Holographic collisions across a phase transition

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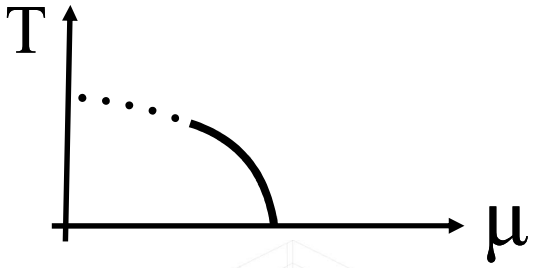
Based on: 1703.02948, 1807.05175

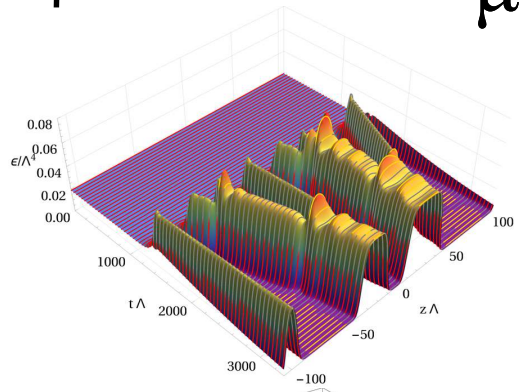
In collaboration with:
M. Attems, J. Casalderrey, D. Mateos, M. Triana, M. Zilhão

Plan

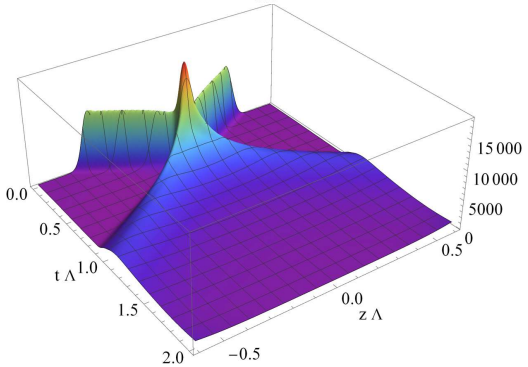
- QCD phase diagram



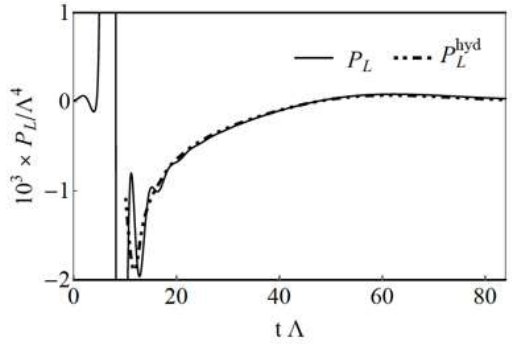
- Spinodal instability



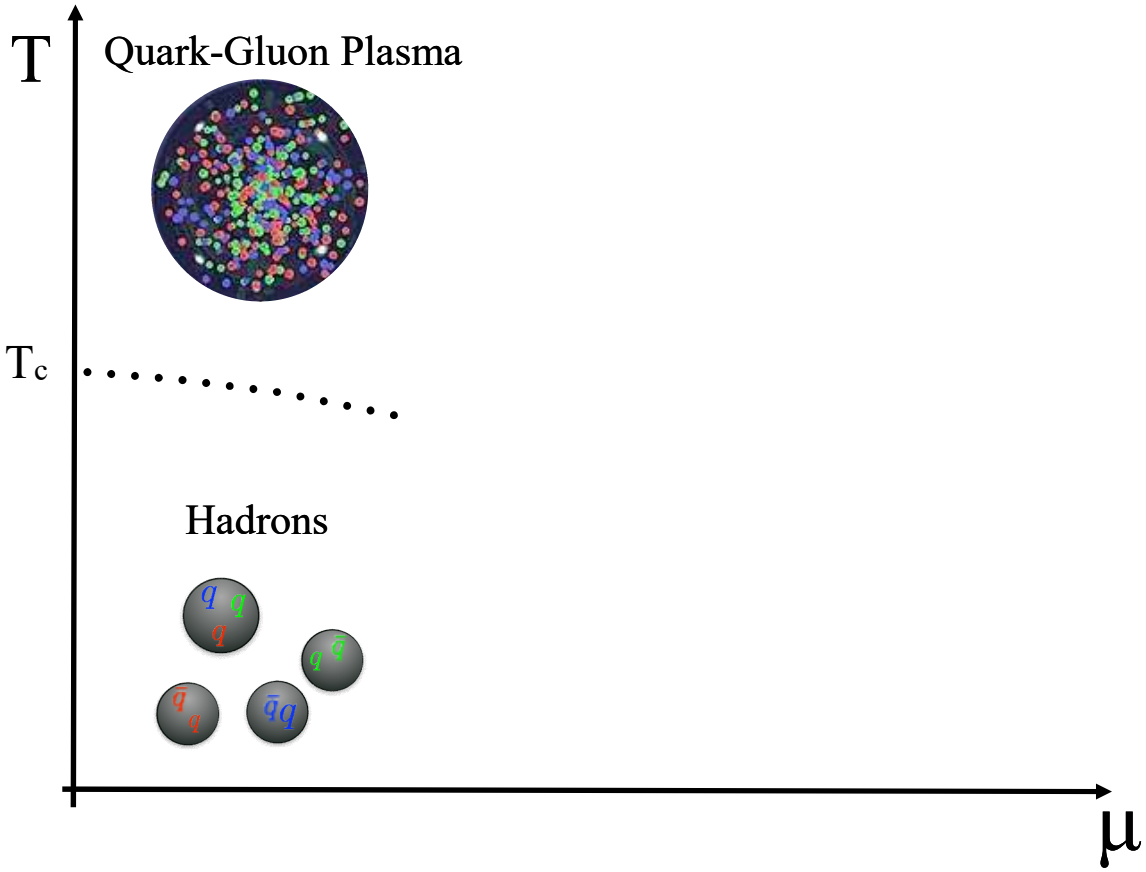
- Holographic collisions



- Hydrodynamics



QCD phase diagram



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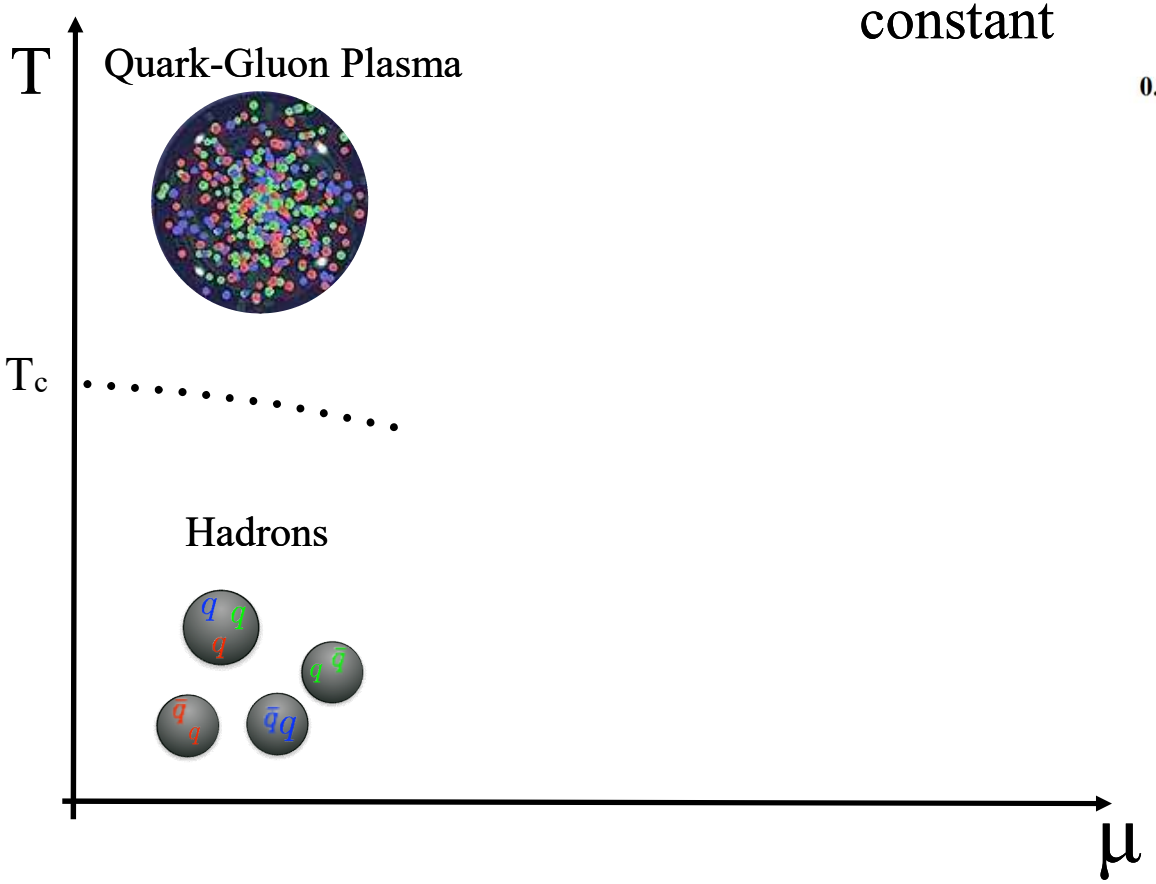
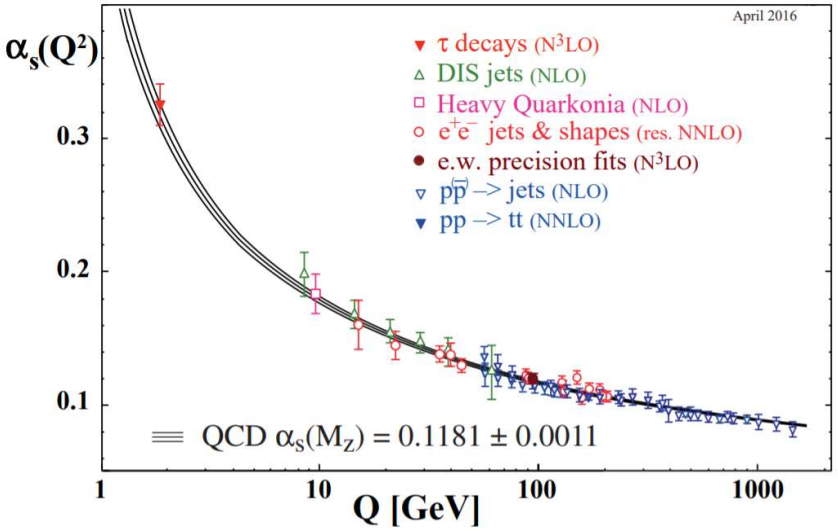


QCD coupling constant



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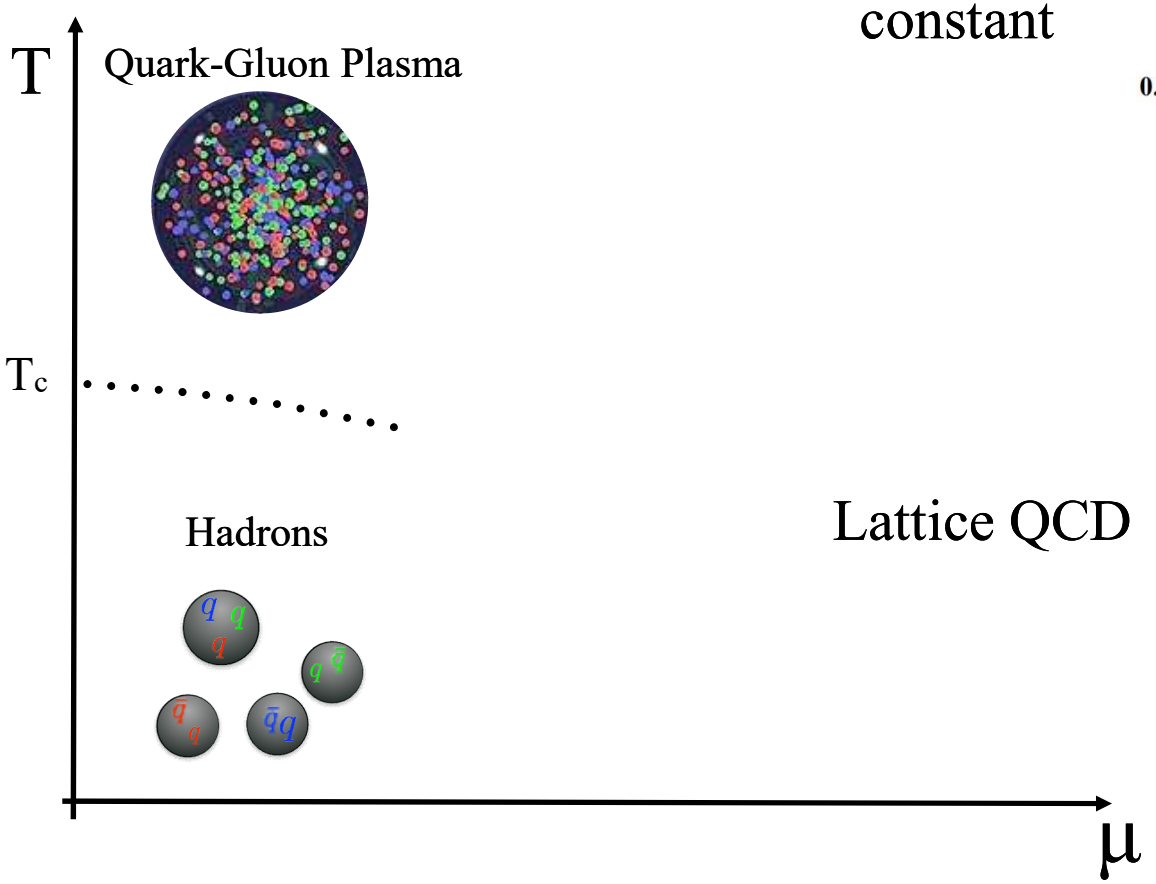

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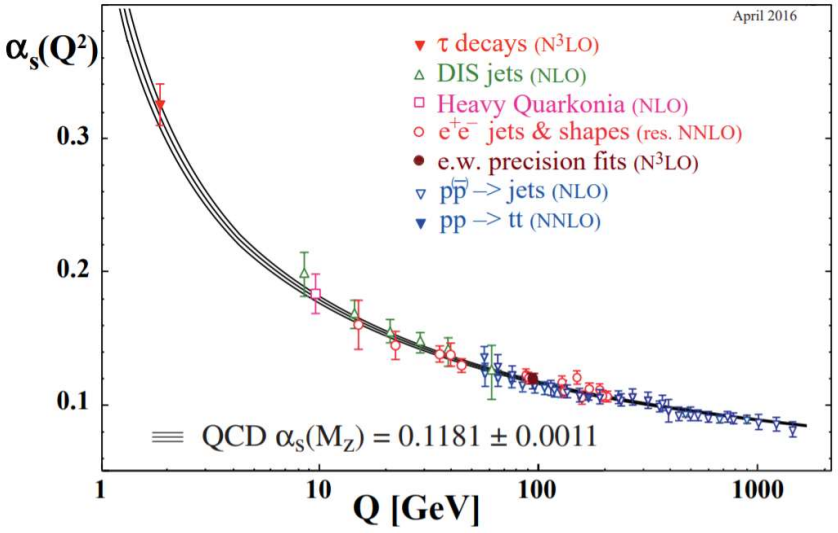
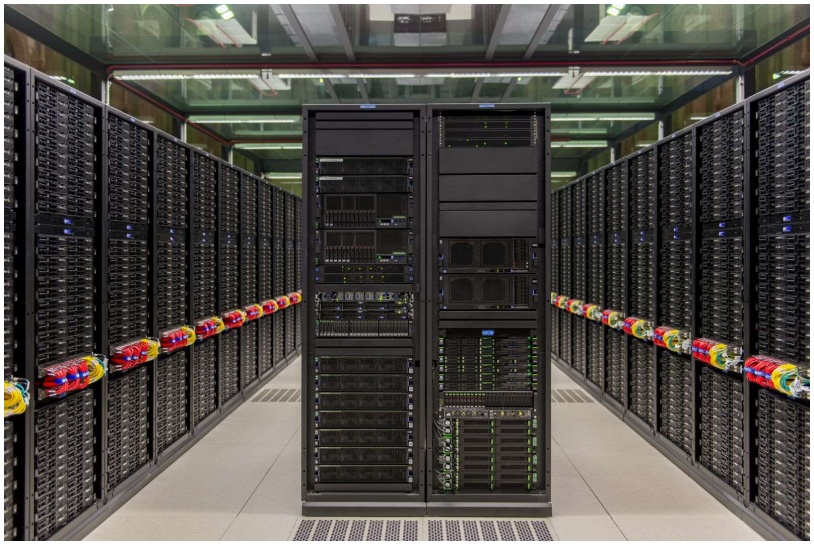


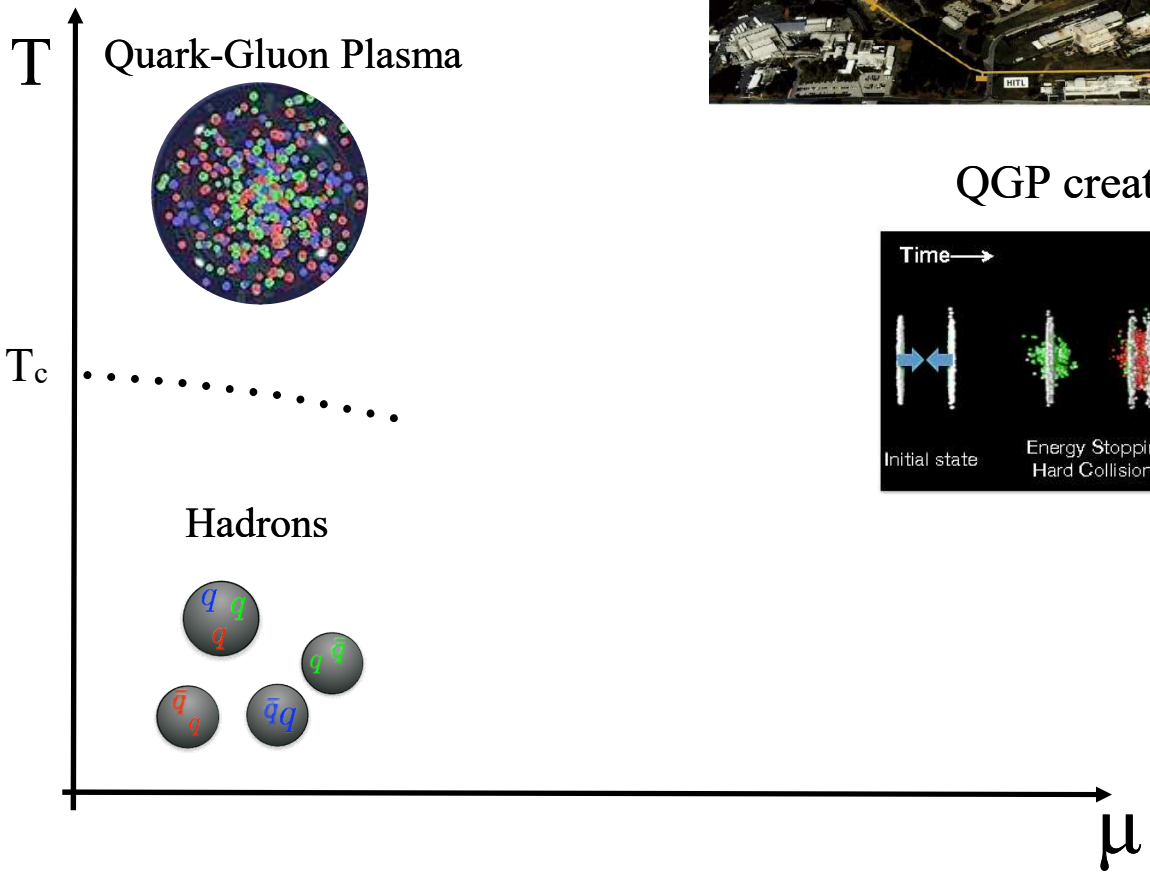
Lattice QCD



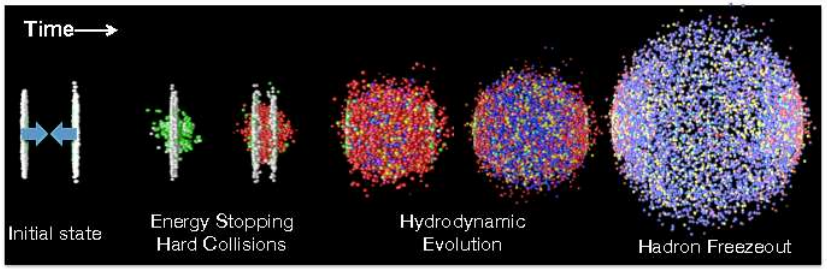
QCD phase diagram

RHIC

LHC



QGP created in heavy ion collision



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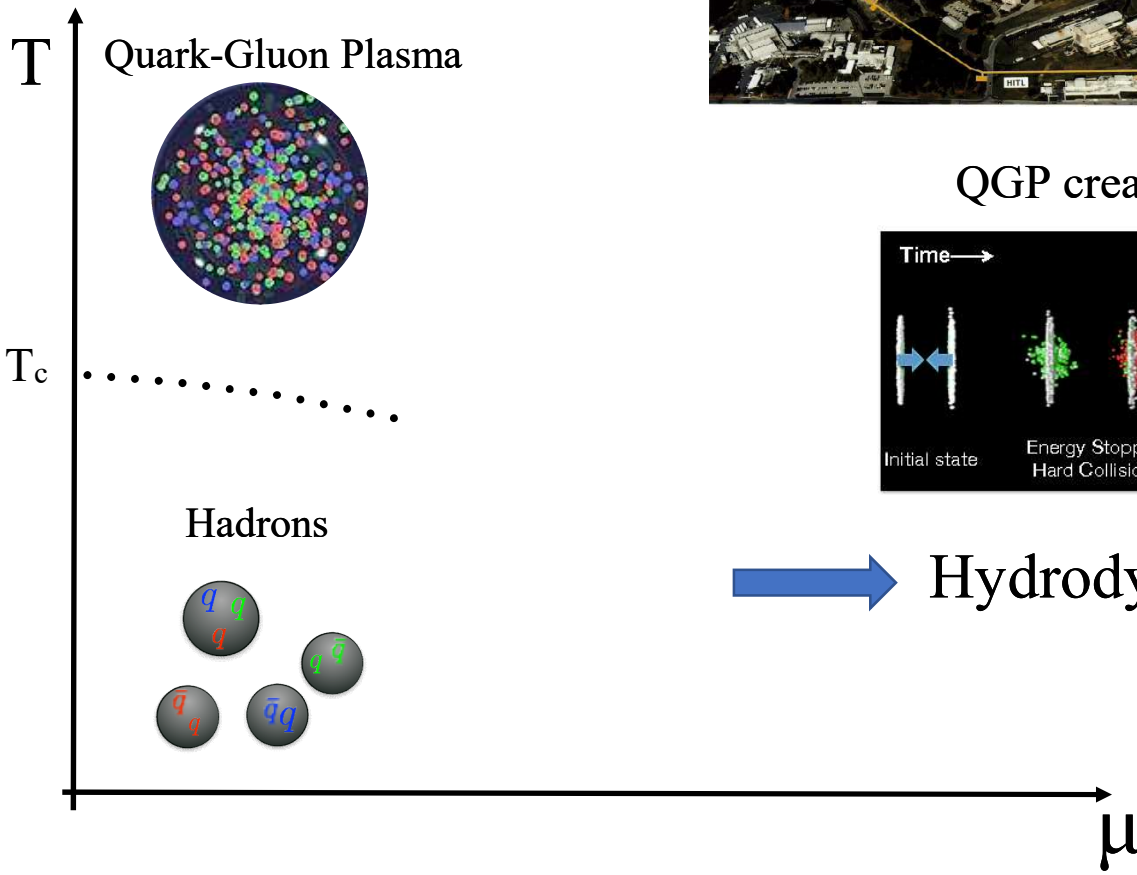

