JAGIELLONIAN UNIVERSITY
IN KRAKÓW

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Quarkonium dissociation in an anisotropic strongly coupled plasma

based on
JHEP **1507** (2015) 053
Phys.Rev. D **94** (2016) 025005
Phys.Rev. D **96** (2017) 034031

in collaboration with
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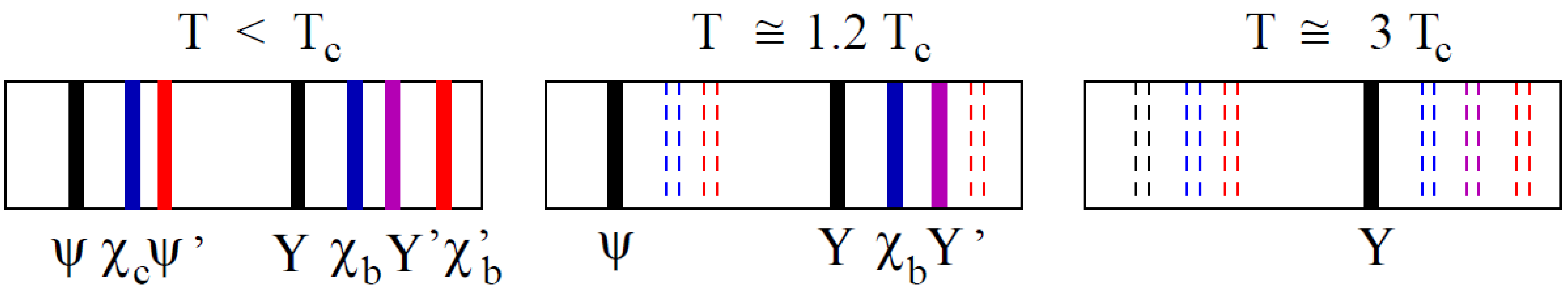
SECONDO INCONTRO SULLA FISICA CON IONI PESANTI A LHC
Torino, 10 Ottobre 2017

Real-time $Q\overline{Q}$ dissociation in QGP

- The binding of a $Q\overline{Q}$ pair in QGP is subject to color screening effects
- The Debye screening length scale $\lambda_D(T)$ decreases with T
- $Q\overline{Q}$ state i with average interquark distance $r_{Q\overline{Q},i}$ ⟶

⟶ dissociation temperature T_i defined through $\lambda_D(T_i) = r_{Q\overline{Q},i}$



$Q\overline{Q}$ spectral lines as a thermometer of QGP (from H. Satz, *Nucl. Phys. A* 2007)

OUR FOCUS

real-time $Q\overline{Q}$ dissociation in a far-from-equilibrium non-Abelian plasma

Summary

- Time evolution and relaxation of a strongly-coupled non-Abelian plasma, from a far-from-equilibrium anisotropic state
- Real-time $Q\overline{Q}$ dissociation in this kind of medium

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- Real-time $Q\overline{Q}$ dissociation in this kind of medium

⬇

Evolution of strongly coupled systems:

Non perturbative computational methods are required

Summary

- Outline of AdS/QCD $\longrightarrow$ applicable to time-dependent problems
- Time evolution and relaxation of a strongly-coupled non-Abelian plasma, from a far-from-equilibrium anisotropic state
- Real-time $Q\overline{Q}$ dissociation in this kind of medium

$\Downarrow$

Evolution of strongly coupled systems:

Non perturbative computational methods are required

The AdS/CFT correspondence

Strongly-coupled

Conformal **F**ield **T**heory

on the Minkowski space

$\mathcal{M}_4$

A conformal compactification gives

the *Boundary* of

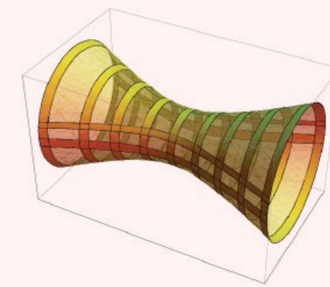
duality

Wealky-coupled gravitational string theory on

$AdS_5 \times S^5$

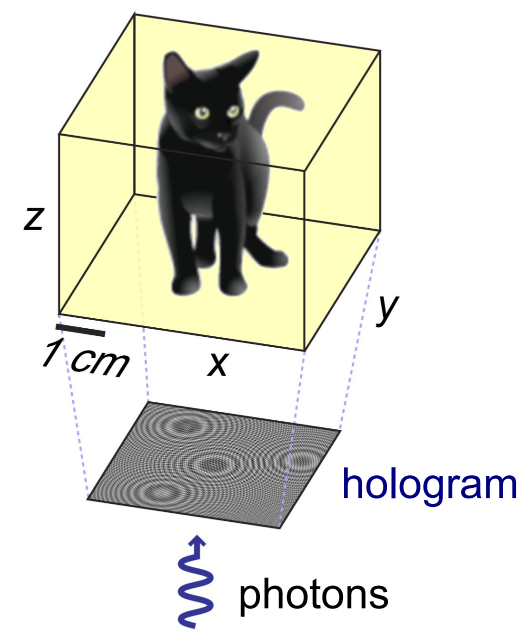
Anti-**de** **S**itter hyperboloid

solution of Einstein eqs. in vacuum with negative cosmological constant



Bulk

- Holographic principle ('t Hooft, Susskind): states in a spacetime region can equally well be represented by bits of information contained in its surface boundary
- Analogy with holograms produced via optical techniques

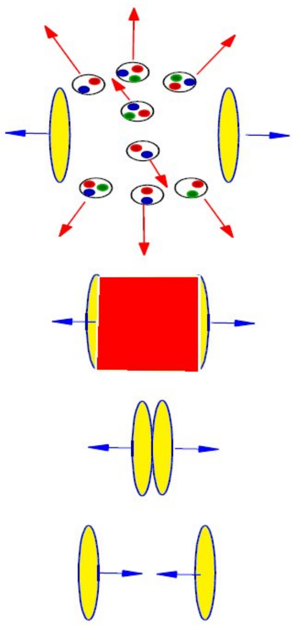


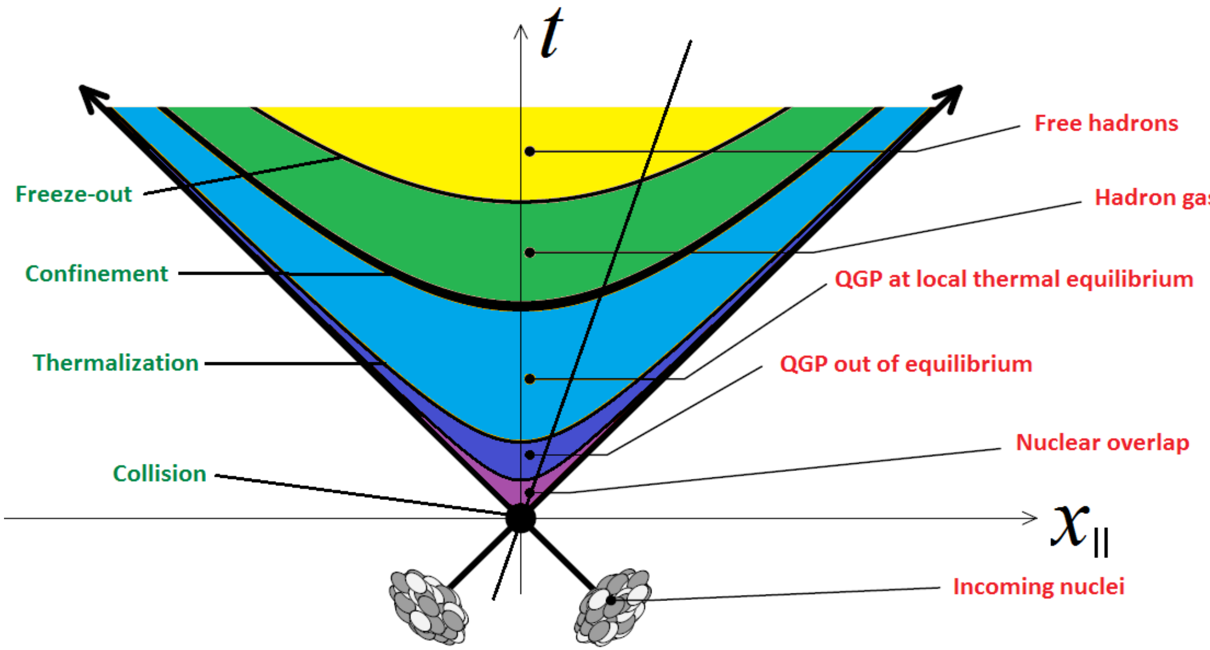
The AdS/CFT dictionary

Boundary	Bulk
Deconfined medium at finite T	Anti-de Sitter Black Hole (AdS/BH) metric $T \propto$ horizon radius, $S \propto$ horizon area
Boundary stress-energy tensor	Bulk metric
Heavy quarkonium $Q\overline{Q}$	String with endpoints (Q and $\overline{Q}$) kept close to the boundary

Relaxation of a far-from-equilibrium QGP

Physical picture of **QGP** formation in Heavy Ion Collisions





Evidence from the RHIC and LHC experiments: QGP behaves as a strongly-coupled fluid; onset of the hydrodynamic regime for time scales **t $\gtrsim$1 fm/c** after the collision

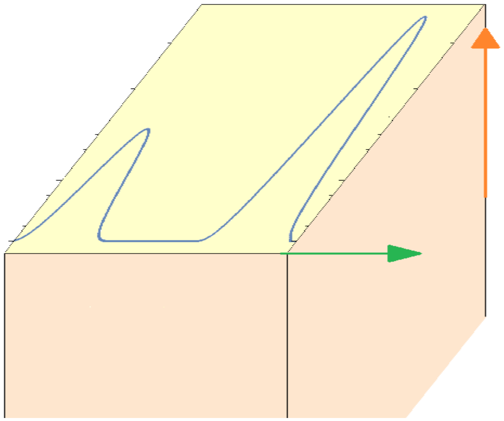
PRE-EQUILIBRIUM EVOLUTION: perturbative and lattice QCD methods inapplicable

⇒ **AdS/QCD** to describe real-time thermalization

OUR FOCUS: evolution of the QGP from a pre-equilibrium state and estimate of physical observables (effective temperature, entropy density, energy density, pressure, non-local probes)

QGP formation and relaxation in holography

BOUNDARY SOURCING:



a time-dependent deformation pulse (quench) is introduced to the metric on the boundary in order to mimic the effects that drive the system out of equilibrium.

QGP evolution towards equilibrium is computed in the 5-dimensional dual space from Einstein equations.

