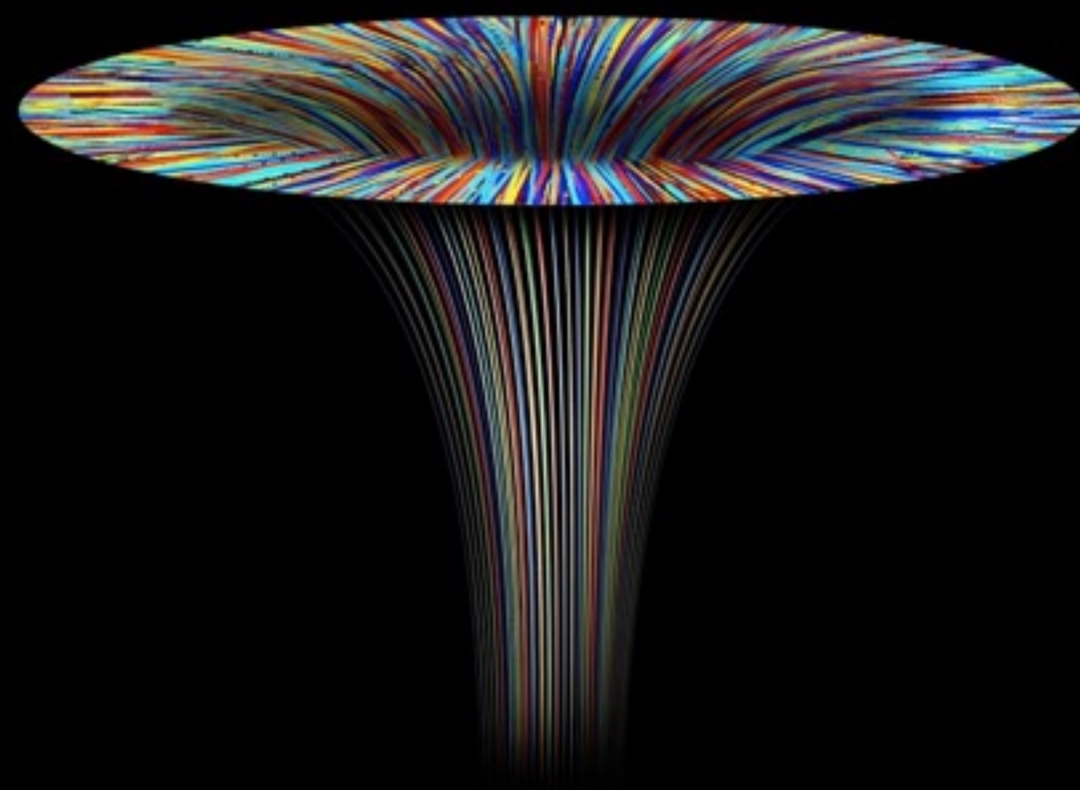
Holographic Heavy Ion Collisions



David Mateos
ICREA & University of Barcelona

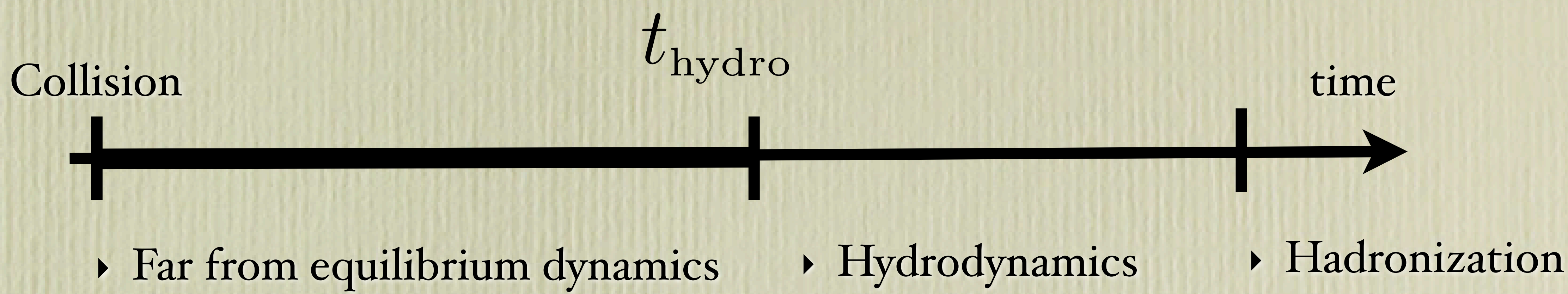
with Maximilian Attems, Jorge Casalderrey, Michal Heller, Daniel Santos-Olivan, Carlos Sopuerta, Miquel Triana, Wilke van der Schee and Miguel Zilhao

Plan

- Holography applied to QCD — limitations.
- Holography applied to heavy ion collisions — overview.
  - For newest results (non-conformal theories) see talk by Jorge Casalderrey on Thursday.
- Holography applied to cosmology — not for today.

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

Heavy ion collisions

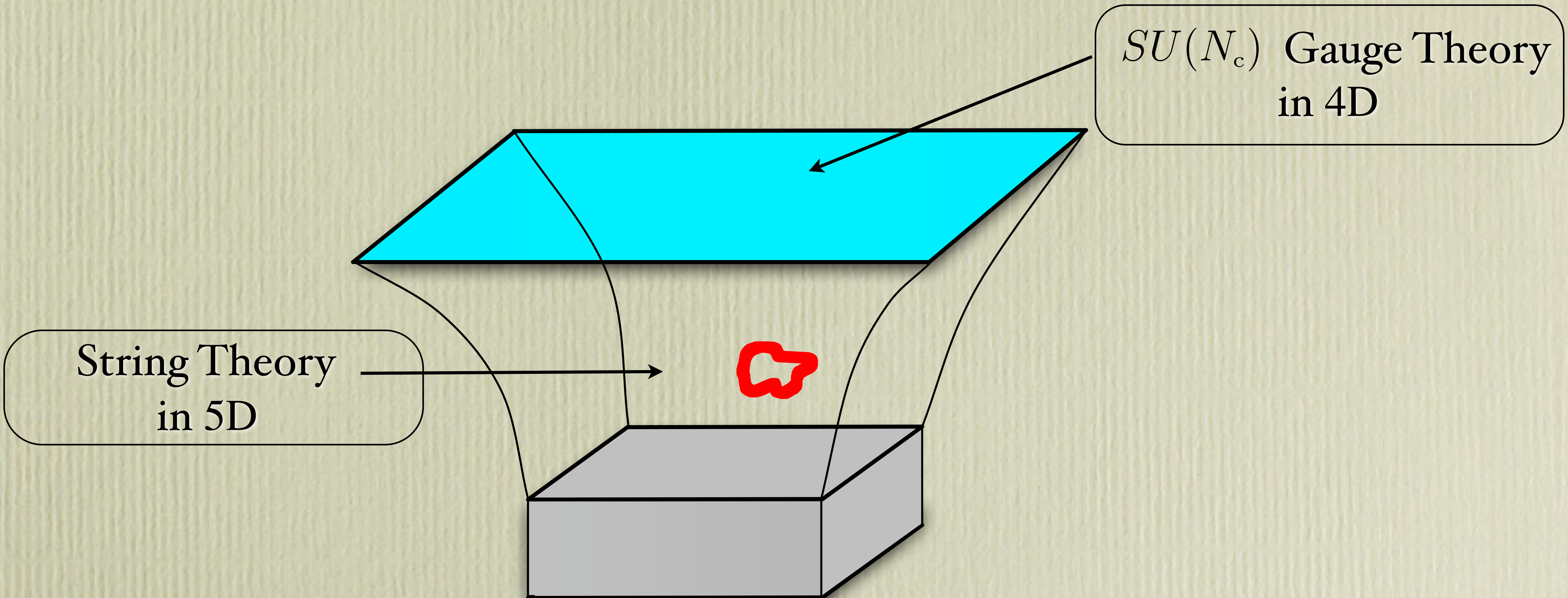


- How long is t_{hydro}? Data indicates $t_{\text{hydro}} T_{\text{hydro}} \leq 1$.
- What determines when hydro becomes applicable?
- What is the nature of the hydro expansion?
- What are the initial conditions for hydro?
- Mixture of strong & weak coupling physics.
- All explained by QCD, but QCD is hard.

The gauge/string duality

Maldacena '97

(= AdS/CFT correspondence = Holography)



From viewpoint of a *theorist*

- Duality is a remarkable development:

Quantum gravity	=	Ordinary QFT

In terms of *applications* to QCD

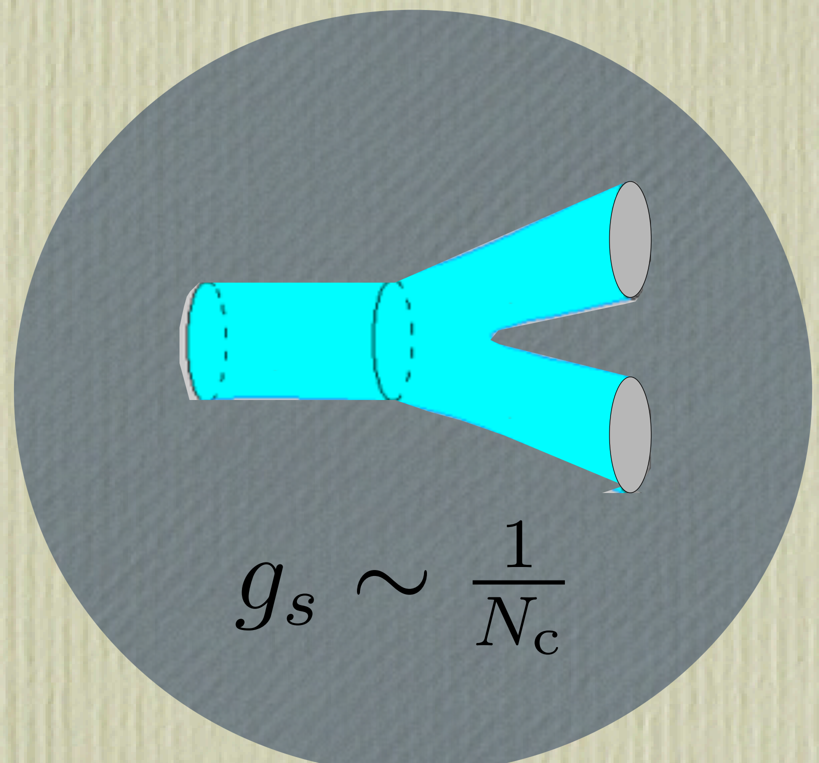
At present the duality has its own limitations

↓

Complementary tool

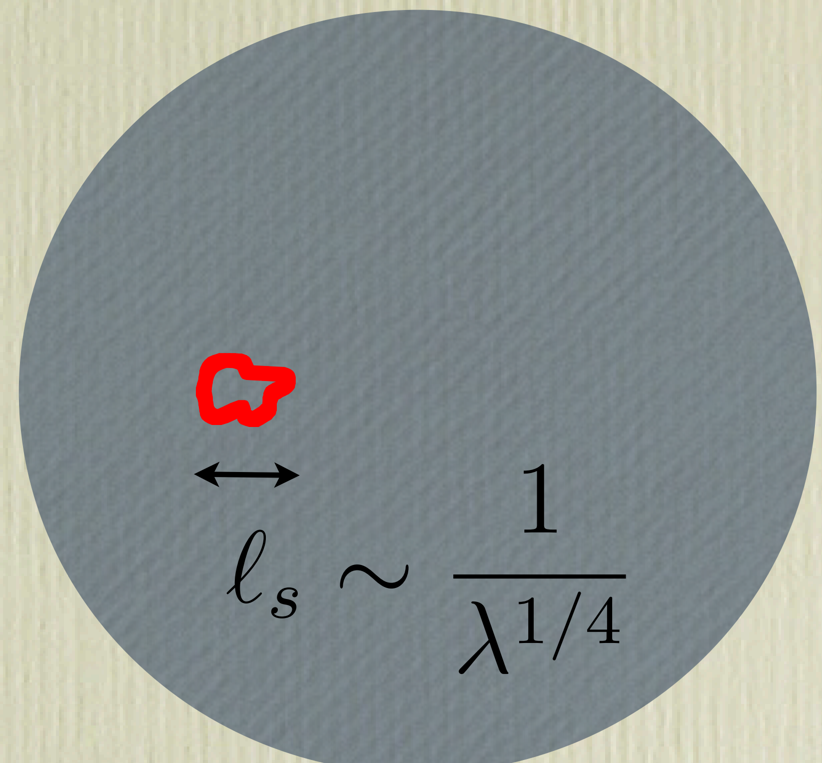
Limitations

$$N_c \longrightarrow \infty$$



Suppresses quantum corrections.

$$\lambda = g^2_{YM} N_c \longrightarrow \infty$$

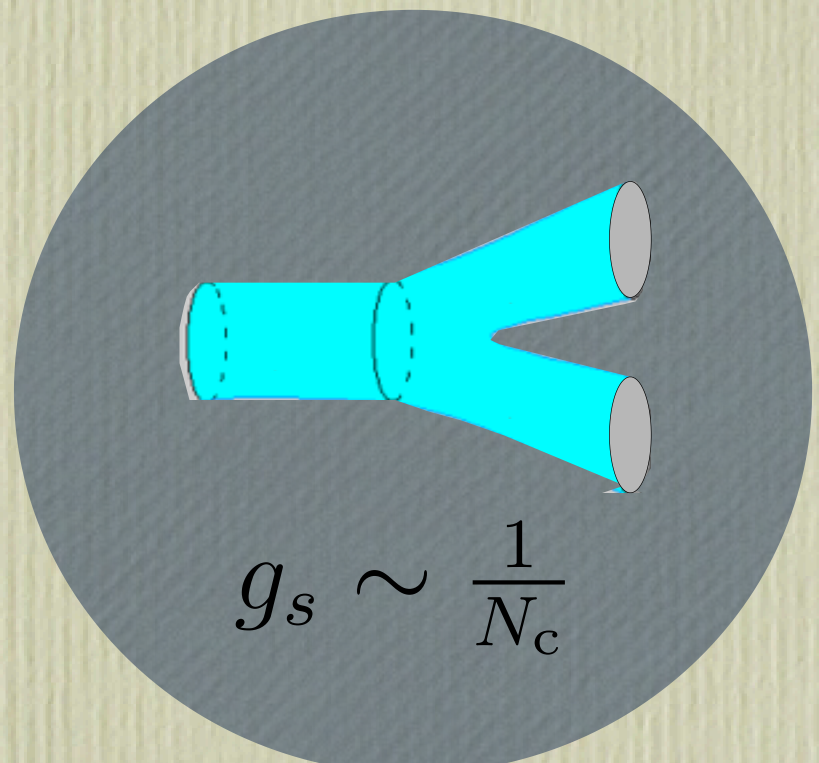


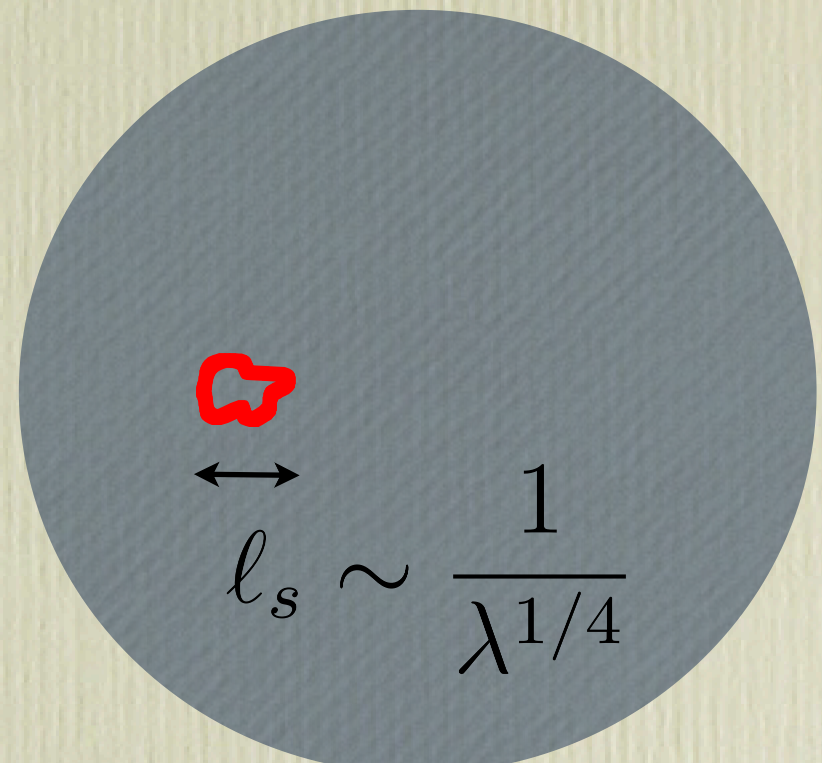
Suppresses string corrections.

Limitations

$N_c \to \infty$

$\lambda = g_{YM}^2 N_c \to \infty$





Suppresses quantum corrections.

