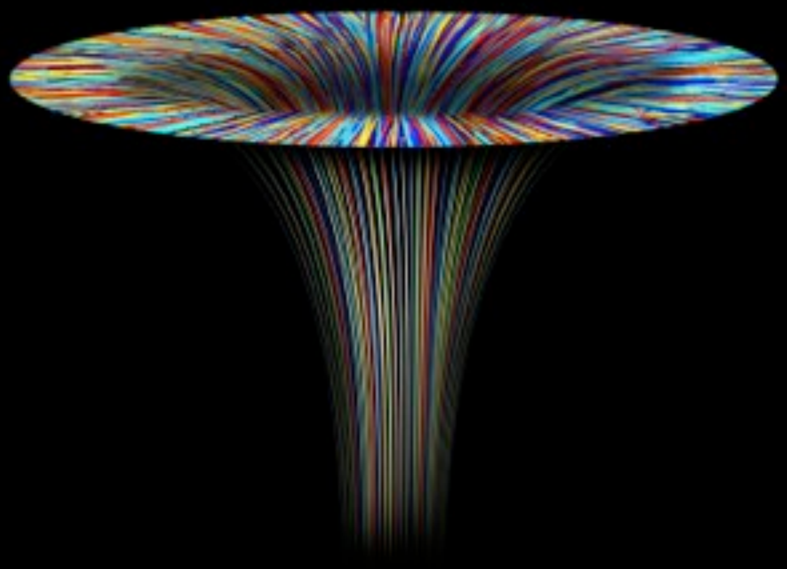
Far-from-equilibrium Holography
and
Heavy Ion Collisions



David Mateos
ICREA & University of Barcelona

Work with Casalderrey, Heller and van der Schee

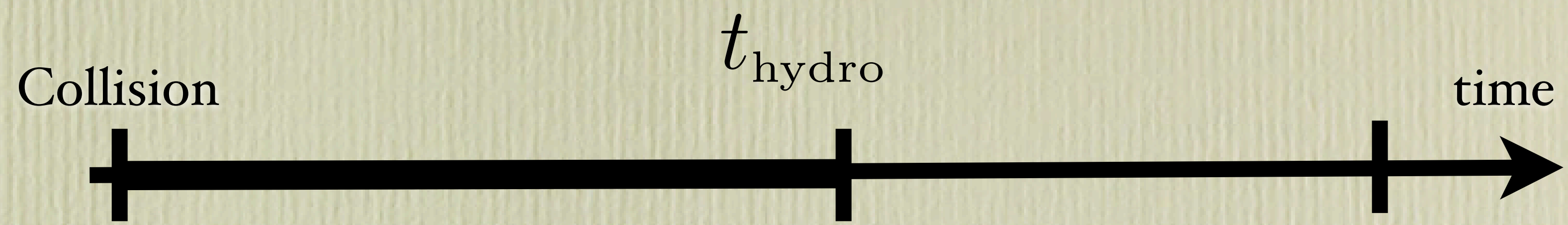
The QCD challenge

- QCD remains a challenge after 40 years.
- We have some good tools but they all have limitations. For example:
    - Perturbation theory: Weak coupling.
    - Lattice: Difficult to apply to real-time phenomena.
    - Etc.
- A string reformulation might help.
- Topic of this talk with focus on far-from-equilibrium.
- Of theoretical *and* experimental interest:

Heavy Ion Collisions

Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration

Heavy Ion Collisions



- Far from equilibrium dynamics
- Hydrodynamics
- Hadronization

- How long is t_{hydro}? Data indicates $t_{\text{hydro}} T_{\text{hydro}} \leq 1$.
- What determines when hydro becomes applicable?
- What is the nature of the hydro expansion? Michal Heller's talk
- What are the initial conditions for hydro?
- Is there a qualitative mechanism/model?
- How do initial-state fluctuations evolve?
- And general questions about far-from-equilibrium QFT.

Gauge/Gravity Duality

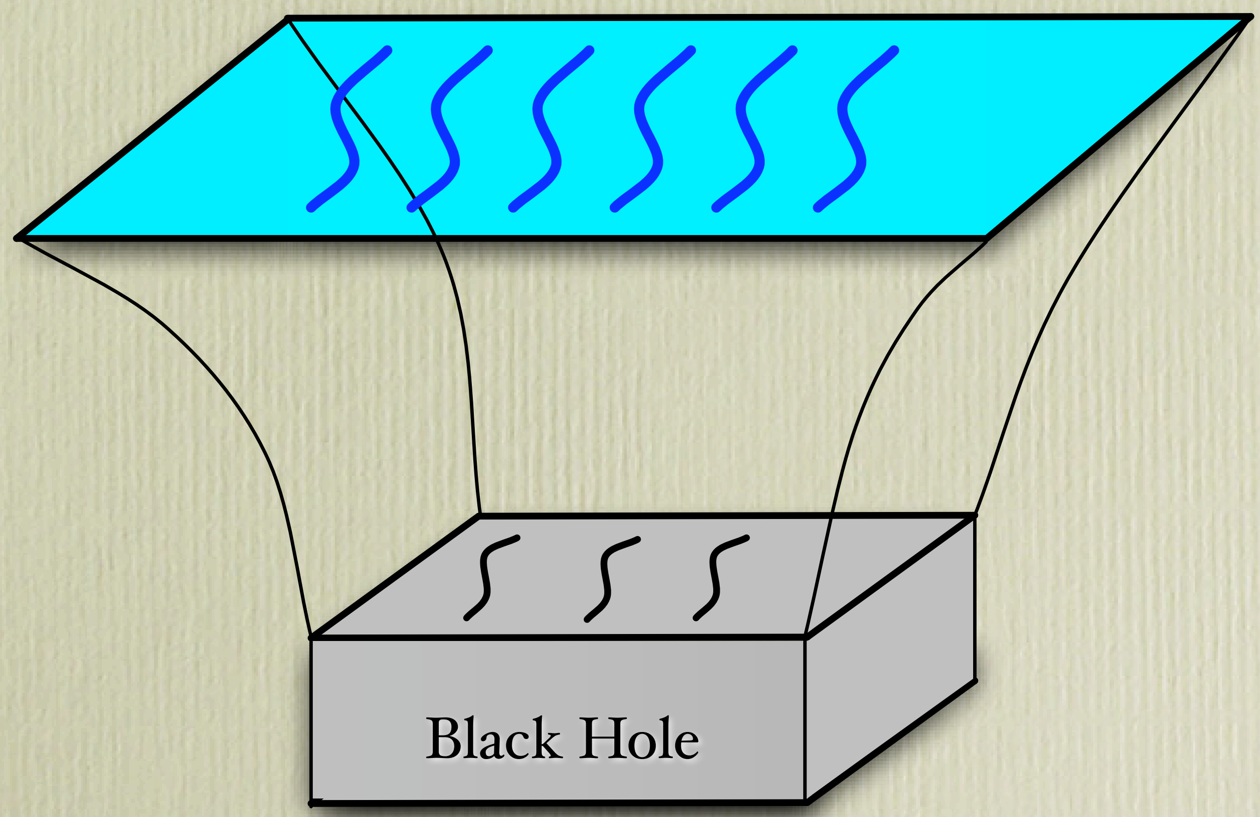
- At present gauge/gravity duality is not a tool for *precision* QCD physics:
  - Large N.
  - No asymptotic freedom.

- However, it may still provide useful:
  - Quantitative ballpark estimates.
  - Qualitative insights.

- In particular, if strong coupling + far from equilibrium, then holography is the *only* first-principle tool.

