2024/10/07
Compact Stars in the QCD Phase diagram@YITP

Equation of state in neutron stars from a bottom-up holographic QCD model

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An ultimate purpose of QCD studies

To obtain the QCD phase diagram

▼

To challenge it

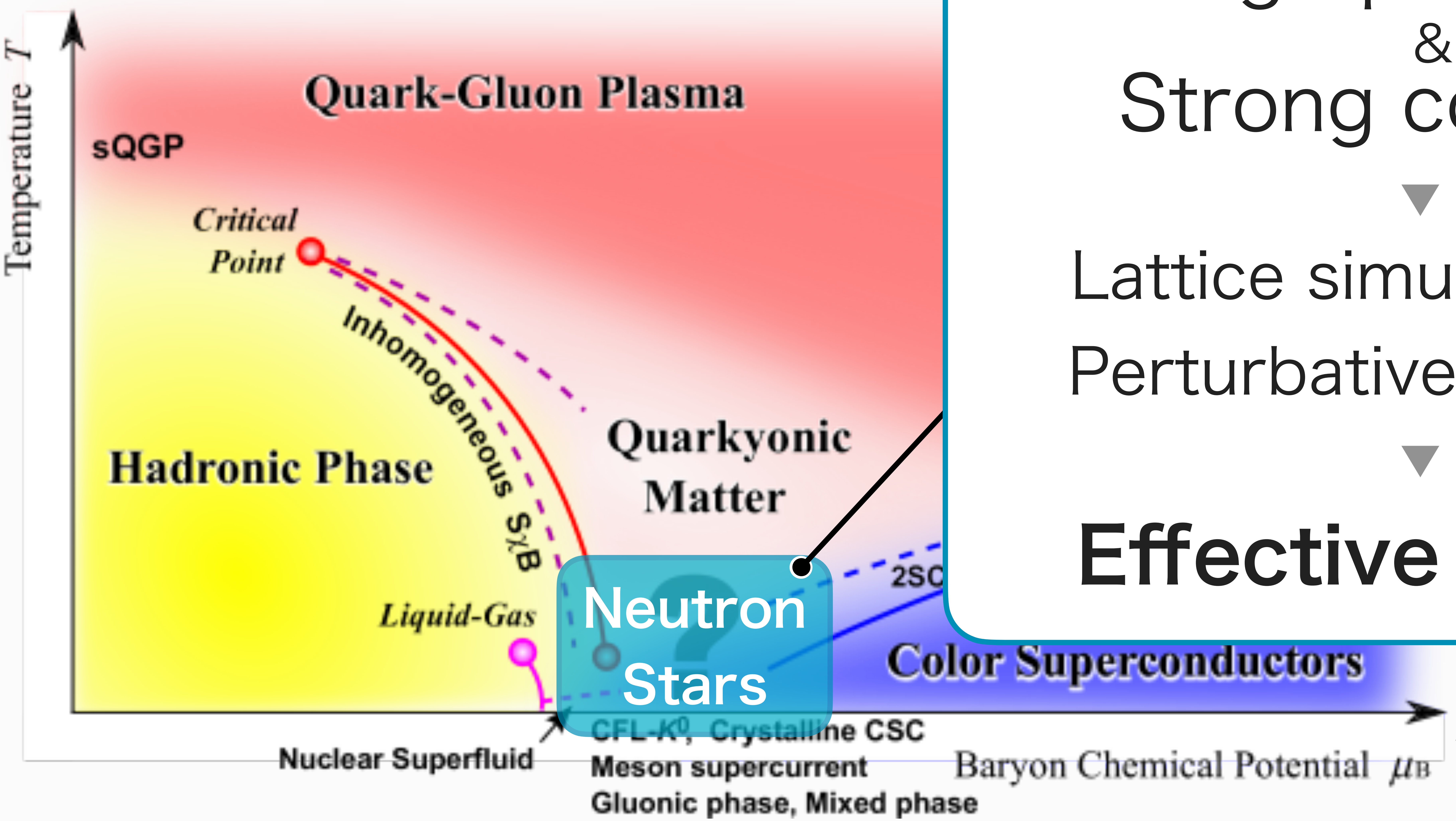
Focus on neutron stars

QCD phase diagram

K. Fukushima and T. Hatsuda,
Rep. Prog. Phys. **74** 014001 (2011)

Temperature

T



μ_B Baryon chemical potential

Sign problem

&

Strong coupling

▼

Lattice simulation → ×

Perturbative QCD → ×

▼

Effective models

Which model is better?

