Holographic quarkyonic matter

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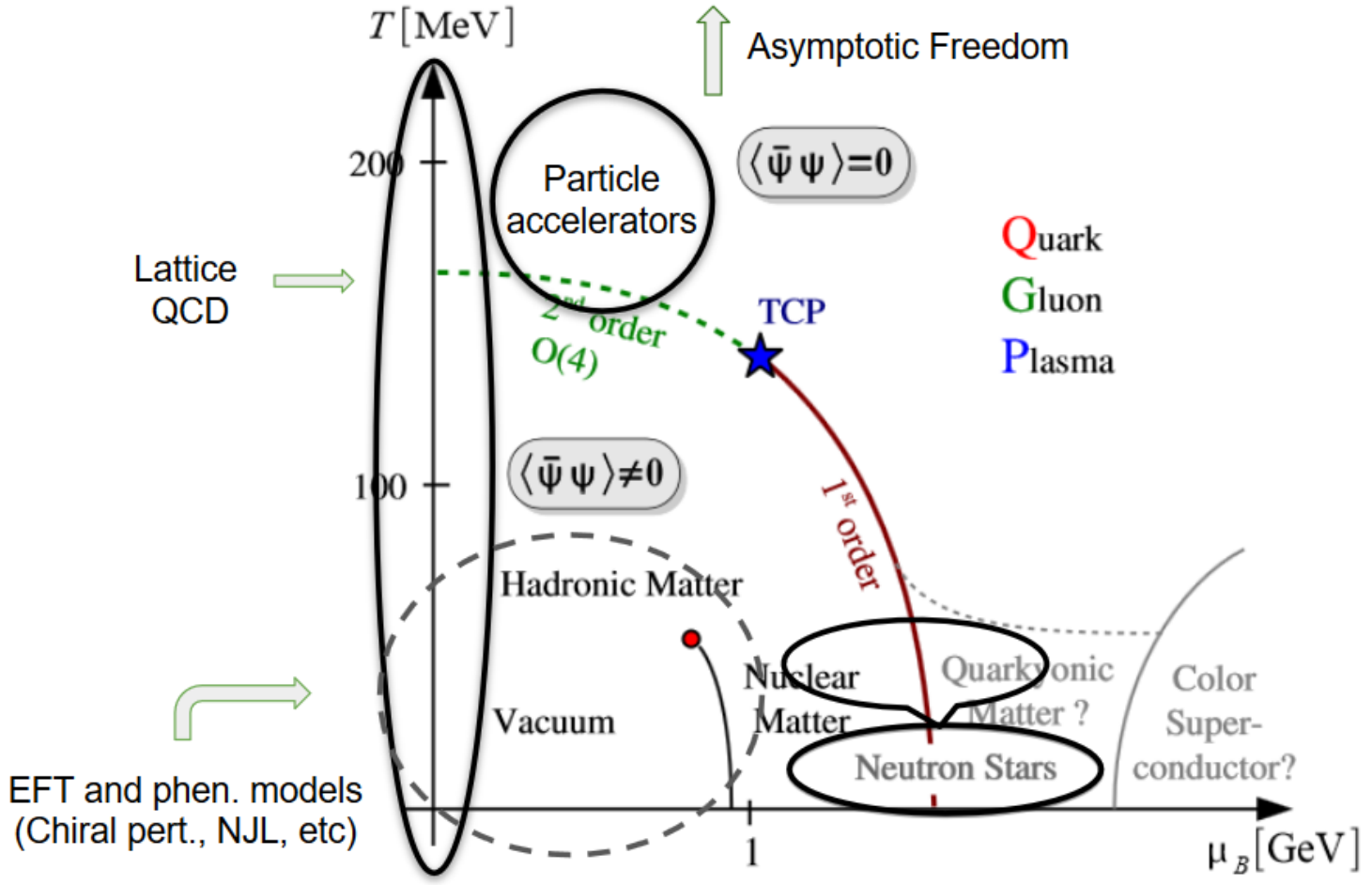
A Virtual Tribute to Quark Confinement and the Hadron Spectrum 2021

Based on ArXiv:1911.08433 (JHEP), 2006.13739 (JHEP) and 2105.03218 (SciPost Physics)
in collaboration with **Andreas Schmitt**.

Introduction and motivations

QCD vacuum structure ($m_q = 0$) [de Forcrand et al '15]



Today we focus on one of the possible phases at **cold and dense** QCD: **quarkyonic matter**.

Why is it so interesting? Why is it so difficult?

- Understanding the QCD phase diagram is crucial for a wide range of phenomena: heavy ions, early cosmology, compact stars, ...
- **Neutron Stars** are our own cold and dense QCD matter laboratories! (through grav waves, and not so cold for **mergers**).

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- The cold and dense regime is hard to describe analytically.
- The phase structure is believed to be strongly **dependent on the parameters** (m_q and N_c, N_f, B, μ_I).
- There are almost no effective or phenomenological models describing **quarks, mesons and baryons** at the same time.

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Can holography help? We argue it provides an alternative strongly coupled description of quarkyonic matter.

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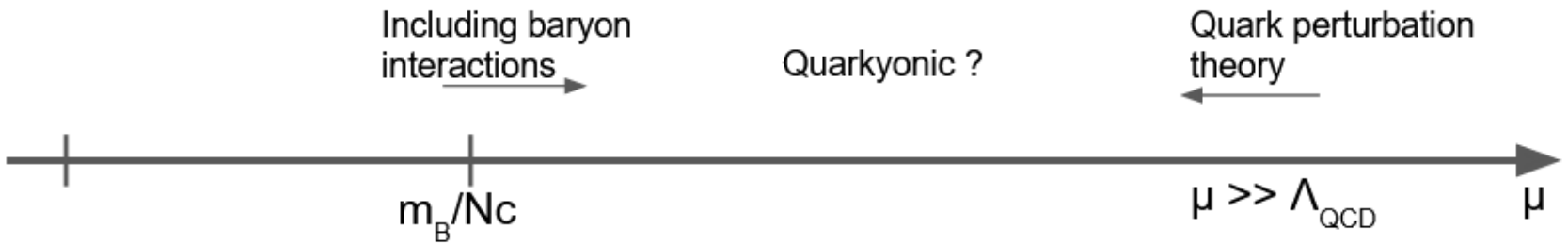