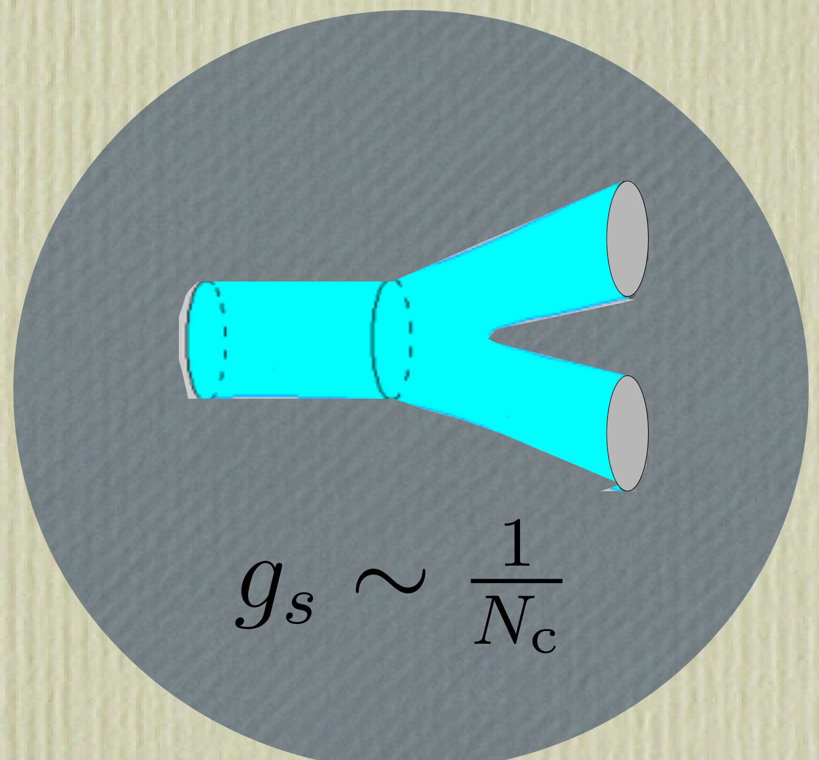
Suppresses string corrections.

→ Classical Gravity!

Limitations

$N_c \longrightarrow \infty$

$\lambda = g_{\rm YM}^2 N_c \to \infty$



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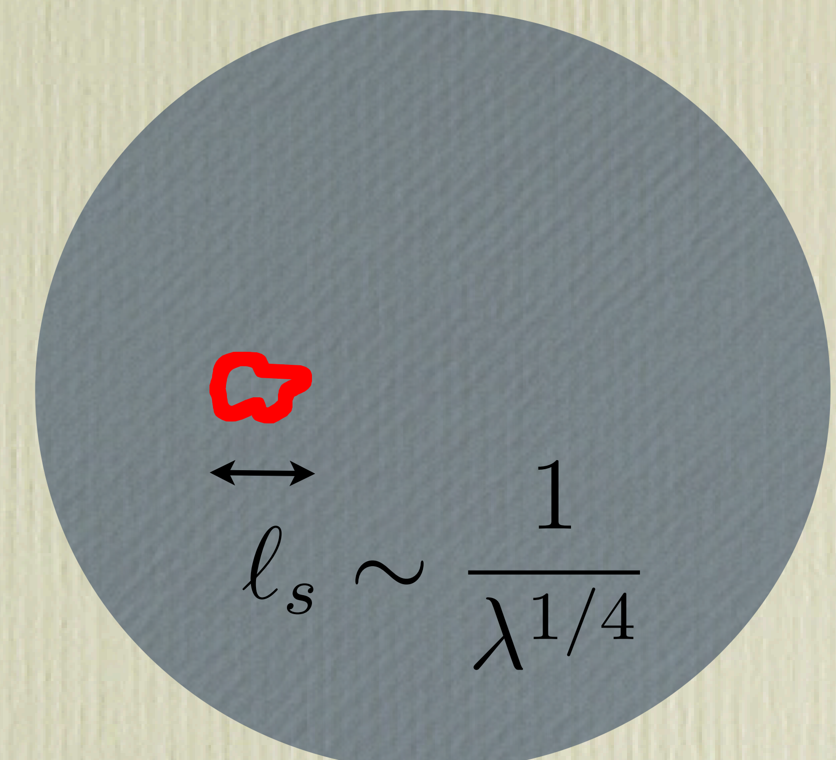


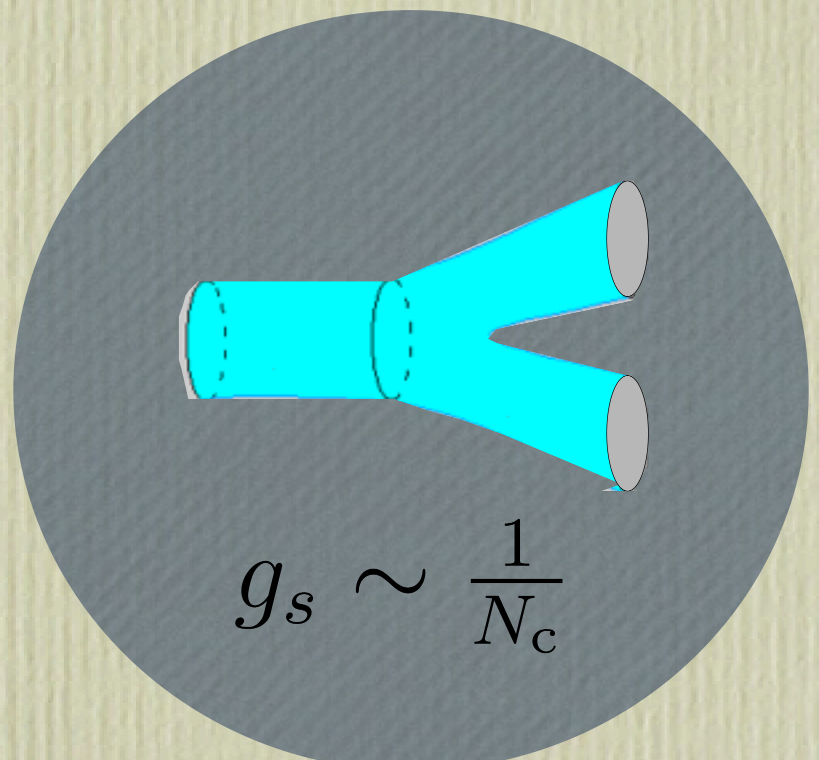
Makes the string tiny.

Solving large- N_c would be great progress!

Limitations

$N_c \longrightarrow \infty$

$\lambda = g_{YM}^2 N_c \longrightarrow \infty$



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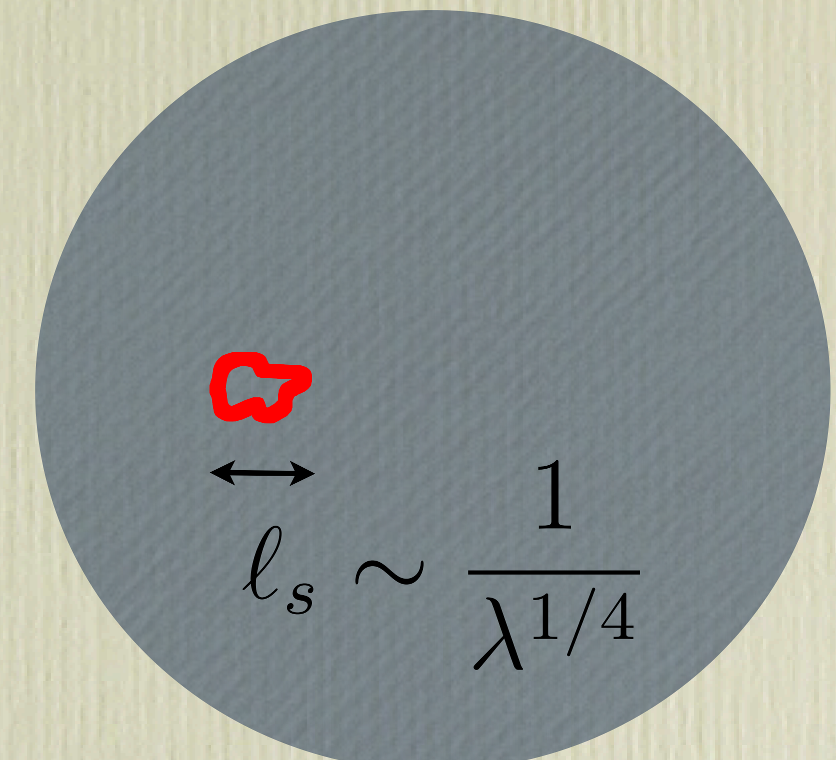


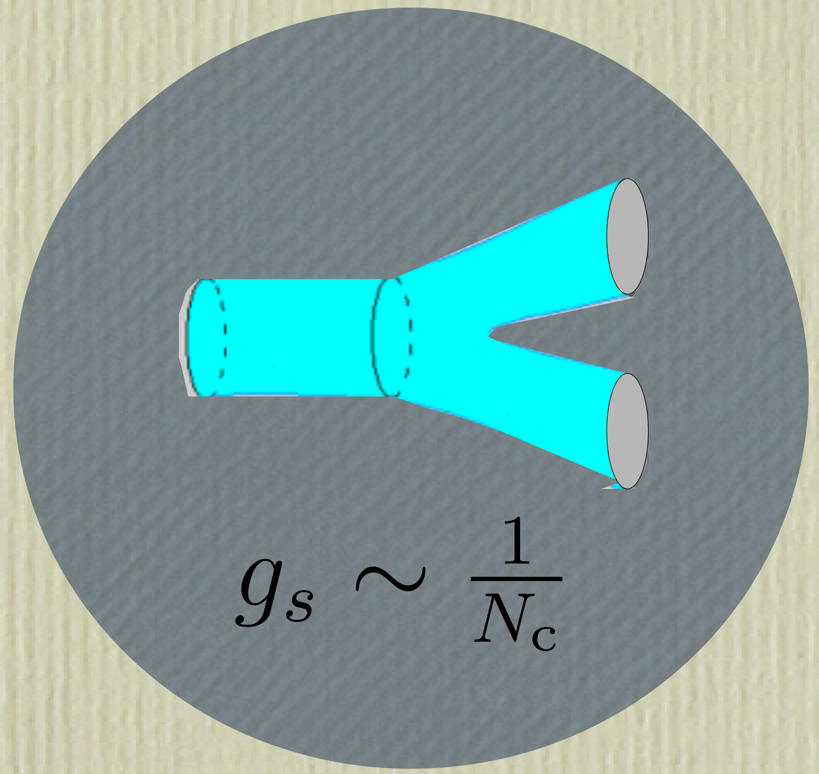
Makes the string tiny.

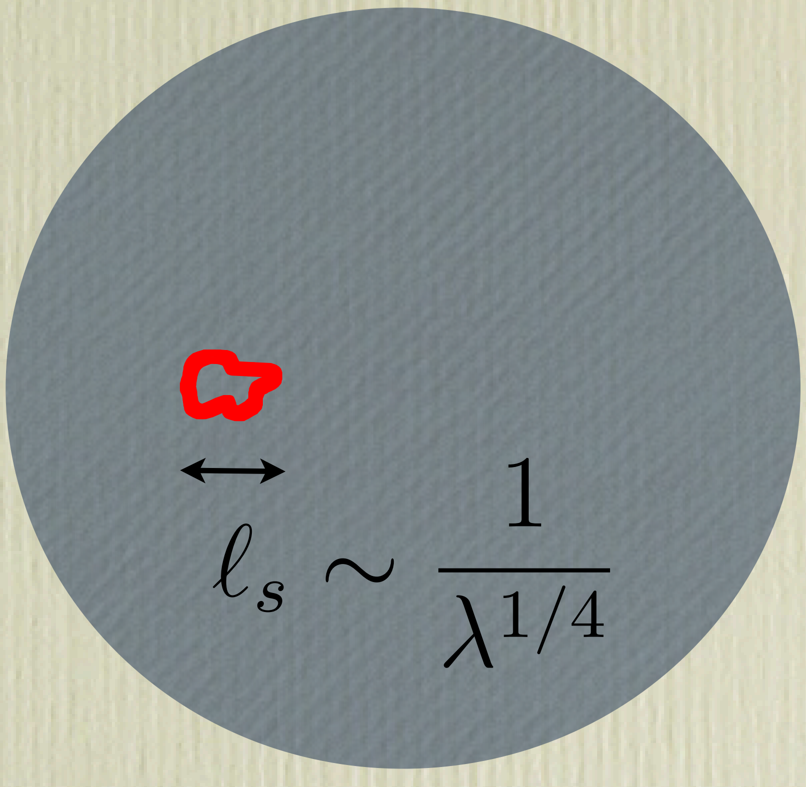
- Asymptotically free.
- Dynamically generated scale.
- Confinement.
- Deconfinement phase transition.
- ...

Limitations

$N_c \rightarrow \infty$

$\lambda = g_{YM}^2 N_c \rightarrow \infty$



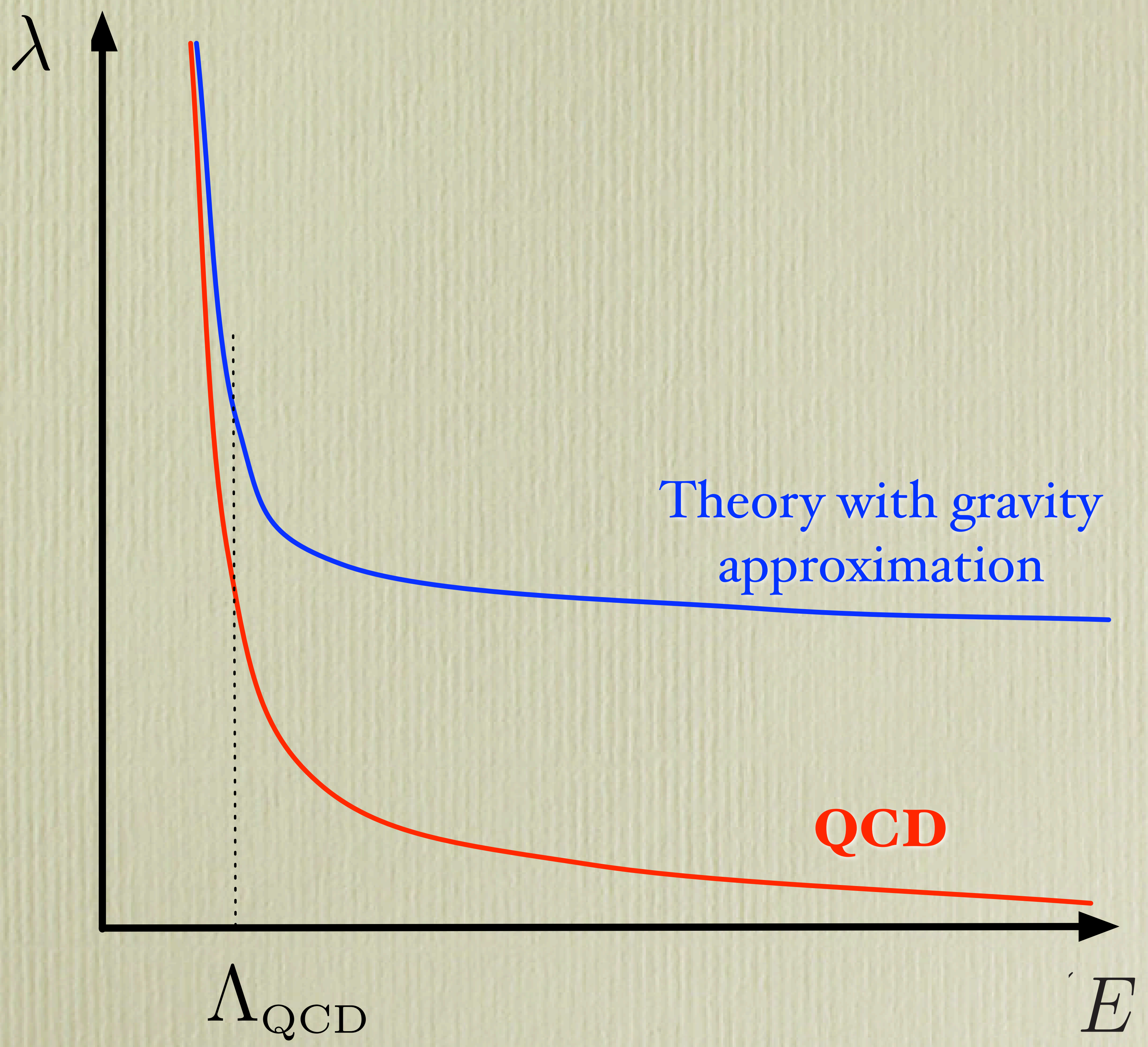


Suppresses quantum corrections.