Last decade: Near equilibrium QGP

Near-equilibrium QGP = Near-equilibrium Black Hole



Far from equilibrium

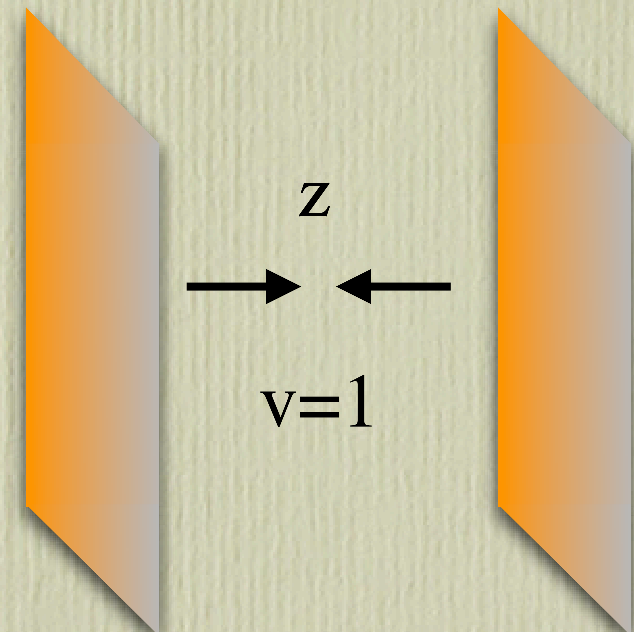
Far-from-equilibrium QFT

↕

Classical but fully Dynamical General Relativity in AdS

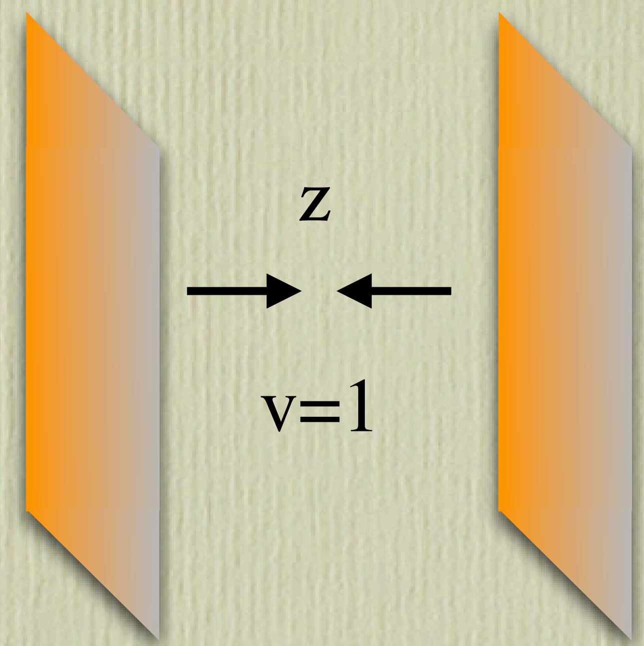
Holographic Heavy Ion Collisions

Chesler & Yaffe '10
Casalderrey, Heller, D.M. & van der Schee '13

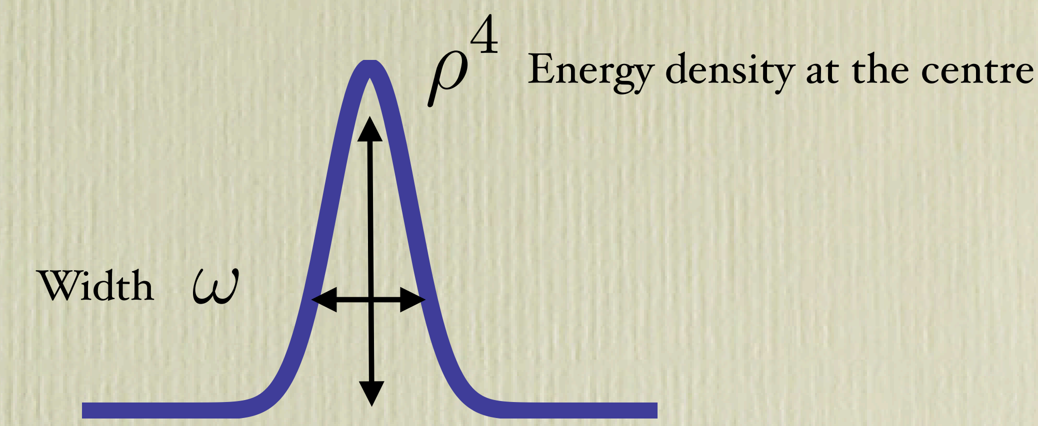


- Collide two infinite sheets of energy in N=4 SYM.
- Toy model for central collision of large nuclei.
- Collision of gravitational shock waves in AdS (2+1 problem).

