Exploring First-Order Quark Matter Phase Transitions in Neutron Stars

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

GSI Darmstadt
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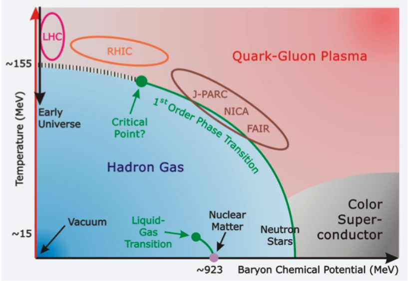
EMMI Workshop: Collective phenomena and the Equation-of-State of dense baryonic matter

Motivation

We know:

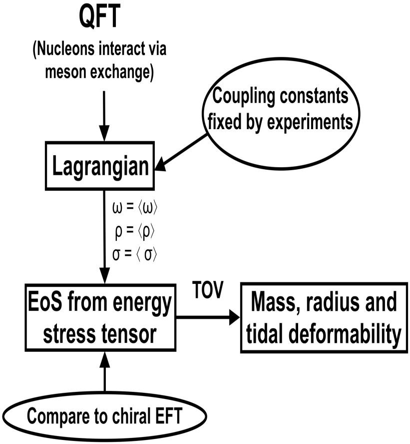
- Low density from terrestrial experiments and theory.
- Astrophysical constraints work at high density.
- A phase transition to QM **will** take place at some point.

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



[QCD phase diagram sketch, GSI]

Relativistic Mean Field Approach



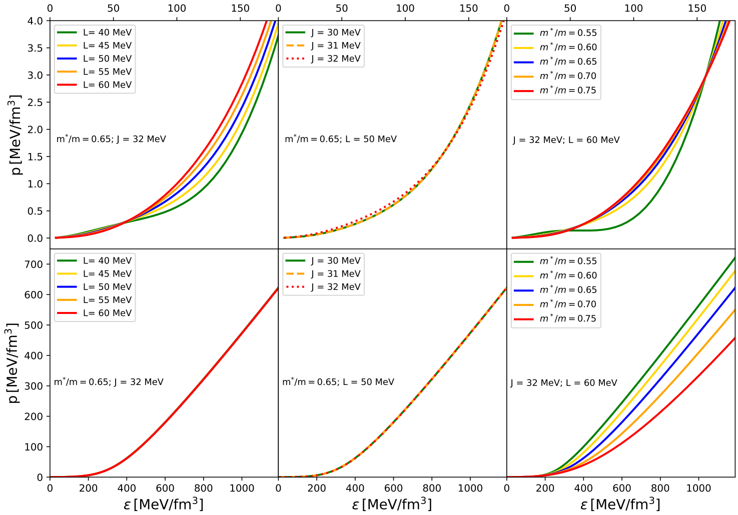
n_0	$0.16\,\mathrm{fm}^{-3}$	g_σ, g_ω, b, c
E/A	-16.3 MeV	
K	240 MeV	
m^*/m	0.55 - 0.75	
J	30 - 32 MeV	g_ρ, Λ_ω
L	40 - 60 MeV	

Values fixed at n_0. Note:
$m^* = m_{\mathrm{nucleon}} - g_\sigma \sigma$

We vary J, L, m^*/m.

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

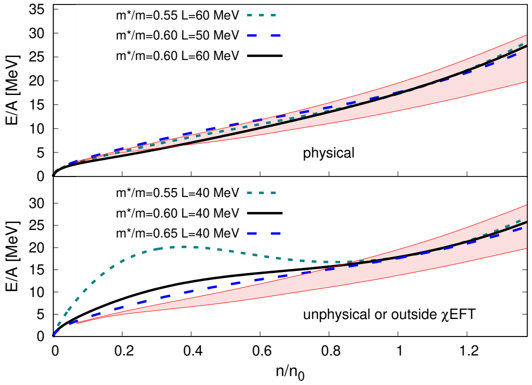
Parameter Variation



[Christian 2023]

Chiral Effective Field Theory Constraints

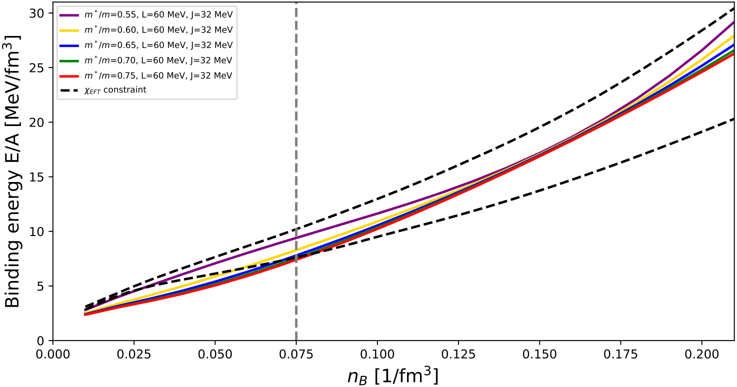
- Ab initio approach describing nucleonic matter up to about 1.2 n_0
- We compare with: Drischler et al., 2016); see also: (Carbone and Schwenk, 2019)



