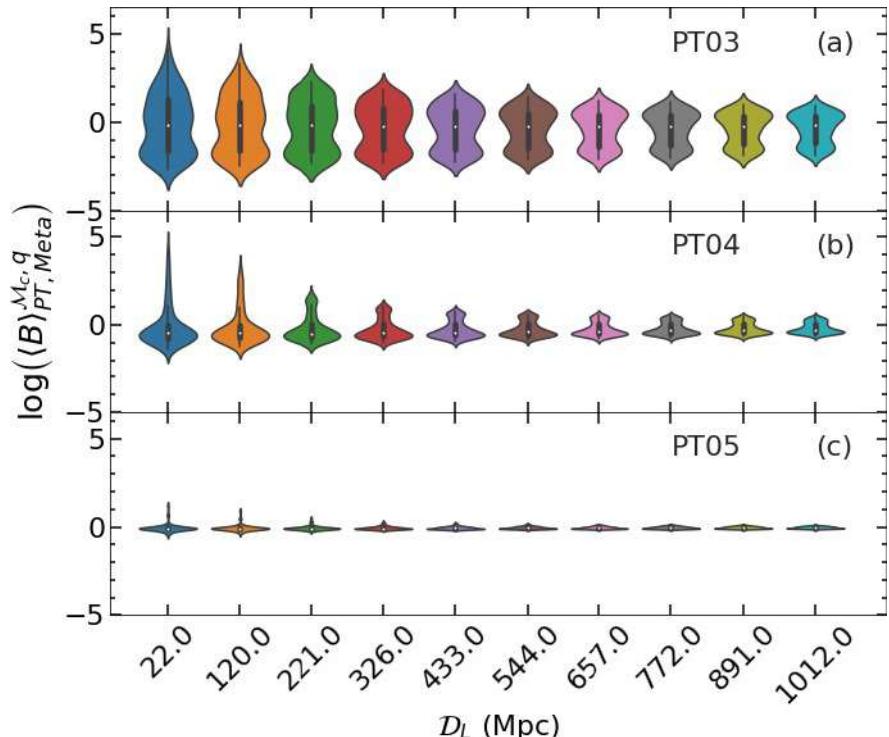
INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma



# Detectability of a phase transition in neutron star matter with third generation gravitational wave interferometers

Chiranjib Mondal

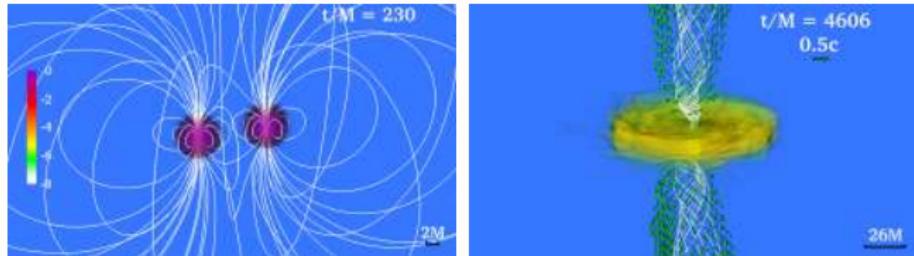
M. Antonelli, F. Gulminelli, M. Mancini, J. Novak, M. Oertel



# Impact of the geometry of the seed magnetic field on jet launching in binary neutron stars

Inês Rainho <sup>1</sup>

<sup>1</sup>Departamento de Astronomía y Astrofísica, Universitat de València, Spain



- The aim is to understand if more general magnetic field configurations can launch magnetically driven jets. The results may explain NICER observations of pulsars, which show they have non-dipolar magnetic fields.

# Numerical simulations of NS using primitive variables and spectral methods

The variables  $D = m_B n_B \Gamma^2$ ,  $S_j = (e + p) \Gamma^2 U_j$  and  $\tau = (e + p) \Gamma^2 - p$ , with  $\Gamma = (1 - U_i U^i)^{-1/2}$  in  $\mathbf{u} = (D, S_j, \tau)$  obey

$$\partial_t \mathbf{u} + \operatorname{div}(F(\mathbf{u})) = \text{source}$$

Recovery procedures to compute the metric + solving Riemann problems is **expensive**. Idea:

$$\partial_t n_B = ???$$

$$\partial_t U_i = ???$$

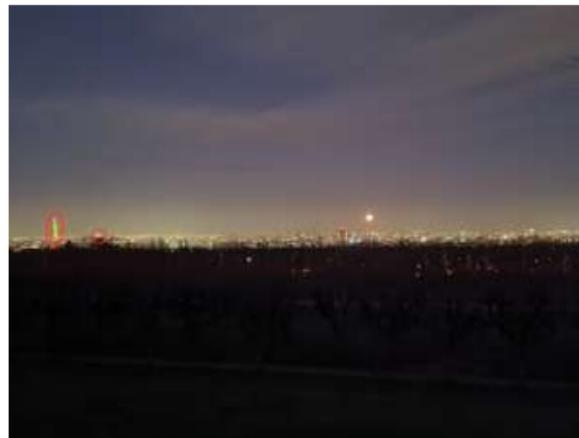
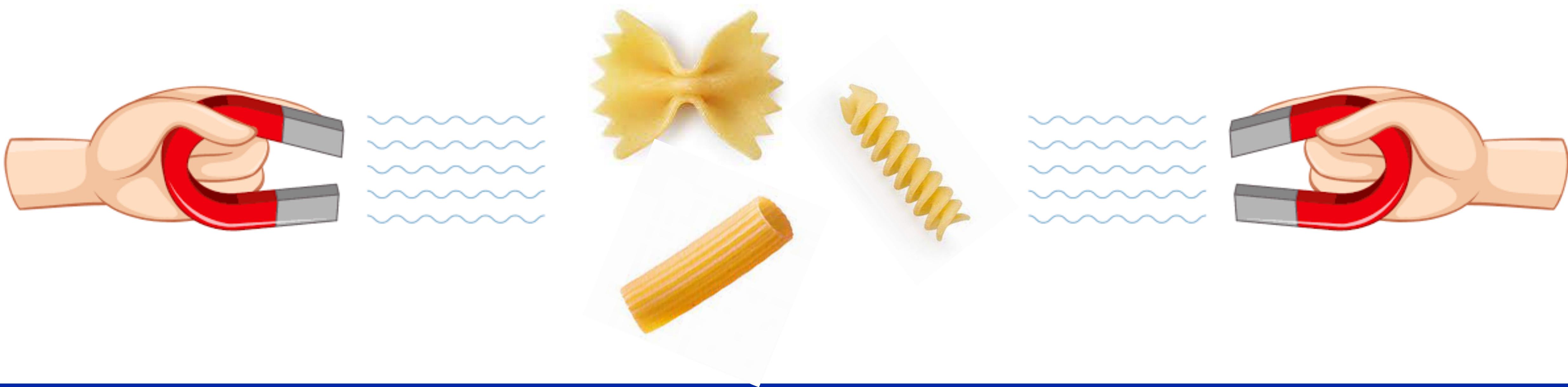


Figure: Lights of Paris from Meudon

# Strong magnetic fields and pasta phases reexamined



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<sup>2</sup>Department of Fundamental Physics, University of Salamanca, E-37008 Salamanca, Spain

<sup>3</sup>Normandie Univ., ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France

Results from: Phys. Rev. C 107, 045806(2023)

