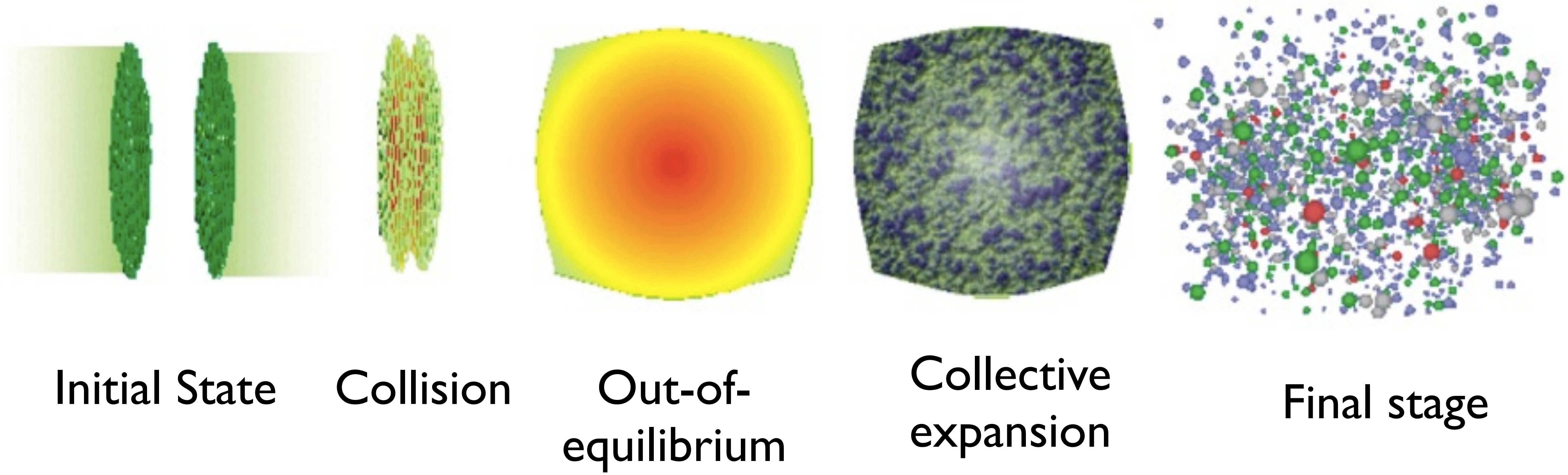
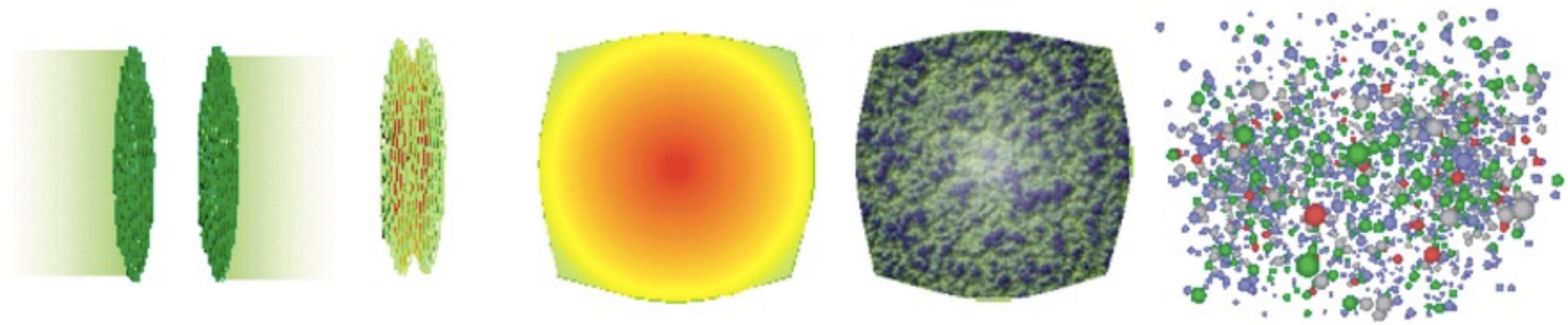
Collisions in Non-Conformal Theories: Hydrodynamisation without Equilibration

Jorge Casalderrey-Solana

From Initial to Final State in HIC



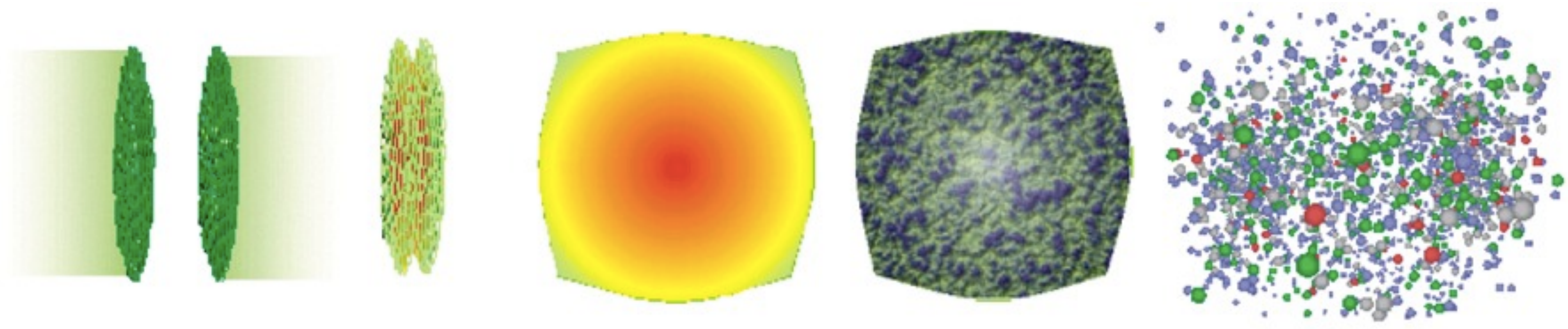
From Initial to Final State in HIC



Initial State | Collision | Out-of-equilibrium | Collective expansion | Final stage

Properties of nuclei at high energy

From Initial to Final State in HIC



Initial State | Collision | Out-of-equilibrium | Collective expansion | Final stage

↓ Initial State:

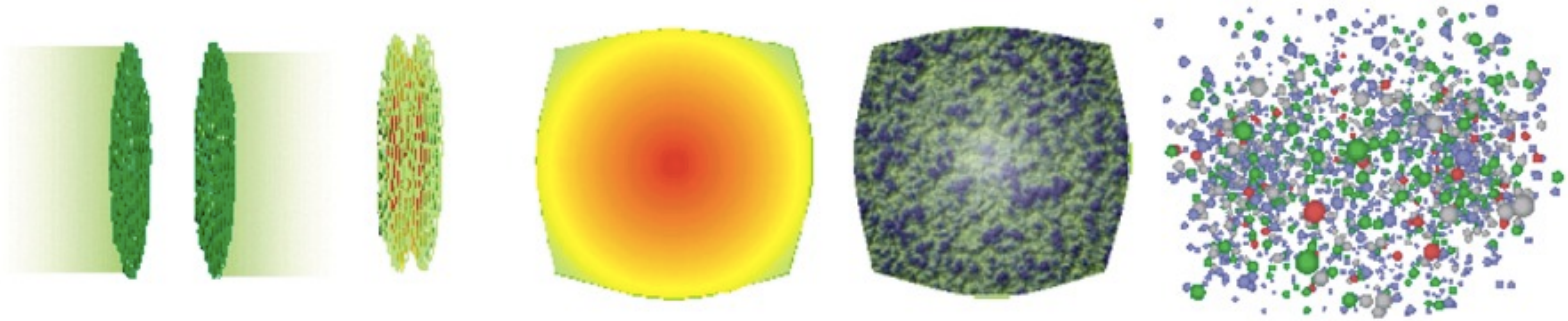
Properties of nuclei at high energy

↓ Collective expansion:

Hydrodynamics

Strongly coupled fluid

From Initial to Final State in HIC



Initial State | Collision | Out-of-equilibrium | Collective expansion | Final stage

Collision → Liberation of partons
Perturbation theory

Collective expansion → Hydrodynamics
Strongly coupled fluid

Initial State → Properties of nuclei
at high energy

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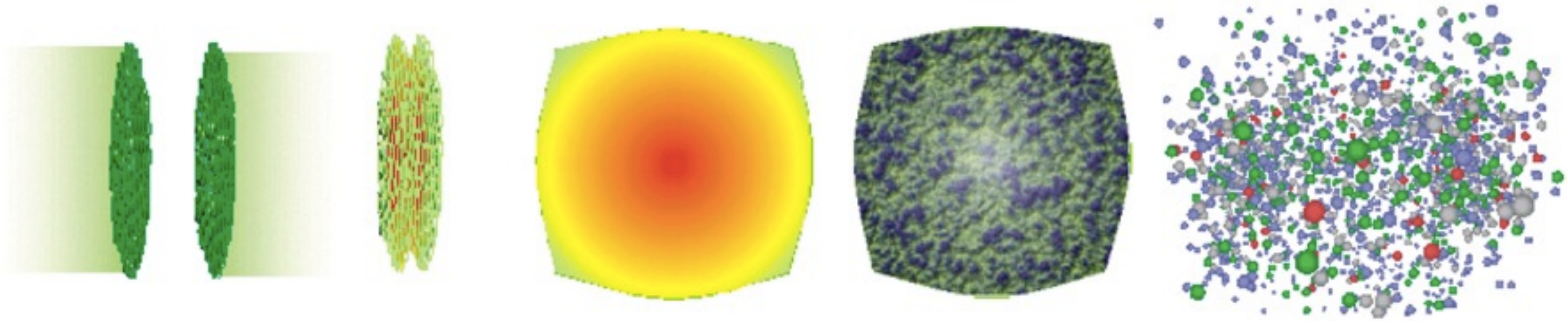


Initial State → Properties of nuclei at high energy

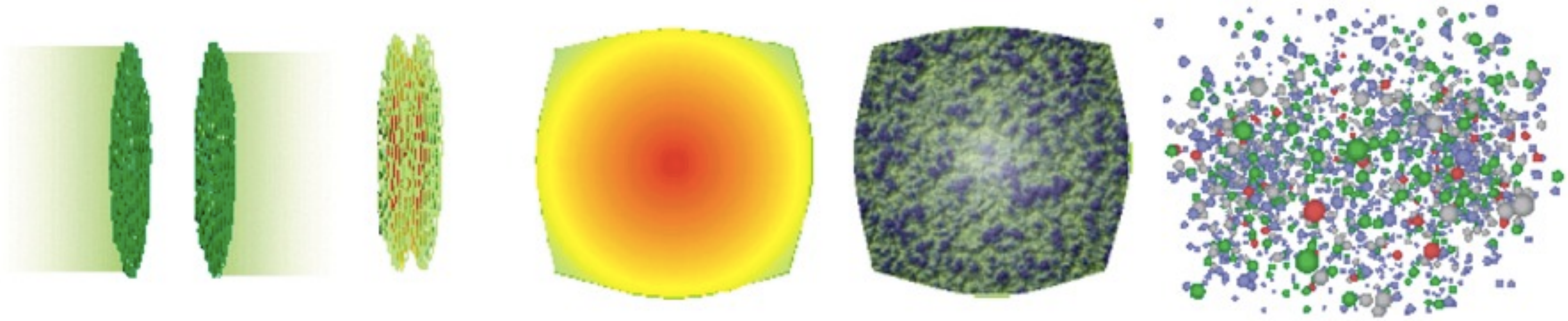
Collision → Liberation of partons; Perturbation theory

Out-of-equilibrium → Equilibration, Isotropization, Hydrodynamization

Collective expansion → Hydrodynamics; Strongly coupled fluid

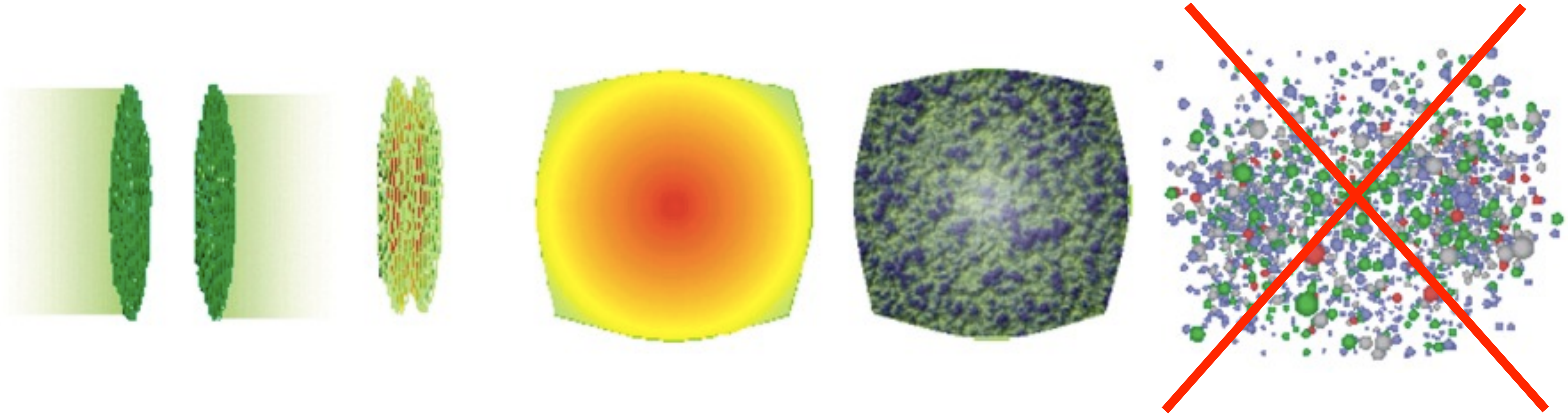
Final stage

From Initial to Final State in Holography



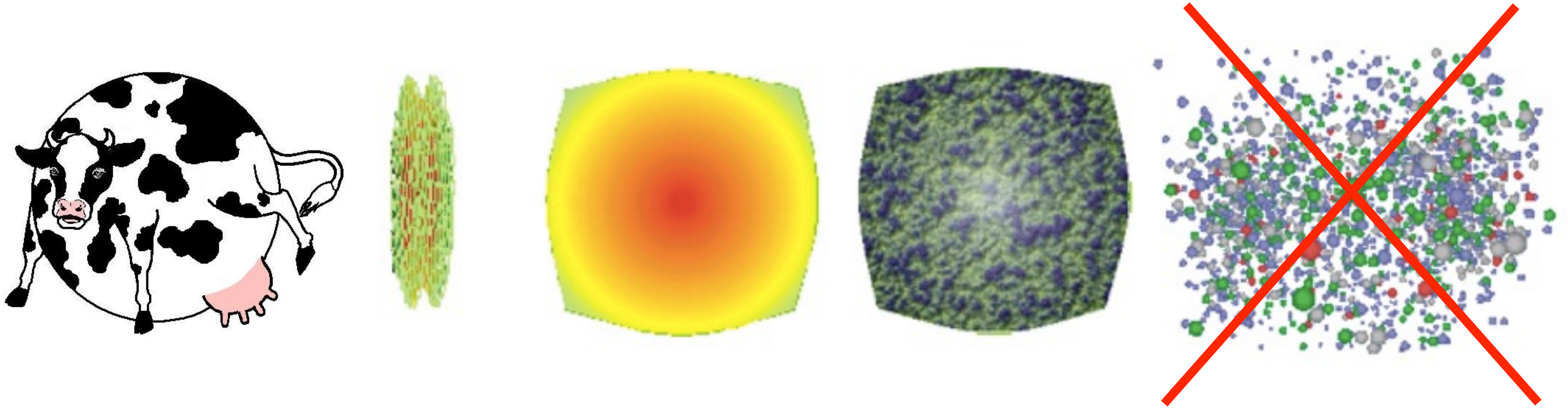
- Can we describes all these stages in a single framework?

