Quark matter in Neutron Stars

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September 12th, 2023

EMMI Workshop

Functional Methods in Strongly Correlated Systems (FUNSCS2023)

Hirschegg, Kleinwalsertal, Austria, September 10 - September 15, 2023

agenda

- Hybrid and quark star matter based on a nonperturbative equation of state

  Konstantin Otto (Giessen U.), Micaela Oertel (LUTH, Meudon), Bernd-Jochen Schaefer (Giessen U.)

  Published in: *Phys.Rev.D* 101 (2020) 10, 103021 • e-Print: 1910.11929 [hep-ph]

- Nonperturbative quark matter equations of state with vector interactions

  Konstantin Otto (Giessen U.), Micaela Oertel (LUTH, Meudon), Bernd-Jochen Schaefer (Giessen U.)

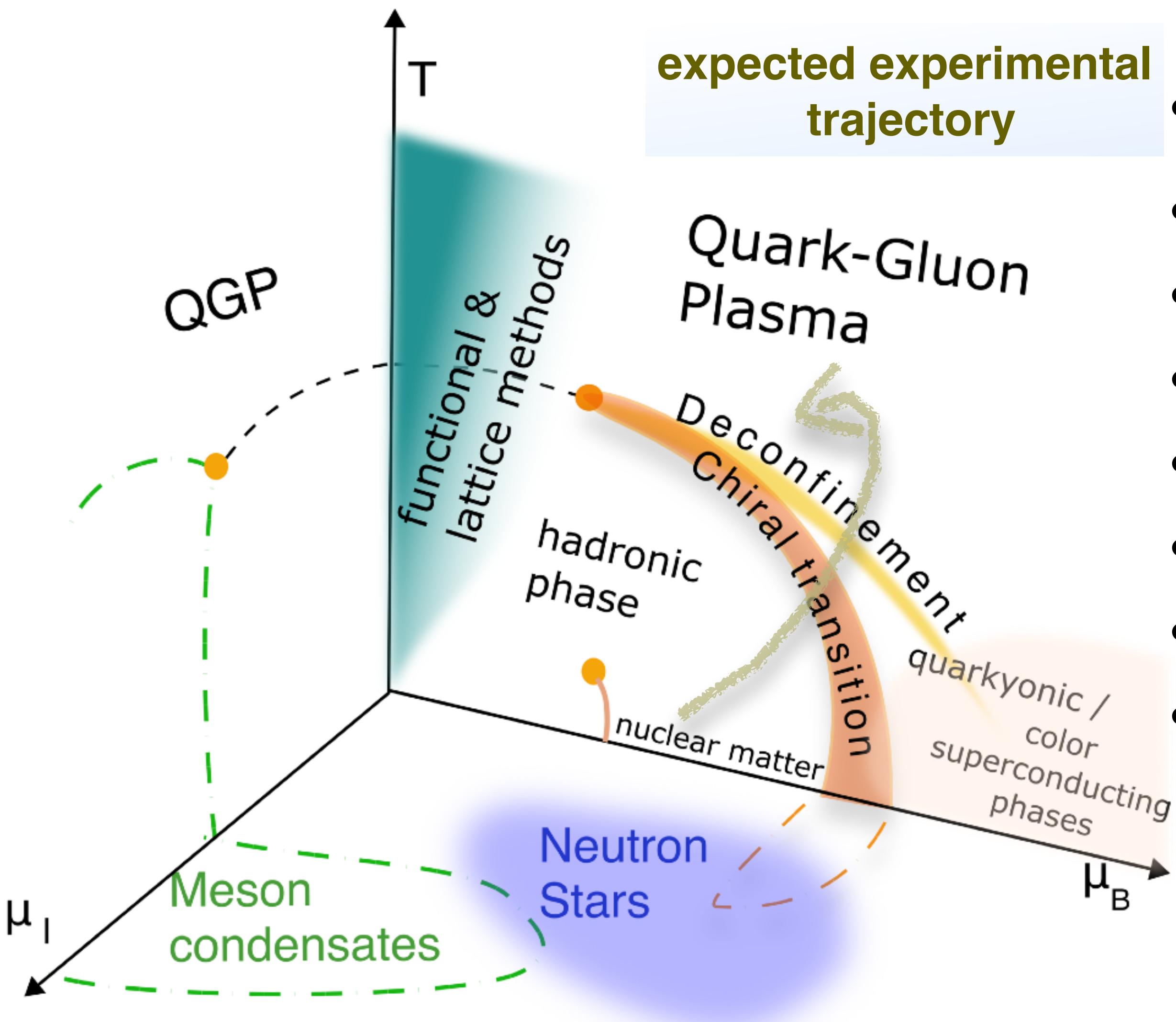
  Published in: *Eur.Phys.J.ST* 229 (2020) 22-23, 3629-3649 • e-Print: 2007.07394 [hep-ph]

- Regulator scheme dependence of the chiral phase transition at high densities

  Konstantin Otto (Giessen U.), Christopher Busch (Giessen U.), Bernd-Jochen Schaefer (Giessen U.)

  Published in: *Phys.Rev.D* 106 (2022) 9, 094018 • e-Print: 2206.13067 [hep-ph]

conjectured QCD phase structure

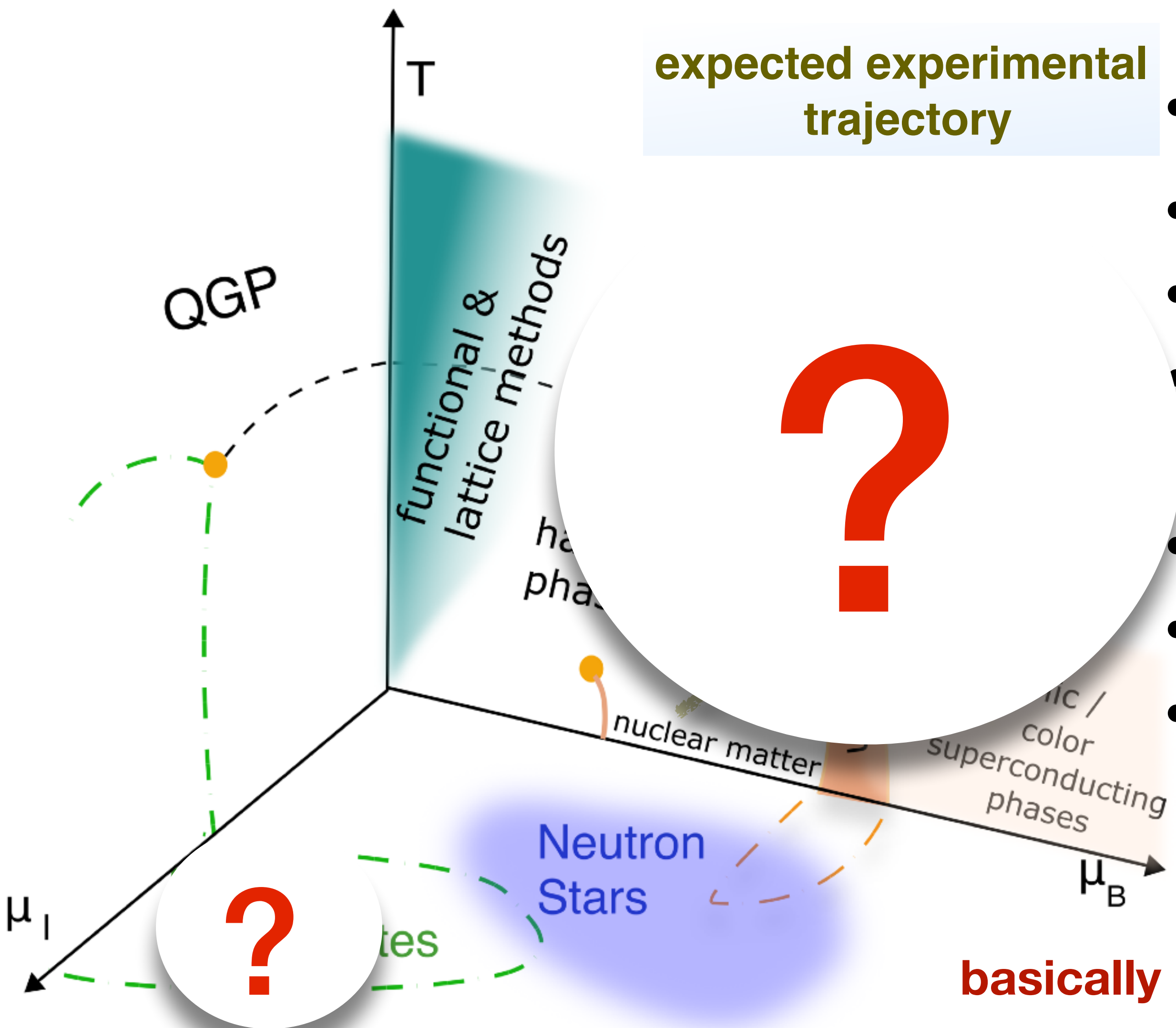


Open issues

- **Critical endpoint (CEP)?** chiral ⇔ deconfinement?
- **Chiral-Spin symmetry / Quarkyonic phase/s?**
- **inhomogeneous phase/s?**
- **axial anomaly restoration?**
- **finite volume effects?**
- **role of fluctuations?**
- **experimental signatures?**
- ....

usual assumptions: equilibrium, homogeneous phases, infinite volume, ...

conjectured QCD phase structure



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- ….

basically only corners known from first principle QCD

alternative to HIC to probe cold dense QCD matter ➜ **massive neutron star** (e.g. PSR J0348+0432)

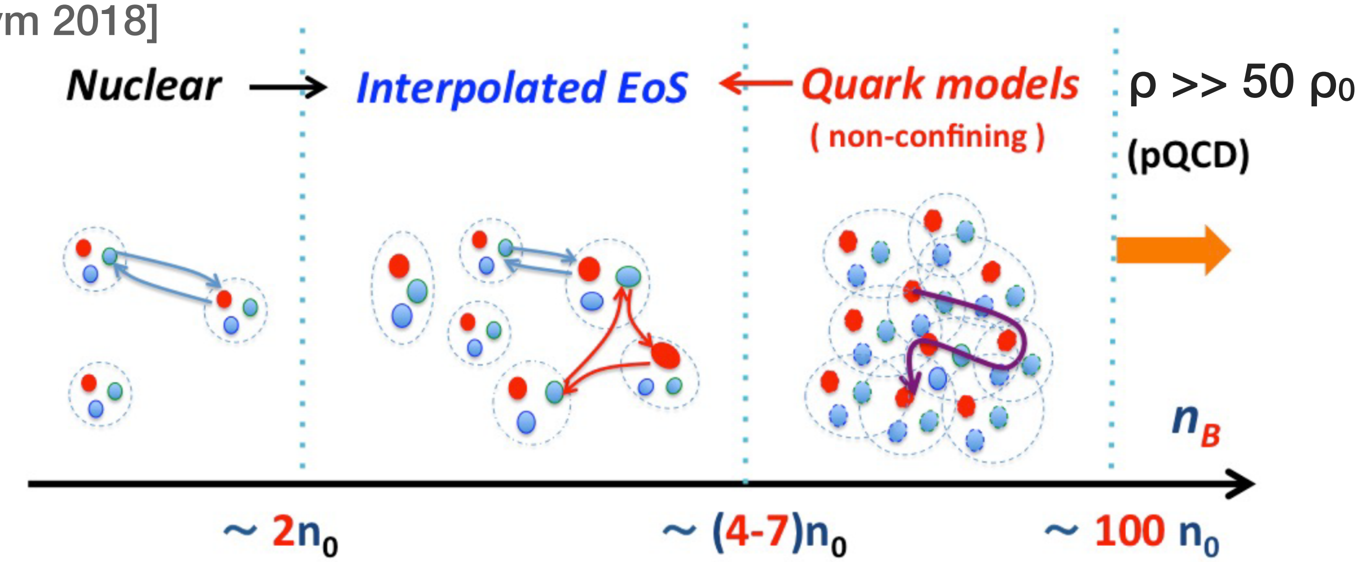
cold dense QCD matter: **only effective low-energy realisation** of QCD: e.g. (P)QM models

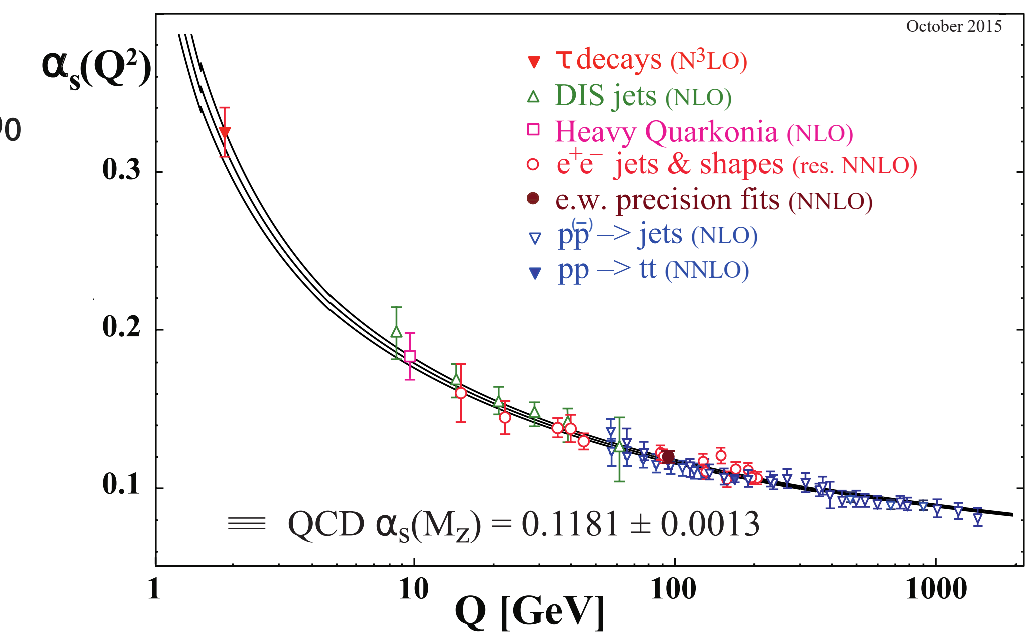
ultimate goal: microscopic description of EoS guided by QCD first principle

EoS for dense matter

Kojo et al.: three window model of dense matter

[Baym 2018]





Nuclear phase:
1-2 meson/quark exchanges

interpolated EoS
many meson/quark exchanges

Quark phase:
quarks no longer specific to baryons

EoS from
nuclear physics
$\rho < 2\rho_0$ χEFT

system gradually changes from hadronic to quark matter
- diquarks, colored quarks virtually …

