Nonlocal Observables in Holography

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Steklov Mathematical Institute, Russian Academy of Sciences

International conference in memory of M. K. Polivanov
«Polivanov–90»

16 - 17 December, 2020

Outlook

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- **Non-local observables in QFT**

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- Results

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$$W(\Gamma) =< \mathrm{Tr}(g(\Gamma)) >$$

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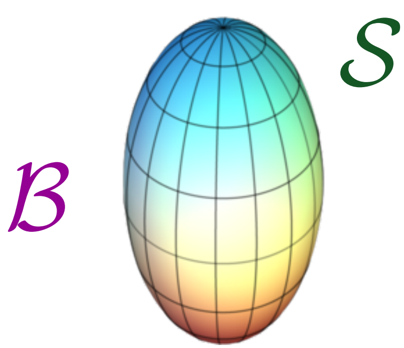

- **Bags in QCD?**

Loop approach to YM equations

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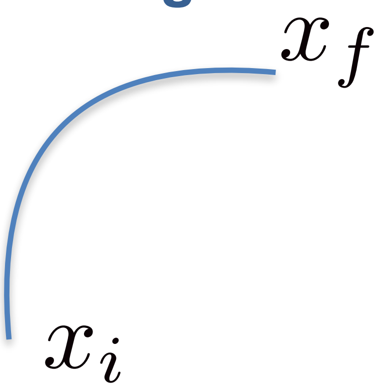
- **Gauge invariance of Wilson loops**



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Loop approach to YM equations

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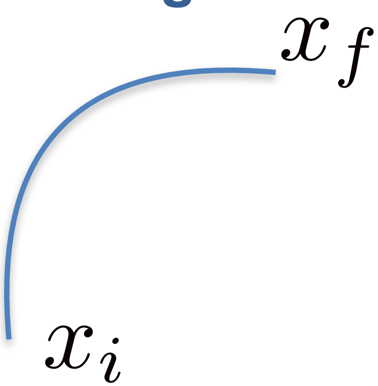

$$g(\Gamma_{i,f}) \to \Omega(x_i) g(\Gamma_{i,f}) \Omega^*(x_i)$$

- **Dynamical equations in terms of Wilson loops**

$$\mathcal{L}(\Gamma, x) \equiv g^*(\Gamma) \cdot \delta_{\Gamma,x}\, g(\Gamma)$$

$$\delta_{\Gamma,y}\mathcal{L}(\Gamma, x) - \delta_{\Gamma,x}\mathcal{L}(\Gamma, y) + [\mathcal{L}(\Gamma, x), \mathcal{L}(\Gamma, y)] = 0$$

$$\lim_{x\to y} \delta_{\Gamma,y}\,\mathcal{L}(\Gamma, x) = 0 \quad \Longleftrightarrow \quad D_\mu F_{\mu\nu} = 0$$

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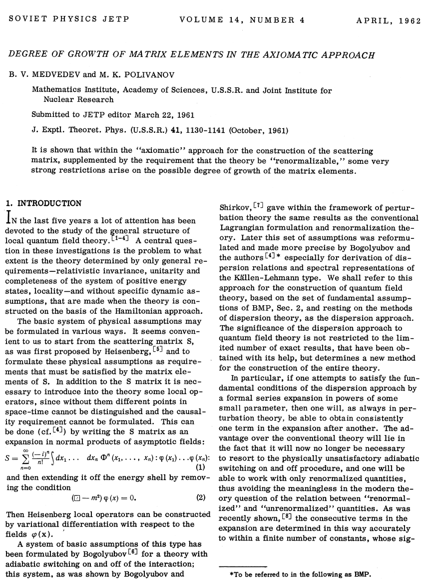
SOVIET PHYSICS JETP VOLUME 14, NUMBER 4 APRIL, 1962

DEGREE OF GROWTH OF MATRIX ELEMENTS IN THE AXIOMATIC APPROACH

B. V. MEDVEDEV and M. K. POLIVANOV

Mathematics Institute, Academy of Sciences, U.S.S.R. and Joint Institute for Nuclear Research

Submitted to JETP editor March 22, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1130-1141 (October, 1961)

It is shown that within the "axiomatic" approach for the construction of the scattering matrix, supplemented by the requirement that the theory be "renormalizable," some very strong restrictions arise on the possible degree of growth of the matrix elements.

1. INTRODUCTION

IN the last five years a lot of attention has been devoted to the study of the general structure of local quantum field theory.[1-4] A central question in these investigations is the problem to what extent is the theory determined by only general requirements—relativistic invariance, unitarity and completeness of the system of positive energy states, locality—and without specific dynamic assumptions, that are made when the theory is constructed on the basis of the Hamiltonian approach.

The basic system of physical assumptions may be formulated in various ways. It seems convenient to us to start from the scattering matrix S, as was first proposed by Heisenberg,[5] and to formulate these physical assumptions as requirements that must be satisfied by the matrix elements of S. In addition to the S matrix it is necessary to introduce into the theory some local operators, since without them different points in space-time cannot be distinguished and the causality requirement cannot be formulated. This can be done (cf.[4]) by writing the S matrix as an expansion in normal products of asymptotic fields:

$$S = \sum_{n=0}^{\infty} \frac{(-i)^n}{n!} \int dx_1 \ldots dx_n\, \Phi^n(x_1, \ldots, x_n) : \varphi(x_1) \ldots \varphi(x_n): \quad (1)$$

and then extending it off the energy shell by removing the condition

$$(\Box - m^2)\, \varphi(x) = 0. \quad (2)$$

Then Heisenberg local operators can be constructed by variational differentiation with respect to the fields $\varphi(x)$.

A system of basic assumptions of this type has been formulated by Bogolyubov[6] for a theory with adiabatic switching on and off of the interaction; this system, as was shown by Bogolyubov and Shirkov,[7] gave within the framework of perturbation theory the same results as the conventional Lagrangian formulation and renormalization theory. Later this set of assumptions was reformulated and made more precise by Bogolyubov and the authors[4]* especially for derivation of dispersion relations and spectral representations of the Källen-Lehmann type. We shall refer to this approach for the construction of quantum field theory, based on the set of fundamental assumptions of BMP, Sec. 2, and resting on the methods of dispersion theory, as the dispersion approach. The significance of the dispersion approach to quantum field theory is not restricted to the limited number of exact results, that have been obtained with its help, but determines a new method for the construction of the entire theory.

In particular, if one attempts to satisfy the fundamental conditions of the dispersion approach by a formal series expansion in powers of some small parameter, then one will, as always in perturbation theory, be able to obtain consistently one term in the expansion after another. The advantage over the conventional theory will lie in the fact that it will now no longer be necessary to resort to the physically unsatisfactory adiabatic switching on and off procedure, and one will be able to work with only renormalized quantities, thus avoiding the meaningless in the modern theory question of the relation between "renormalized" and "unrenormalized" quantities. As was recently shown,[8] the consecutive terms in the expansion are determined in this way accurately to within a finite number of constants, whose sig-

*To be referred to in the following as BMP.

- **B. V. Medvedev and M. K. Polivanov, JETP 41, 1130 (1961),**
- **Soviet Phys. JETP 14, 807 (1962)**

$$j(x) = i\,\frac{\delta S}{\delta\varphi(x)}\,S^{+}.$$

$$\mathcal{L}(\Gamma, x) \equiv g^*(\Gamma) \cdot \delta_{\Gamma,x}\, g(\Gamma)$$

- **T-Dyson vs T-Wick**
- **T-exp is just a Wilson line for time segment**

Wilson Loops in Holography

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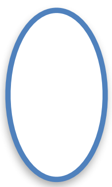

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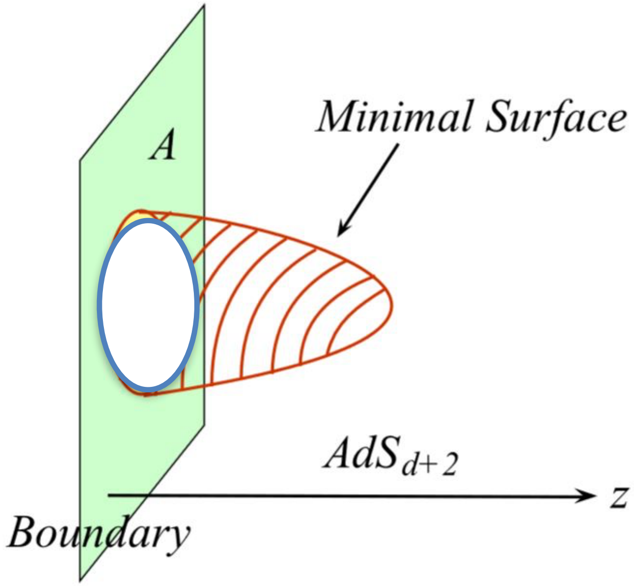

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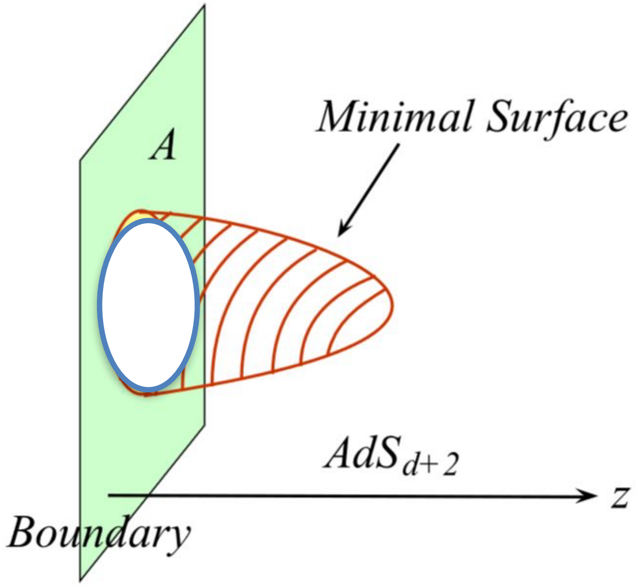

The recipe by Maldacena ('98),
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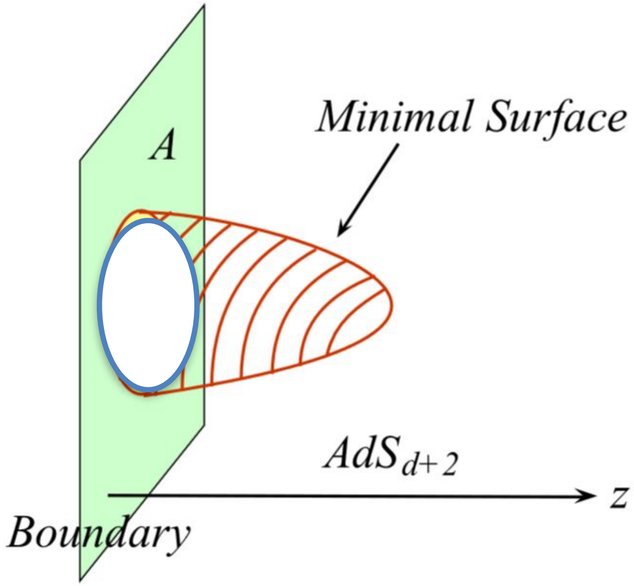

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$$S = \frac{1}{2\pi\alpha'} \int d\sigma_1 d\sigma_2 \sqrt{-\det h_{\alpha\beta}}$$

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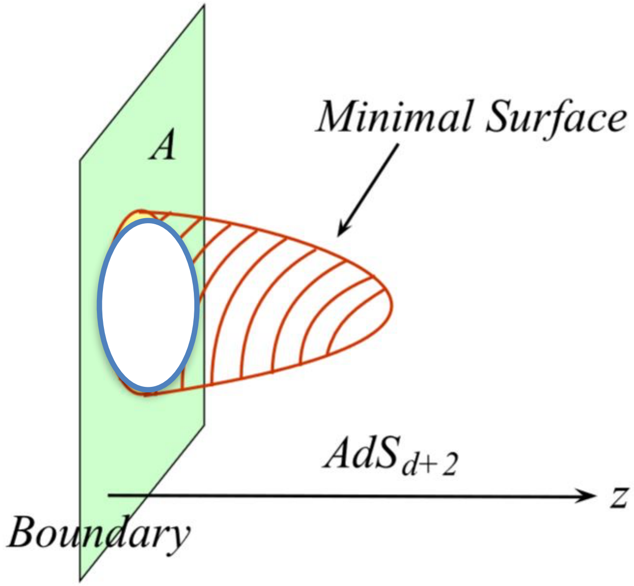

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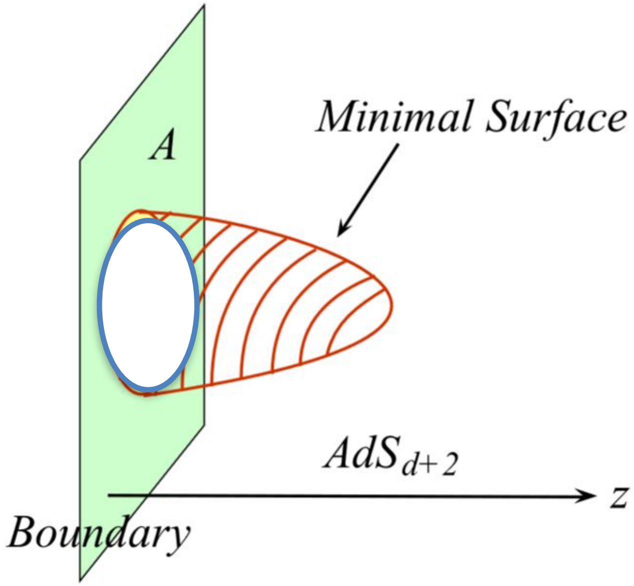