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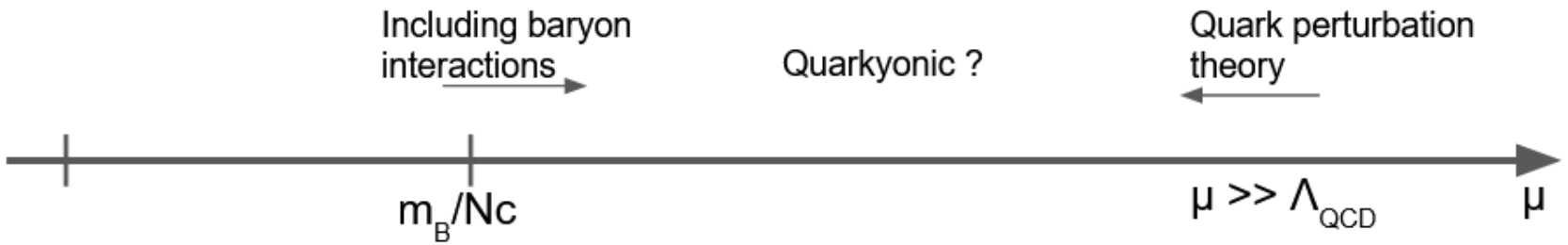

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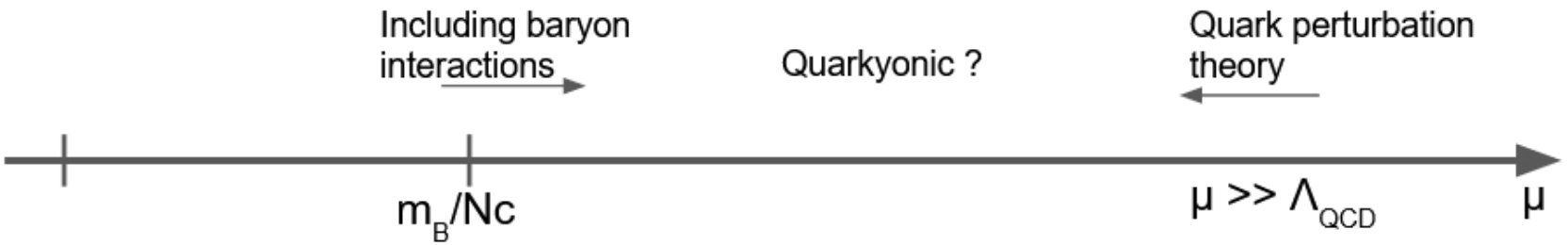

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Are both descriptions valid? Are there transitions or a QH continuity? What happens with χ_{SB}? What about at $N_c = 3$?

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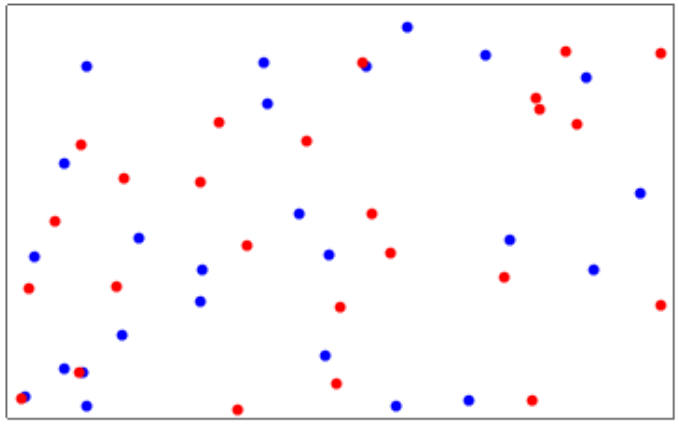
- a phase where 2 **independent gases** of baryons and quarks coexist.



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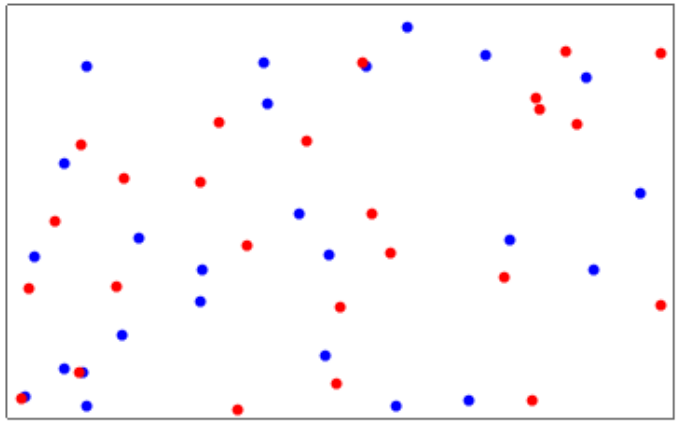
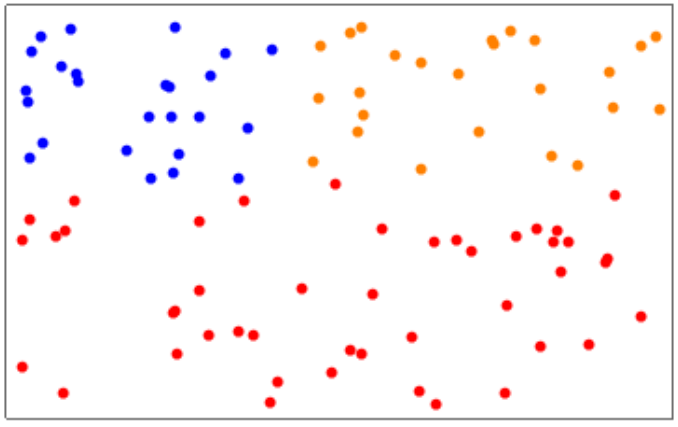


- a **mixed phase** where the ground state is baryonic in some regions of space and quark-like in others.