From Initial to Final State in Holography



- Can we describes all these stages in a single framework?
  - Holography says: yes! (up to the last one)

From Initial to Final State in Holography



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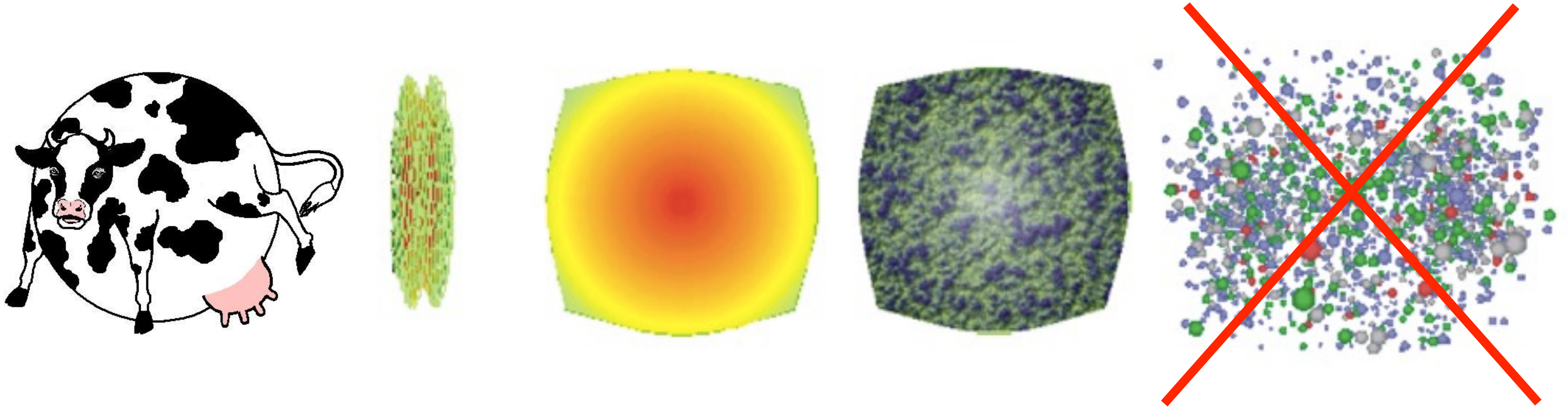
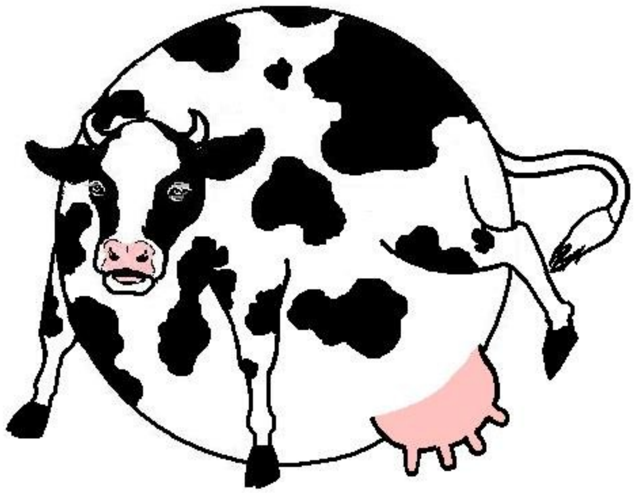
From Initial to Final State in Holography



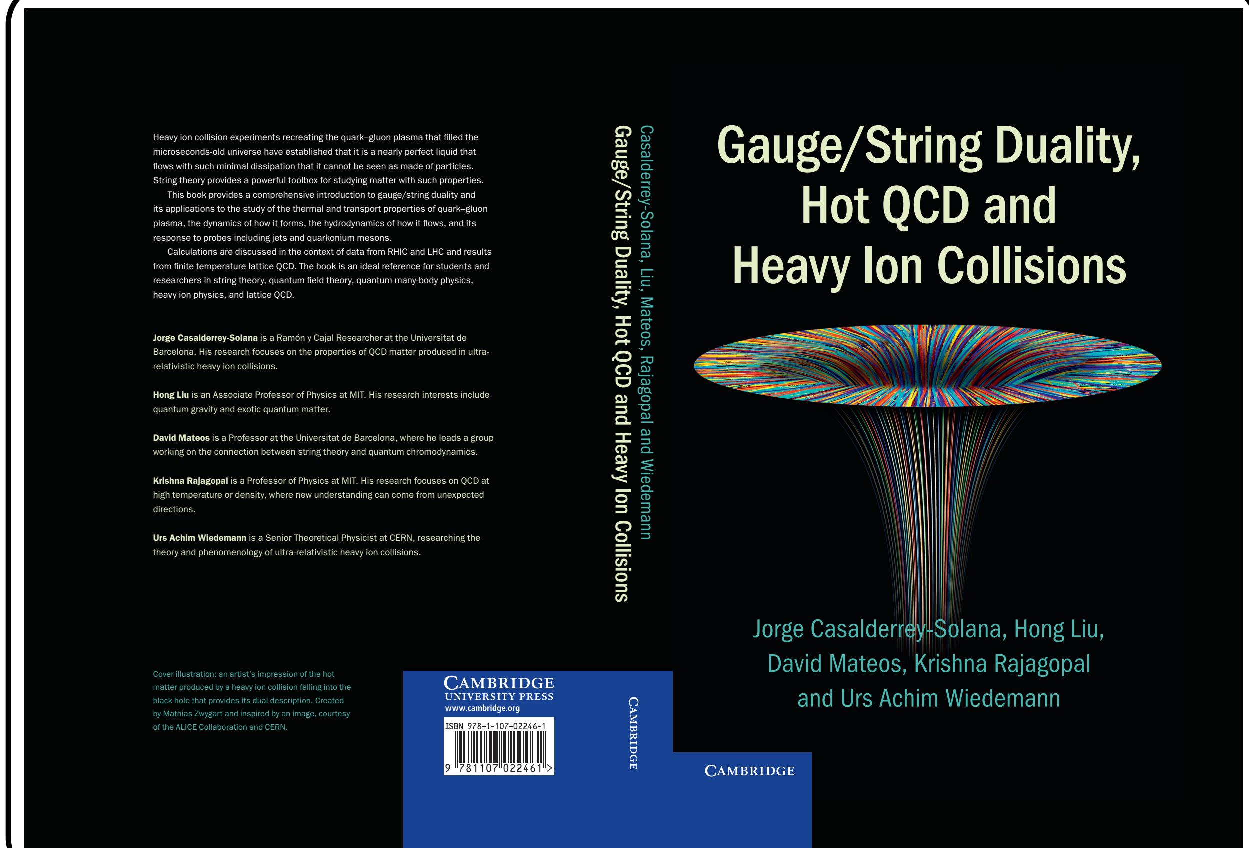
- Can we describes all these stages in a single framework?
  - Holography says: yes! (up to the last one)
  - As long as we are happy with an oversimplified “nucleus”

- As long as we are happy with other strongly coupled theory



- Gauge Theories in the limit

$$\lambda = g^2 N_c \to \infty$$



Holography

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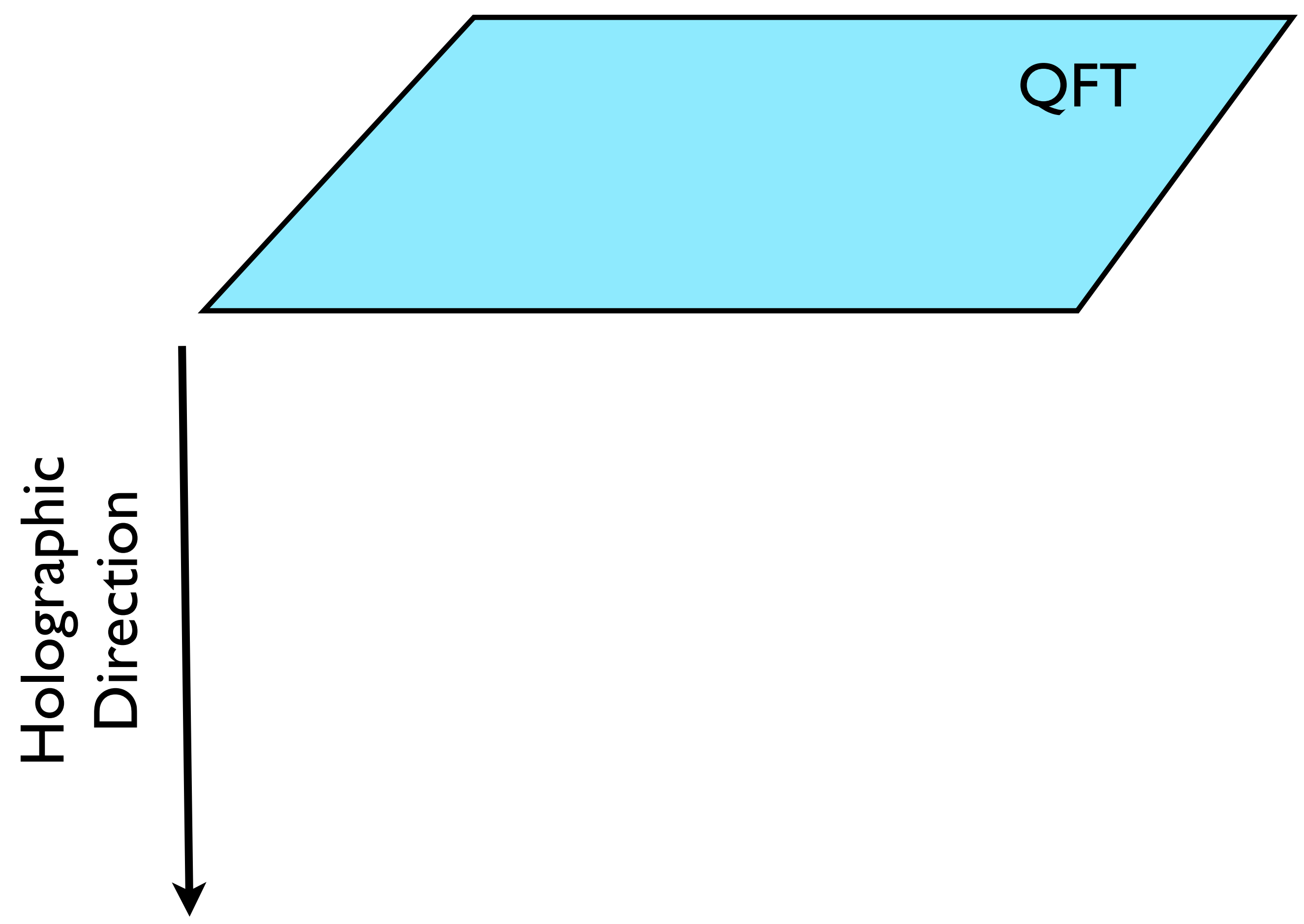
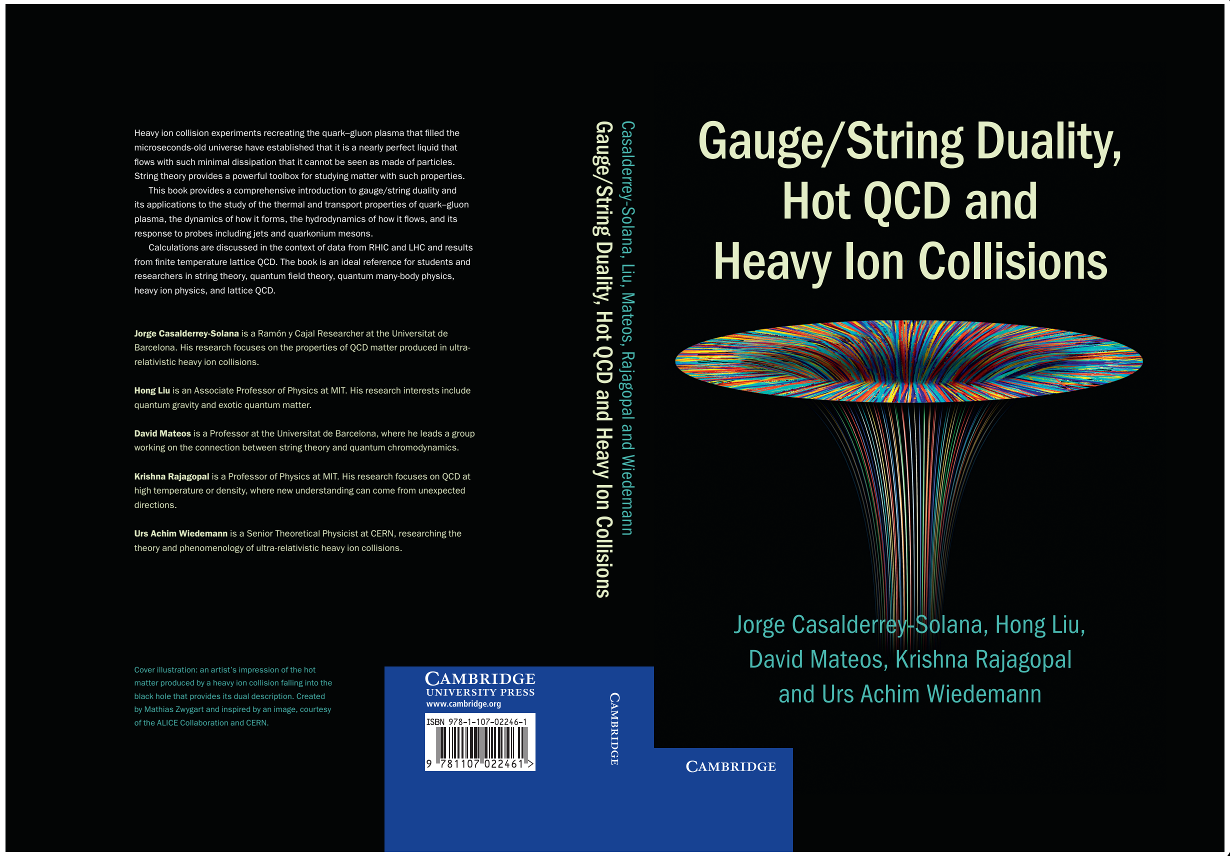


