Constraints on Phase Transition in Neutron Stars in a Generalized Setup

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Rome, February 12, 2024

Bottom-Up Cross-Cutting Workshop of the JENAS Initiative "Gravitational Wave Probes of Fundamental Physics"

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

[arXiv: 2312.10148]

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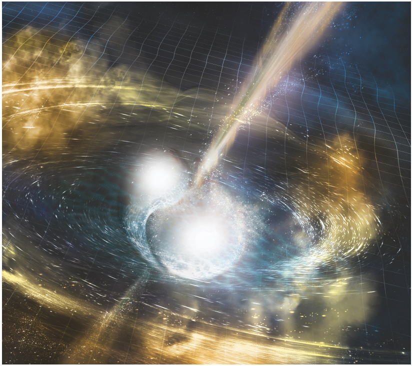
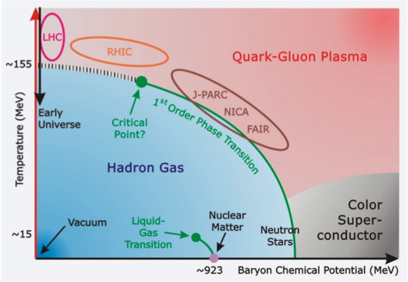
Neutron Stars

- Extremely dense final stage of stellar evolution.
- Used to test GR and emit gravitational waves.
- Masses are well known, radii less so.
- Observables can be calculated with the equation of state (EoS).



[Artistic render of neutron star merger, LIGO]

Motivation



[QCD phase diagram sketch, GSI]

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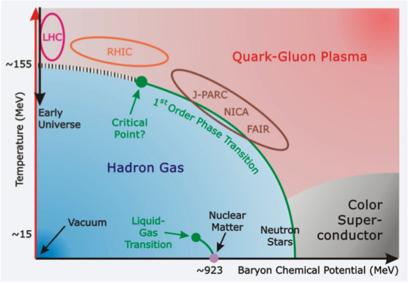

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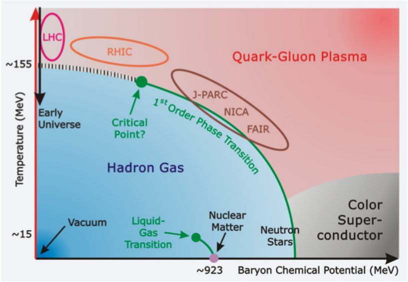

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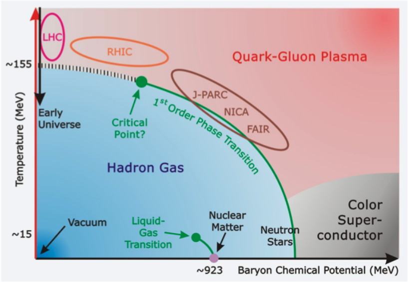

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We know:

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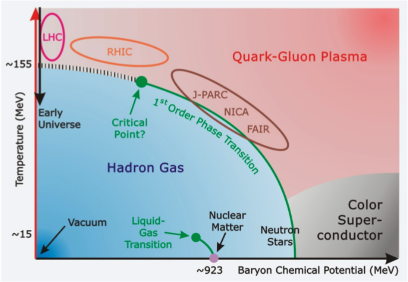
- A phase transition to QM **will** take place at some point.



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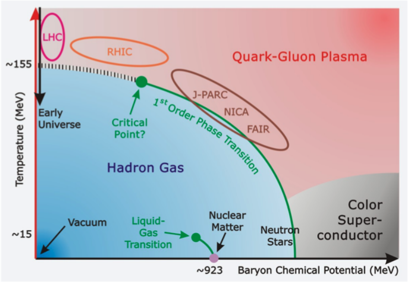
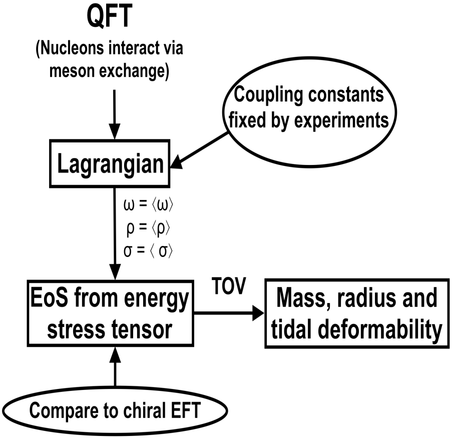


