Title: Real-time dynamics of plasma balls in a confining background

Speakers: Pau Figueras

Series: Strong Gravity

Date: October 31, 2019 - 1:00 PM

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Abstract: Black holes in the background of the AdS soliton are, according to the gauge/gravity correspondence, dual to droplets of deconfined plasma surrounded by a confining vacuum. In this talk I will present, for the first time, the real time dynamics of finite energy black holes in these backgrounds. We consider horizonless initial data sourced by a massless scalar field. Upon time evolution, prompt scalar field collapse produces an excited black hole that eventually settles down to equilibrium at the bottom of the AdS soliton. Radiation in these backgrounds is carried by a set of massive states that, in the dual field theory, can be interpreted as particles. Thus, our results are relevant to describe the out-of-equilibrium dynamics in strongly coupled gauge theories that exhibit confinement. This is work in progress in collaboration with Hans Bantilan and David Mateos.

Real time dynamics of plasma balls in a confining background

Pau Figueras
w/Hans Bantilan and David Mateos

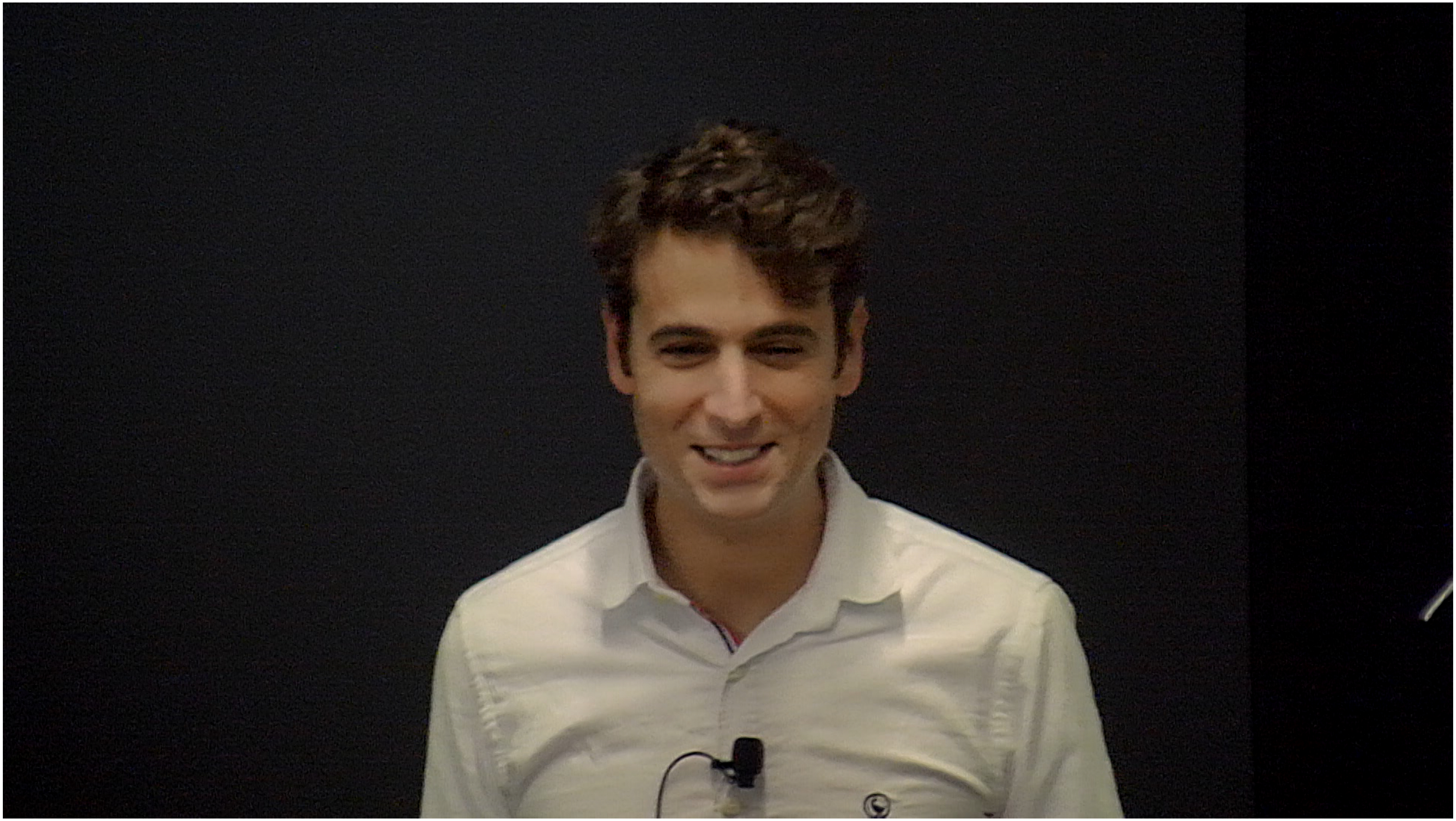
School of Mathematical Sciences
Queen Mary University of London

Strong Gravity Seminar, Perimeter Institute

erc
European Research Council

31st of October 2019

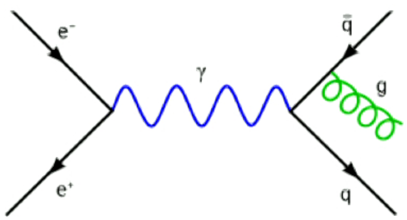
THE ROYAL SOCIETY



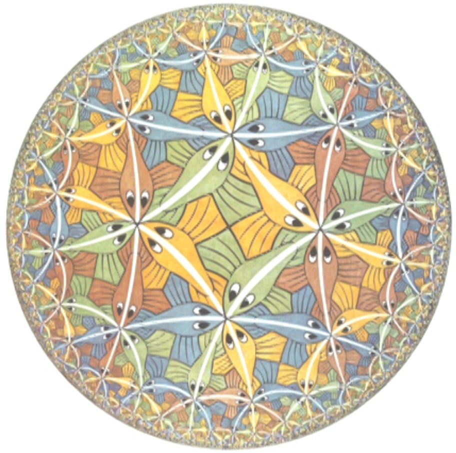
Holography

- Conjecture: gauge/gravity duality [Maldacena]

strongly interacting gauge theory ⟷ *General Relativity (GR) in AdS*



⟷



⇒ *GR as a calculational tool*

- **Holography as a tool**:

  first principles access to the out-of-equilibrium dynamics of *certain* strongly coupled gauge theories

- **Principle**:

  Map the physics of interest to the *classical* evolution of some asymptotically AdS spacetime

- **Aim**:

  Find some universal behaviour, independent of holography

⇒ Solve the Einstein equation in AdS:

Initial boundary value problem

⇒ Geometrisation of dynamics of certain strongly coupled systems

⇒ Discovery of new gravitational phenomena, unique to asymptotically AdS spacetimes

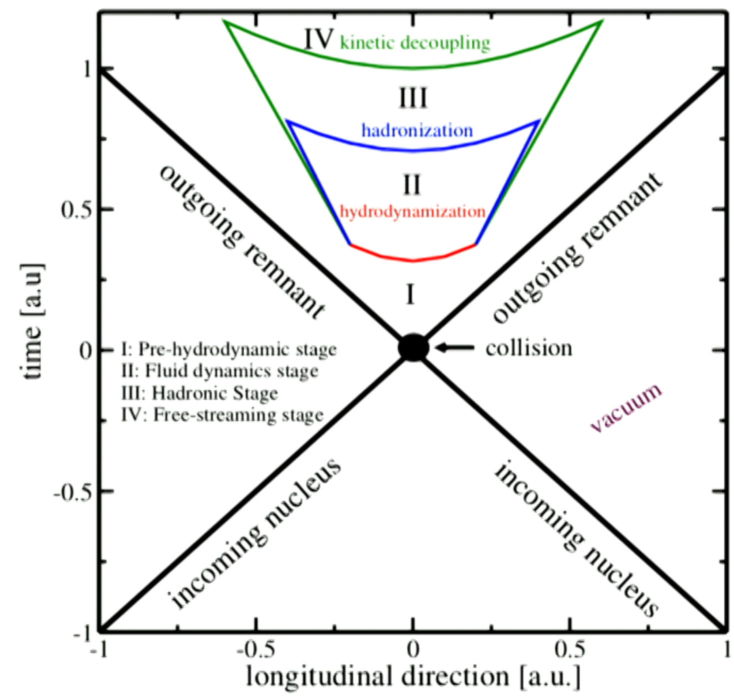
⇒ Finite temperature phenomena dual to the evolution of some black hole spacetime

Heavy ion collisions

- The Quark/Gluon Plasma created at the LHC is strongly coupled and behaves as one of the most perfect fluids in Nature

$\Rightarrow$ hard to model from first principles (QCD)

$\Rightarrow$ use holography to model the far-from-equilibrium stage



[Romatschke & Romatschke]

- What are the initial conditions for hydro?
- Effects of confinement near Λ_{QCD}?
- Finite size effects? Inhomogeneities? ....

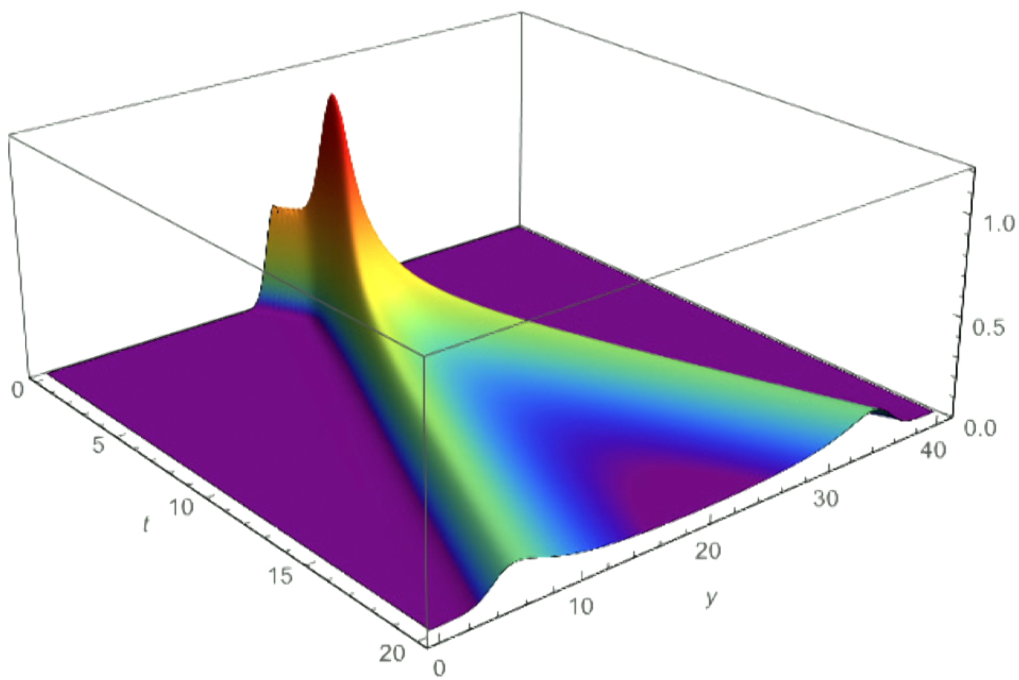
GR simulations

[Chesler & Yaffe,...]

Collisions of shock waves in (Poincare-)AdS

=

infinite sheets of energy in conformal theories



- Most of the work so far has been in conformal theories

- Can we model heavy ion collisions in theories with more features in common with QCD?

- In this talk we will take the first steps towards modelling the dynamics in theories with confinement

➡ Access to new stages: hadronisation and decoupling

Outline

- Gravitational dual of a confining gauge theory
- Numerical evolution in the AdS soliton background
- Results
- Conclusions

AdS soliton

- Consider the planar black hole in AdS (black brane):

$$ds^2 = \frac{L^2}{z^2}\left[-f(z)dt^2 + dx^2 + dy^2 + dw^2 + \frac{dz^2}{f(z)}\right] \qquad f(z) = 1 - \frac{z^d}{z_0^d}$$

AdS soliton

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Coordinate transformation (Wick rotation): $t = -\mathrm{i}\theta \quad w = \mathrm{i}t$

$$ds^2 = \frac{L^2}{z^2}\left[-dt^2 + dx^2 + dy^2 + f(z)d\theta^2 + \frac{dz^2}{f(z)}\right] \qquad \theta \sim \theta + \frac{4\pi z_0}{d}$$

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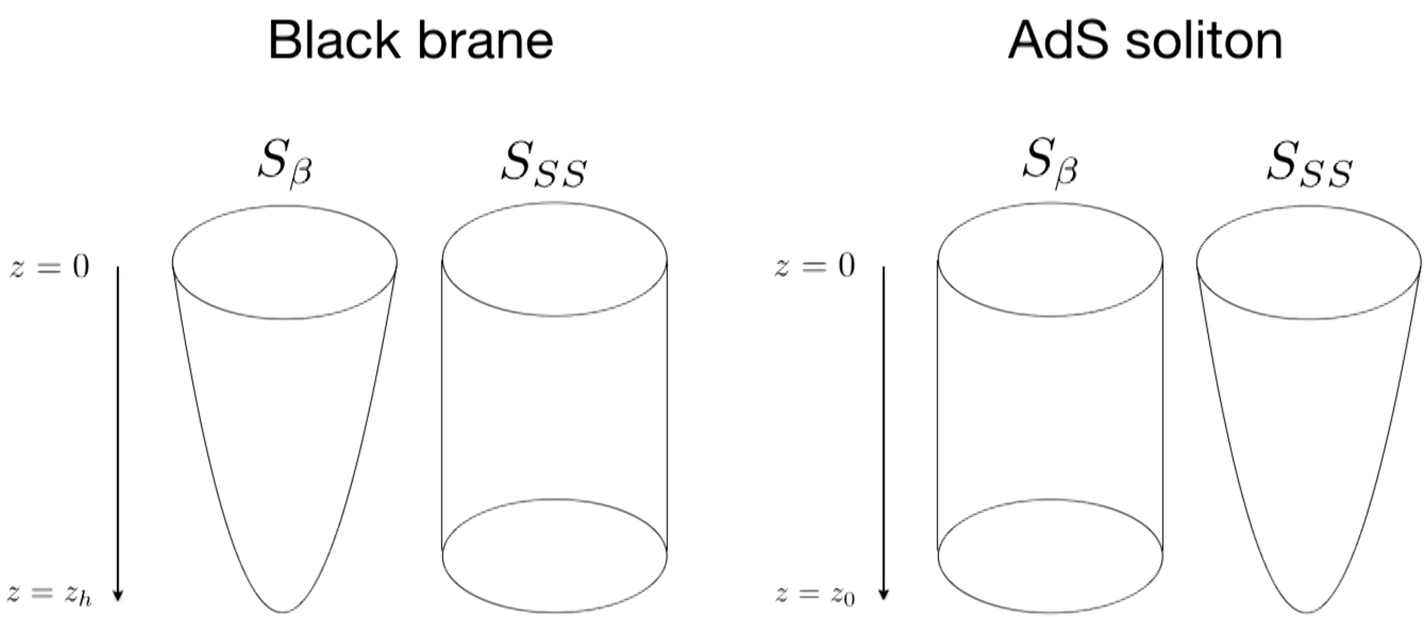
Coordinate transformation (Wick rotation): $t = -\mathrm{i}\theta \quad w = \mathrm{i}t$

$$ds^2 = \frac{L^2}{z^2}\left[-dt^2 + dx^2 + dy^2 + f(z)d\theta^2 + \frac{dz^2}{f(z)}\right] \qquad \theta \sim \theta + \frac{4\pi z_0}{d}$$

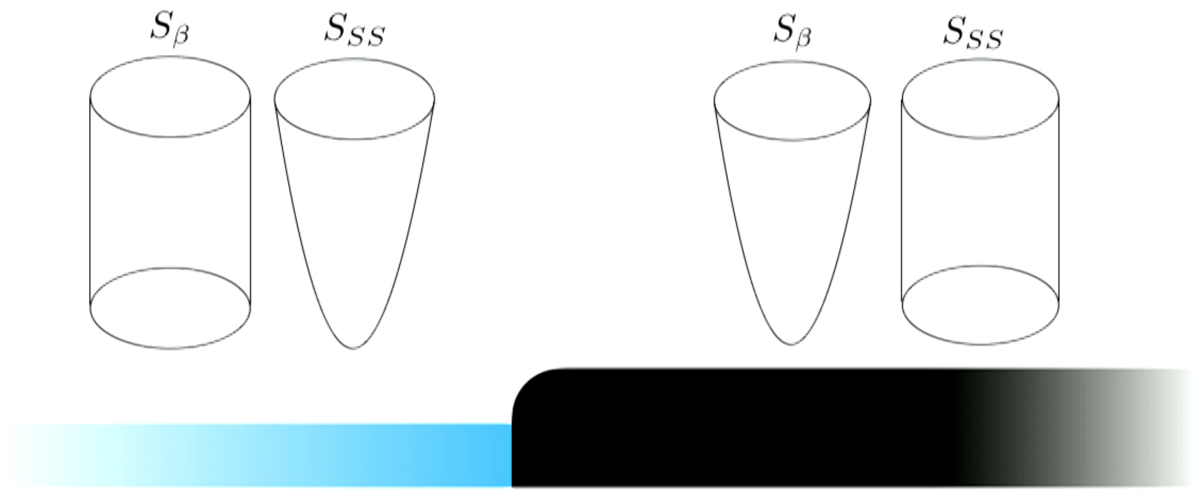
- **Conjecture**: this is the minimum energy solution among all solutions with the same BCs [Horowitz & Myers]