1. $\mathcal{M}_4$ + quench deformation pulse

→ duality →

2. 5d curved metric driven out of equilibrium

→ Einstein equations →

3. Intermediate and late time solution

→

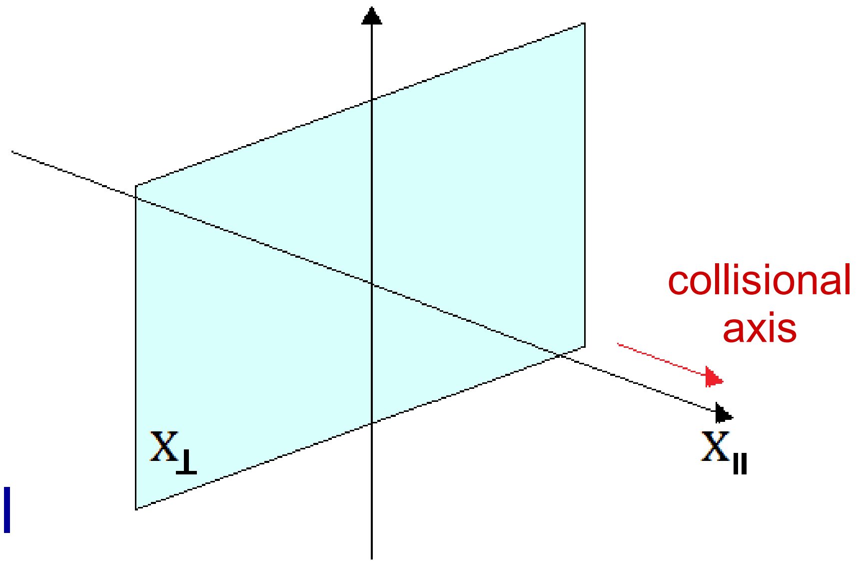
4. Relaxation and hydrodynamic regime: thermalization and isotropization of QGP

Simplification

Space-time symmetries

- Translation and rotation invariance in the $x_\perp$ plane
- Boost invariance along the $x_\parallel$ direction

Approximately realized at the central part of the QGP



Local thermal equilibrium : expansion is much slower than relaxation

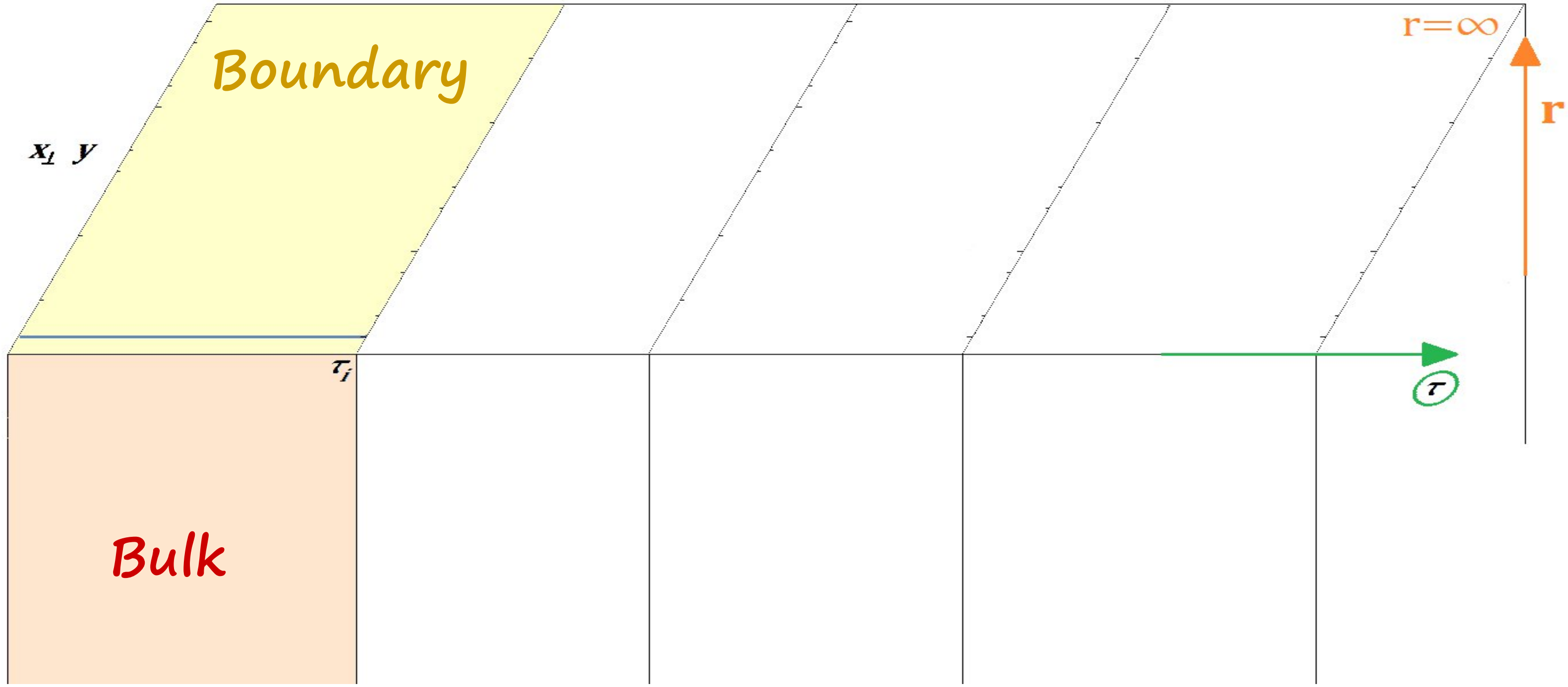
All the portions of the fluid share the same (time dependent) temperature

Boundary sourcing and QGP evolution

Coordinates: $(\tau, \boldsymbol{x}_\perp, y)$ — τ → proper time, y → rapidity

$$\begin{cases} x^0 = \tau \cosh y \\ x_\parallel = \tau \sinh y \end{cases}$$

Fifth holographic coordinate: bulk radius r



INITIAL STATE

$$\mathcal{M}_4: \; ds^2 = -d\tau^2 + d\boldsymbol{x}_\perp^2 + \tau^2 dy^2$$

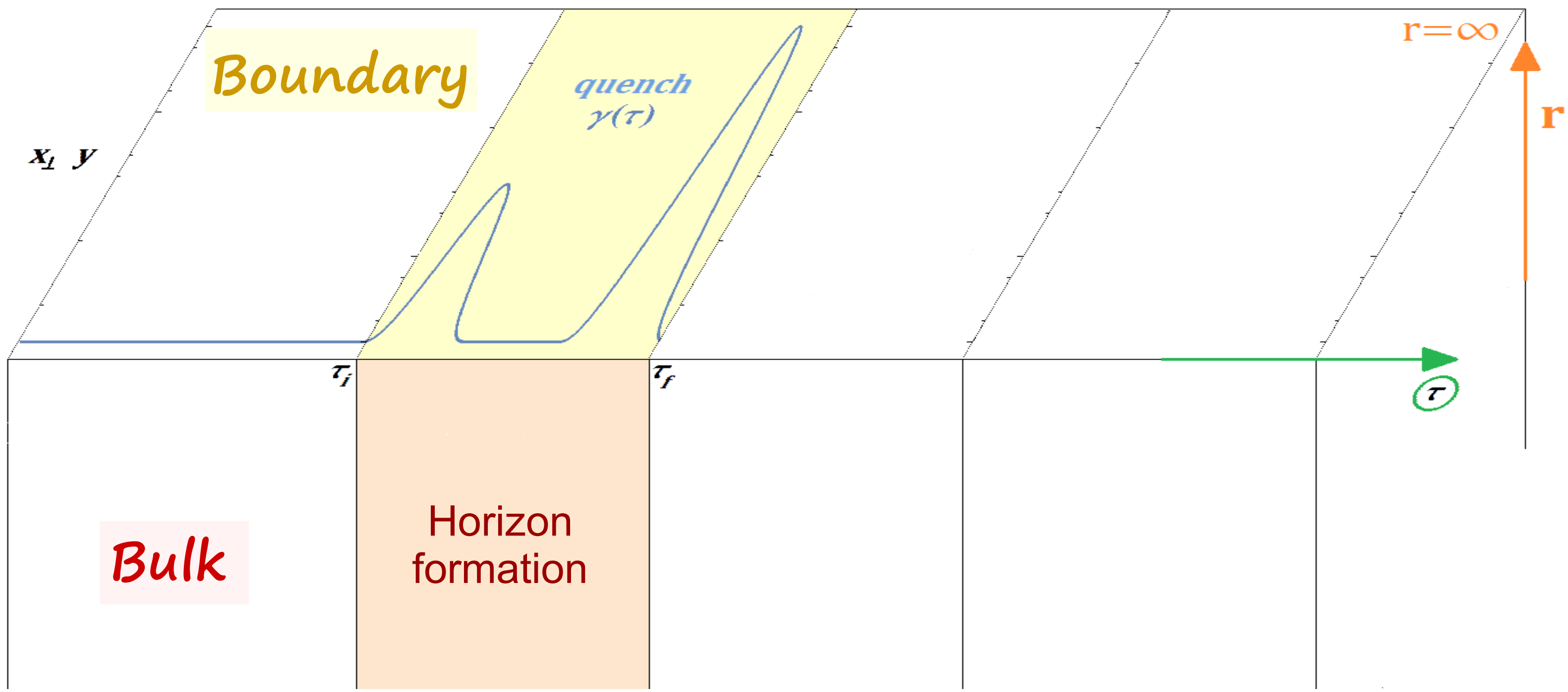
$$AdS_5: \; ds^2 = r^2\left[-d\tau^2 + d\boldsymbol{x}_\perp^2 + \left(\tau + \frac{1}{r}\right)^2 dy^2\right] + 2\,dr\,d\tau$$

Boundary sourcing and QGP evolution

Coordinates: $(\tau, \mathbf{x}_\perp, y)$ — y: rapidity; τ: proper time

$$\begin{cases} x^0 = \tau \cosh y \\ x_\parallel = \tau \sinh y \end{cases}$$

Fifth holographic coordinate: bulk radius r



BOOST-INVARIANT DEFORMATION

4d : $ds^2 = -d\tau^2 + e^{\gamma(\tau)} d\mathbf{x}_\perp^2 + \tau^2 e^{-2\gamma(\tau)} dy^2$

5d : $ds^2 = -A(r,\tau) d\tau^2 + \Sigma^2(r,\tau)\left[e^{B(r,\tau)} d\mathbf{x}_\perp^2 + e^{-2B(r,\tau)} dy^2\right] + 2\,dr\,d\tau$