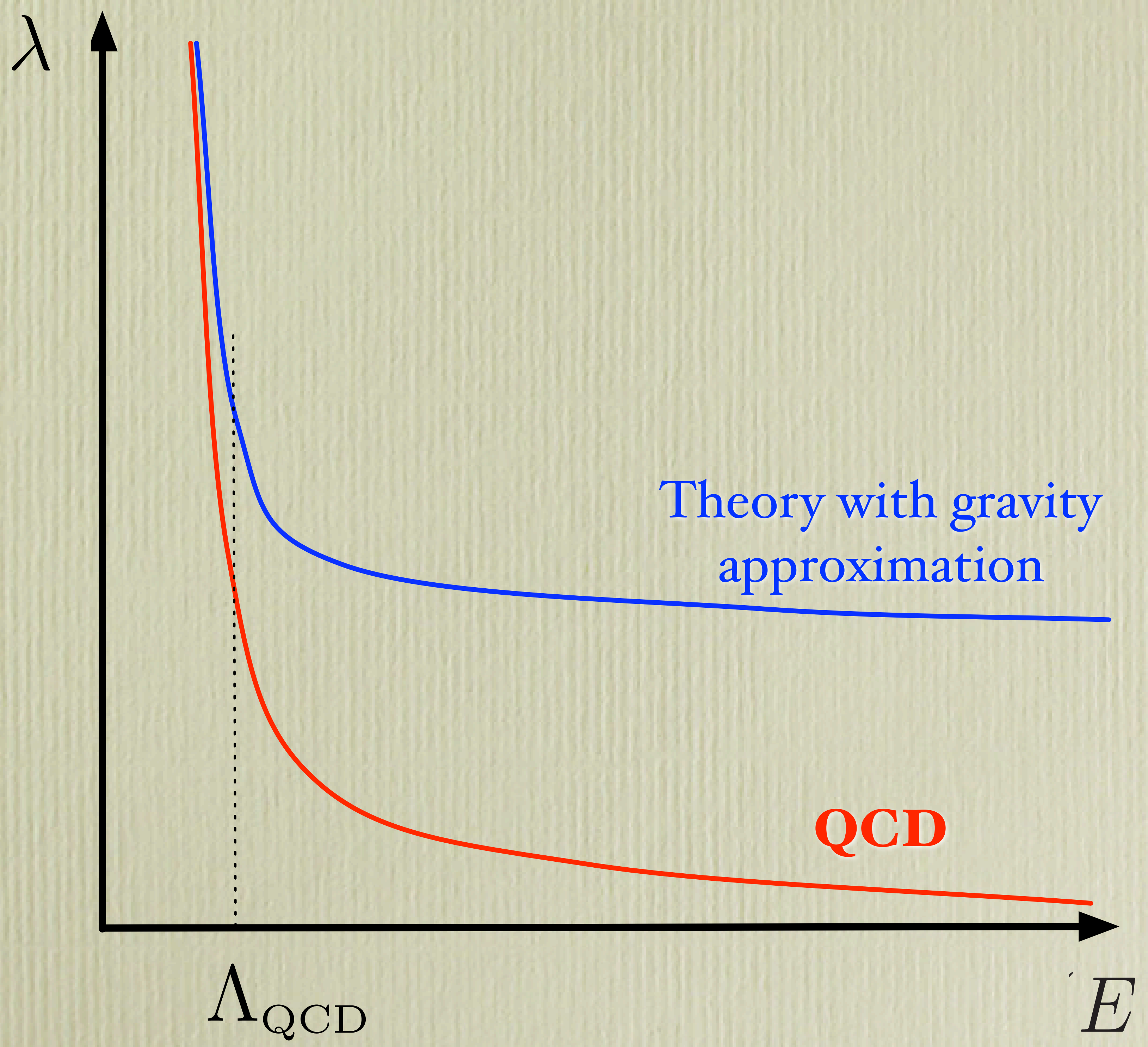
Makes the string tiny.

Strong coupling means *no* asymptotic freedom!

Limitations



Limitations

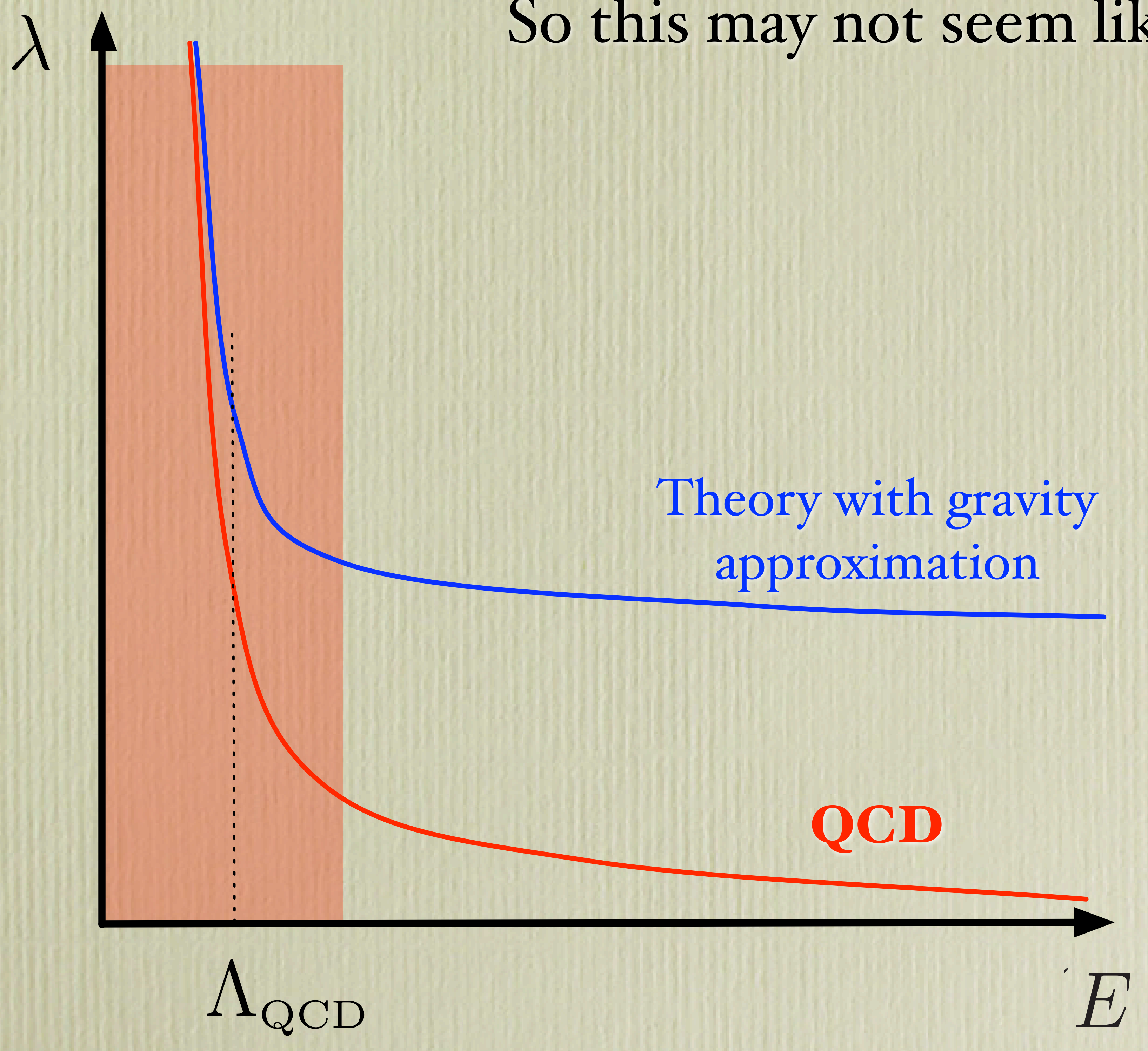


Need not be CFT!

- Confinement.
- SχSB.
- Thermal phase transitions.
- Etc.

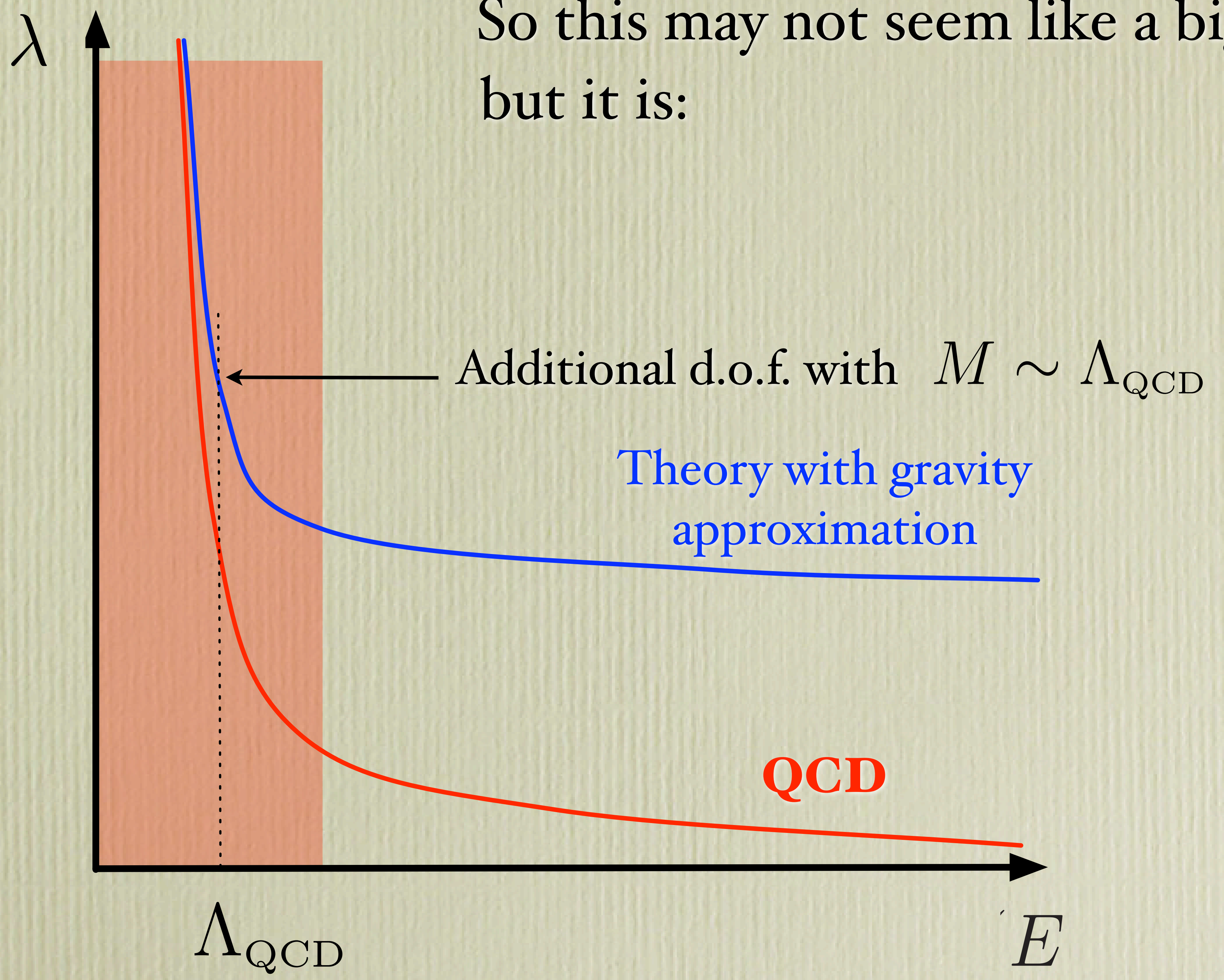
Limitations

So this may not seem like a big deal...



Limitations

So this may not seem like a big deal...
but it is:



Therefore

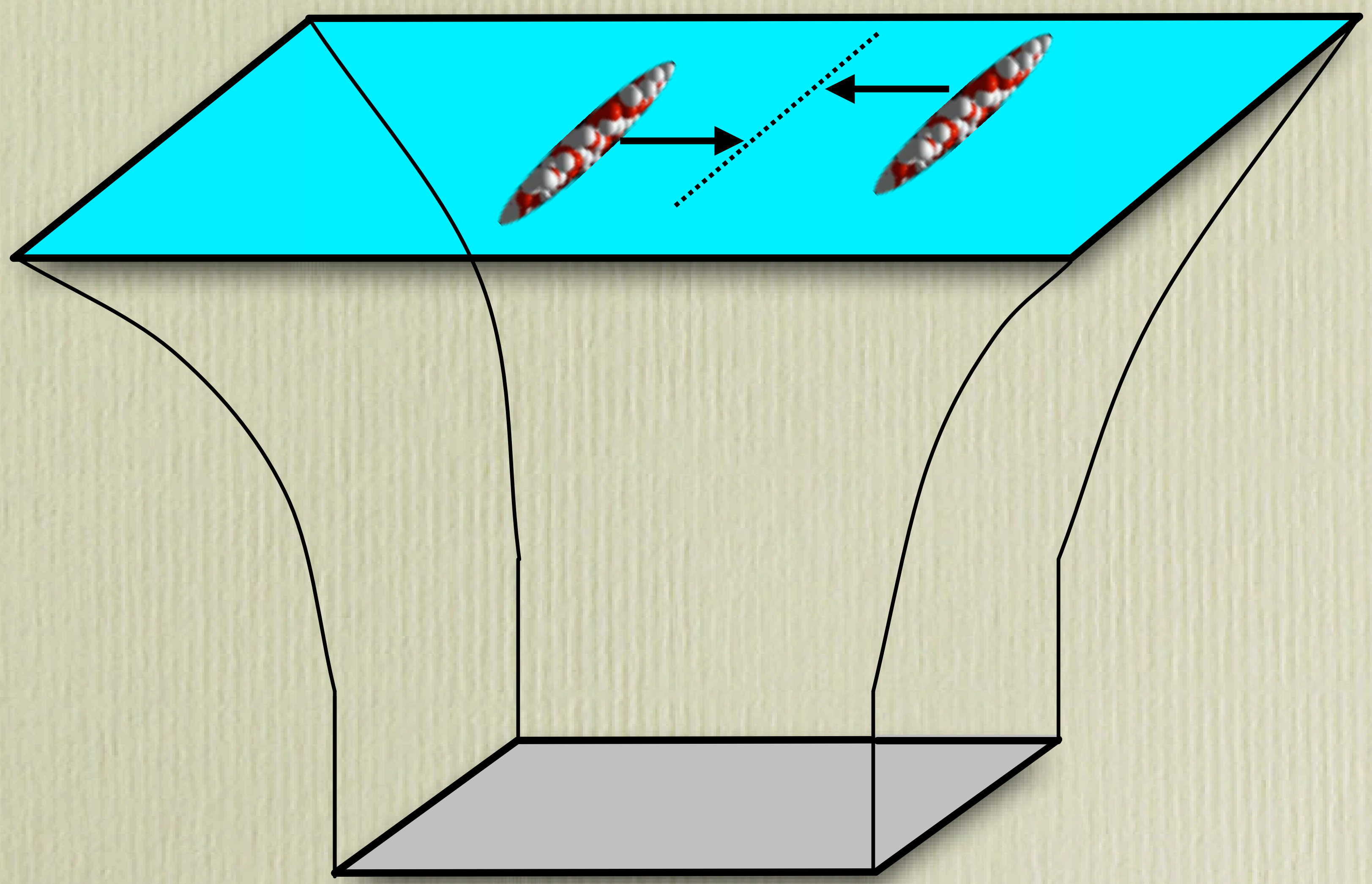
- At present gauge/string duality is not a tool for *precision* QCD physics.

- However, it may still provide useful insights.