Holographic QCD

01 Finite density

02 Strong coupling

03 Chiral transition

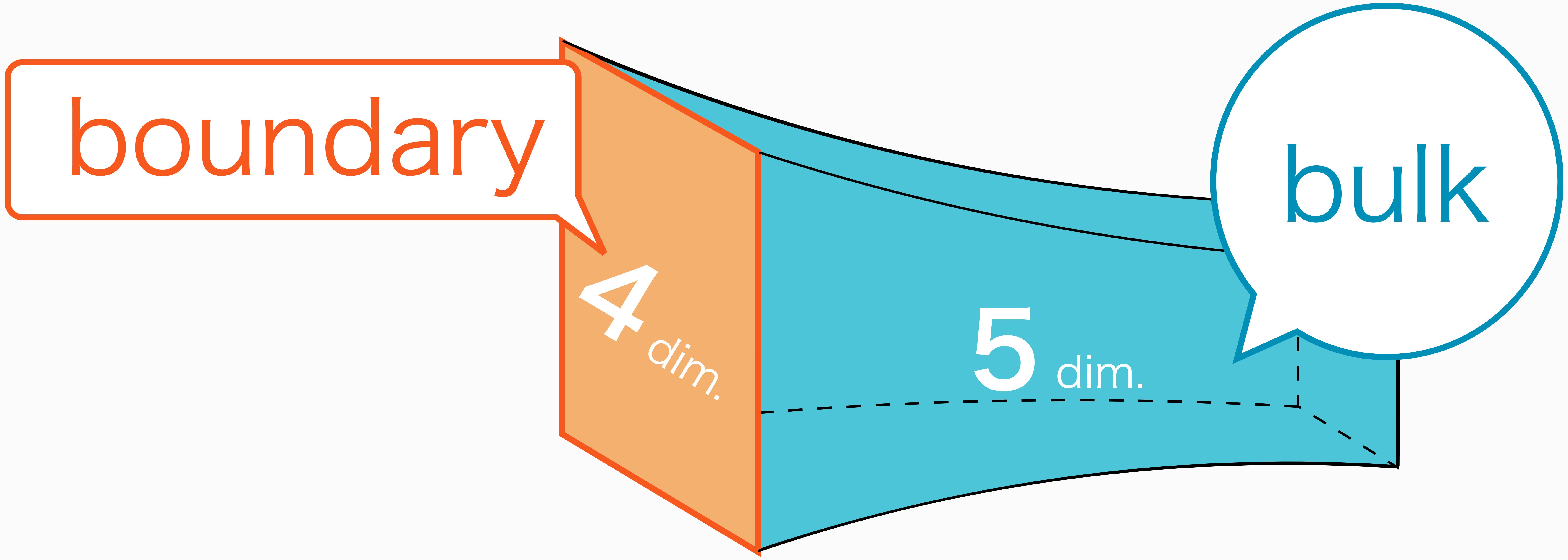
Holographic QCD

Note: Large N_c limit

4 dim.
QCD
Strong

↔

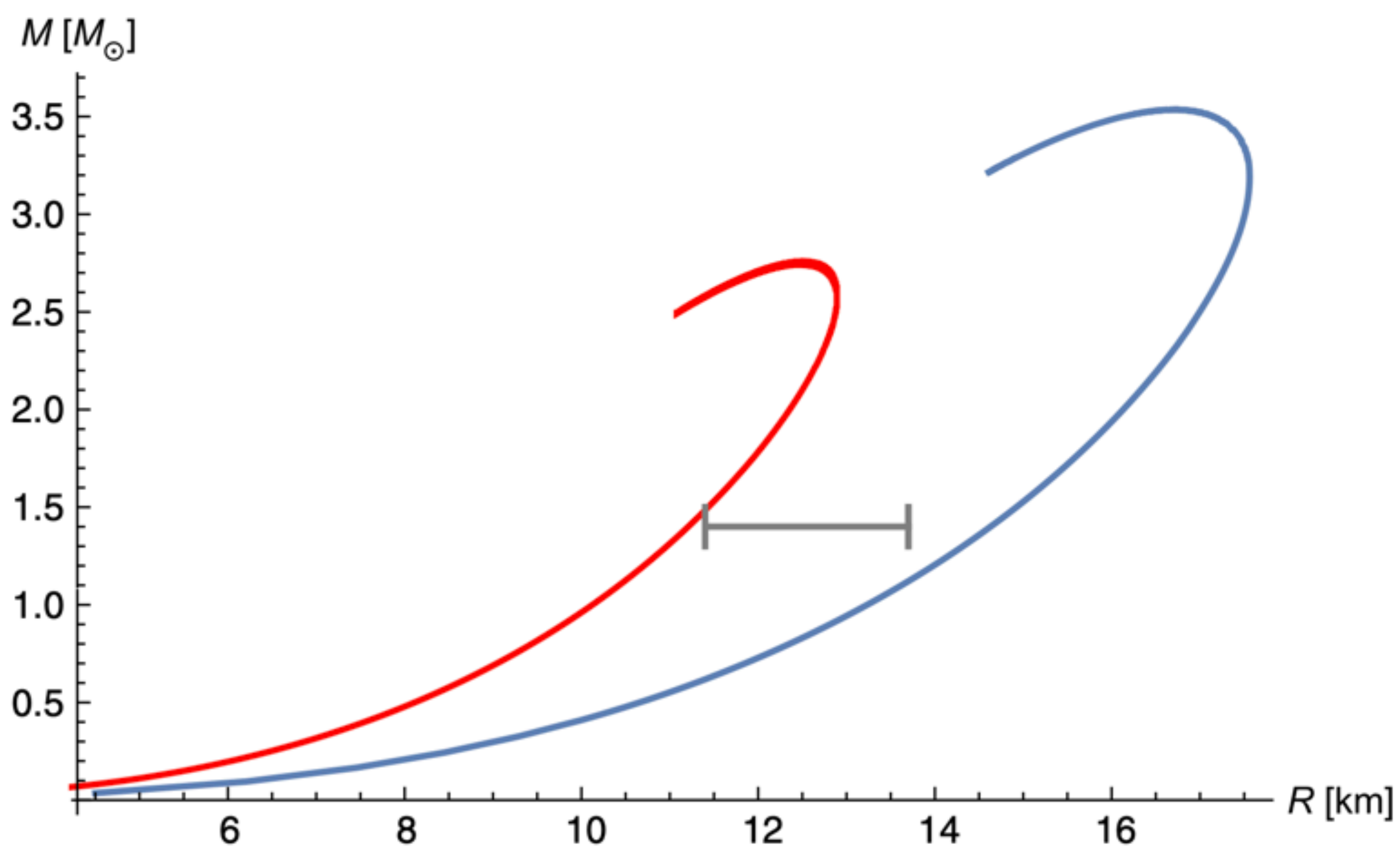
5 dim
Gravity
Weak



Previous study

Hard-wall model

Lorenzo Bartolini, et al., Phys. Rev. D **105**, 126014 (2022)



Problems

- Definition of μ_B
- Selection of IR b.c.
- Selection of variables
- Renormalization

⋮

▼

Revisit the model

Method

Hard-wall model

J. Erlich, et al., PRL **95**, 261602 (2005)

Cut-off AdS
(Confined phase)