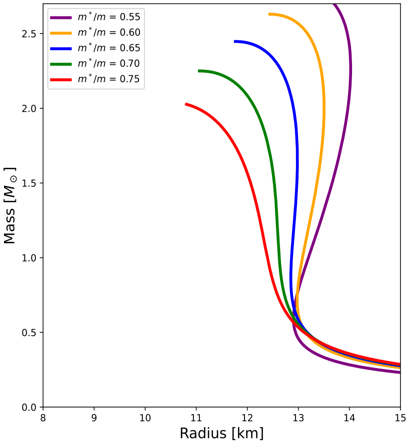
[Hornick et al. 2018, Phys. Rev. C]

Fixed J and L

- $J = 32\,\mathrm{MeV}$ and $L = 60\,\mathrm{MeV}$ are fixed to allow the greatest m^*/m range



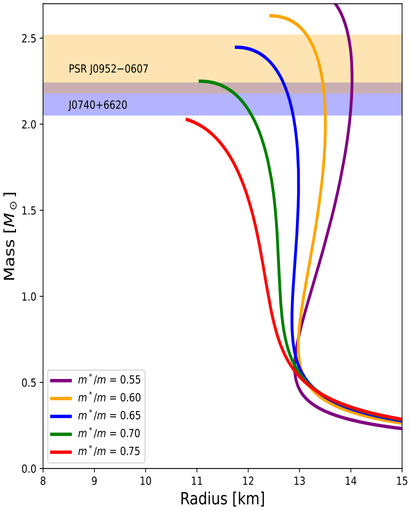
Mass-Radius Constraints



[Christian 2023]

Mass-Radius Constraints

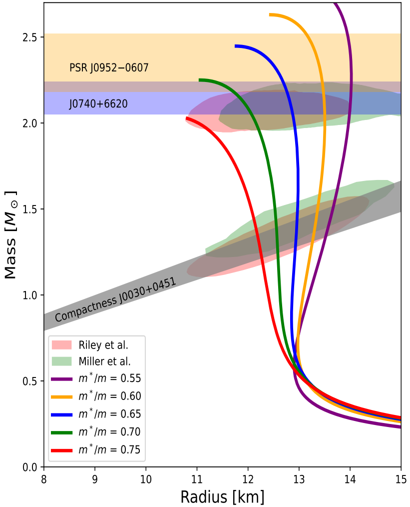
- Neutron stars with $2\,M_\odot$ are known



[Christian 2023]

Mass-Radius Constraints

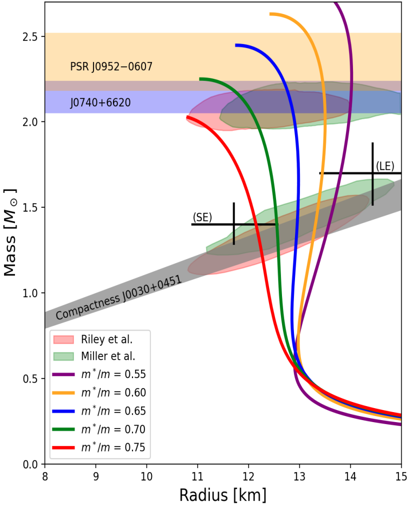
- Neutron stars with $2\,M_\odot$ are known
- NICER measured radii between $11 - 16\,\mathrm{km}$



[Christian 2023]

Mass-Radius Constraints

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



[Christian 2023]

Gravitational Wave Event GW170817

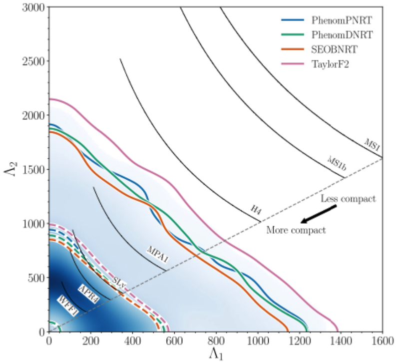
- In a binary system the companions tidal field induce a quadrupole moment:

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

- Obtain dimensionless form:

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

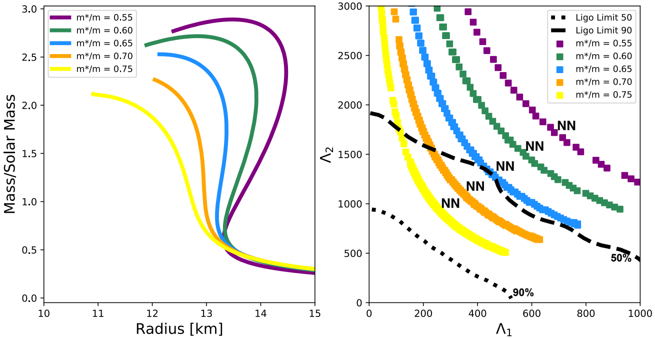
- Upper limit for combined value:



[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

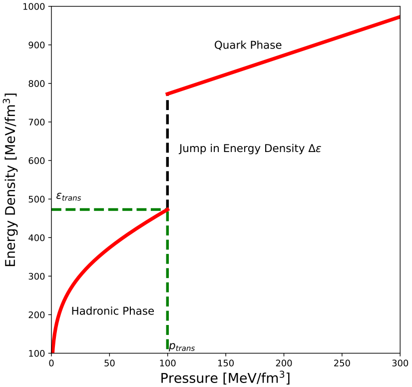


[Christian and Schaffner-Bielich (2019), ApJL]

- 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 $c_{QM} = 1$.

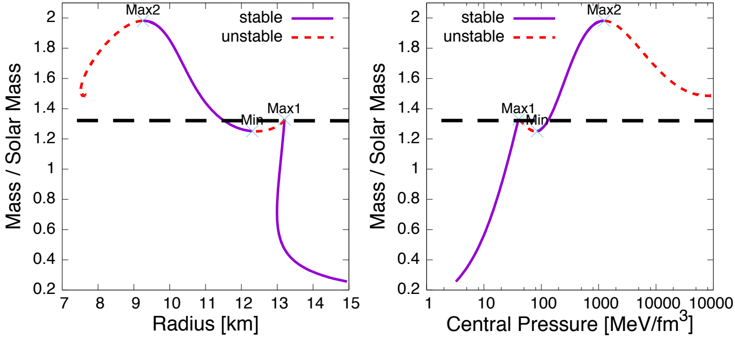


[Christian 2023]

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

Twin Star Solutions

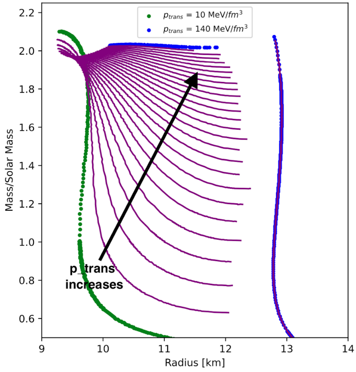
- Phase transition can lead to twin star solutions, where two stars have the same mass, but different radii.



[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.



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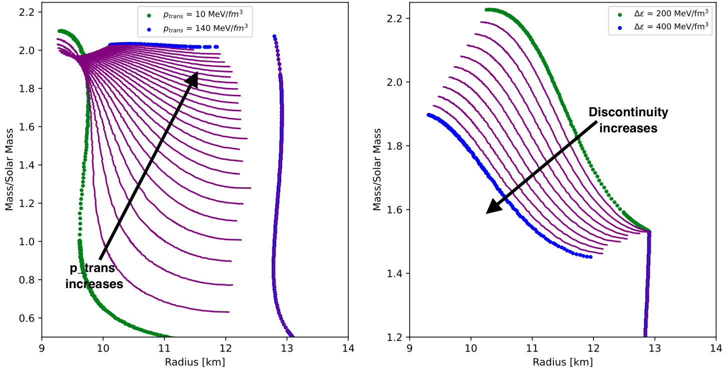
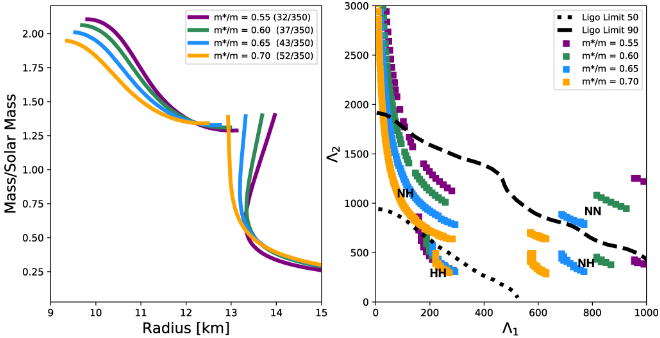
- $\Delta\epsilon$ strongly influences the second's maximum by determining the position of the second branch.



