Dynamical Meson Melting in Holography

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Based on **arXiv:1401.5106**

Dynamical Meson Melting in Holography

- Meson in quark-gluon plasma
- Heat up mesons → Dissociates (melts) into quark pairs

- Holographically realized by D3/D7 system:

  Meson excitations = Dynamics of probe brane in $\mathrm{AdS}_5 \times \mathrm{S}^5$

  – Gauge theory: Meson melting phase transition

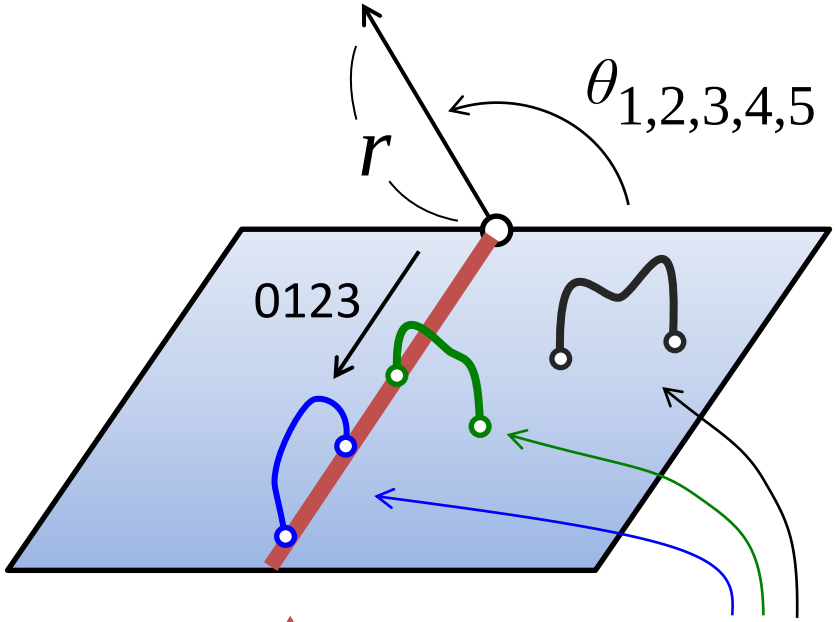
  – Bulk Gravity : Phase transition in brane configurations

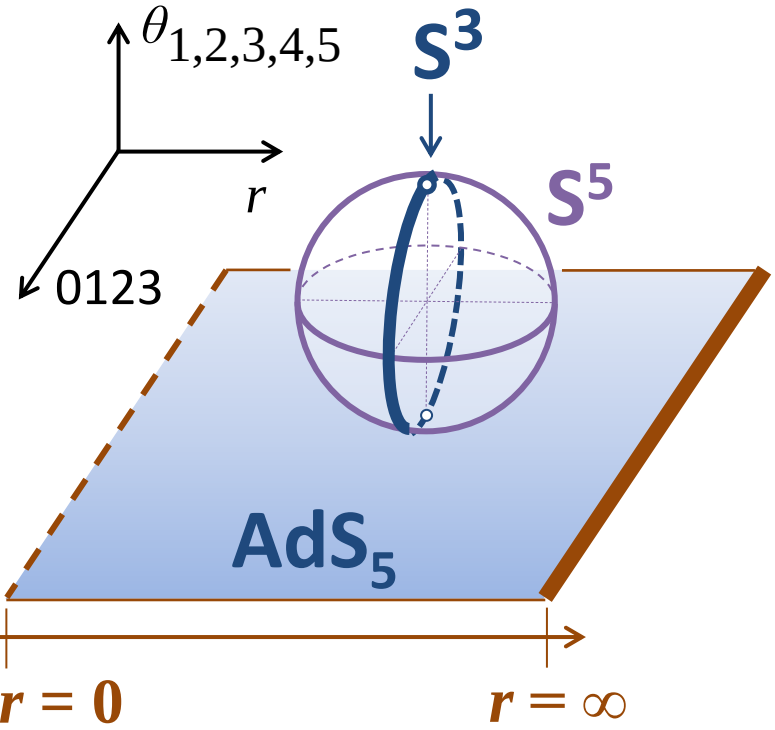
- Heat up mesons dynamically using bulk gravity

  → New transient phase due to nonlinear dynamics?

- D3/D7 system $\Leftrightarrow$ $\mathcal{N}=2$ SQCD [Karch & Katz 2002, . . .]