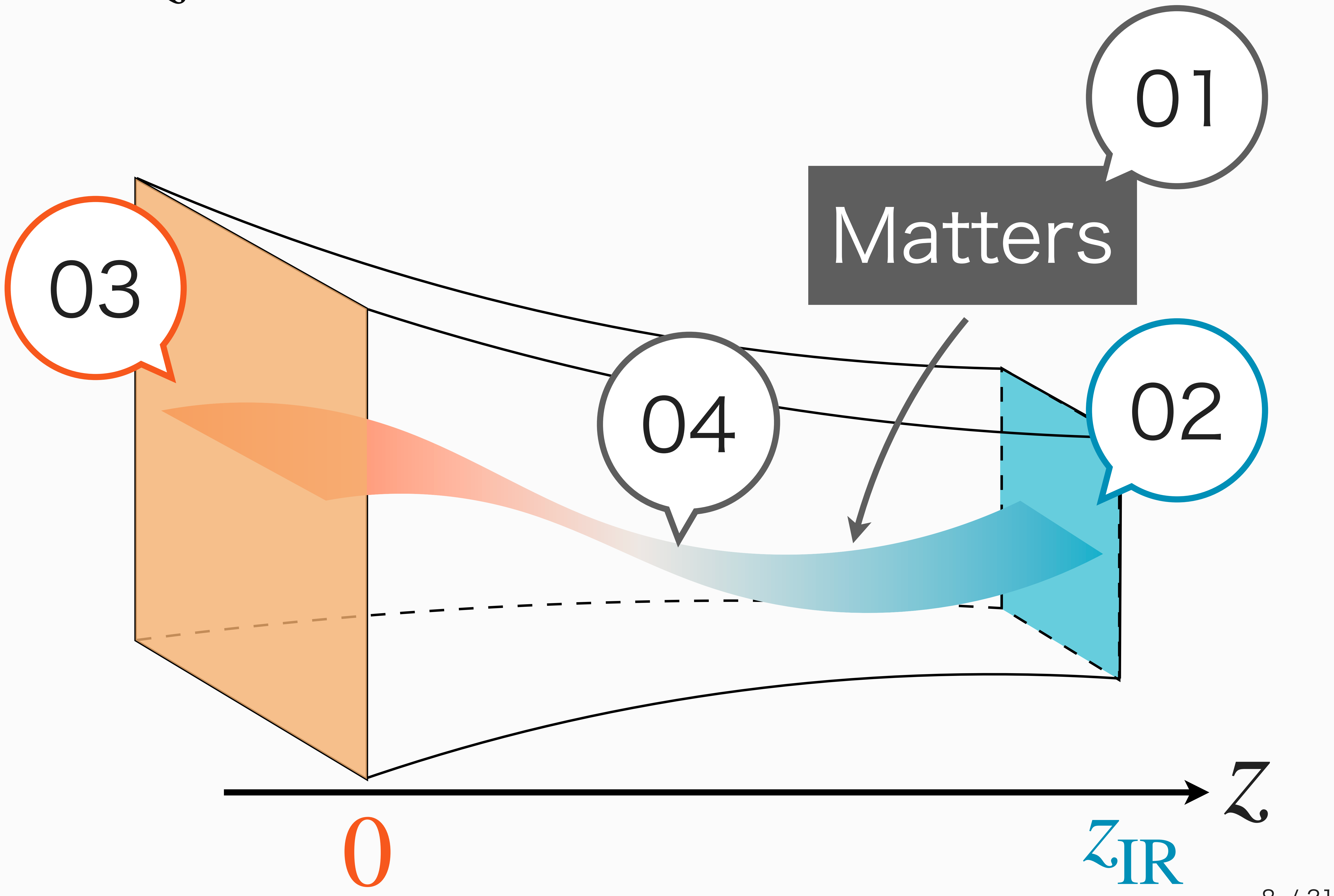
$$ds^2 = \frac{L^2}{z^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right), \quad 0 \le z \le z_{\rm IR}$$

01 Add matters

02 IR b.c.

03 UV b.c.

04 Solving EoM



01. Action of matters

$$S = S_{\mathrm{g}} + S_{\mathrm{CS}} + S_{\Phi} + S_{\mathrm{IR}} + S_{\mathrm{c}}$$

- S_{g}: $U(2)$ Flavor gauge fields (Left&Right)
- S_{CS}: Chern-Simons term
- S_{Φ}: Bi-fundamental Scalar fields
- S_{IR}: Potential on the hard-wall

$$S_{\mathrm{g}} = -\frac{N_c}{12\pi^2}\int d^4x dz \sqrt{-g}\left[\frac{1}{2}\mathrm{Tr}(L_{MN}L^{MN}) + \frac{1}{4}\hat{L}_{MN}\hat{L}^{MN} + \{R \leftrightarrow L\}\right],$$

$$S_{\mathrm{CS}} = \frac{N_c}{16\pi^2}\int d^4x dz\, \epsilon_{MNPQR}\left[\frac{1}{4}\hat{L}_M\left(\mathrm{Tr}[L_{NP}L_{QR}] + \frac{1}{6}\hat{L}_{NP}\hat{L}_{QR}\right) - \{R \leftrightarrow L\}\right],$$

$$S_{\Phi} = \frac{N_c}{12\pi^2}\int d^4x dz \sqrt{-g}\left\{\mathrm{Tr}\left[(D_M\Phi)^\dagger D^M\Phi\right] + 3\mathrm{Tr}[\Phi^\dagger\Phi]\right\},$$

$$S_{\mathrm{IR}} = -\int_{z=z_{\mathrm{IR}}} d^4x\, m_b^2\, \mathrm{tr}[\Phi^\dagger\Phi].$$

$$\mathscr{L}_z = \mathscr{R}_z = 0 \quad \text{(gauge fixing)}$$

$L_M,\ R_M$:$SU(2)$ gauge field

$\hat{L}_M,\ \hat{R}_M$:$U(1)$ gauge field

Φ :scalar field

$M, N, \cdots = 0,1,2,3,z$

$$L_{MN} = \partial_M L_N - \partial_N L_M - i[L_M, L_N],$$
$$L^a_{MN} = \partial_M L^a_N - \partial_N L^a_M + f^{abc}L^b_M L^c_N,$$
$$D_M\Phi = \partial_M\Phi - i\mathscr{L}_M\Phi + i\Phi\mathscr{R}_M,$$
$$\mathscr{L}_M = L^a_M\frac{\tau^a}{2} + \hat{L}_M\frac{I_2}{2}$$

(τ^a :Pauli matrix, $a = 1,2,3$),

$N_c = 3,\ L = 1.$

Ansatz

Homogeneous Ansatz

"Mean-field approximation"

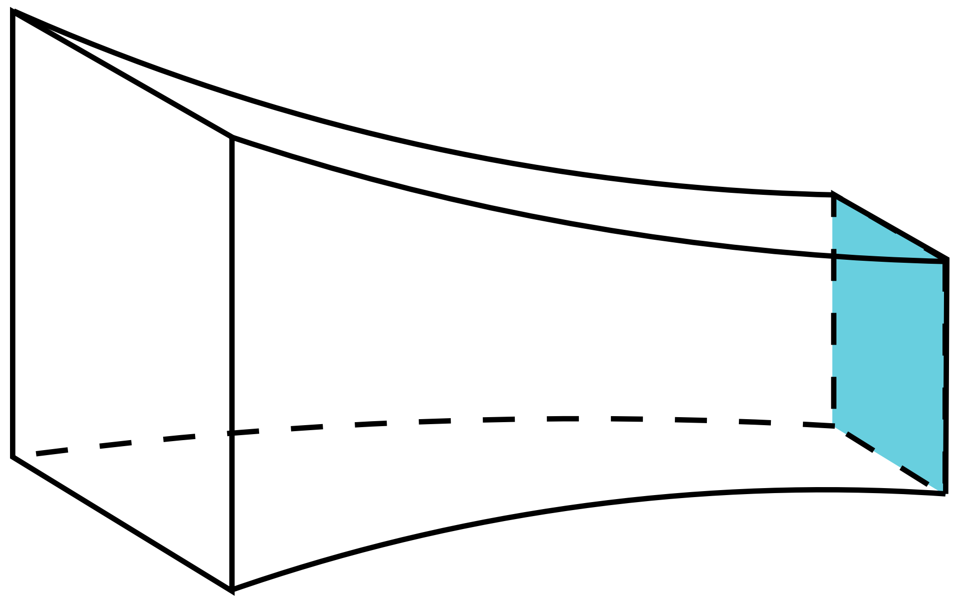
$\Phi = \omega_0(z)\dfrac{I_2}{2}$	$\longleftrightarrow$	Current quark mass Chiral condensate
$\mathscr{L}_0 = -\mathscr{R}_0 = \hat{a}_0(z)\dfrac{I_2}{2}$	$\longleftrightarrow$	Baryon chemical potential Baryon number density
$\mathscr{L}_i = -\mathscr{R}_i = -H(z)\dfrac{\tau^i}{2}$	$\longleftrightarrow$	Axial vector potential Axial vector meson condensate

