# Maximum mass of compact stars from gravitational wave events with finite-temperature equations of state

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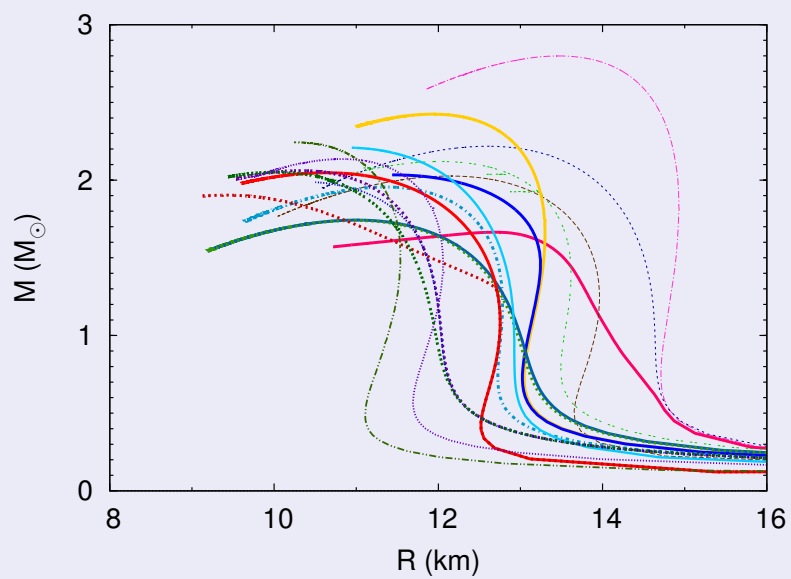
# Introduction

## Mass-radius relation and the TOV mass

- $M$ and $R$
  - GR, stationarity+spherical symmetry $\rightarrow$TOV system
  - Closed by an equation of state (EoS)
- Matter in old NSs can be considered as cold and in weak ($\beta$) equilibrium
- Maximum mass $M^{\star}_{\rm TOV}$ is a GR effect, value given by the EoS
  $\rightarrow$ strong constraint on the EoS

Different EoS models (taken from https://compose.obspm.fr)




- Measured pulsar masses give a lower limit on $M^{\star}_{\rm TOV}$
- Precise mass determinations from three NS-WD binaries around 2 $M_{\odot}$ :

| PSR J1614-2230 | PSR J0348+0432 | PSR J0740+6620 |
|---|---|---|
| $M = 1.908 \pm 0.016 M_{\odot}$ | $M = 2.01 \pm 0.04 M_{\odot}$ | $M = 2.08 \pm 0.07 M_{\odot}$ |
| [Arzoumanian+ 2018] | [Antoniadis+ 2013] | [Fonseca+ 2021 ] |

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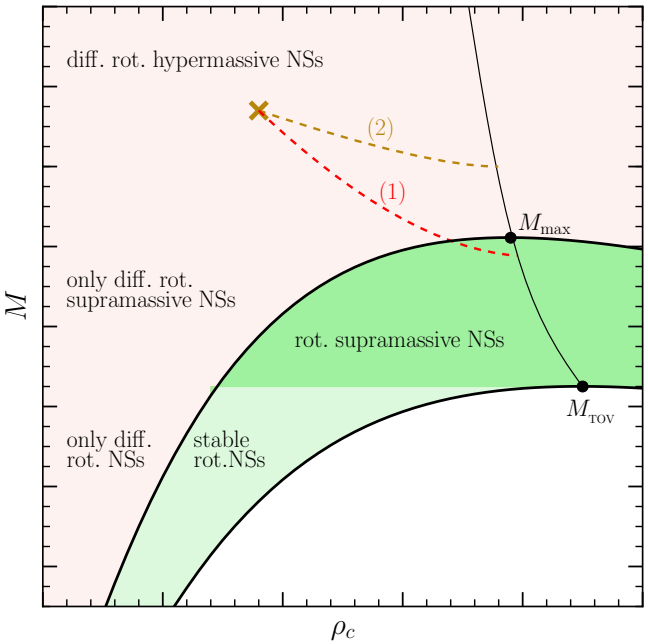
# Constraints on TOV mass from GW170817

- Different authors have extracted limits from GW170817

[Margalit & Metzger 2017, Rezzolla+2018, Shibata+ 2019, Ruiz+ 2019,...]




[Rezzolla+ 2018]

Idea :

- No prompt collapse for GW170817, but formation of a differentially rotating HMNS
- Internal viscosities lead to rigid rotation, the star collapses upon crossing the stability line for rigid rotation
- Assumption : stability line crossed close to $M_K^\star$ [Rezzolla+], limits slightly relaxed if $M < M_K^\star$ [Shibata+]
- Universal relation between $M_K^\star$ and $M_{\rm TOV}^\star$

- But the merger remnant might still be hot and (partly) out of $\beta$-equilibrium upon collapse !

