Chaos in a $Q\bar{Q}$ system at finite temperature and baryon density

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arXiv:2007.06980, PRD 102 (20) 074016

Frontiers of holographic duality - 2
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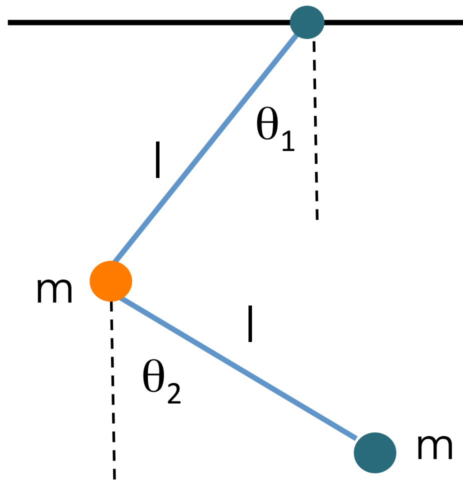
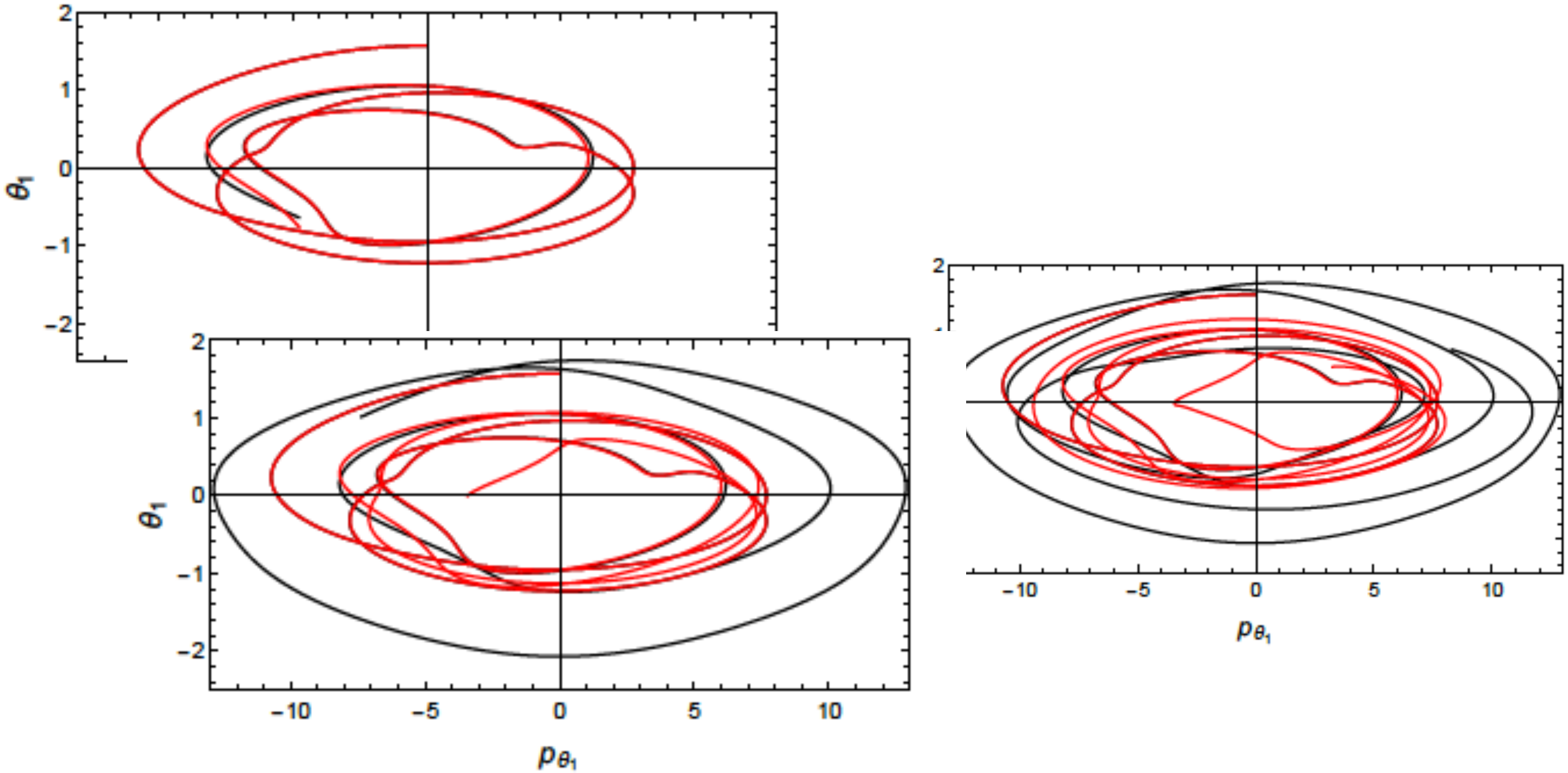
outline

- MSS bound on chaos
- Proposed (in the literature) generalization of the bound to the case of systems with global symmetry
- Test of the generalized bound using the $Q\bar{Q}$ system at finite T and μ
- Conclusions, Perspectives

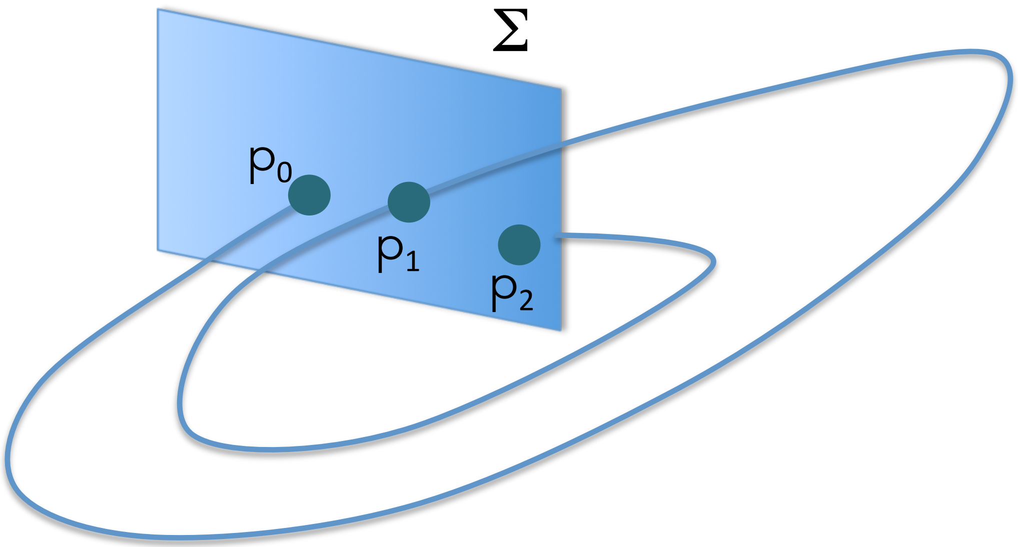
Classical chaos

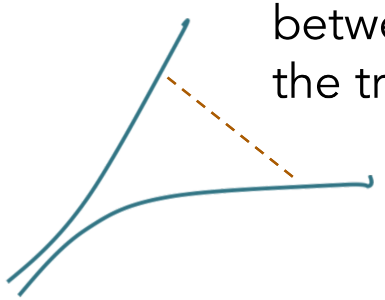


chaotic dynamics characterized by aperiodic trajectories exhibiting a strong dependence on the initial conditions

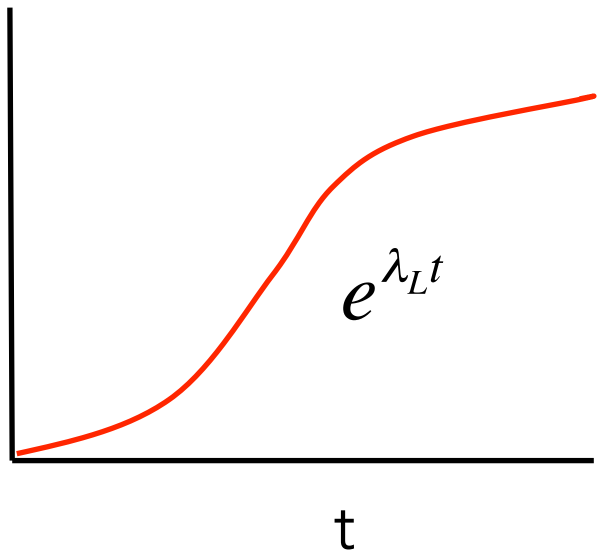


Poincare' section

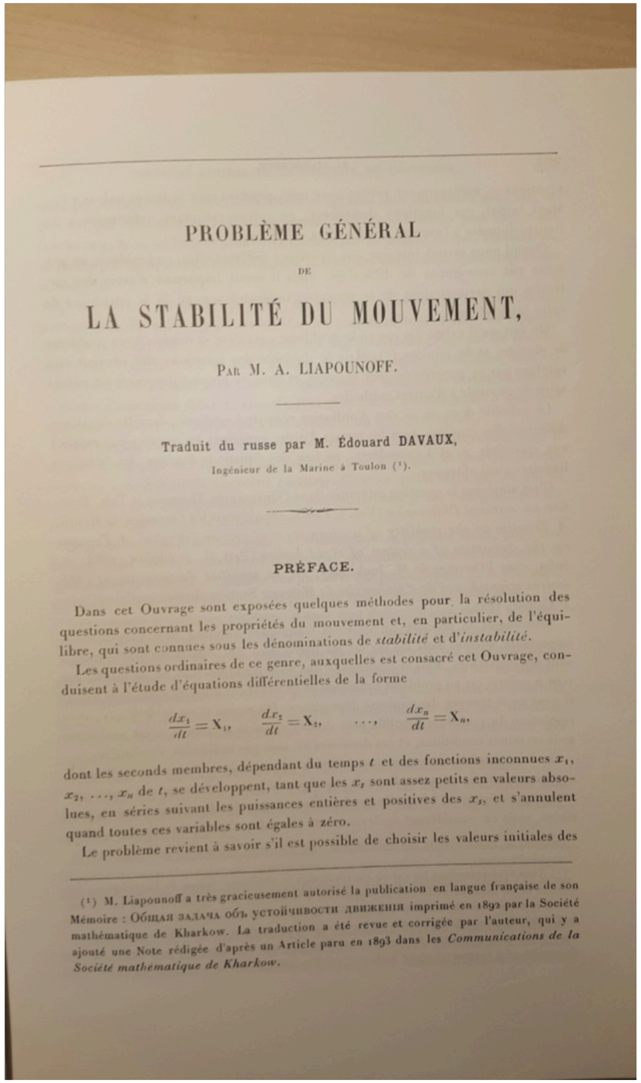




mean distance between the trajectories



λ_L Lyapunov exponent



PROBLÈME GÉNÉRAL

DE

LA STABILITÉ DU MOUVEMENT,

PAR M. A. LIAPOUNOFF.

Traduit du russe par M. Édouard DAVAUX,

Ingénieur de la Marine à Toulon (1).

PRÉFACE.

Dans cet Ouvrage sont exposées quelques méthodes pour la résolution des questions concernant les propriétés du mouvement et, en particulier, de l'équilibre, qui sont connues sous les dénominations de *stabilité* et d'*instabilité*.

Les questions ordinaires de ce genre, auxquelles est consacré cet Ouvrage, conduisent à l'étude d'équations différentielles de la forme

$$\frac{dx_1}{dt} = X_1, \quad \frac{dx_2}{dt} = X_2, \quad \ldots, \quad \frac{dx_n}{dt} = X_n,$$

dont les seconds membres, dépendant du temps t et des fonctions inconnues x_1, $x_2, \ldots, x_n$ de t, se développent, tant que les x_s sont assez petits en valeurs absolues, en séries suivant les puissances entières et positives des x_s, et s'annulent quand toutes ces variables sont égales à zéro.

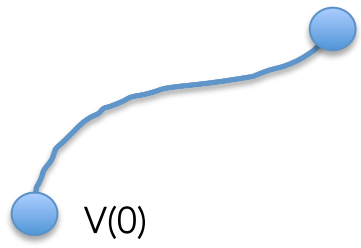
Le problème revient à savoir s'il est possible de choisir les valeurs initiales des

(1) M. Liapounoff a très gracieusement autorisé la publication en langue française de son Mémoire : Общая задача объ устойчивости движенія imprimé en 1892 par la Société mathématique de Kharkow. La traduction a été revue et corrigée par l'auteur, qui y a ajouté une Note rédigée d'après un Article paru en 1893 dans les *Communications de la Société mathématique de Kharkow*.

Quantum chaos

Quantum dynamics unitary and linear: two initially close states will remain close during the time evolution.

