# Which first order phase transitions to quark matter are possible in neutron stars?

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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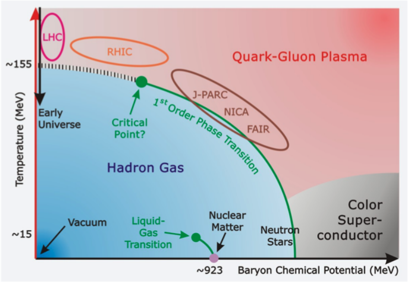
# Motivation




[QCD phase diagram sketch, GSI]

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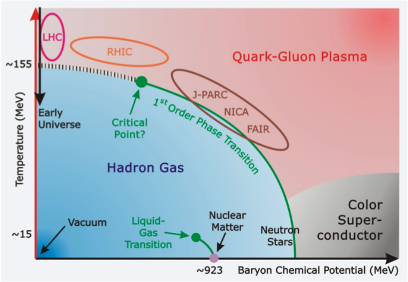


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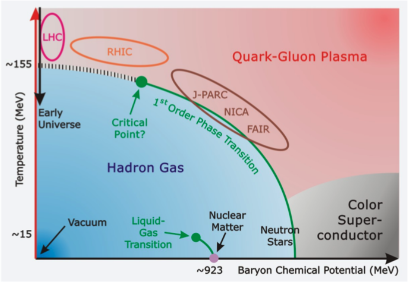
We know:

- Low density from terrestrial experiments and theory.

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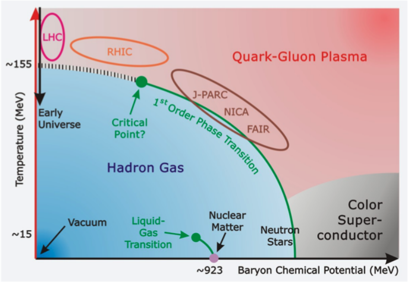


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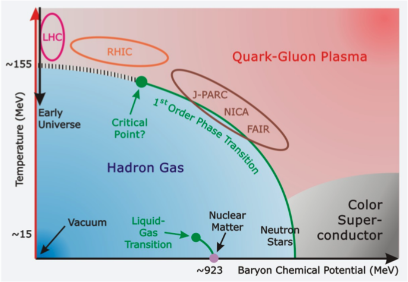
- A phase transition to QM **will** take place at some point.

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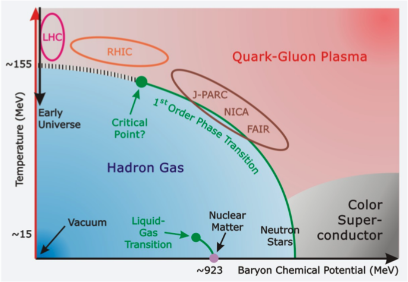
- Where is the phase transition and how can we tell from mass, radius and tidal deformability constraints?

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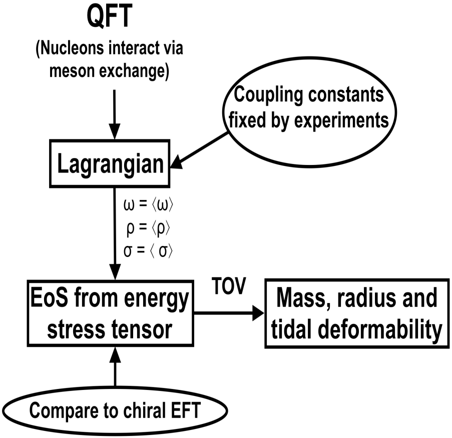
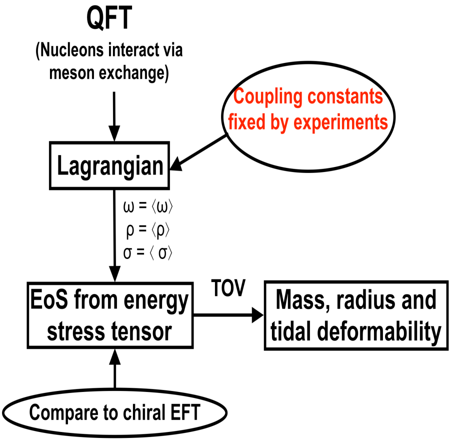
# Relativistic Mean Field Approach