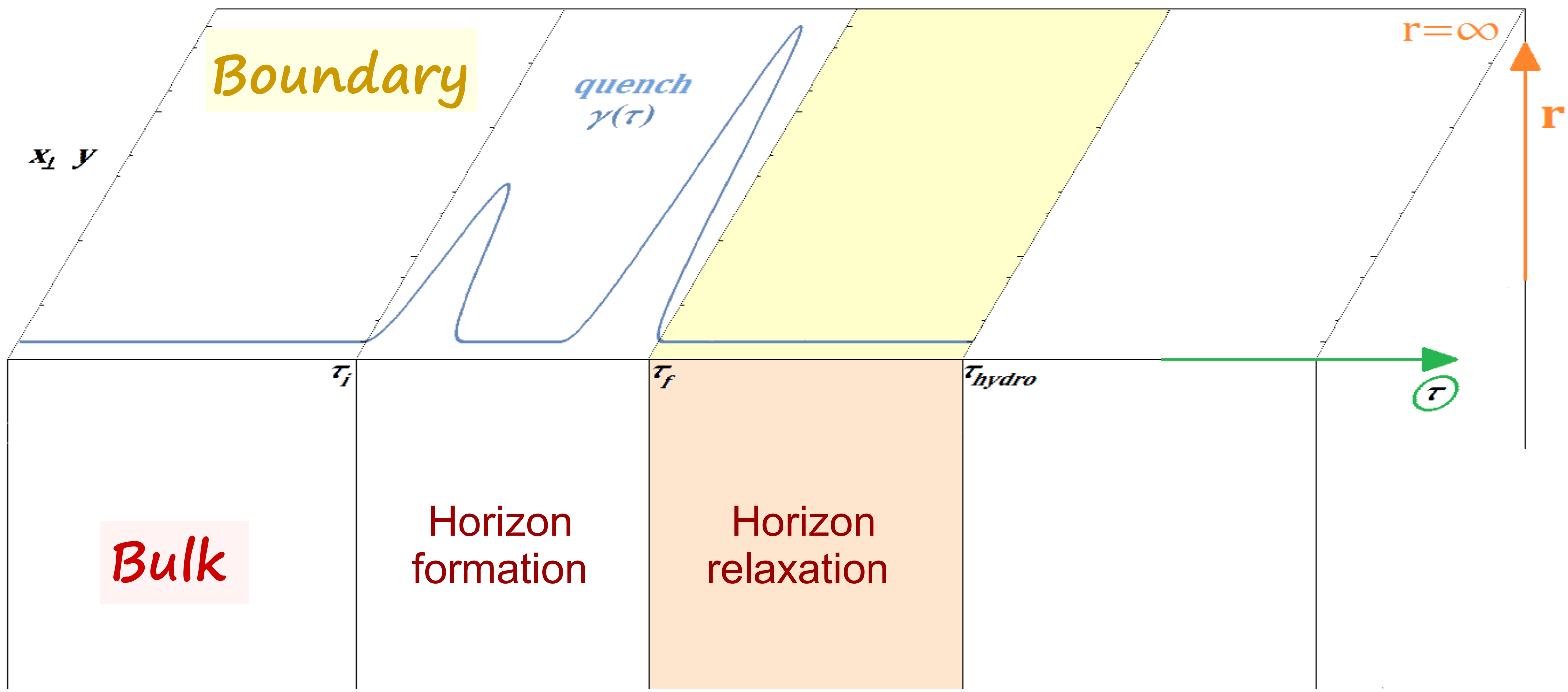
Einstein equations

Boundary sourcing and QGP evolution

Coordinates: $(\tau, \mathbf{x}_\perp, y)$ — y: rapidity; τ: proper time

$$\begin{cases} x^0 = \tau \cosh y \\ x_\parallel = \tau \sinh y \end{cases}$$

Fifth holographic coordinate: bulk radius r



$$\tau_f \le \tau \le \tau_{\text{hydro}}$$

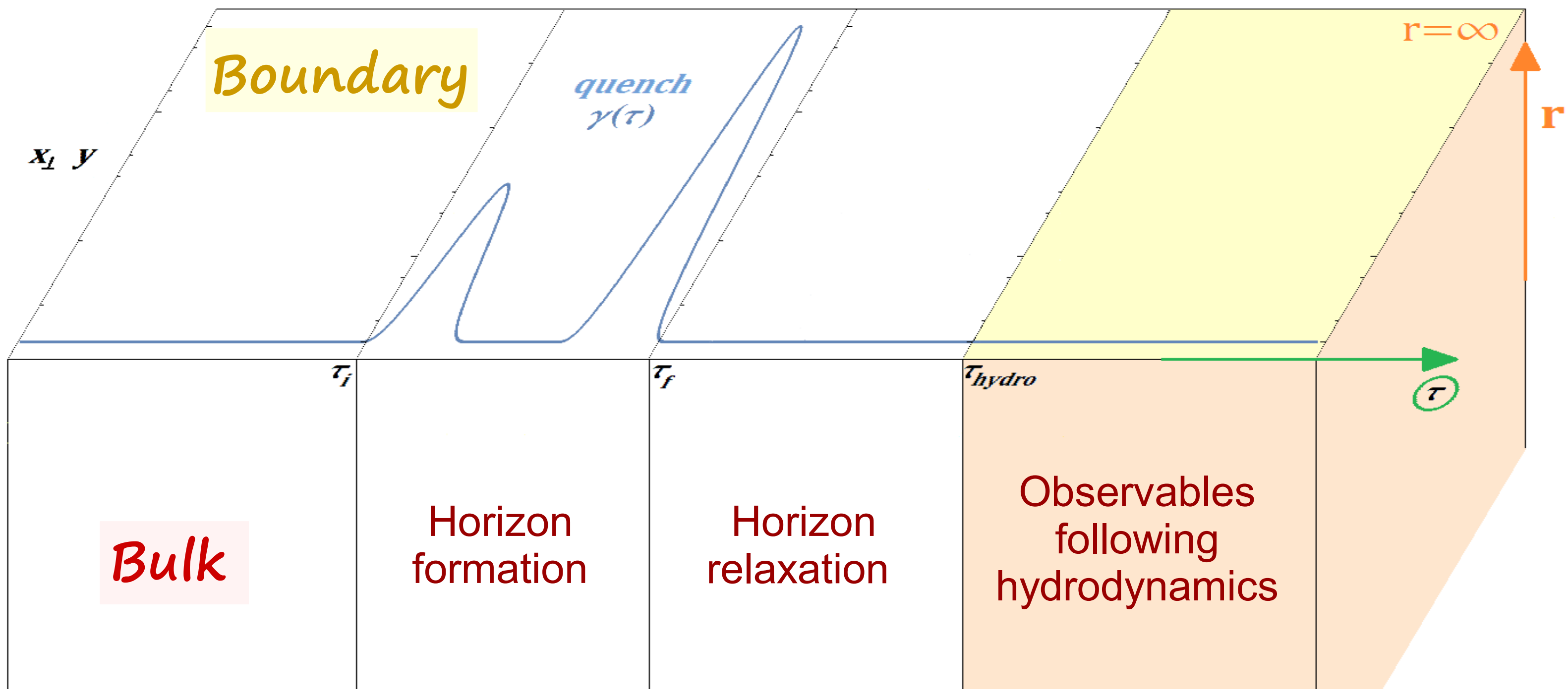
TERMALIZATION and **ISOTROPIZATION** of the system after the quench

Boundary sourcing and QGP evolution

Coordinates: $(\tau, \boldsymbol{x}_\perp, y)$ $\begin{cases} x^0 = \tau \cosh y \\ x_\parallel = \tau \sinh y \end{cases}$ Fifth holographic coordinate: bulk radius r

rapidity

proper time



$\tau \geq \tau_{\text{hydro}}$

HYDRODYNAMIC REGIME: both temperature and stress-energy tensor follow

$$T_{\text{eff}}(\tau) \propto \tau^{-1/3}, \qquad \mathcal{E}(\tau), \mathcal{P}_\perp(\tau), \mathcal{P}_\parallel(\tau) \propto \tau^{-4/3}$$

Bjorken, *Phys.Rev. D* 1983

Temperature and entropy density

At late times the *Bulk* geometry evolves towards the AdS_5 / BH form

The computed horizon $r_h(\tau)$:

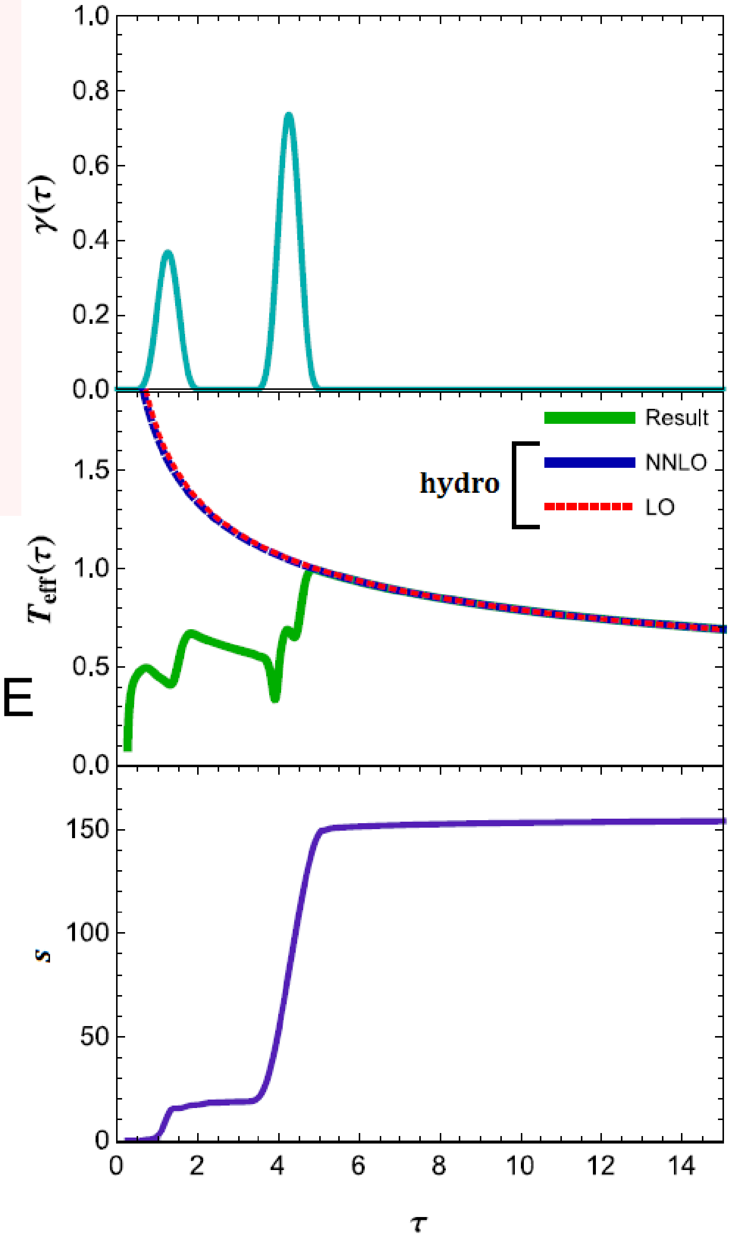
- follows the distortion profile
- asymptotically relaxes as $r_h(\tau) \propto \tau^{-1/3}$

BH THERMODYNAMICS + HOLOGRAPHIC PRINCIPLE allow to define:

- Effective temperature from horizon position

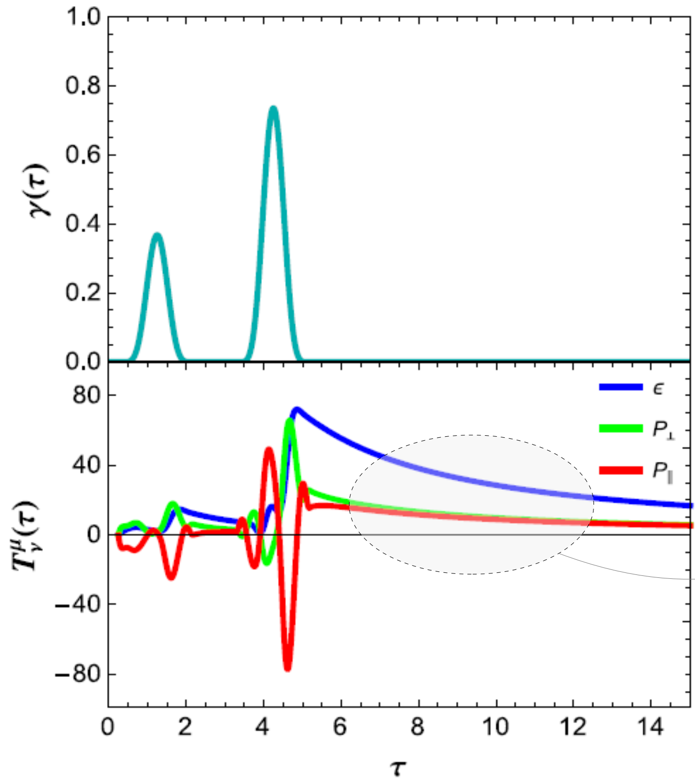
$$T_{\rm eff}(\tau) = \frac{r_h(\tau)}{\pi}$$