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

What we would like to do

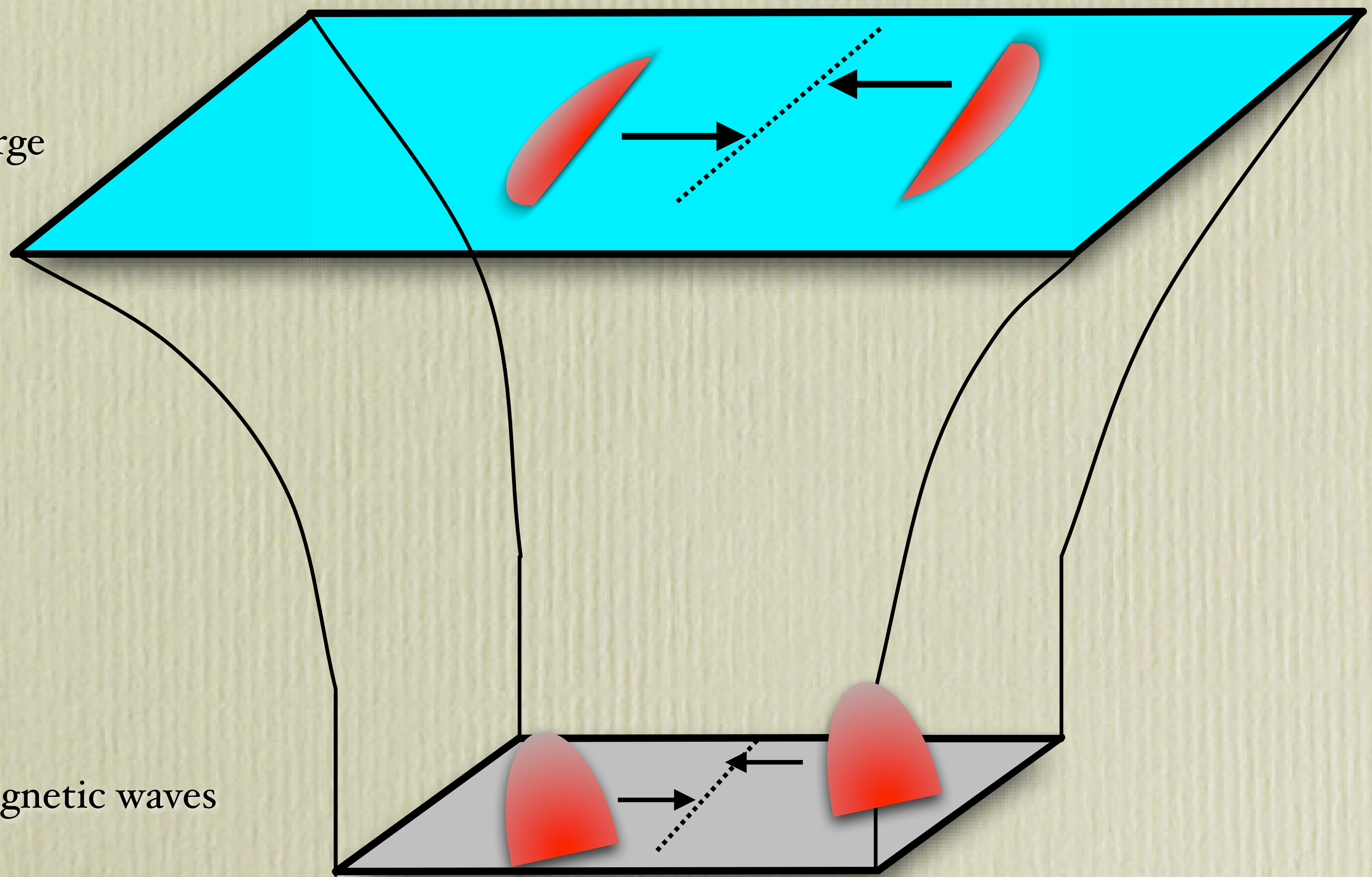
Heavy ion collisions in QCD



What we can do

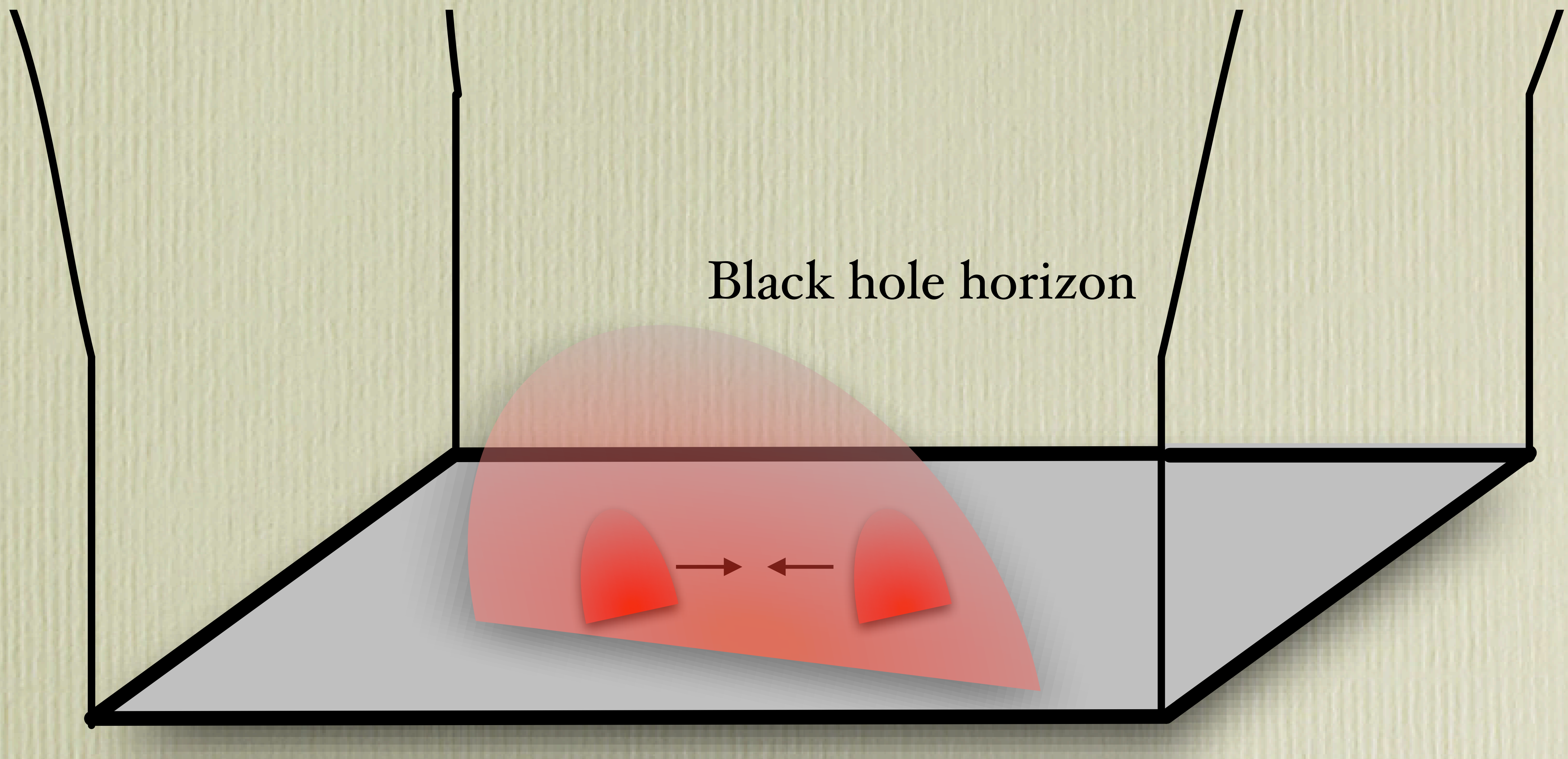
Holographic heavy ion collisions

Caricatures:
Lumps of energy and charge



Gravitational + electromagnetic waves

Formation and evolution of the QGP

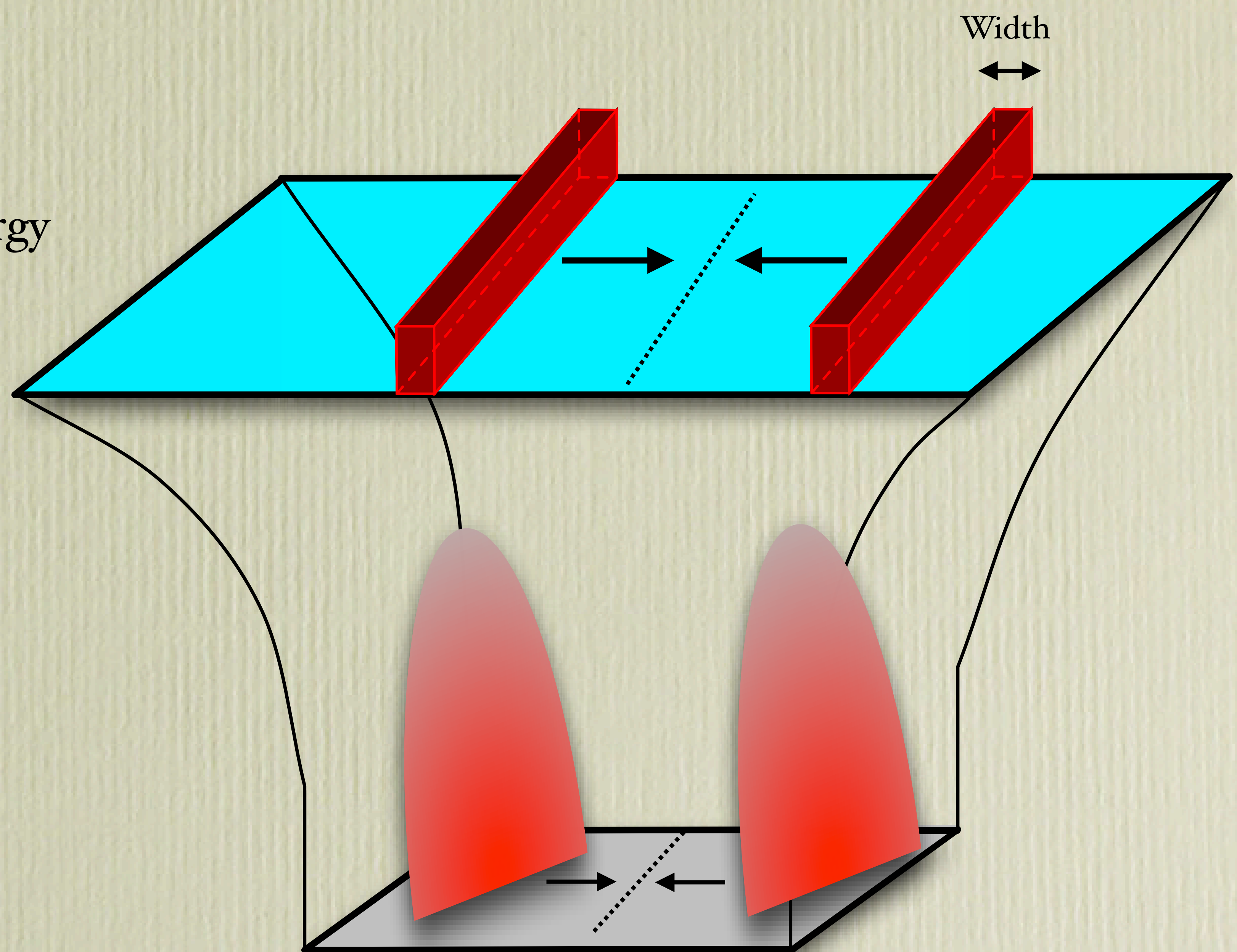


Holographic heavy ion collisions in CFT

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

Holographic heavy ion collisions in CFT

Chesler & Yaffe '10

- No transverse dynamics.

- CFT implies EOS obeyed in and out of equilibrium:

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

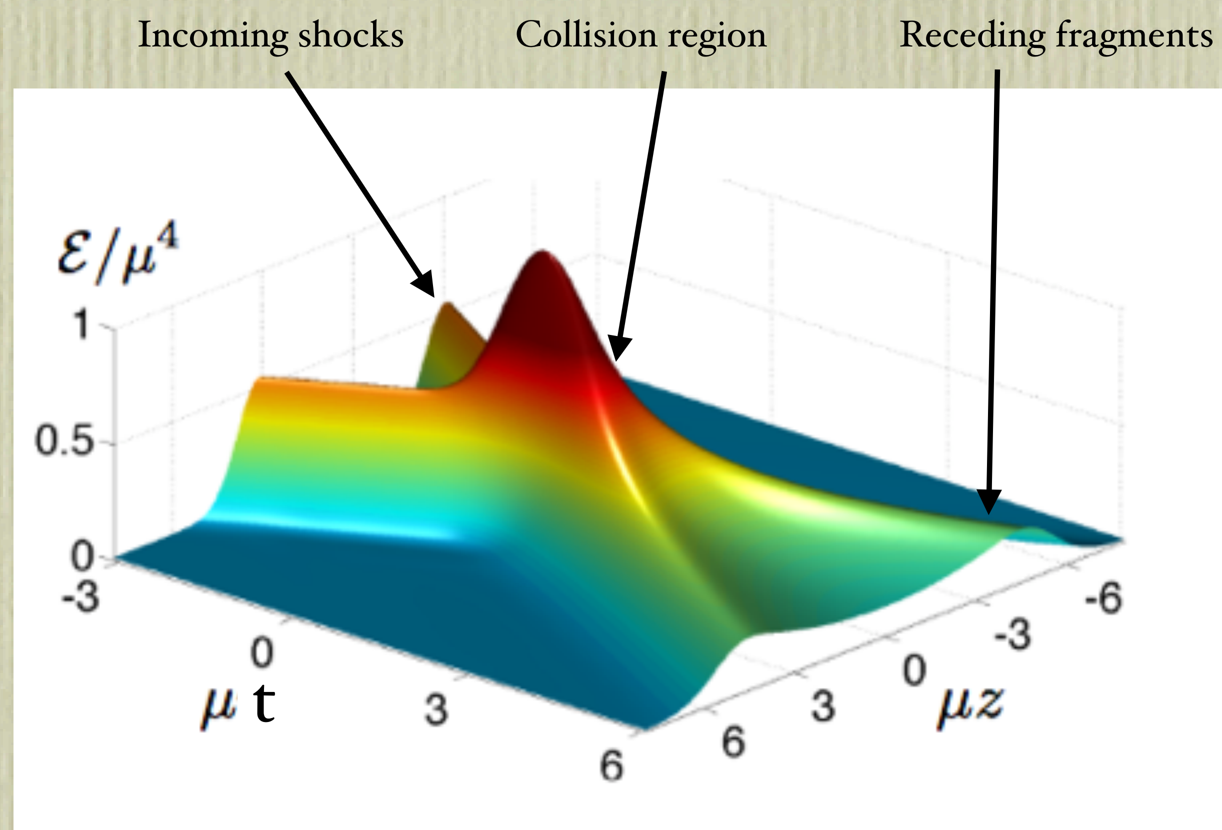
$$\bar{P} = \frac{1}{3}\left(P_L + 2P_T\right)$$

- I emphasize: EOS is a statement about **average** pressure.

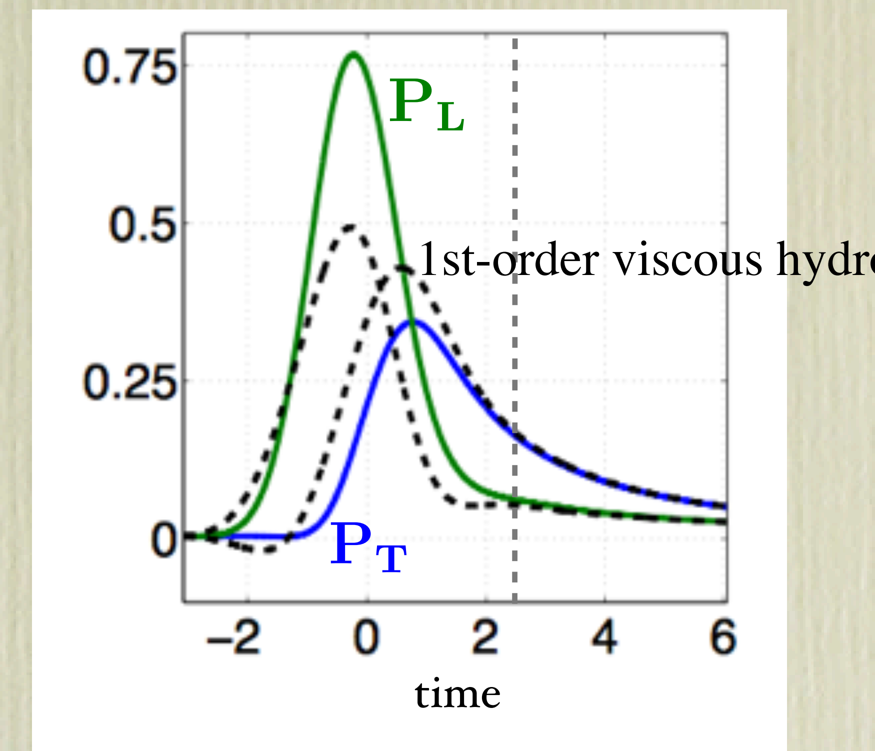
- Therefore P_L and P_T can deviate a lot from $P_{\rm eq}$!

Holographic heavy ion collisions in CFT

Chesler & Yaffe '10



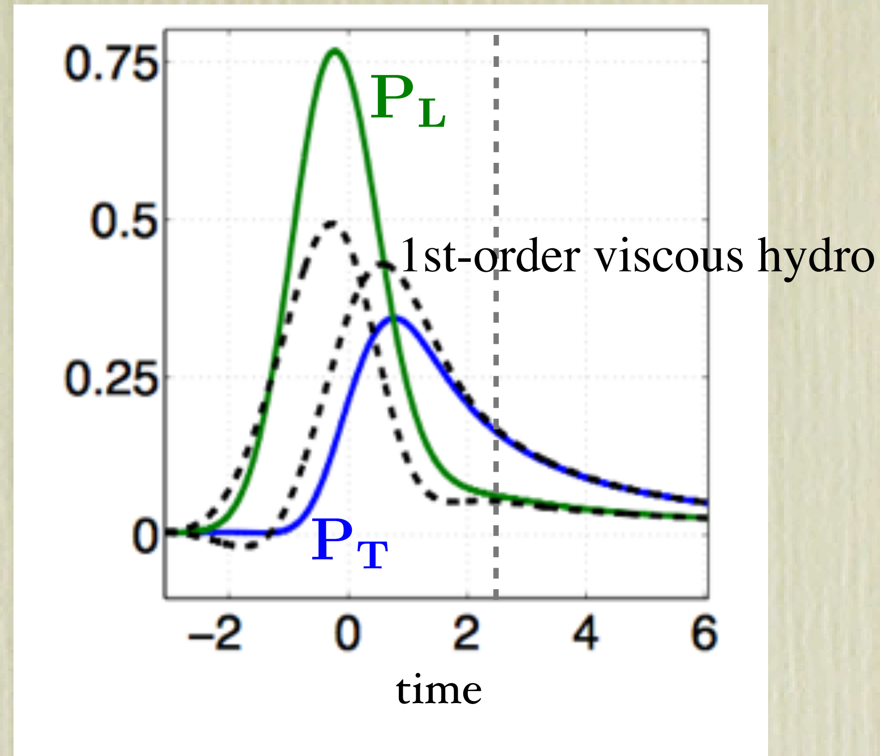
Pressures at mid rapidity



Holographic heavy ion collisions in CFT

Chesler & Yaffe '10

Pressures at mid rapidity



- Hydro applies at $t_{\rm hydro} T_{\rm hydro} \simeq 0.65$.
- Hydrodynamization without isotropization:

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

- Hydro works when gradients are still very large:

$$P_L^{\rm hyd} = P_{\rm eq} + P_\eta + \not{P_\zeta}$$

$$P_T^{\rm hyd} = P_{\rm eq} - \frac{1}{2} P_\eta + \not{P_\zeta}$$

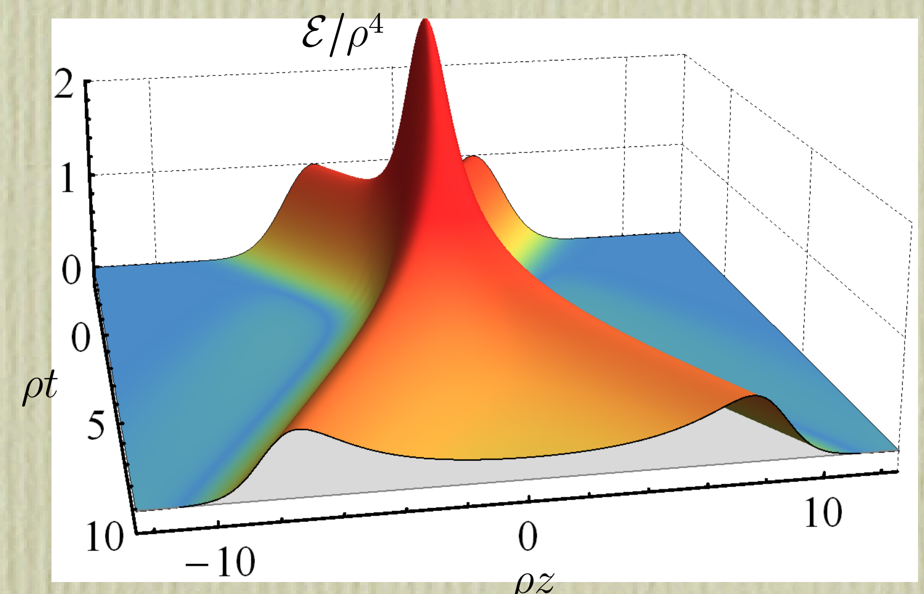
shear viscosity ↑ (under P_η)

bulk viscosity ↑ (under P_ζ)

A dynamical cross-over

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

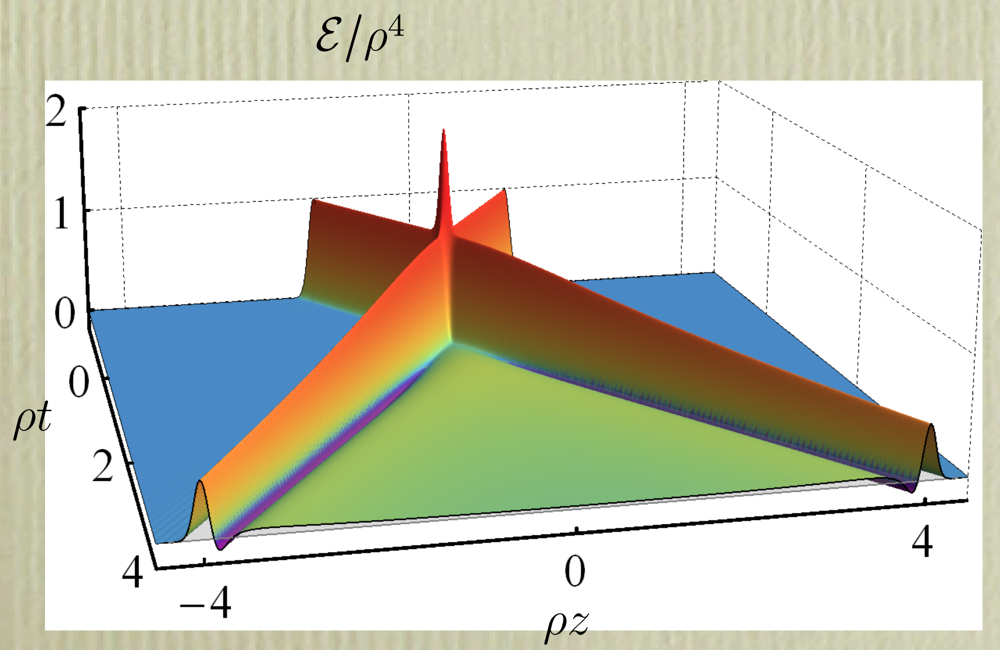
Qualitatively different dynamics depending on the collision energy:



Low energy collision (thick shocks)

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.



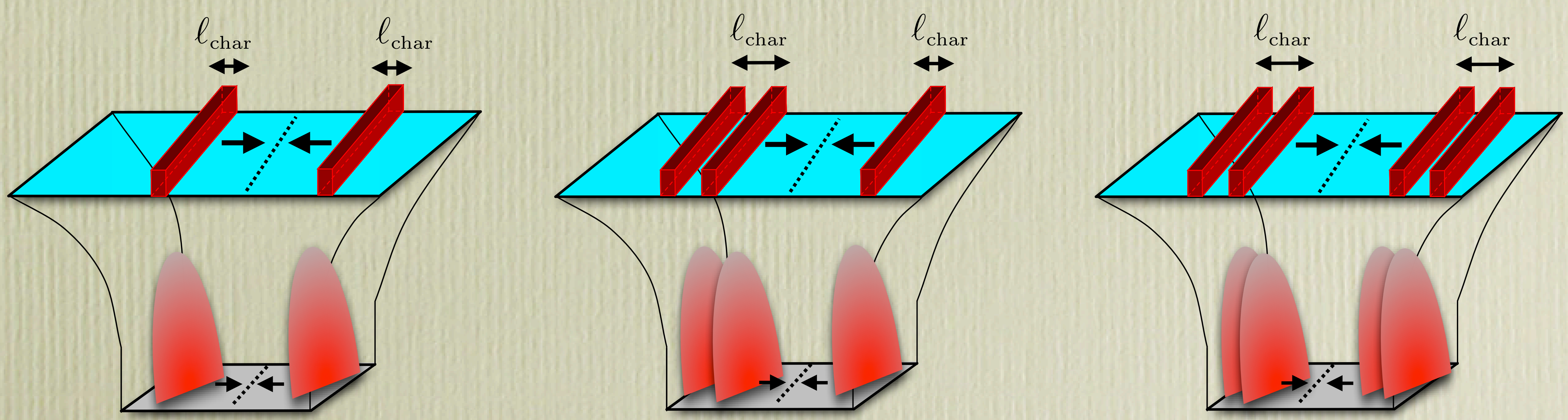
High energy collision (thin shocks)

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.

Longitudinal coherence and asymmetric collisions

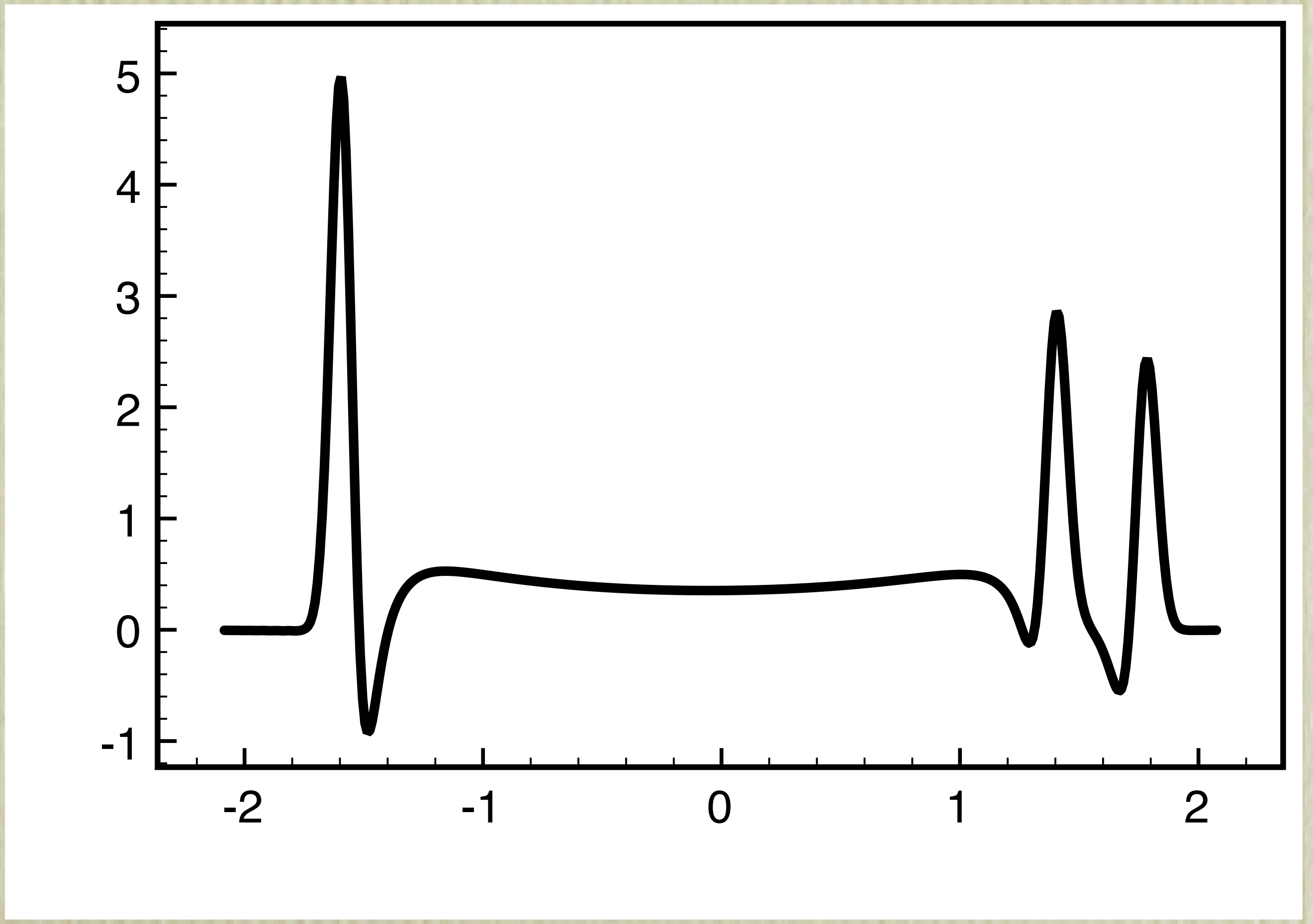
- **Motivation**: p+A collisions have asymmetric longitudinal extent/structure.
- **Motivation**: In fact, A+A collisions also have longitudinal structure (albeit symmetric).
- **Question**: Does any of this leave an imprint on the resulting plasma?
- **Compare** the following collisions (at fixed total energy):



Single-Single   Single-Double   Double-Double

Longitudinal coherence and asymmetric collisions

- **Answer**: Longitudinal structure leaves no imprint if $\ell_{\rm char} \lesssim 0.26/T_{\rm hyd}$ (coherence).



Coherent regime

Longitudinal coherence and asymmetric collisions

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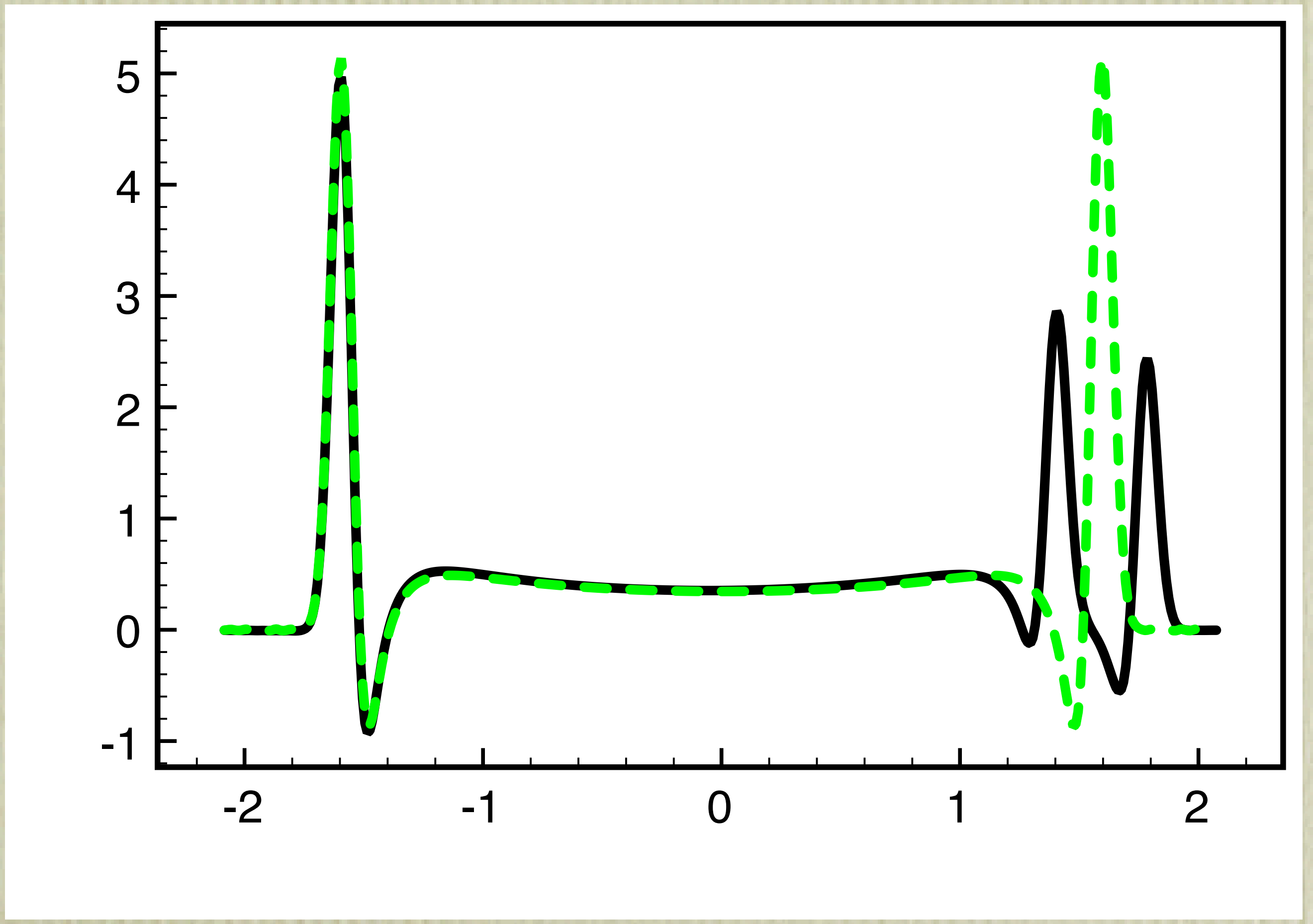

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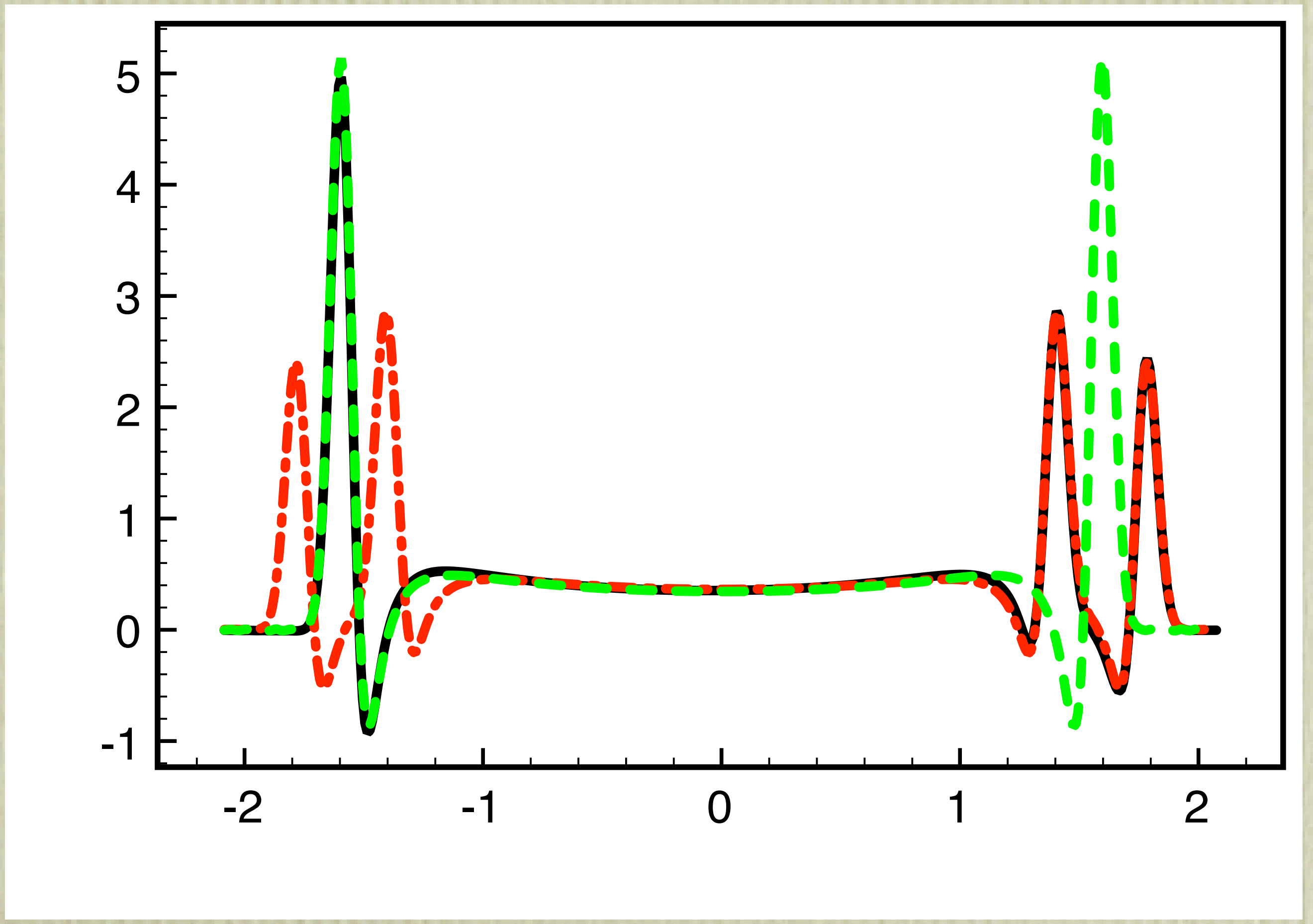