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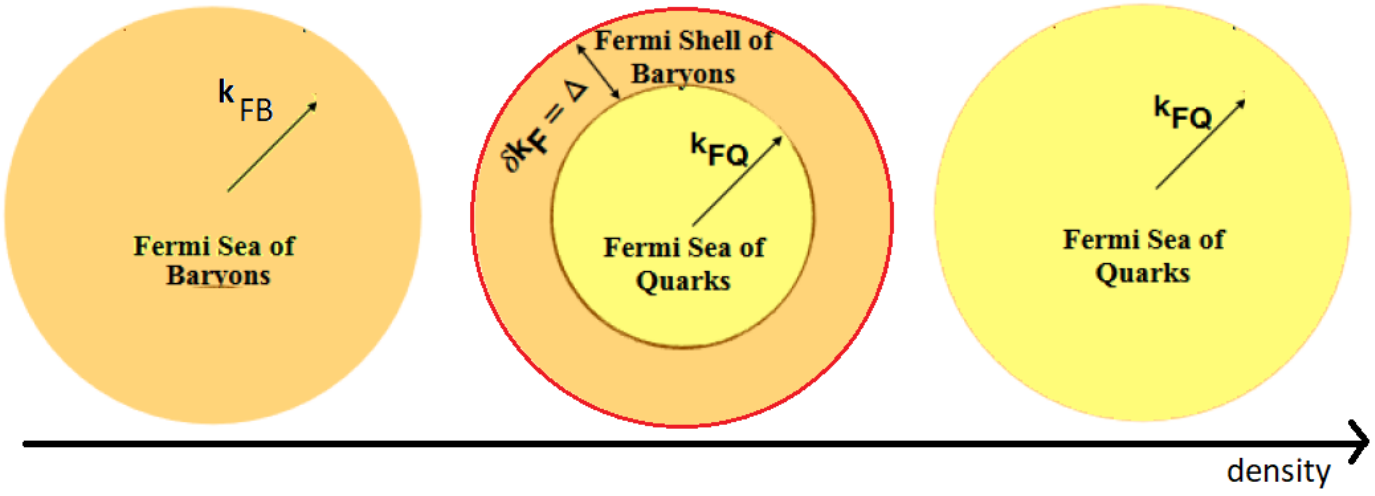

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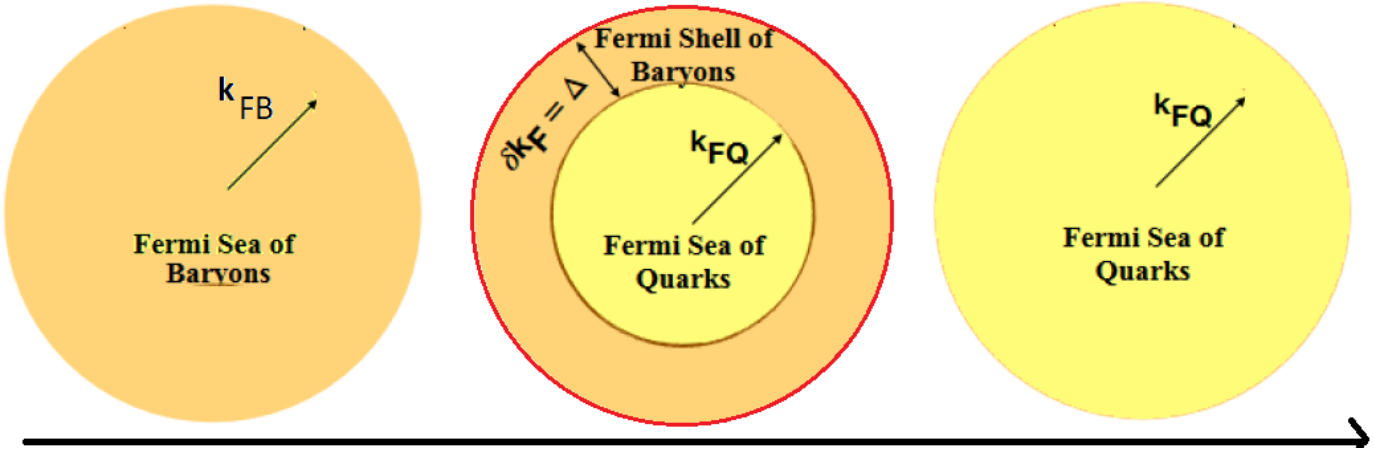
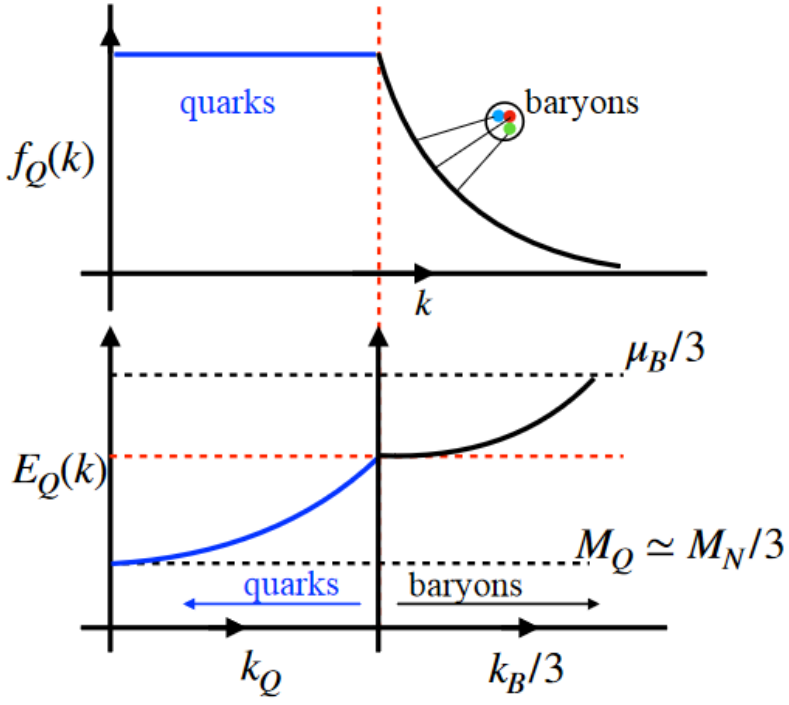


Physical consequences:

- Low-energy excitations are dominated by baryons.
- Bulk properties (P) have quark contributions.