AdS soliton

- Equilibrium finite T states: $t = -\mathrm{i}\tau \quad \tau \sim \tau + \beta$



- $T = T_c$

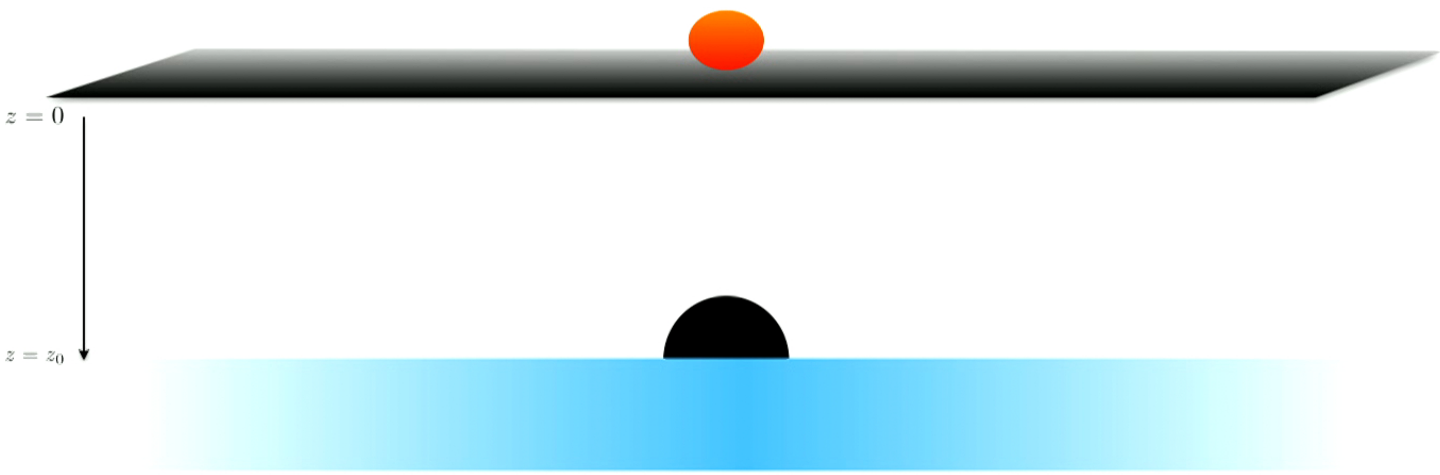


[Aharony, Minwalla and Wiseman]

- $T > T_c$

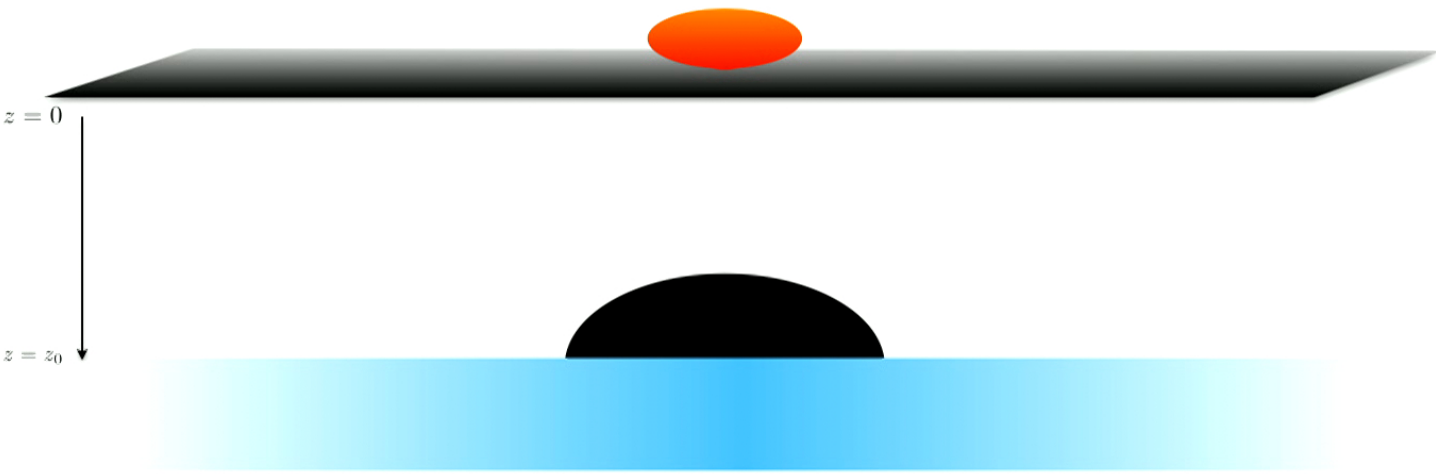
[PF & Tunyasuvunakool]

- $T > T_c$



[PF & Tunyasuvunakool]

- $T > T_c$



[PF & Tunyasuvunakool]

- $T > T_c$

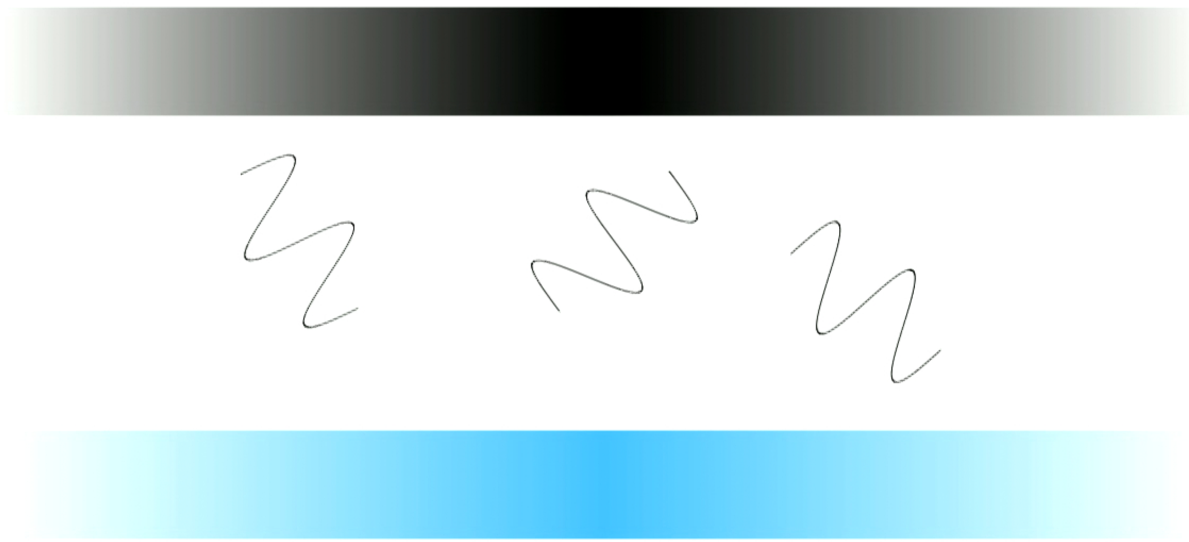
[PF & Tunyasuvunakool]

- Black holes as gravitational duals of static bubbles of deconfined plasma sitting in the vacuum

- Expectation: localised black holes are classically stable

- Interpolate between AF black holes and black branes

- Gravitational perturbations of the AdS soliton form a complete set of gapped normal modes



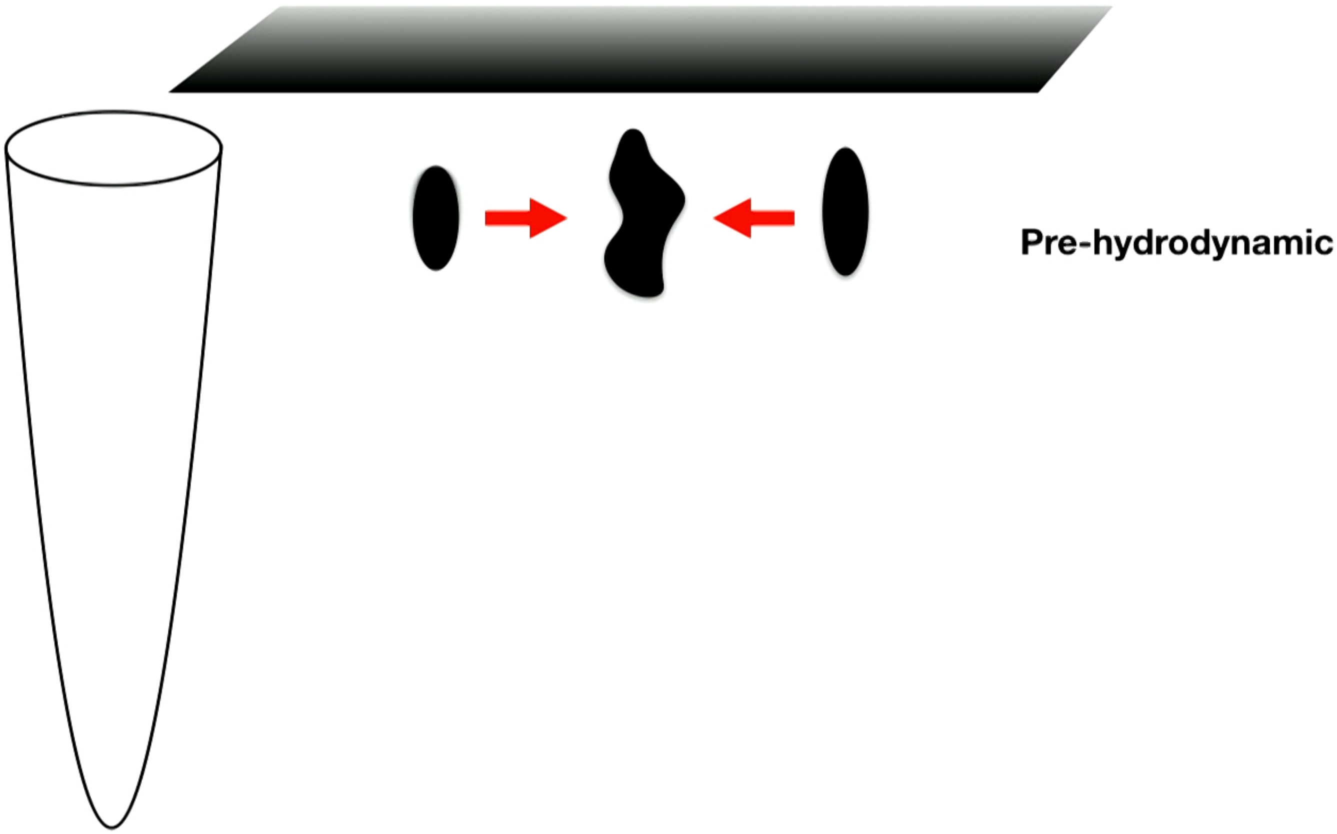
$$M_{\rm gap} \sim \Lambda_{\rm QCD}$$

Gravitational waves = particles

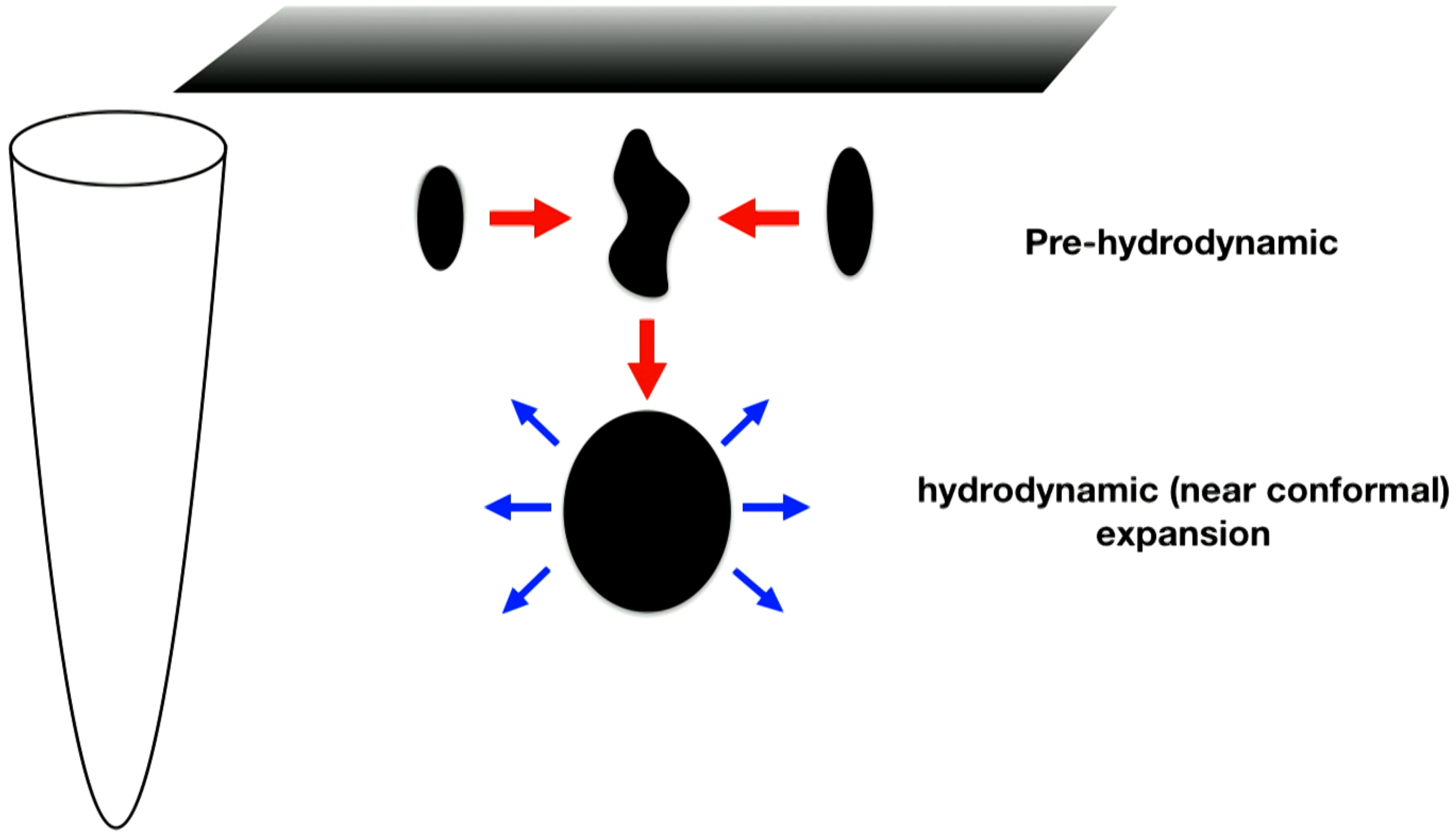
- **Goal 1**: study the dynamics of localised black holes in the AdS soliton background
  - How they equilibrate?
  - When is hydrodynamics valid?