02. IR b.c.

Note: $z_{\rm IR} = 1$

Mesonic IR b.c. $(z = z_{\rm IR})$

$\mu_B < \mu_c$



b.c. Neumann

$$\partial_z \omega_0(z_{\rm IR}) = -\frac{12\pi^2}{N_c}\left(3kH^2\omega_0 + m_b^2\omega_0 + \frac{\lambda}{4}\omega_0^3\right),$$

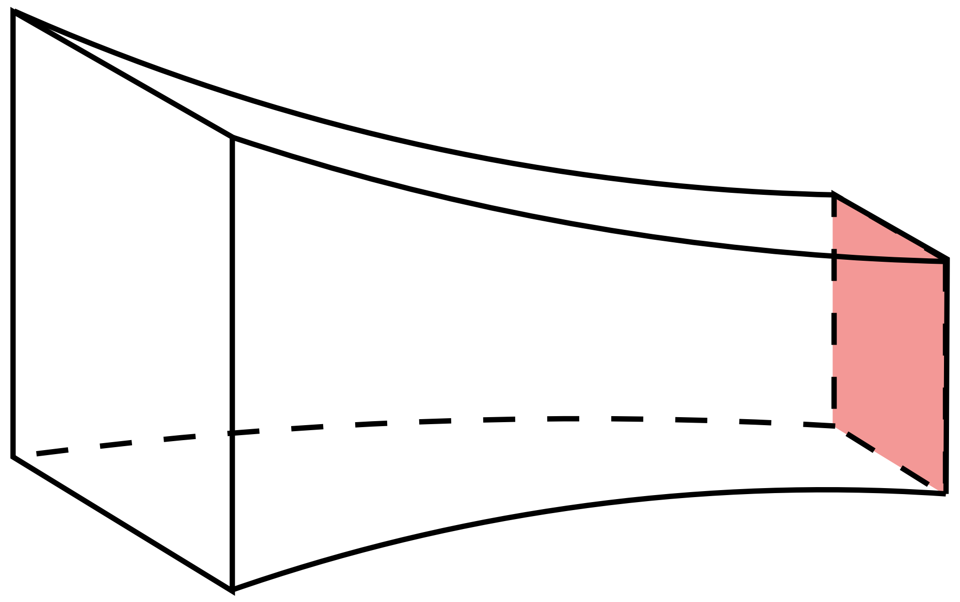
$$\partial_z \hat{a}_0(z_{\rm IR}) = 0,$$

$$\partial_z H(z_{\rm IR}) = 0.$$

▶

Baryonic IR b.c. $(z = z_{\rm IR})$

$\mu_B \geq \mu_c$



b.c. Neumann + Dirichlet

$$\partial_z \omega_0(z_{\rm IR}) = -\frac{12\pi^2}{N_c}\left(3kH^2\omega_0 + m_b^2\omega_0 + \frac{\lambda}{4}\omega_0^3\right),$$

$$\hat{a}_0(z_{\rm IR}) = A = 4,$$

$$H(z_{\rm IR}) = B\,.$$

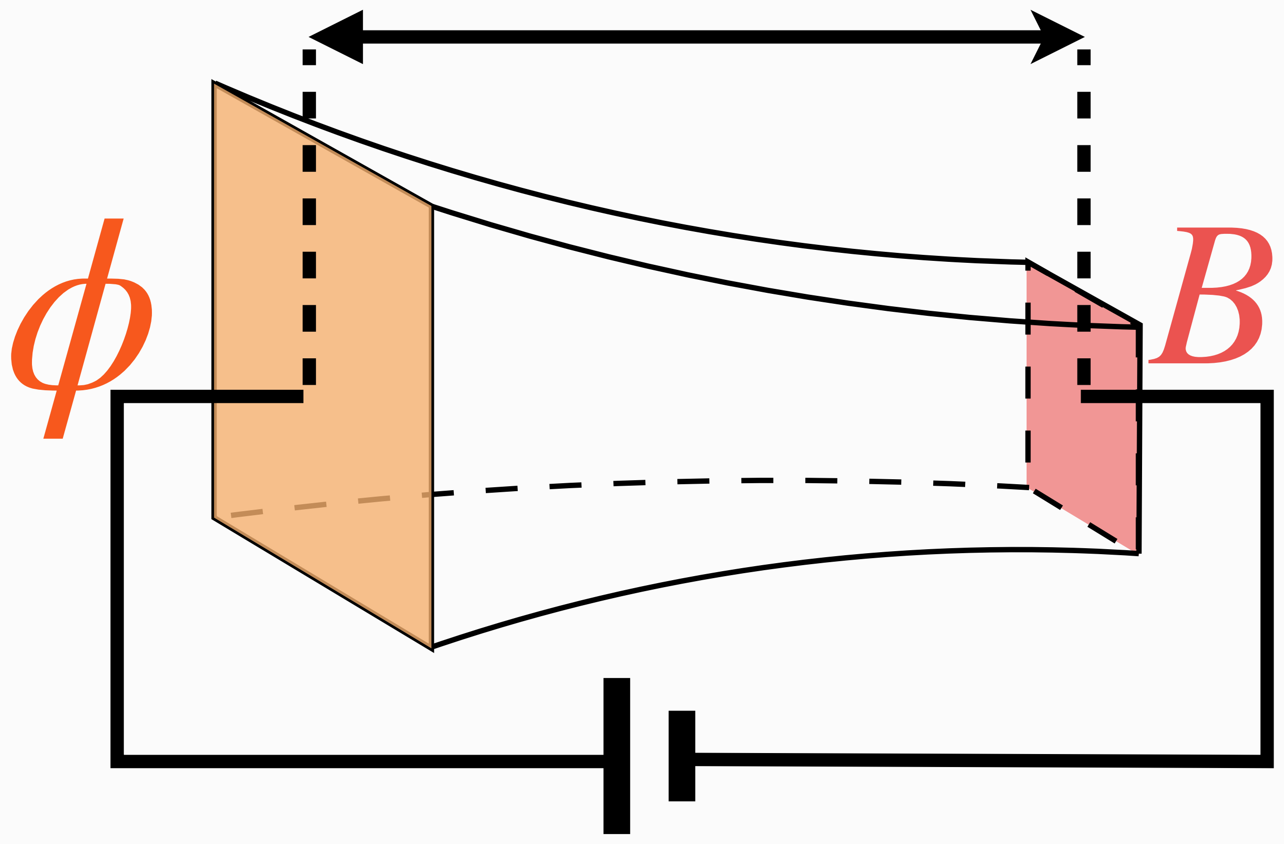
03. UV b.c.

