Dynamical meson melting in holography

Keio University

Keiju Murata

with S. Kinoshita (Osaka City Univ.), T. Ishii (Univ of Crete), N. Tanahashi (DAMTP)

"Dynamical Meson Melting in Holography", JHEP04(2014)099, [arXiv:1401.5106]

1.Introduction

AdS/CFT correspondence

N=4 super Yang Mills theory ⟺ Type IIB SUGRA on AdS5 xS5

N=4 Super Yang-Mills theory

$$S = -\int d^4x\sqrt{-g}\,\mathrm{tr}\left[\frac{1}{2}(F_{\mu\nu})^2 + (D_\mu\phi_m)^2 + i\bar{\lambda}^A\Gamma^\mu D_\mu\lambda_A - \frac{g^2}{2}[\phi_m,\phi_n]^2 - g\bar{\lambda}^A\Gamma^m[\phi_m,\lambda_A]\right]$$

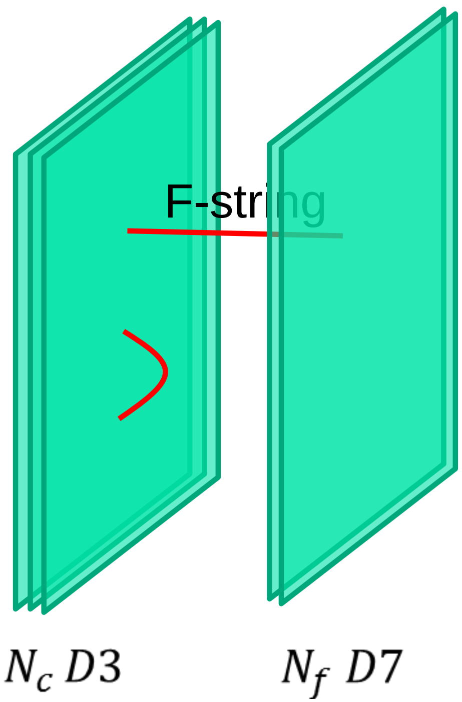
There is no quark degrees of freedom.

How can we take into account quarks in AdS/CFT?

D3/D7 model

Karch&Katz, 02

	0	1	2	3	4	5	6	7	8	9
Nc D3	✓	✓	✓	✓						
Nf D7	✓	✓	✓	✓	✓	✓	✓	✓		



D3-D7 strings compose fields with fundamental representation of SU(Nc).

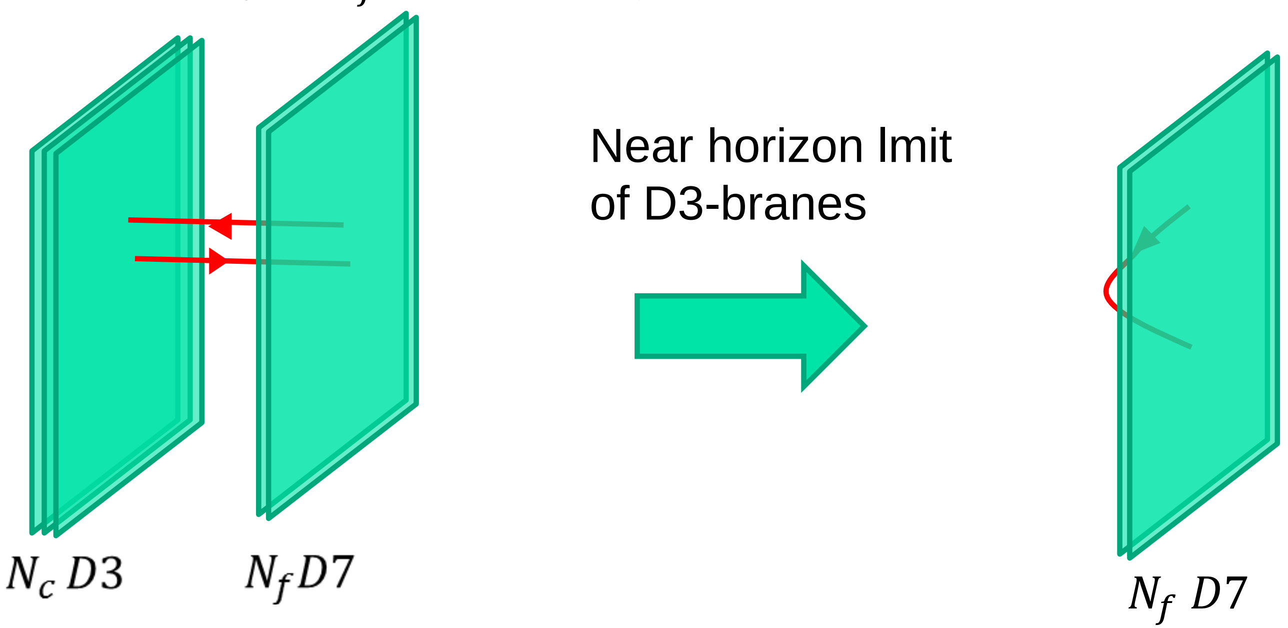
→ Quark degree of freedom

$$L = L_{SYM} + \sum_{r=1}^{N_f} [\ \bar{\psi}_r (i\gamma^\mu D_\mu + m)\psi_r + \frac{1}{2}(Dq_r)^*(Dq_r) + \frac{1}{2}(D\tilde{q}_r)^*(D\tilde{q}_r) - \frac{m^2}{2}(q_r^* q_r + \tilde{q}_r^{\ *}\tilde{q}_r) + \ldots]$$

Super symmetric QCD

Gravity dual

In the limit of $N_c \gg N_f$, we can neglect the back reaction from D7-branes.



in AdS5 x S5.

Motion of D7-brane is described by the DBI action.

$$S_{\rm D7} = -\mu_7 \int {\rm d}^8 y \sqrt{-\det\left(g_{\mu\nu}(X)\frac{\partial X^\mu}{\partial y^a}\frac{\partial X^\nu}{\partial y^b}\right)}$$

D7-brane fluctuations correspond to meson excitations.