	0	1	2	3	r	θ_1	θ_2	θ_3	θ_4	θ_5
N_c D3 branes	X	X	X	X						
N_f D7 branes	X	X	X	X	X	X	X	X		



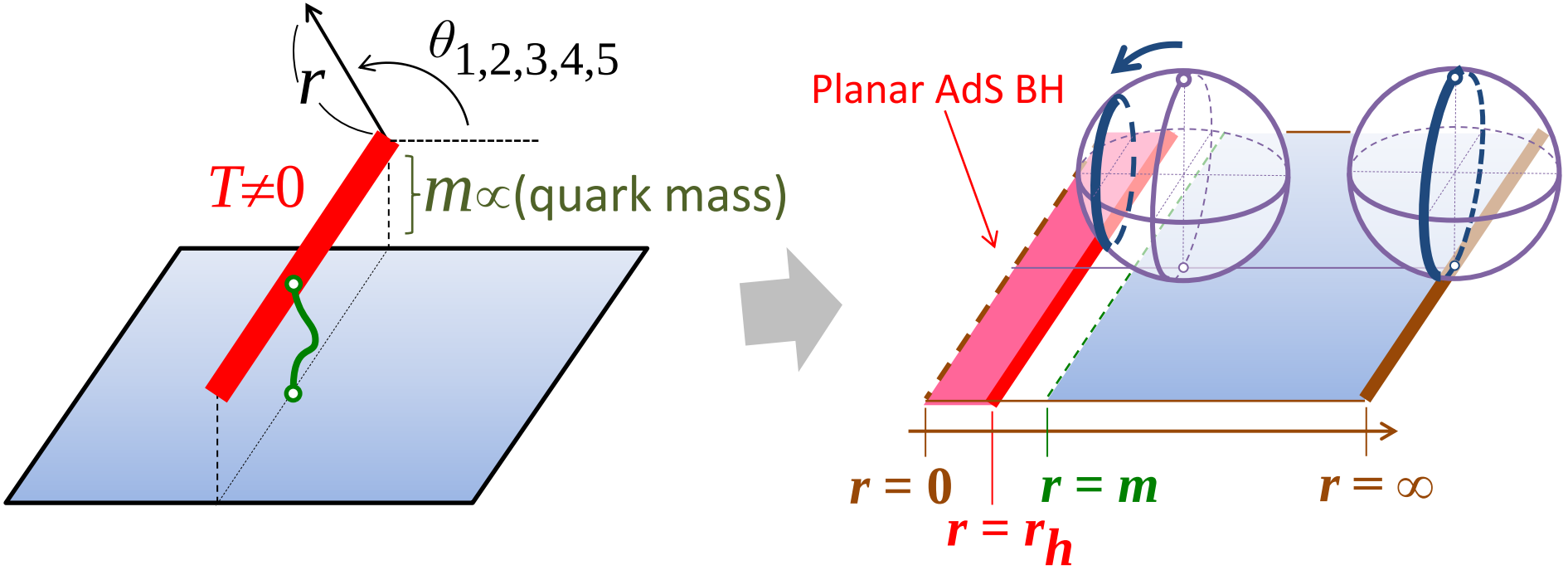


N_c D3 branes

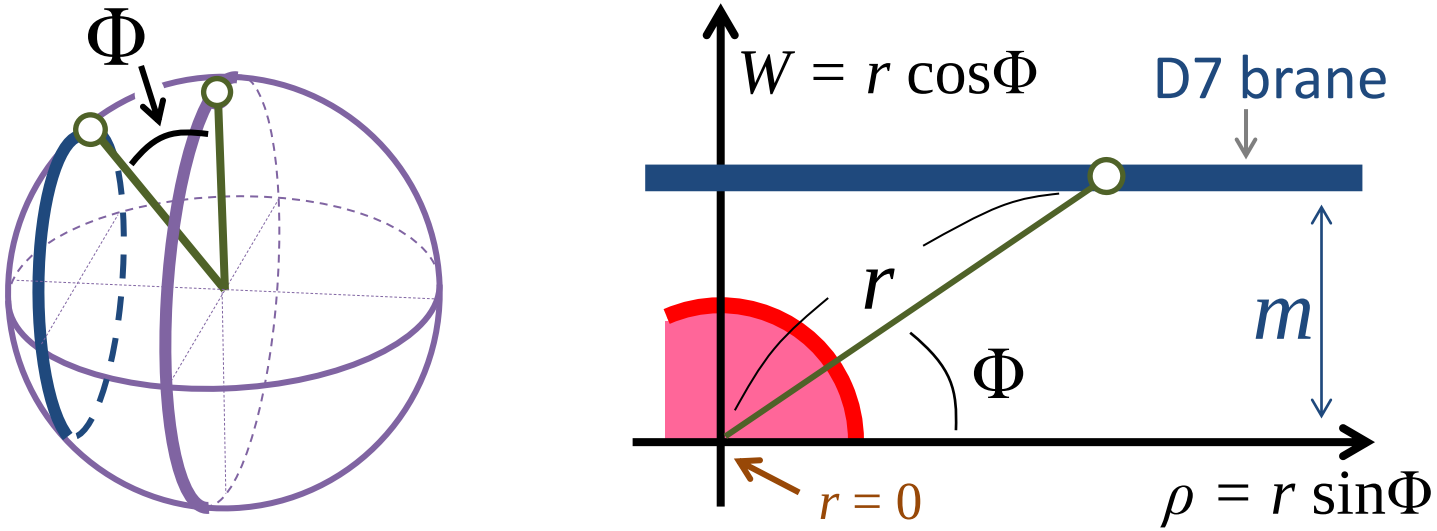
N_f ($<< N_c$) D7 branes

3-3 string: "gluon"
3-7 string: "quark"
7-7 string: "meson"

