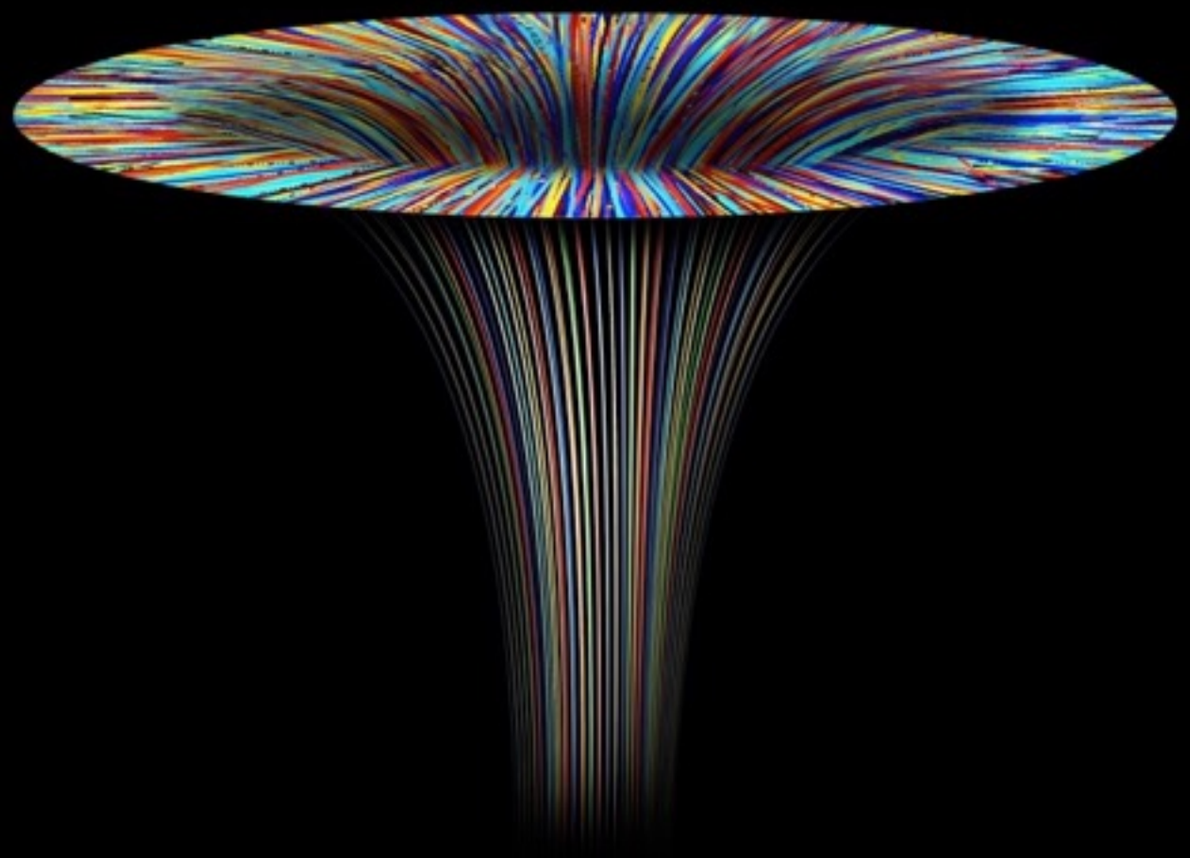
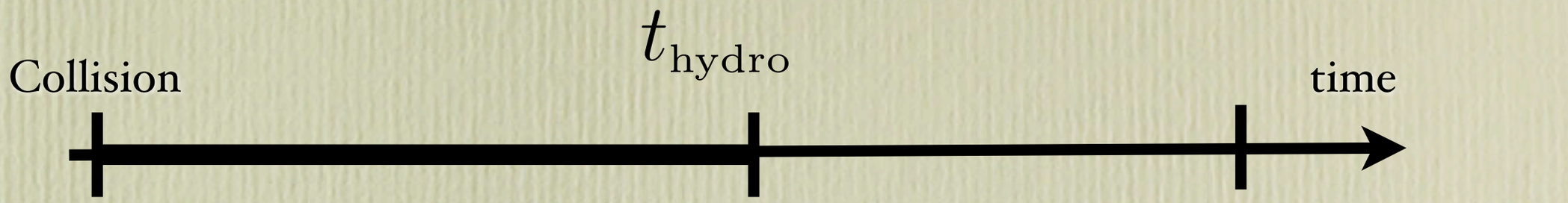
Strongly Coupled Approaches to Equilibration in Heavy Ion Collisions



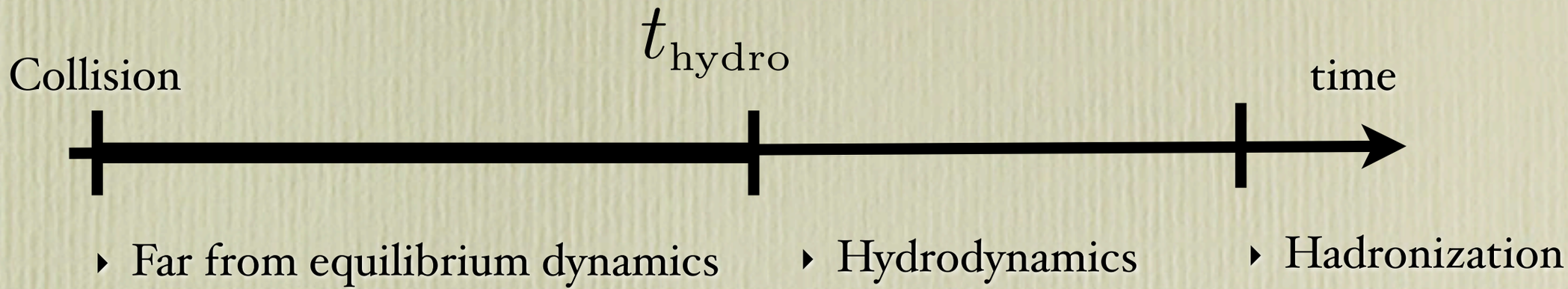
David Mateos
ICREA & University of Barcelona

Heavy ion collisions



- Far from equilibrium dynamics
- Hydrodynamics
- Hadronization

Heavy ion collisions



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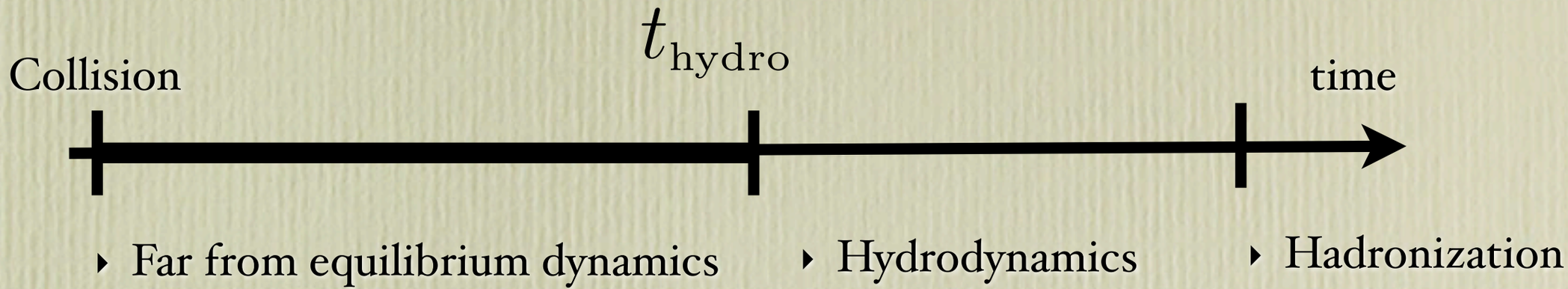
Heavy ion collisions



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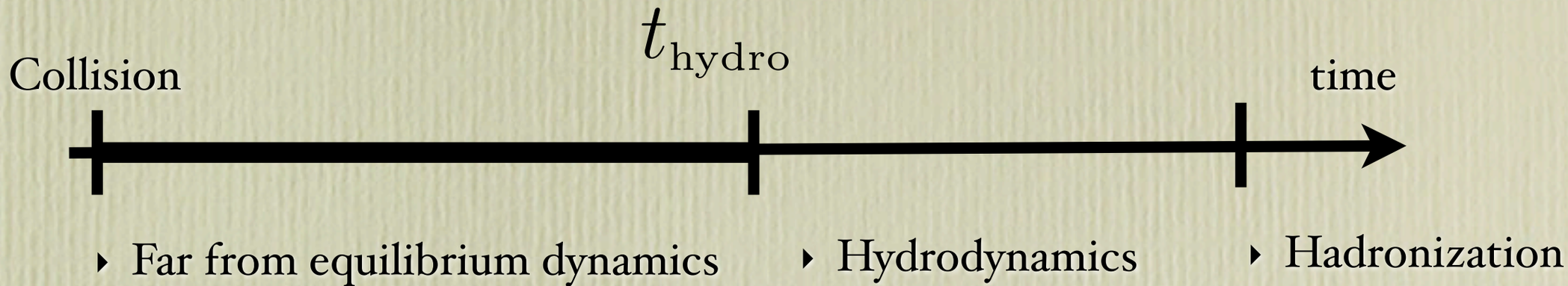

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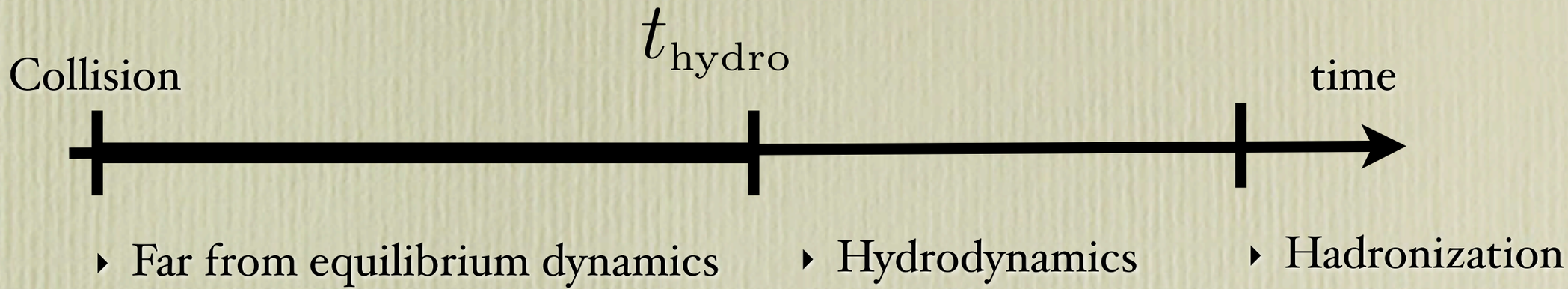

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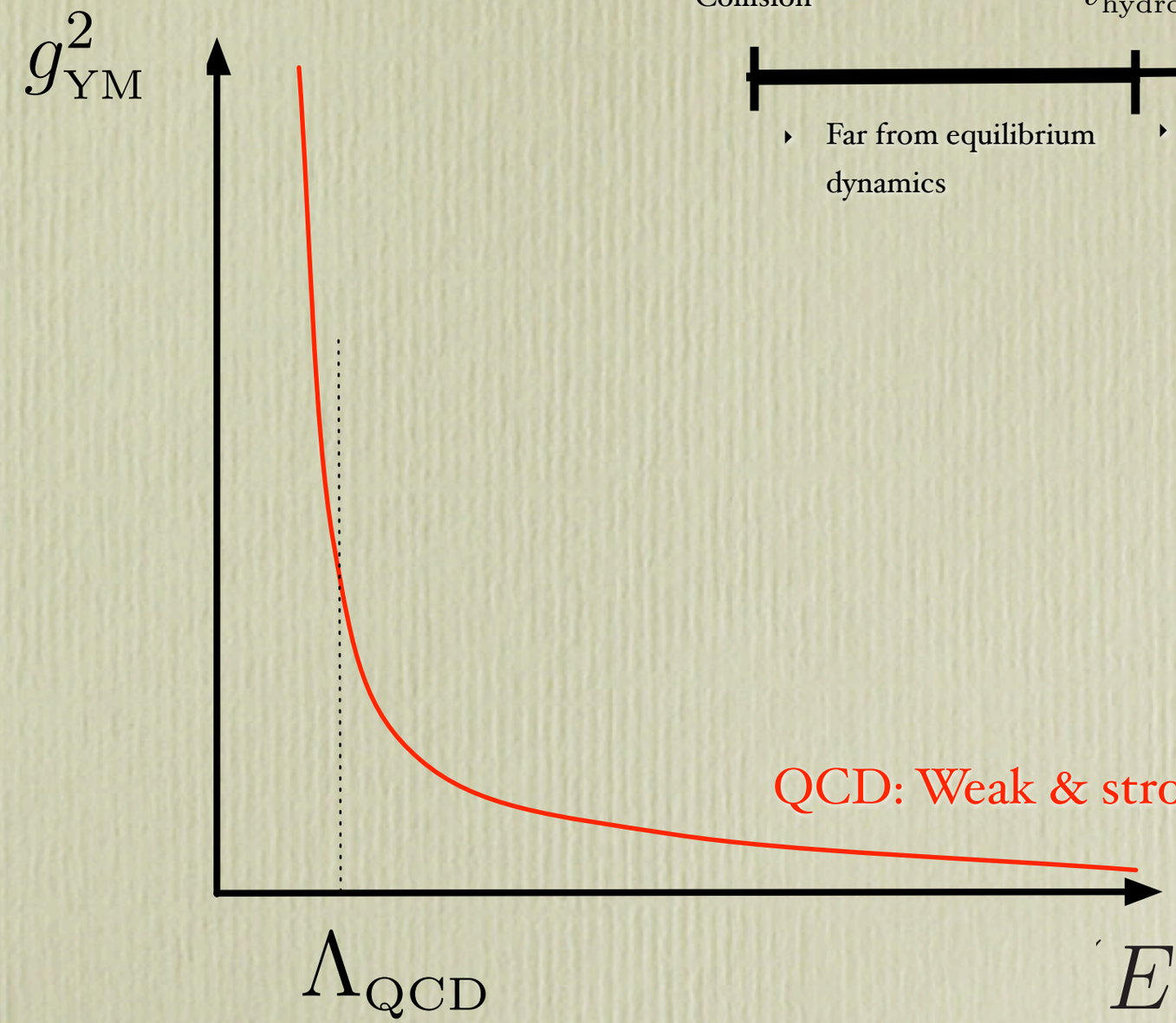
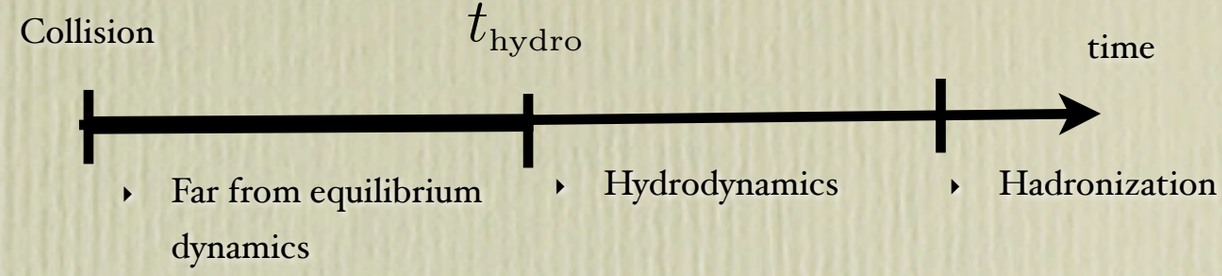
- What are the initial conditions for hydro?

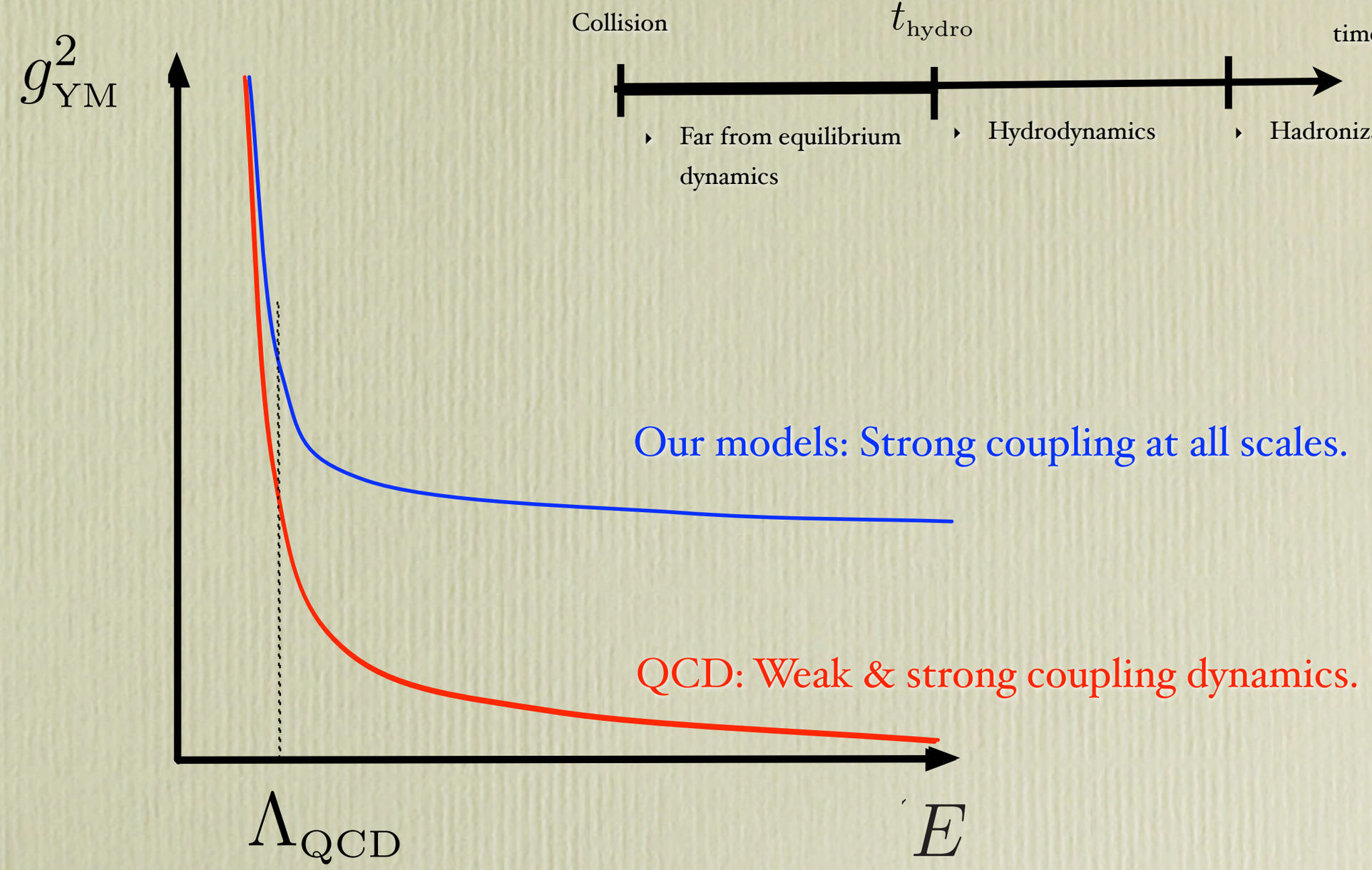
Strong & weak coupling





QCD: Weak & strong coupling dynamics.