Consider a thermodynamic quantum system with $T=\beta^{-1}$, and two (simple) Hermitian operators V , W



$$C(t) = -\left\langle \left[W(t), V(0)\right]^2 \right\rangle_\beta$$

$\langle \cdot \rangle_\beta = Z^{-1} Tr\left[e^{-\beta H} \cdot\right]$ thermal average

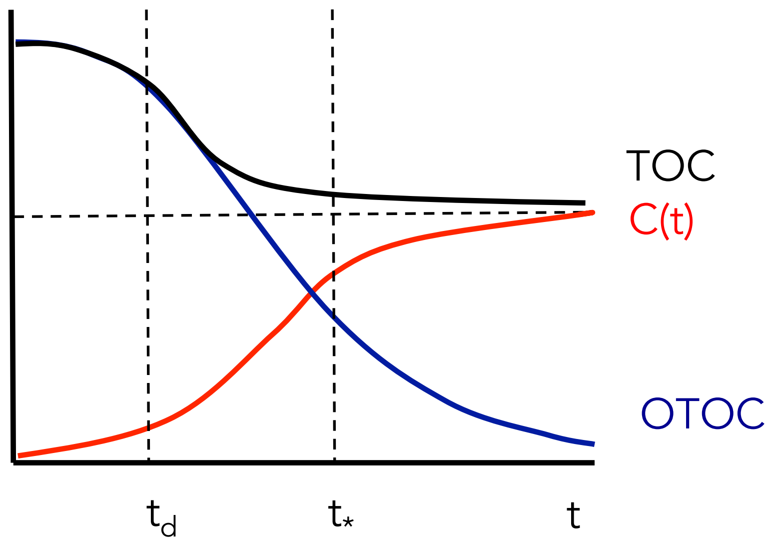
$\langle V \rangle_\beta = \langle W \rangle_\beta = 0$

C(t) measures the effect of the perturbation induced by V on later measurements of W

classical analog: $\dfrac{\partial q(t)}{\partial q(0)} = \{q(t), p(0)\}$ measures the sensitivity of a classical system evolution to the initial conditions

$$C(t) = -\langle VWVW \rangle_\beta - \langle WVWV \rangle_\beta$$ Out-of-Time Order (OTOC)

$$+\langle VWWV \rangle_\beta + \langle WVVW \rangle_\beta$$ Time Order Correlator (TOC)



t_d dissipation time: decay time of the two-point functions <V(t)V(0)>, <W(t)W(0)>

t_* scrambling time: time scale needed for a perturbation involving a few dof of the system to spread among all dof

$t \gg t_* \gg t_d$ OTOC small

$$C(t) \to 2\langle WW\rangle_\beta \langle VV\rangle_\beta$$

$t_d < t < t_*$ $C(t) \approx \varepsilon \, e^{\lambda_L t}$ λ_L Lyapunov exponent

Bound on chaos (MSS)

J. Maldacena, S.H. Shenker, D. Stanford, JHEP 08 (2016) 106

$$\lambda_L \leq \frac{2\pi}{\beta} = 2\pi T$$

saturated in conformal field theories by thermal states dual to AdS black holes

Gravitational derivation: time-ordered high-energy bulk scattering of particle excitations created by the insertion of the operators V and W

S.H. Shenker, D. Stanford, JHEP 1505 (2015) 132

MSS bound conjectured to be universal

Y. Sekino, L. Susskind, JHEP 10 (2008) 065; L. Susskind arXiv:1101.6048; S.H.Shenker, D. Stanford, JHEP 03 (2014) 067; A. Kitaev, KITP Symposium (2014); J. Polchinski, arXiv:1505.08108;

Bound on chaos (MSS)

J. Maldacena, S.H. Shenker, D. Stanford, JHEP 08 (2016) 106

$$\lambda_L \leq \frac{2\pi}{\beta} = 2\pi T$$

Analytic properties of the function

$$F(t) = Tr\left[yV(0)yW(t)yV(0)yW(t)\right]$$

$$F_d = Tr\left[y^2Vy^2V\right]Tr\left[y^2Wy^2W\right] \quad \text{disconnected}$$

$$y^4 = \frac{1}{Z}e^{-\beta H}$$

- F(t) real
- $F(t+i\tau)$ analytic in the strip $(t,+\beta/4)$, $(t,-\beta/4)$
- $|F(t+i\tau)| < F_d$

Pick-Schwarz theorem

$$\frac{\partial}{\partial t}\left(F_d - F(t)\right) \leq \frac{2\pi}{\beta}\left(F_d - F(t)\right)$$

"Global symmetry and maximal chaos"

I. Halder, arXiv:1908.05281

quantum system with a continuum global symmetry

Q global symmetry generator   [Q,H]=0

$$C(t) = -\left\langle \left[W(t), V(0) \right]^2 \right\rangle_{\beta,\mu} \qquad \langle \cdot \rangle_{\beta,\mu} = Z[T,\mu]^{-1} Tr\left[e^{-\beta H+\beta\mu Q} \cdot \right]$$

Analytic properties of the function

$$F(t) = Tr\left[yzV(0)yzW(t)yzV(0)yzW(t) \right]$$

$$y^4 = \frac{1}{Z} e^{-\beta H} \qquad z^4 = e^{\beta\mu Q}$$

- $F(t+i\tau)$ analytic in the strip $(t,+\beta_{eff}/4)$, $(t,-\beta_{eff}/4)$

new proposed bound

$$\lambda_L \leq \frac{2\pi}{\beta_{eff}} = \frac{2\pi T}{1-\left|\frac{\mu}{\mu_c}\right|}$$

μ chemical potential

μ_c critical value

$\mu \ll \mu_c$

This bound exceeds the MSS bound

Our purpose is to challenge it

dual geometry for a system at finite T and μ : AdS-RN

B.-H. Lee, C. Park, S.-J. Sin, JHEP 07 (2009) 087
Giannuzzi, Nicotri, PC, PRD 83 (2011) 035015, JHEP 05 (2012) 076

$$ds^2 = -r^2 f(r) dt^2 + r^2 d\vec{x}^2 + \frac{1}{r^2 f(r)} dr^2$$

$$f(r) = 1 - \frac{r_H^4}{r^4} - \frac{\mu^2 r_H^2}{r^4} + \frac{\mu^2 r_H^4}{r^6}$$

$$T_H = \frac{r_H}{\pi}\left(1 - \frac{\mu^2}{2 r_H^2}\right) \qquad \mu \le \sqrt{2} r_H$$

μ baryon chemical potential, related to the BH charge: $Q=\mu^2/r_H^2$

dual of heavy quark-antiquark ($Q\bar{Q}$) system: string in the AdS-RN background with endpoints on the boundary

investigate the chaotic behaviour of the string

K.Hashimoto, K.Murata, N.Tanahashi, PRD 98 (2018) 086007

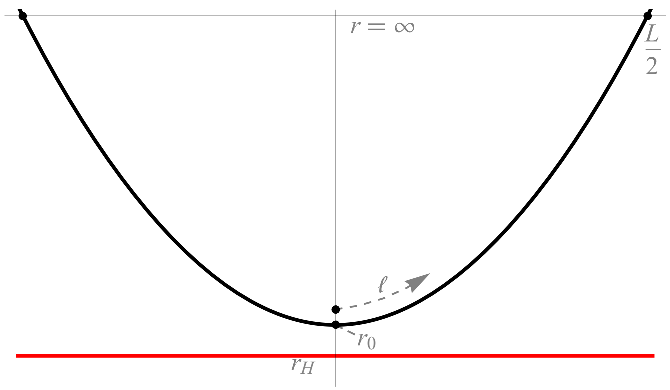
$$ds^2 = -g_{tt}dt^2 + g_{xx}(r)d\vec{x}^2 + g_{rr}(r)dr^2$$

Nambu-Goto $$S = -\frac{1}{2\pi\alpha'}\int d\tau d\sigma \sqrt{\det\left(g_{MN}\partial_a X^M \partial_b X^N\right)}$$

$$X^M = \left(t, x(l), 0, 0, r(l)\right)$$

$$S = -\frac{T}{2\pi\alpha'}\int_{-\infty}^{+\infty} dl \sqrt{F^2(r)x'^2(l) + G^2(r)r'^2(l)}$$

$$F^2(r) = g_{tt}(r)g_{xx}(r) \qquad G^2(r) = g_{tt}(r)g_{rr}(r)$$



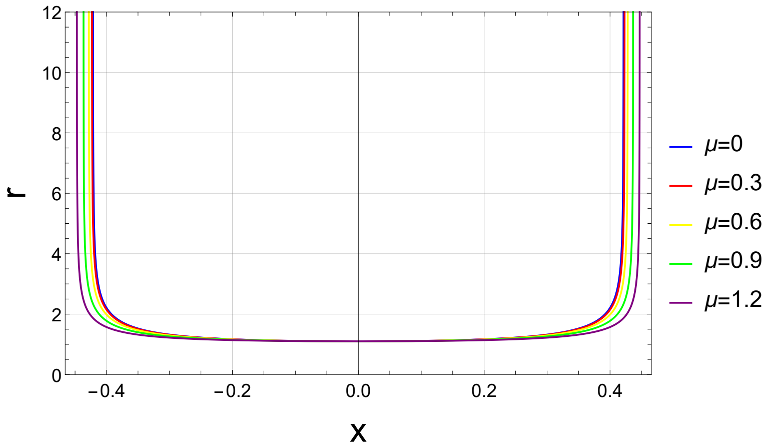
AdS-RN

$$x'(l) = \pm\frac{r'(l)}{\sqrt{\frac{r^4 f(r)}{r_0^4 f(r_0)}\left(r^4 f(r) - r_0^4 f(r_0)\right)}}$$

$$\boxed{r' = \pm\frac{\sqrt{r^4 f(r) - r_0^4 f(r_0)}}{r} \qquad x' = \pm\frac{\sqrt{r_0^4 f(r_0)}}{r^3\sqrt{f(r)}}}$$

$$t^M = \left(0, x'(l), 0, 0, r'(l)\right)$$ unit vector tangent to the string at the point l

$$g_{MN}t^M t^N = g_{xx}(r)x'^2(l) + \frac{1}{r^2 f(r)}r'^2(l) = 1$$



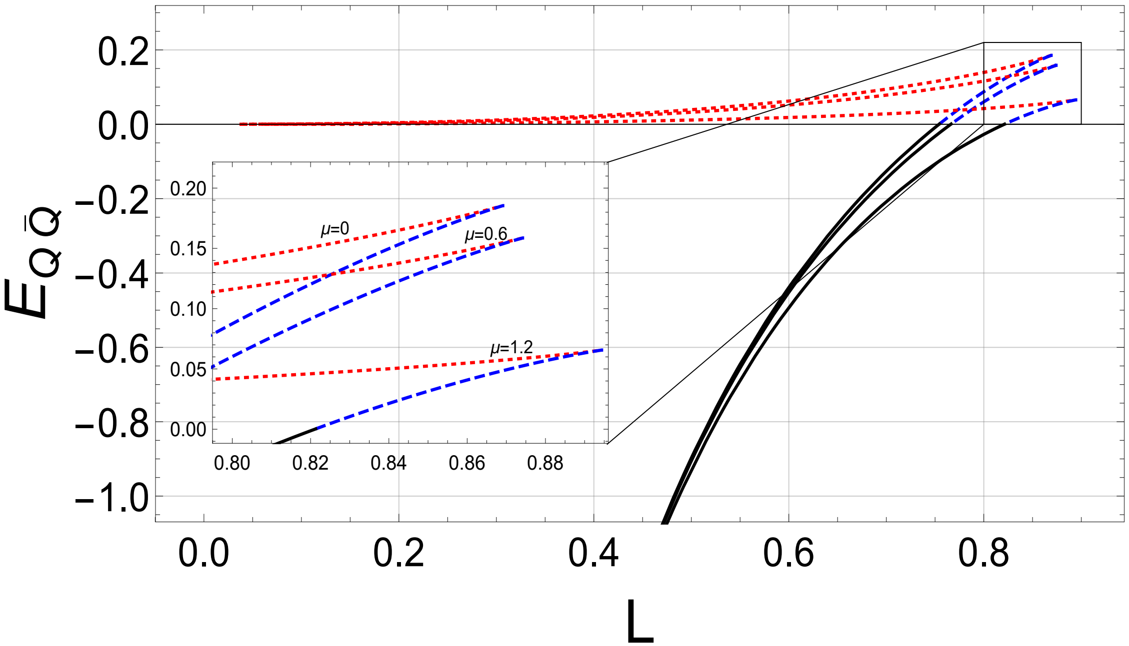
$r_H=1$
$r_0=1.1$

$$L(r_0) = 2\int_{r_0}^{\infty} dr \frac{r_0^2\sqrt{f(r_0)}}{r^2\sqrt{f(r)}\sqrt{r^4 f(r) - r_0^4 f(r_0)}}$$

$$E_{Q\bar{Q}}(r_0) = \frac{1}{\pi\alpha'}\left(\int_{r_0}^{\infty} dr \frac{r^2\sqrt{f(r)}}{\sqrt{r^4 f(r) - r_0^4 f(r_0)}} - \int_{r_H}^{\infty} dr\right) \qquad \text{(regularized)}$$

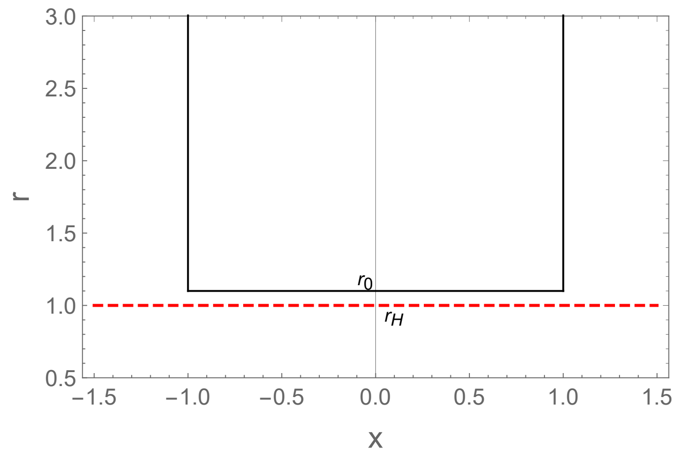
E_{QQ} vs L not single valued function ->

stable and unstable configurations



model: square string

$$S = -\frac{1}{2\pi\alpha'}\int \mathrm{d}t\mathrm{d}r\sqrt{1+\acute{x}^2\left(r^4 f(r) - \frac{1}{f(r)}\dot{r}^2\right)}.$$



static solution

$$X^M = (t, x(r), 0, 0, r)$$

$$S^{reg} = -\frac{T}{2\pi\alpha'}\left(Lr_0^2\sqrt{f(r_0)} - 2(r_0 - r_H)\right)$$