- Introduce quark mass m and finite temperature T



- Radial coordinates (r, Φ) for D7 brane position



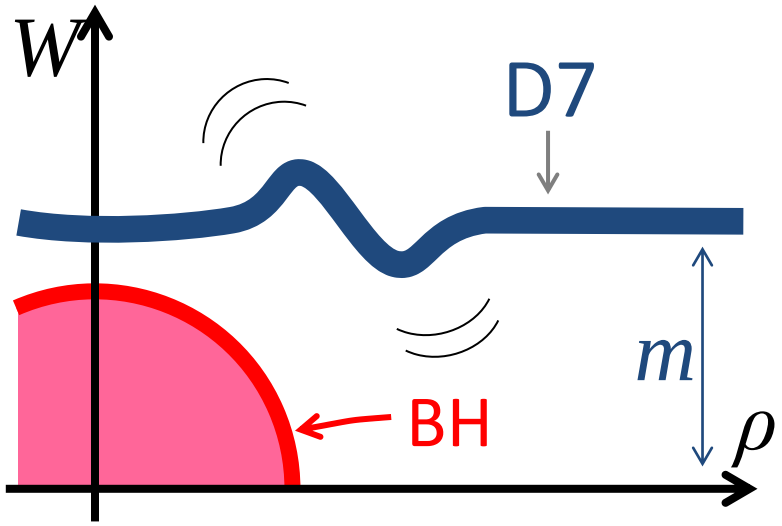
- High/low temperature phases:

Mateos, Myers & Thomson 2006
Hoyos, Landsteiner & Montero 2007
. . .

Subcritical phase for $T < T_{crit} \propto m$

– D7 *away* BH (*Minkowski* embedding)
– Normal mode oscillation

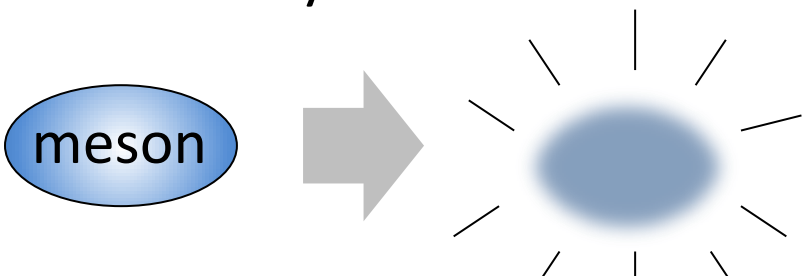
➔ Stable meson excitation

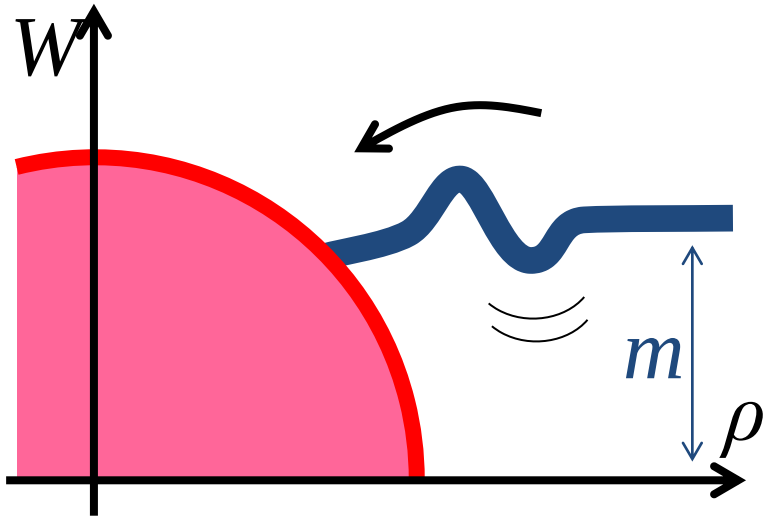


Supercritical phase for $T > T_{crit}$:

– D7 *touching* BH (*Black hole* embedding)
– Brane oscillation = Quasi-normal modes

➔ Meson decays and melts





Setup & Formulation

- *Static + perturbations* have been mainly studied

➔ Inject energy to change temperature dynamically.

QFT side

Heat up the “QCD plasma”, and see what happens.

Gravity side

Background: AdS-Vaidya metric with BH formation

Solve the probe DBI brane motion

induced by BH formation in the bulk.