Coherent regime

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

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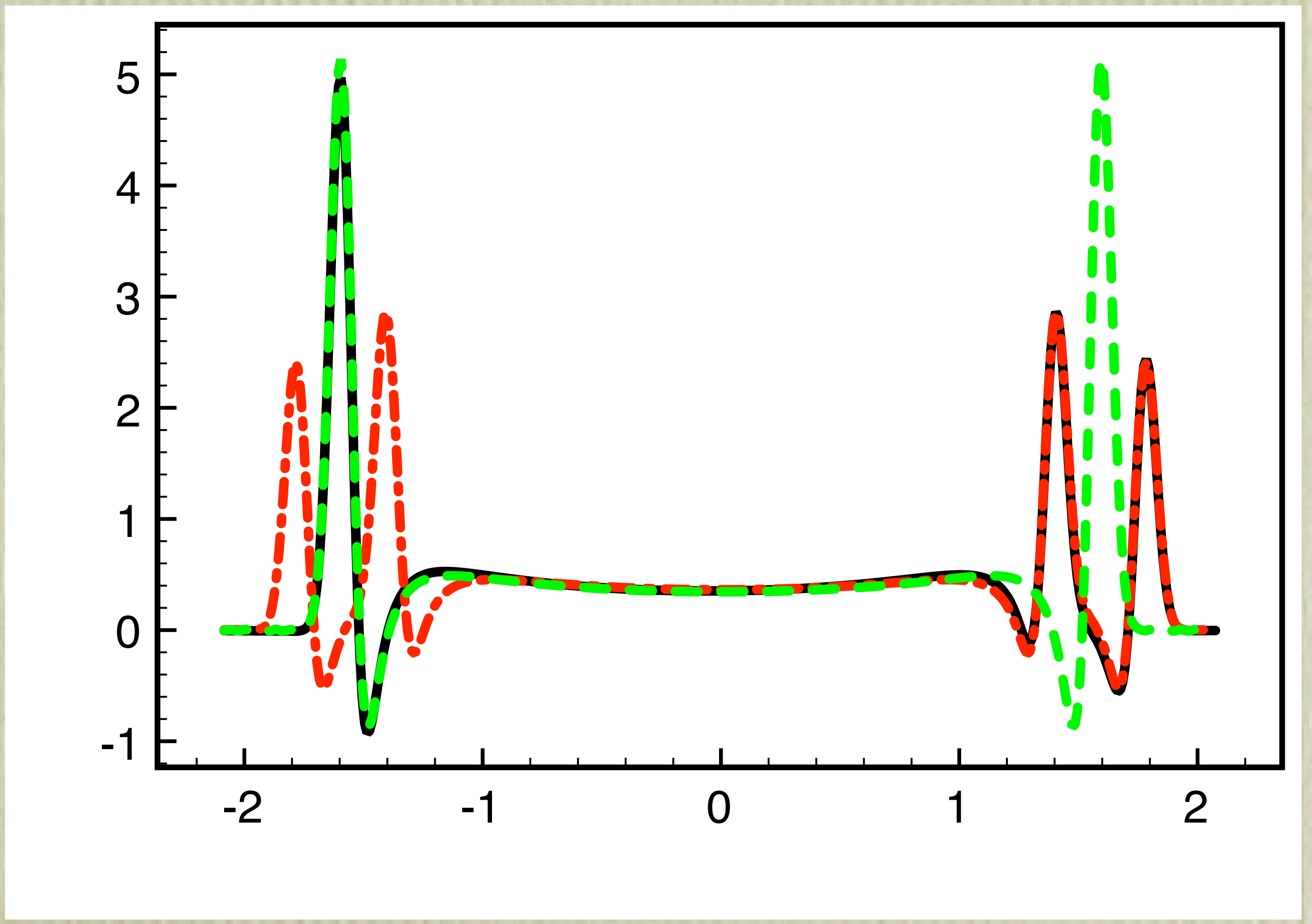
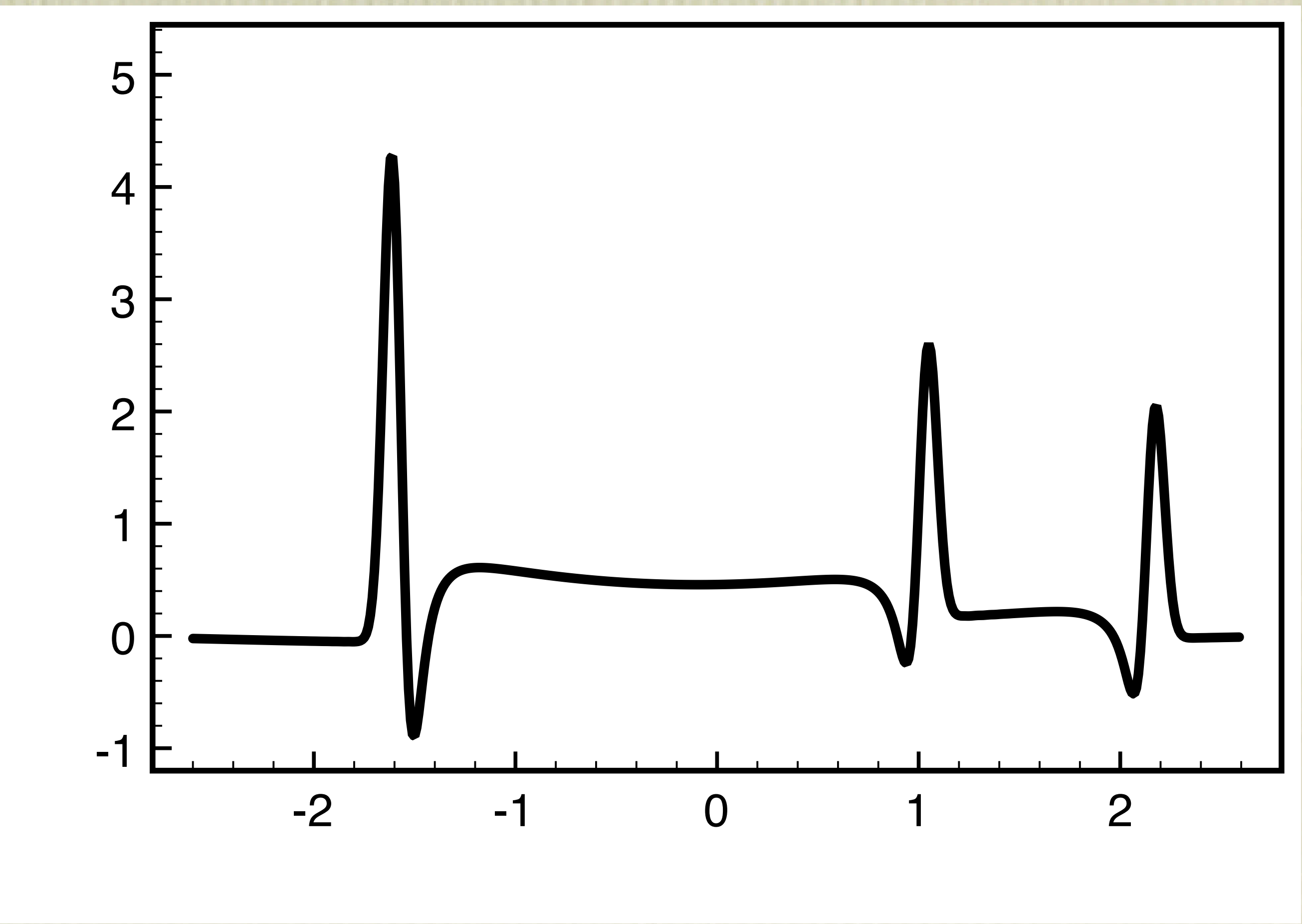


Coherent regime



Incoherent regime

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

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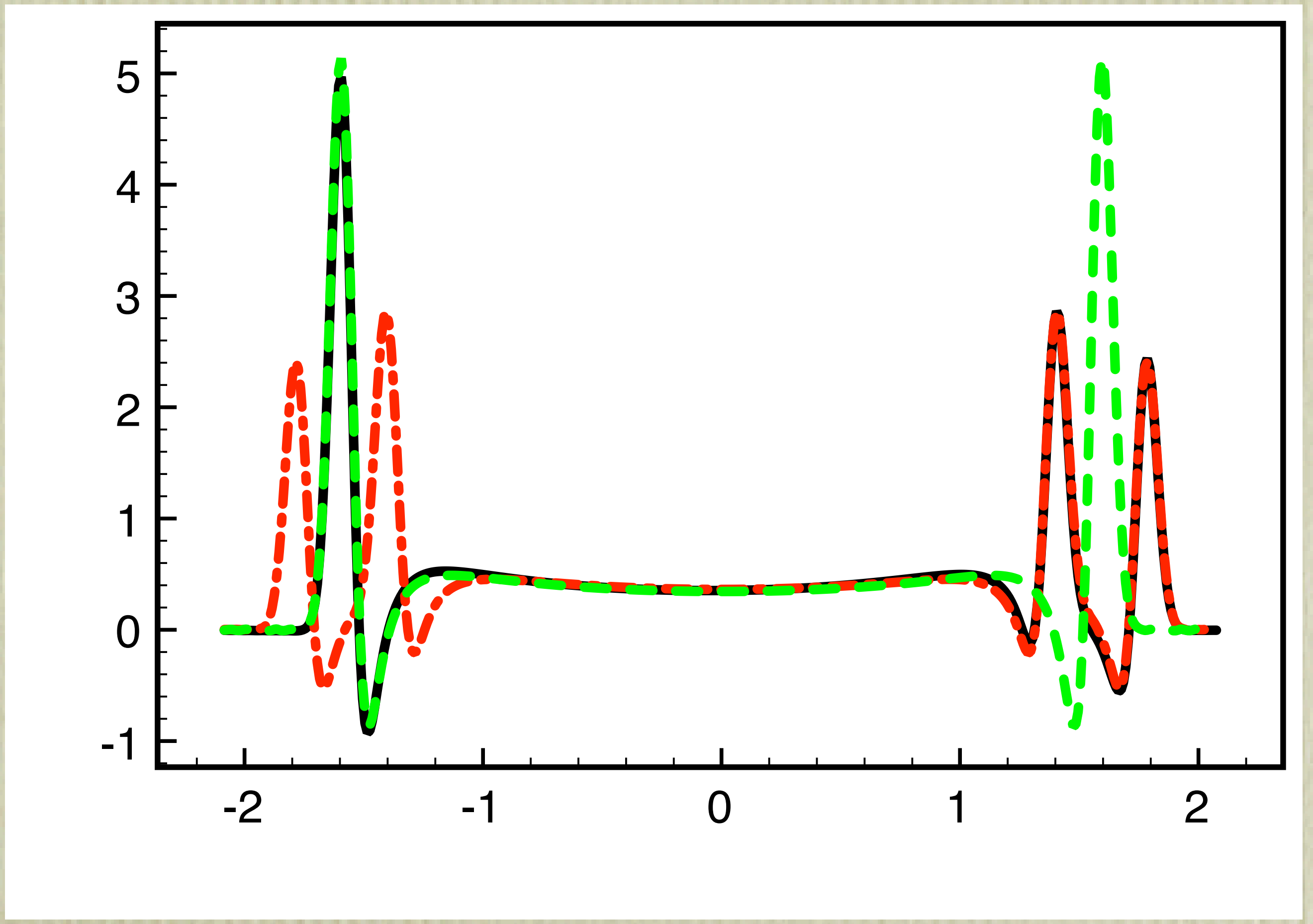
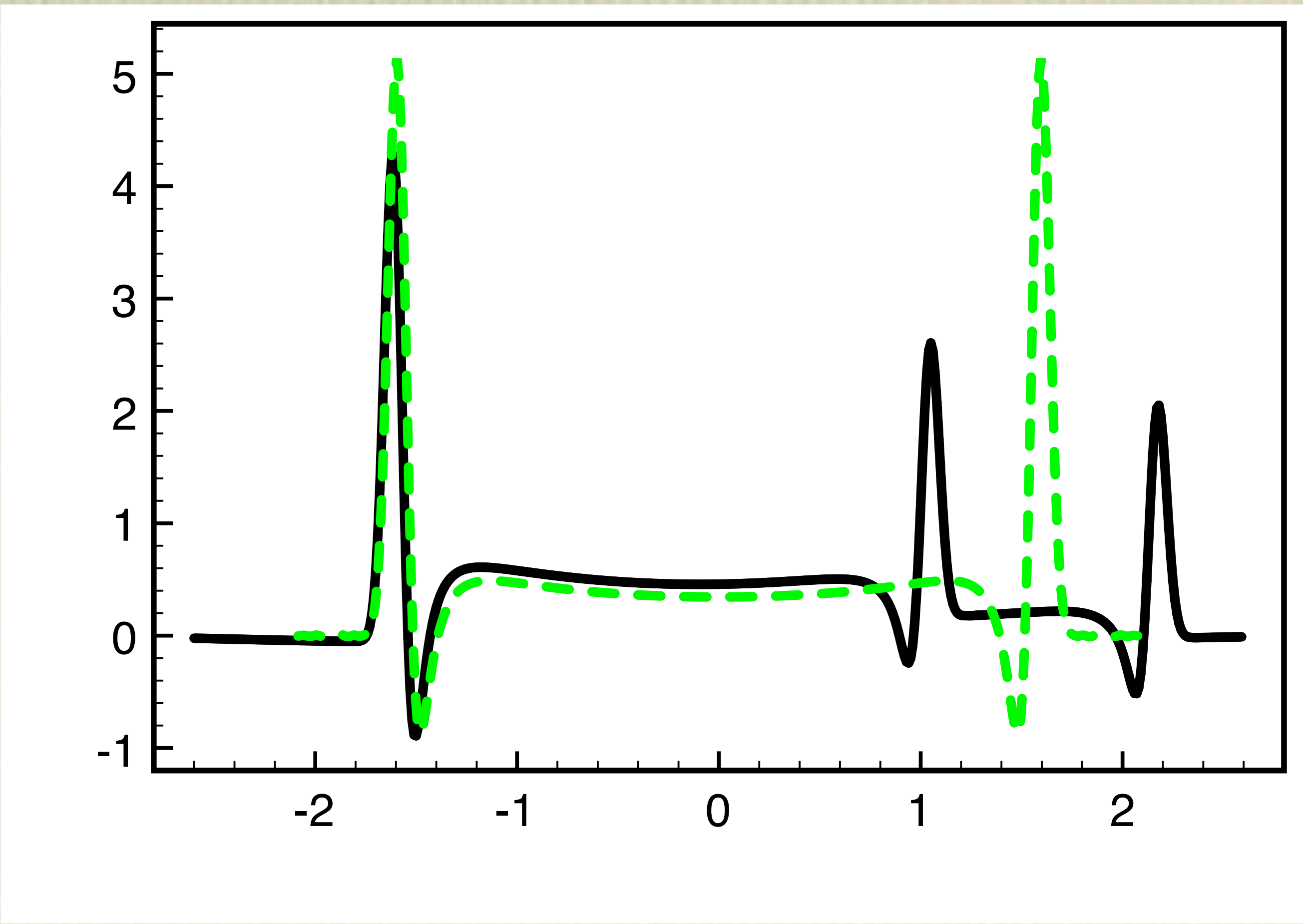