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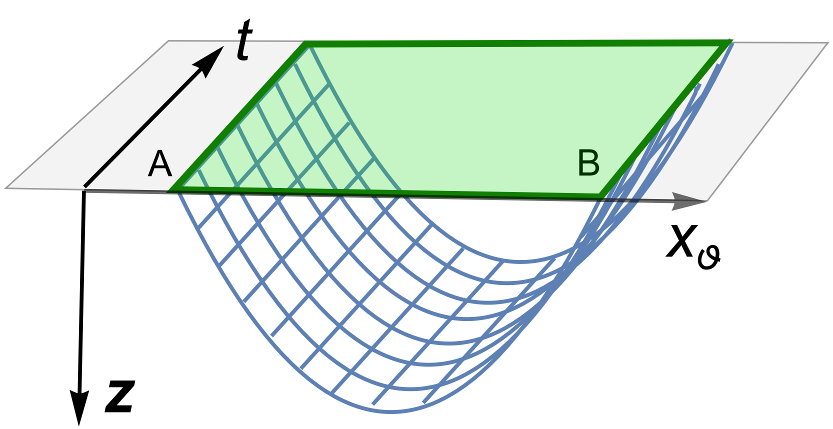

Functional on a surface

=Entanglement Entropy

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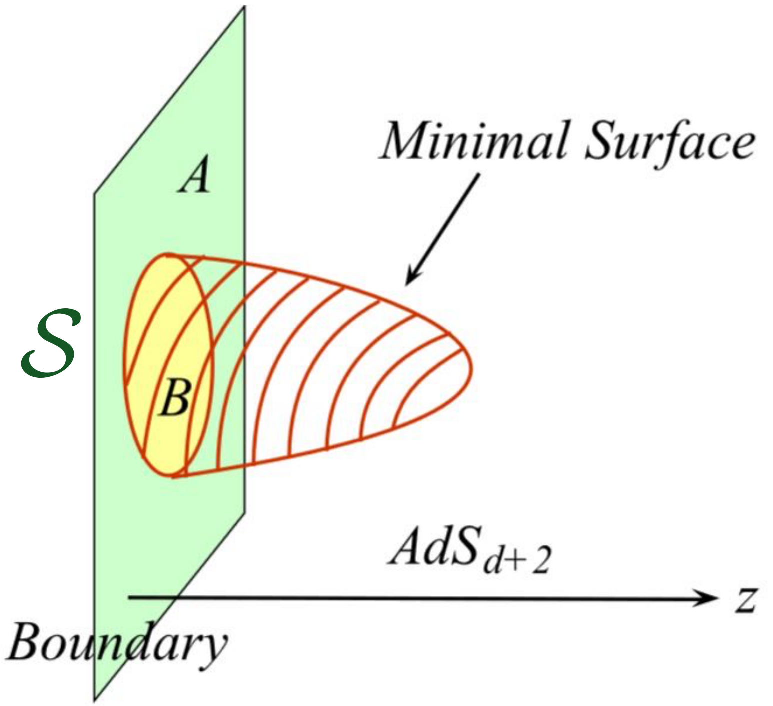

The holographic calculation of entanglement entropy via AdS/CFT.

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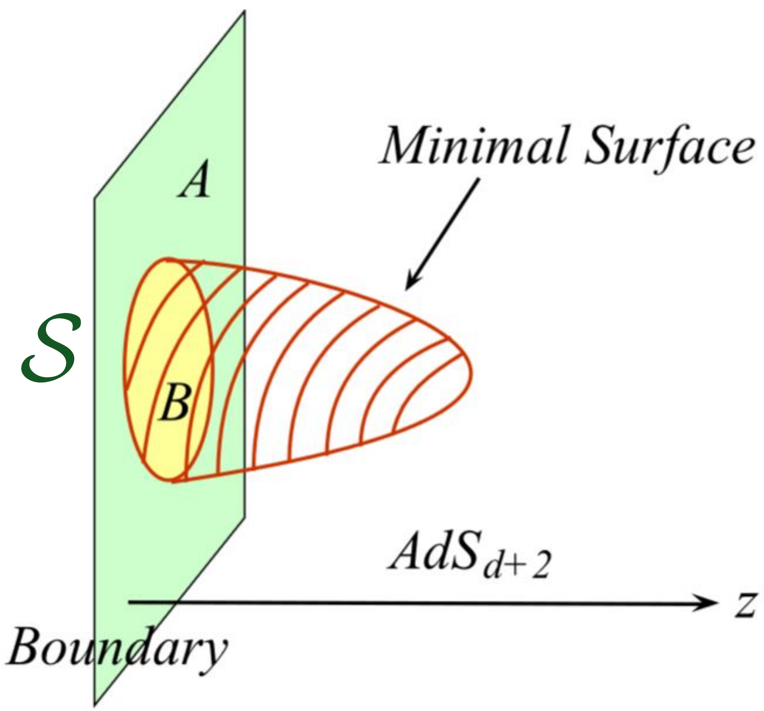

Ryu-Takayanagi Formula

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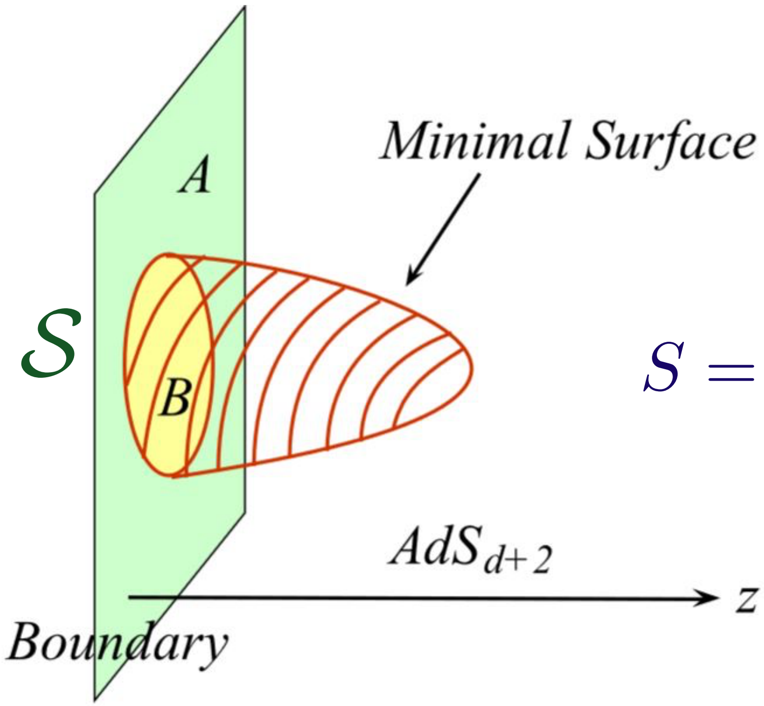

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Applications to study phase transition in QGP

The expected QCD phase diagram

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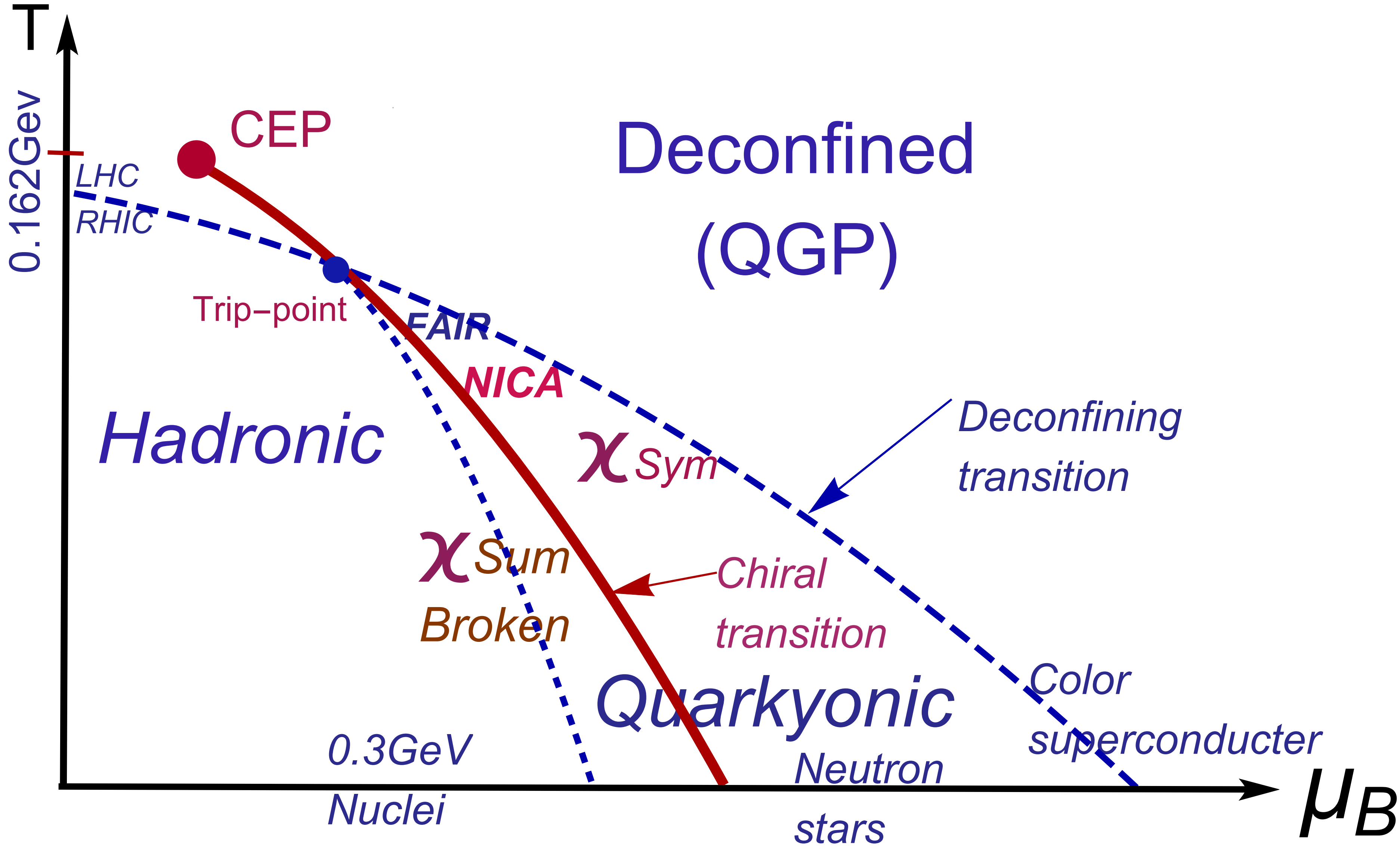

Few remarks on holography (AdS/CFT)

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Holography translates the physics of quantum many body systems into a dual classical gravitational problem in a space-time with an extra dimension.

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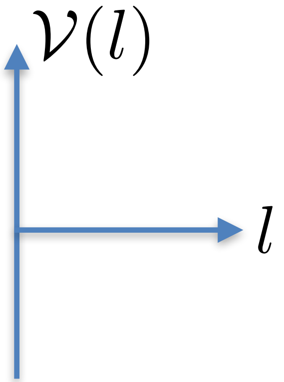

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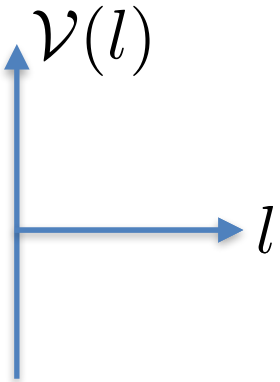

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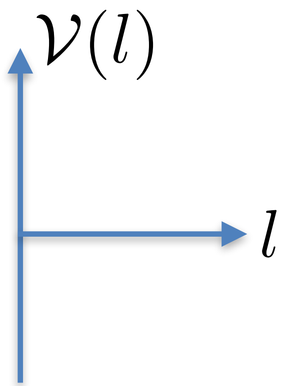

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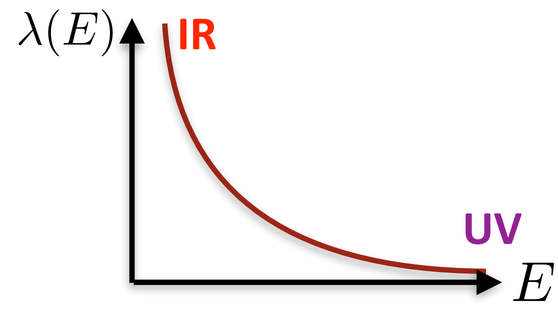

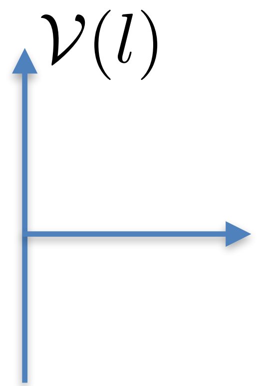

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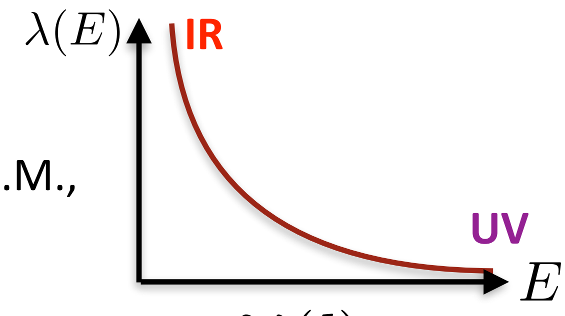