- **Goal 2**: study collisions of black holes in these backgrounds as holographic models of heavy ion collisions

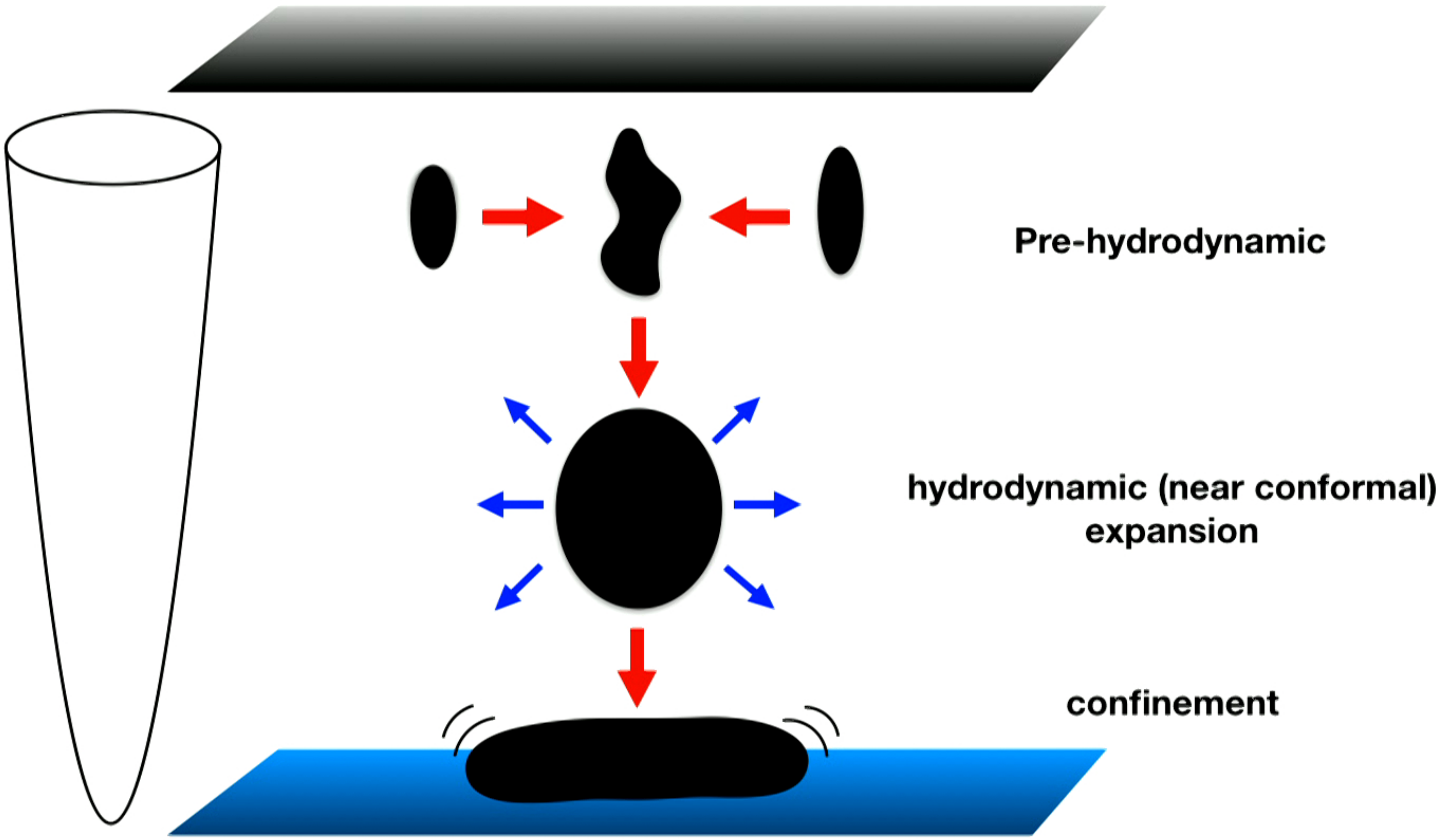
- Holography provides a geometrisation of the various stages of the collision



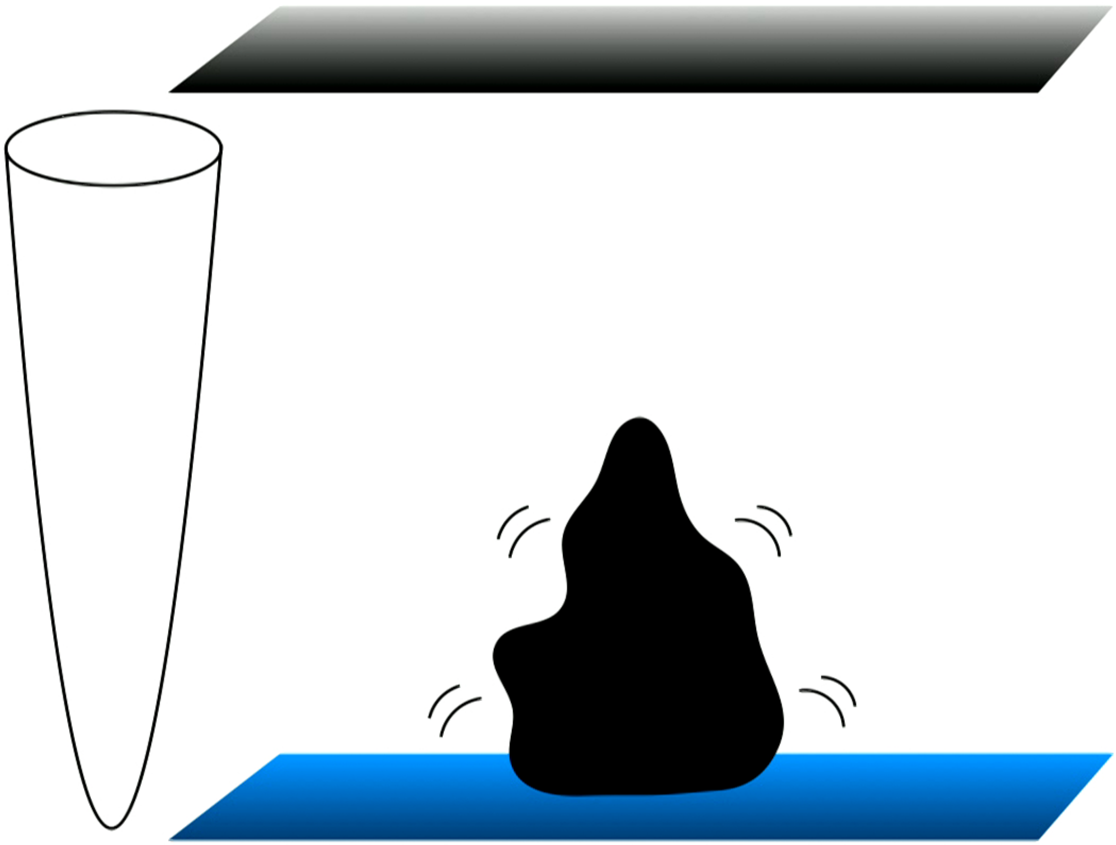
- Holography provides a geometrisation of the various stages of the collision



- Holography provides a geometrisation of the various stages of the collision



In this talk:



Numerical evolution

Numerical evolution

- Initial boundary value problem
- Solve the Einstein equations in generalised harmonic coordinates coupled to a massless scalar

$$0 = -\frac{1}{2}g^{\alpha\beta}g_{\mu\nu,\alpha\beta} - g^{\alpha\beta}{}_{,(\mu}g_{\nu)\alpha,\beta} - H_{(\mu,\nu)} + H_{\alpha}\Gamma^{\alpha}{}_{\mu\nu} - \Gamma^{\alpha}{}_{\beta\mu}\Gamma^{\beta}{}_{\alpha\nu}$$
$$- \frac{2}{3}\Lambda_5\, g_{\mu\nu} - 8\pi\left(T_{\mu\nu} - \frac{1}{3}T\, g_{\mu\nu}\right)$$

$$\Box_g x^{\mu} = H^{\mu}$$

$$\Box_g \phi = 0$$

- Look for solutions of the form: $g_{\mu\nu} = \hat{g}_{\mu\nu} + h_{\mu\nu}$

  AdS soliton (with compactified holographic direction):

$$\hat{g} = \frac{L^2}{(1-\rho^2)^2}\left(-dt^2 + 4\rho^2 f(\rho)^{-1} d\rho^2 + dx_1^2 + dx_2^2 + f(\rho) d\theta^2\right)$$

$$f(\rho) = 1 - (1-\rho^2)^4$$

- Only assume U(1) symmetry along θ

- Initial data: time-symmetric and a deformed Gaussian profile (or superposition of various profiles) for the scalar field, localised at the IR bottom

- We choose strong data so that an apparent horizon forms immediately

- Evolved variables and BCs

$$g_{tt} = \hat{g}_{tt} + (1-\rho^2)\bar{h}_{tt} \qquad H_t = \hat{H}_t + (1-\rho^2)^2 \bar{H}_t$$

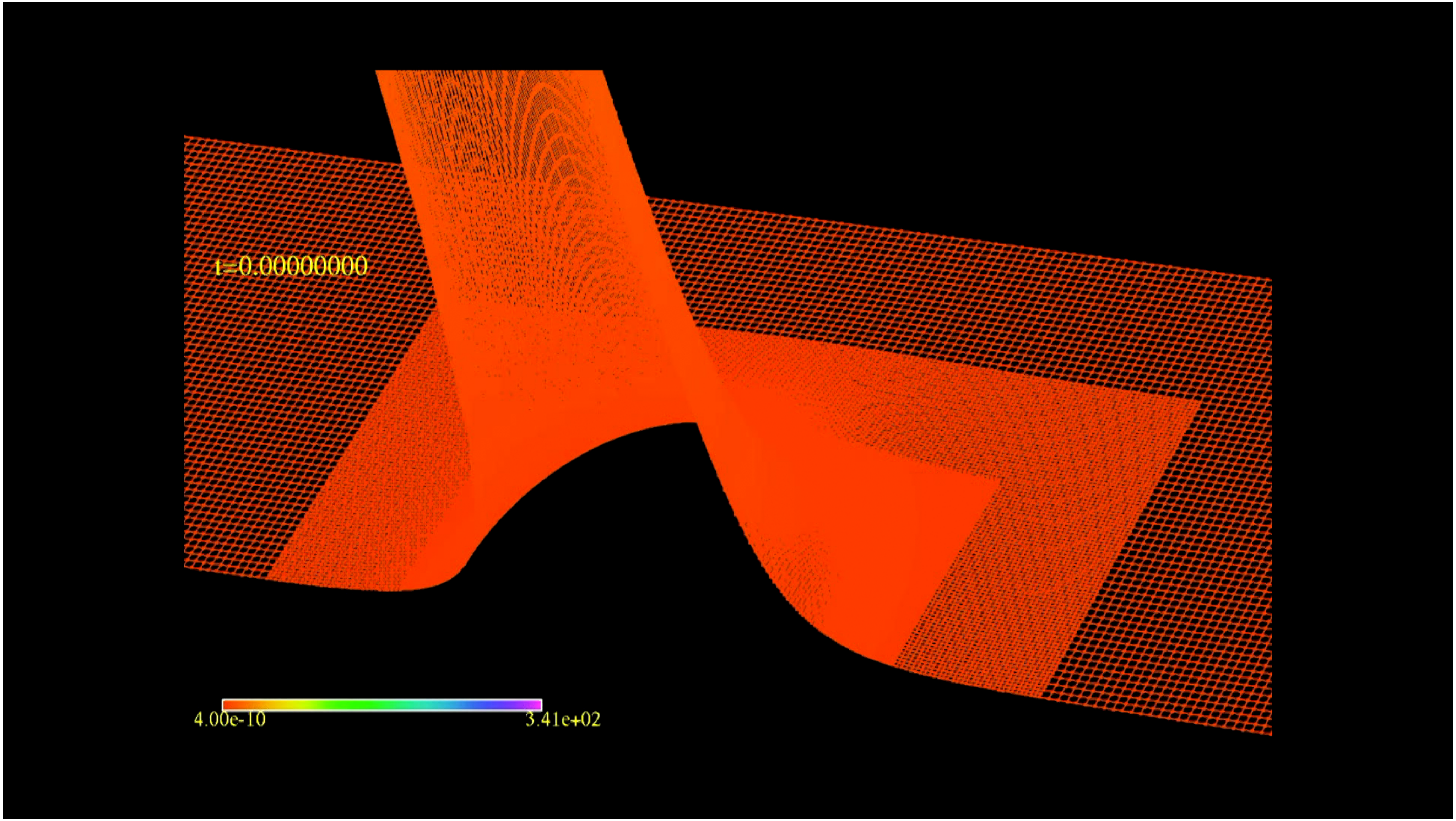
$$\vdots \qquad\qquad \vdots$$

$$g_{\theta\theta} = \hat{g}_{\theta\theta} + \rho^2(1-\rho^2)\bar{h}_{\theta\theta} \qquad \phi = (1-\rho^2)^3\bar{\phi}$$

- Dirichlet at infinity (ρ = 1)
- Regularity at the IR bottom (ρ = 0)
- Dirichlet along the boundary directions
- Fix the gauge from the near boundary behaviour

- Embedding of the apparent horizon (2d section)