Kruczenski et al, 03

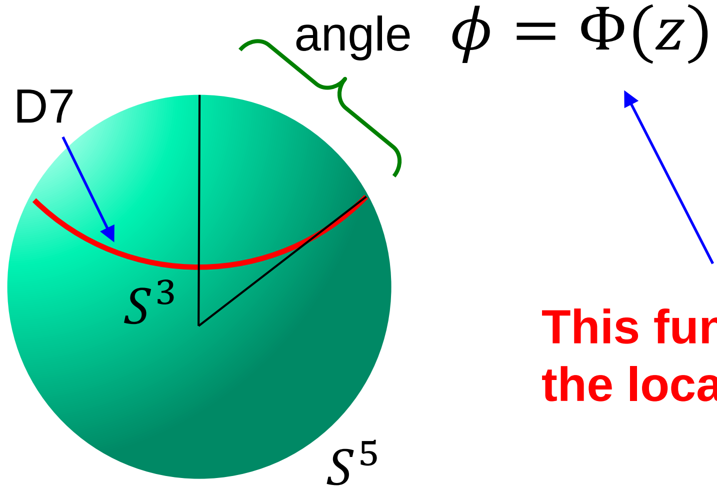
D7-brane in Sch-AdS5 x S5

Sch-AdS5 x S5（finite tempareture）

$$ds^2 = \frac{1}{z^2}\left[-f(z)dt^2 + \frac{dz^2}{f(z)} + d\vec{x}^2\right] + d\phi^2 + \sin^2\phi\, d\Omega_3^2 + \cos^2\phi\, d\psi^2$$

$$\left[\ f(z) = 1 - r_h z^4\ \right]$$

D7 direction

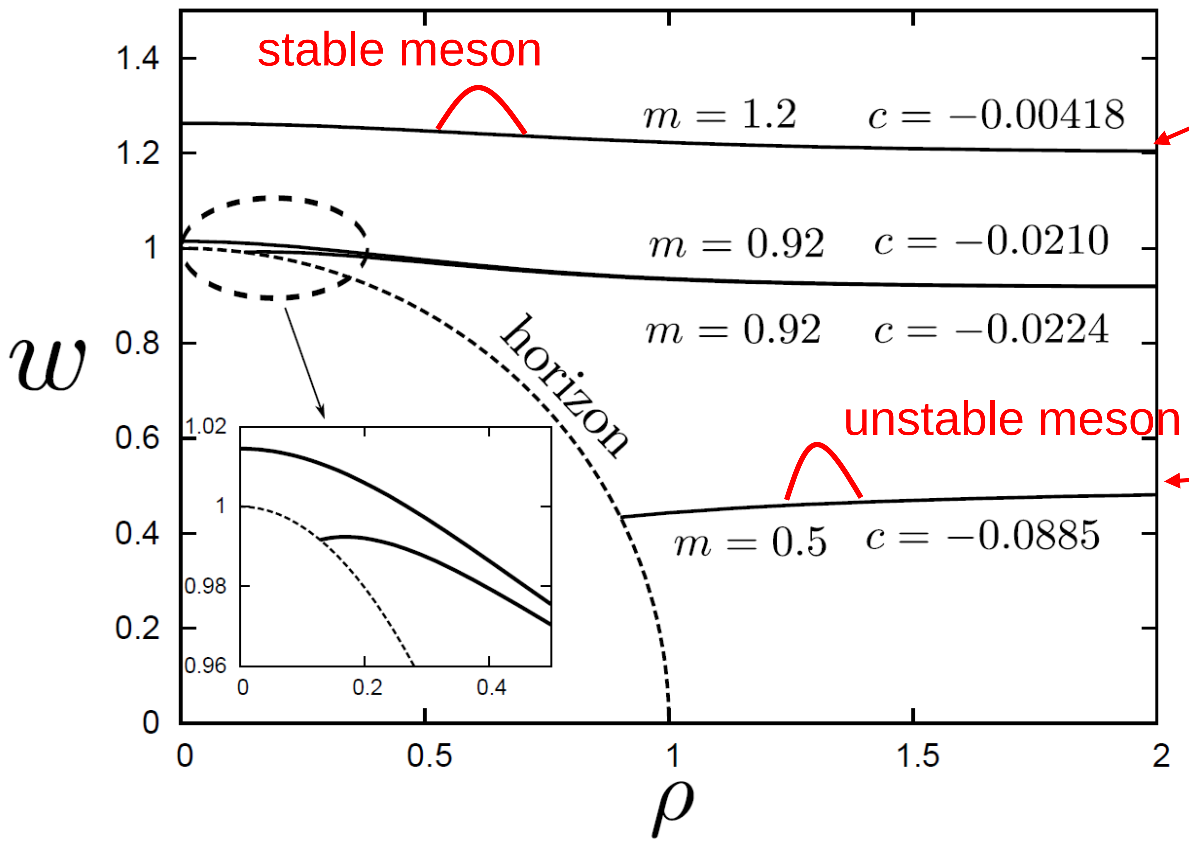


This function determines the location of the D7-brane.

Static embeddings in Sch-AdS5xS5

Babington et at, 03

$$w = \frac{1}{z}\cos\Phi(z) \qquad \rho = \frac{1}{z}\sin\Phi(z)$$



Mesons are stable.

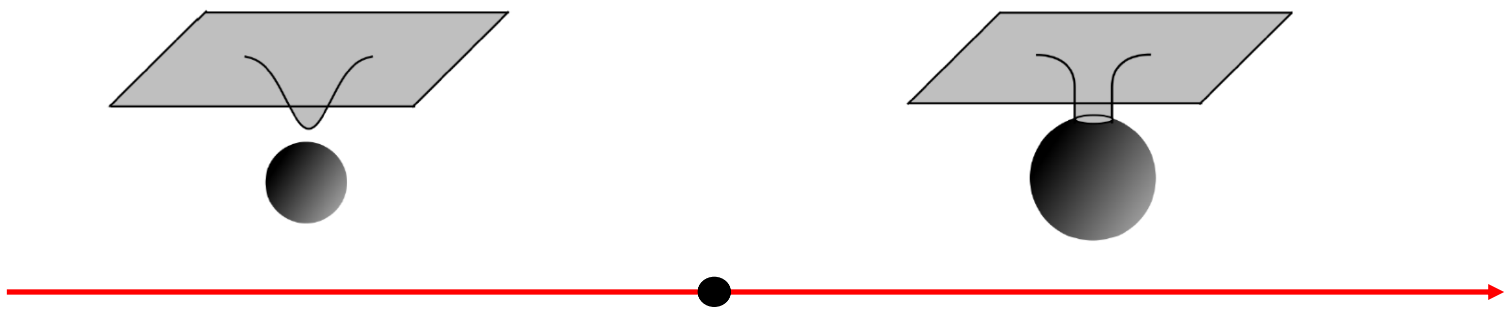
Mesons are unstable.

Quark mass

Phase diagram

The brane does not intersect with BH.

The brane intersects with BH.



Mesons are stable.

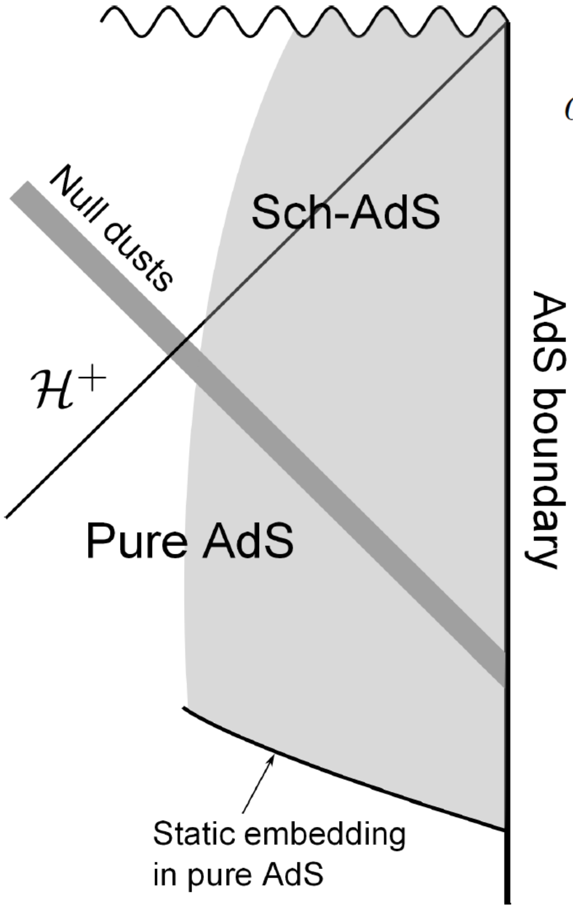
Tc

Mesons are unstable.

