Quark matter in Neutron Stars

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FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

From first-principles QCD to experiments

May 22 – 26, 2023
ECT*

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.)

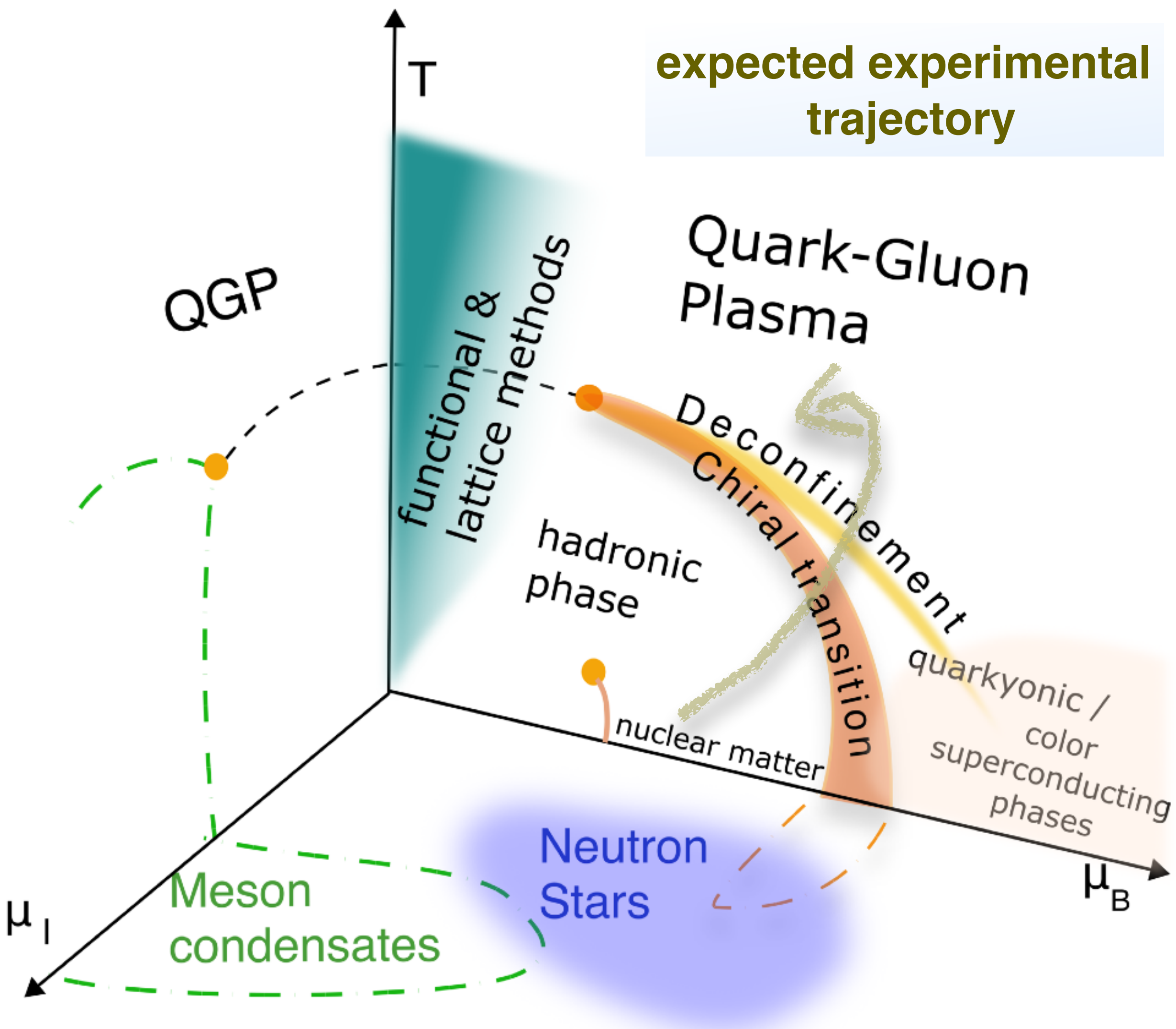
  Published in: *Eur.Phys.J.ST* 229 (2020) 22-23, 3629-3649 • e-Print: 2007.07394 [hep-ph]

- **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

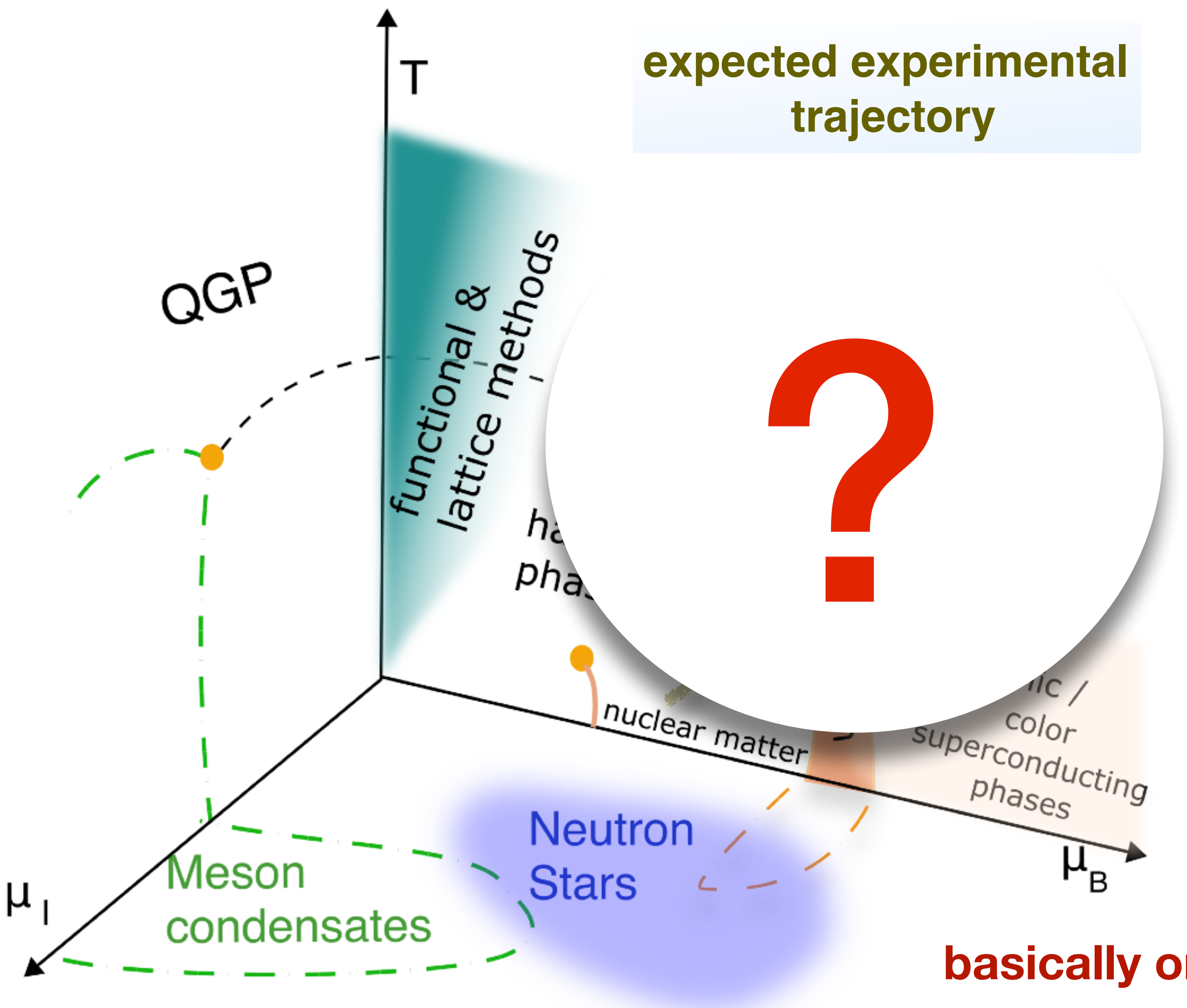


Open issues

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

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

conjectured QCD phase structure



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- ….

basically only corners known from first principle QCD

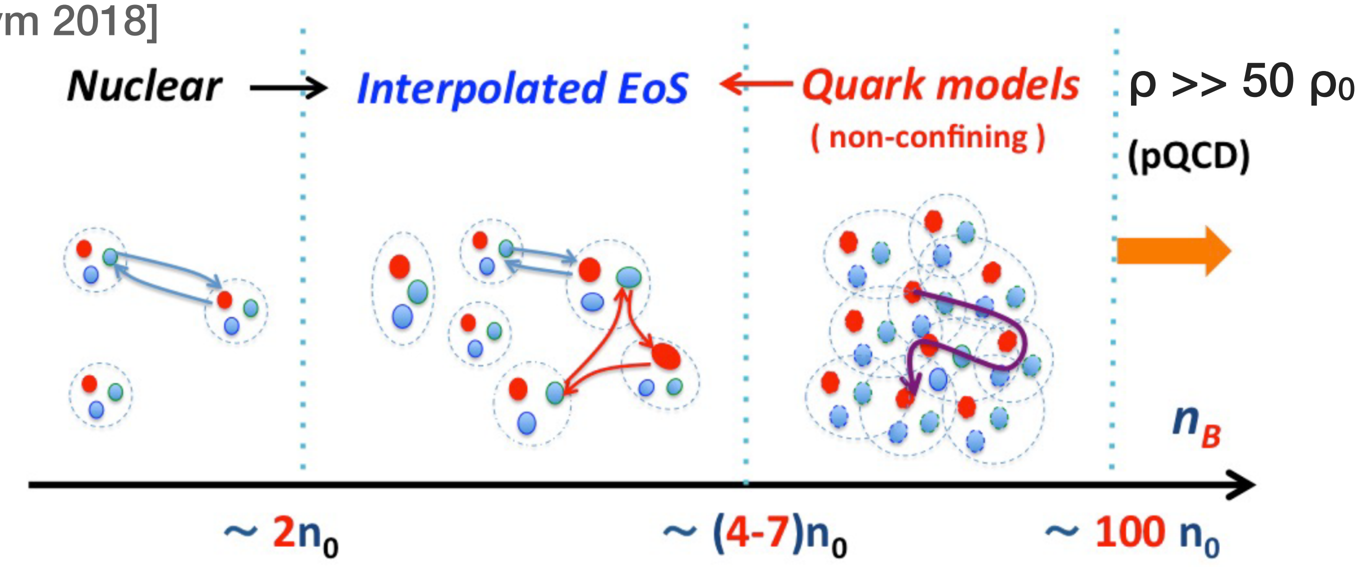
alternative to HIC to probe cold dense QCD matter ➜ **massive neutron star** (e.g. J0348+0432 ,…)

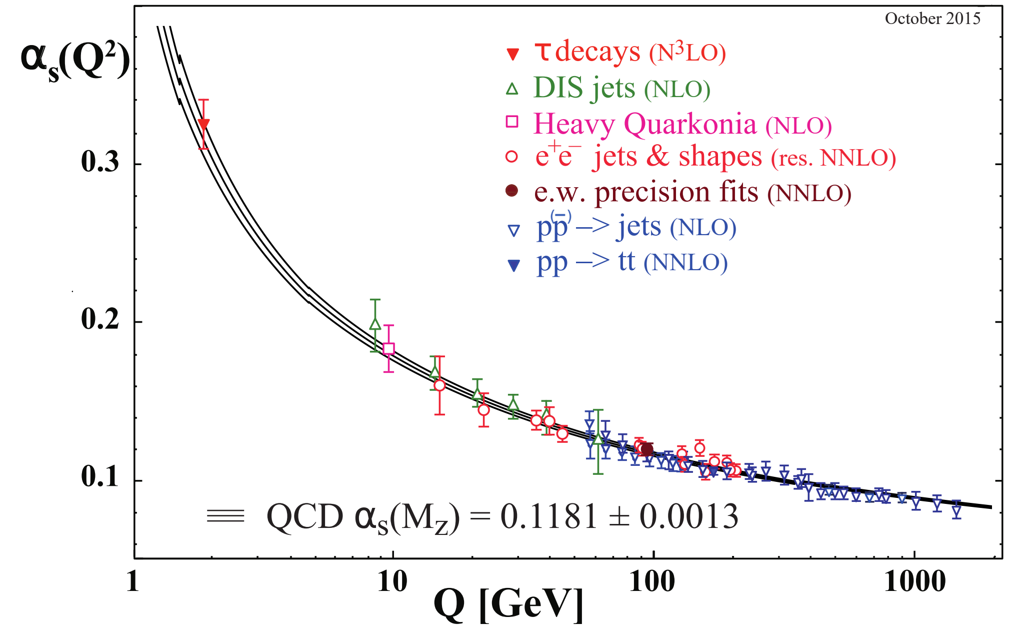
cold dense QCD matter: **only effective low-energy realisation** of QCD: e.g. (P)QM models

deconfined quarks very likely not a realistic description of neutron stars

Equation of State (EoS) for 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

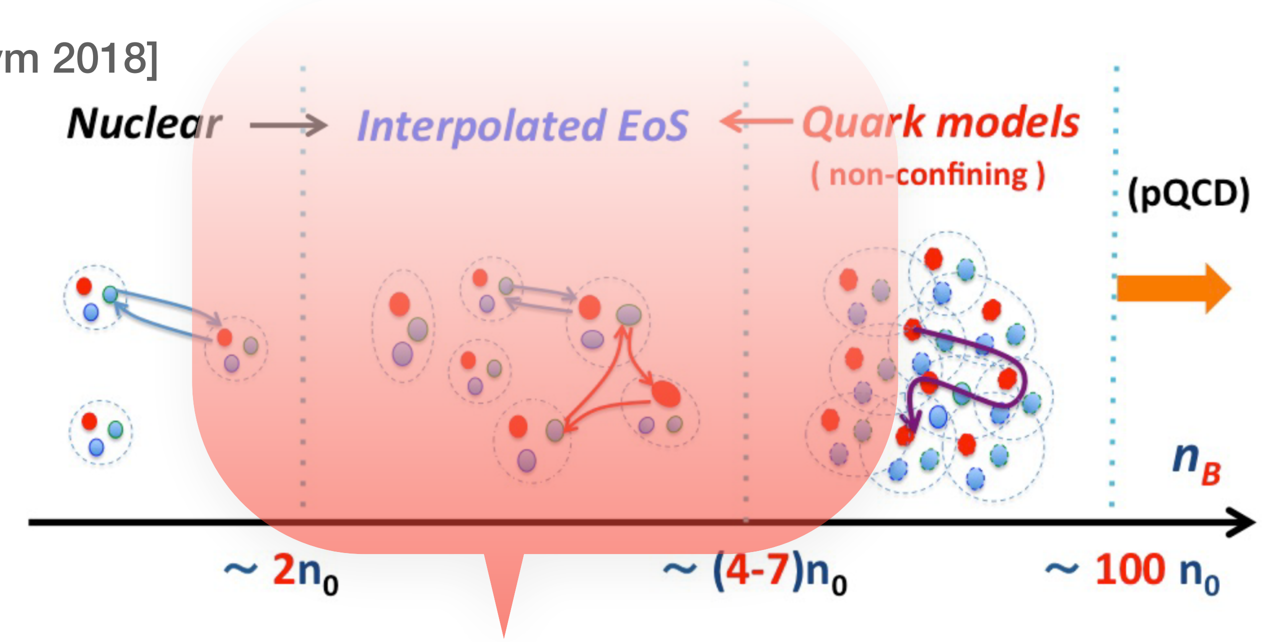
mostly **mean-field investigations** like NJL-type or phenomenological models

➜ upgrade with FRG methods

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

Experimental Facts

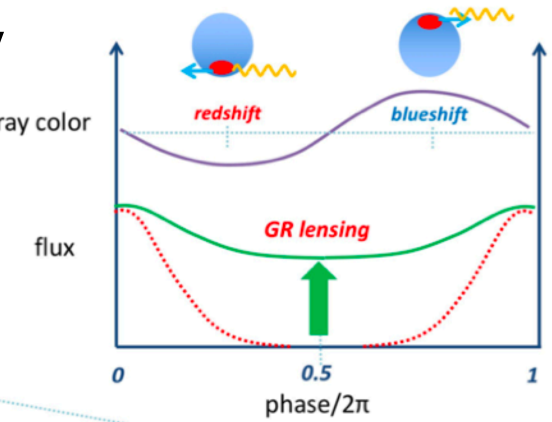
[Baym 2018]

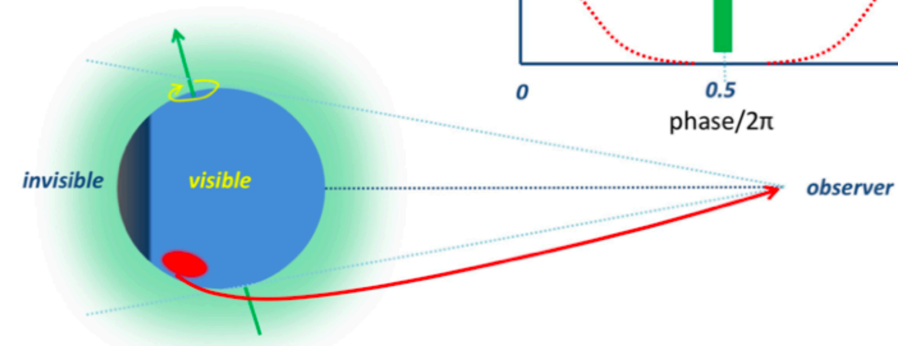


nearest ~ 400 ly

R ~ 10 - 13 km

M > 2 Msol



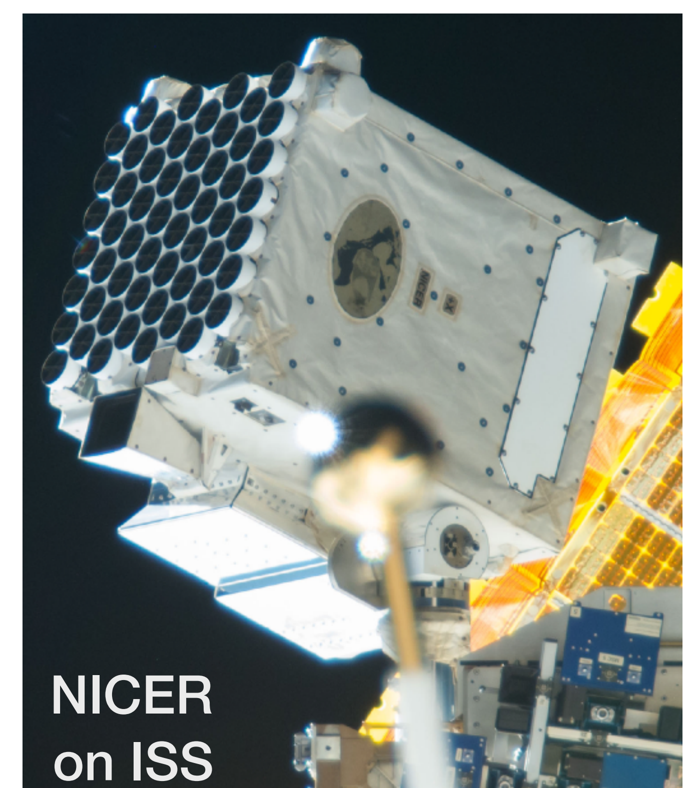


- M_{max} = 2.05 M_o & R ~ 12.8 km ; $\rho_{central}$ ~ $5\rho_0$
- M = 1.4 M_o & R = 12,8 km ; ΔR = 0
- M = 2.4 M_o & R = 12,8 km ; ~ as 1.4 M_o stars
- <u>PSR J0740+6620 & J0030+0451</u>
  both M (> M_o) & R measured
  GW170817 constraints tidal deformability -> R
- **detection phase transition possible:**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

future: ~ 2035

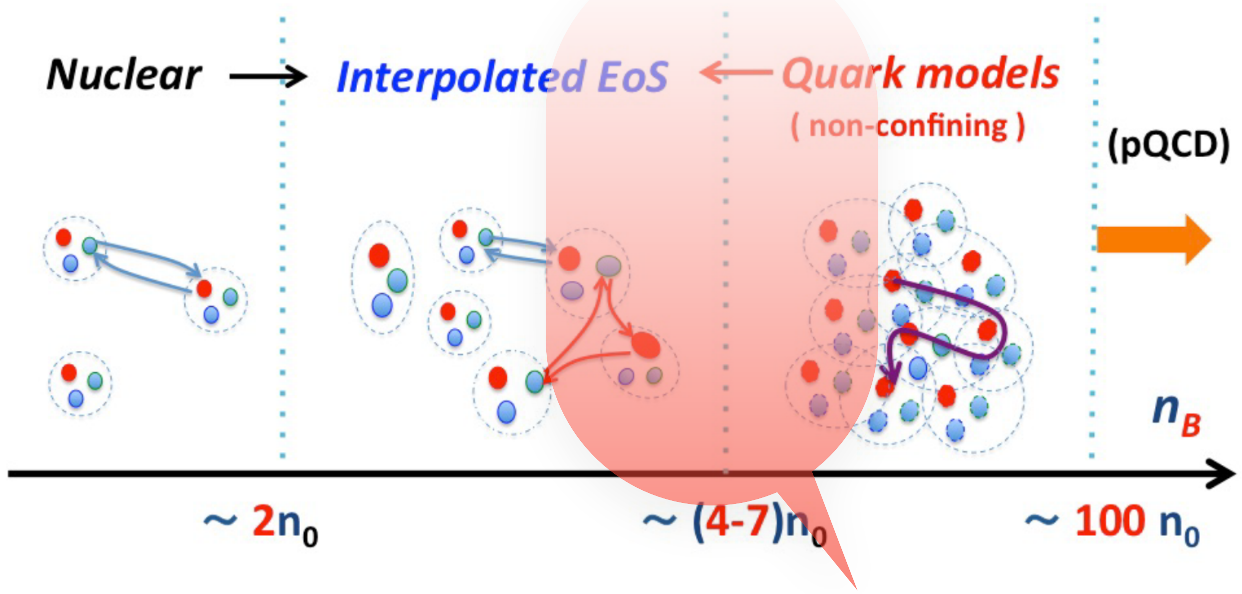
- new 3rd generation detectors:
- American Cosmic Explorer
- European Einstein Telescope

running „accelerator“



Transition from hadronic to quark matter

[Bayr



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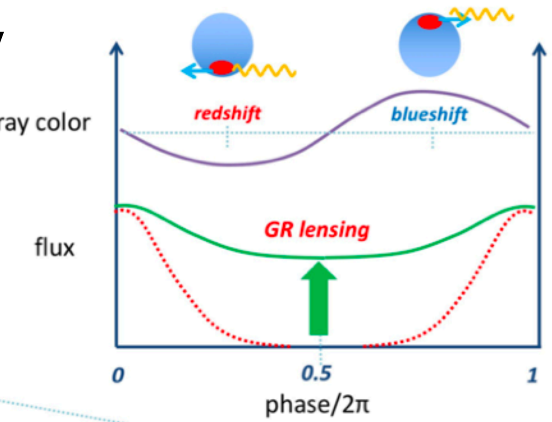
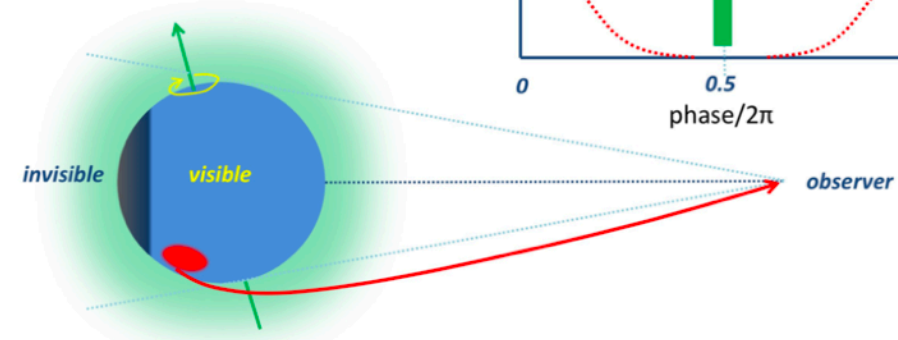