Results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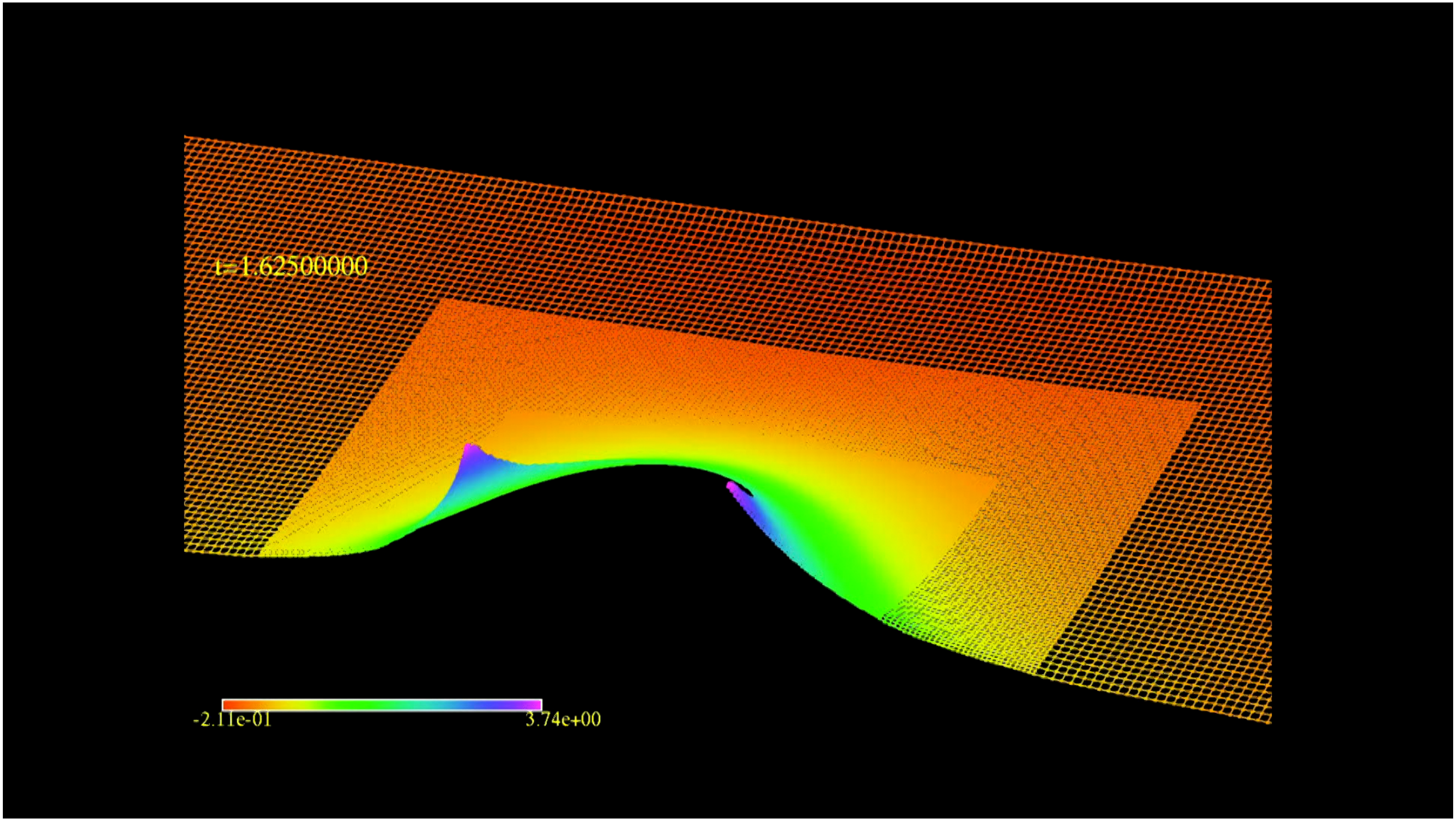
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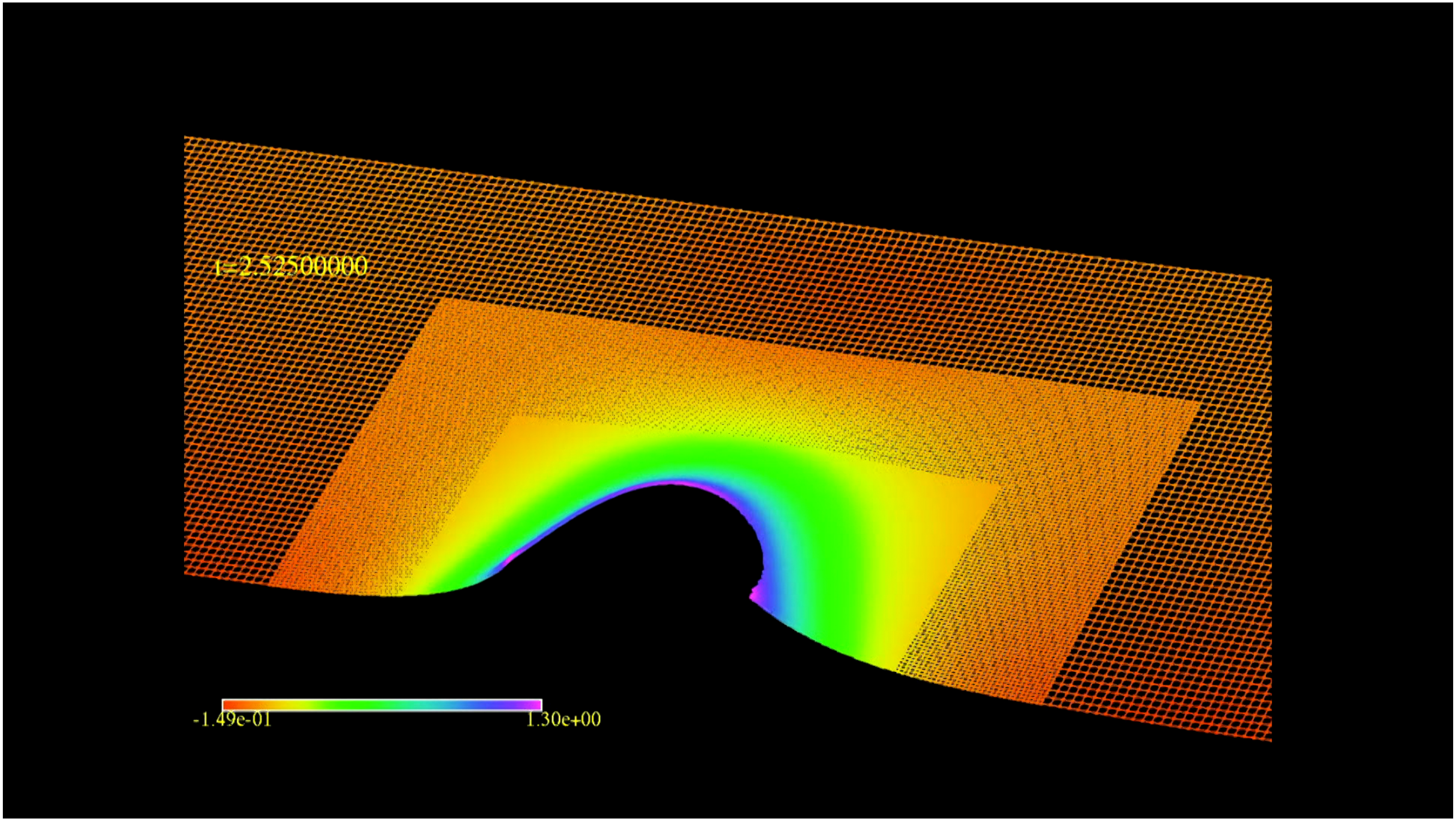
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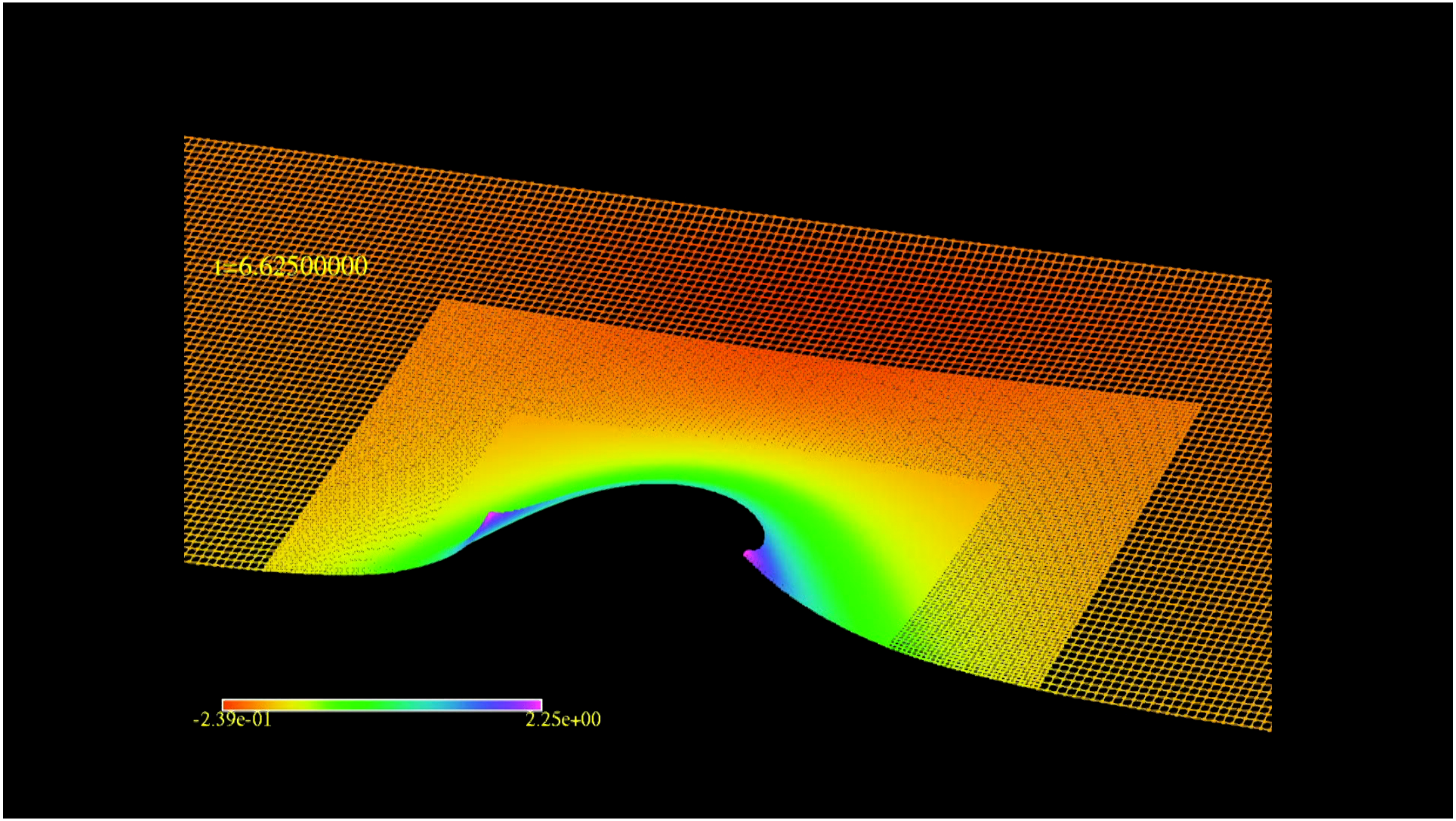
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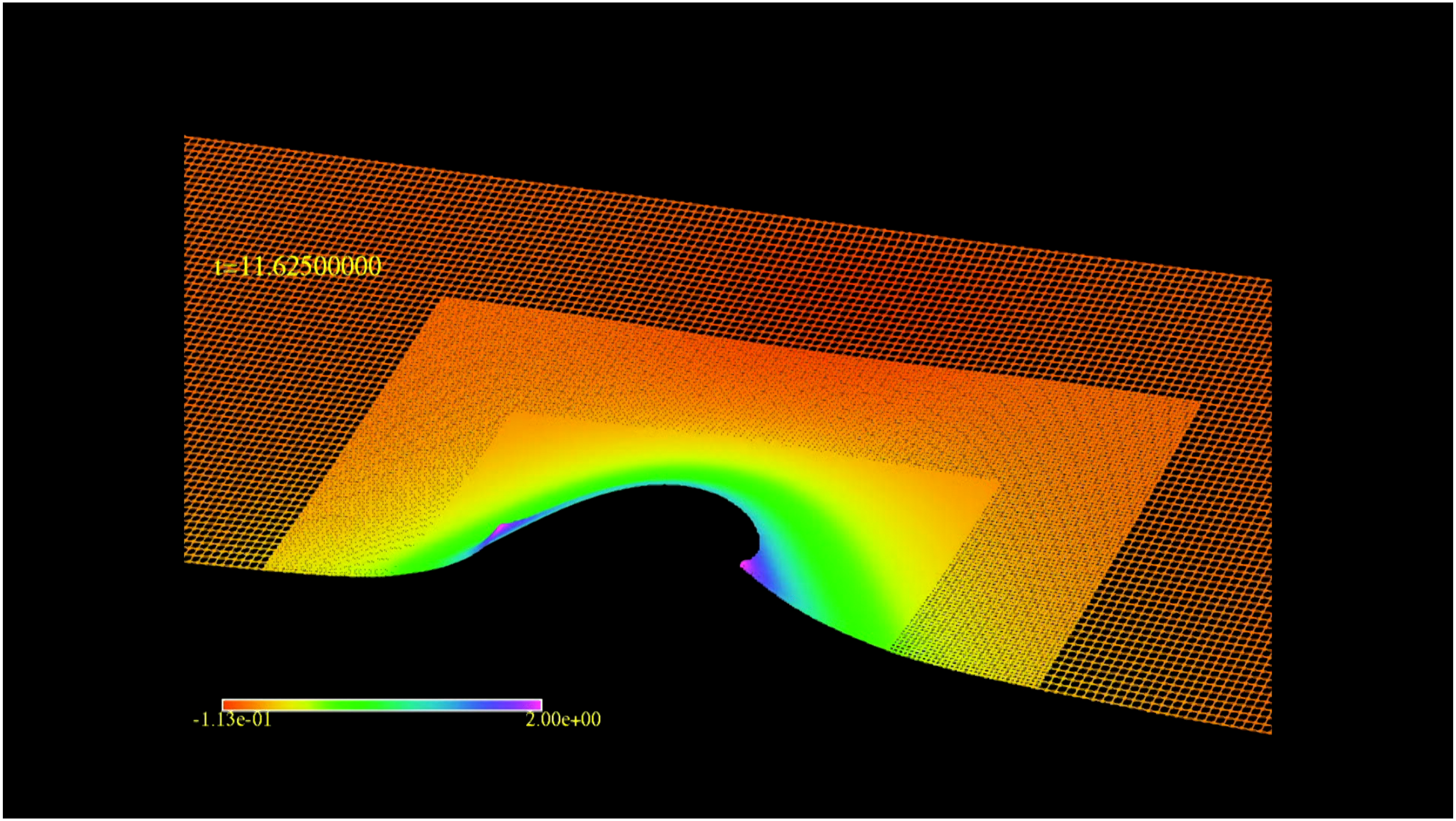
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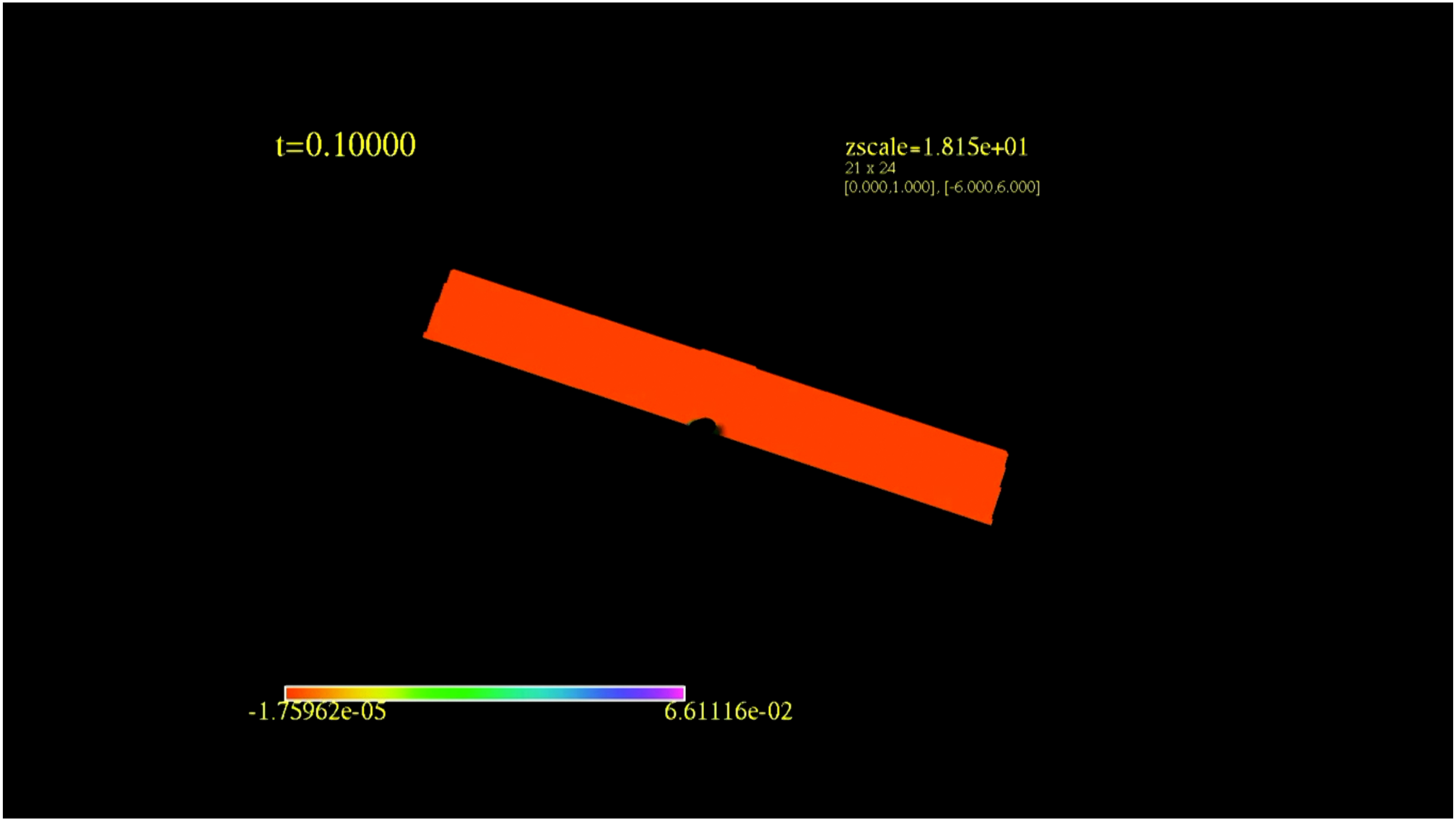
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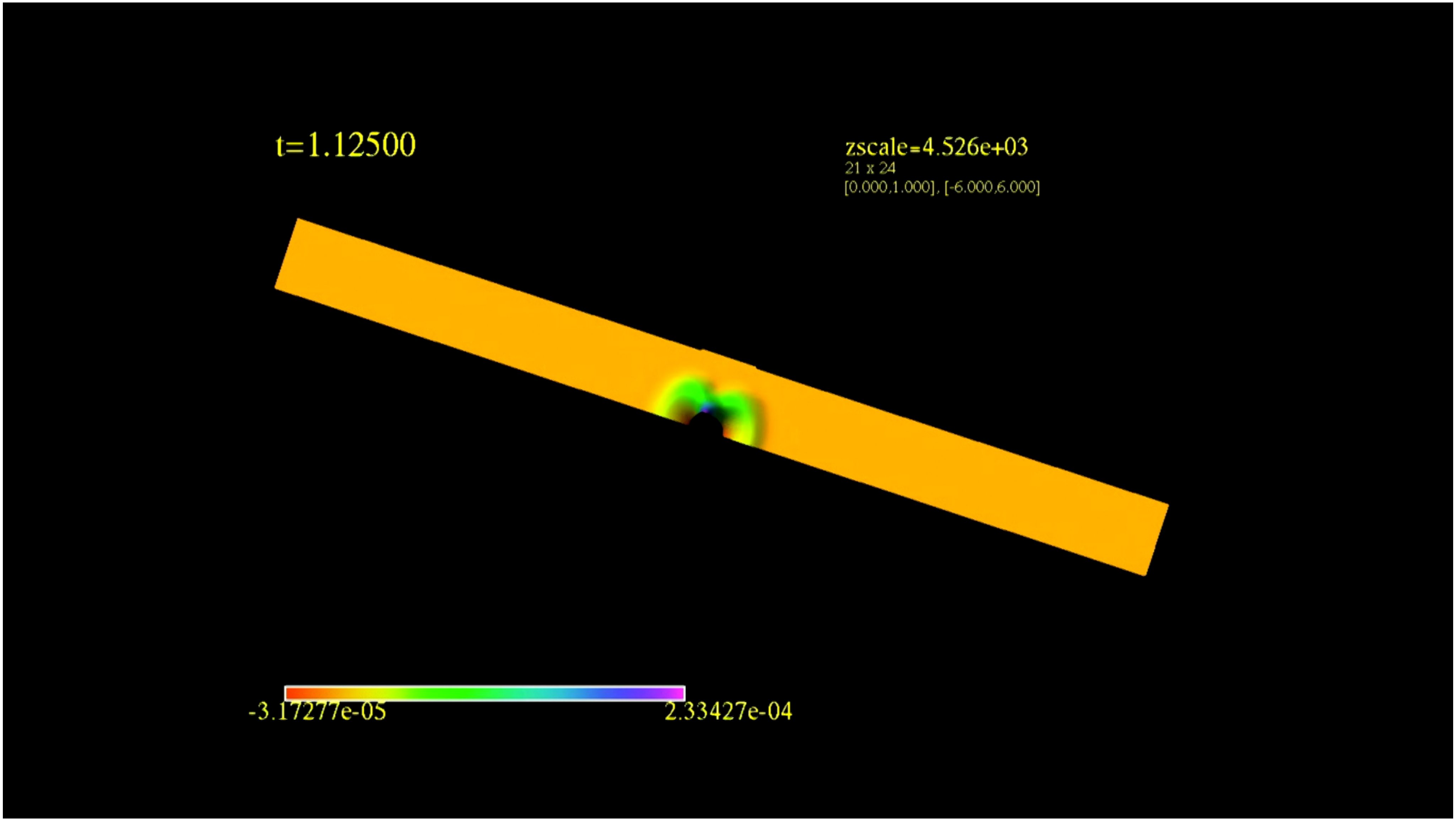
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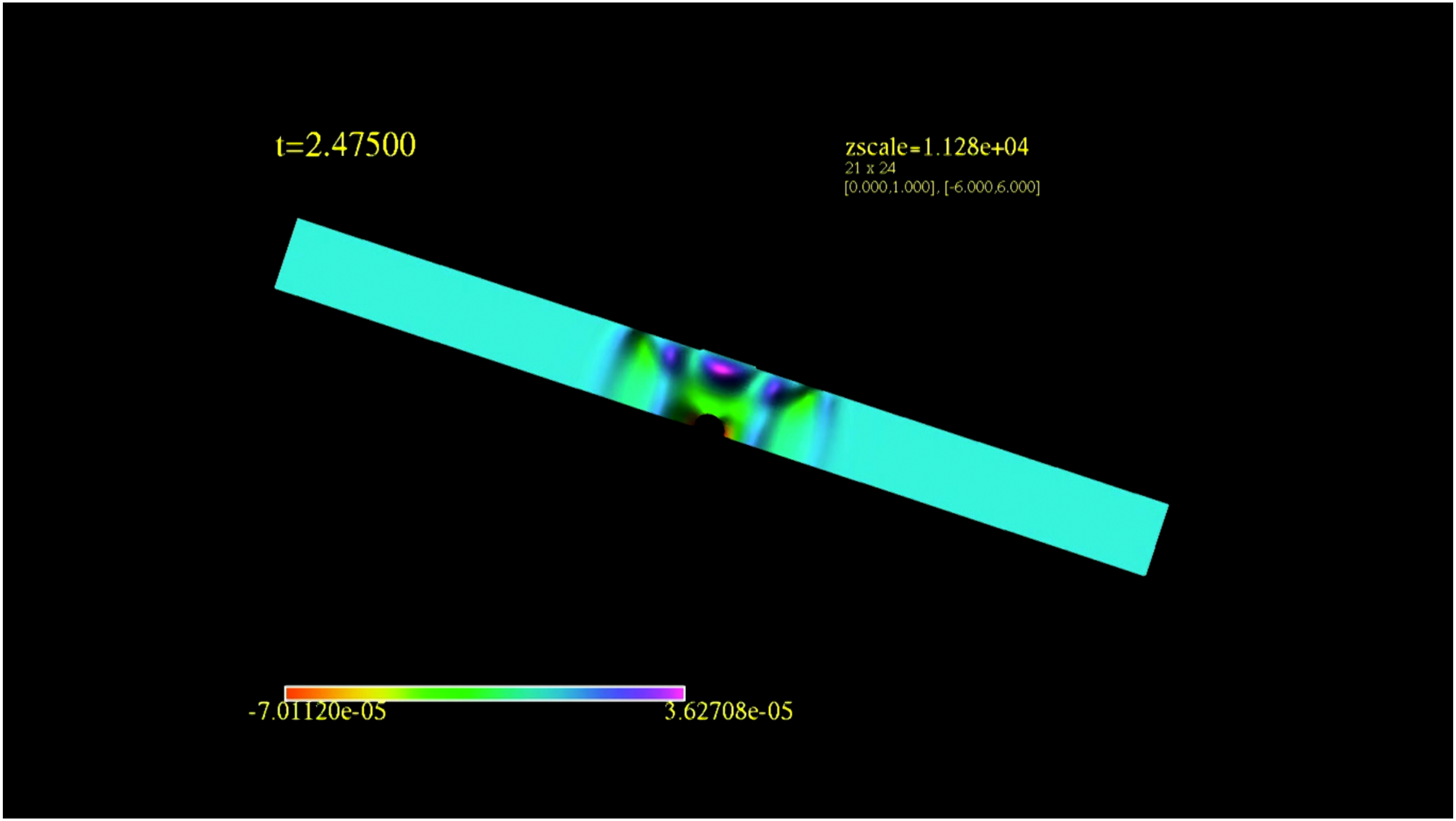
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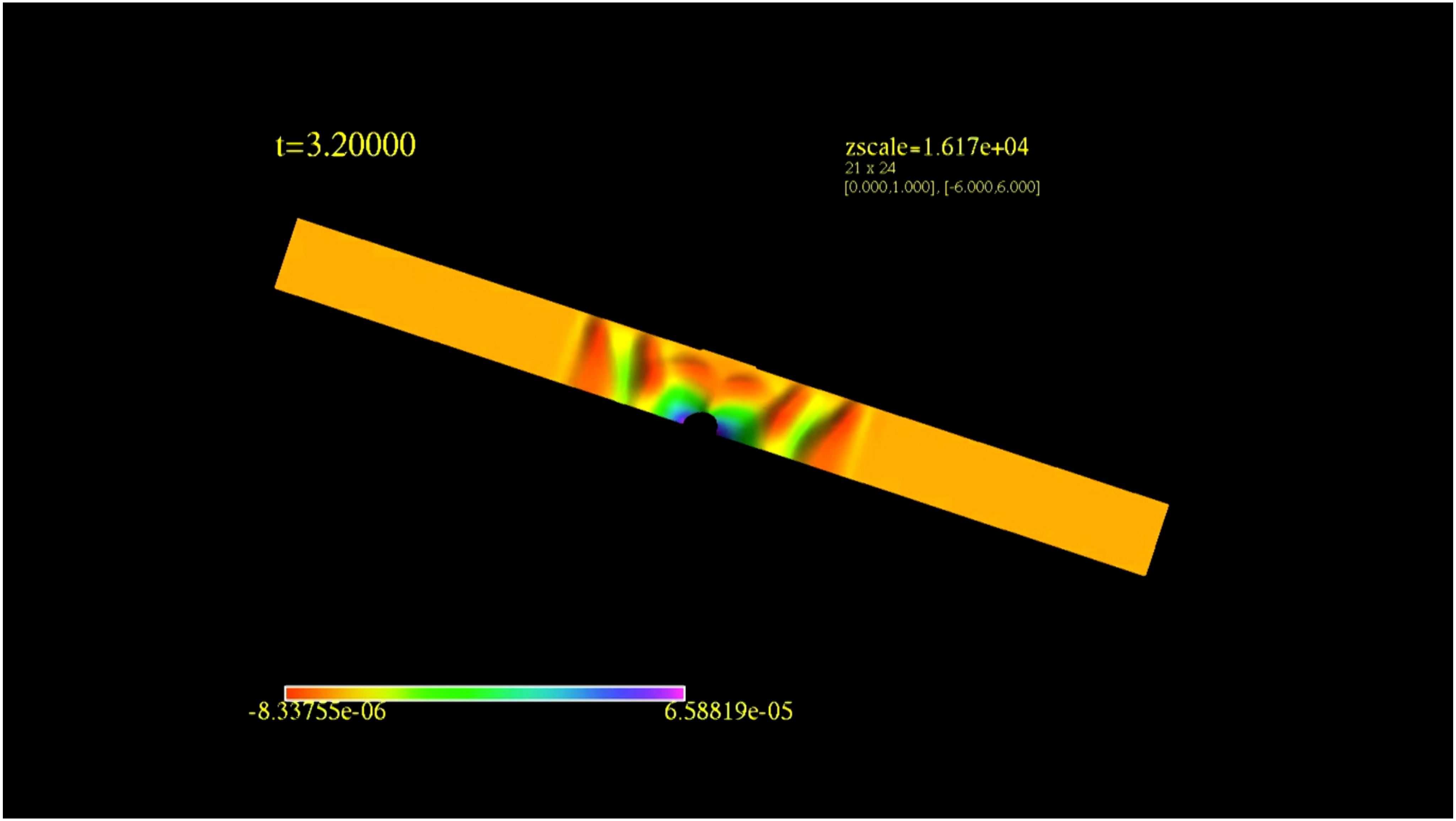
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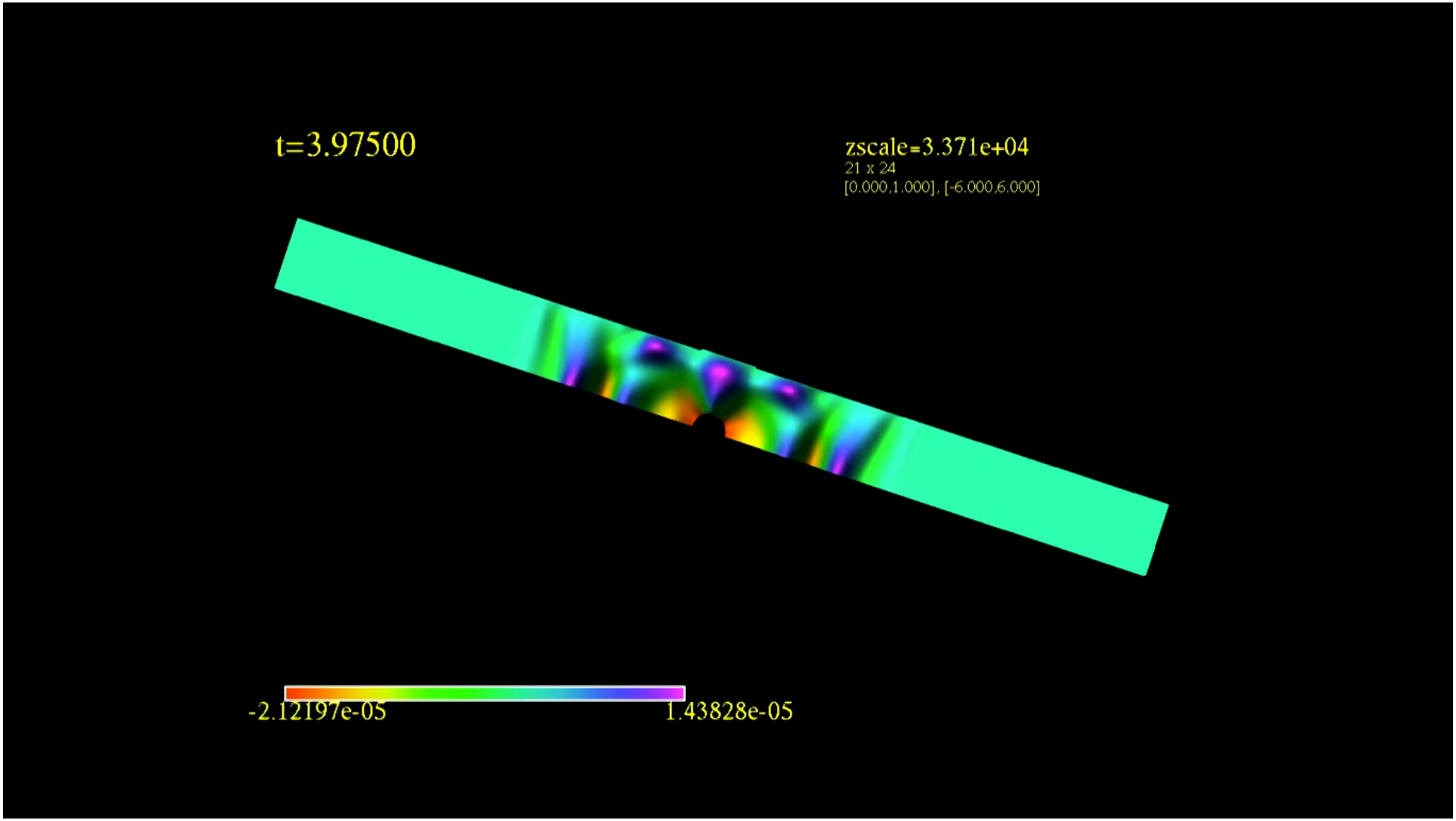
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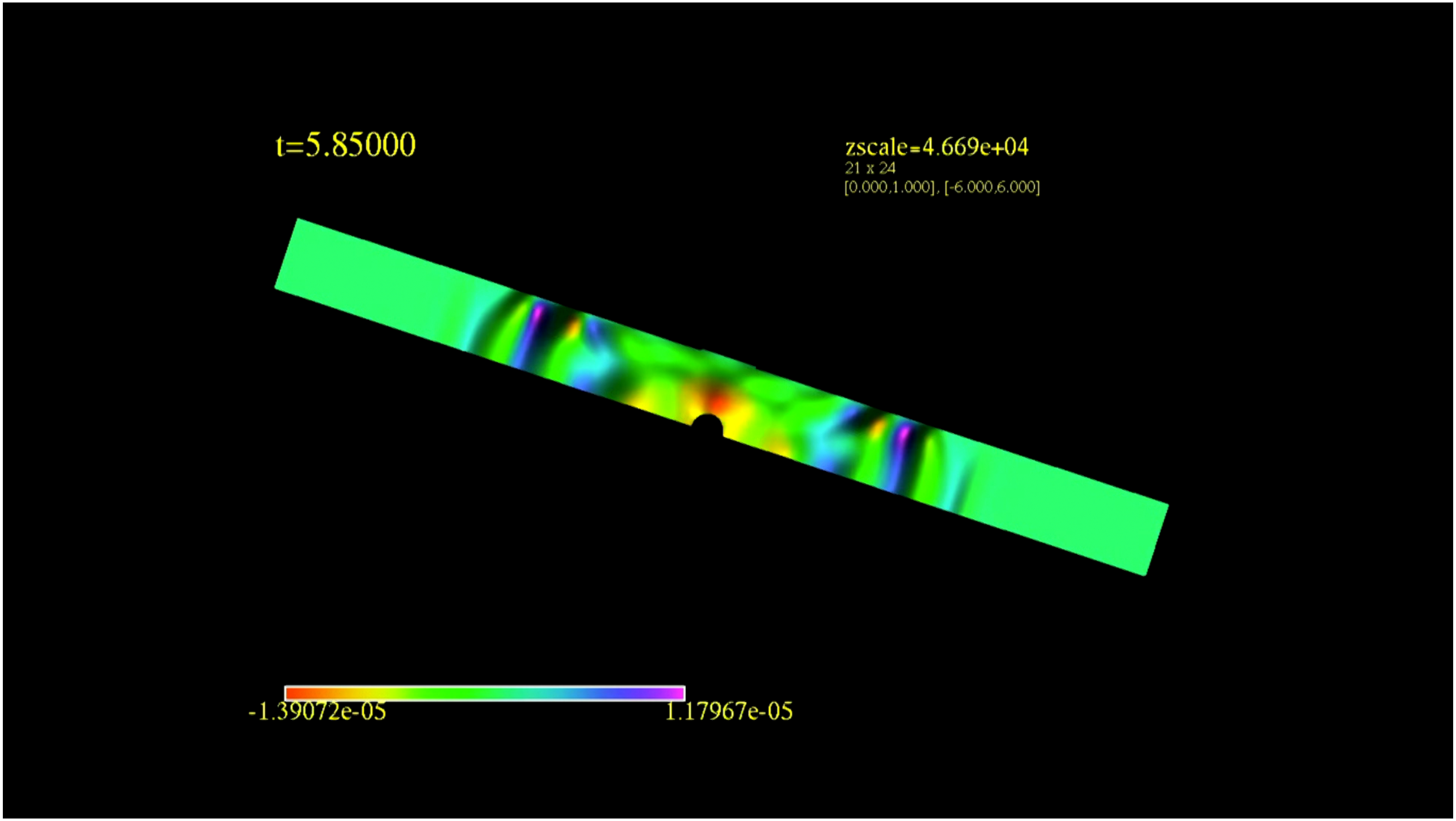
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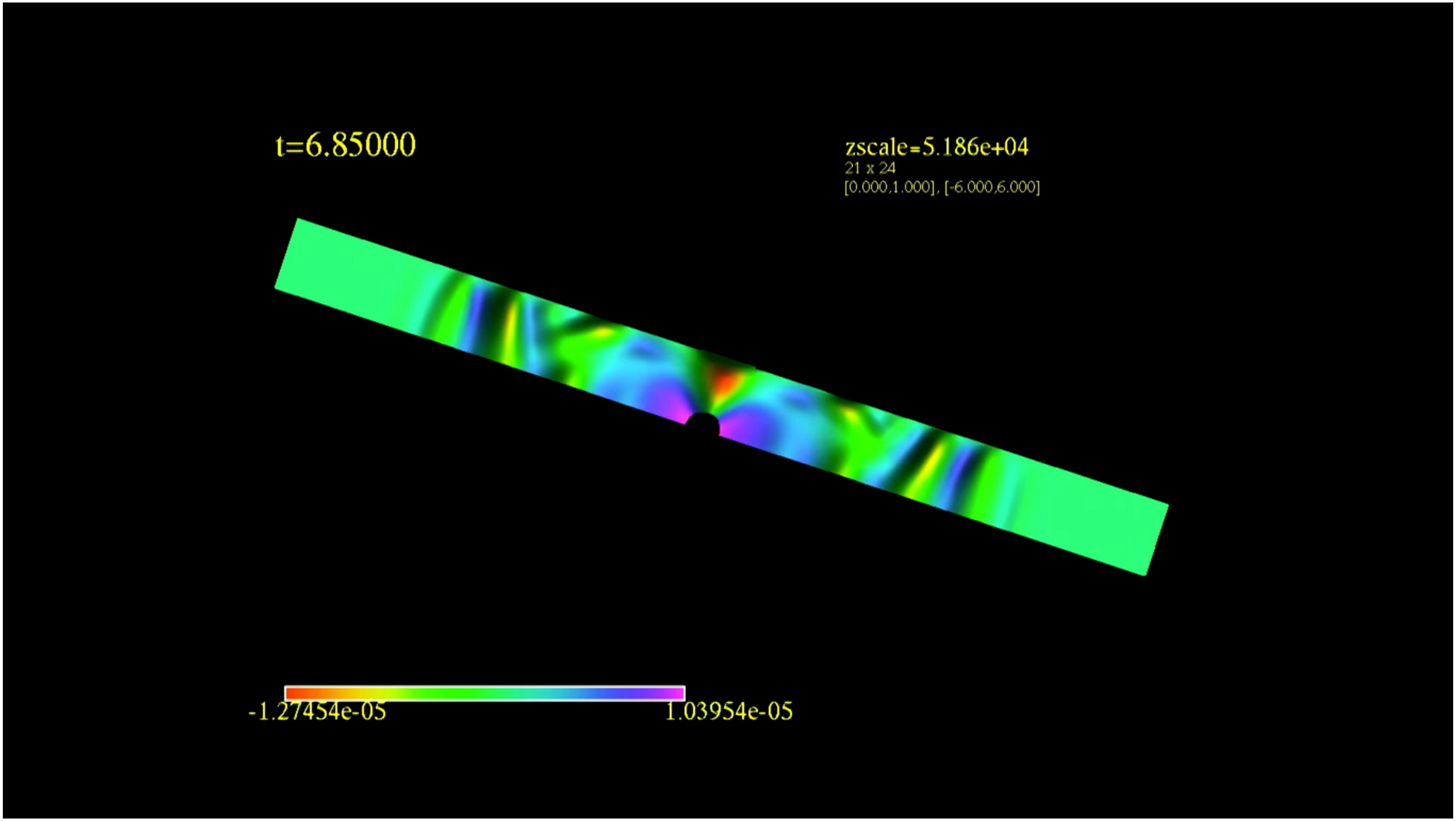
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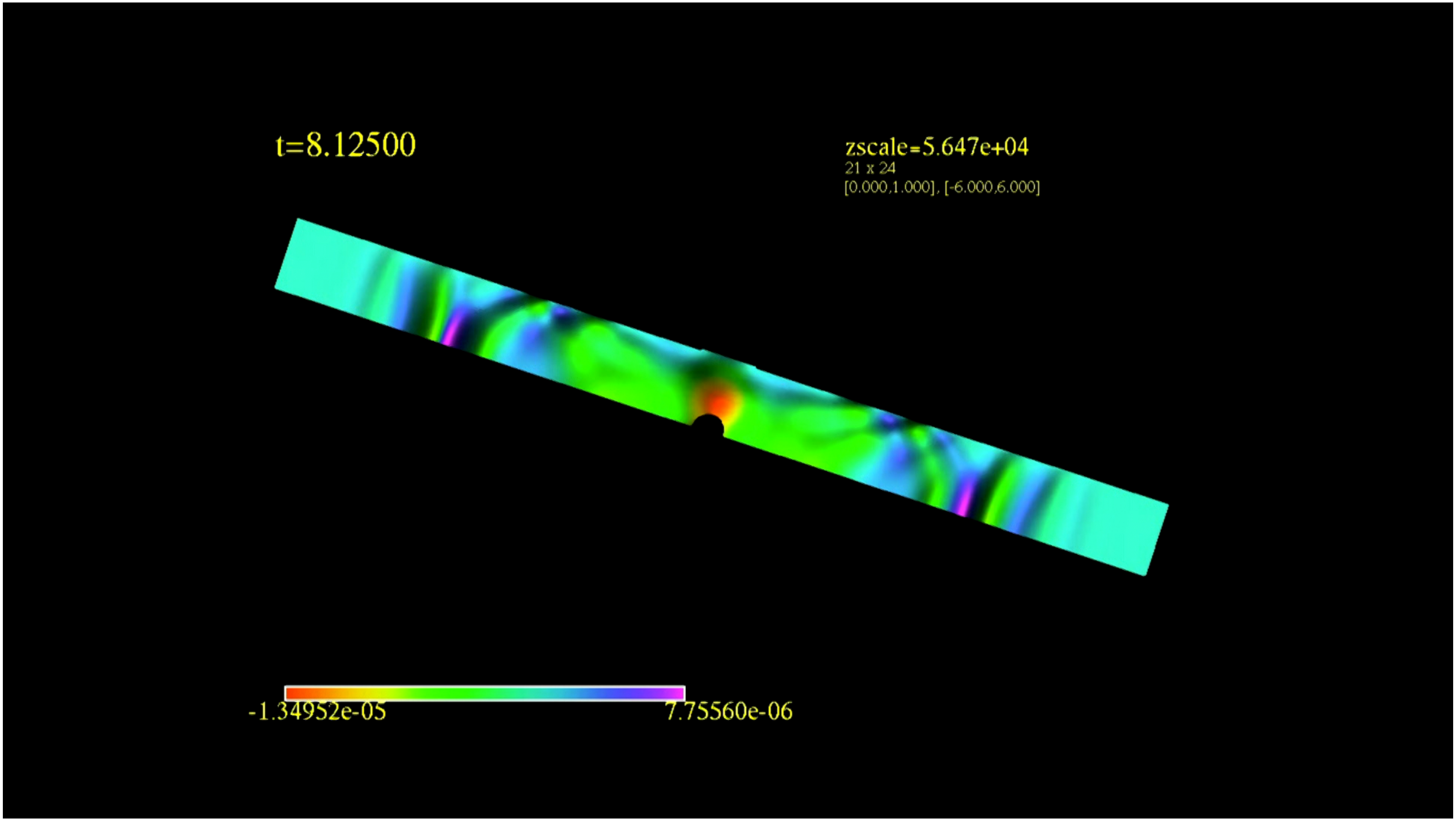
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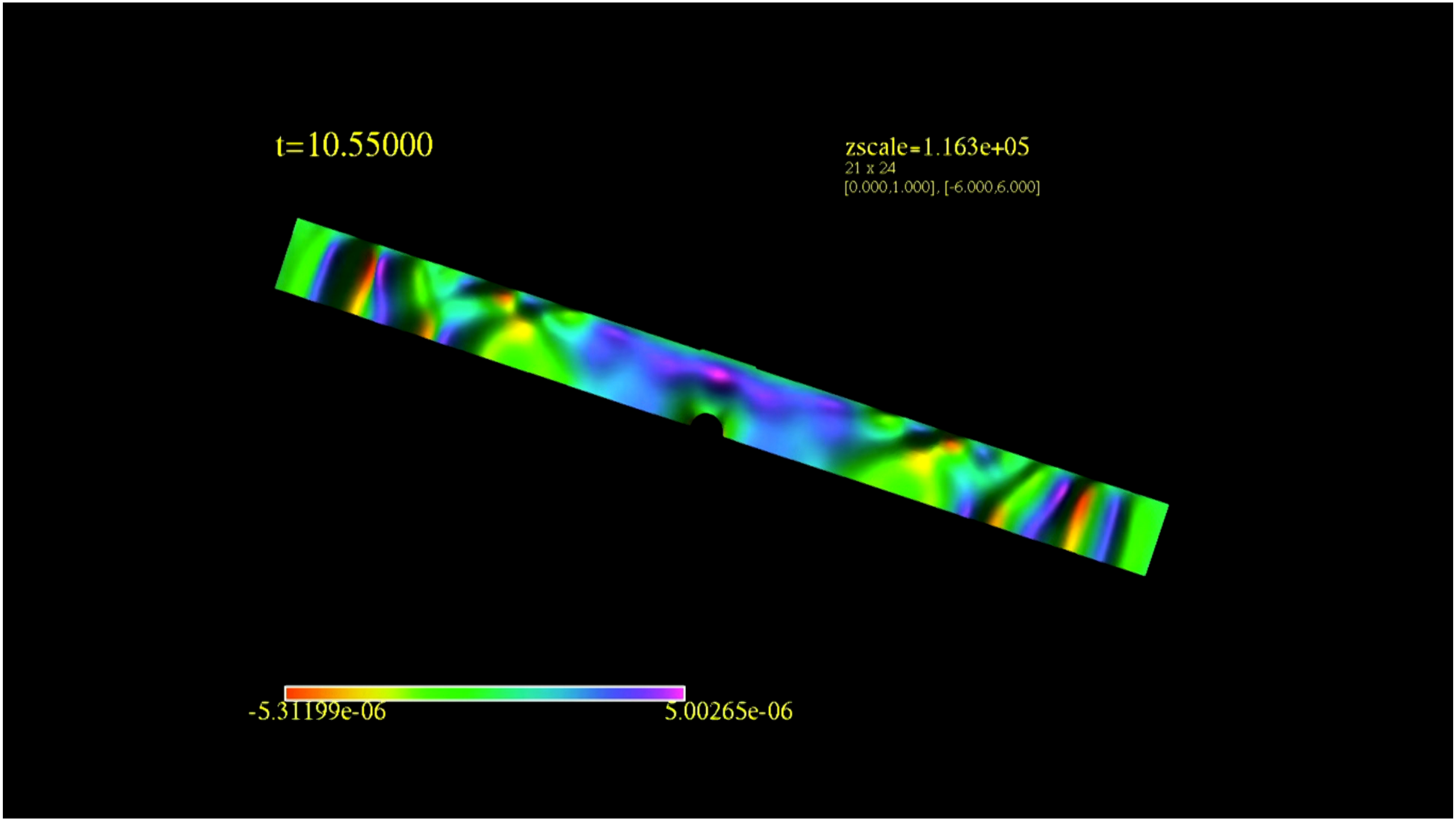
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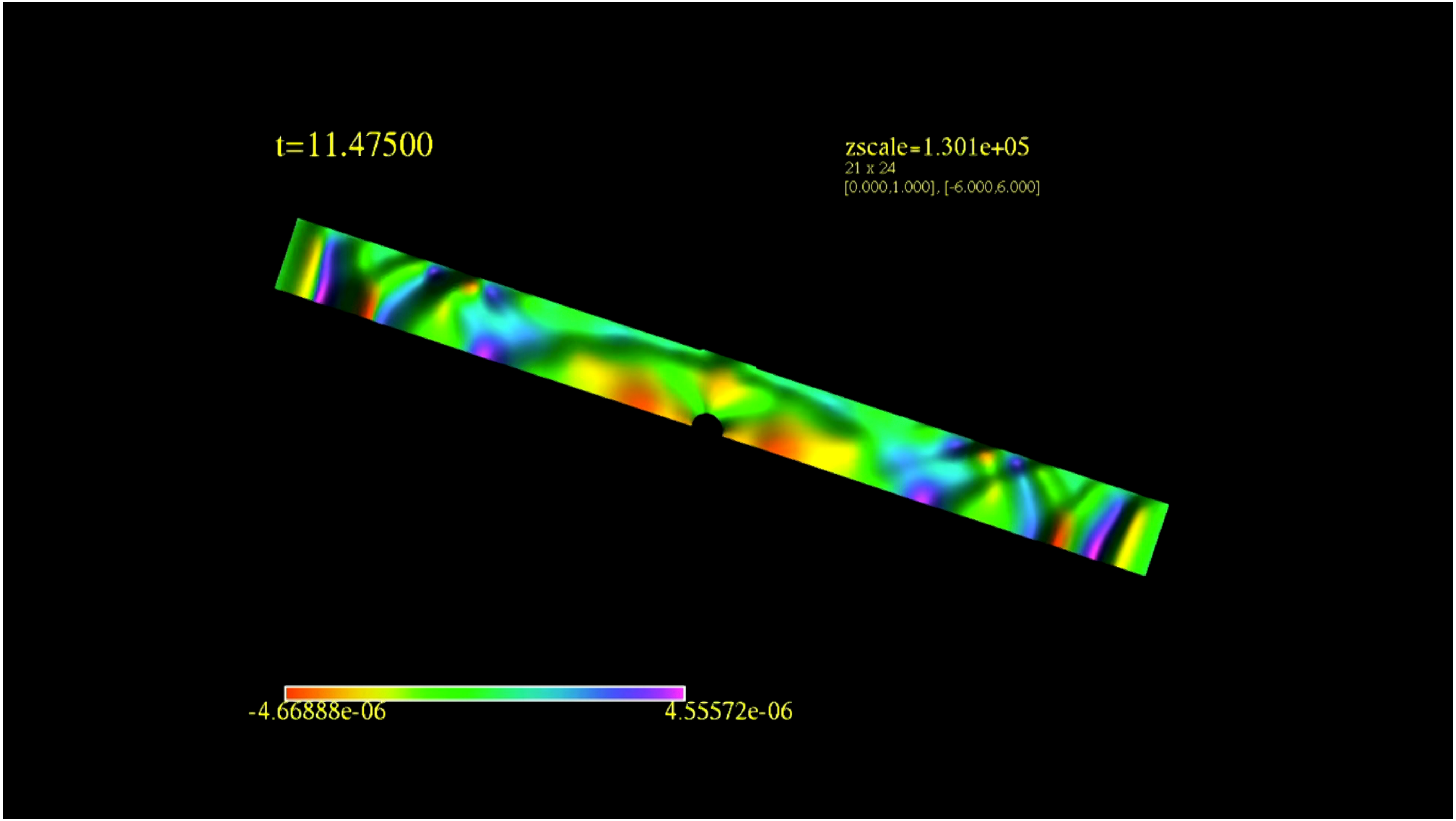
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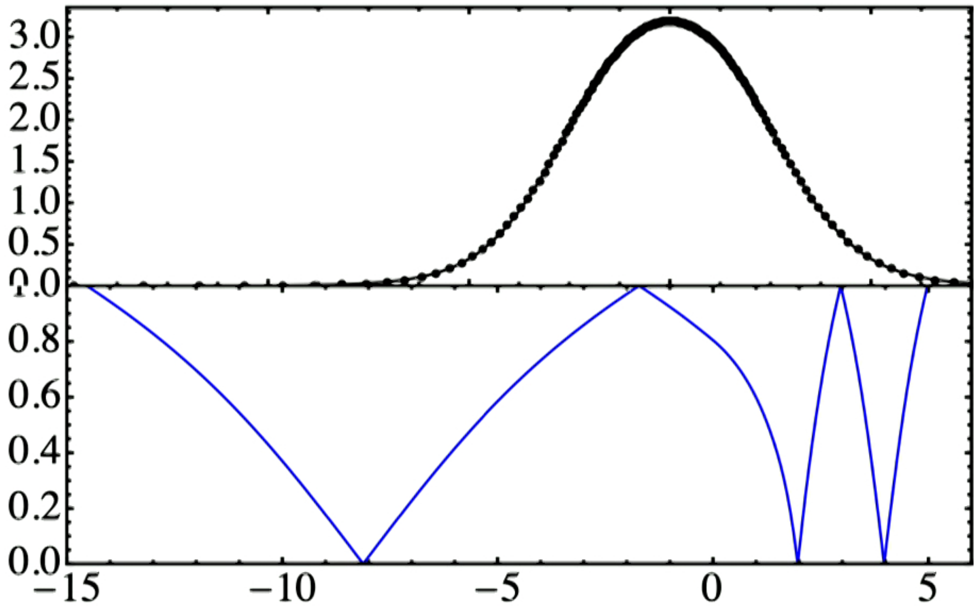