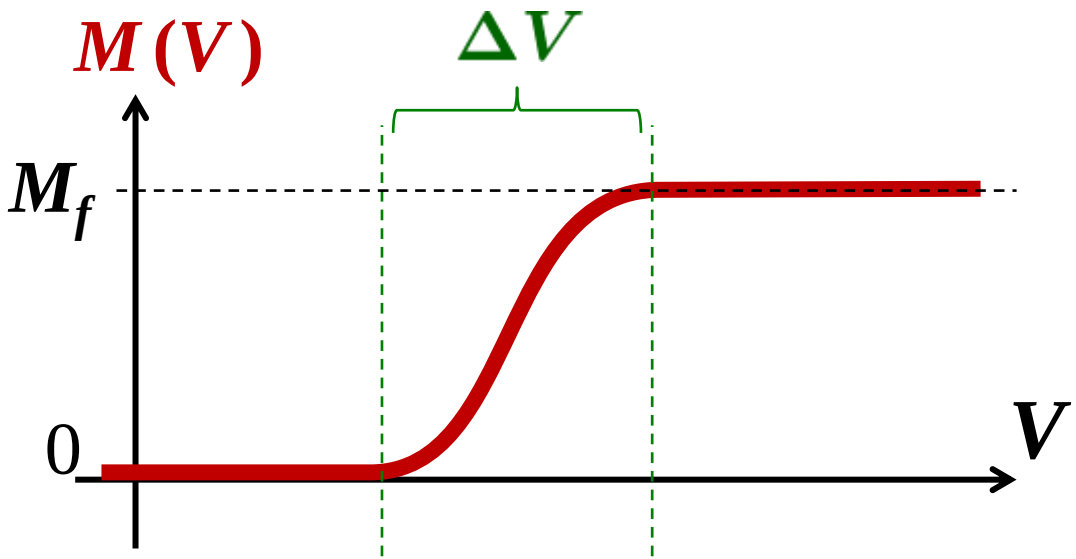
➢ Background spacetime = AdS-Vaidya spacetime

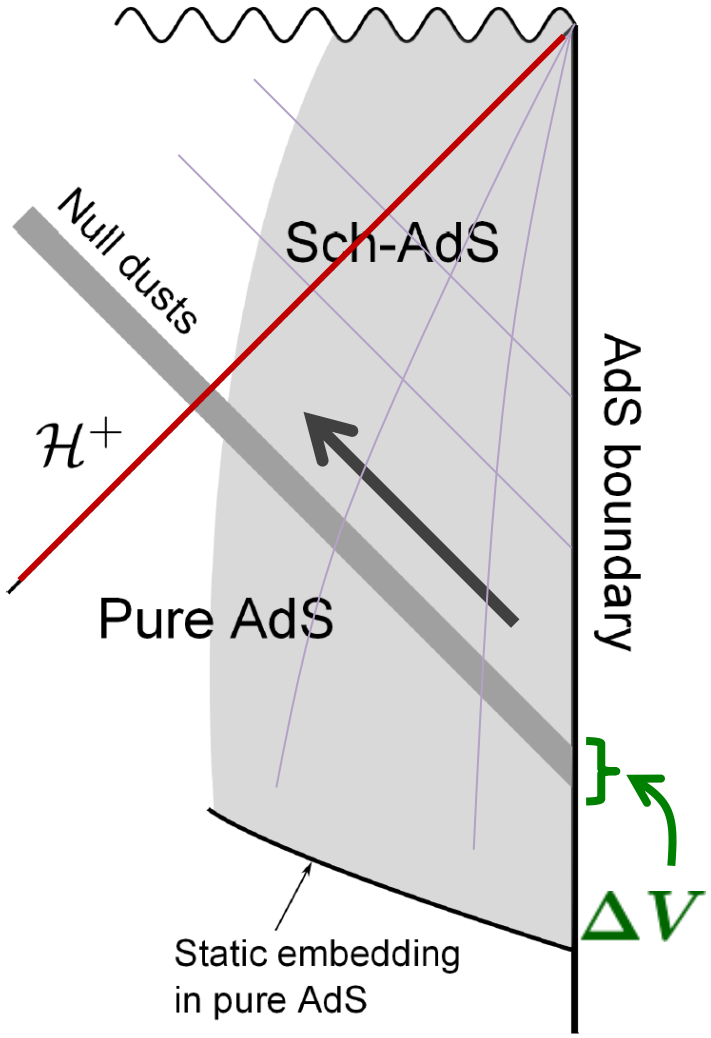
with BH formation due to energy injection from AdS boundary

