ACHT 2021: PERSPECTIVES IN PARTICLE, COSMO- AND ASTROPARTICLE THEORY

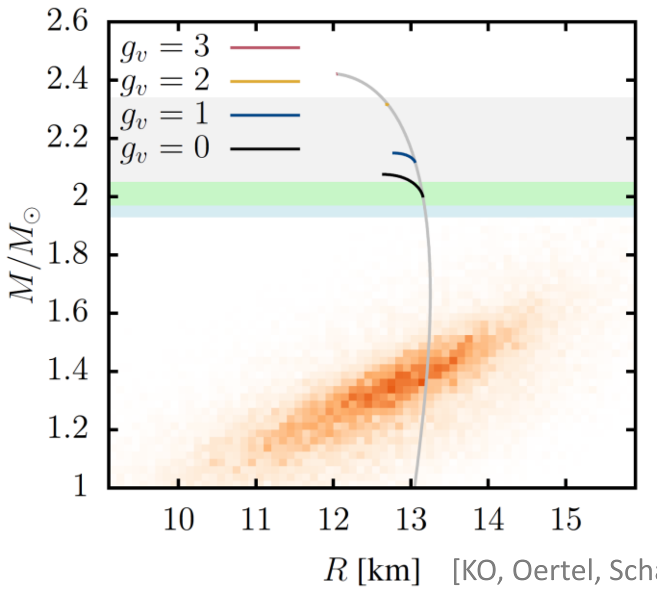
Neutron Stars from the Functional Renormalization Group

KONSTANTIN OTTO

KO, Oertel, Schaefer, Phys. Rev. D 101, 103021 (2020)
KO, Oertel, Schaefer, Eur. Phys. J. Spec. Top. 229, 3629–3649 (2020)

Neutron Stars – Experimental Progress

- Precise mass measurements for heavy stars:
  - PSR J1614-2230 $M = 1.97 \pm 0.04\, M_\odot$
    [Demorest et al. 2010]
  - PSR J0348+0432 $M = 2.01 \pm 0.04\, M_\odot$
    [Antoniadis et al. 2013]
  - MSP J0740+6620 $M = 2.14 + 0.20 - 0.18\, M_\odot$
    [Cromartie et al. 2019]



[KO, Oertel, Schaefer 2020]

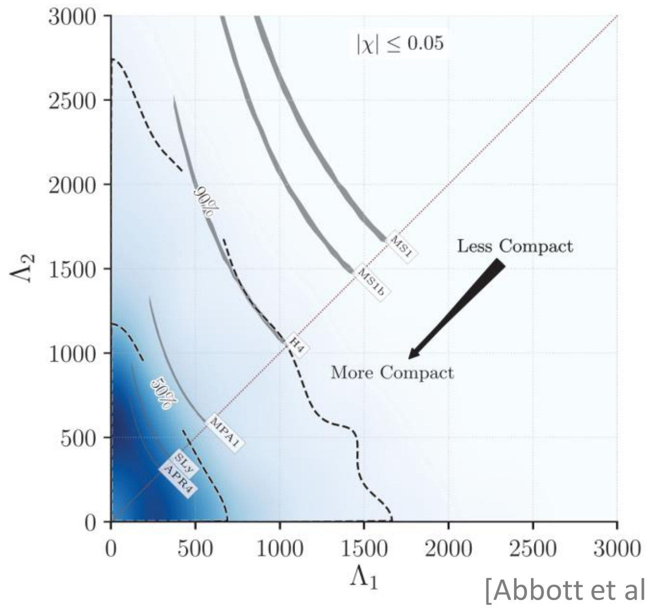
- First radius determinations from NICER experiment:
  [Riley et al. 2019][Miller et al. 2019]

  $R(1.4\, M_\odot) \sim 12 - 14$ km

  → hopefully even more precise measurements to come

- Tidal deformability Λ:
  [Abbott et al. 2017]

  $\Lambda(1.4\, M_\odot) \leq 800$ from GW170817 merger event

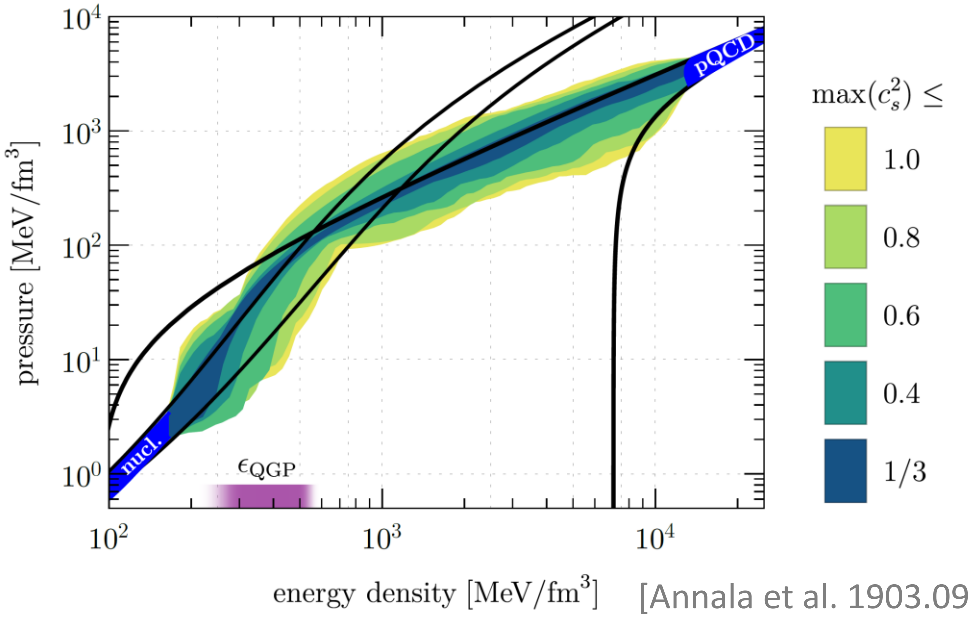


[Abbott et al. 2017]