[Christian 2023]

Tidal Deformability of Hybrid Stars

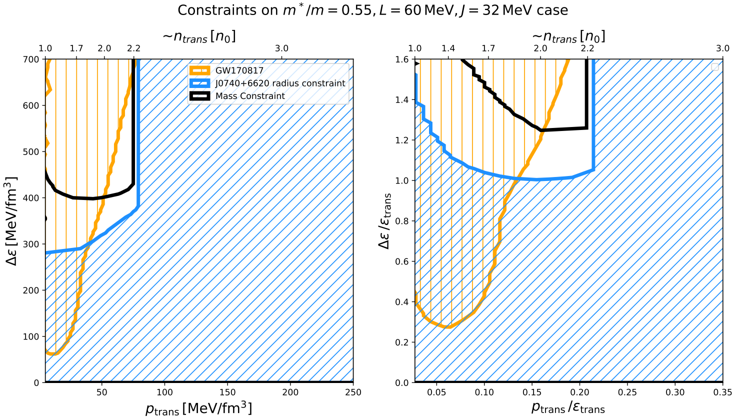


[Christian and Schaffner-Bielich (2019), ApJL]

- Hybrid EoSs are more compatible with GW170817

Constraints on Stiff Equation of State

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



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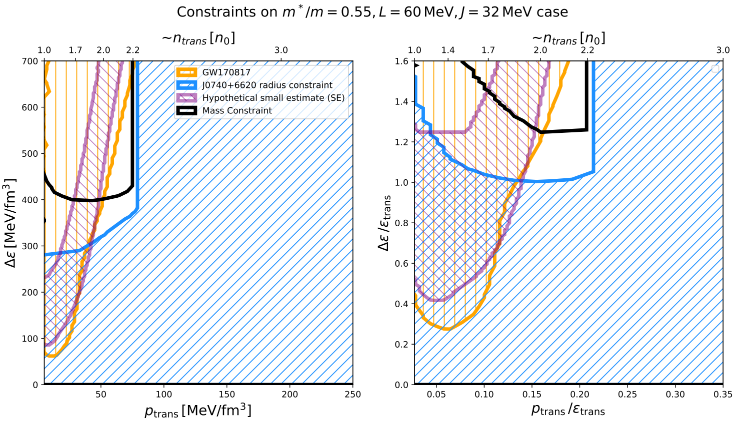
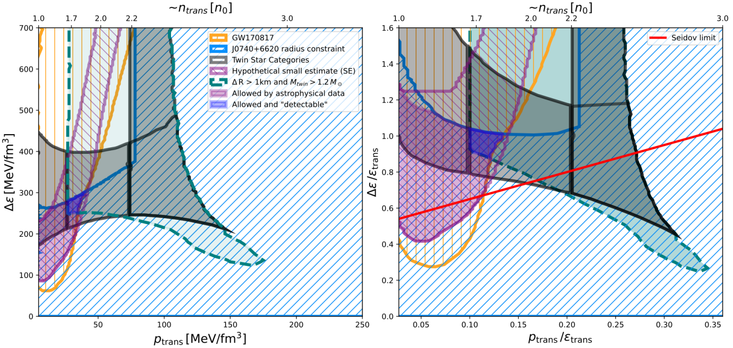
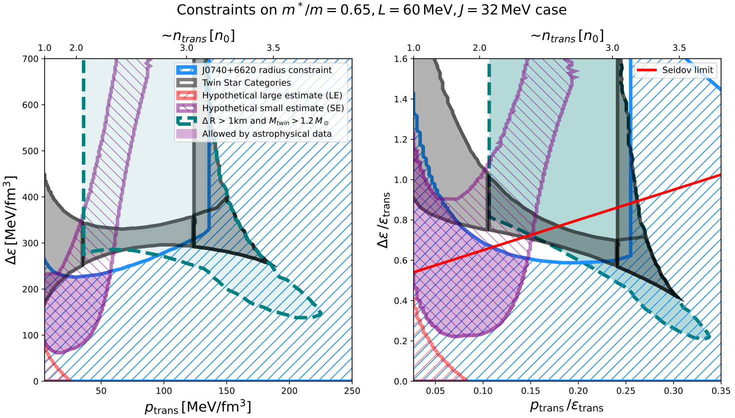