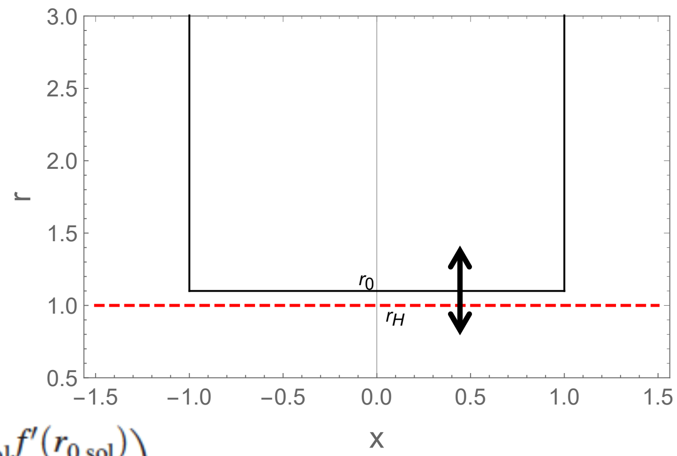
$$E = -\frac{S^{reg}}{T}$$

$$2Lr_0\sqrt{f(r_0)} + \frac{r_0^2 L}{2\sqrt{f(r_0)}}\frac{\partial f(r_0)}{\partial r_0} - 2 = 0$$

$$r_0 \to r_H$$
$$L \to 0$$

$$\longrightarrow \quad \boxed{r_{0,sol} = r_H\left(1 + \frac{L^2}{8}\left(2r_H^2 - \mu^2\right)\right)}$$

$$\mathcal{L} = L\sqrt{r_0^4 f(r_0) - \frac{1}{f(r_0)}\dot{r}_0^2} - 2(r_0 - r_H)$$



small perturbation $\quad r_0(t) = r_{0,sol} + \delta r(t)$

$$\mathcal{L} \approx -2r_{0,\mathrm{sol}} + 2r_H + Lr_{0,\mathrm{sol}}^2\sqrt{f(r_{0,\mathrm{sol}})} + \delta r(t)\left(-2 + 2Lr_{0,\mathrm{sol}}\sqrt{f(r_{0,\mathrm{sol}})} + \frac{Lr_{0,\mathrm{sol}}^2 f'(r_{0,\mathrm{sol}})}{2\sqrt{f(r_{0,\mathrm{sol}})}}\right)$$
$$+ L\delta r(t)^2\left(\sqrt{f(r_{0,\mathrm{sol}})} + \frac{r_{0,\mathrm{sol}} f'(r_{0,\mathrm{sol}})}{\sqrt{f(r_{0,\mathrm{sol}})}} - \frac{r_{0,\mathrm{sol}}^2 f'(r_{0,\mathrm{sol}})^2}{8f(r_{0,\mathrm{sol}})^{3/2}} + \frac{r_{0,\mathrm{sol}}^2 f''(r_{0,\mathrm{sol}})}{4\sqrt{f(r_{0,\mathrm{sol}})}}\right) - \delta\dot{r}(t)^2 \frac{L}{2r_{0,\mathrm{sol}}^2 f(r_{0,\mathrm{sol}})^{3/2}}$$

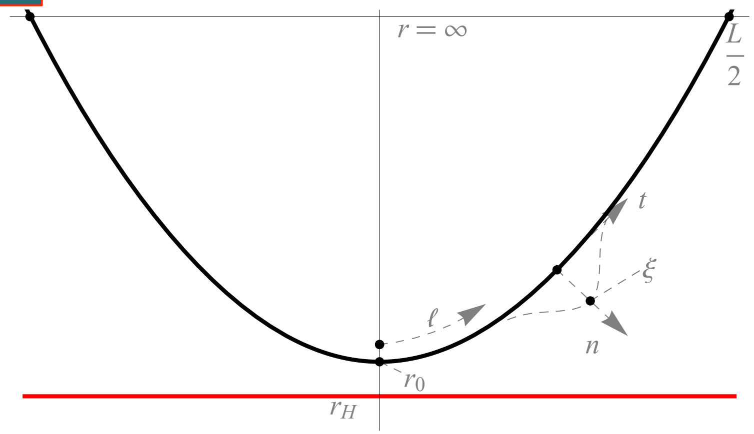
solution $\quad \boxed{\delta r(t) = A\exp(\lambda t) + B\exp(-\lambda t)}$

$$\begin{array}{l} r_0 \to r_H \\ L \to 0 \end{array} \longrightarrow \lambda = 2r_H\left(1 - \frac{\mu^2}{2r_H^2}\right)\left(1 - \frac{L^2}{4}\left(2r_H^2 - \mu^2\right)\right)$$

$$\boxed{\lambda = 2\pi T_H\left(1 - \frac{L^2}{4}\pi^2 T_H^2\left(1 + \sqrt{1 + \frac{2\mu^2}{\pi^2 T_H^2}}\right)\right)} \leq 2\pi T_H$$

λ decreasing function of μ

perturbed string



$$n^M = \left(0, n^x(l), 0, 0, n^r(l)\right)$$

unit vector orthogonal to t
at the point l

$$g_{rr}(r)\left(n^r\right)^2 + g_{xx}(r)\left(n^x\right)^2 = 1$$

$$r'(l) g_{rr}(r) n^r + x'(l) g_{xx}(r) n^x = 0$$

$$n^x(l) = \sqrt{\frac{g_{rr}}{g_{xx}}}\; r'(l) \qquad n^r(l) = -\sqrt{\frac{g_{xx}}{g_{rr}}}\; x'(l)$$

t-dependent perturbation along n

$$r(t,l) = r_{BG}(l) + \xi(t,l)\; n^r(l)$$

$$x(t,l) = x_{BG}(l) + \xi(t,l)\; n^x(l)$$

expand the NG action in ξ

quadratic term

$$S^{(2)} = \frac{1}{2\pi\alpha'}\int dt \int_{-\infty}^{+\infty} dl \left(C_{tt}(\dot{\xi})^2 + C_{ll}(\xi')^2 + C_{00}\xi^2 \right)$$

$$C_{tt}(l) = \frac{1}{2r_{BG}\sqrt{f(r_{BG})}},$$

$$C_{ll}(l) = -\frac{1}{4C_{tt}(l)},$$

$$C_{00}(l) = \frac{1}{4r_{BG}^3 f(r_{BG})^{3/2}}\{(-2r_{BG}^4 f(r_{BG})^2(2f(r_{BG}) + r_{BG}f'(r_{BG})) + r_0^4 f(r_0)(4f(r_{BG})^2 + r_{BG}^2 f'(r_{BG})^2 + r_{BG}f(r_{BG})(f'(r_{BG}) - r_{BG}f''(r_{BG})))\}.$$

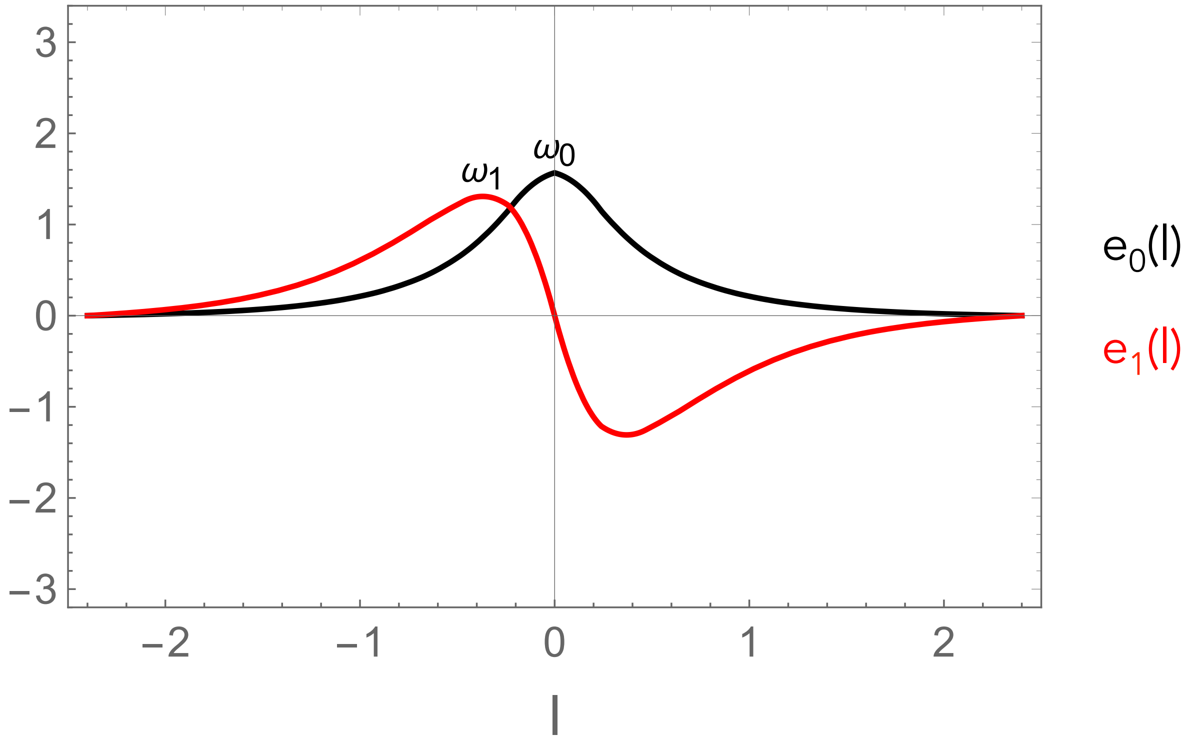
$$C_{tt}\ddot{\xi} + \partial_l\left(C_{ll}\xi'\right) - C_{00}\xi = 0$$

$$\xi(t,l) = \xi(l)\ e^{i\omega t}$$

Sturm-Liouville

$$\partial_l\left(C_{ll}\xi'\right) - C_{00}\xi = \omega^2 C_{tt}\xi$$

$$\xi(l)_{l\to\pm\infty} \to 0$$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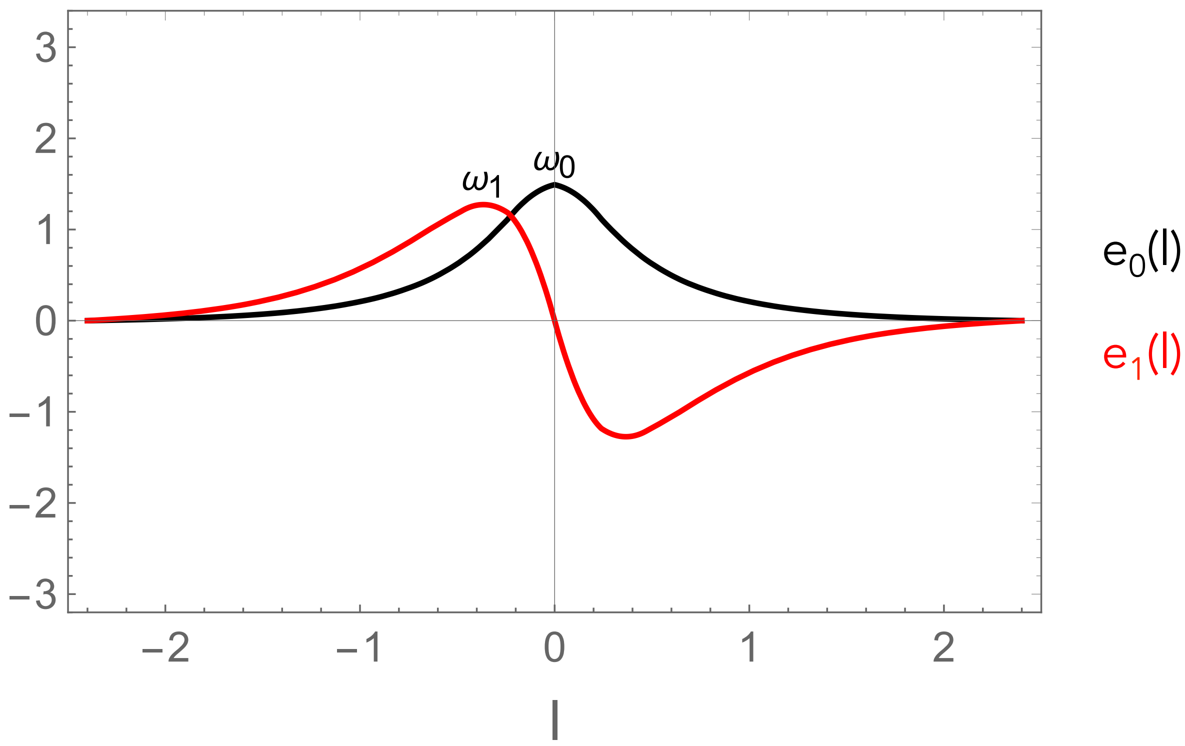