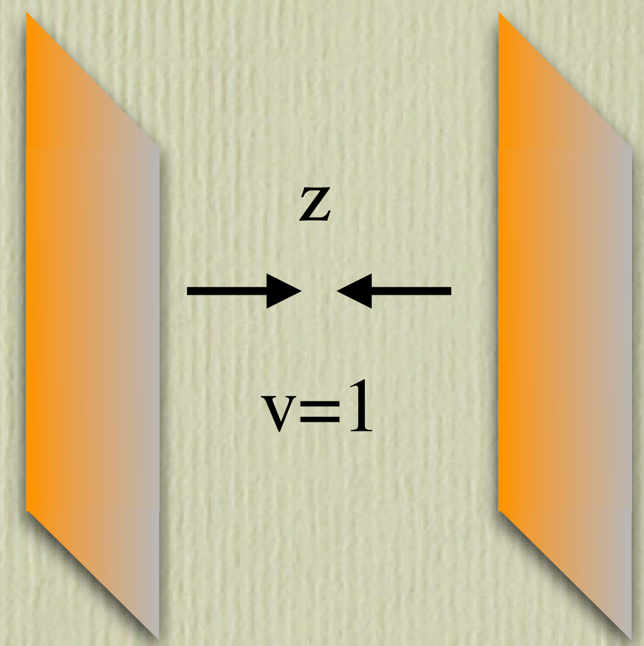
Holographic Heavy Ion Collisions



Gaussian Profile for $\mathcal{E}$



Holographic Heavy Ion Collisions



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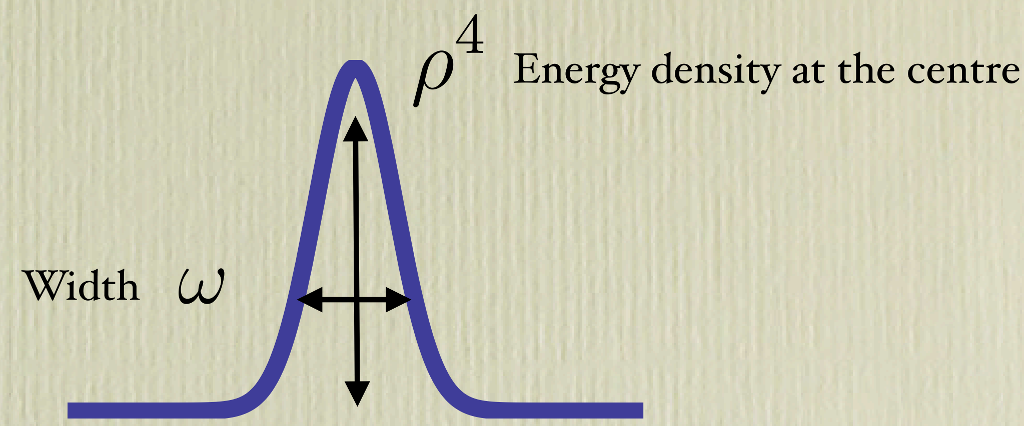
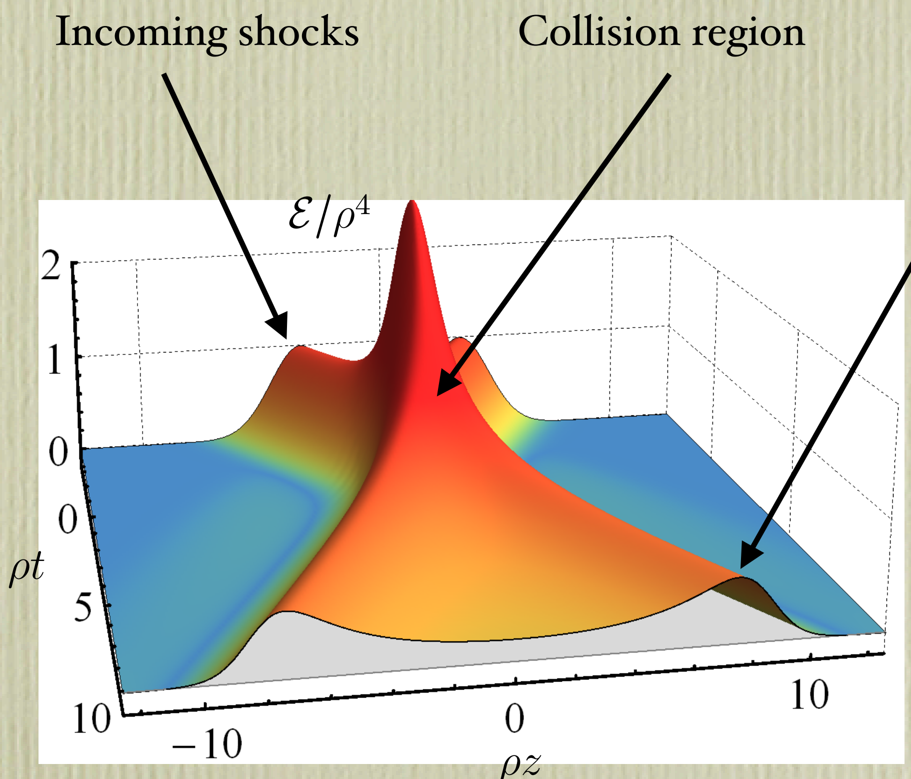


- Scale invariance: Results depend only on $\rho\omega$
- Chesler & Yaffe choose $\rho\omega_{\rm CY} \simeq 0.64$
- In a real HIC $\rho\omega \sim \gamma^{-1/2}$
- We therefore simulate values between $\frac{1}{8}\rho\omega_{\rm CY}$ and $2\rho w_{\rm CY}$

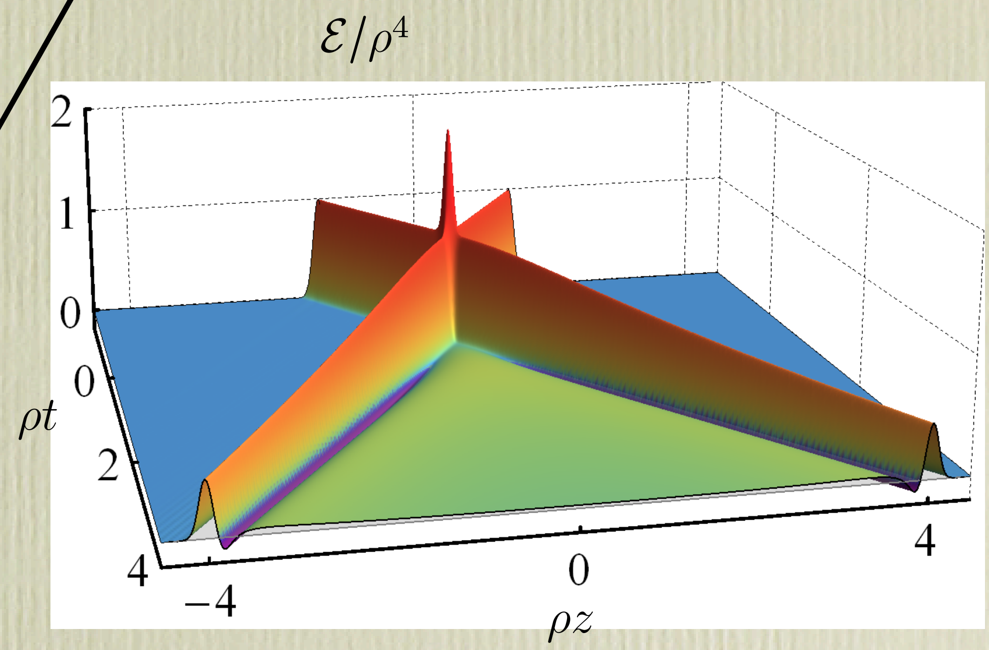
Thin (high E) → $\frac{1}{8}\rho\omega_{\rm CY}$; Thick (low E) → $2\rho w_{\rm CY}$

- Dynamical crossover between *full-stopping* and *transparency* scenarios

Holographic Heavy Ion Collisions



Thick shocks collision

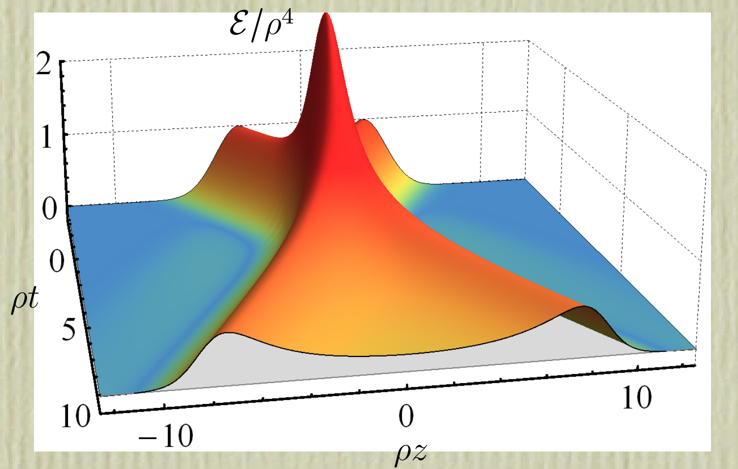


Thin shocks collision

Thick shocks approx. realize Landau model

Landau '53

Energy gets compressed, stops and explodes hydrodynamically.



- At $\rho t_{\max} \simeq 0.58$, 90% of the energy density is moving with v < 0.1.

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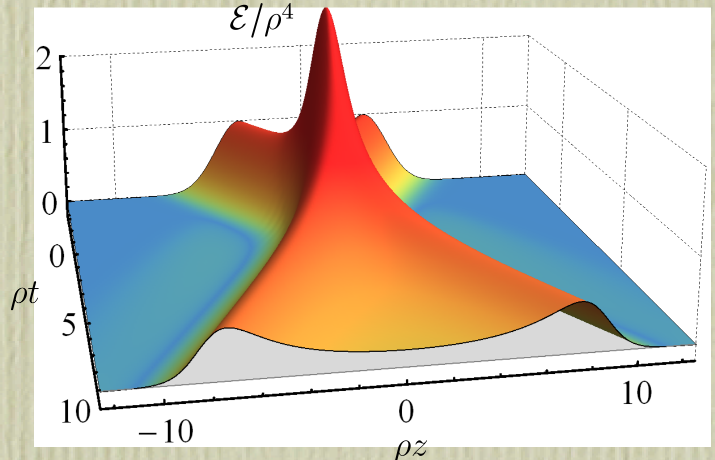

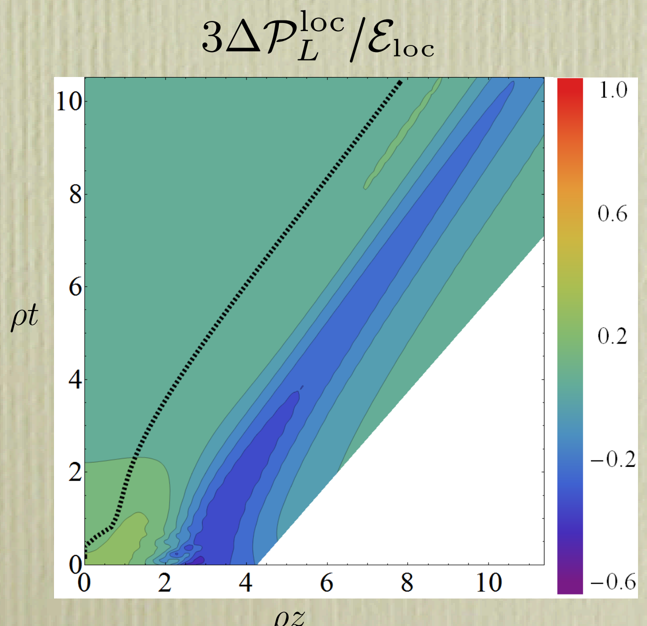

- At $\rho t_{\rm max} \simeq 0.58$, 90% of the energy density is moving with v < 0.1.
- Deviation from hydrodynamics less than 20% everywhere.
- At z=0: $t_{\rm hydro} T_{\rm hydro} \simeq 0$
- Anisotropy: $\mathcal{P}_T/\mathcal{P}_L \simeq 0.5$
- No clear separation between plasma and receding fragments.