Constraints on Stiff Equation of State

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

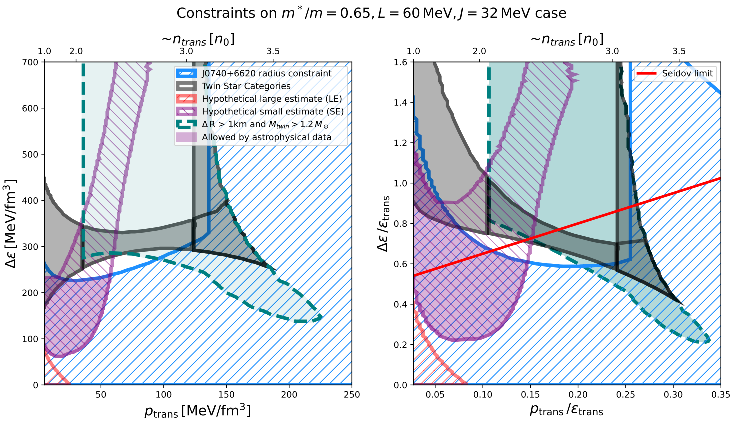


Constraints on Softer Equation of state



Constraints on Softer Equation of state

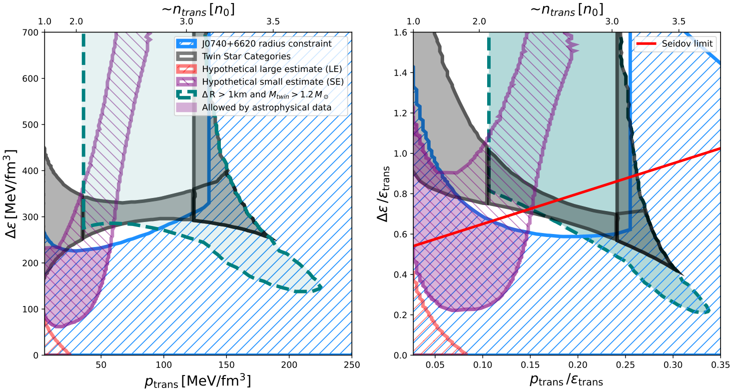
- Large parameter space allowed by constraints.



Constraints on Softer Equation of state

- Large parameter space allowed by constraints.
- No significant ΔR in allowed parameter space.

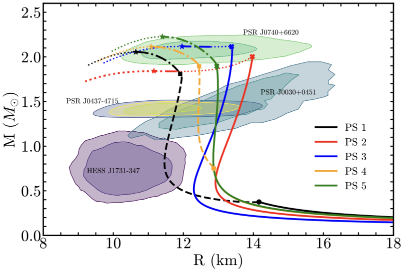
Constraints on $m^*/m = 0.65, L = 60\,\mathrm{MeV}, J = 32\,\mathrm{MeV}$ case

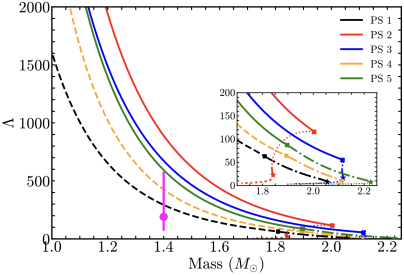


[Christian et al., Phys. Rev. D, 2023]

Twin Stars with the RG-NJL model

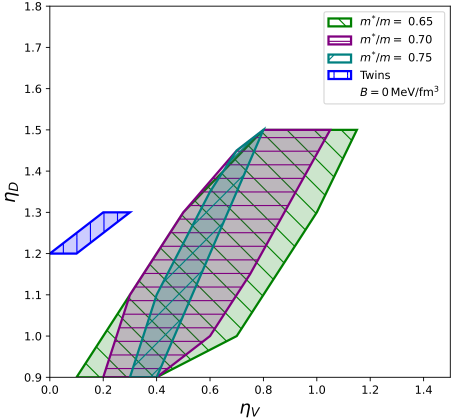
- Microphysical quark phase (→ Hosein and Marcos talk)
- Twin stars are possible, if one or more constraint is ignored.
- Tidal deformability is the biggest concern.





Constraints on Microphysical Quarkphase

- Stiffer EoSs allow much easier to combine with a quark phase.
- Twin stars and allowed parameter sets are mutually exclusive.



[Christian et al., A&A, 2025]

Constraints on Microphysical Quarkphase

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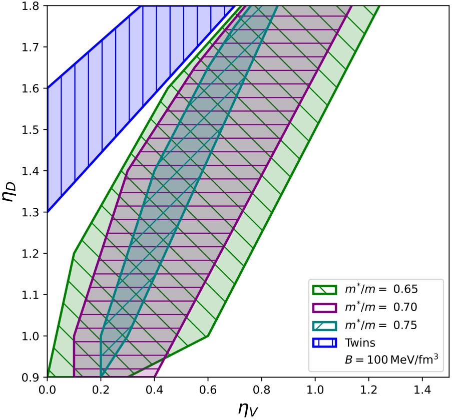
- Increasing B increases all parameter spaces.



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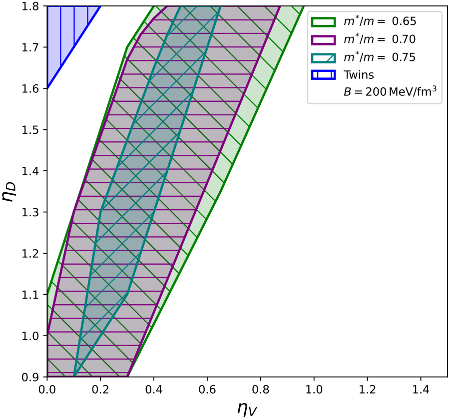

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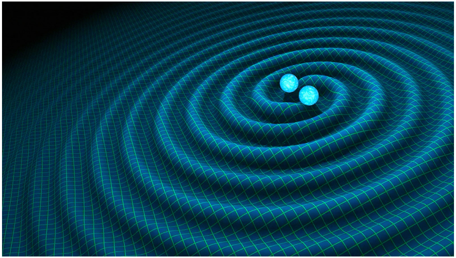
Wrap Up



[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.
- Merger signals will be able to probe the area inaccessible by mass and radius constrains.