Strong & weak coupling



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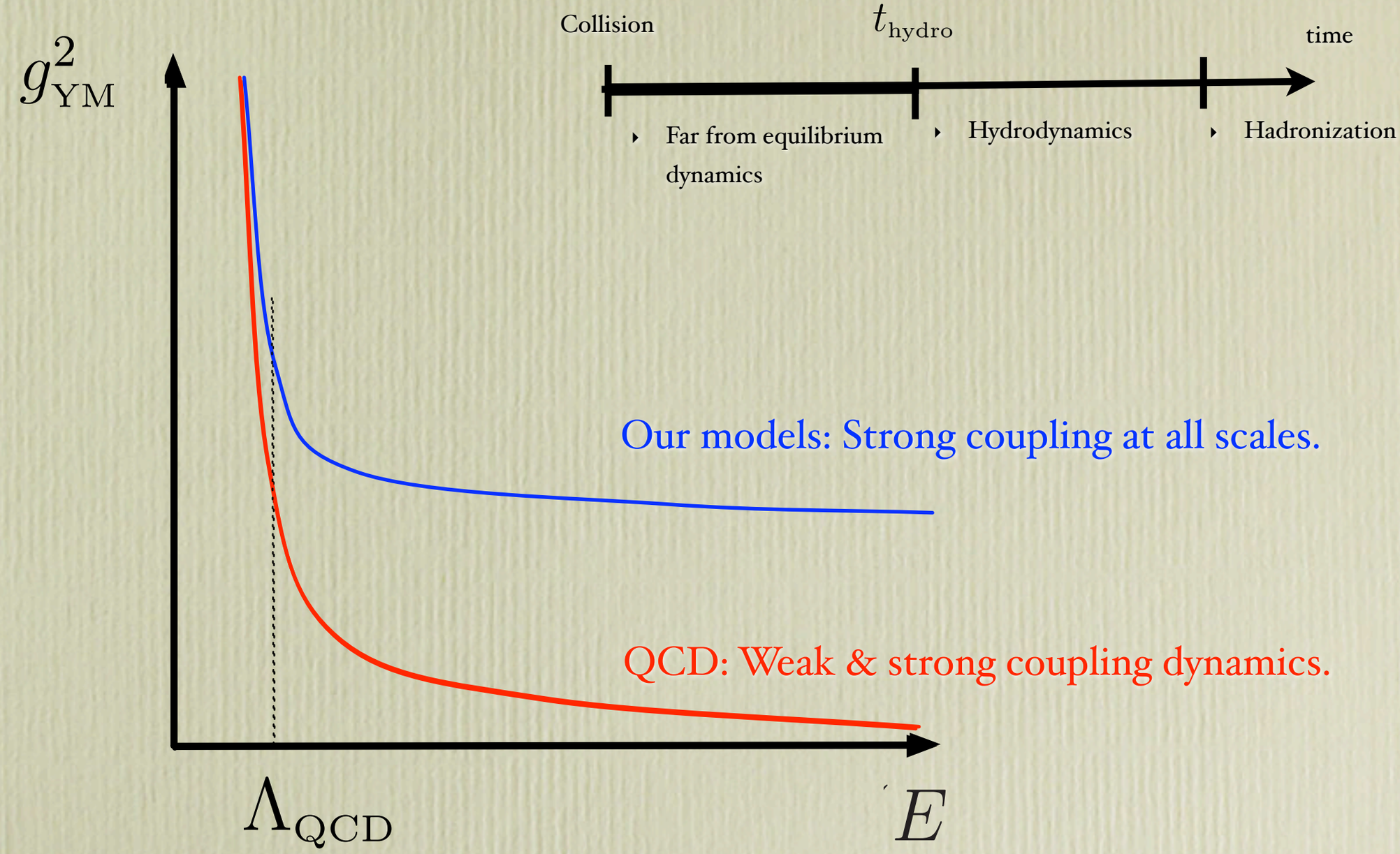

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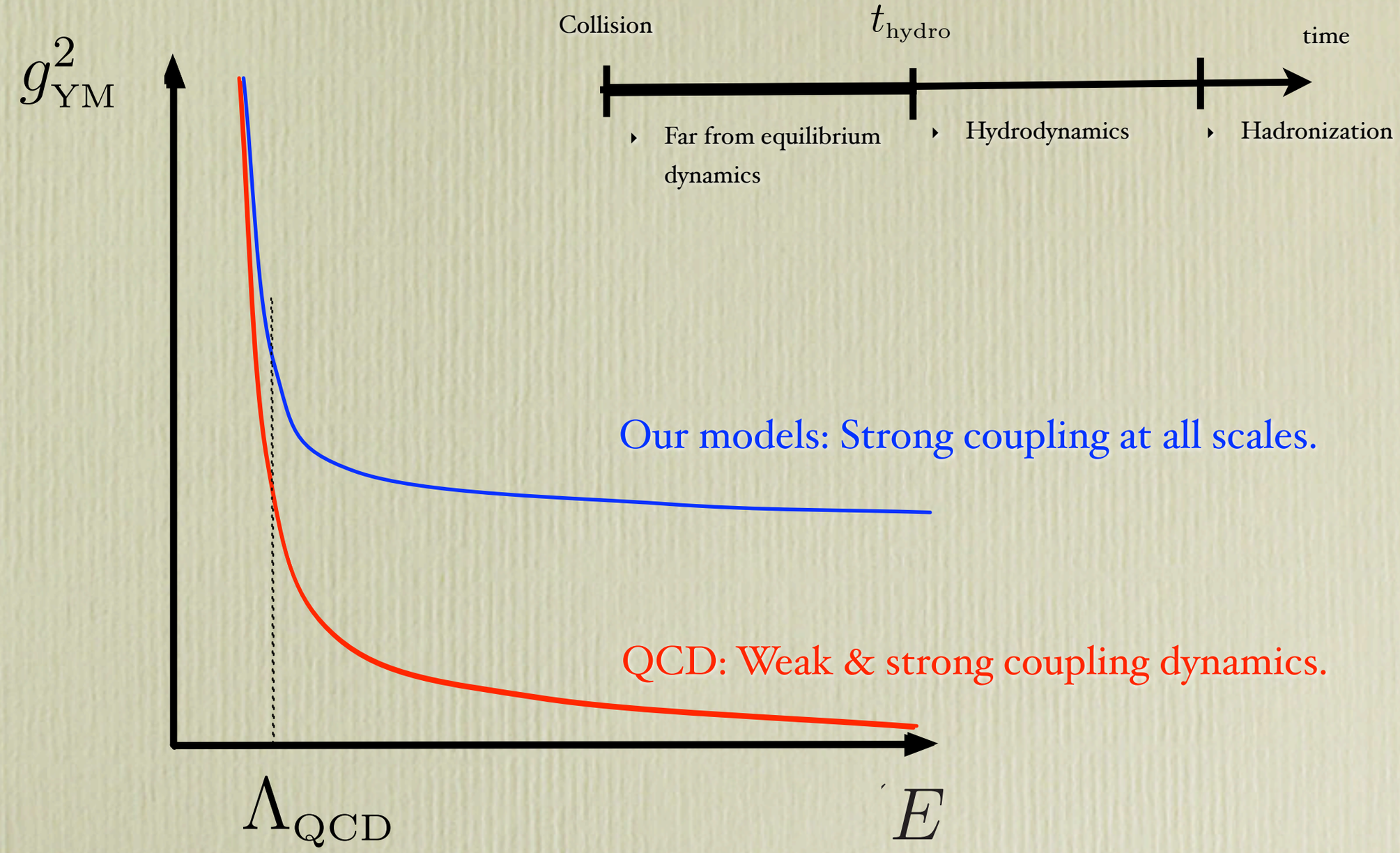
Strong & weak coupling



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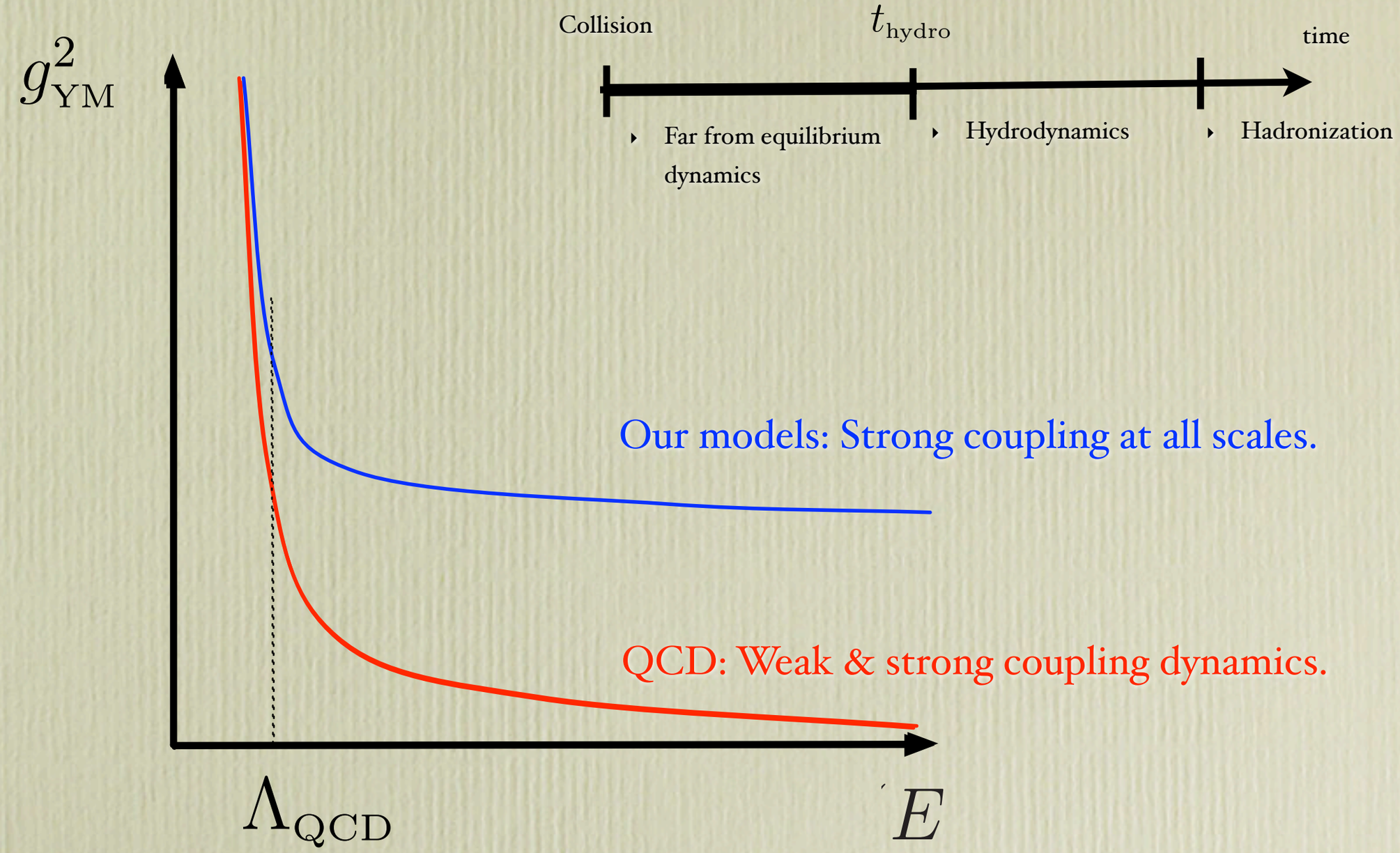
Strong & weak coupling



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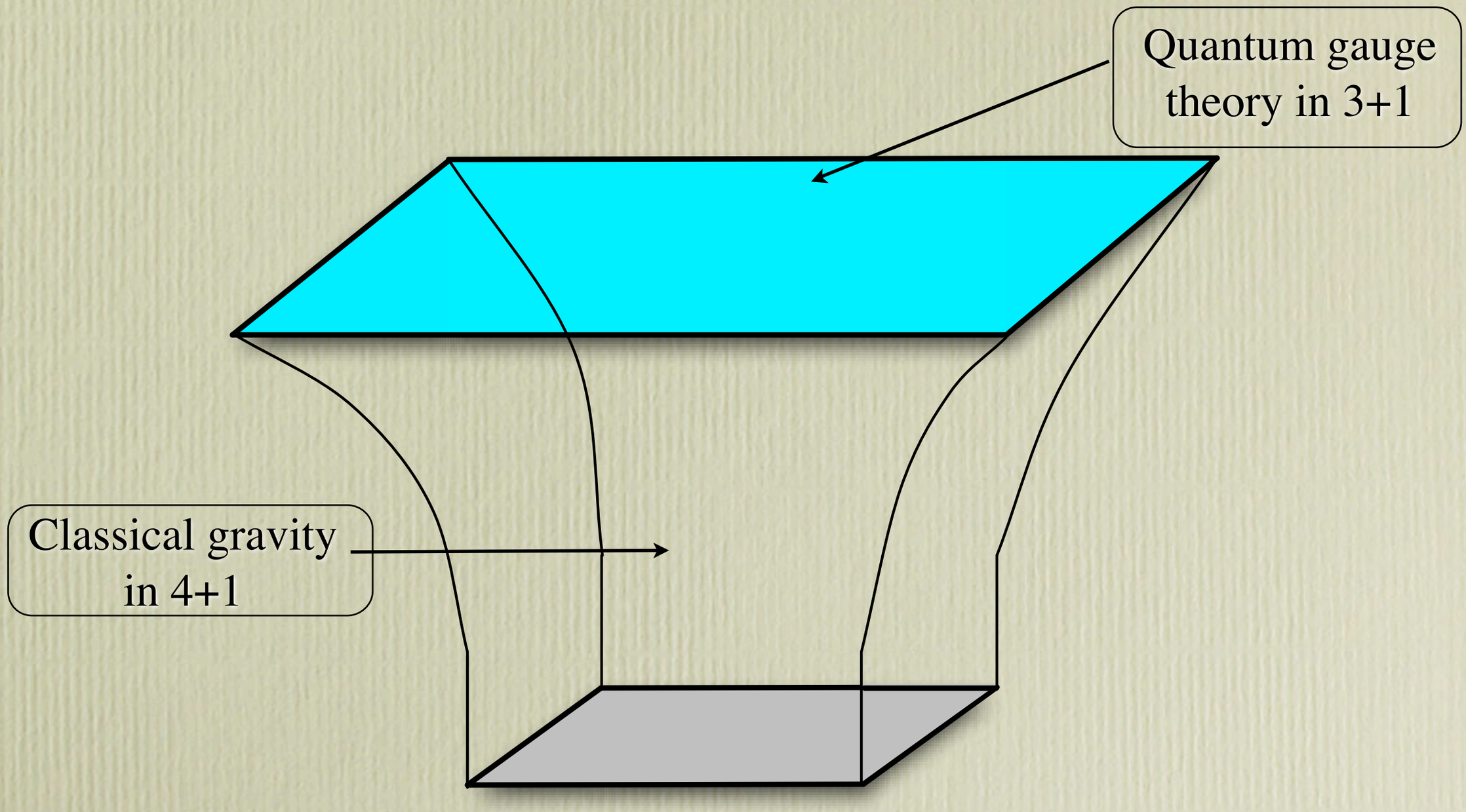
- **Disclaimer**: Complementary tool and not a precision one.