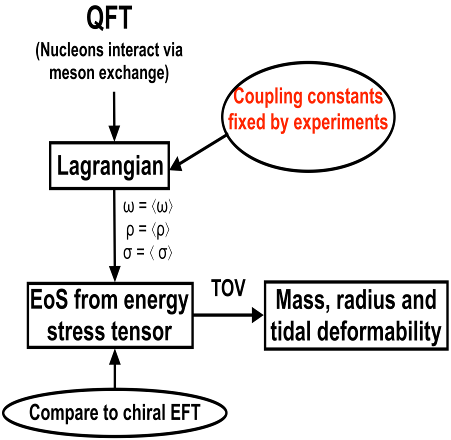
[QCD phase diagram sketch, GSI]

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

Relativistic Mean Field Approach

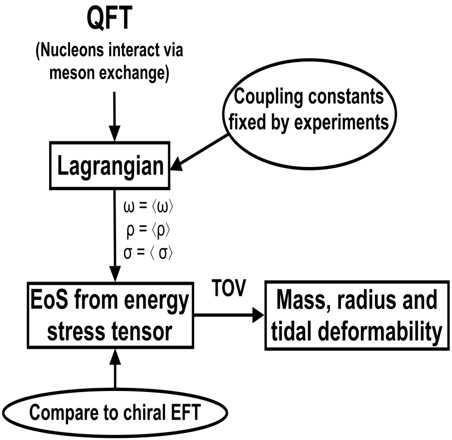


Relativistic Mean Field Approach



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

Relativistic Mean Field Approach



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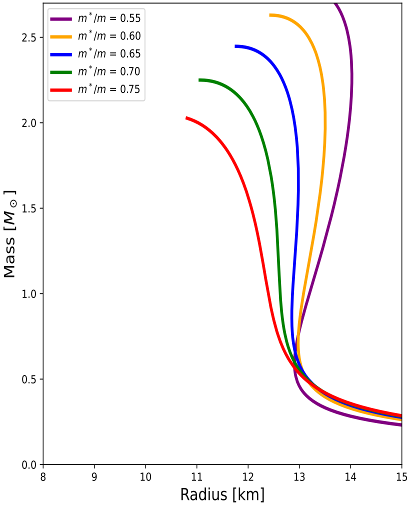
$J = 32\,\text{MeV}$ and $L = 60\,\text{MeV}$ from chiral EFT.

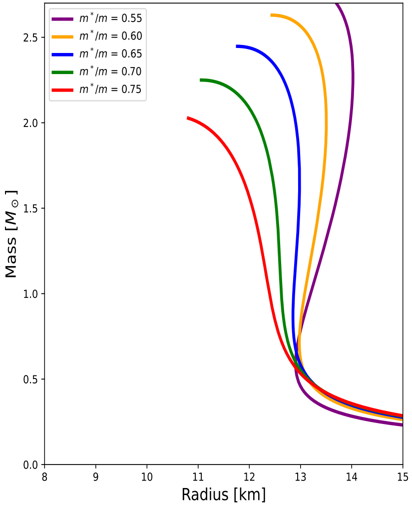
- Setup following: [Hornick et al. 2018, Phys. Rev. C]