- role of strangeness / hyperons

$2\rho_0 < \rho < 7\rho_0$ Neutron stars

mostly mean-field investigations like NJL-type or phenomenological models

➜ upgrade with FRG methods

[Hebeler, Lattimer, Pethick,Schwenk et al. 2010]
[Schaffner-Bielich et al. 2008]
[Blaschke, Fischer, Oertel et al. 2018]

experimental facts

Kojo et al.: three window model of dense matter

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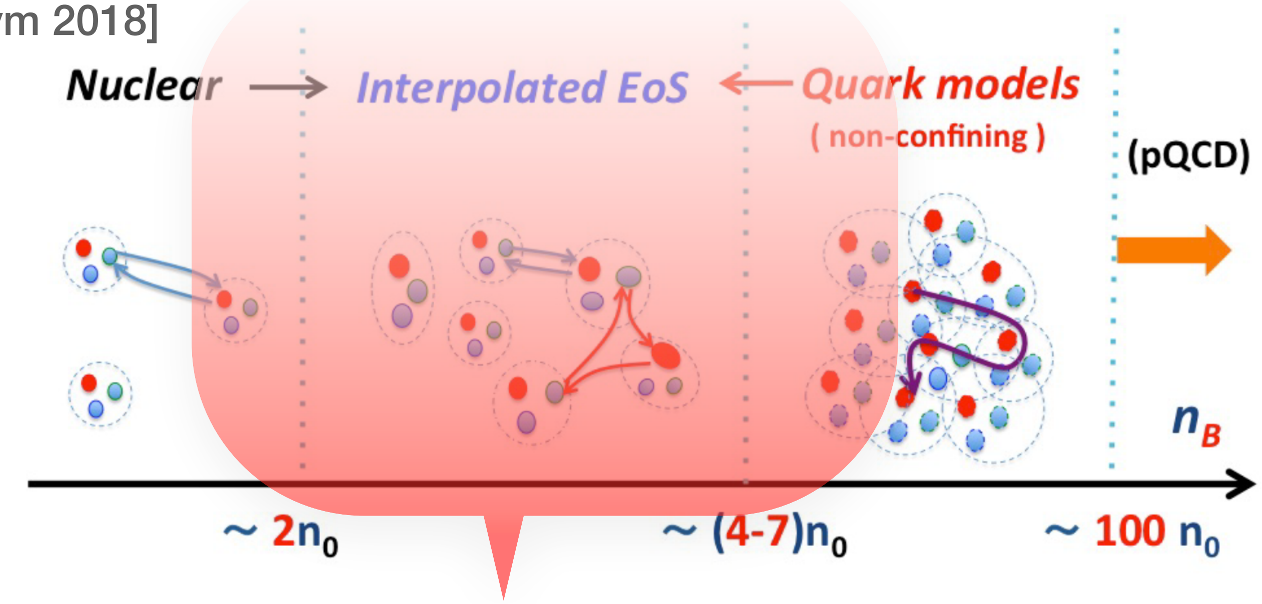
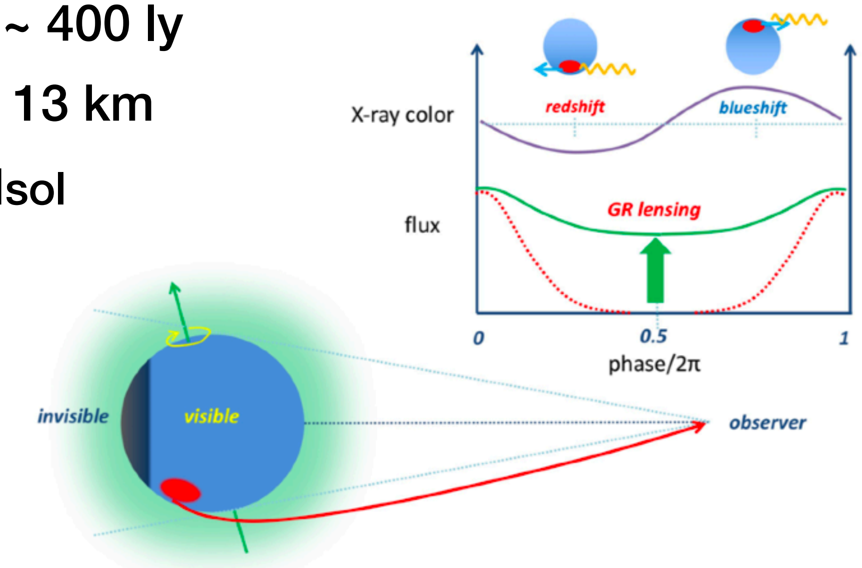


nearest ~ 400 ly

R ~ 10 - 13 km

M > 2 Msol

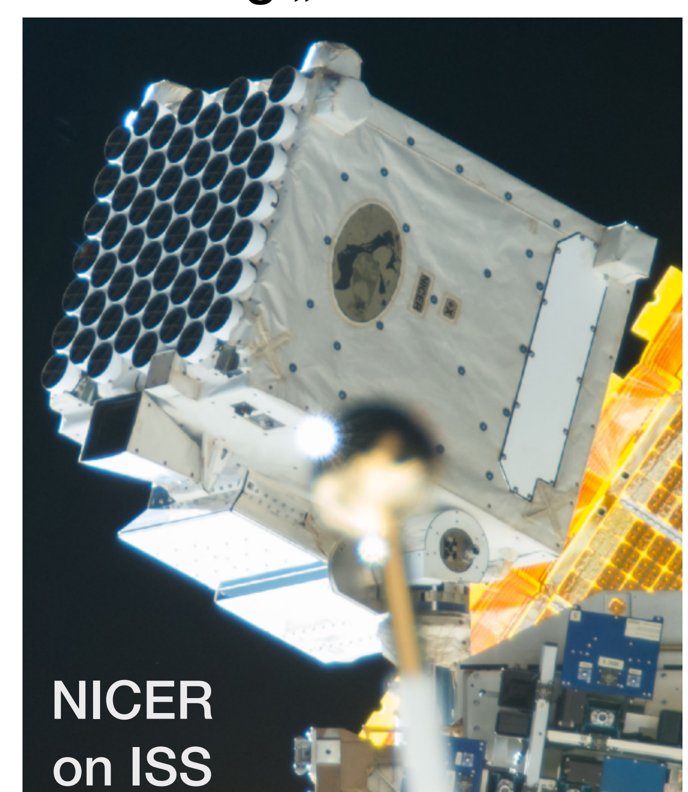


- $M_{max} = 2.05\ M_o$ & $R \sim 12.8$ km ; $\rho_{central} \sim 5\rho_0$
- $M = 1.4\ M_o$ & $R = 12{,}8$ km ; $\Delta R = 0$
- $M = 2.4\ M_o$ & $R = 12{,}8$ km ; ~ as $1.4\ M_o$ stars
- PSR J0740+6620 & J0030+0451
  both M (> M_o) & R measured
  GW170817 constraints tidal deformability -> R
- detection phase transition possible:
  increase post-merger dominant oscillation frequency
  only a few events expected (even w/ 3rd generation detectors)

future: ~ 2035

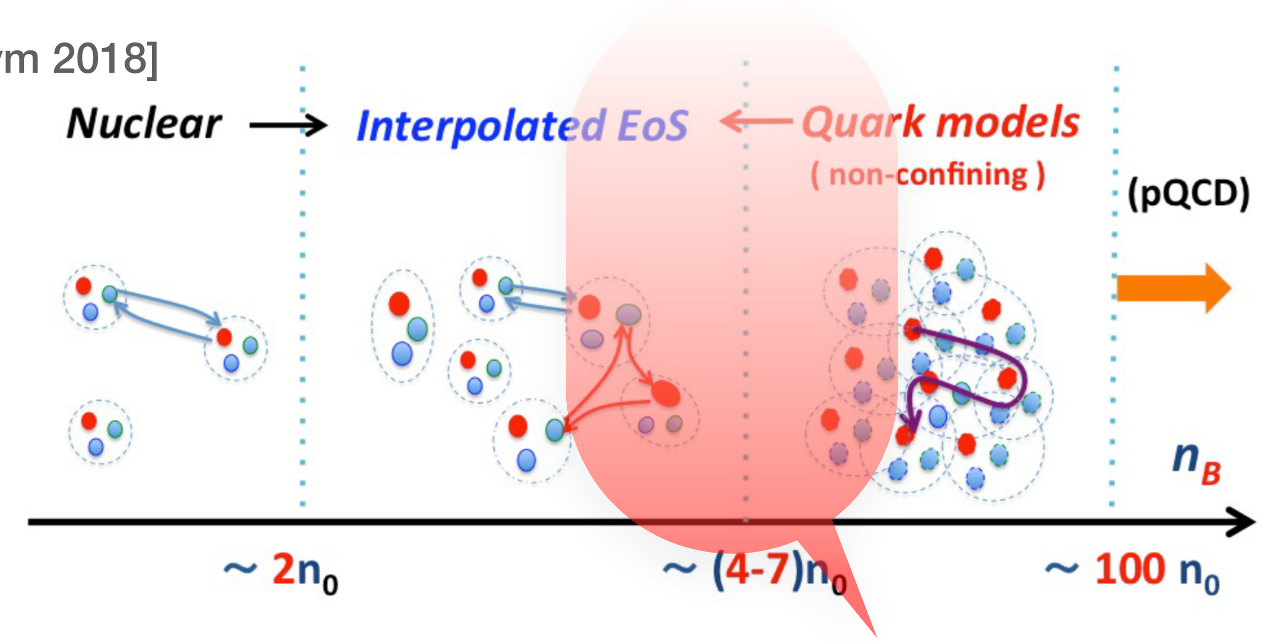
- new 3rd generation detectors:
- (American) Cosmic Explorer
- (European) Einstein Telescope

running „accelerator“



transition from hadronic to quark matter

[Baym 2018]



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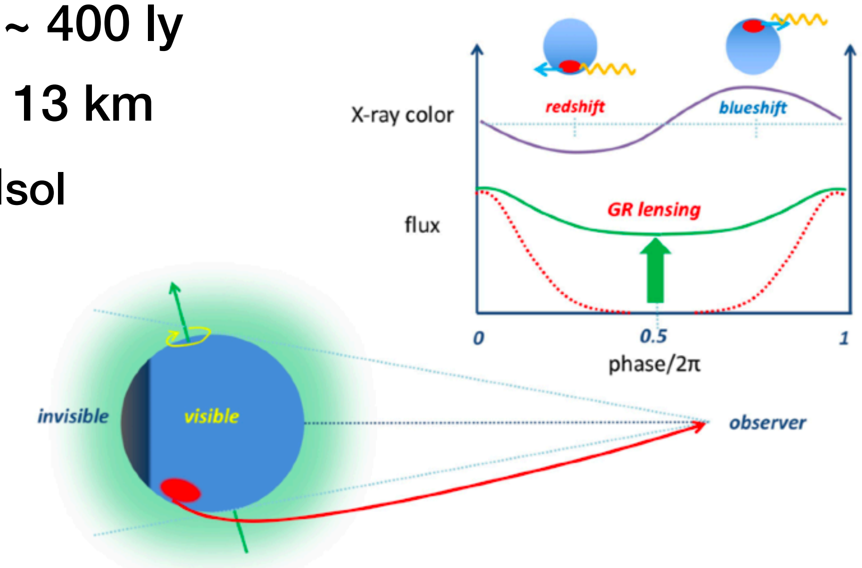
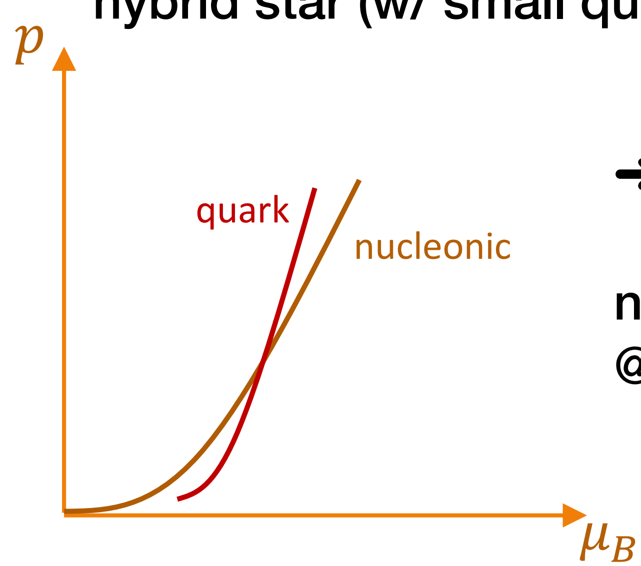


several possibilities (if transition): Maxwell construction or continuous interpolation

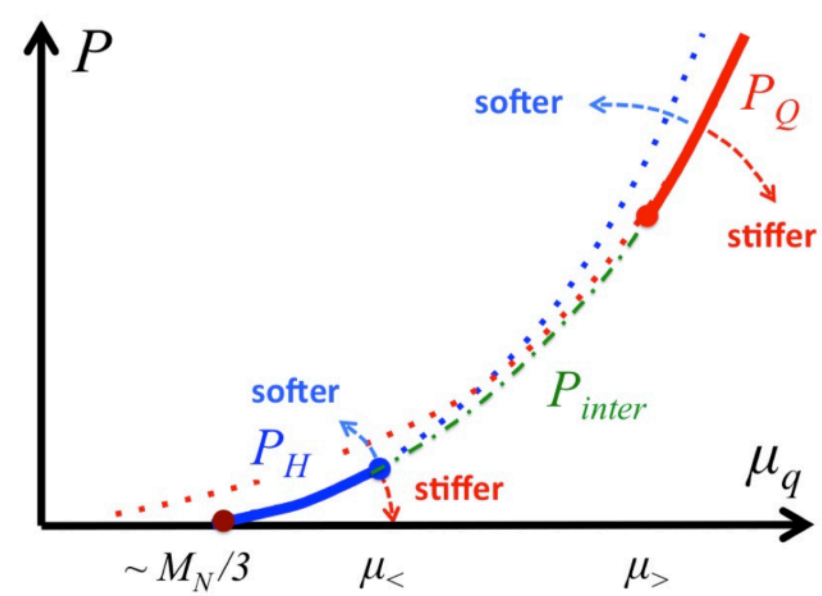
first-order transition

quark-hadron continuity

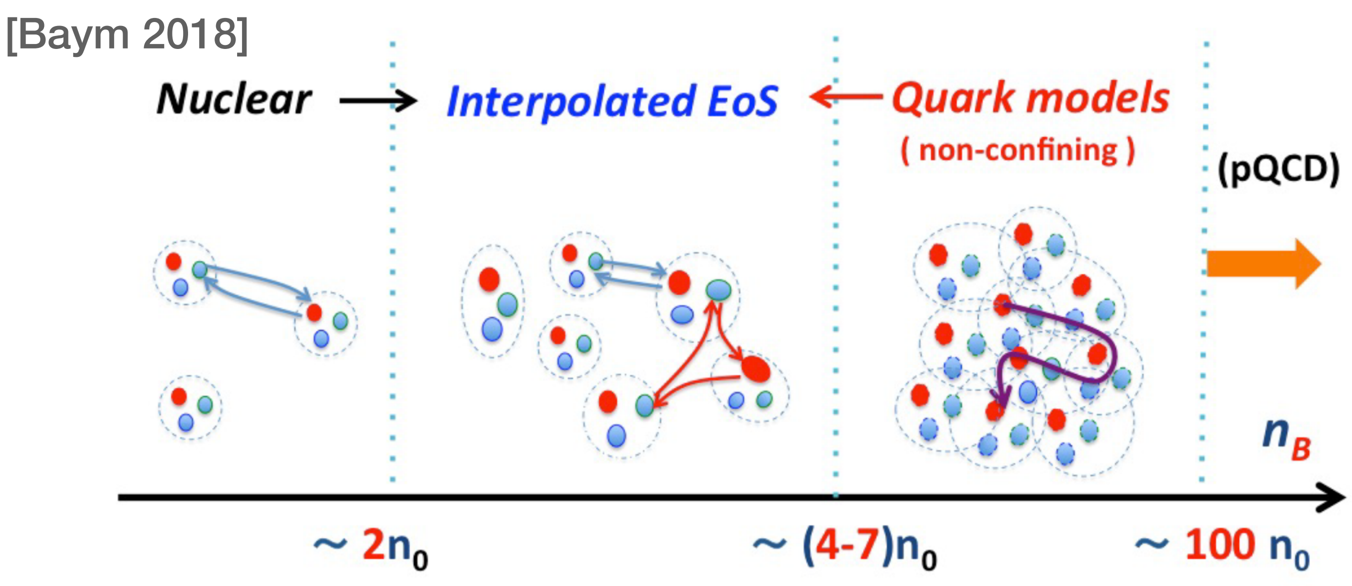
hybrid star (w/ small quark core)