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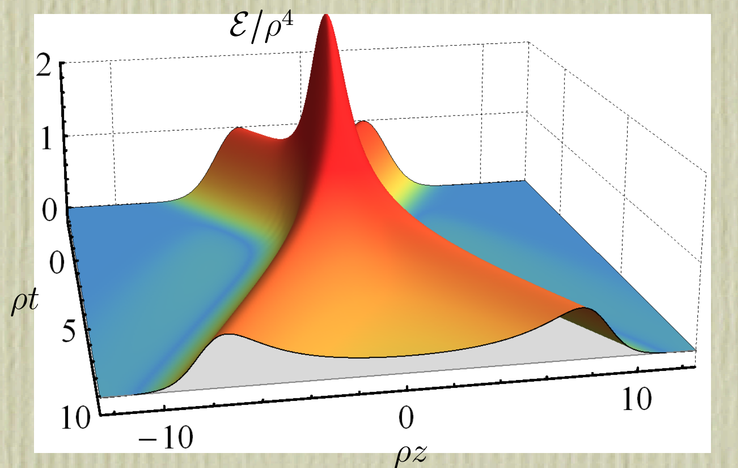

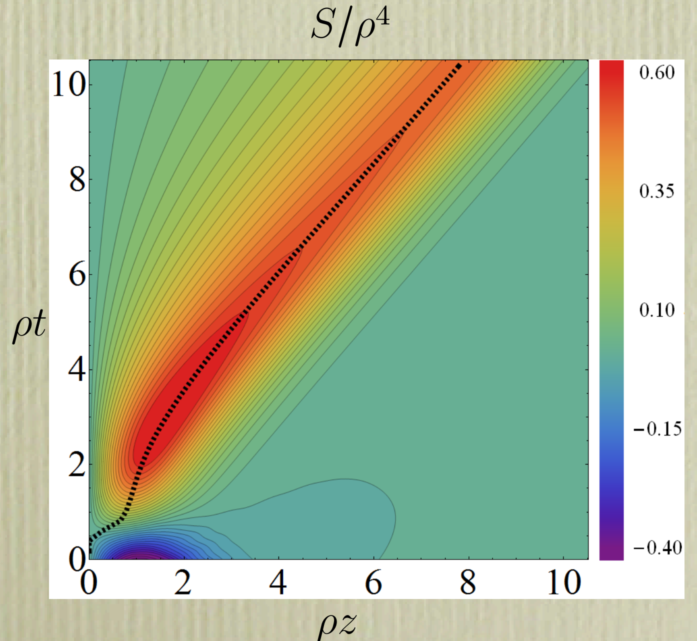

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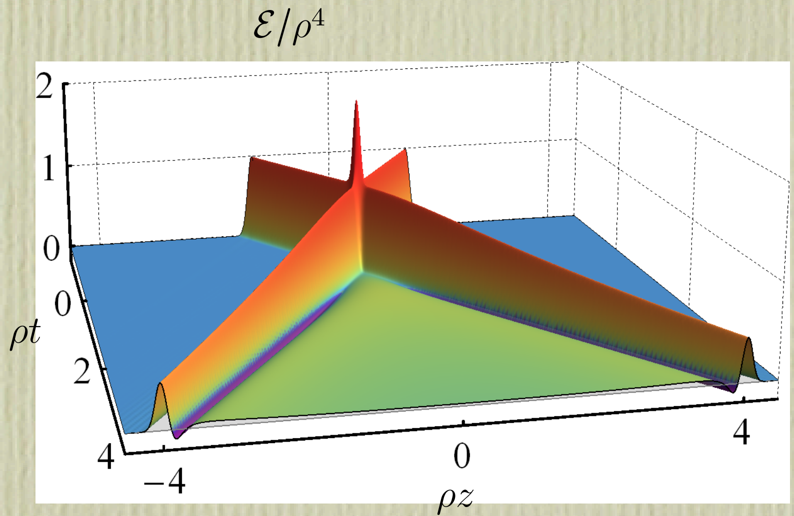
- Anisotropy: $\mathcal{P}_T/\mathcal{P}_L \simeq 0.5$
- No clear separation between plasma and receding fragments.
- The receding maxima move at v ~ 0.88.

Thin shocks realize transparency

Shocks pass through one another and plasma gets created in between.



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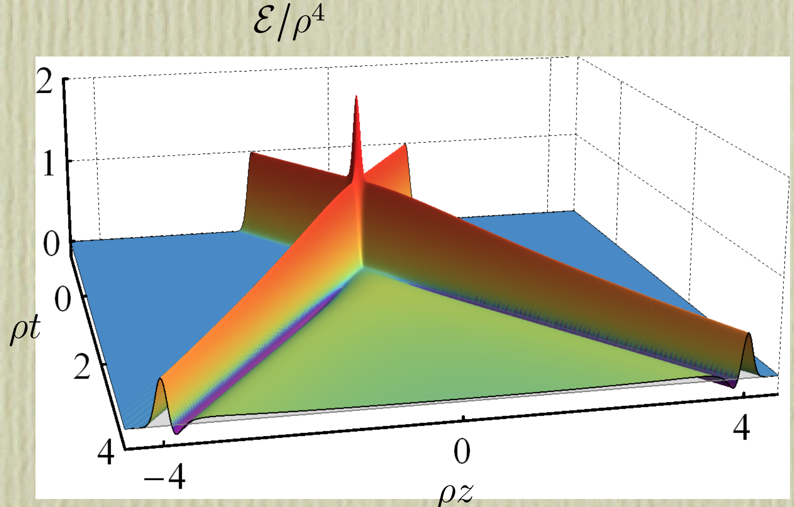

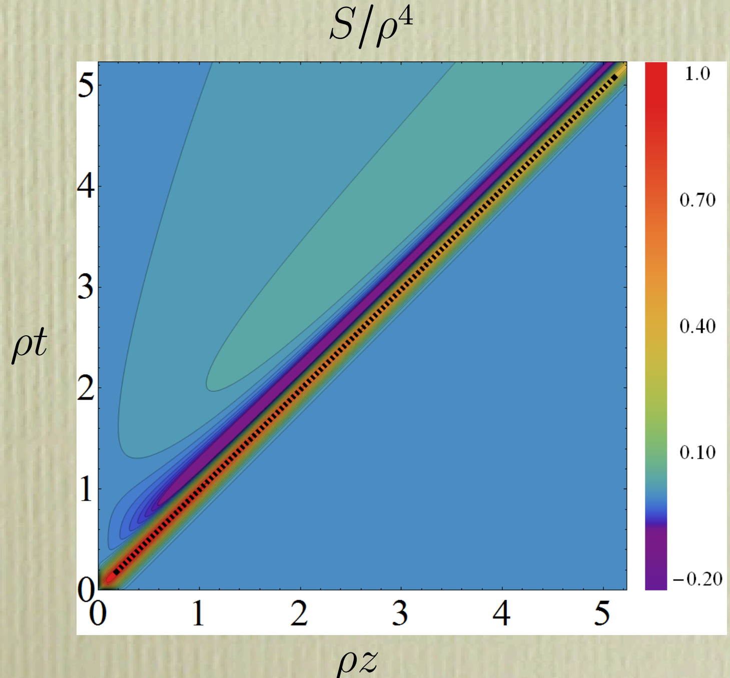

- Shape of shocks gets altered but they keep moving at v=1.
- Most dramatic change is region of negative energy near the receding fragments.