Mass-Radius Relations



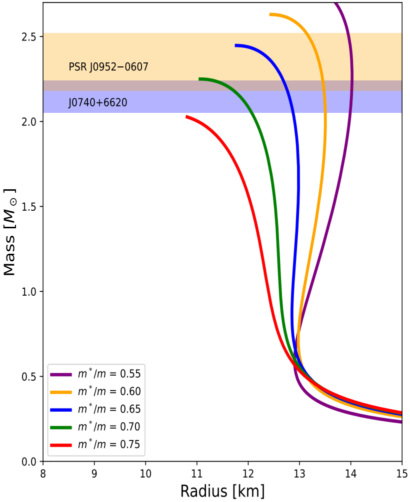
Mass-Radius Relations

- 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

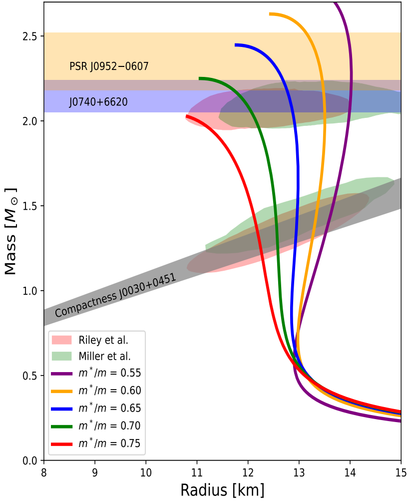
- Neutron stars with $2\,M_\odot$ are known



[Christian 2023]

Mass-Radius Constraints

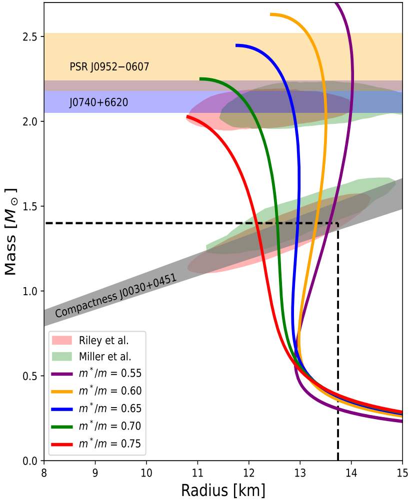
- Neutron stars with $2\,M_\odot$ are known
- NICER measured radii between $11-16\,\mathrm{km}$



[Christian 2023]

Mass-Radius Constraints

- Neutron stars with 2 $M_\odot$ are known
- NICER measured radii between 11 − 16 km
- GW170817 constraints the radius with tidal deformability



[Christian 2023]

Gravitational Wave Event GW170817

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

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

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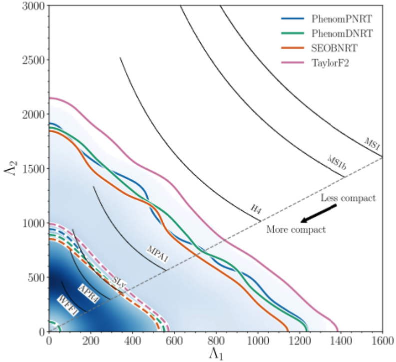

[Abbott et al. 2019, Phys. Rev. X]

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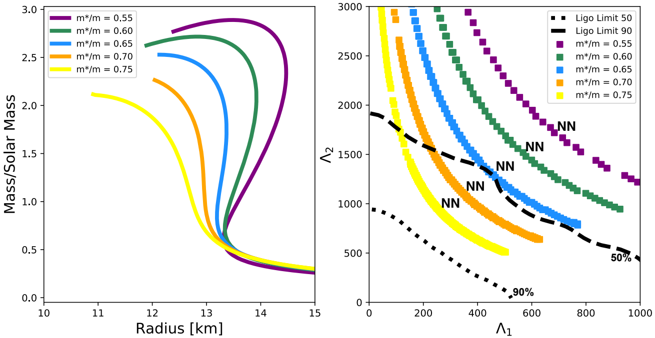
Closer Look: Tidal Deformability Constraint

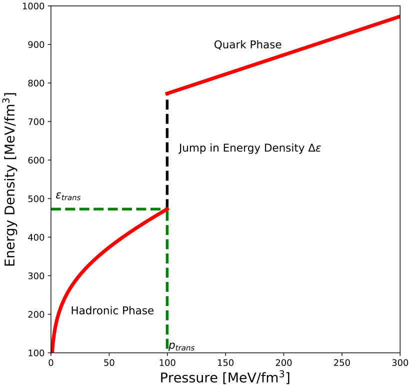


[Christian and Schaffner-Bielich (2019), ApJL]

- 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 $c_{QM} = 1$.