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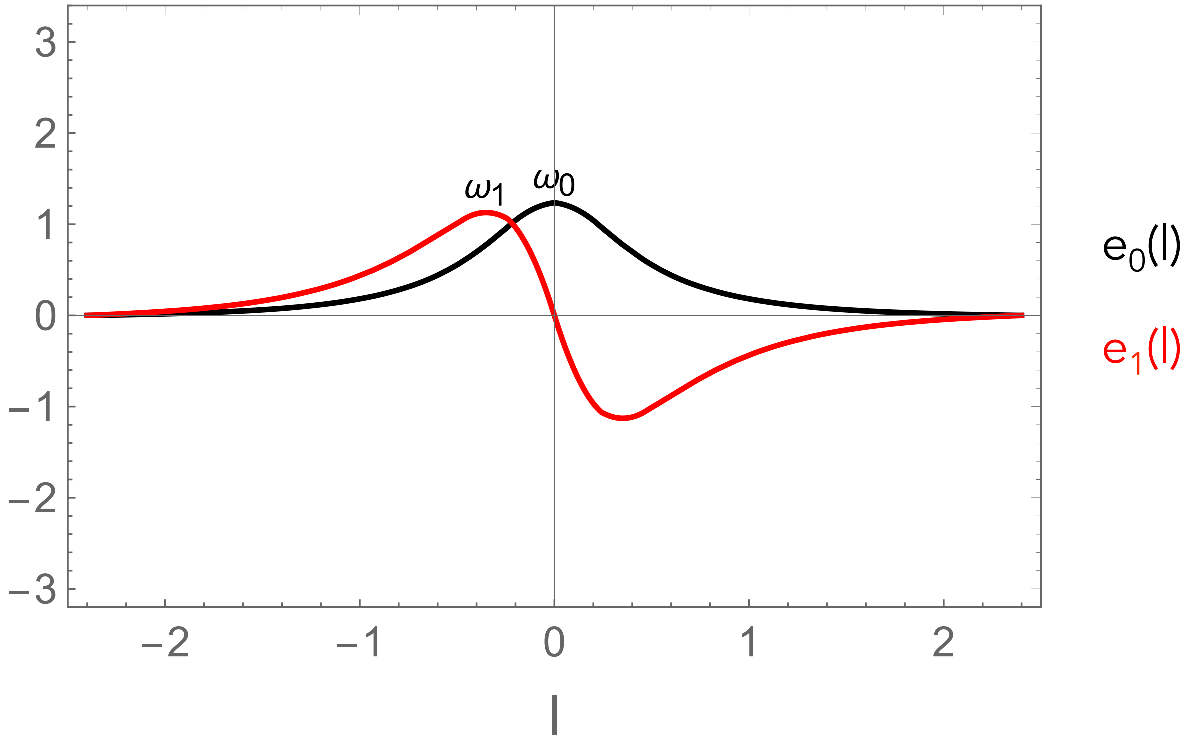

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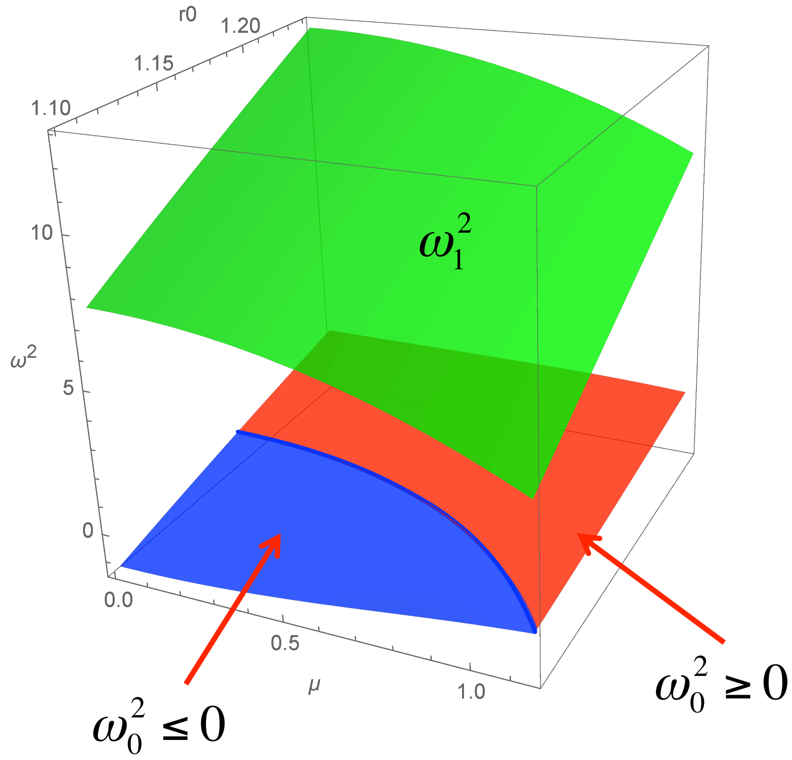
$e_0(l)$
$e_1(l)$

$r_0 = 1.1$			$r_0 = 1.172$		
μ	ω_0^2	ω_1^2	μ	ω_0^2	ω_1^2
0	−1.370	7.638	0	−0.064	10.458
0.3	−1.235	7.418	0.3	−0.005	10.239
0.6	−0.870	6.748	0.6	0.148	9.574
0.9	−0.388	5.605	0.9	0.324	8.428
1.2	0.006	3.938	1.2	0.397	6.735
$r_0 = 1.18$			$r_0 = 5$		
μ	ω_0^2	ω_1^2	μ	ω_0^2	ω_1^2
0	0.071	10.754	0	81.726	275.477
0.3	0.124	10.537	0.3	81.706	275.458
0.6	0.258	9.874	0.6	81.648	275.400
0.9	0.406	8.733	0.9	81.551	275.303
1.2	0.449	7.046	1.2	81.415	275.168



cubic term $$S^{(3)} = \frac{1}{2\pi\alpha'} \int \mathrm{d}t \int_{-\infty}^{\infty} \mathrm{d}l \left\{ D_0 \xi^3 + D_1 \xi \acute{\xi}^2 + D_2 \xi \dot{\xi}^2 \right\},$$

expand ξ over the first two eigenfunctions $\xi(t,l) = c_0(t)\, e_0(l) + c_1(t)\, e_1(l)$

$$S^{(3)} = \frac{1}{2\pi\alpha'} \int \mathrm{d}t \int_{-\infty}^{\infty} \mathrm{d}l \{ (D_0 e_0^3 + D_1 e_0 \acute{e}_0^2) c_0^3(t) + (3D_0 e_0 e_1^2 + D_1 (2\acute{e}_0 e_1 \acute{e}_1 + e_0 \acute{e}_1^2)) c_0(t) c_1^2(t) + D_2 (e_0 e_1^2 c_0 \dot{c}_1^2 + e_0^3 e_1^2 c_0 \dot{c}_0^2 + 2 e_0 e_1^2 \dot{c}_0 c_1 \dot{c}_1) \}.$$

integrate over l in $S^{(2)}+S^{(3)}$

$$\boxed{S^{(2)} + S^{(3)} = \frac{1}{2\pi\alpha'} \int \mathrm{d}t \left[\sum_{n=0,1} (\dot{c}_n^2 - \omega_n^2 c_n^2) + K_1 c_0^3 + K_2 c_0 c_1^2 + K_3 c_0 \dot{c}_0^2 + K_4 c_0 \dot{c}_1^2 + K_5 \dot{c}_0 c_1 \dot{c}_1 \right]}$$

solve the eom for c_n

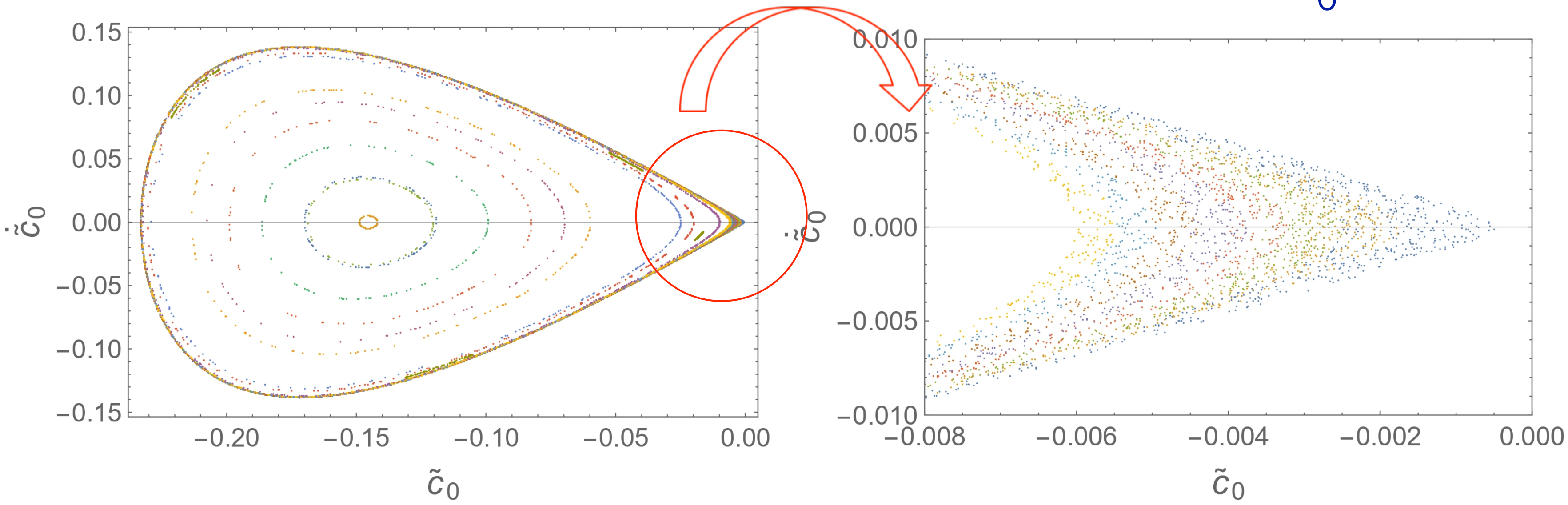
	μ	K_1	K_2	K_3	K_4	K_5
$r_0 = 1.1$						
	0	11.36	21.72	10.58	3.37	6.73
	0.6	7.22	16.76	9.98	3.44	6.88
	1.2	0.81	5.84	8.29	3.64	7.28
$r_0 = 1.172$	μ	K_1	K_2	K_3	K_4	K_5
	0	7.63	20.61	8.17	2.69	5.39
	0.6	5.13	17.30	8.04	2.81	5.62
	1.2	0.86	9.30	7.81	3.22	6.44
$r_0 = 1.18$	μ	K_1	K_2	K_3	K_4	K_5
	0	7.36	20.64	8.00	2.65	5.29
	0.6	4.97	17.45	7.90	2.76	5.53
	1.2	0.88	9.69	7.76	3.18	6.36
$r_0 = 5$	μ	K_1	K_2	K_3	K_4	K_5
	0	−15.01	560.52	7.44	2.84	5.67
	0.6	−14.88	560.57	7.44	2.84	5.67
	1.2	−14.49	560.73	7.46	2.84	5.69

Poincare′ section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

$\mu=0.0$

$r_0=1.1$

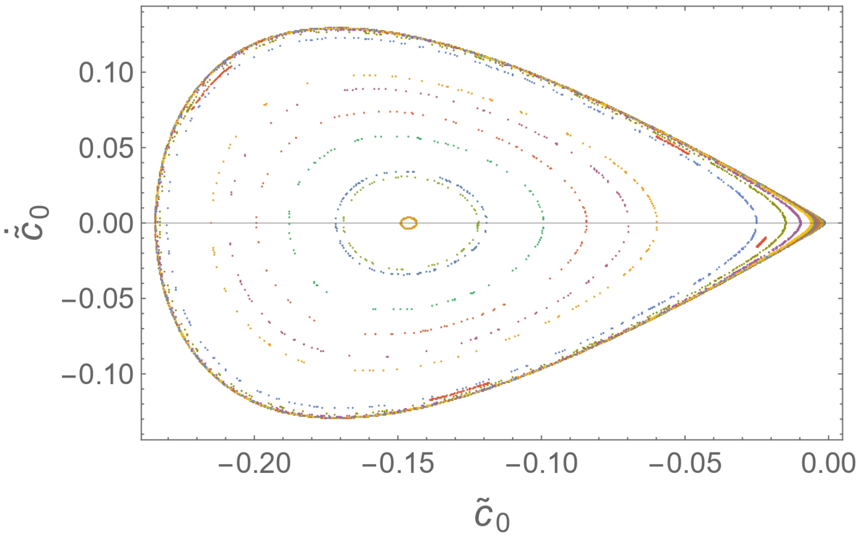


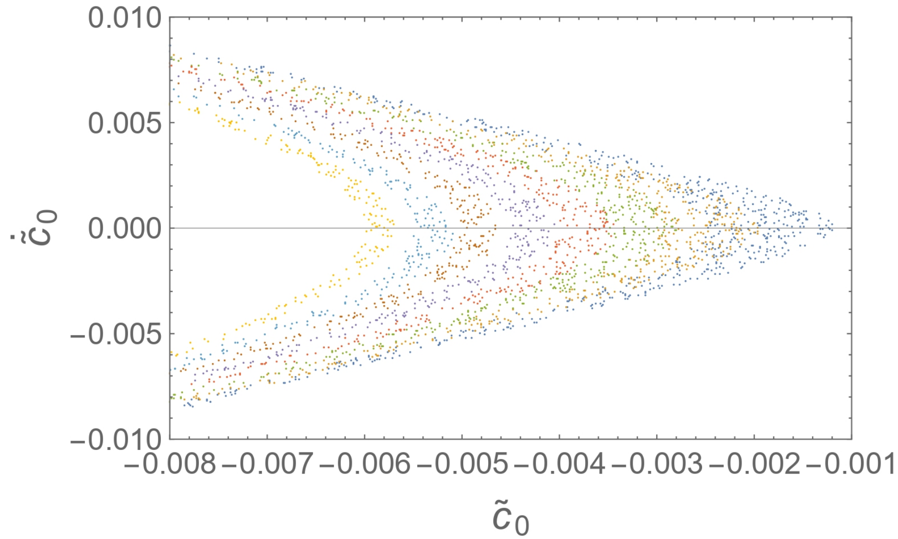
Poincare' section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