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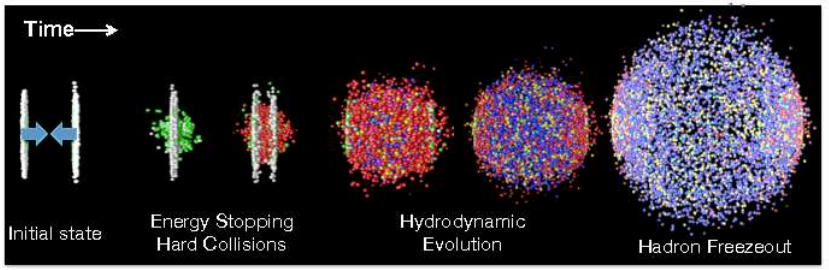
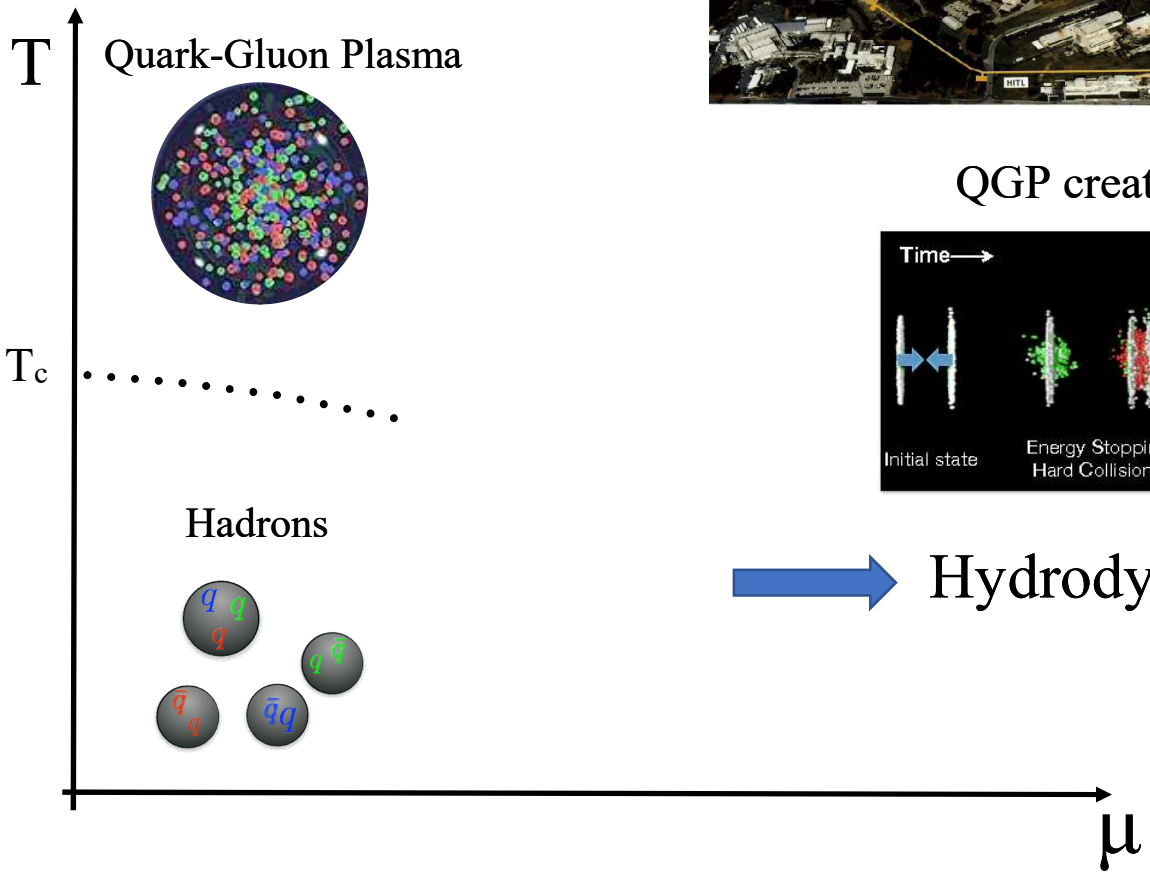


→ Hydrodynamics describes the QGP!

QCD phase diagram

RHIC

LHC



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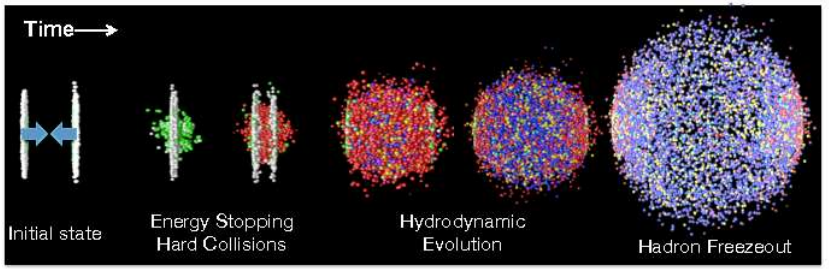
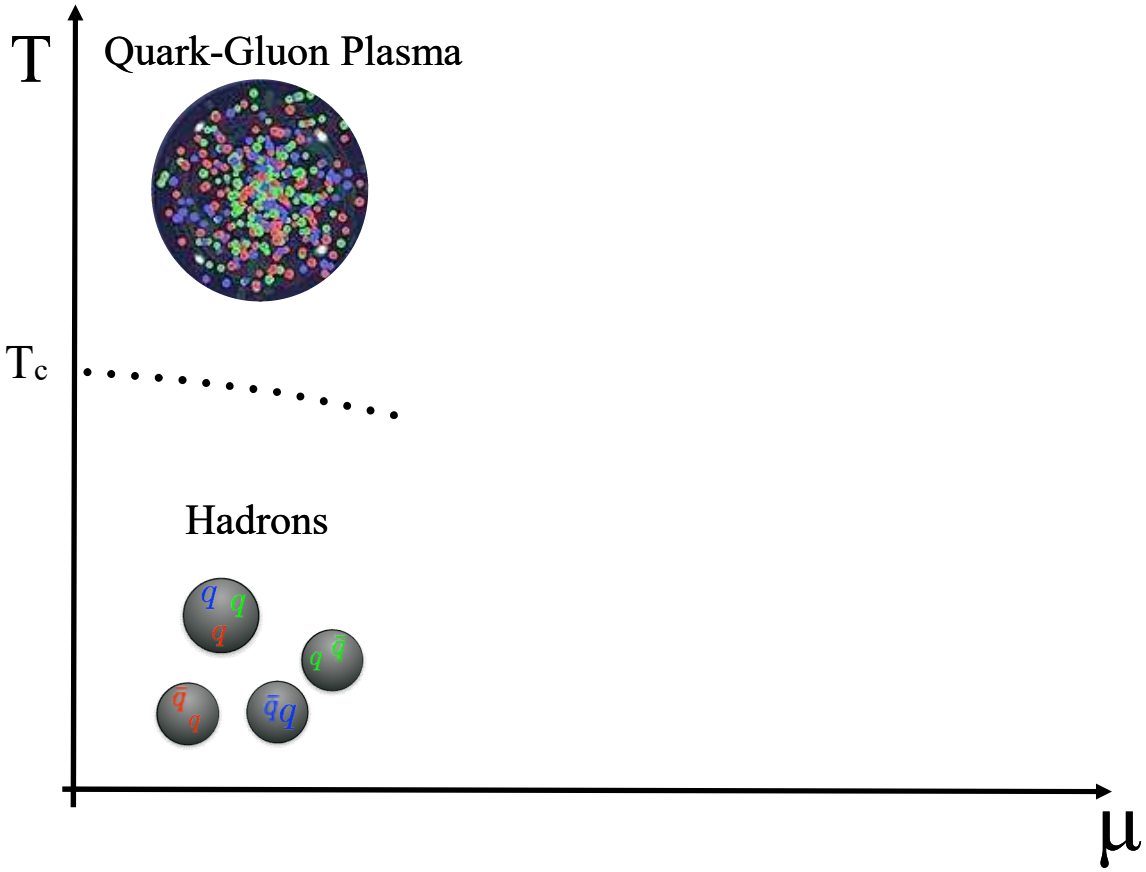


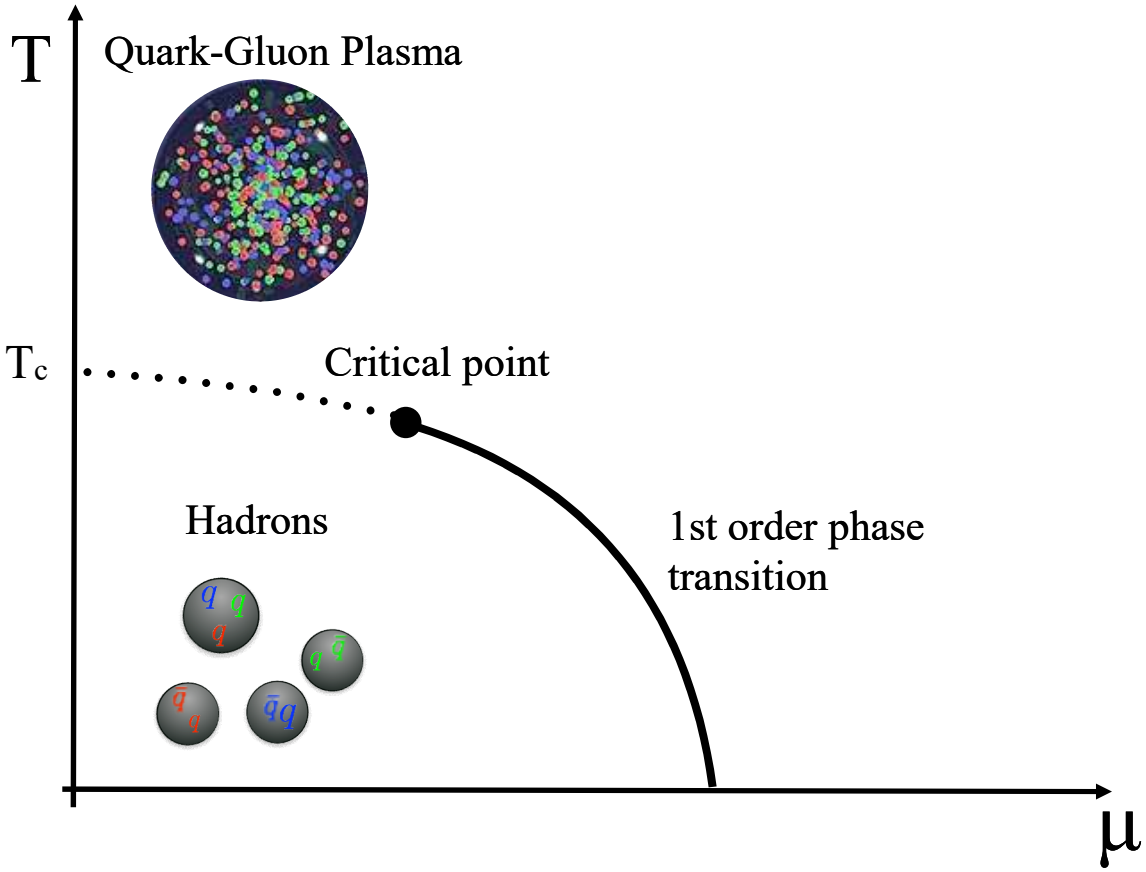
→ Hydrodynamics describes the QGP!

- Early hydrodynamization times
- Large gradients

QCD phase diagram



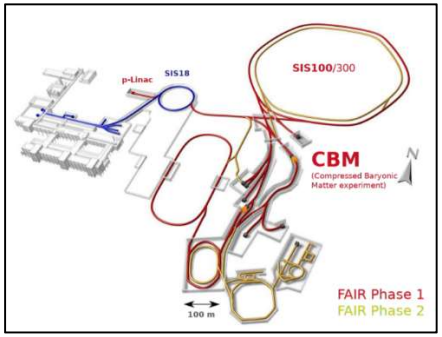
QCD phase diagram



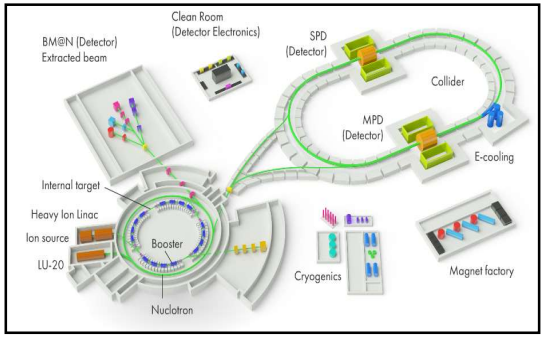
QCD phase diagram

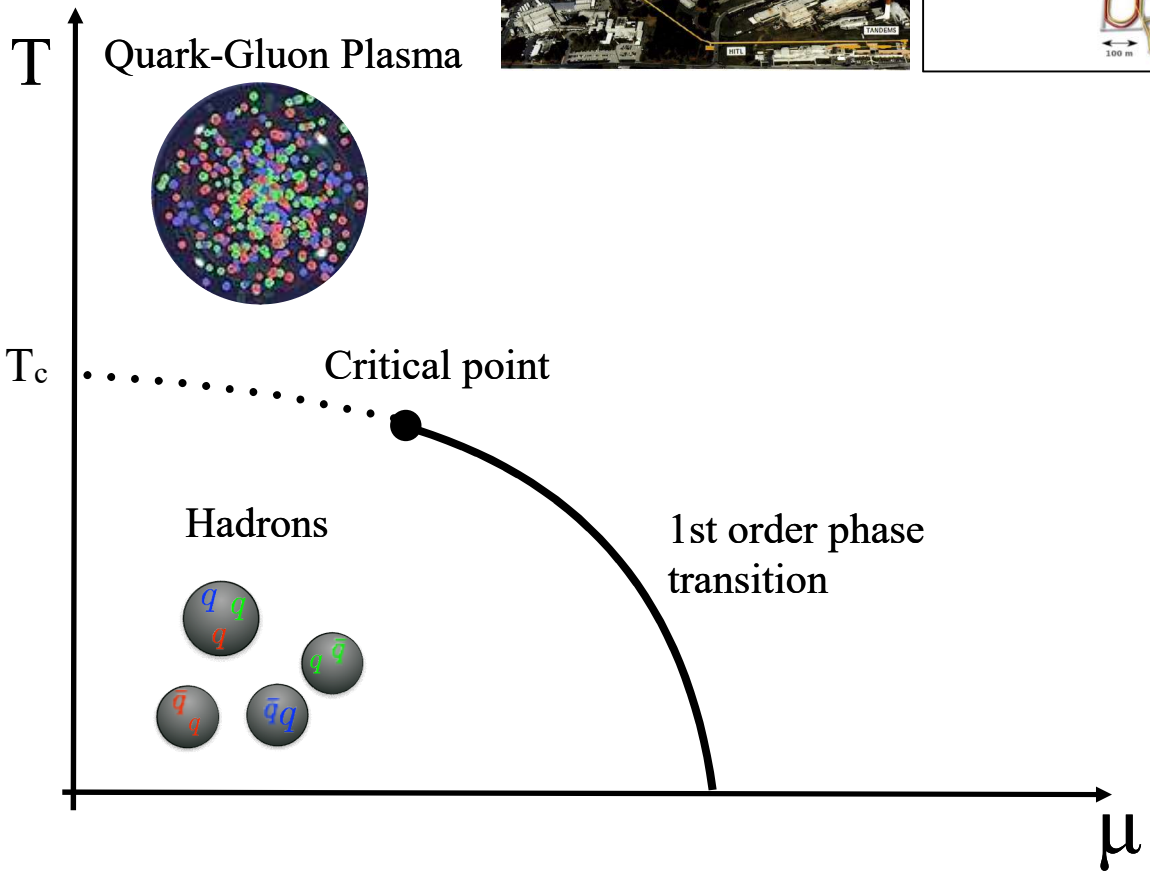
RHIC

FAIR



NICA





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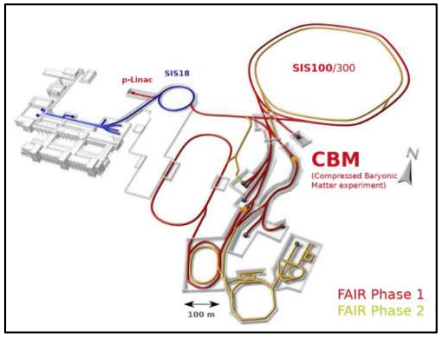

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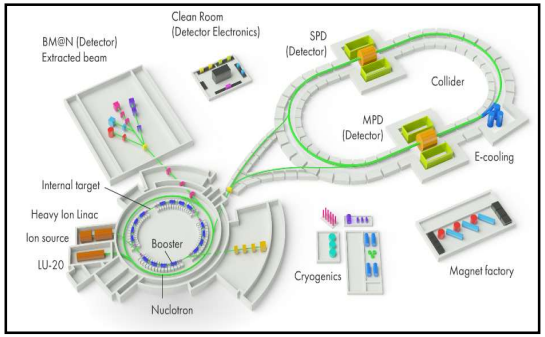
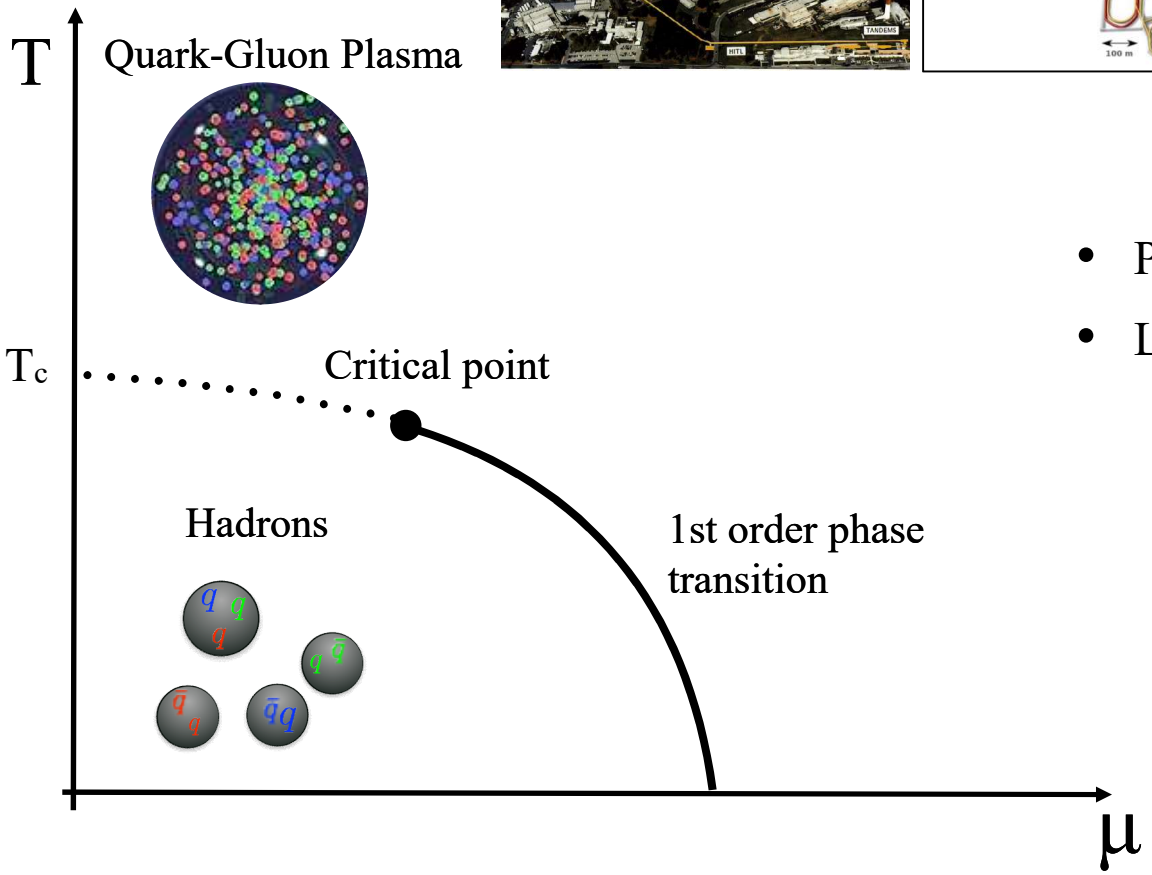