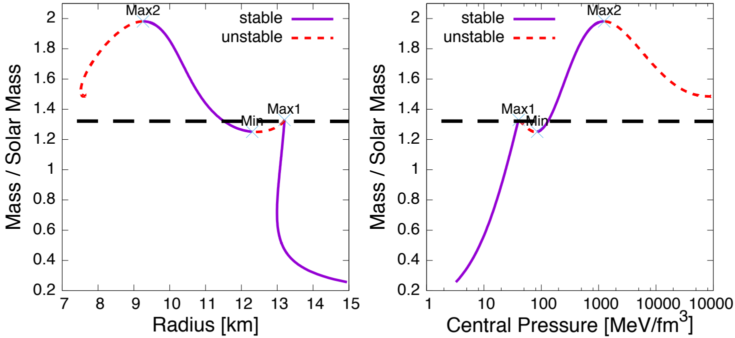


[Christian 2023]

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

Twin Star Solutions

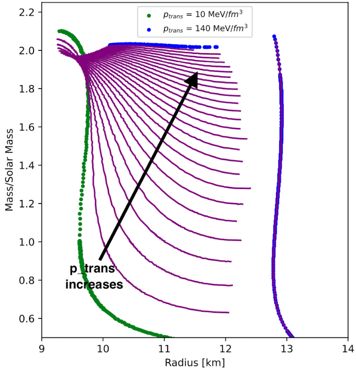
- Phase transition can lead to twin star solutions, where two stars have the same mass, but different radii.



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

Parameter Effects on MR Relation; Hybrid vs Twin

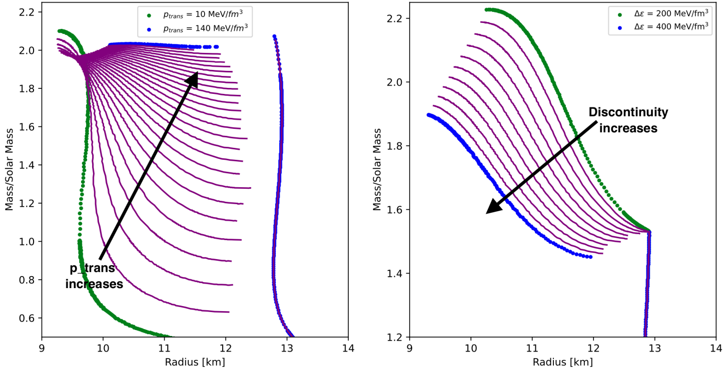
- p_{trans} determines the first branch's maximum and the shape of the second branch.



[Christian 2023]

Parameter Effects on MR Relation; Hybrid vs Twin

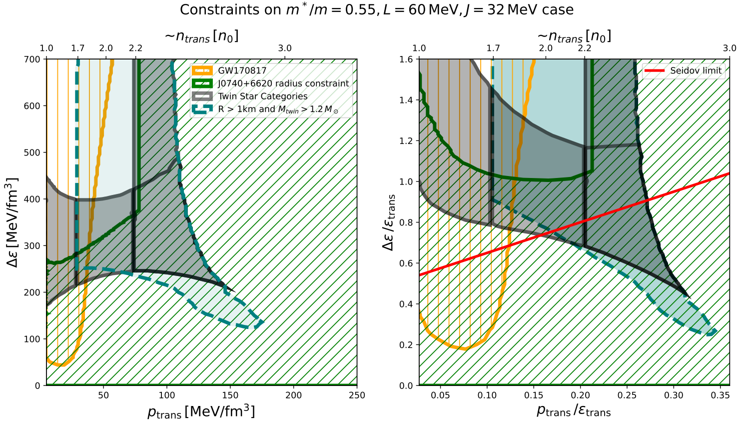
- p_{trans} determines the first branch's maximum and the shape of the second branch.
- $\Delta\epsilon$ strongly influences the second's maximum by determining the position of the second branch.