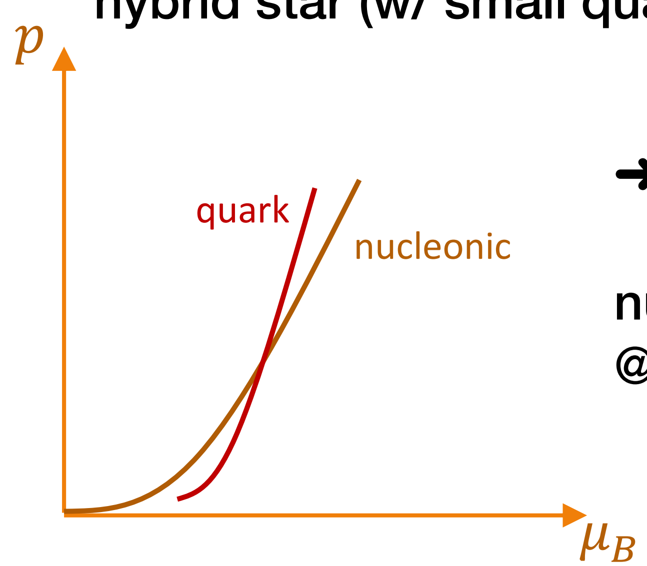


several possibilities (if transition): Maxwell construction or continuous interpolation

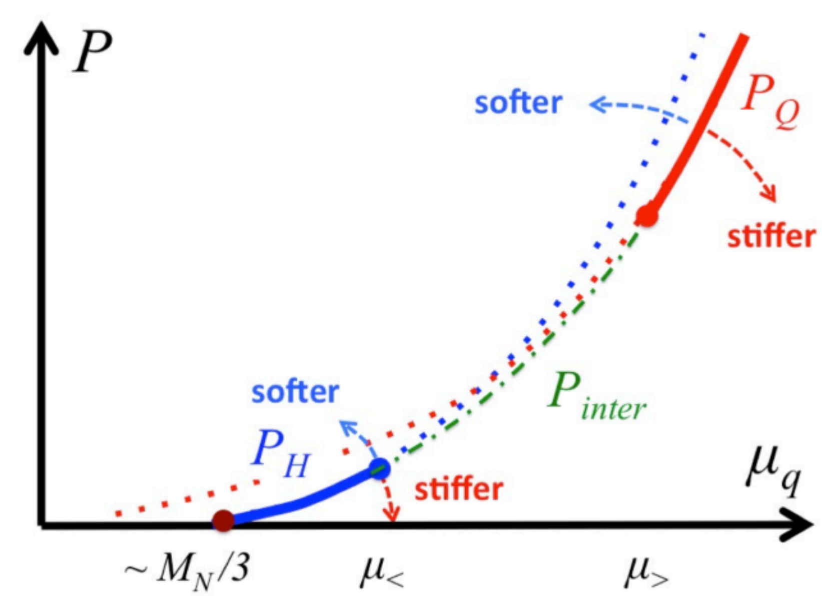
first-order transition

quark-hadron continuity

hybrid star (w/ small quark core)

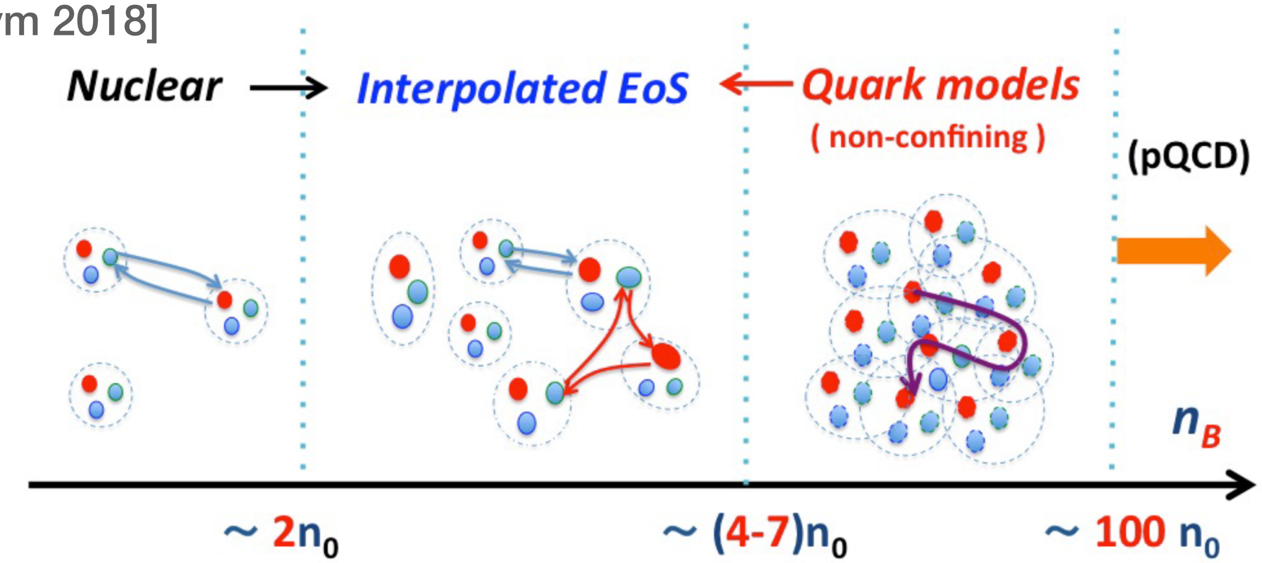


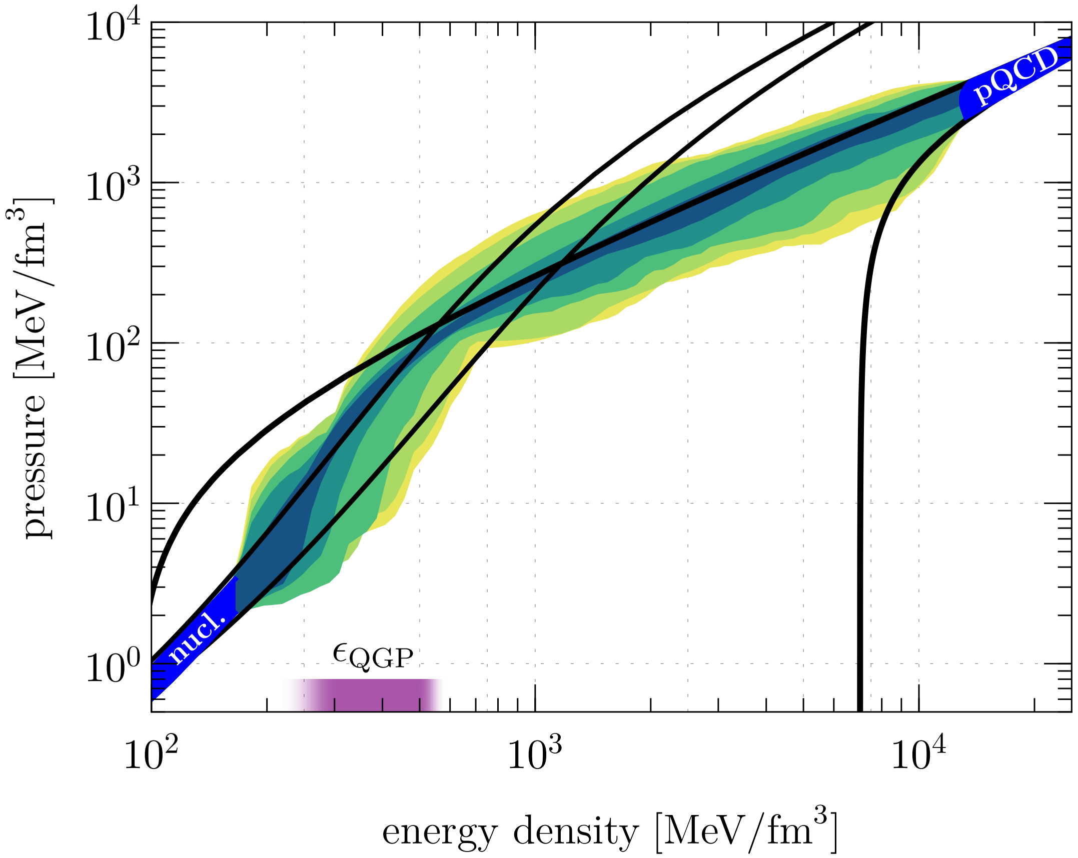
➜ quark EoS softer than nucleonic EoS @ higher densities



conflicting constraints on EoS

[Baym 2018]





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

conflicting constraints on EoS

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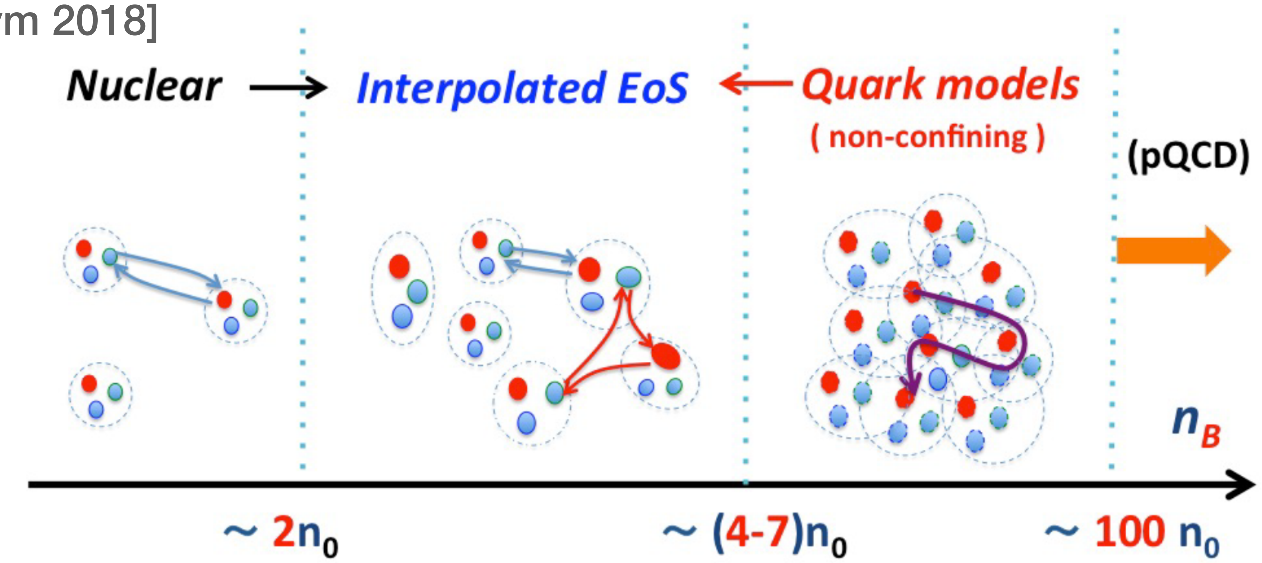
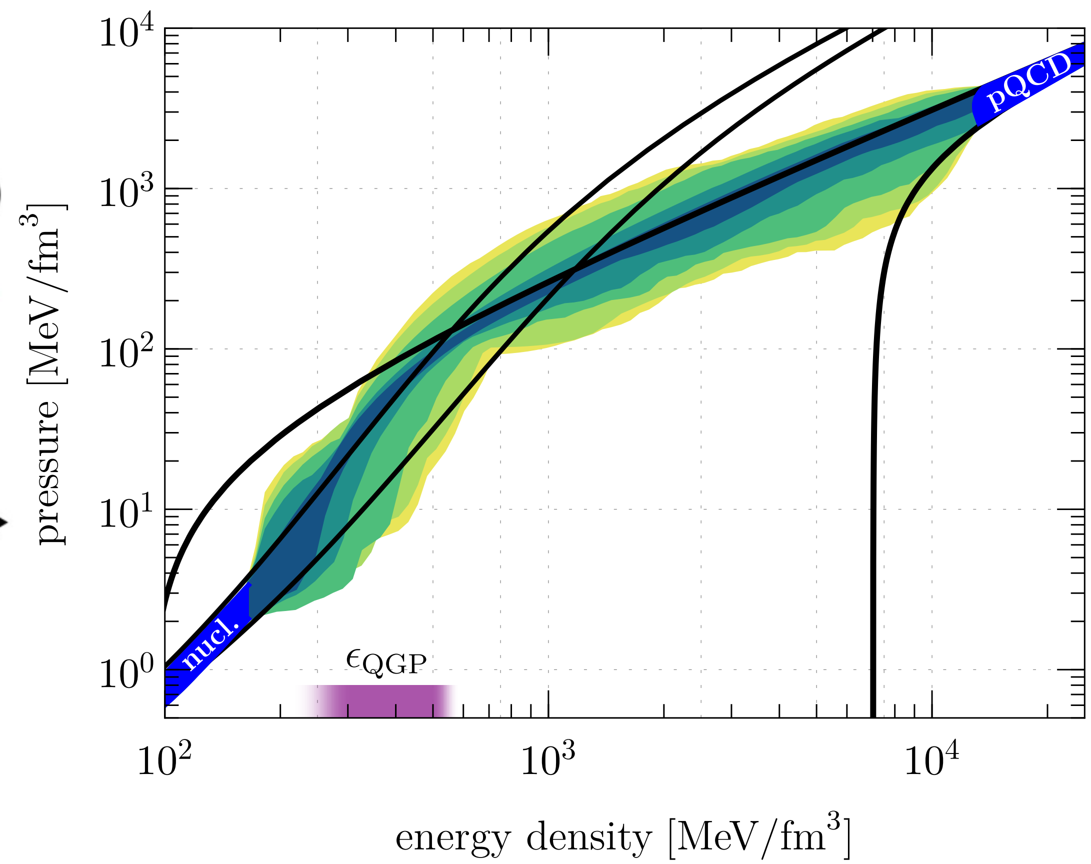
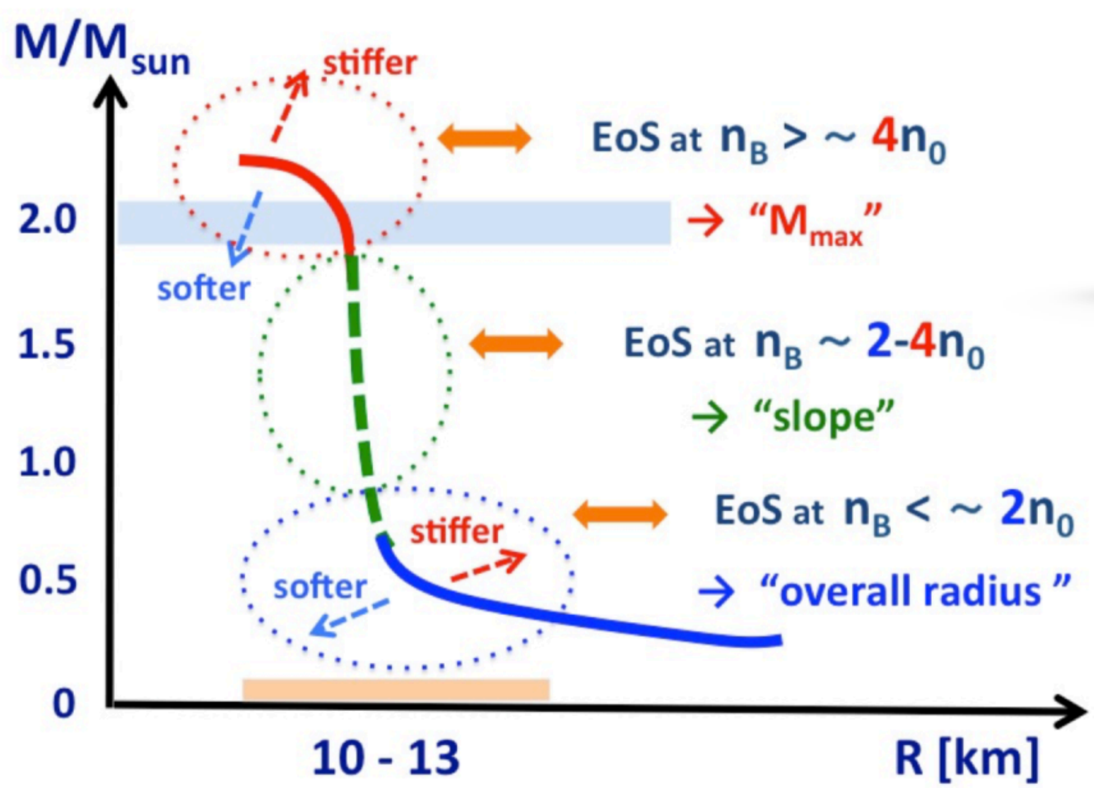






EoS ↔ TOV equation ↔ M-R relation (observables)