Thin shocks realize transparency

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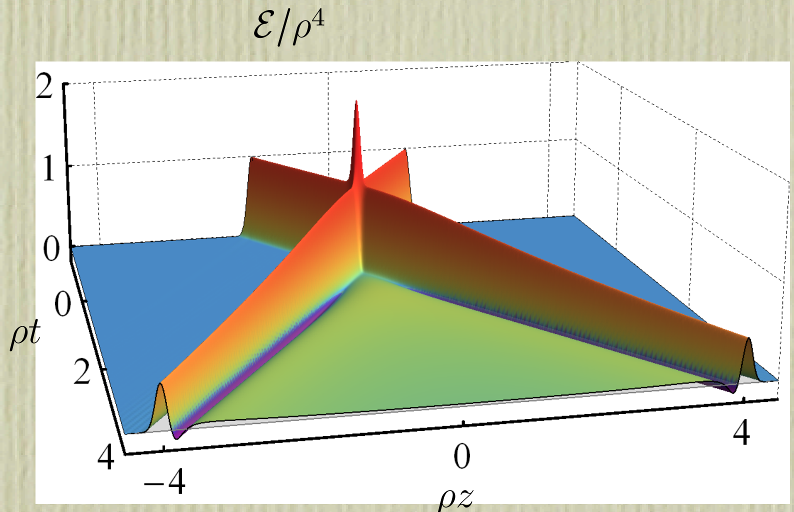
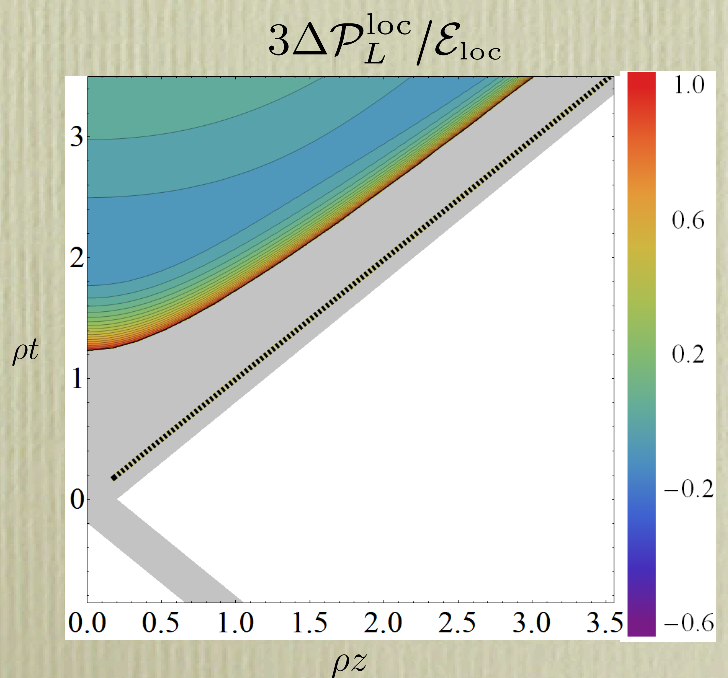


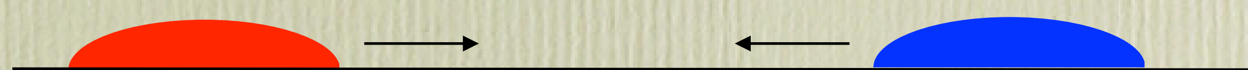


- Shape of shocks gets altered but they keep moving at v=1.
- Most dramatic change is region of negative energy near the receding fragments.
- Hydrodynamics only applicable away from receding fragments and at late times.
- $t_{\rm hydro} T_{\rm hydro} \simeq 0.26$
- Anisotropy: $\mathcal{P}_T/\mathcal{P}_L \simeq 15$
- Clear separation between receding fragments and plasma in between.

Dynamical crossover, qualitatively

Thin
shocks

Thick
shocks



Dynamical crossover, qualitatively

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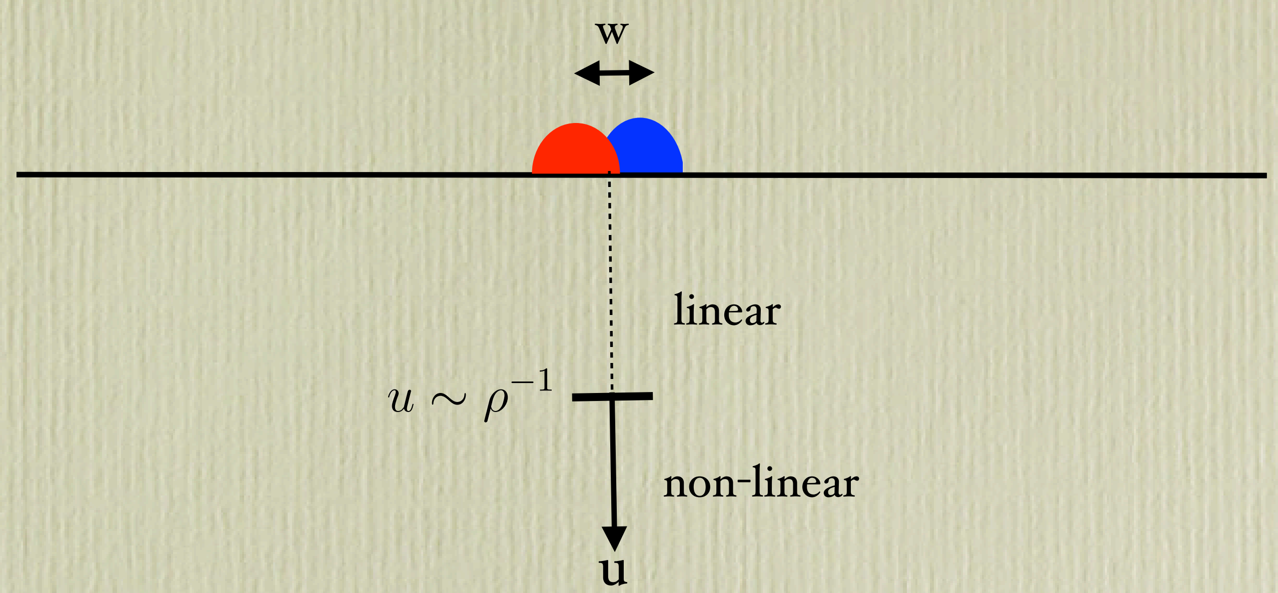
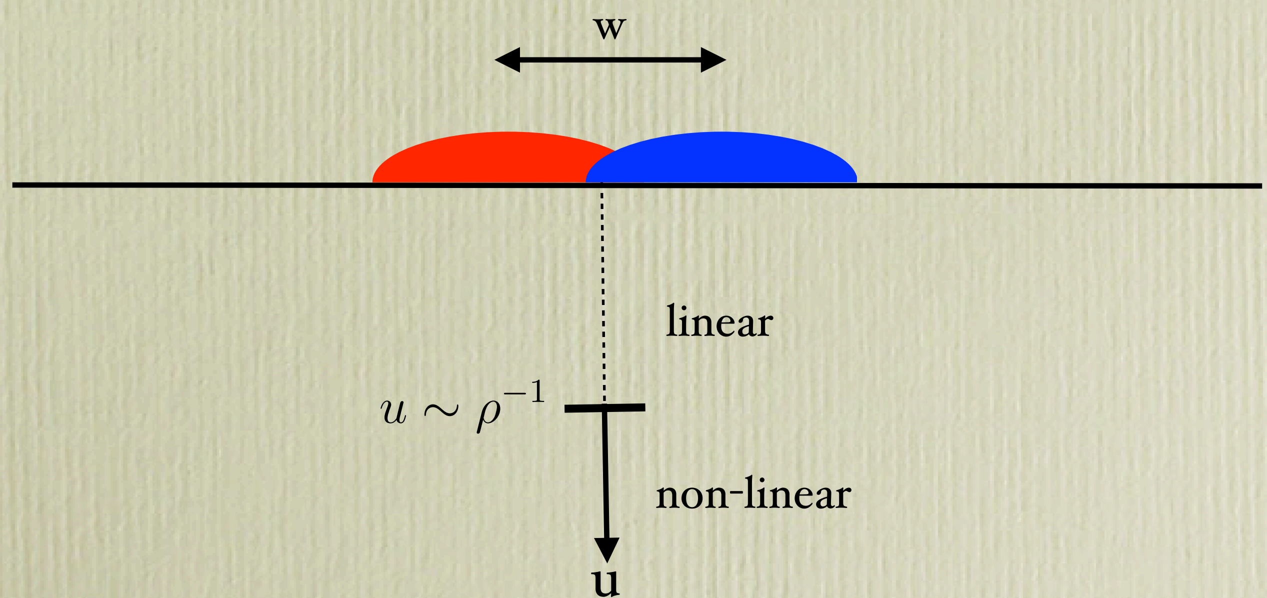