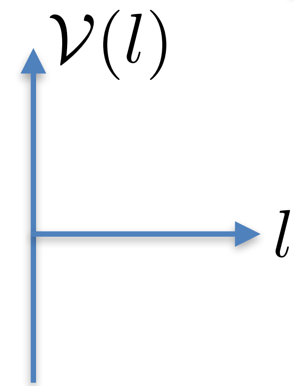

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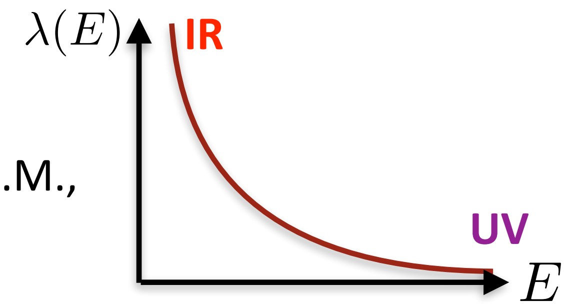

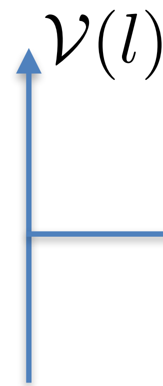

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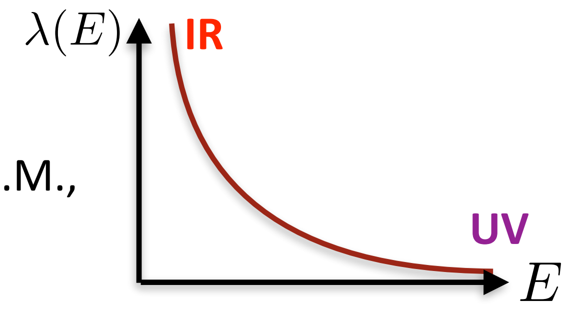

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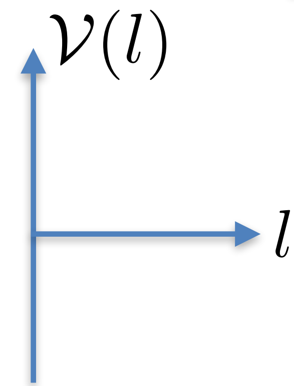

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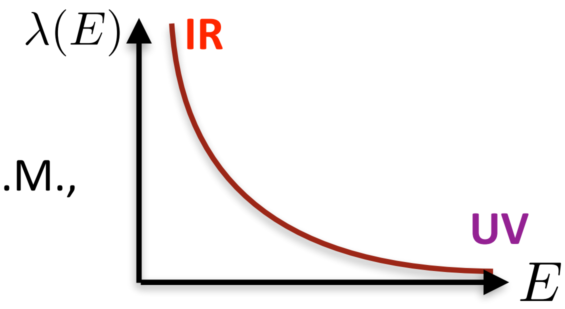

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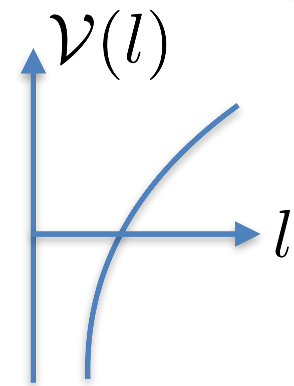

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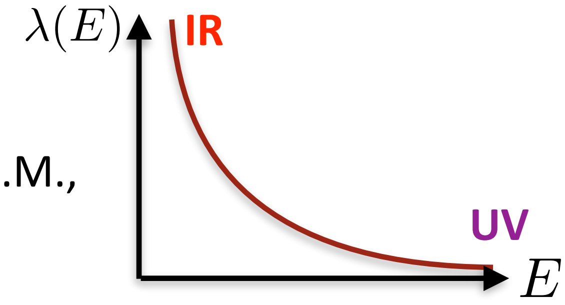

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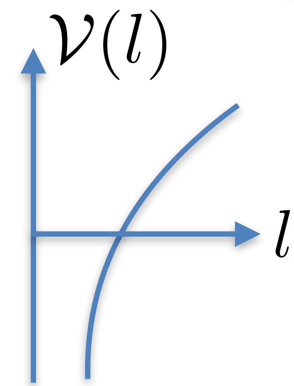

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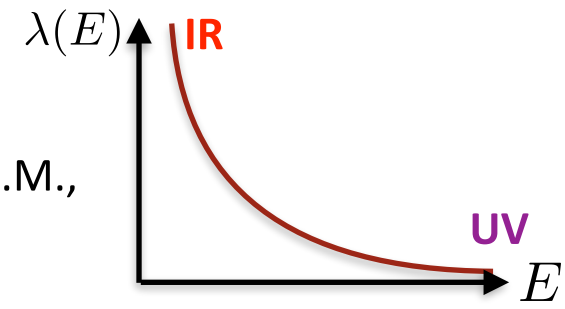

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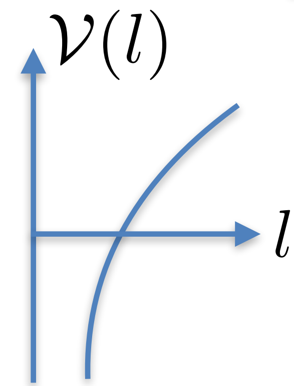

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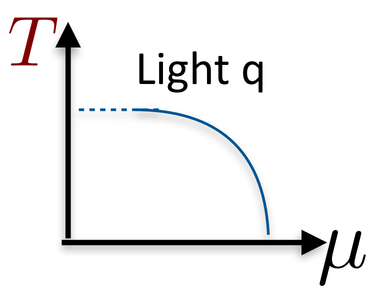

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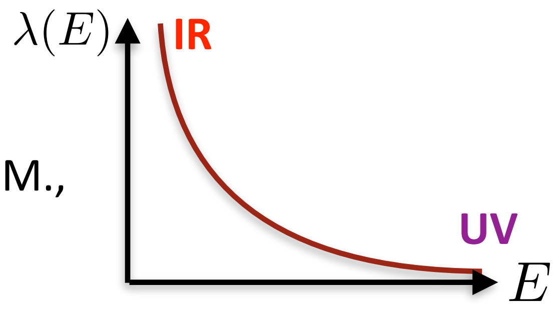

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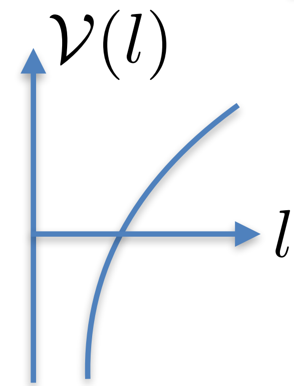

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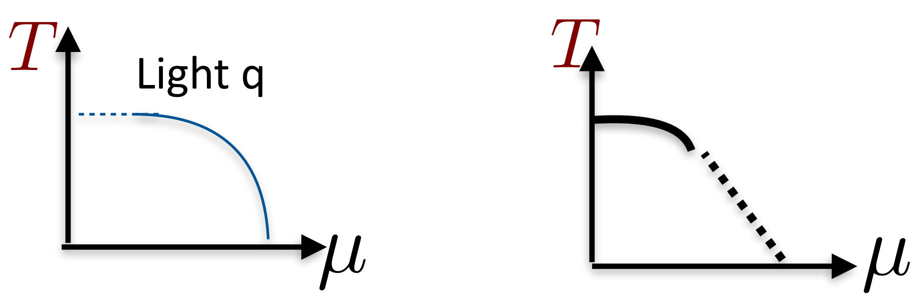

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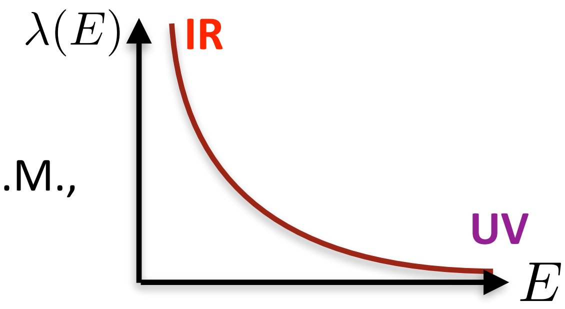

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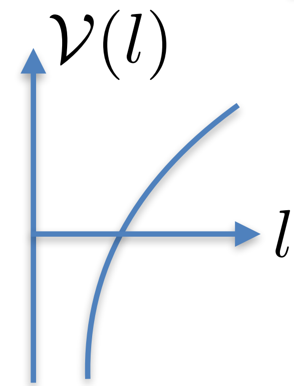

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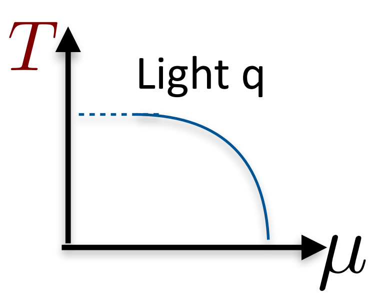
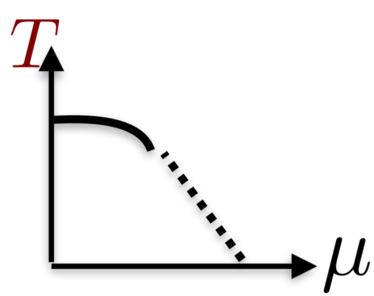
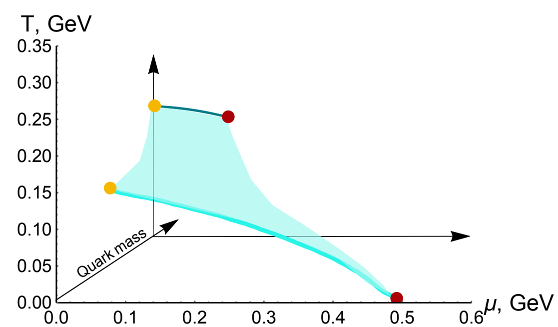
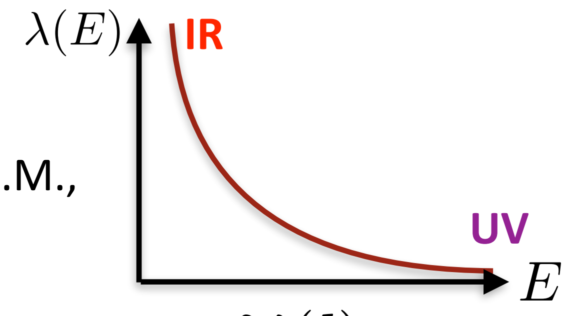






• Holography is a new type of phenomenology

Starting point - 5-dim background. 5-th coordinate - energy scale



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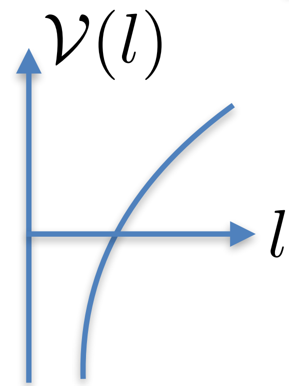

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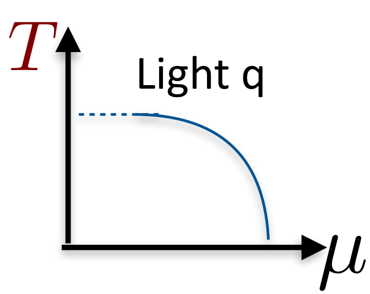
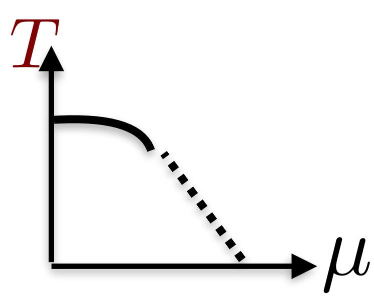
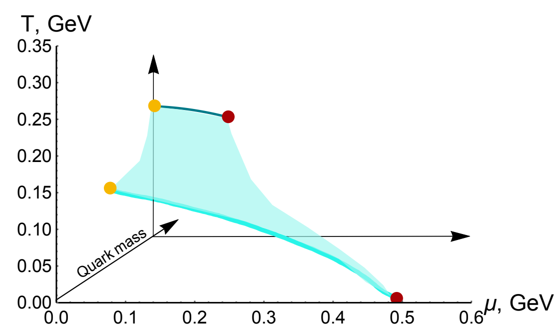
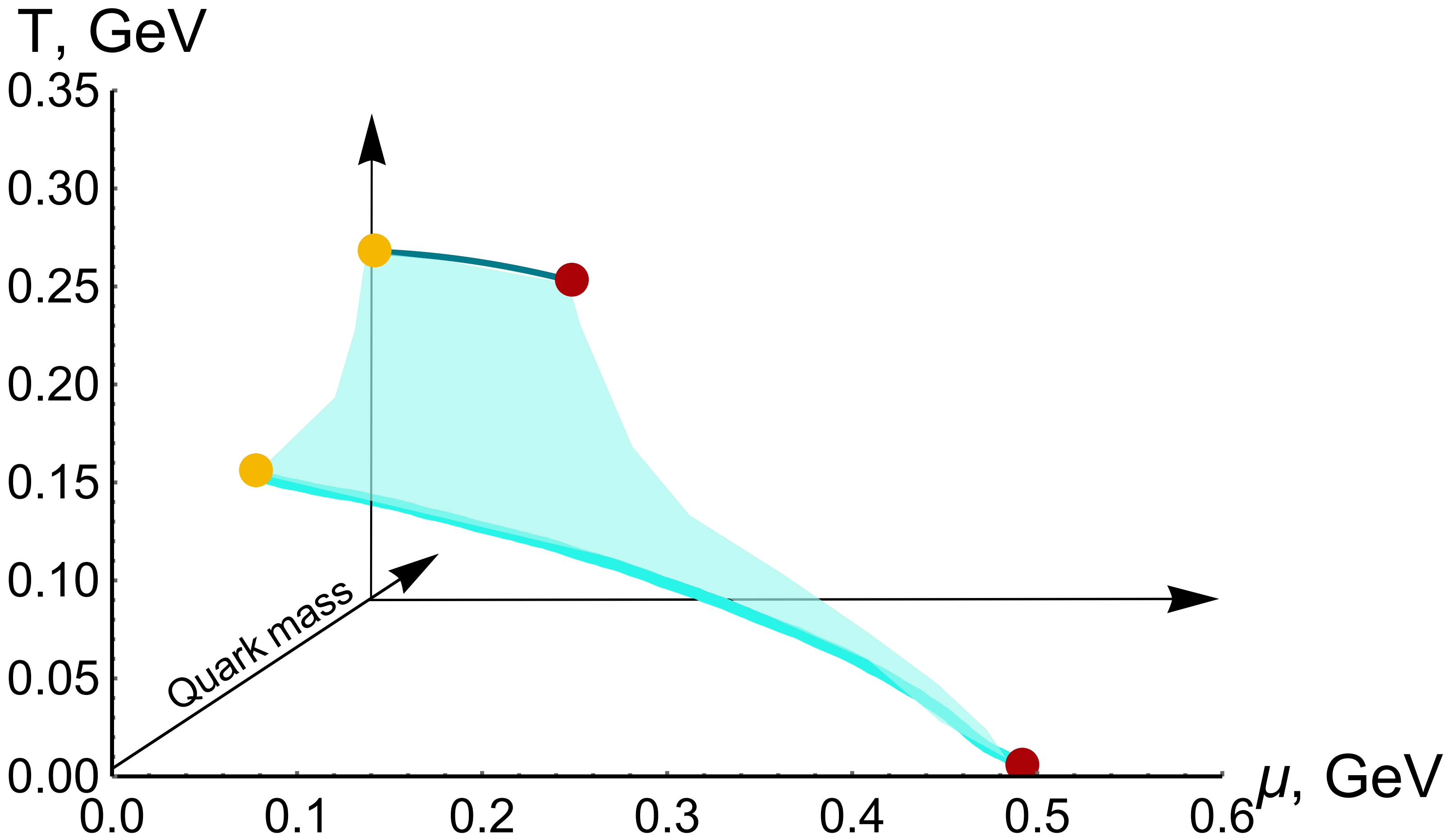