$\mu = 0.3$

$r_0 = 1.1$



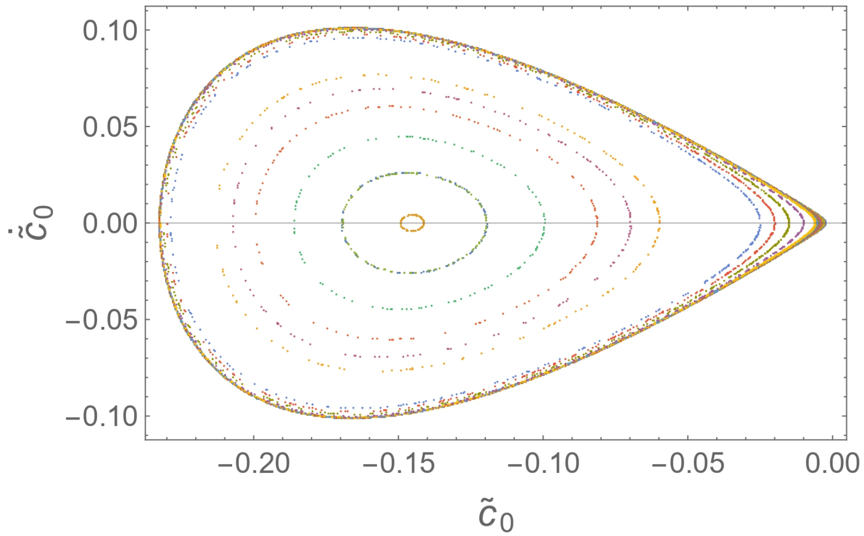


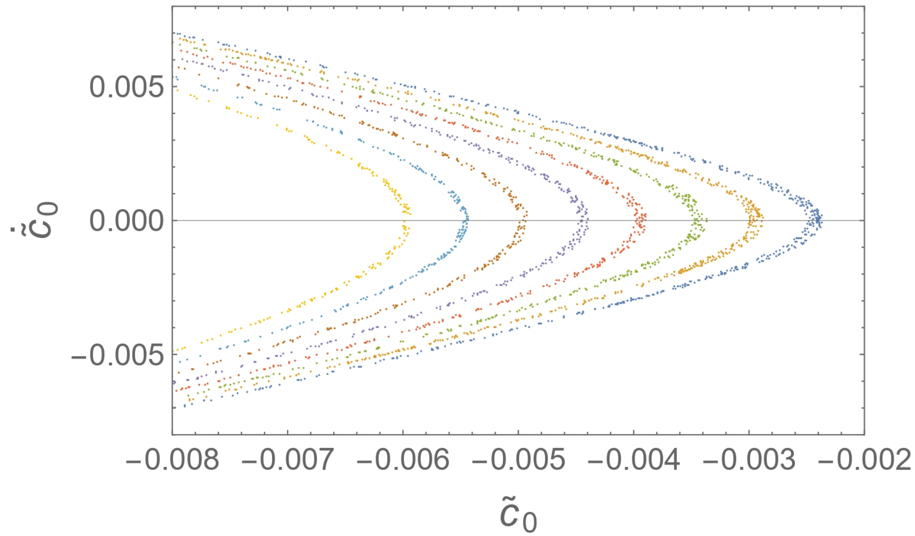
Poincare' section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

μ=0.6

r_0=1.1



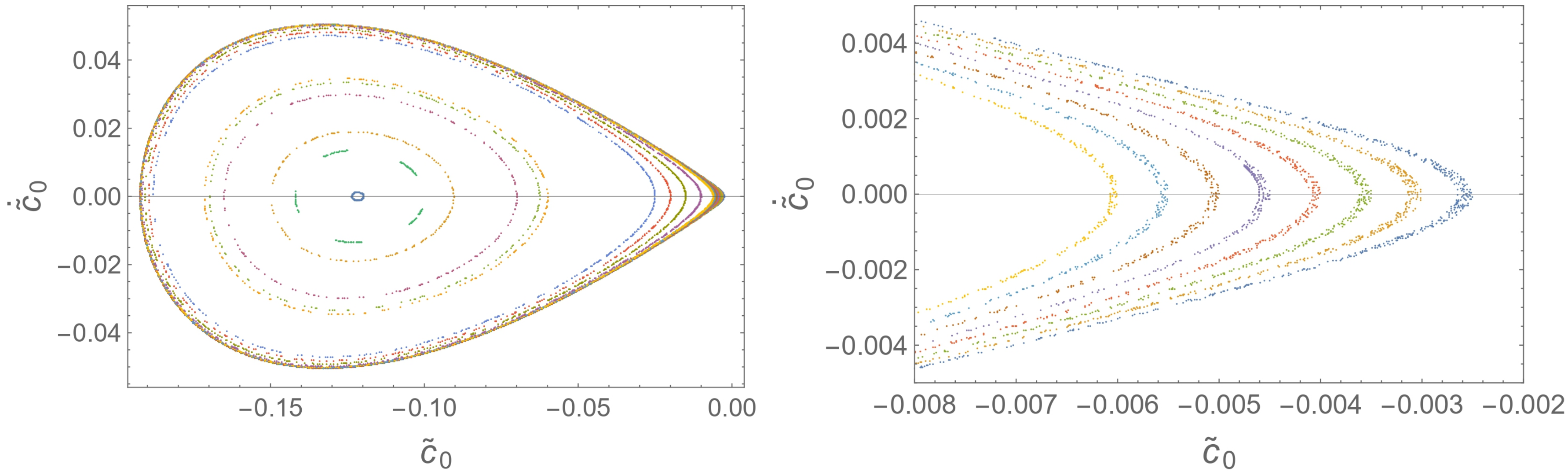


Poincare′ section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

$\mu = 0.9$

$r_0 = 1.1$

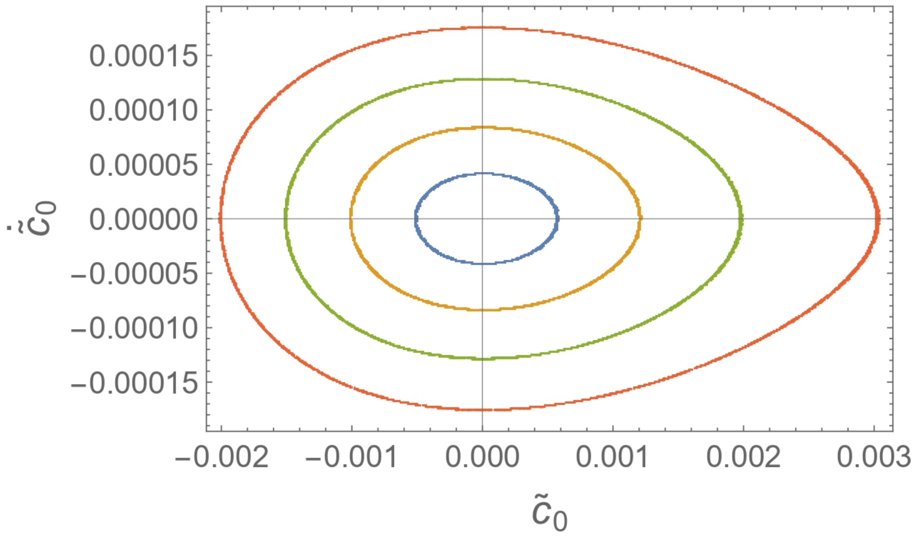


Poincare' section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

$\mu=1.2$

$r_0=1.1$

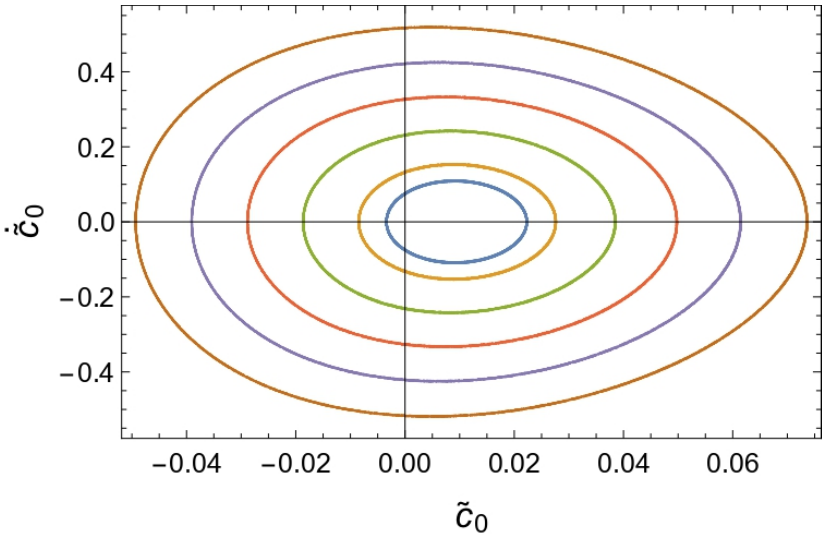


increasing μ -> regular tori

Poincare' section

$\tilde{c}_1(t) = 0 \quad \dot{\tilde{c}}_1(t) \geq 0$

$\mu=0$
$r_0=5$

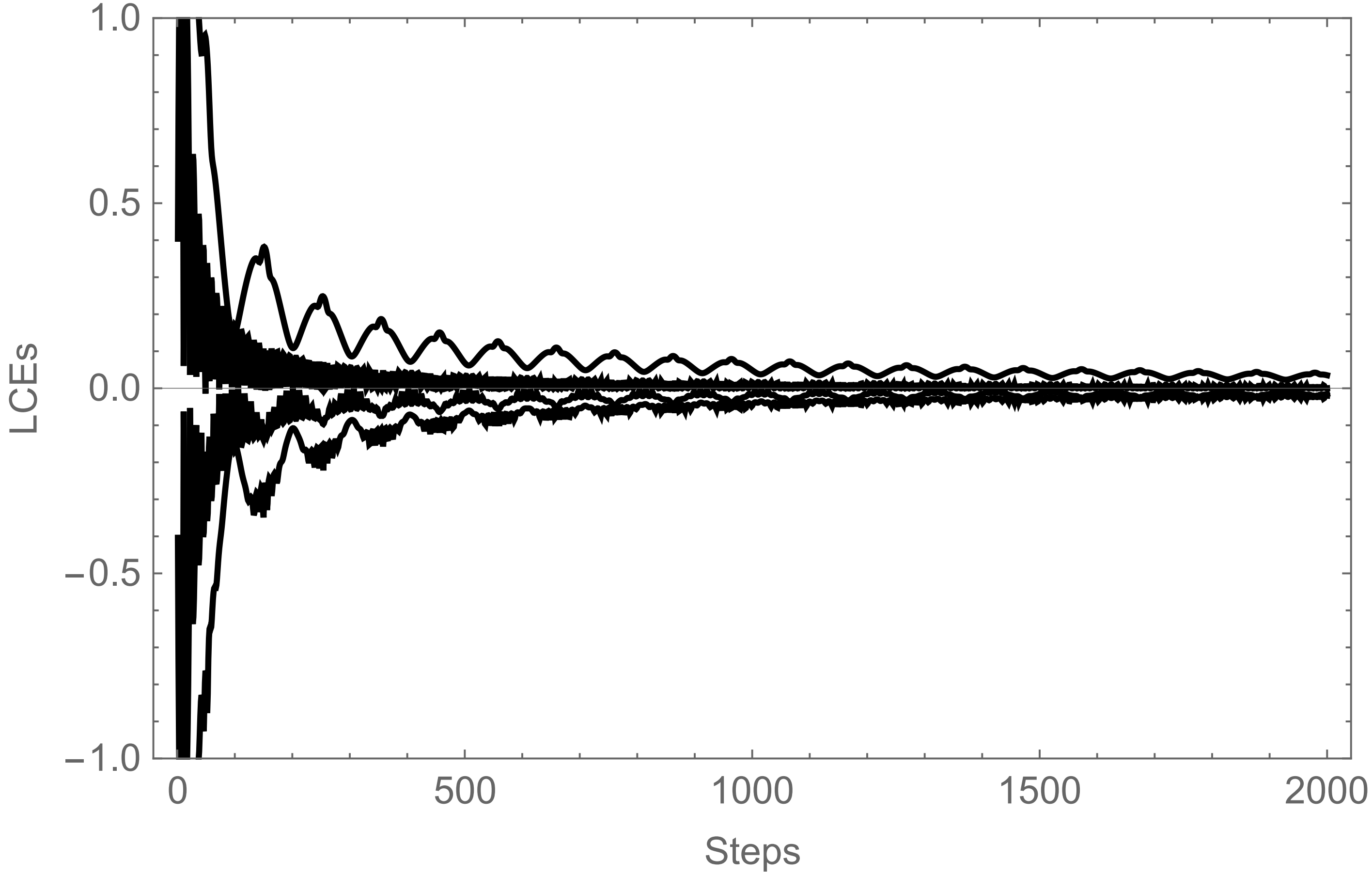


increasing r_0 -> regular tori

Lyapunov exponents (variables c_0 c_1 and their conjugate momenta)