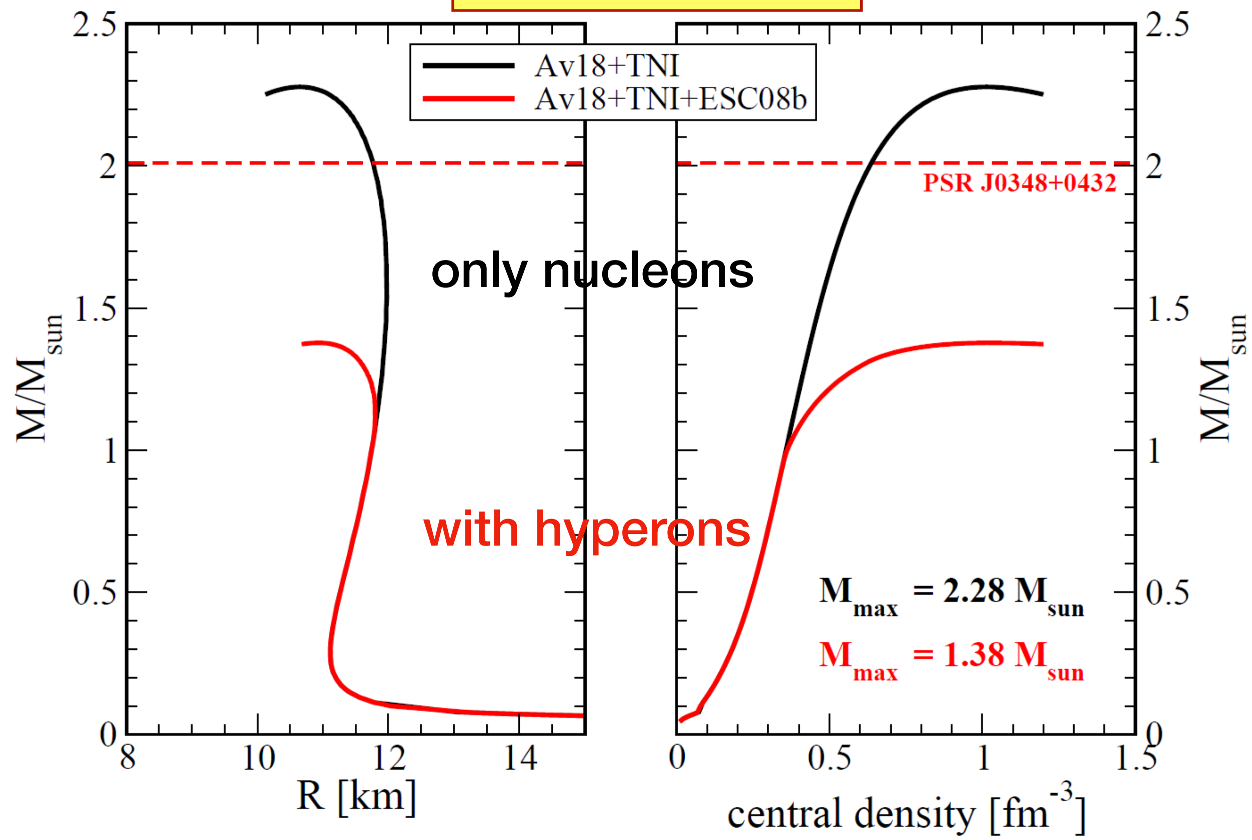
<u>three constraints on the EoS:</u>

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: $n_p = n_e + n_\mu$

beta 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]

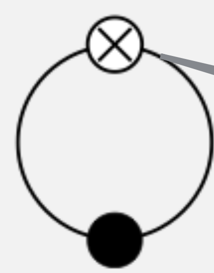
➜ masquerade problem — many EoS look similar ➜ hybrid stars have similar M-R relation
increasing #dof soften EoS,
repulsive interactions stiffen EoS [Alvarez-Castillo, Blaschke 2014]

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

[Wetterich 1993]

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

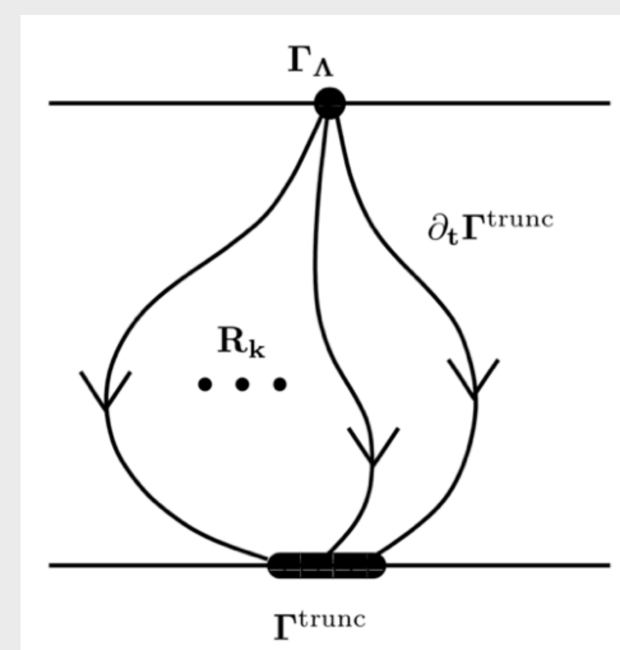
$$\Gamma_k^{(2)} = \frac{\delta^2 \Gamma_k}{\delta\phi\delta\phi}$$

in practise: several truncations ...

shape function conditions:

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

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



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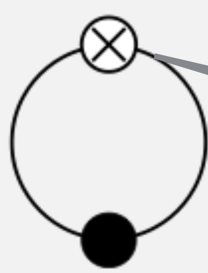

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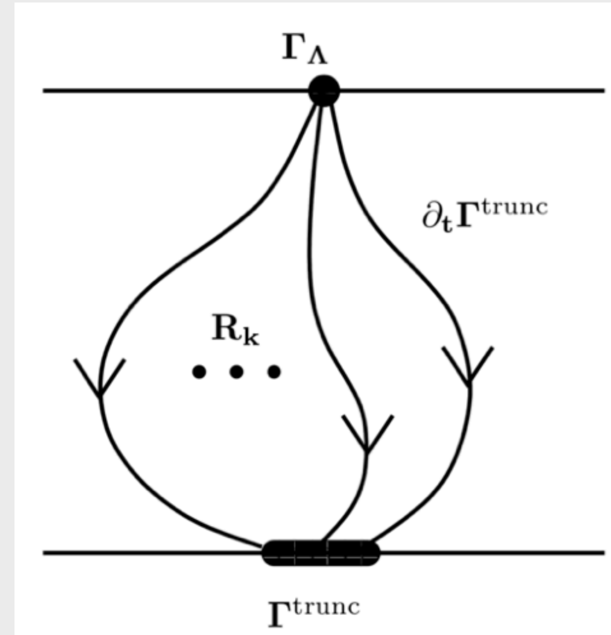


■ Ansatz effective action Quark-Meson truncation in LPA (LO derivative expansion)

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

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

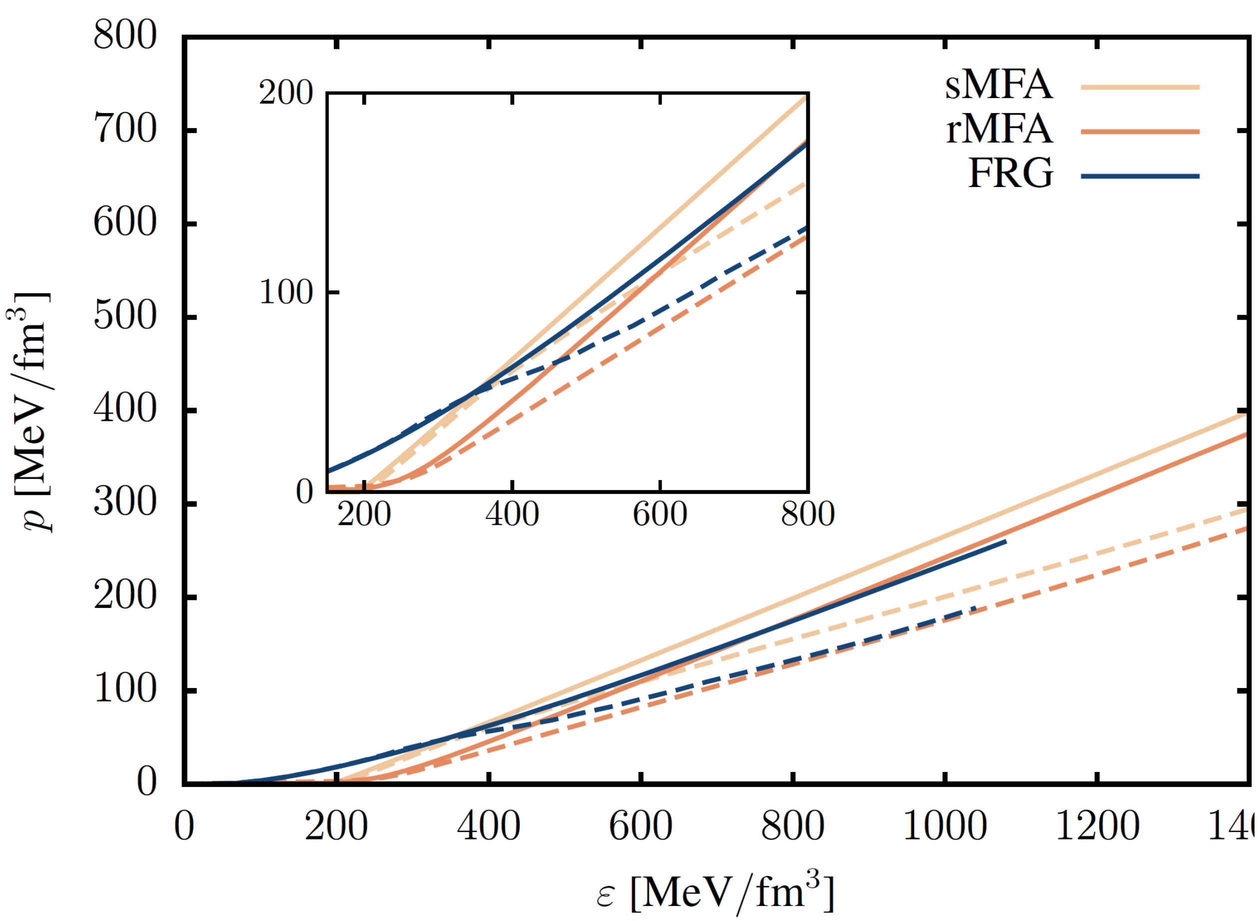
[Otto, Oertel, BJS 2020]

Impose beta equilibrium and charge neutrality conditions

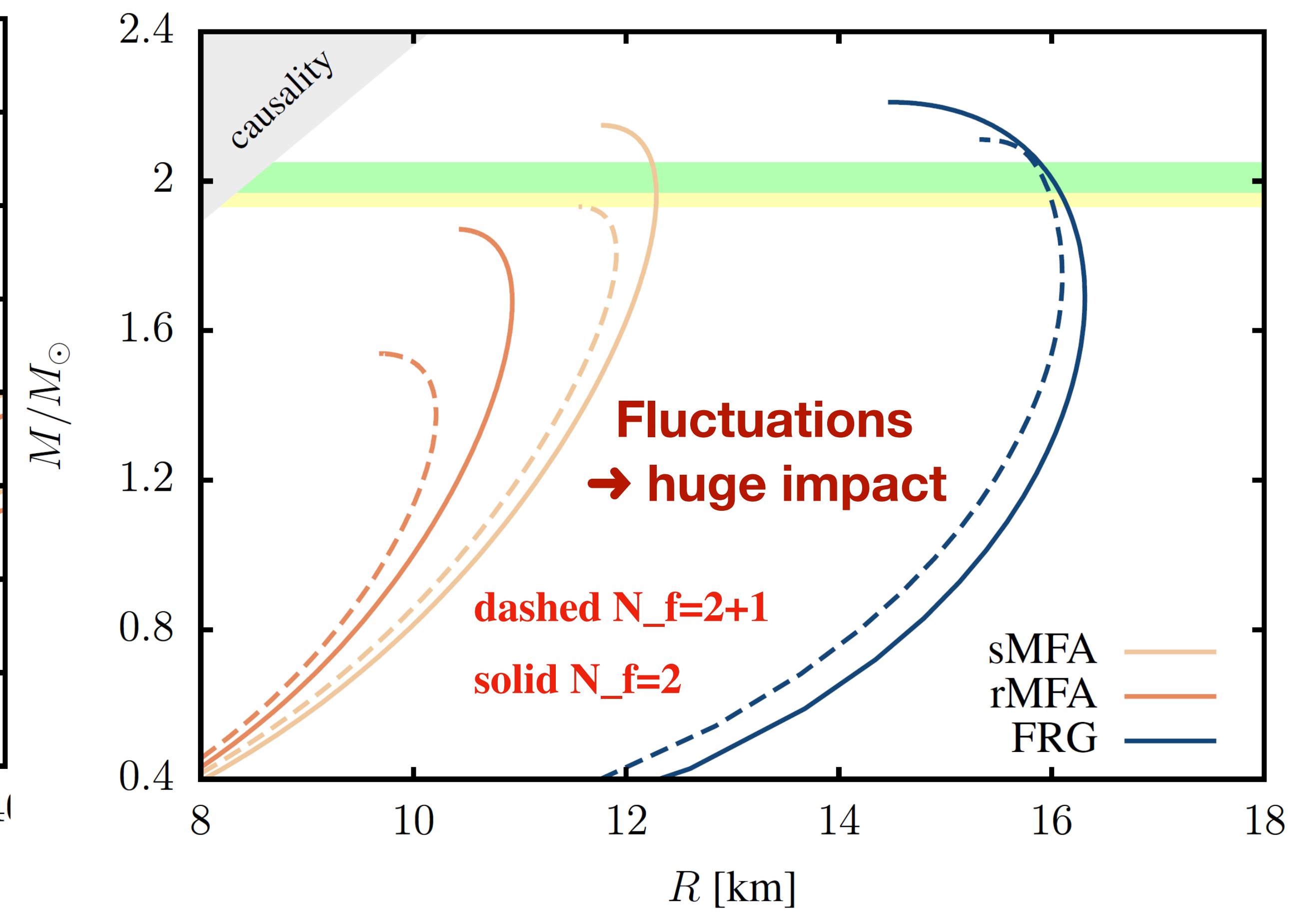
$$\mu_u = \mu_q - \frac{2}{3}\mu_e$$
$$\mu_d = \mu_q + \frac{1}{3}\mu_e$$
$$\mu_s = \mu_q + \frac{1}{3}\mu_e$$

Tolman-Oppenheimer-Volkoff equations

EoS



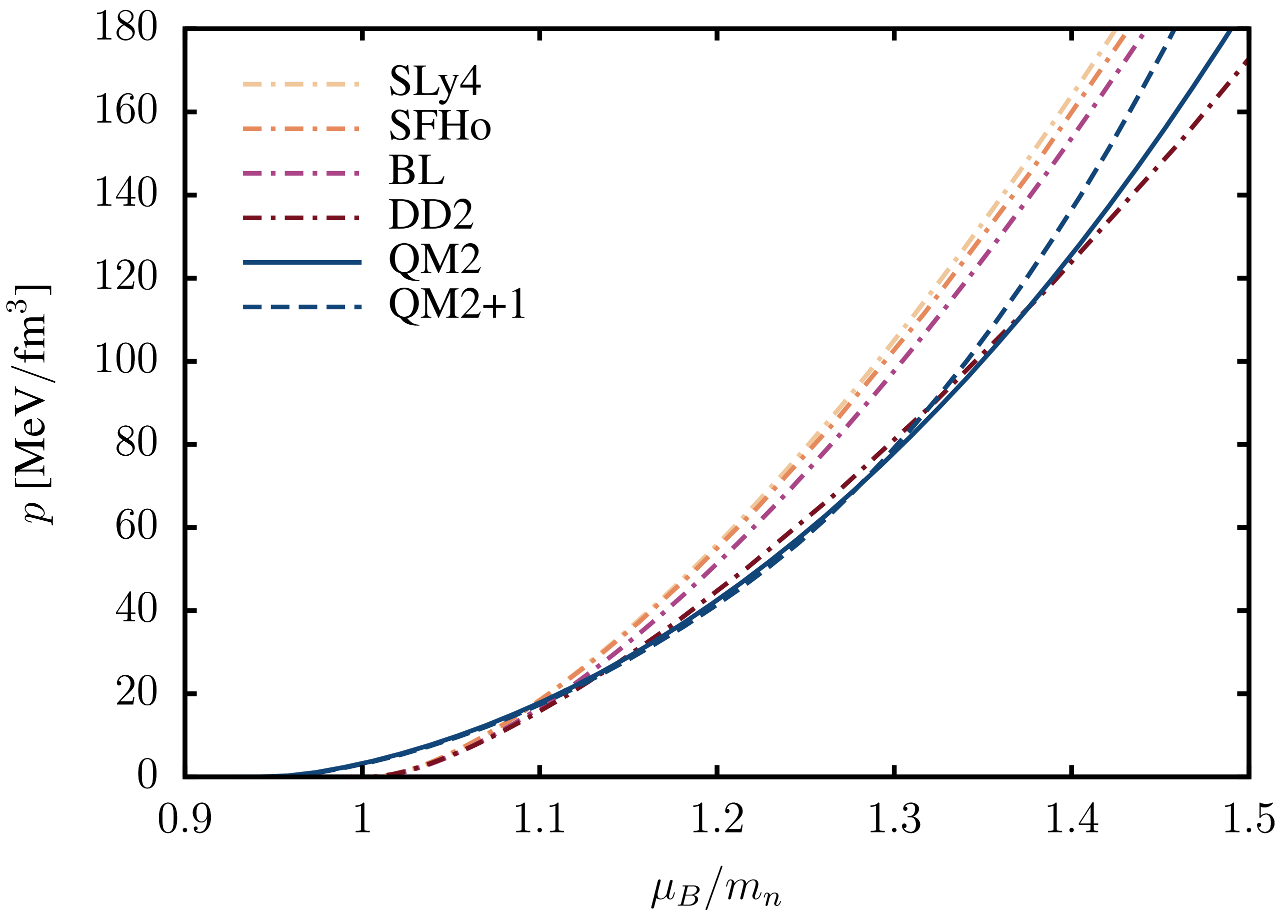
Mass-Radius relation

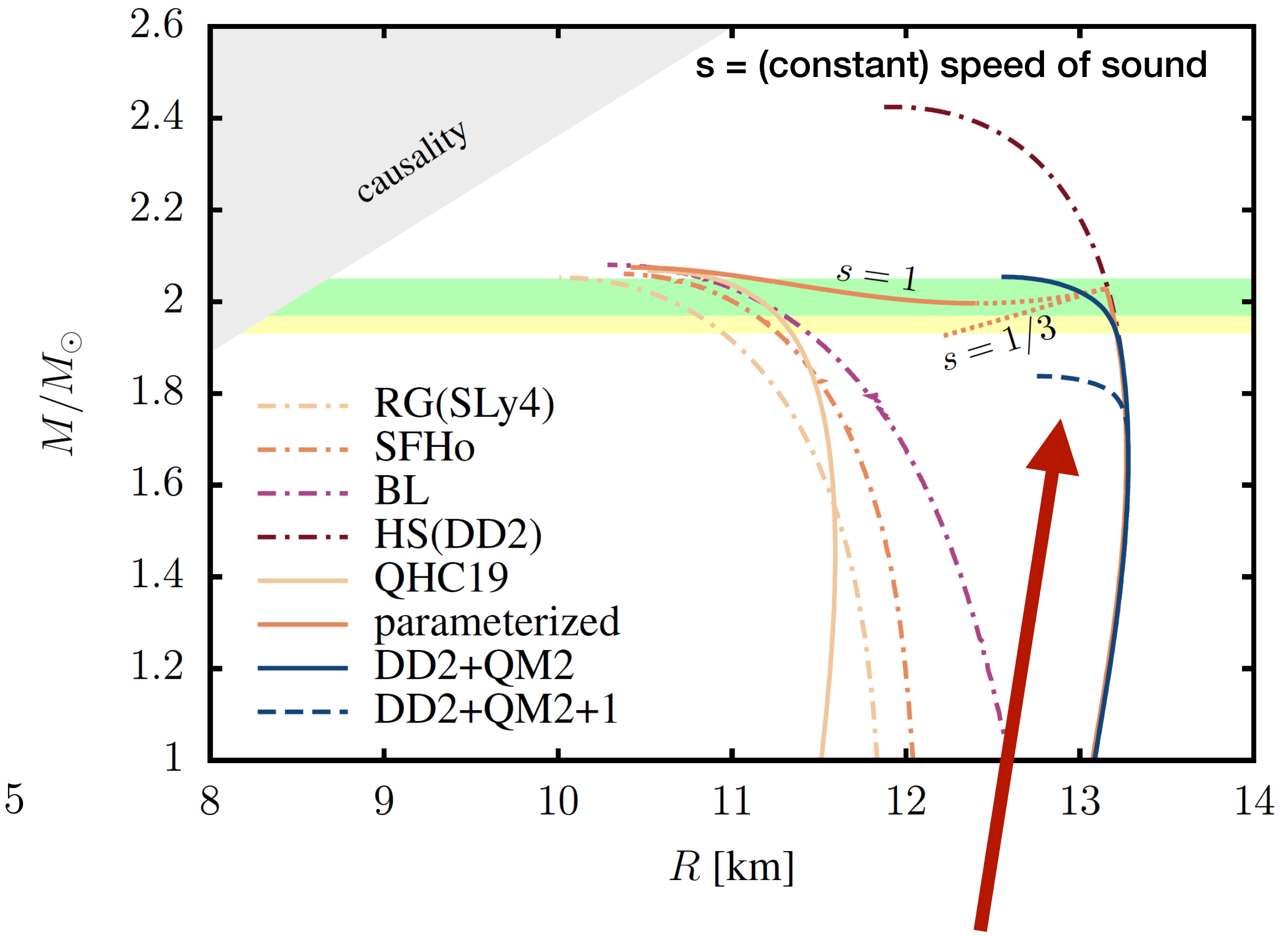


Hybrid star construction possible? - yes

[Otto, Oertel, BJS 2020]

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





2 M⊙ limit violated for N_f= 2+1

can a repulsive vector interaction remedy this behavior?