UV b.c. $(z = 0)$

$\partial_z \omega_0(0) = m = 3\ \mathrm{MeV}$ $\longleftrightarrow$ Current quark mass

$\hat{a}_0(0) = \mu$ $\longleftrightarrow$ Baryon chemical potential

$H(0) = \phi = B \in \{0.2,\ 0.4,\ 0.6\}$ $\longleftrightarrow$ Axial vector potential



Make "no difference of potential"

$$\hat{\phi} \propto \phi - B = 0$$

Parameters

01 AdS radius
&
place of the hard-wall

▼

Fit from M-R plot

$$L = z_{\mathrm{IR}} = (800\ \mathrm{MeV})^{-1}$$

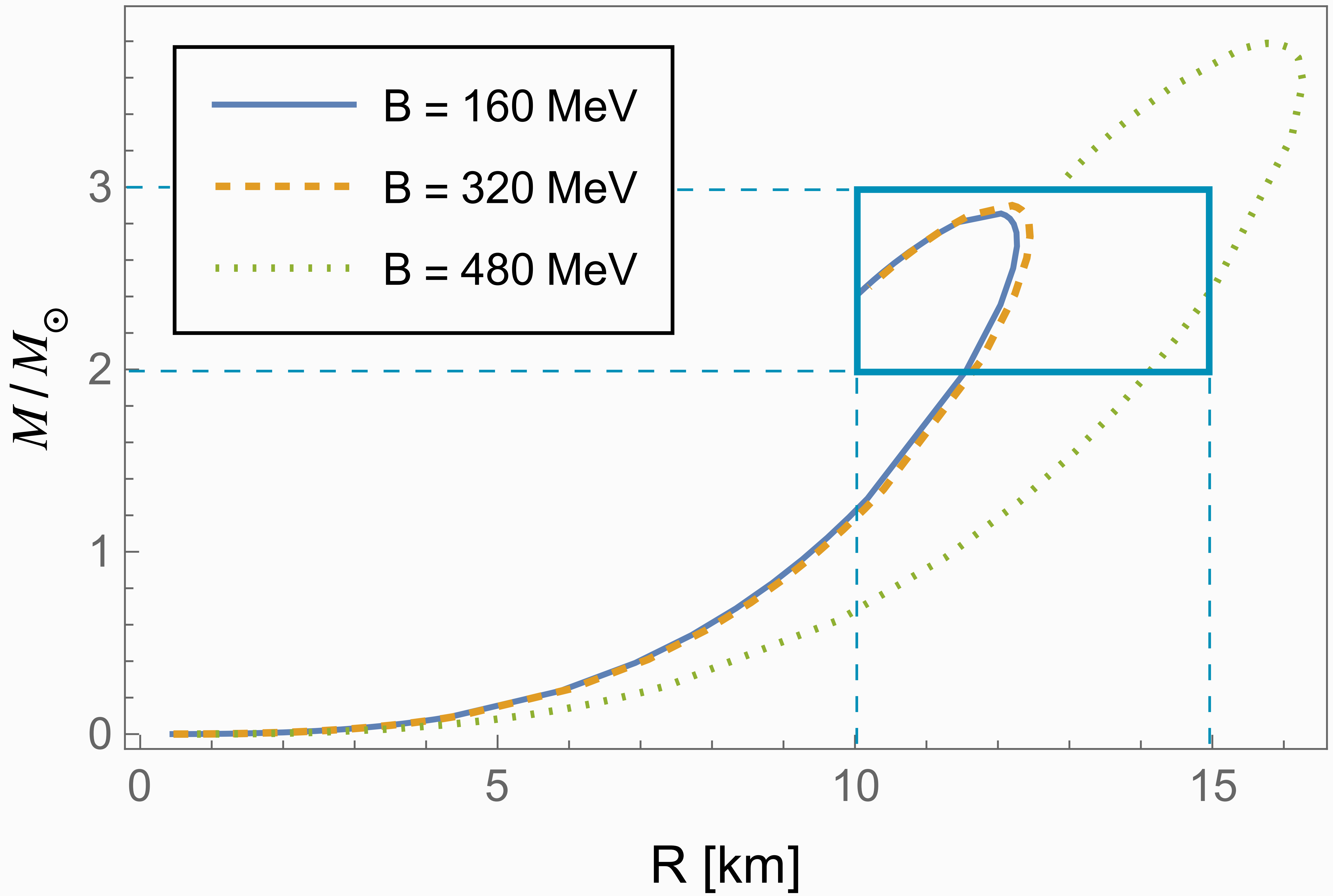
02 Chiral condensate
in the mesonic phase

▼

Lattice result

$$\xi_0 = (251\ \mathrm{MeV})^3$$

H. Fukaya, et al., PRL **98**, 172001 (2007)



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Self-binding(?), stiff matter

(Quark star like)