$\mu=0.0$

$r_0=1.1$

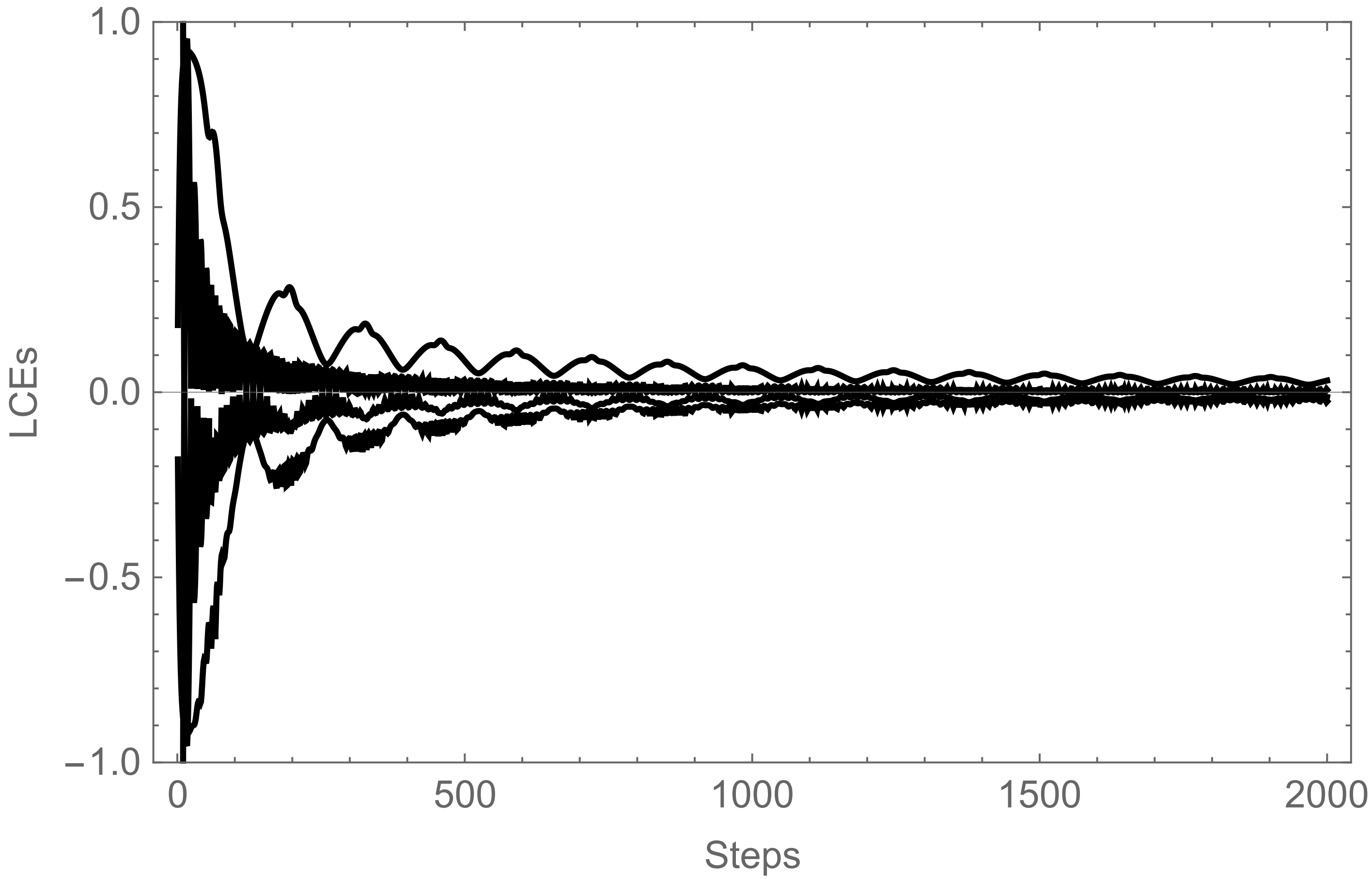


numerical algorithm described in M. Sandri, Math. J. 6 (1996) 78

Lyapunov exponents

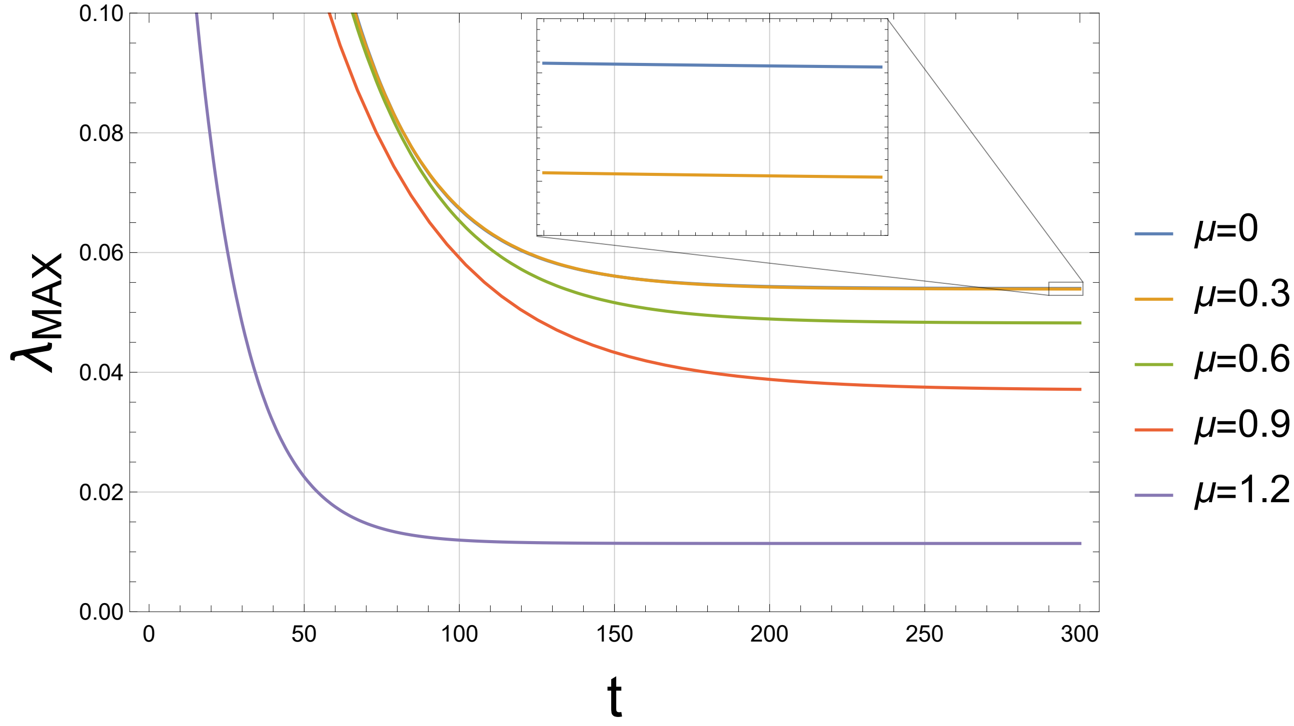
μ=0.6

r_0=1.1

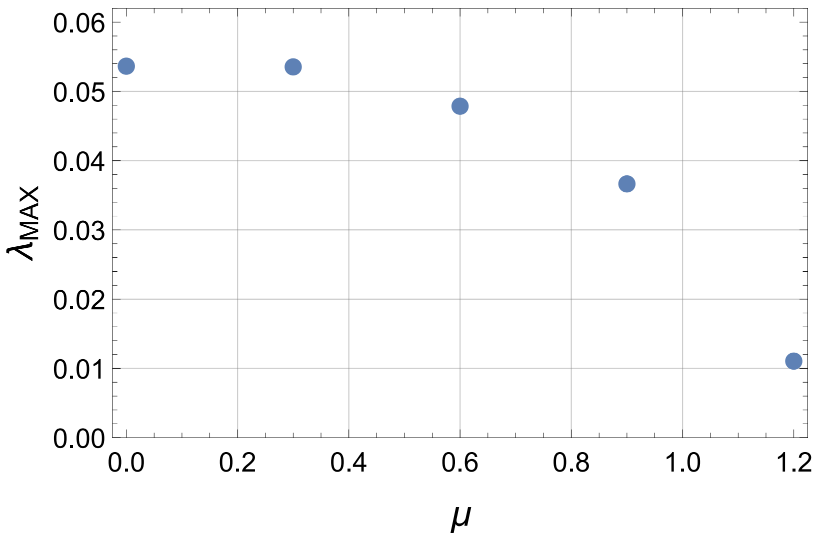


Lyapunov exponents

$r_0=1.1$



Lyapunov exponents



λ_{max} vs μ

$r_0=1.1$

String less chaotic away from the BH horizon

Increasing the baryon chemical potential the system is less chaotic

D.S. Ageev, I. Aref'eva, JHEP 01 (2019) 100

MSS bound satisfied:

$$r_H = 1$$
$$r_0 = 1.1$$
$$\mu = 0.6$$

$$\boxed{\lambda \cong \left(2.7 \times 10^{-2}\right) \times 2\pi T_H}$$

Away from the case of small perturbations, the analysis of the full nonlinear string evolution is not expected to lead to a different conclusion

BH + dilaton

holographic model for confinement-deconfinement transition

Karch et al., PRD 74 (2006)015005
Giannuzzi, Nicotri, PC, PRD 83 (2011) 035015

$$ds^2 = e^{-\frac{c^2}{r^2}}\left(-r^2 f(r)dt^2 + r^2 dx^2 + \frac{1}{r^2 f(r)}dr^2\right)$$

$$f(r) = 1 - \frac{r_H^4}{r^4}$$

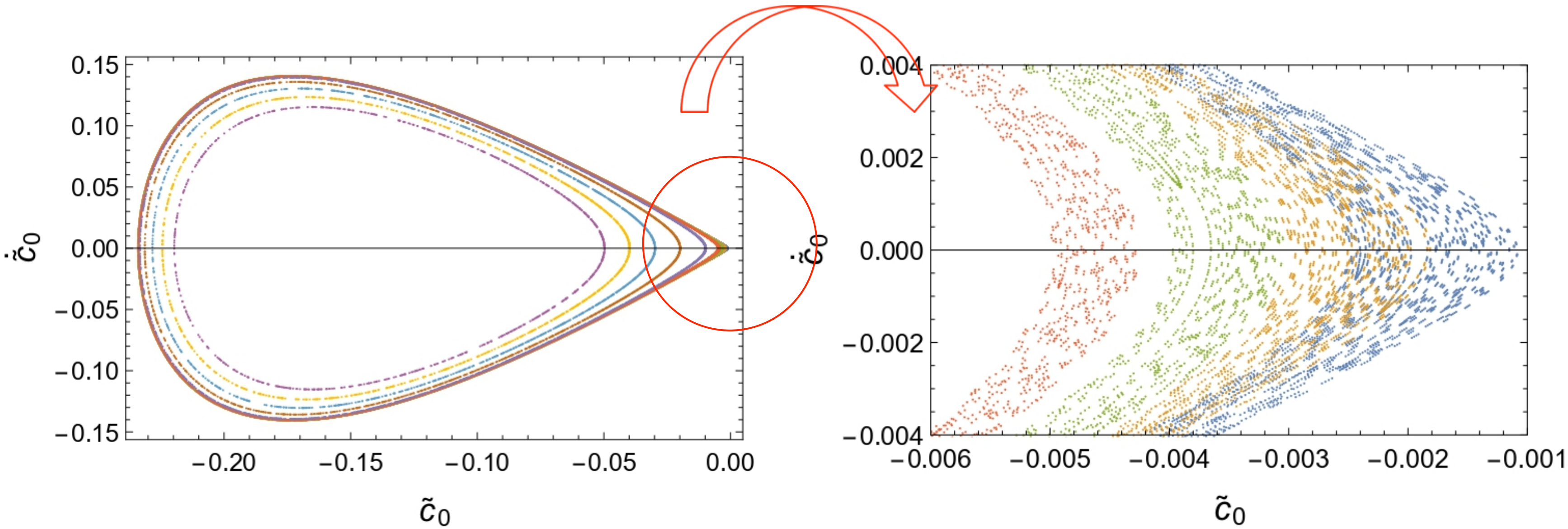
$$T_H = \frac{r_H}{\pi}$$

square string

$$\boxed{\lambda = 2\pi T_H\left(1 - \frac{L^2}{4}\pi T_H r_H\left(1 + \frac{c^2}{r_H^2}\right)\right)} \quad \leq 2\pi T_H$$

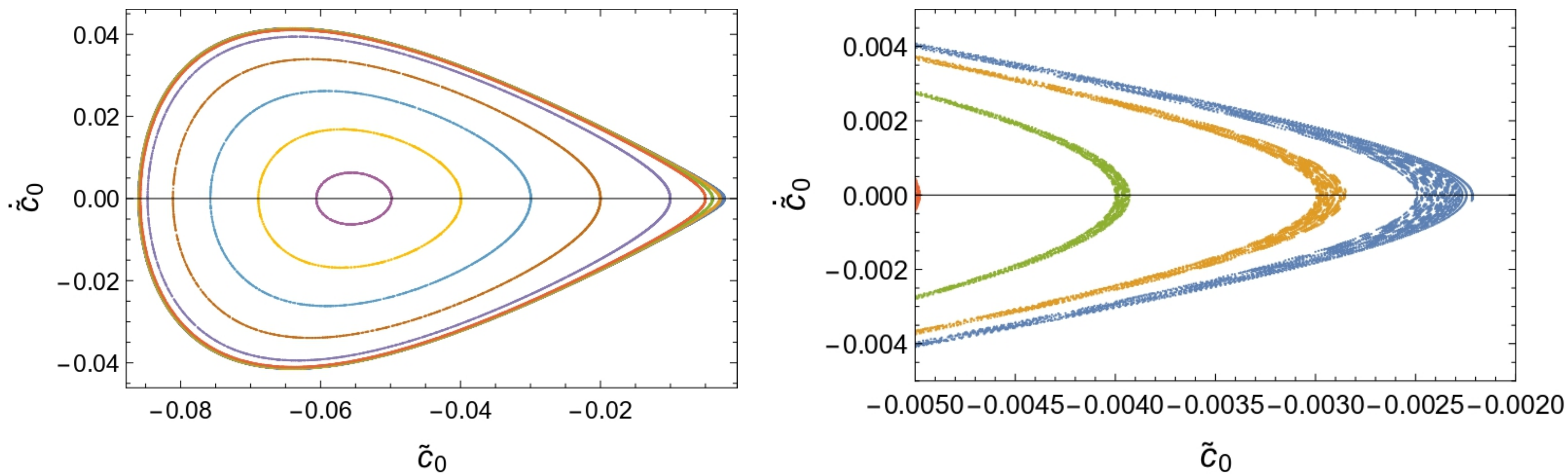
Poincare' section

$r_H=1$
$r_0=1.1$
$c=1$



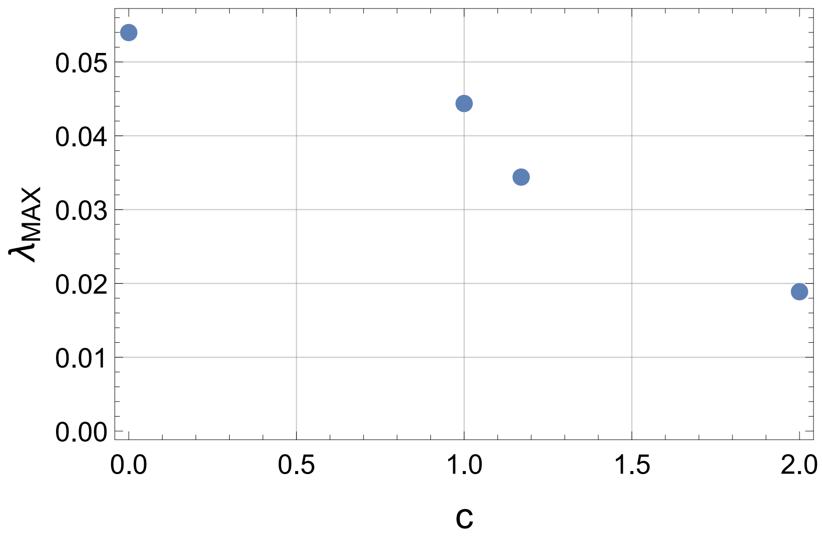
Poincare′ section

$r_H=1$
$r_0=1.1$
$c=2$



Lyapunov exponents

λ_{max} vs c



increasing the dilaton factor the system is less chaotic

Conclusions

confirmation of the MSS bound in all considered cases

$Q\bar{Q}$ system less chaotic

- moving away from the BH horizon
- increasing the baryon chemical potential
- increasing the dilaton factor

no need of relaxing the bound, as in I.Halder, arXiv:1908.05281

Still, there are several other issues deserving a scrutiny, e.g.:

- Wilson and Polyakov loop
- External fields
- Chaos in t-dependent background

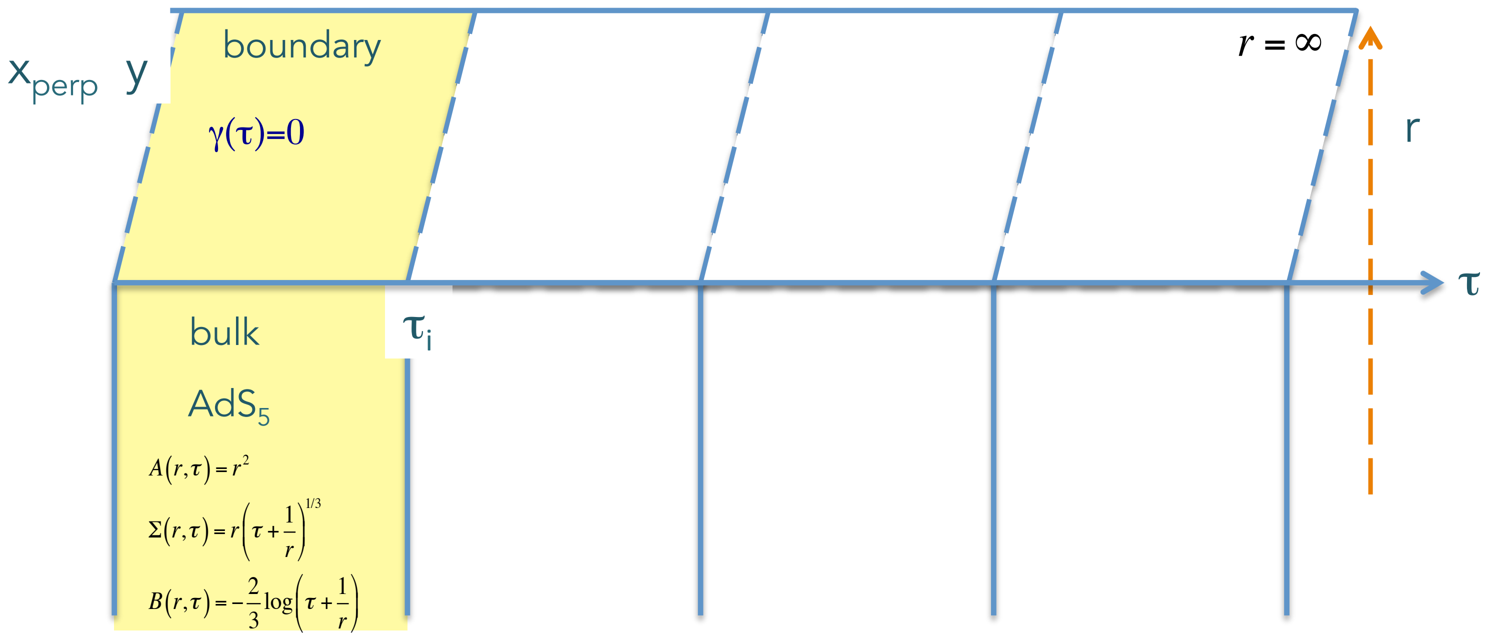
Perspectives: Chaos in t-dependent framework

4D $\quad ds_4^2 = -d\tau^2 + e^{\gamma(\tau)} dx_\perp^2 + \tau^2 e^{-2\gamma(\tau)} dy^2$

5D $\quad ds_5^2 = 2 dr d\tau - A\, d\tau^2 + \Sigma^2 e^B dx_\perp^2 + \Sigma^2 e^{-2B} dy^2$

P. Chesler, L. Yaffe,
PRL 102 (09) 211601, PRD 82 (10) 026006

proper time τ, spatial rapidity y, transverse coordinates x



Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005,
PRD 96 (2017) 034031

Perspectives: Chaos in t-dependent framework

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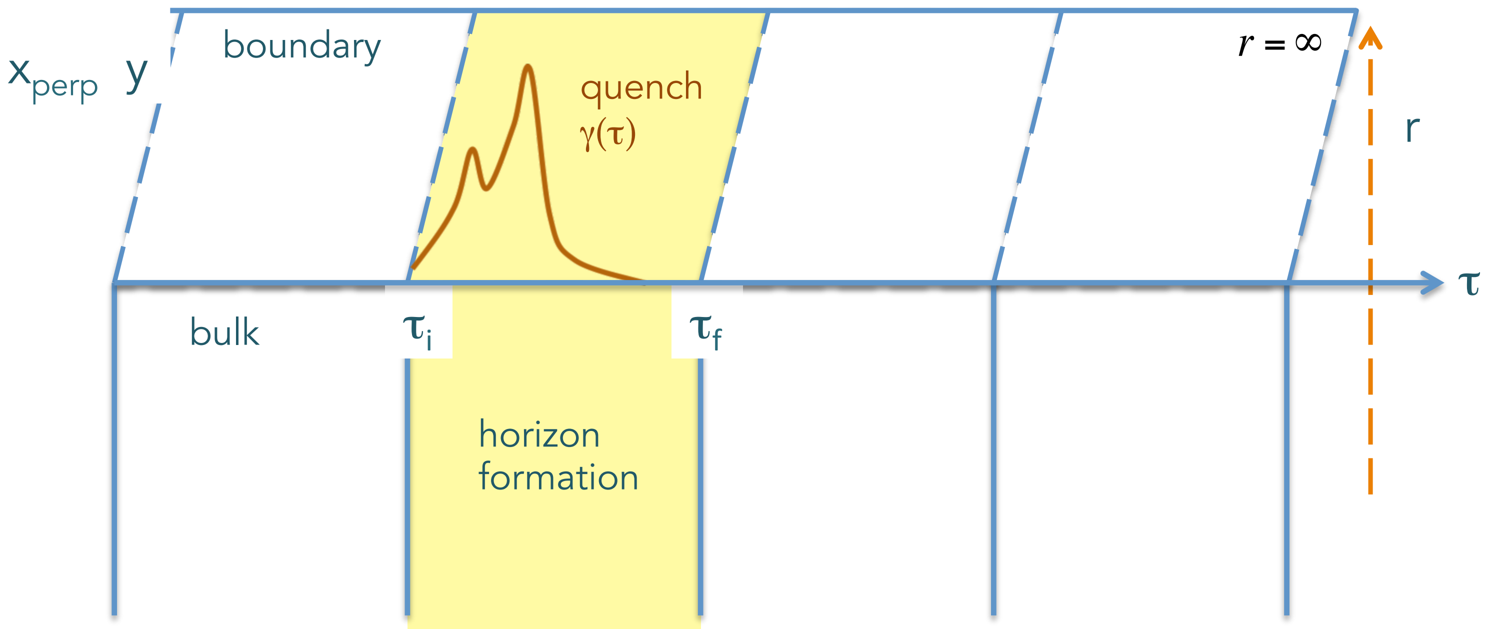

Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005, PRD 96 (2017) 034031

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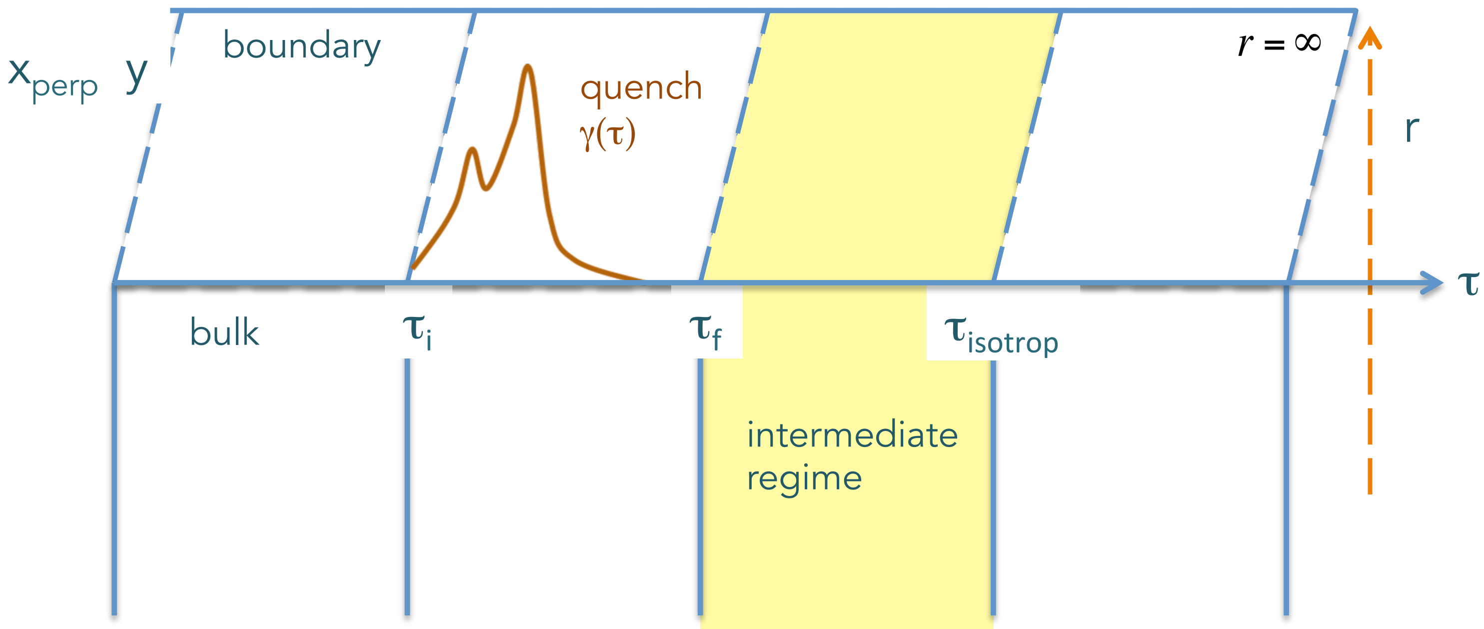

Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005, PRD 96 (2017) 034031

Perspectives: Chaos in t-dependent framework

4D $$ds_4^2 = -d\tau^2 + e^{\gamma(\tau)}dx_\perp^2 + \tau^2 e^{-2\gamma(\tau)}dy^2$$