Vector mesons to the FRG EoS

[Otto, Oertel, BJS 2020]

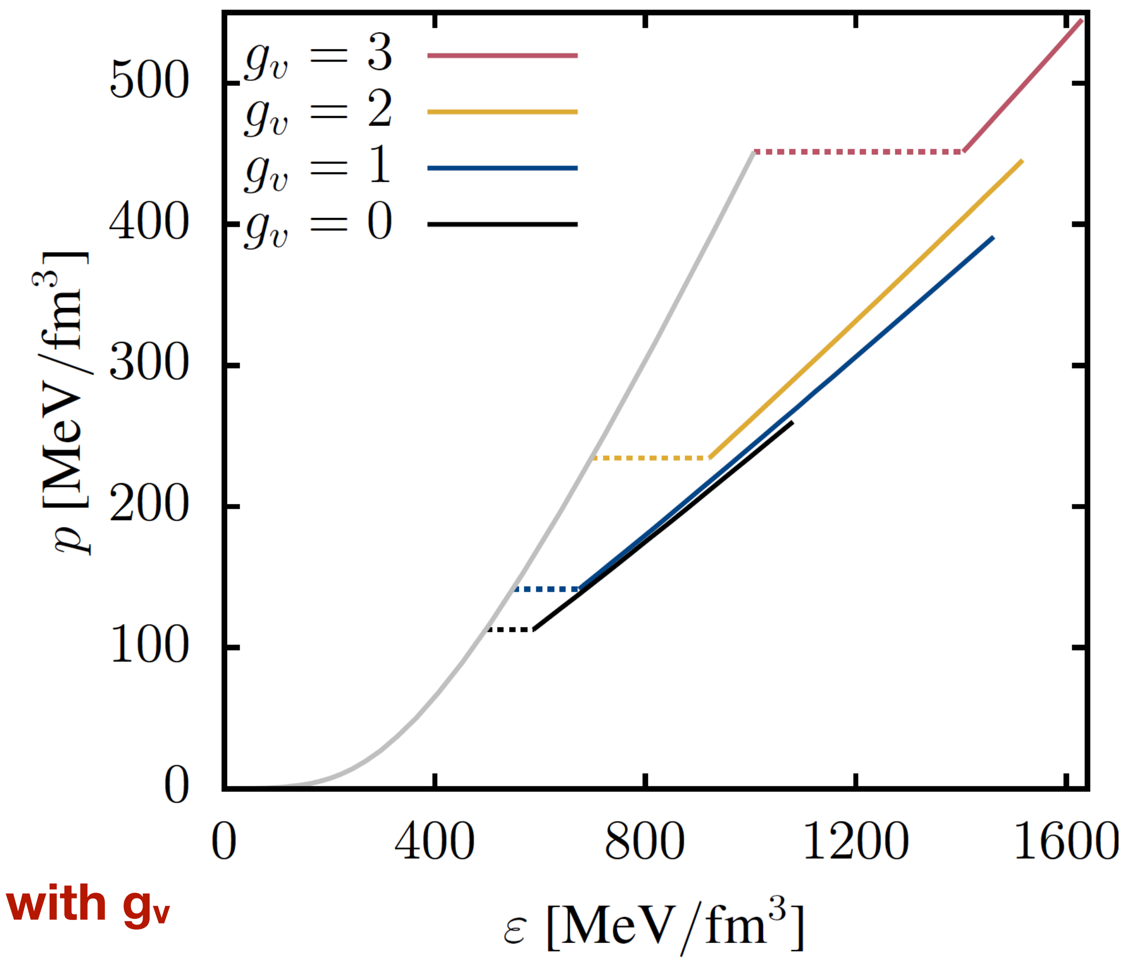
[Rennecke 2015]
[Pereira, Stiele, Costa 2020]

- 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:

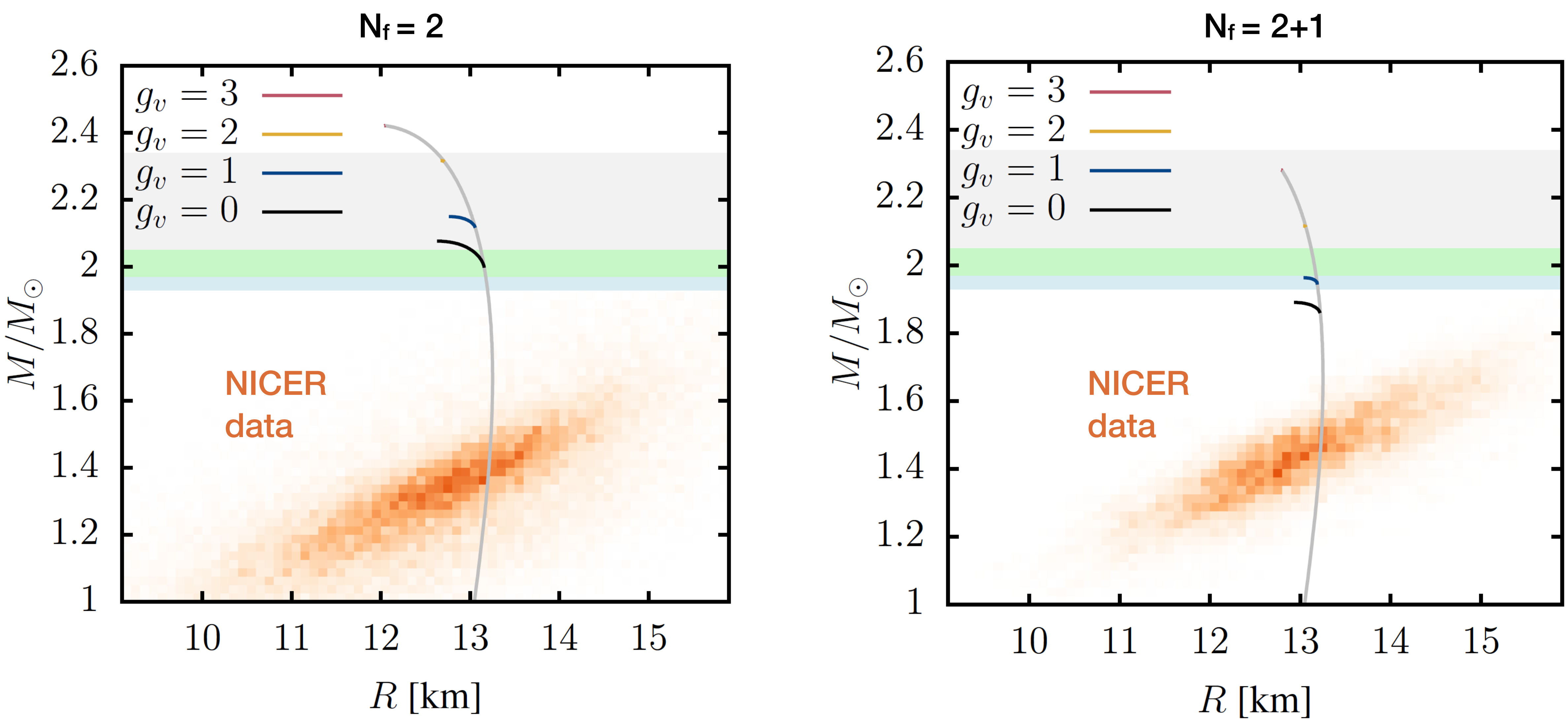
$$\tilde{\mu}_u = \mu_q - \frac{2}{3}\mu_e - \frac{g_v}{2}\omega$$
$$\tilde{\mu}_d = \mu_q + \frac{1}{3}\mu_e - \frac{g_v}{2}\omega$$
$$\tilde{\mu}_s = \mu_q + \frac{1}{3}\mu_e - \frac{g_v}{\sqrt{2}}\phi$$



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

Mass-Radius relations

[Otto, Oertel, BJS 2020]

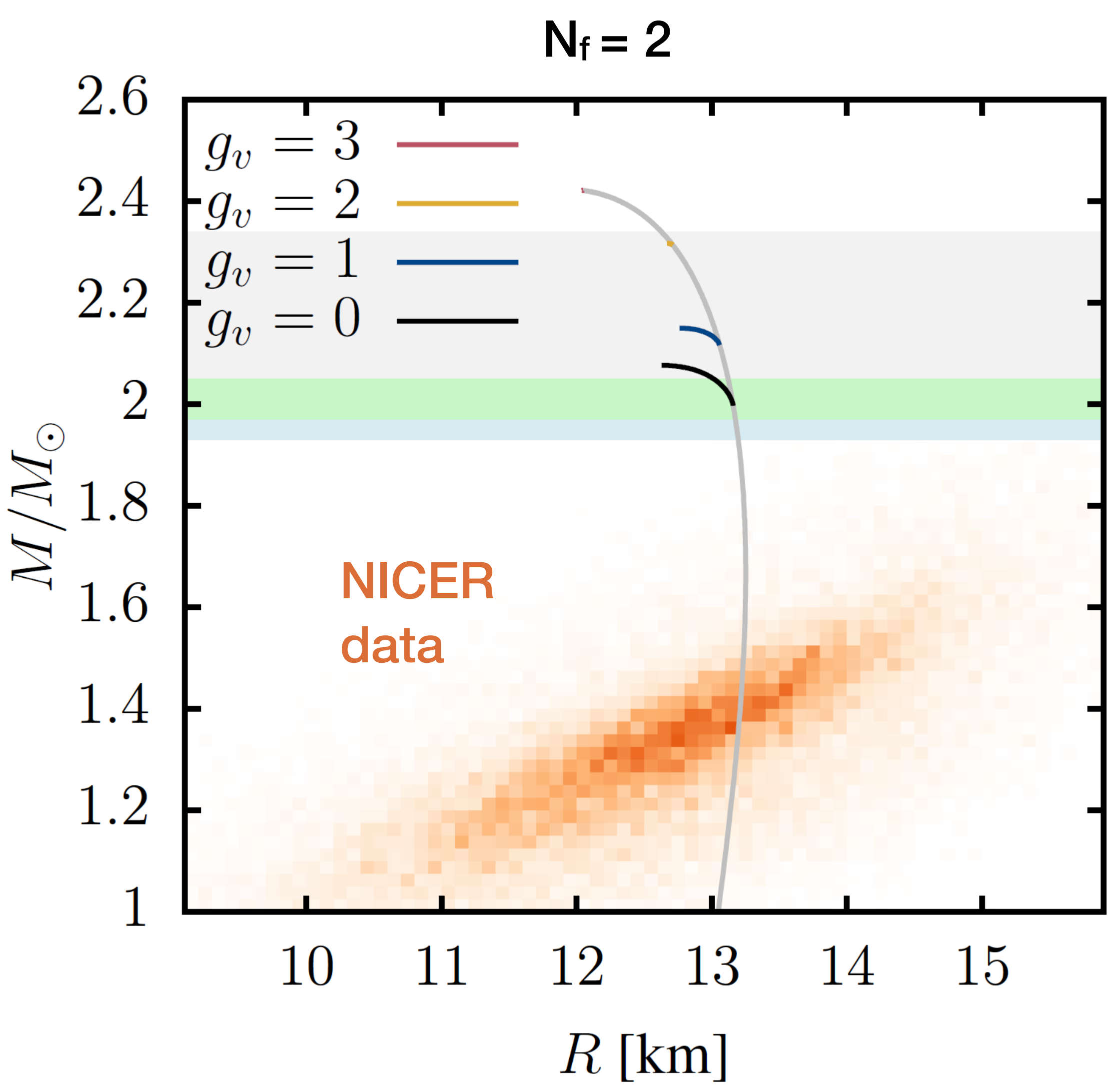


➜ including strange quarks: **finite vector coupling is needed to achieve $2M_\odot$ limit**

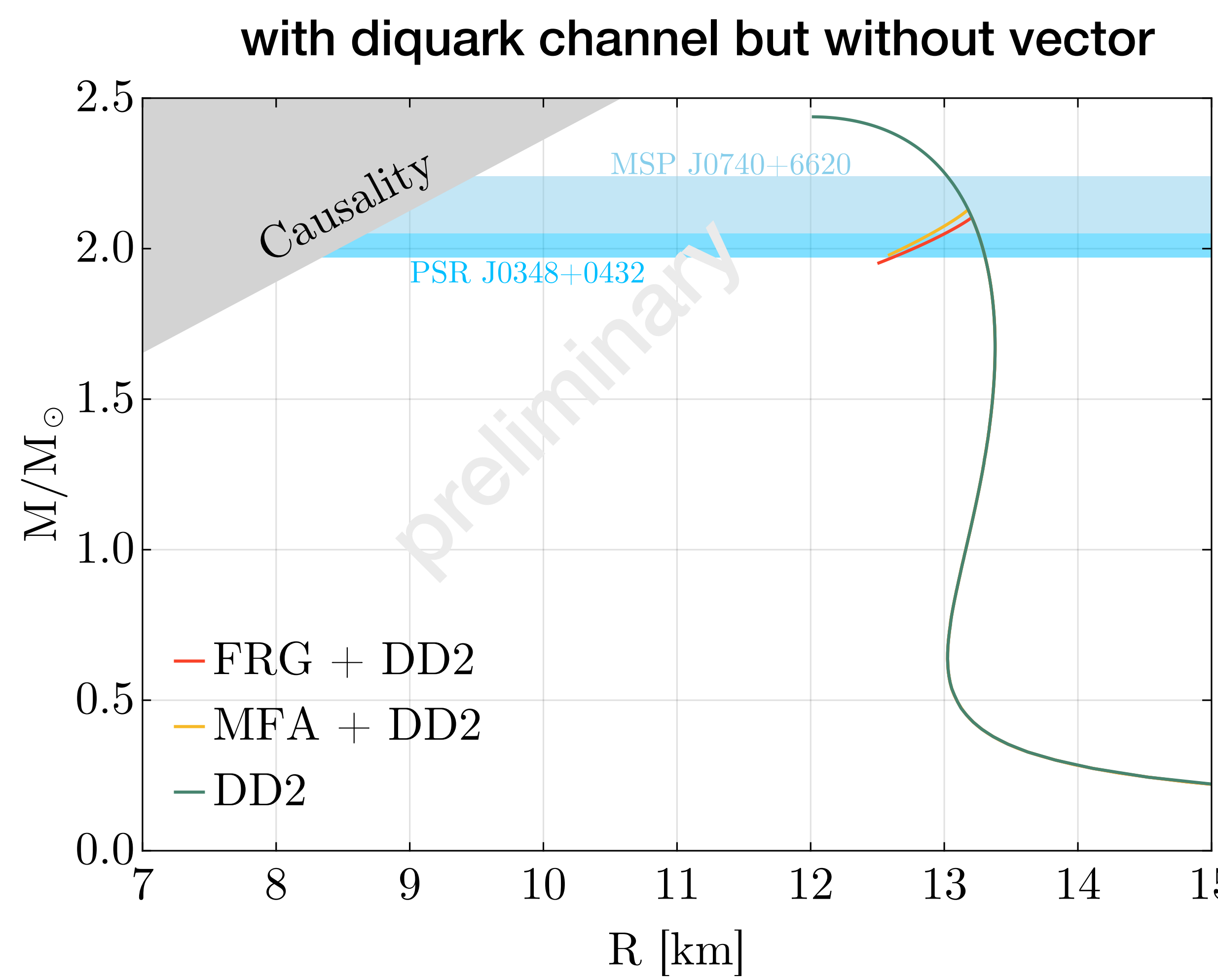
➜ at the same time: **larger vector coupling lead to smaller quark cores!**

Mass-Radius relations

[Otto, Oertel, BJS 2020]



[Mire, BJS … stay tuned]



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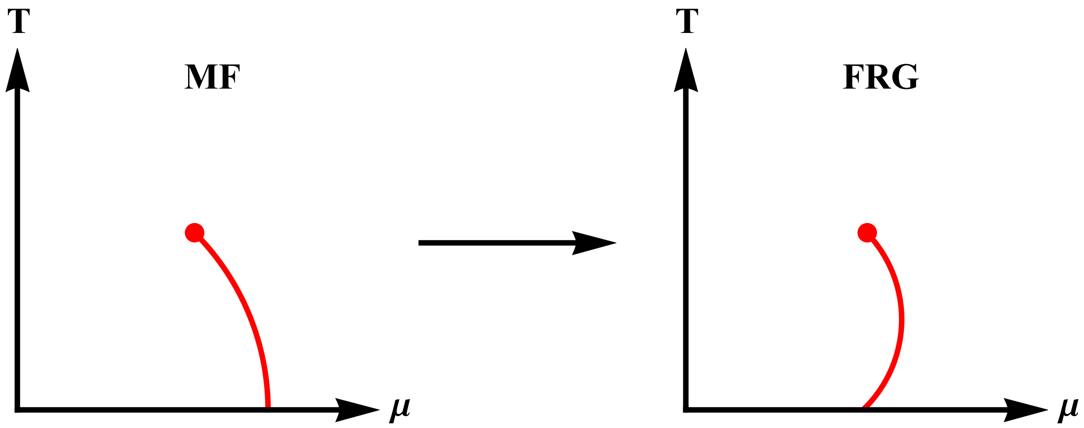
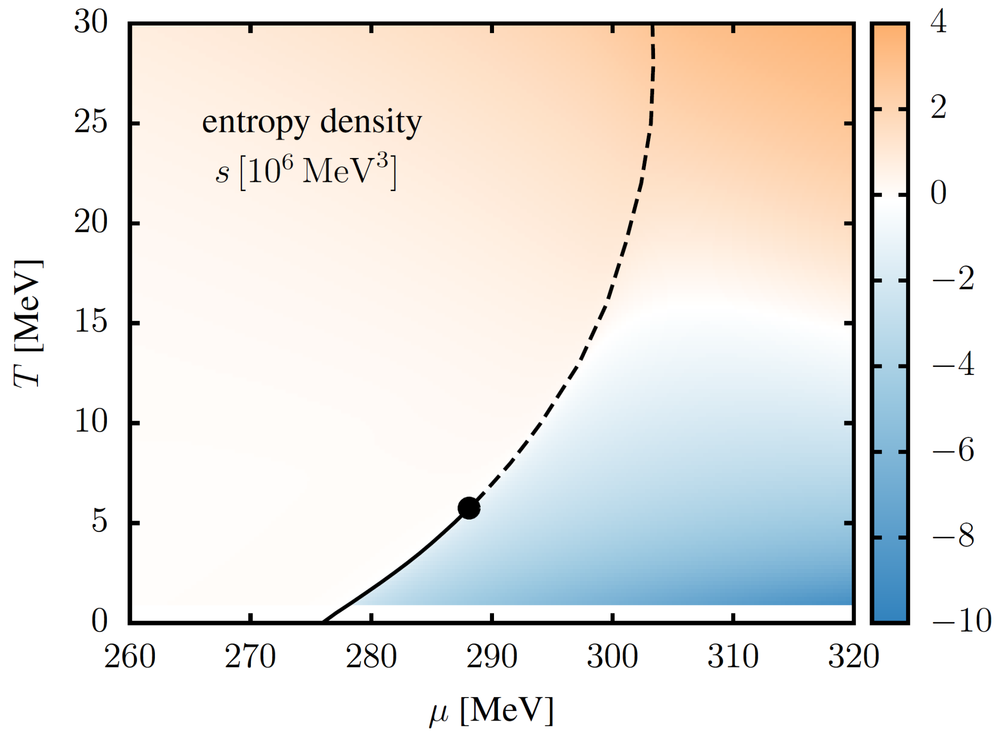
so far so good ... BUT