J. M. Maldacena, *Adv. Theor. Math. Phys* 2, 231 *(1998)*



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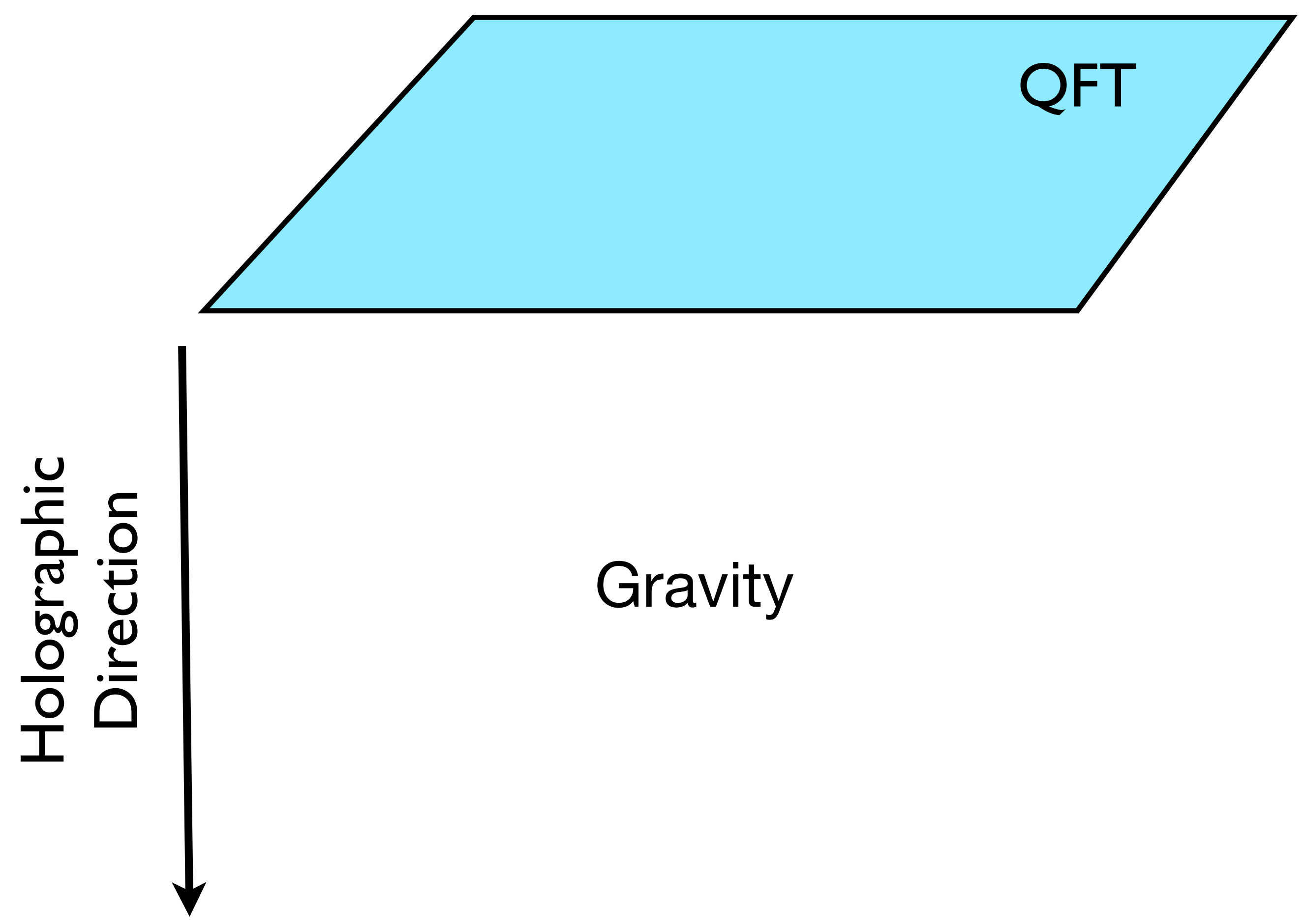

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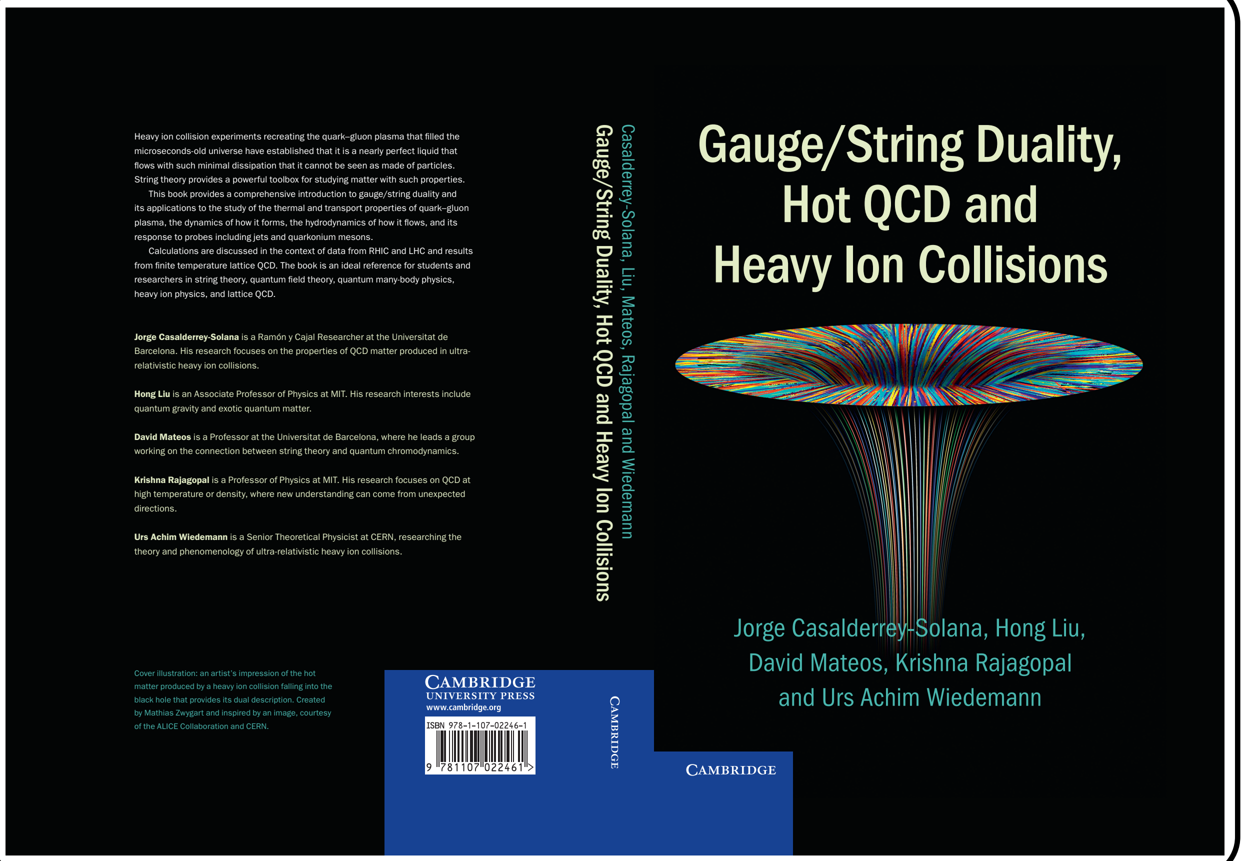

Dictionary

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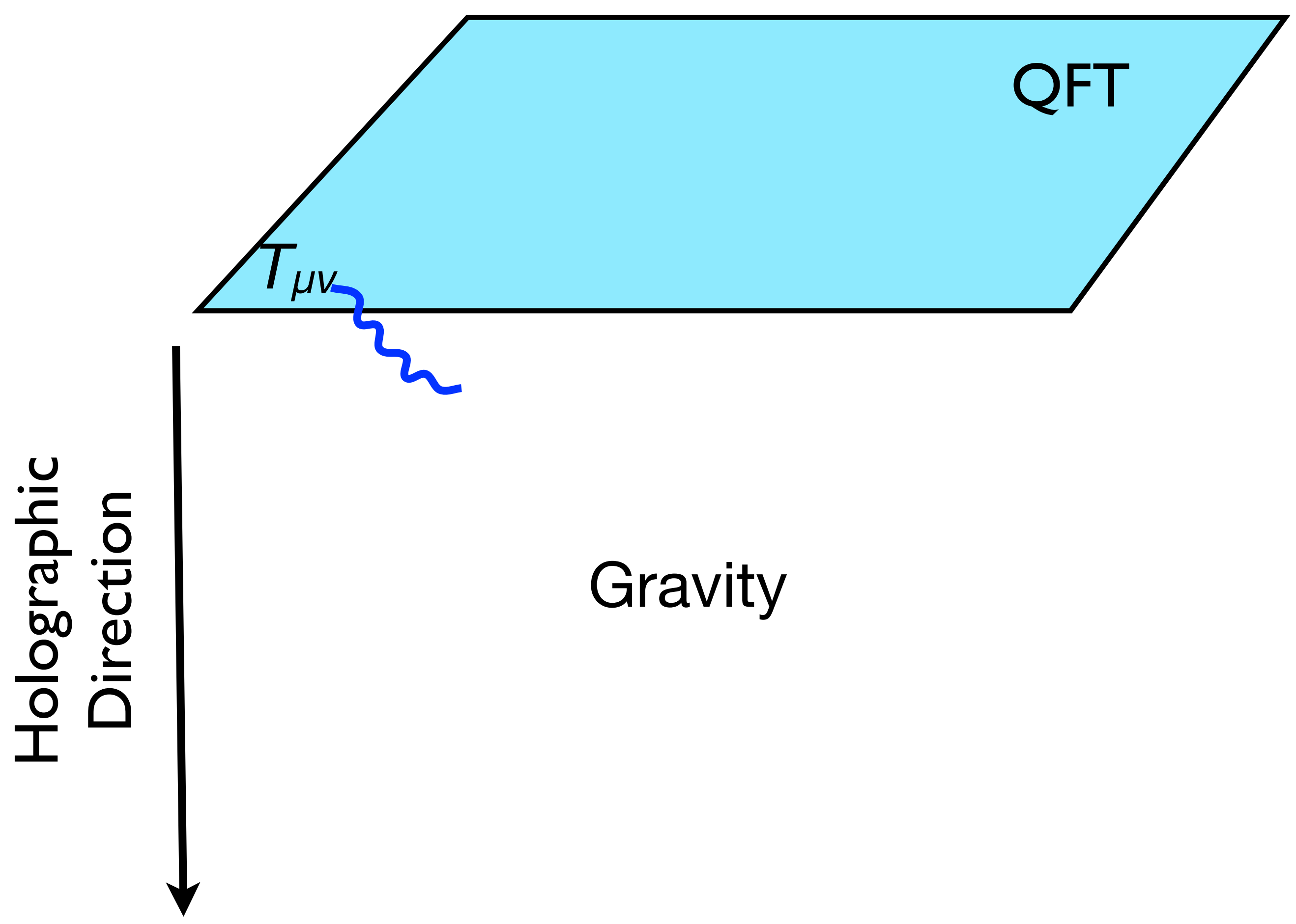

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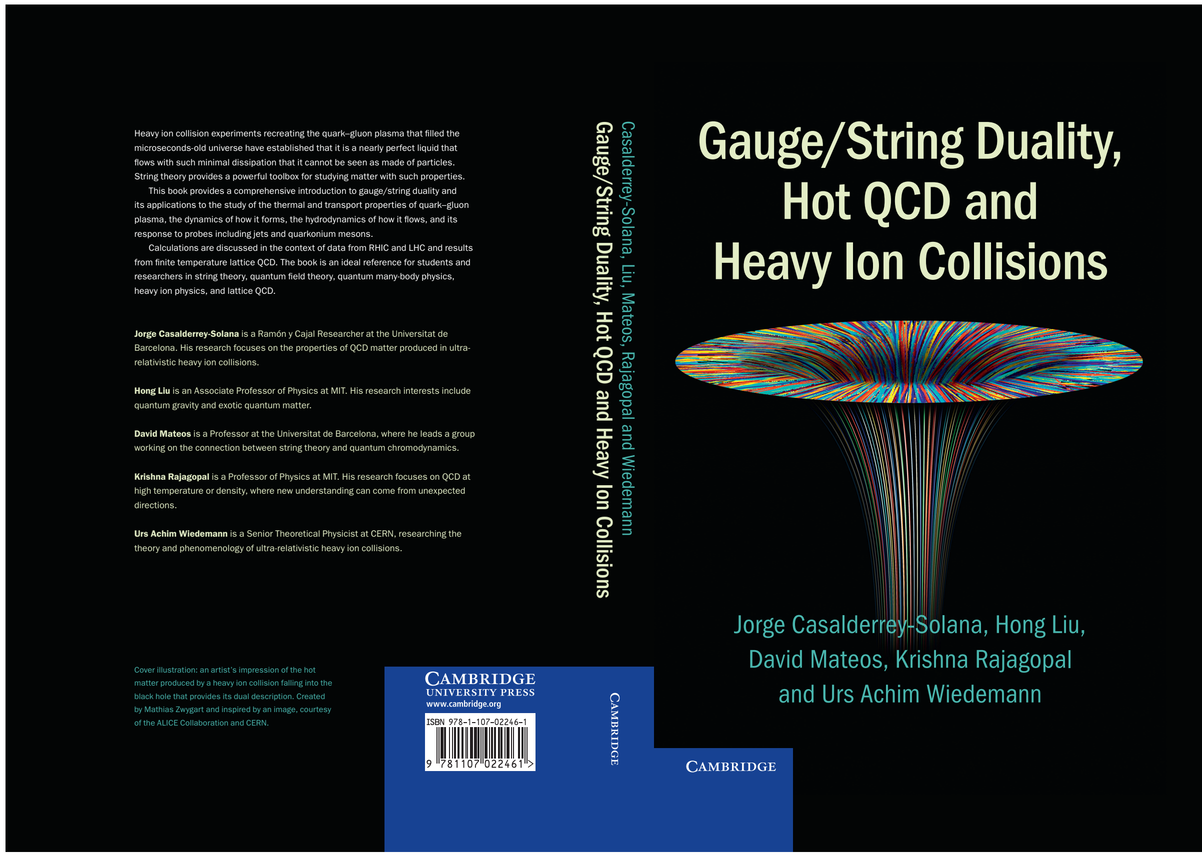