- Perturbative QCD
- Lattice QCD

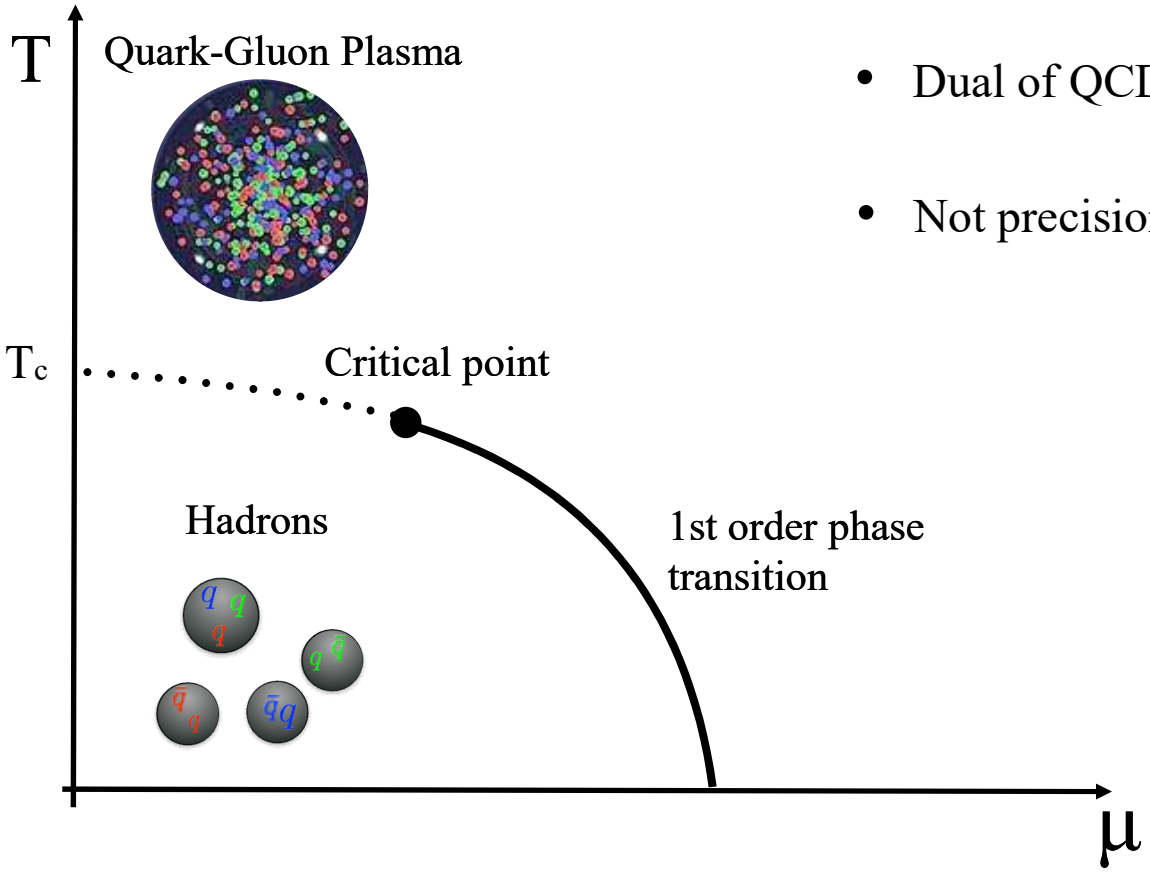
→ Limited applicability

QCD phase diagram

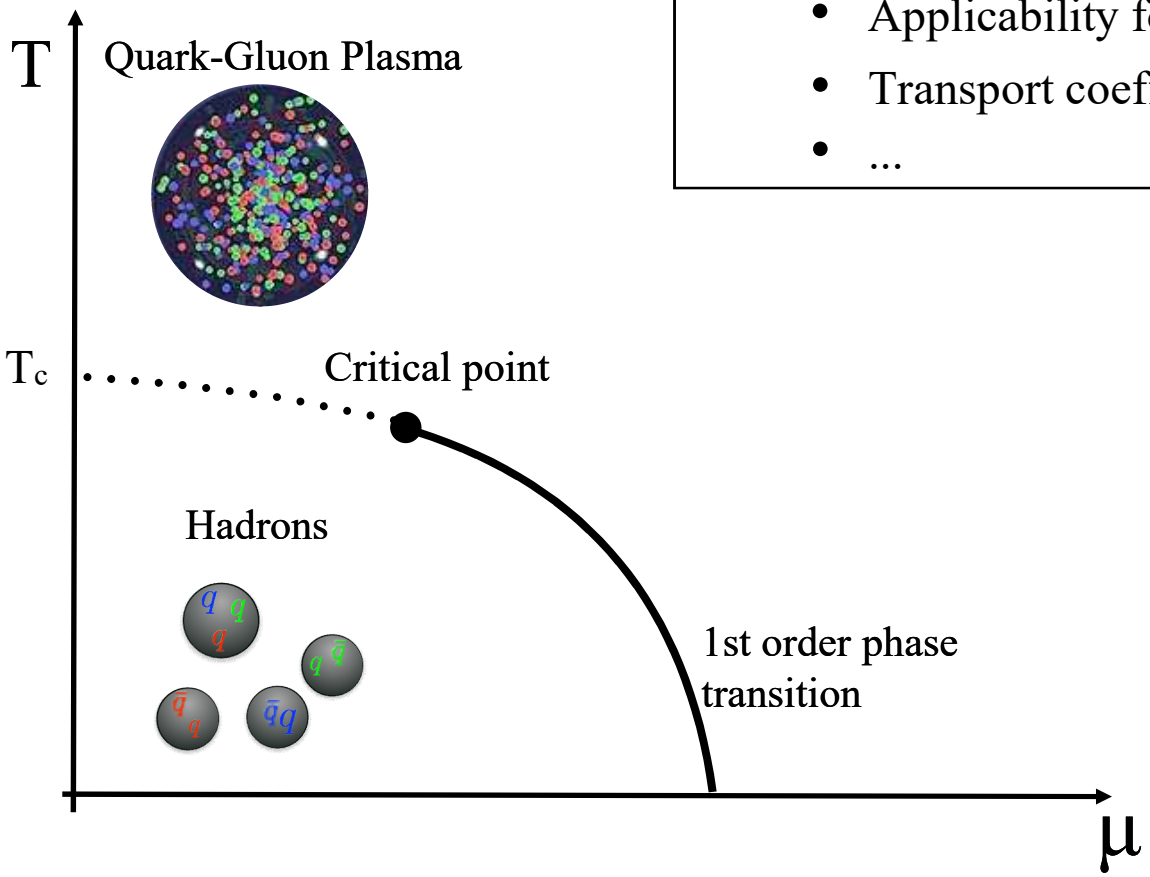
Holography

- Strongly coupled QFT
- Out of equilibrium physics
- Dual of QCD not known…
- Not precision holography

→ Qualitative aspects



QCD phase diagram

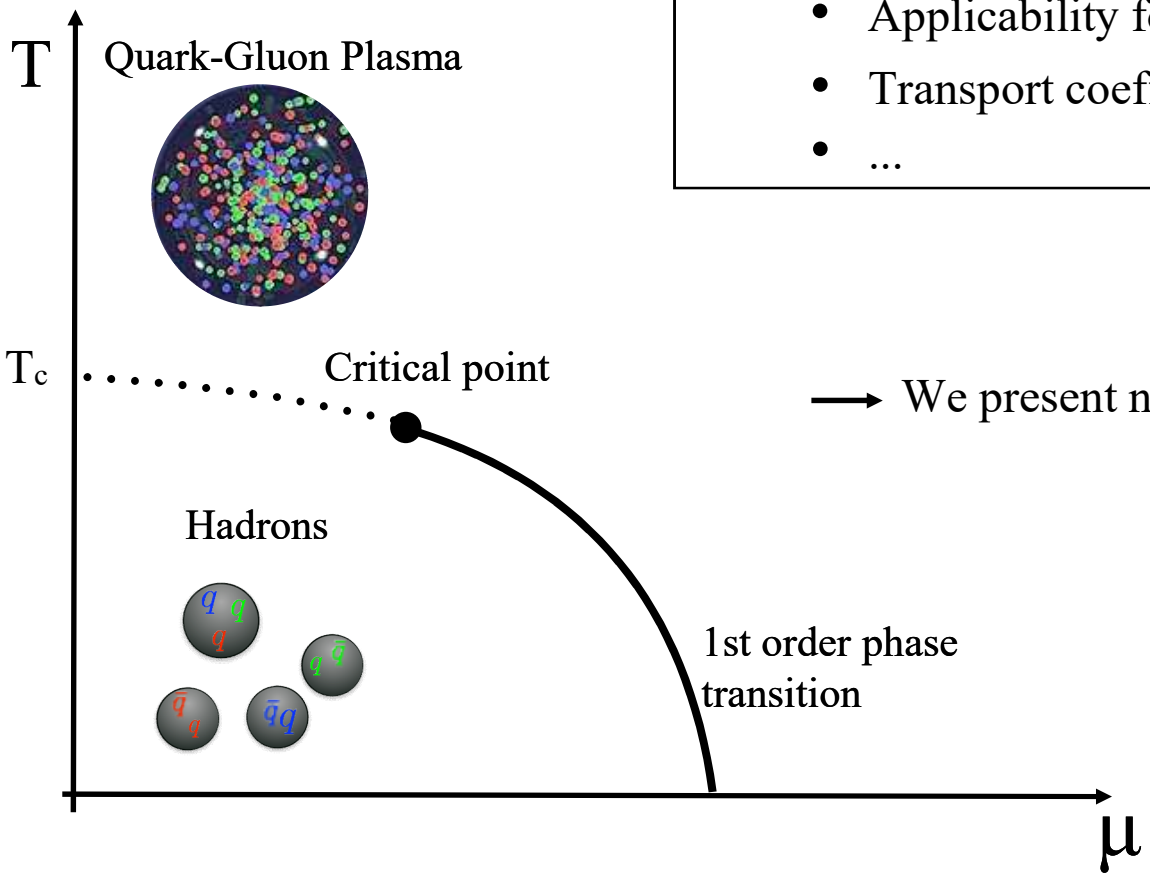


What have we learned from holography so far?

Chesler, Yaffe, Casalderrey, Mateos, Heller, van der Schee, …

- Early hydrodynamization times
- Applicability with large gradients
- Applicability for small systems
- Transport coefficients
- …

QCD phase diagram



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- Early hydrodynamization times
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→ We present new qualitative insights

We will see what holography can say…

Holography

Holography: The model

- Einstein+Scalar

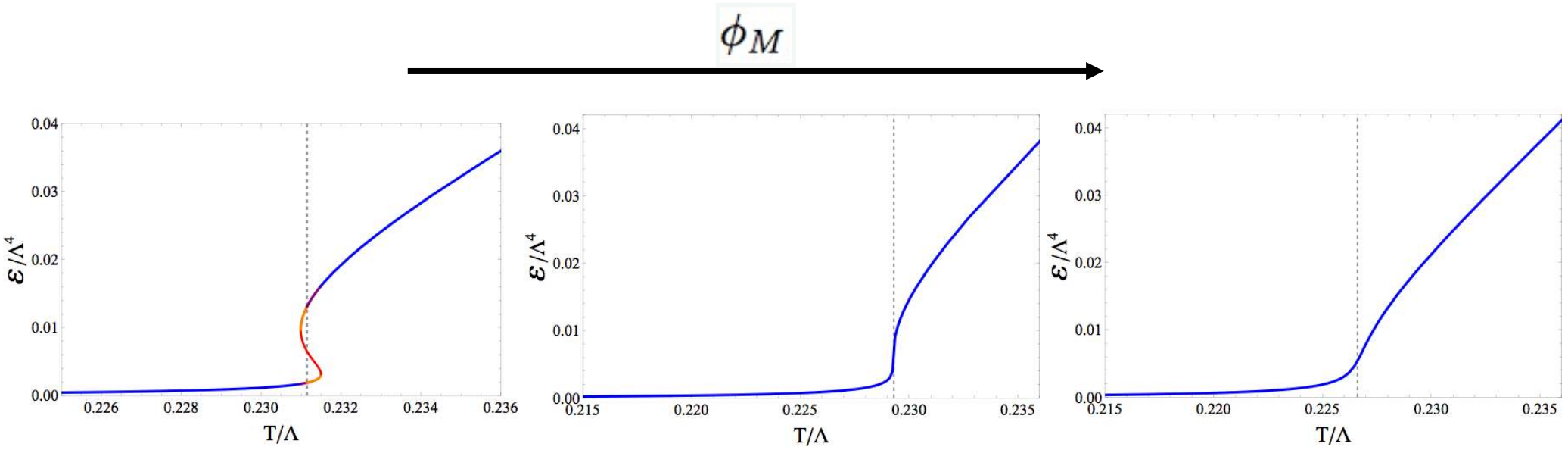
$$S = \frac{2}{\kappa_5^2}\int d^5x\sqrt{-g}\left[\frac{1}{4}\mathcal{R} - \frac{1}{2}\left(\nabla\phi\right)^2 - V(\phi)\right].$$

- Potential

$$\ell V = -3 - \frac{3\phi^2}{2} - \frac{\phi^4}{3} - \frac{\phi^6}{3\phi_M^2} + \frac{\phi^6}{2\phi_M^4} - \frac{\phi^8}{12\phi_M^4}$$

  - Simplicity: minimal ingredients
  - One parameter ϕ_M

From 1st-order to 2nd-order to crossover

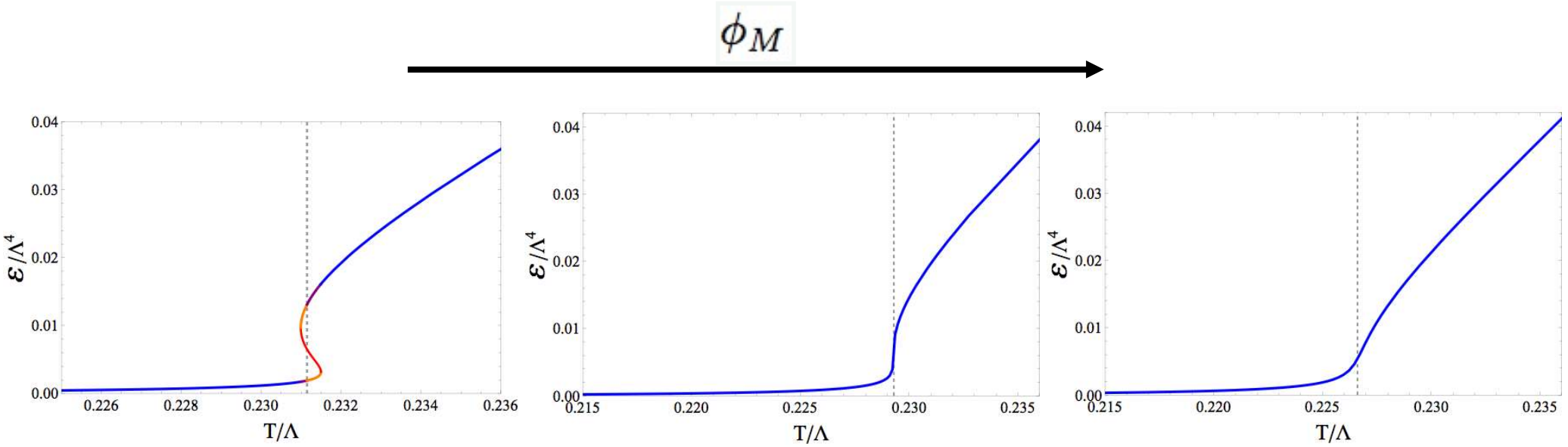


1st order

2nd order

Crossover

From 1st-order to 2nd-order to crossover



1st order

2nd order

Crossover

$$c_V < 0 \quad \Rightarrow \quad c_s^2 = \frac{s}{c_V} \quad \Rightarrow \quad c_s \; is \; imaginary$$

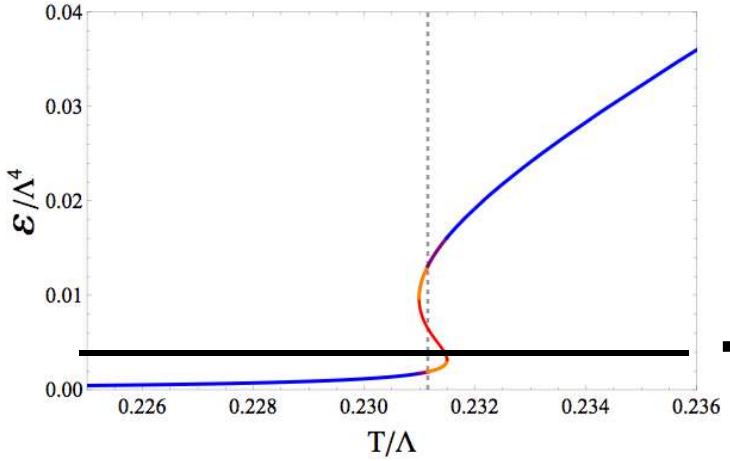
$$\omega = c_s k \quad \Rightarrow \quad e^{-i\omega t} = e^{+|c_s| kt}$$

Spinodal Instability

Spinodal Instability

Spinodal instability

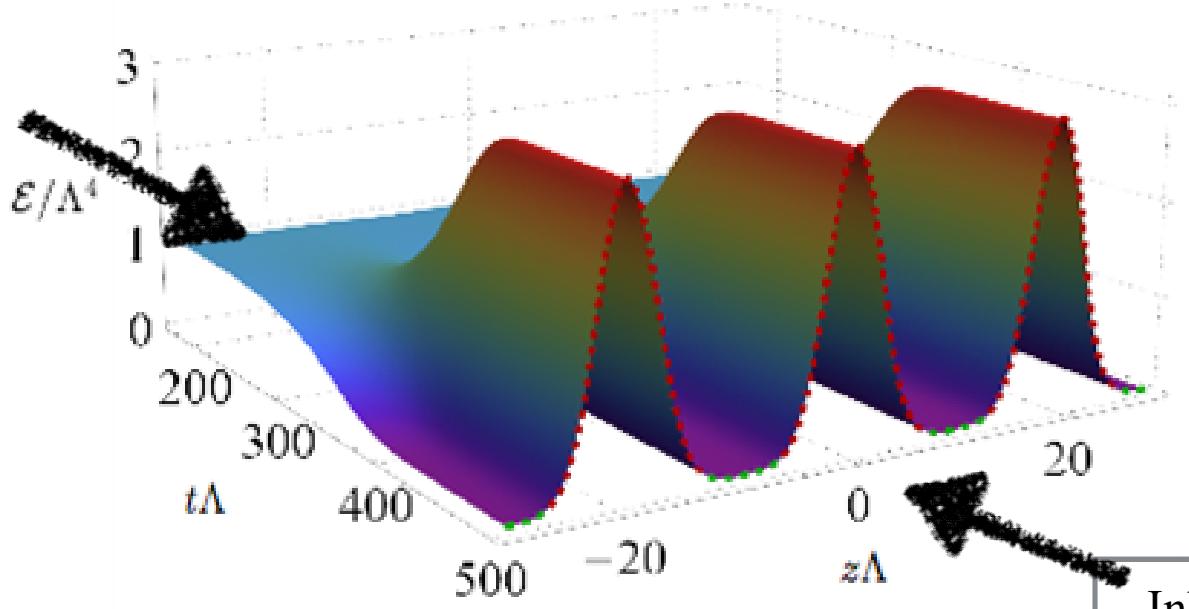
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '17



Unstable initial energy

Numerical evolution

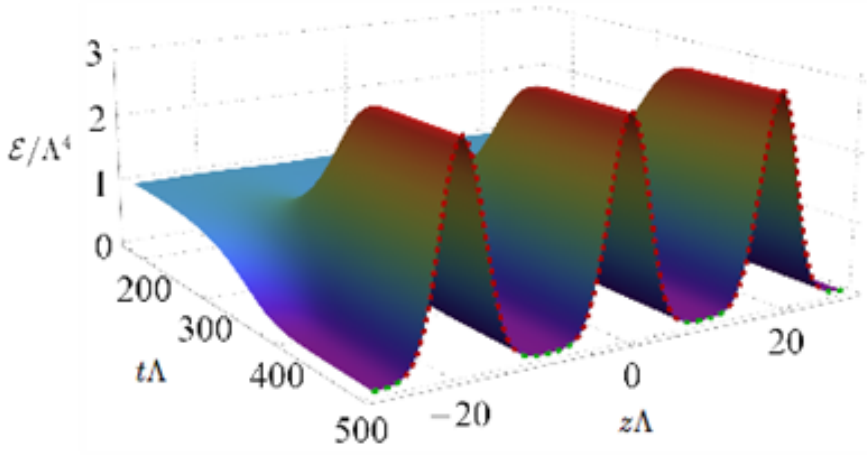
Homogeneous initial state
+
Perturbation



Inhomogeneous final state

Spinodal instability: Hydrodynamics

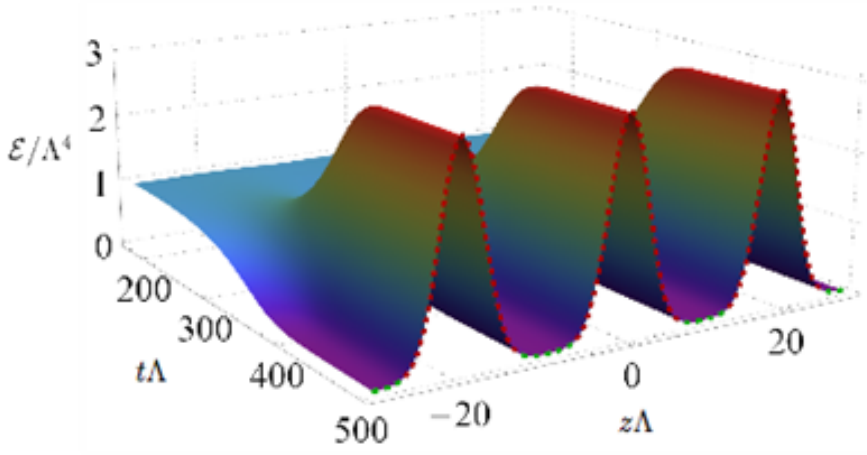
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '17



$$T^{\rm hyd}_{\mu\nu} = T^{\rm ideal}_{\mu\nu} - \eta\,\sigma_{\mu\nu} - \zeta\,\Pi\,\Delta_{\mu\nu} + \Pi^{(2)}_{\mu\nu}$$

Spinodal instability: Hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '17



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$$P^{\rm hyd}_{L} = P_{\rm eq}(\mathcal{E}) + c_{\rm L}(\mathcal{E})(\partial_z\mathcal{E})^2 + f_{\rm L}(\mathcal{E})(\partial_z^2\mathcal{E})$$
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Spinodal instability: Hydrodynamics

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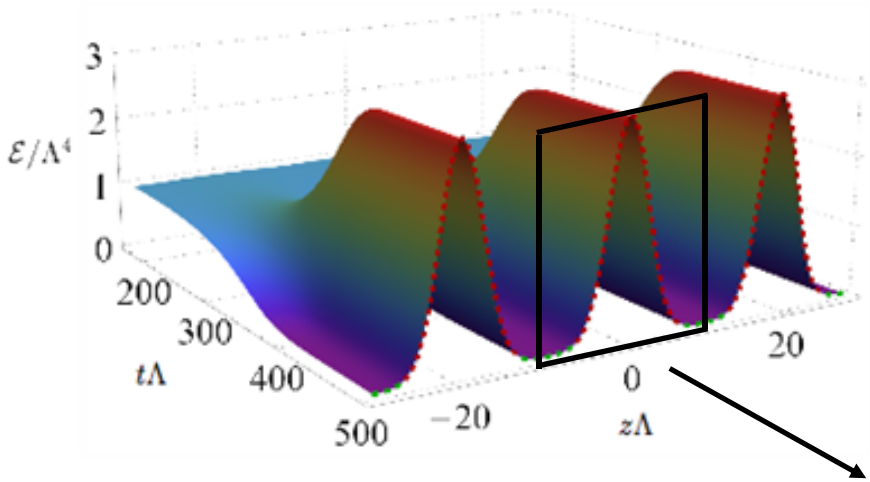
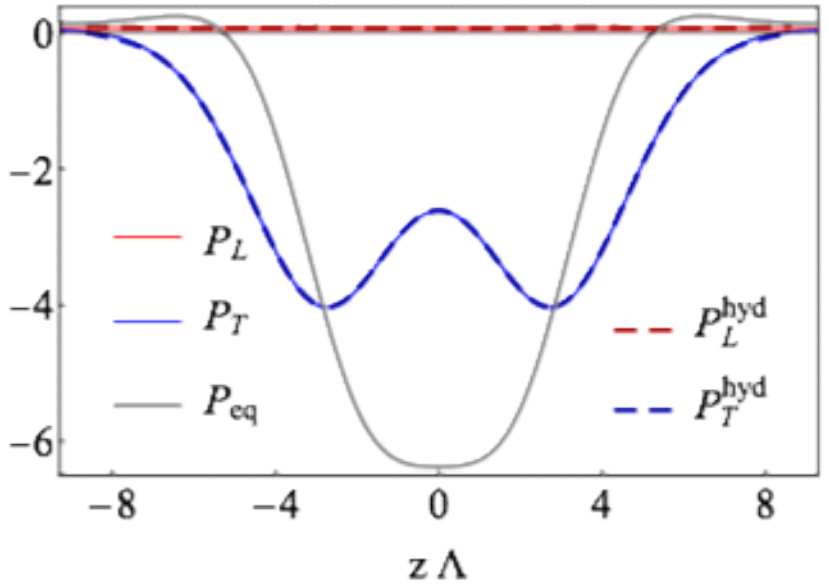