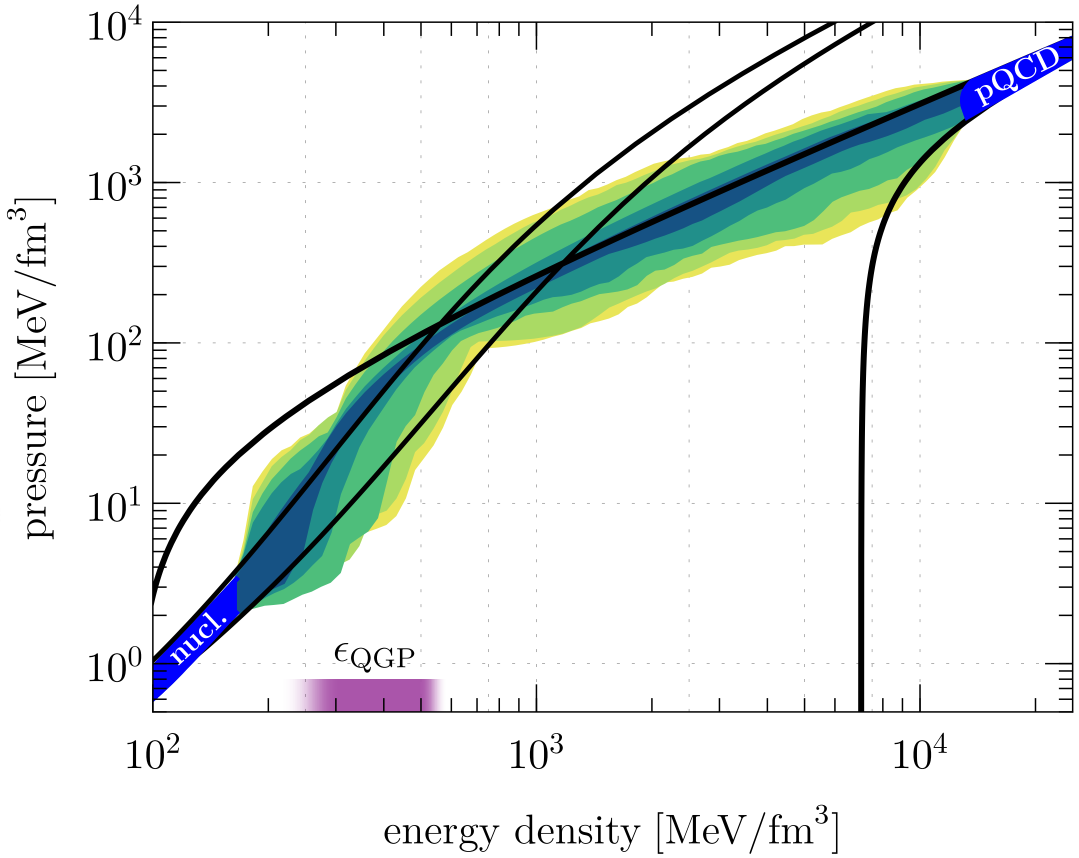


➜ quark EoS softer than nucleonic EoS @ higher densities



conflicting constraints on EoS

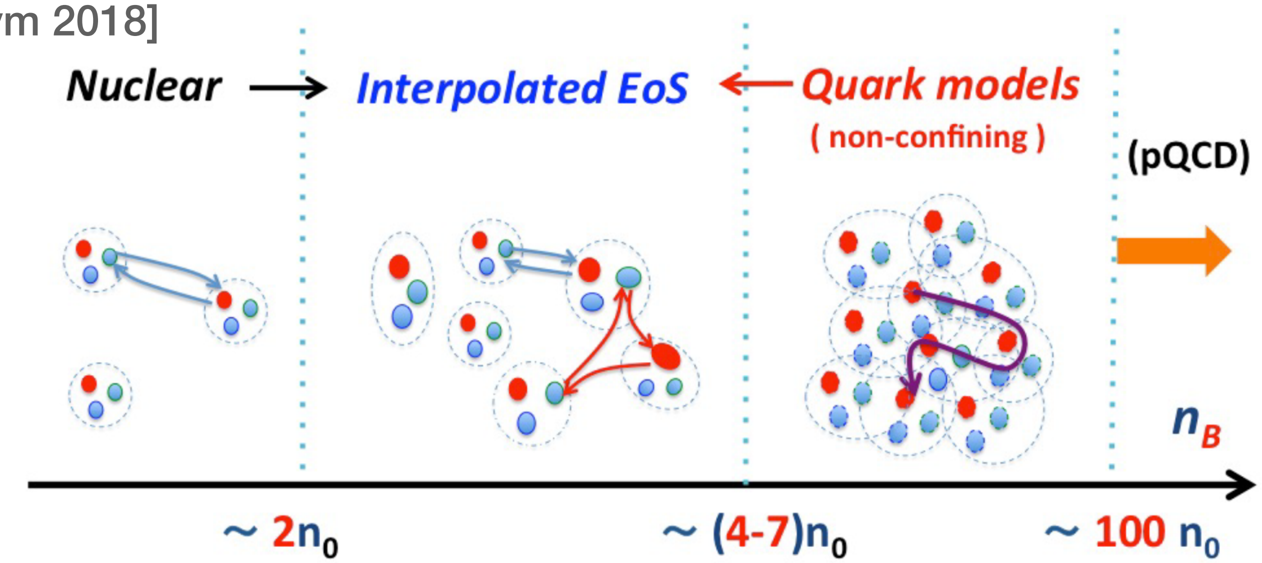


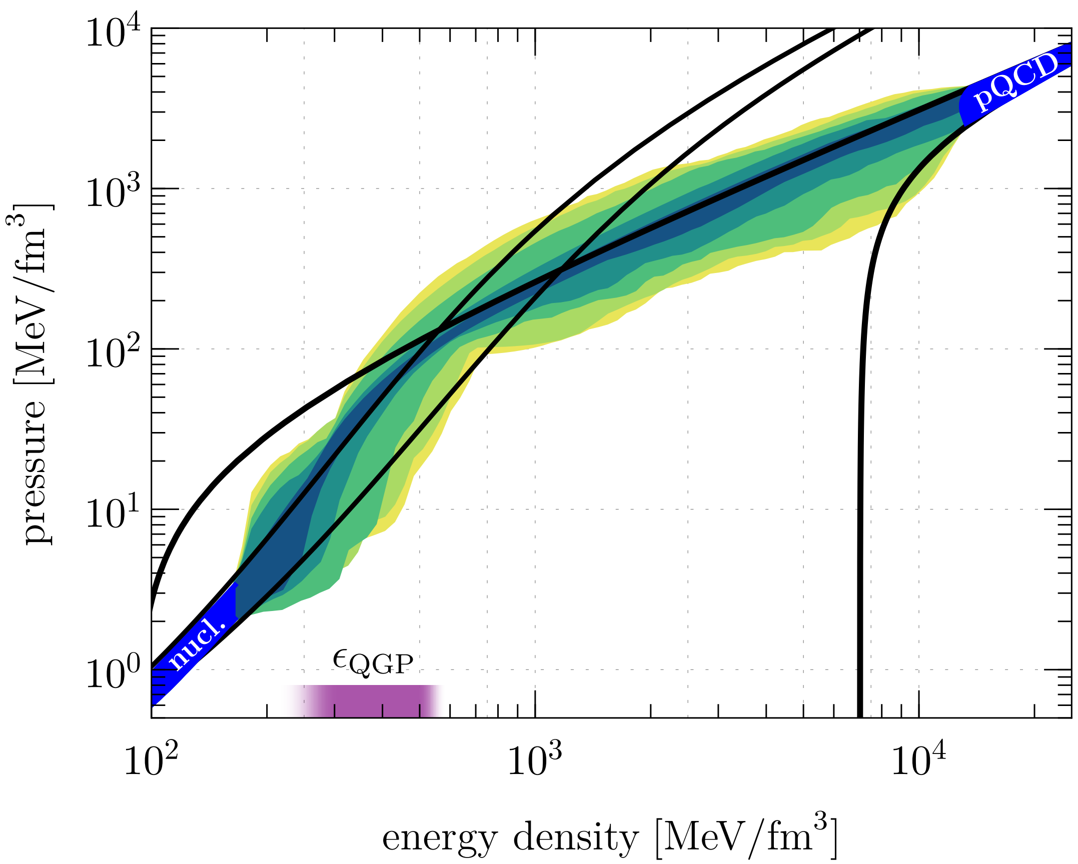


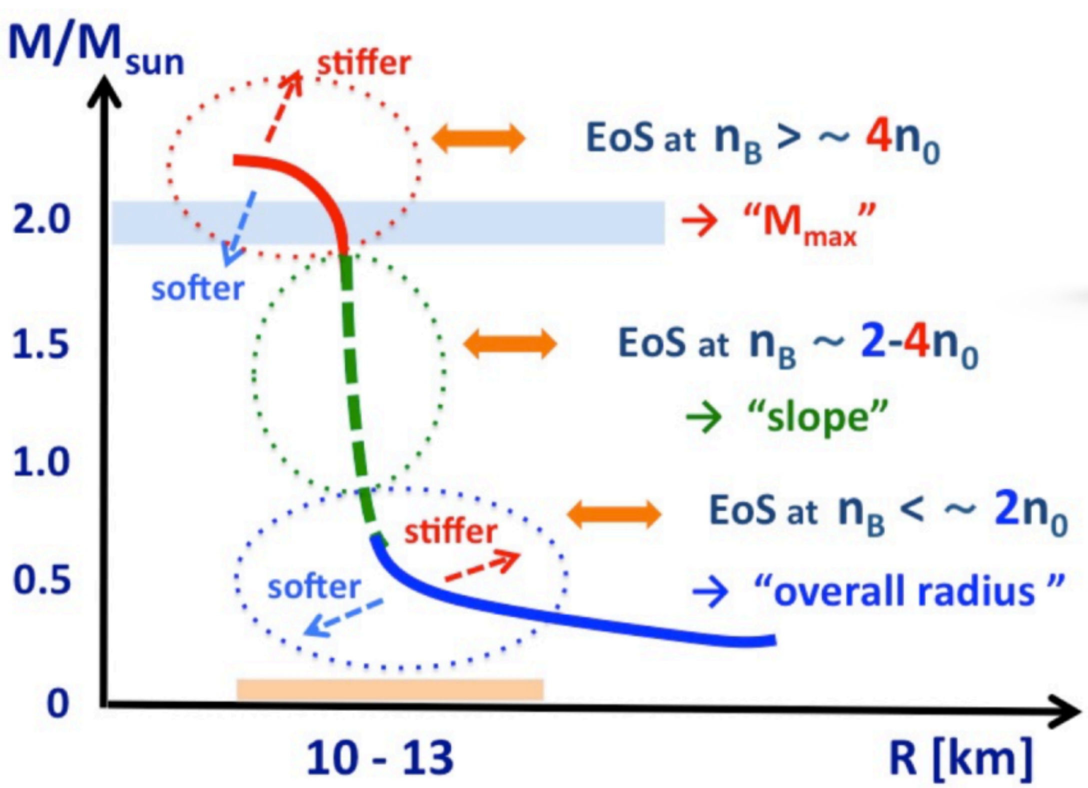
EoS ↔ TOV equation ↔ M-R relation (observables)

conflicting constraints on EoS

[Baym 2018]







EoS ↔ TOV equation ↔ M-R relation (observables)

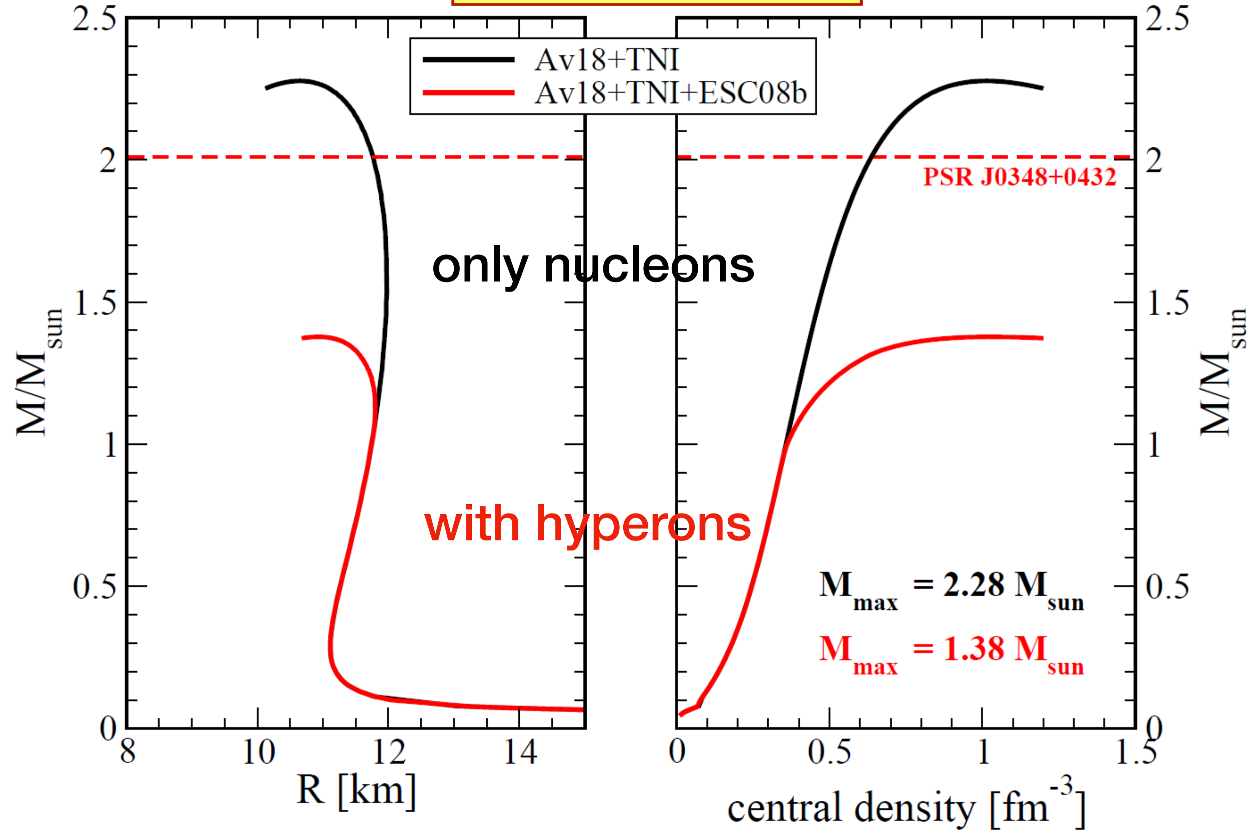
<u>three constraints on the EoS:</u>

1. stiff enough (@high density) ➜ 2M⊙
2. soft enough (@low density) ➜ Radius
3. speed of sound < 1

unsolved puzzles / open issues

[Bombaci 2016]

hyperons puzzle



Further constraints:

causality

charge neutrality: $n_p = n_e + n_\mu$

β-equilibrium: $\mu_n = \mu_p + \mu_e$

simplification:

➜ electrons and muons as free Fermi gas in EoS

General problems (physical theory input required):

➜ hyperon puzzle

onset of strangeness in hadronic phase or quark phase
➜ soften EoS

[Djapo, BJS, Wambach 2010]

➜ masquerade problem

many EoS look similar ➜ similar M-R relation
increasing #dof soften EoS,
repulsive interactions stiffen EoS

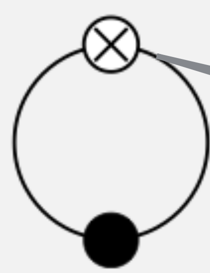
[Alvarez-Castillo, Blaschke 2014]

Functional Renormalization Group

■ Wetterich Equation (average effective action)

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \mathrm{Tr}\, \partial_t R_k \left(\frac{1}{\Gamma_k^{(2)} + R_k} \right)$$

$$k\partial_k \Gamma_k[\phi] \sim \frac{1}{2}$$



R_k regulators

$$t = \ln(k/\Lambda)$$

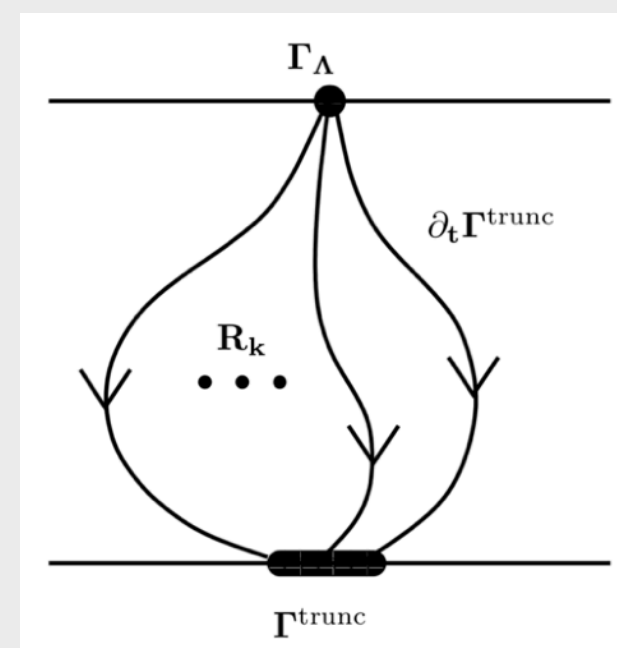
$$\Gamma_k^{(2)} = \frac{\delta^2 \Gamma_k}{\delta\phi\delta\phi}$$

[Wetterich 1993]

shape function conditions:

$$R_k(p^2) = p^2 r(p^2/k^2)$$

- $\lim_{p^2/k^2 \to \infty} R_k(p^2) = 0$
- $\lim_{p^2/k^2 \to 0} R_k(p^2) > 0 \; (= k^2)$
- $\lim_{k \to \infty} R_k(p^2) \to \infty$



■ Ansatz effective action   Quark-Meson truncation in LPA (LO derivative expansion)

$$\Gamma_k = \int d^4x \bar{q}[i\gamma_\mu\partial^\mu - g(\sigma + i\vec{\tau}\vec{\pi}\gamma_5)]q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + V_k(\phi^2)$$

arbitrary potential

$$V_{k=\Lambda}(\phi^2) = \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2 - v^2)^2 - c\sigma$$