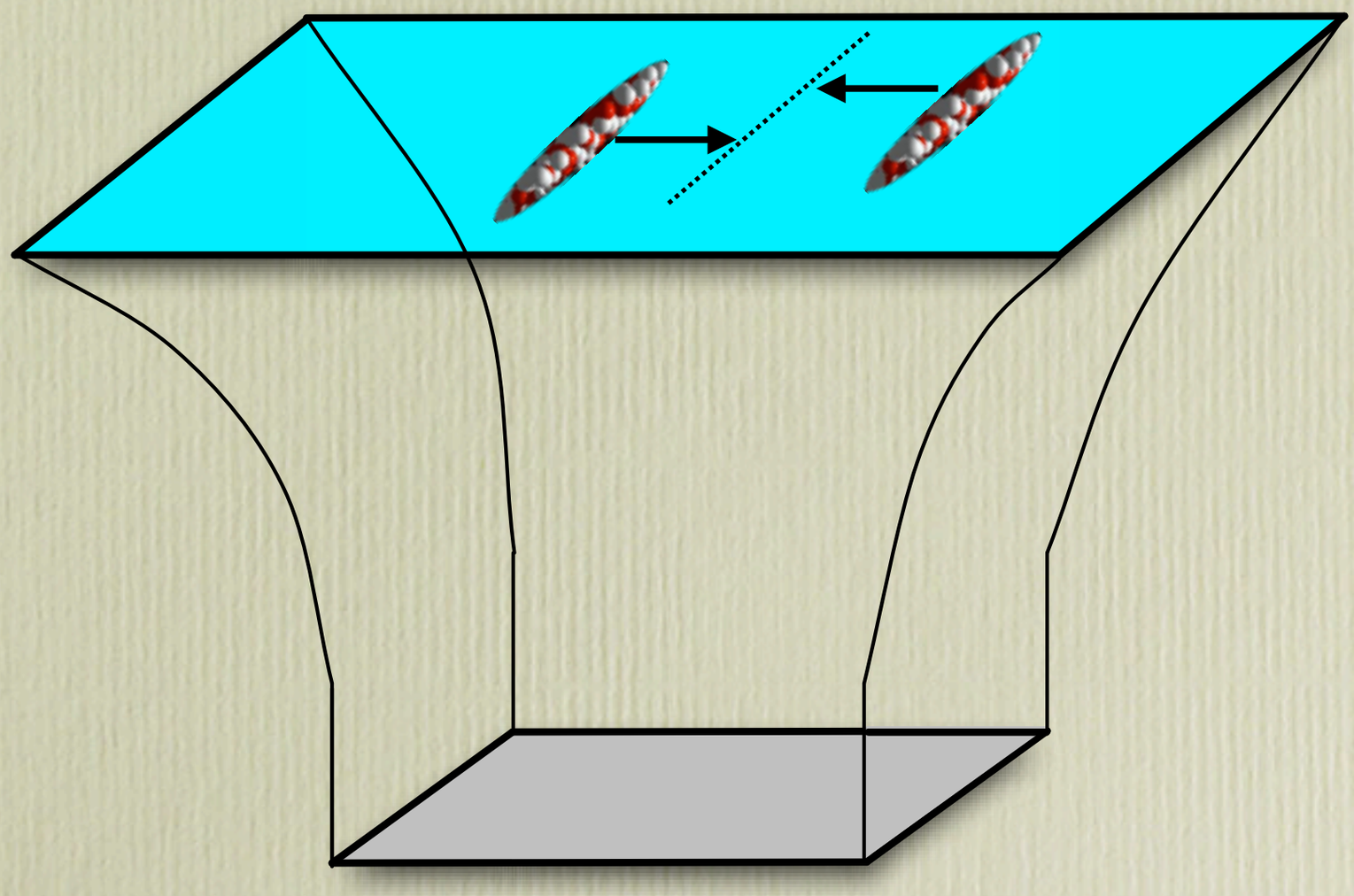
Holography

Maldacena '97



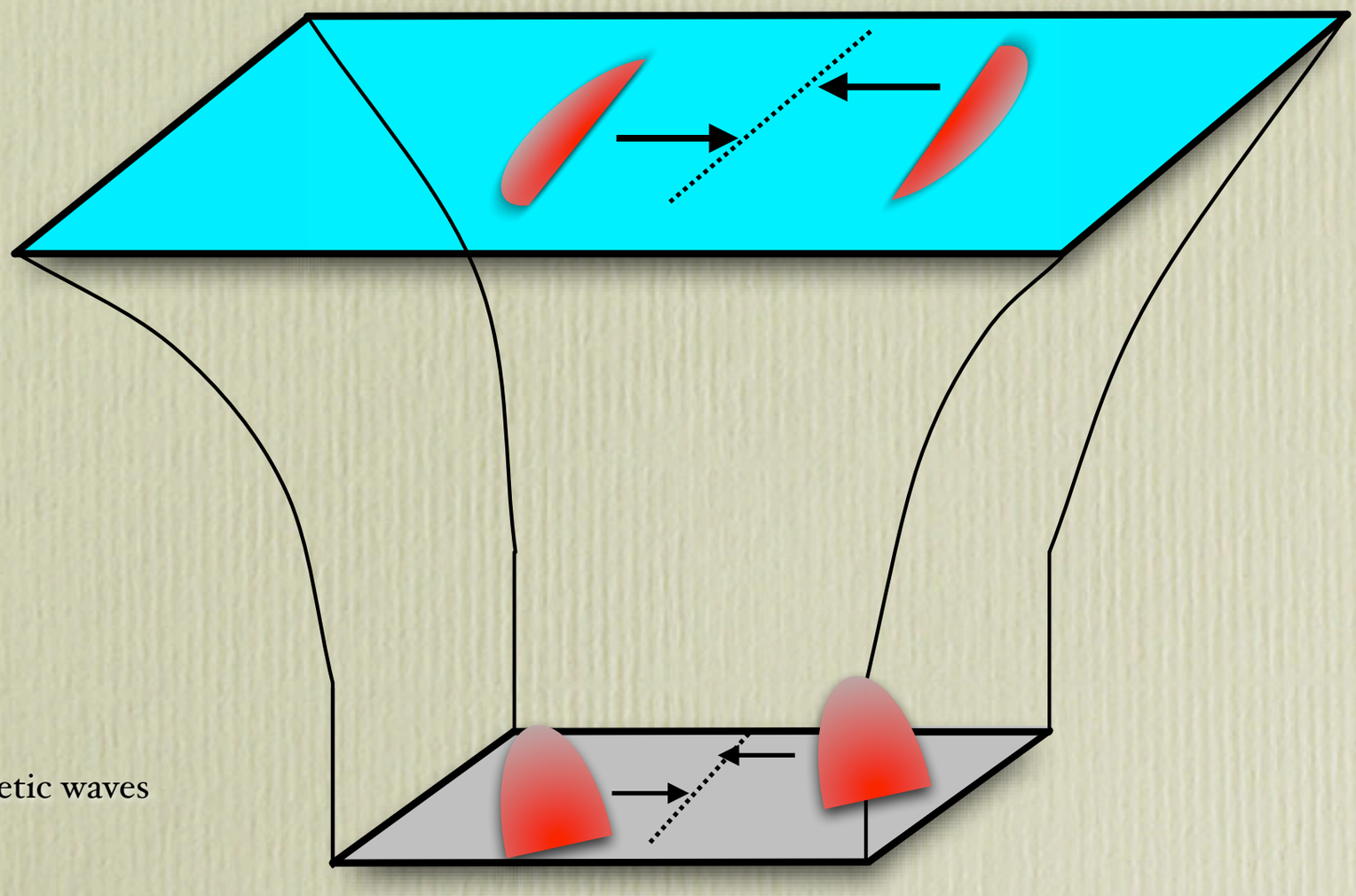
What we would like to do

Heavy ion collisions in QCD



What we can do

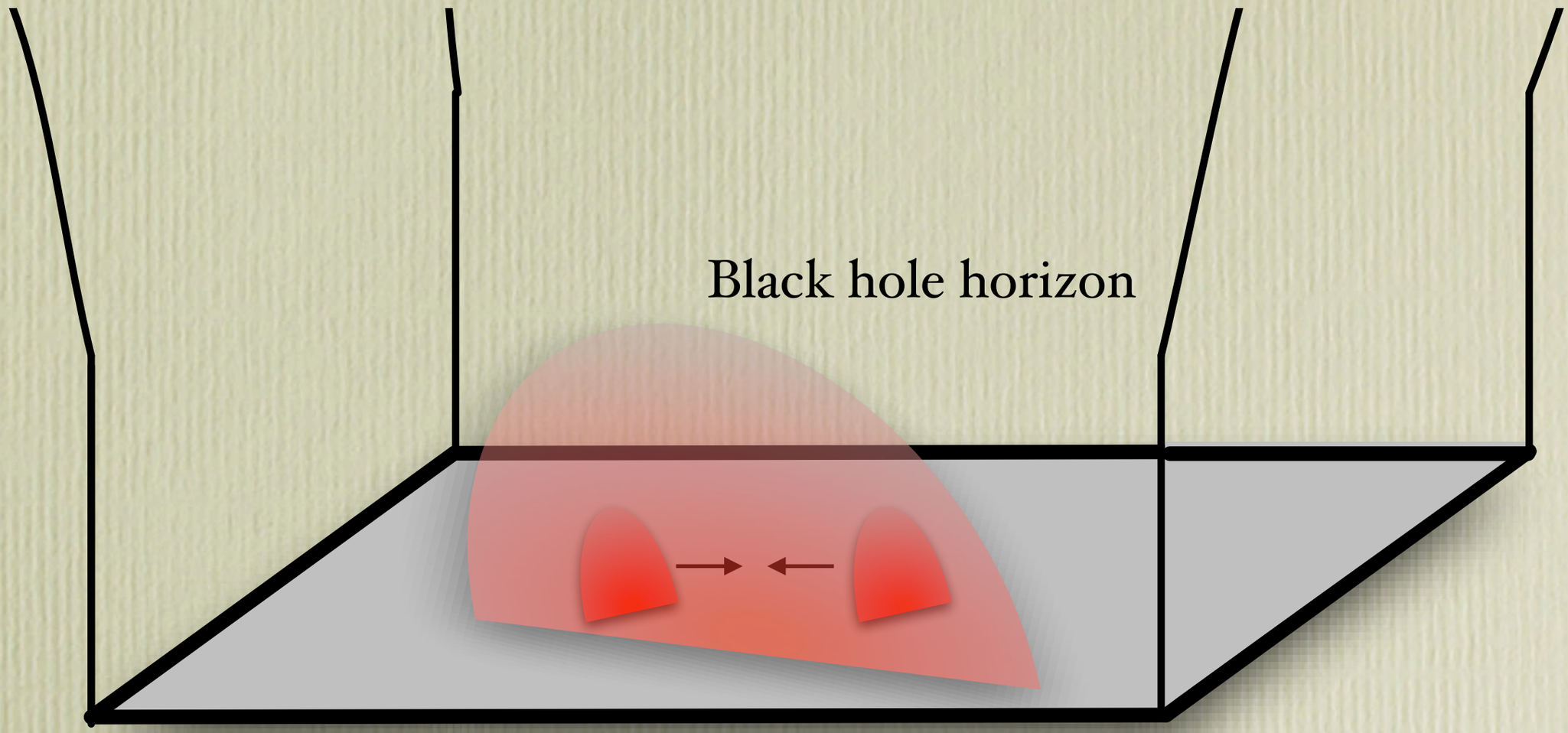
Holographic heavy ion collisions



Caricatures:
Lumps of energy and charge

Gravitational + electromagnetic waves

Formation and evolution of the QGP



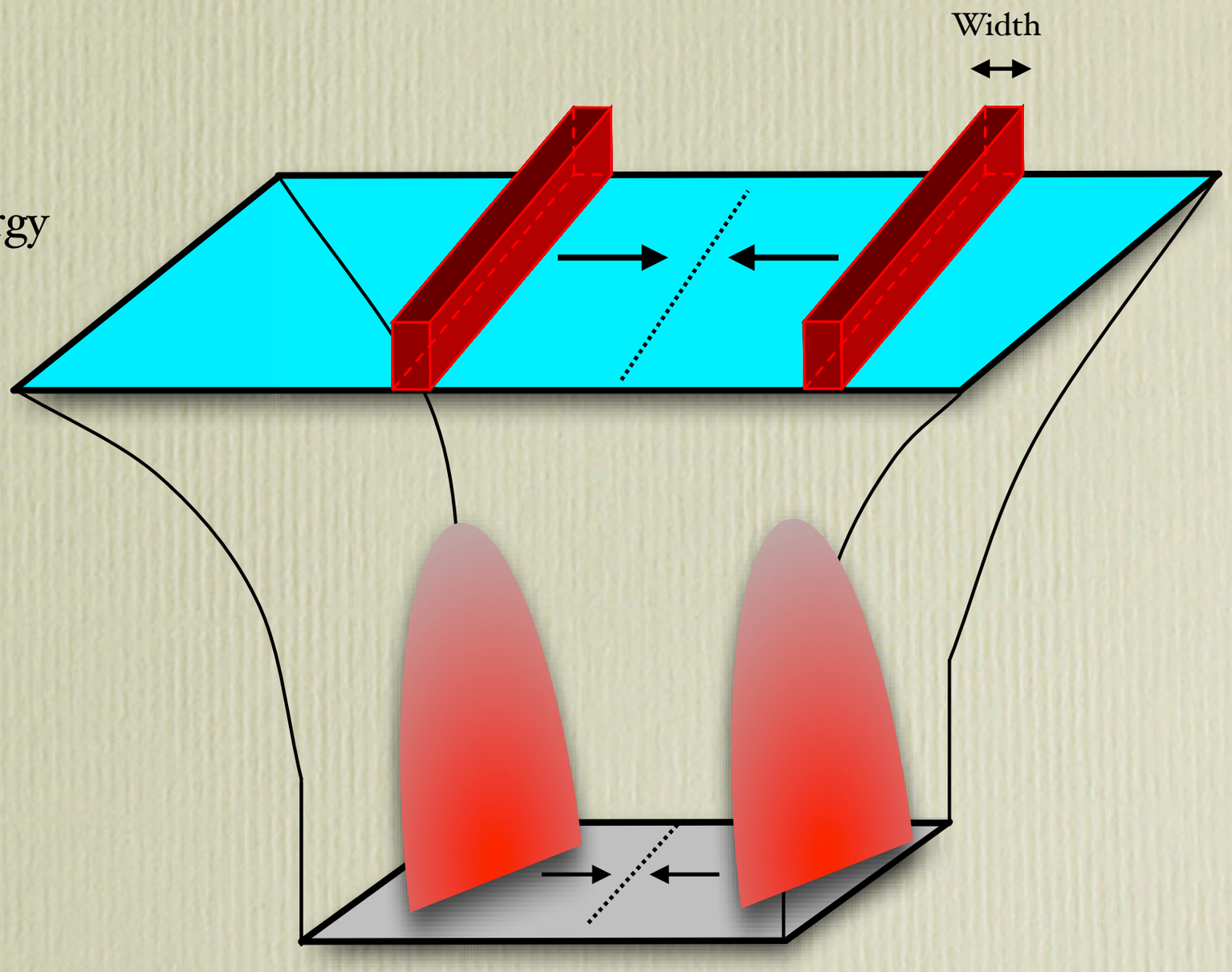
Holographic heavy ion collisions in CFT

Chesler & Yaffe '10

Toy model for collisions of infinite nuclei with no baryon charge:

Two infinite bricks of energy in transverse plane

Two gravitational shock waves



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$$T^\mu_\mu = 0 \qquad \rightarrow \qquad \bar{P} = P_{\rm eq}(\mathcal{E}) = \frac{1}{3}\mathcal{E}$$

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- Therefore P_L and P_T can deviate a lot from $P_{\rm eq}$!

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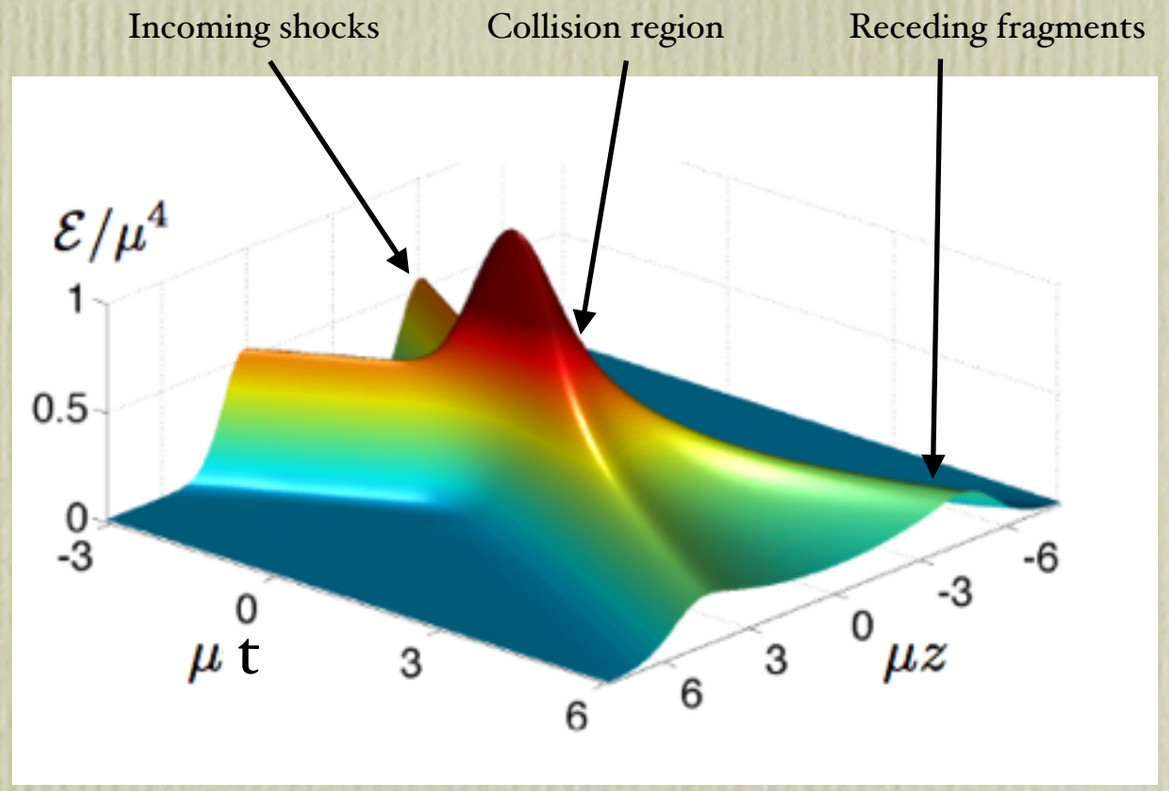

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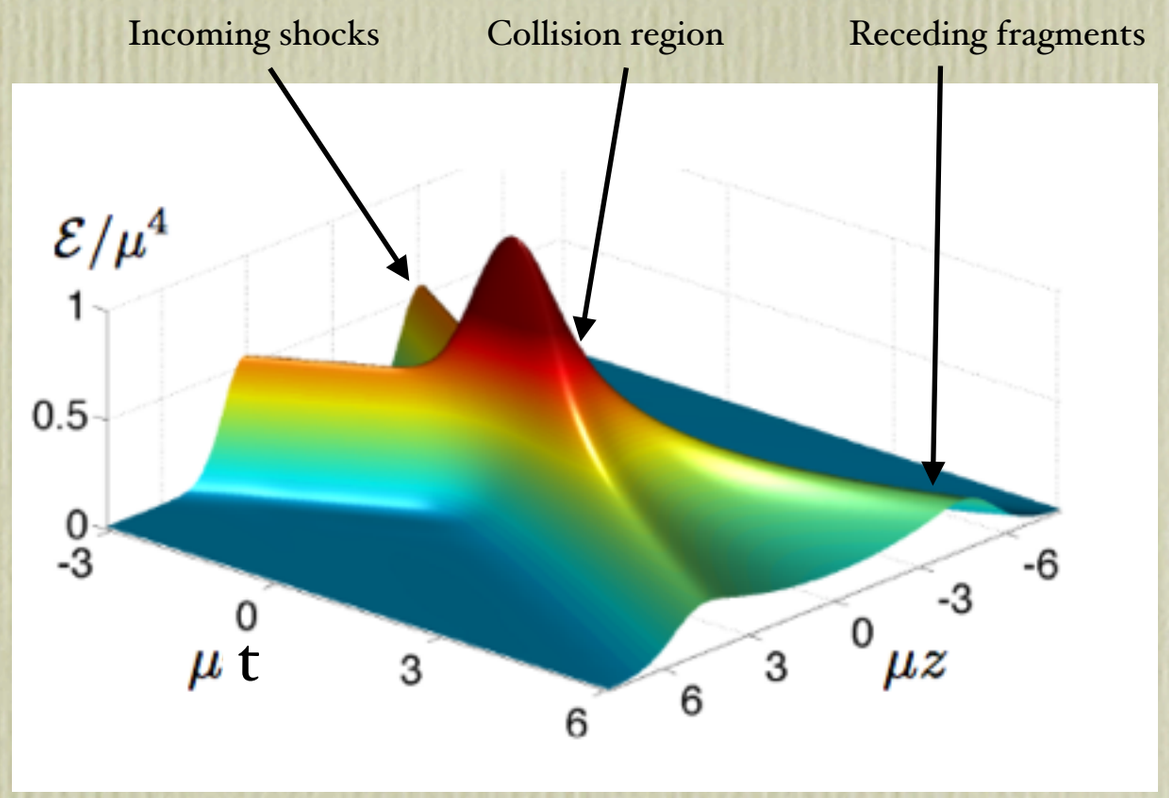
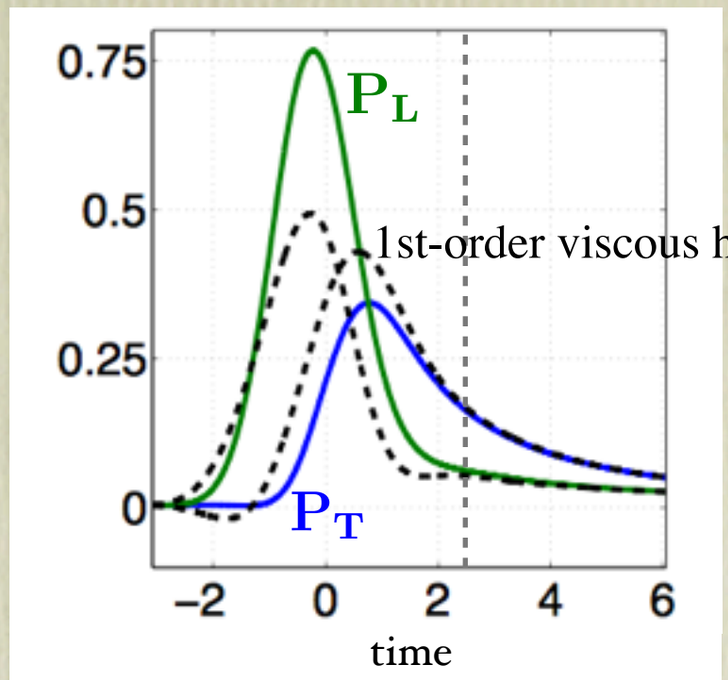