Dictionary

$$T_{\mu\nu} \leftrightarrow g_{\mu\nu}$$

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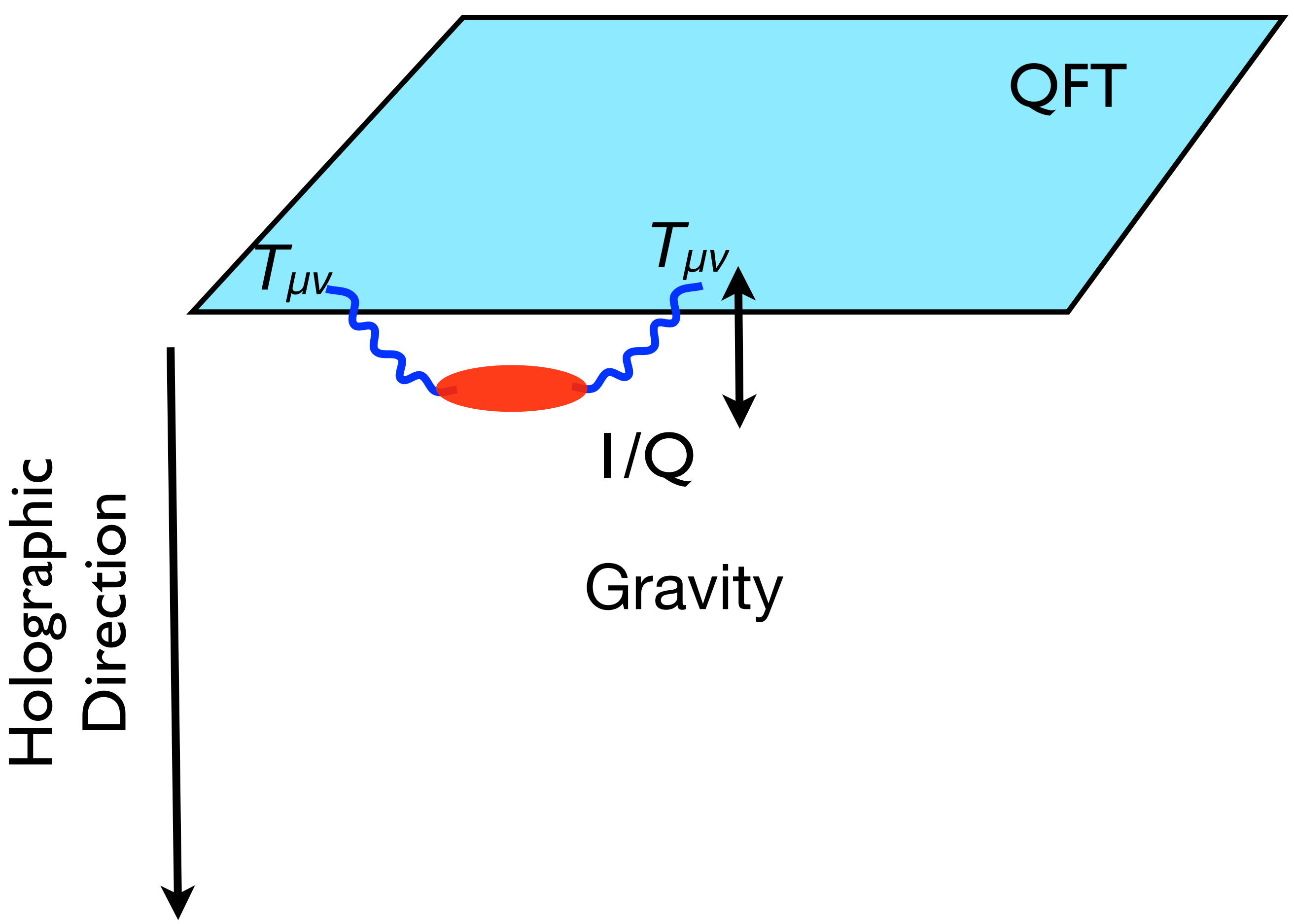

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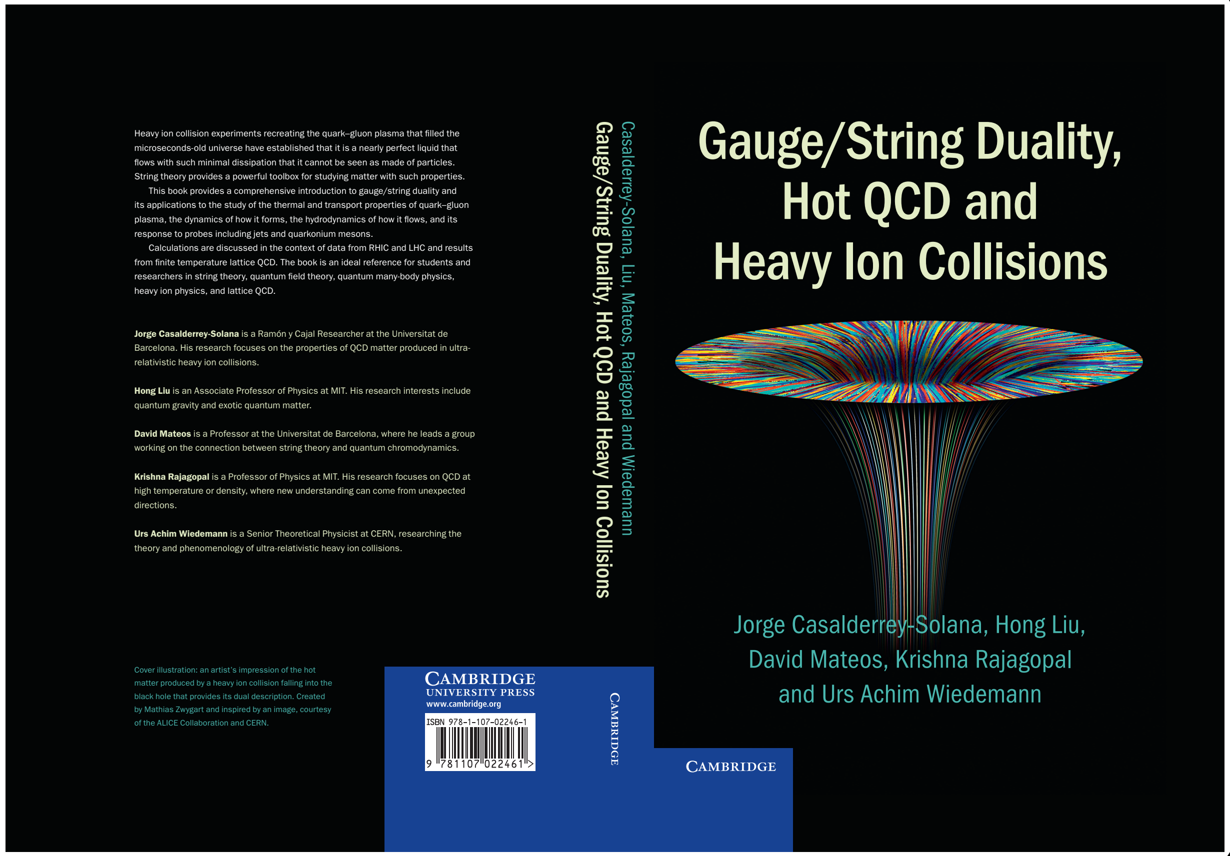

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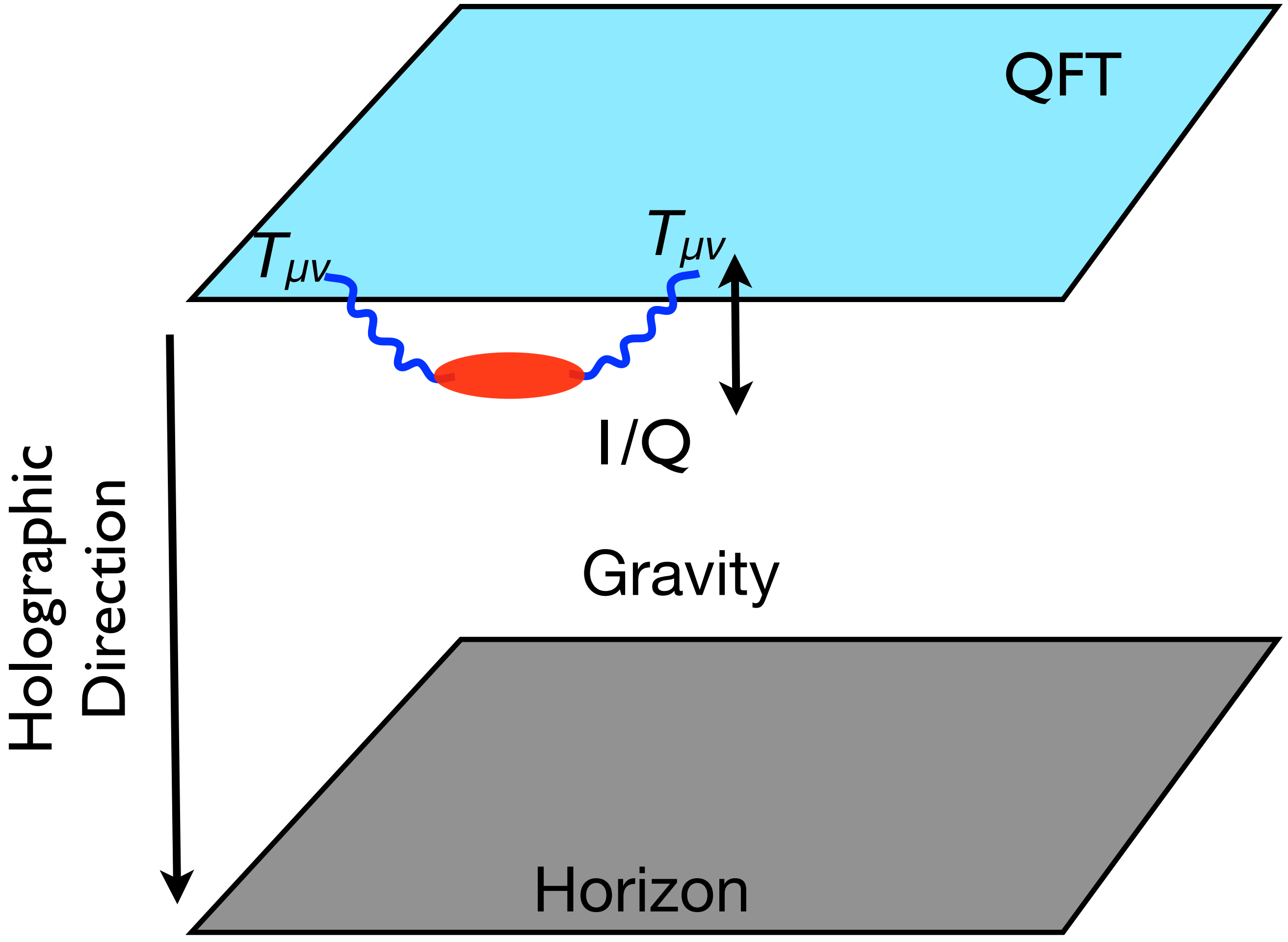

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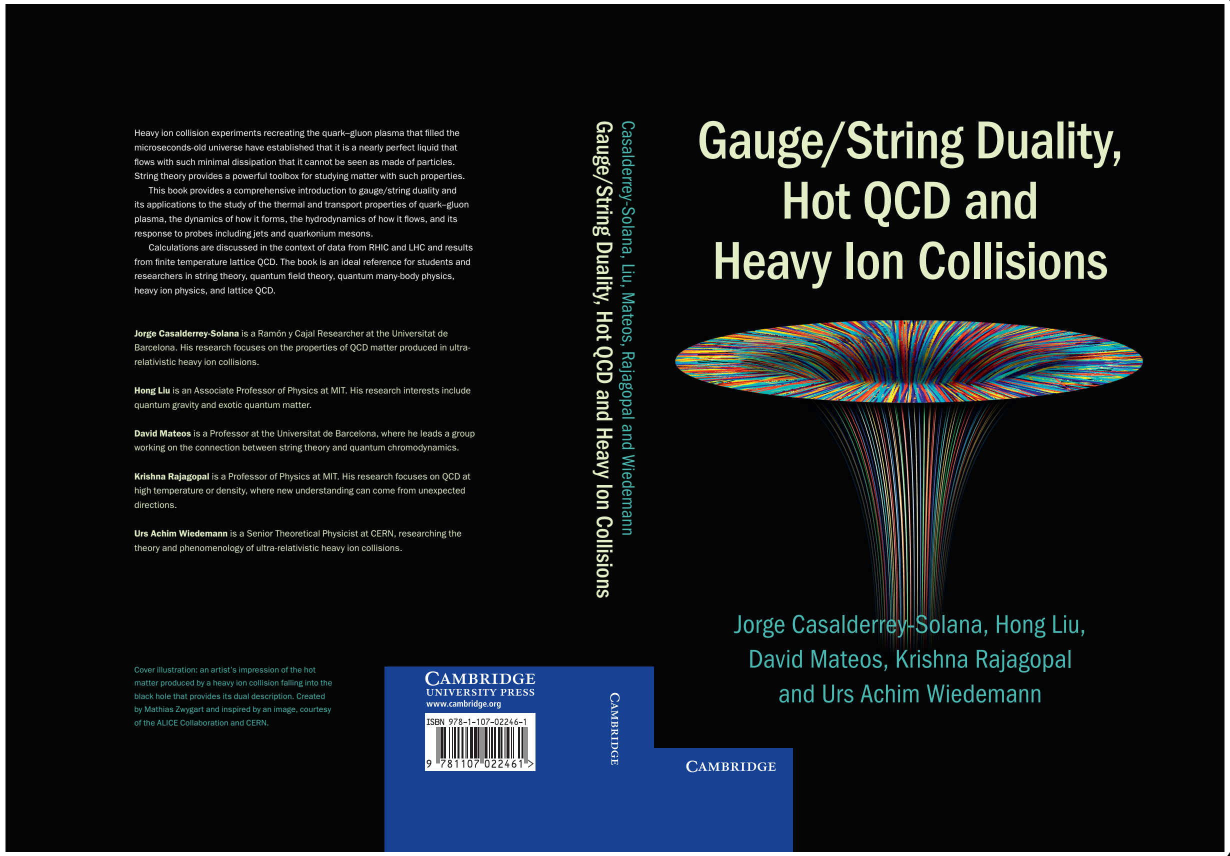