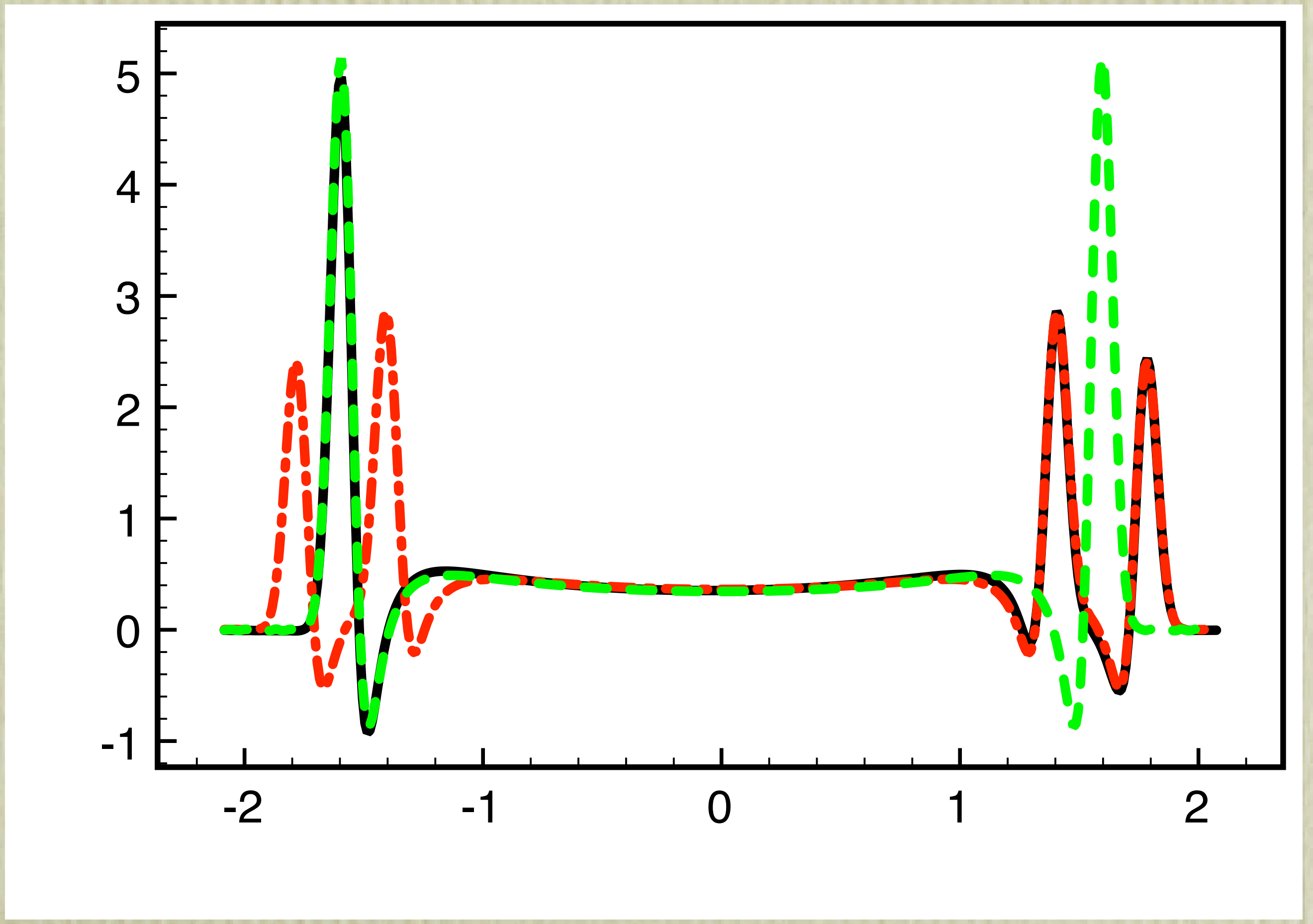
Coherent regime

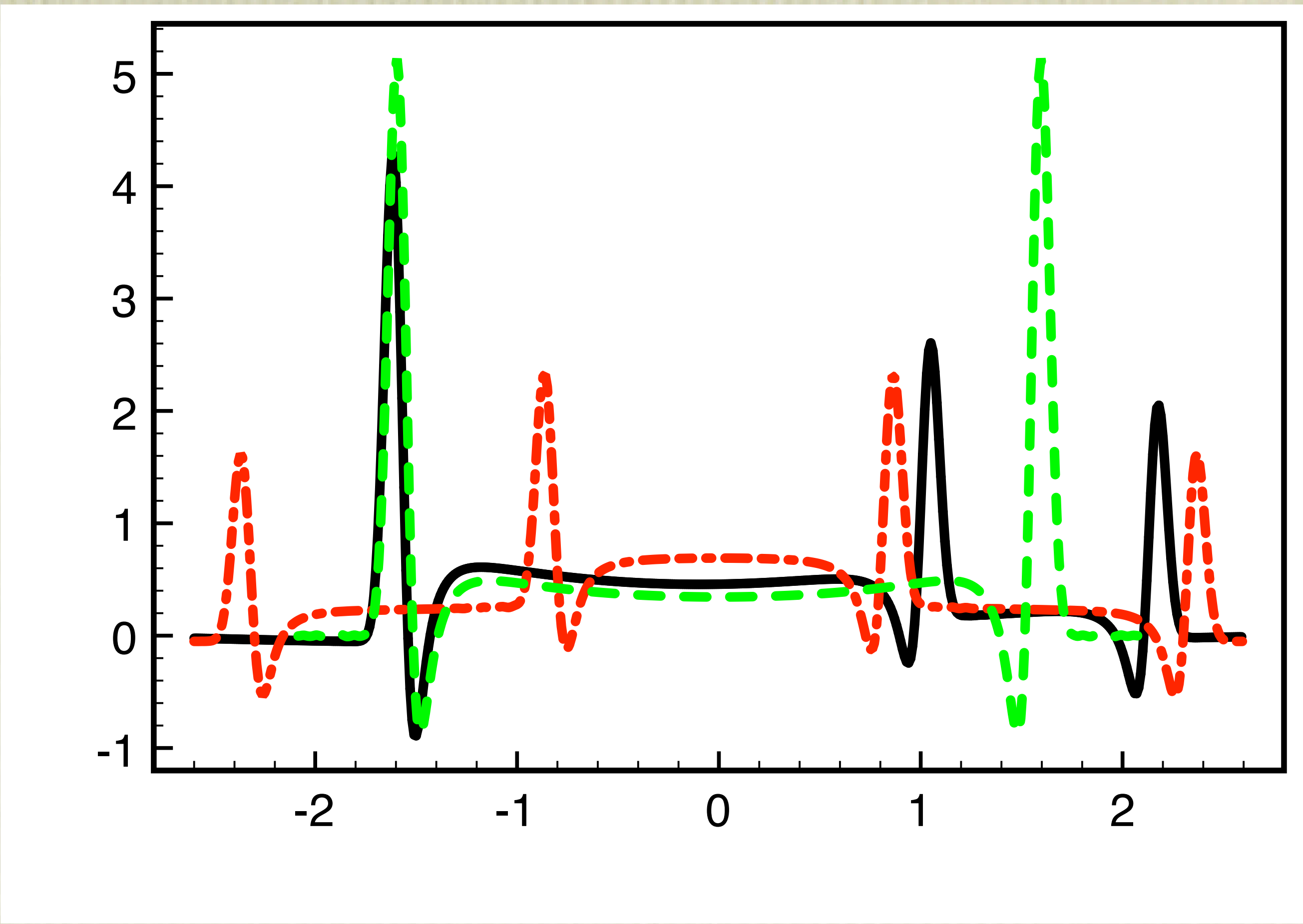


Incoherent regime

Longitudinal coherence and asymmetric collisions

- **Answer**: Longitudinal structure leaves no imprint if $\ell_{\rm char} \lesssim 0.26/T_{\rm hyd}$ (coherence).
- **Implication**: In coherent regime c.o.m. of QGP equals c.o.m. of all participating nucleons.





Coherent regime

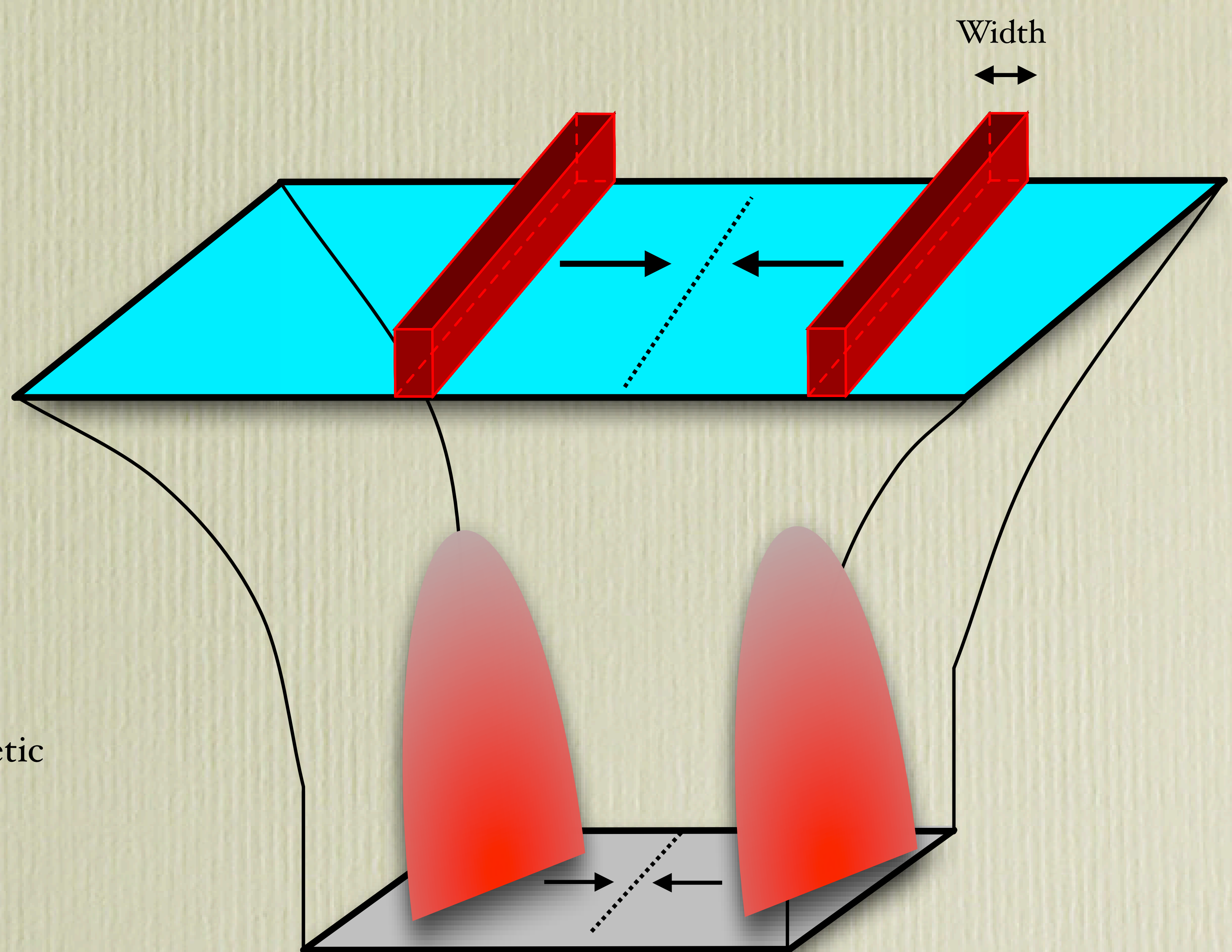
Incoherent regime

Collisions with baryon charge

Casalderrey, D.M., van der Schee & Triana ’16

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

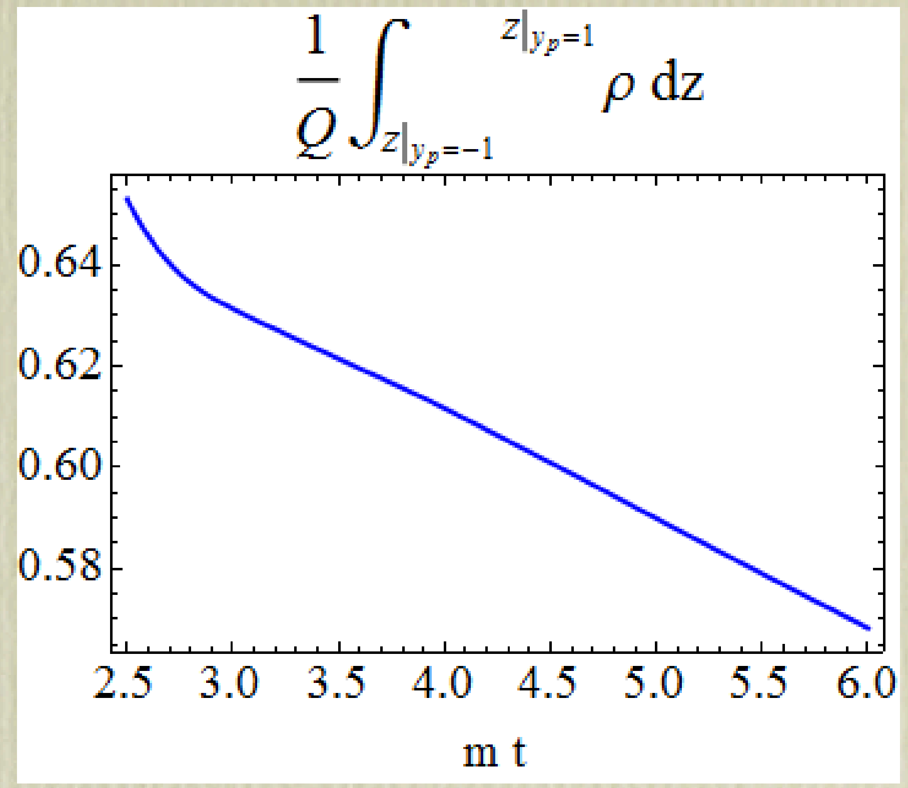
Casalderrey, D.M., van der Schee & Triana ’16

- 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.



Casalderrey, Gulhan, Milhano, Pablos & Rajagopal ’14

Iancu & Mukhopadhyay ’15

Mukhopadhyay, Preis, Rebhan & Stricker ’16

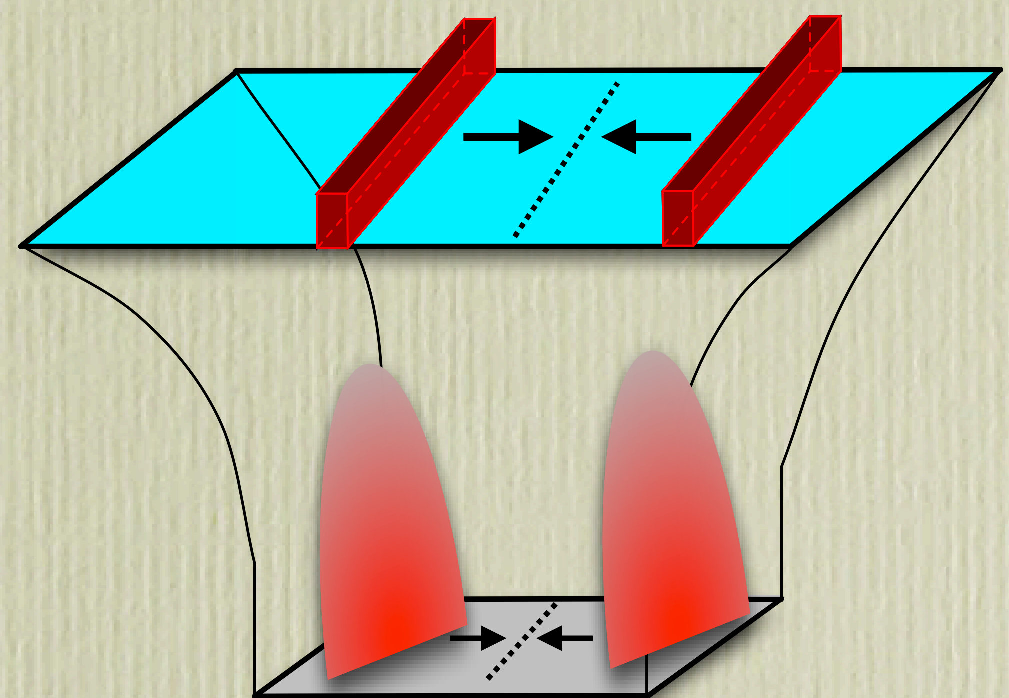
Beyond conformal symmetry

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

For details see talk by Jorge Casalderrey on Thursday.

Infinite bricks of energy

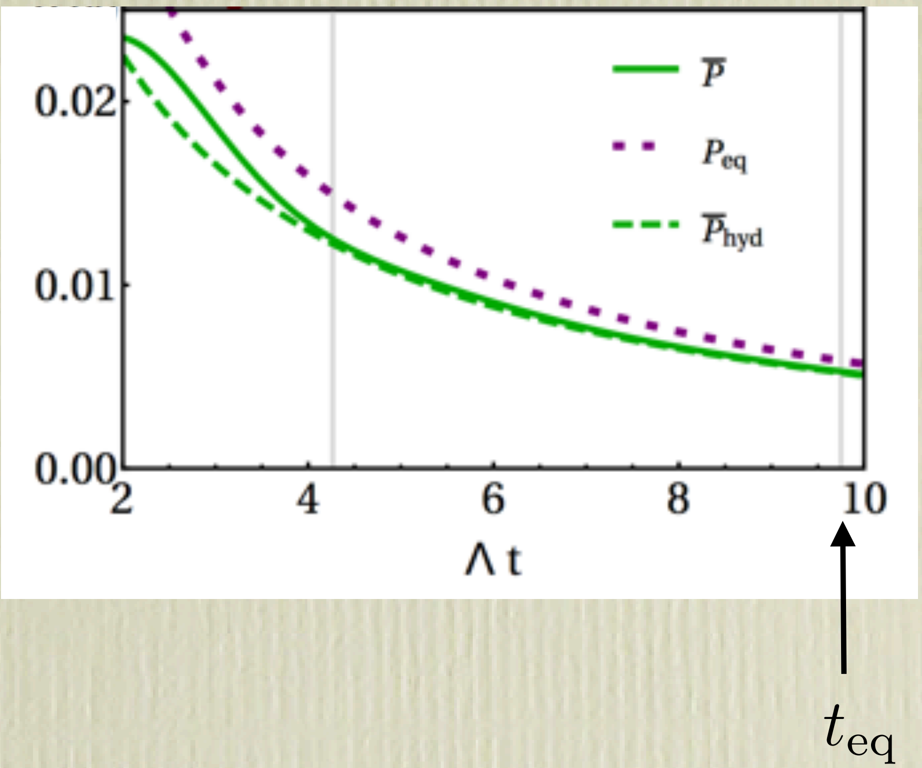
Gravitational waves



Beyond conformal symmetry

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

- Main conclusions:
    - EOS does NOT hold out of equilibrium.