The action has to be found by «**trial and error method**».What is a «**best**» 5-dim background?

QCD diagram



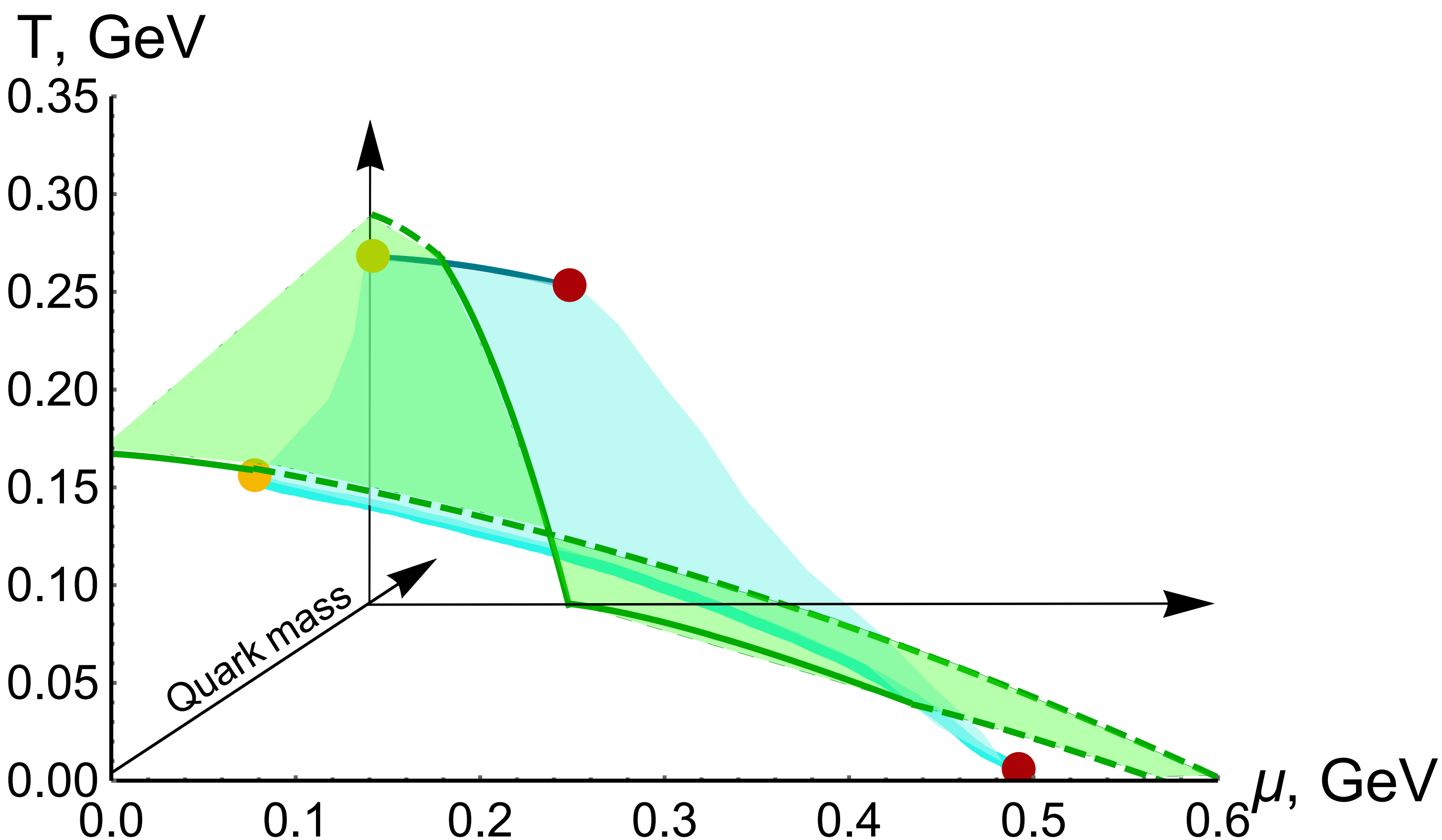
1-st order phase transition

QCD diagrams

QCD diagrams

1-st order phase transition
and Wilson loop phase transition

QCD diagrams



1-st order phase transition and Wilson loop phase transition

• Holographic anisotropic phenomenological models

- Origins of anisotropy

- **Holographic anisotropic phenomenological models**

  - **Origins of anisotropy**

    - **Longitudinal and 2 transversal directions**

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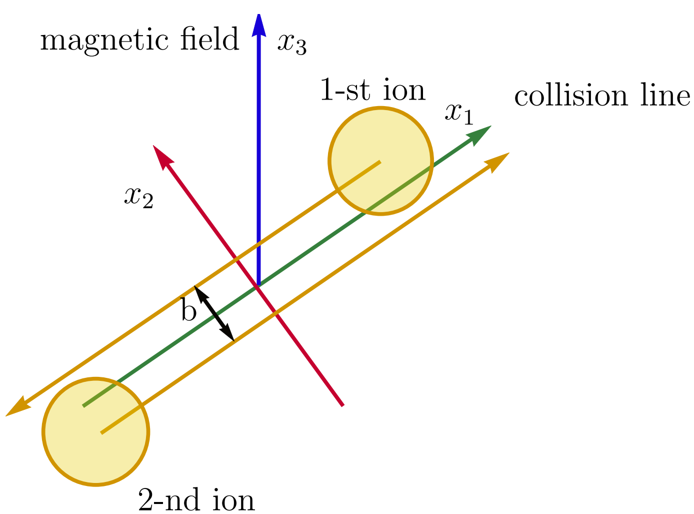

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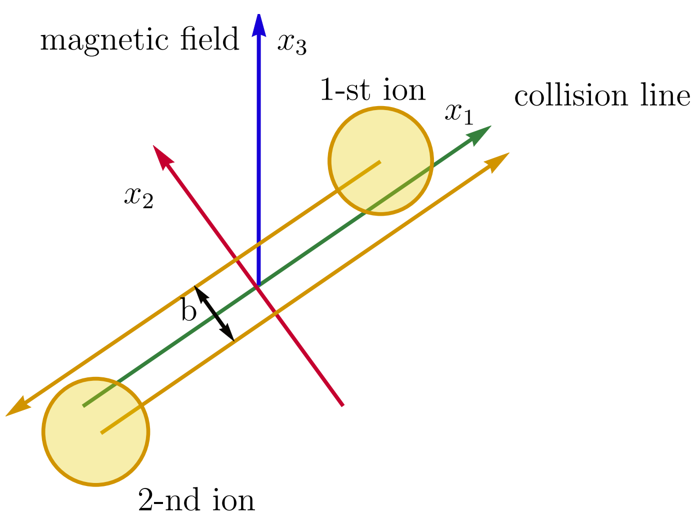

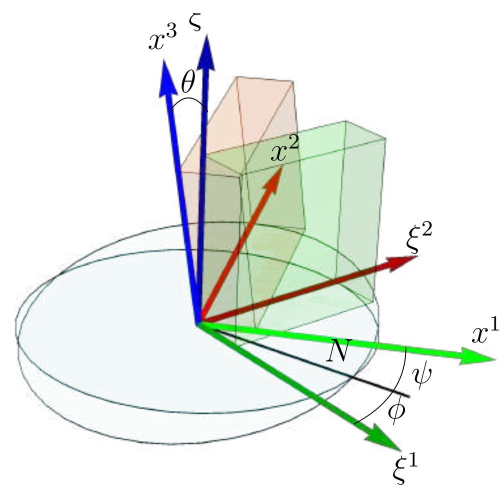

5-dim Anisotropic Background

5-dim Anisotropic Background

Einstein-dilaton-two-Maxwell

I.A., K. Rannu, JHEP' 18

$$S = \int \frac{d^5x}{16\pi G_5} \sqrt{-\det(g_{\mu\nu})} \left[R - \frac{f_1(\phi)}{4} F_{(1)}^2 - \frac{f_2(\phi)}{4} F_{(2)}^2 - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right]$$

5-dim Anisotropic Background

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$$ds^2 = \frac{Lb(z)}{z^2} \left[-g(z)dt^2 + dx^2 + R(z)(dy_1^2 + dy_2^2) + \frac{1}{g(z)} dz^2 \right]$$

$$\phi = \phi(z), \qquad A_\mu^{(1)} = A_t(z)\delta_\mu^0, \qquad F_{\mu\nu}^{(2)} = q\ dy^1 \wedge dy^2$$

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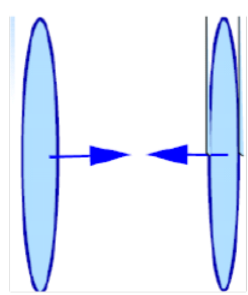
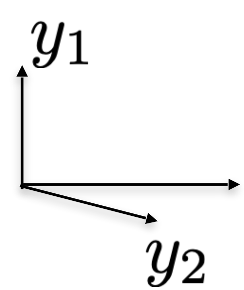
Schematic picture of central HIC





$\vec{y}=(y_1,y_2)$

x — beamer line

Full Anisotropic Background

Full Anisotropic Background

IA, Rannu,Slepov, 2011.07023

$$S = \frac{1}{16\pi G_5}\int d^5x\,\sqrt{-g}\left[R - \frac{f_1(\phi)}{4}\,F_{(1)}^2 - \frac{f_2(\phi)}{4}\,F_{(2)}^2 - \frac{f_B(\phi)}{4}\,F_{(B)}^2 - \frac{1}{2}\,\partial_\mu\phi\partial^\mu\phi - V(\phi)\right],$$

$$ds^2 = \frac{L^2}{z^2}\,e^{2\mathcal{A}(z)}\left[-\,g(z)dt^2 + dx^2 + \left(\frac{z}{L}\right)^{2-\frac{2}{\nu}}dy_1^2 + e^{c_B z^2}\left(\frac{z}{L}\right)^{2-\frac{2}{\nu}}dy_2^2 + \frac{dz^2}{g(z)}\right]$$

Full Anisotropic Background

IA, Rannu,Slepov, 2011.07023

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$$S=\frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R+\mathcal{L}_M\right],$$

Gursoy, Jarvinen, Nijs,Pedraza, 2011.09474

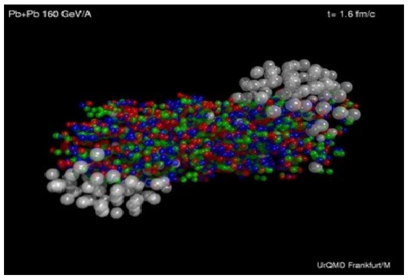
$$\mathcal{L}_M=-\frac{1}{2}(\partial\phi)^2+V(\phi)-\frac{1}{2}Z(\phi)(\partial\chi)^2$$

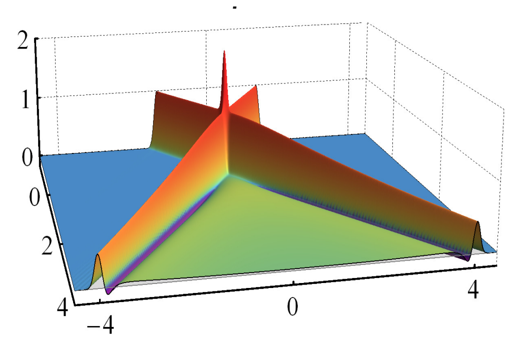
$$ds^2=e^{2A(r)}\left[-f(r)dt^2+dx_1^2+e^{2U(r)}dx_2^2+e^{2W(r)}dx_3^2+\frac{dr^2}{f(r)}\right]$$

Thermalization via Holography

Thermalization via Holography

Thermalization in D ⟺ BH formation in D+1





Yaffe et al

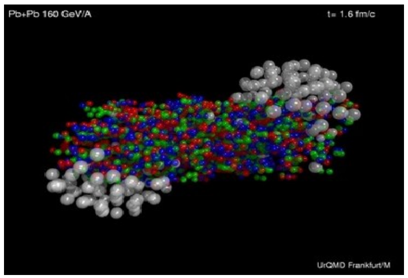
Vaiday

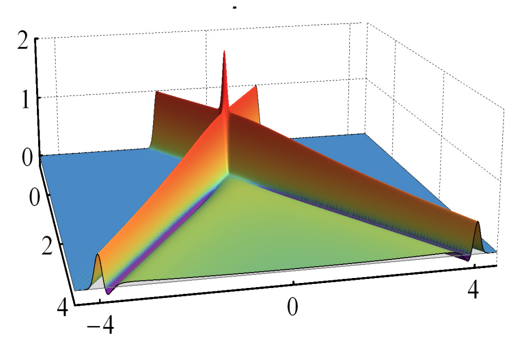
Compare with W. Heisenberg, "Production of mesons as a shockwave problem," Zeit.Phys. 133 (1952) 65.