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$T \leftrightarrow$ *black hole*

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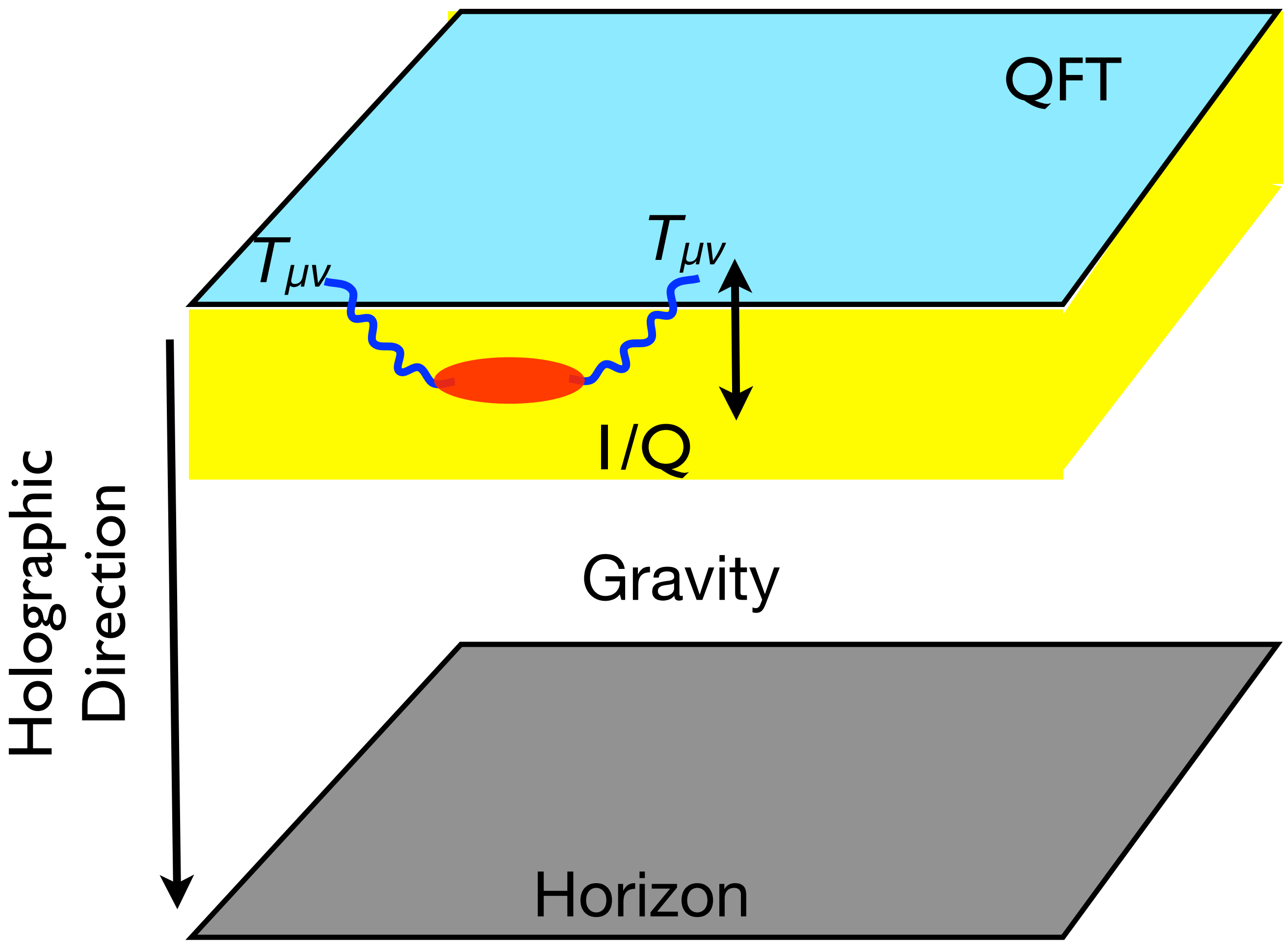

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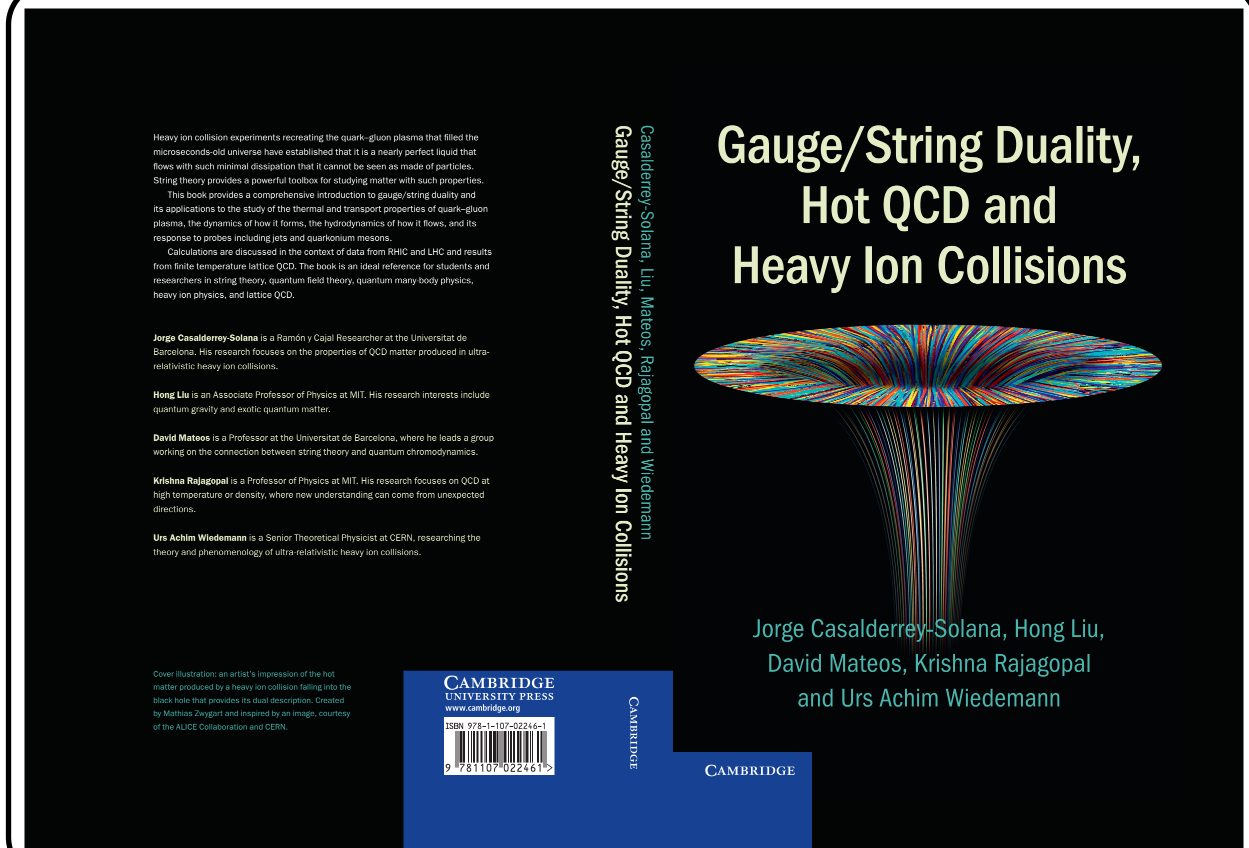

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$T \leftrightarrow$ *black hole*

flavor $\leftrightarrow$ *brane*

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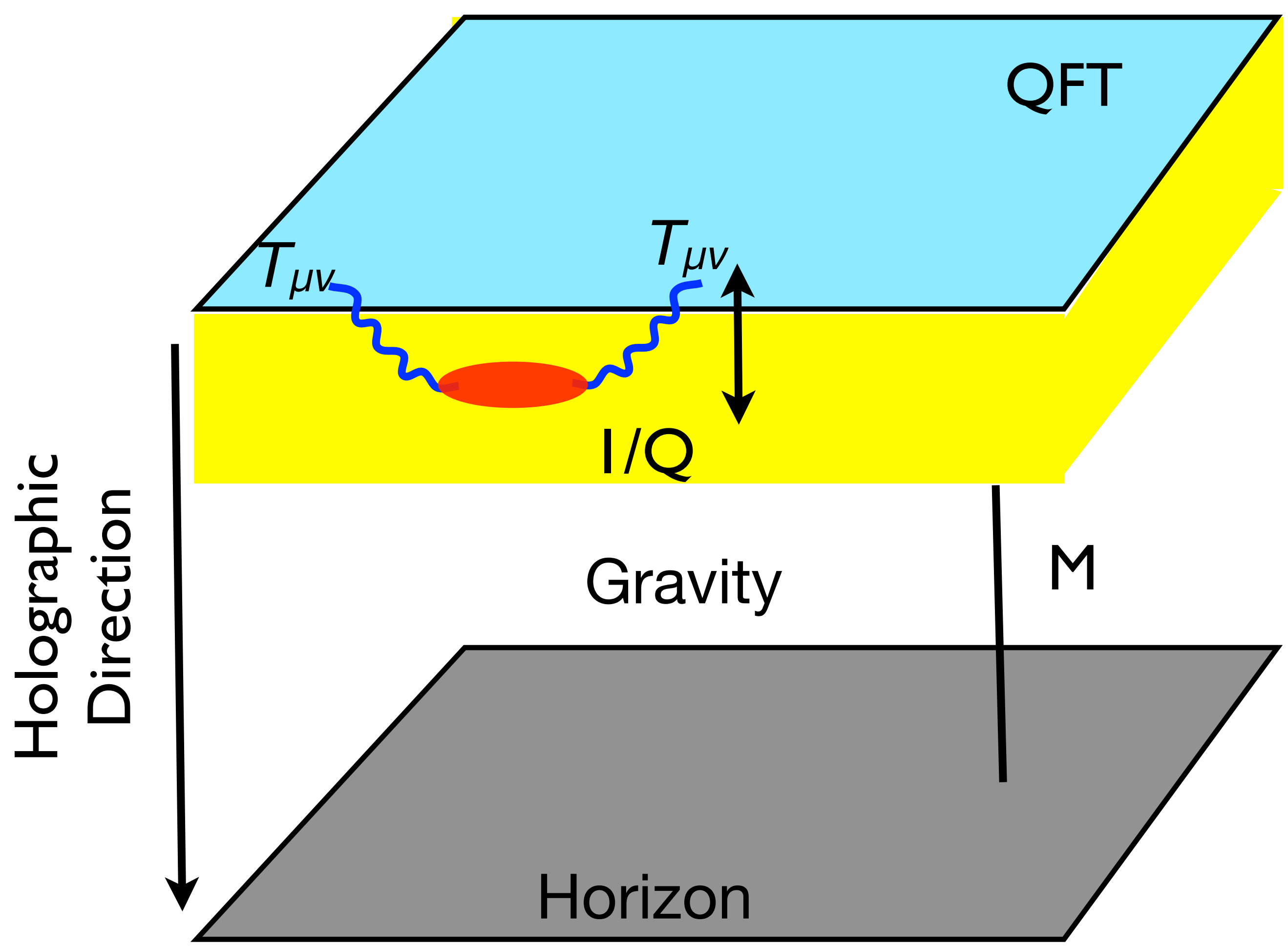

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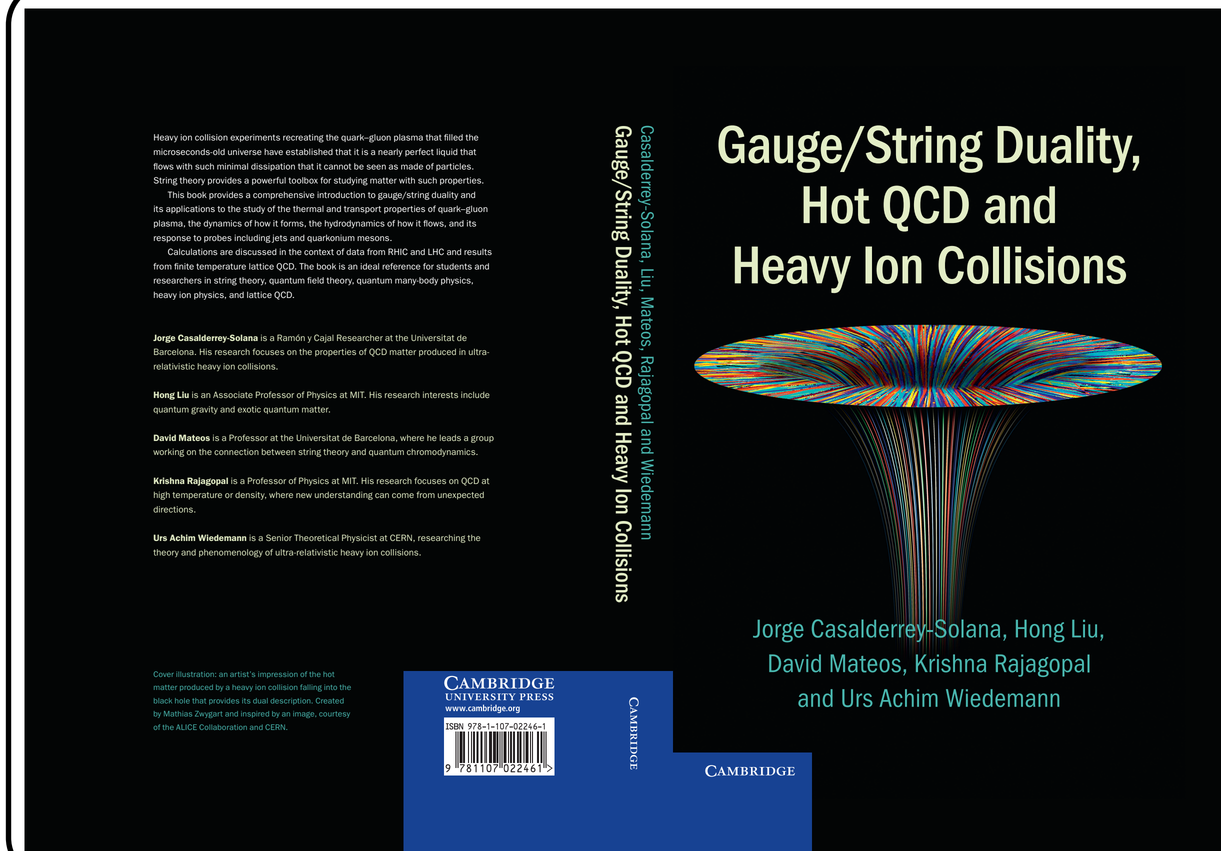