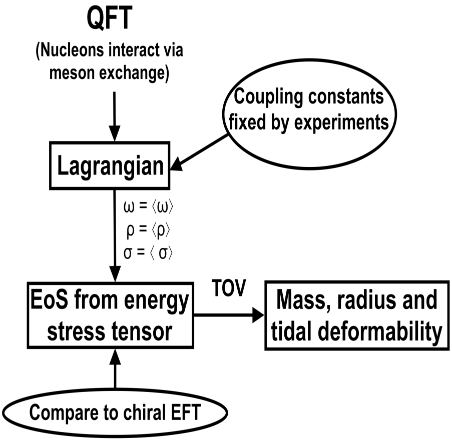


# Relativistic Mean Field Approach




Effective mass:
$m^*/m = 0.55 - 0.75$
Symmetry energy:
$J = 30 - 32\,\mathrm{MeV}$
Slope parameter:
$L = 40 - 60\,\mathrm{MeV}$

# Relativistic Mean Field Approach

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$m^*/m = 0.55 - 0.75$
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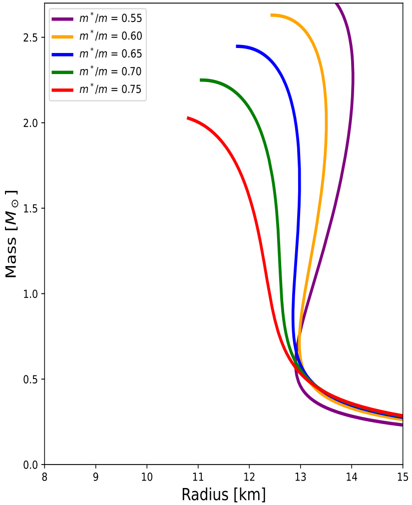
$J = 32\,\text{MeV}$ and $L = 60\,\text{MeV}$ from chiral EFT.

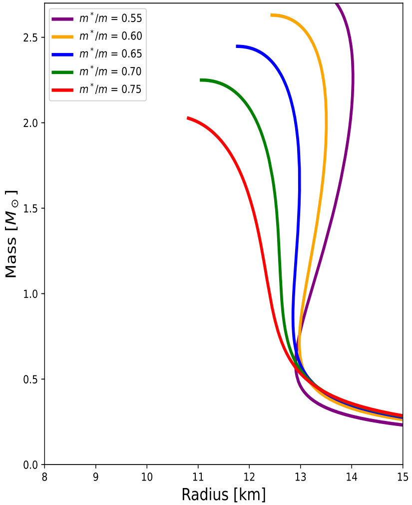
- Setup following: [Hornick et al. 2018, Phys. Rev. C]

# Mass-Radius Relations



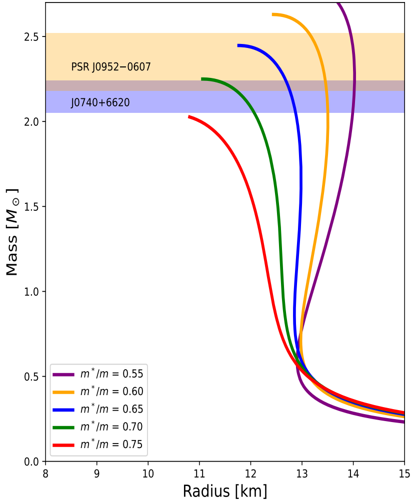
# Mass-Radius Relations

- Increasing the central pressure increases the mass.
- $m^*/m$ is directly linked to an EoS's stiffness.
- **Stiffer EoSs** feature higher maximal masses and larger radii, they **are less compact**.