Pressures at mid rapidity



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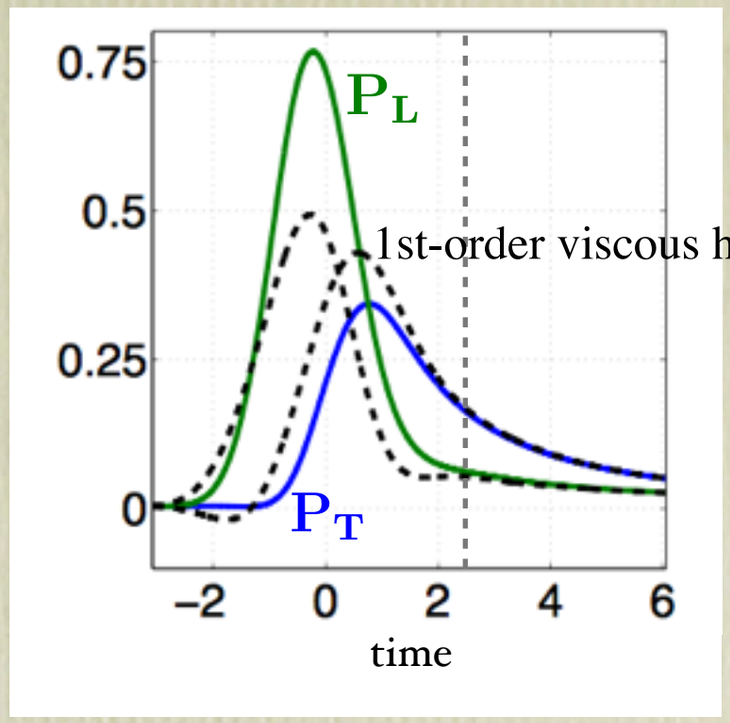

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$$\left.\frac{P_T}{P_L}\right|_{t_{\rm hydro}} \simeq 3$$

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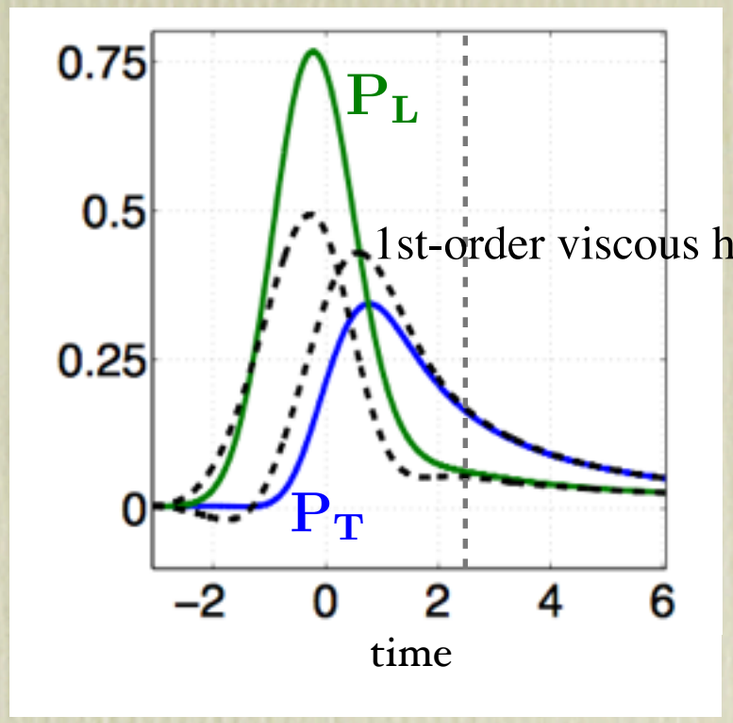

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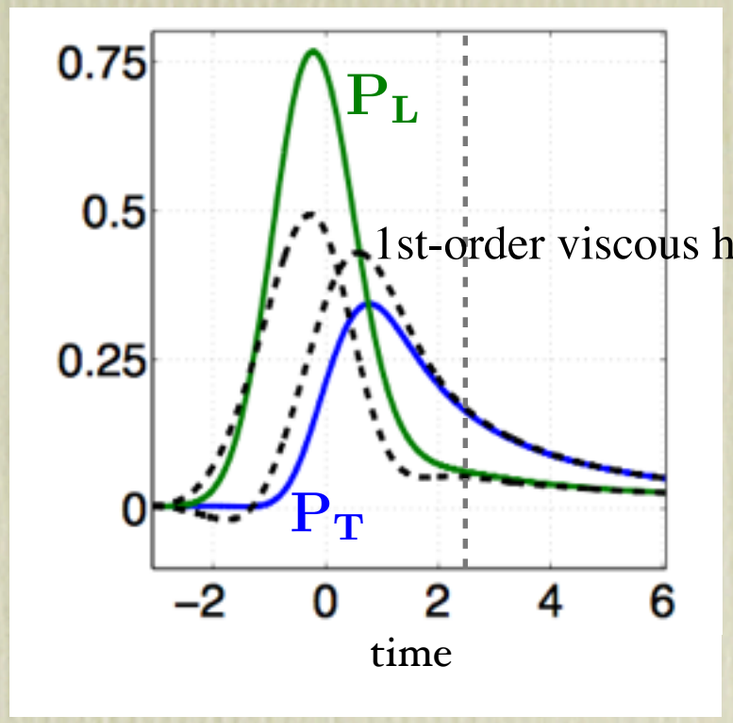
- Hydro works when gradients are still very large:

Pressures at mid rapidity



$$P_L^{\rm hyd} = P_{\rm eq} + P_\eta + \cancel{P_\zeta}$$

$$P_T^{\rm hyd} = P_{\rm eq} - \frac{1}{2} P_\eta + \cancel{P_\zeta}$$

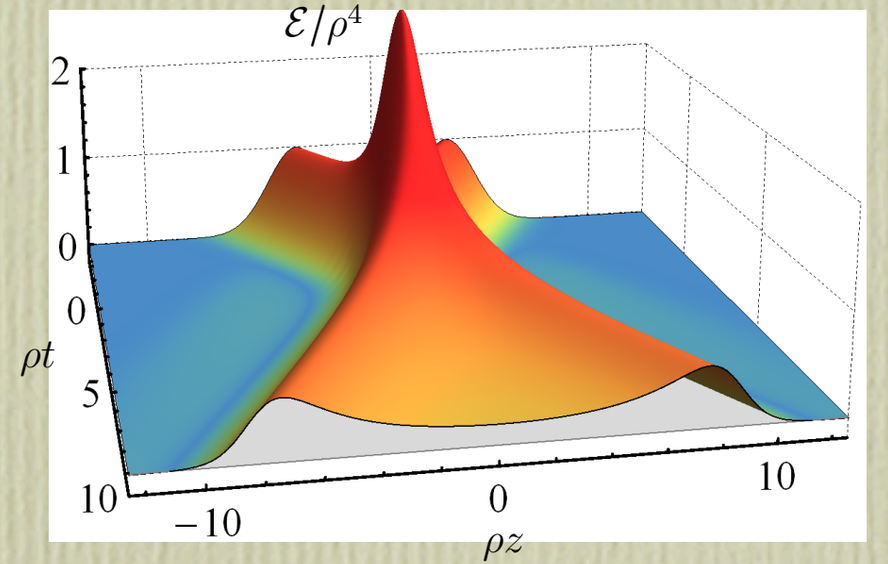
shear viscosity

bulk viscosity

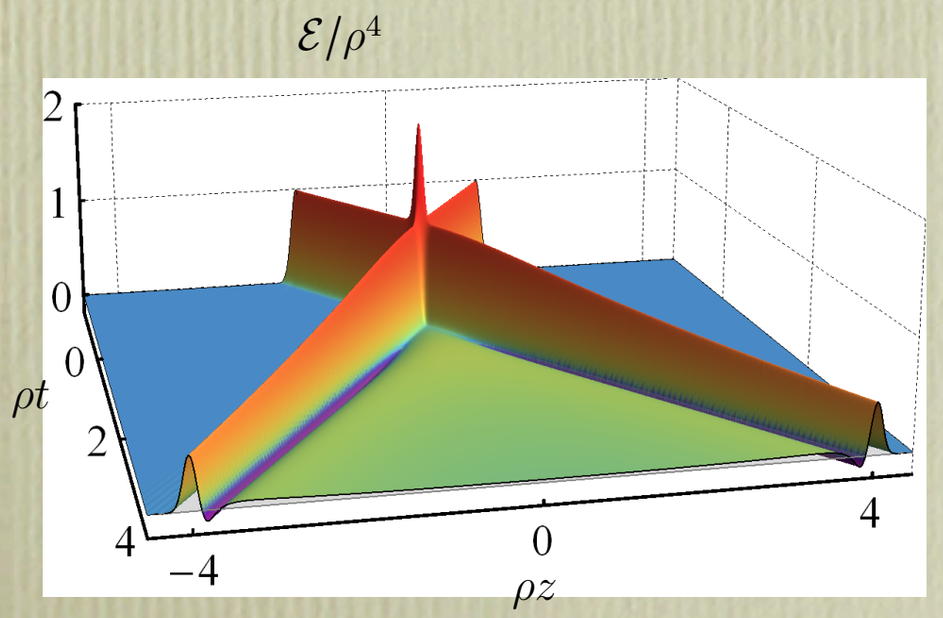
A dynamical cross-over

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

Qualitatively different dynamics depending on the collision energy:



Low energy collision (thick shocks)



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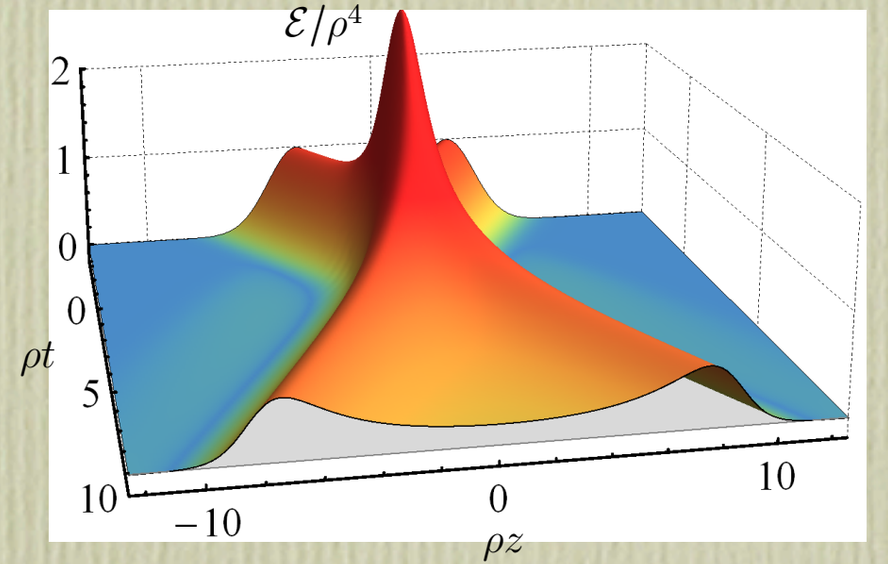

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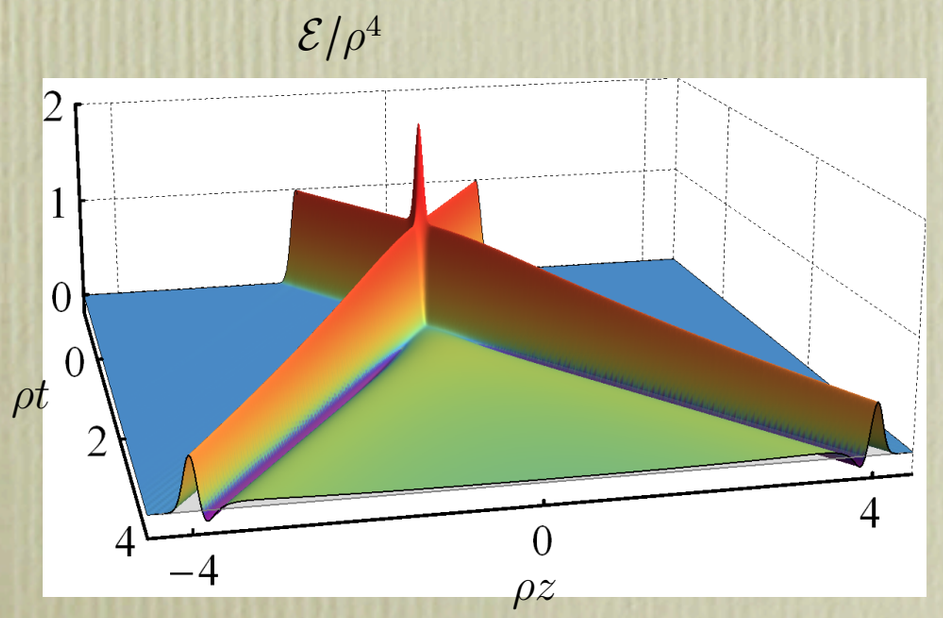

High energy collision (thin shocks)

Full-stopping scenario

- Realizes Landau model approximately:
  Energy gets compressed, stops and explodes hydrodynamically.
- No clear separation between plasma and receding fragments.
- The receding maxima move at v ~ 0.88.

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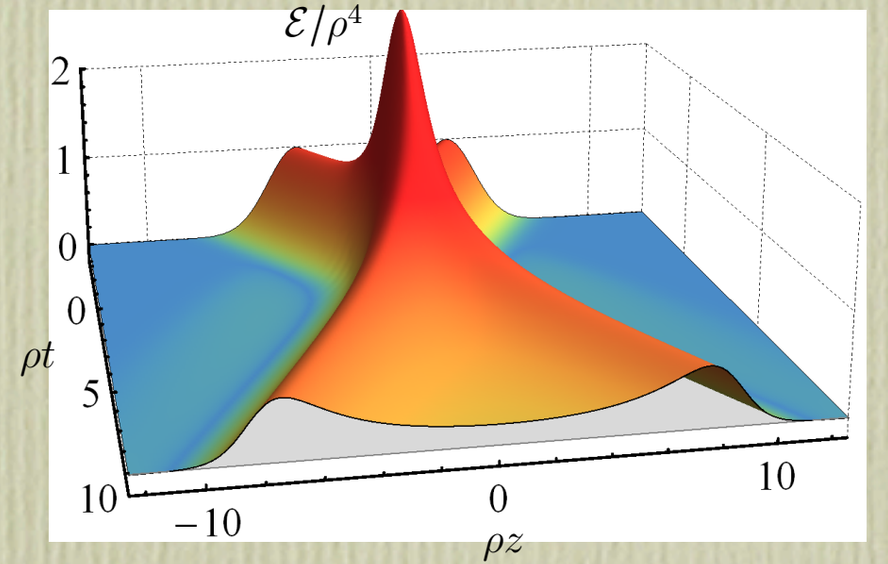

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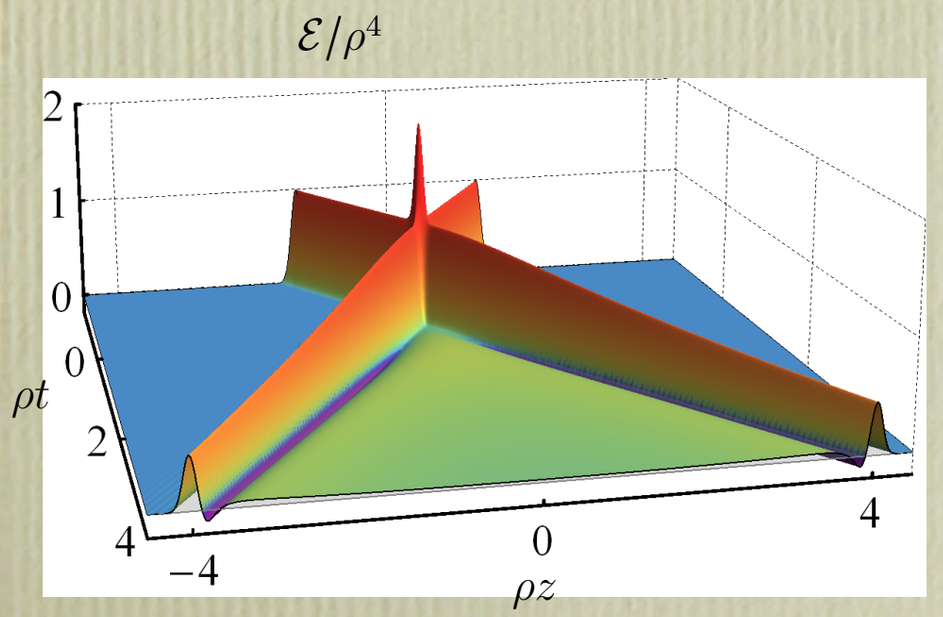

High energy collision (thin shocks)

Transparency scenario

- Shocks pass through one another and plasma gets created in between.
- The receding maxima move at v ~ 1 despite infinite coupling.
- Clear separation between receding fragments and plasma.