Neutron Stars – Theoretical Progress

- M, R, and Λ uniquely determined by **equation of state (EoS)**
- For vanishing temperature: $\boldsymbol{p(\mu_B),\ \varepsilon(\mu_B) \to p(\varepsilon)}$

→ **EoS of cold and dense matter still largely unknown!**



[Annala et al. 1903.09121]

„physics“ calculation

DSE

FRG

AdS/CFT

Effective theories/models

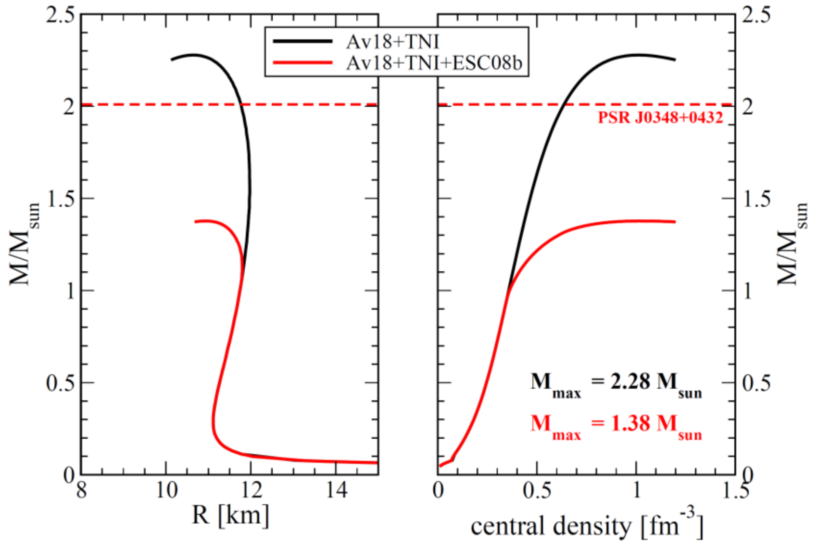
…

parameter studies

Progress also driven by experimental results:

- Find exclusion regions
- Use the help of e.g. artificial intelligence
  [e.g. Fujimoto et al. 2019]

→ **Many questions concerning the state of matter require a physical theory!**



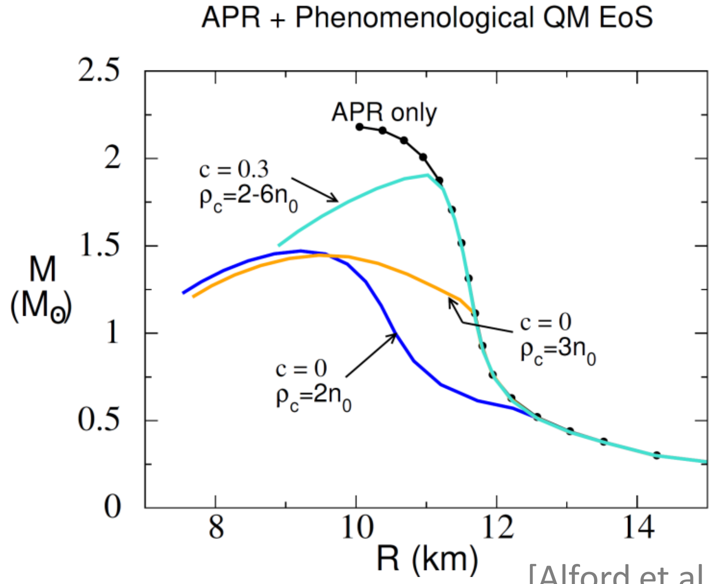
[Bombaci 2016]

E.g. …

- Occurrence of strangeness (hyperon puzzle)?
- Quark cores (hybrid stars)?
- (spatially) inhomogeneous phases/color superconductivity?

→ „Masquerade problem“

- increasing degrees of freedom **softens** EoS, repulsive interactions **stiffen** it
- Hybrid stars have very similar M-R-relation as neutron stars



[Alford et al. nucl-th/0411016]