The holographic framework

Witten-Sakai-Sugimoto and related models [W 98, SS 04]

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- **Top-down** model in string theory with only 3 free parameters.
- Provide **analytic methods** at strong coupling.
- Give a **geometric description** of QCD phenomena.
- Disentangle confinement and $\chi_{\rm SB}$.
- Connect QCD to pheno models such as NJL.
- Provide $S = S$[quark+mesons+baryons](T) from first principles.

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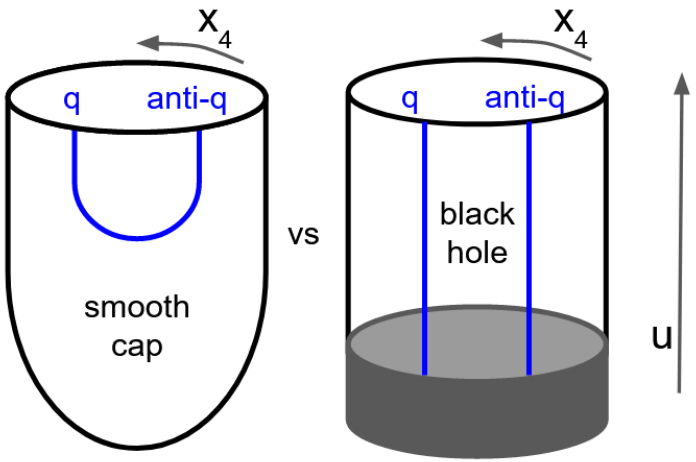
- The precise dual to QCD is not known.
- Works (mostly) at large N_c.
- No asymptotic freedom (in general, see however V-QCD).
- Not easy to include the pion mass. [NK-A.Schmitt 19]

Geometric interpretation

Confinement: gluon physics and holographic grav background



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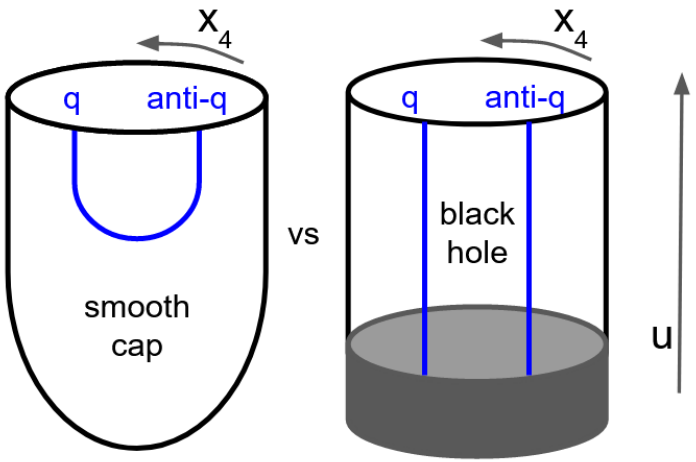
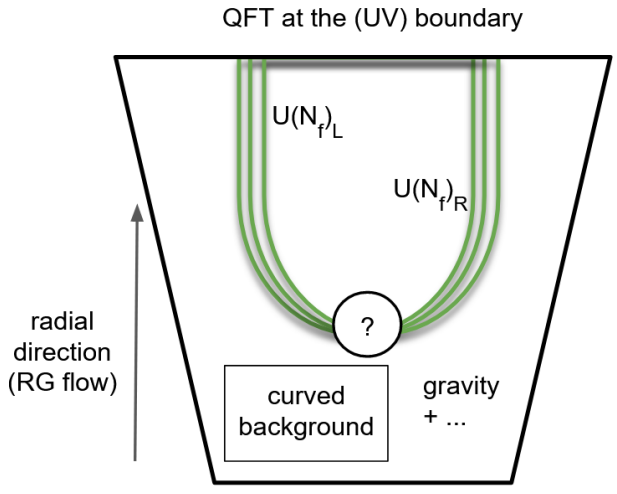


Chiral sym. breaking: flavor physics and D-branes



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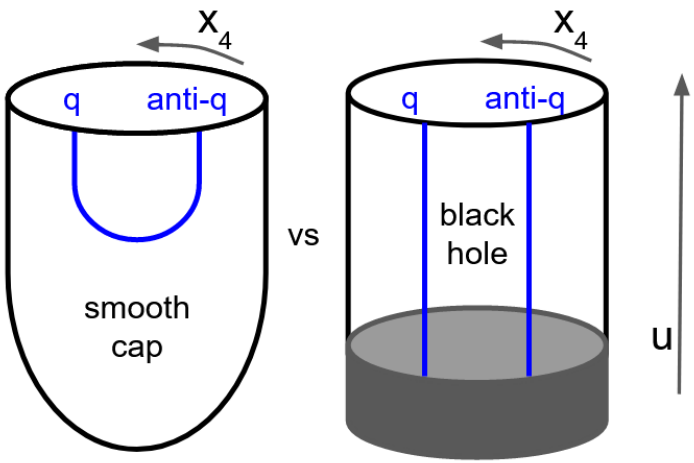