Tempareture (or BH size)

2.Far-from-equilibrium process in Holographic QCD

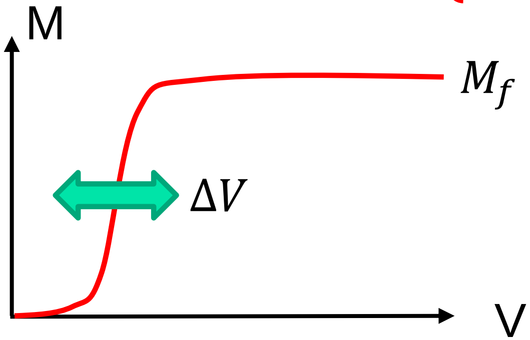
Set up



We use Vaidya-AdS spacetime as the background solution and study the dynamics of the probe D7-brane.

$$ds_{10}^2 = \frac{1}{z^2}[-F(V,z)dV^2 - 2dVdz + d\vec{x}_3^2]$$

$$+ d\phi^2 + \cos^2\phi d\Omega_3^2 + \sin^2\phi d\psi^2 \quad F(V,z) = 1 - M(V)z^4$$



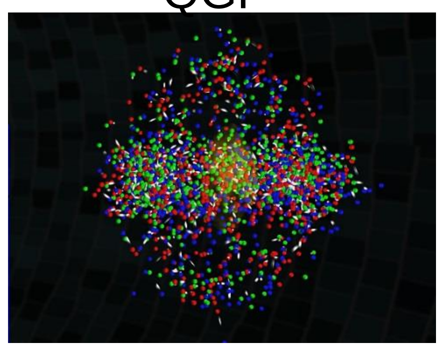
Initial data in the static embedding in pure AdS. ⇨ The spacetime becomes dynamical.

⇨ The brane start moving.

This corresponds to the simulation of the particle collision.

p → ← p

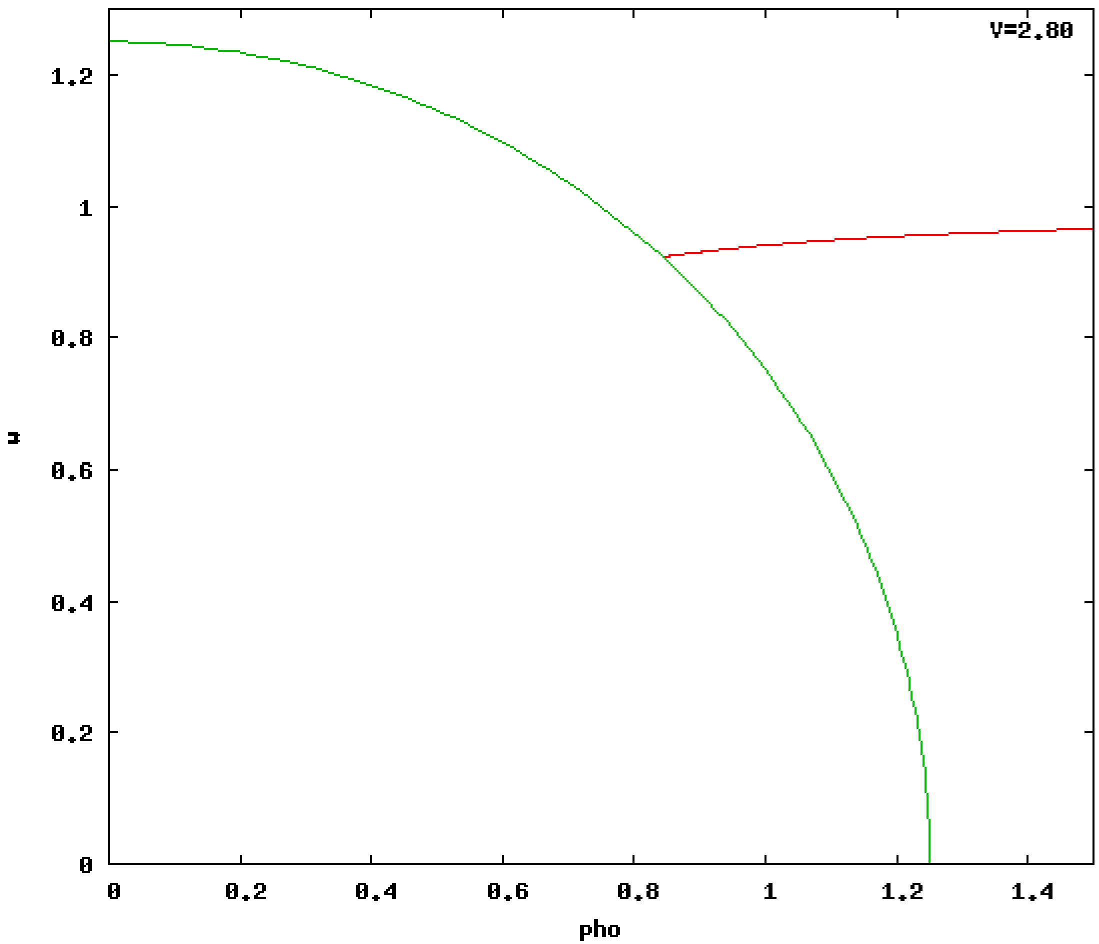
QGP

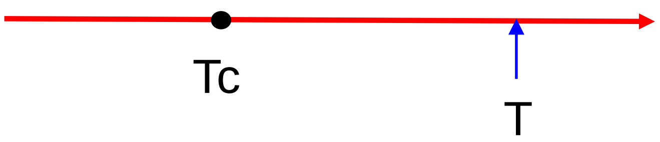


Gluon plasma becomes finite tempareture.
How do quarks behave in the time-dependent background?