Impact of fluctuations on EoS

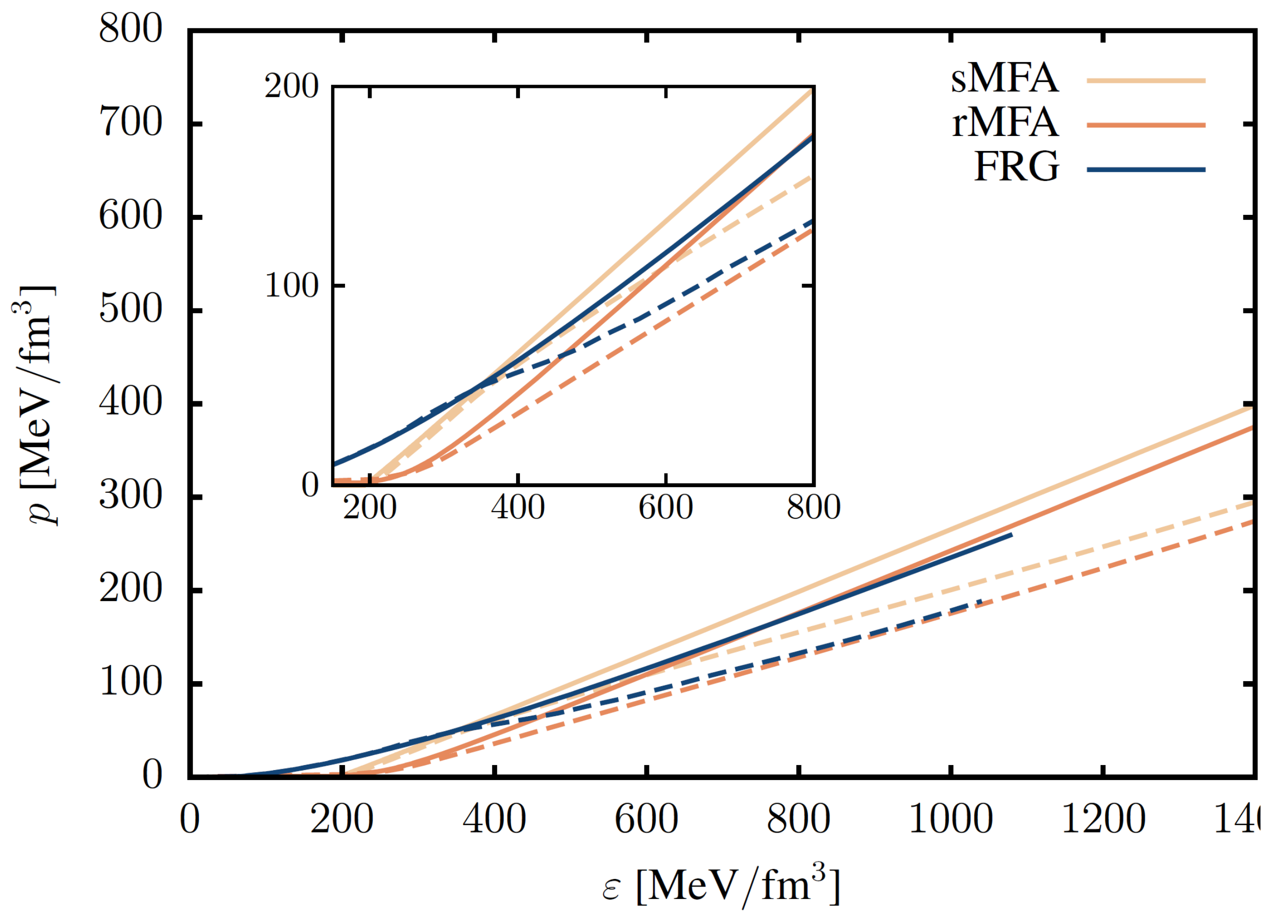
[Otto, Oertel, BJS 2020]

Impose β-equilibrium and charge neutrality conditions

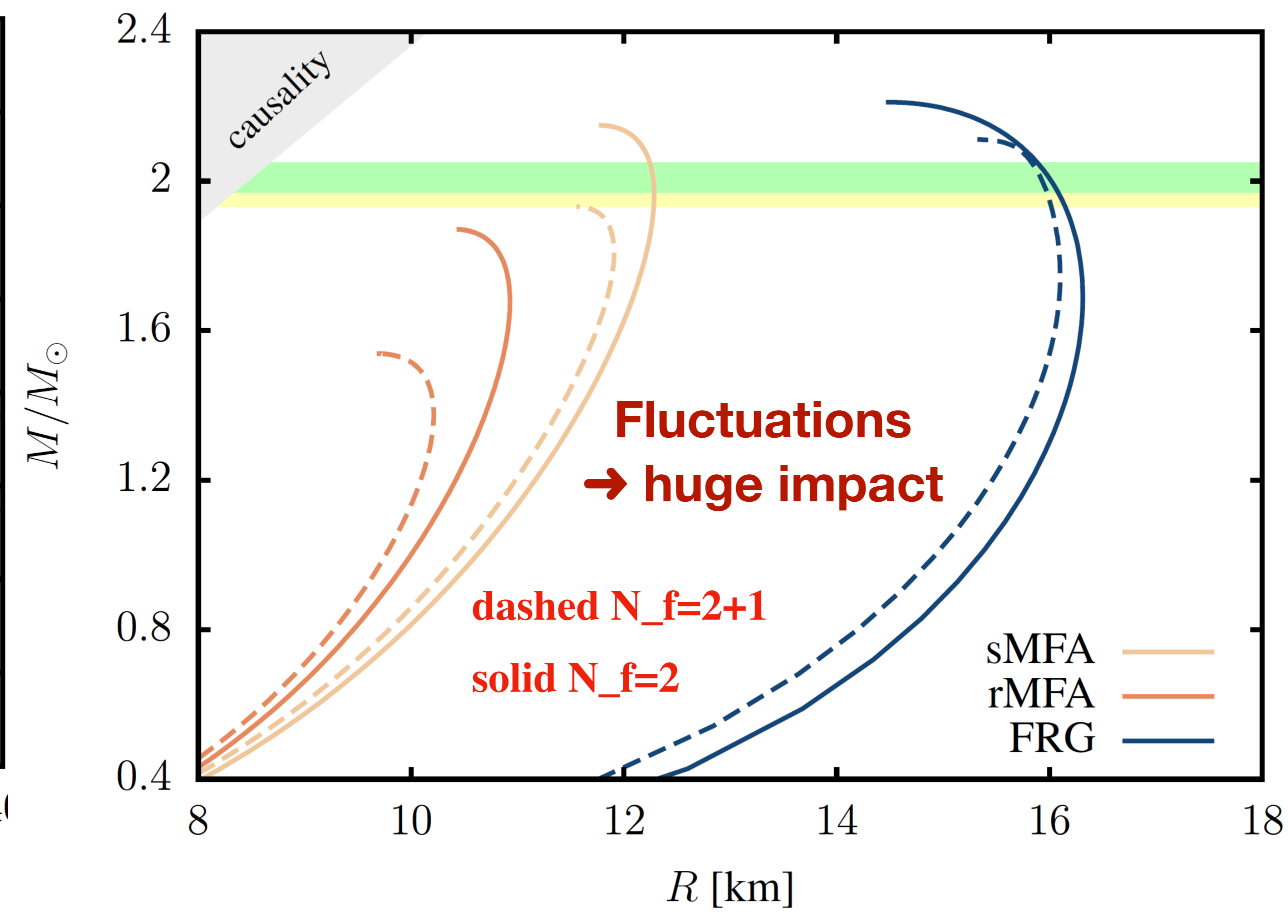
$$\mu_u = \mu_q - \frac{2}{3}\mu_e$$
$$\mu_d = \mu_q + \frac{1}{3}\mu_e$$
$$\mu_s = \mu_q + \frac{1}{3}\mu_e$$

Tolman-Oppenheimer-Volkoff equations

EoS



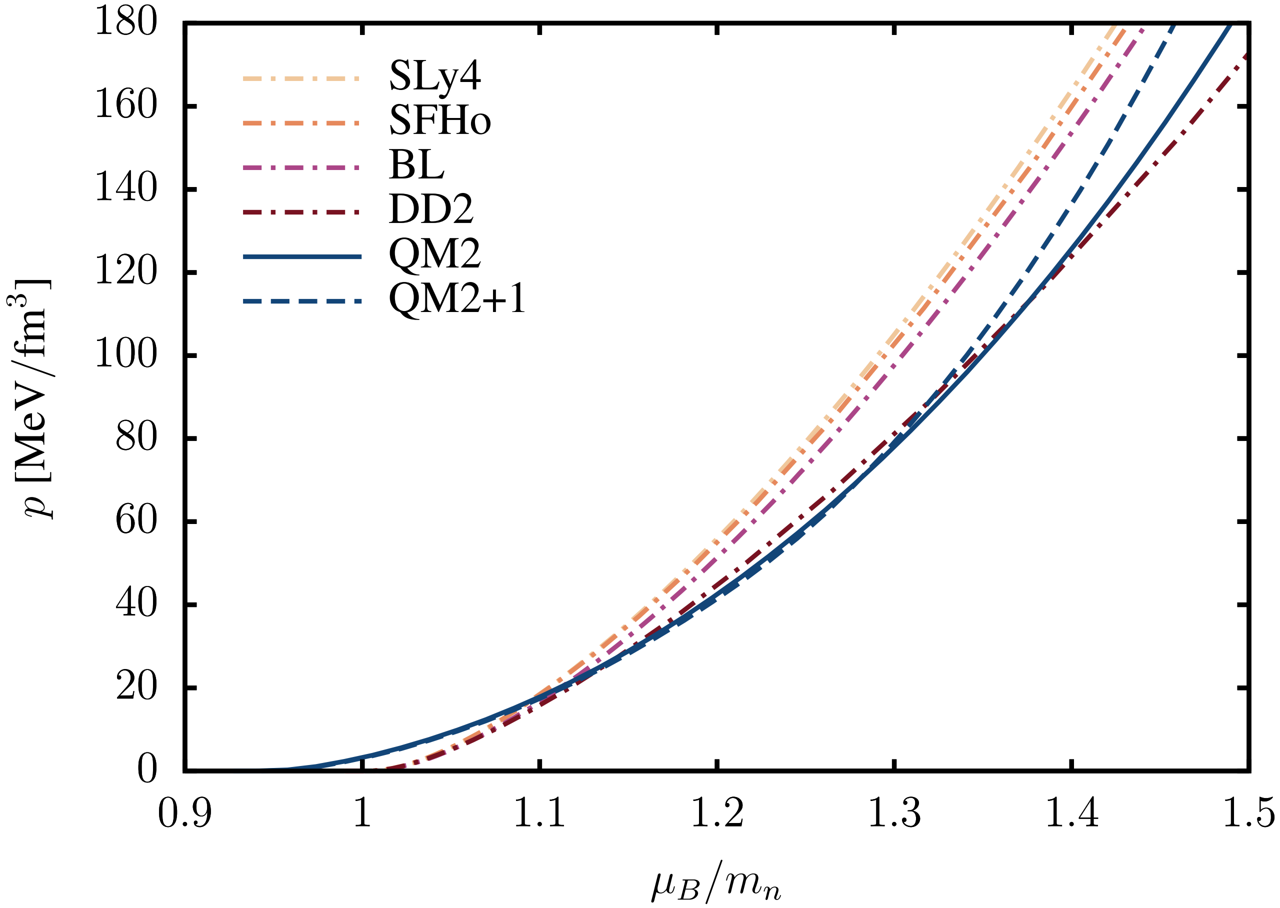
Mass-Radius relation

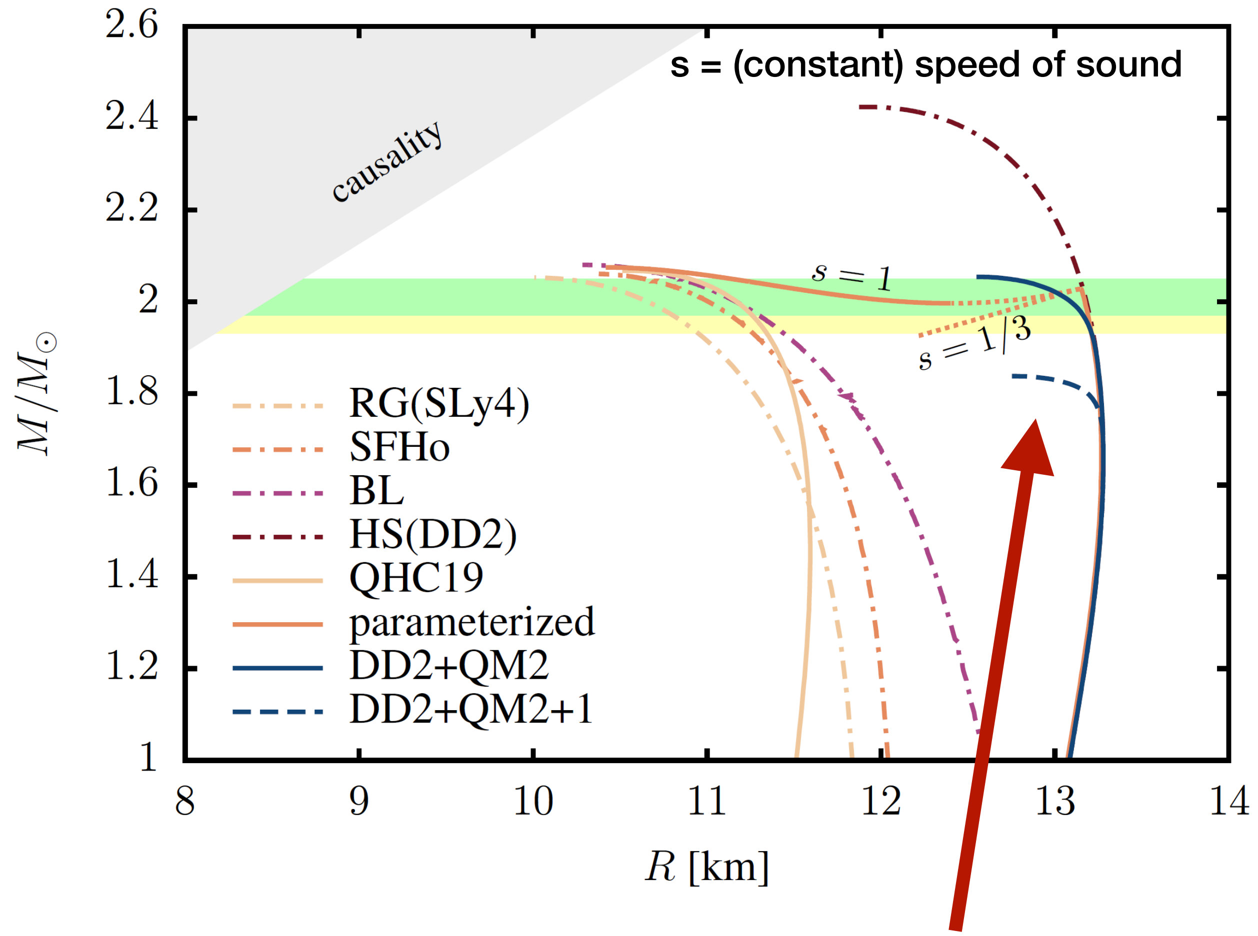


Hybrid star construction possible? - yes

[Otto, Oertel, BJS 2020]

combine nuclear EoS (DD2) with FRG QM truncation ➜ continuous nuclear-hybrid branch





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

can a repulsive vector interaction remedy this behavior?

vector mesons & the FRG EoS

[Otto, Oertel, BJS 2020]

[Rennecke 2015]
[Pereira, Stiele, Costa 2020]