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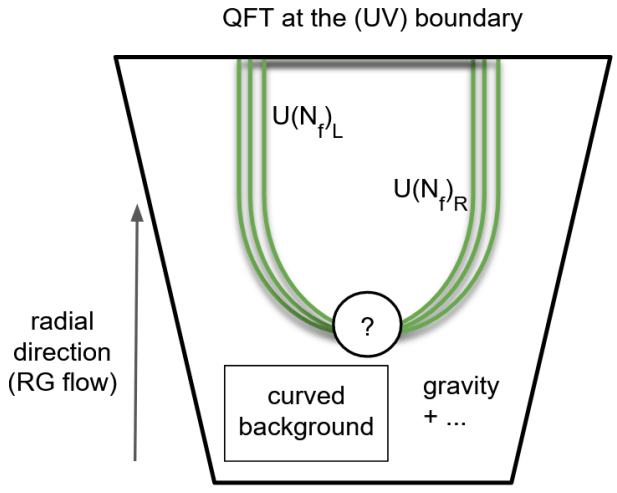
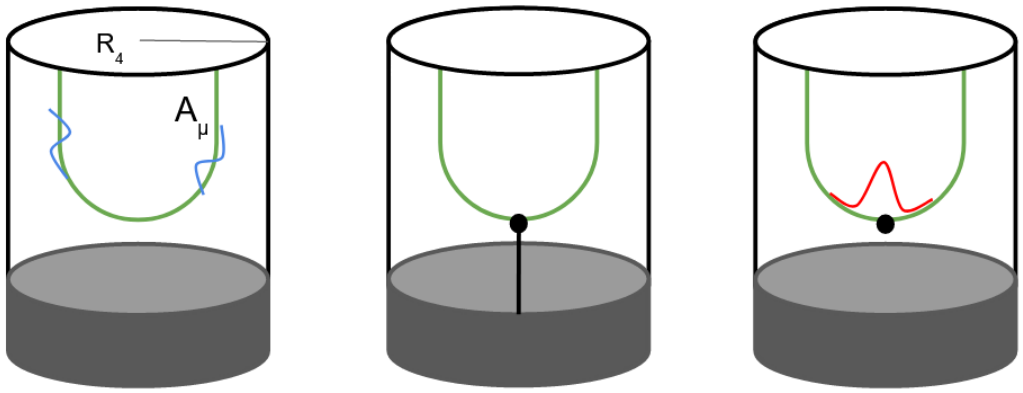


Holographic matter: Gauge fields, strings, instantons [Bergman et al 07]



Holographic Quarkyonic Matter

Quarkyonic matter at strong coupling [NK-A.Schmitt 20]

We construct a new phase: **holographic quarkyonic matter**

- Weak coupling: Layered Fermi surfaces in momentum space.
- Strong coupling: Layered structure in holographic direction, which is dual to the QFT energy scale.

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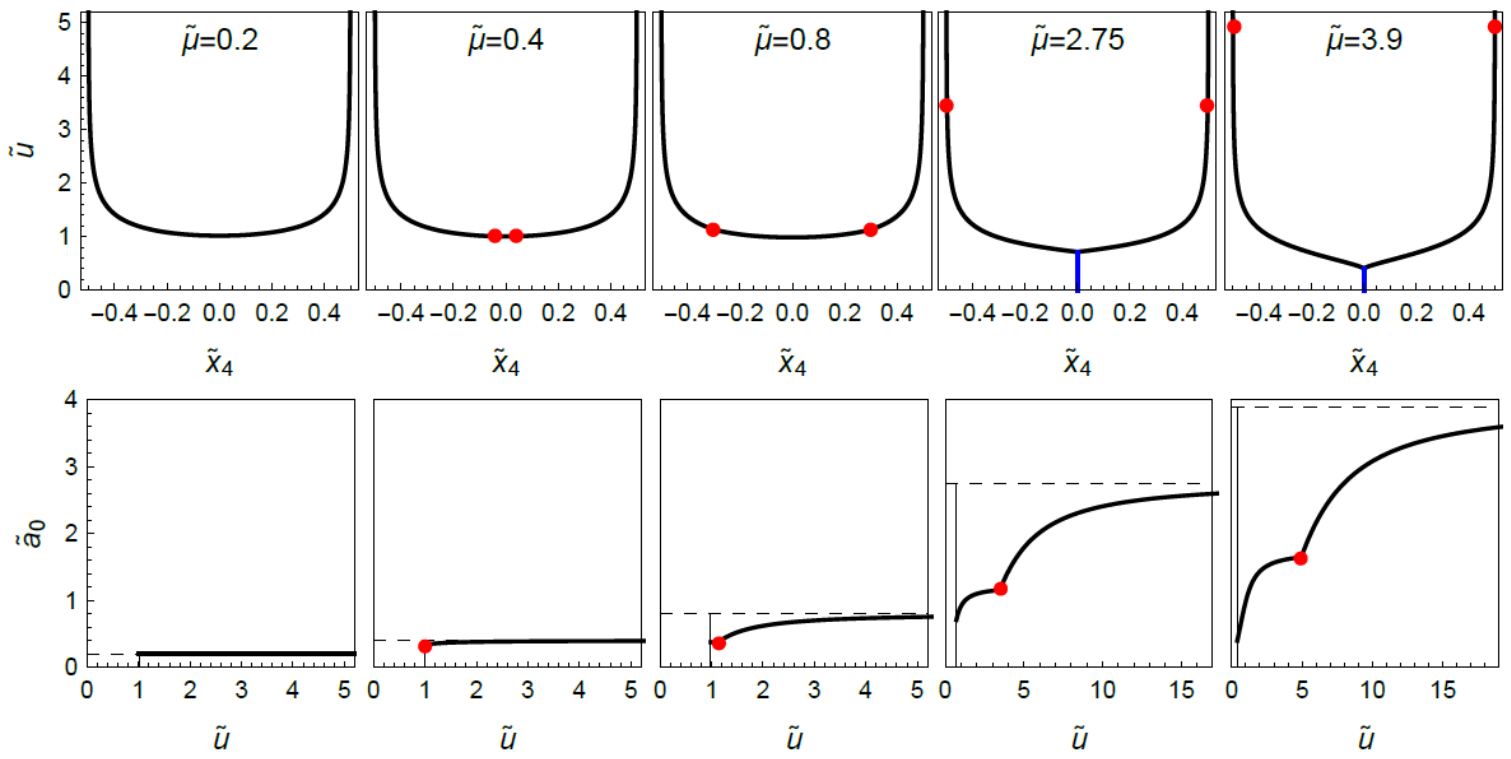
Intuitive **geometric** picture from evolution with μ_B at $T = 0$:



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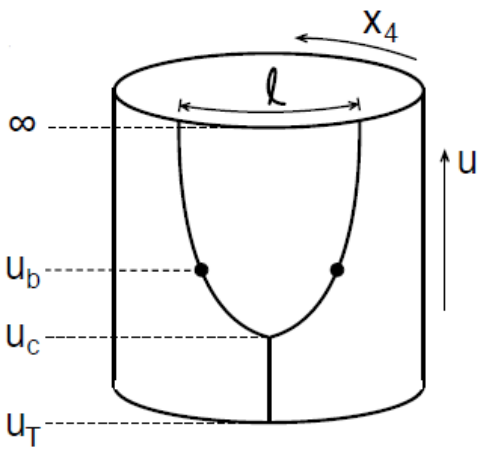
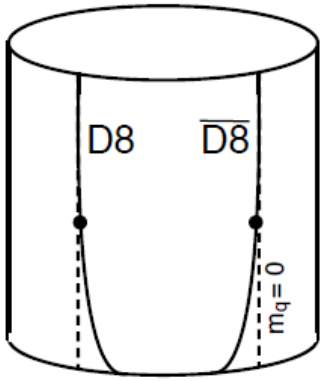


LTQy



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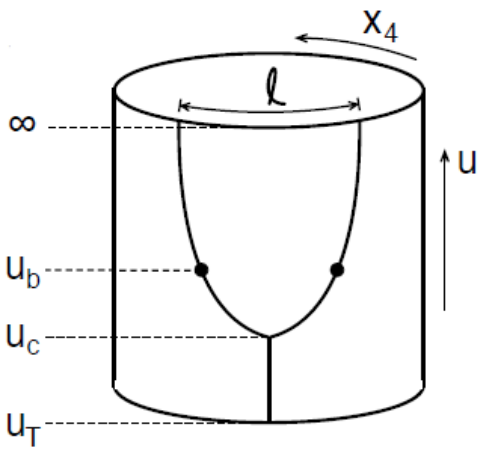

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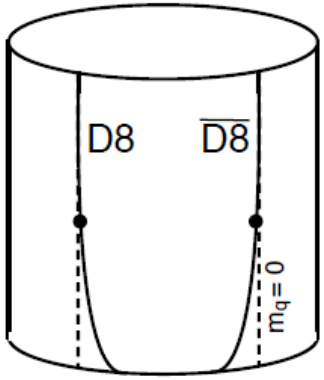

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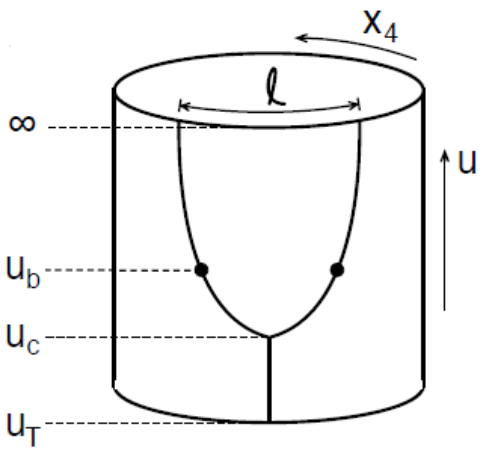

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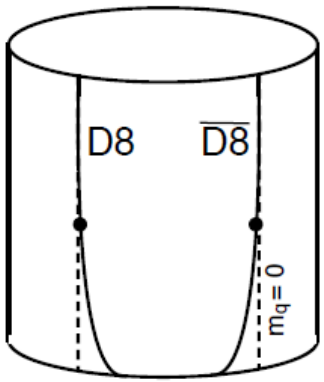

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Some details about this phase:

- continuous melting of baryons to QGP.
- some properties are similar to the quark phase, and others to the baryonic one.
- baryons do not disappear at high μ_B (*).

Is there a quark-hadron continuity?

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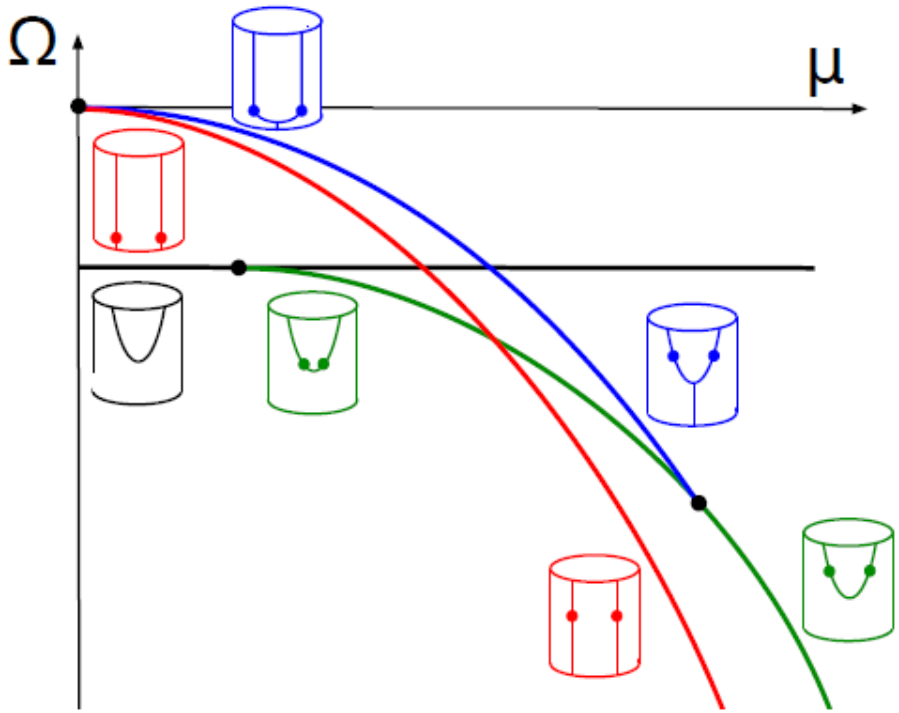