3.Results

Large final temperature

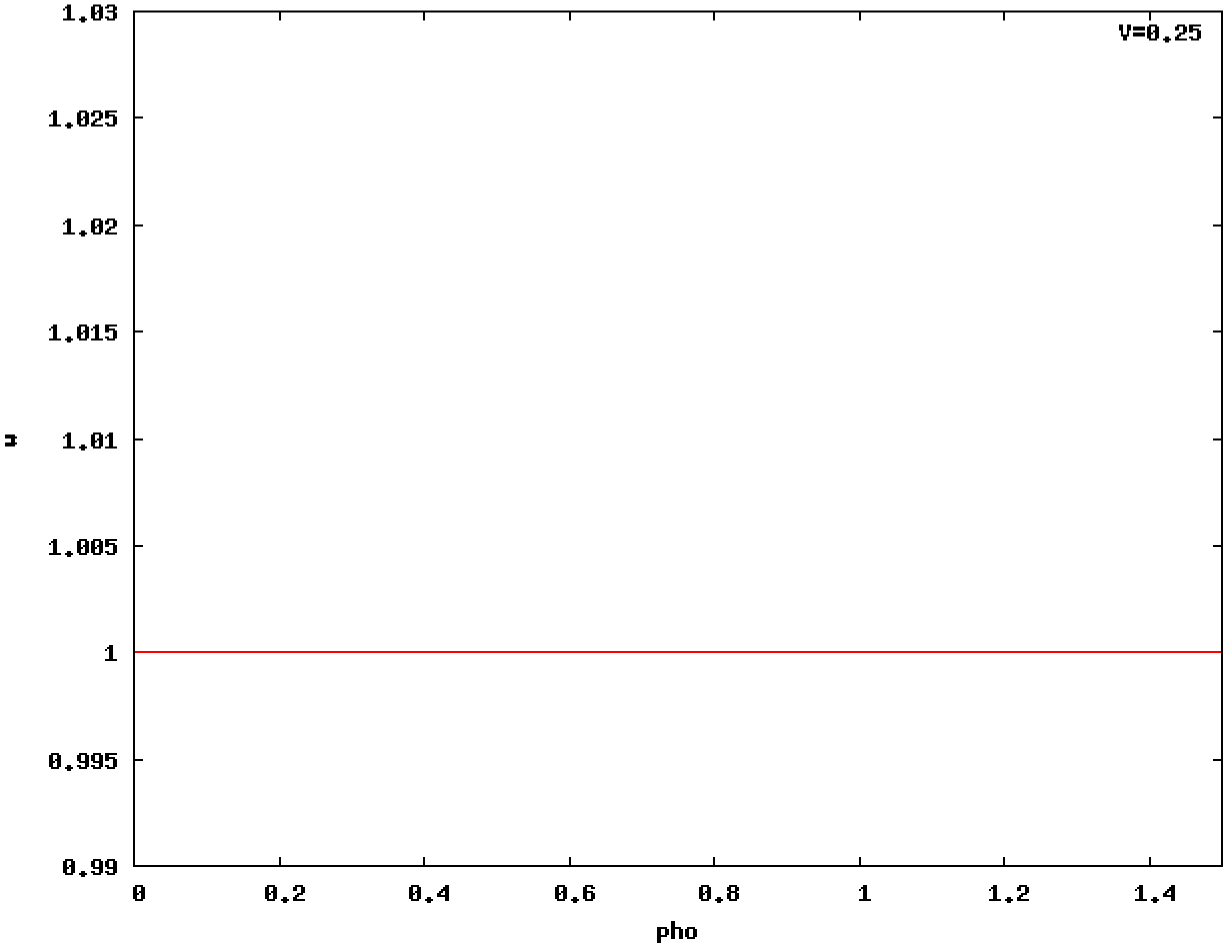


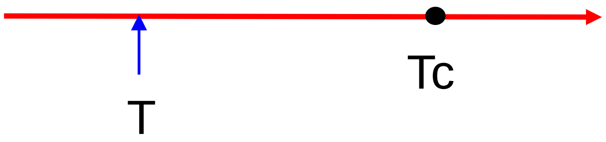


$$r_h = 1.25, \Delta V = 1.0$$

The brane intersects with the event horizon and approaches a static configuration.

Small final temperature





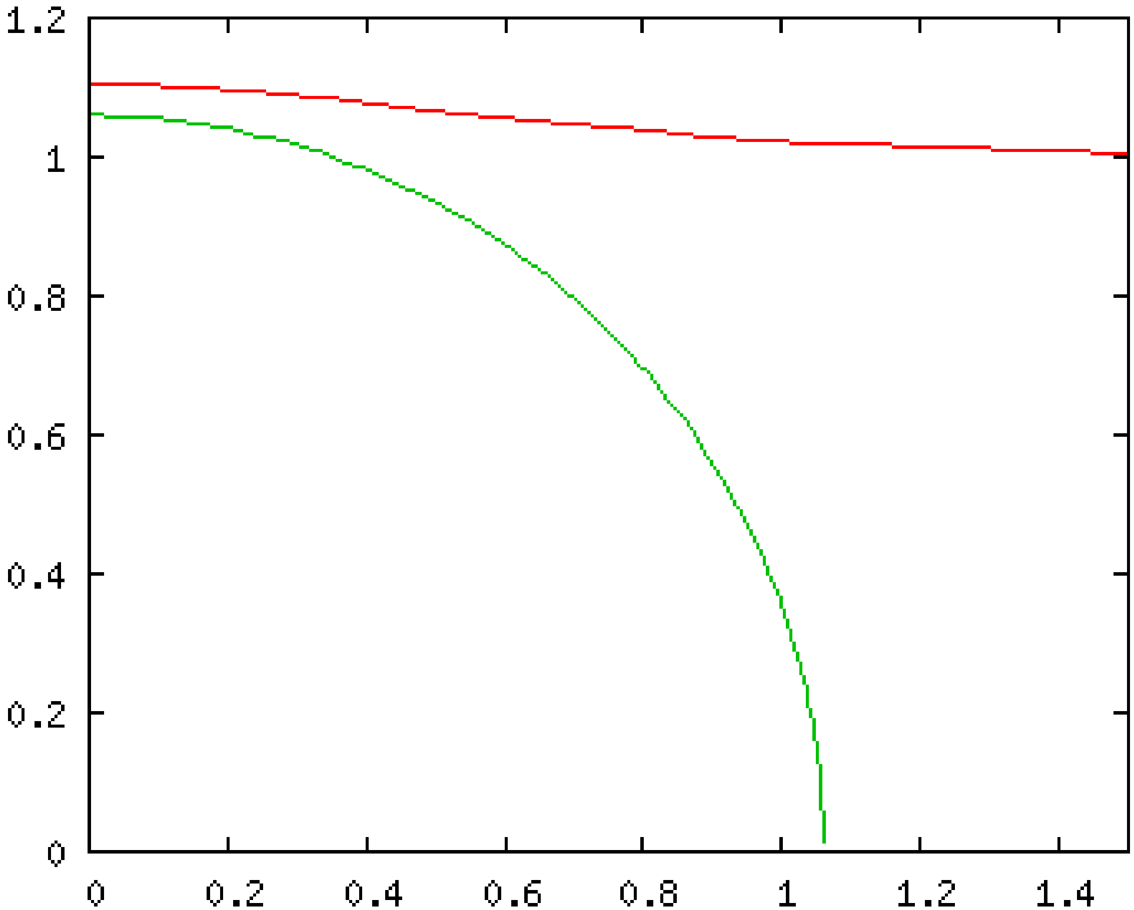
$$r_h = 0.5, \Delta V = 0.5$$

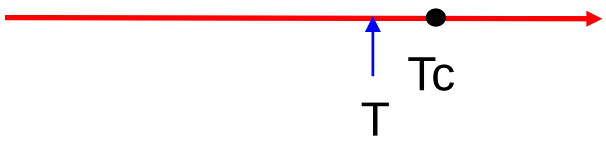
The brane oscillate forever.