Results

Grand potential density

Two transitions

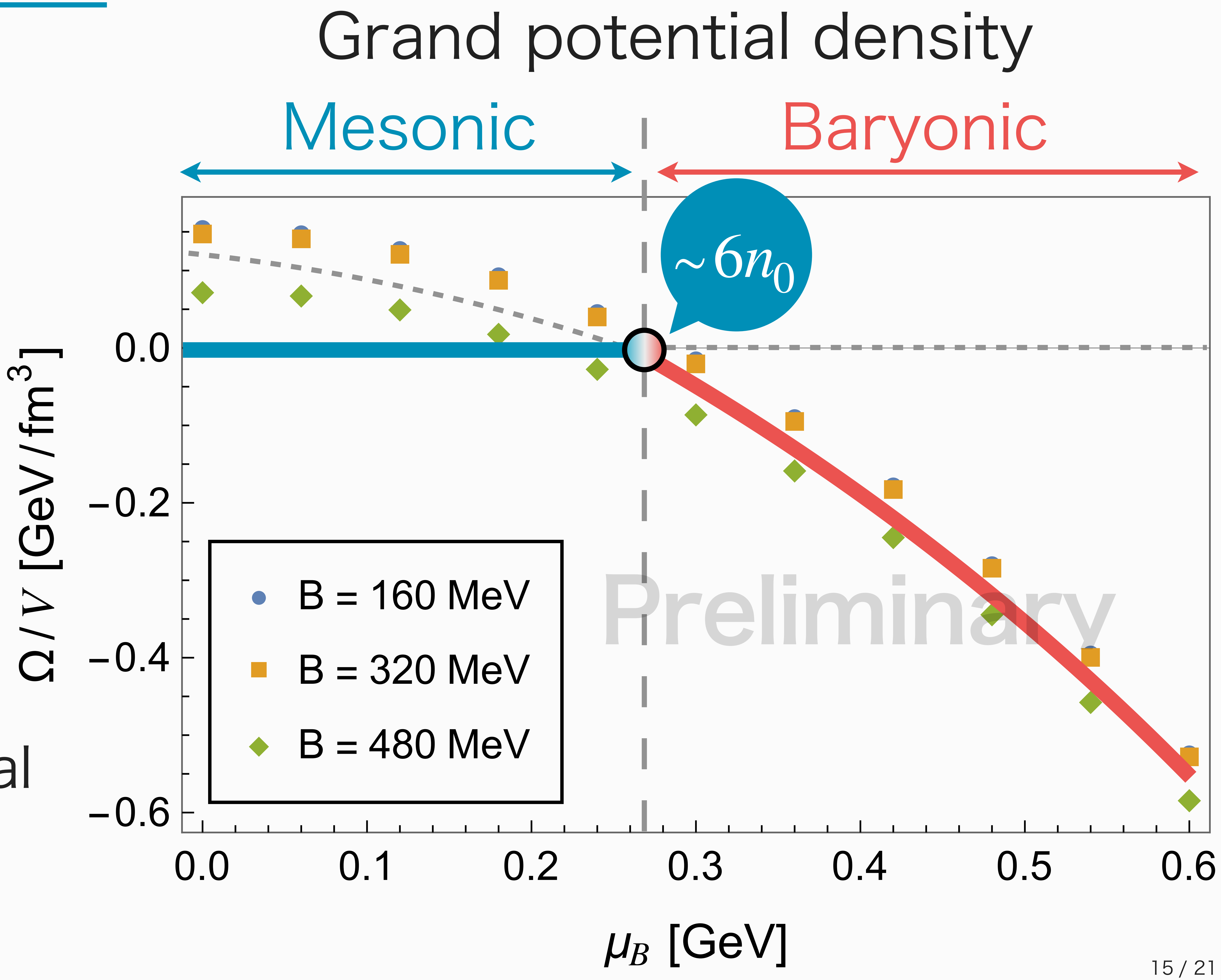
- Chirality
- Baryon number density

All transitions are

1 st transition

Critical chemical potential

$$\mu_B \sim 270 \text{ MeV}$$



Chiral condensate

Chiral condensate remains