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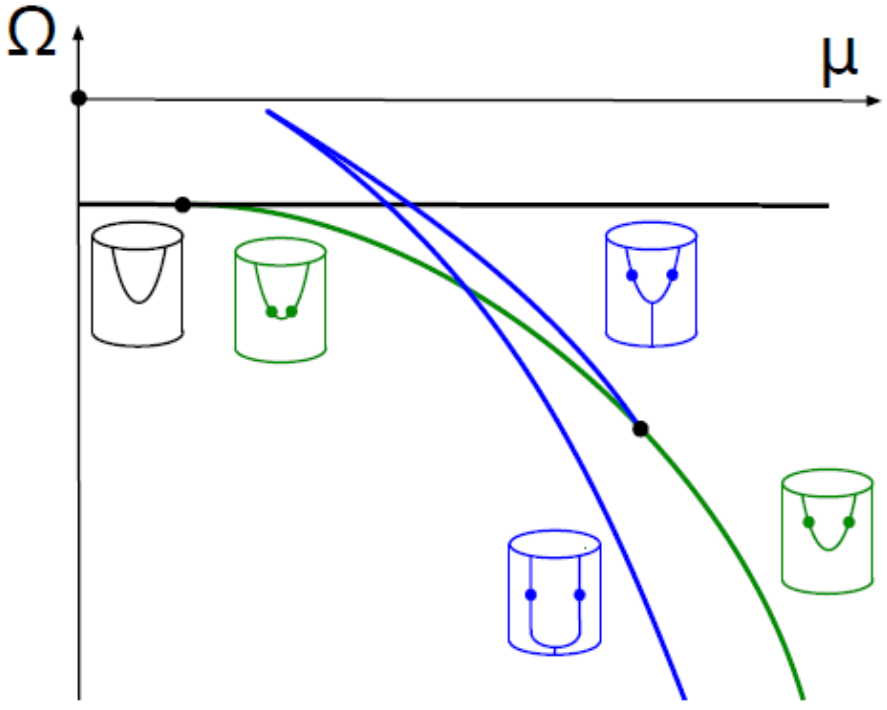

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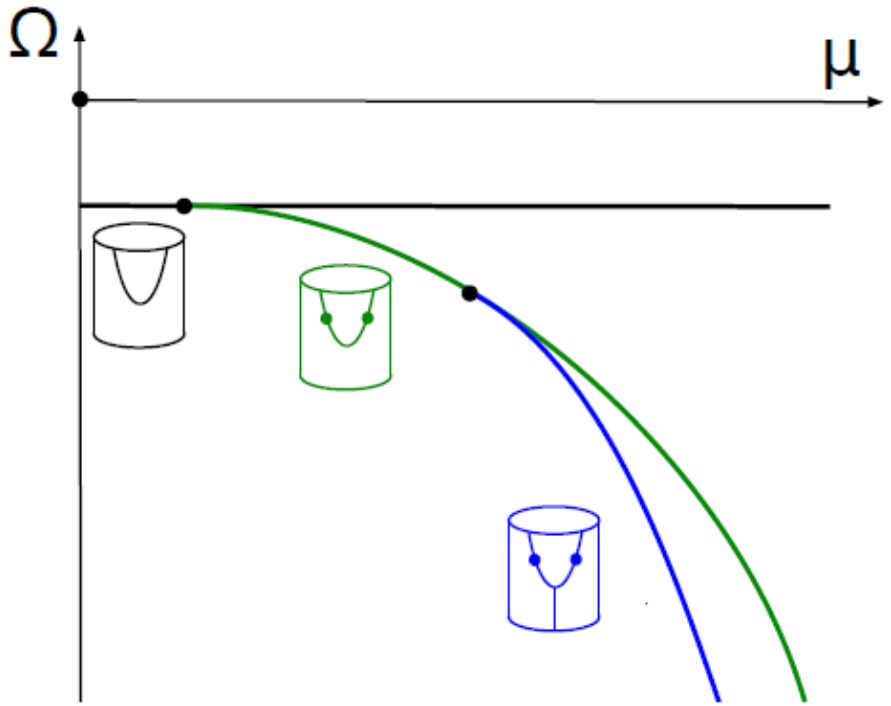
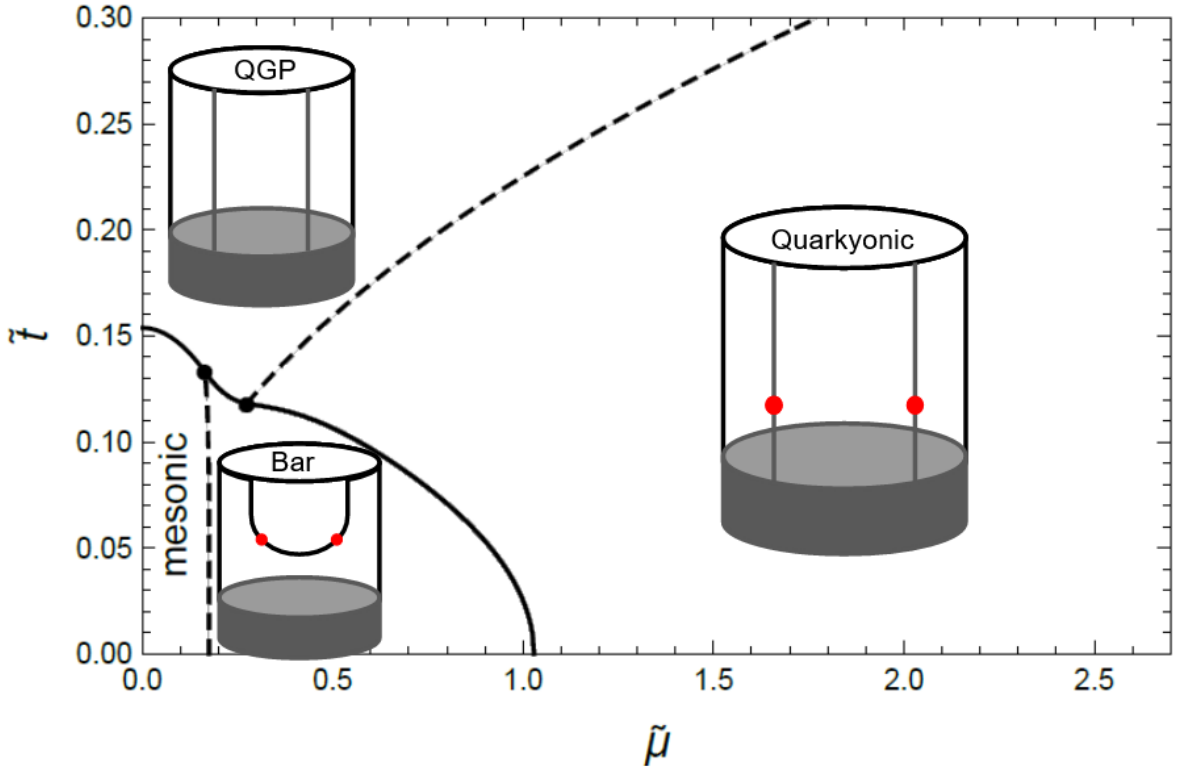