3.0
2.5
2.0
1.5
1.0
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1.0
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0.4
0.2
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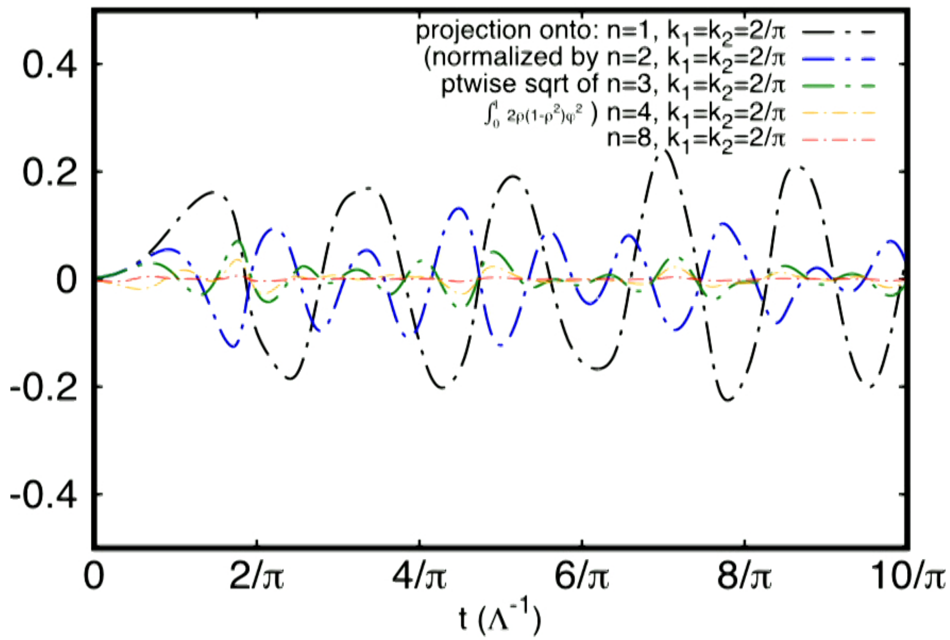
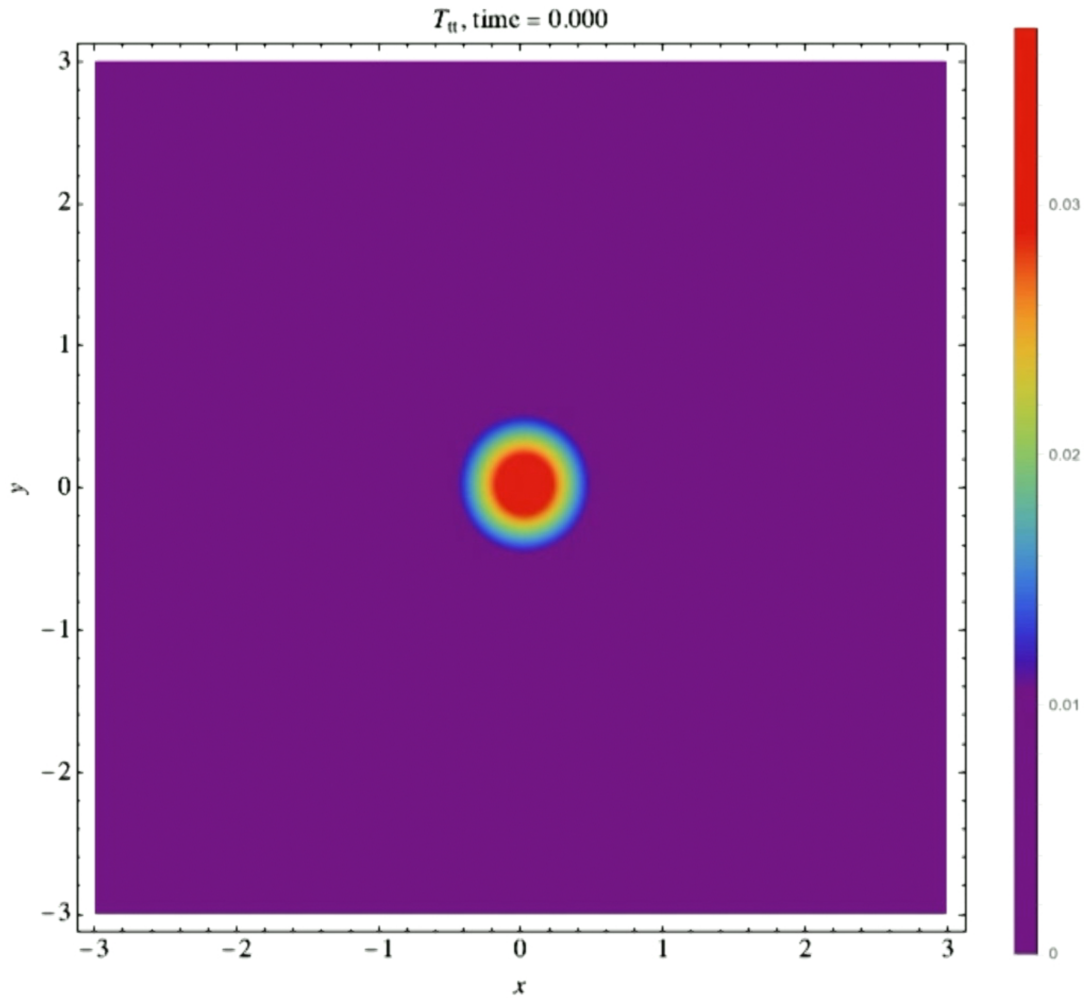
−10
−5
0
5