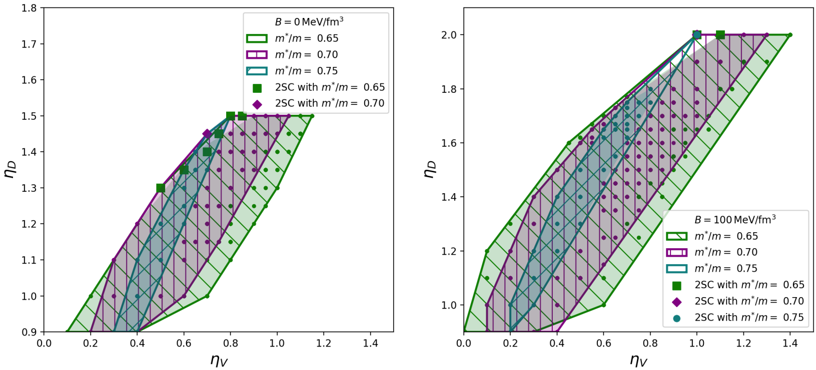
Lagrangian

- Relativistic mean field Lagrangian (Hornick et al. 2018):

$$\begin{aligned}\mathcal{L} = &\sum_B \overline{\psi}_B \left(i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - \frac{1}{2} g_{\vec{\rho} B}\gamma_\mu \vec{\tau} \cdot \rho^\mu \right) \psi_B \\ &+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2\right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu \\ &- \frac{1}{4}\vec{\rho}_{\mu\nu} \cdot \vec{\rho}^{\mu\nu} + \frac{1}{2} m_{\vec{\rho}}^2 \vec{\rho}_\mu \cdot \rho^\mu - \frac{1}{3} b m_n \left(g_\sigma \sigma\right)^3 - \frac{1}{4} c \left(g_\sigma \sigma\right)^4 \\ &+ \Lambda_\omega \left(g_\rho^2 \vec{\rho}_\mu \vec{\rho}^\mu\right)\left(g_\omega^2 \omega_\mu \omega^\mu\right) + \frac{\zeta}{4!}\left(g_\omega^2 \omega_\mu \omega^\mu\right)^2\end{aligned}$$

- At high baryon densities: $\overline{\omega} = \langle \omega \rangle$, $\overline{\sigma} = \langle \sigma^0 \rangle$ and $\overline{\rho} = \langle \rho_3^0 \rangle \Rightarrow$ mean field theory

CSC Phase in Neutron Stars



[Christian et al. (2025)]

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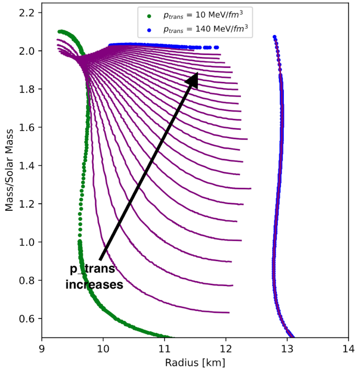

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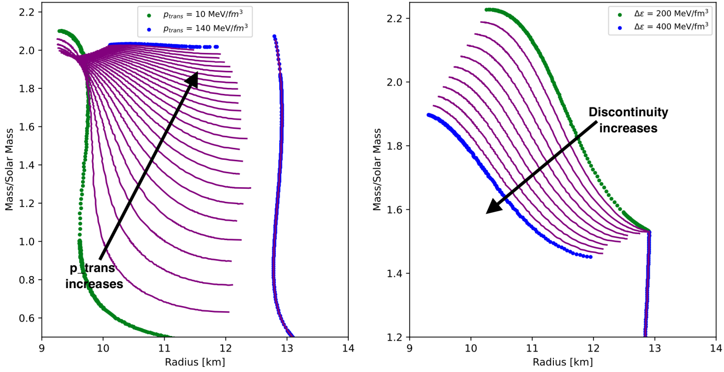
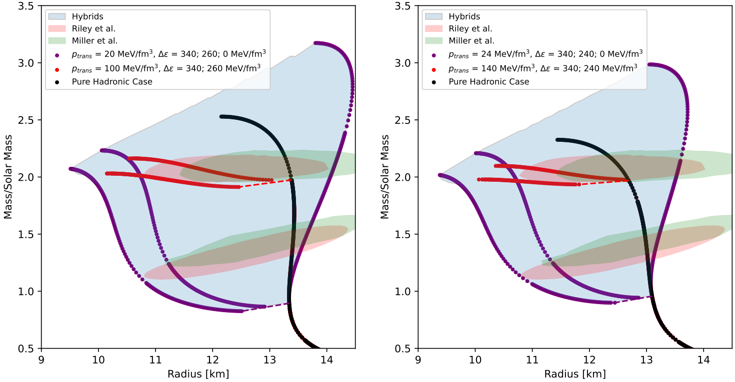