Neutron Stars – Theoretical Progress

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- DSE
- FRG
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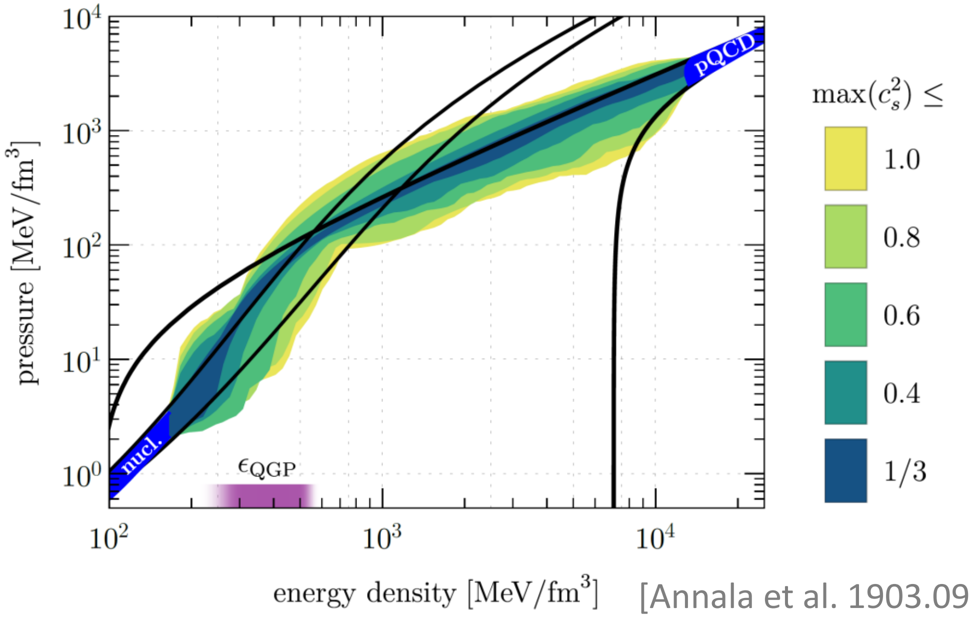


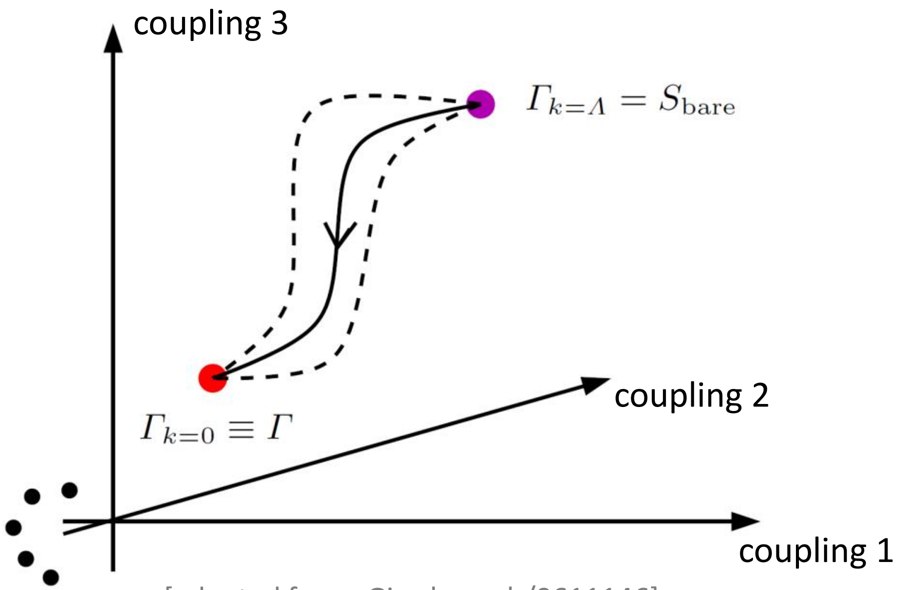
[Annala et al. 1903.09121]

Functional Renormalization Group (FRG)

→ integrate out fluctuations from high to low momenta

FRG flow equation: $\partial_k \Gamma_k = \frac{1}{2} \mathrm{Tr}\left[\left(\Gamma_k^{(2)} + R_k\right)^{-1} \cdot \partial_k R_k\right]$

[Wetterich '93]



[adapted from: Gies hep-ph/0611146]

Quark-meson truncation:

(pseudo)scalar mesons: $\Phi = \sum_{a=0}^{N_f^2-1} T_a(\sigma_a + i\pi_a)$

Chiral invariants: $\rho_n = \mathrm{Tr}\left[\left(\Phi^\dagger \cdot \Phi\right)^n\right], \quad n = 1, \dots, N_f$

quarks + Yukawa interaction — (pseudo)scalar mesons + chiral potential

action: $$\Gamma_k = \int_x \left[\bar{q}\left(\partial\!\!\!/ + g_s T_a(\sigma_a + i\gamma_5 \pi_a)\right)q + \mathrm{Tr}\left(\partial_\mu \Phi^\dagger \partial_\mu \Phi\right) + U_k\left(\rho_1, \dots, \rho_{N_f}\right) - c\left(\det \Phi^\dagger + \det \Phi\right) - \mathrm{Tr}\left(H\left(\Phi + \Phi^\dagger\right)\right) \right]$$