Dictionary

$T_{\mu\nu} \leftrightarrow g_{\mu\nu}$

T ↔ *black hole*

flavor ↔ *brane*

heavy quark ↔ *string*

Einstein Equation

- Numerically solve in 5D

$$R_{MN} - \frac{1}{2} R\, G_{MN} + \Lambda\, G_{MN} = 0$$

- Specify initial data: shock wave solutions

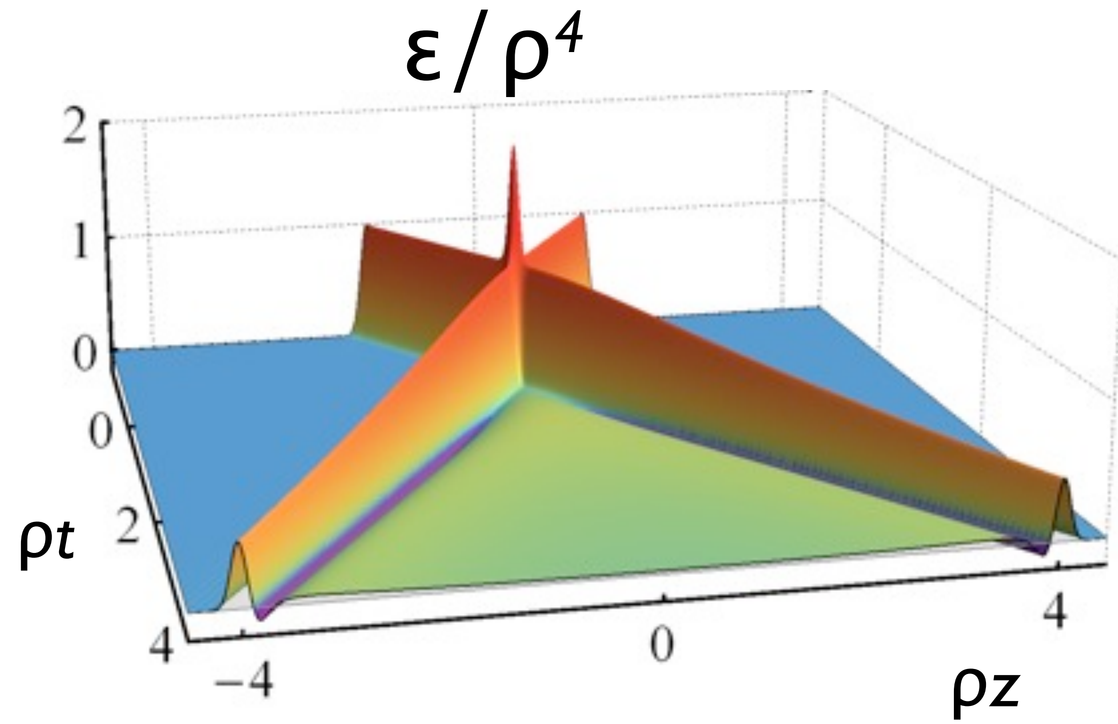
- Read off the dual stress tensor using the dictionary:

$$ds^2 = \frac{1}{z^2} \left\{ dz^2 + \left(g_{\mu\nu} + z^4 T_{\mu\nu} + \ldots \right) dx^\mu dx^\nu \right\}$$

Colliding Sheets of Energy

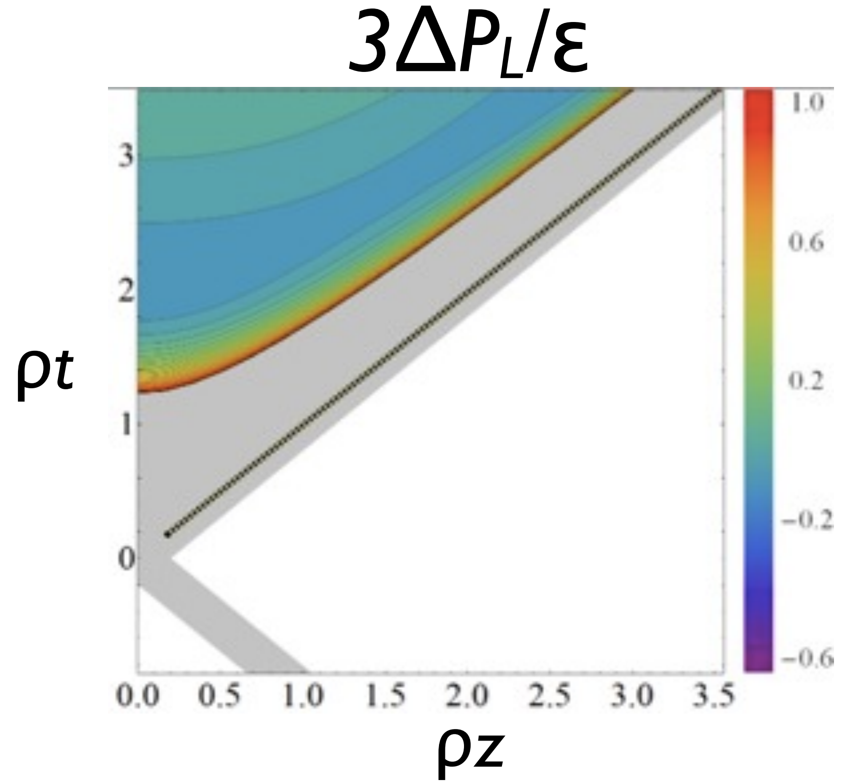
- Shock wave collisions in GR
  - Full access to the QFT stress tensor
  - Conformal field theory dual

$$\zeta=0$$



JCS, Heller, Mateos, van der Schee, 2013

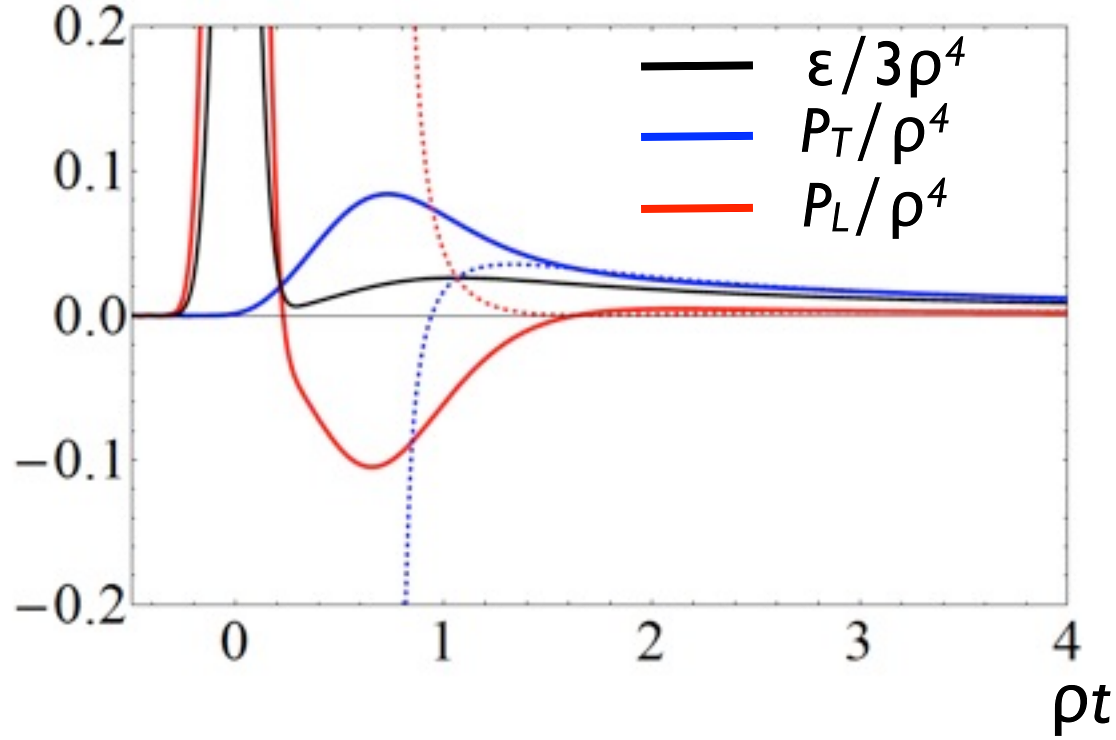
Chesler & Yaffe 2011

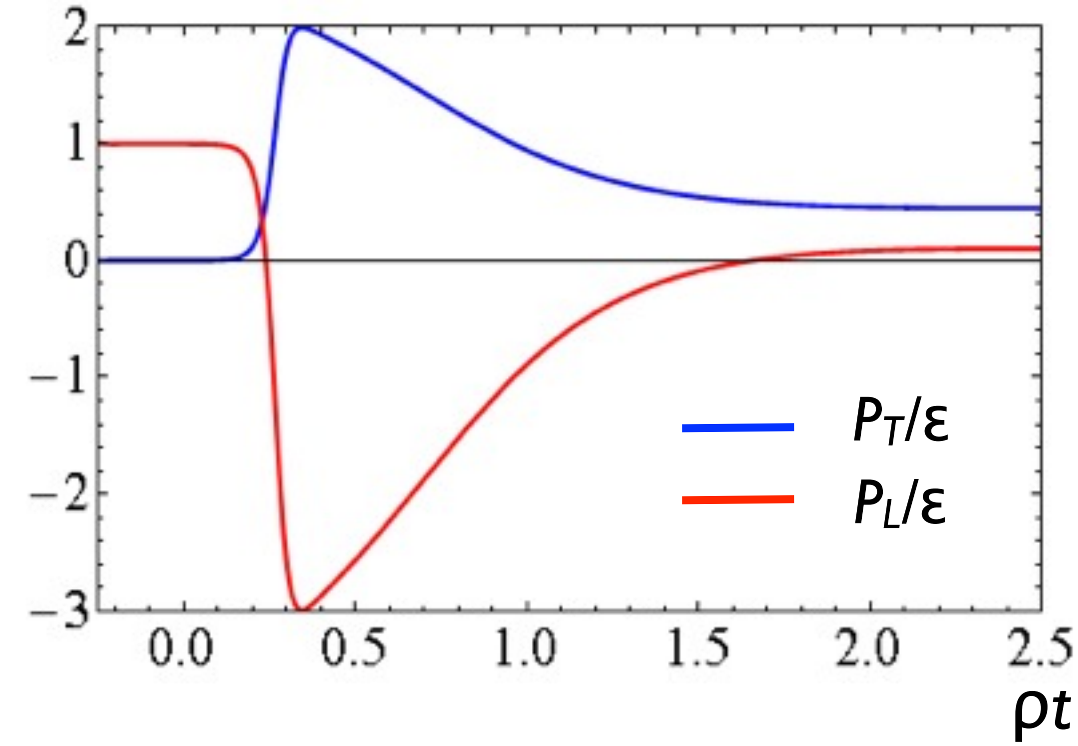


- Onset of hydrodynamic behavior at very early times

$$t_{hydro} = 0.63 \frac{1}{T_{hydro}}$$

Surprisingly Hydrodynamic





- Hydrodynamics works even where it should not work
  - Good description even when gradient corrections are large!
  - Hydrodynamization without isotropization

Chesler & Yaffe, Wu & Romatschke, Heller, Janik & Witaszczyk, Heller, Mateos, van der Schee, Trancanelli

- Similar conclusions reached in a perturbative framework

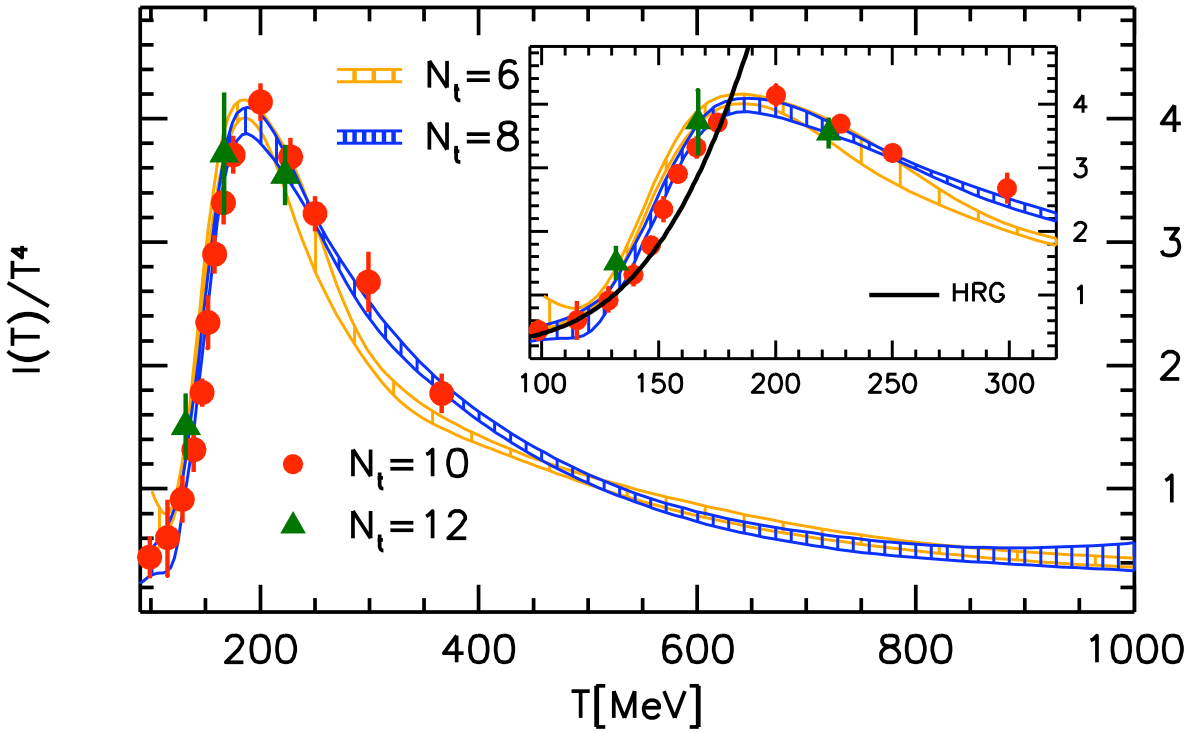
Kurkela and Zhu 15, Keegan, Kurkela, Mazeliausksa and Teaney 16