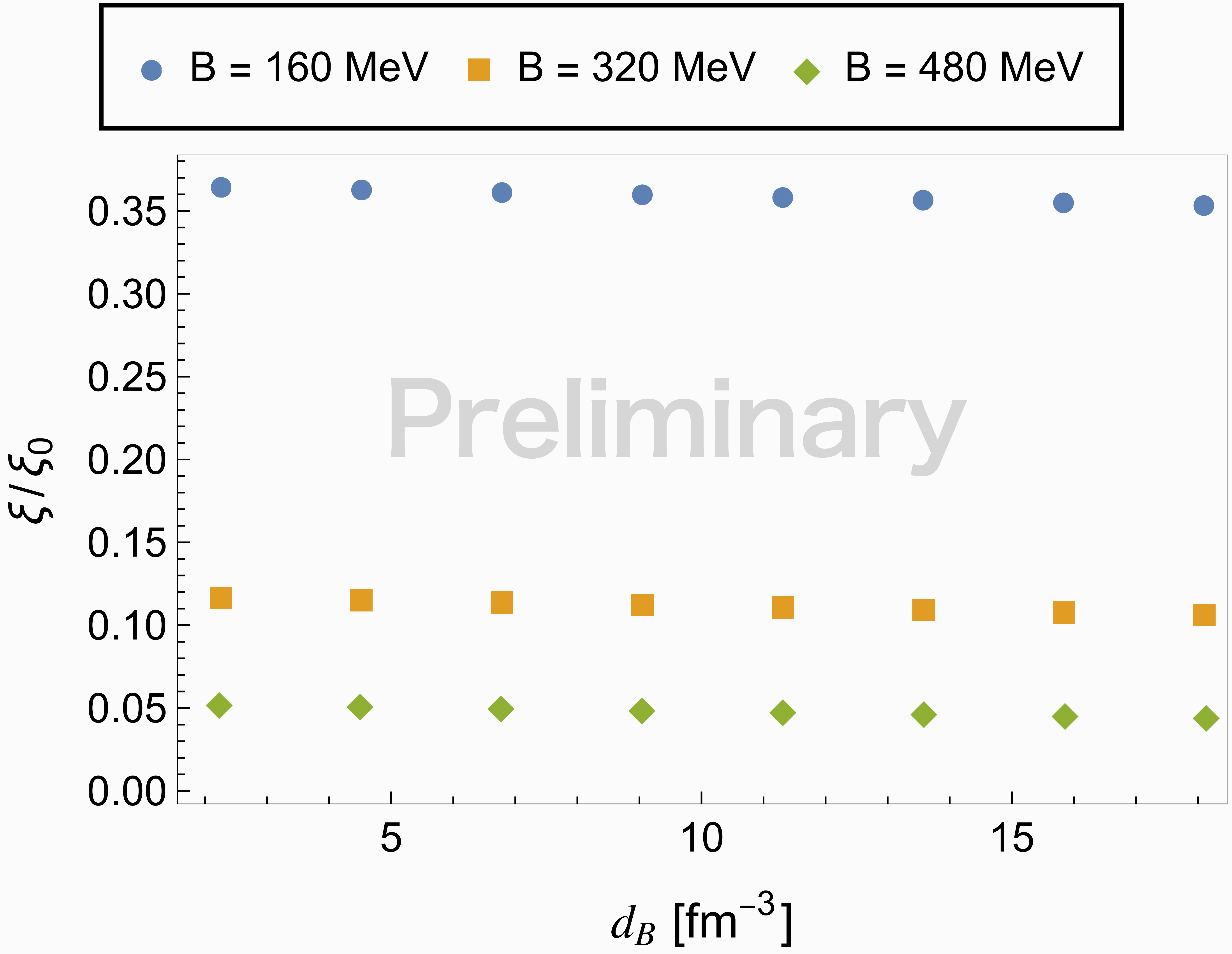
~ 35%

Maximally

Partial restoration of Chiral symmetry

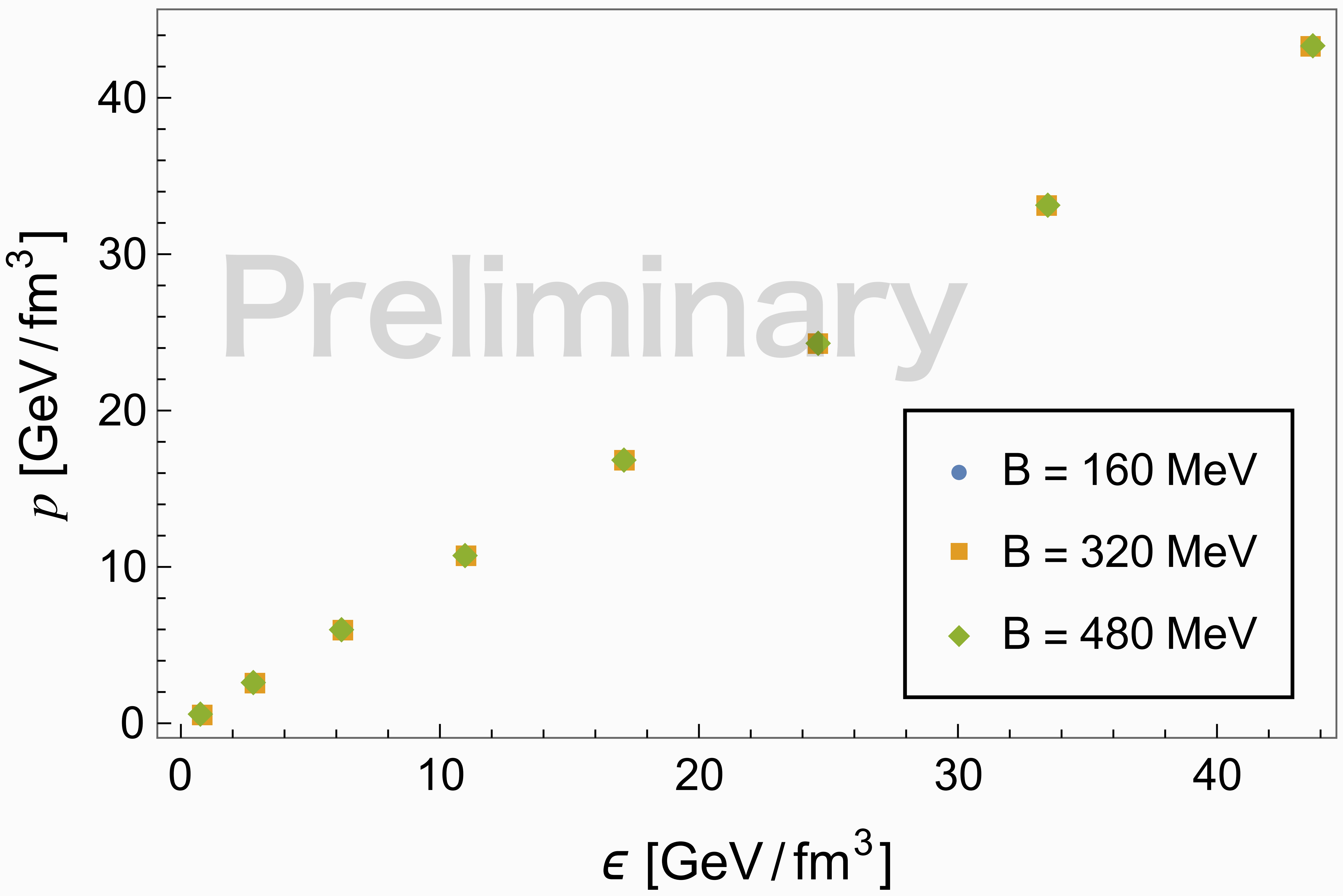
T. D. Cohen, et al., PRC. 45. 1881 (1992)
M.C. Birse, J.Phys. Nucl. Part. Phys. 20. 1537 (1994)
K. Suzuki, et. al. PRL. 92. 072302 (2004)

Chiral condensate (baryonic phase)