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

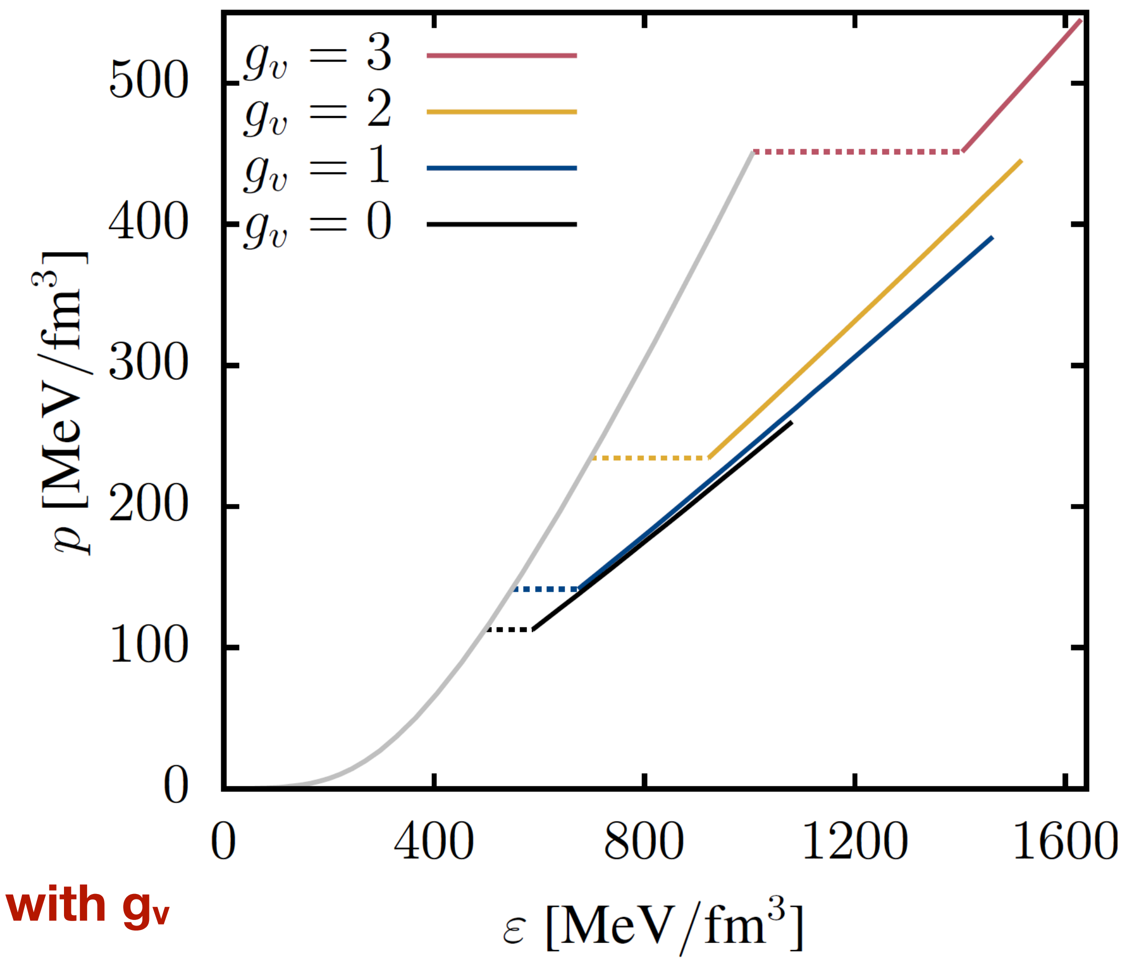
$$\Gamma_{\text{vec}} = \int_x \left[\frac{g_v}{2}\, \bar{q}\, \gamma_0\, \text{diag}_f(\omega, \omega, \sqrt{2}\phi)\, q - \frac{1}{2}\left(m_\omega^2 \omega^2 + m_\phi^2 \phi^2\right) \right]$$

- effectively shifts the chemical potentials:

$$\tilde{\mu}_u = \mu_q - \frac{2}{3}\mu_e - \frac{g_v}{2}\omega$$

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

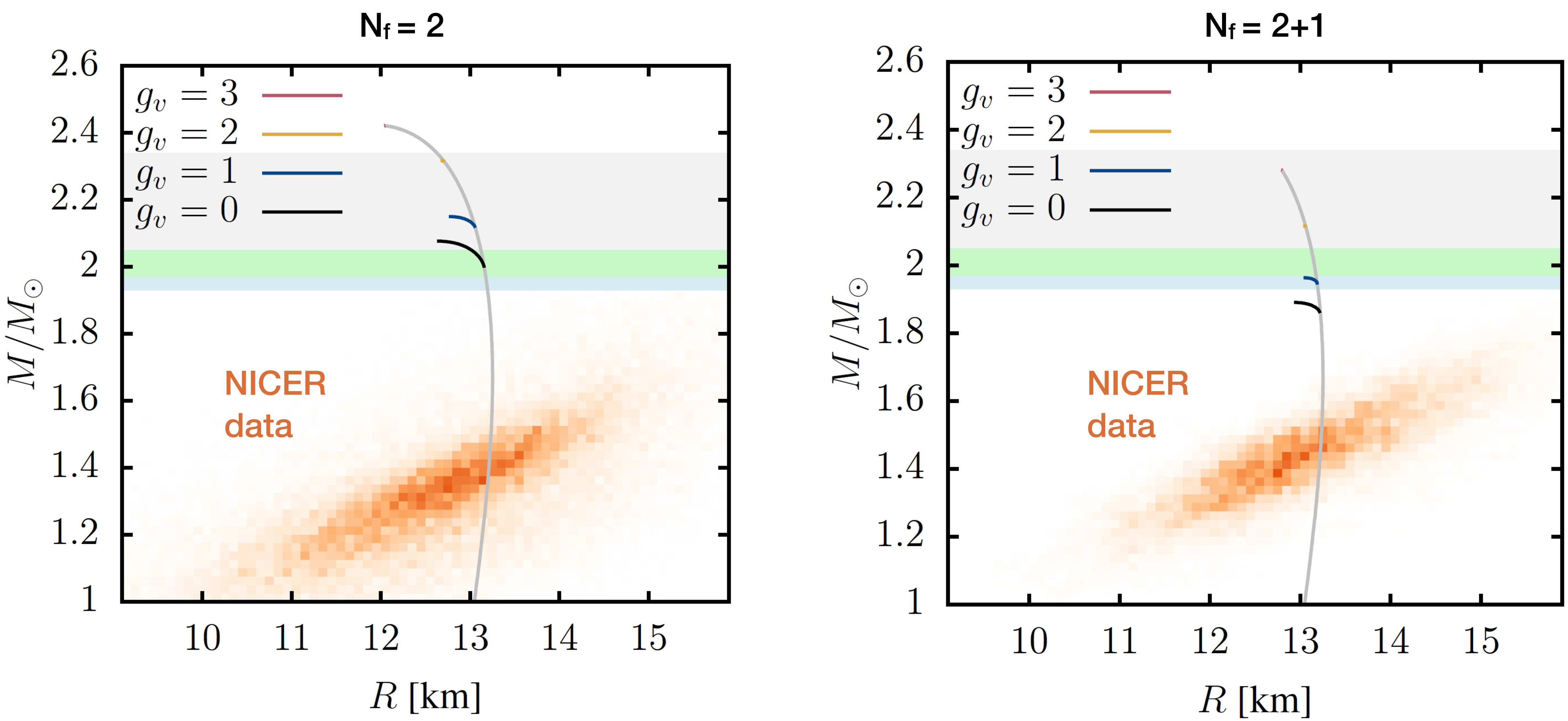
$$\tilde{\mu}_s = \mu_q + \frac{1}{3}\mu_e - \frac{g_v}{\sqrt{2}}\phi$$



➜ **energy gap and transition pressure increases with g_v**

Mass-Radius relations

[Otto, Oertel, BJS 2020]

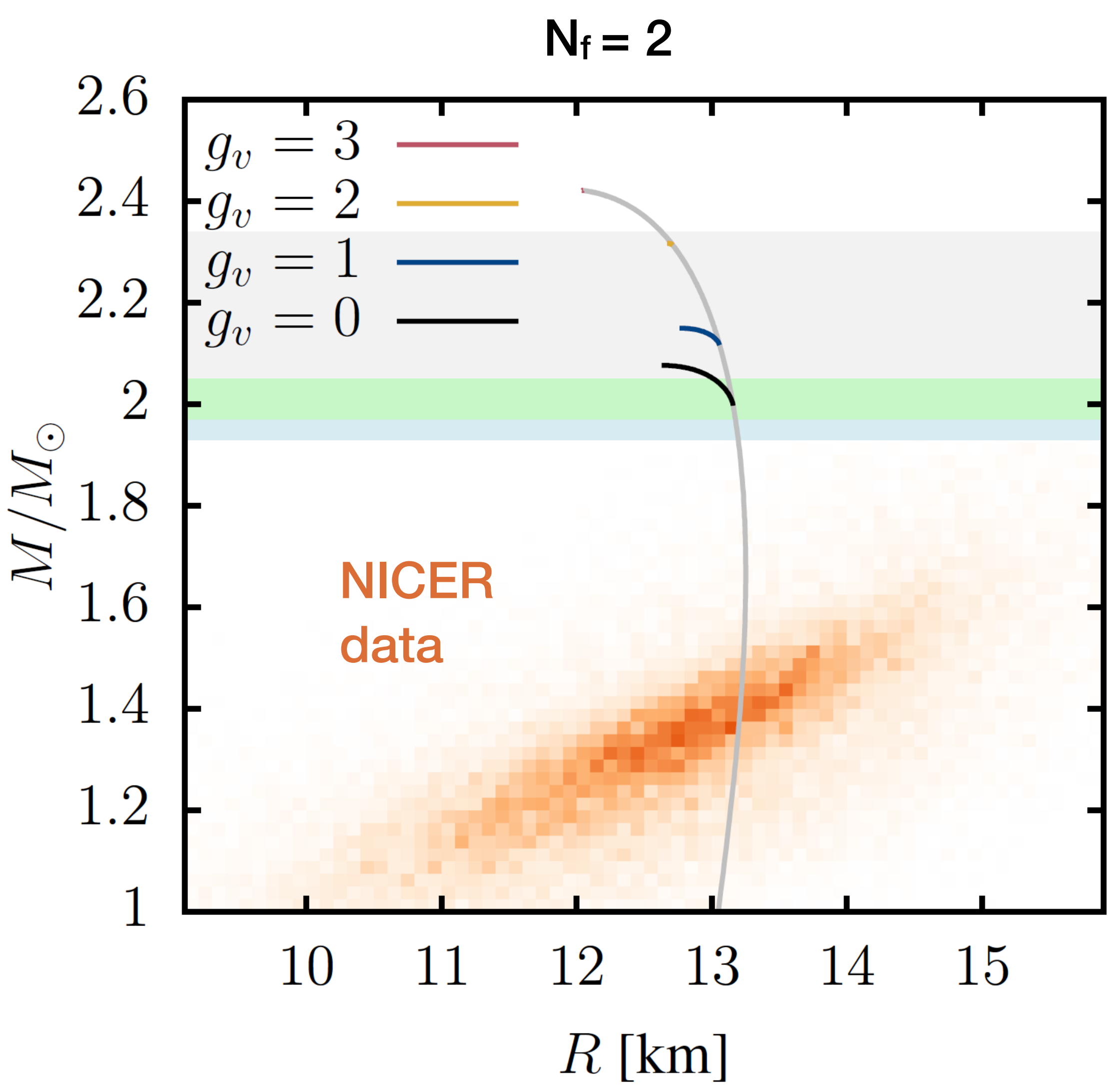


➜ including strange quarks: **finite vector coupling is needed to achieve $2M_\odot$ limit**

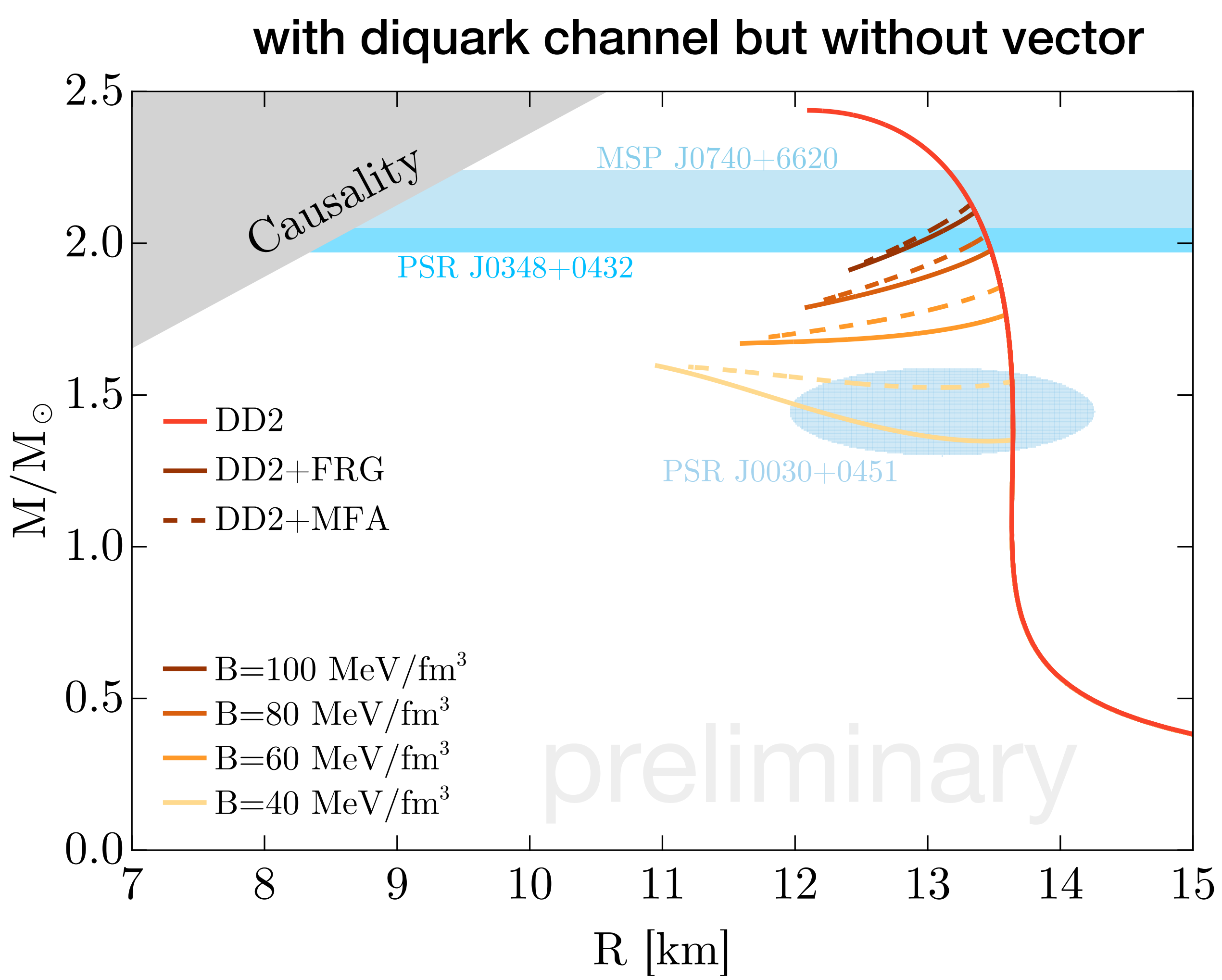
➜ at the same time: **larger vector coupling lead to smaller quark cores!**

Mass-Radius relations

[Otto, Oertel, BJS 2020]



[Mire, BJS … next talk]



➜ including strange quarks: **finite vector coupling is needed to achieve 2M$_\odot$ limit**

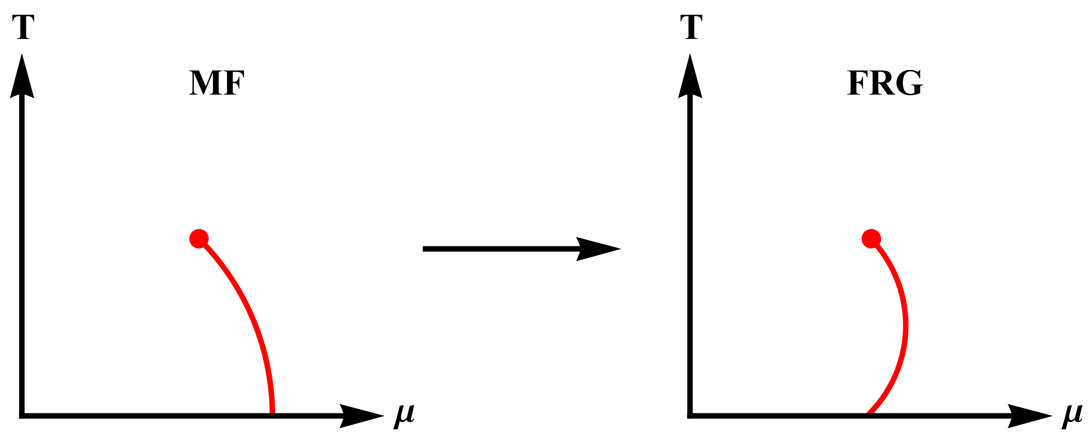
➜ at the same time: **larger vector coupling lead to smaller quark cores!**