- Final end-state accurately described by second-order hydrostatics:



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$$P_L^{\rm hyd} = P_{\rm eq}(\mathcal{E}) + c_{\rm L}(\mathcal{E})(\partial_z\mathcal{E})^2 + f_{\rm L}(\mathcal{E})(\partial_z^2\mathcal{E})$$
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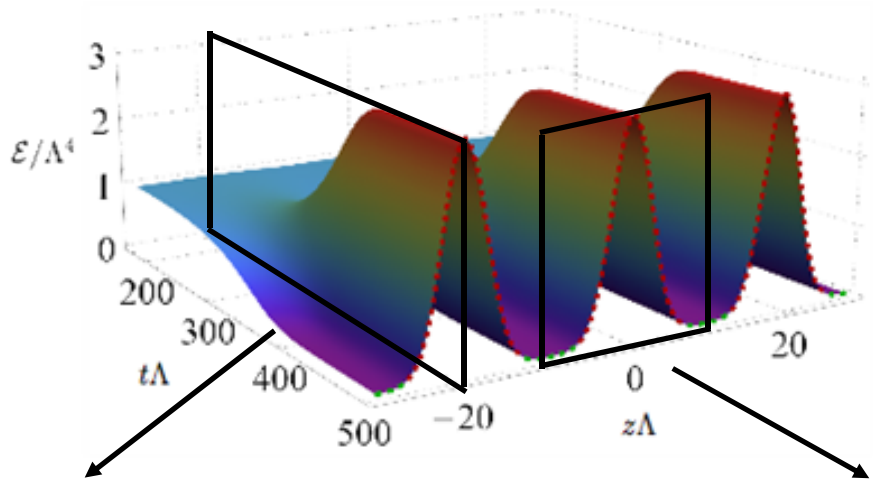
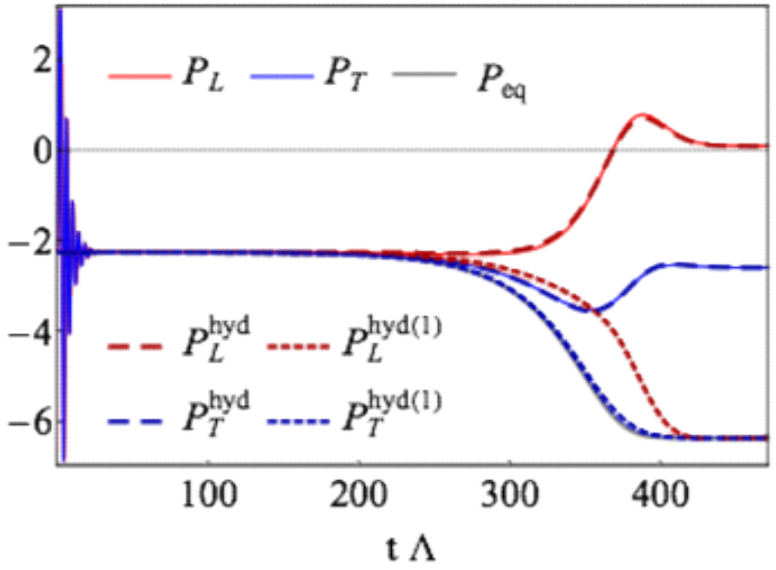
Spinodal instability: Hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '17

- Evolution also described by hydro





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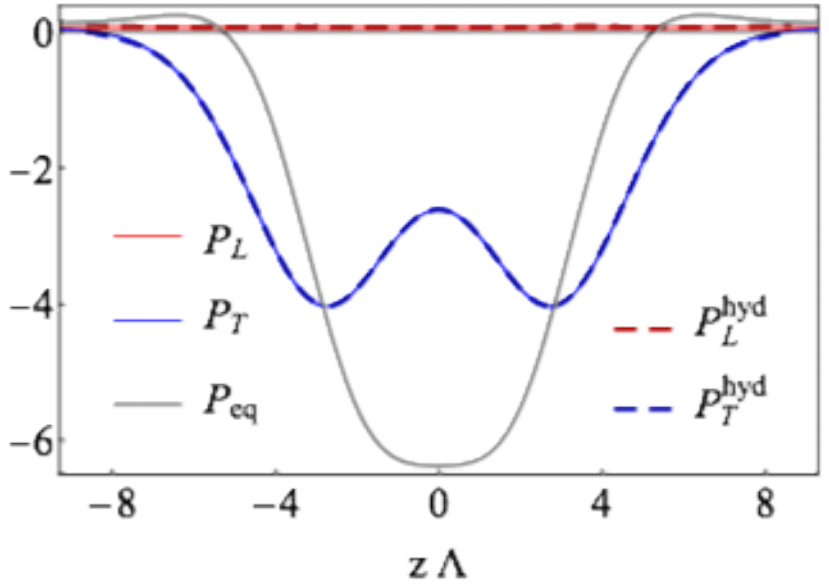

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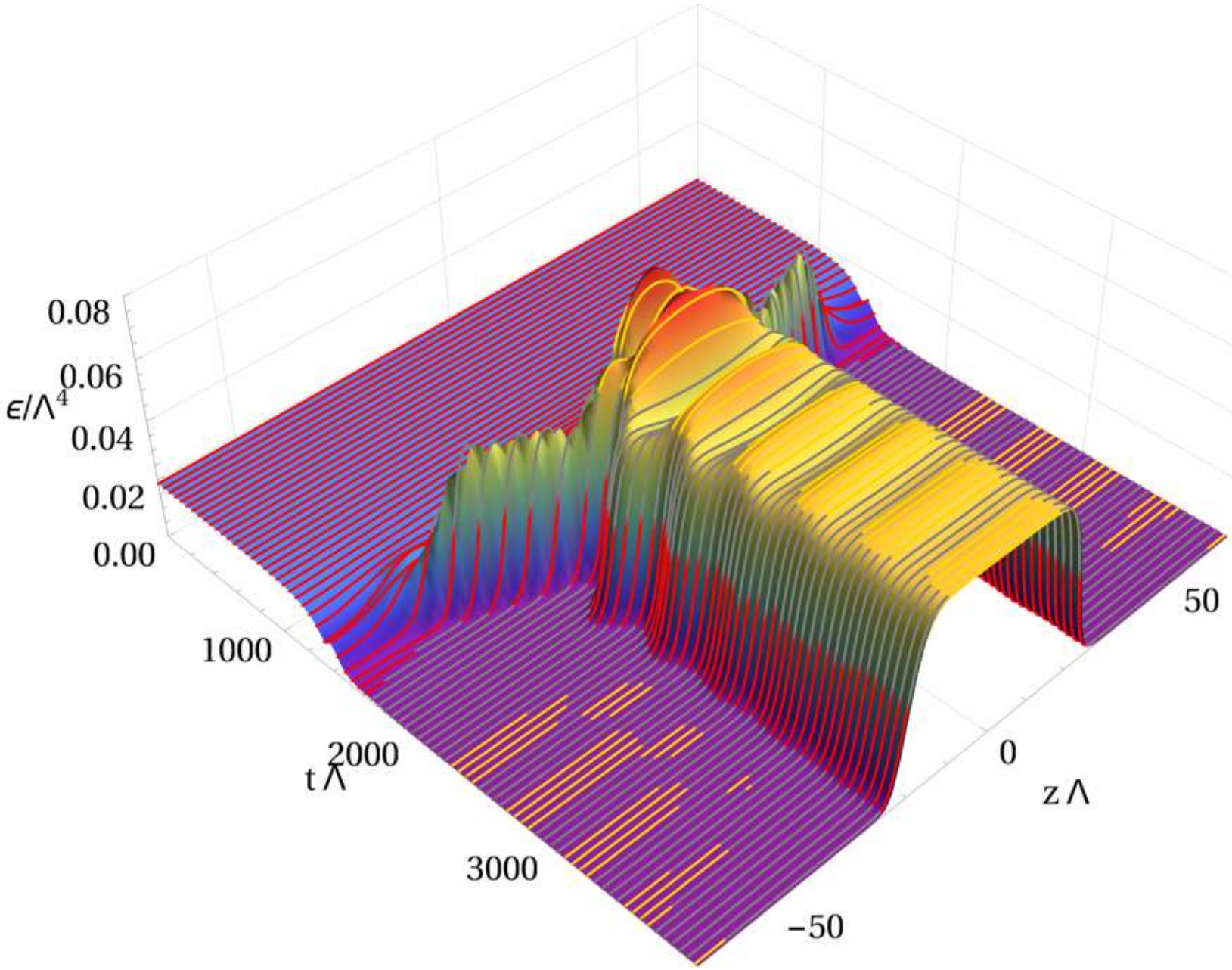
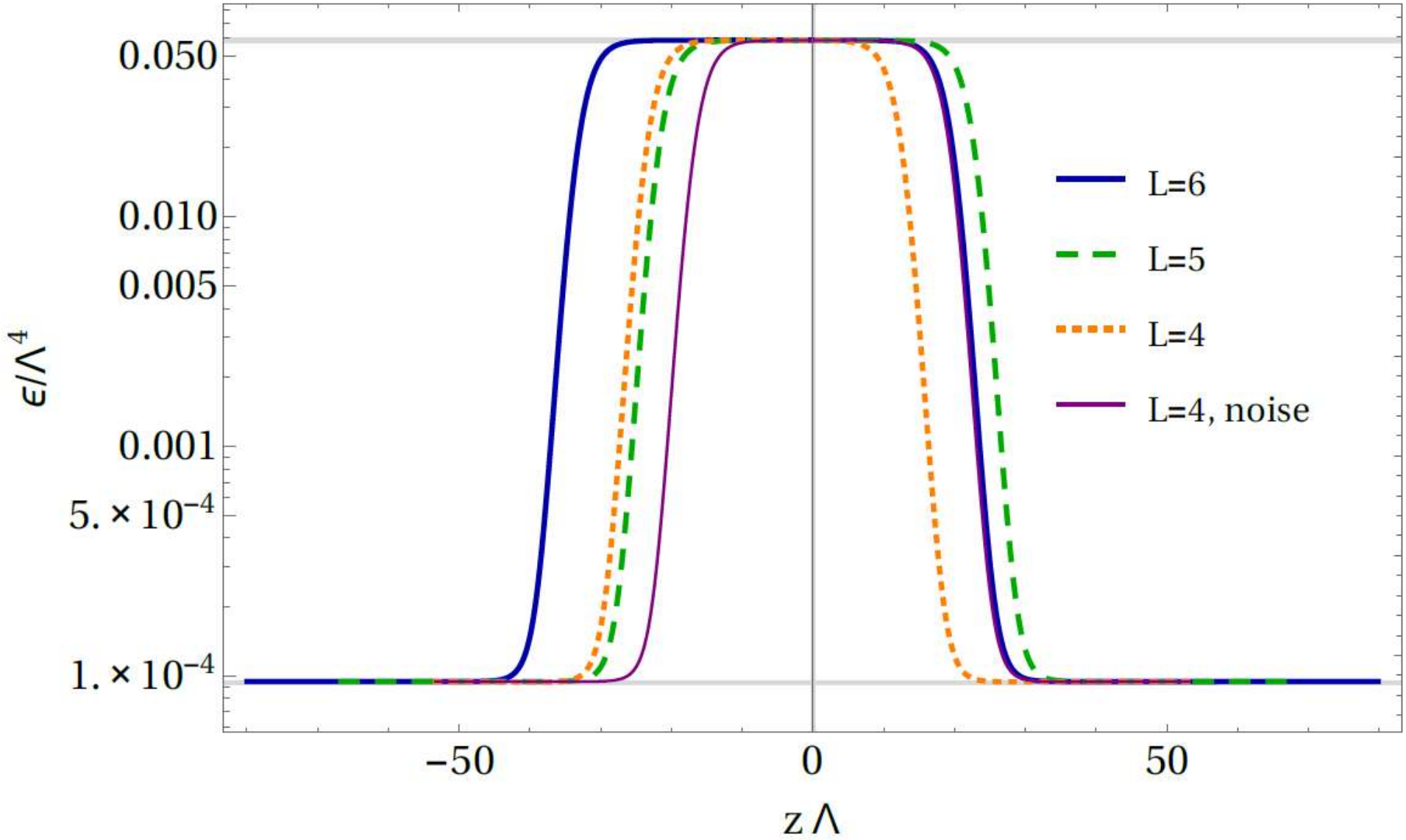
Spinodal instability: phase separation

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao, in progress



Spinodal instability: phase separation

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao, in progress



Spinodal instability: phase separation

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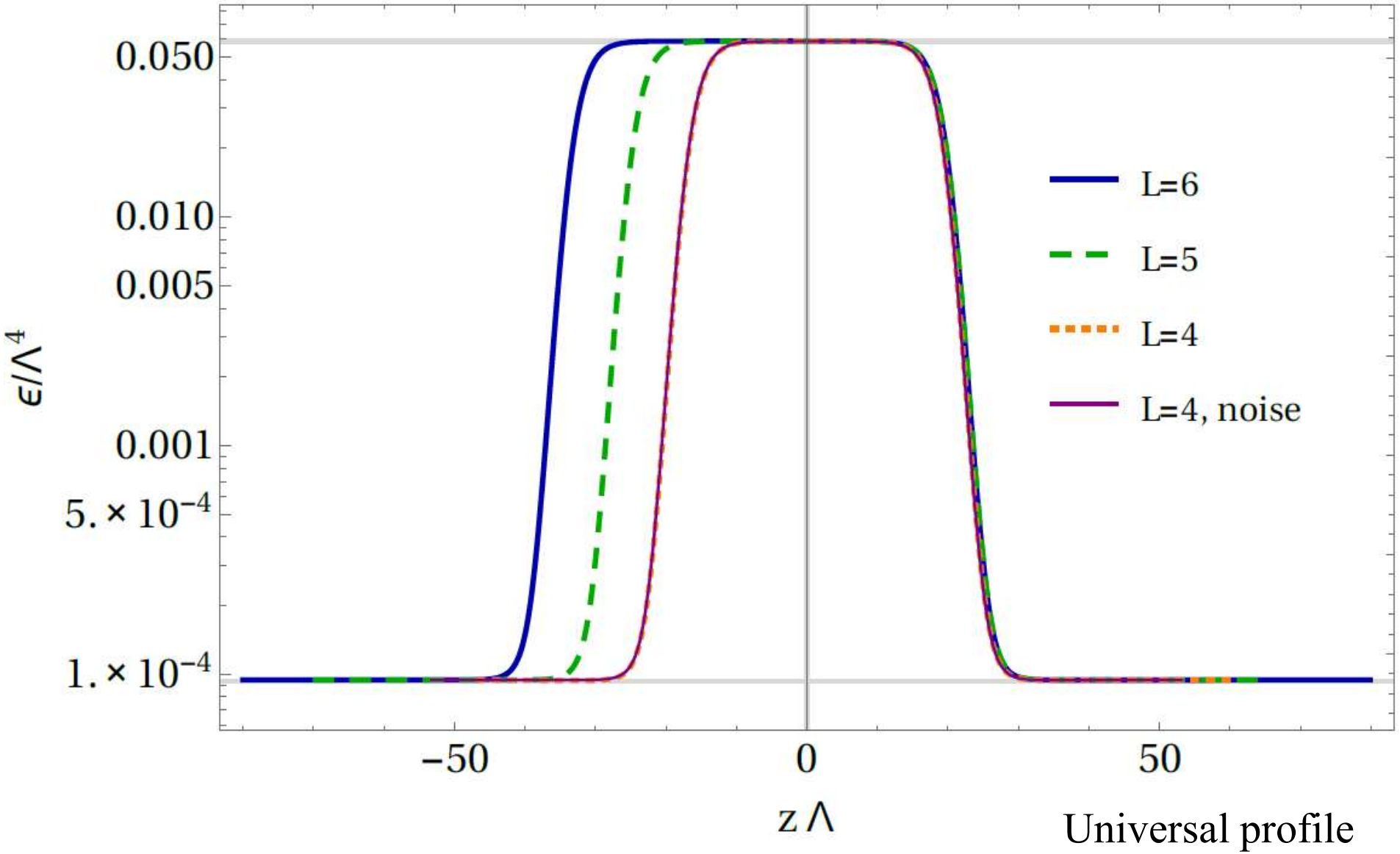
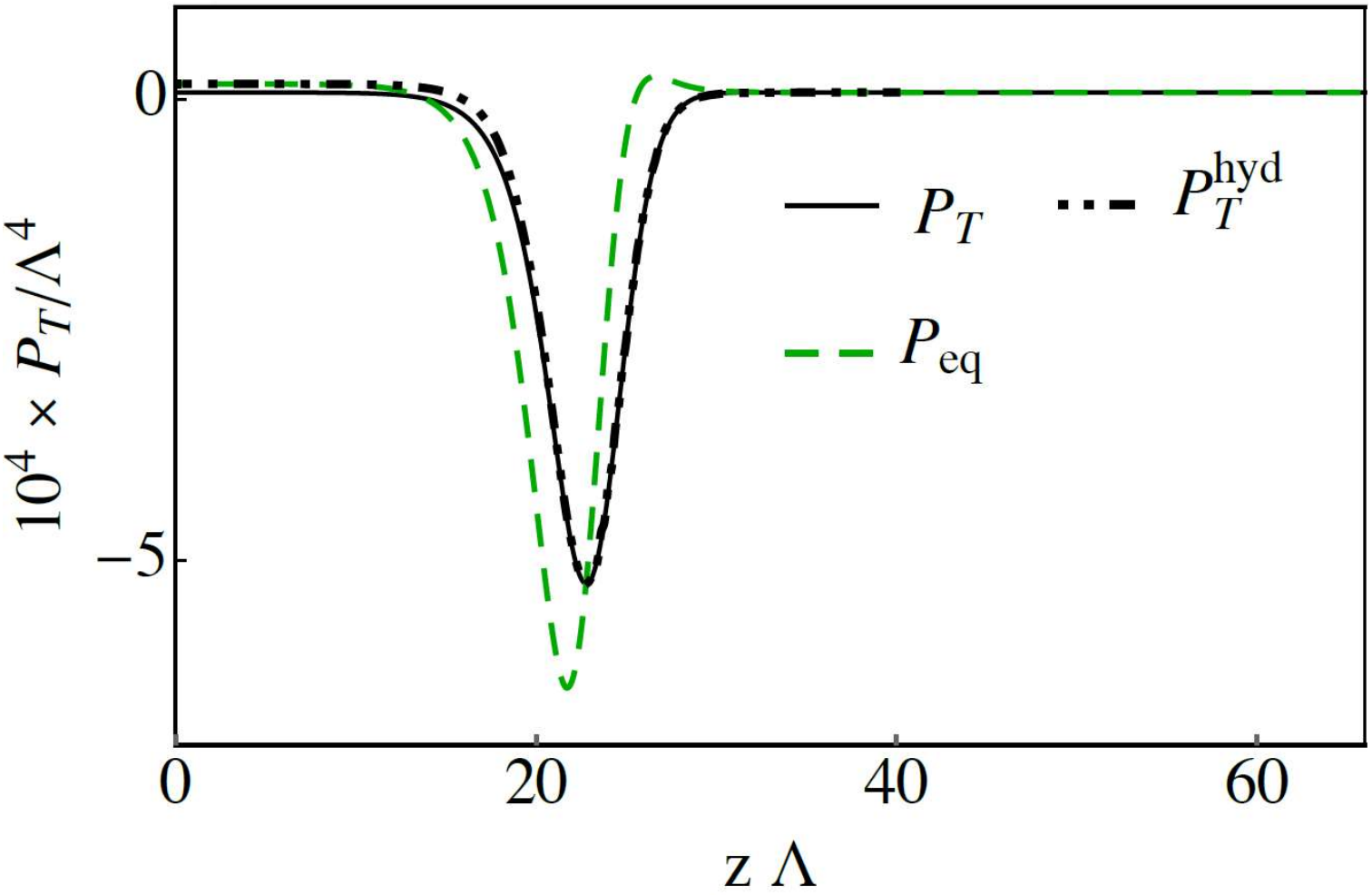


Universal profile

Spinodal instability: phase separation

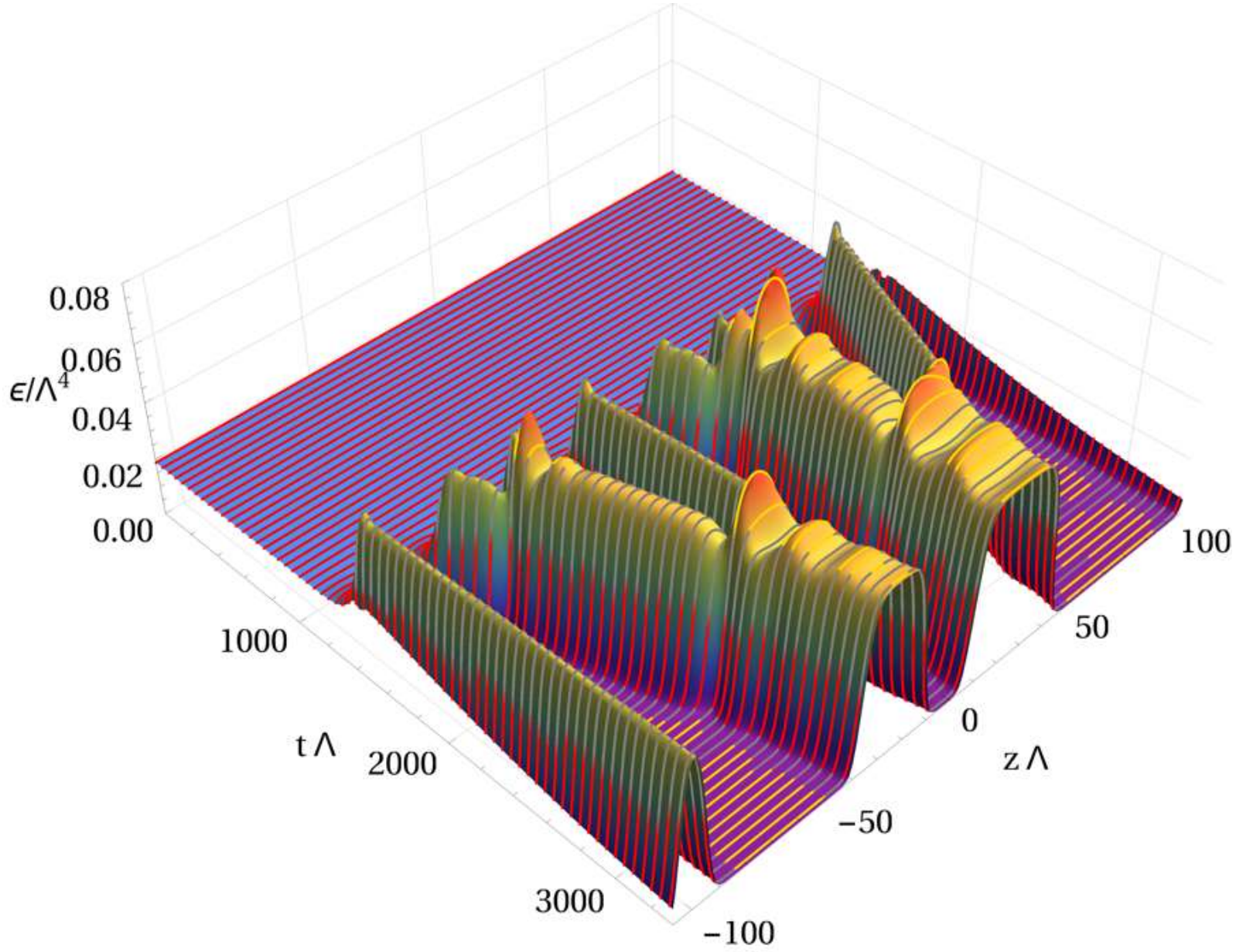
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao, in progress



Also described by hydrodynamics!