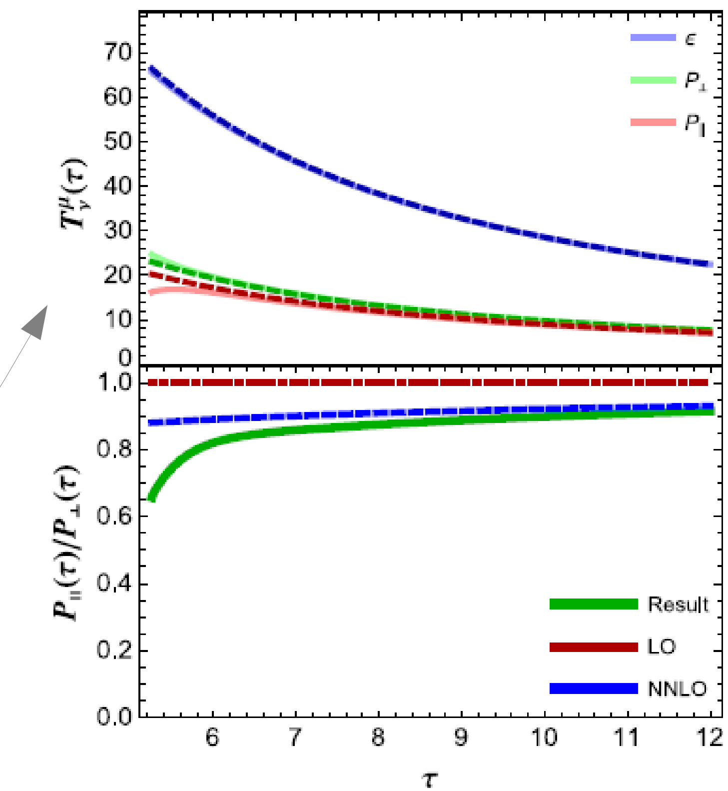
- Entropy from horizon area (Bekenstein-Hawking definition)



Energy density and pressure

Boundary Stress-Energy Tensor $T_{\mu\nu} = \frac{N_c^2}{2\pi^2}\,\mathrm{diag}\left(\mathcal{E}, \mathcal{P}_\perp, \mathcal{P}_\perp, \mathcal{P}_\parallel\right)$





Energy density $\mathcal{E}(\tau) = \frac{3}{4}\pi^4 T_{\mathrm{eff}}(\tau)^4$ starts to follow hydrodynamics as soon as the quench is switched off $(\tau = \tau_f)$

Setting the scale $T_{\mathrm{eff}}(\tau_f) = 500\ \mathrm{MeV}$, pressure isotropy is reached after a time

$\tau_{\mathrm{hydro}} - \tau_f \simeq 0.6\ \mathrm{fm}/c$

L.B. *et al.*, *JHEP* 2015

Quarks and $Q\overline{Q}$ in AdS/QCD

Quark ⟷ Open string in the bulk, with dynamics dictated by the Nambu-Goto action S_{NG}

Heavy quark moving in a strongly coupled plasma: drag force on it, energy loss, diffusion

$Q\overline{Q}$ ⟷ String with endpoints kept close to the boundary, at fixed $r=r_0$, identified with the Q mass

Application: screening length of $Q\overline{Q}$ in a hot wind

Quarks and $Q\overline{Q}$ in AdS/QCD

Quark ⟷ Open string in the bulk, with dynamics dictated by the Nambu-Goto action S_{NG}

$Q\overline{Q}$ ⟷ String with endpoints kept close to the boundary, at fixed $r = r_0$, identified with the Q mass

↓ Eqs. of motion from S_{NG} at finite T

In-medium $Q\overline{Q}$ dissociation ⟷ The string falls in the bulk under gravity and reaches the BH horizon

Lin and Shuryak, *Phys.Rev. D* 2008, Iatrakis and Karzeev, *Phys.Rev. D* 2016

Real-time $Q\overline{Q}$ dissociation in a far-from-equilibrium anisotropic setup

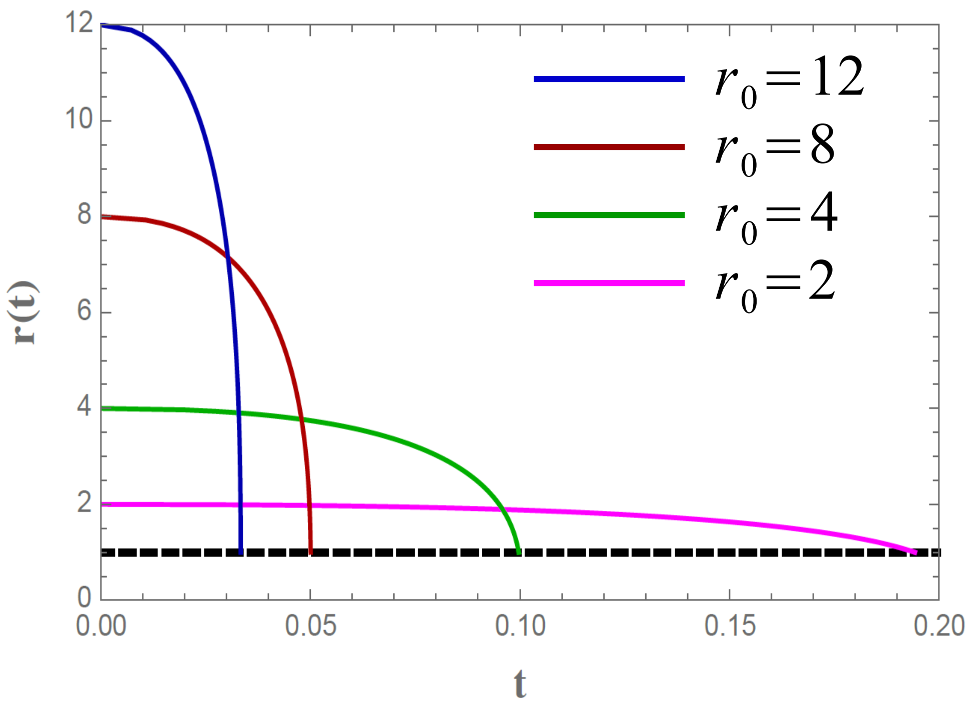
$\longrightarrow$ L.B. *et. al.*, *Phys.Rev. D* 2017

$Q\overline{Q}$ dissociation in AdS/BH

A simplified case: string profile $r(t)$ in the AdS/BH geometry

$$S_{NG} \propto \int dt\, r \sqrt{r^2\left(1-\frac{r_H^4}{r^4}\right) - 2r'}$$

Analytic results for $r(t)$; dissociation time t_D expressed as a function of the initial position r_0 and the horizon position r_H



r_0 identified with Q mass

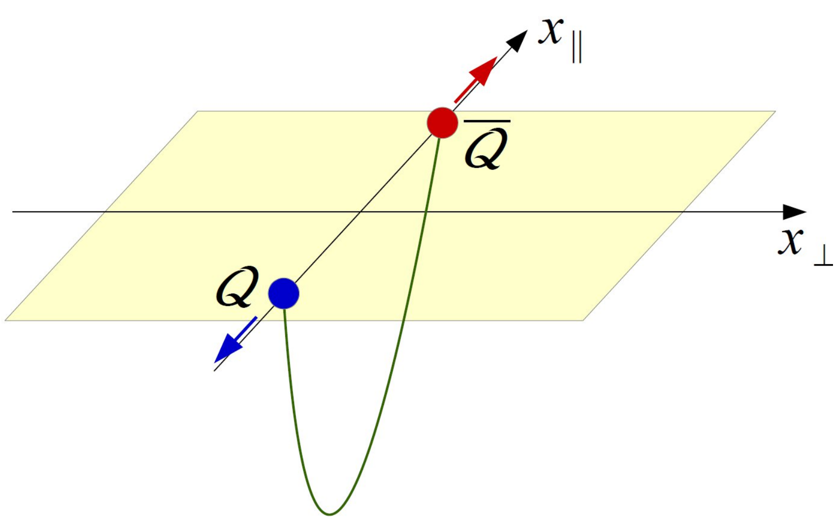
Heavier quarkonium dissociates faster

$Q\overline{Q}$ dissociation in the anisotropic plasma

$$S_{\mathrm{NG}} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r) - 2\partial_t r\right] + \left(\partial_w r\right)^2}$$

LONGITUDINAL STRING:

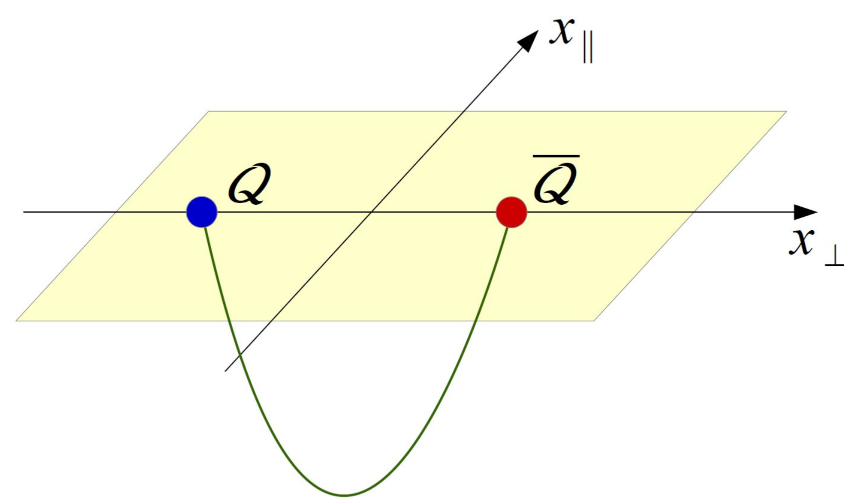
$$w = y\,,\, \Sigma_w = \Sigma^2 \mathrm{e}^{-2B}$$



Q and Q move away from each other along the $x_{\parallel}$ axis with rapidity $w_Q = -y_L\,,\, w_{\overline{Q}} = y_L$

TRANSVERSE STRING:

$$w = x_{\perp}\,,\, \Sigma_w = \Sigma^2 \mathrm{e}^{B}$$



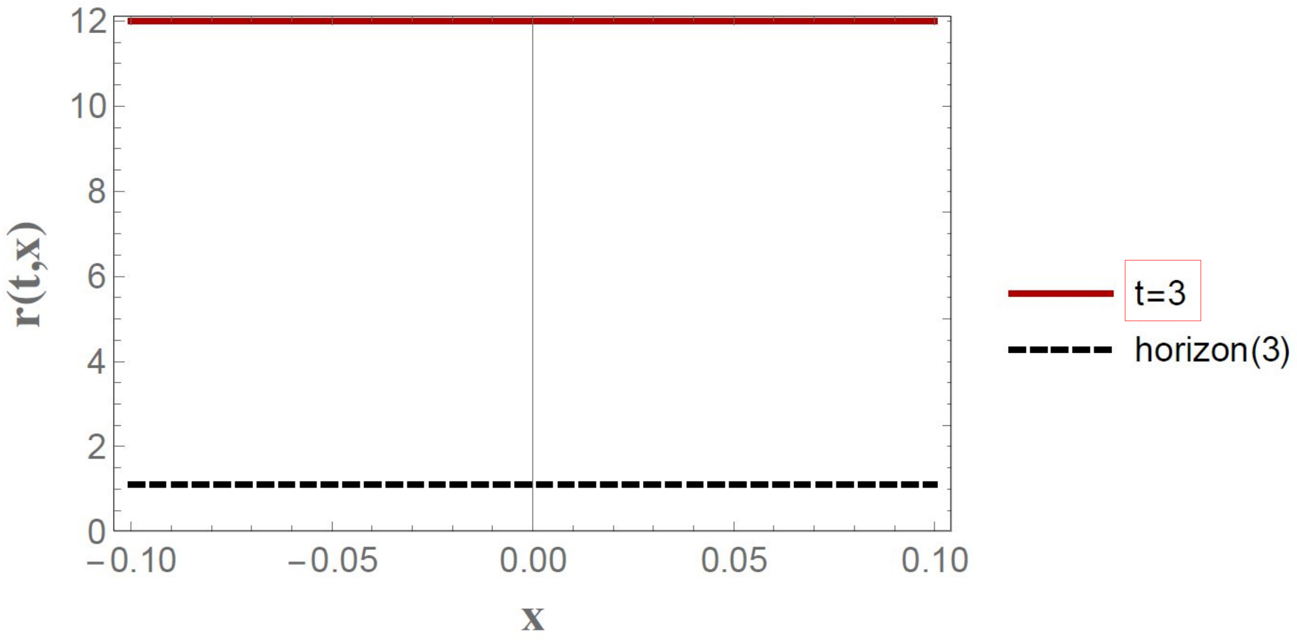
Q and Q are kept at a fixed mutual distance: $w_Q = -L\,,\, w_{\overline{Q}} = L$