Non-Conformal QCD

- Most out-off-equilibrium analyses focus on conformal theories

- However, QCD is non-conformal, specially close to the transition

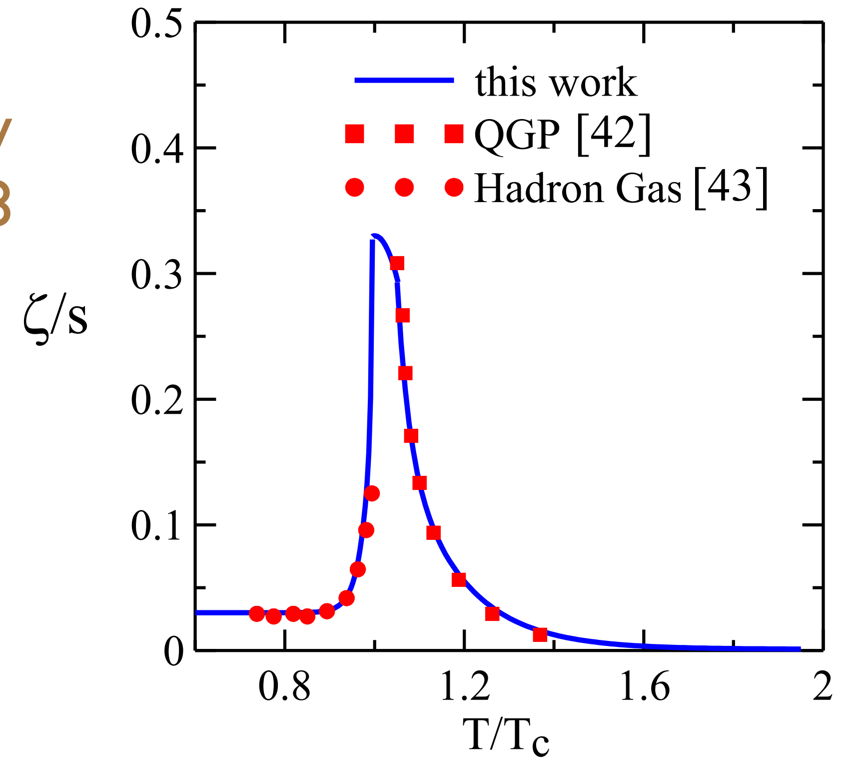
Borsanyi et al. 2010



Karsch, Kharzeev and Tuchin 2008

⇒

Ryu et al. 2015

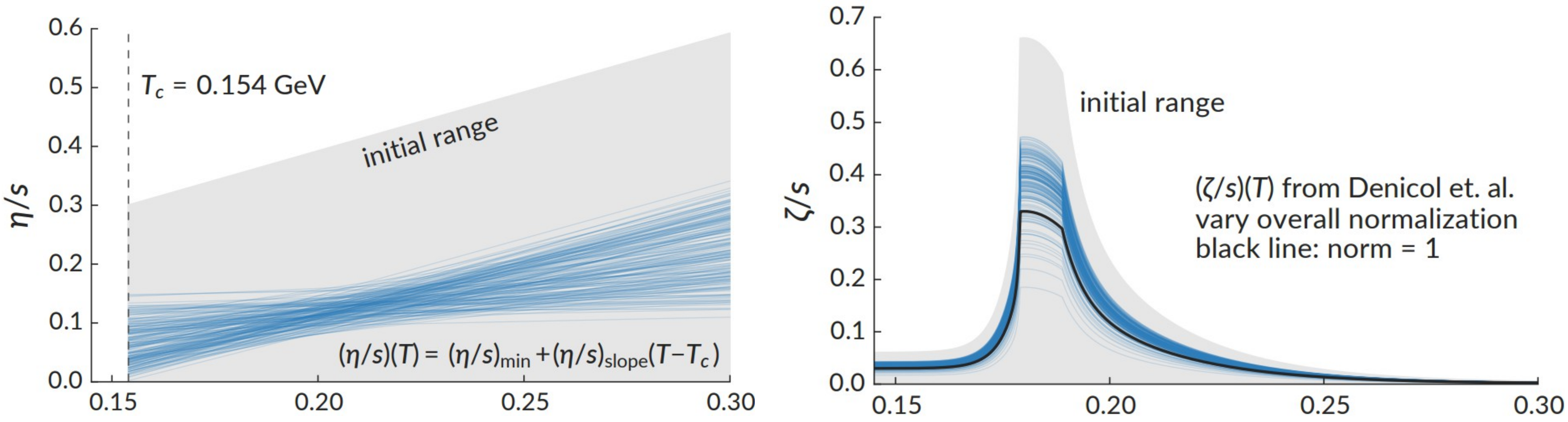


- Bulk viscosity effects become important to accurately describe heavy ion data

Extracting Transport Coefficients

Global fit to several sets of data

J. Bernhard, J.S. Moreland, S. Bass, J. Liu, U. Heinz arXiv:1605.03954



$$\left(\frac{\eta}{s}\right)_{\mathrm{T_c}} = 0.08 \pm 0.05$$

A Bottom-up Non-Conformal Model

- Einstein gravity + Scalar

$$S = \frac{2}{\kappa_5^2}\int d^5x\sqrt{-g}\left[\frac{1}{4}\mathcal{R} - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right]$$

- Phenomenological (family of) potential(s)

$$V = -3 - \frac{3}{2}\phi^2 - \frac{1}{3}\phi^4 + \left(\frac{1}{3\phi_M^2} + \frac{1}{2\phi_M^4}\right)\phi^6 - \frac{1}{12\phi_M^4}\phi^8$$

ϕ_M → parameter

- Dual field theory: "mimics" a deformation of N=4 SYM with a dimension 3 operator

$$S_{\text{Gauge Theory}} = S_{\text{conformal}} + \int d^4x\, \Lambda\, \mathcal{O} \qquad \mathcal{O} \sim \bar{\psi}\psi + \cdots$$

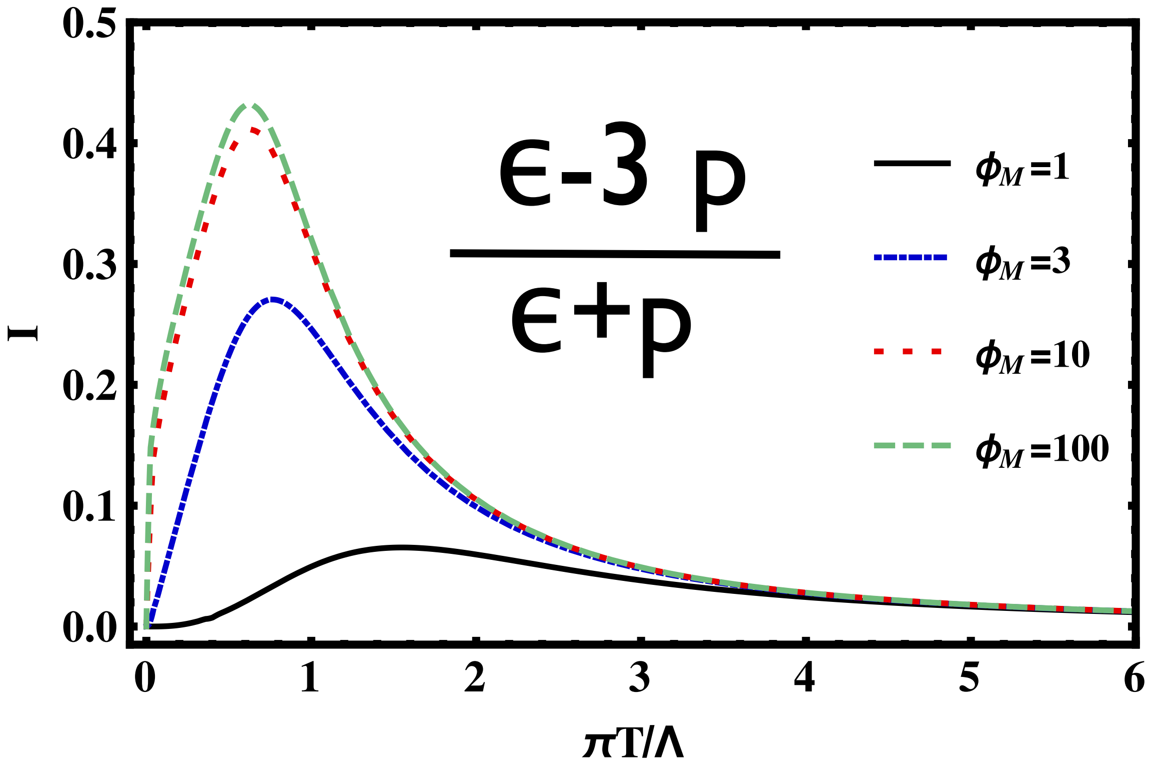
Λ ↓ "mass"

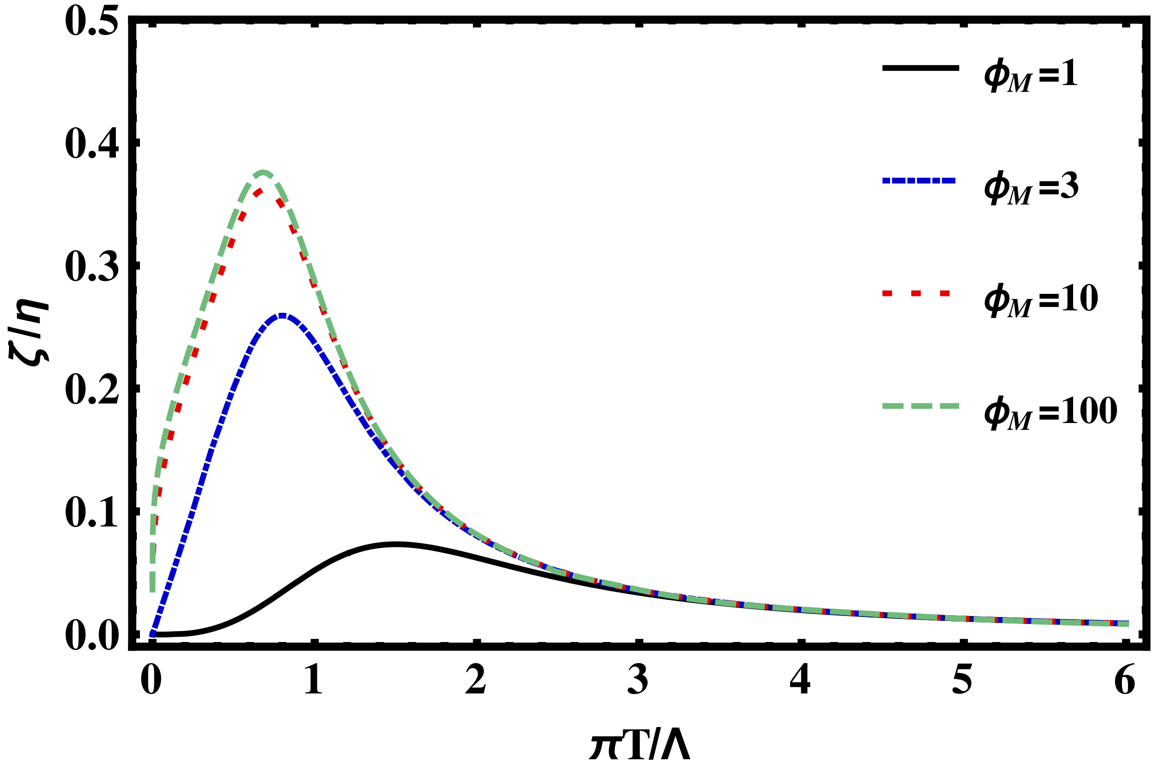
- Rich thermodynamic and transport properties