$U(1)_A$ symmetry breaking — explicit chiral symmetry breaking

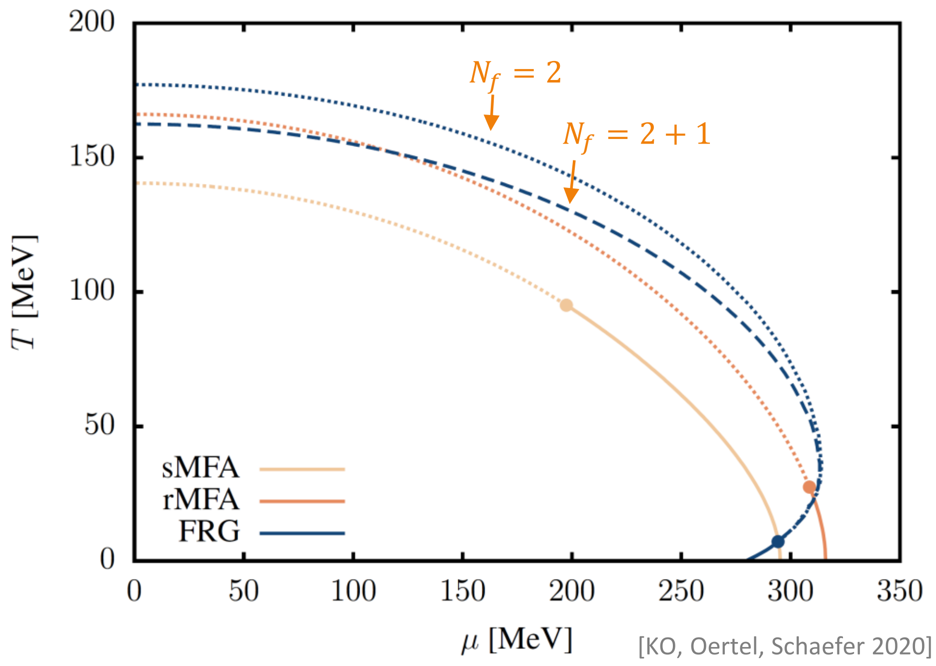
Many studies so far in mean-field approximation!

→ Compare FRG with different mean-field approximations:

sMFA: standard mean-field approximation (without vacuum term)

rMFA: renormalized mean-field approximation (only solve quark loop in FRG flow)

FRG: full functional renormalization group flow



[KO, Oertel, Schaefer 2020]

→ Meson fluctuations soften the first-order transition, push CEP towards smaller temperatures!

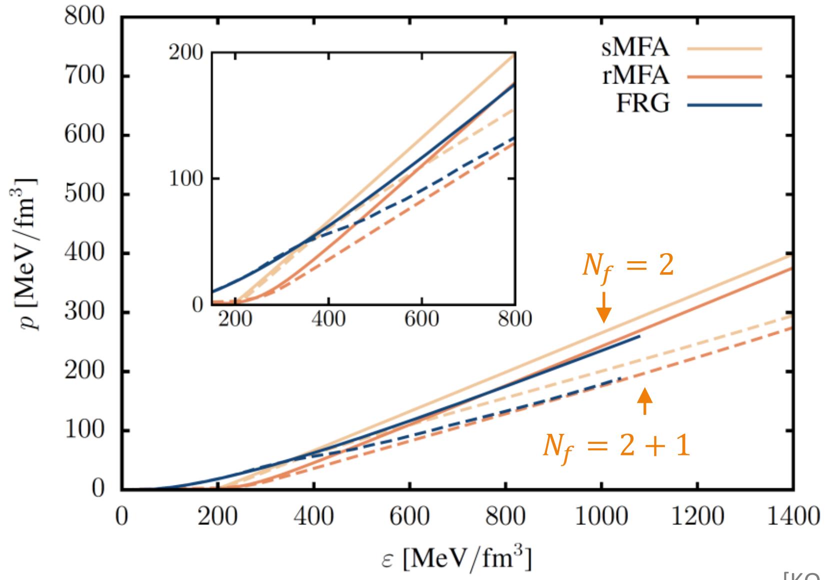
Impact of fluctuations on the equation of state (EoS)?

$$\mu_u = \mu_q - \frac{2}{3}\mu_e$$
$$\mu_d = \mu_q + \frac{1}{3}\mu_e$$
$$\mu_s = \mu_q + \frac{1}{3}\mu_e$$

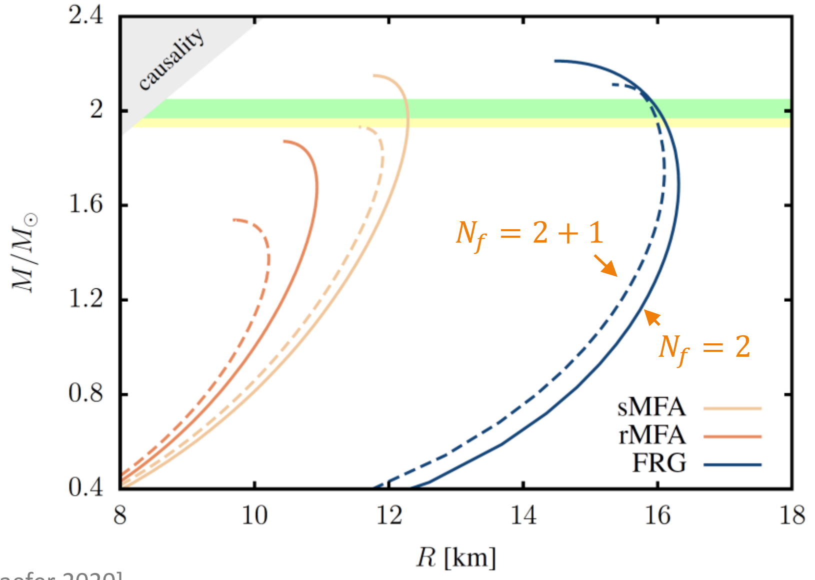
→ Impose beta equilibrium and charge neutrality conditions

Tolman-Oppenheimer-Volkoff equations

equation of state



mass-radius relations



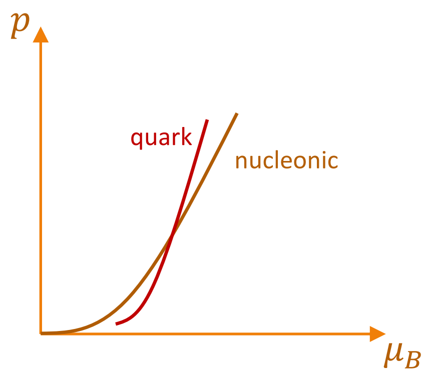
[KO, Oertel, Schaefer 2020]