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

Longitudinal coherence and asymmetric collisions

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

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

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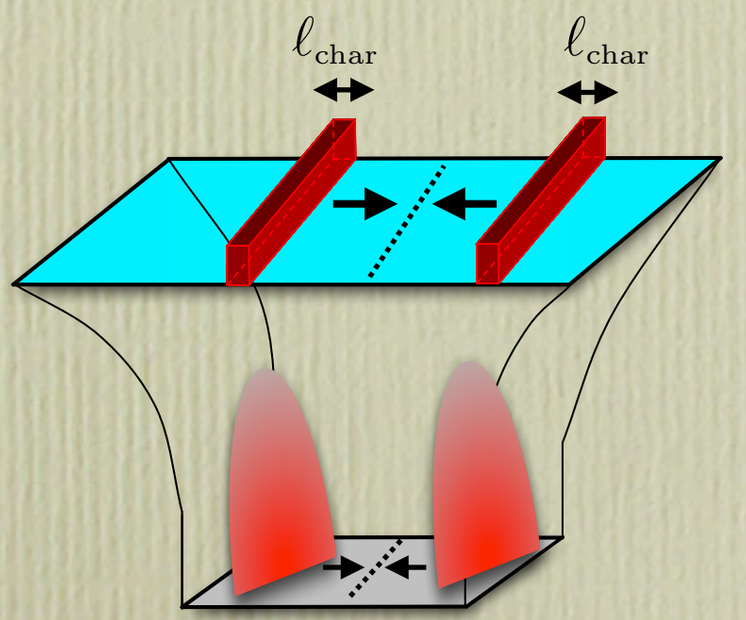
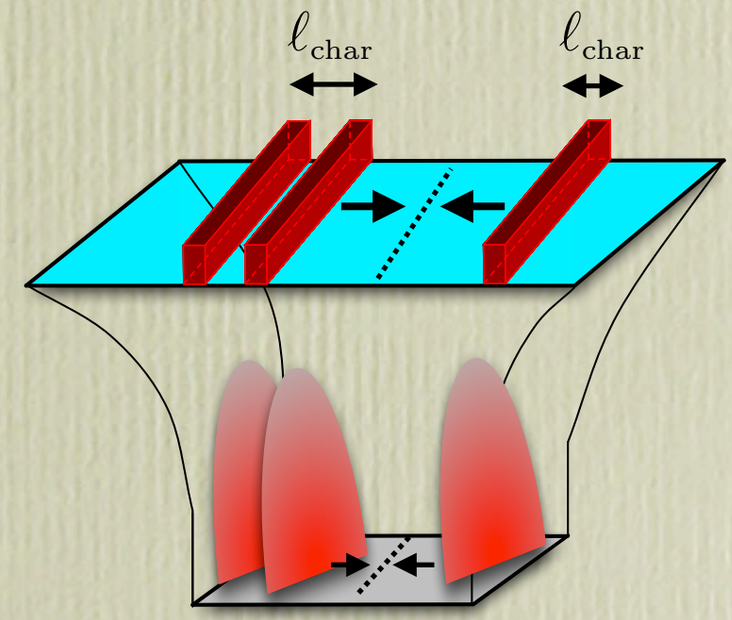
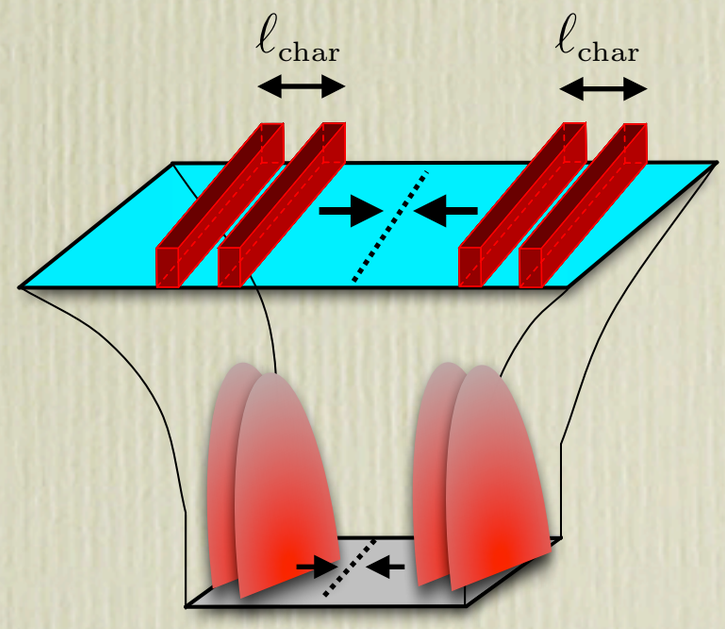
- **Compare** the following collisions (at fixed total energy):



Single-Single



Single-Double



Double-Double

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

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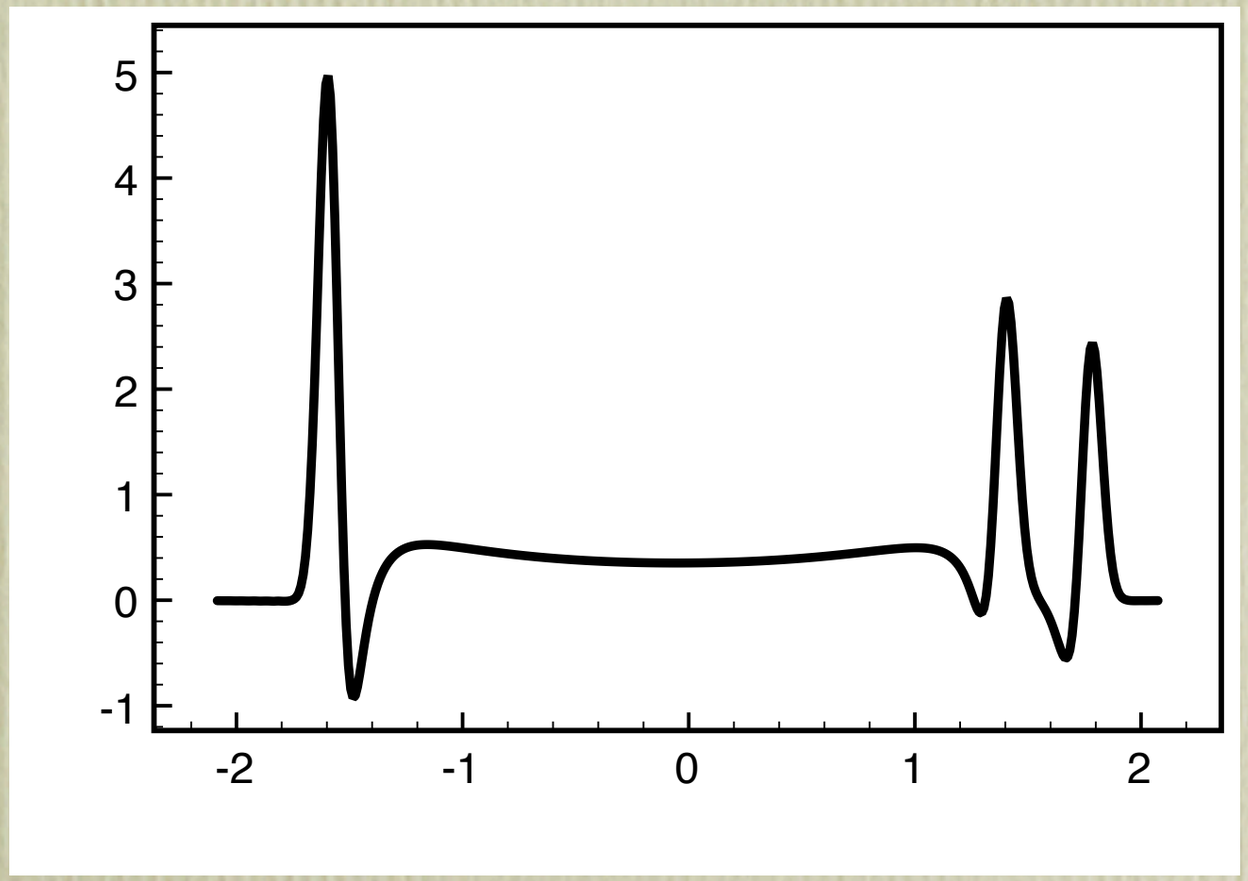

Coherent regime

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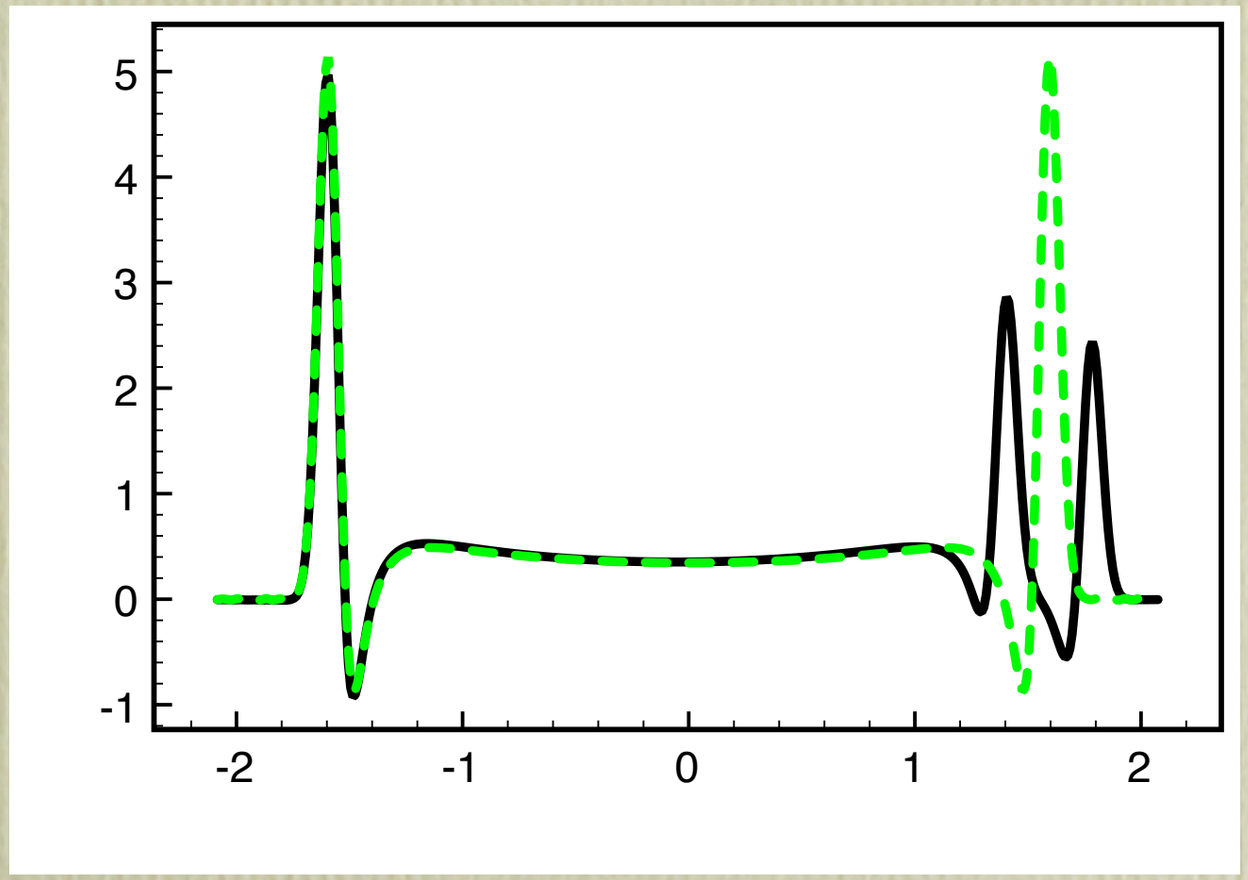

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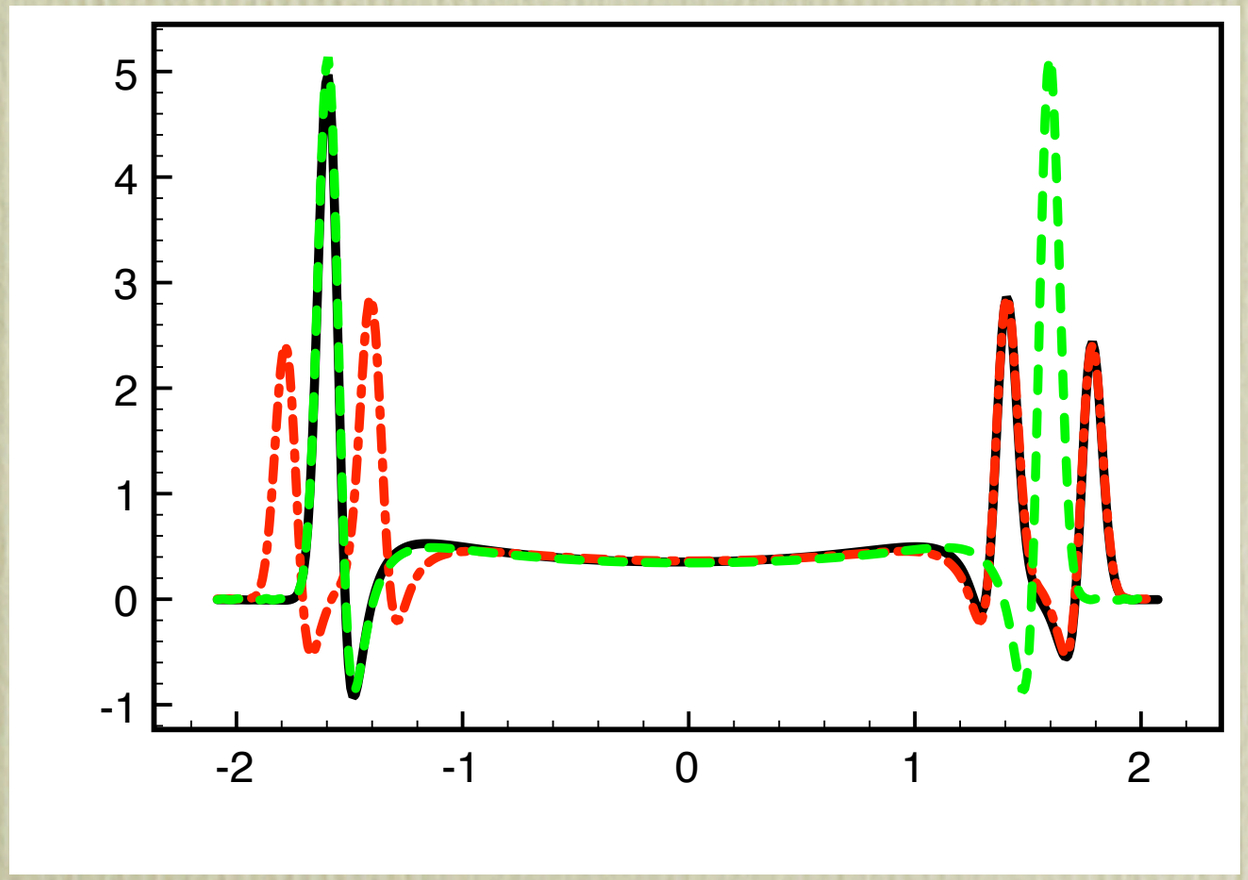

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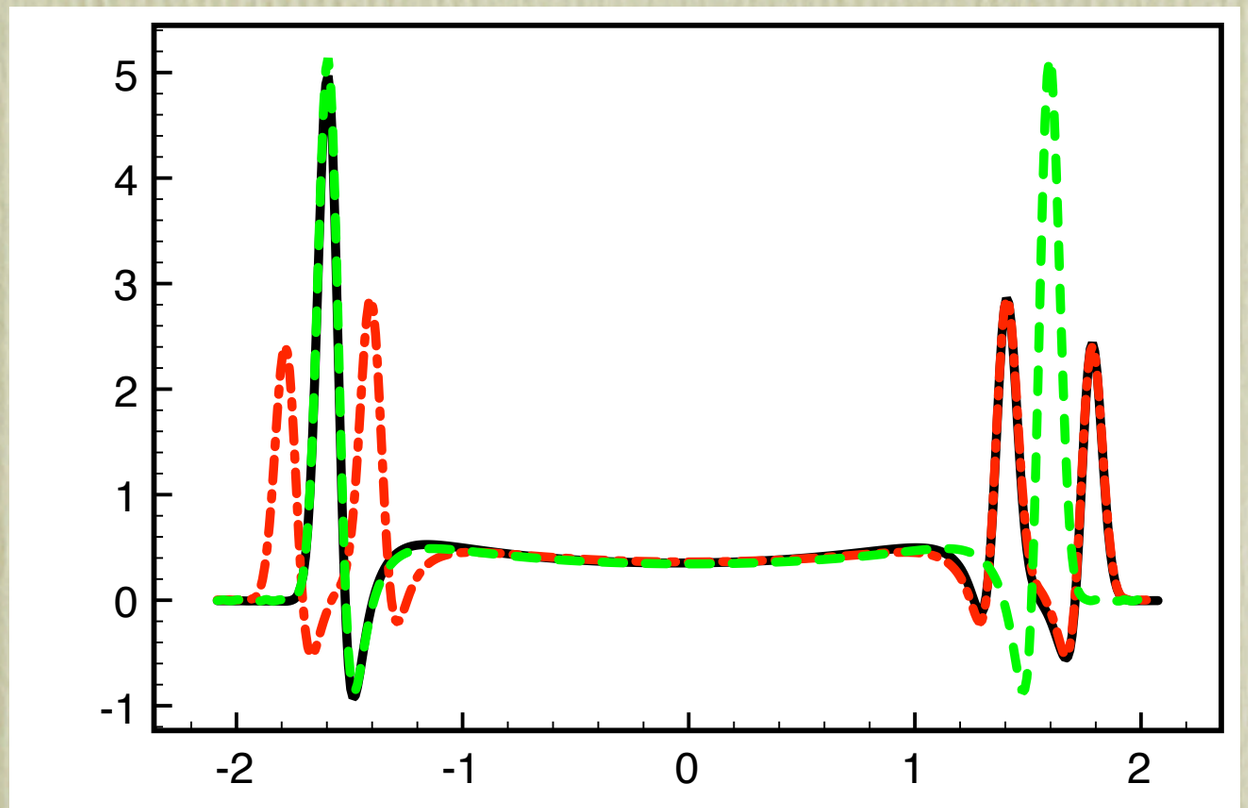

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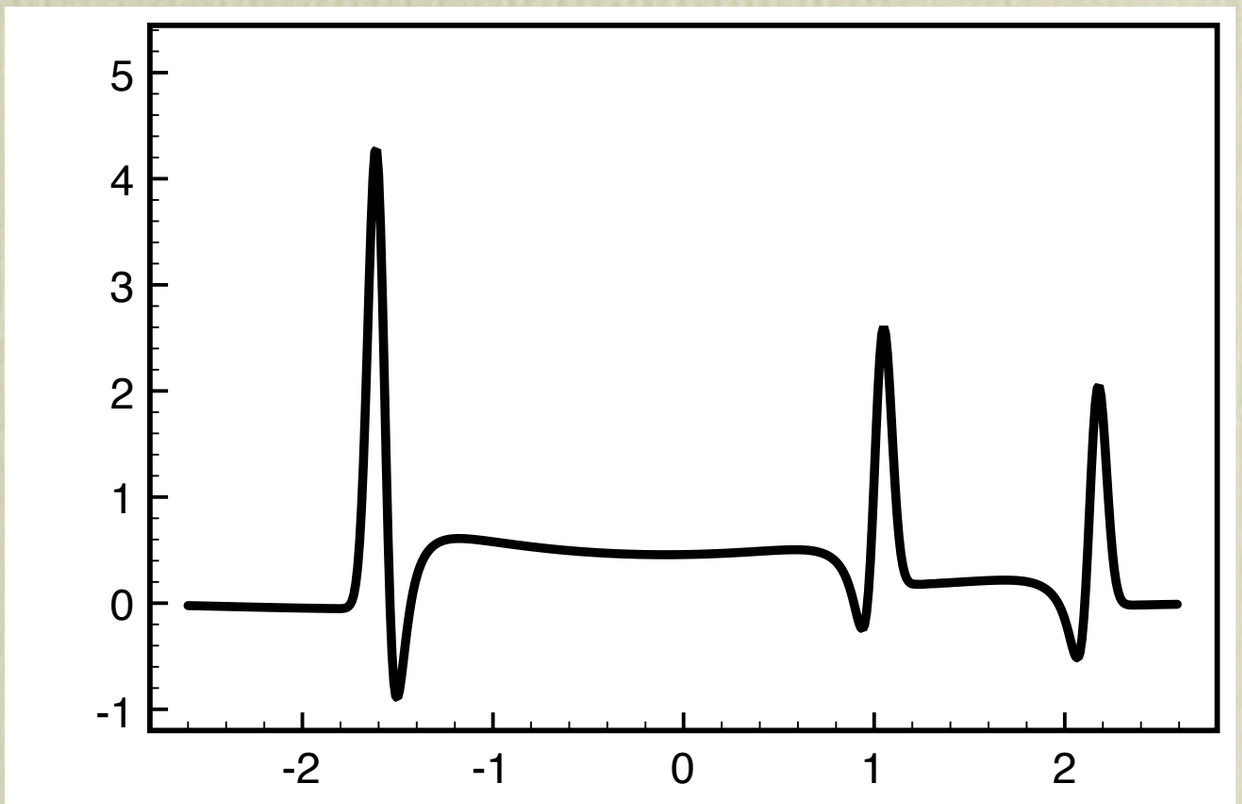