[Christian 2023]

Constraints on Stiff Equation of State

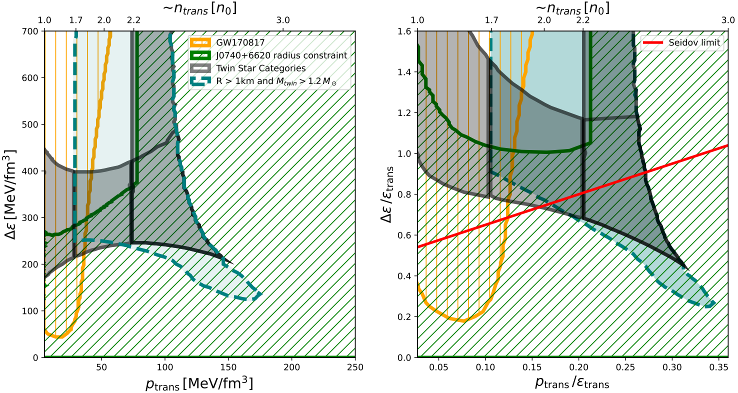
- The GW170817 constraint can be met with a phase transition.



Constraints on Stiff Equation of State

- The GW170817 constraint can be met with a phase transition.
- Only a small area is possible as well as likely observable.

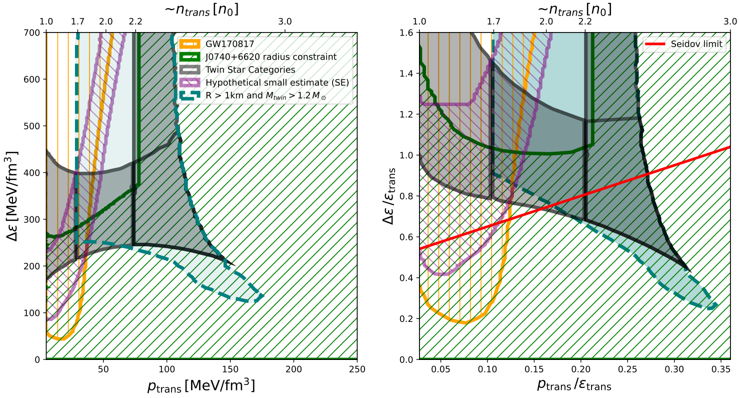
Constraints on $m^*/m = 0.55, L = 60\,\text{MeV}, J = 32\,\text{MeV}$ case



Constraints on Stiff Equation of State

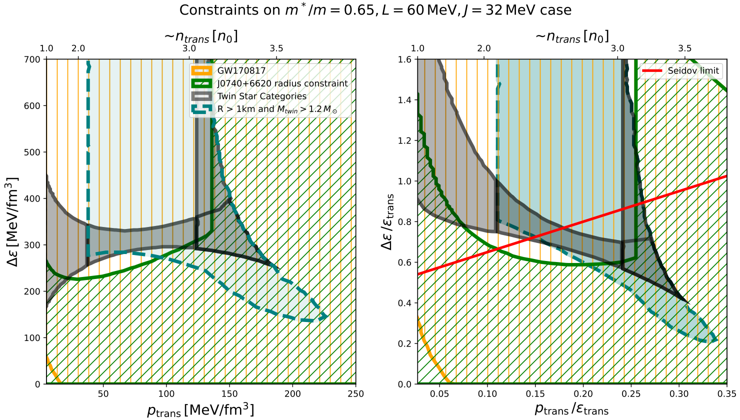
- A hypothetical well determined "small" star does not constrain a stiff EoS further.