→ **Fluctuations have large impact on M-R-relations!**

From hadrons to quarks

review: see [Baym et al. 2018]

- Deconfined quark very likely not a realistic description of neutron star!
- Connect quark matter EoS with a nucleonic EoS at densities $\lesssim 2\rho_0$
- Possible existence of hybrid stars with quark matter core

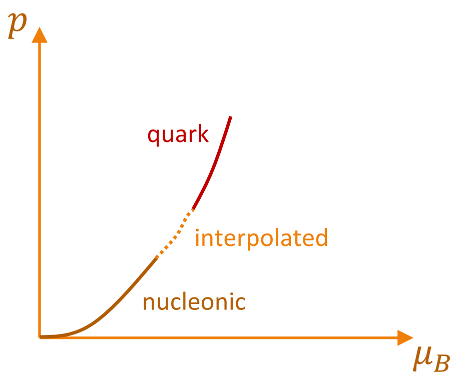


two scenarios


first-order transition

quark-hadron continuity

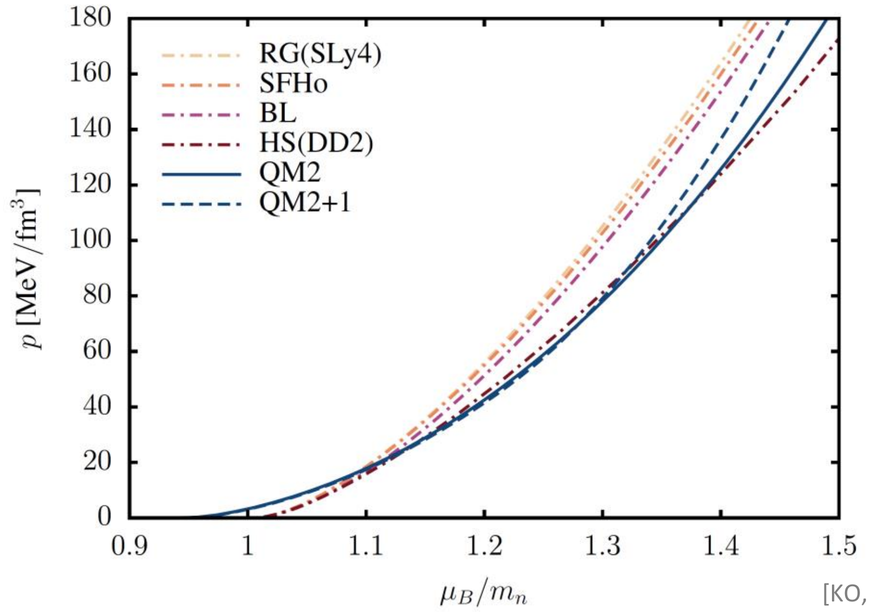
e.g. QHC19 [Baym et al. 2019]

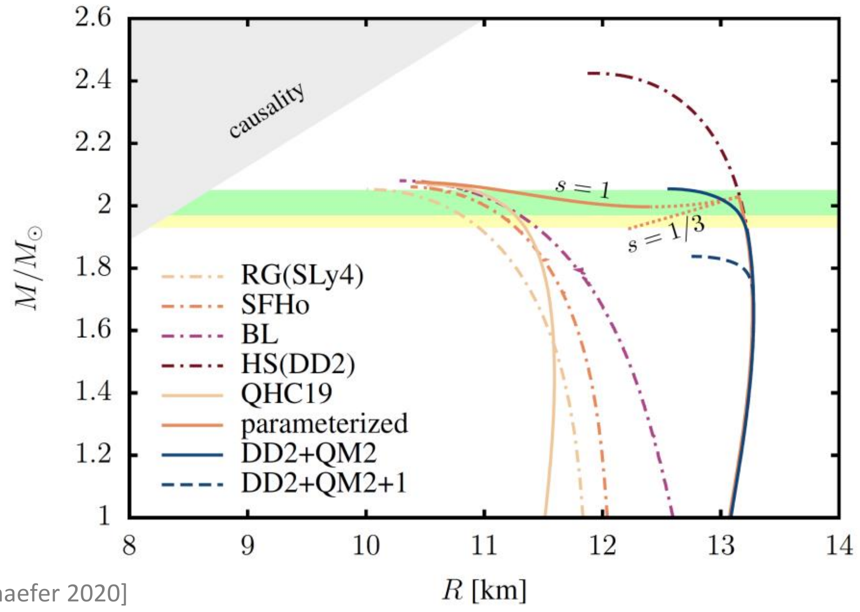


Hybrid star construction possible?

→ Combine nuclear EoS **HS(DD2)** with EoS from FRG QM-truncation [Hempel, Schaffner-Bielich 2010]

→ Use **Maxwell construction** to obtain first-order transition





[KO, Oertel, Schaefer 2020]

→ Construction possible with DD2 EoS if first intersection neglected!