# Mass-Radius Constraints

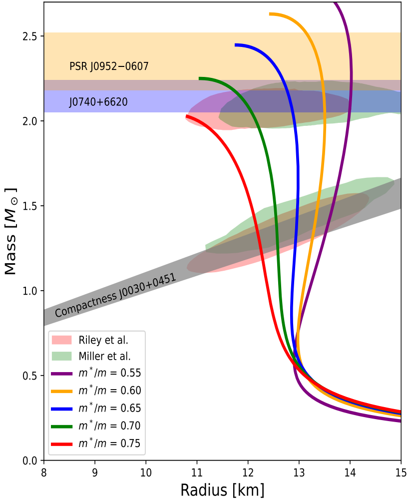
- Neutron stars with $2\,M_\odot$ are known




[Christian 2023]

# Mass-Radius Constraints

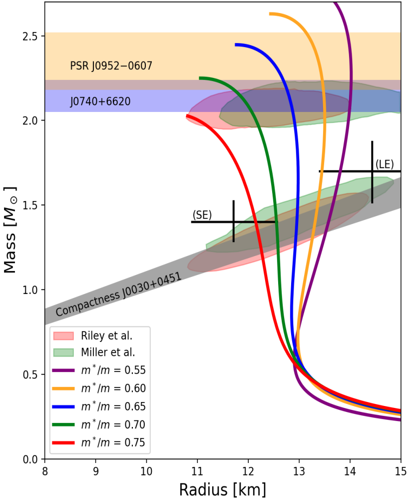
- Neutron stars with $2\,M_{\odot}$ are known
- NICER measured radii between $11 - 16\,\text{km}$




[Christian 2023]

# Mass-Radius Constraints

- Neutron stars with $2\,M_{\odot}$ are known
- NICER measured radii between $11 - 16\,\mathrm{km}$
- Potential candidates after NICER reanalysis (Vinciguerra et al. 2023)




[Christian 2023]

# Gravitational Wave Event GW170817

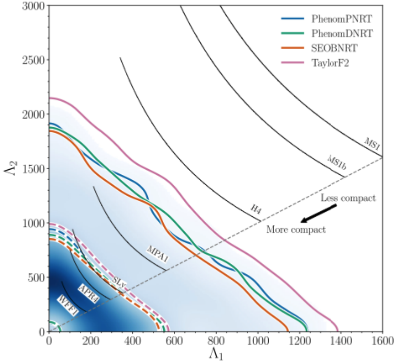
- In a binary system the companions tidal field induce a quadrupole moment:

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

- Obtain dimensionless form:

$$\Lambda = \frac{\lambda}{m^5}$$

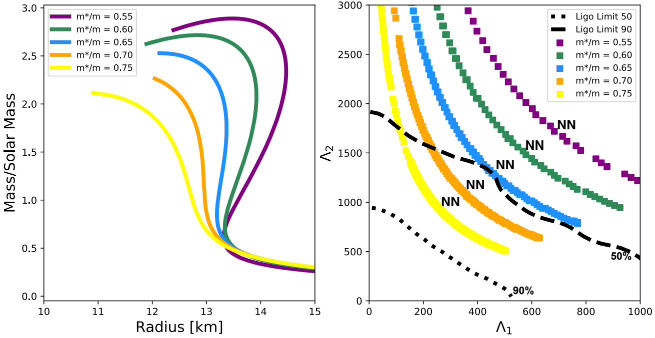
- Upper limit for combined value:




[Abbott et al. 2019, Phys. Rev. X]

$$\tilde{\Lambda} = \tilde{\Lambda}\left(\Lambda_1, m_1, \Lambda_2, m_2\right) \leq 720$$

# Closer Look: Tidal Deformability Constraint

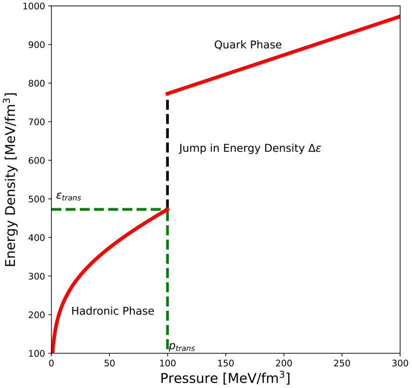



[Christian and Schaffner-Bielich (2019), ApJL]

- Only EoSs with $m^*/m \geq 0.65$ are soft enough to fit the data.