Incoherent regime

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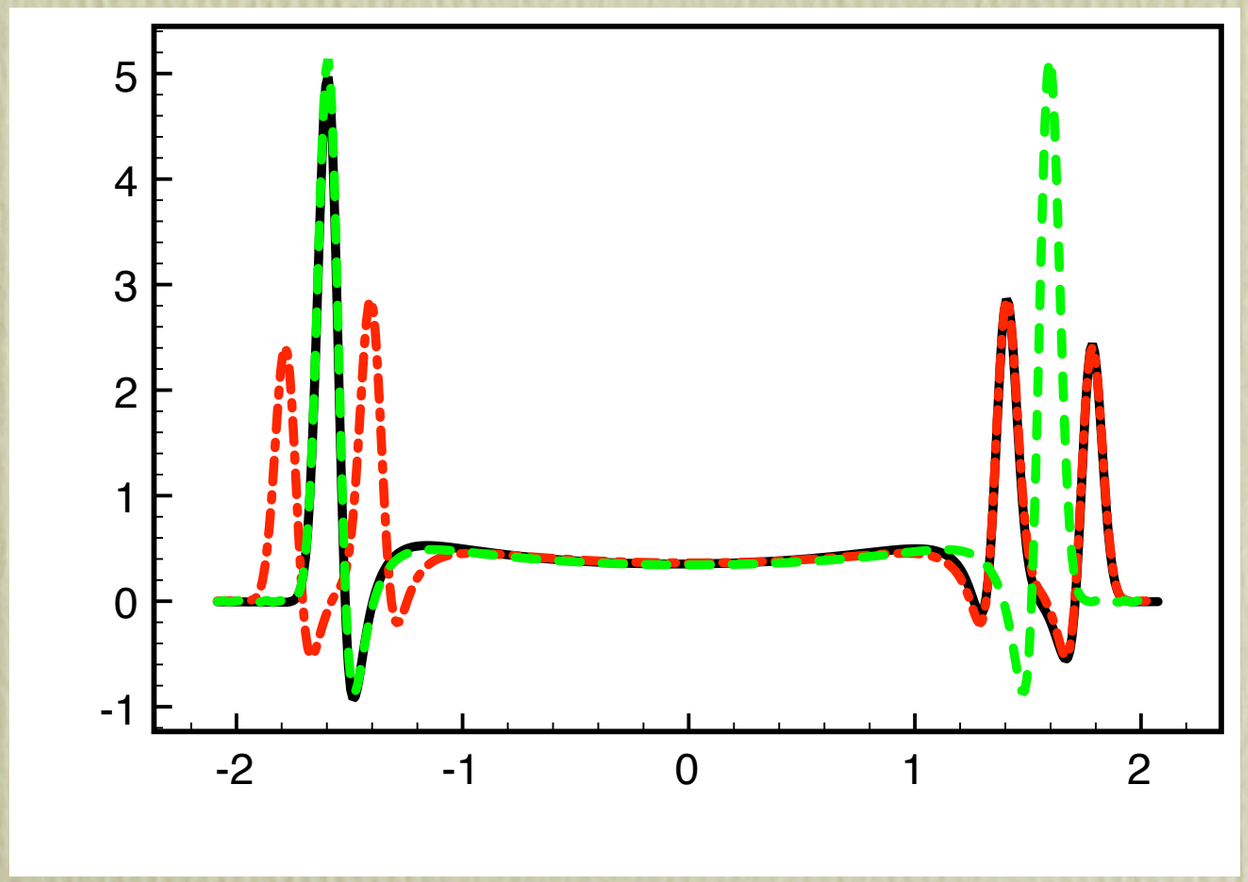

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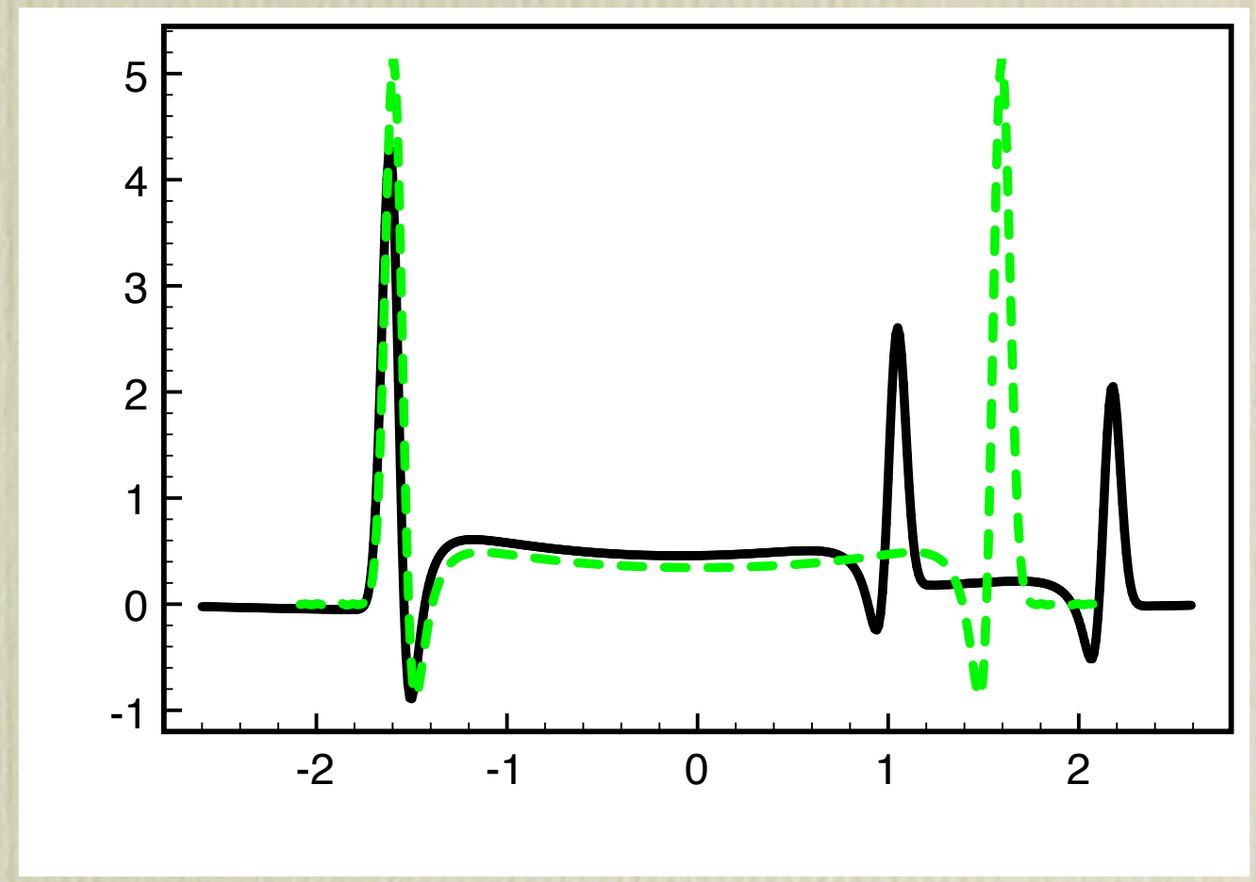

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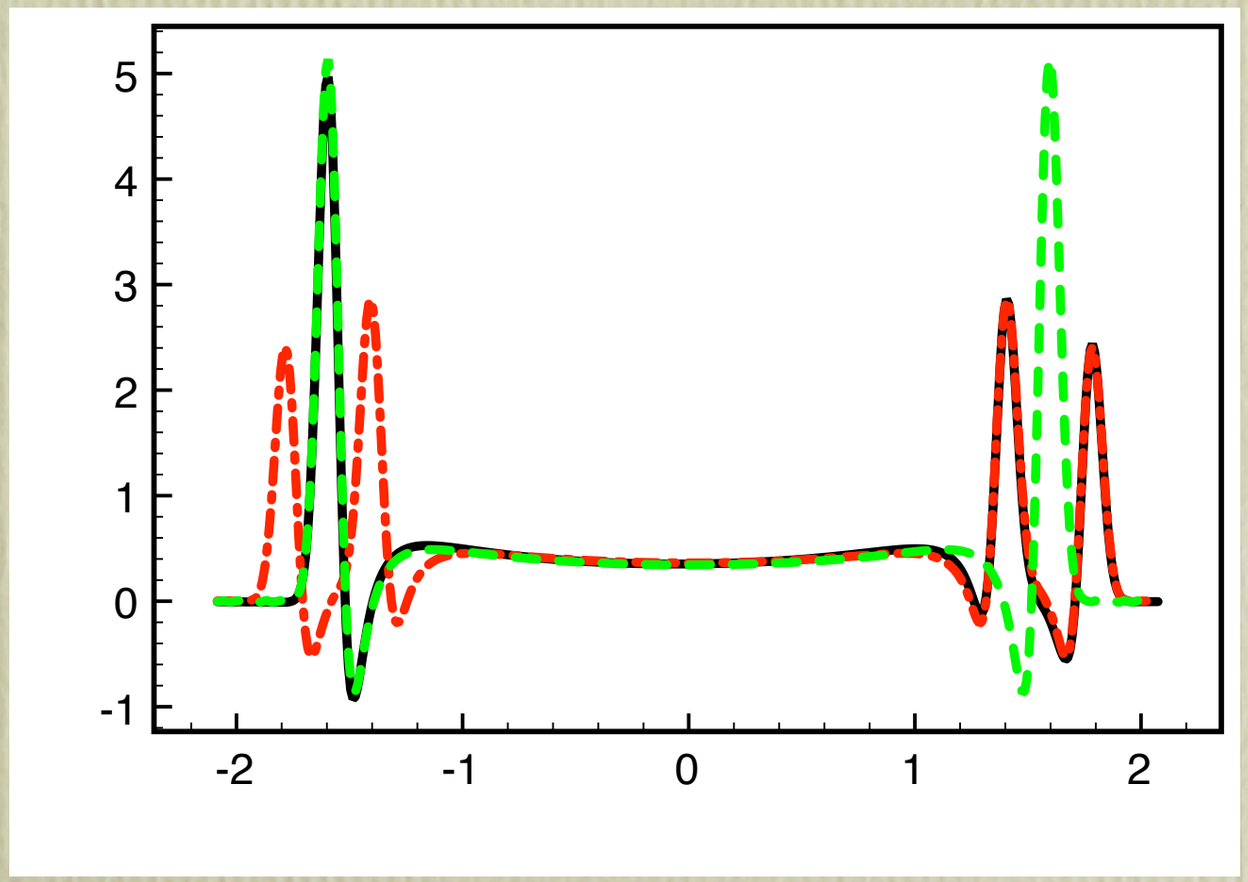

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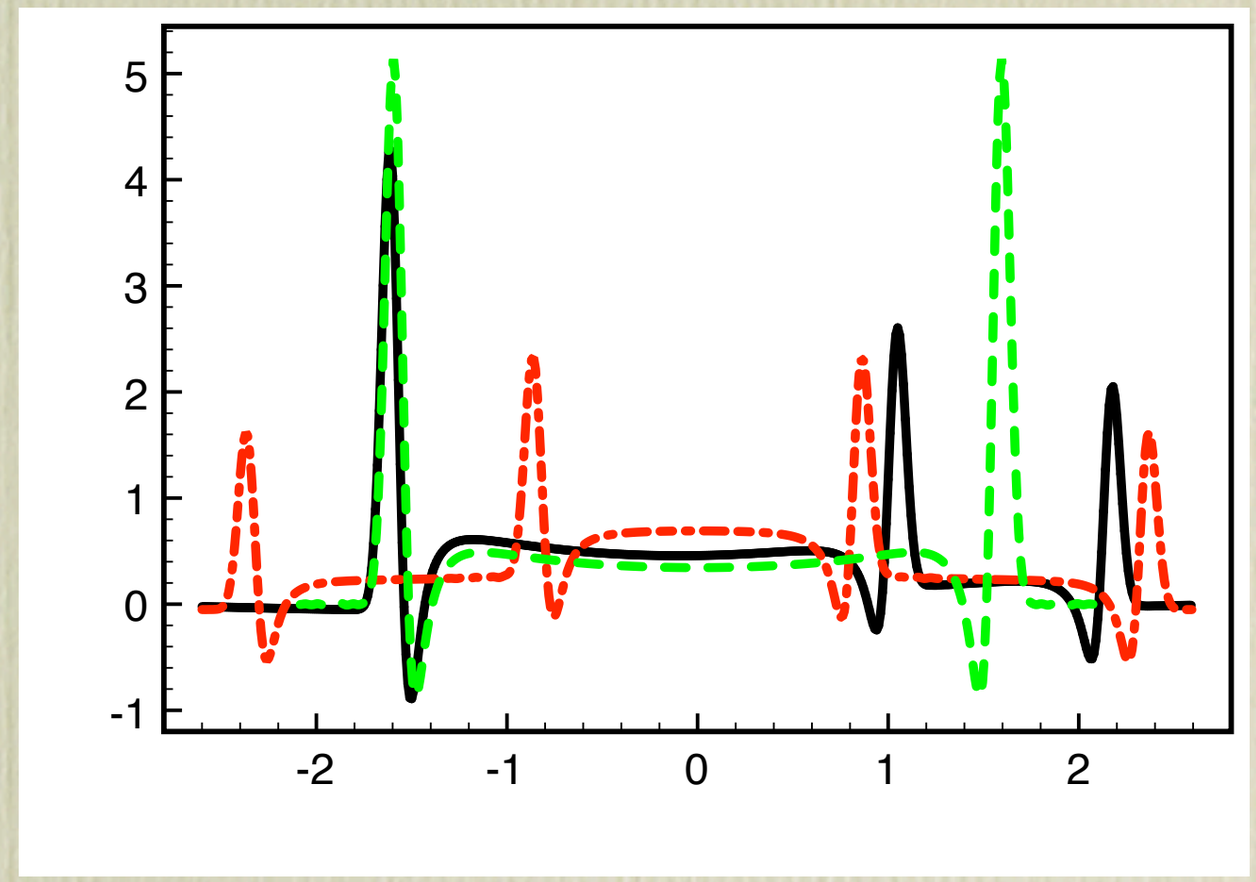

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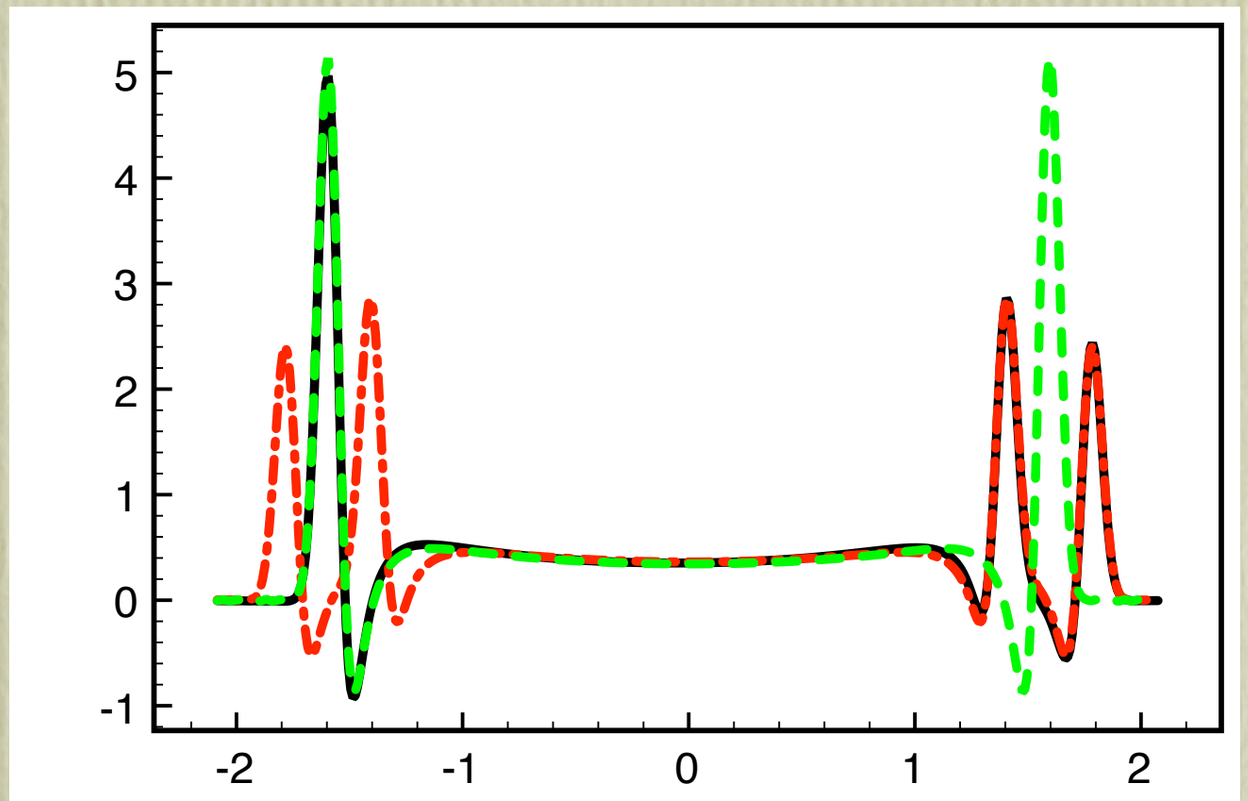
- **Implication**: In coherent regime c.o.m. of QGP equals c.o.m. of all participating nucleons.