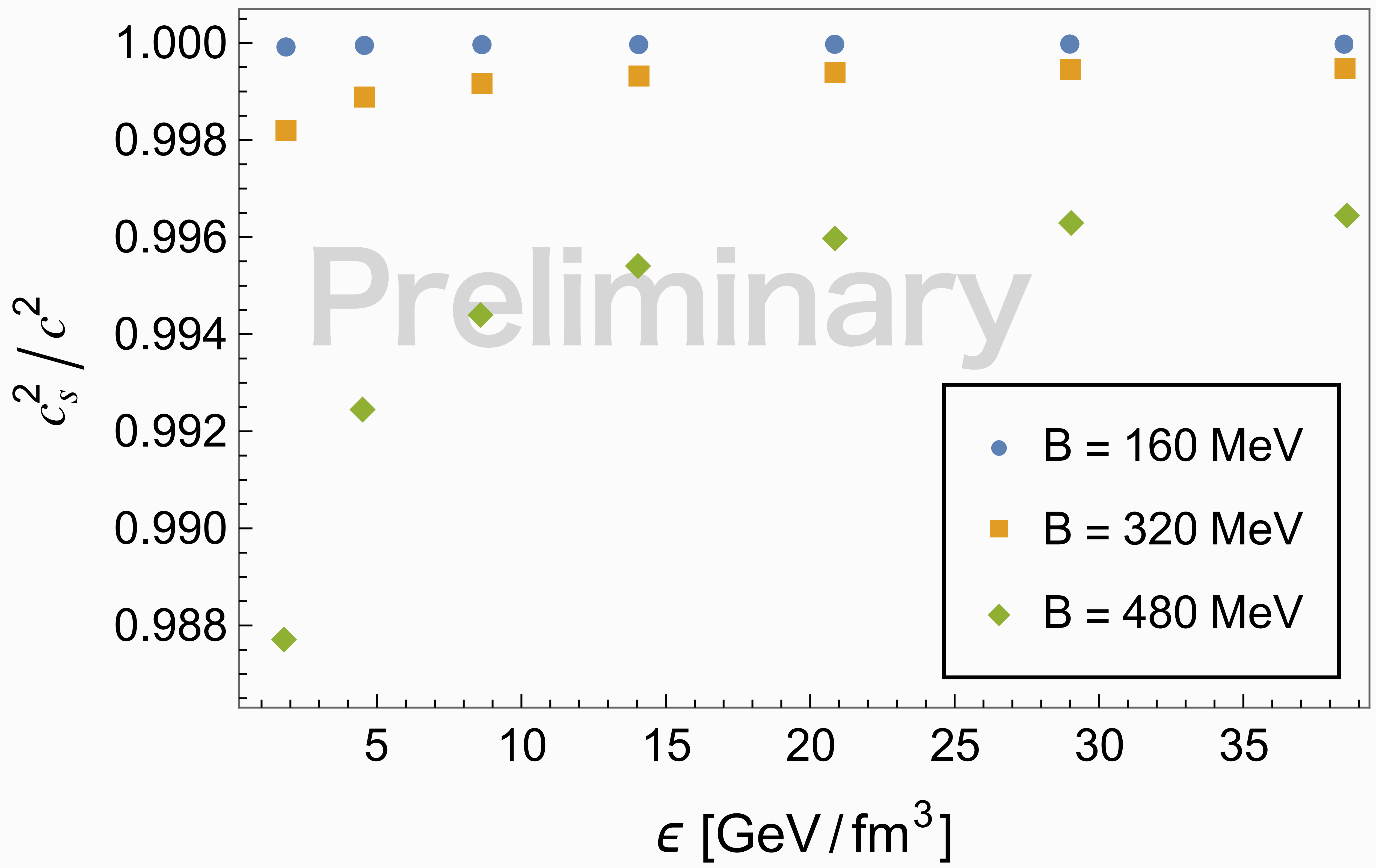


EoS & Speed of sound

EoS (baryonic phase)



Speed of sound (baryonic phase)



The EoS is

Linear function with gradient $\simeq 1$

▶ **Speed of sound $\simeq 1$**

Discussion

What is the matter?

Properties

- Six times $n_0 \simeq 1.7\ \mathrm{fm}^{-3}$
- Self-binding matter (?)
- Speed of sound ~ 1
- Color confinement

▼

High density nuclear matter

What is the matter?

Properties

- Six times $n_0 \simeq 1.7\ \mathrm{fm}^{-3}$

Unreliable

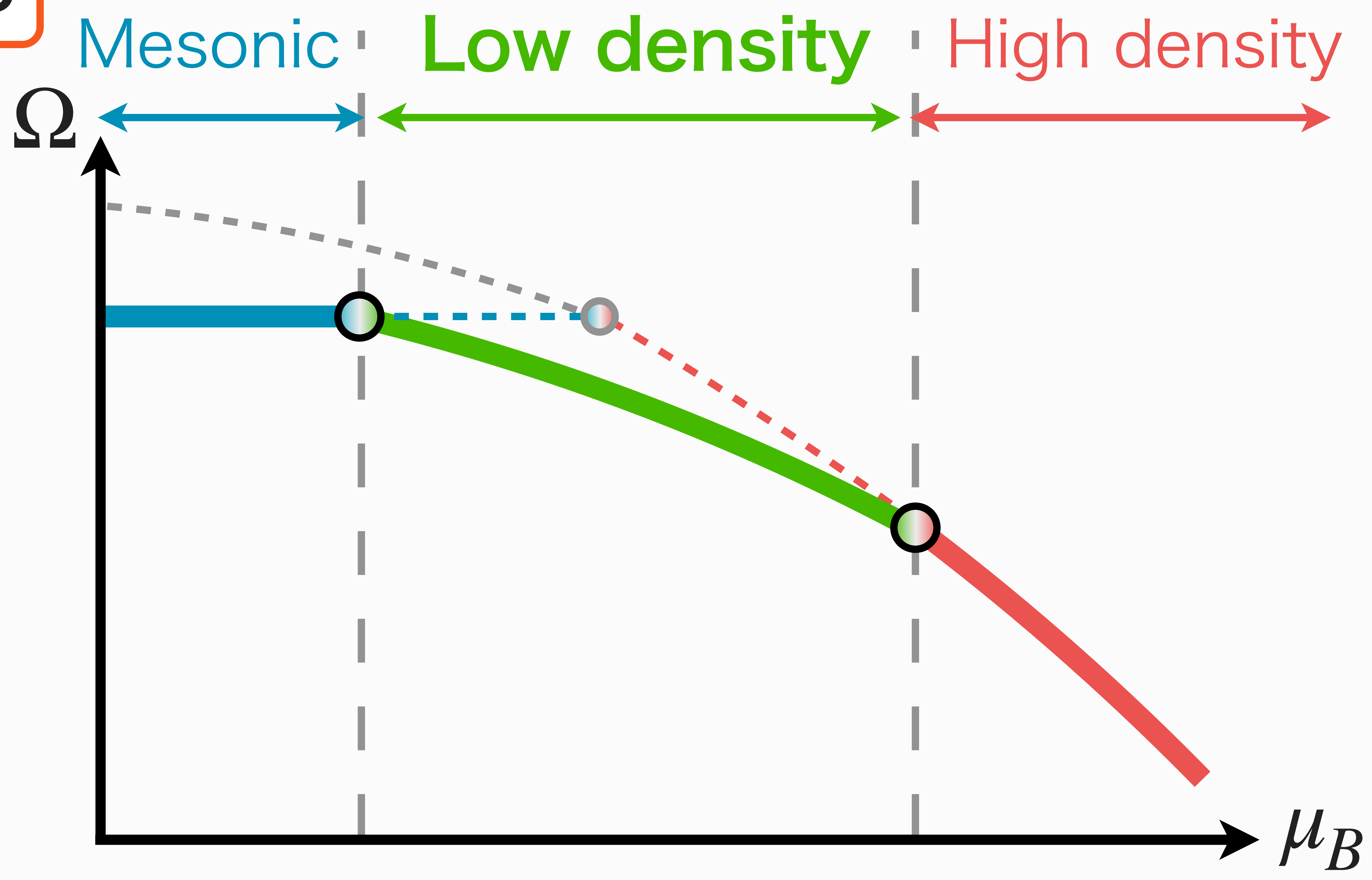
- Self-binding matter (?)
- Speed of sound ~ 1
- Color confinement

▼

High density nuclear matter

The Ansatz is not suitable for low density region

Need another Ansatz



Abstract

Pourpose

- Studying the QCD EoS from holographic QCD

Method

- Hard-wall model + Switching IR b.c.

Result

- Baryonic matter appears with first transition
- Partial restoration of chiral symmetry

Discussion

- The matter is a high density nuclear matter
- We need low density Ansatz

Fin.