$r(t, w_{\overline{Q}}) = r(t, w_Q) = r_0$ at all times during the evolution

$A(t,r)\,,\, B(r,t)\,,\, \Sigma(r,t)$ from Einstein equations

$Q\bar{Q}$ dissociation in the anisotropic plasma

$$S_{\rm NG} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r) - 2\partial_t r\right] + \left(\partial_w r\right)^2}$$



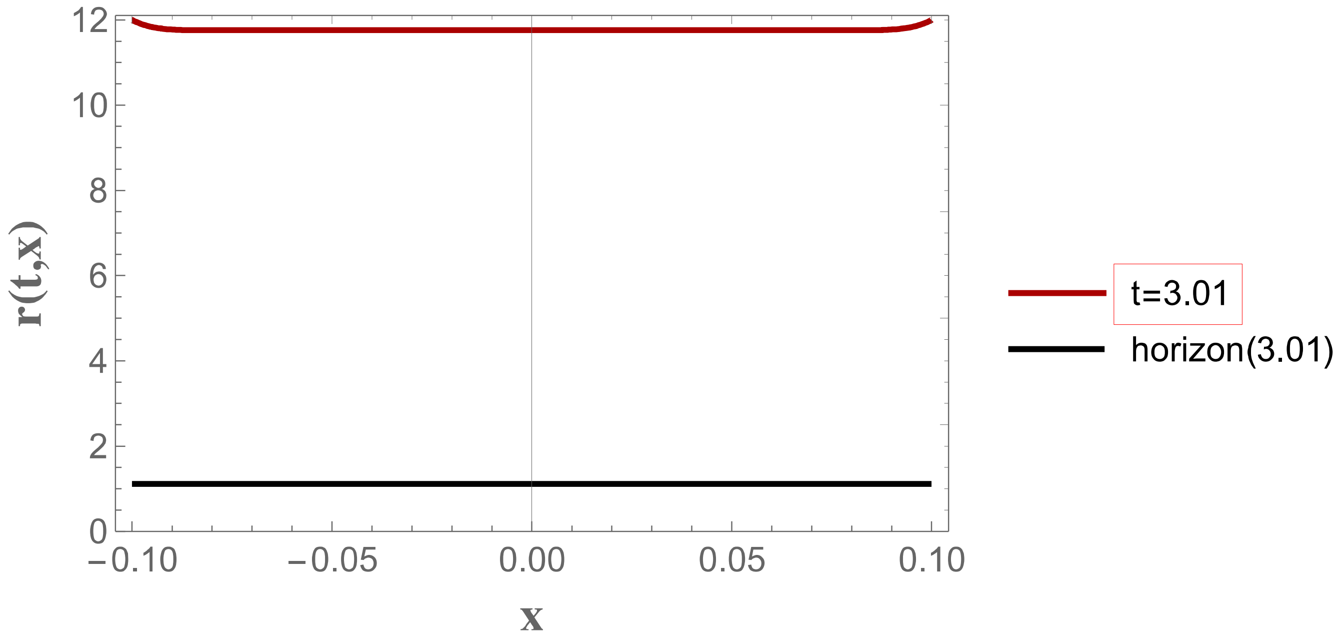
Initial time $t_{\rm i}$: string completely stretched close to the boundary

$r(t_{\rm i}, w) = r_0$ for all w, initial velocity $\partial_t r\big|_{t=t_{\rm i}} = v$

$Q\overline{Q}$ dissociation in the anisotropic plasma

$$S_{\rm NG} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r) - 2\partial_t r\right] + \left(\partial_w r\right)^2}$$

$$r(t_{\rm i}, w) = r_{0,} \quad \partial_t r\big|_{t=t_{\rm i}} = v$$



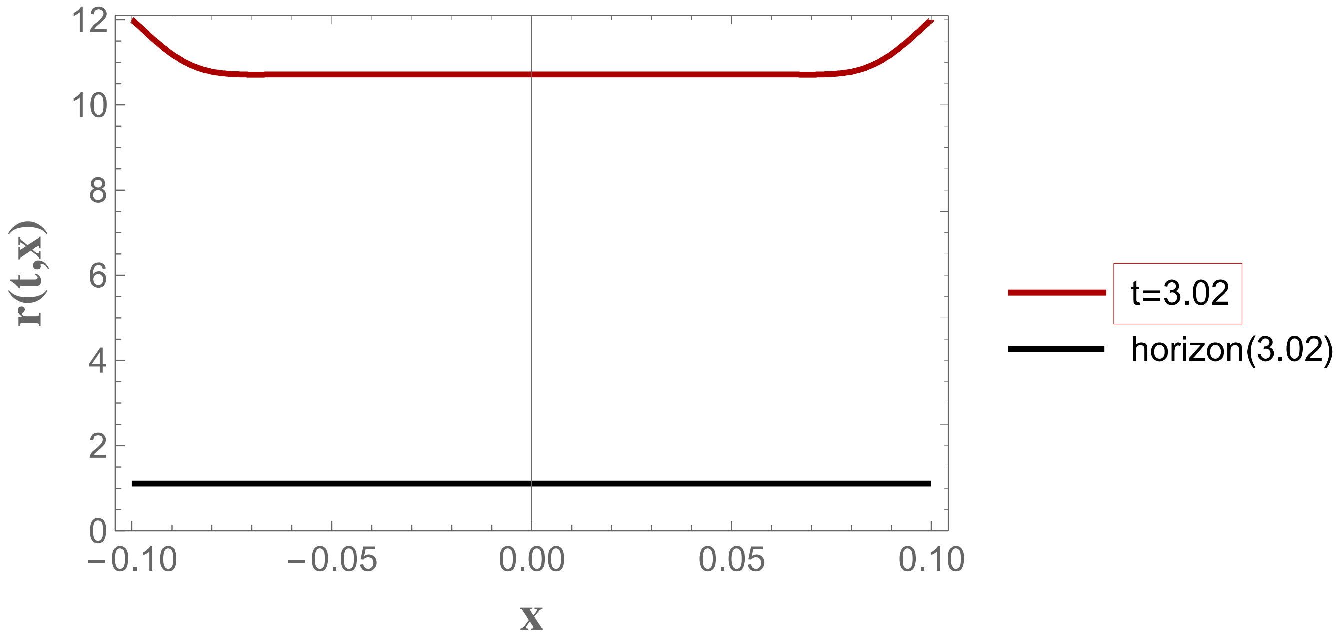
String falls in the bulk under gravity, with endpoints on the boundary

$$r(t_{\rm i}, w_Q) = r(t_{\rm i}, w_{\overline{Q}}) = r_0 \text{ for all } t$$

$Q\bar{Q}$ dissociation in the anisotropic plasma

$$S_{\mathrm{NG}} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r)-2\partial_t r\right]+\left(\partial_w r\right)^2}$$

$$r(t_{\mathrm{i}},w)=r_{0,} \quad \partial_t r\big|_{t=t_{\mathrm{i}}}=v$$



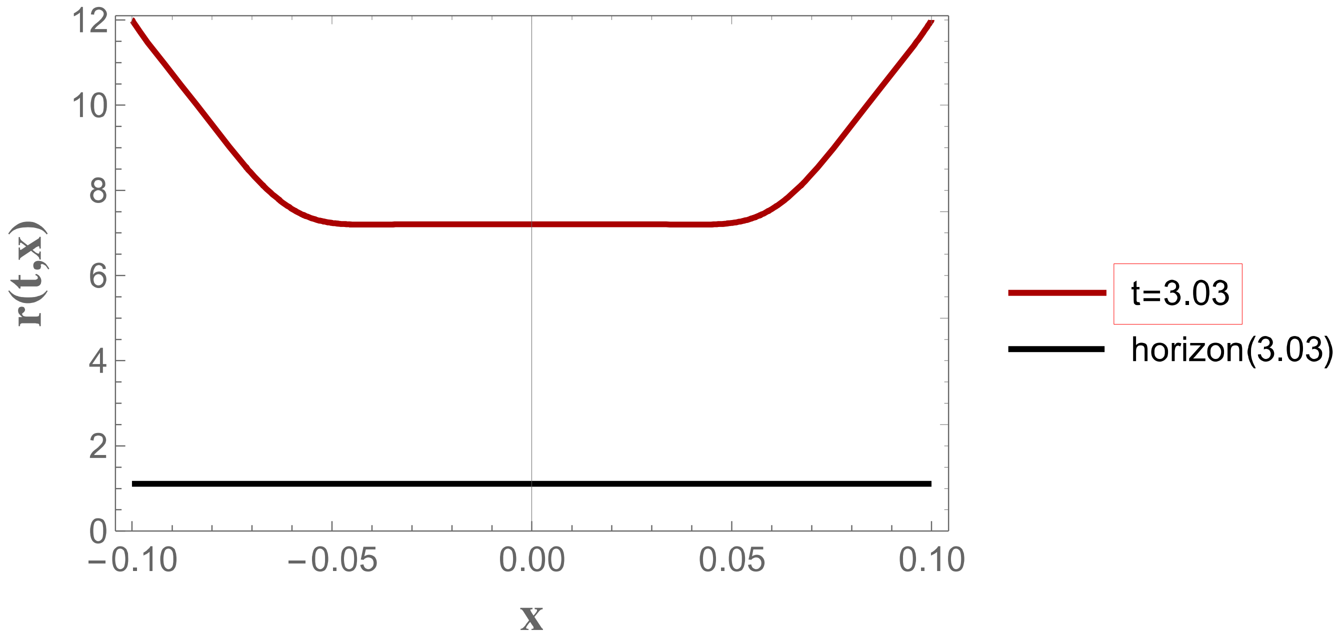
String falls in the bulk under gravity, with endpoints on the boundary

$$r(t_{\mathrm{i}},w_Q)=r(t_{\mathrm{i}},w_{\bar{Q}})=r_0 \text{ for all } t$$

$Q\overline{Q}$ dissociation in the anisotropic plasma

$$S_{\mathrm{NG}} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r) - 2\partial_t r\right] + \left(\partial_w r\right)^2}$$