# Constant Speed of Sound Quark Matter

- First order phase transition at critical pressure $p_{trans}$.
- Parameterization is well known. [Alford et. al. 2013, Phys. Rev. D]
- We use $c_{QM} = 1$.

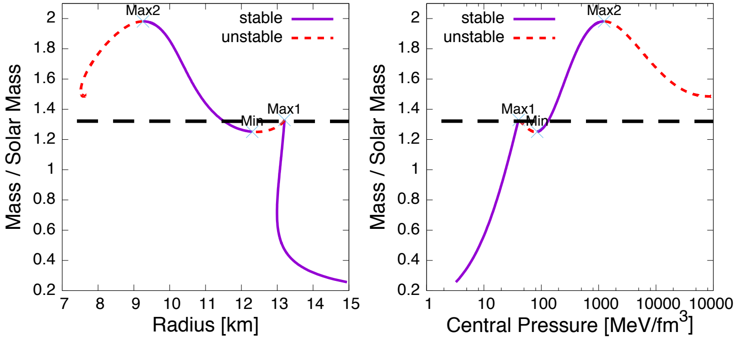



[Christian 2023]

$$\epsilon(p) = \begin{cases} \epsilon_{HM}(p) \\ \epsilon_{HM}(p_{trans}) + \Delta\epsilon + c_{QM}^{-2}(p - p_{trans}) \end{cases}$$

# Twin Star Solutions

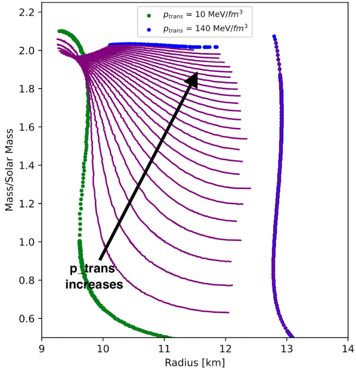
- Phase transition can lead to twin star solutions, where two stars have the same mass, but different radii.




[Christian, Zacchi and Schaffner-Bielich (2018), Eur. Phys. J. A ]

# Parameter Effects on MR Relation; Hybrid vs Twin

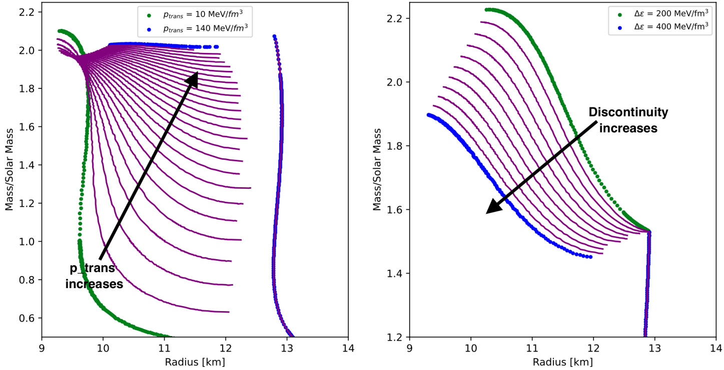
- $p_{trans}$ determines the first branch's maximum and the shape of the second branch.




[Christian 2023]

# Parameter Effects on MR Relation; Hybrid vs Twin

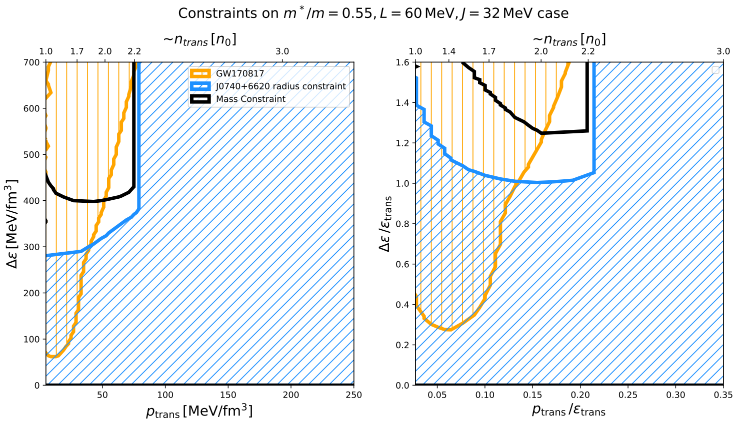
- $p_{trans}$ determines the first branch's maximum and the shape of the second branch.
- $\Delta\epsilon$ strongly influences the second's maximum by determining the position of the second branch.