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

$$+ d\phi^2 + \cos^2\phi\, d\Omega_3^2 + \sin^2\phi\, d\psi^2$$

$$\left[F(V,z) = 1 - M(V)z^4\right]$$





➢ Probe D7 brane and EoM

DBI action: Low-energy effective action of D-brane

$$S_{\mathrm{DBI}} \propto \int d^8\sigma \sqrt{-h}$$

Brane position: Functions of world-sheet coords. σ^a

$$X^\mu = (V, z, \phi, \psi)\Big|_{\mathrm{Brane}} = \Big(V(\sigma^a), Z(\sigma^a), \Phi(\sigma^a), 0\Big)$$

Induced metric on the brane:

$$h_{ab}d\sigma^a d\sigma^b = \frac{1}{Z^2}\left[-F(V,Z)dV^2 - 2dV\,dZ + d\vec{x}_3^2\right] + \cos^2\Phi\, d\Omega_3^2$$

Equations of motion for brane position X^μ:

$$D^2X^\mu + \Gamma^\mu_{\rho\sigma} D_a X^\rho D^a X^\sigma = 0$$

D^a : Cov. derivative of h^{ab}

$\Gamma^\mu{}_{\rho\sigma}$: Christoffel of $g^{\mu\nu}$

➢ Numerical procedure:

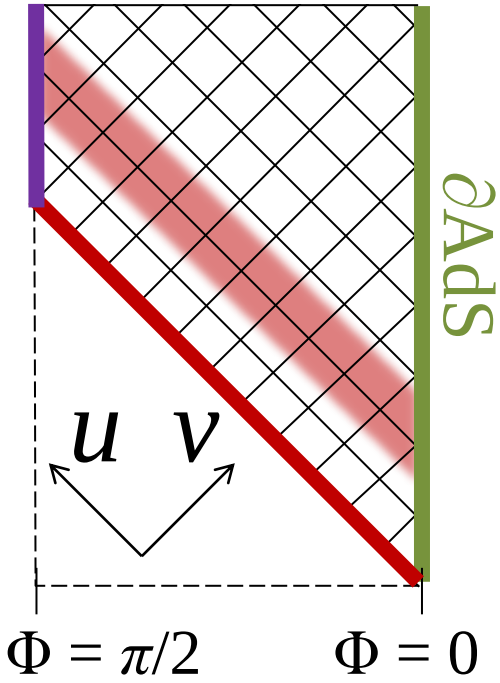
- Take null coordinates $(\sigma^a) = (u, v)$ on brane, and use double null formalism to solve EoM
- Boundary conditions:
  - Axis: regularity condition

$$V = V_{\text{Axis}} + a\left(u - v - \frac{\pi}{2}\right)^2 , \quad \cdots$$

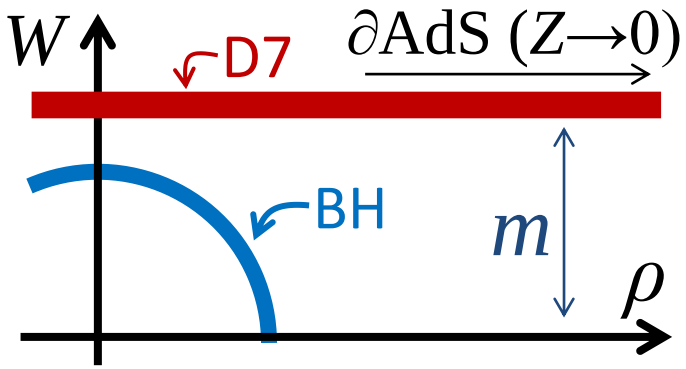
  - AdS boundary: quark mass=m

$$Z = 0 , \quad \dot{V}(v) = 2Z_{,u} , \quad W = m$$

- Initial data: Static brane in vacuum



- Focus on "quark condensate" $c(V)$ in boundary QFT



✓Brane configuration near AdS boundary:

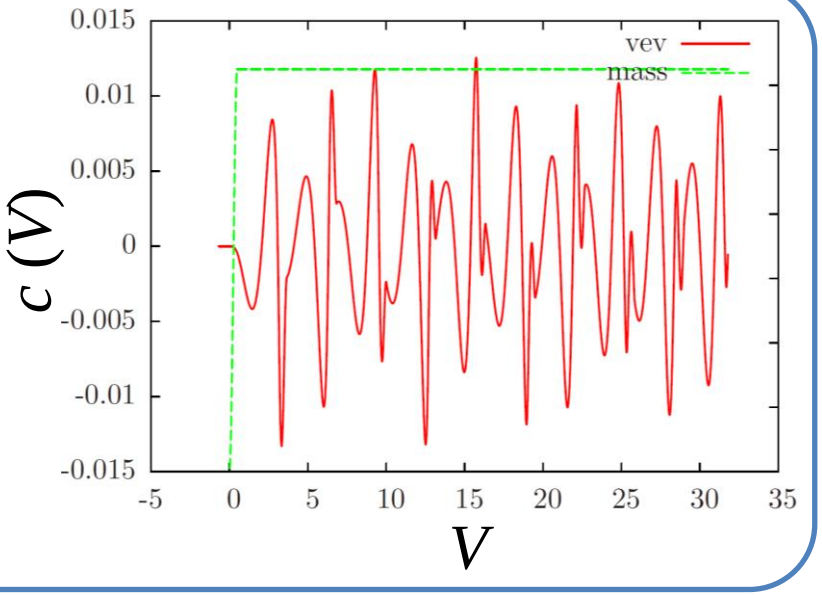
$$W = m + c(V)Z^2 + \cdots$$

→ Read out "quark condensate" $c(V)$ by

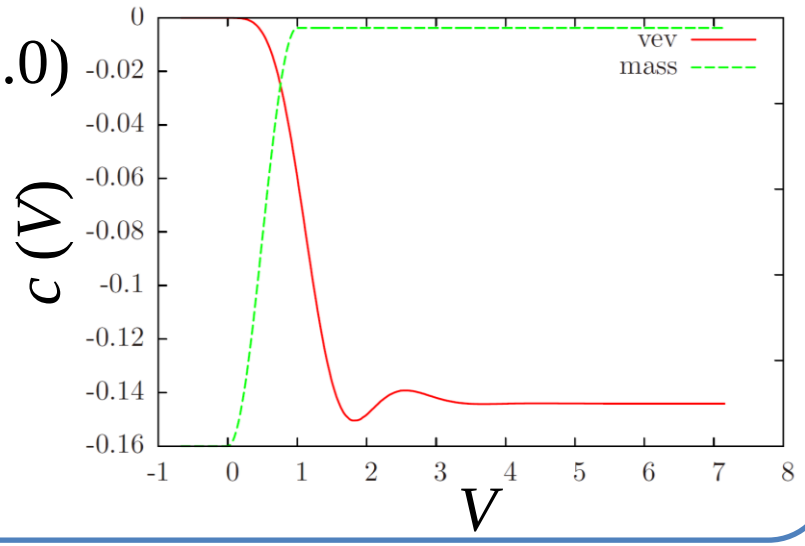
$$\text{“}\langle\bar{q}q\rangle\text{”} = -\frac{N_f}{16\pi^4 g_s l_s^6}\, c(V)$$

Numerical Results and interpretations

- Sub-critical case ($r_h = 0.5, \Delta V = 0.5$)
  - Results in Minkowski embedding with oscillations
  - $c(V)$ oscillates without decaying



- Super-critical case ($r_h = 1.25, \Delta V = 1.0$)
  - Brane falls into BH
    - → Results in BH embedding
  - $c(V)$ shows decaying oscillations



➢ ***Marginally sub-critical*** case ($r_h = 1.06$, $T_f < T_{crit}$)

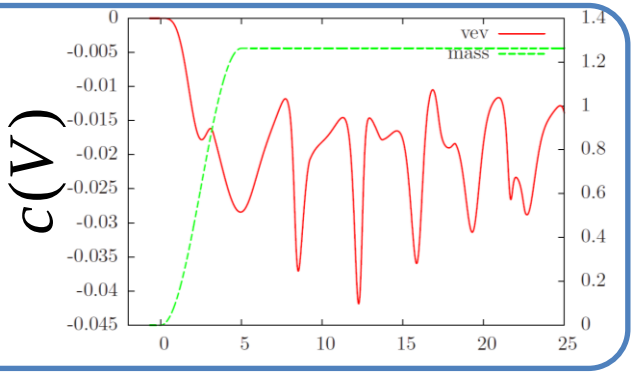
Only Minkowski embedding is realized as a static solution in this case.

→Final equilibrium state should be Minkowski embedding.

Results depend on time scale ΔV in this case:

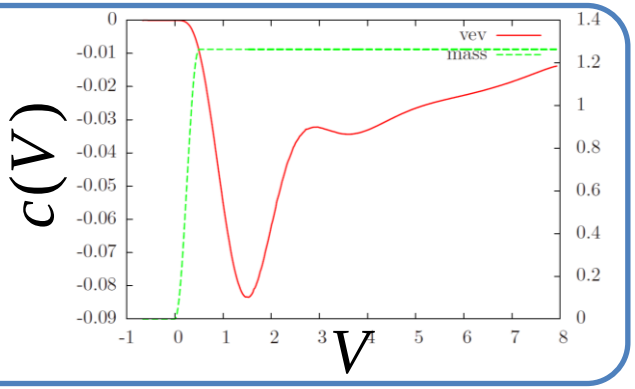
✓ ***Slow*** energy injection ($\Delta V = 5.0$)