# Universal relations

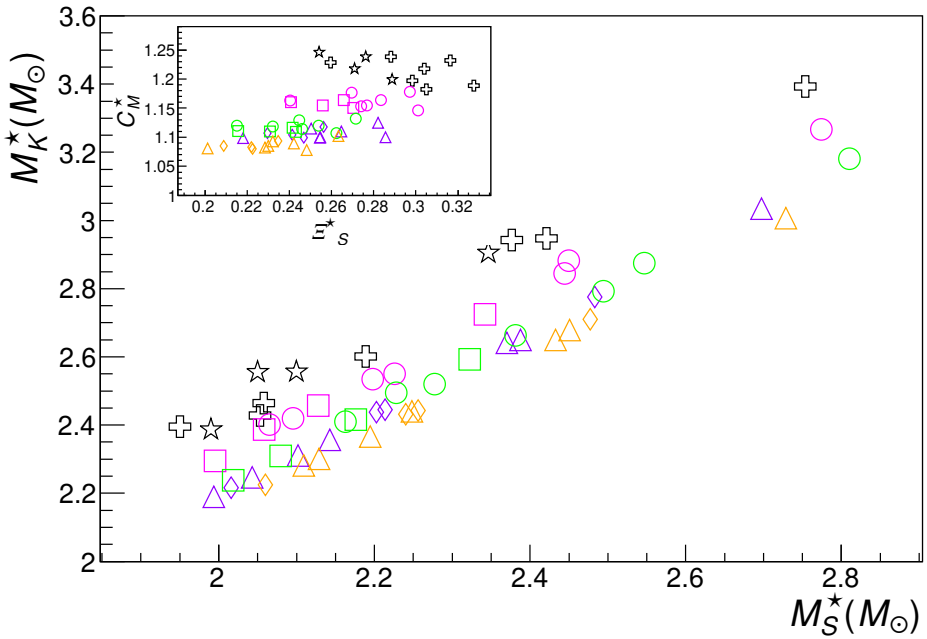
- Universality : relating star's properties independently of the EoS
- Many phenomenologically established ones for cold, $\beta$-equilibrated stars, e.g. $I$-Love-$Q$ relations [Yagi & Yunes]

- Here : maximum (gravitational) mass at the Kepler limit as function of the maximum mass of the nonrotating configuration

[Cook+94,Lasota+96,Breu&Rezzolla2016]

$$M_K^\star = C_M^\star M_S^\star$$

- Valid at finite $T$, too, if same thermodynamical conditions are considered [Raduta+2020,Khadkikar+2021]




- Similar findings for other relations : Kepler frequency in terms of nonrotating mass and radius, ...

# Maximum TOV mass from GW170817

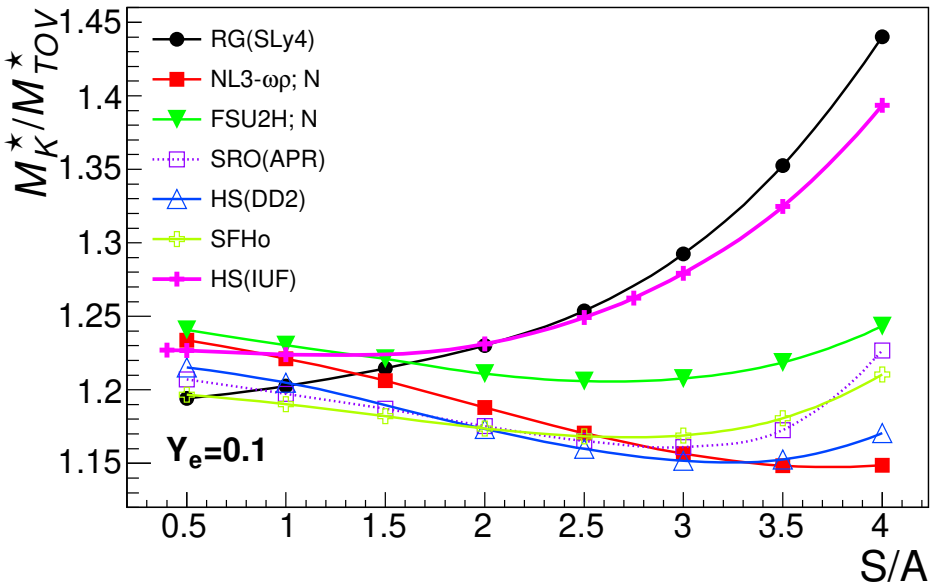
## Including thermal effects in the merger remnant

Thermal effects potentially modify two points in the analysis

1. Baryon mass ($A$) conservation to estimate mass loss from ejection needs $A(M_K^\star)$ at collapse
2. Relating $M_K^\star$ to $M_{\rm TOV}^\star$ (no longer universal !)

- Calculations with LORENE library ; $S/A = \text{const}$ and $Y_e = \text{const}$ and a set of finite-temperature EoS
- Competing thermal effects :
  - extend the star (low $S/A$)
  - increase the supported mass (high $S/A$)

  $\rightarrow$ minimum in $M_K^\star/M_{\rm TOV}^\star(S/A)$




- Typical ranges for merger remnant $Y_e \approx 0.1$ and $2 \lesssim S/A \lesssim 3$ [Perego+ 2019]

# Summary

We find from GW170817 [Khadkikar+ 2021]

**Universal limits for HOT non-rotating stars**

$$M_S^\star(\tfrac{S}{A}=2, Y_e=0.1) = 2.19^{+0.05}_{-0.03} M_\odot, \quad M_S^\star(\tfrac{S}{A}=3, Y_e=0.1) = 2.36^{+0.05}_{-0.04} M_\odot$$

and

**Limits for TOV mass (with $C_M^\star \approx 1.18$)**

$$2.15^{+0.10}_{-0.07} M_\odot < M_{\rm TOV}^\star < 2.24^{+0.12}_{-0.10} M_\odot$$

Comments :

- Thermal effects relax previous limits, but attention, final value EoS dependent (our EoS set gives a range $1.15 \lesssim C_M^\star \lesssim 1.3$ )
- Higher electron fraction $\rightarrow$ smaller $C_M^\star$ $\rightarrow$ limits further relaxed