[Christian 2023]

# Constraints on Stiff Equation of State

- The GW170817 constraint can be met with a phase transition.



# Constraints on Stiff Equation of State

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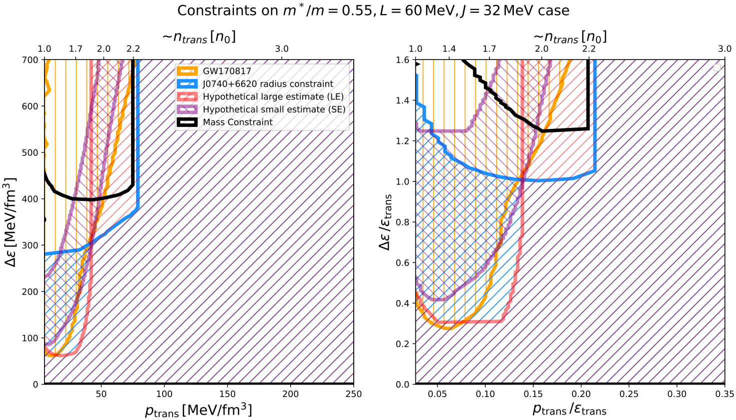
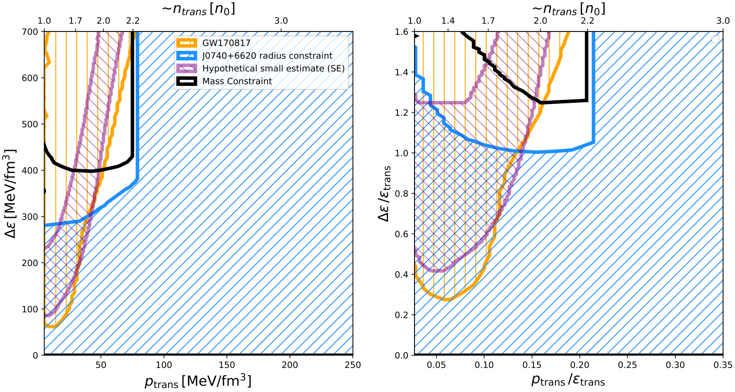


# Constraints on Stiff Equation of State

- The GW170817 constraint can be met with a phase transition.
- A hypothetical well determined "small" star does not constrain a stiff EoS further.

Constraints on $m^*/m = 0.55, L = 60\,\mathrm{MeV}, J = 32\,\mathrm{MeV}$ case



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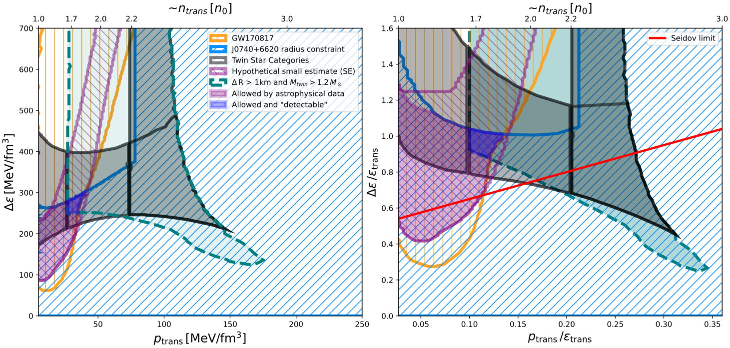