projection onto: n=1, k1=k2=2/π
(normalized by n=2, k1=k2=2/π
ptwise sqrt of n=3, k1=k2=2/π
) n=4, k1=k2=2/π
n=8, k1=k2=2/π
0.4
0.2
0
-0.2
-0.4
0
2/π
4/π
6/π
8/π
10/π
t (Λ-1)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y
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1
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−2
−3
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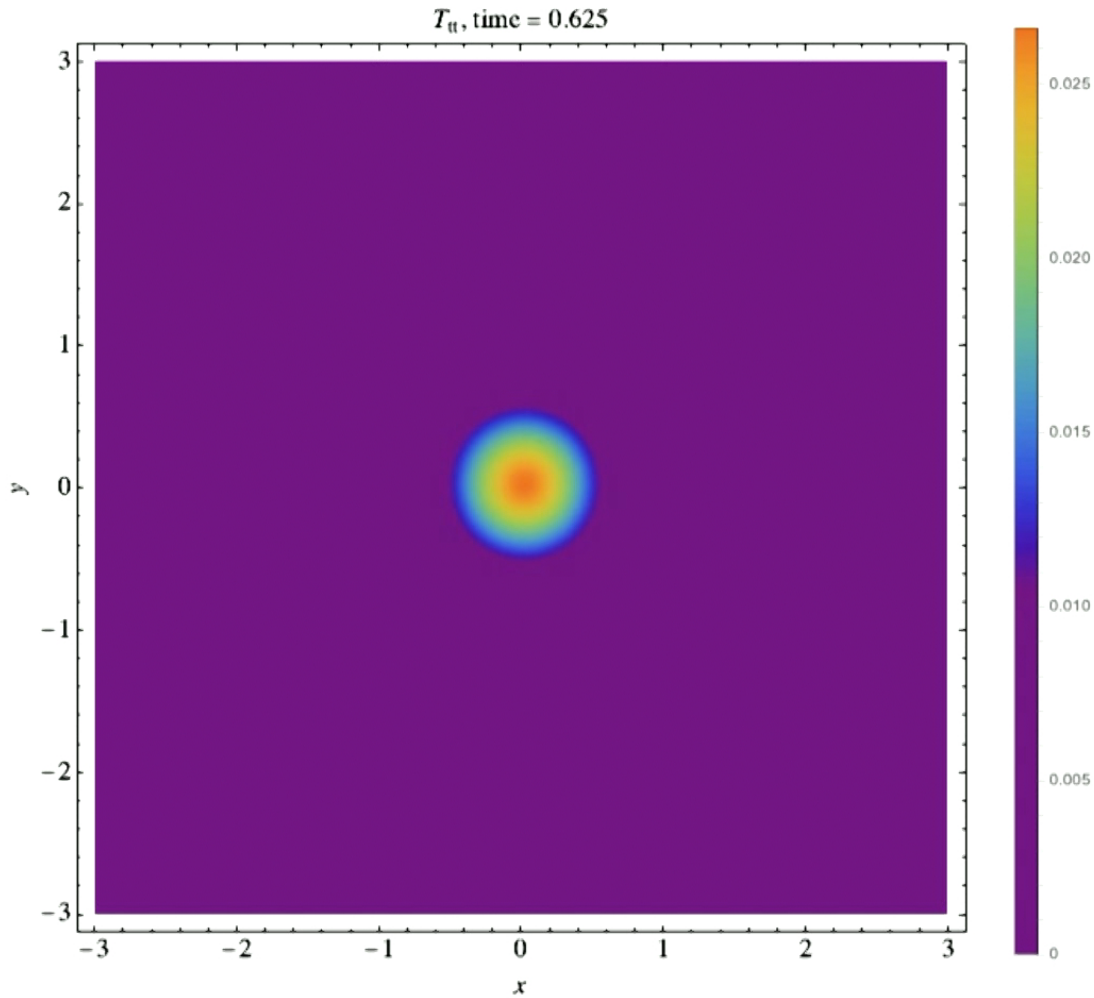
0.02
0.01
0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2
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x
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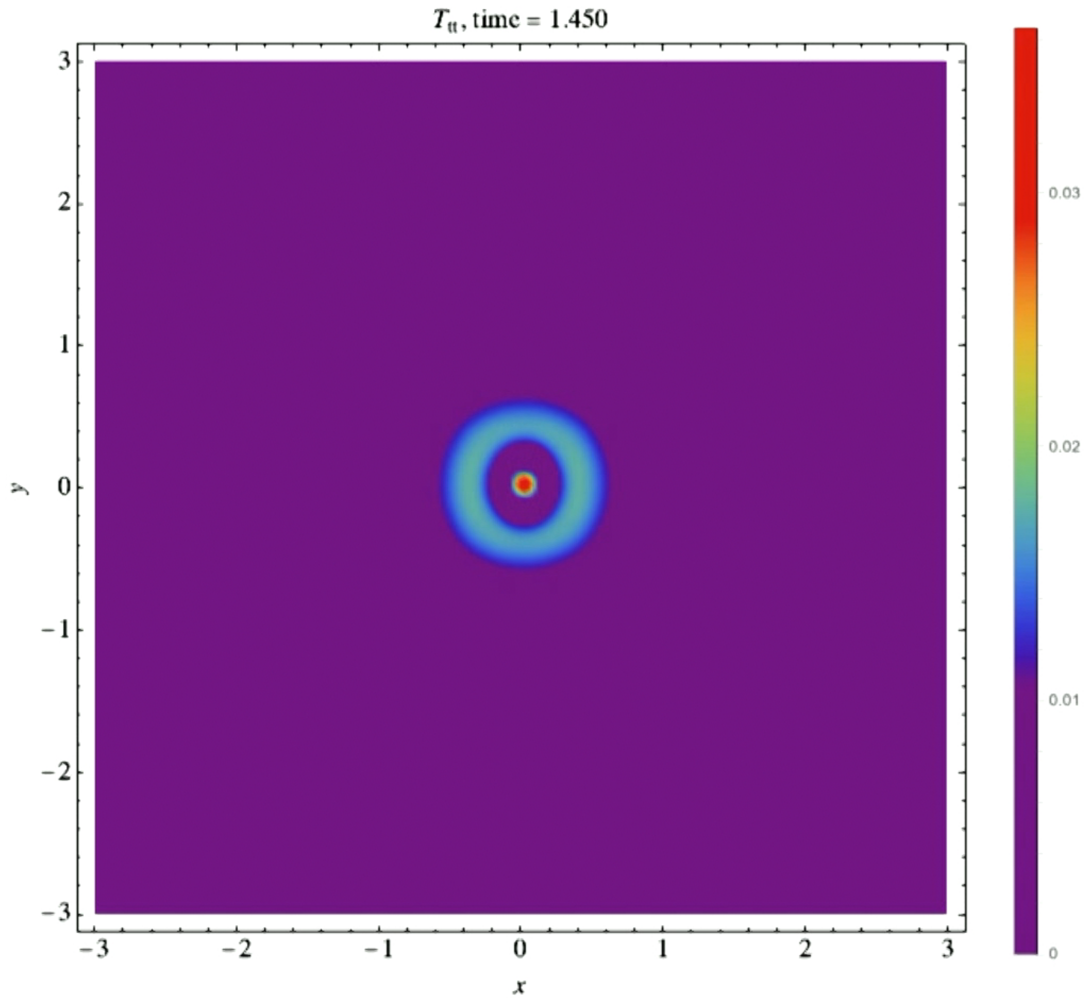
0.020
0.015
0.010
0.005
0