D=2 example

Thermalization via Holography

Thermalization in D ⟺ BH formation in D+1





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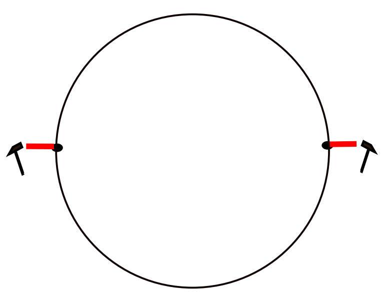
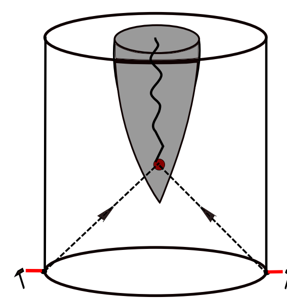
D=2 example

`Thermalization after holographic bilocal quench`



Bilocal quench



`I.A., Khramtsov, Tikhanovskaya` *JHEP09(2017)115*
`D.Ageev,I.A.` *JHEP* 03 (2018) 103

Dependence of the first-order phase transition location on the anisotropic parameters.

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Thermodynamics of the anisotropic background

Dependence of the first-order phase transition location on the anisotropic parameters.

$\Updownarrow$

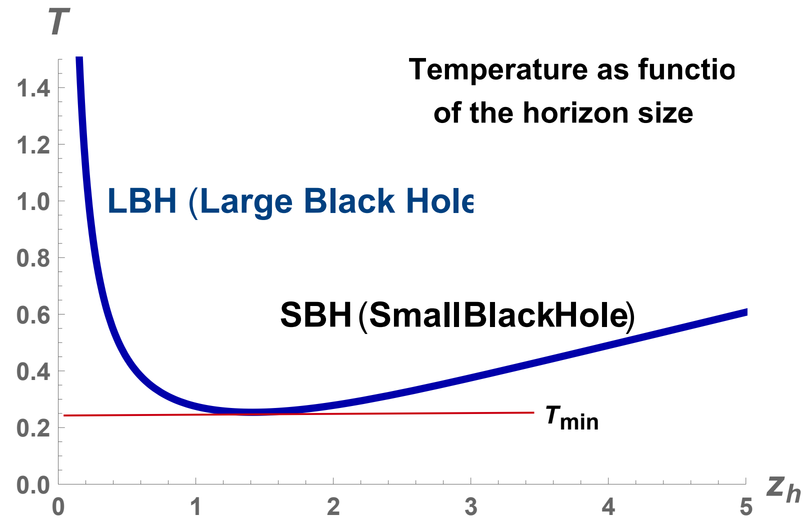
Thermodynamics of the anisotropic background

Thermodynamics for HIC (compare with Landau, 1952, Fermi, 1952)

Here thermodynamics for 5-dim BH

Temperature as function of horizon

Temperature as function of horizon



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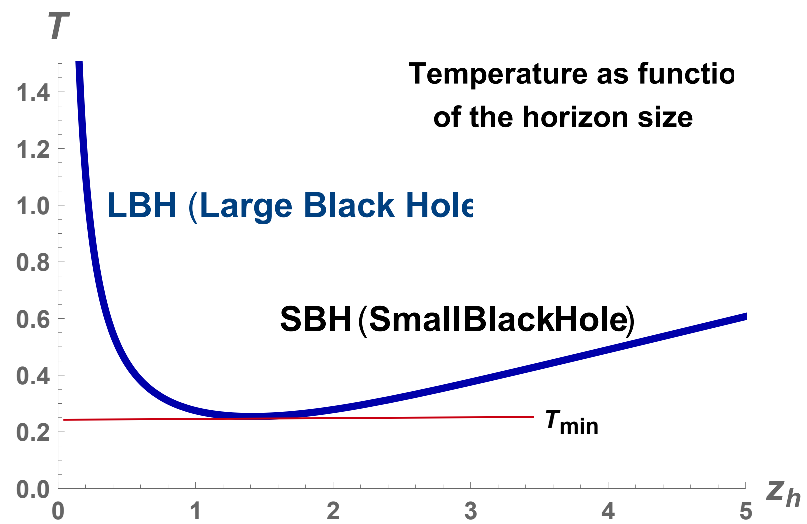

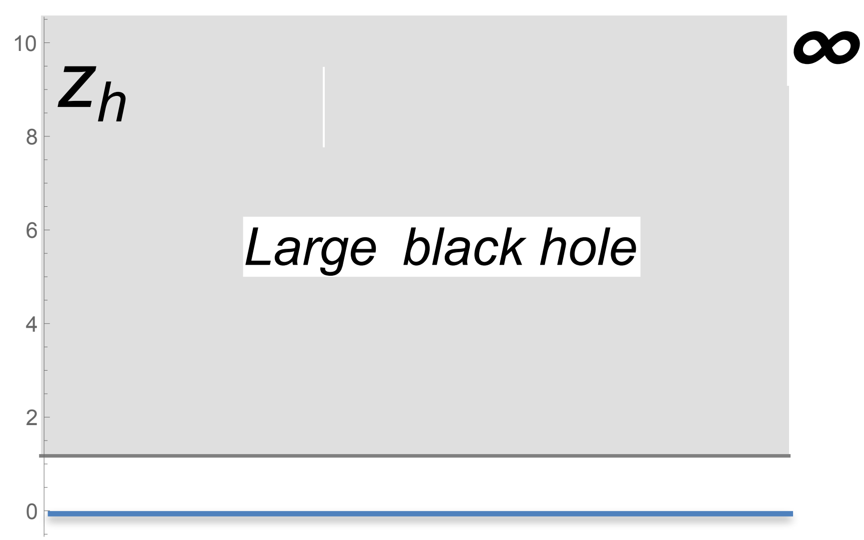

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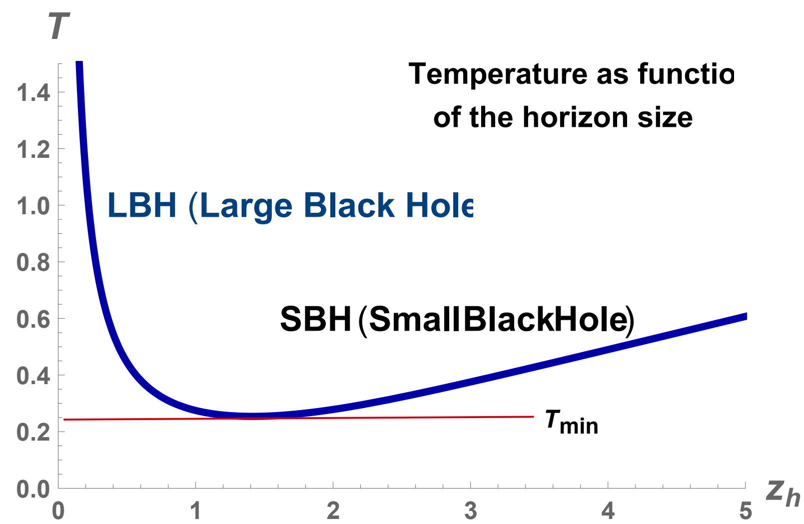
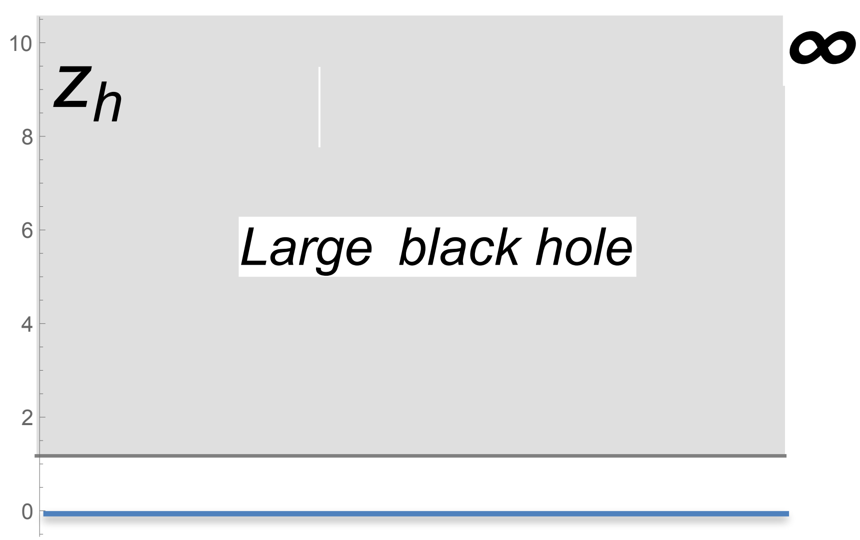
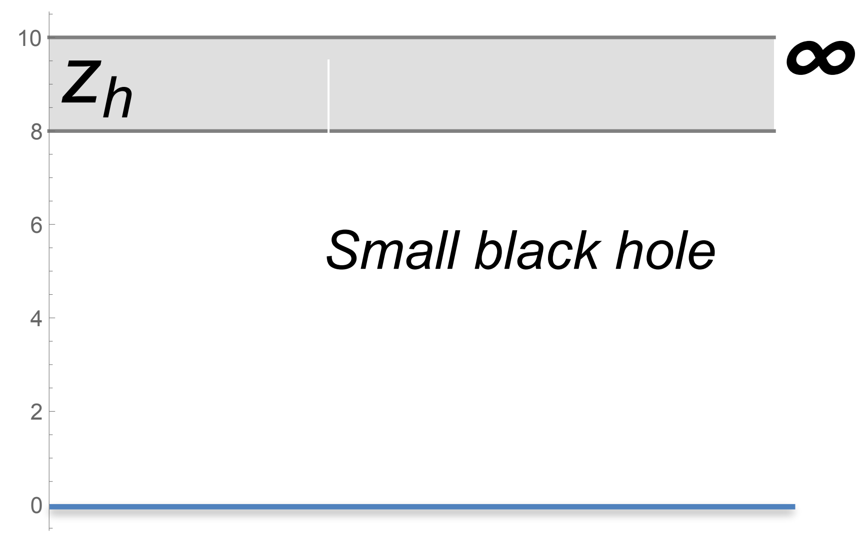
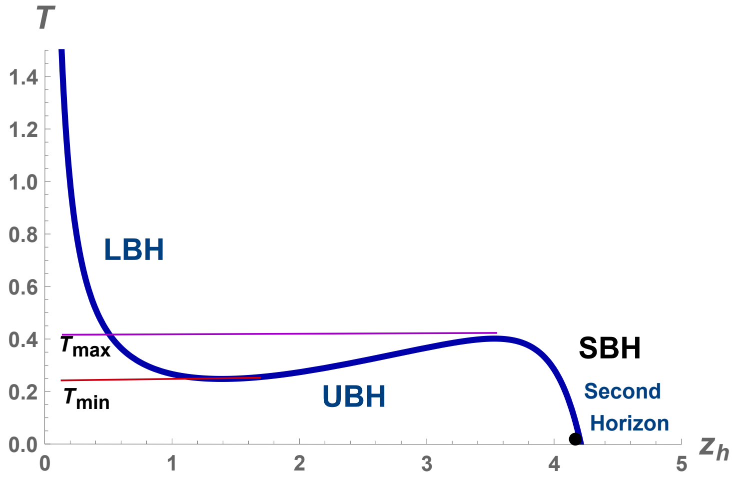






Free energy as function of temperature



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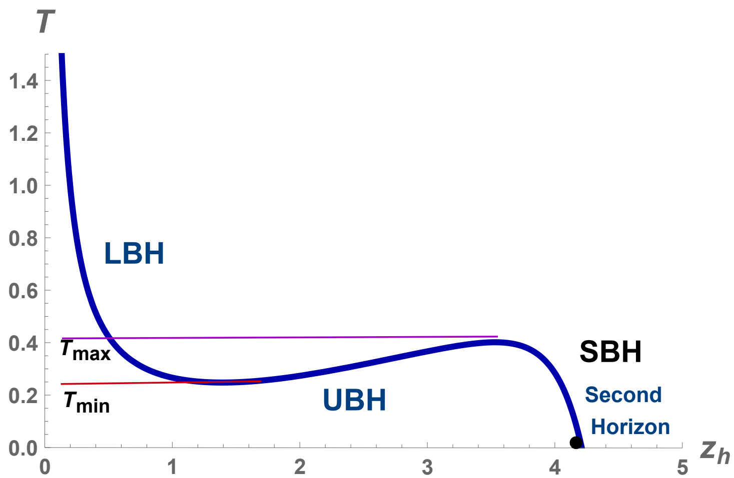