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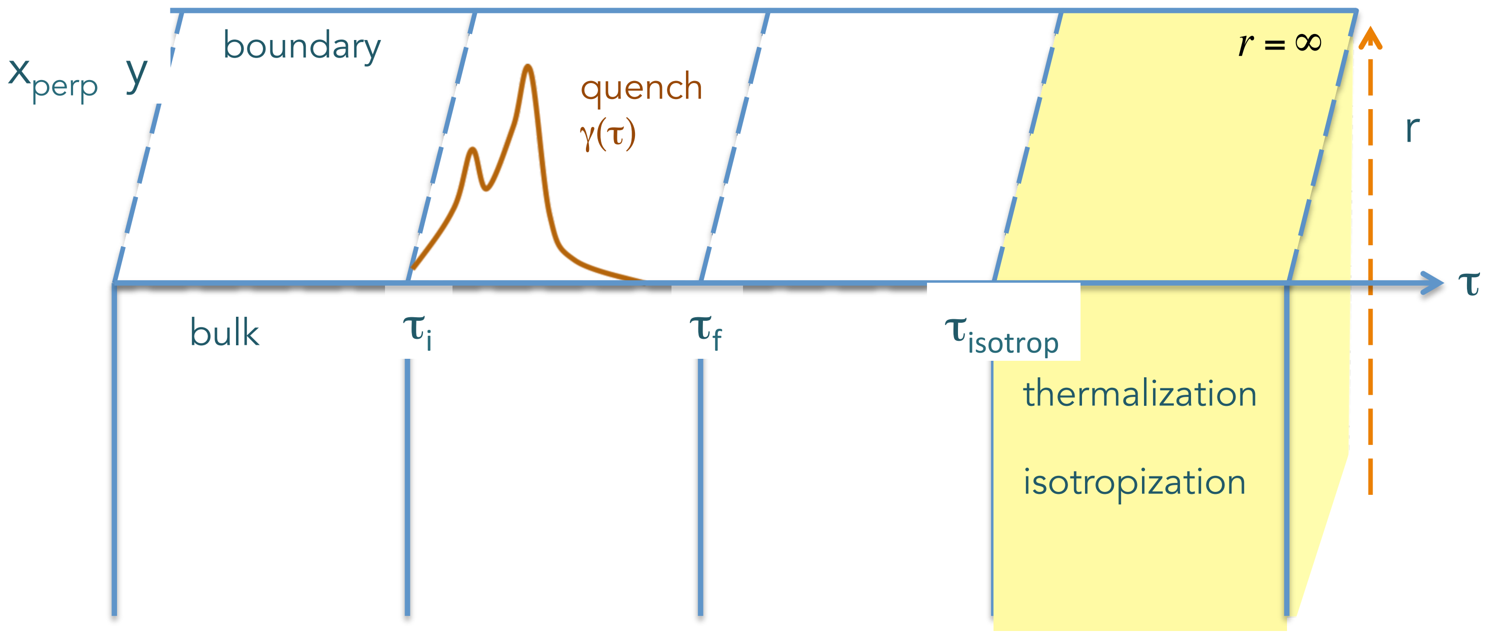
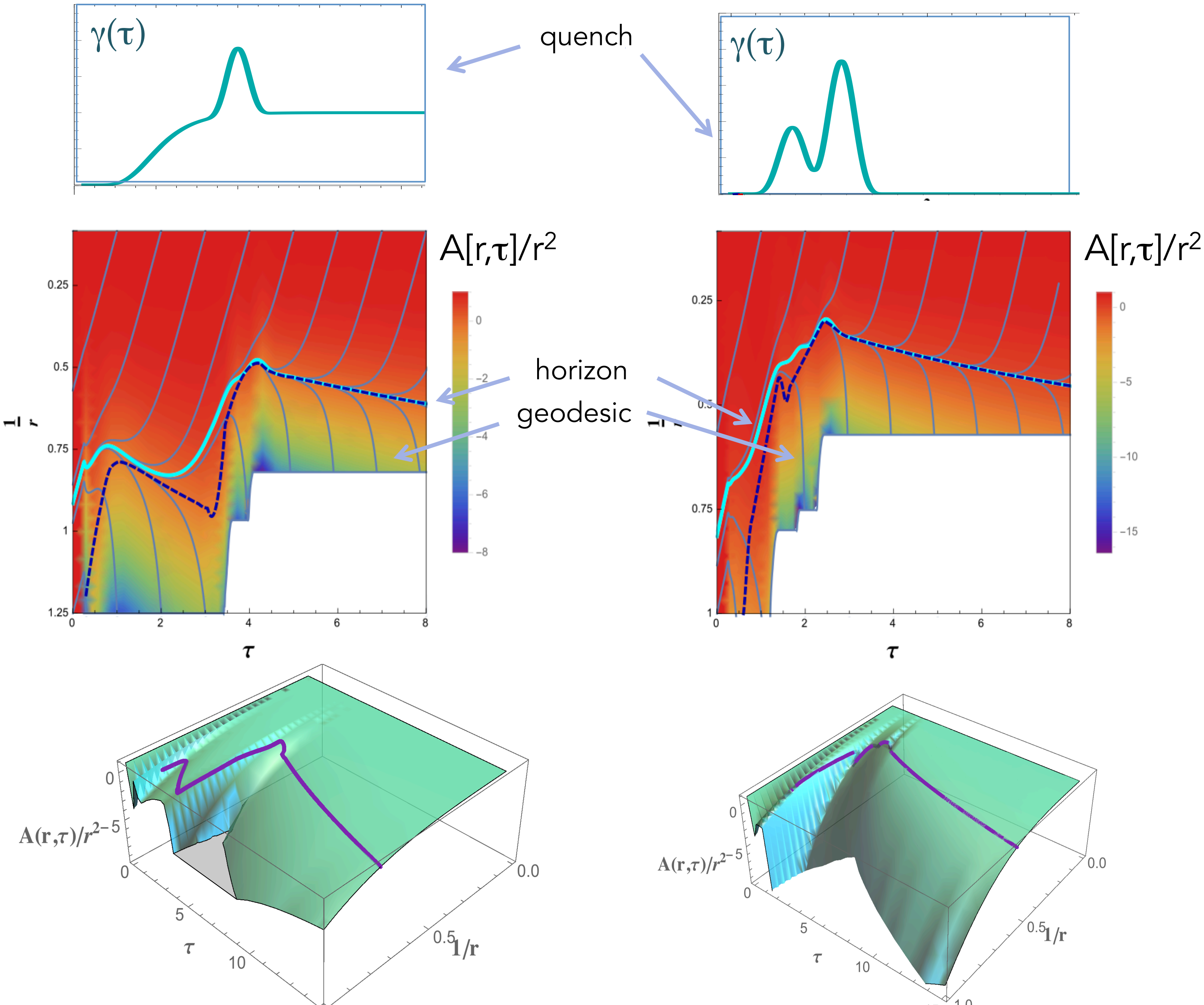
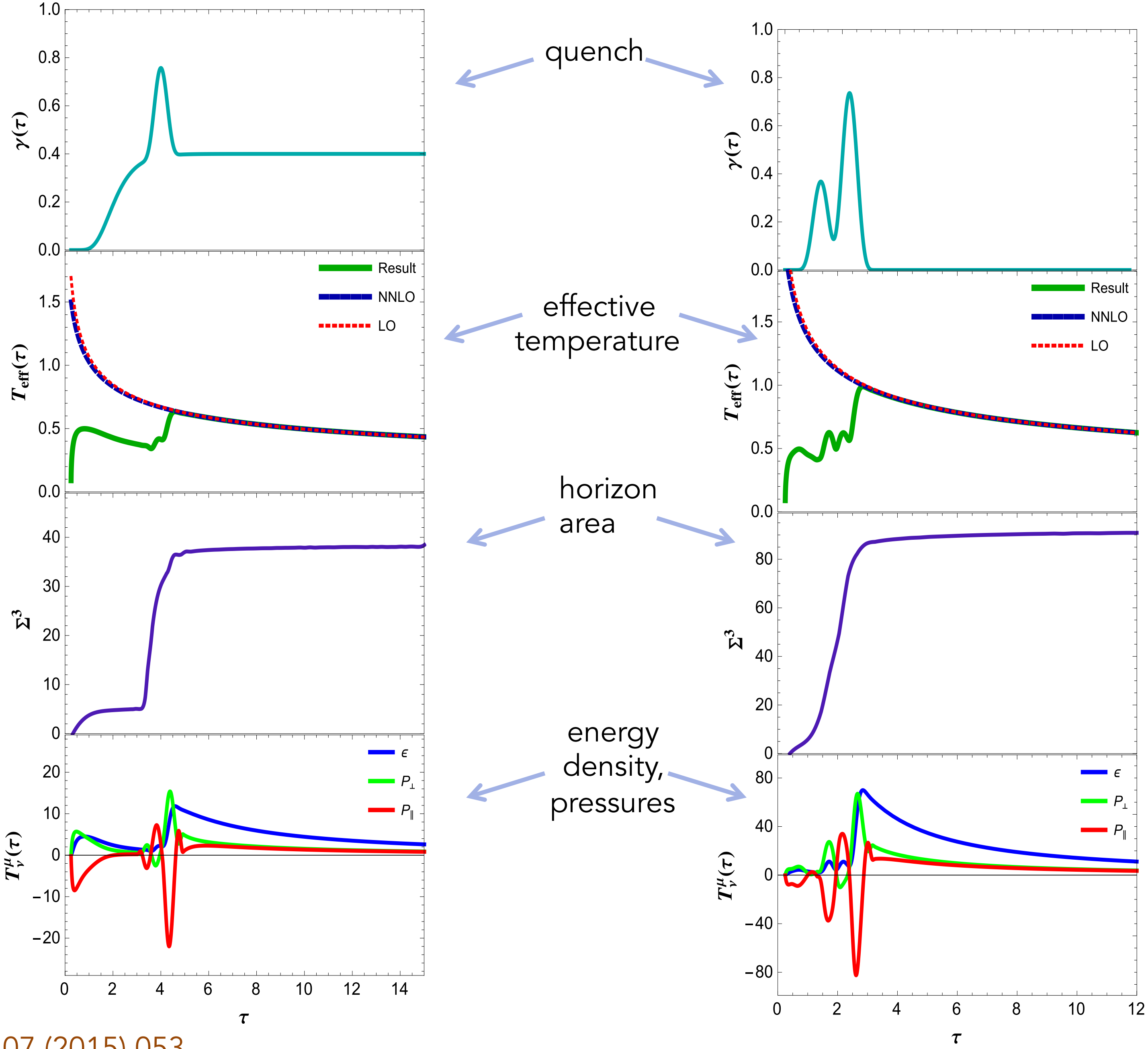


Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005, PRD 96 (2017) 034031

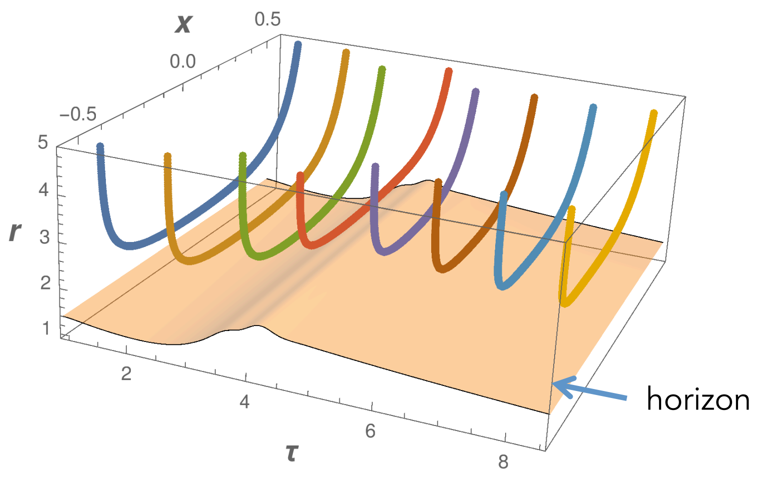


JHEP 07 (2015) 053



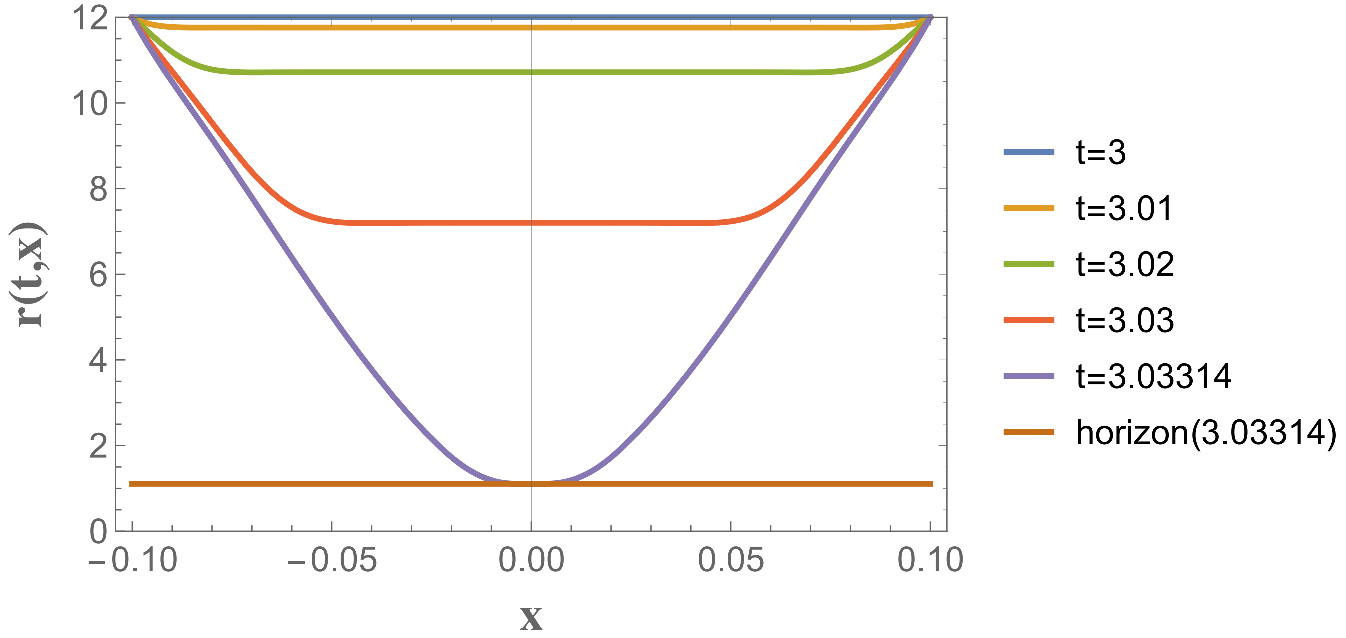
JHEP 07 (2015) 053

Perspectives: Chaos in t-dependent framework



Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005, PRD 96 (2017) 034031

quarkonium dissociation



Bellantuono, De Fazio, Giannuzzi, Nicotri, PC, JHEP 07 (2015) 053, PRD 94 (2016) 025005, PRD 96 (2017) 034031

Questions

What is the interplay between time behaviour of the background and chaos in the $Q\bar{Q}$ string?

MSS bound for non-static cases?

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and at AcademicJobsOnline https://academicjobsonline.org/ajo/jobs/16926

In the list, the position

1) Bari – Theory and Phenomenology of fundamental interactions

corresponds to a fellowship to work in our group in Bari.
Applications are welcome, interested persons can contact us for further information.

Deadline for applications: November 9th.