Spinodal instability: phase merger

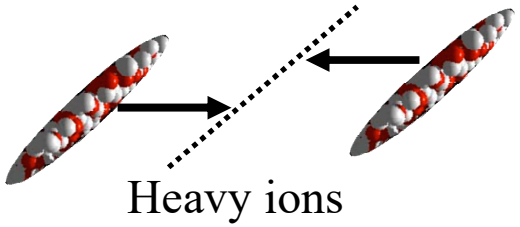
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao, in progress



Holographic Collisions

Holographic collisions

QCD



Holographic collisions

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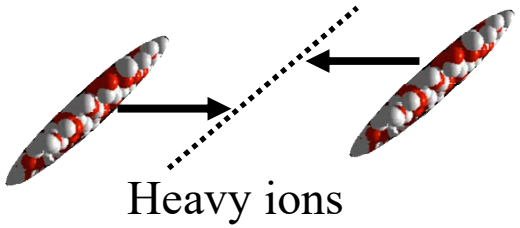
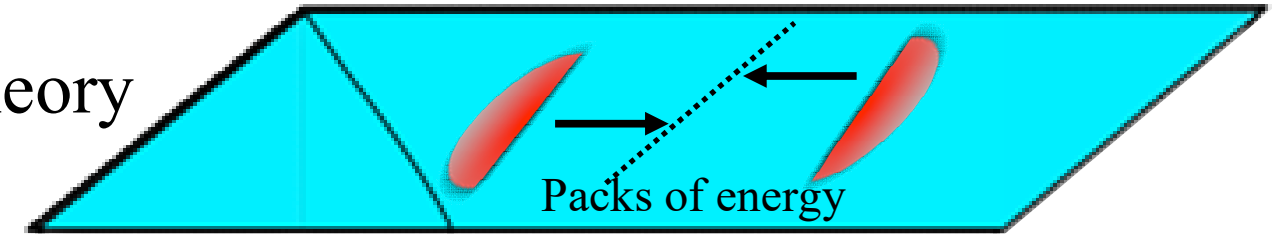


Holographic field theory



Holographic collisions

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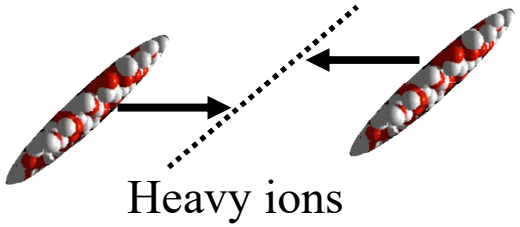
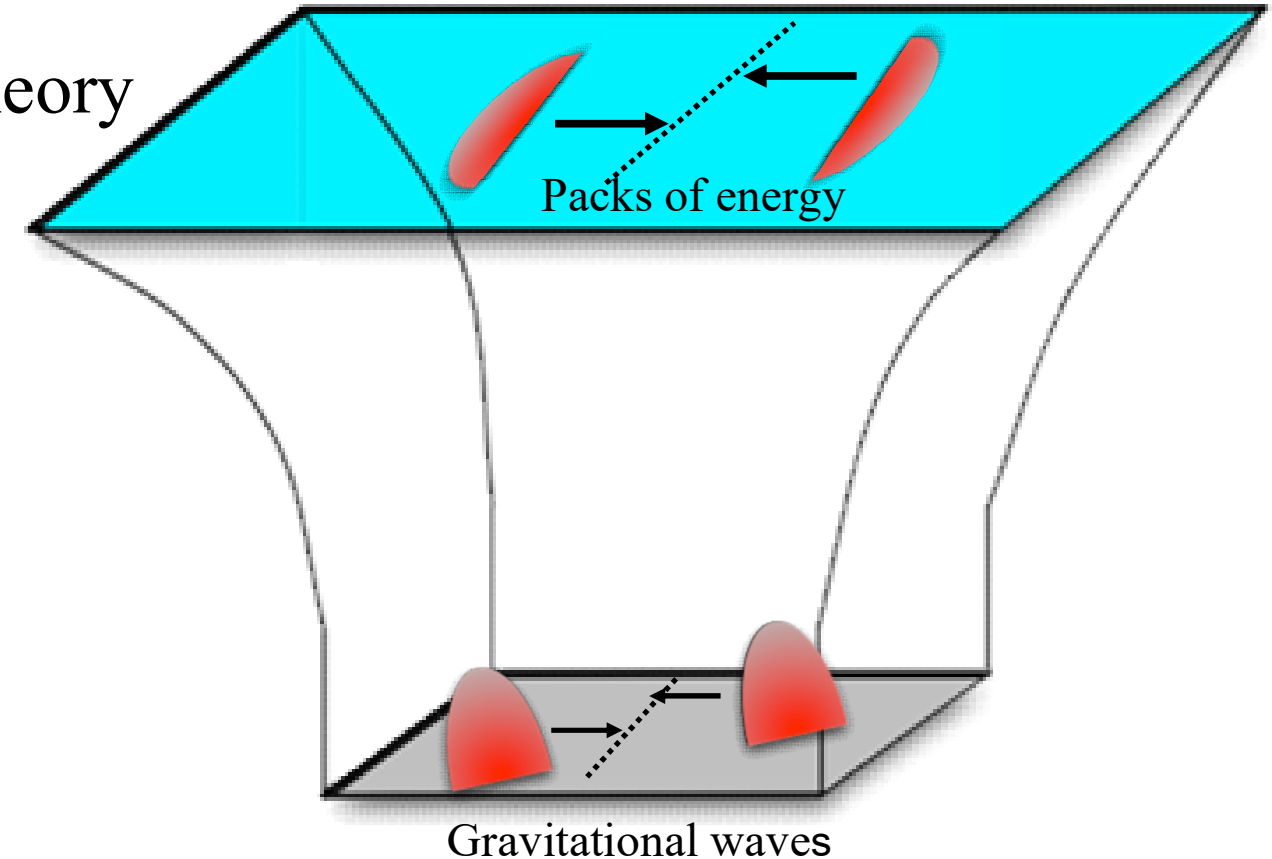
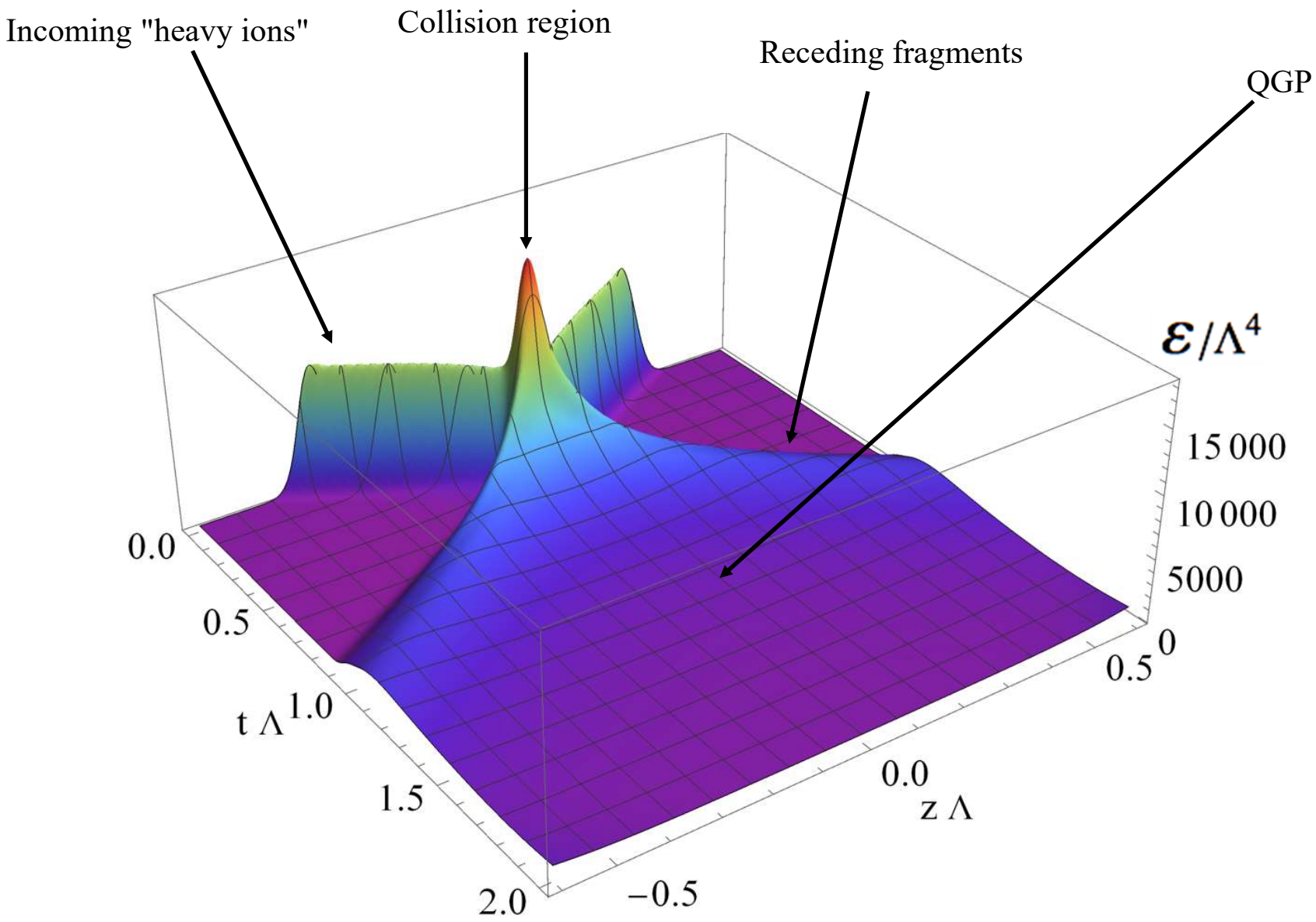


Holographic field theory



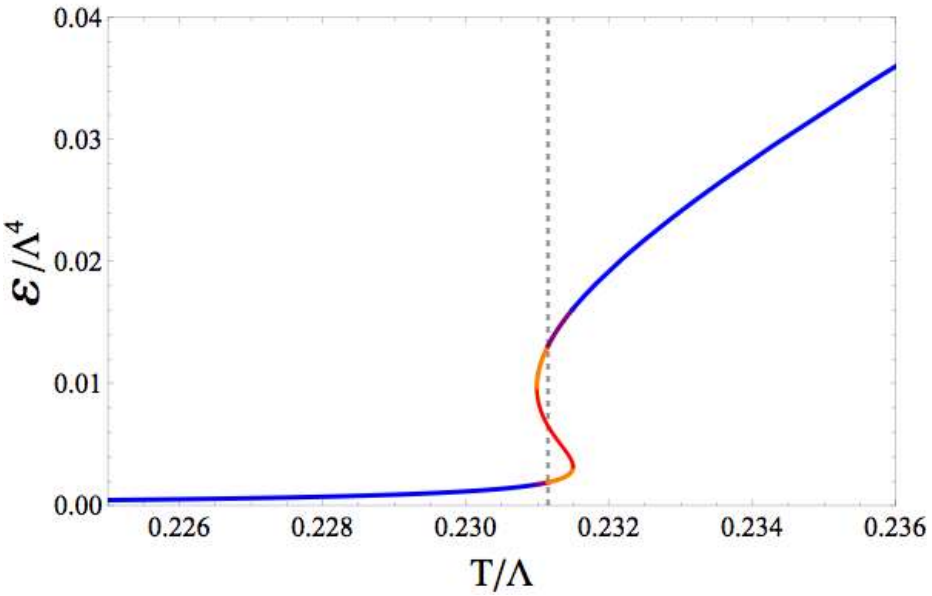
Example: CFT

Chesler & Yaffe ’10



Collisions across a 1st-order phase transition

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao ’18



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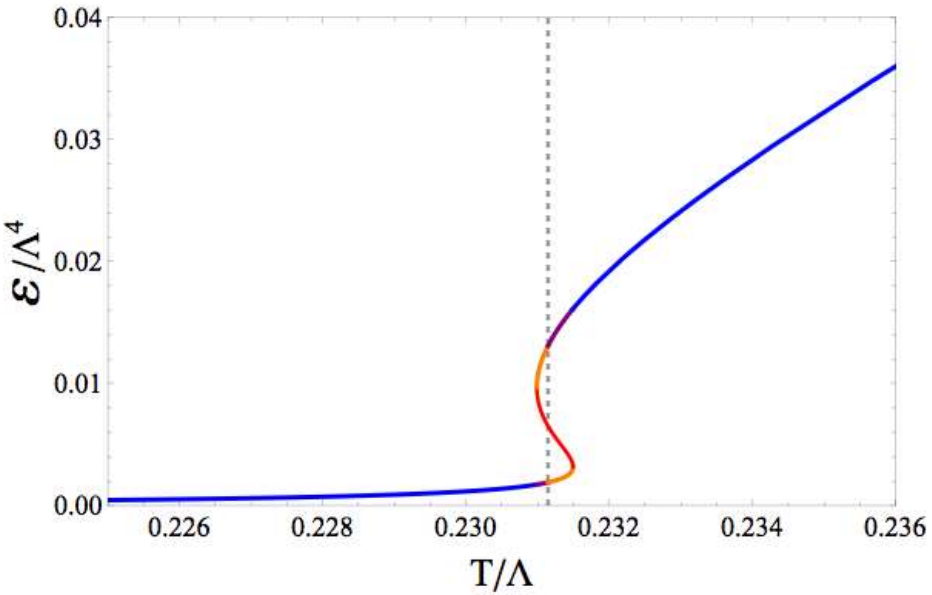
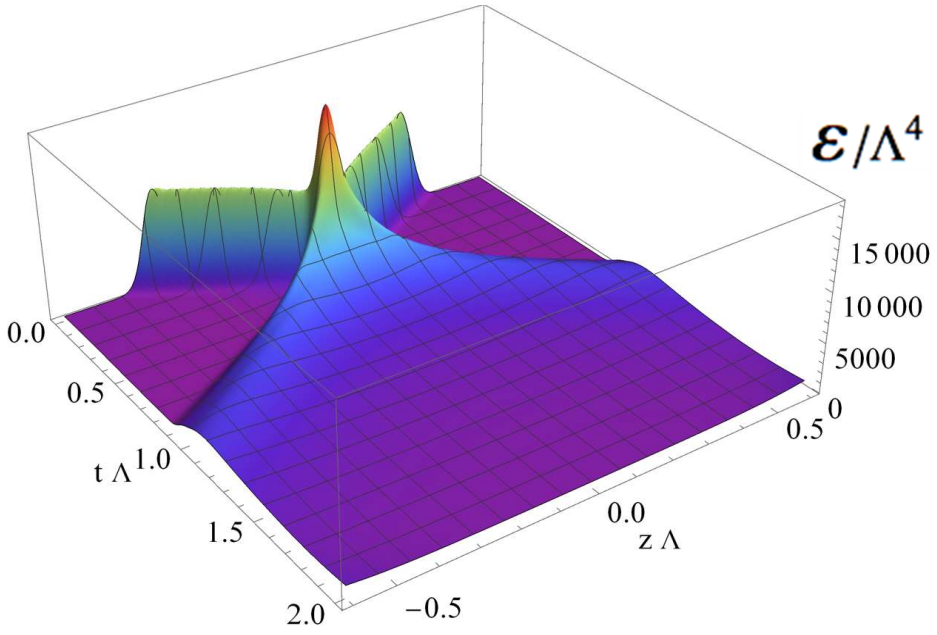
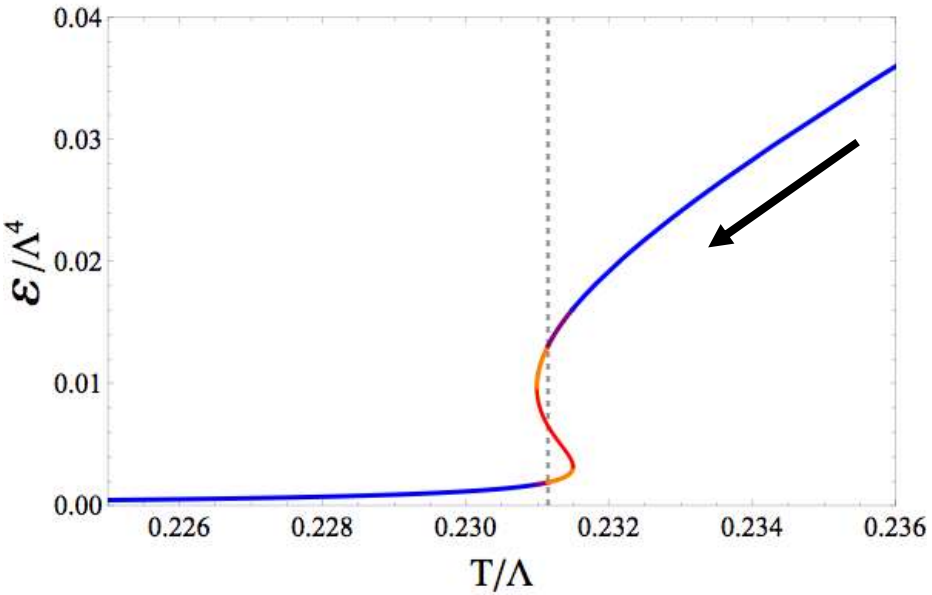


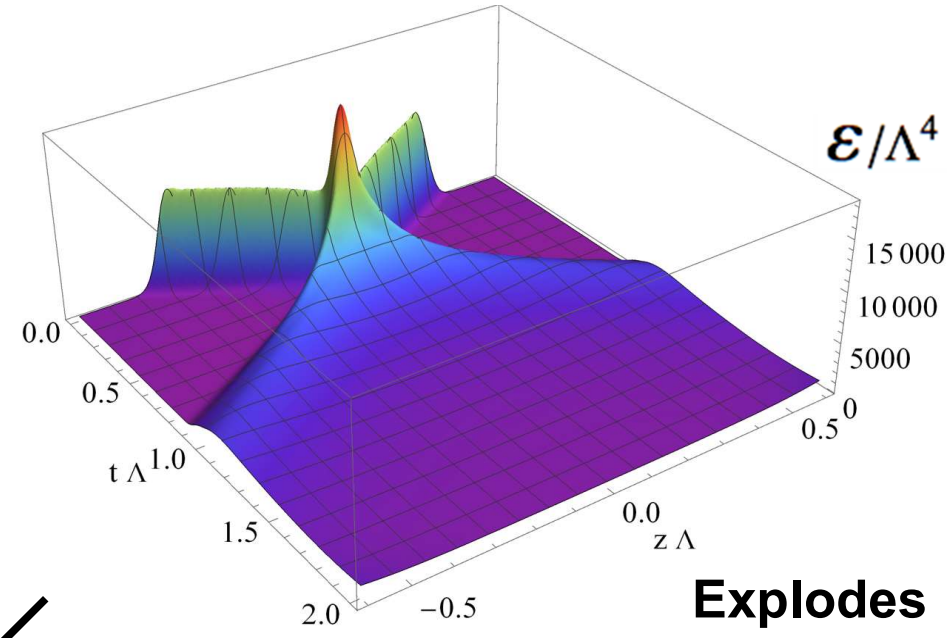


Extremely high energy: Recover CFT result

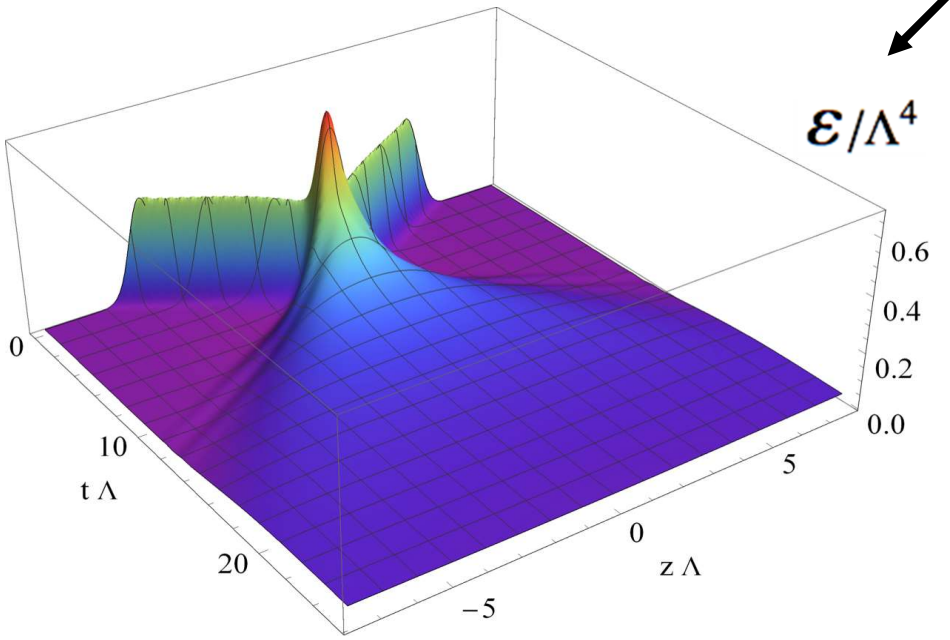
Collisions across a 1st-order phase transition