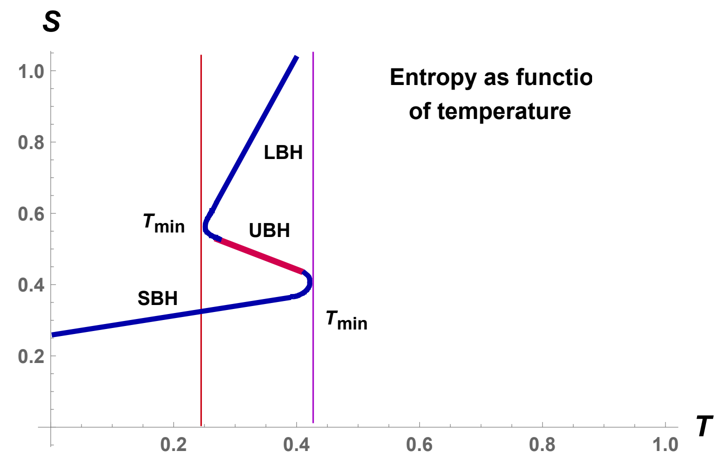

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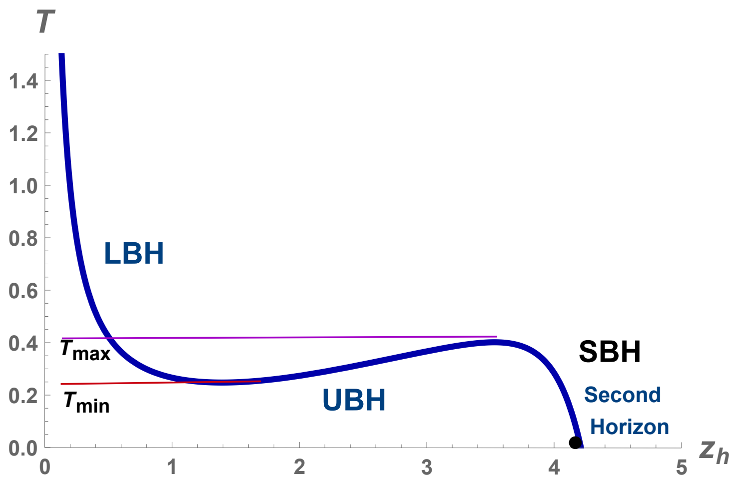
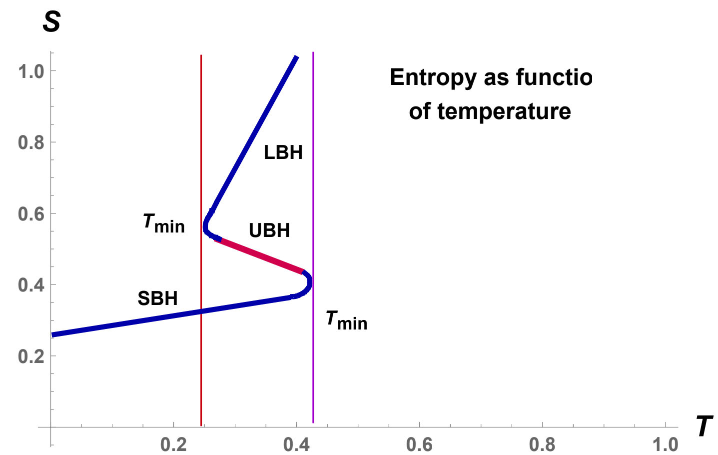
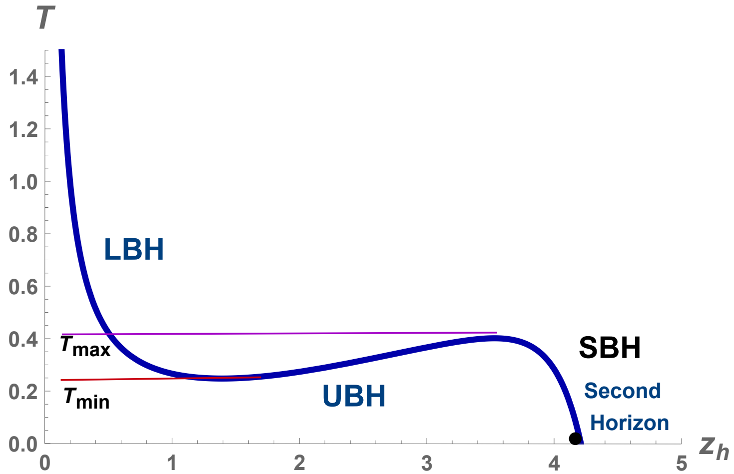
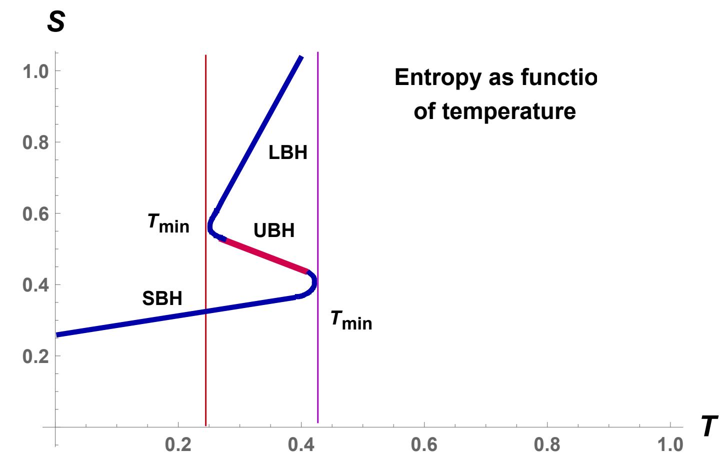




$$F(z_h, c, \nu) = \int_{z_h}^{\infty} s(z_h, c, \nu)\, T'(z_h, c, \nu)\, dz_h$$

Free energy as function of temperature





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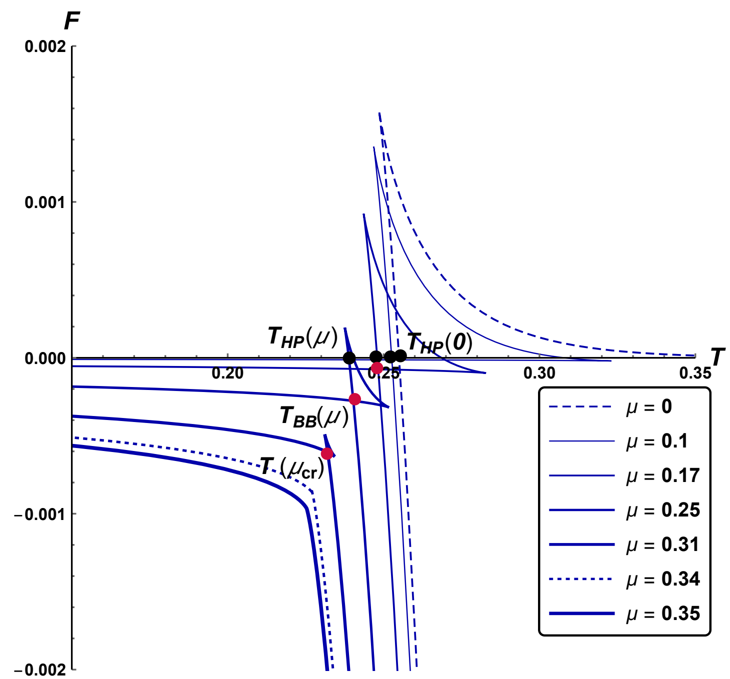

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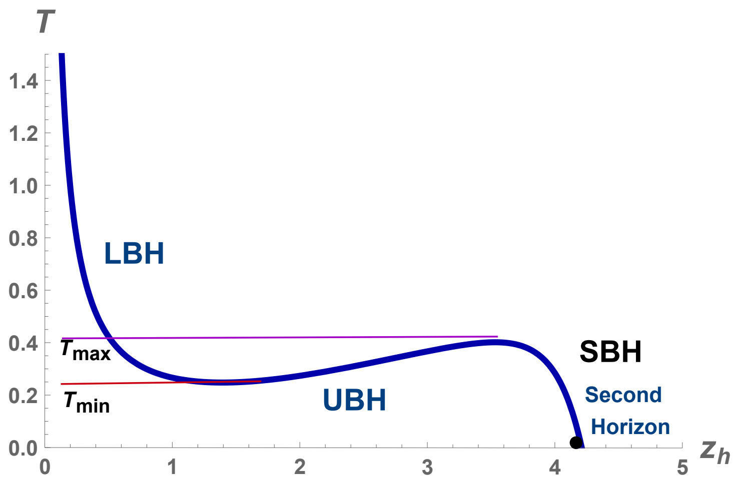

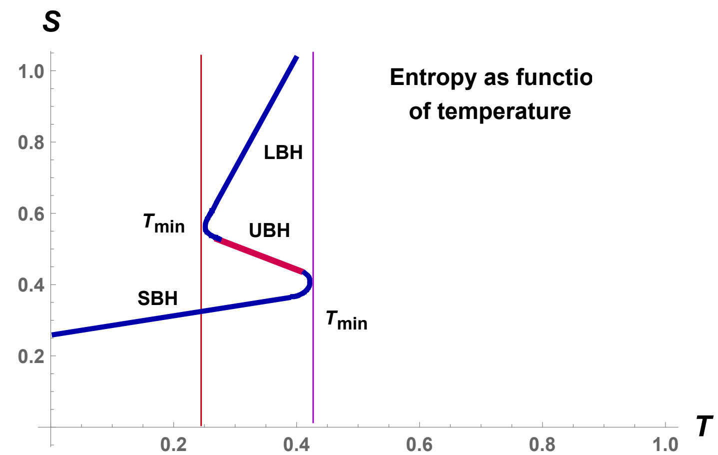

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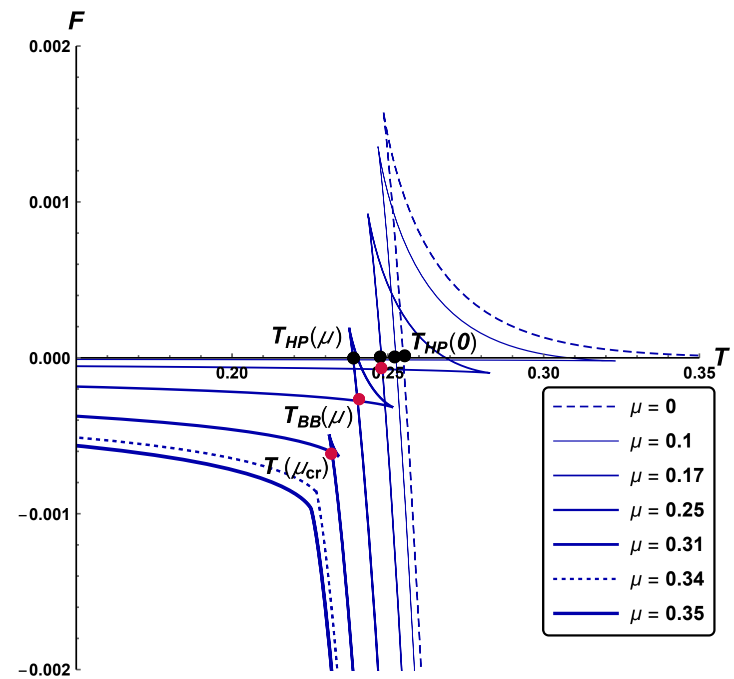
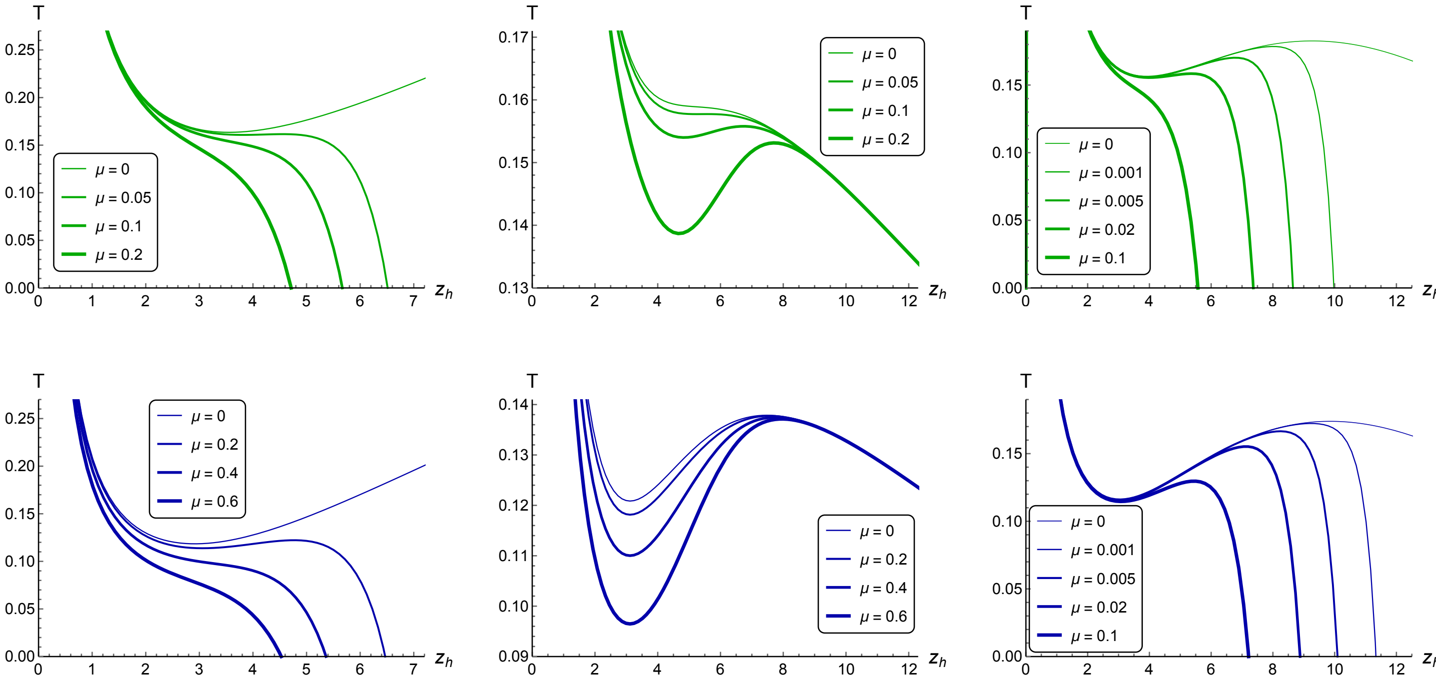