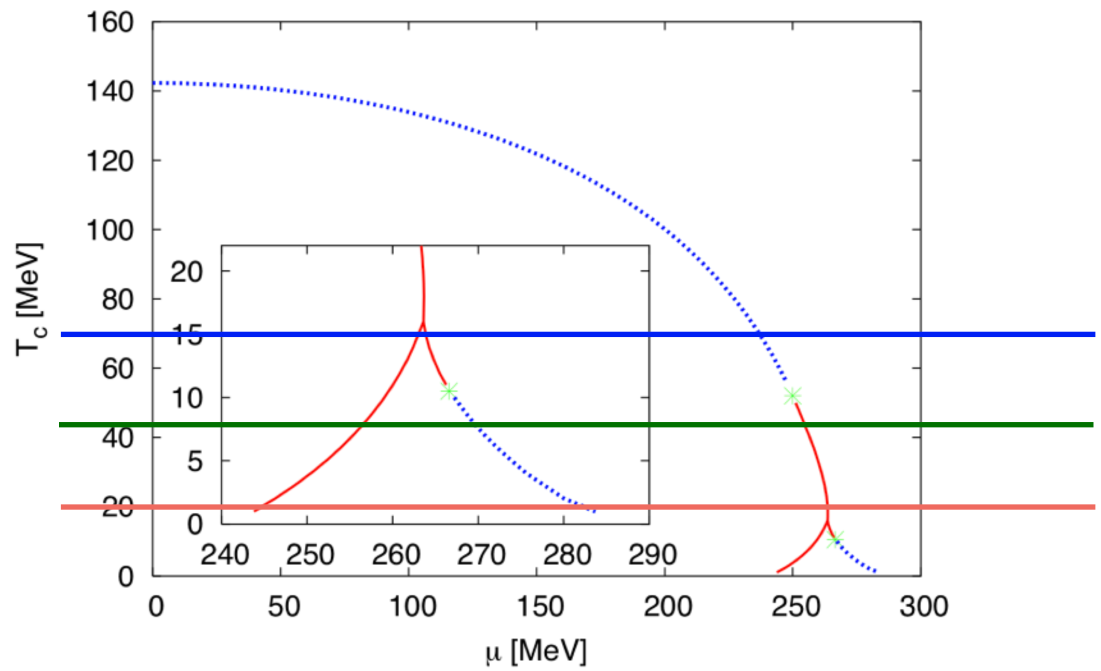
so far so good ... BUT

back-bending / negative entropy density

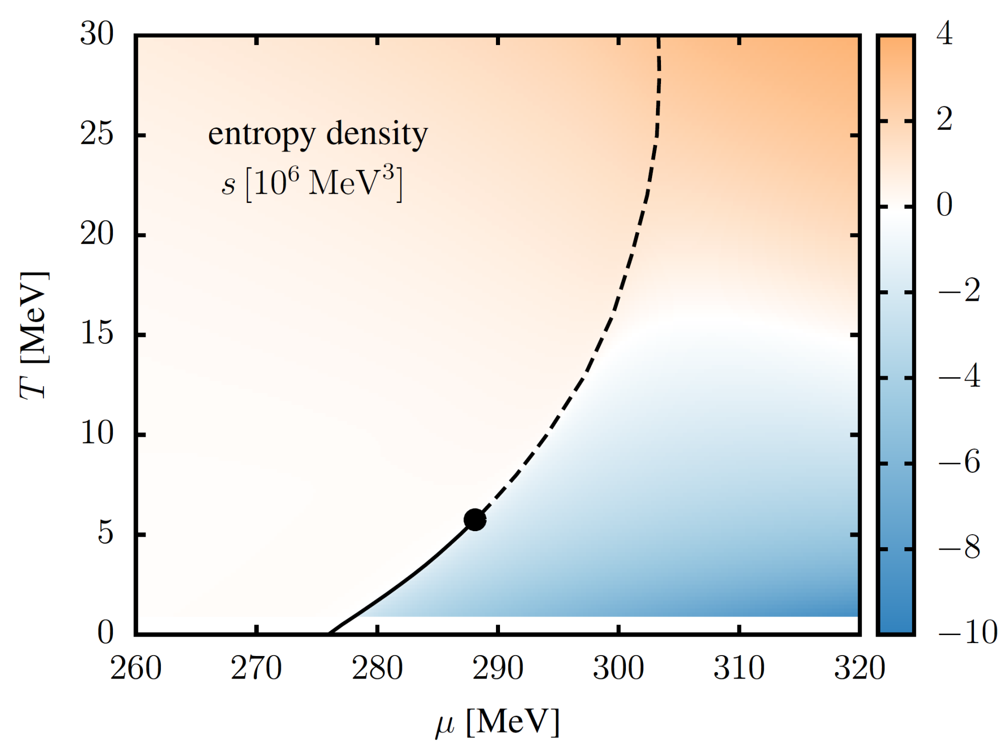
[R-A Tripolt, BJS, L von Smekal, J Wambach 2018]

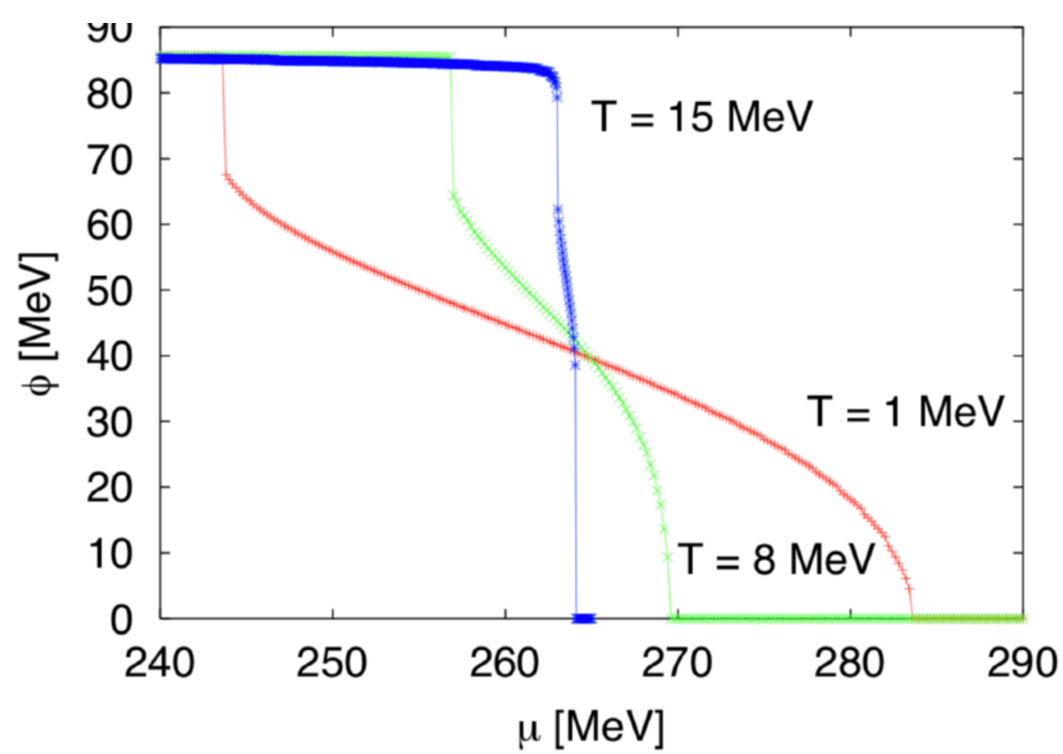
[BJS, Wambach 2005]





- Phase diagram quark-meson model
- Entropy density: s/T^3





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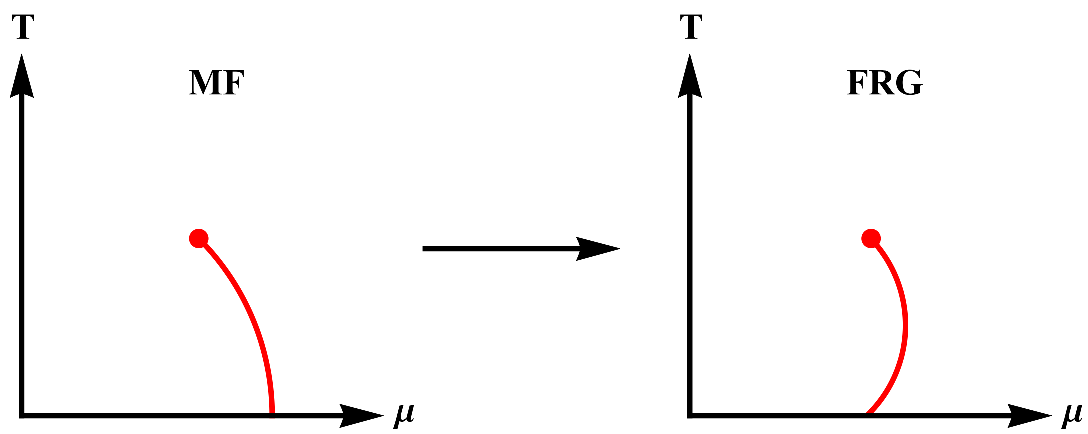
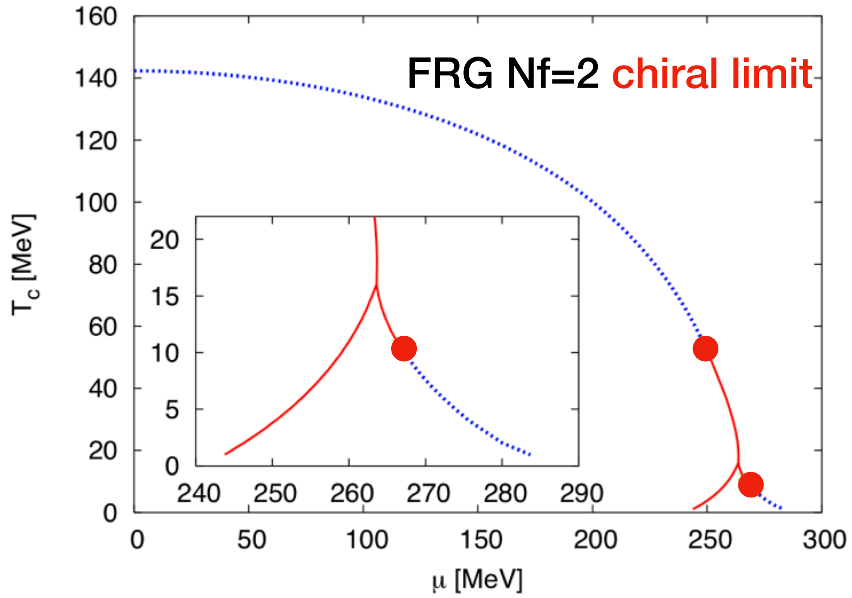


[BJS, Wambach 2005]



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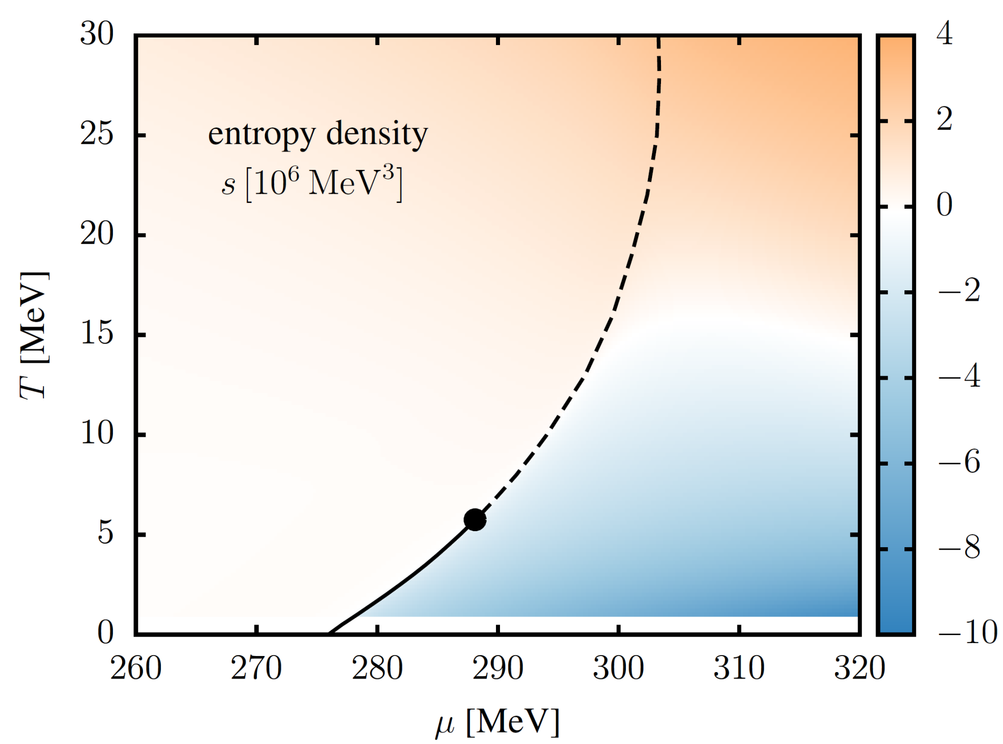

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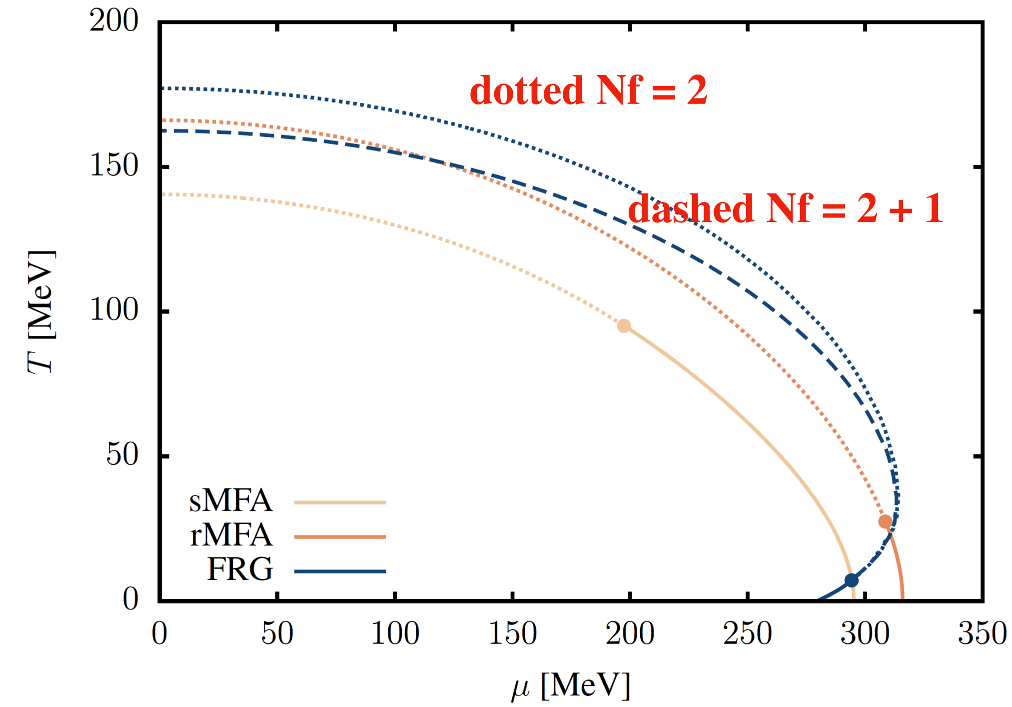

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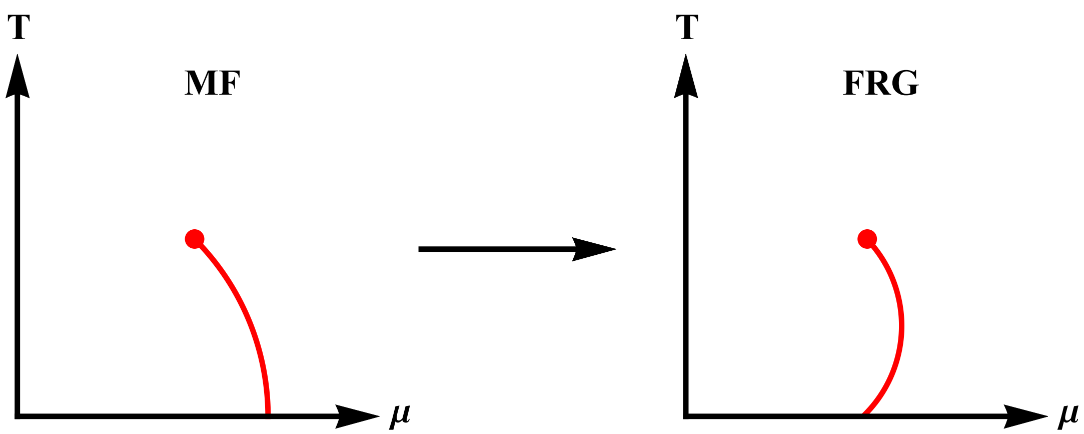