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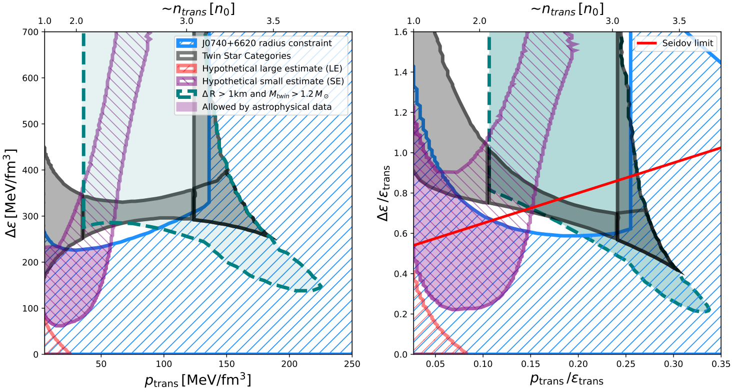
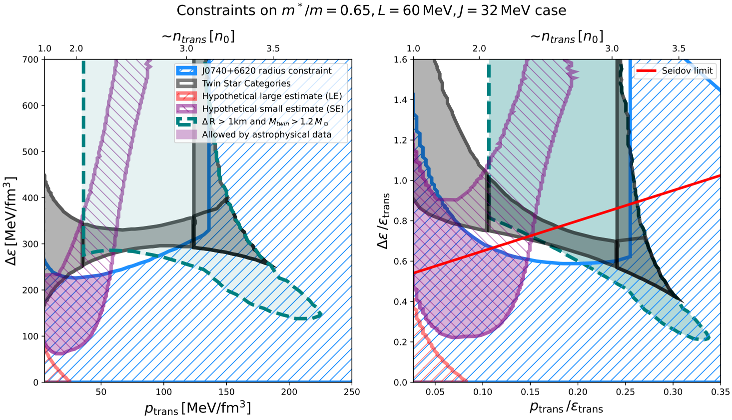


# Constraints on Softer Equation of state

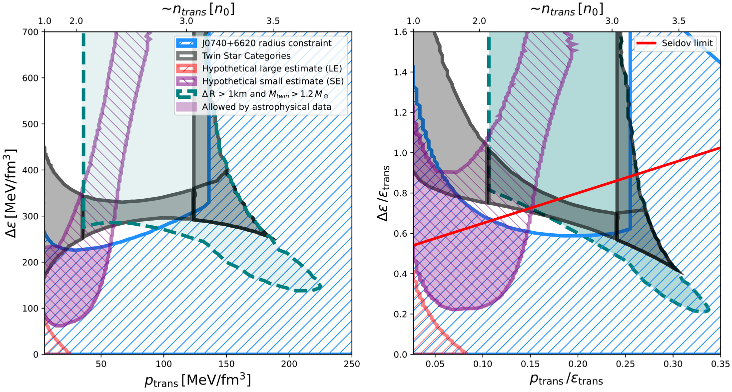
- Large parameter space allowed by constraints.



# Constraints on Softer Equation of state

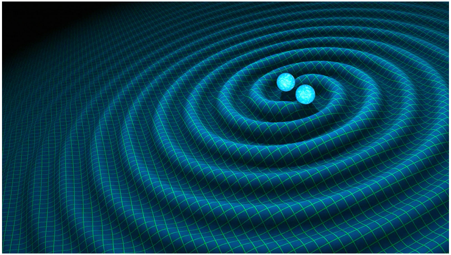
- Large parameter space allowed by constraints.
- No significant $\Delta R$ in allowed parameter space.

Constraints on $m^*/m = 0.65, L = 60\,\mathrm{MeV}, J = 32\,\mathrm{MeV}$ case




[Christian et al. 2023]

# Summary and Outlook

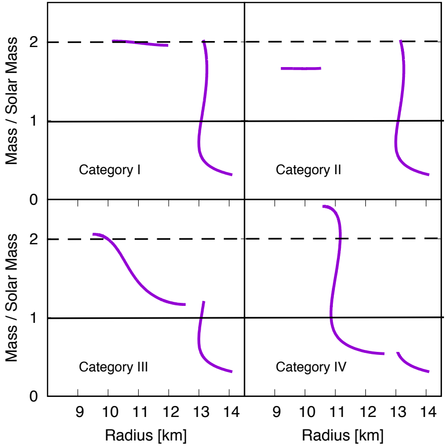


[LIGO]

- Phase transitions in neutron stars create unique mass radius relations and tidal deformability.
- The overlap between easily detectable and possible solution is shrinking rapidly.
- Gravitational wave measurements should be able to probe the area inaccessible by mass and radius constrains.