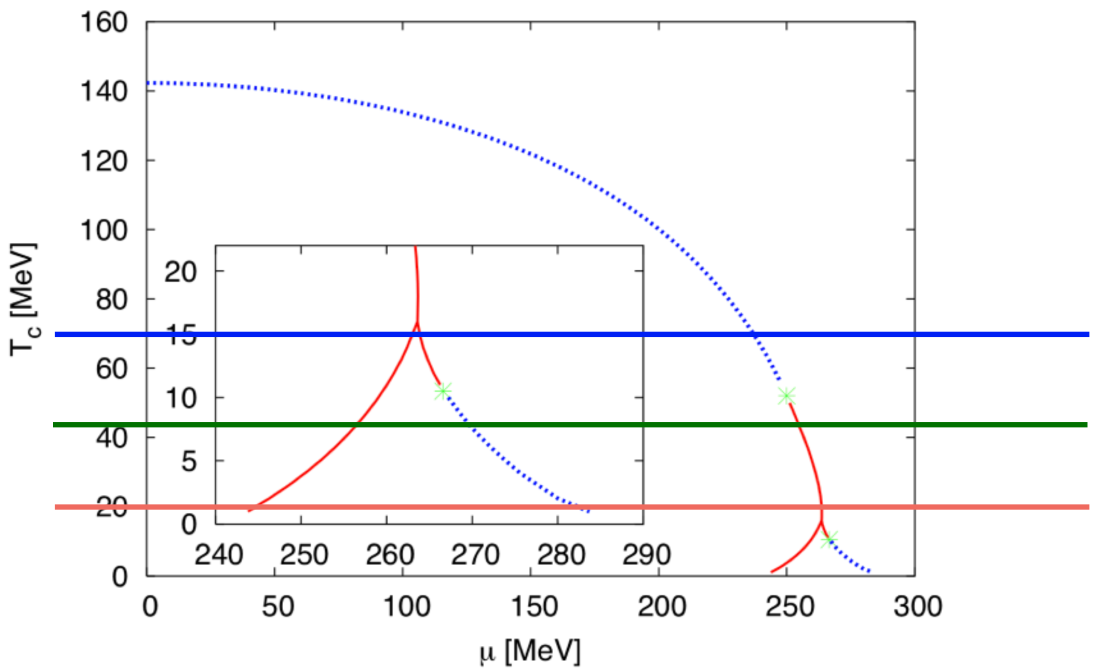
back-bending / negative entropy density

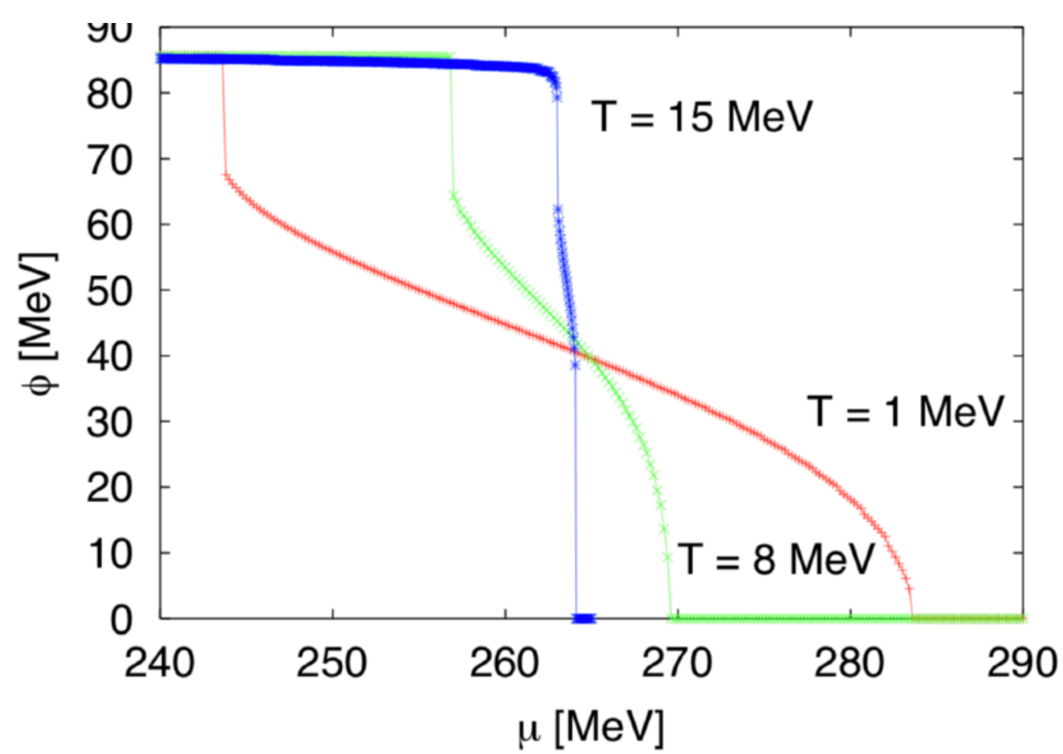
[R-A Tripolt, BJS, L von Smekal, J Wambach 2018] [BJS, Wambach 2005]



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







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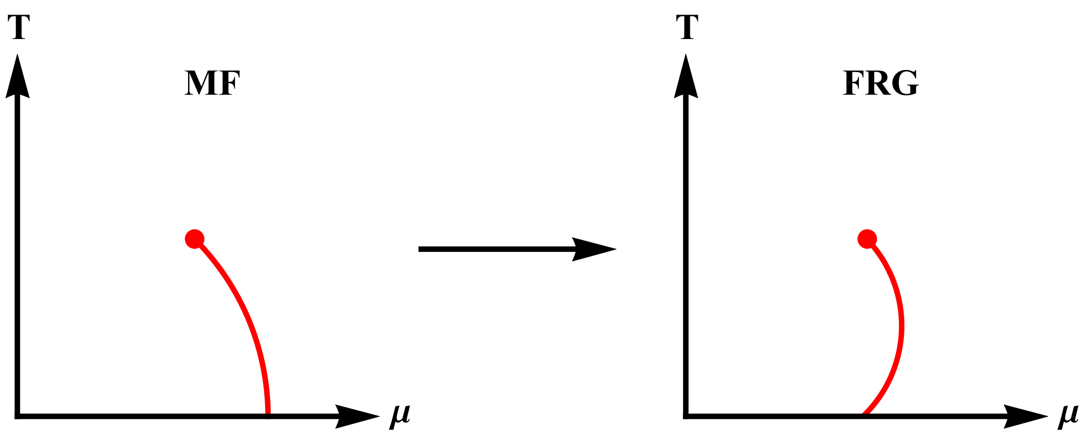
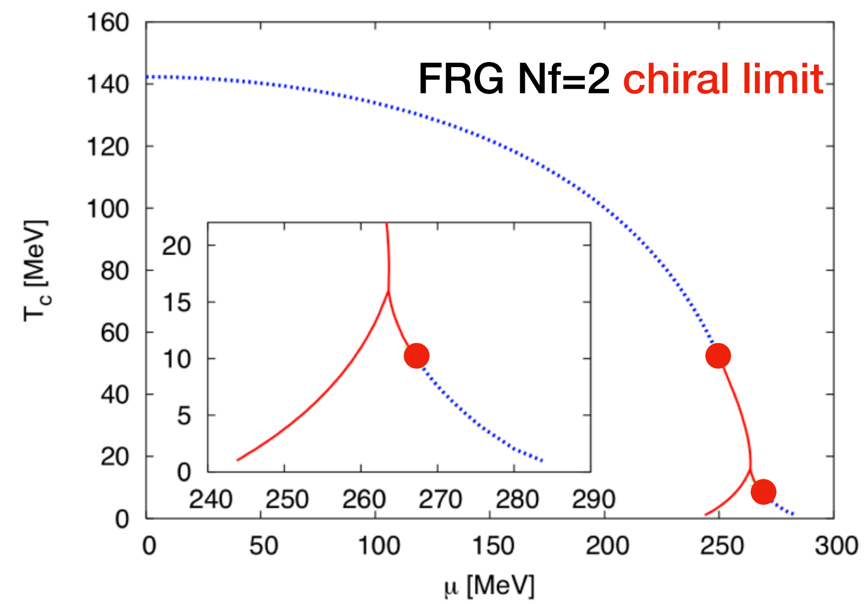


[BJS, Wambach 2005]



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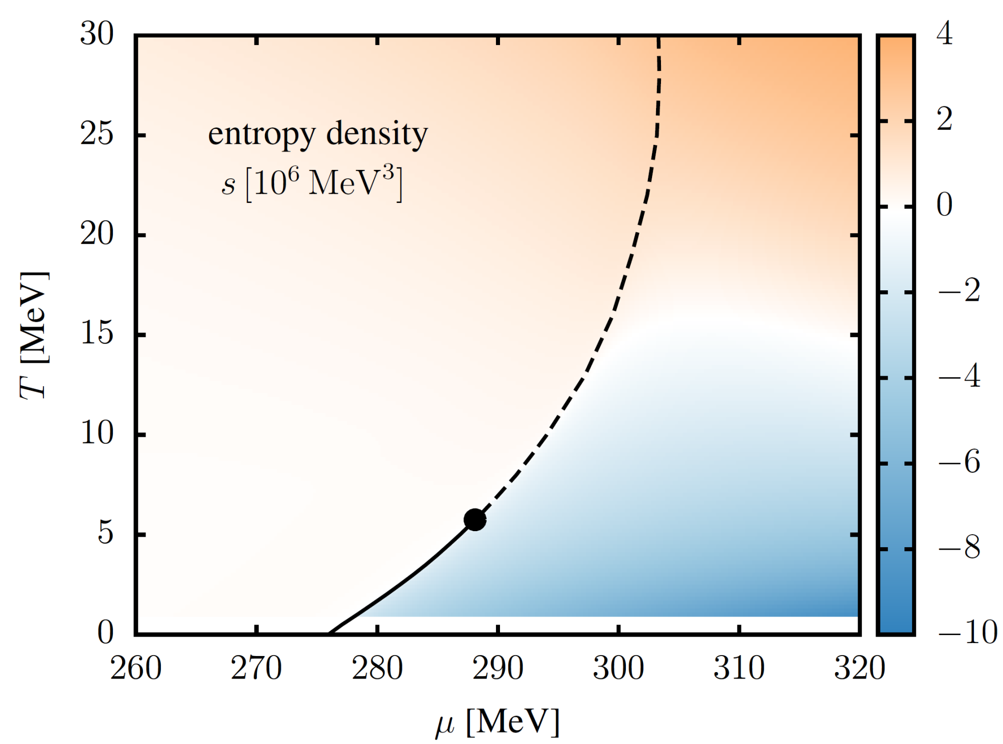

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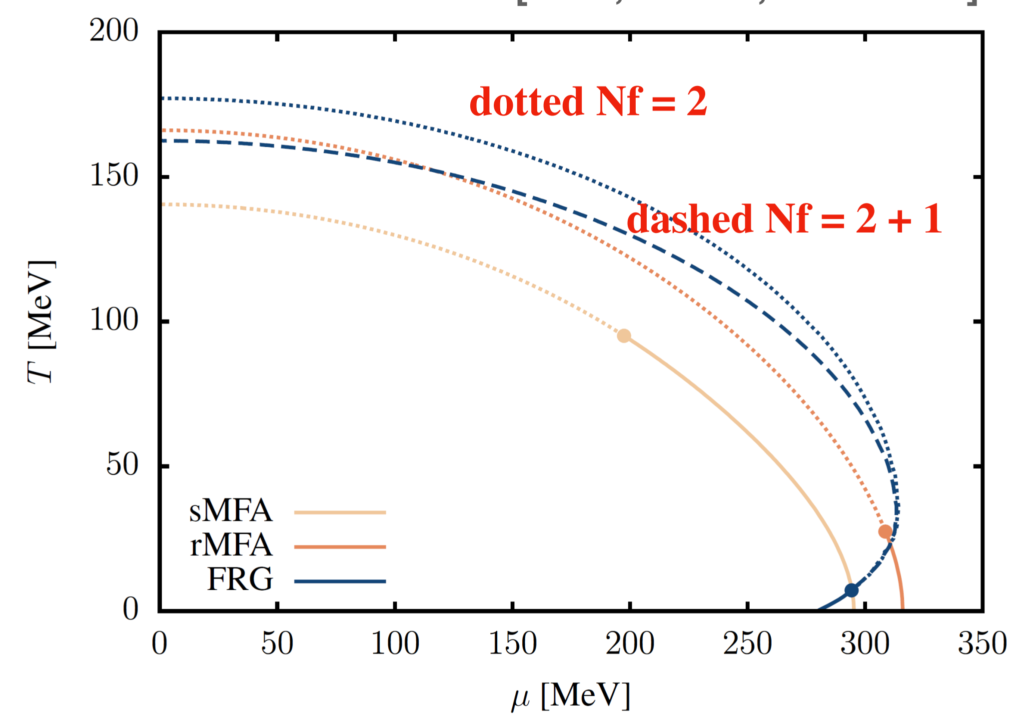

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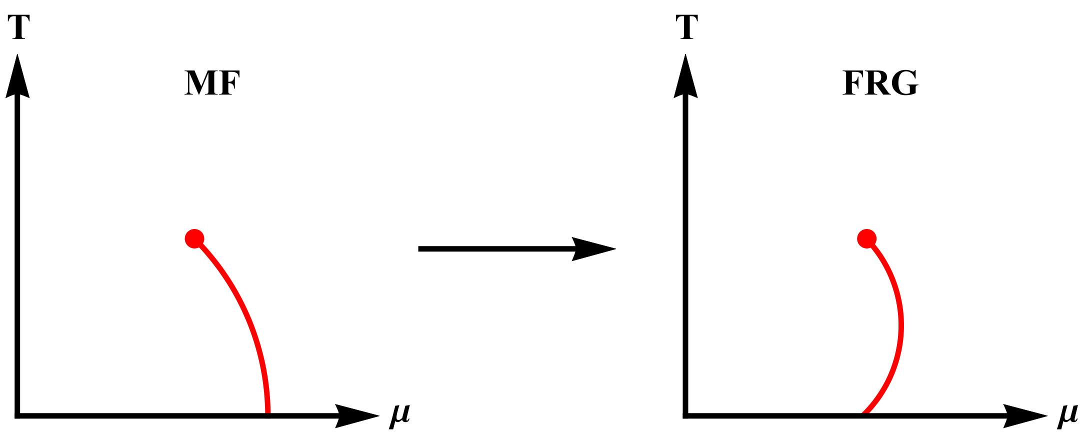

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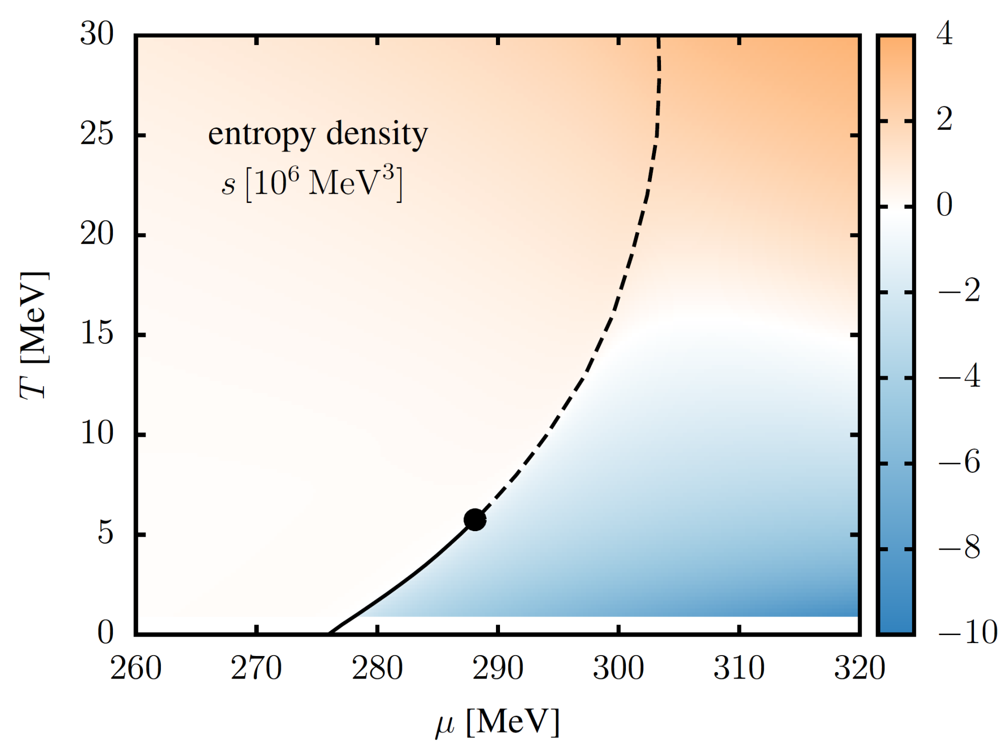
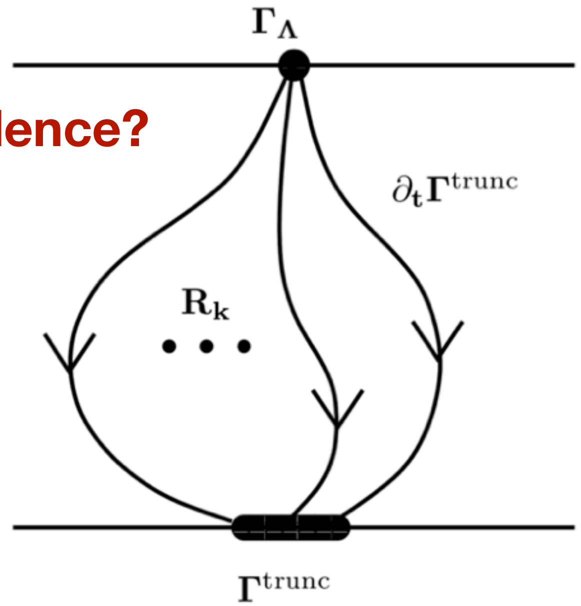


➜ **Regulator scheme dependence?**

less pronounced when more channels are included
e.g. pairing channel
s. 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)

- example:

exponential regulator fulfills SB but

➜ additional (unphysical)

poles that break Silver Blaze

Callan-Symanzik type regulators

- **solution:** CS regulator: $R_k(p^2) = k^2$

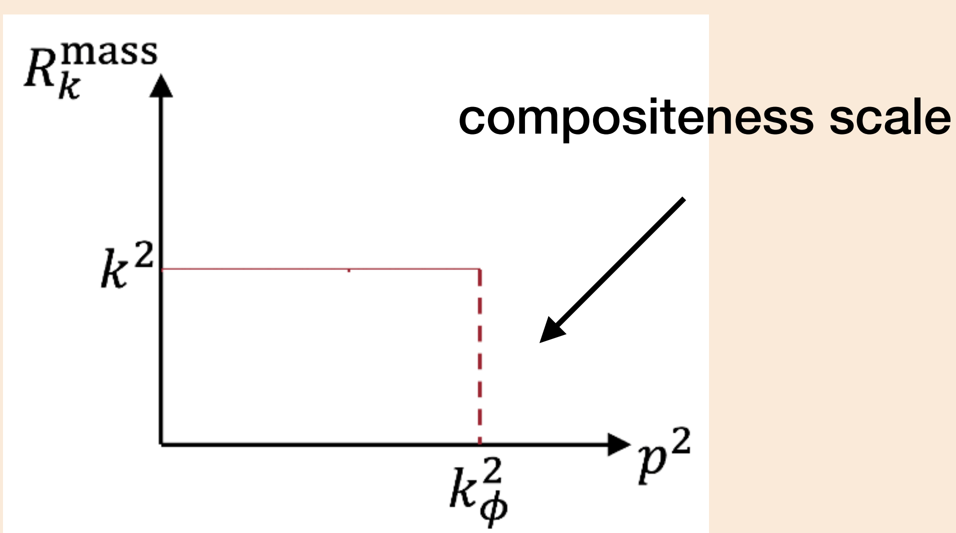
  3dim regulators: $R_k(\vec{p}^2)$

  UV divergent → partial IR fixed point enables parameter fixing

- **comparison:**

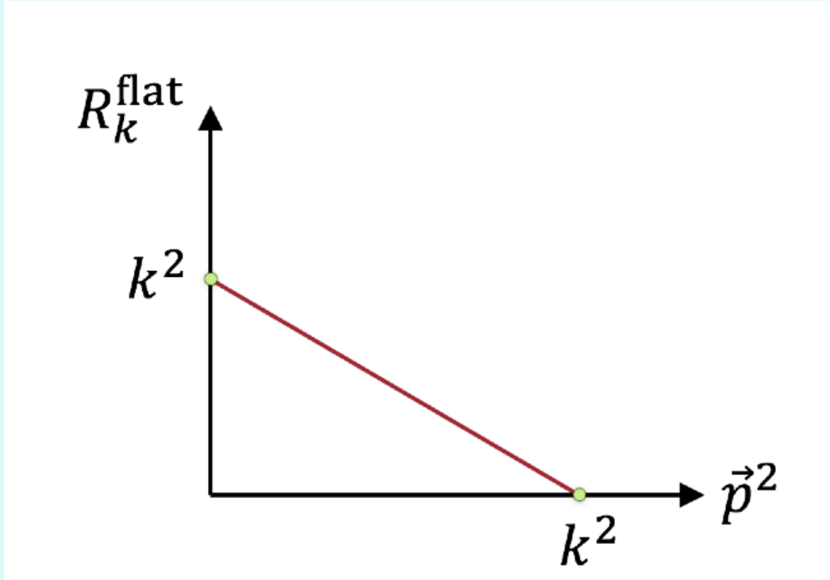
CS (mass-like) regulators

- **4dim:** $R_k^{\mathrm{mass}}(p^2) = k^2\,\Theta(k_\Phi^2 - p^2)$
- **3dim:** $R_k^{\mathrm{mass}}(\vec{p}^2) = k^2\,\Theta(k_\Phi^2 - \vec{p}^2)$



3dim flat (Litim) regulators

$$R_k^{\mathrm{flat}}(\vec{p}^2) = (k^2 - \vec{p}^2)\Theta(k^2 - \vec{p}^2)$$



Partial IR fixed point

- **usual UV procedure not applicable :**

CS regulator: $R_k(p^2) = k^2$ UV divergent

Λ ~ O(10GeV)