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x
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0
1
2
3
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0.01
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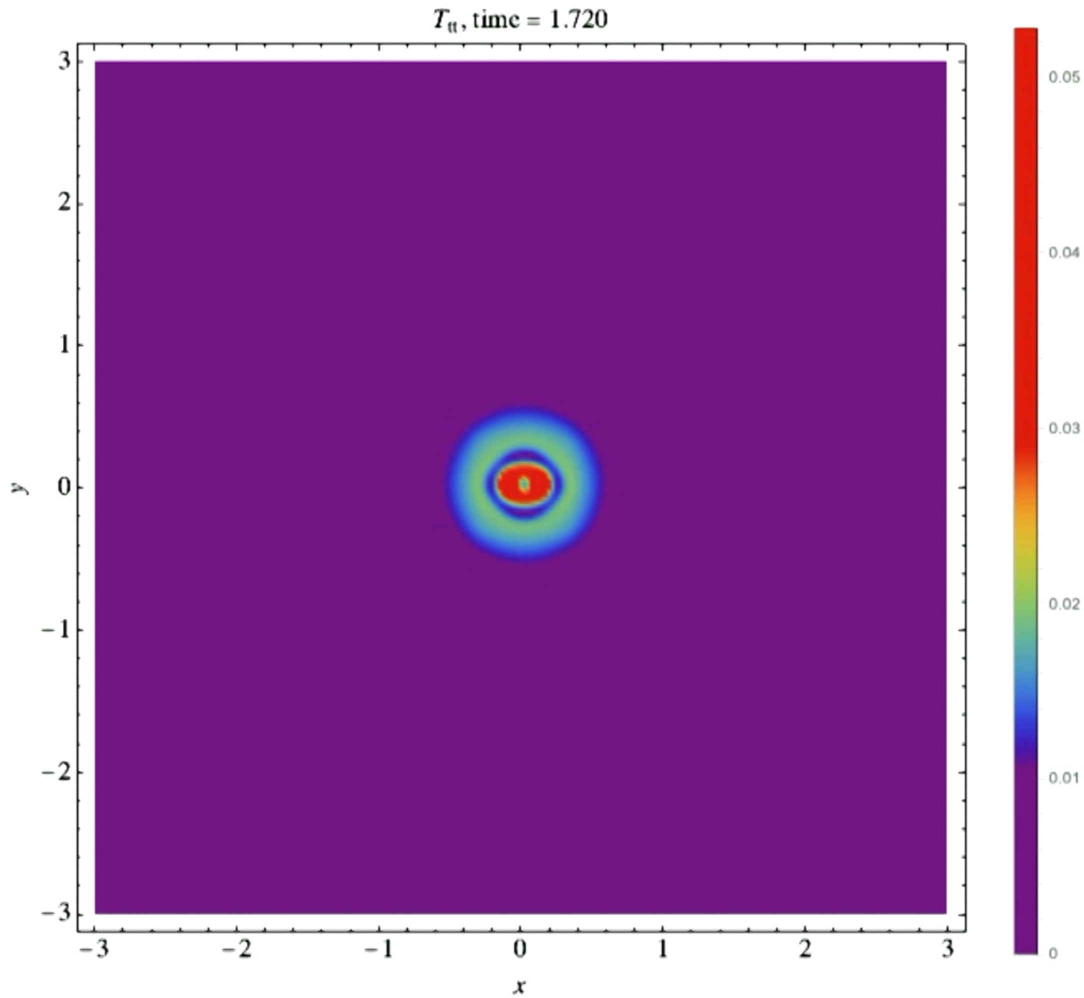
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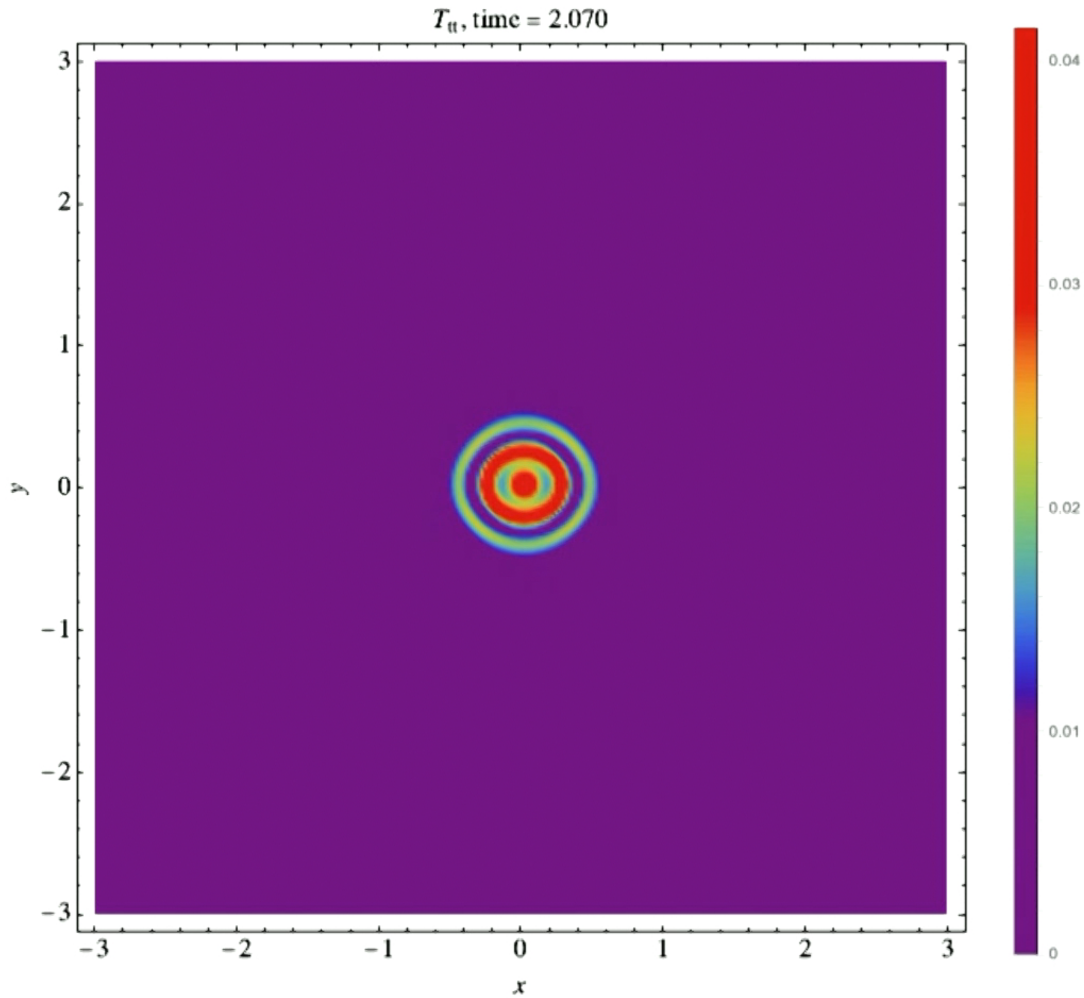
0.01
0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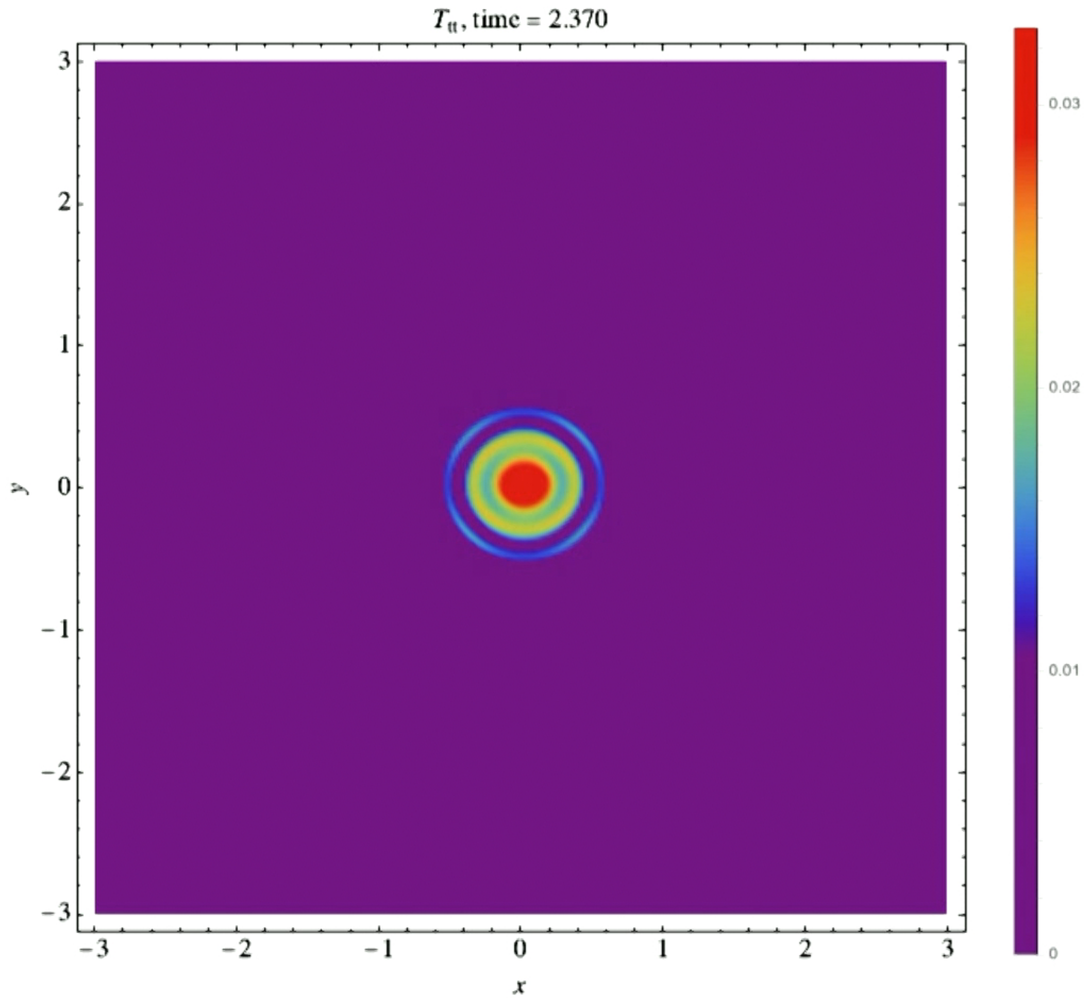
0.02
0.01
0