The swallow-tailed shape

Temperature vs horizon

Temperature vs horizon



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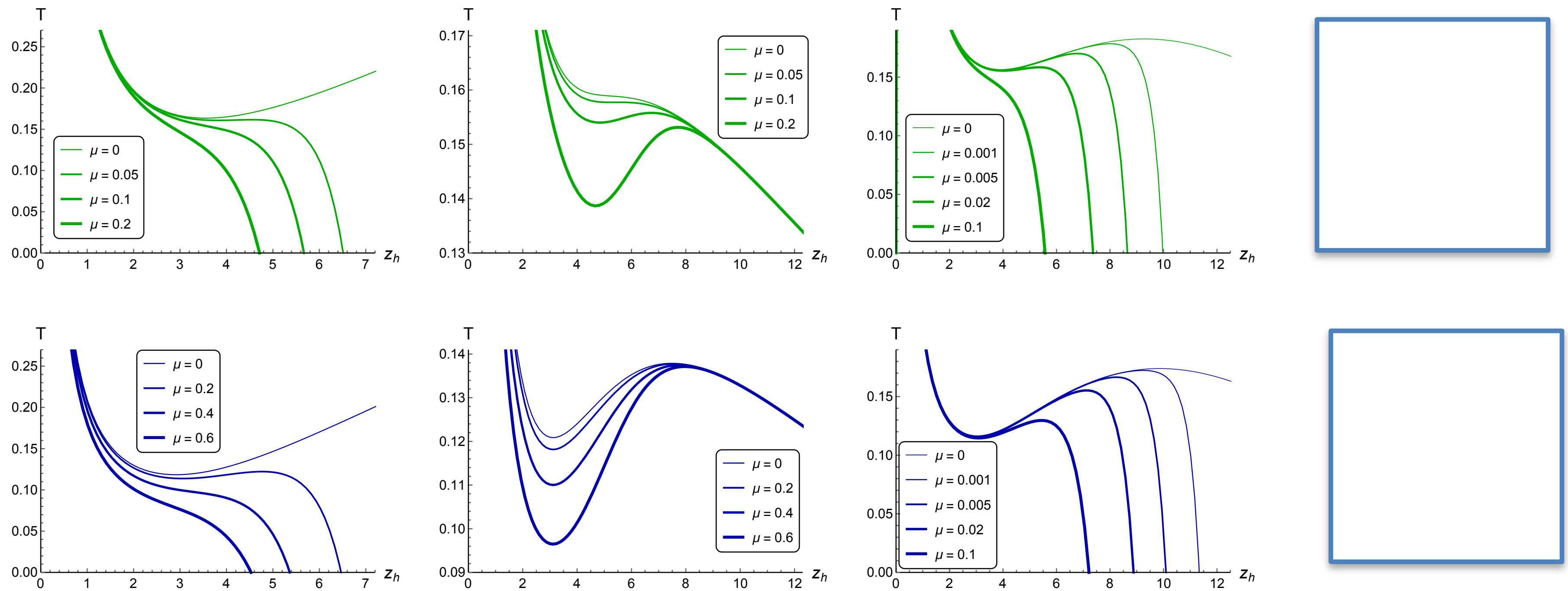
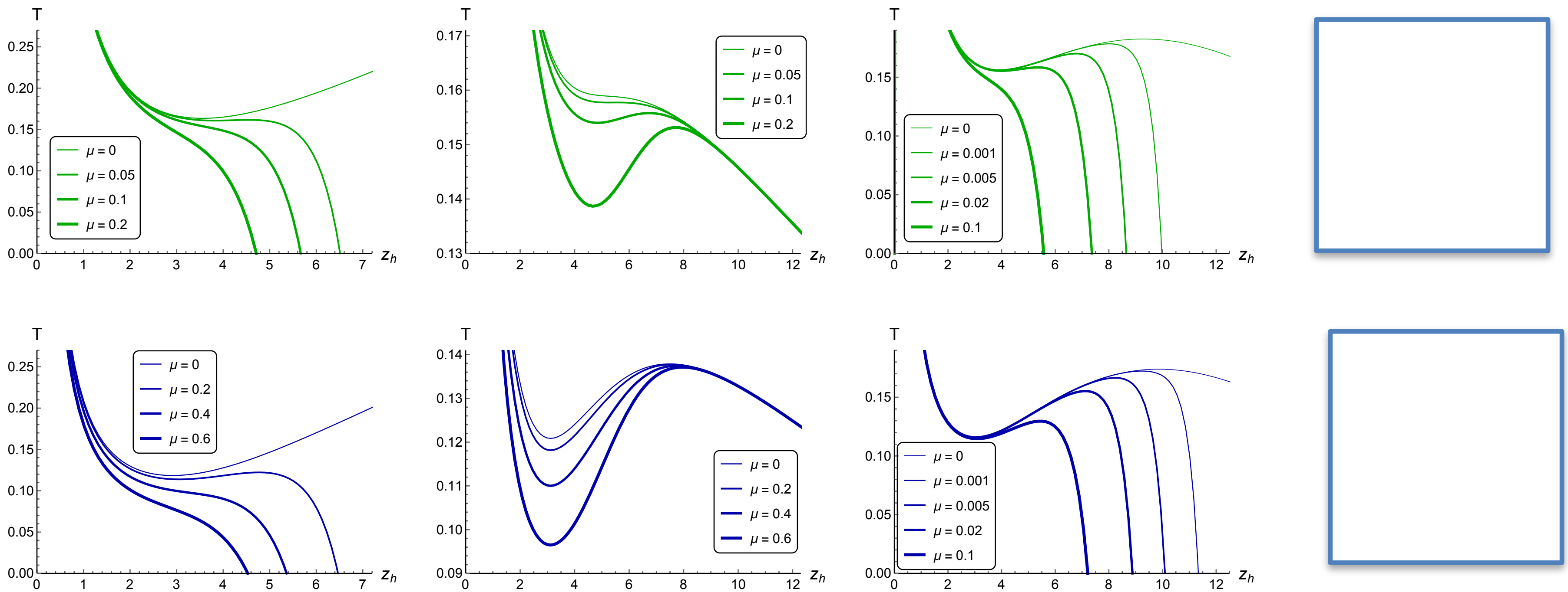


A) B) C) D)

Temperature as function of horizon for different μ in isotropic model for heavy A) and light B) quarks without magnetic field and with magnetic field C), $c_B = -0.005$, in the isotropic case, $\nu = 1$ (top line) and anisotropic case, $\nu = 4.5$ (bottom line).

Temperature vs horizon



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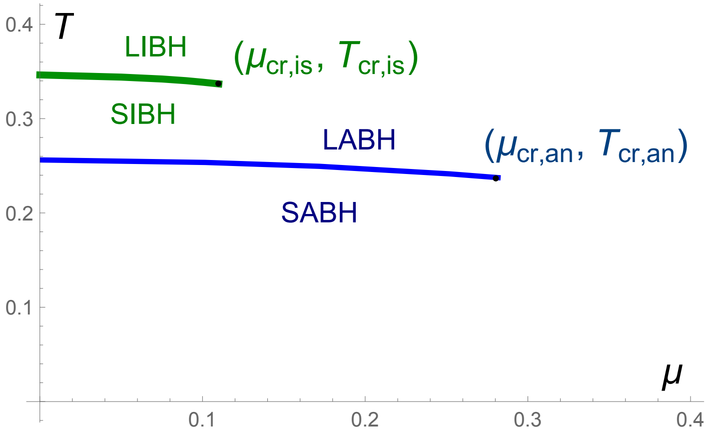
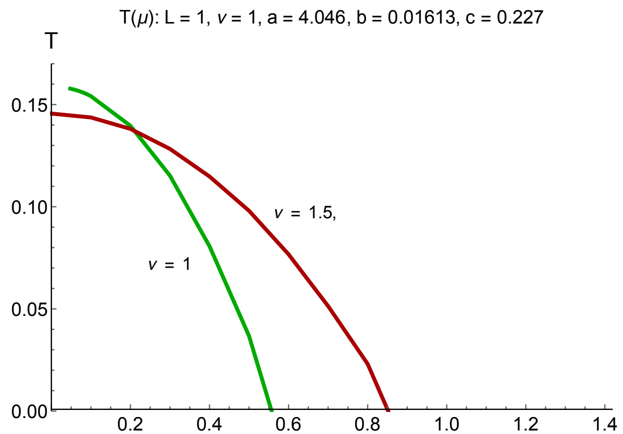
D) Light quarks with magnetic field - work in progress