- Results in Minkowski embedding
- $c(V)$ oscillates without decaying



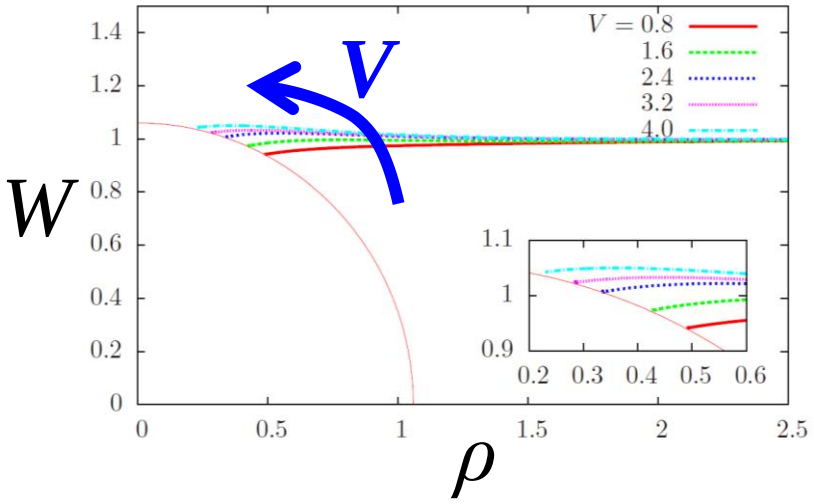
✓ ***Fast*** energy injection ($\Delta V = 0.5$)

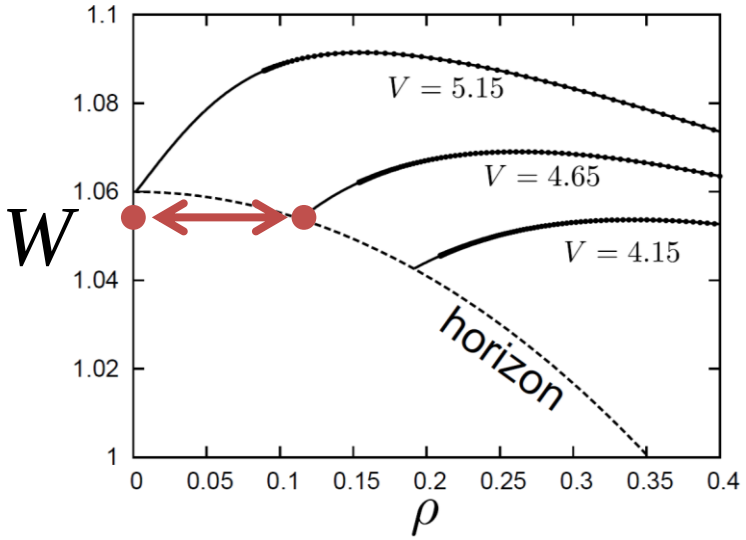
- $c(V)$ oscillates around time-evolving mean value
- Different from both Minkowski and BH embedding cases?



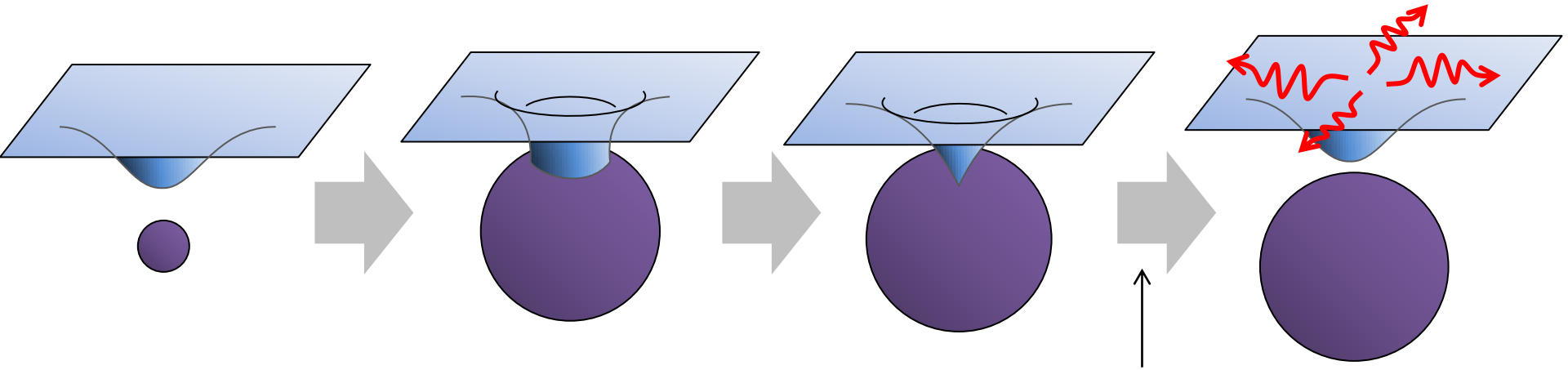
➢ What is the final state for Marginally sub-critical case ?