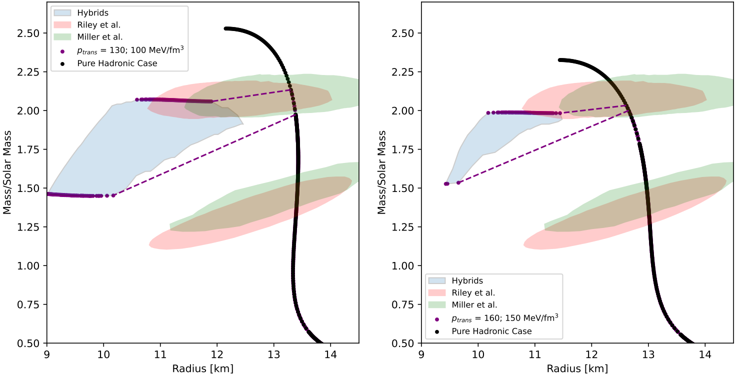
# Categories of Twin Stars

- **Category I**: Both maxima meet mass constraint $M_{data}$.
- **Category II**: Only the hadronic maximum exceeds $M_{data}$.
- **Category III**: Only the hybrid maximum exceeds $M_{data}$.
- **Category IV**: Only hybrid stars can be observed.



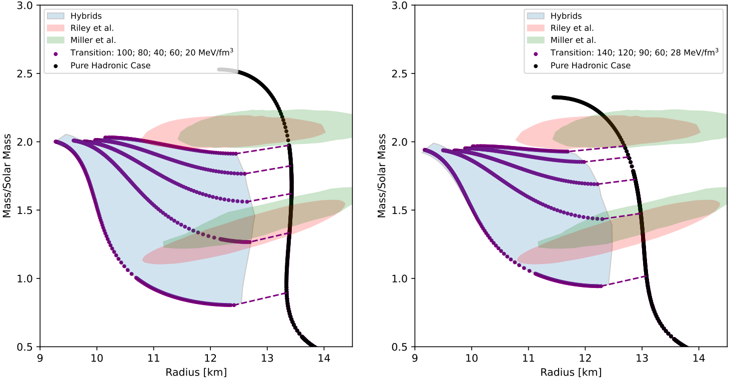

[Christian, Zacchi and Schaffner-Bielich (2018), Eur. Phys. J. A ]

# Category I and II NICER constraints



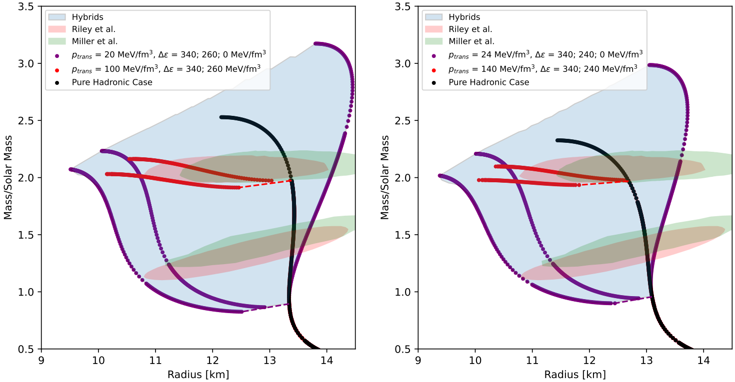

[Christian and Schaffner-Bielich (2021), Phys. Rev. D]

# Category III NICER constraints



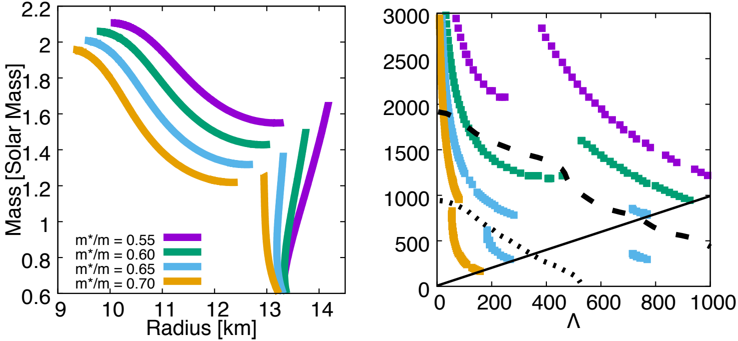

[Christian and Schaffner-Bielich (2021), Phys. Rev. D]