- symmetric regime

k_Φ

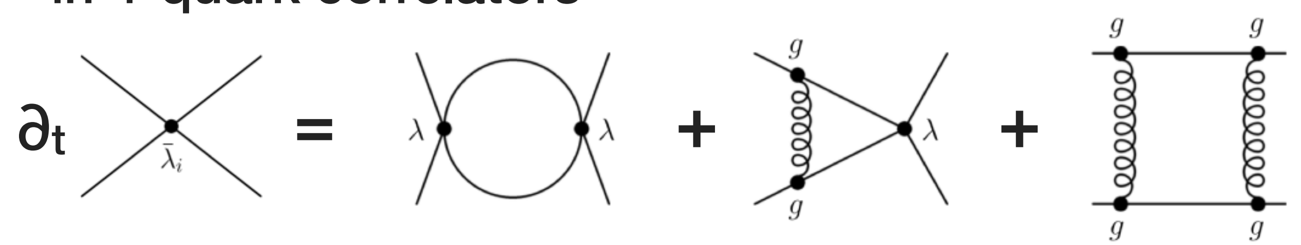
- symmetry-broken regime

k_{IR}

- ideal procedure: [Braun et al. 2012++]
  Start with QCD at high scales O(100 GeV)

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

- pointlike limit: neglect momentum structure
  in 4-quark correlators



- pointlike limit ➜ only symmetric high energy regime
  ➜ no bound states

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

➜ Ginzburg-Landau effective potential

Quark-meson-diquark truncation

Partial IR fixed point

- **usual UV procedure not applicable :**

CS regulator: $R_k(p^2) = k^2$ UV divergent

Λ ~ O(10GeV)

- symmetric regime

k_Φ

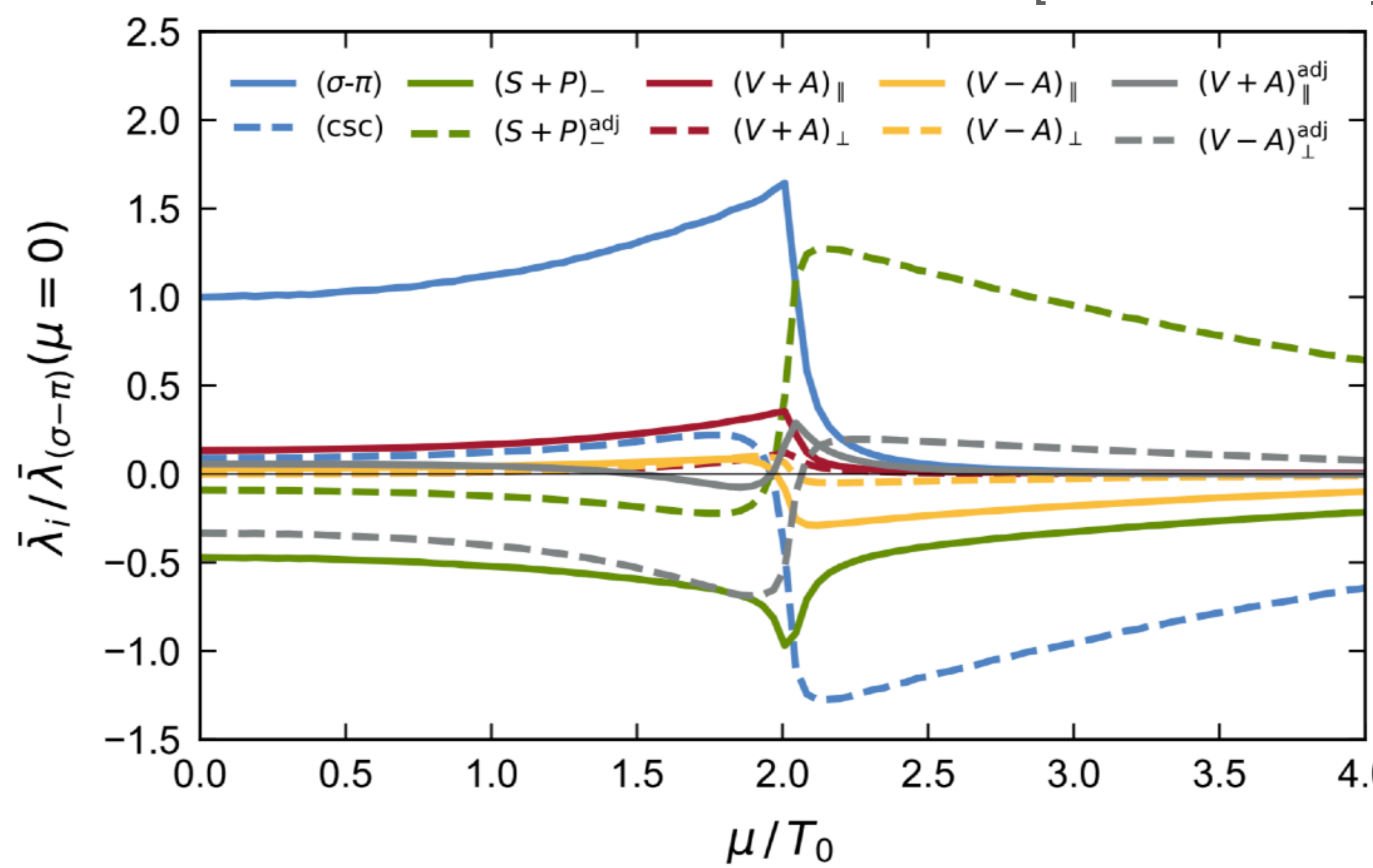
- symmetry-broken regime

k_{IR}

- ideal procedure: [Braun et al. 2012++]
  Start with QCD at high scales O(100 GeV)

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

[Braun et al. 2020]



Partial IR fixed point

- **usual UV procedure not applicable :**

[Wetterich,Jungnickel et al]

CS regulator: $R_k(p^2) = k^2$ UV divergent

k_Φ

approximated flow in LPA' down to chiral sym breaking scale k_χ

➜ partial IR fixed point

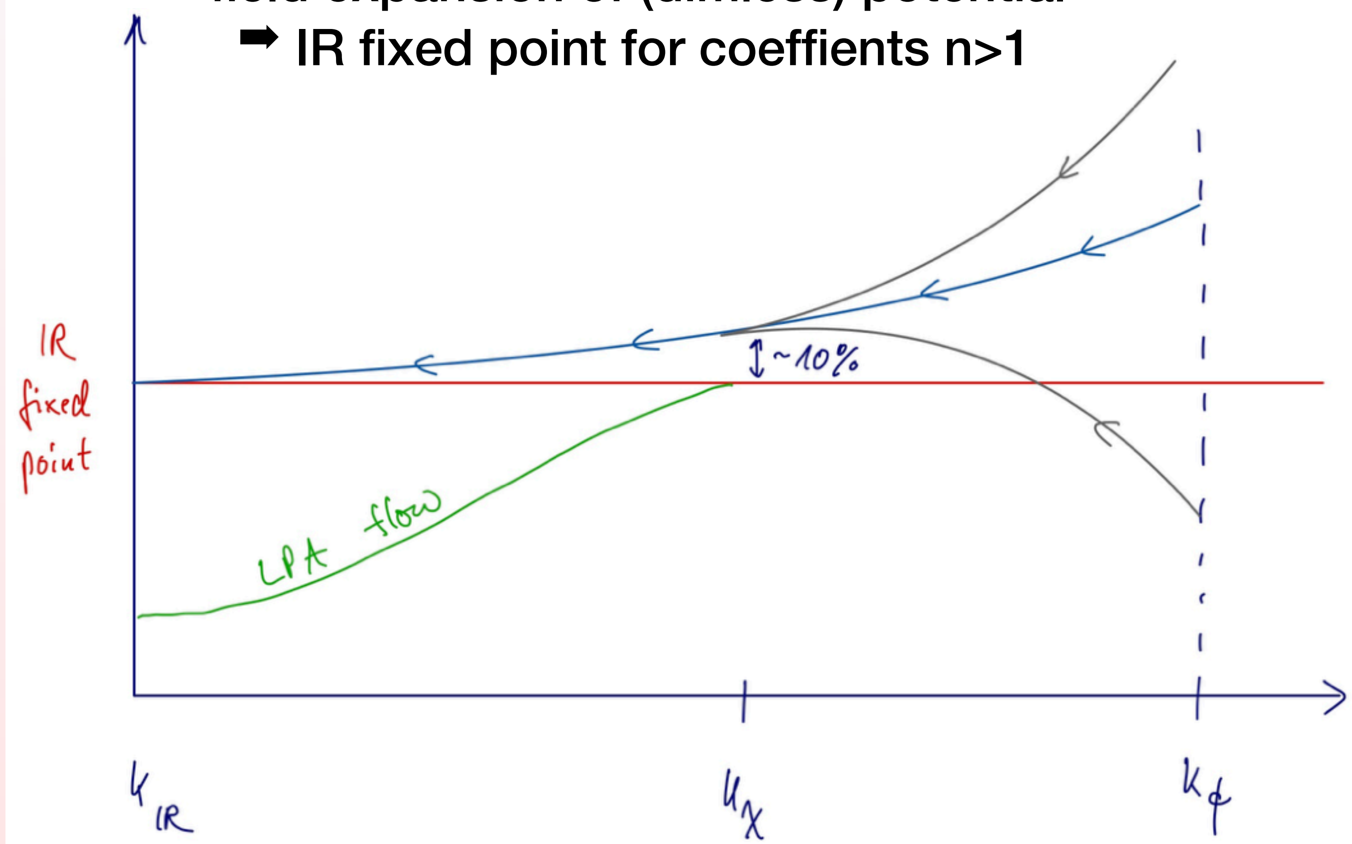
k_χ

solve flow in LPA starting at fixed point

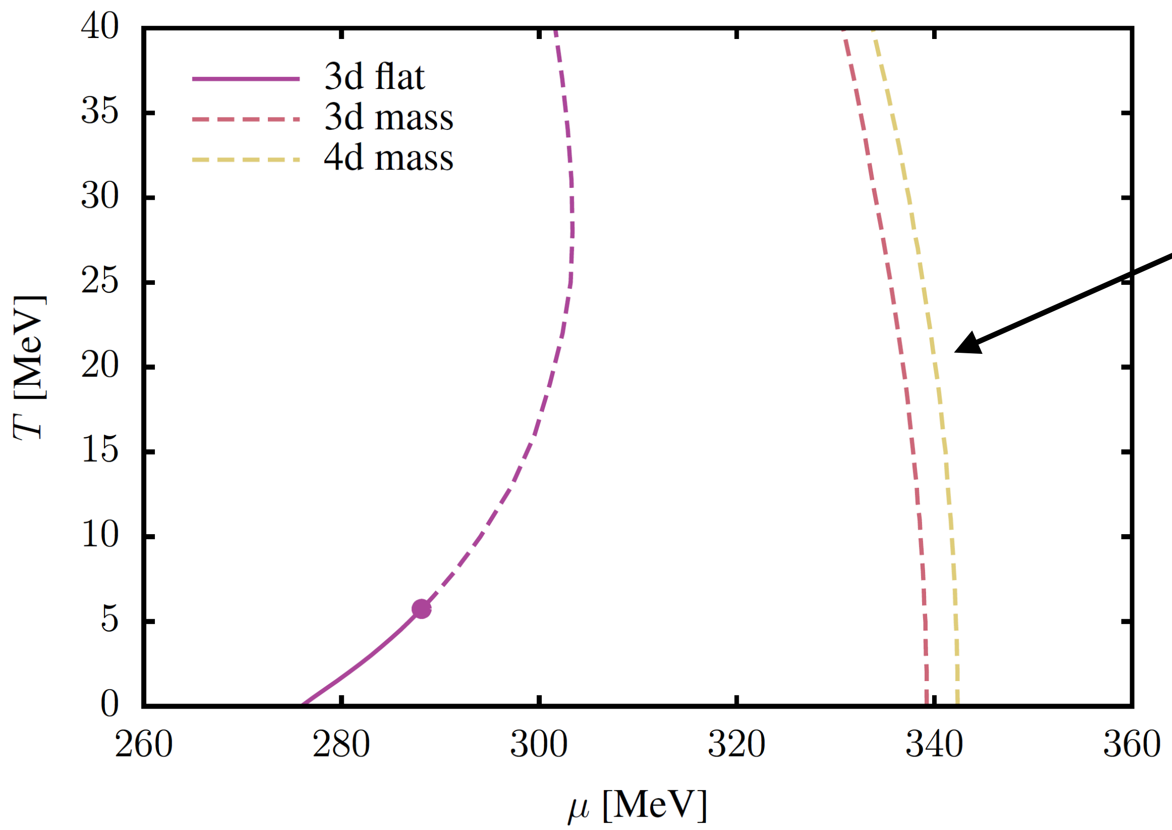
k_{IR}

adjust IR values by variation of k_Φ and k_χ

- scales around compositeness scale:
  - neglect mesons, quarks dominate
  - simple flows for
    - ➡ Yukawa coupling
    - ➡ mesonic wave function renormalization
  - field expansion of (dimless) potential
    - ➡ IR fixed point for coeffients n>1