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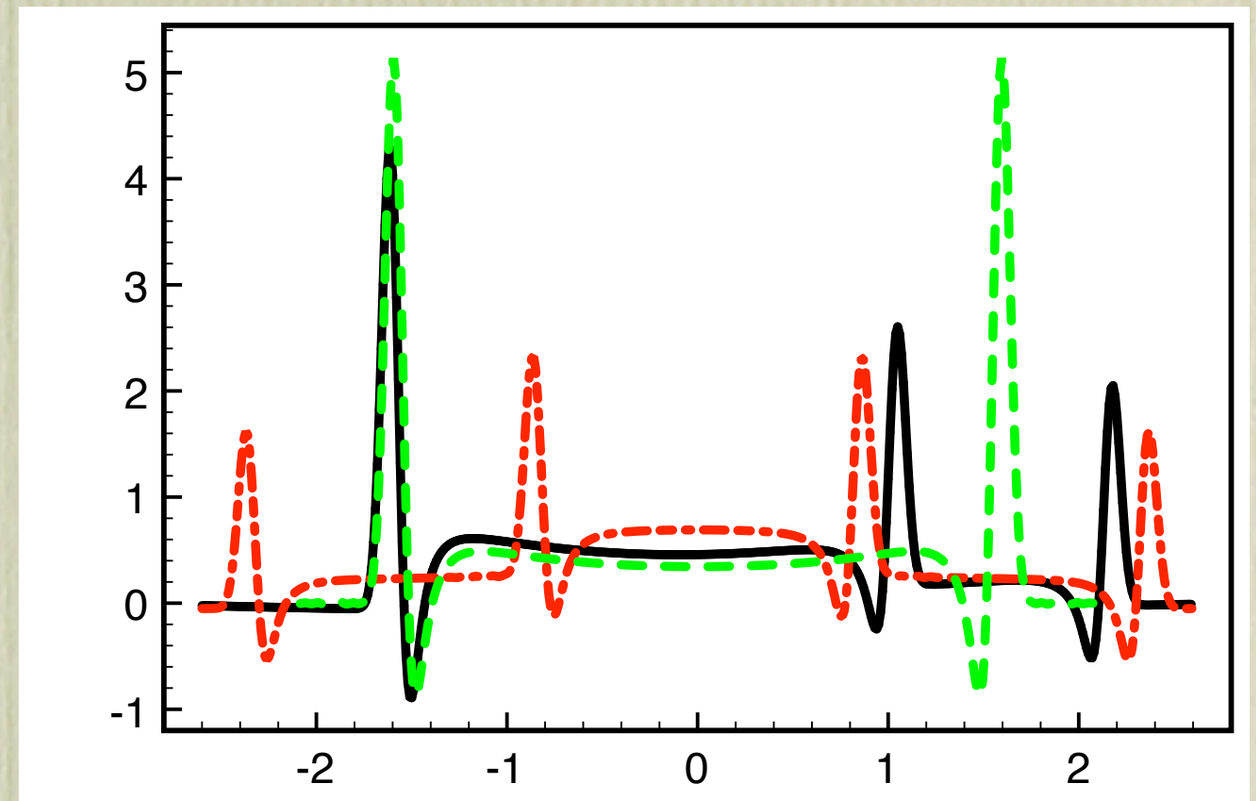


Incoherent regime

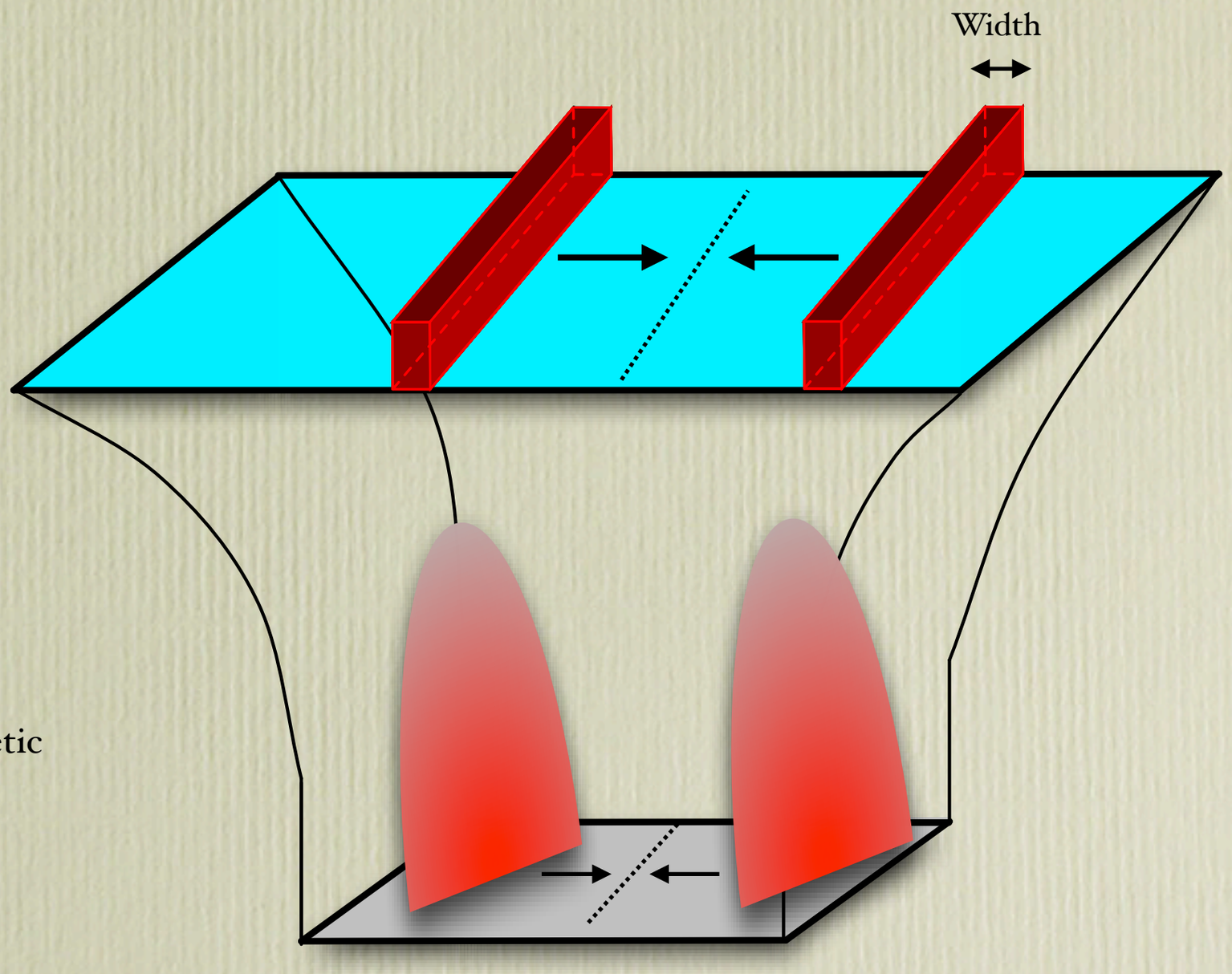
Collisions with baryon charge

Casalderrey, D.M., van der Schee & Triana '16
(imminent appearance)

Toy model for collisions of infinite nuclei with baryon charge:

Two infinite bricks of energy and conserved U(1) charge

Two gravitational + electromagnetic shock waves



Collisions with baryon charge

Casalderrey, D.M., van der Schee & Triana '13

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- We find significant stopping of baryon number.

- Hence good model for low- and moderate-energy collisions but not for high-energy.

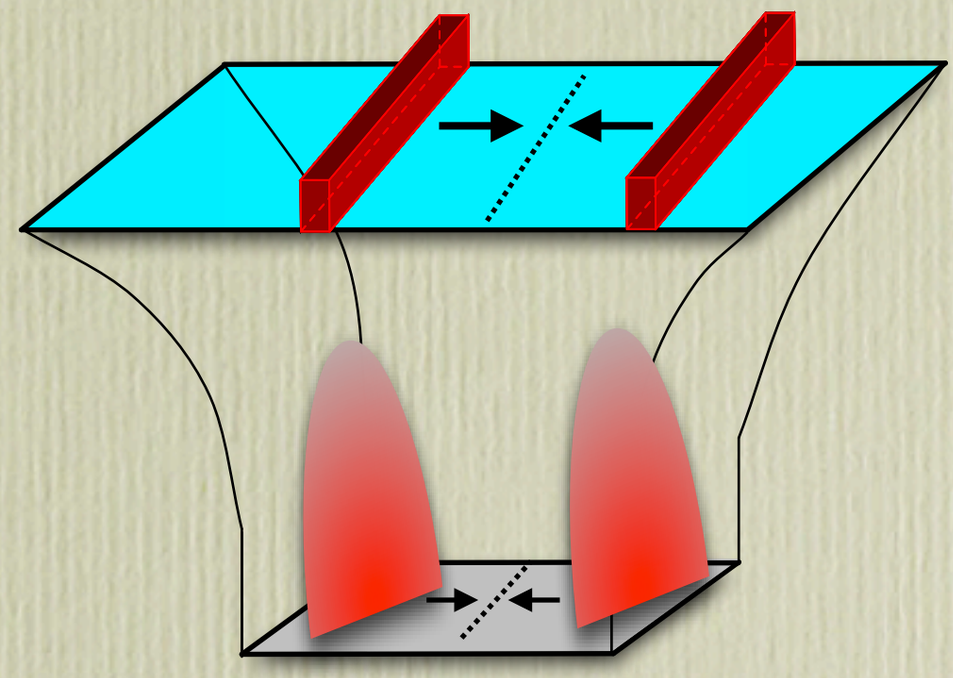
- At high energies, rapidity shifts of valence quarks involve large momentum transfers and are suppressed by asymptotic freedom.

- Suggests using a hybrid model.

Beyond conformal symmetry

Attems, Casalderrey, D.M., Santos-Olivan, Sopuerta, Triana & Zilhao '16

Infinite bricks of energy



Gravitational waves

- Details in parallel talk tomorrow by Maximilian Attems, so I will give main conclusions.

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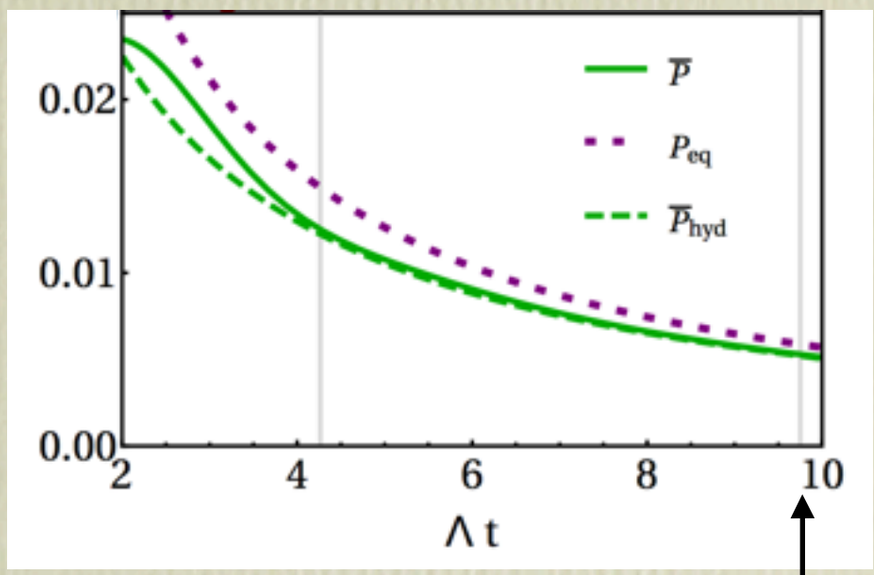

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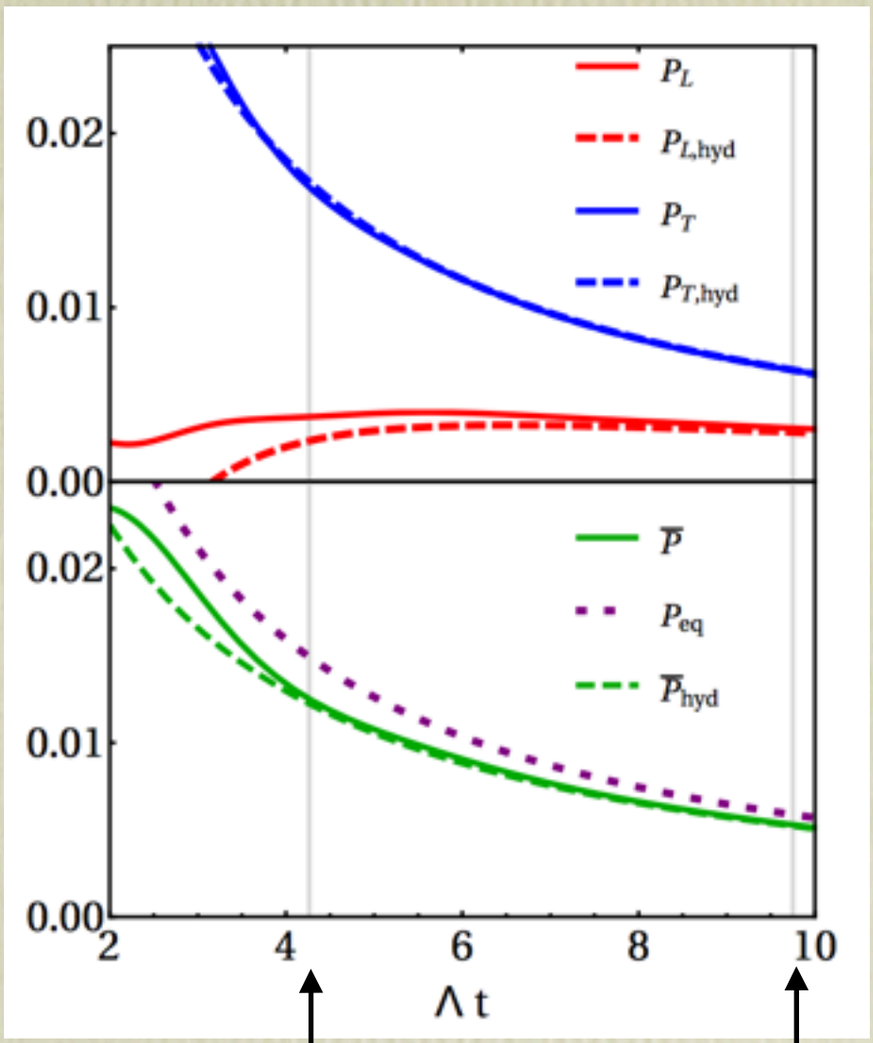

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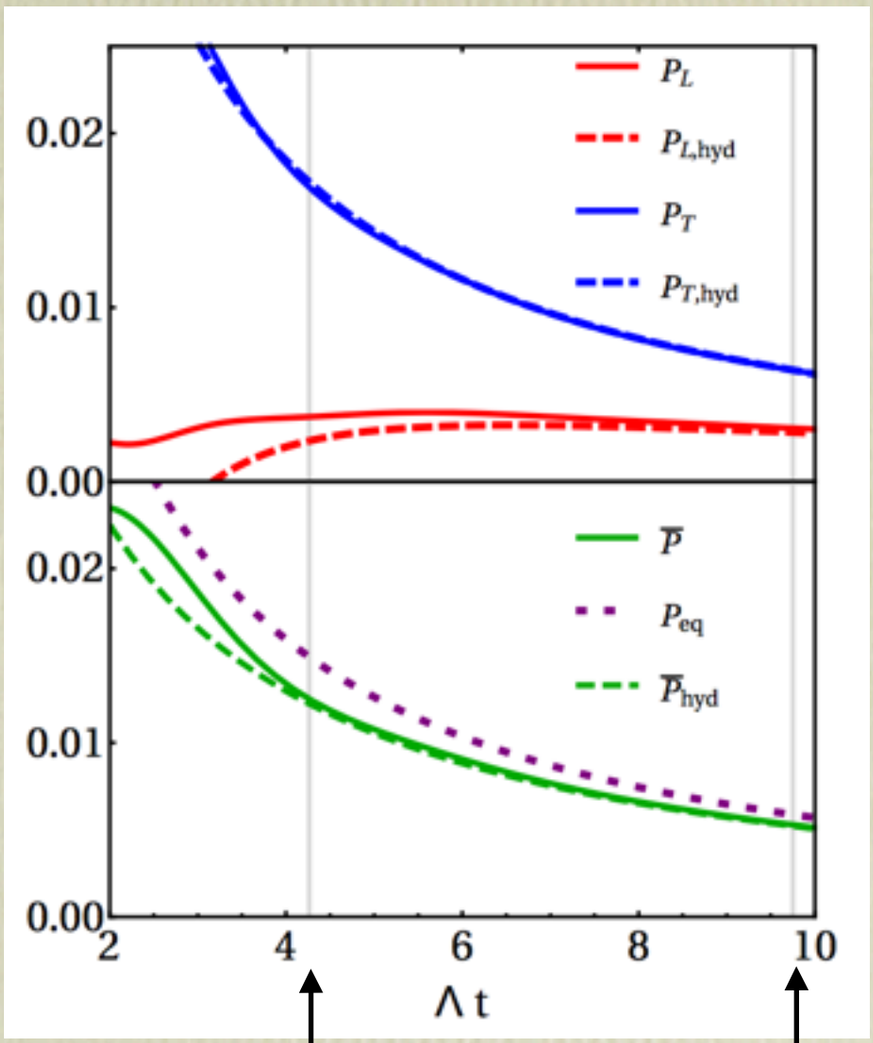
$$P_T^{\rm hyd} = P_{\rm eq} - \frac{1}{2}P_\eta + P_\zeta$$

Responsible for anisotropy

Responsible for $\bar{P} \neq P_{\rm eq}(\mathcal{E})$



$t_{\rm hyd}$

$t_{\rm eq}$

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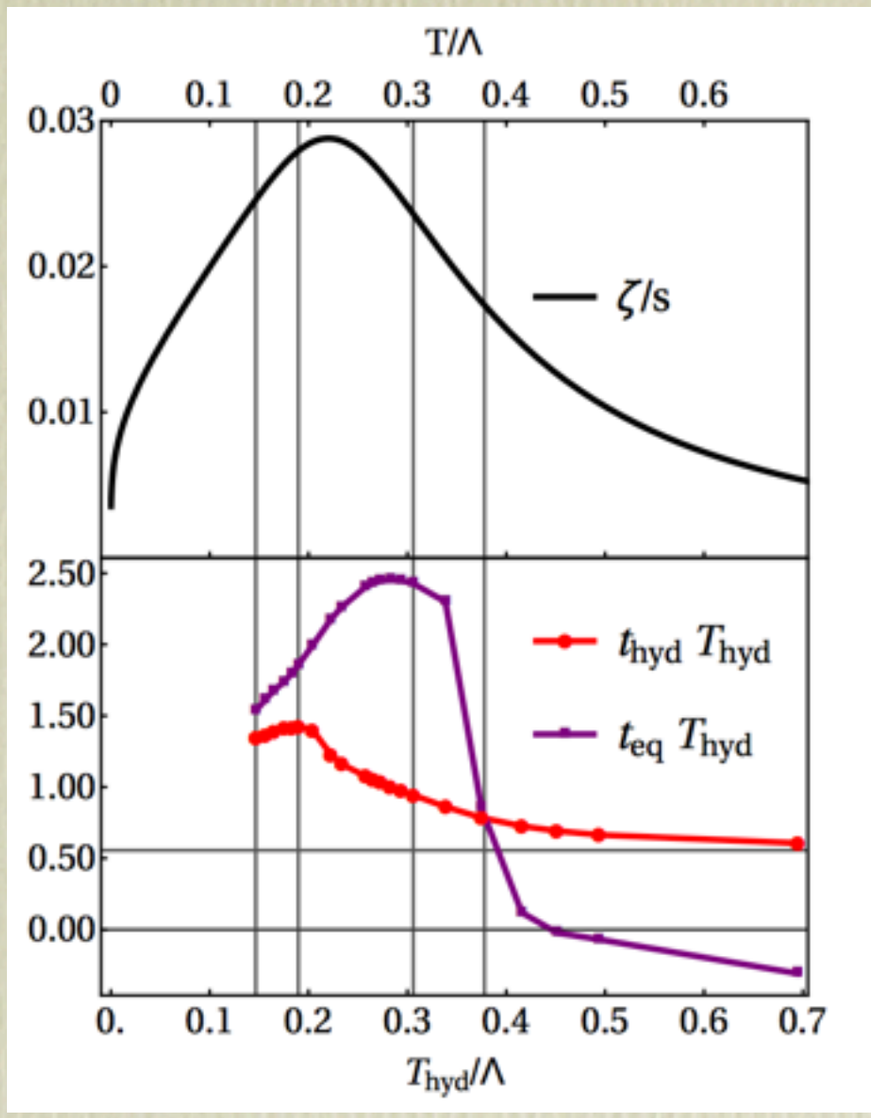