At large m_q all phases can be connected continuously!

Phase diagram in the chiral limit



- The **Qy** phase covers a significant part of the phase diagram.
- We find a novel **1st order chiral transition** at low temperatures.
- A **triple point** appears in the right ballpark of QCD estimates.
- The $c_s^2(\mu)$ at $T = 0$ is non-monotonic.
- This structure remains for physical pion masses.

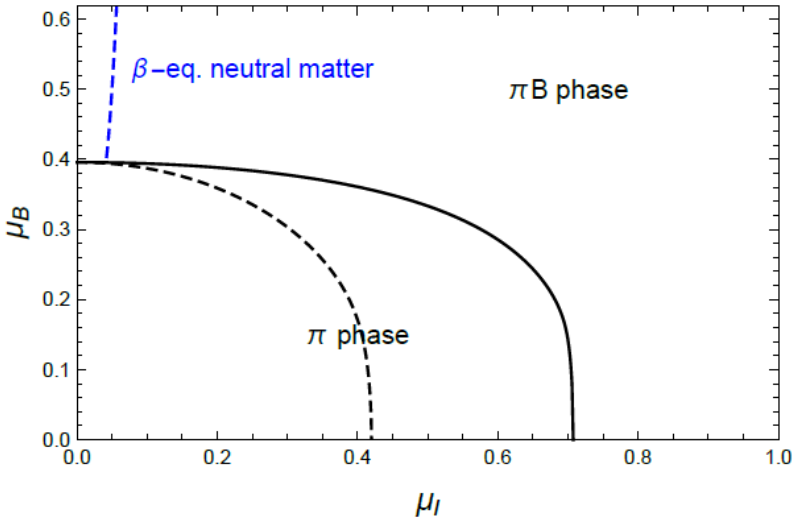
Isospin Asymmetry

Some isospin results at zero temperature [NK-A.Schmitt 21]

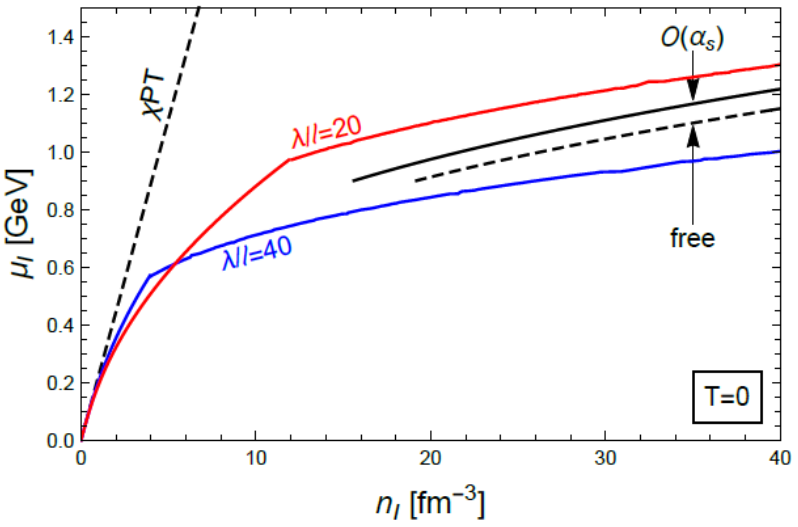
We have constructed a holographic model that

- deals with μ_I,μ_B and T at the same time.
- allows for baryons and condensed pions to coexist.

Phase diagram (μ_B, μ_I).**Prediction:** baryons appear even at $\mu_B = 0$.



Comparison with $\chi_{\rm PT}$ and pQCD.



Summary and outlook

- Holography provides models that describe **mesons, baryons** and **quarks** simultaneously.
- We have used it to describe the **quarkyonic phase at strong coupling**.
- The layered structure in momentum space now appears in the **holographic direction**, associated to the QFT RG flow.
- In our model, quarkyonic matter is **chirally symmetric** at $m_q = 0$.
- Also, the QH continuity hypothesis is realized at large m_q.

- How does this change for smaller N_c? Is it affected by more realistic baryon interactions? And by an isospin asymmetry?
- How much of this is relevant in for Neutron stars? How does it affect the Mass-Radius curves? [NK-A.Poole-A.Schmitt, in progress]

Thank you! Any questions?