Since the brane does not intersect with the BH, energy of the brane does not dissipate.

Intermediate temperature (static solution)

$r_h = 1.06$

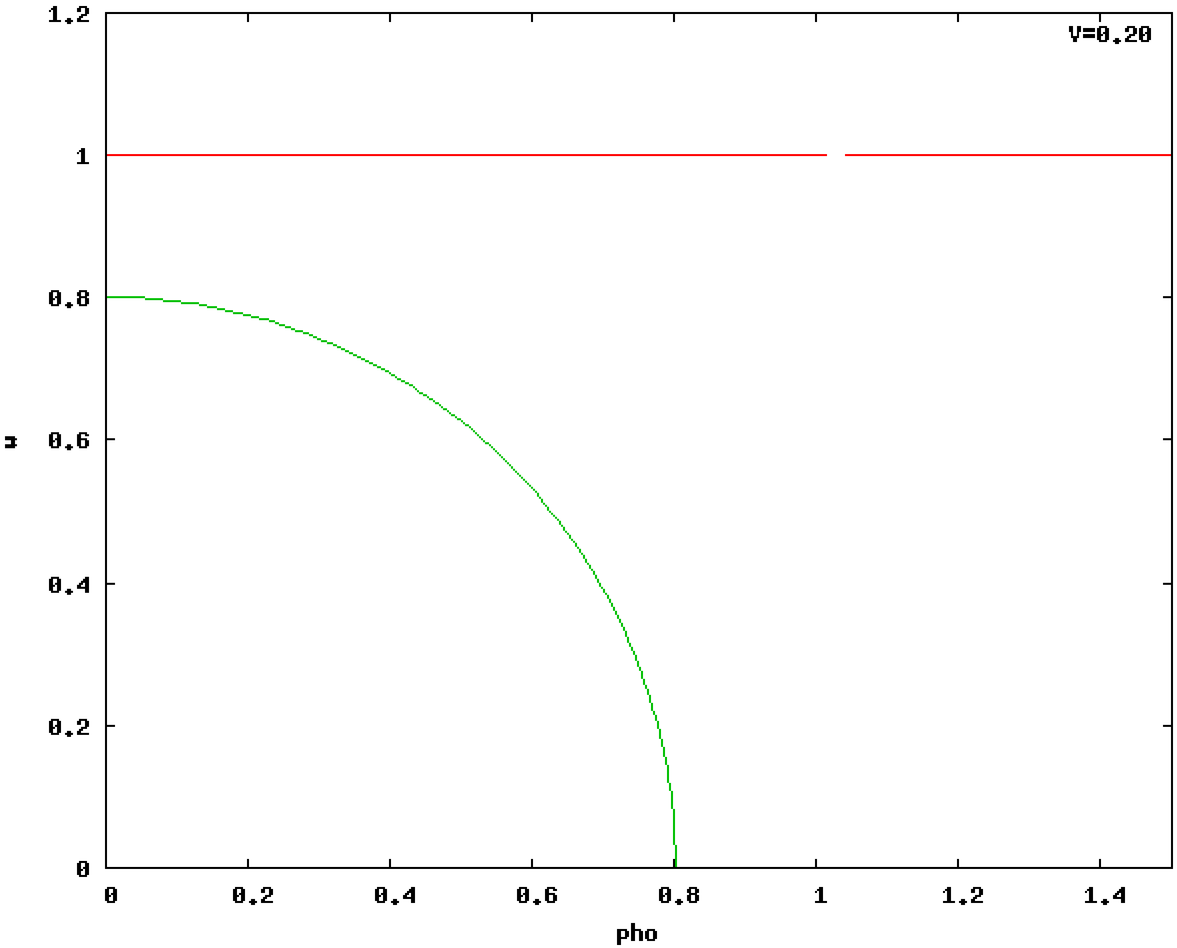


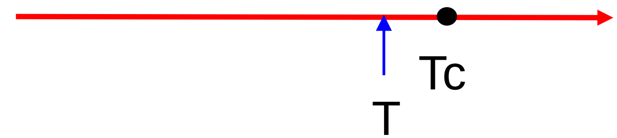


For this parameter, there is no static solution which intersect with the horizon.

Intermediate temperature (Dynamical solution)

$r_h = 1.06, \Delta V = 0.5$





However, if we consider dynamics, the brane can intersect with the horizon because of its inertia.

overeager

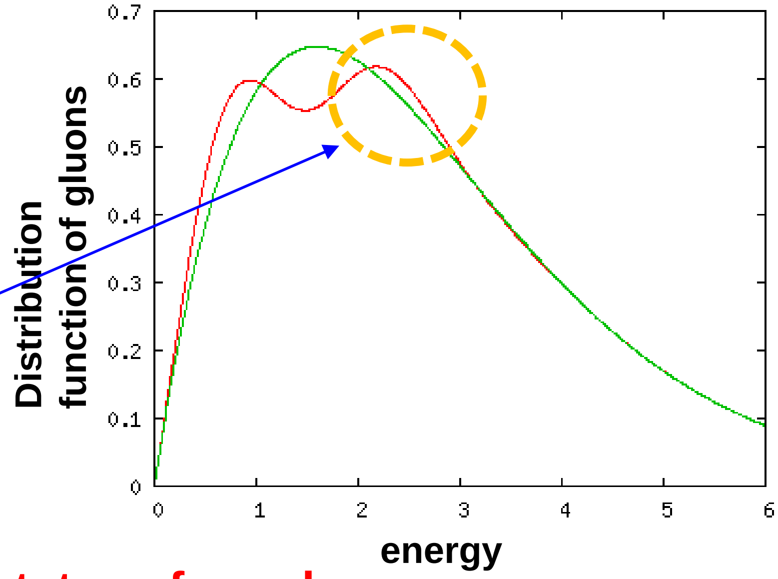
Field theory interpretation of the overeager phenomena

Even for T<Tc, mesons can be in melting phase temporally.

Why does it occur?

Just after the energy injection, the distribution function of gluons deviates from the thermal one.

There can be more high energy gluons than thermal case.



Such high energy gluons may break bound states of quarks.

