QCD Matter in de Sitter Spacetime

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Introduction | Explore QCD in extreme conditions!

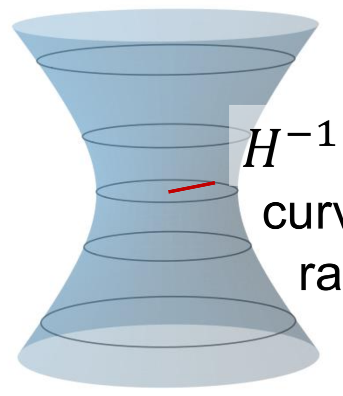
Spacetime affects quantum matter

$$R \longrightarrow T_{\mathrm{critical}}(R)$$

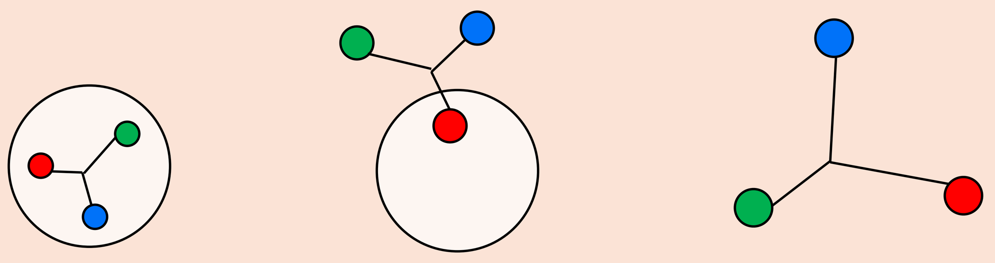
e.g. curvature shifts the chiral transition temperature [1,2]

What happens to QCD matter in extremely rapidly expanding spacetime?

$H \uparrow$ (expansion rate) $\Longrightarrow$ $R = 12H^2 \uparrow$, (curvature) $T_{\mathrm{dS}} = \dfrac{H}{2\pi} \uparrow$ (dS temperature)



Hadrons $\longrightarrow$ Quarks & gluons ??



Purpose We calculate the energy density ρ of a hadron gas and massless QCD, and compare the energetic ordering.

Method | HRG model and massless QCD

Hadrons

Hadron resonance gas (HRG) model

$$\ln Z_{\text{hadron gas}}(H) = \sum_{\substack{i\,\in\,\text{hadrons}\\ \text{and resonances}}} \ln Z^{\text{free}}_{i,\text{ren}}(H)$$

Euclidean path integral of free massive fields [3]

$$\ln Z^{\text{free}}_{i,\text{bare}}(H) = (-1)^{F_s}\int_0^\infty \frac{dt}{t} \sum_{\Delta=3/2\pm i\nu(m_i/H)}\ \sum_{n=-1+F_s/2}^{\infty} D^5_{n,s_i}\, e^{-(n+\Delta)t}$$

($F_s = 0(1)$ for B(F))

Decoupling condition

$$\lim_{m_i/H\to\infty} \ln Z^{\text{free}}_{i,\text{ren}}(H) = 0$$

Massless Quarks and Gluons

pQCD at Gaussian level (μ: renormalization scale)

$$\ln Z^{(0)}_{\text{pQCD}}(H) = \frac{N_c^2-1}{2}\ln\left(\frac{g^2_{\text{YM}}(\mu)}{4\pi}\right) - \left(\frac{11}{90}N_cN_f + \frac{31}{45}(N_c^2-1)\right)\ln\left(\frac{\mu}{H}\right)$$

Bag Constant $\quad \ln Z_{\text{QG}}(H) = \ln Z^{(0)}_{\text{pQCD}}(H) - BV_{S^4}$

Energy Density [3]

dS invariant state $\quad\Longrightarrow\quad \langle T_{\mu\nu}\rangle = -\rho g_{\mu\nu}$

Energy density $\quad \rho = \dfrac{H}{4V_{S^4}}\dfrac{\partial}{\partial H}\ln Z$