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18





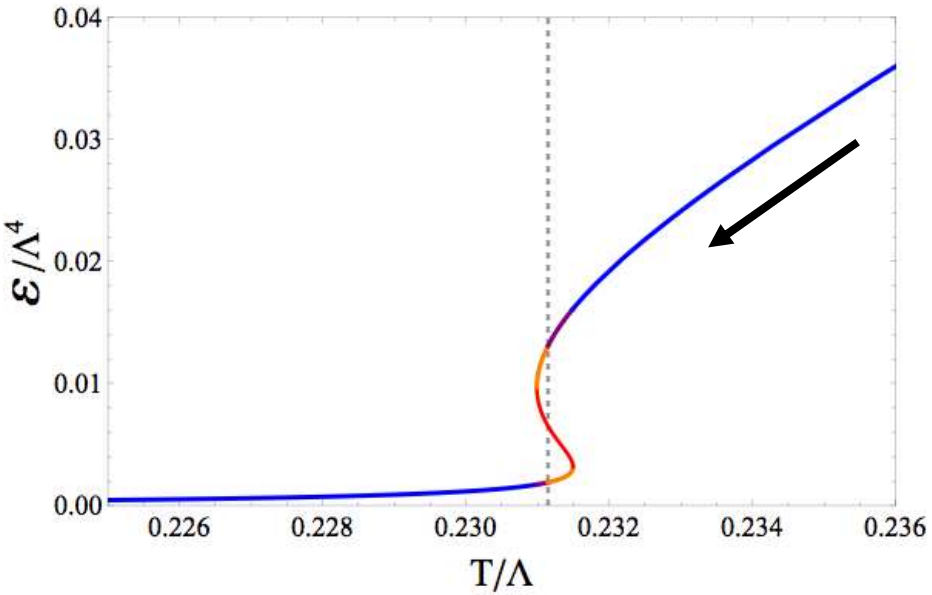
Explodes

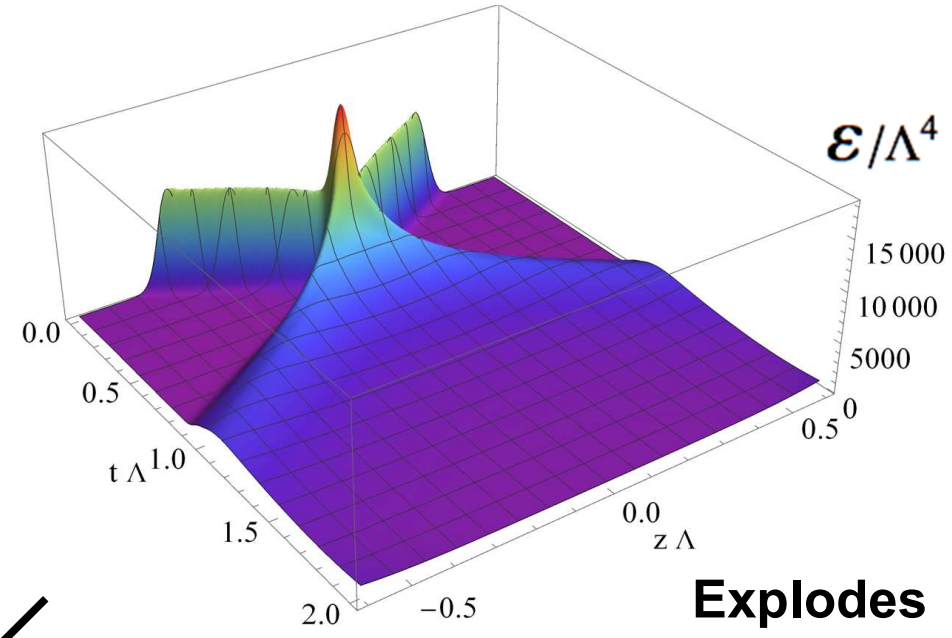


- More time to explode
- Slower receding fragments

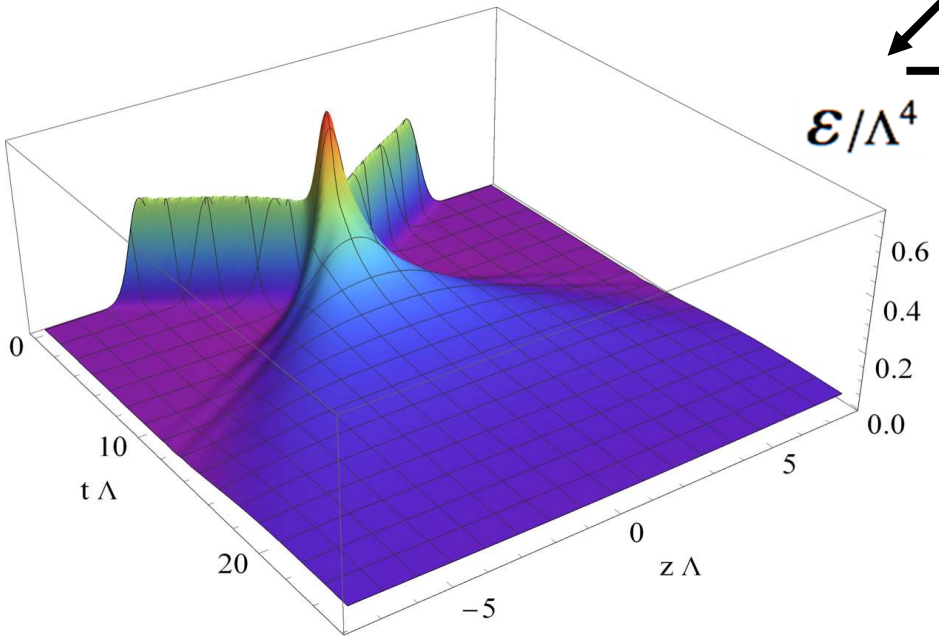
Collisions across a 1st-order phase transition

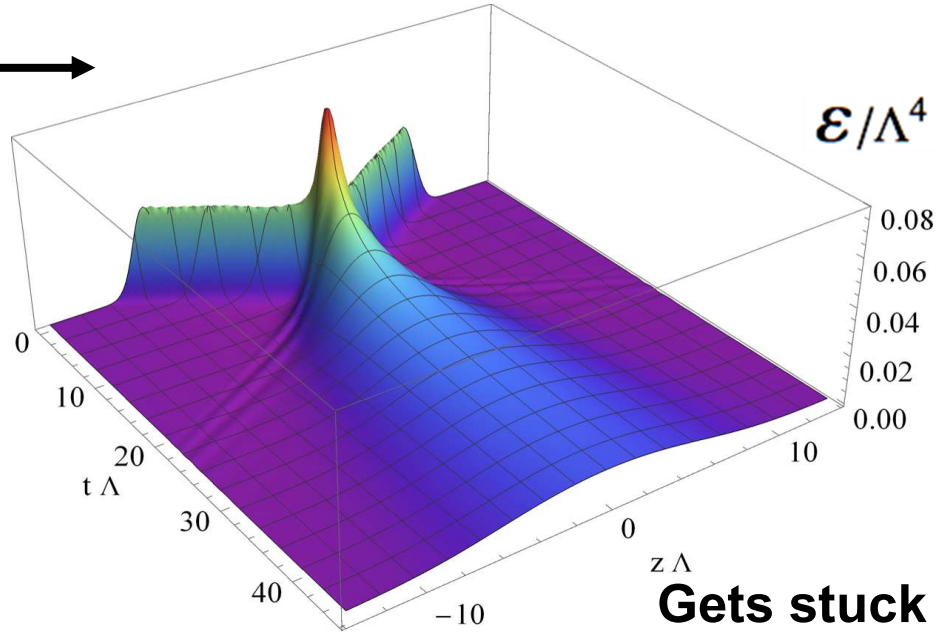
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18





Explodes

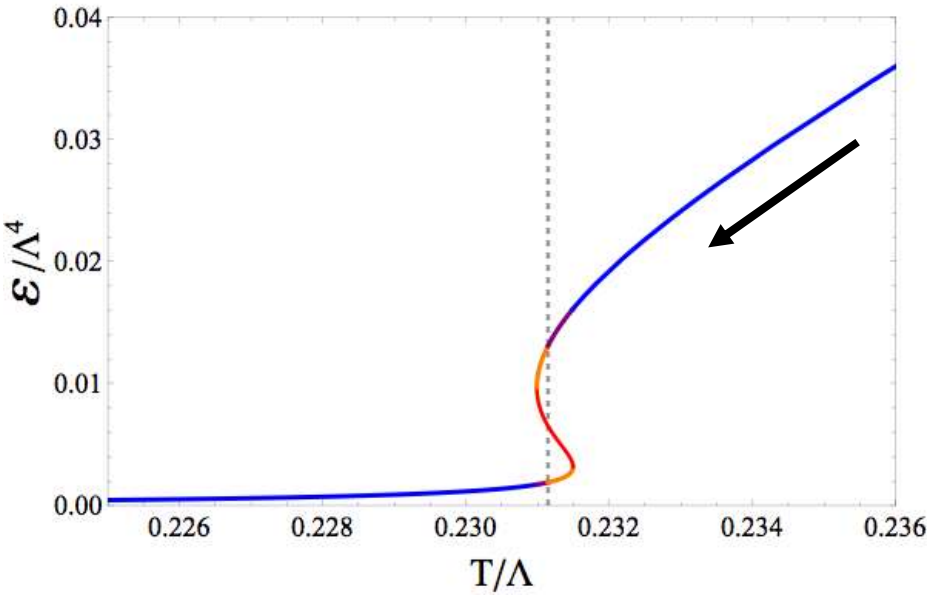


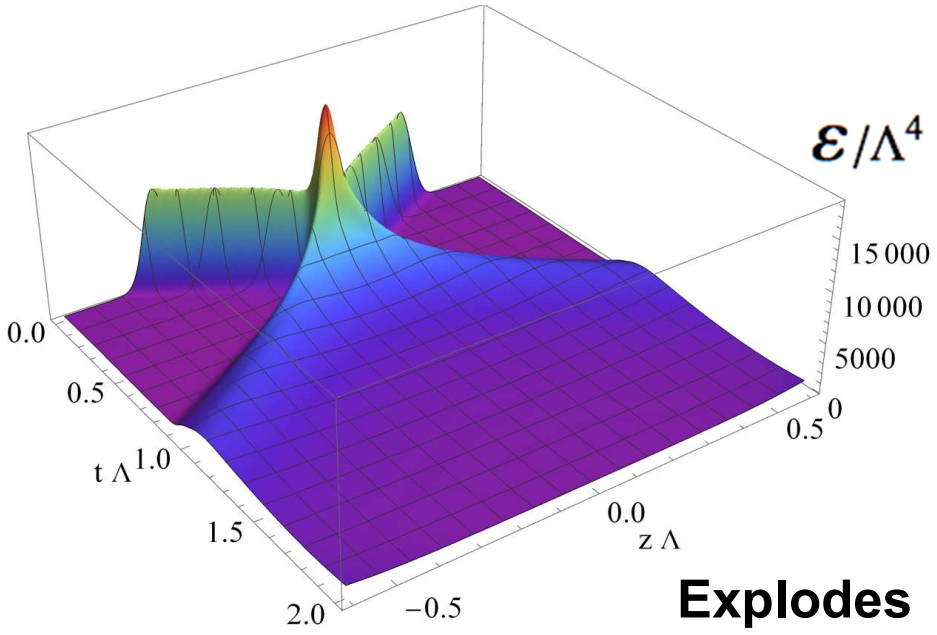


Gets stuck

Collisions across a 1st-order phase transition

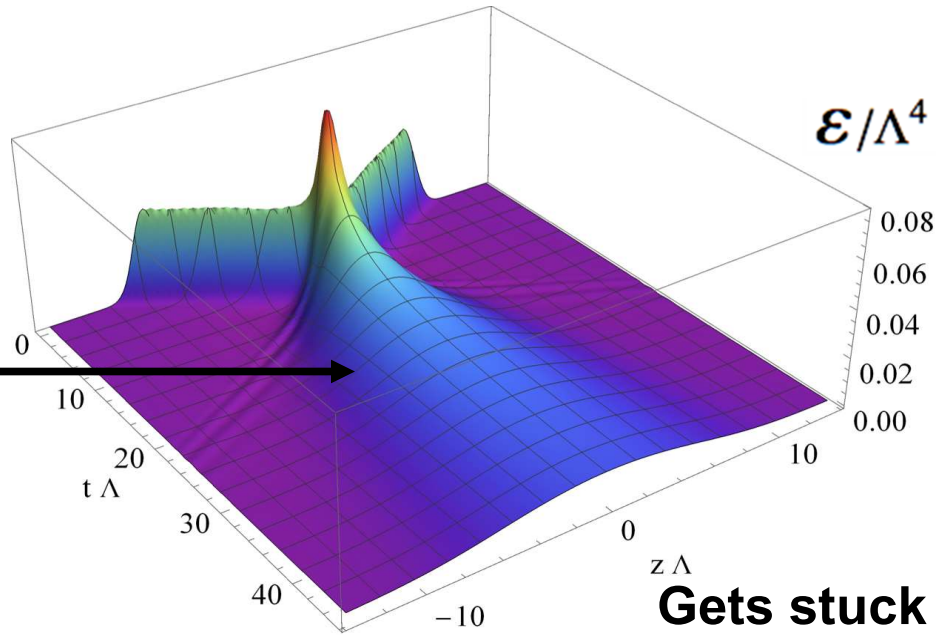
Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18





Explodes

Hydro describes the blob



Gets stuck

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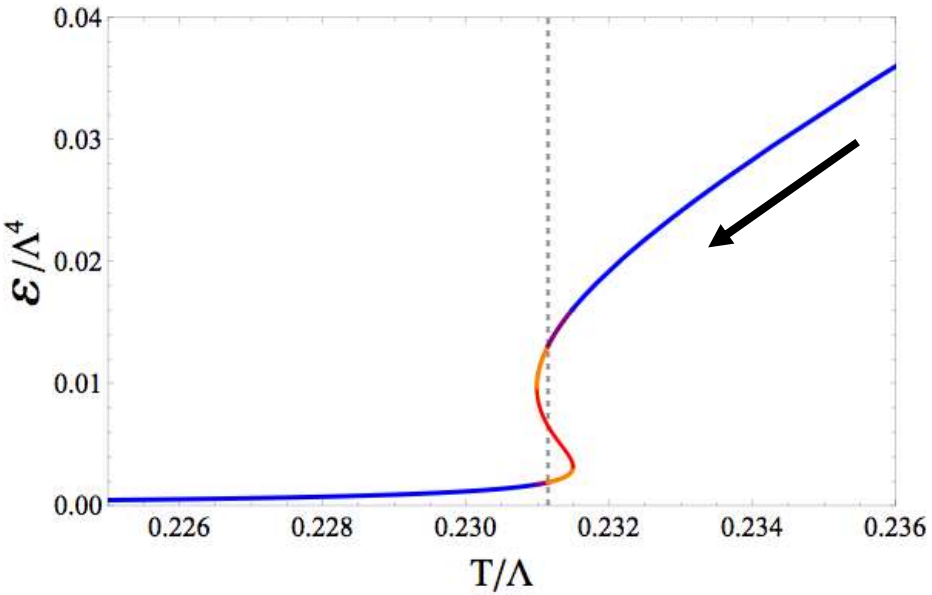
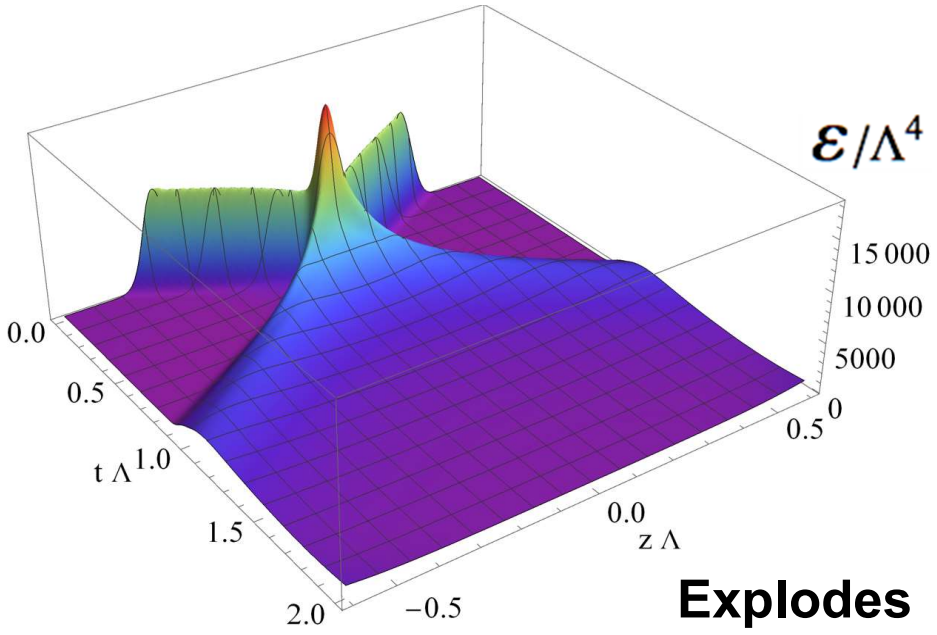


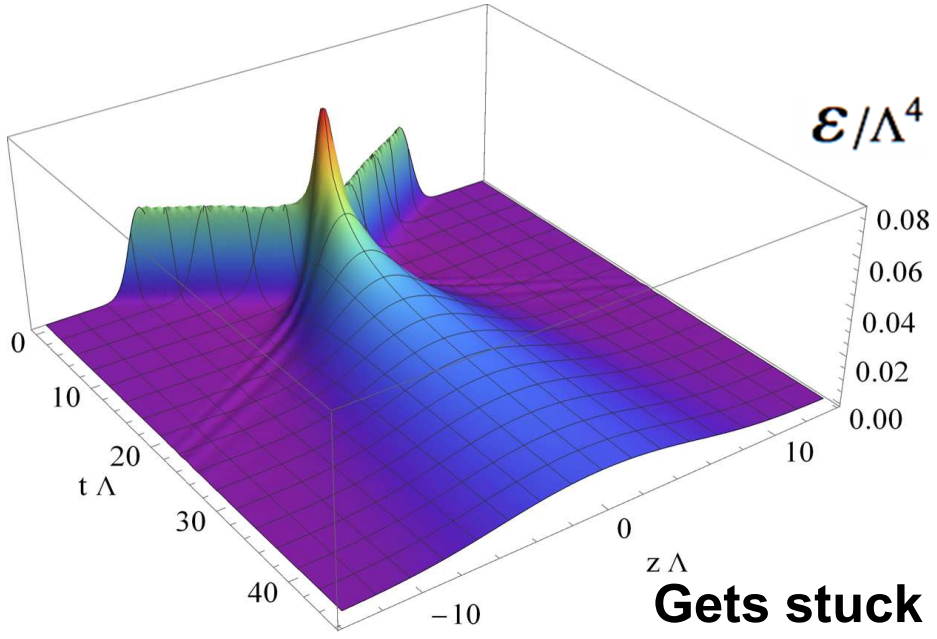


Explodes

Mechanism explaining the blob

$|c_s^2| \leq 10^{-2}$

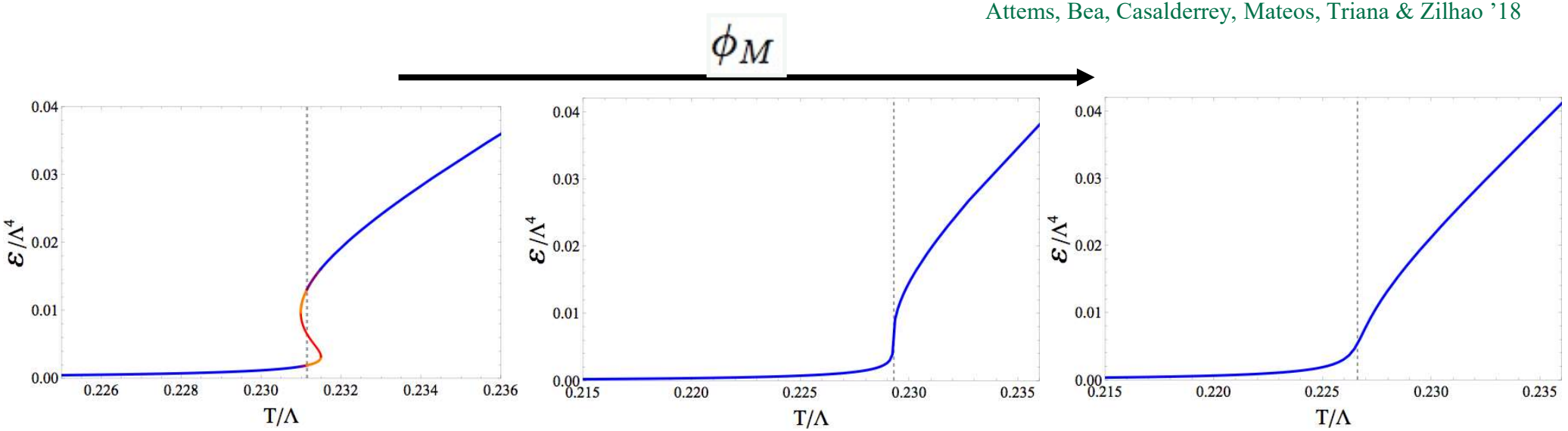
Freezing of the dynamics



Gets stuck

From 1st-order to 2nd-order to crossover

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18



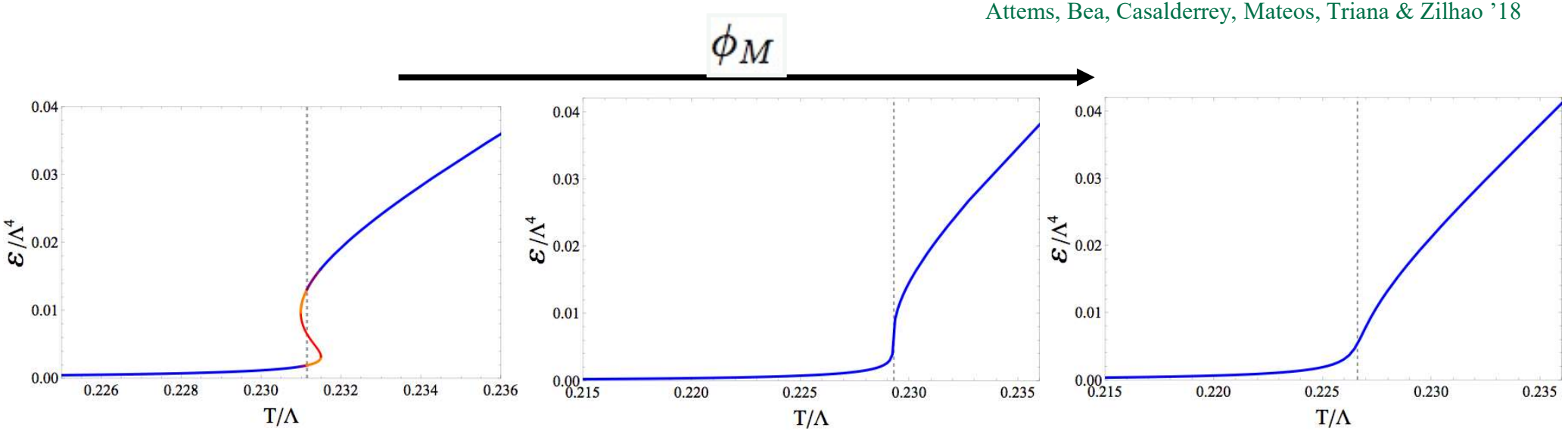
1st order

2nd order

Crossover

From 1st-order to 2nd-order to crossover

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18

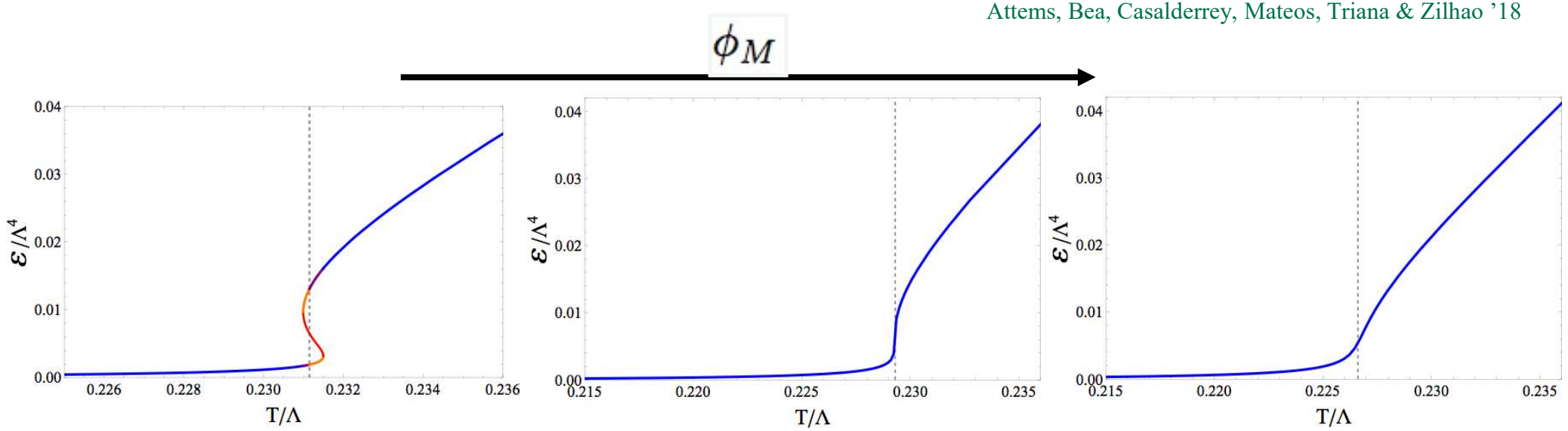


1st order 2nd order Crossover

Equilibrium physics is qualitatively very different

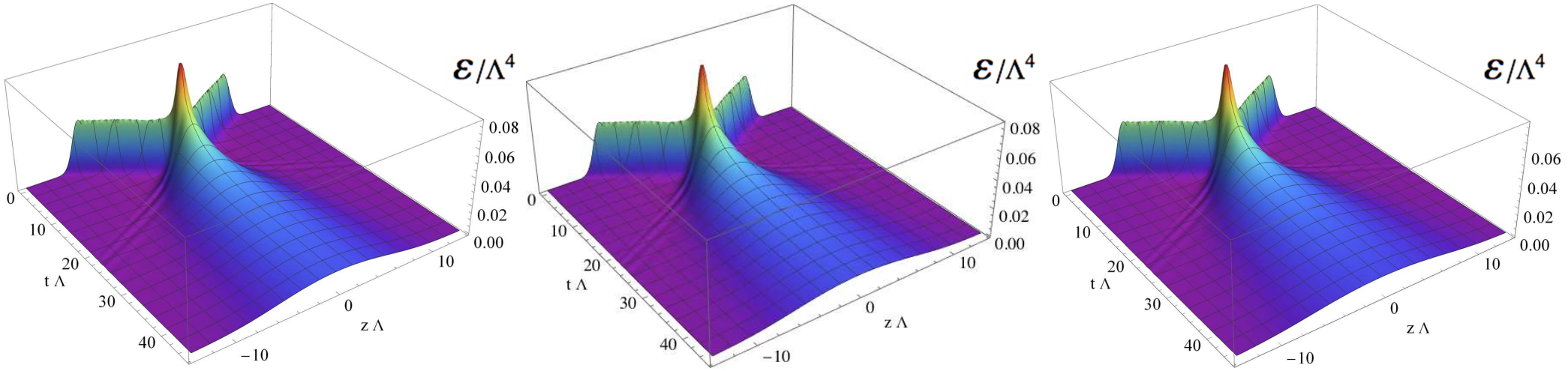
From 1st-order to 2nd-order to crossover