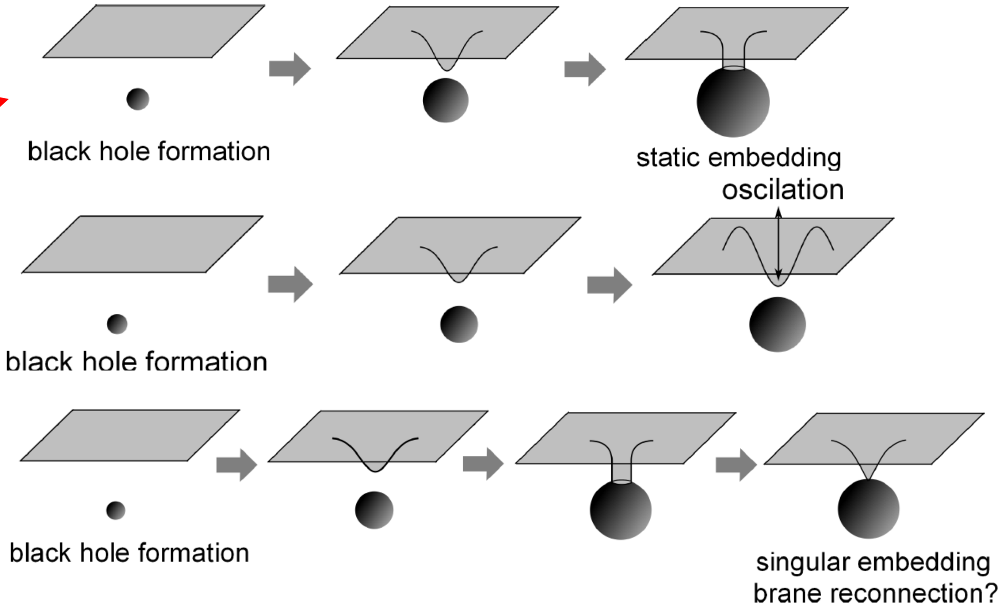
Mesons become unstable even for T<Tc.

Summary

We studied dynamics of meson melting using D3D7 model.

There are three cases depending on parameters

- intersects with BH.
- oscillates forever.
- overeager.



The overeager case is specific for non-equilibrium system.

Mesons can be in melting phase even for T<Tc.

Future works

- More realistic models (Sakai-Sugimoto or D4/D6 models)

  The overeager phenomena is probably universal for any brane-BH systems.

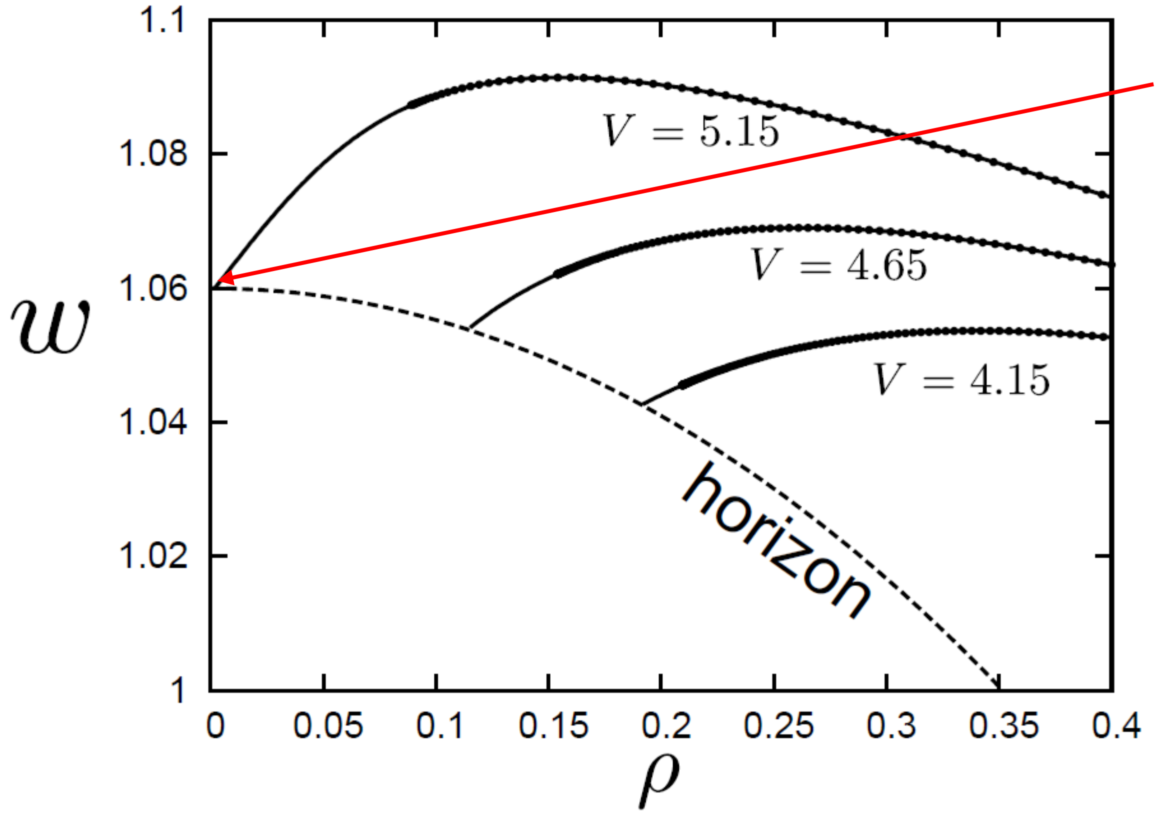
- Expanding background (Bjorken flow)

- External electric field (Vacuum instability of QCD)

Appendix

Final fate for overeager case

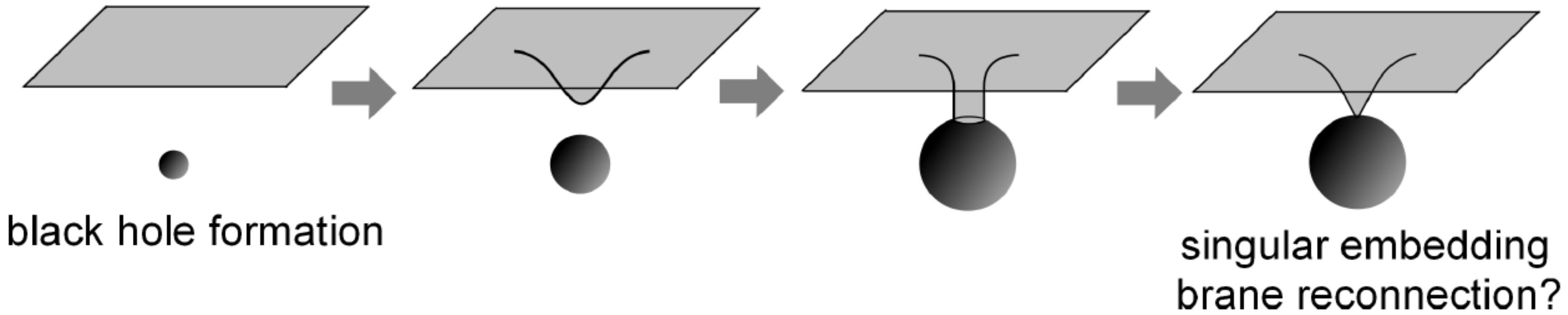
late time motion of the brane



Eventually, the brane becomes singular.

Our conjecture:
There is a brane reconnection and the brane is pinched off from the BH.