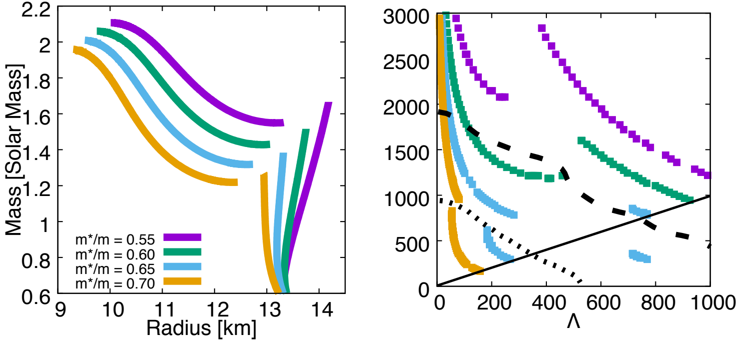
[Christian 2023]

Hybrid stars NICER constraints



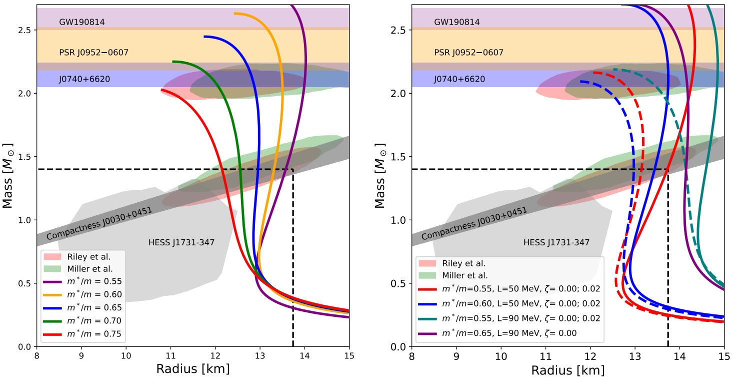
[Christian and Schaffner-Bielich (2021), Phys. Rev. D]

Tidal deformability changes GW170817



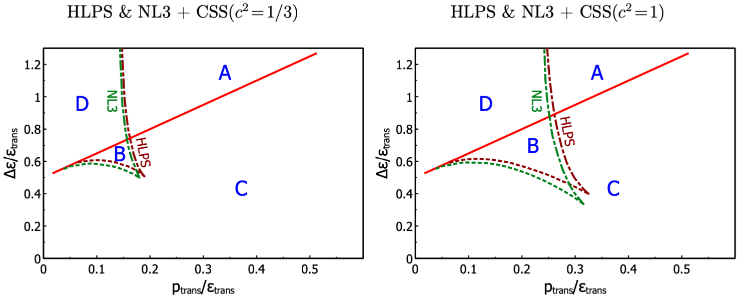
[Christian and Schaffner-Bielich (2019), ApJL]

MR constraints for more RMF models



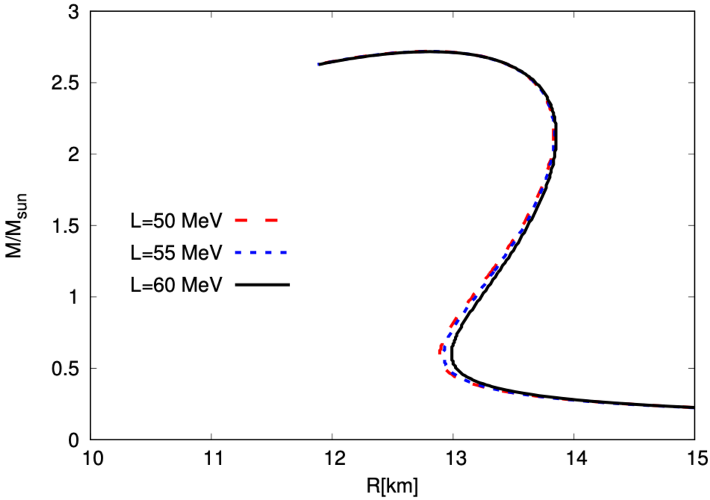
[Christian 2023]

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]