Chiral transition at low temperature

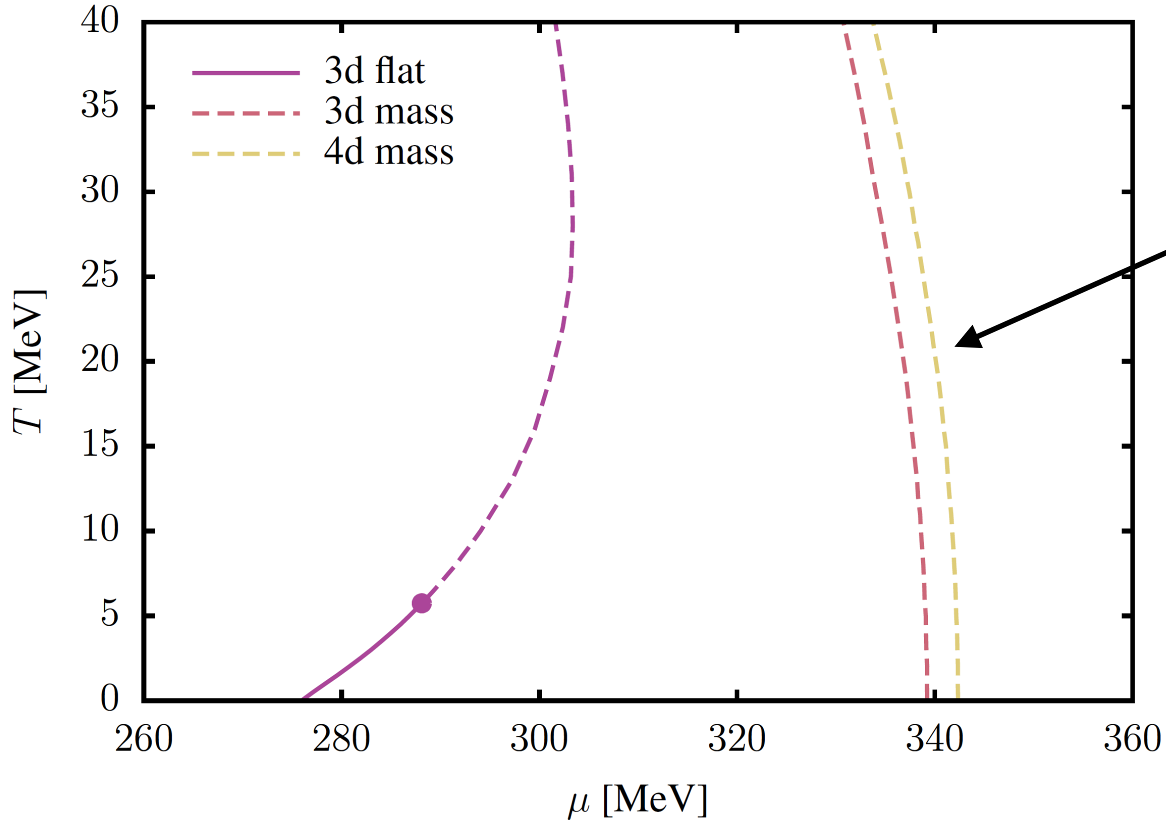


no back-bending with CS mass-like regulator

small differences between 3d and 4d regulators

purely crossover ➜ pseudocritical μ_c larger than m_q

Chiral transition at low temperature

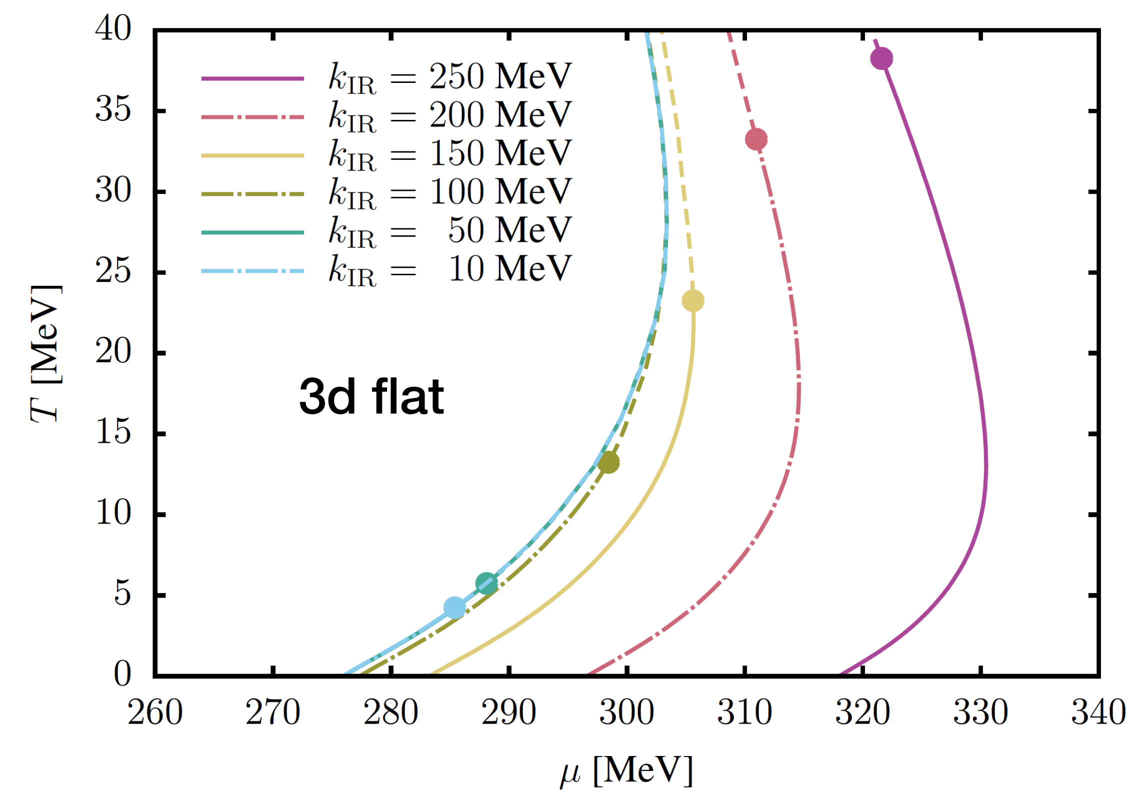


no back-bending with CS mass-like regulator

small differences between 3d and 4d regulators

purely crossover ➜ pseudocritical μ_c larger than m_q

could finite IR cutoff play a role? ➜ No

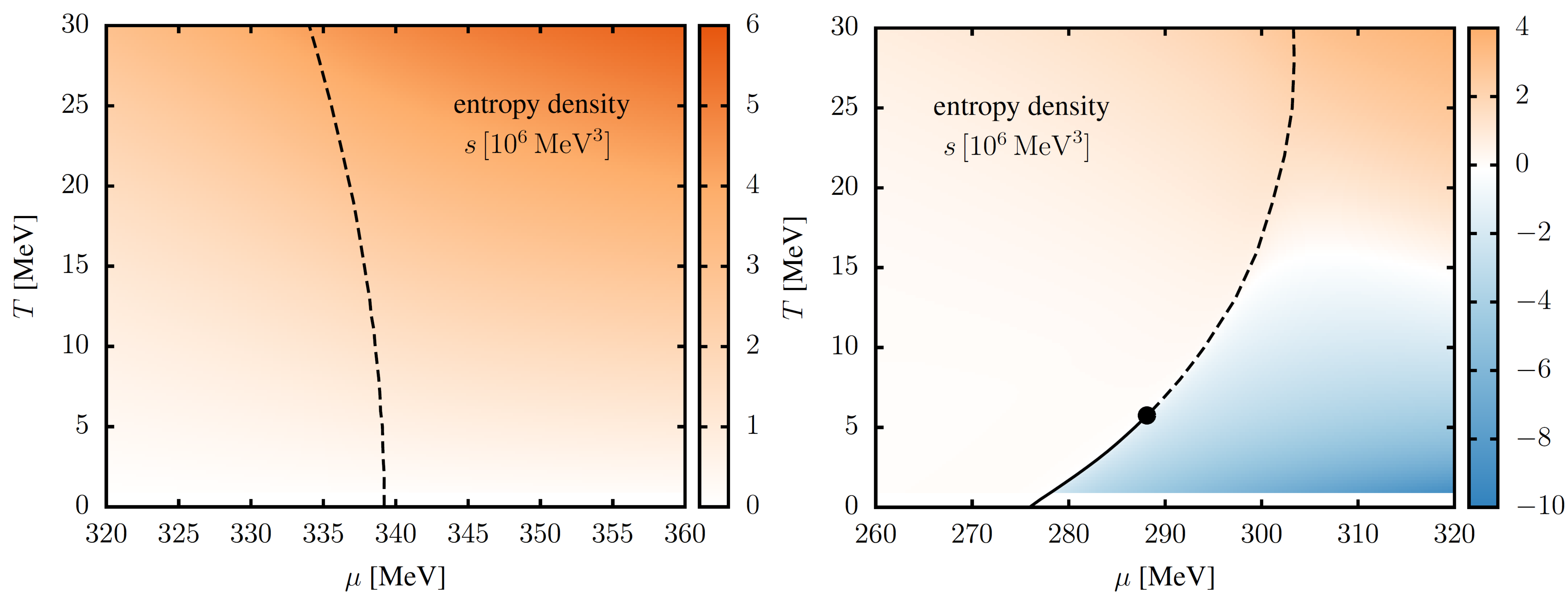


transition line shifts and CEP moves down

but back-bending over large k_{IR} range

Chiral transition at low temperature

➜ no negative entropy density anymore for CS mass-like regulator

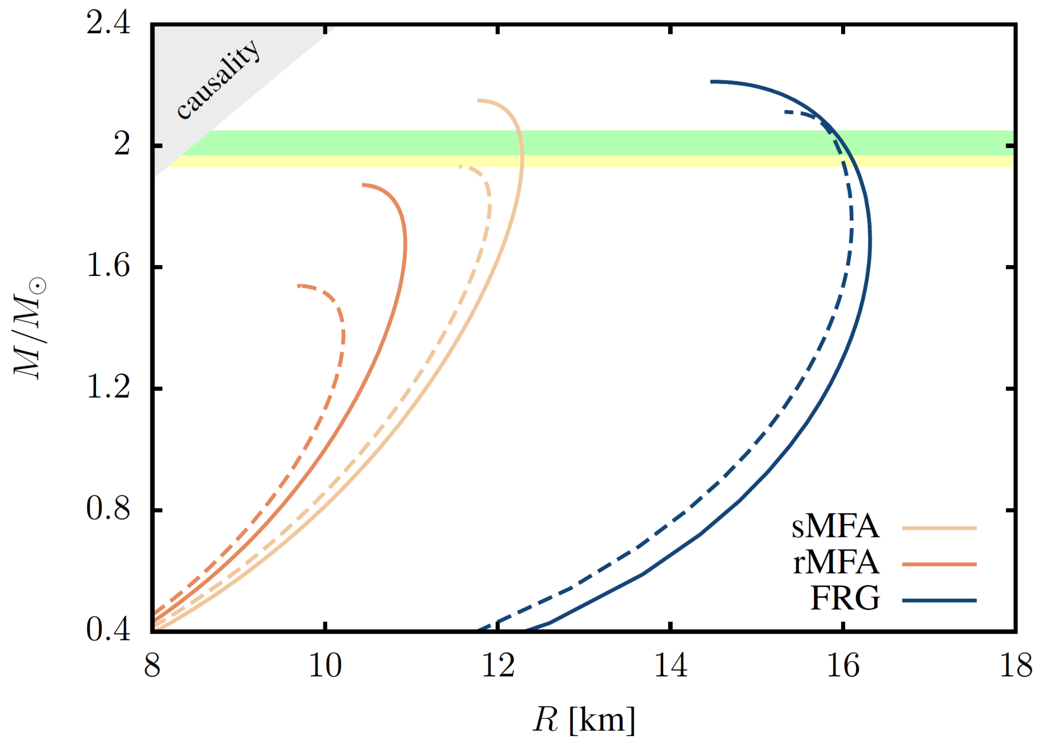


Summary

Three home messages:

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

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



Summary

Three home messages:

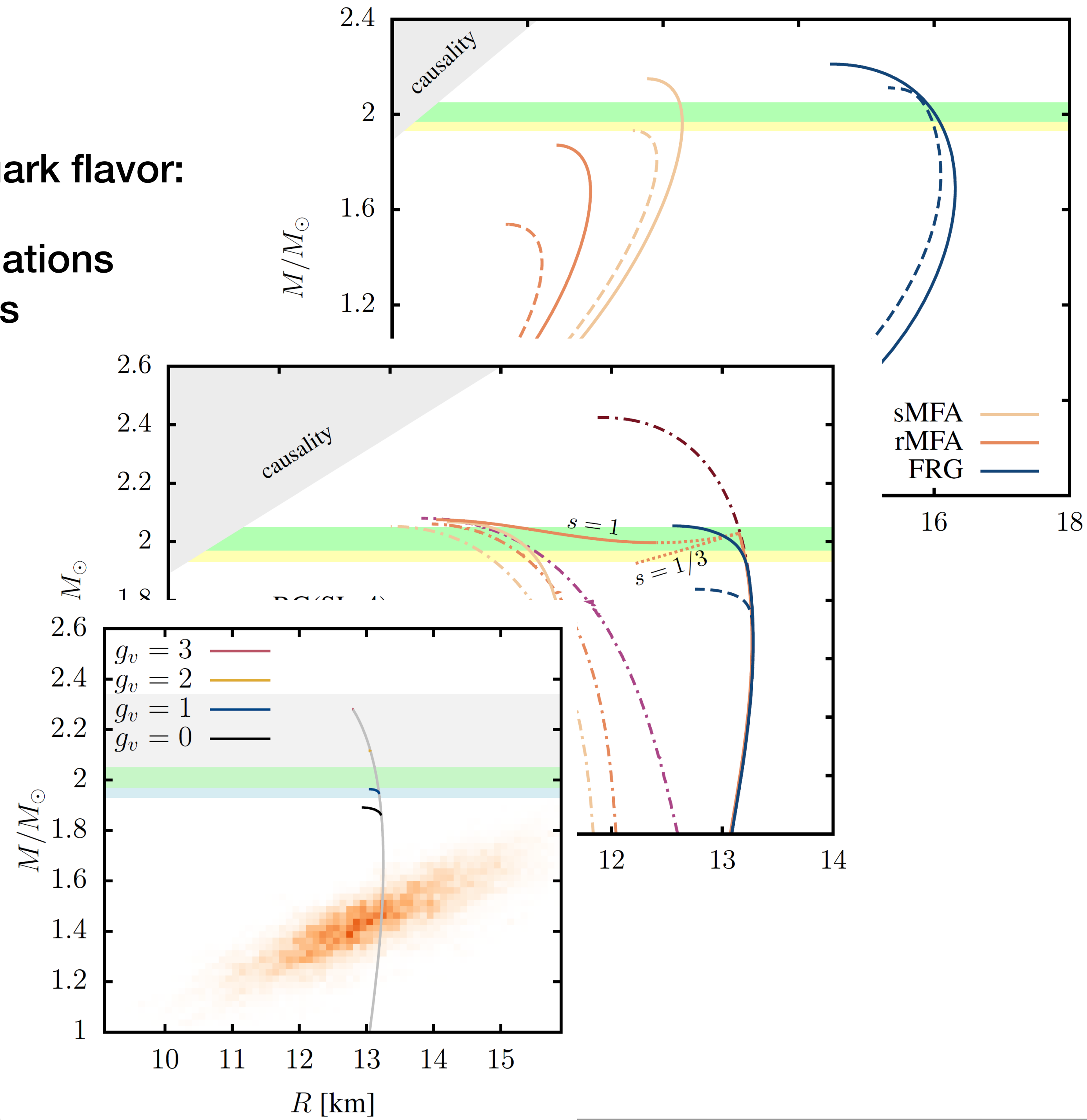
1. EoS with the FRG for two and three quark flavor:

   ➜ 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



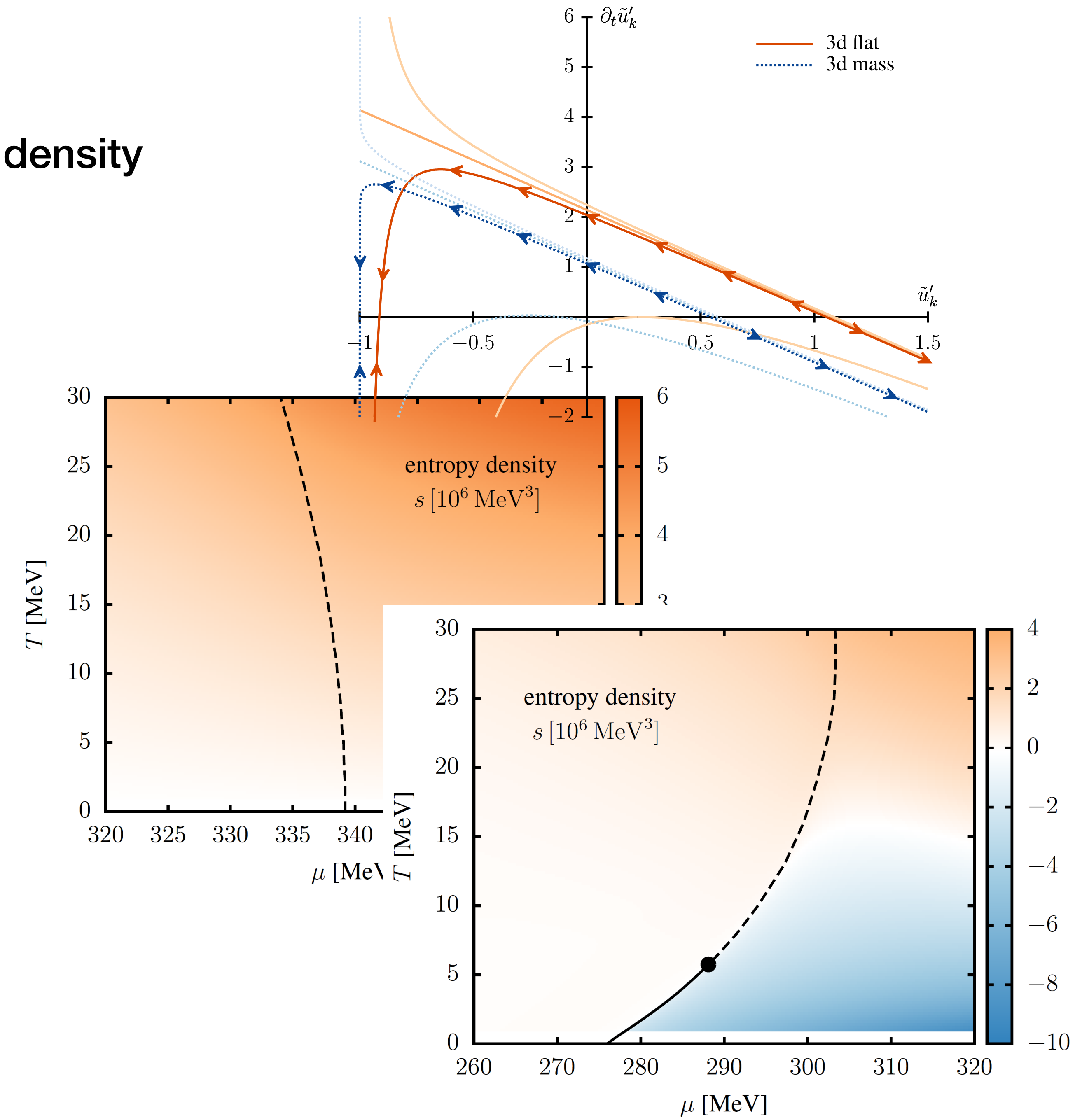
Summary

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



BACKUP slides

Pole proximity of vacuum flow

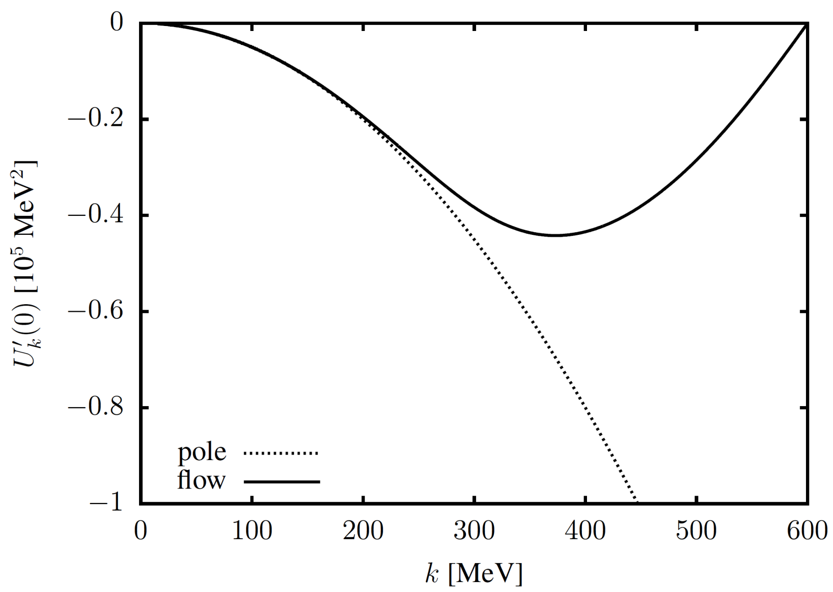
why are flows with CS mass-like regulators hard to solve in vacuum?

example: flat regulator (no problem)

$$\partial_t U_k^{\text{vac,flat}}(0) = \frac{k^5}{12\pi^2}\left(\frac{4}{E_\pi} - \frac{4N_c N_f}{k}\right)$$

$$E_\pi = \sqrt{k^2 + 2U_k'(0)}$$

pion pole



Pole proximity of vacuum flow

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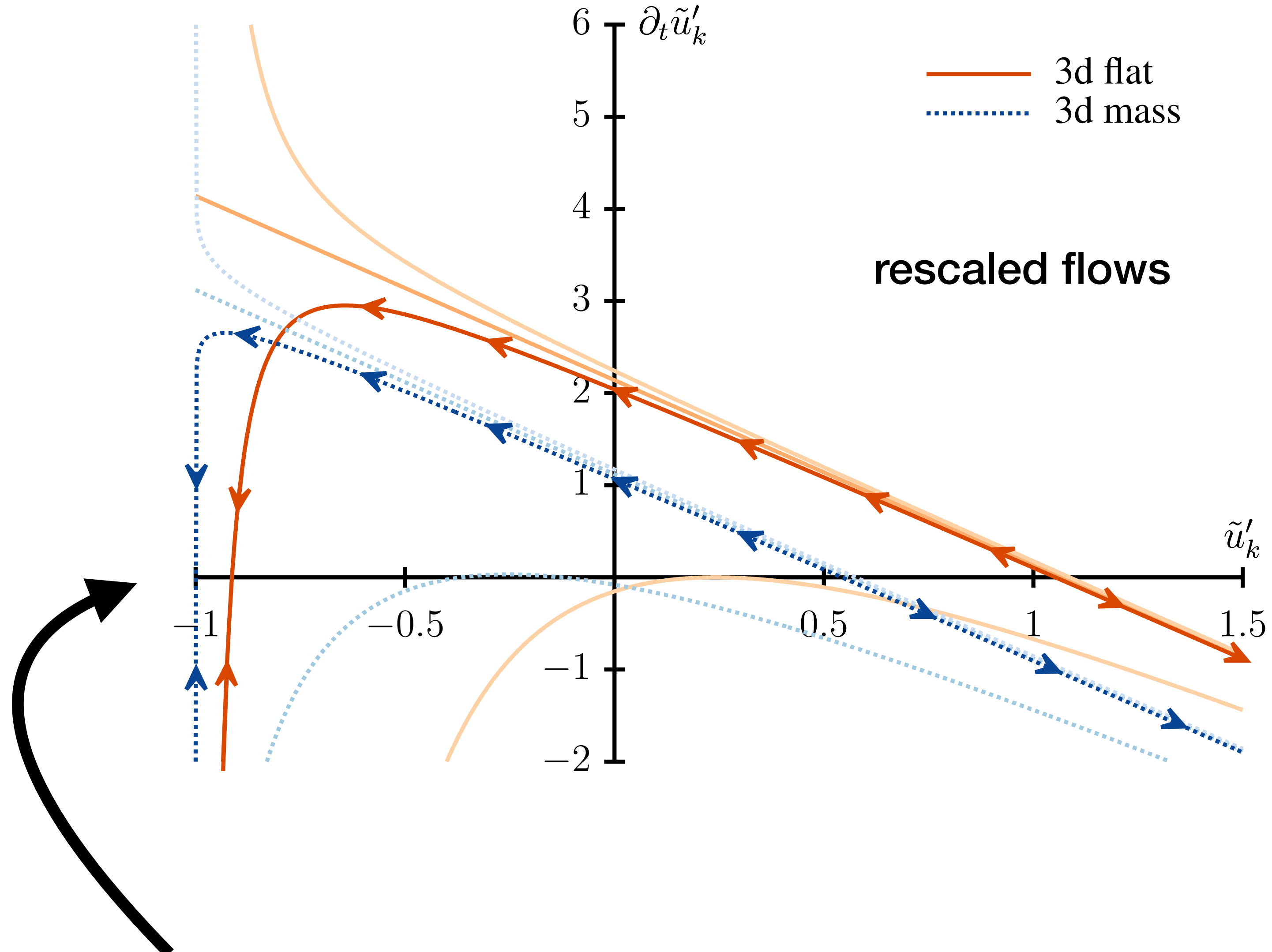

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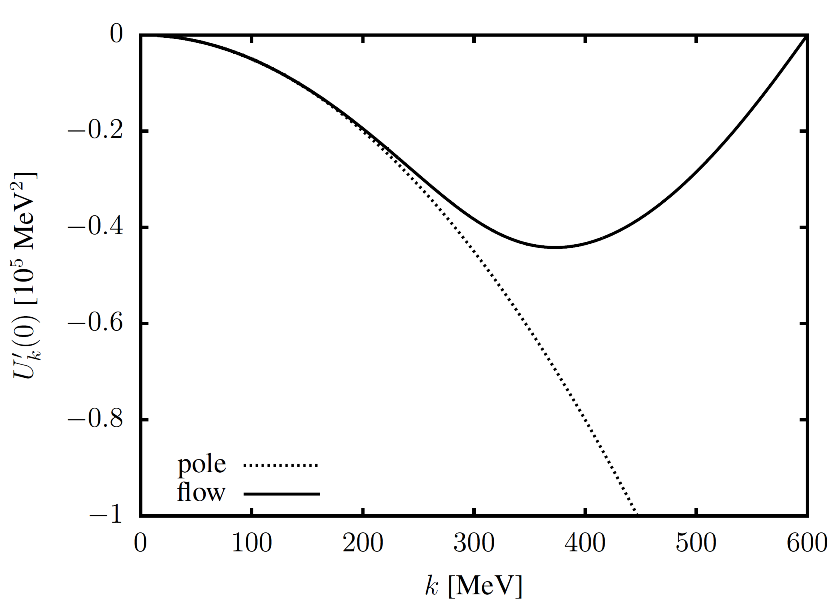

CS regulator run much closer to pole

Pole proximity of vacuum flow

why are flows with CS mass-like regulators hard to solve in vacuum?