Brane reconnection



The brane may pinch off from the BH by the brane reconnection.

➡ **Brane oscillation**

Basic equations

$$\phi = \Phi(V, z) \quad \Longrightarrow \quad \begin{aligned} V &= V(u,v) \\ z &= Z(u,v) \\ \phi &= \Phi(u,v) \end{aligned}$$

(u,v) are double null coordinates on D7.

Evolution eqs

$$2\partial_u\partial_v V - 3\frac{\sin\Phi}{\cos\Phi}(\partial_u\Phi\partial_v V + \partial_u V\partial_v\Phi) - \left(F_{,Z} - 5\frac{F}{Z}\right)\partial_u V\partial_v V - 3Z\partial_u\Phi\partial_v\Phi = 0,$$

$$2\partial_u\partial_v Z - \frac{10}{Z}\partial_u Z\partial_v Z - 3\frac{\sin\Phi}{\cos\Phi}(\partial_u\Phi\partial_v Z + \partial_u Z\partial_v\Phi) + \left(F_{,V} + FF_{,Z} - 5\frac{F^2}{Z}\right)\partial_u V\partial_v V$$
$$+ \left(F_{,Z} - \frac{5F}{Z}\right)(\partial_u V\partial_v Z + \partial_u Z\partial_v V) + 3ZF\partial_u\Phi\partial_v\Phi = 0,$$

$$2\partial_u\partial_v\Phi - \frac{3}{Z}(\partial_u Z\partial_v\Phi + \partial_u\Phi\partial_v Z) - 3\frac{\sin\Phi}{\cos\Phi}\partial_u\Phi\partial_v\Phi - \frac{\sin\Phi}{\cos\Phi}\frac{3}{Z^2}$$
$$\times (F\partial_u V\partial_v V + \partial_u V\partial_v Z + \partial_u Z\partial_v V) = 0,$$

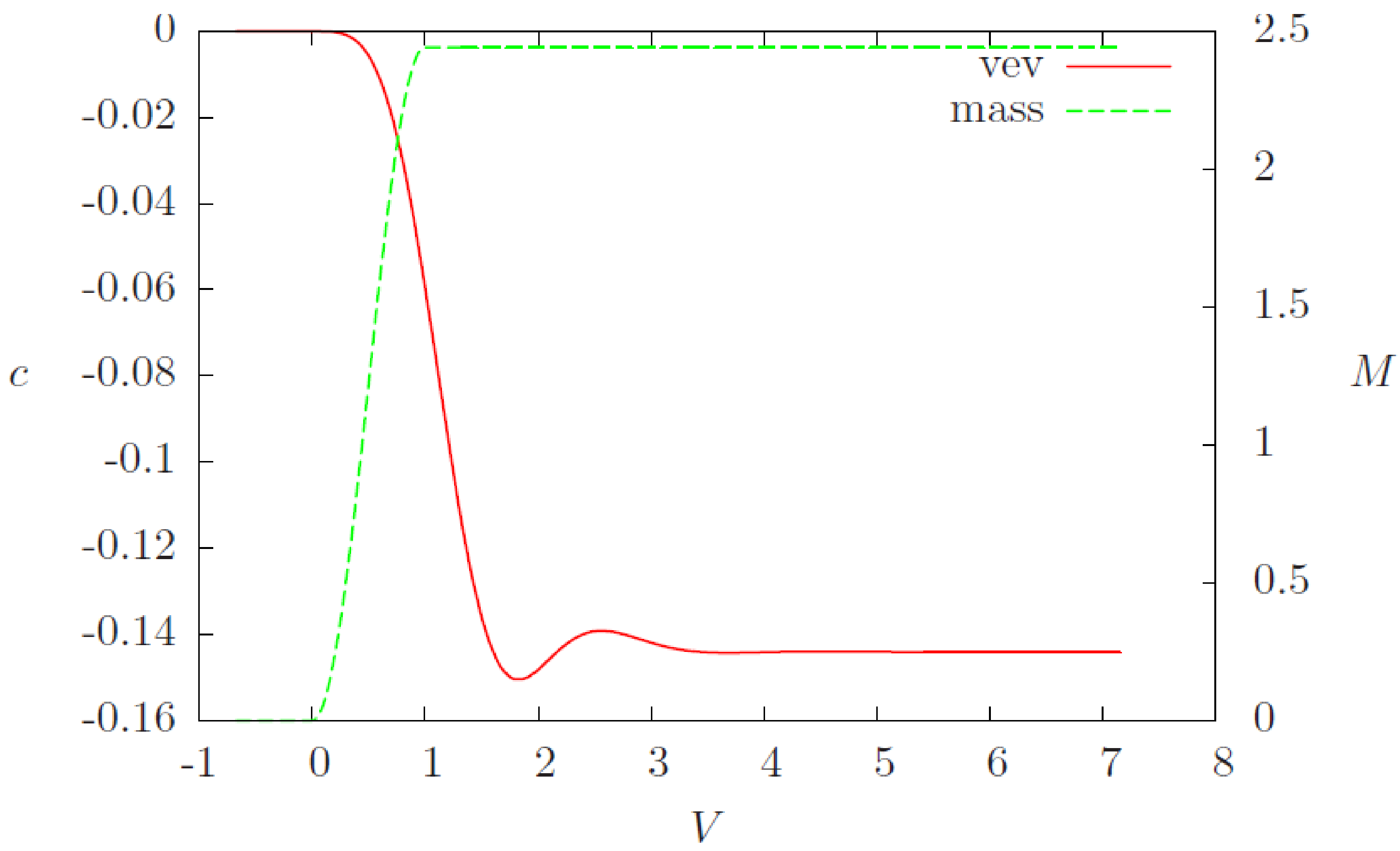
We solved these PDEs numerically.

Constraints

$$C_1 \equiv -F(\partial_u V)^2 - 2\partial_u V\partial_u Z + Z^2(\partial_u\Phi)^2 = 0,$$