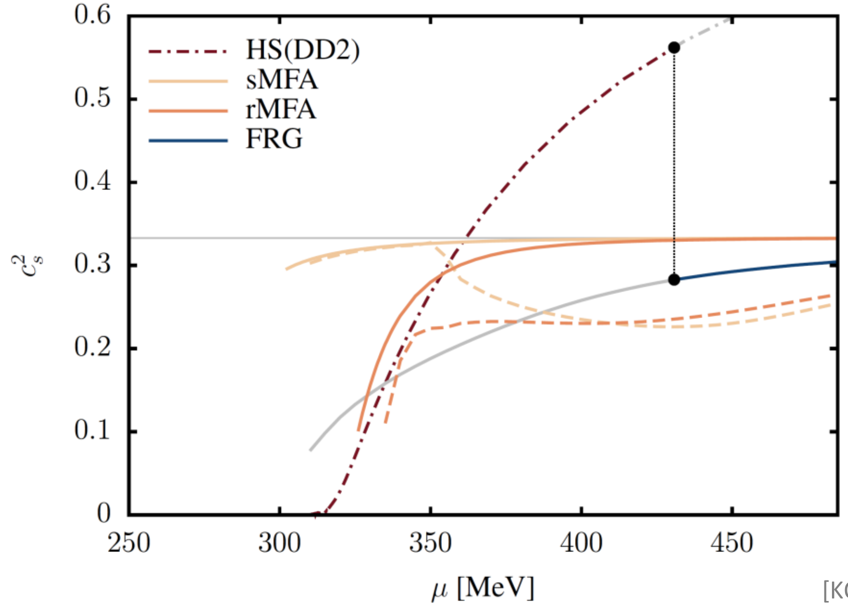
→ Continuous nuclear-hybrid branch

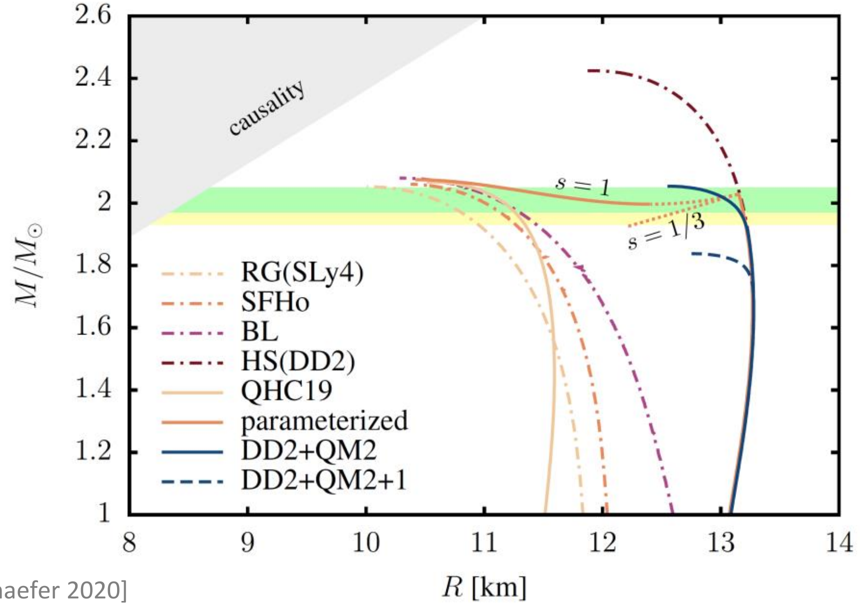
Twin stars?

→ increase energy gap Δε: hybrid branch becomes unstable

→ Also increase speed of sound (see parameterized curve) second twin branch forms

see [Alford, Han, Prakash 1302.4732]





[KO, Oertel, Schaefer 2020]

→ QM EoS asymptotically approaches conformal limit from below!

→ $2M_\odot$ limit violated for $N_f = 2+1$

→ Repulsive vector interactions could remedy this!

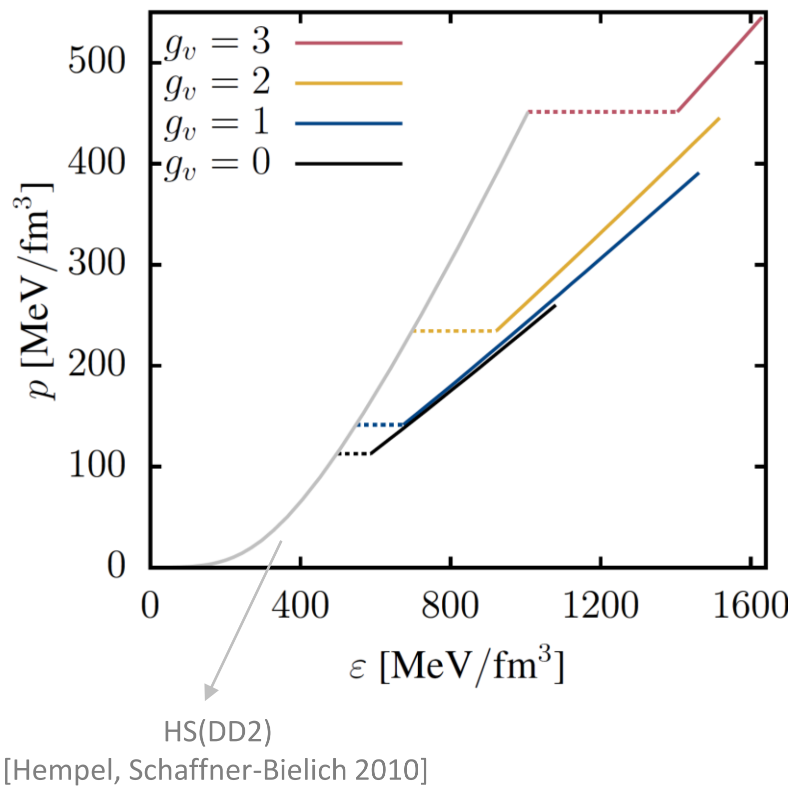
Adding vector mesons:

Yukawa type interaction of temporal component and mean-field potential:

$$\Gamma_{\text{vec}} = \int_x \left[\frac{g_v}{2}\, \bar{q}\, \gamma_0\, \text{diag}_f(\omega, \omega, \sqrt{2}\phi)\, q - \frac{1}{2}\left(m_\omega^2 \omega^2 + m_\phi^2 \phi^2 \right) \right]$$

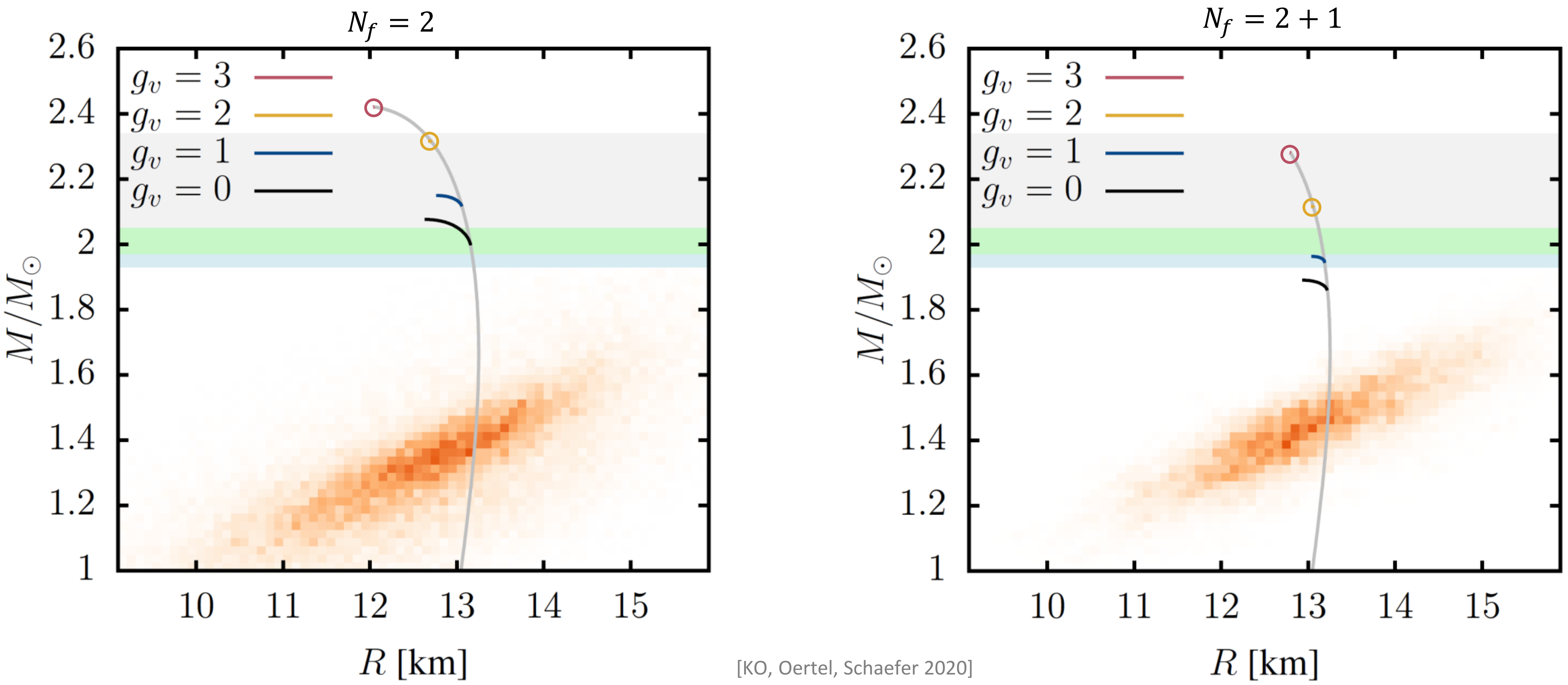
Effectively shifts chemical potentials:

$$\tilde{\mu}_u = \mu_q - \frac{2}{3}\mu_e - \frac{g_v}{2}\omega$$
$$\tilde{\mu}_d = \mu_q + \frac{1}{3}\mu_e - \frac{g_v}{2}\omega$$
$$\tilde{\mu}_s = \mu_q + \frac{1}{3}\mu_e - \frac{g_v}{\sqrt{2}}\phi$$



→ Energy gap and transition pressure increase with g_v

Mass-radius relations:



[KO, Oertel, Schaefer 2020]

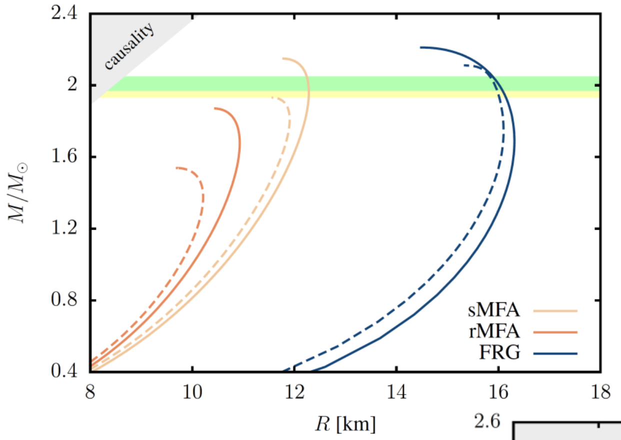
Findings:

→ Including strange quarks, finite vector coupling g_v is needed to achieve $2M_\odot$ limit!