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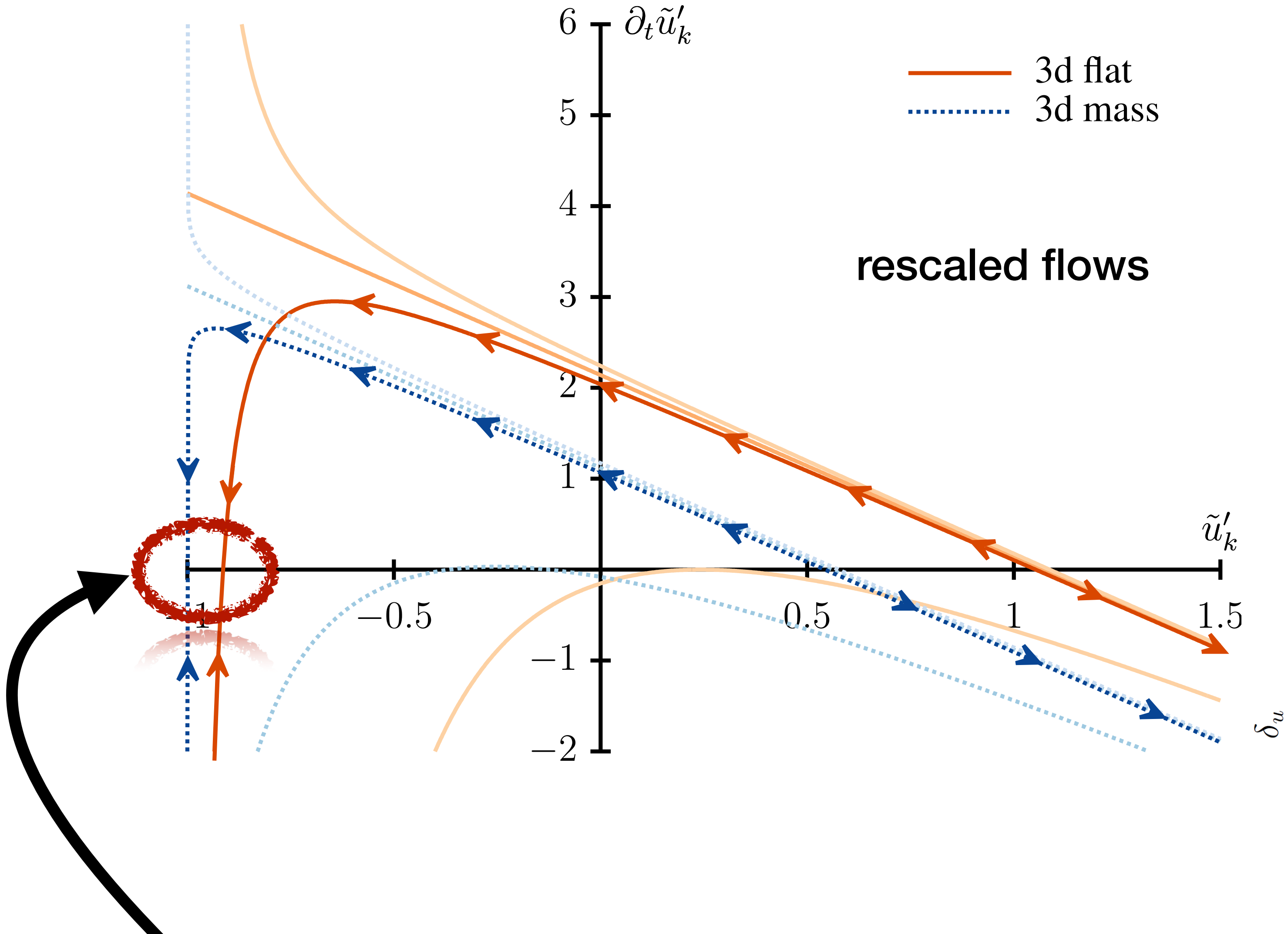

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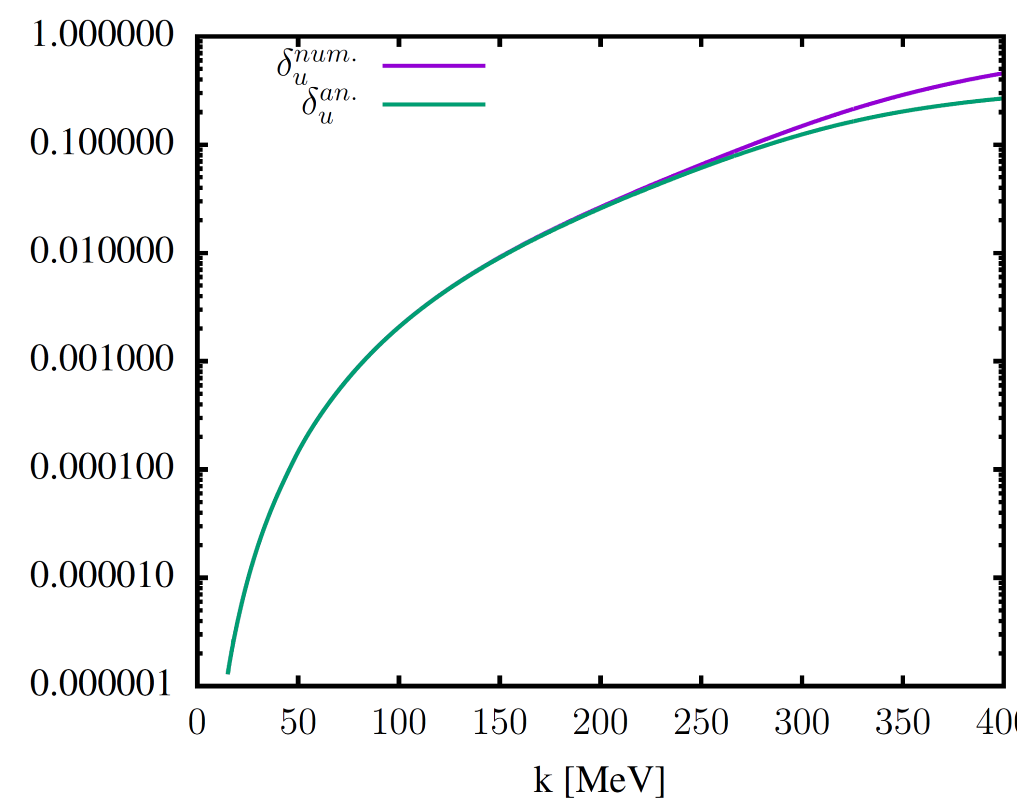
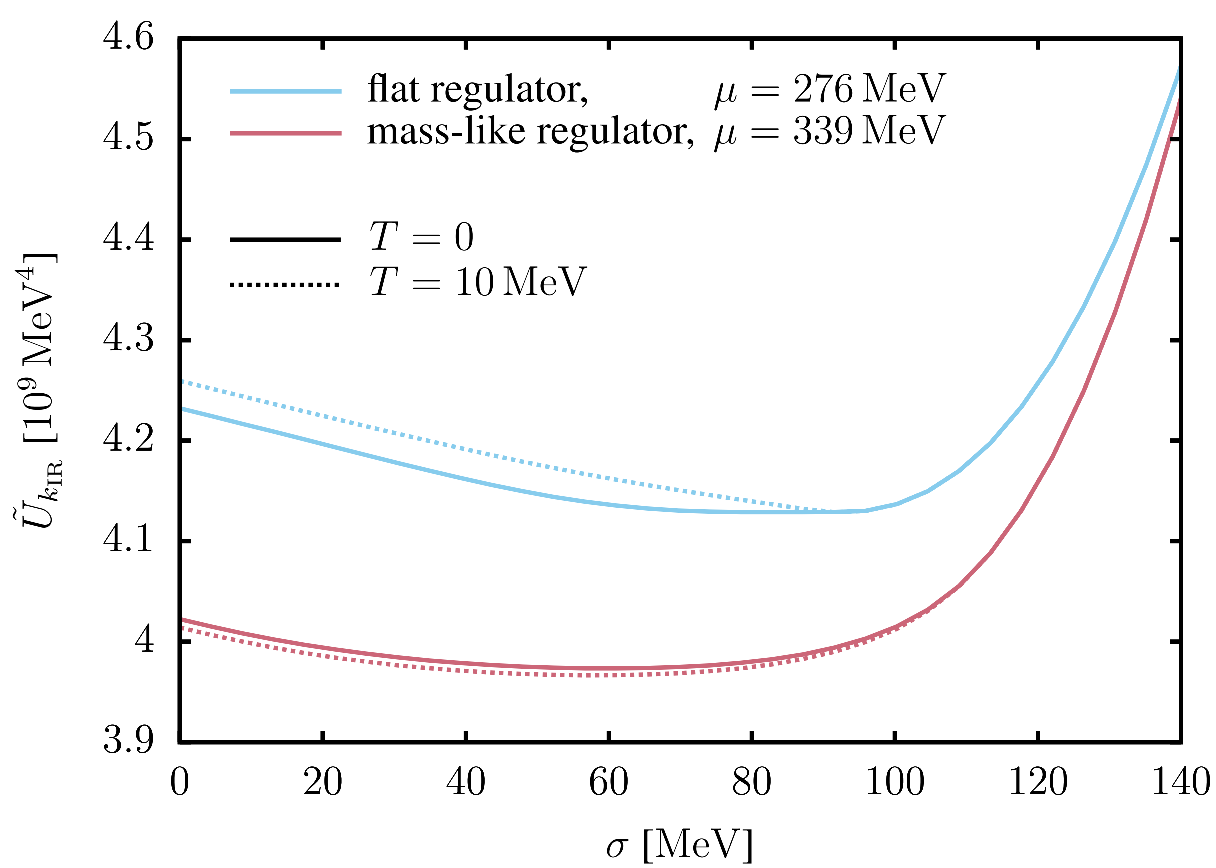
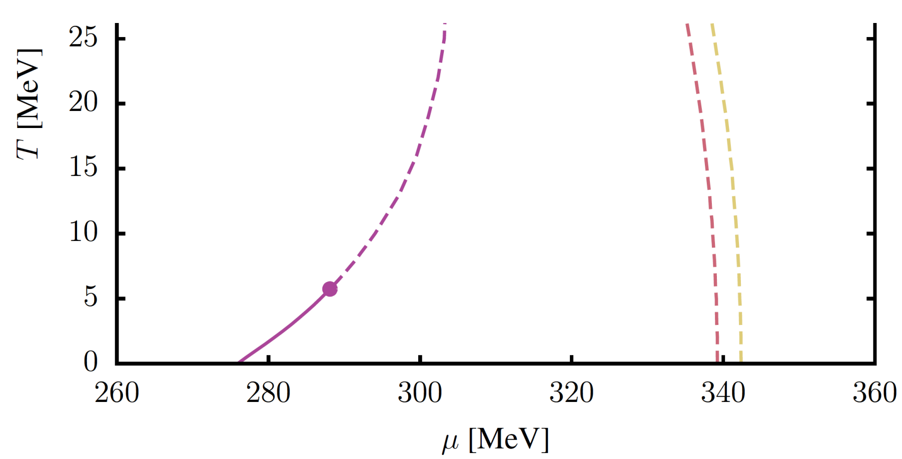


CS regulator run much closer to pole

distance to pole: useful as general criterion?

Origin of back-bending





flat (Litim) regulator

larger variations between two temperatures

potential moves **upwards**

➜ chiral symmetry breaking

➜ back-bending

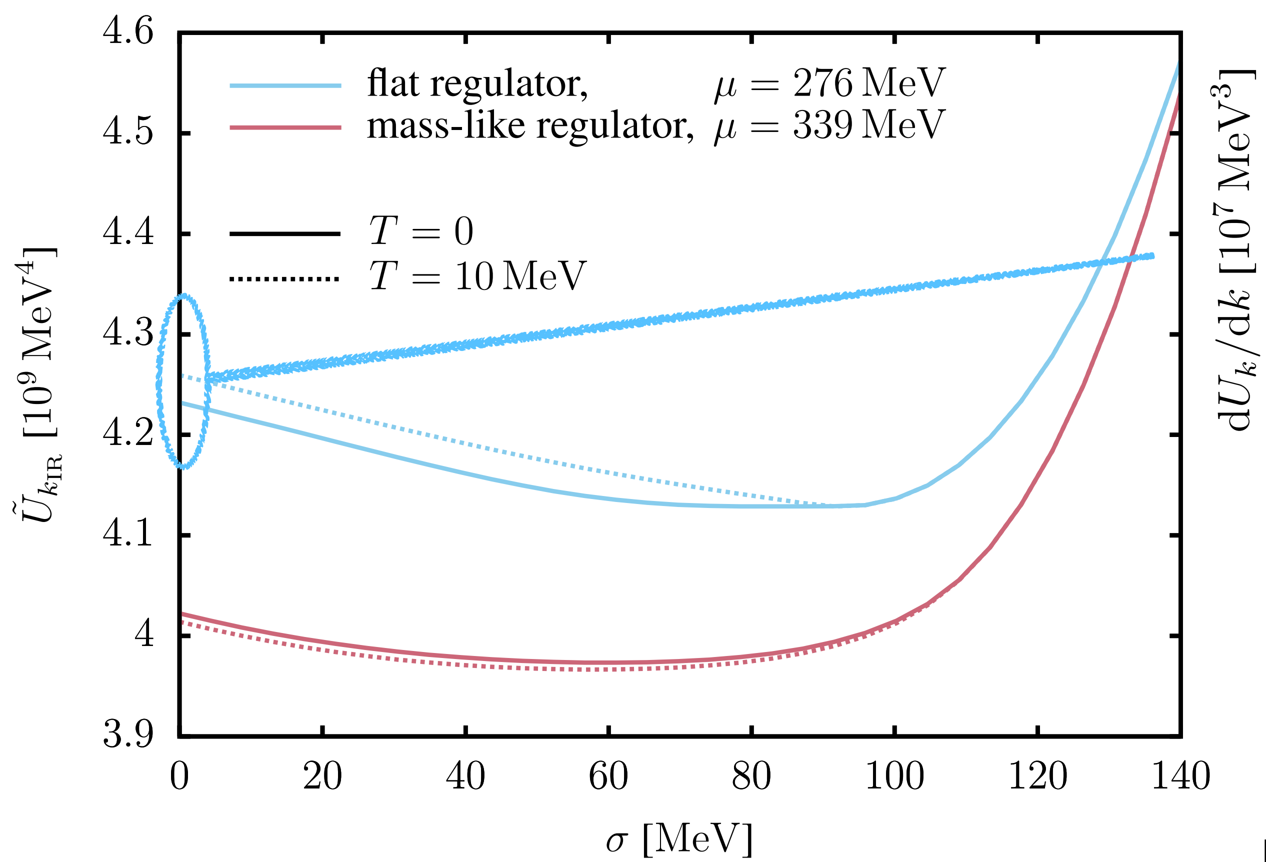
CS mass-like regulator

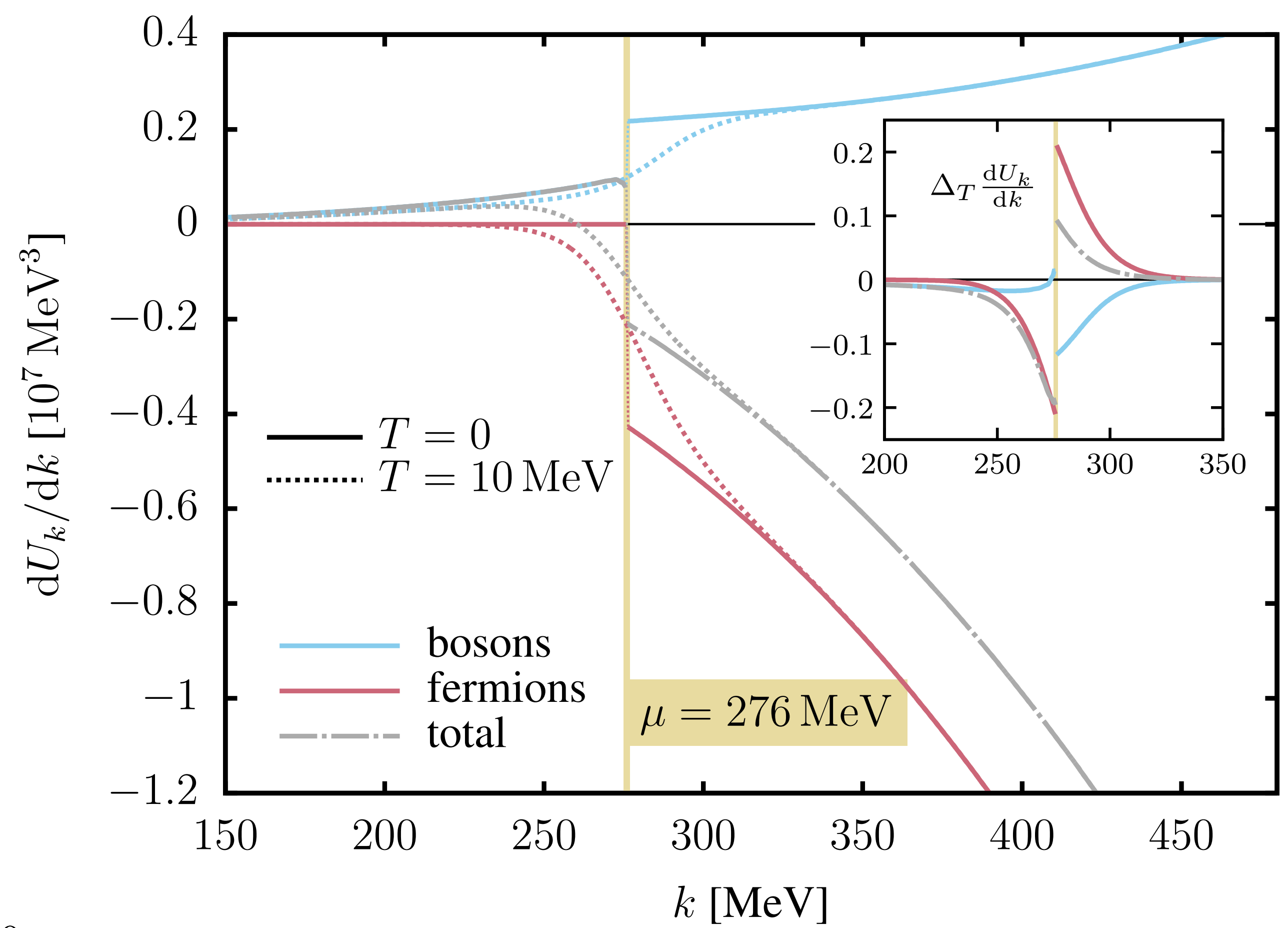
smaller variations between two temperatures

potential moves **downwards**

➜ chiral symmetry restoration

Origin of back-bending





Fermi distribution not integrated out ➜ discontinuity

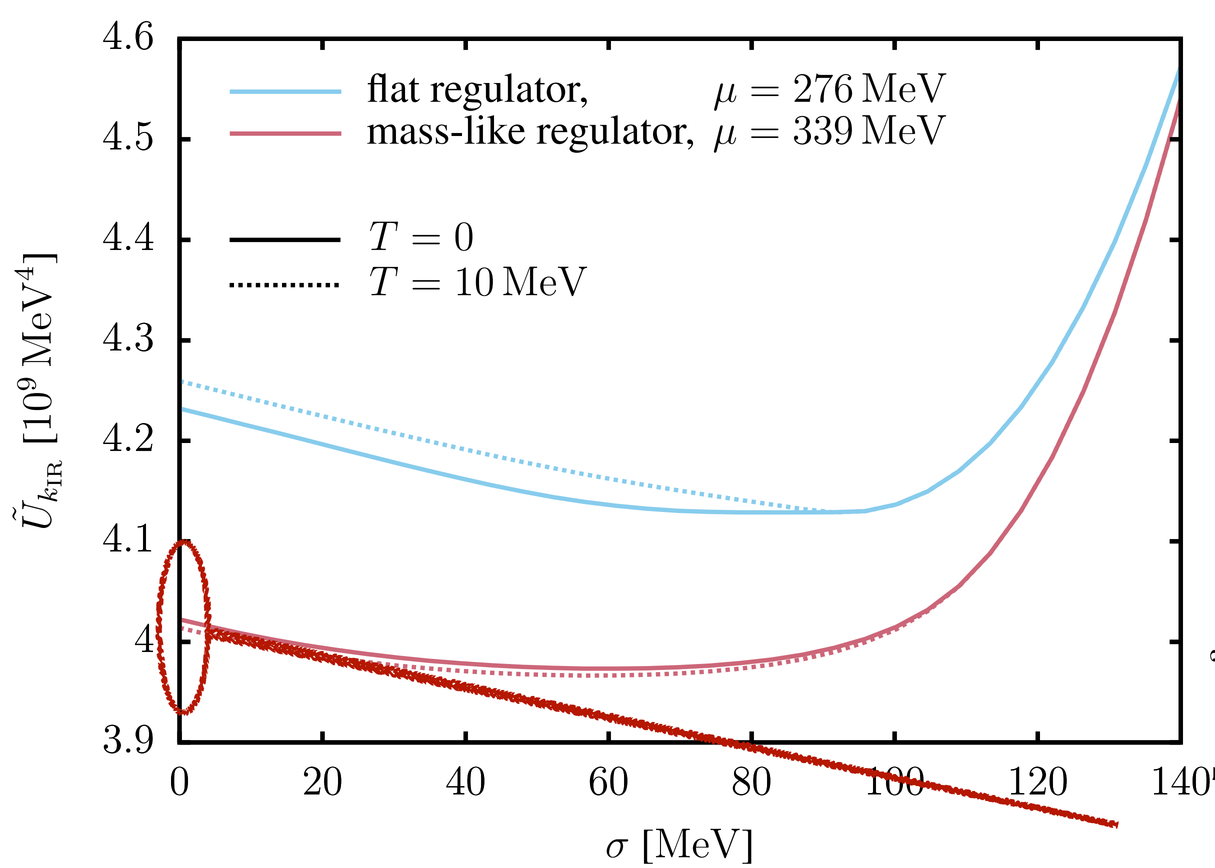
fermionic fluctuations decoupling at $k = \sqrt{\mu^2 - m_q^2}$

mean-field approximation works because net integral of relative flow for fermions close to zero

bosons cannot mimic this behavior, become weaker at finite T

$$\partial_t U_k^{F,\mathrm{flat}} = -\frac{N_c N_f k^2}{\pi^2 E_q}\,\Theta(E_q - \mu)\int_0^k \mathrm{d}p\, p^2 = -\frac{N_c N_f k^5}{3\pi^2 E_q}\,\Theta(E_q - \mu)$$

Origin of back-bending



fermionic fluctuations decouple for increasing mu

Fermi distribution integrated out in the loop

$$\partial_t U_k^{F,\mathrm{mass}} = -\frac{N_c N_f k^2}{\pi^2} \int_{p_F}^{k_\phi} \mathrm{d}p \, \frac{p^2}{\sqrt{p^2 + k^2 + m_q^2}}$$

$$p_F := \begin{cases} \sqrt{\mu^2 - k^2 - m_q^2}, & \mu^2 > k^2 + m_q^2 \\ 0, & \text{else} \end{cases}$$