✓ Brane keeps moving to escape from BH region



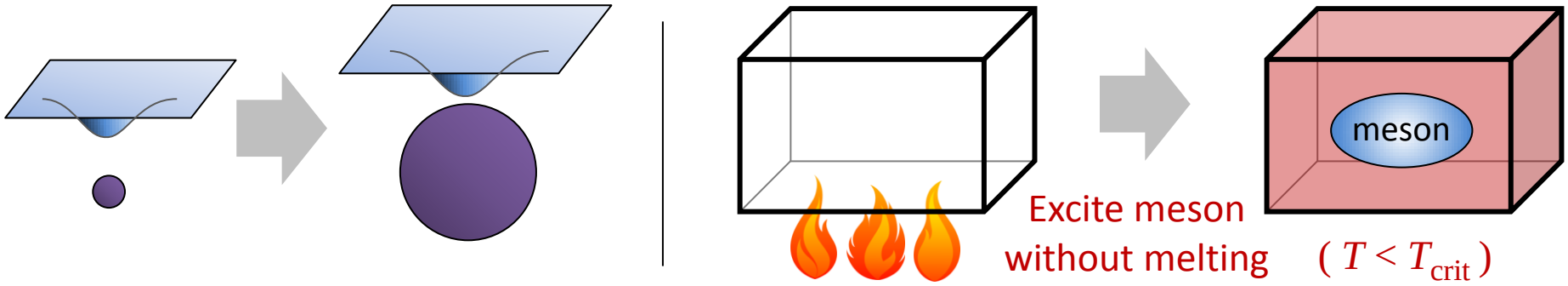


✓ Brane intersection with BH shrinks to zero size within finite time

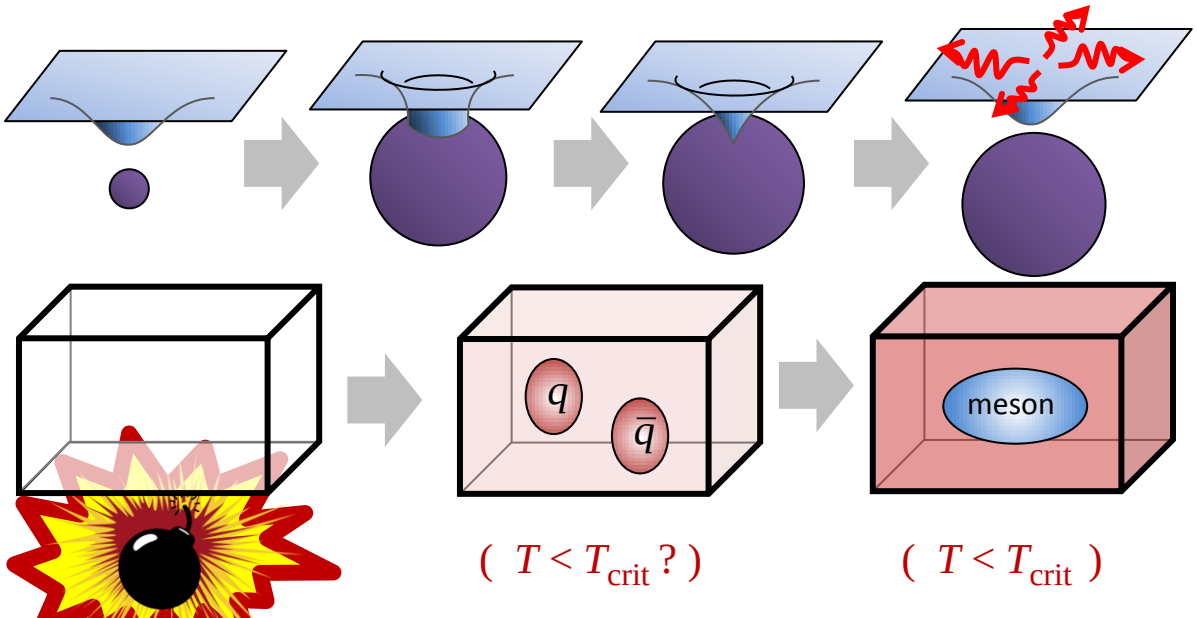


➢ Boundary QFT interpretation?

- ***Slow*** energy injection: Meson excitation without melting



- ***Fast*** energy injection:
  Meson melts temporarily due to non-thermal effects
  → Recombines into meson (corresponding to brane reconnection)?



Summary

- Dynamical Meson Melting in Holography
  - Marginally sub-critical case shows interesting phases:
    - ***Slow*** energy injection: Meson excitation without melting
    - ***Fast*** energy injection: Meson melts though $T_{\rm f} < T_{\rm crit}$

→ Brane reconnection?

Highly excited state of mesons by off-equilibrium effects?

- Future directions:
  - Generalizations to include E & $B \neq 0$ and inhomogeneity
  - Application to other brane systems to realize more realistic setup
  - Numerical technique to solve nonlinear dynamics of probe brane in AdS bulk was developed in this study → Any applications?