→ At the same time, larger vector couplings lead to smaller quark cores!

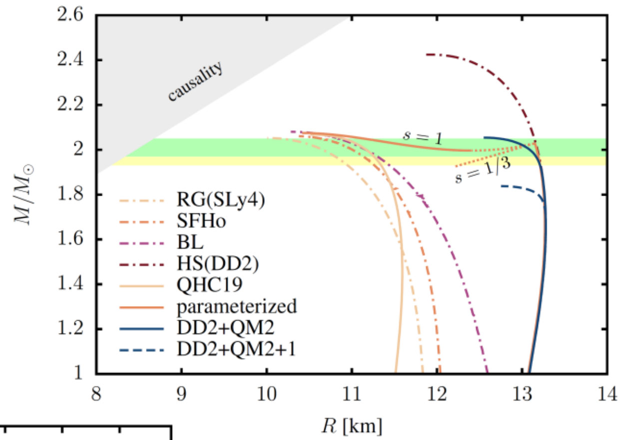
NICER posterior probability distributions:
[Riley et al., arXiv:1912.05702] (left)
[Miller et al., arXiv:1912.05705] (right)

Summary and Outlook



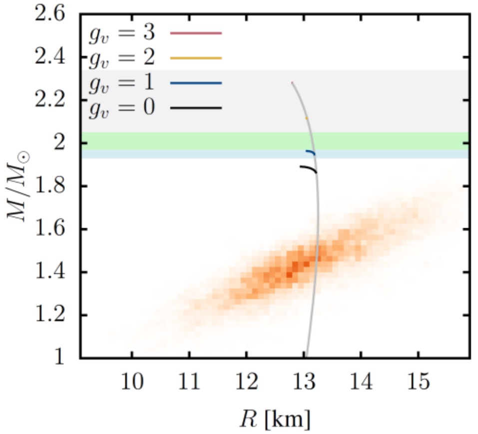
- FRG calculation feasible
- Significant changes compared to mean-field approximation
- Non-zero vector coupling to reach two solar masses with strangeness

  → only small quark cores



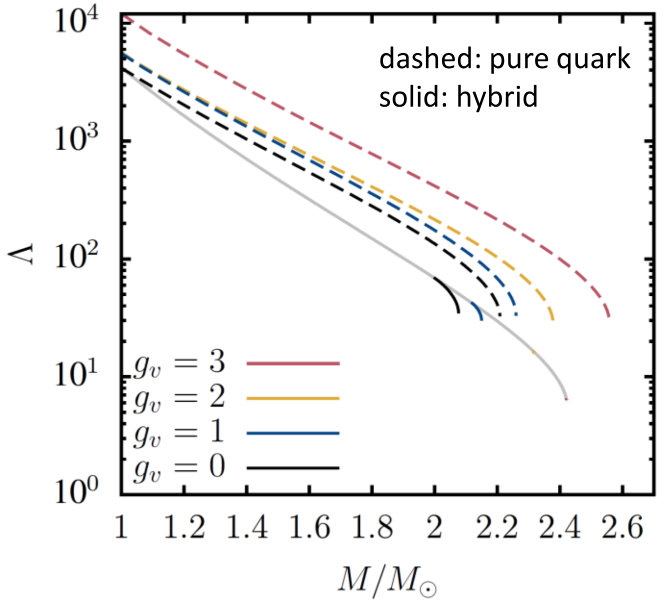
→ Still **many open questions**:

- truncation and scheme dependence
- correct degrees of freedom
- …

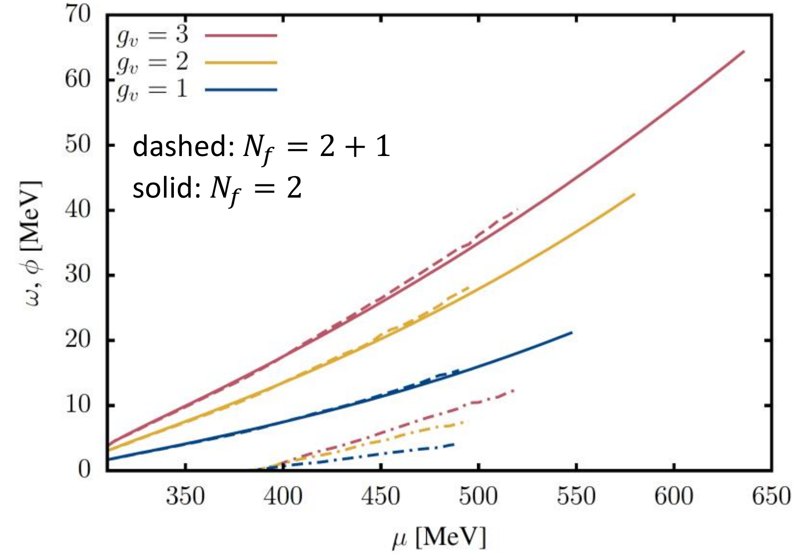


Further Numerical results

tidal deformabilities ($N_f = 2$)



vector meson condensates



pure quark stars