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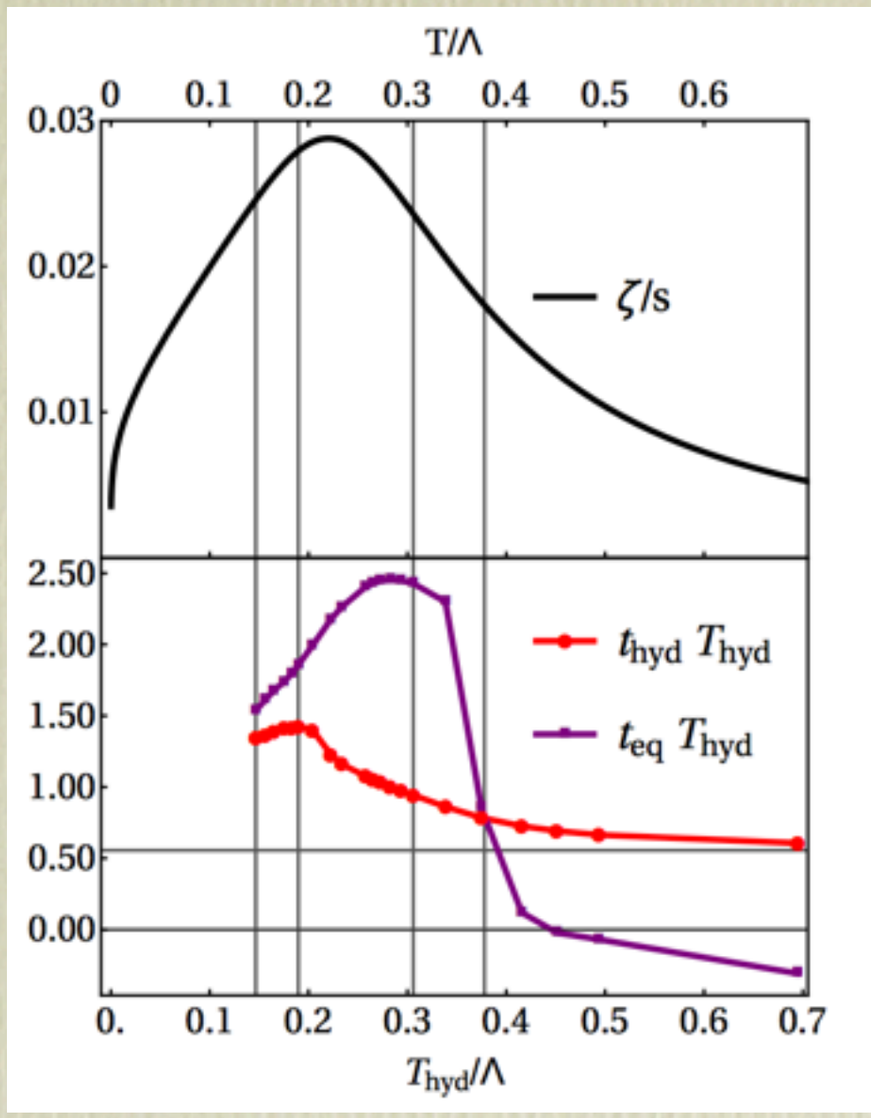
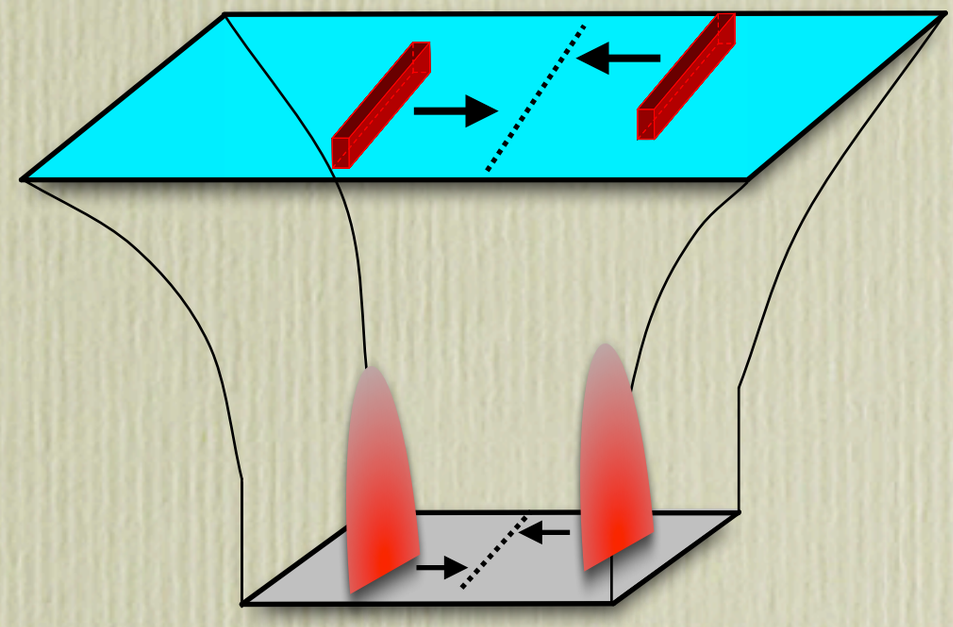


- Required bulk viscosity about 1/10 of QCD at Tc.
- Hydro time 2.5 longer than in CFT.

Off-centre collisions of finite nuclei

Chesler & Yaffe '15

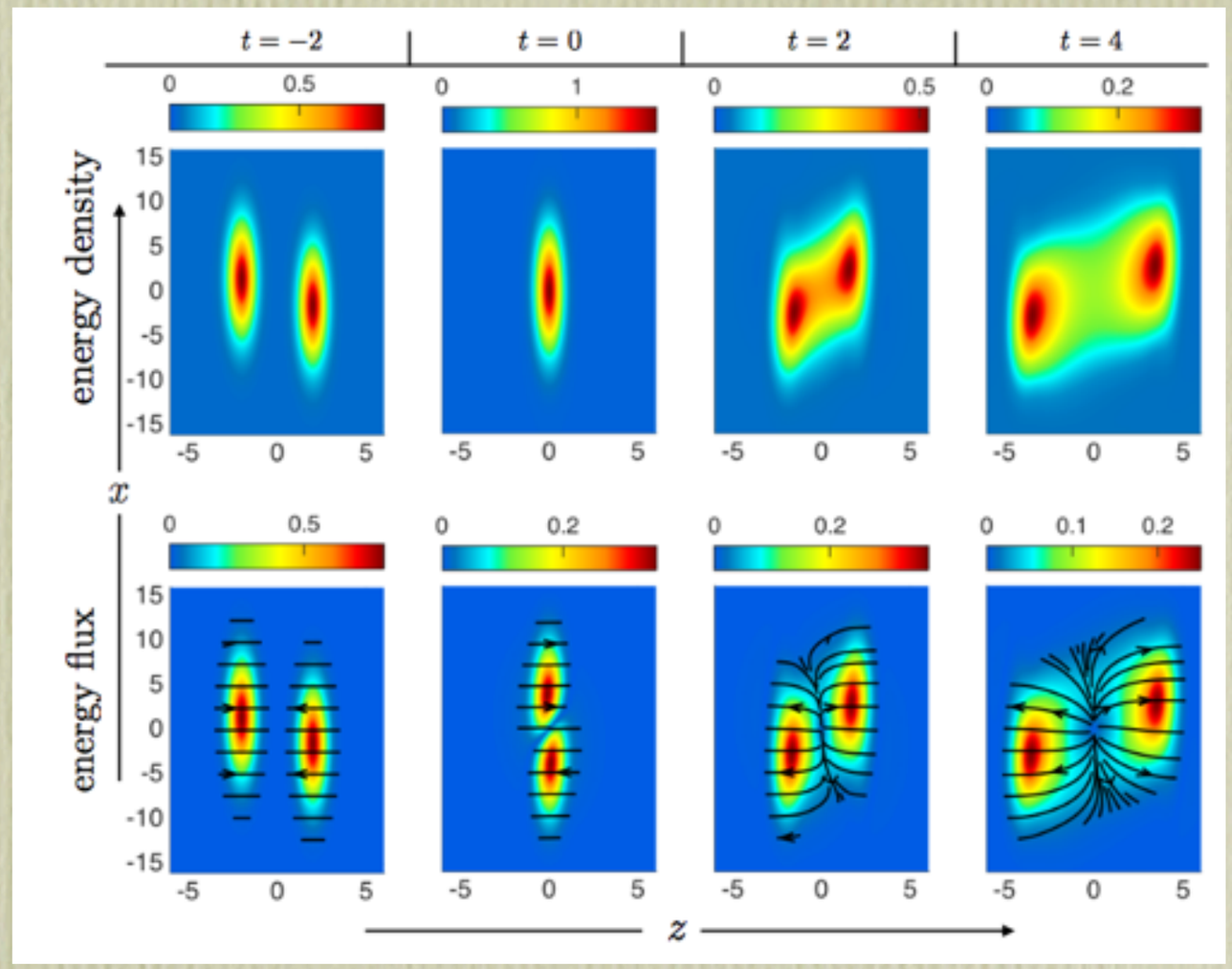
Localised lumps of energy
Non-zero impact parameter



Gravitational waves

Off-centre collisions of finite nuclei

Chesler & Yaffe ’15



See development of transverse flow.

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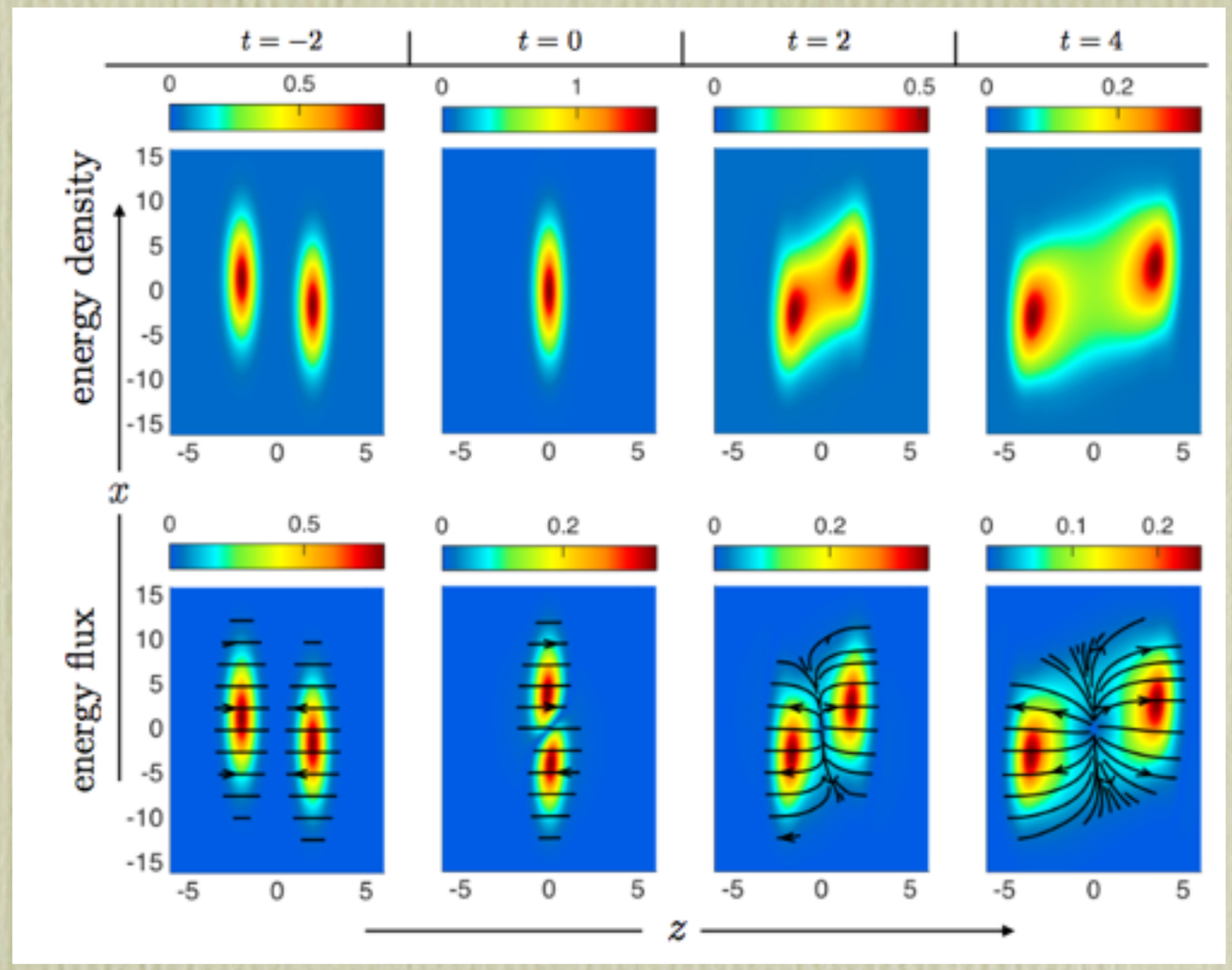

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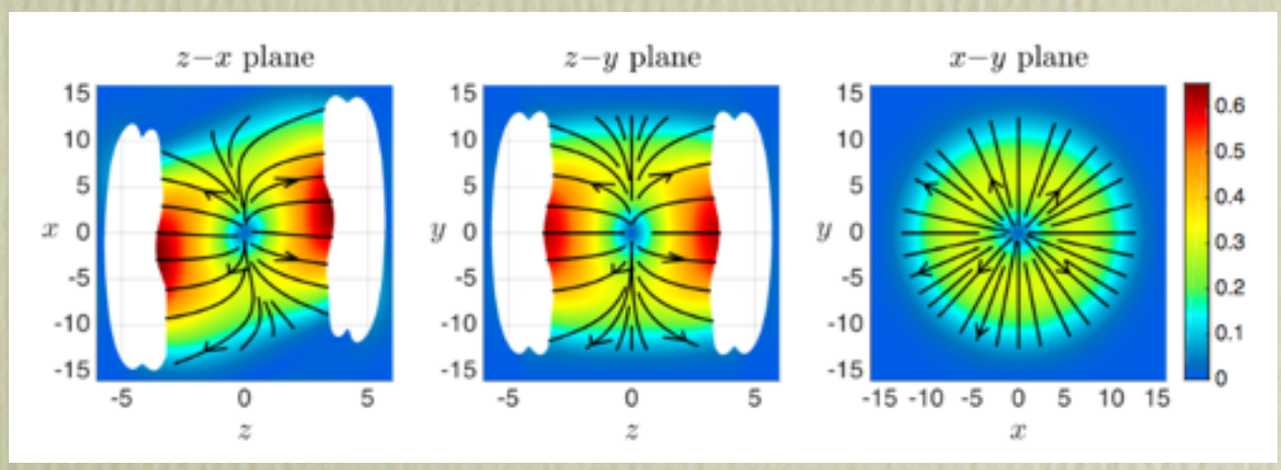


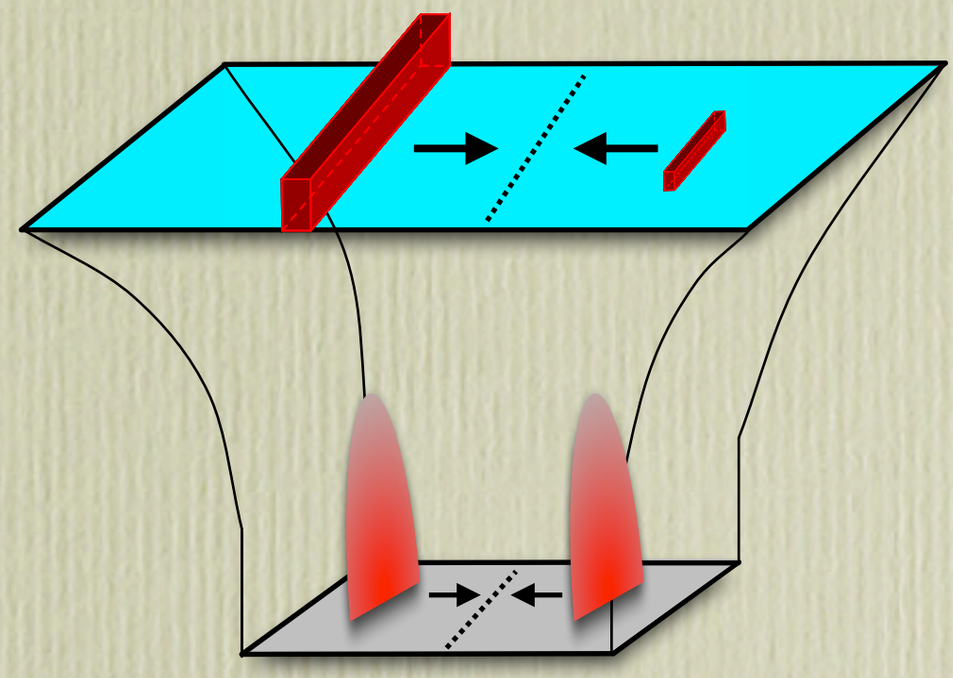
But essentially no elliptic flow.
(perhaps due to transverse Gaussians).

p+A collisions and the smallest drops of QGP

Chesler '15

Infinite vs finite brick

Gravitational waves



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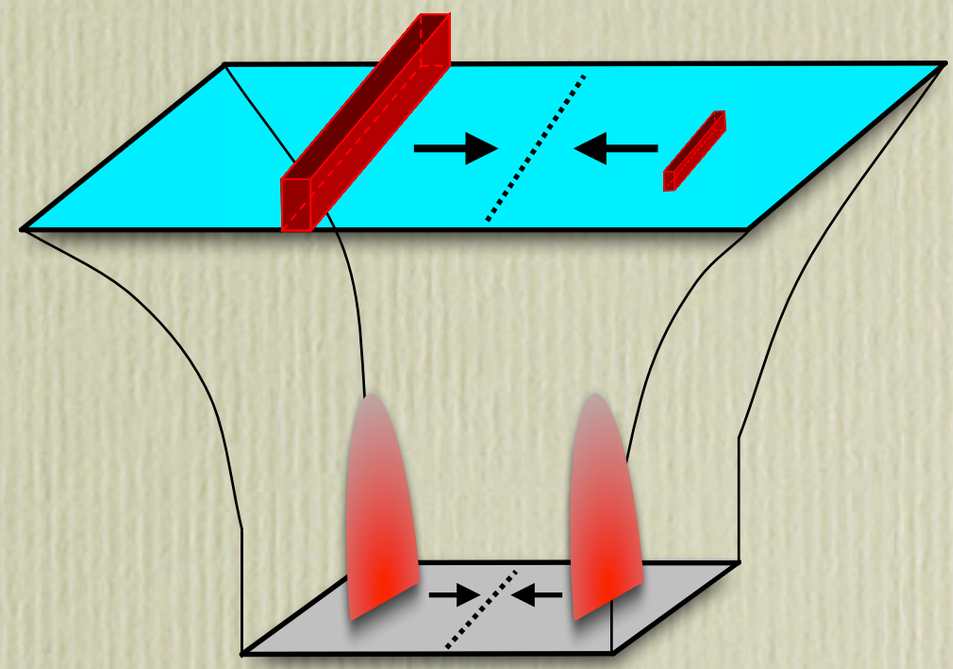

- Produce droplets of size $R \sim 1/T_{\rm hyd}$ that are well described by hydro.

Thank you.