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1
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y
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2
3
x
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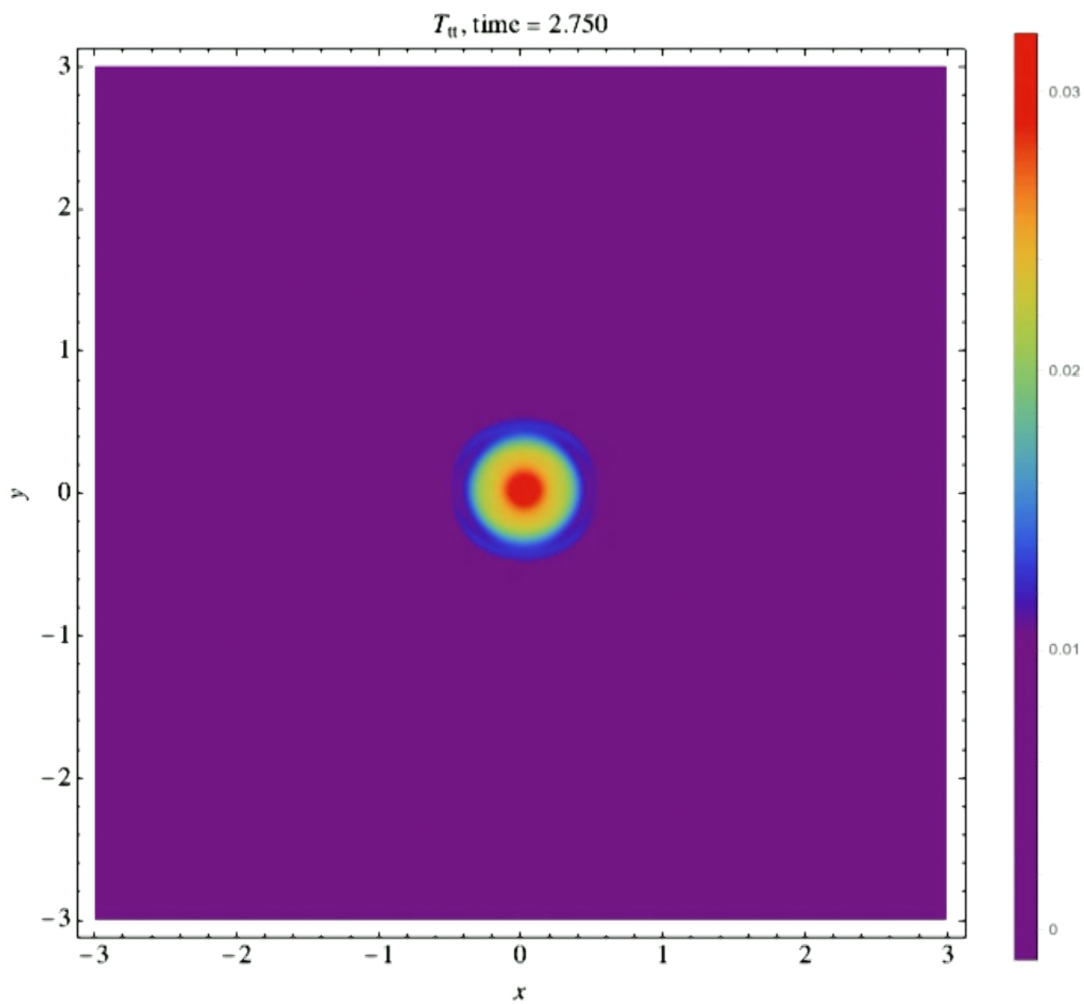
0.02
0.01
0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1
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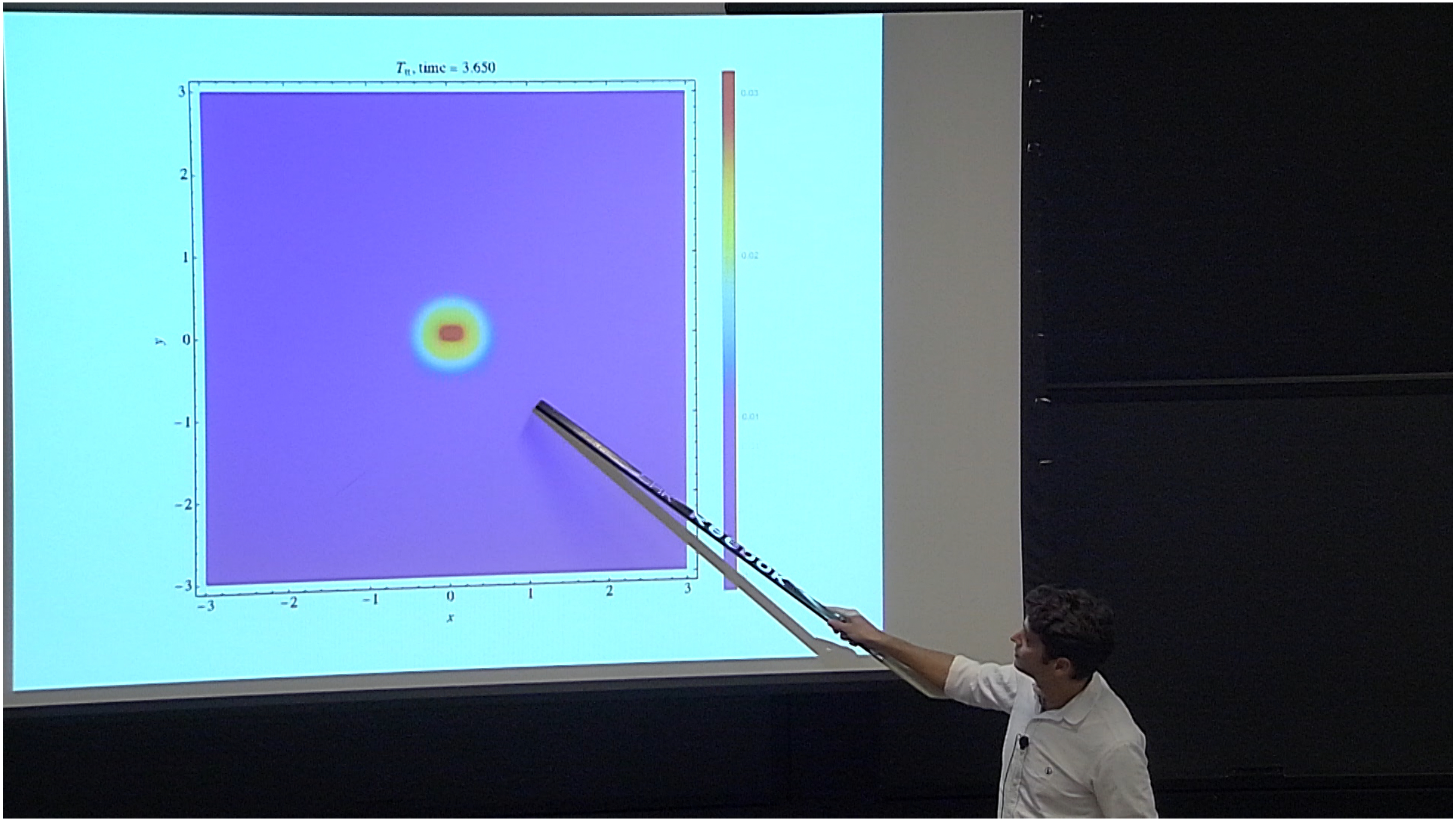
0.02
0.01
0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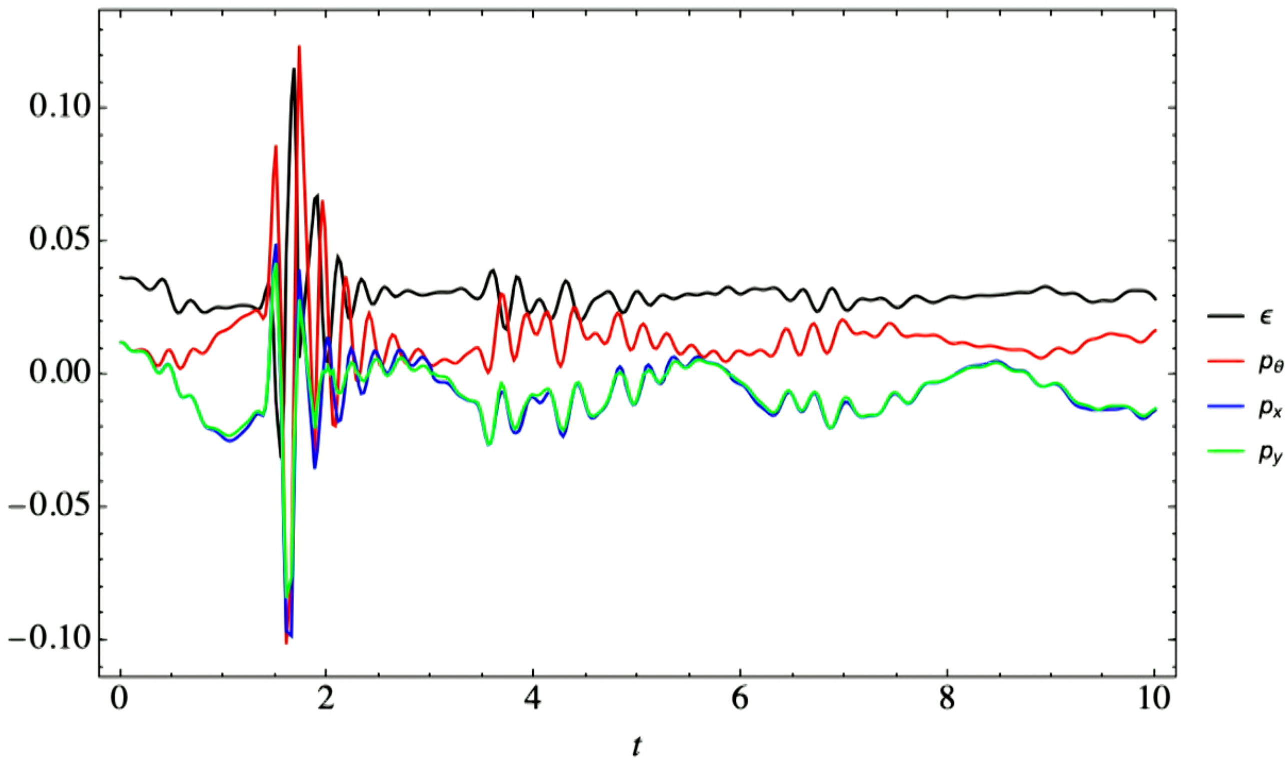
x
y


0.10
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0.00
−0.05
−0.10
0
2
4
6
8
10
t
ϵ
p_θ
p_x
p_y

Conclusions

- We have studied the dynamics of black holes in confining geometries
- Not freeze out yet
- When is hydro applicable?
- Detailed understanding of relaxation still missing…
- TODO: simulate collisions of compact objects

We send the EU £350 million
let's fund our NHS instead
Happy Halloween!!!
The Sun
FREE £5
BONUS
Kate that got the cream
JUDGES' BREXIT BLOW
WHO DO EU THINK YOU ARE?
Daily Mail
Fury over 'out of touch' judges who defied 17.4m Brexit voters and could trigger constitutional crisis
ENEMIES OF
BREXIT
ECONOMY