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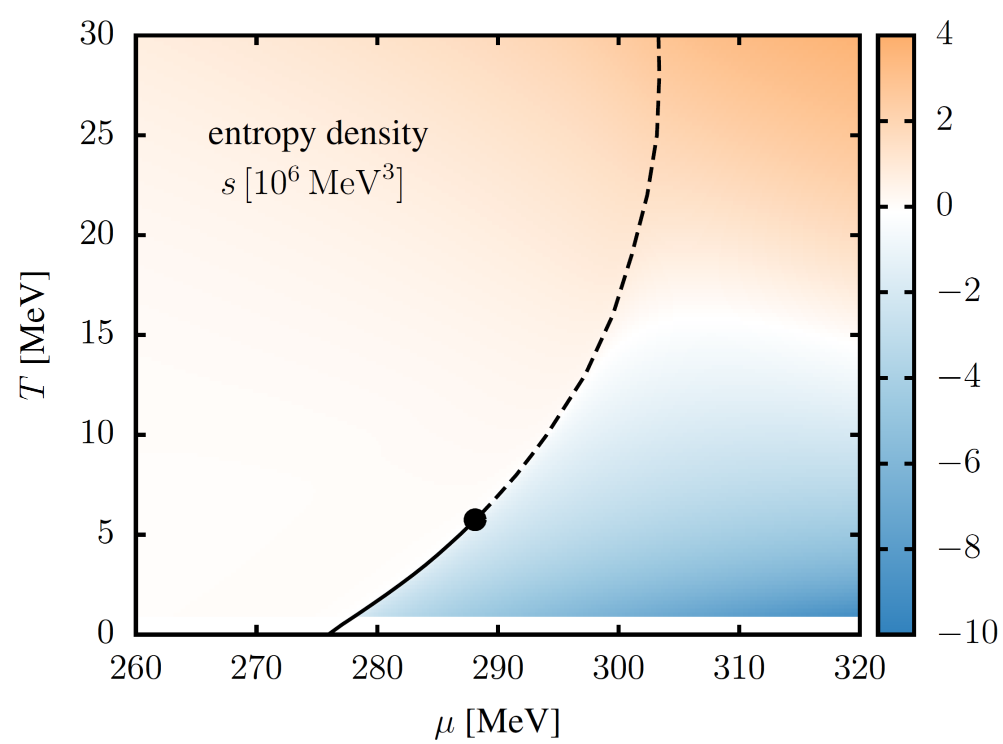
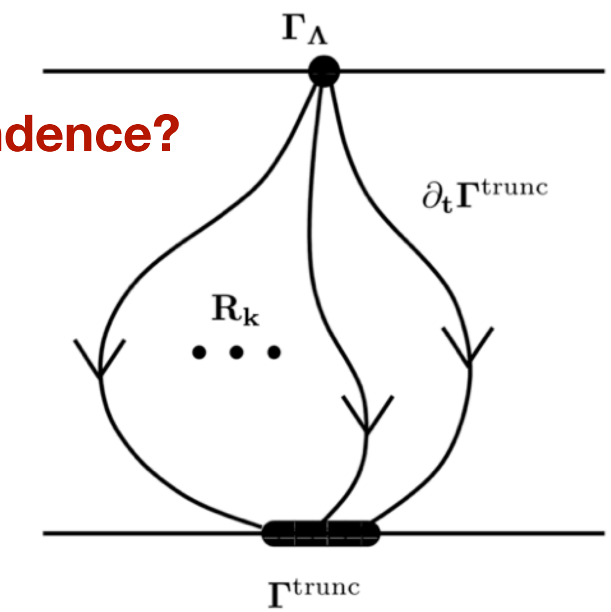


➜ **Regulator scheme dependence?**

less pronounced when more channels are included
e.g. pairing channel
s. next talk by Ugo Mire



- fermionic regulator

$$R_k^F(p,\mu) = R_k^F(\tilde{p},0) \qquad \tilde{p} = \begin{pmatrix} p_0 + i\mu \\ \vec{p} \end{pmatrix}$$

shift required to preserve **Silver Blaze** property (T=0)

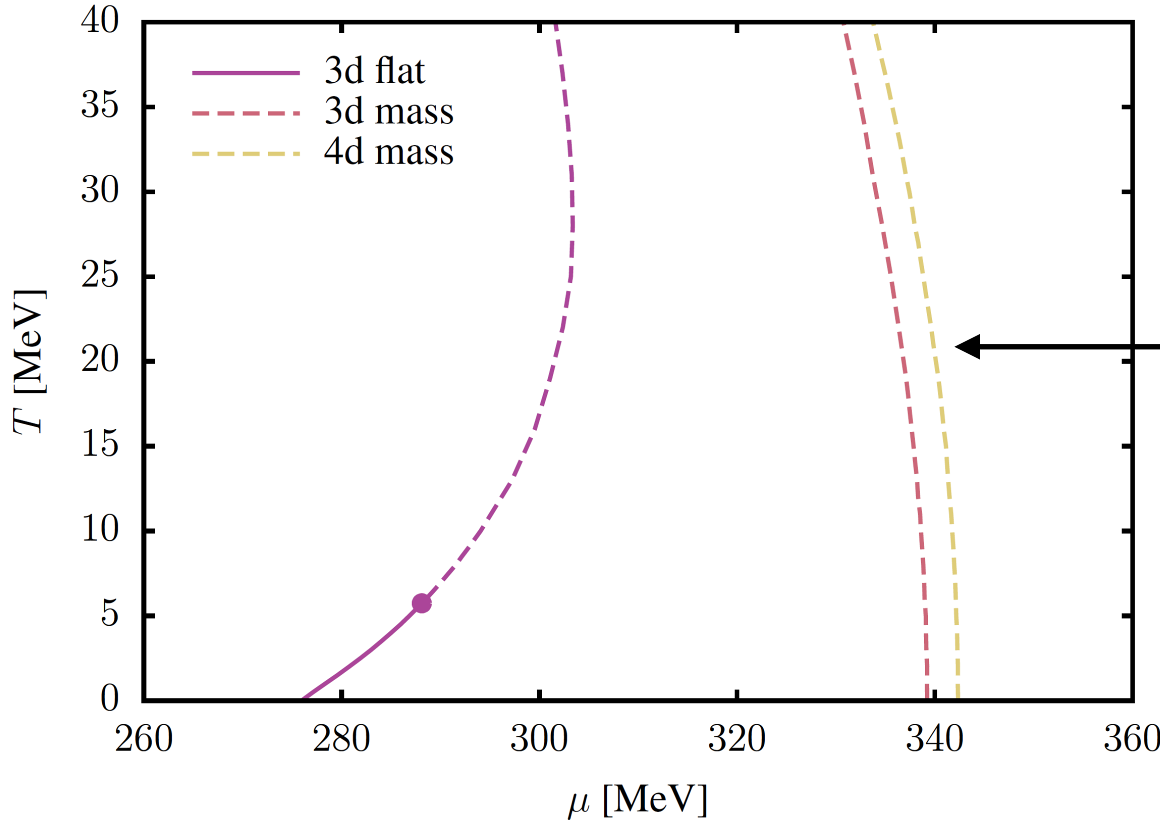
(necessary but not sufficient)

- relative shift in the cutoff-scales between bosonic & fermionic regulator
  ➜ is needed beyond LPA

  e.g. field-dependent Yukawa-coupling

  (multi quark-antiquark-meson scatterings)

Chiral transition at low temperature



no back-bending with

Callan-Symanzik mass-like regulator

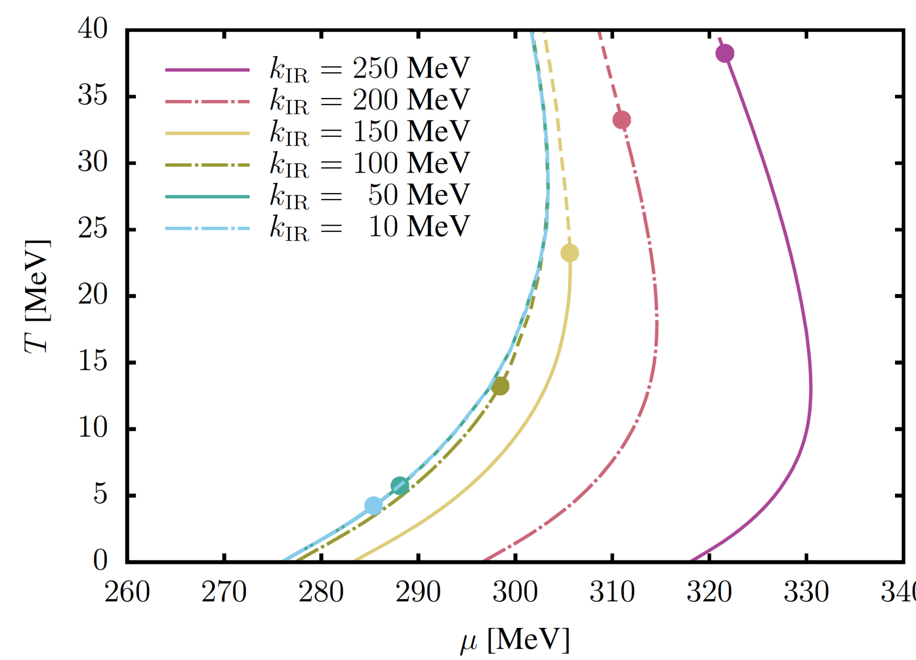
small differences between 3d and 4d regulators

purely crossover ➜ pseudocritical μ_c
larger than m_q

could finite IR cutoff play a role? ➜ No

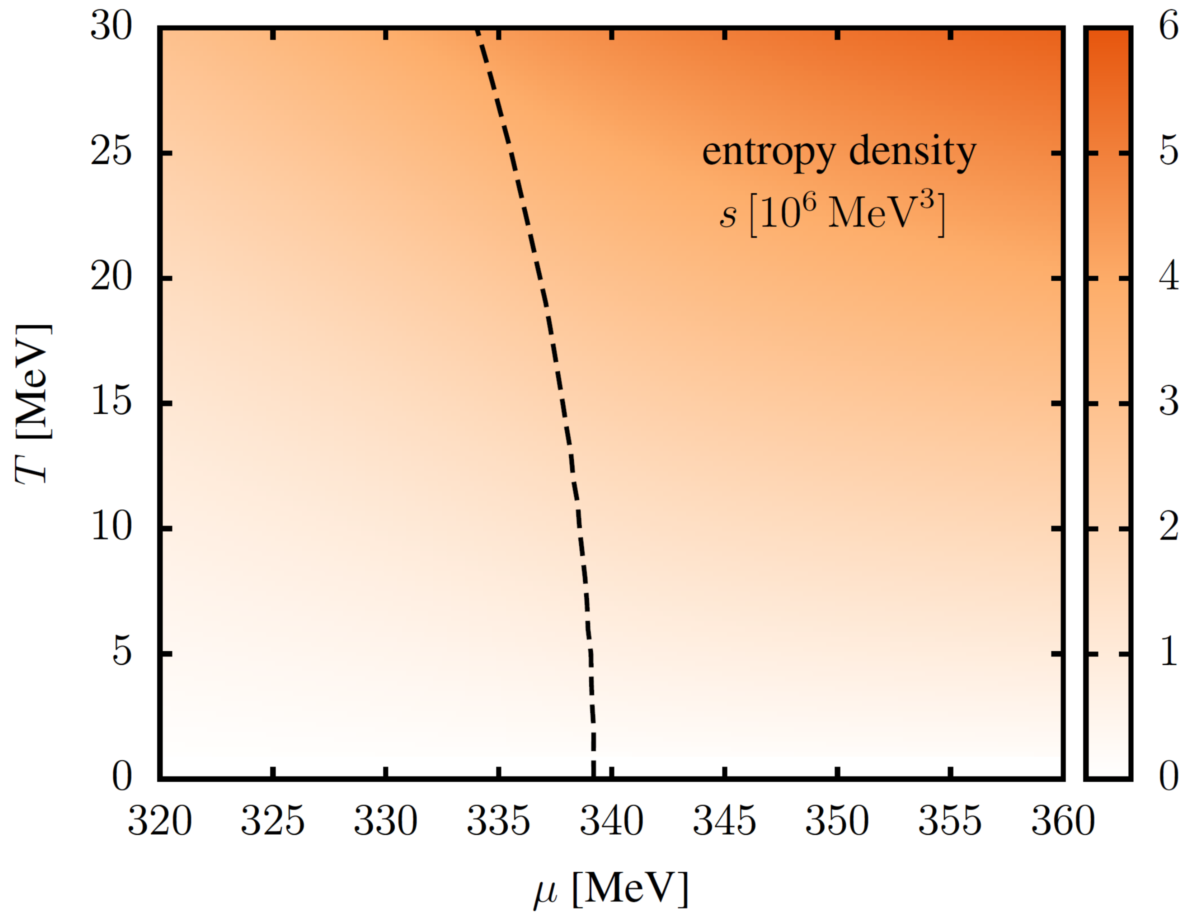
transition line shifts and CEP moves down

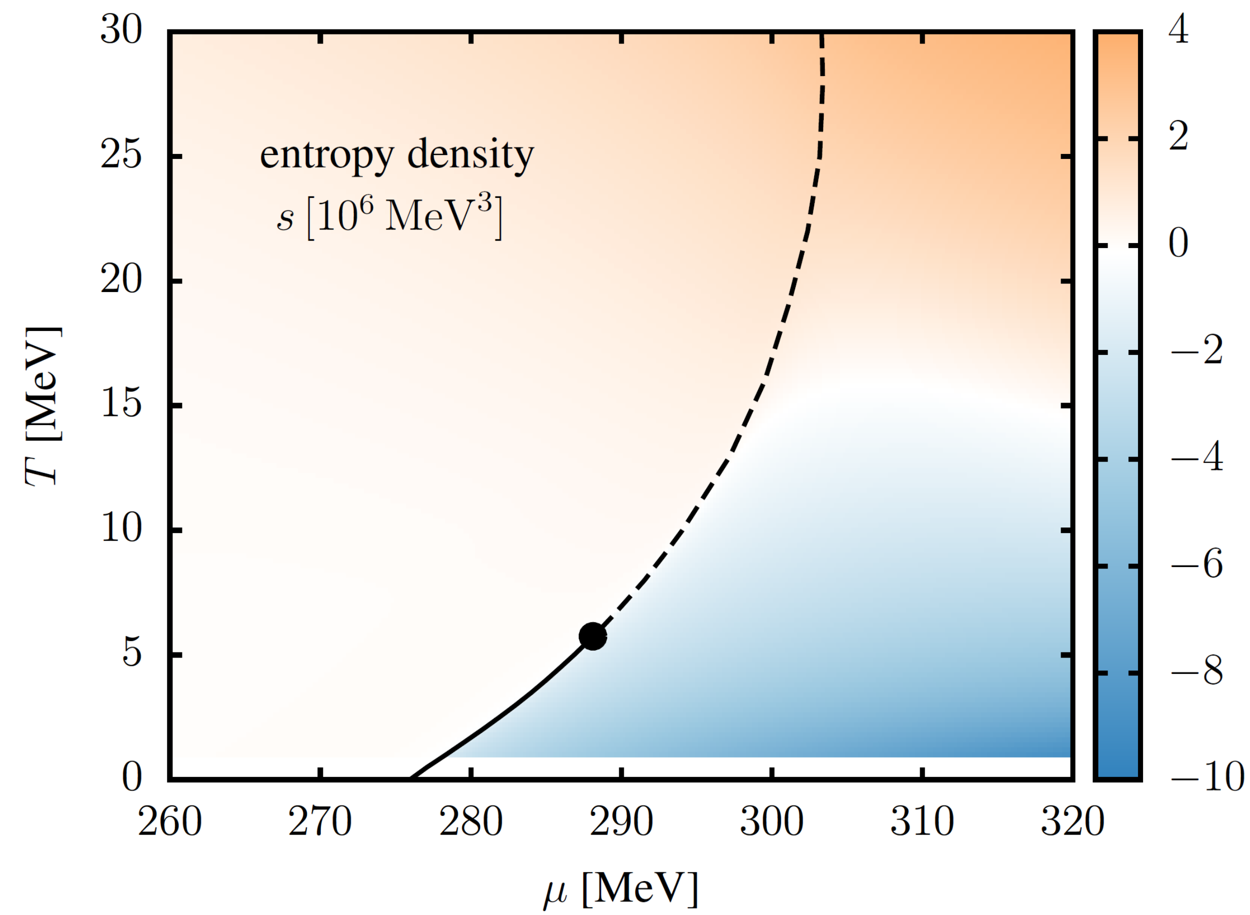
but back-bending over large k_{IR} range