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18



1st order 2nd order Crossover

Equilibrium physics is qualitatively very different

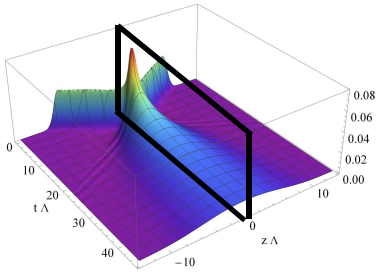


But off-equilibrium physics is qualitatively very similar

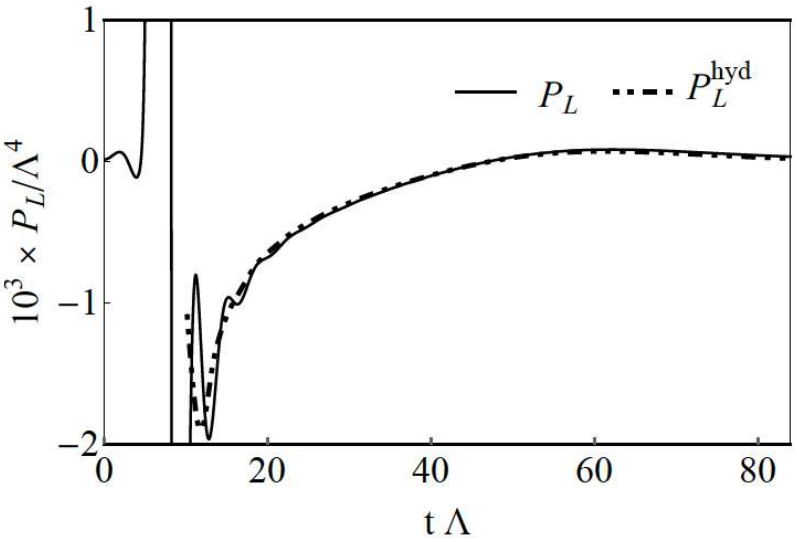
Hydrodynamics

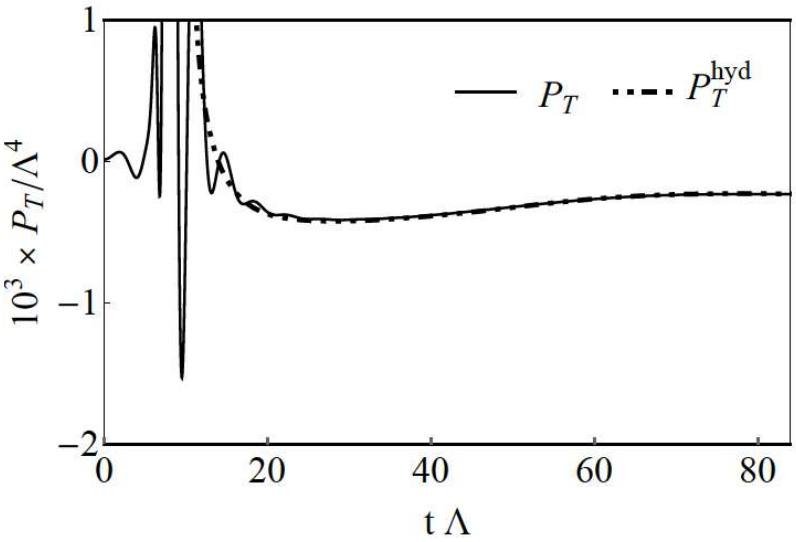
Blob well described by 2nd-order hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao ’18



Time evolution at mid-rapidity

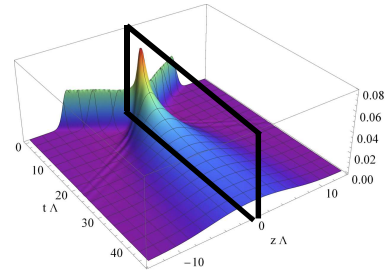




$$T^{\rm hyd}_{\mu\nu} = T^{\rm ideal}_{\mu\nu} - \eta\,\sigma_{\mu\nu} - \zeta\,\Pi\,\Delta_{\mu\nu} + \Pi^{(2)}_{\mu\nu}$$

Blob well described by 2nd-order hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18



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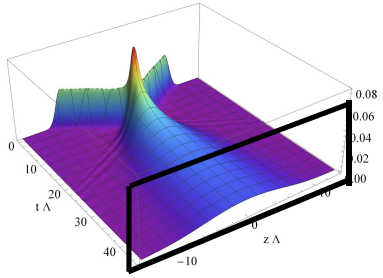
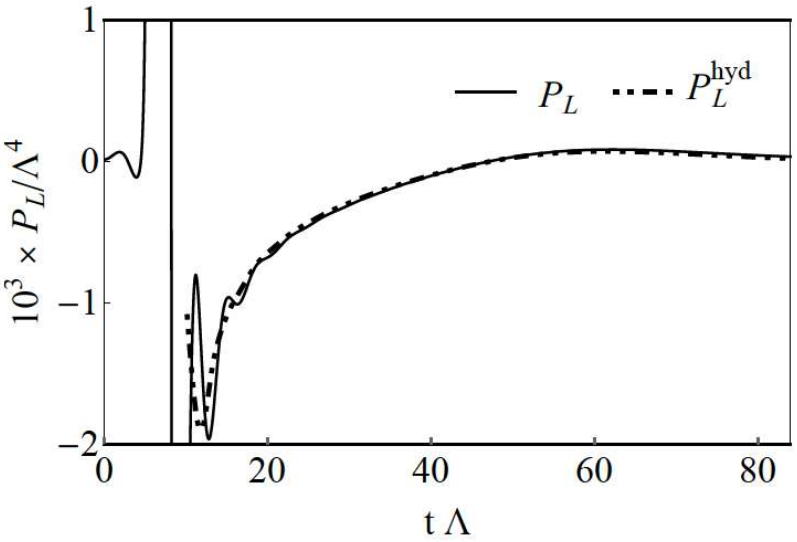
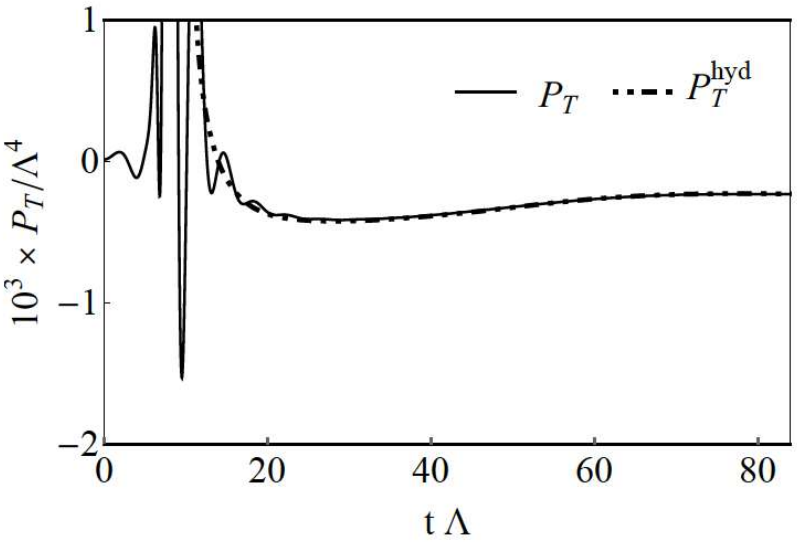
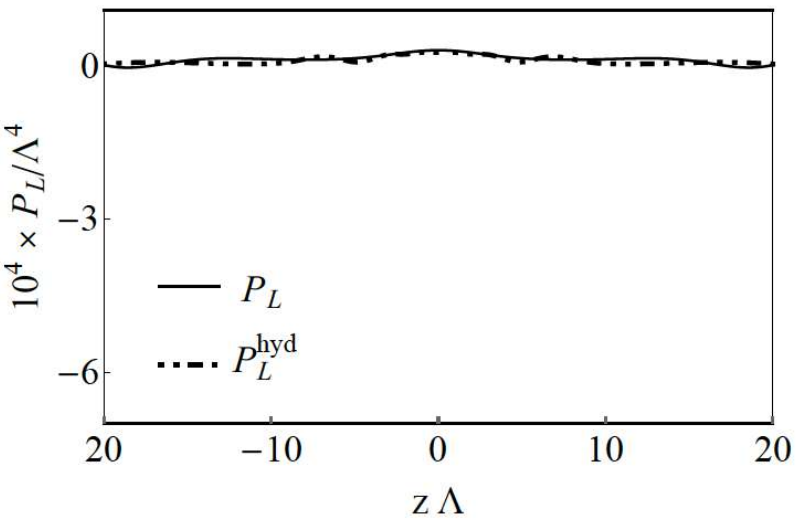
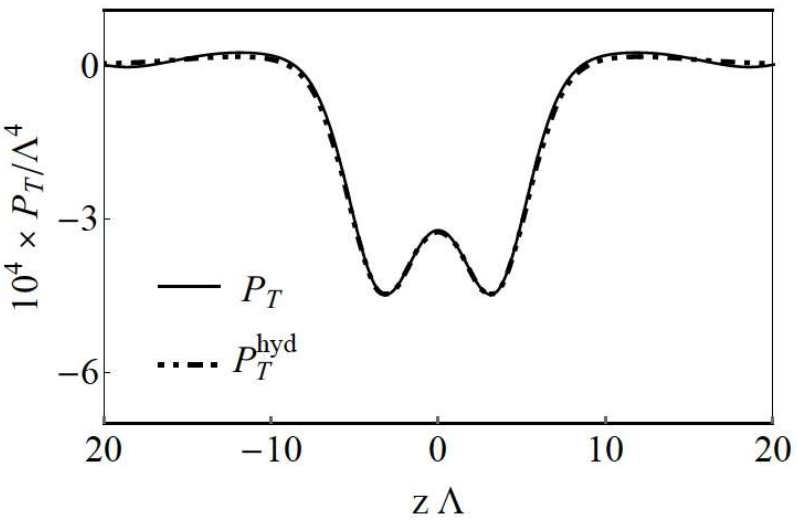


Snapshots of spatial profile after hydrodynamization









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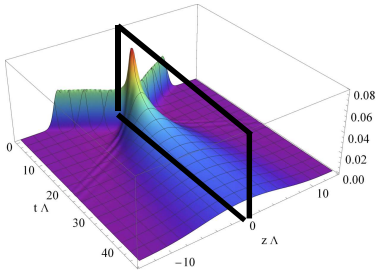

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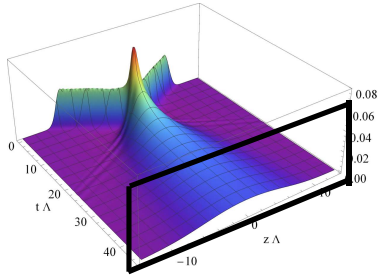

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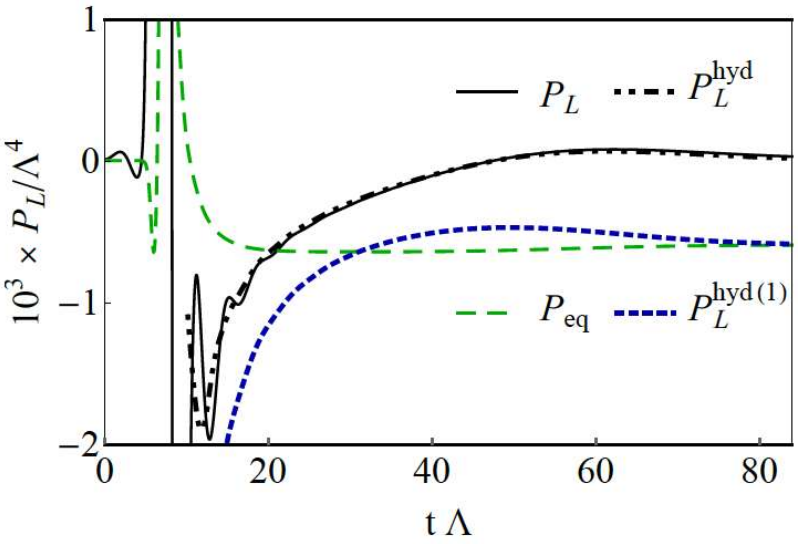

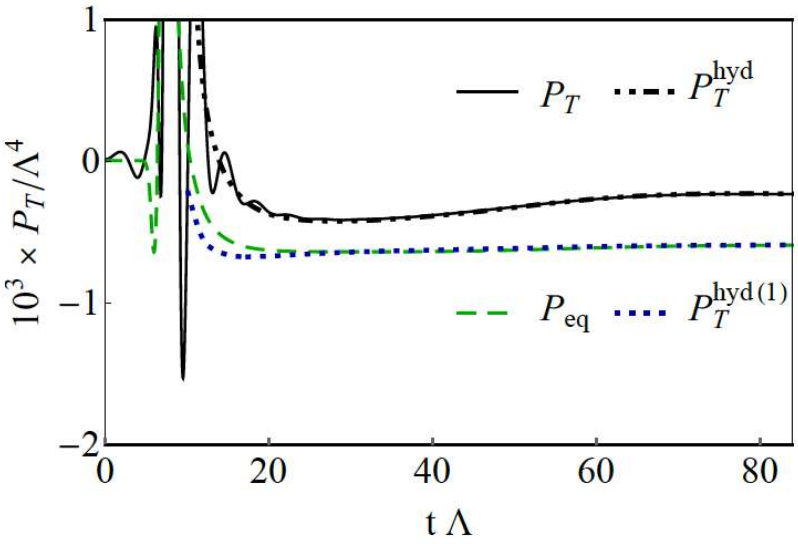

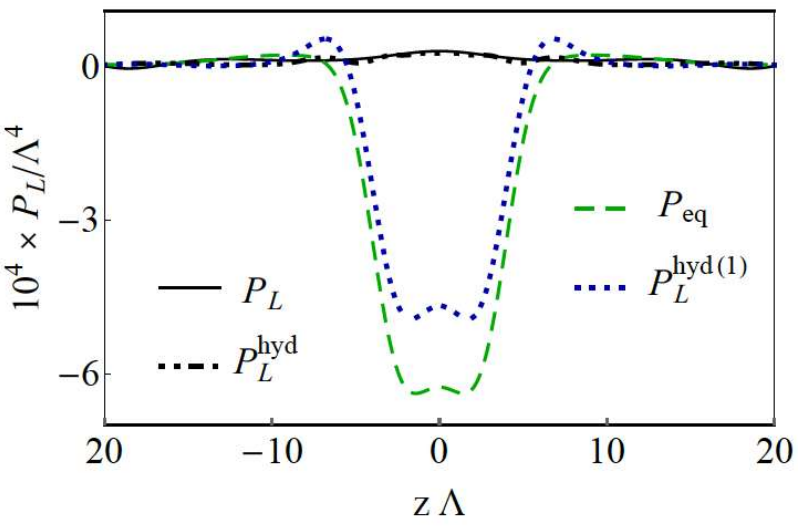

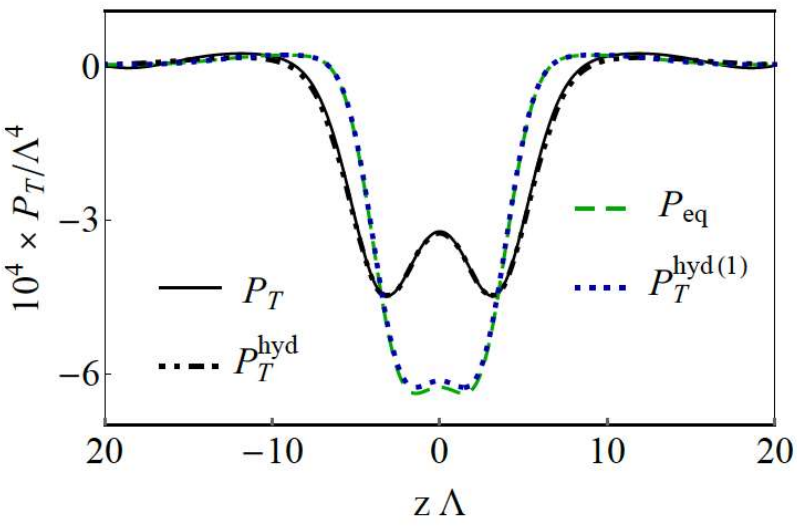

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Blob well described by 2nd-order hydrodynamics

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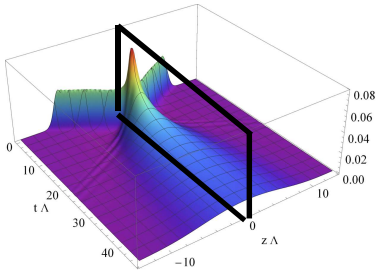

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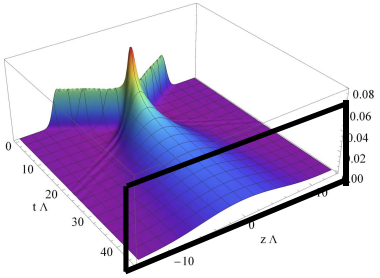

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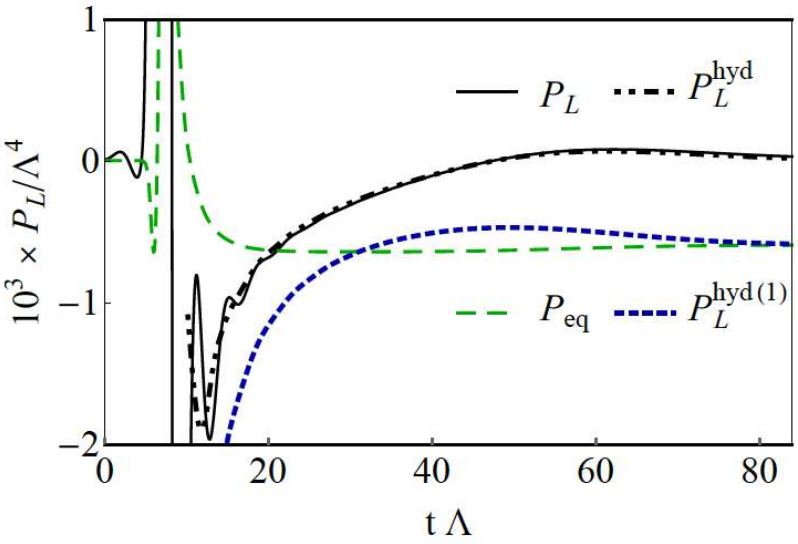

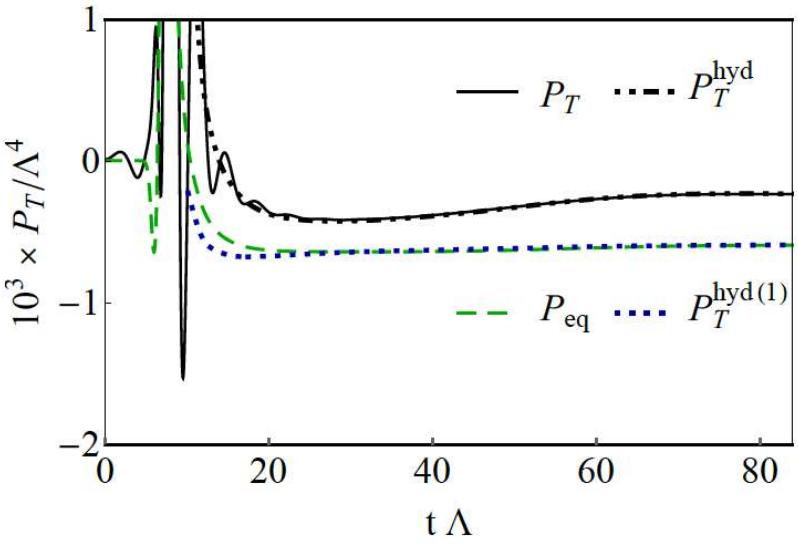

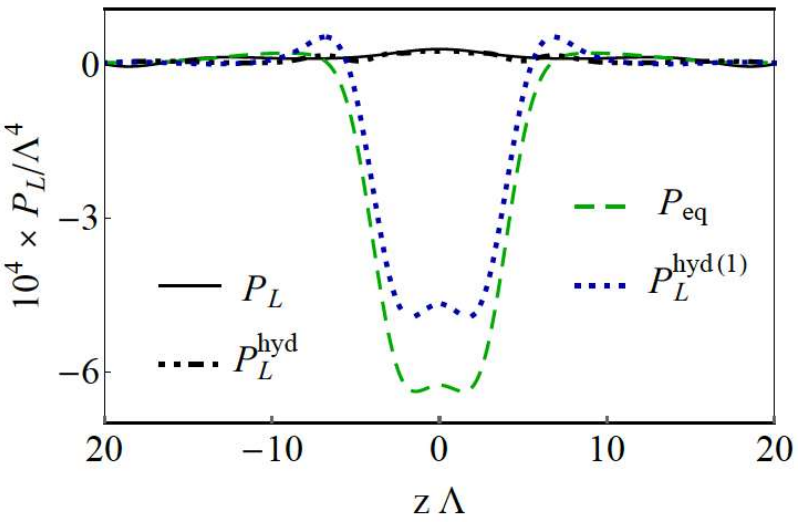

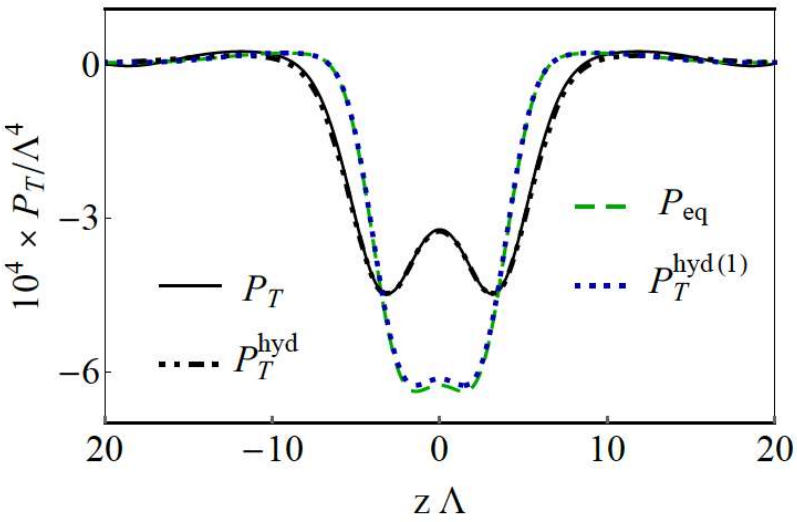

$$T^{\rm hyd}_{\mu\nu} = T^{\rm ideal}_{\mu\nu} - \eta\,\sigma_{\mu\nu} - \zeta\,\Pi\,\Delta_{\mu\nu} + \Pi^{(2)}_{\mu\nu}$$

➡ Second-order gradients are large

Blob well described by 2nd-order hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18

$$T_{\mu\nu} = T_{\mu\nu}^{ideal} + \partial_{spatial} + \partial_{spatial}^{2}$$ Purely spatial formulation

- Problem for time evolution: Hydrodynamics is acausal.