Relativistic Mean Field Approach

- Nucleon interactions are modeled with σ, ω and ρ mesons
- At high baryon densities: $\overline{\omega} = \langle\omega\rangle$, $\overline{\sigma} = \langle\sigma^0\rangle$ and $\overline{\rho} = \langle\rho_3^0\rangle \Rightarrow$ mean field theory

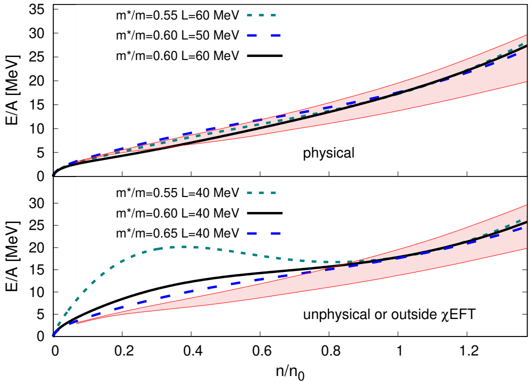
- Fix coupling constants from experiments:

Saturation density	n_0	$0.16\,\mathrm{fm}^{-3}$	
Binding Energy	E/A	-16.3 MeV	g_σ, g_ω, b, c
Compressibility	K	240 MeV	
Effective mass	m^*/m	0.55 - 0.75	
Symmetry energy	J	30 - 32 MeV	g_ρ, Λ_ω
Slope parameter	L	40 - 60 MeV	

- In this case $J = 32\,\mathrm{MeV}$ and $L = 60\,\mathrm{MeV}$ via chiral effective field theory

Chiral Effective Field Theory Constraints

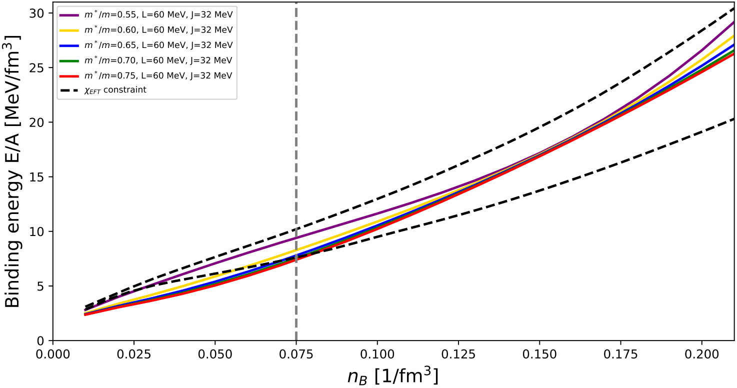
- Ab initio approach describing nucleonic matter up to about 1.2 n_0
- We compare with: Drischler et al., 2016); see also: (Carbone and Schwenk, 2019)



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

Our Selection

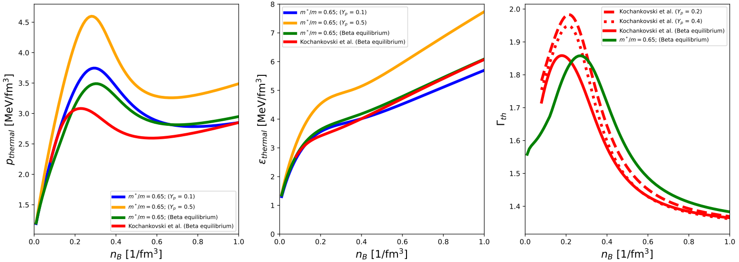
- $J = 32\,\mathrm{MeV}$ and $L = 60\,\mathrm{MeV}$ are fixed to allow the greatest m^*/m range



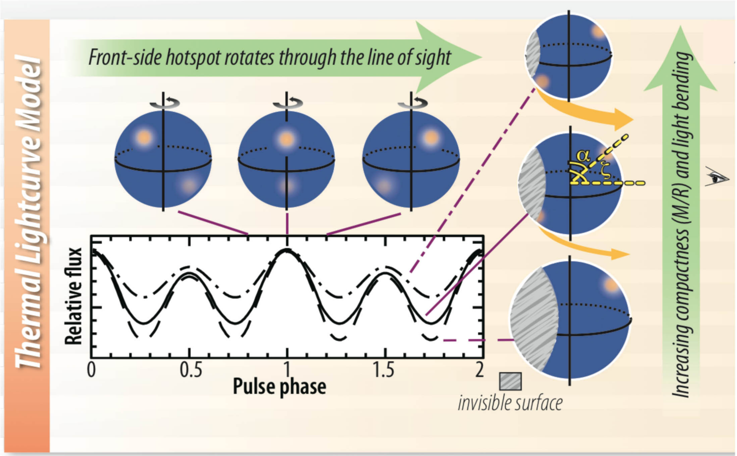
Finite Temperatures

- Thermal index:

$$\Gamma_{th} = \frac{p_{th}}{\epsilon_{th}} + 1$$



NICER



[NASA / NICER]