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



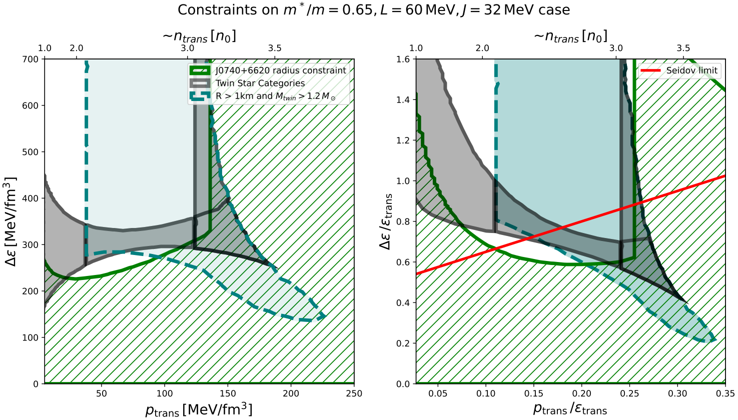
[Christian et al. 2023, 2312.10148]

Constraints on Softer Equation of state



Constraints on Softer Equation of state

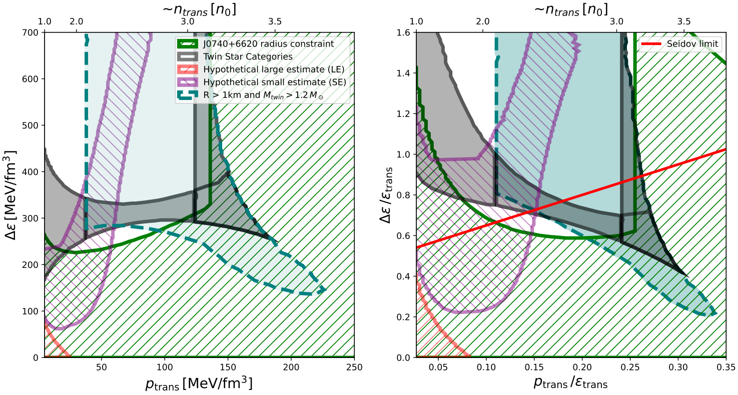
- Large overlap between possible and detectable area...



Constraints on Softer Equation of state

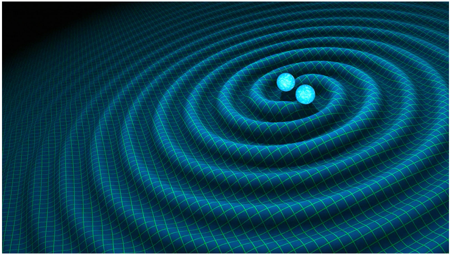
- Large overlap between possible and detectable area...
- ...unless we consider a well determined "small" star.

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



[Christian et al. 2023, 2312.10148]

Summary and Outlook

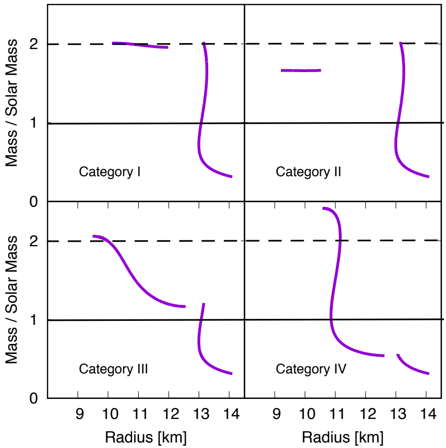


[LIGO]

- 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.

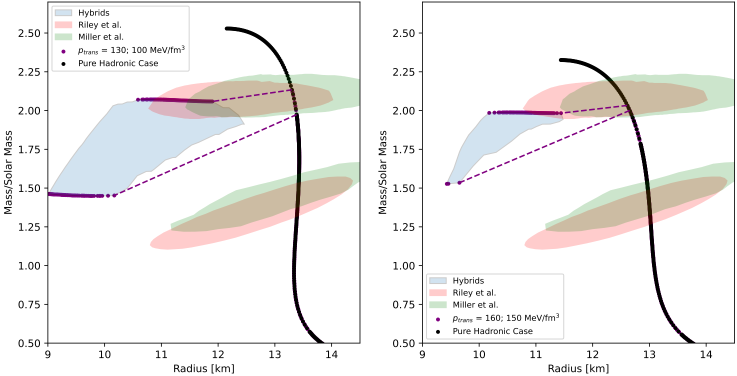
Categories of Twin Stars

- **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.