Thick shocks



Dynamical crossover, qualitatively

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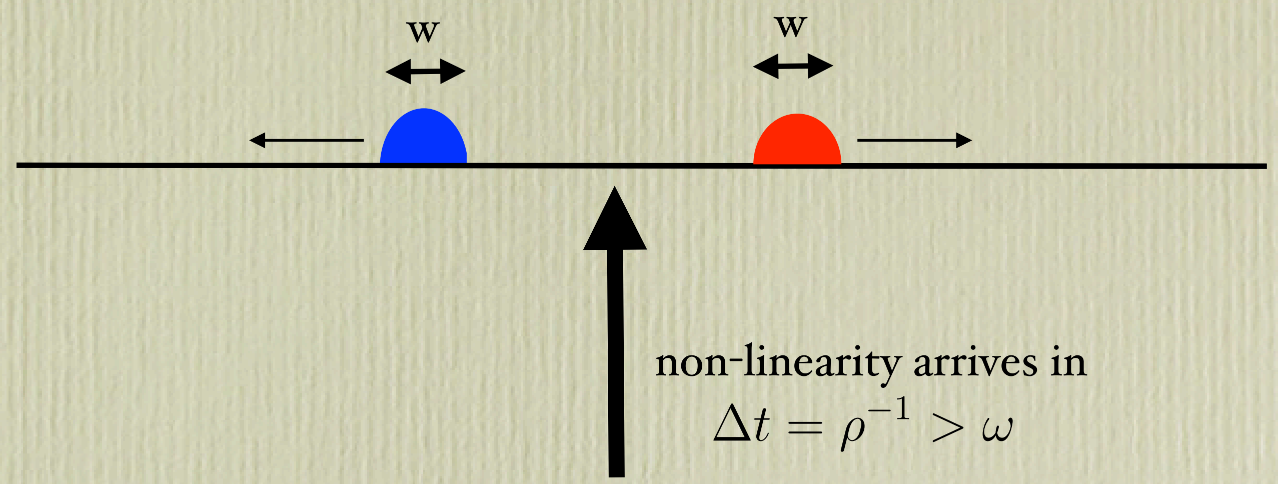

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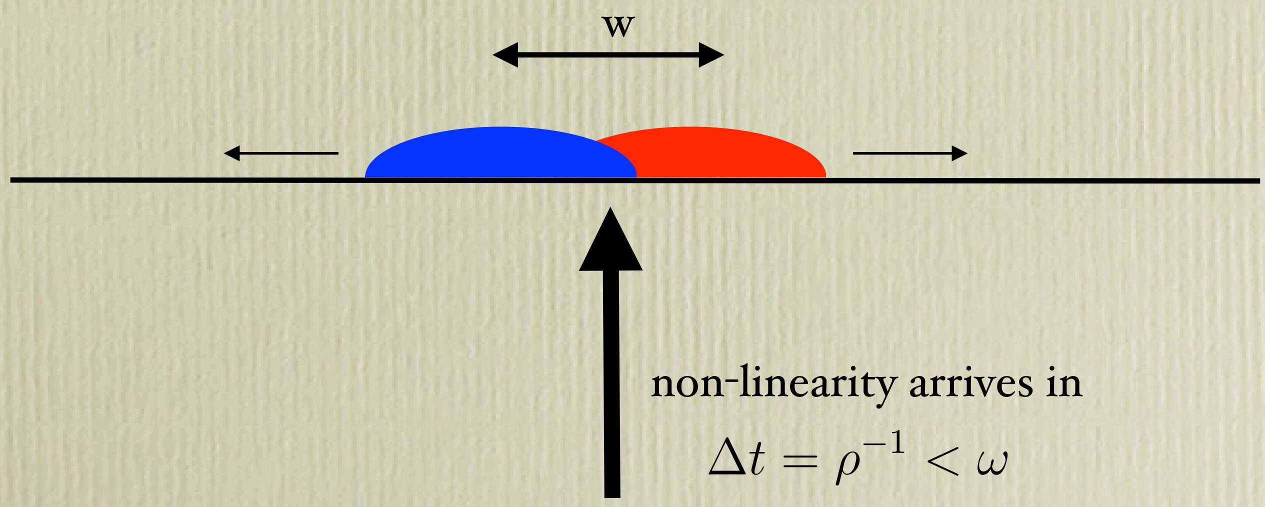

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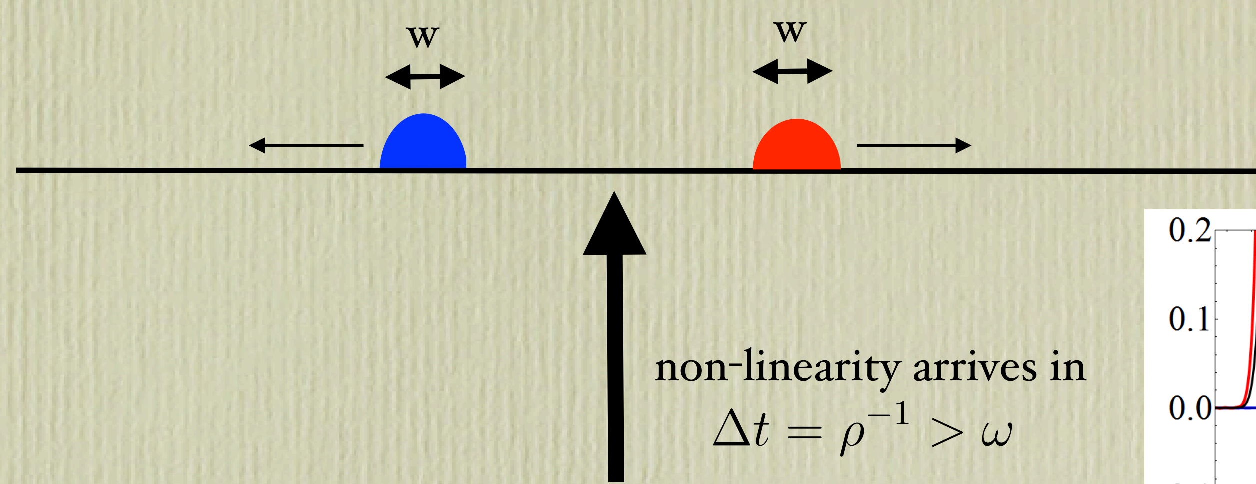