$$r(t_{\mathrm{i}}, w) = r_{0,} \quad \partial_t r\big|_{t=t_{\mathrm{i}}} = v$$



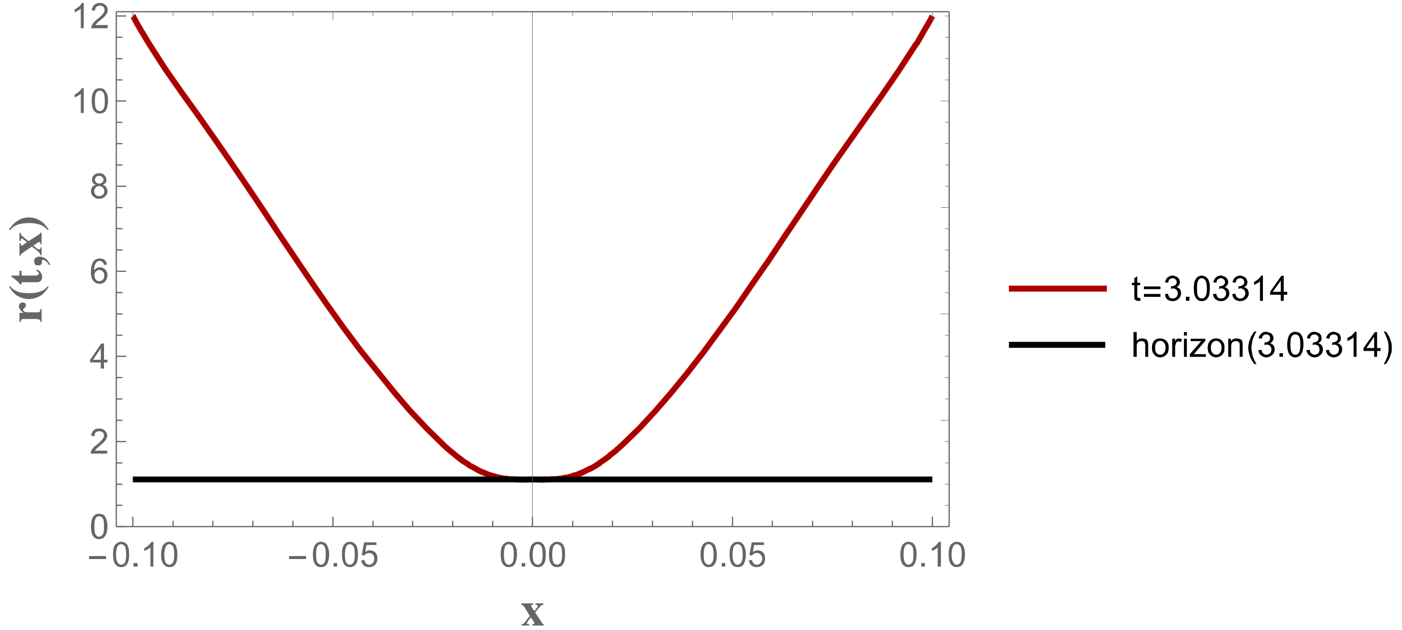
String falls in the bulk under gravity, with endpoints on the boundary

$$r(t_i, w_Q) = r(t_i, w_{\overline{Q}}) = r_0 \text{ for all } t$$

$Q\bar{Q}$ dissociation in the anisotropic plasma

$$S_{\rm NG} \propto \int dt\, dw \sqrt{\Sigma_w(t,r)\left[A(t,r) - 2\partial_t r\right] + \left(\partial_w r\right)^2}$$

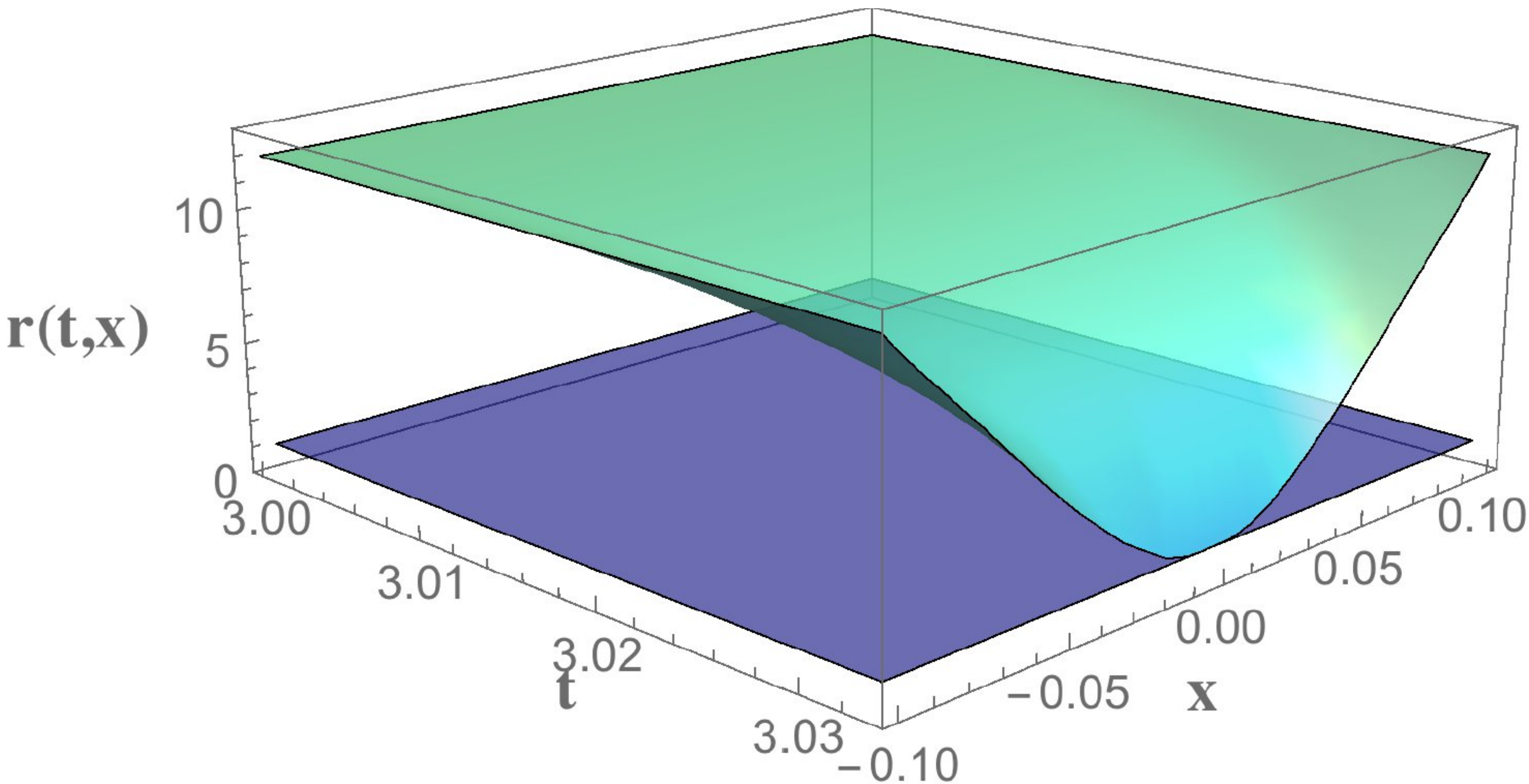
$$r(t_{\rm i}, w) = r_{0,} \quad \partial_t r\big|_{t=t_{\rm i}} = v\,, \quad r(t_i, w_Q) = r(t_i, w_{\bar{Q}}) = r_0$$



Dissociation time $t_{\rm D}$: string reaches the BH horizon

$$r(t_{\rm D}, 0) = r_H(t_{\rm D})$$

$Q\overline{Q}$ dissociation in the anisotropic plasma

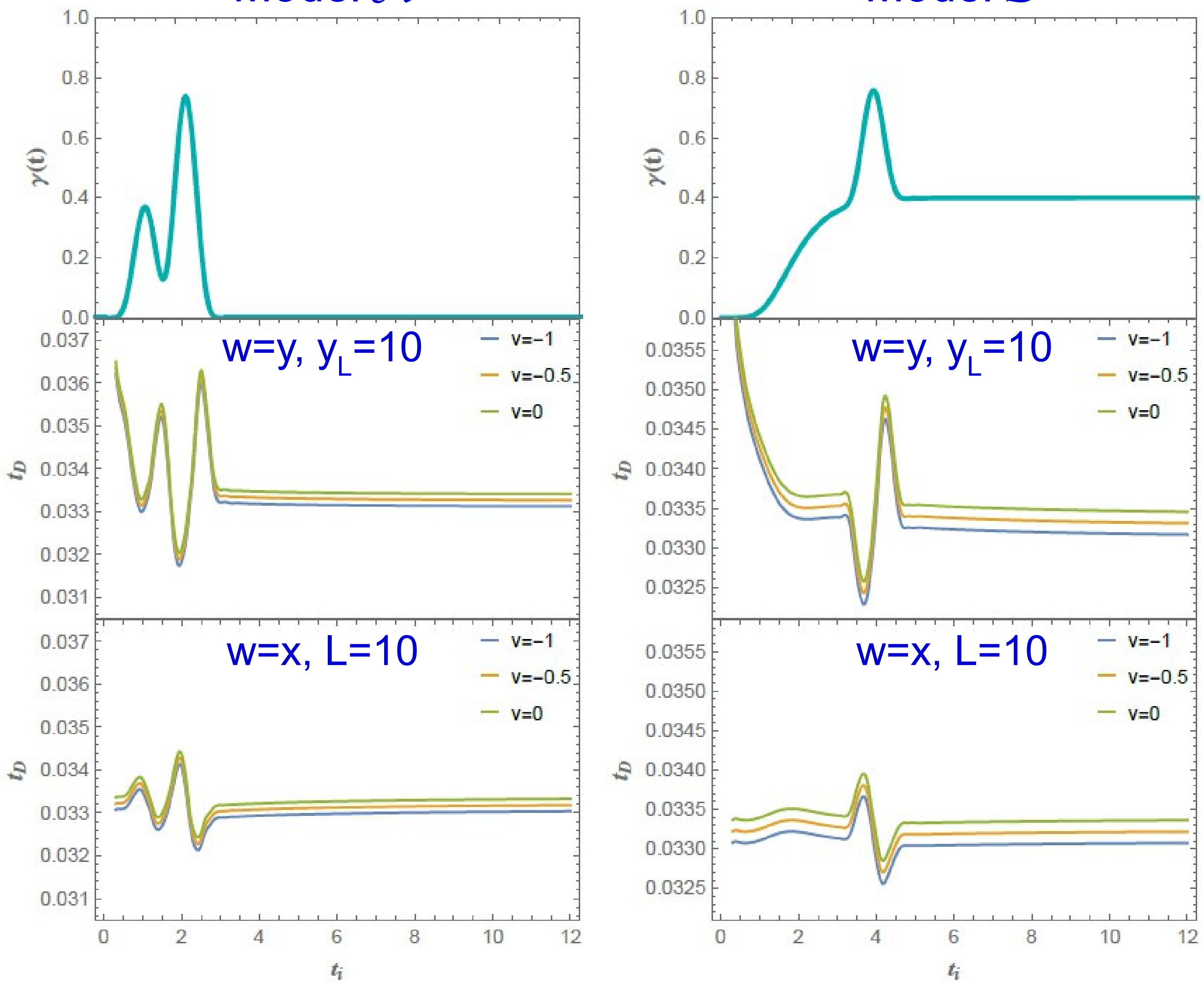


t_D versus t_i

A, B, Σ time-dependent

t_D depends on the initial time t_i, at which the string lies close to the boundary