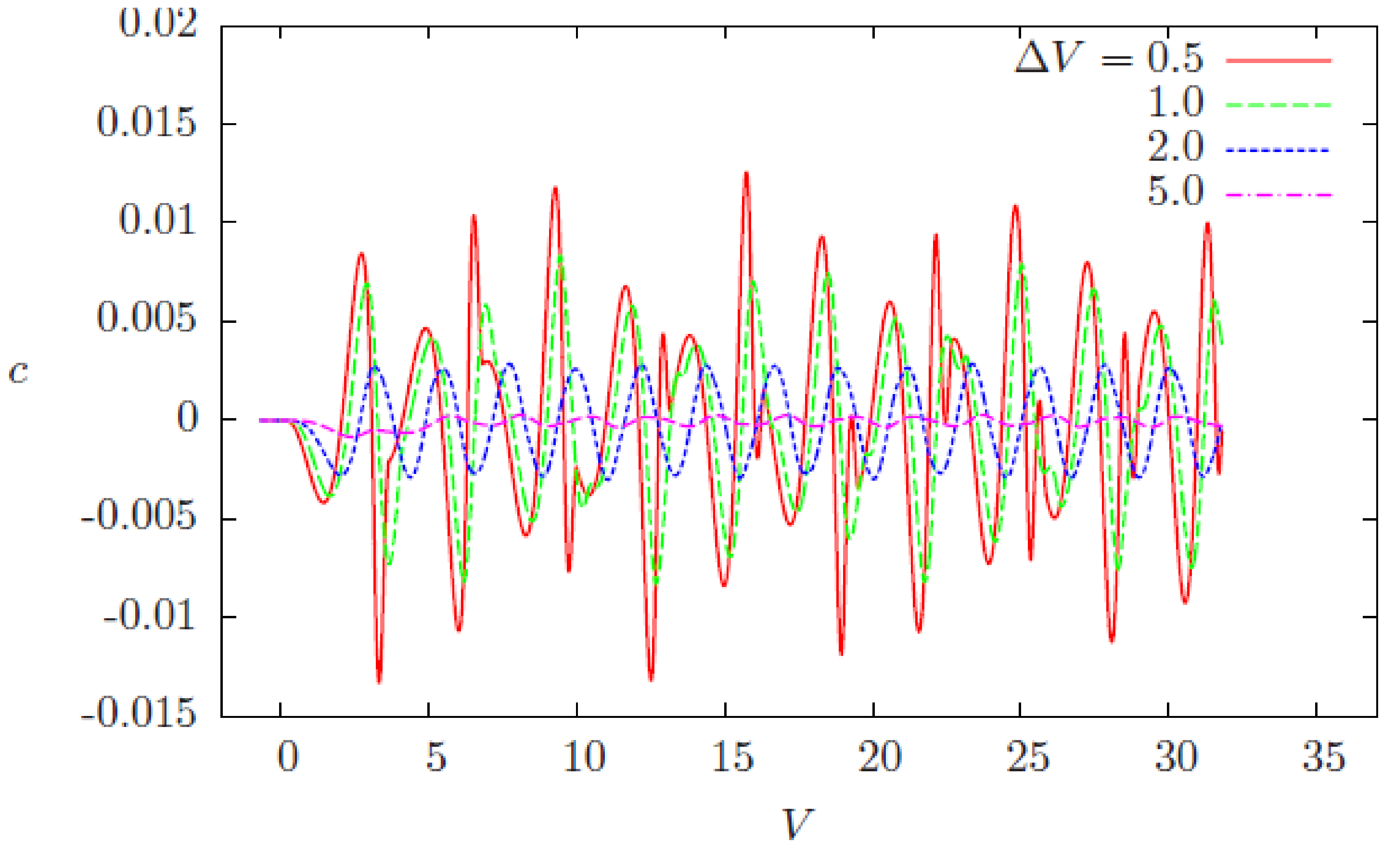
$$C_2 \equiv -F(\partial_v V)^2 - 2\partial_v V\partial_v Z + Z^2(\partial_v\Phi)^2 = 0.$$

T>Tc



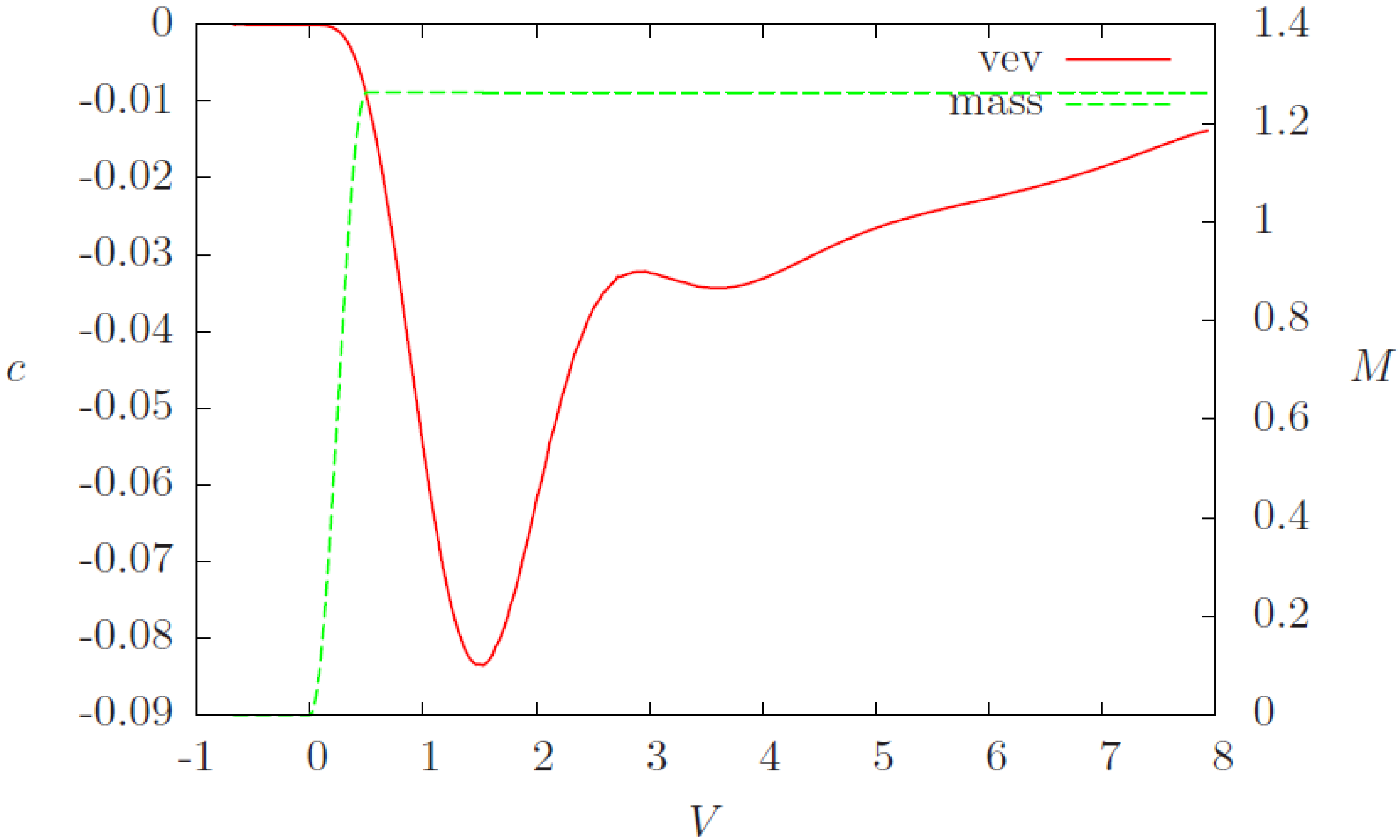
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
c
2.5
2
1.5
1
0.5
0
M
-1
0
1
2
3
4
5
6
7
8
V
vev
mass

T<<Tc



$\Delta V = 0.5$
1.0
2.0
5.0
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
c
0
5
10
15
20
25
30
35
V

T<Tc, T~Tc



vev
mass
c
M
V
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
0
1
2
3
4
5
6
7
8