# Hybrid stars NICER constraints



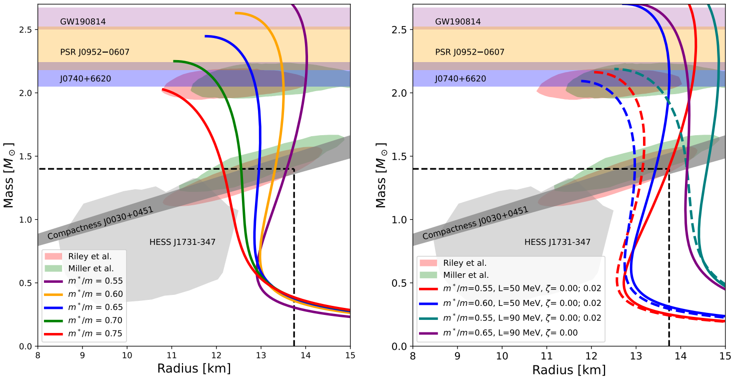

[Christian and Schaffner-Bielich (2021), Phys. Rev. D]

# Tidal deformability changes GW170817



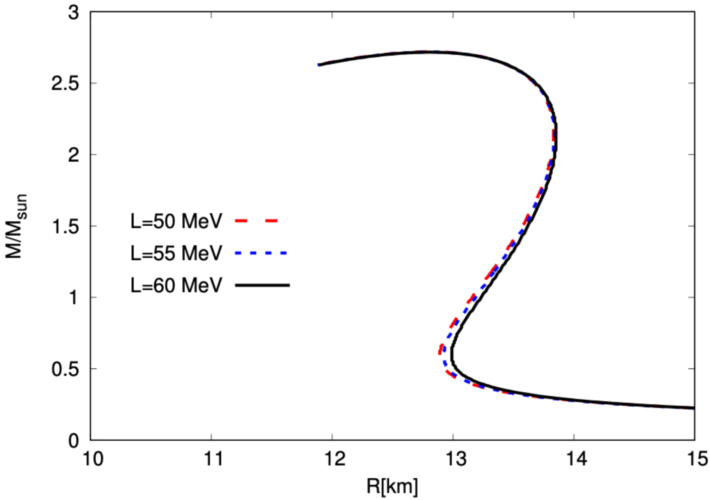

[Christian and Schaffner-Bielich (2019), ApJL]

# MR constraints for more RMF models



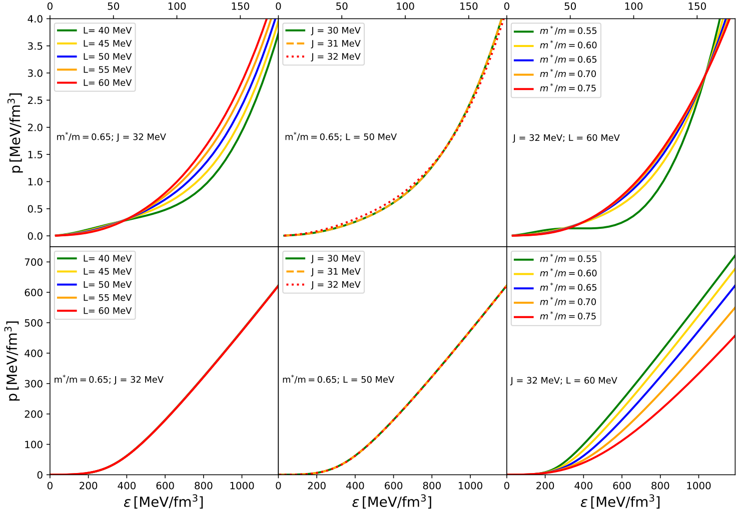

[Christian 2023]

# Backup Slide




[Hornick et al. 2018, Phys. Rev. C]

# Parameter Variation

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