Model $\mathcal{A}$ Model $\mathcal{B}$



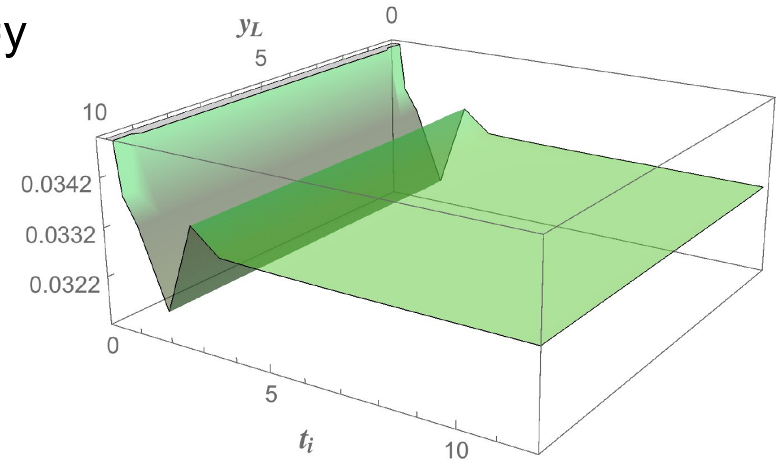
- During the quench: abrupt fluctuations, with maxima and minima switched in longitudinal and transverse string configurations
- After the quench: smooth evolution towards a constant value
- Dissociation is faster for a $Q\overline{Q}$ string in the transverse plane
- Setting the scale $T_{\rm eff}(\tau_f)=500\,{\rm MeV}$ t_D is of order 10^{-2} fm/c

LB et al, *Phys.Rev D* (2017)

t_{D} versus $\left(t_{\mathrm{i}}, w_{\overline{Q}}\right)$

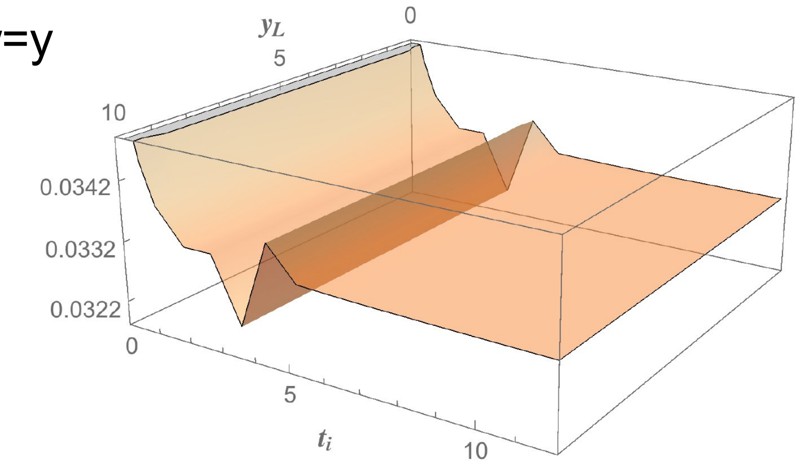
Model $\mathcal{A}$

w=y

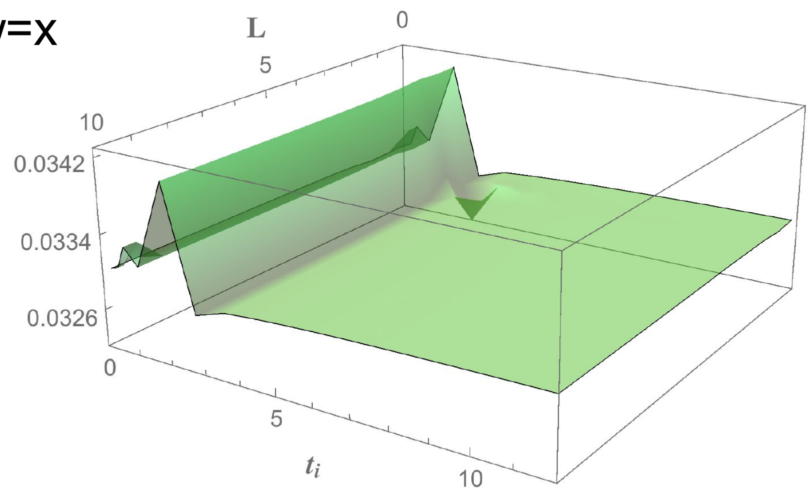


Model $\mathcal{B}$

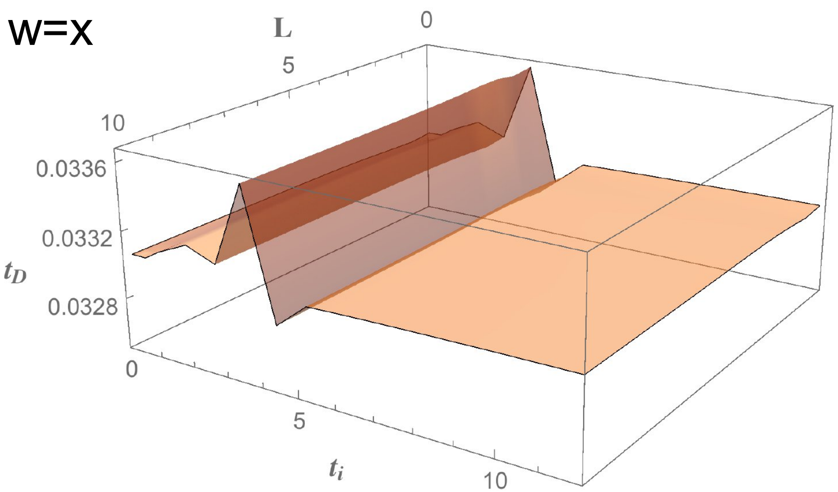
w=y



w=x

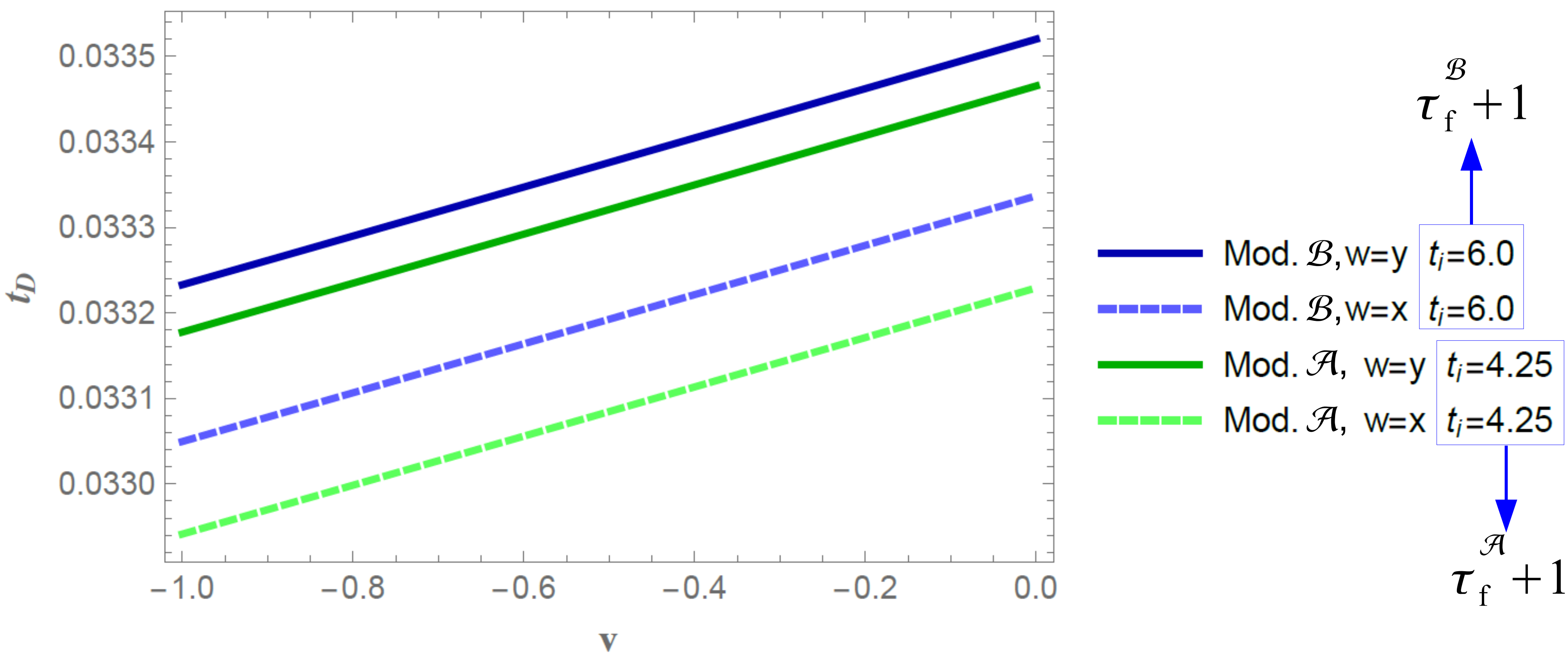


w=x



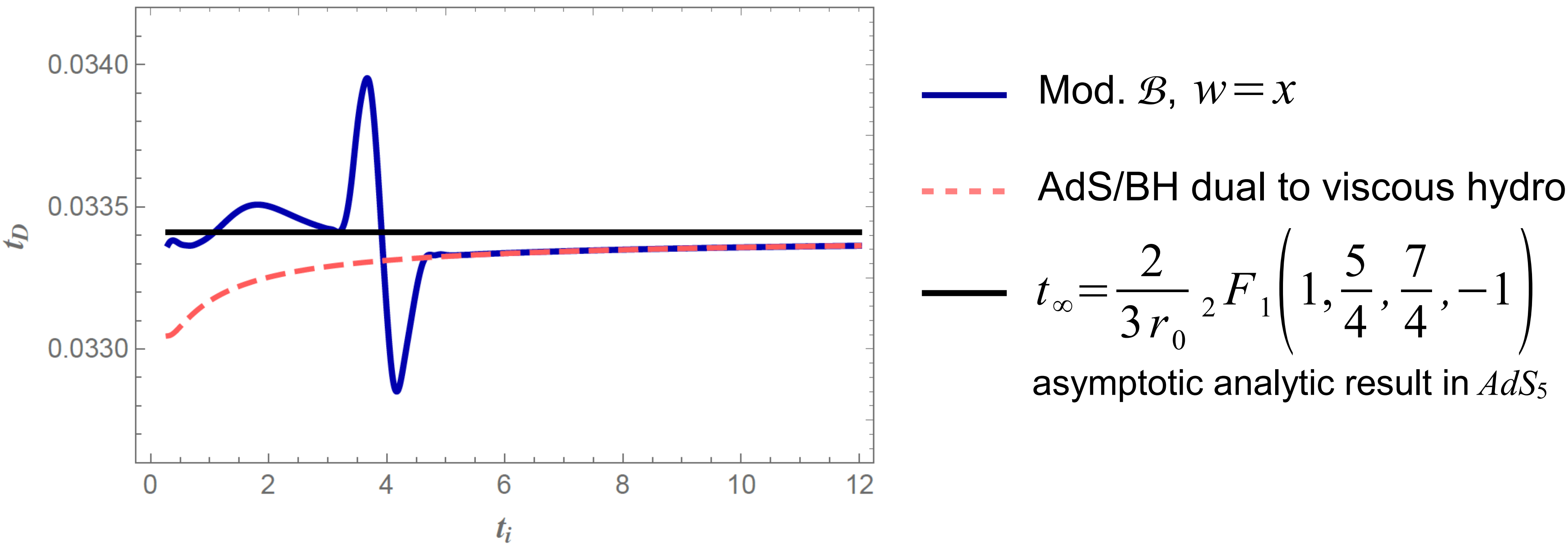
L and y_L varied in the range $[0.1,100]$ → t_{D} mostly independent of the separation between the string endpoints

t_D versus v



t_D displays a linear dependence on the initial velocity $\partial_t r\big|_{t=t_i} = v$ for both the quench models and string configurations

Comparison with t_D in other bulk metrics



At $t_i \simeq \tau_f$ the $Q\bar{Q}$ dissociation time in the anisotropic plasma becomes equal to that in the hydro metric

Conclusions and perspectives

- $Q\overline{Q}$ real-time dissociation in a strongly coupled anisotropic plasma has been analyzed in the AdS/QCD picture.