  ⟶ We are not doing time evolution, just checking constitutive relations.

Blob well described by 2nd-order hydrodynamics

Attems, Bea, Casalderrey, Mateos, Triana & Zilhao '18

$$T_{\mu\nu} = T_{\mu\nu}^{ideal} + \partial_{spatial} + \partial_{spatial}^2$$ Purely spatial formulation

- Problem for time evolution: Hydrodynamics is acausal.

  ⟶ We are not doing time evolution, just checking constitutive relations.

- One fix: use 1st-order equations to get:

$$T_{\mu\nu}^{MIS} = T_{\mu\nu}^{ideal} + \partial_{spatial} + \partial_{spatial}\partial_{time}$$ Muller-Israel-Stewart

- Produces equivalent descriptions if gradients are small, but not in our case.

Blob well described by 2nd-order hydrodynamics

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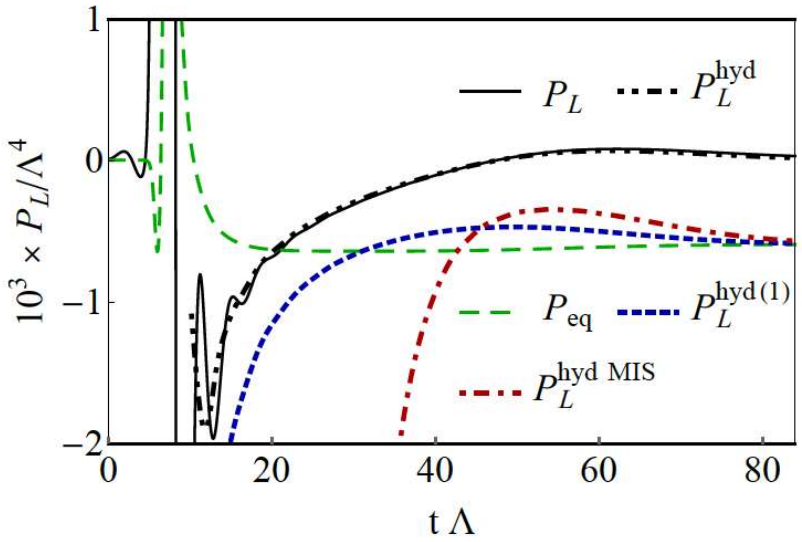

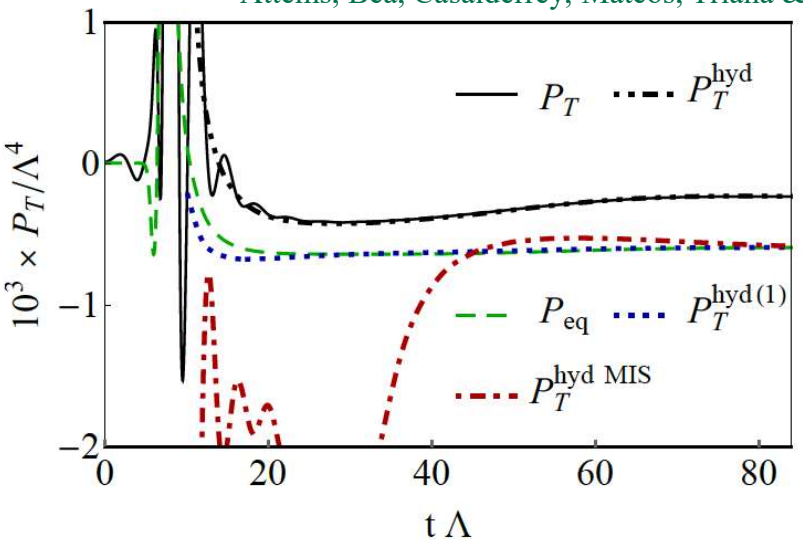

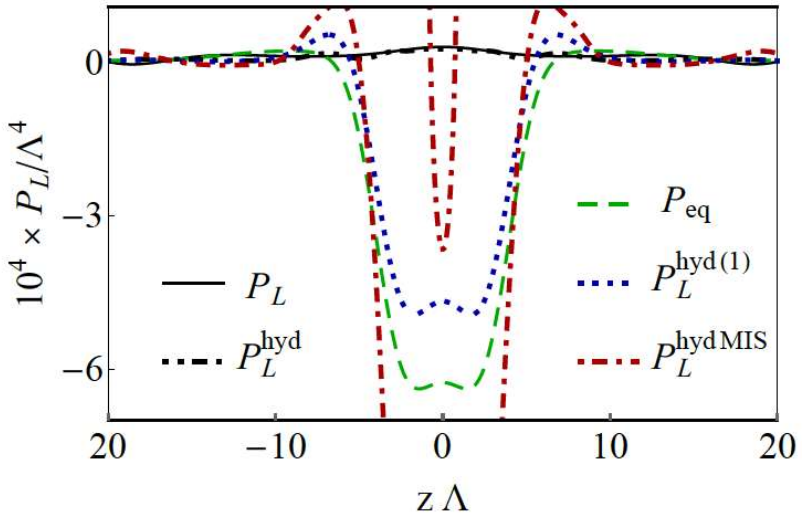

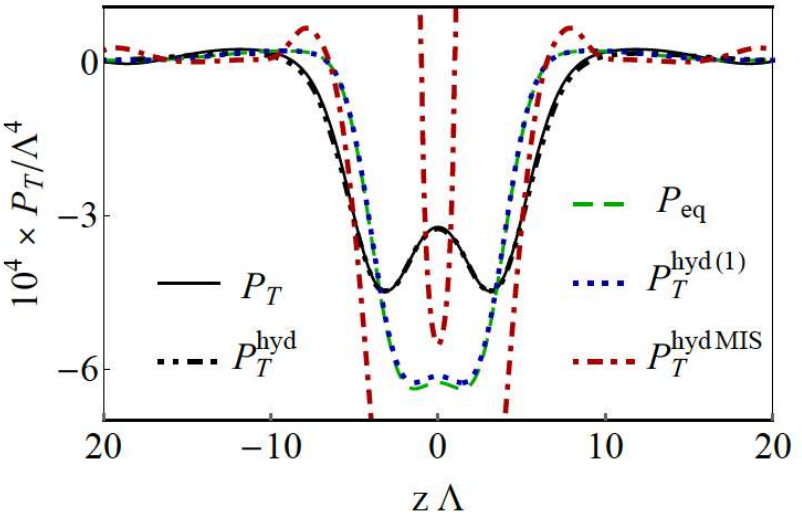

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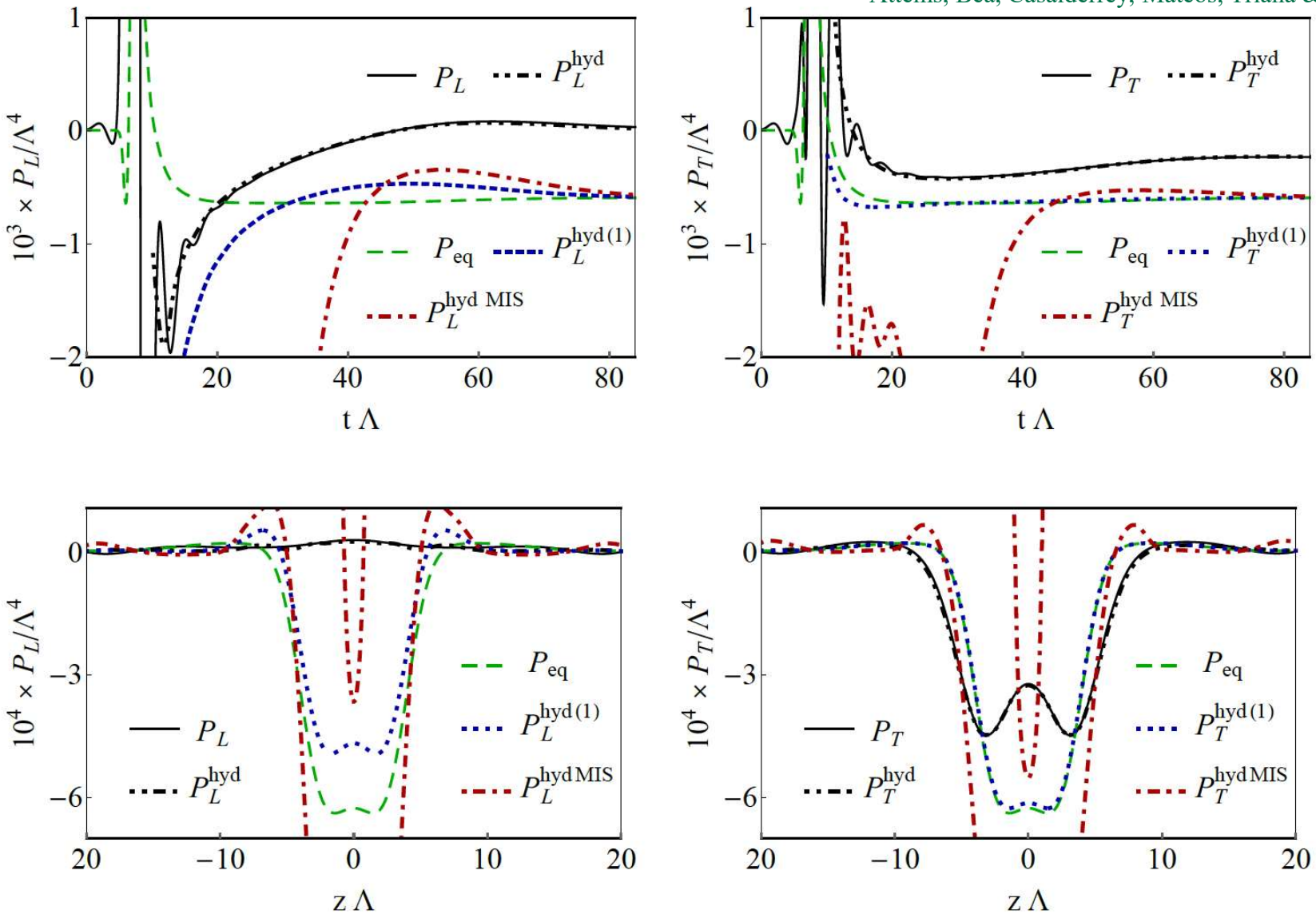


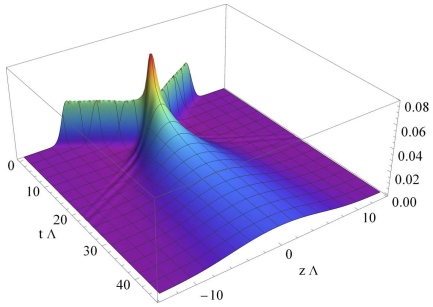
- MIS-type formulation fails to provide a good description
- Hydro codes may need to include the 2nd-order purely spatial terms

Conclusions

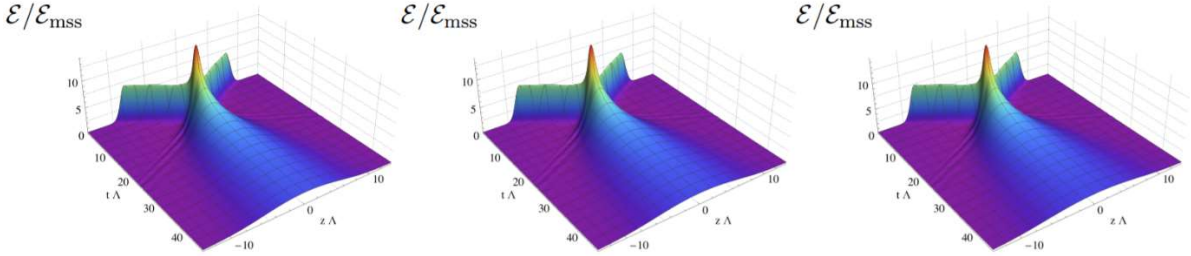
Conclusions

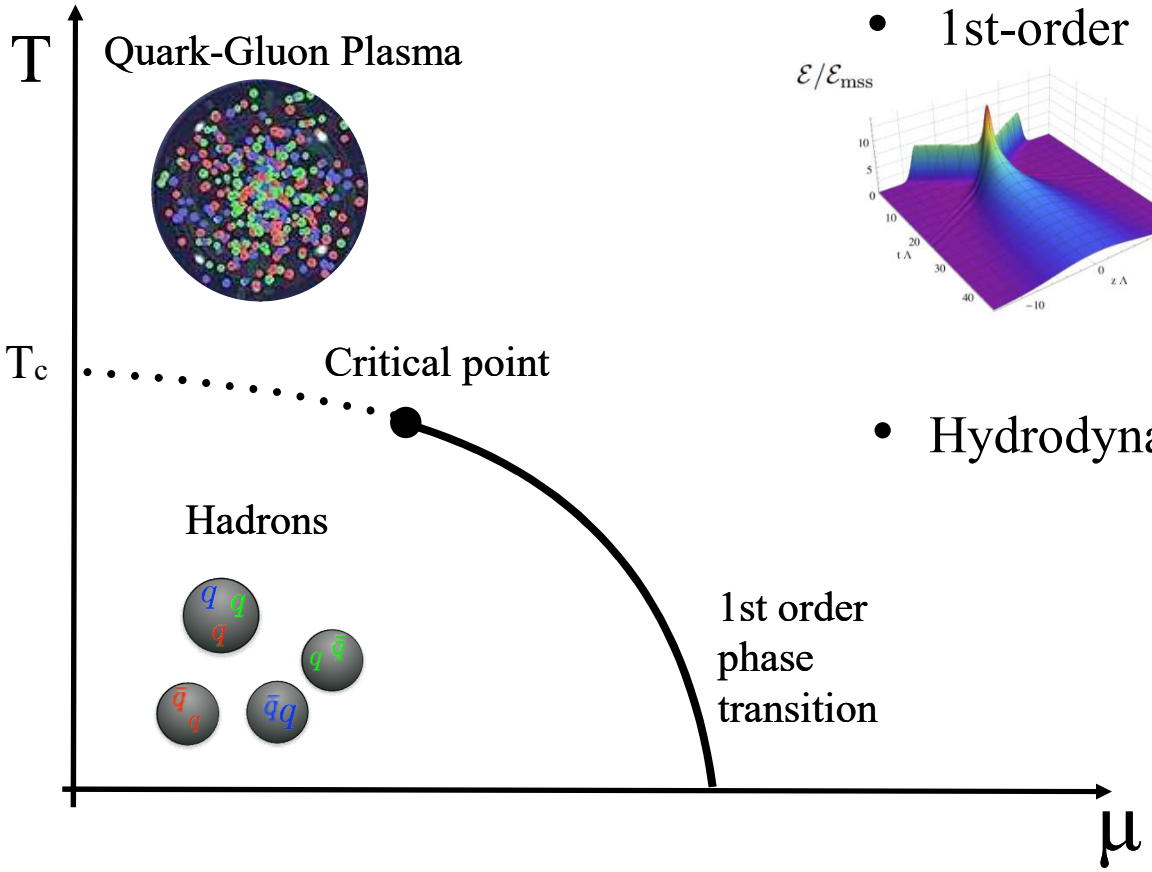
What can we learn from holography?

- Formation of a blob

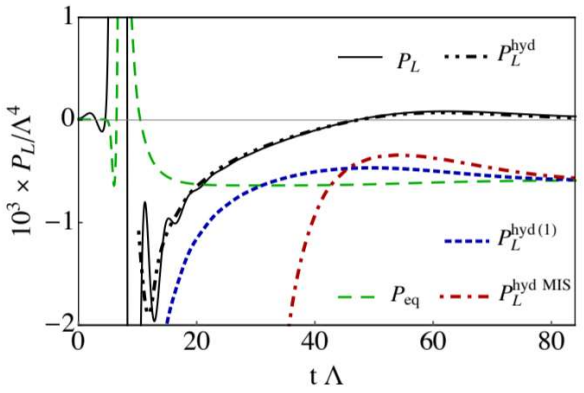


- 1st-order 2nd-order crossover

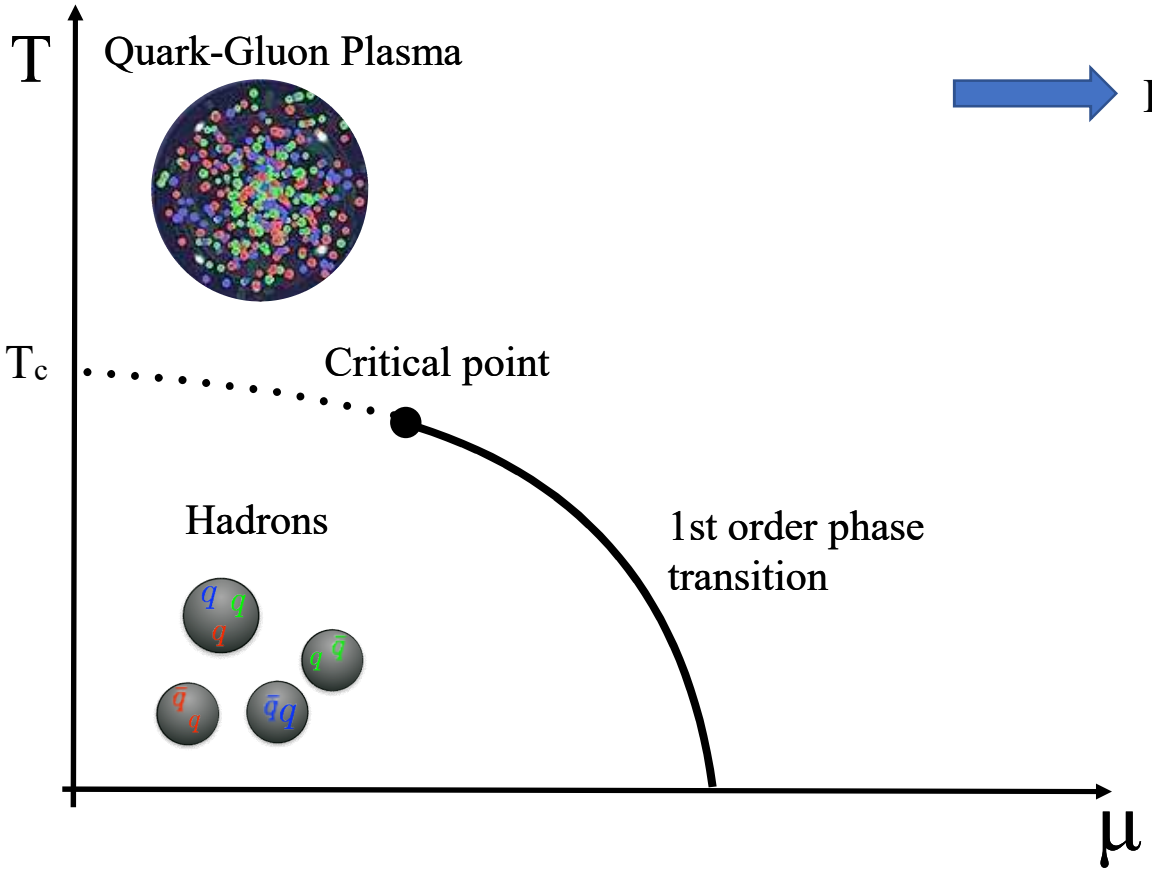




- Hydrodynamics



Future directions

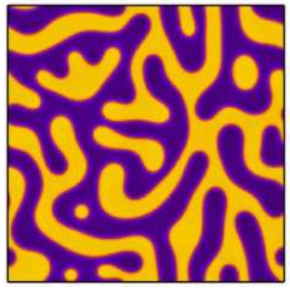


➡ Non-vanishing chemical potential

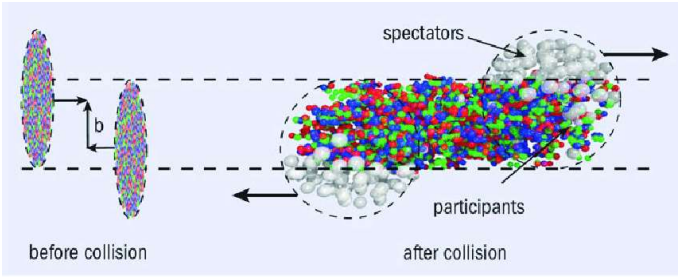
- Spinodal instability
- Collisions

➡ Dynamics in more dimensions

- 1+1 ➡ 2+1 or 3+1
- Spinodal instability



- Off-central collisions



Thank you