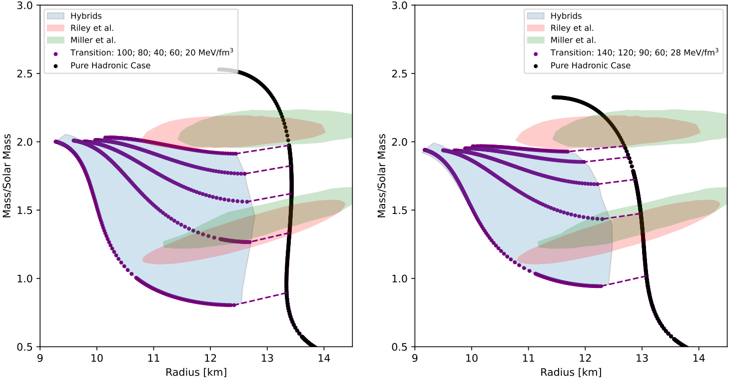
[Christian, Zacchi and Schaffner-Bielich (2018), Eur. Phys. J. A]

Category I and II NICER constraints



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

Category III NICER constraints



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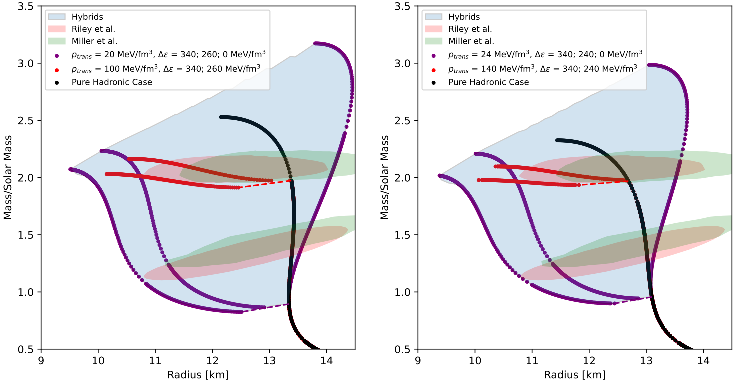
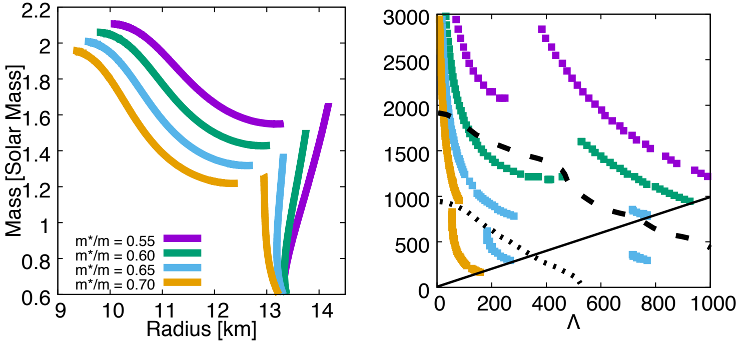
Hybrid stars NICER constraints



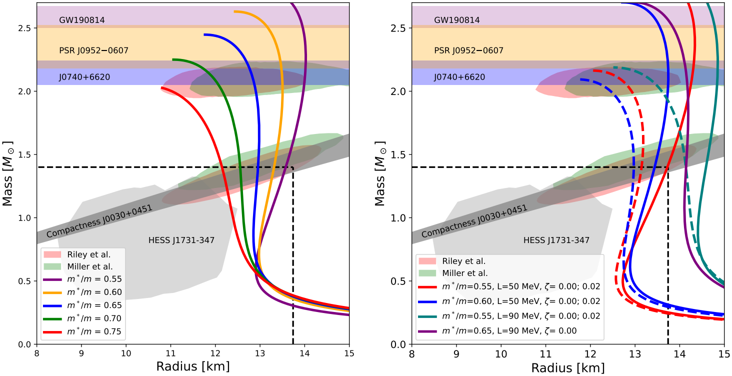
[Christian and Schaffner-Bielich (2021), Phys. Rev. D]