Thermodynamics of the Anisotropic Backgrounds as compare with Isotropic ones

Heavy quarks

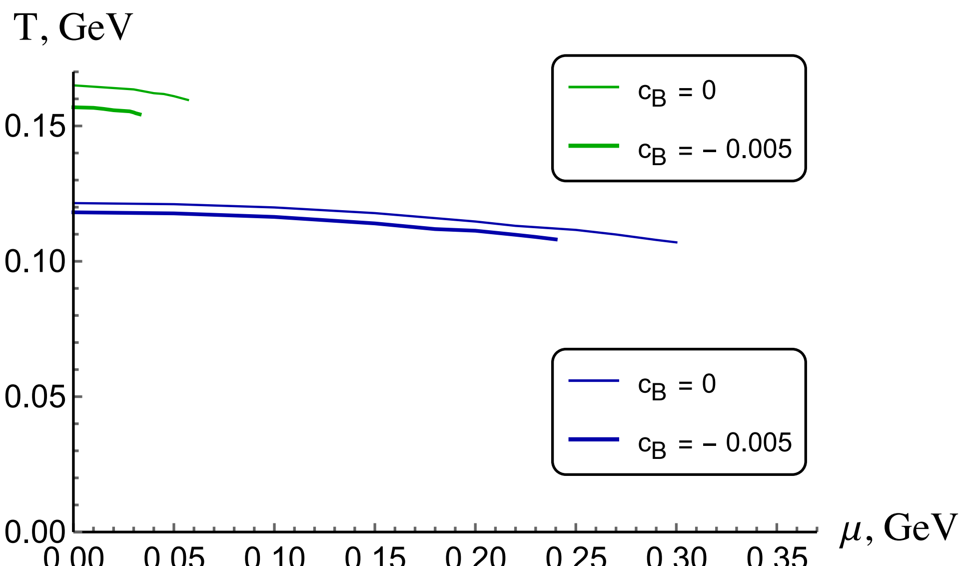


Light quarks

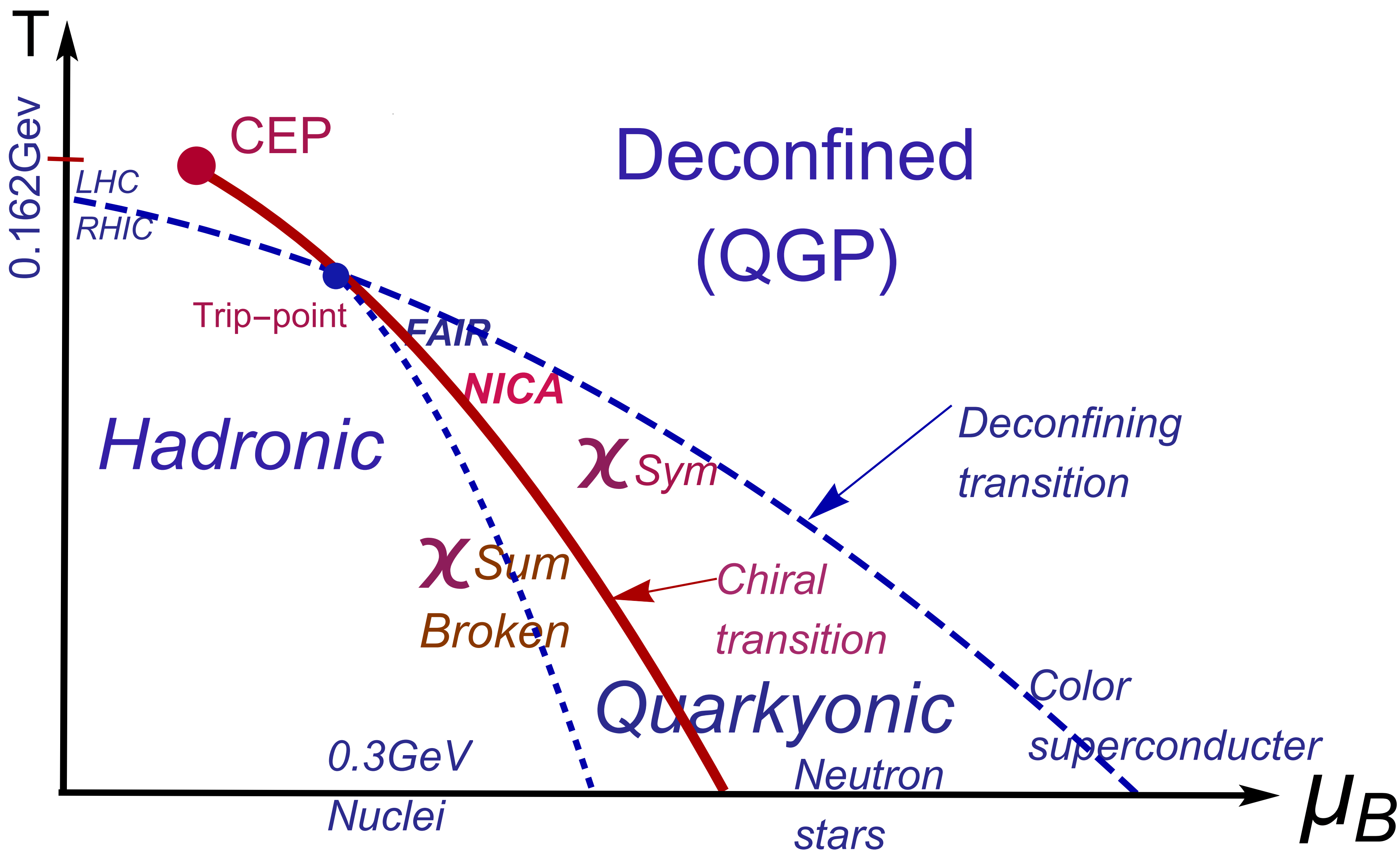


Hybrid model

With magnetic field



The expected QCD phase diagram



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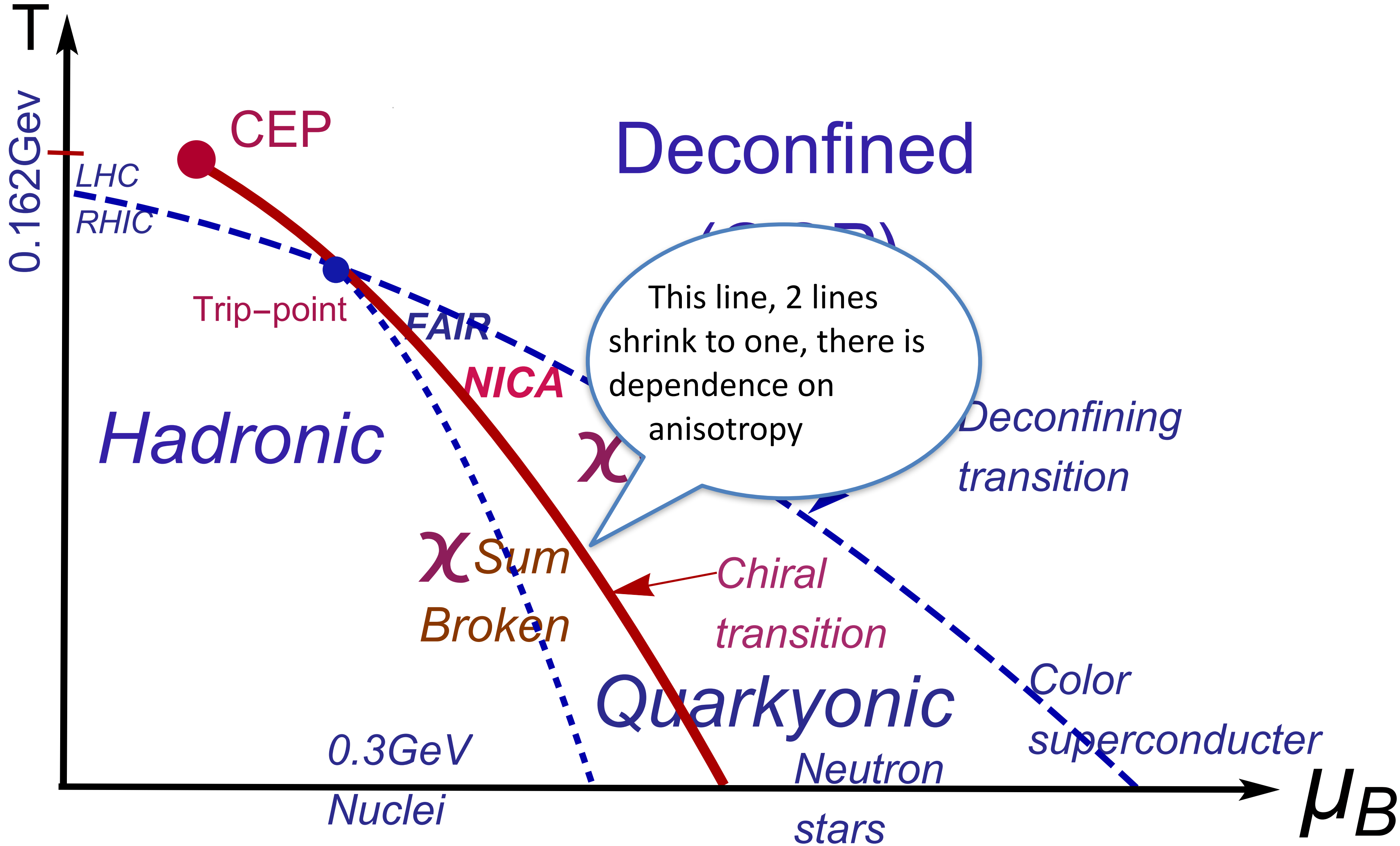

Phase transitions for **non-local observables**

Phase transitions for **non-local observables**

Wilson loop

temporal WL (confinement), spatial WL (drag forces, energy lost)

Light-cone WL (jet quenching)

D.Ageev,IA, A.Golubtsova, E. Gourgoulhon, NuclPhysB,18'
I.A,Golubtsova, Policastro, JHEP19'

IA,Rannu, JHEP18

IA, Rannu,Slepov, PhysLettB,19';

2009.05562,2011.07023,2012.05758,

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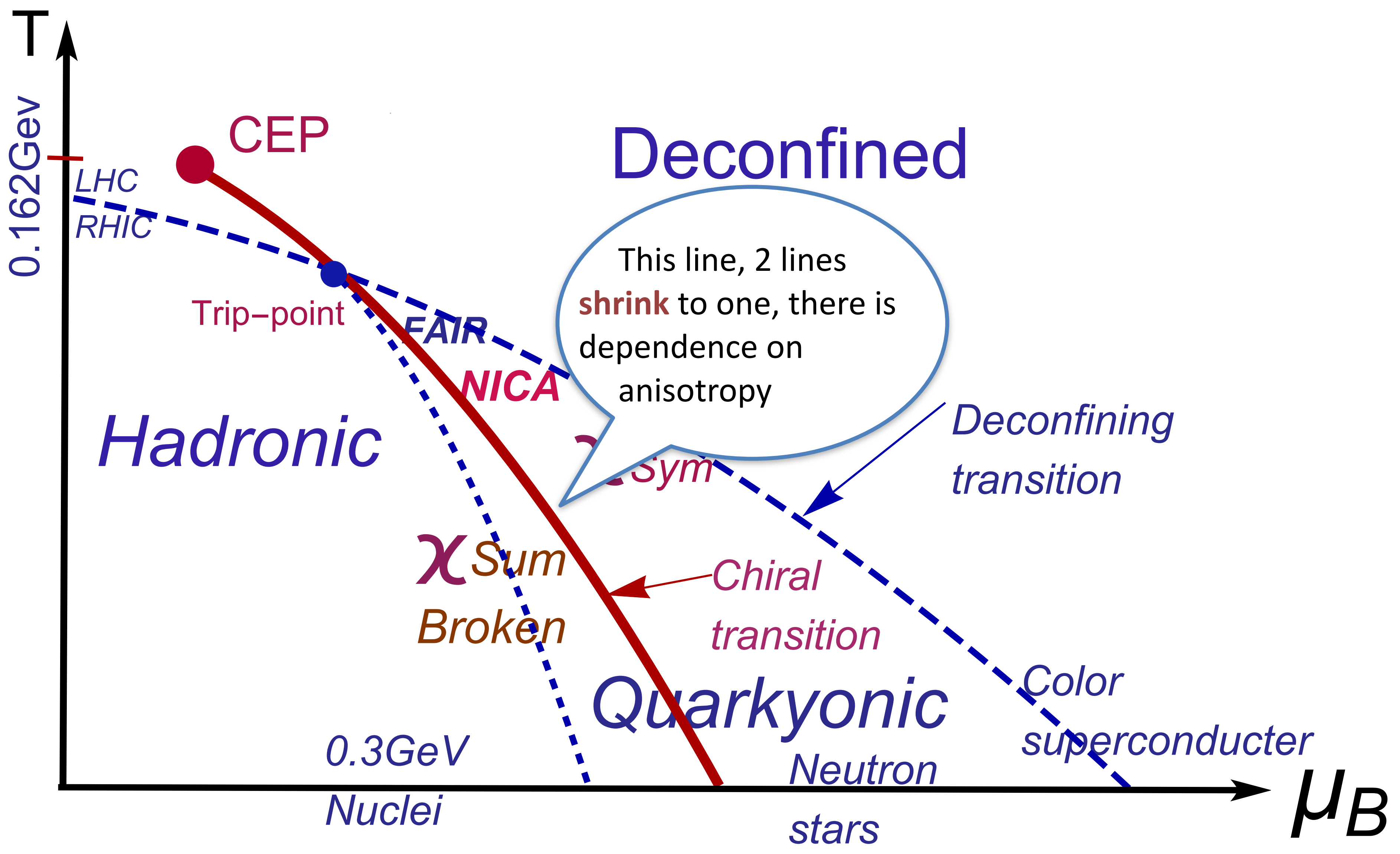
Entanglement Entropy

How to measure in experiments?

May be related with # of particles emitted from given volume

1. **I.A., Patrushev, Slepov, JHEP20’**

The expected QCD phase diagram



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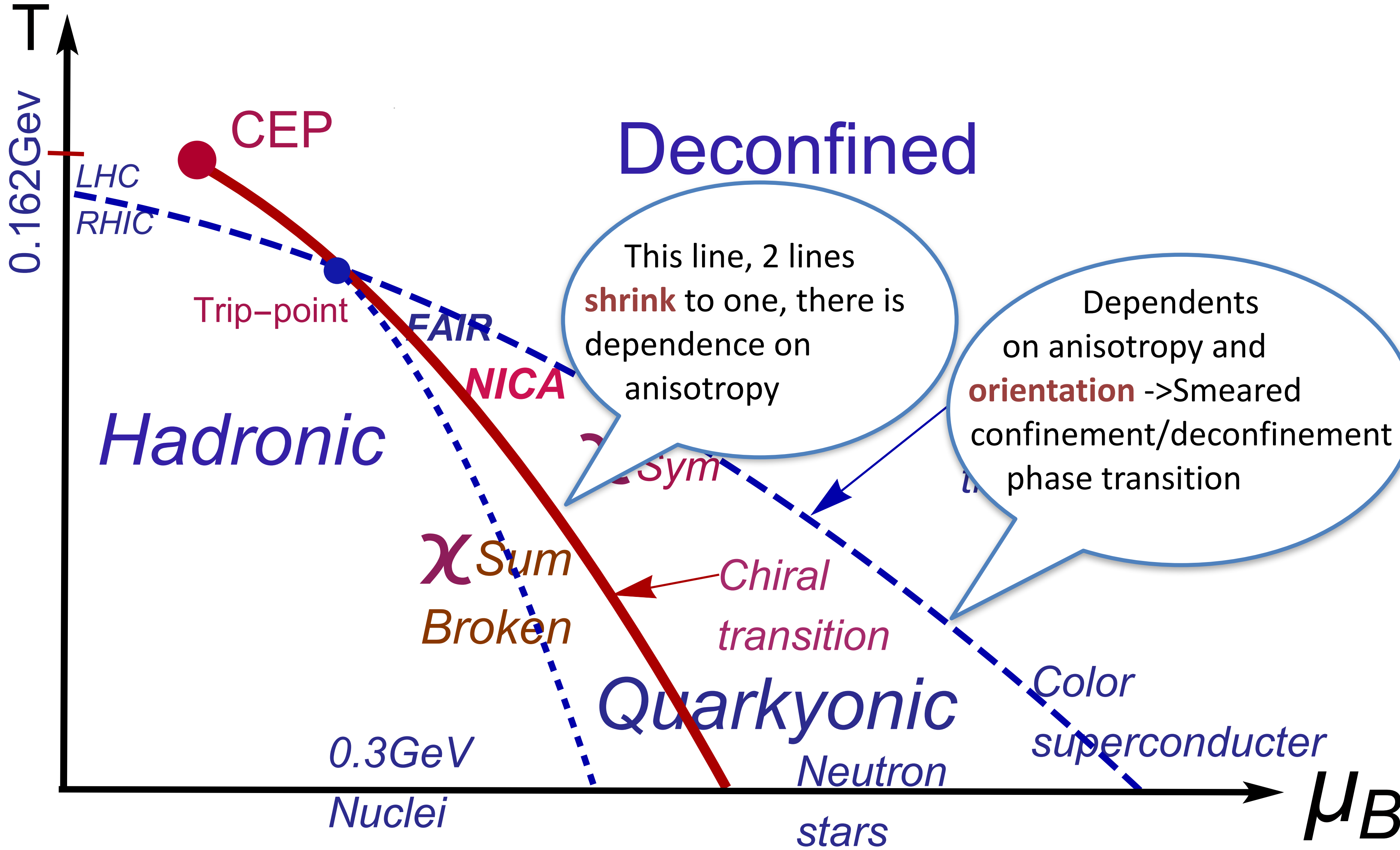

Conclusion

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We have considered the anizotropic HQCD models that describe:
multiplicity, quark confinement;

predict:
smothering of transition lines between confinement/ deconfinement phases
anisotropy parameter dependence of locations of phase transitions in (T,chemical potential, magnetic field)-plane
inverse magnetic catalyse

Thank you!