- The plasma is driven in an anisotropic out-of-equilibrium state through an impulsive deformation (quench) of the Minkowski boundary. The energy density reaches the viscous hydrodynamic form as soon as the quench is switched off, while pressure isotropy is restored with a time delay of $O(\mathrm{fm/c})$ [scale $T_{\mathrm{eff}}(\tau_f)=500\,\mathrm{MeV}$]

- $Q\overline{Q}$ is represented as a string with endpoints close to the boundary ($r = r_0$ fixed); in our setting, dissociation time is of $O(10^{-2}\ \mathrm{fm/c})$, with some fluctuations during the quench

- Dissociation occurs earlier for a $Q\overline{Q}$ string placed in a plane transverse to the direction of the anisotropic flow in the plasma; other studies suggest that in this configuration the $Q\overline{Q}$ screening length is minimum.

OUTLOOK

➡ $Q\overline{Q}$ real-time dissociation in a strongly-coupled plasma which undergoes a phase transition, implemented by a self-interacting scalar field in the bulk.

Thank you!

Bonus material

Evolution in the 5-dimensional bulk

A, B, Σ from Einstein equations

$$\begin{cases} \Sigma\left(\dot{\Sigma}\right)' + 2\Sigma'\dot{\Sigma} - 2\Sigma^2 = 0 \\ \Sigma\left(\dot{B}\right)' + \frac{3}{2}\left(\Sigma'\dot{B} + B'\dot{\Sigma}\right) = 0 \\ A'' + 3B'\dot{B} - 12\frac{\Sigma'\dot{\Sigma}}{\Sigma^2} + 4 = 0 \\ \ddot{\Sigma} + \frac{1}{2}\left(\dot{B}^2\Sigma - A'\dot{\Sigma}\right) = 0 \\ \Sigma'' + \frac{1}{2}B'^2\Sigma = 0 \end{cases}$$

Directional derivatives :

$f' \equiv \partial_r f$ along infalling radial null geodesics

$\dot{f} \equiv \partial_\tau f + \frac{1}{2}A\,\partial_r f$ along outgoing radial null geodesics

Testing the numerical algorithm

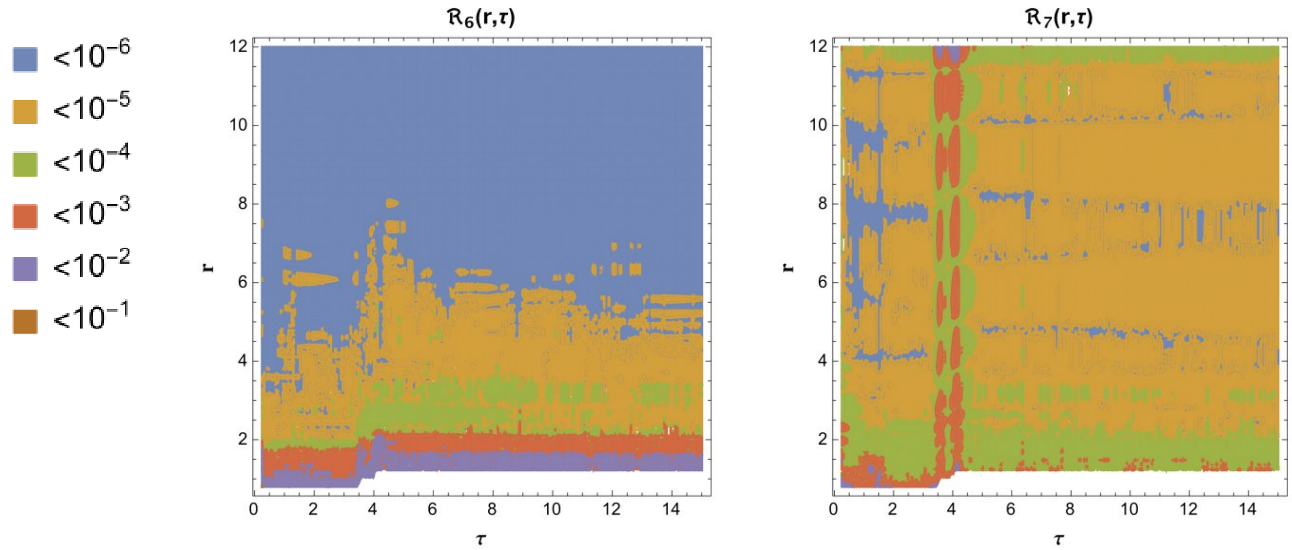
$$\mathcal{R}_6 = \frac{\Sigma(\dot{\Sigma})' + 2\Sigma'\dot{\Sigma} - 2\Sigma^2}{|\Sigma(\dot{\Sigma})'| + |2\Sigma'\dot{\Sigma}| + |2\Sigma^2|}$$

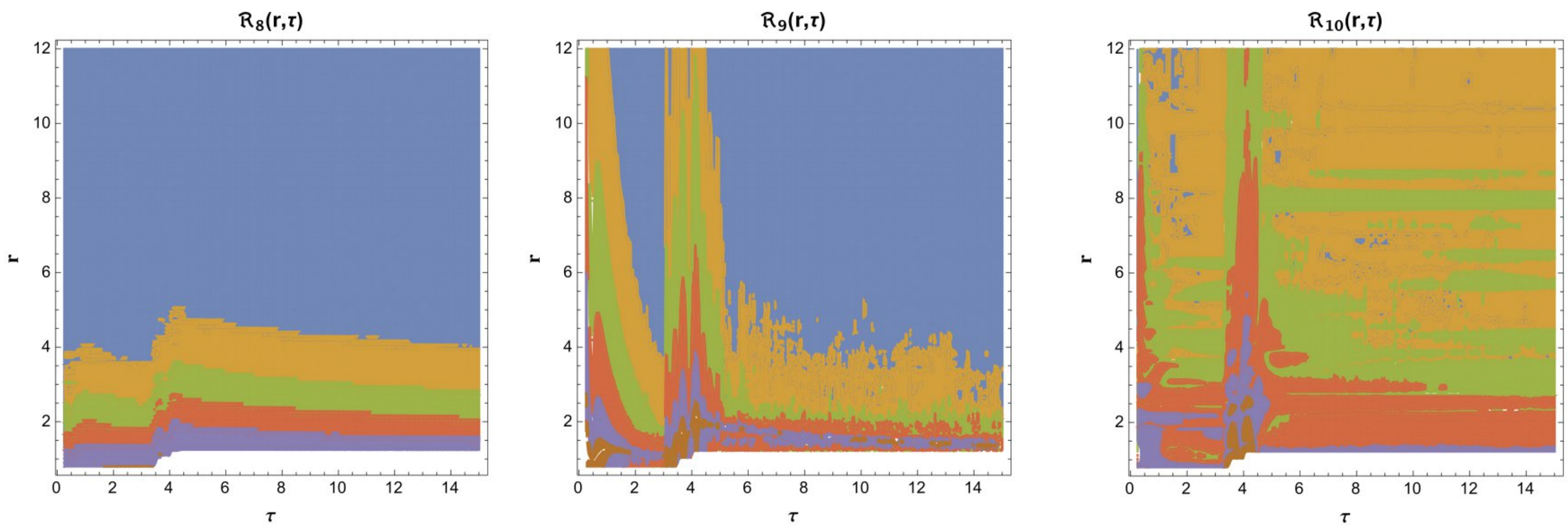
$$\mathcal{R}_7 = \frac{\Sigma(\dot{B})' + (3/2)(\Sigma'\dot{B} + B'\dot{\Sigma})}{|\Sigma(\dot{B})'| + (3/2)(|\Sigma'\dot{B}| + |B'\dot{\Sigma}|)}$$

$$\mathcal{R}_8 = \frac{A'' + 3B'\dot{B} - 12\Sigma'\dot{\Sigma}/\Sigma^2 + 4}{|A''| + 3|B'\dot{B}| + 12|\Sigma'\dot{\Sigma}|/|\Sigma^2| + 4}$$

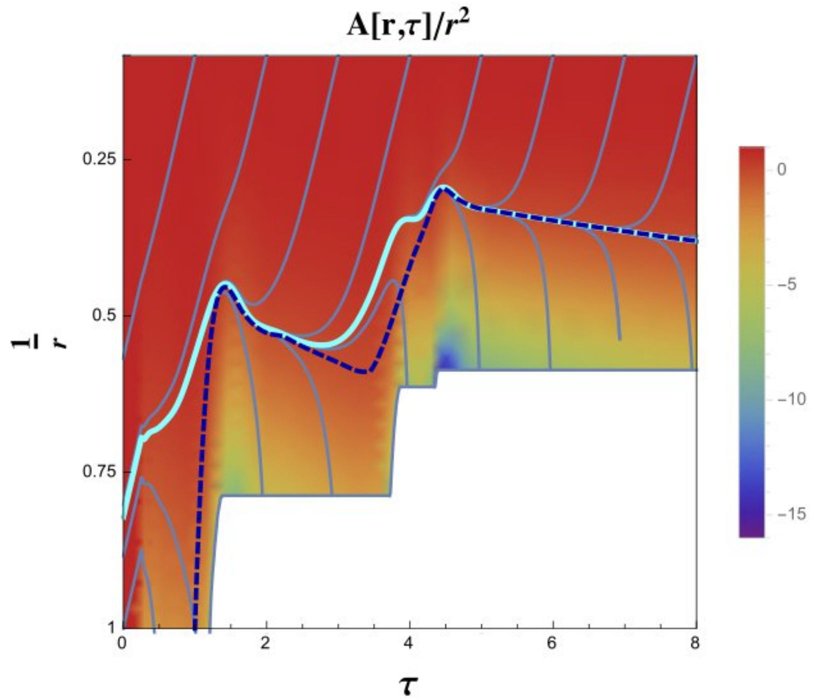
$$\mathcal{R}_9 = \frac{\ddot{\Sigma} + (1/2)(\dot{B}^2\Sigma - A'\dot{\Sigma})}{|\ddot{\Sigma}| + (1/2)(|\dot{B}^2\Sigma| + |A'\dot{\Sigma}|)}$$

$$\mathcal{R}_{10} = \frac{\Sigma'' + (1/2)B'^2\Sigma}{|\Sigma''| + (1/2)|B'^2\Sigma|}$$





Apparent and event horizon



- The gray lines are radial null outgoing geodesics $\frac{dr}{d\tau} = \frac{A(r,\tau)}{2}$;
- The dashed dark blue line is the apparent horizon from $\dot{\Sigma}(r_h(\tau),\tau)=0$;
- The continuos cyan line is the event horizon obtained as the critical geodesics $r_h(\tau)$ such that $\lim_{\tau\to\infty} A(r_h(\tau),\tau)=0$.