Result | Energy Density

Numerical Setups

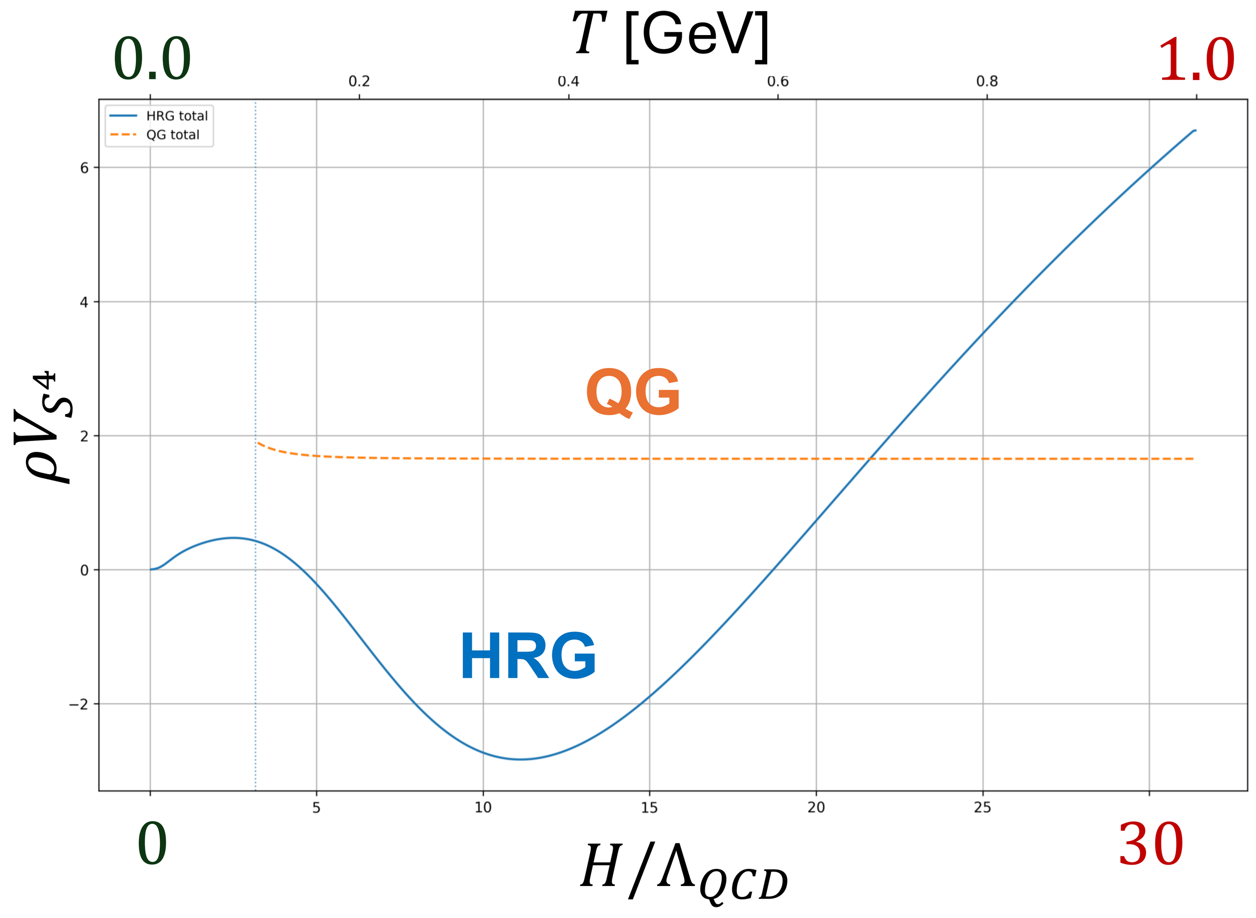
HRG

Scalar mesons: minimally coupled to R
Included hadrons: mass < 2.0 GeV, spin = 0, 1/2, 1, 3/2
Species count: spin=0 38, spin=1 53, fermion 176

QG

$N_c = N_f = 3, \quad B = (0.2\text{GeV})^4$

Result

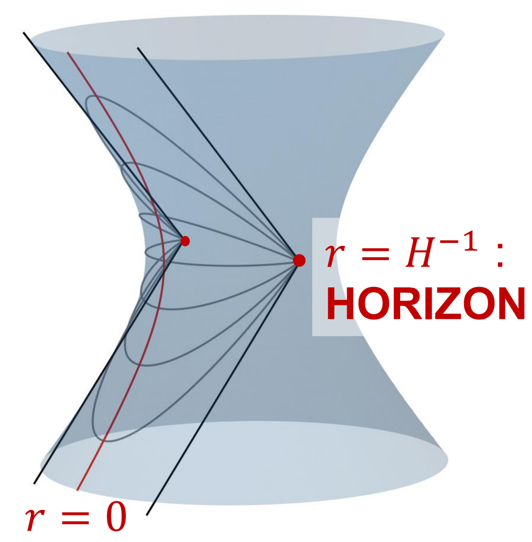


[low H] $\rho^{\text{HRG}} < \rho^{\text{QG}} \quad \Longleftrightarrow \quad$ **[high H]** $\rho^{\text{HRG}} > \rho^{\text{QG}}$

Discussion | Interpretation from the Static Patch

Static patch

Causally accessible region for a static observer in dS



Gibbons-Hawking temperature [4]

$$T_{\mathrm{dS}} = \beta_{\mathrm{dS}}^{-1} = \frac{H}{2\pi}$$

Internal Energy U_{static} in the static patch

$$U_{\text{static}}\beta_{\mathrm{dS}} = \rho V_{S^4}$$

Our result implies the D.o.F. transition

The energetic ordering changes:

[low T]: $U^{\text{HRG}}_{\text{static}} < U^{\text{QG}}_{\text{static}} \quad\Longrightarrow\quad$ **Hadronic regime**
[high T]: $U^{\text{HRG}}_{\text{static}} > U^{\text{QG}}_{\text{static}} \quad\Longrightarrow\quad$ **Quark-gluon regime**

Qualitatively consistent with the D.o.F. transition

Hadrons $\longrightarrow$ Quarks and gluons

**The actual phase transition requires a common free-energy-normalization.

Conclusion and Outlook

We calculate the energy density of a hadron gas in de Sitter spacetime and compare it with the massless quark–gluon sector. From the static-patch viewpoint, the energetic ordering of the hadronic and quark–gluon descriptions reverses as the expansion rate increases. This behavior is qualitatively consistent with a change of the relevant degrees of freedom from hadrons to quarks and gluons. Determining the thermodynamically favored phase, however, requires a comparison of consistently normalized free energies, which we leave for future work.

Reference

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[3] D. Anninos, F. Denef, A. Law, Z. Sun, *JHEP* 01 (2022) 088.
[4] G.W. Gibbons, S.W. Hawking, *Phys.Rev.D* 15 (1977) 2738-2751.