Attems, JCS, Mateos, Papadimitriou, Santos, Sopuerta, Triana, Zilhao, 16

Thermo and Transport

- Non conformal (bottom-up) holographic model: Einstein + Scalar

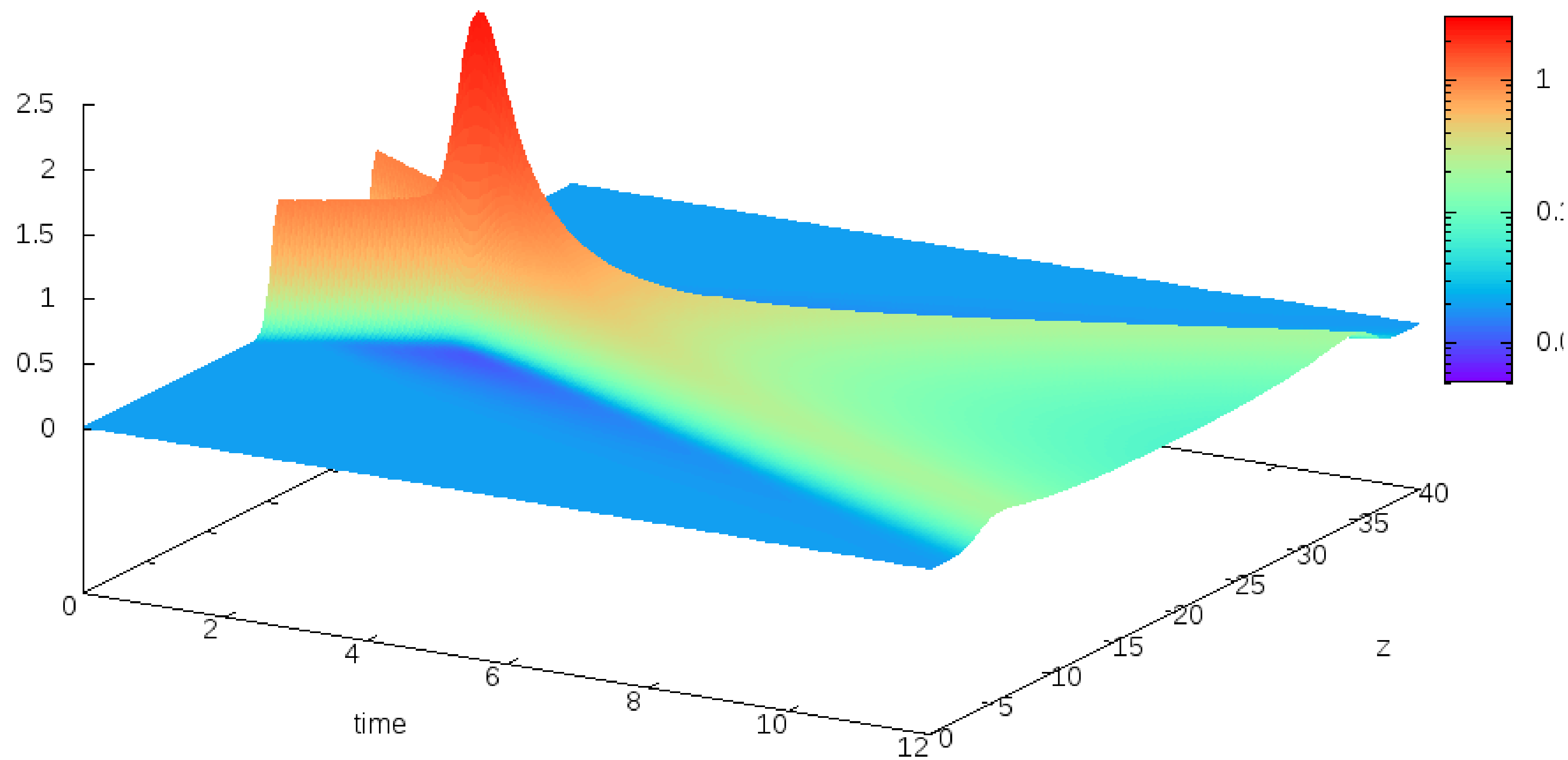




- Universality: $$\frac{\eta}{s} = \frac{1}{4\pi}$$

Attems, JCS, Mateos, Papadimitriou, Santos,Sopuerta, Triana, Zilhao, 16

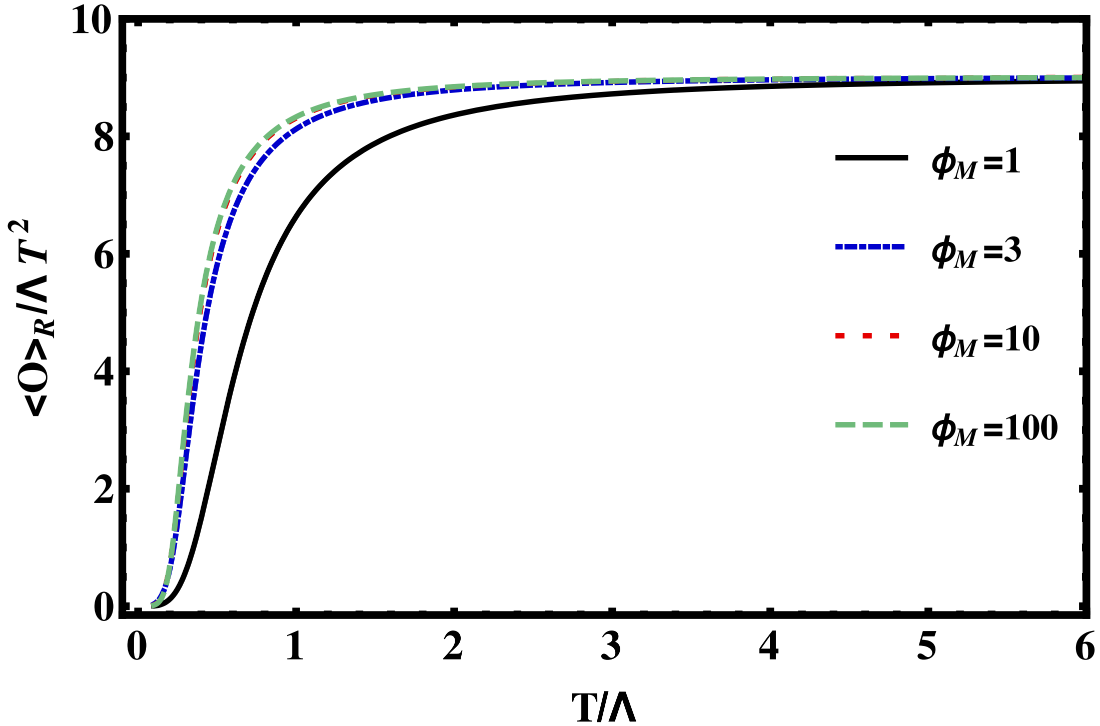
Non conformal Shock Collisions



Attems, JCS, Mateos, Santos,Sopuerta, Triana, Zilhao, 16

EOS and VeV's

- Non-thermodynamic one point function



- Non-trivial T-dependence ⇒ non-trivial e.o.s

$$\langle T^{\mu}_{\mu} \rangle = -\Lambda \langle \mathcal{O} \rangle$$

↑ trace anomaly

equilibrium:

$$P_{\rm eq}(\mathcal{E}) = \frac{1}{3}\left[\mathcal{E} - \Lambda \langle \mathcal{O} \rangle_{\rm eq}(\mathcal{E})\right]$$

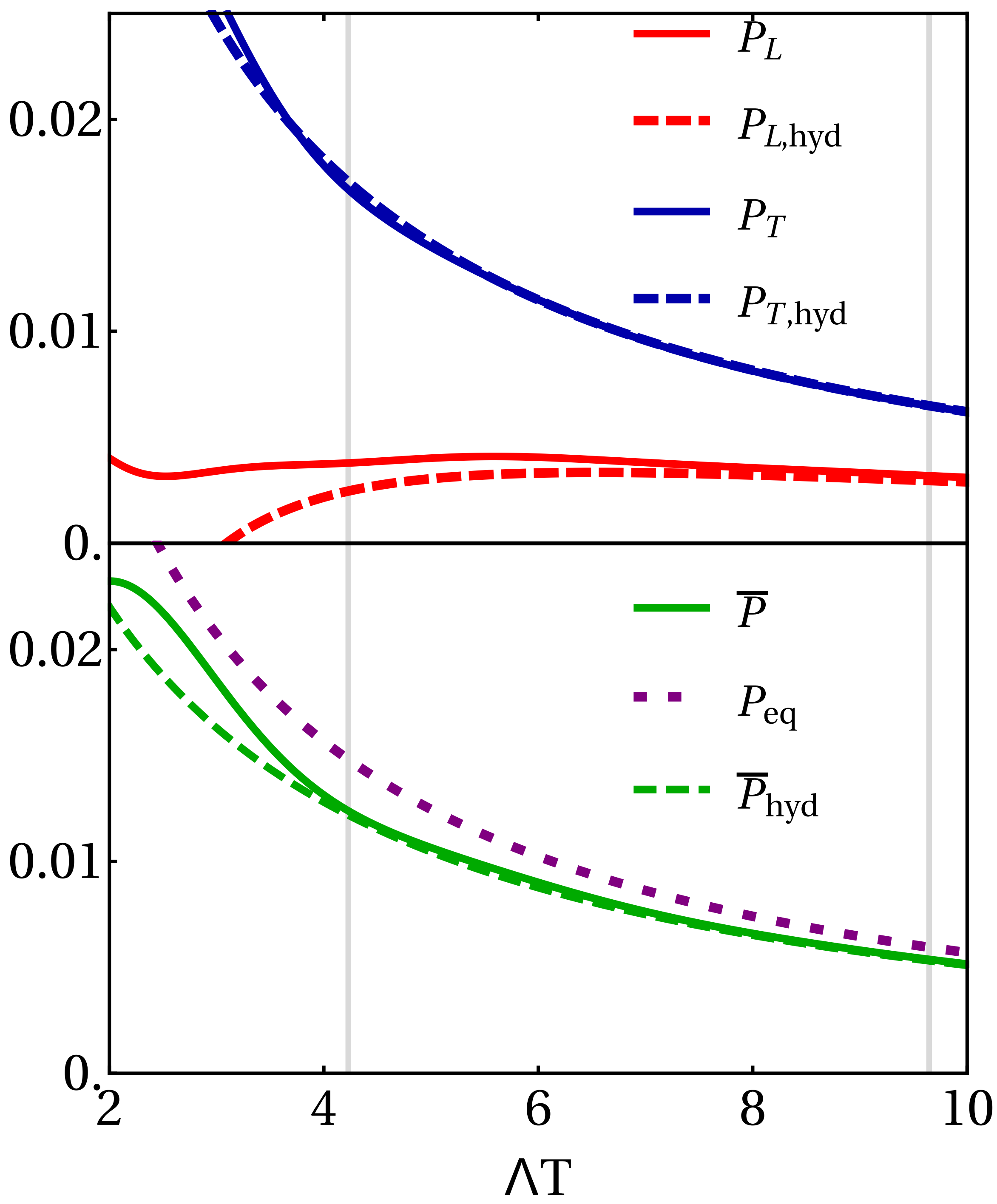
off-equilibrium:

$$\bar{P} \equiv \frac{1}{3}\left[P_{\rm L} + 2P_{\rm T}\right] = \frac{1}{3}\left[\mathcal{E} - \Lambda \langle \mathcal{O} \rangle\right]$$

- e.o.s is satisfied whenever VeV is sufficiently close to thermal

"equilibration"

Hydro without Equilibration



- Comparing full simulations to non-conformal hydro

- Hydrodynamisation: pressure is well described by constitutive relations

$$\left|P_{L,T} - P_{L,T}^{\text{hyd}}\right| / \bar{P} < 0.1$$

- "Equilibration": e.o.s is satisfied (on average)

$$\left|\bar{P} - P_{\text{eq}}\right| / \bar{P} < 0.1$$

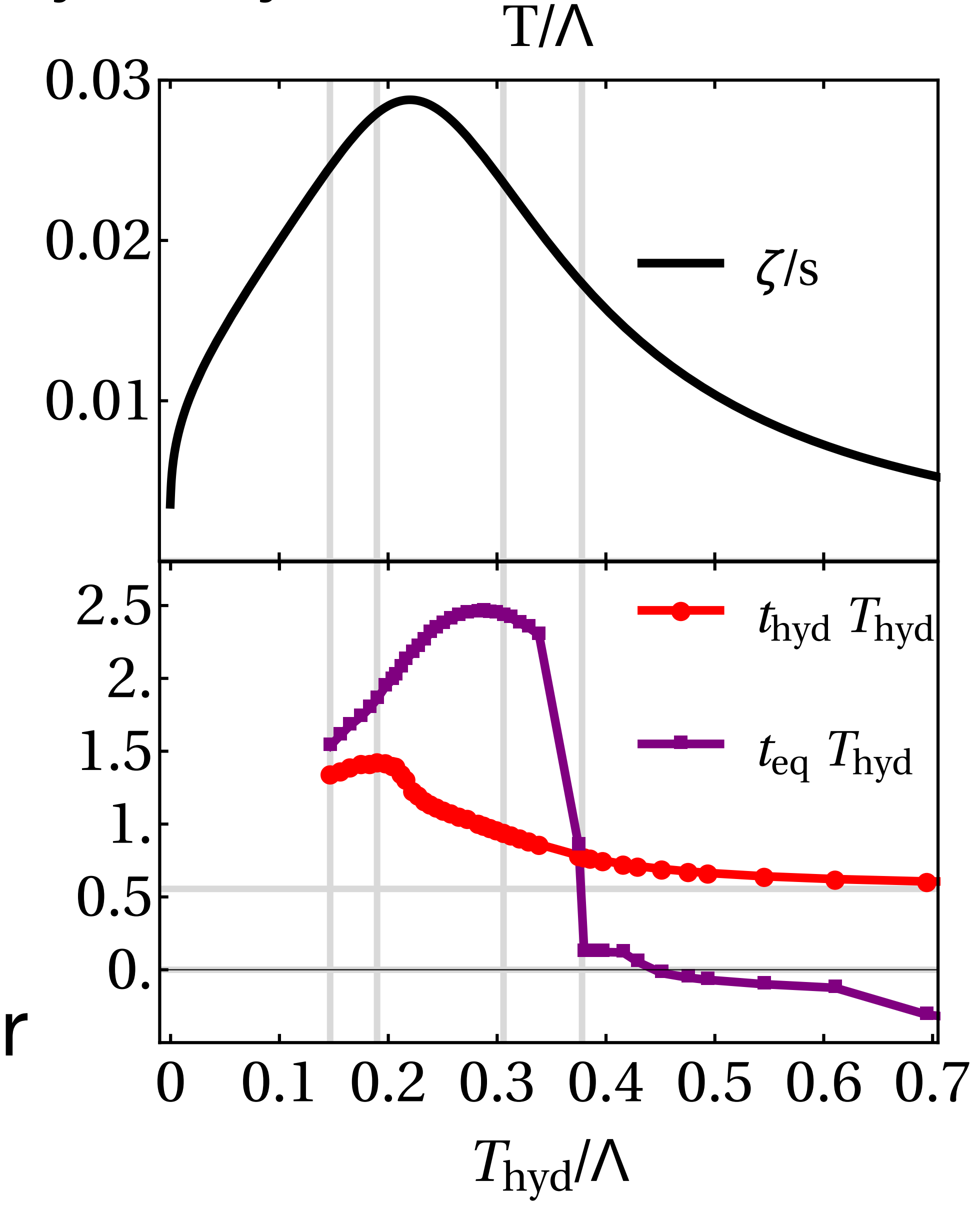
Hydro works even if e.o.s is not satisfied!

Hydrodynamisation vs Equilibration

- Non-conformal theories take longer to hydrodynamise
- Hydro stress tensor:

$$P_L^{\rm hyd} = P_{\rm eq} + P_\eta + P_\zeta \,,$$
$$P_T^{\rm hyd} = P_{\rm eq} - \tfrac{1}{2} P_\eta + P_\zeta$$

shear pressure ↙ ↘ bulk pressure



- Isotropisation vs equilibration

$$P_L^{\rm hyd} - P_T^{\rm hyd} = \tfrac{3}{2} P_\eta \qquad \bar{P}_{\rm hyd} = P_{\rm eq} + P_\zeta$$

- Large bulk corrections responsible for deviations from equilibrium!

- For ζ/s>0.025 hydrodynamisation occurs first.

smaller than the maximum values achieved in the QCD transition!

Conclusions

- First analysis of ultra-relativistic collision dynamics in non-conformal gauge theories.

- Hydrodynamics provides an (unreasonably) good description of dynamics
    - Large anisotropies
    - Large deviation from equilibrium
    - What controls the applicability of hydro?

- Heavy Ion collisions allow us to explore the different paths for the onset of hydrodynamic behavior