Tidal deformability changes GW170817



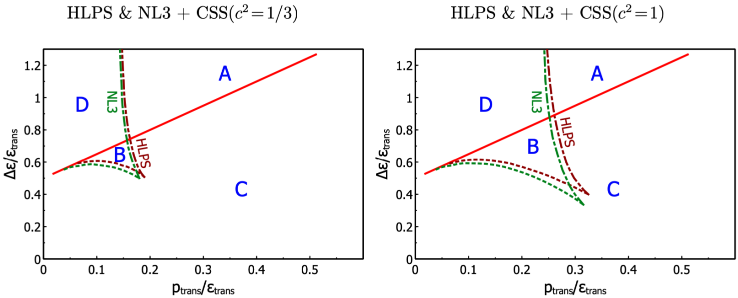
[Christian and Schaffner-Bielich (2019), ApJL]

MR constraints for more RMF models



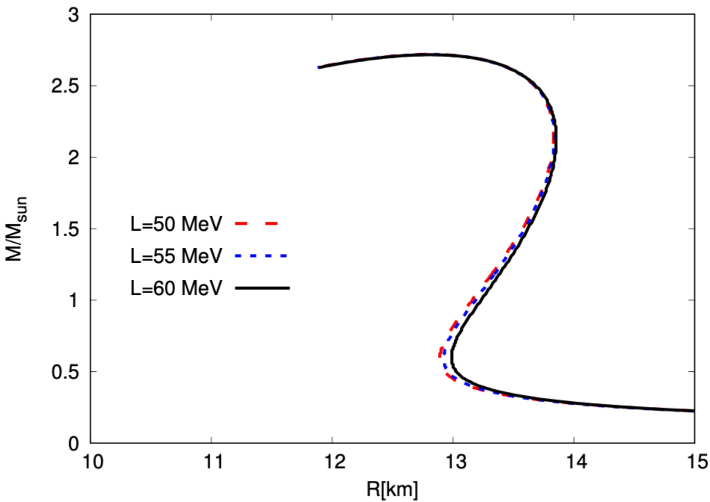
[Christian 2023]

Influence of c_{QM} and hadronic EoS on parameter space



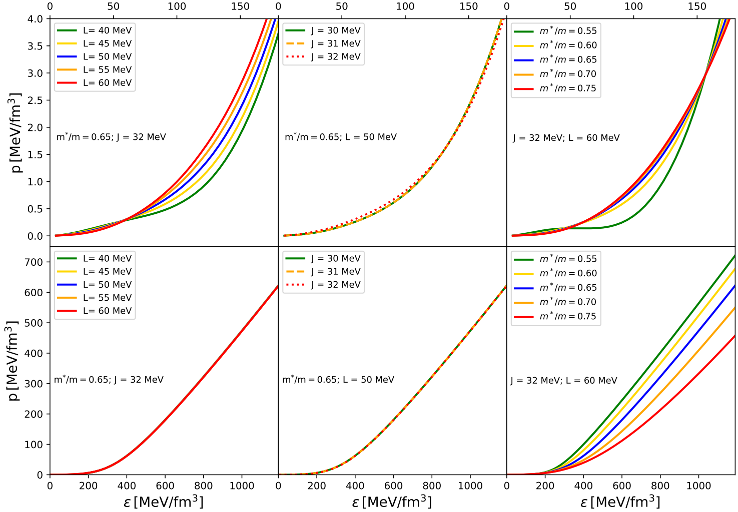
Alford et al. 2013, Phys. Rev. D

Backup Slide



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

Parameter Variation



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