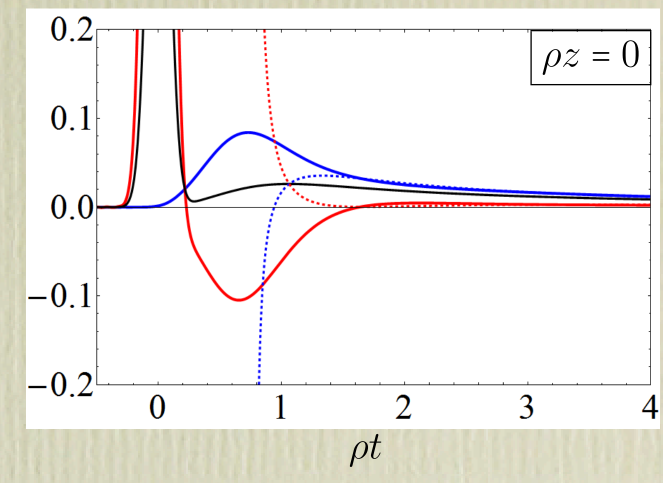

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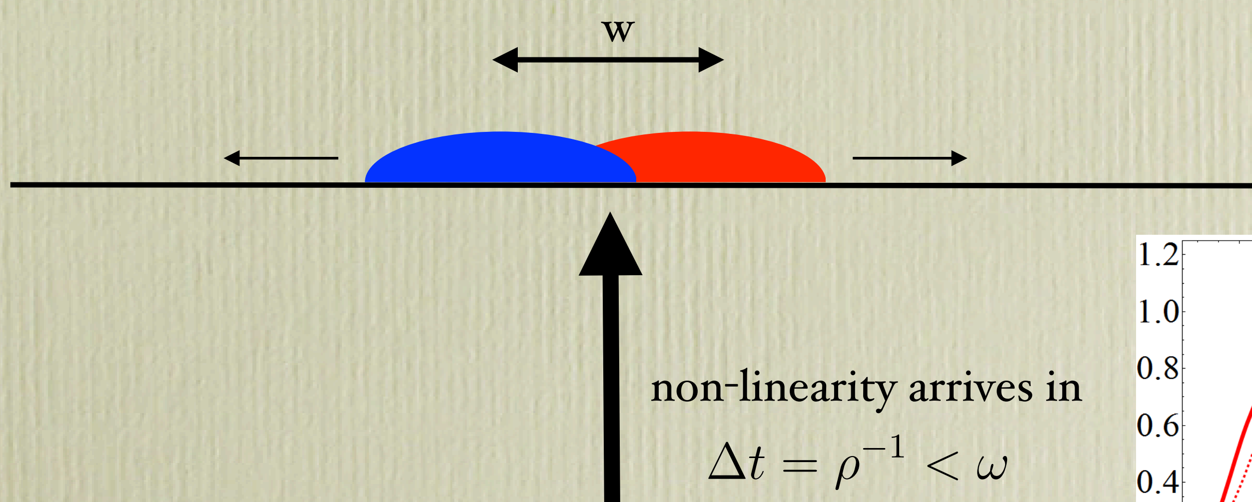
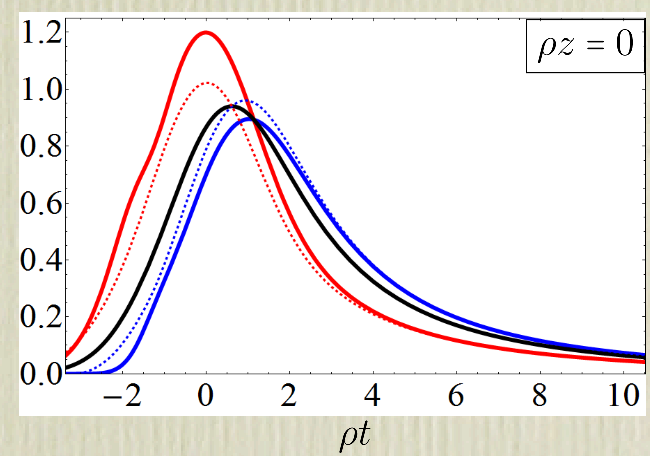


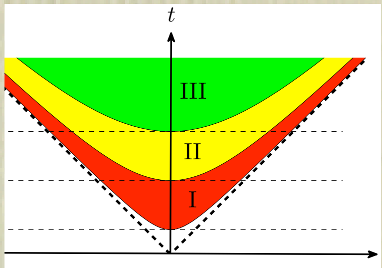


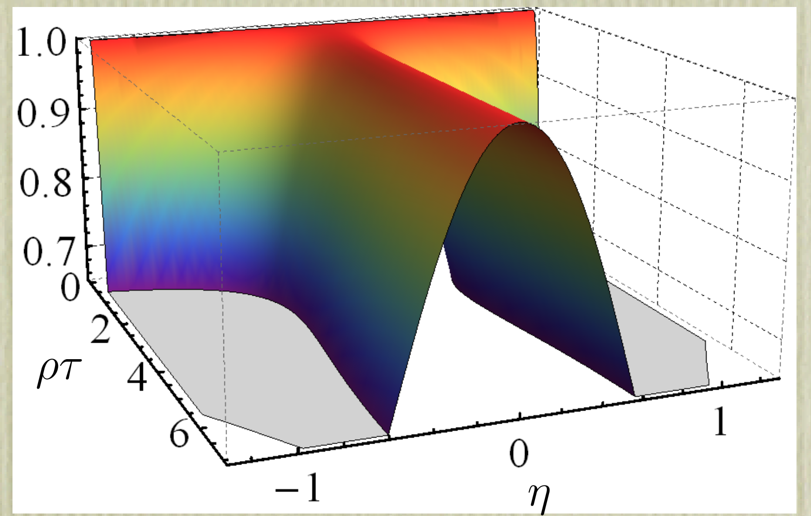
Two preconceptions dispelled

1. Strong coupling in the gauge theory may not lead to any significant stopping.
   - In particular, it is compatible with receding fragments moving at $v=1$.

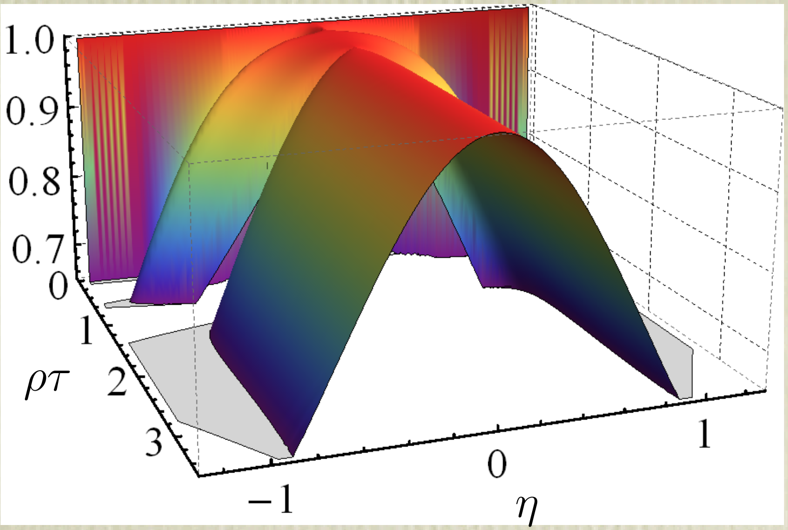
Two preconceptions dispelled

2. But this does not necessarily lead to Bjorken boost-invariance at mid-rapidity.
   - Rapidity distribution is not flat but Gaussian.