Chiral transition at low temperature

➜ no negative entropy density anymore for Callan-Symanzik mass-like regulator





EoS from QCD

[Braun et al. 2012++]

- QCD procedure: start @O(100 GeV) (deep high-energy perturbative region)

Λ ~ O(10GeV) quarks, gluons

- symmetric regime

quarks, gluons ➜ mesons

k_Φ

- symmetry-broken regime

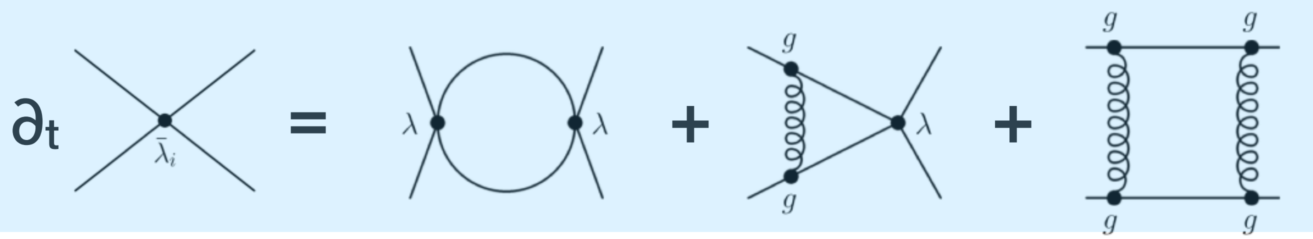
quarks, diquarks, mesons etc

k_{IR}

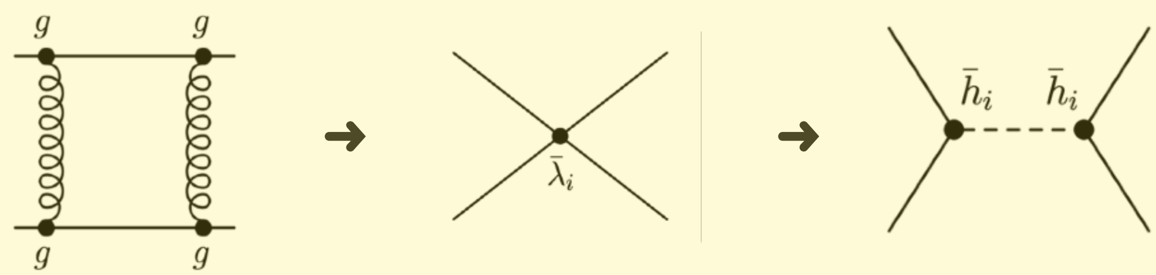
$$S = \int \mathrm{d}^4x \left\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{\psi} \left(\mathrm{i}\not{\partial} + \bar{g} \not{A} + \mathrm{i}\gamma_0 \mu \right) \psi \right\}$$

- quark-gluon vertex ➜ many quark self-interaction channels
- dynamical hadronisation:

  4-quark correlators ➜ bound states /resonances



- general picture:



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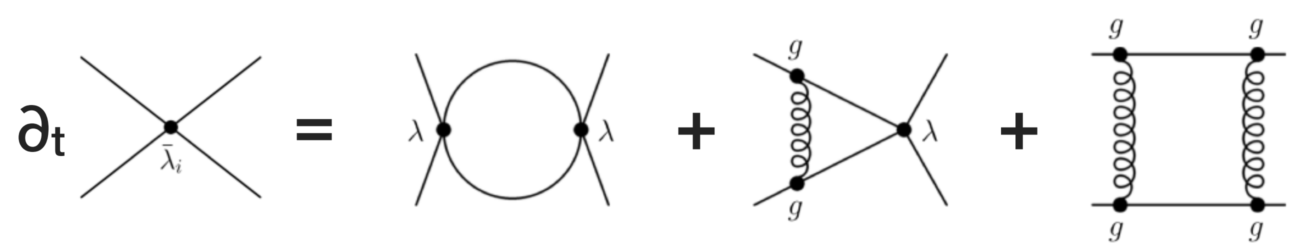
quarks, diquarks, mesons etc

k_{IR}

$$S = \int \mathrm{d}^4x \left\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{\psi} \left(\mathrm{i}\partial\!\!\!/ + \bar{g} A\!\!\!/ + \mathrm{i}\gamma_0 \mu \right) \psi \right\}$$



- symmetry breaking ➜ condensates

➜ onset Landau-pole-type behavior
λ ~ 1/m

➜ Ginzburg-Landau effective potential

Quark-meson-diquark truncation

EoS from QCD

- QCD procedure: start @O(100 GeV) (deep high-energy perturbative region)

[Braun et al. 2012++]

Λ ~ O(10GeV) quarks, gluons

- symmetric regime

quarks, gluons ➜ mesons

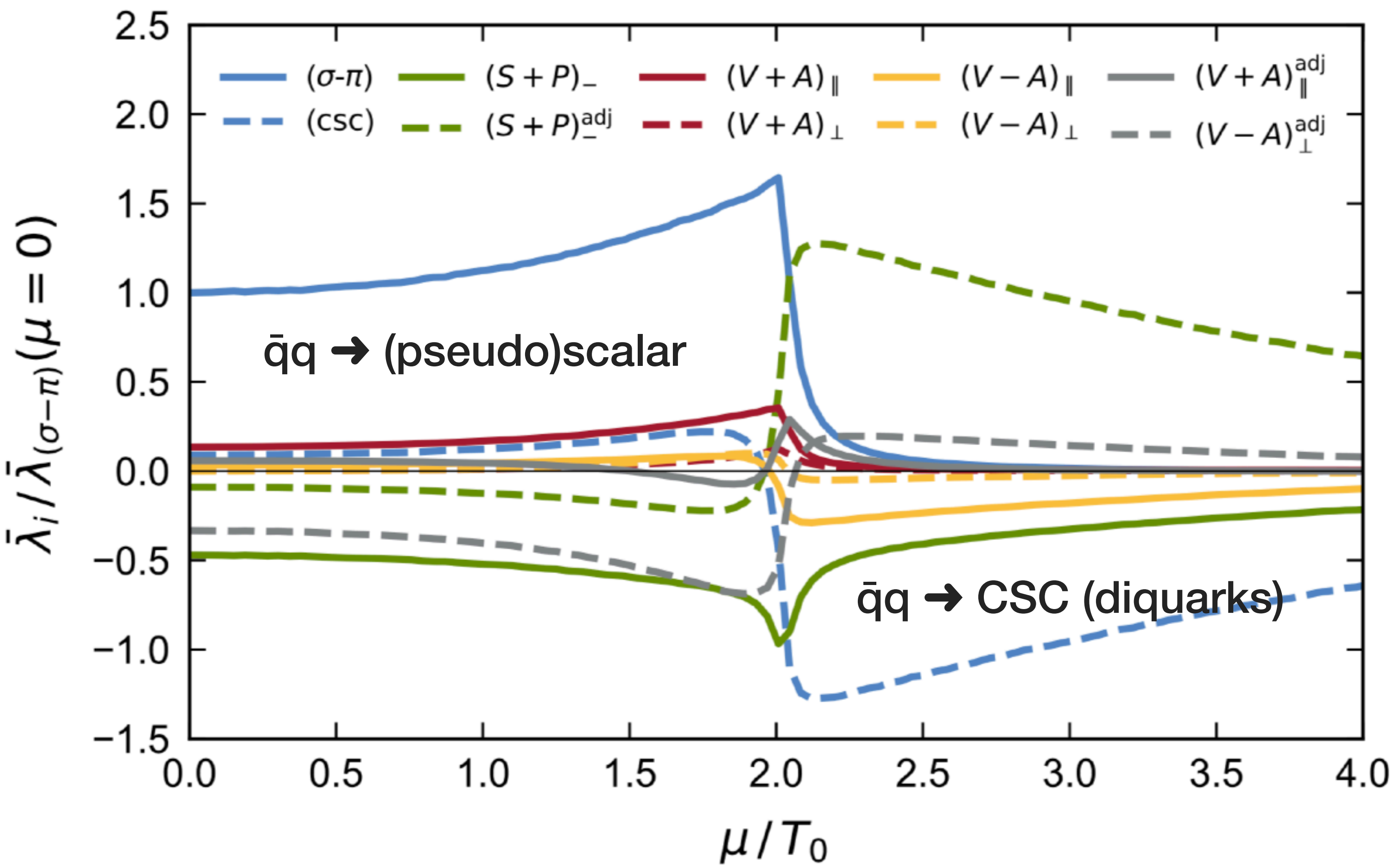
k_Φ

- symmetry-broken regime

quarks, diquarks, mesons etc

k_{IR}

[Braun et al. 2020]



Summary

Three home messages:

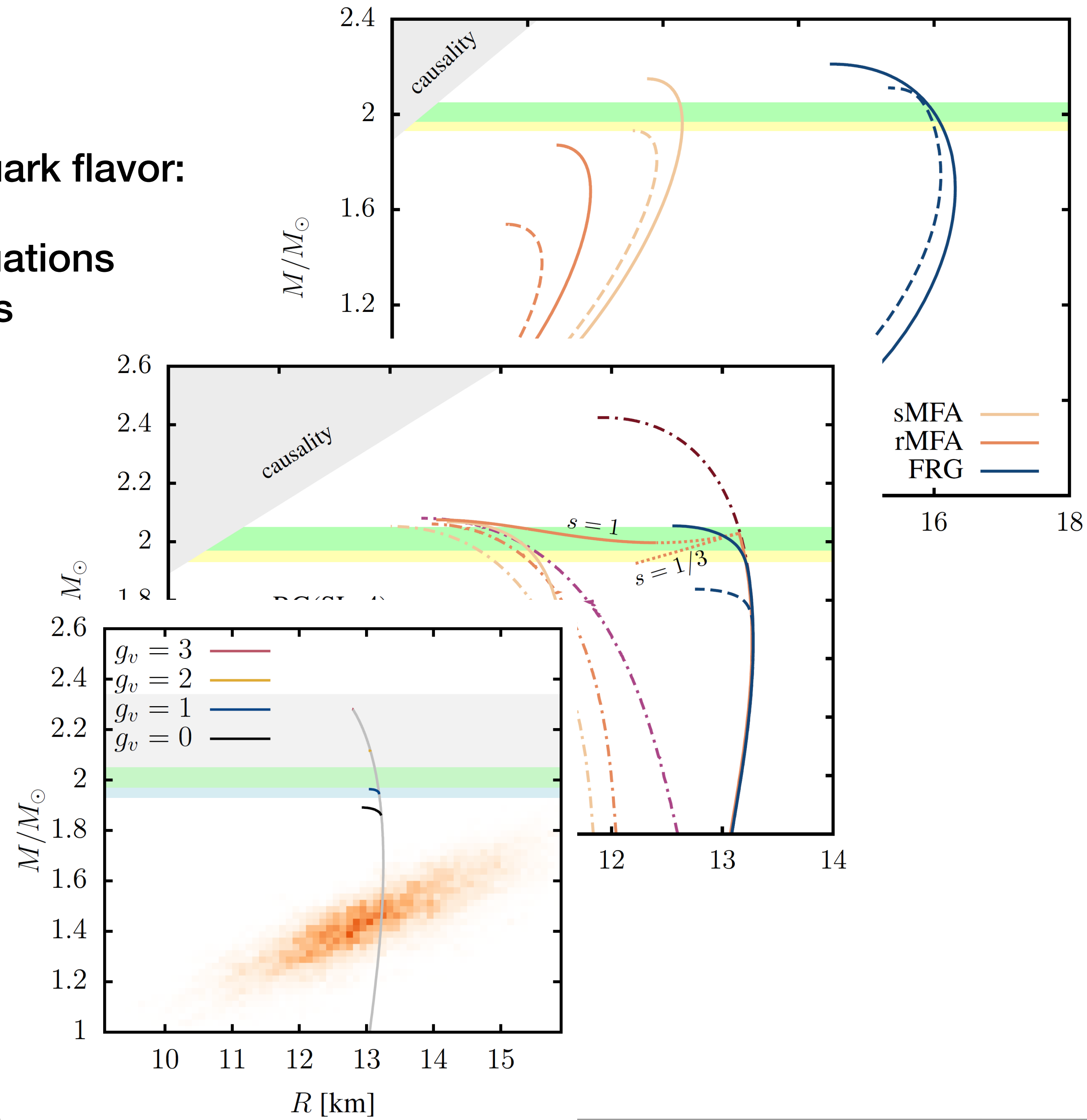
1. EoS with the FRG for two and three quark flavor:

   ➜ significant impact of fluctuations on M-R relation for NSs

2. hybrid stars are possible

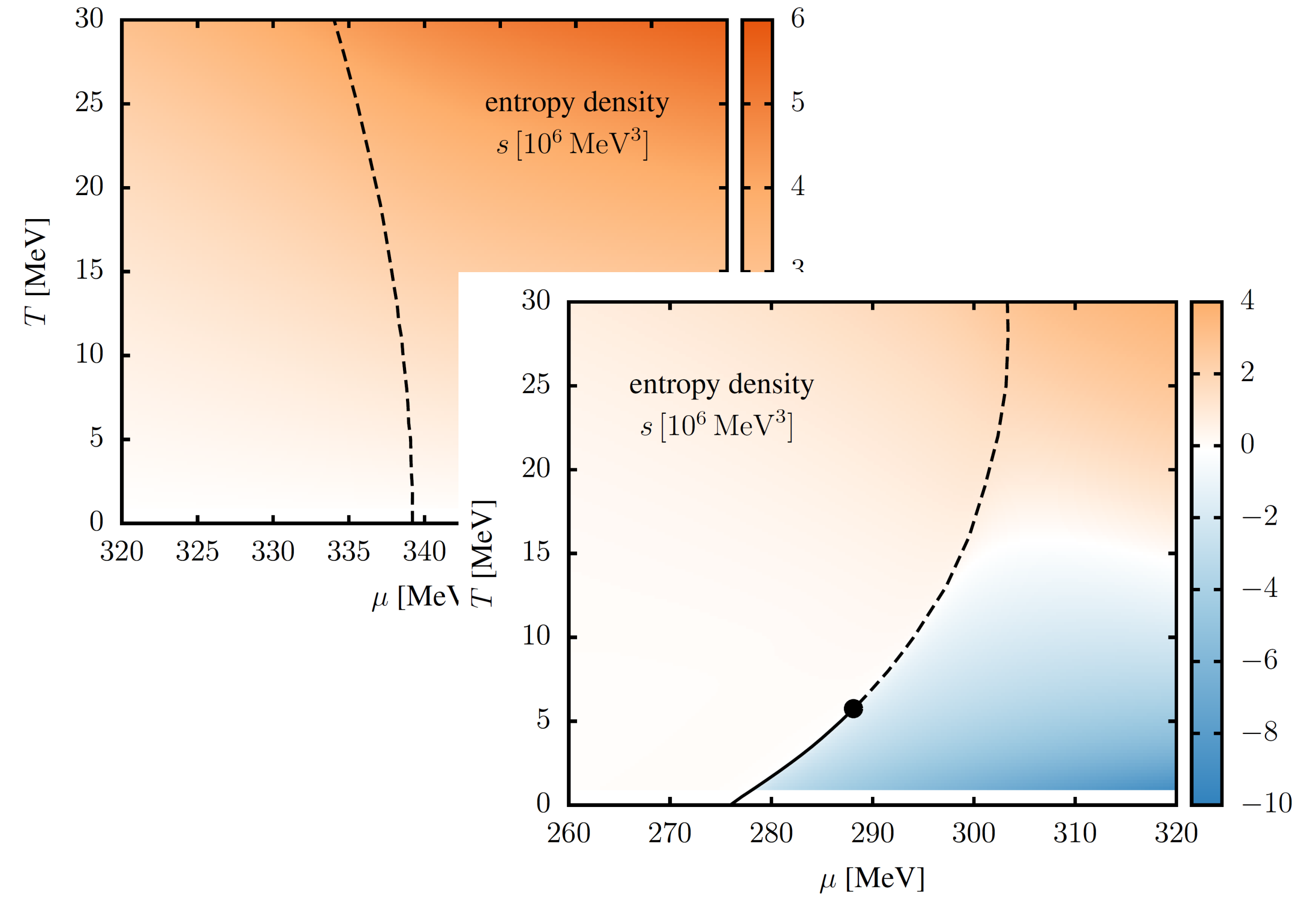
Non-zero vector coupling needed
➜ to reach 2 M⊙ with strangeness

similar findings with pairing channels
see next talk by Ugo Mire



Summary

3. in LPA no back-bending / negative entropy density
   for
   CS mass-like regulators



CS type regulators closer to

poles compared to flat regulator

➜ (vacuum) flows numerically harder