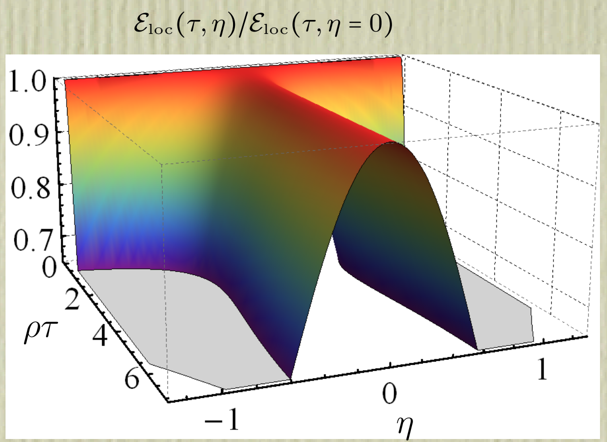


Thick shocks collision



Thin shocks collision

Gaussianity and experimental data



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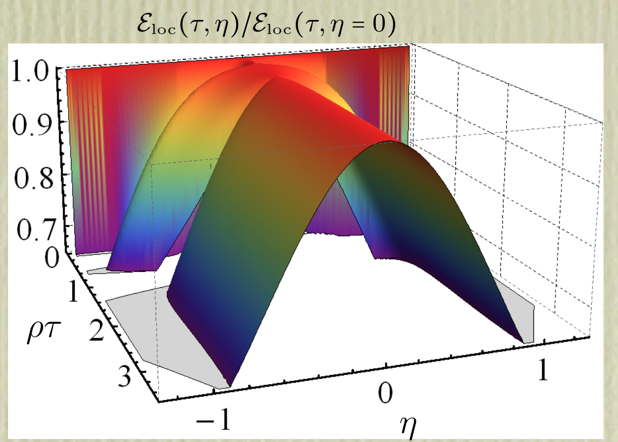
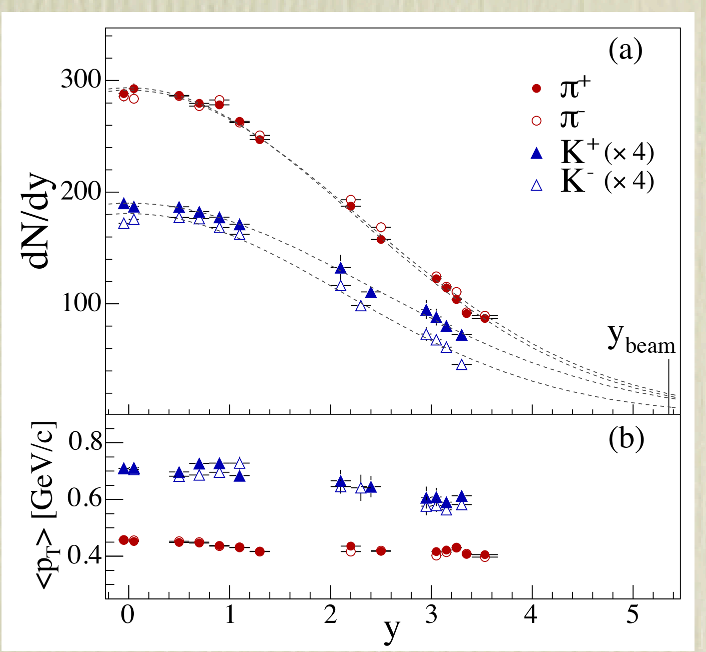


Thin shocks collision

- To really compare with data we should run the simulation to later times (+many other things), but Gaussianity is encouraging:

- It is also nice that the width increases with energy, as expected.



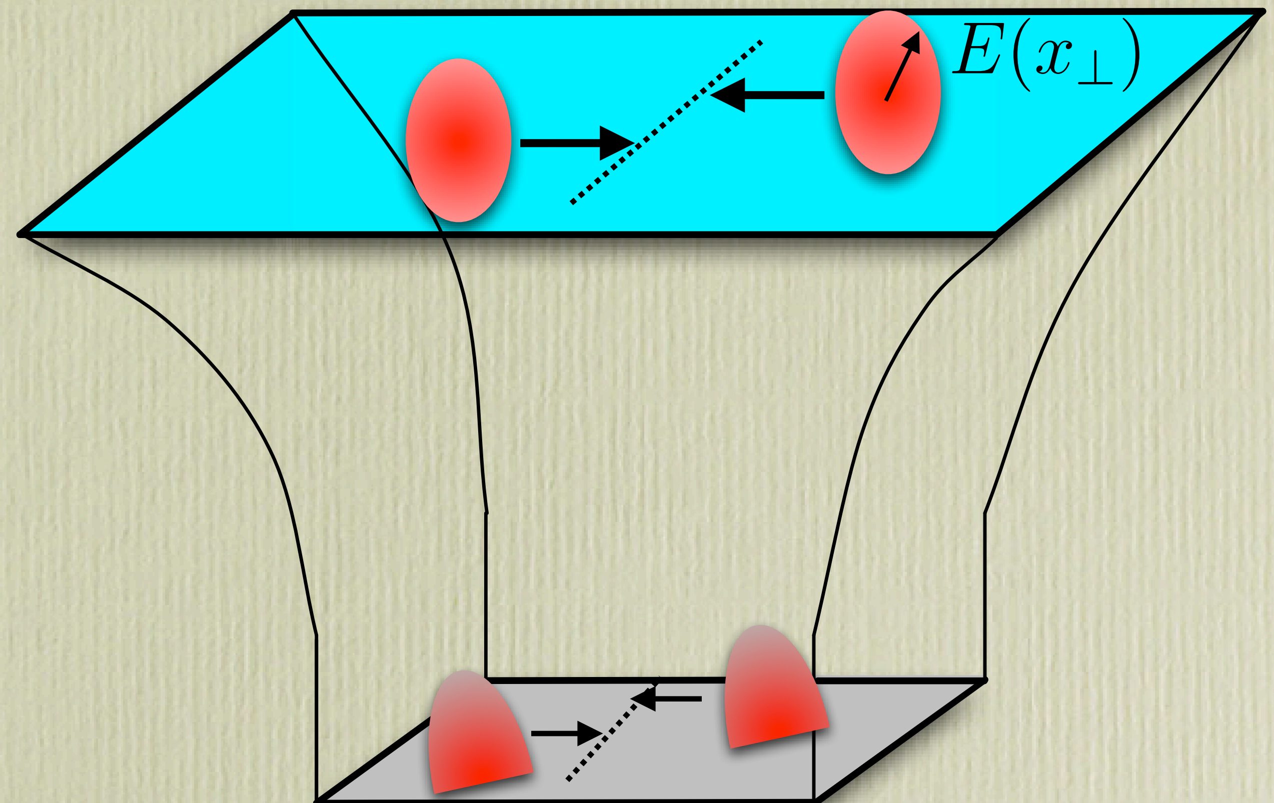
BRAHMS Collaboration for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Two universal lessons

1. Hydrodynamization time can be significantly shorter than $1/T_{\rm hydro}$.
   - Such short times are hard to achieve at weak coupling.
   - Suggestive, but remember caveats.

2. Hydrodynamics can work despite large anisotropies.
   - In other words, at strong coupling $t_{\rm hydro} < t_{\rm iso}$.
   - In contrast, at weak coupling $t_{\rm iso} < t_{\rm hydro}$. Arnold, Moore & Yaffe '04
   - Mysterious from effective field theory viewpoint.
   - Applicability of hydro governed by relaxation of non-hydro QNMs. Chesler & Yaffe '09
   - Hydro expansion seems to be asymptotic. Heller, Janik & Witaszczyk '13

Outlook: General collisions in confining theories



Finite impact parameter: d=4+1 in AdS

- Transverse plane dynamics.
- Event-by-event fluctuations.

Thank you.