Beyond conformal symmetry

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

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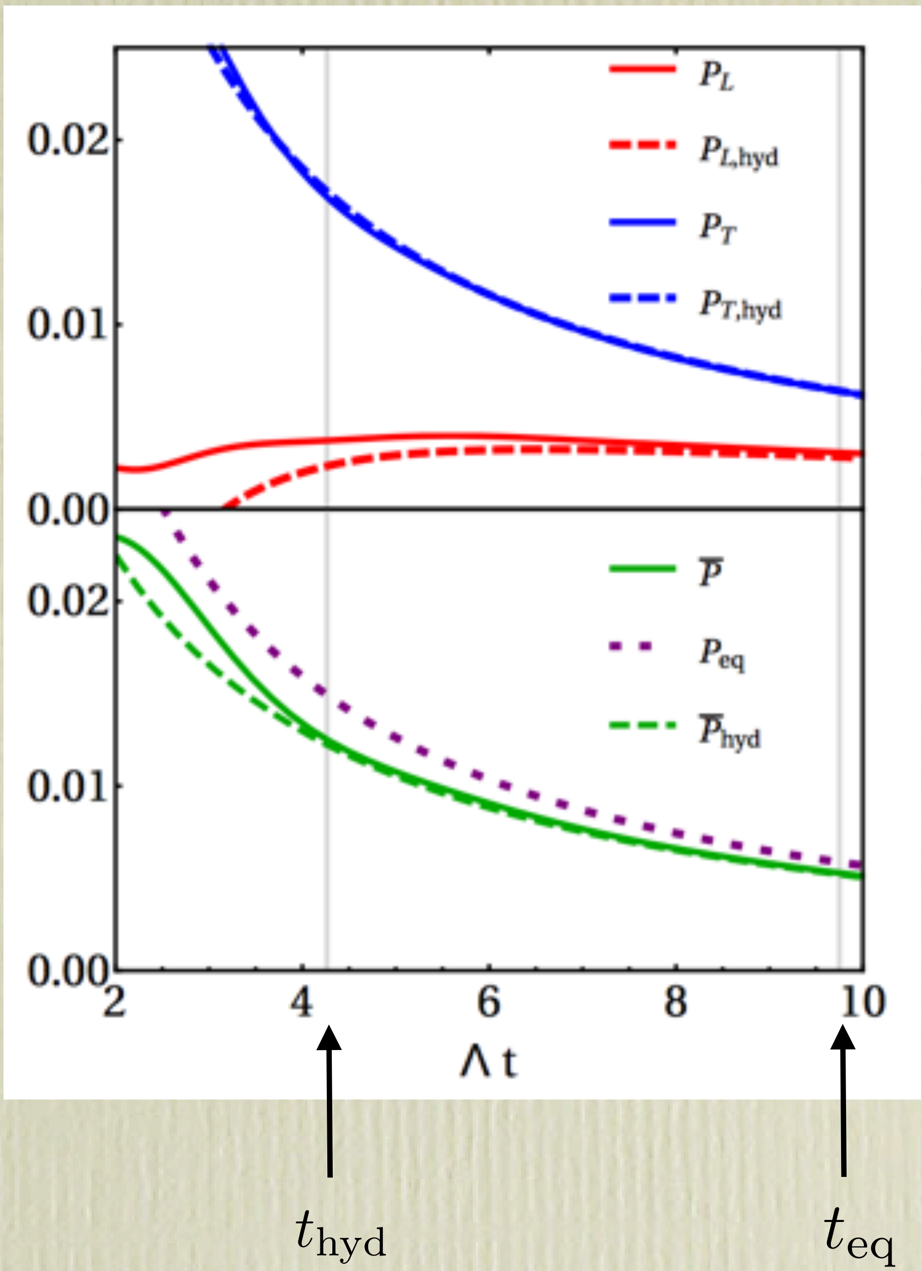

Beyond conformal symmetry

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

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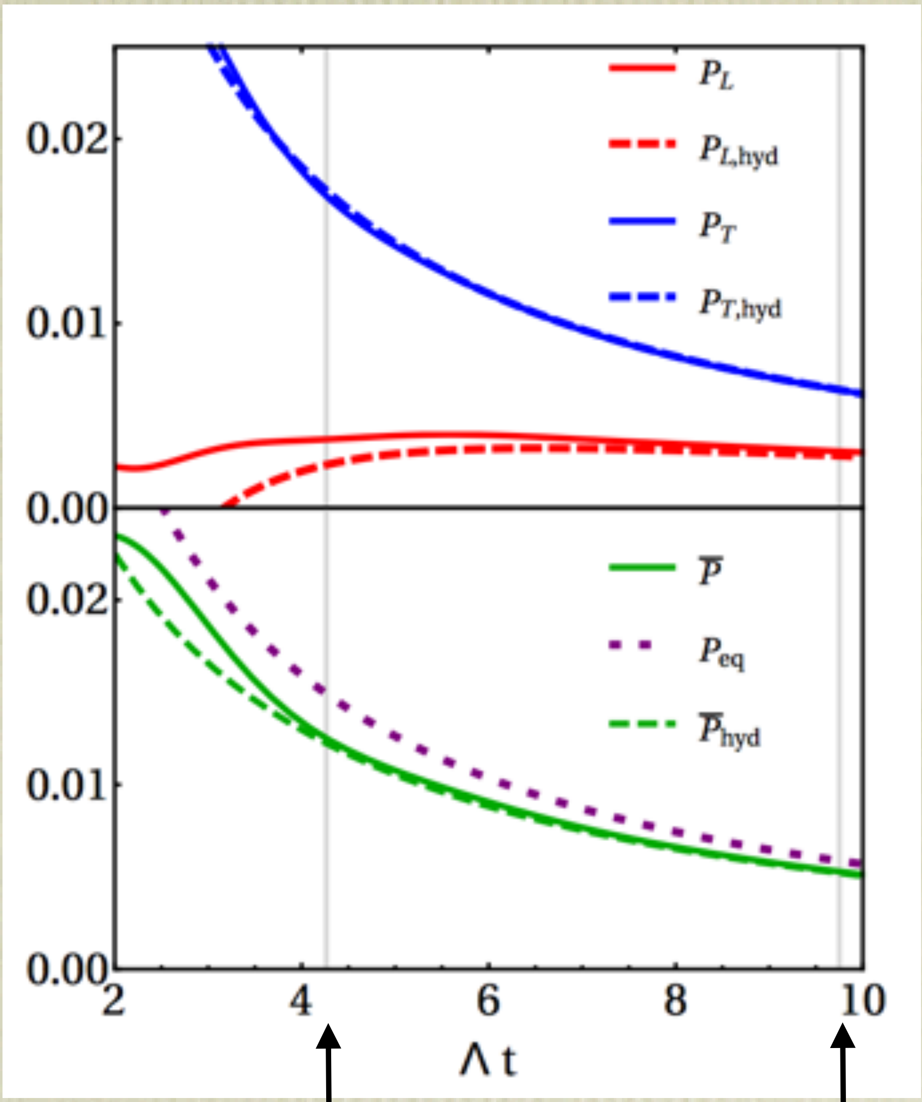
$$P_L^{\text{hyd}} = P_{\text{eq}} + P_\eta + P_\zeta$$

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

Responsible for anisotropy

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



t_{hyd} t_{eq}

Beyond conformal symmetry

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

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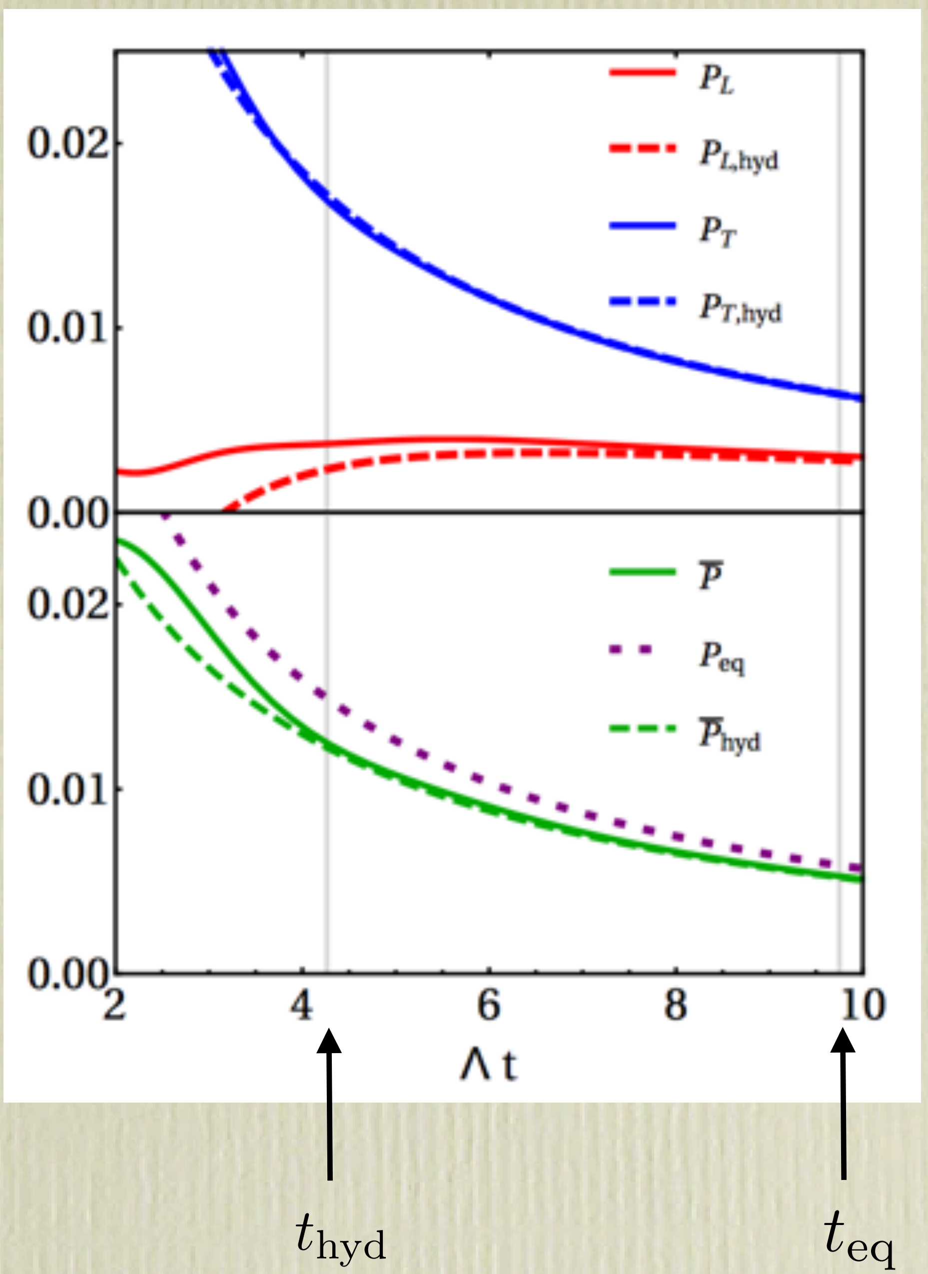
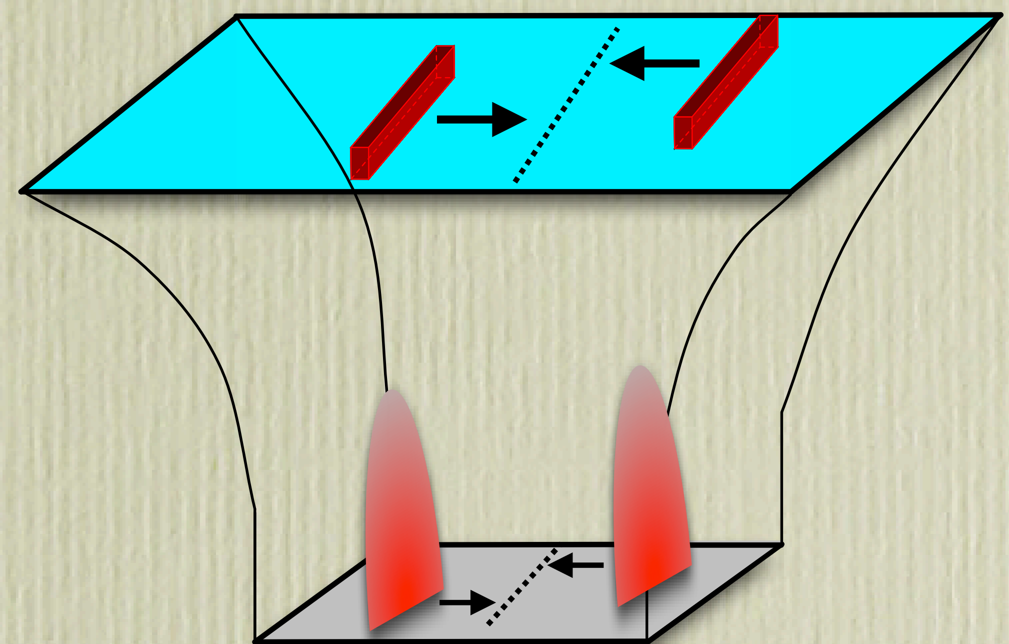


  - Required bulk viscosity about 1/10 of QCD at Tc.
  - Hydro time 2.5 longer than in CFT.

Off-centre collisions of finite nuclei

Chesler & Yaffe '15

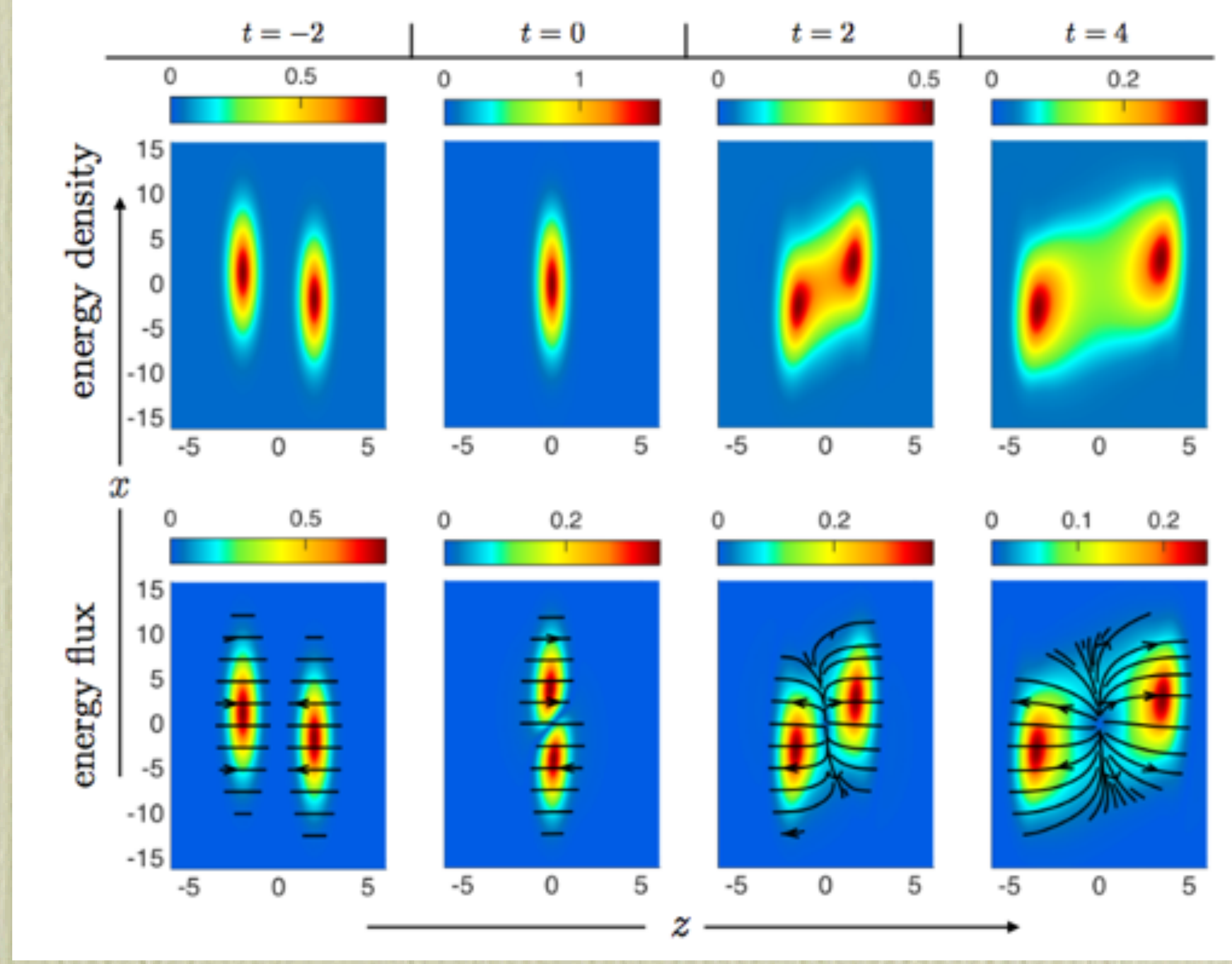
Localised lumps of energy
Non-zero impact parameter



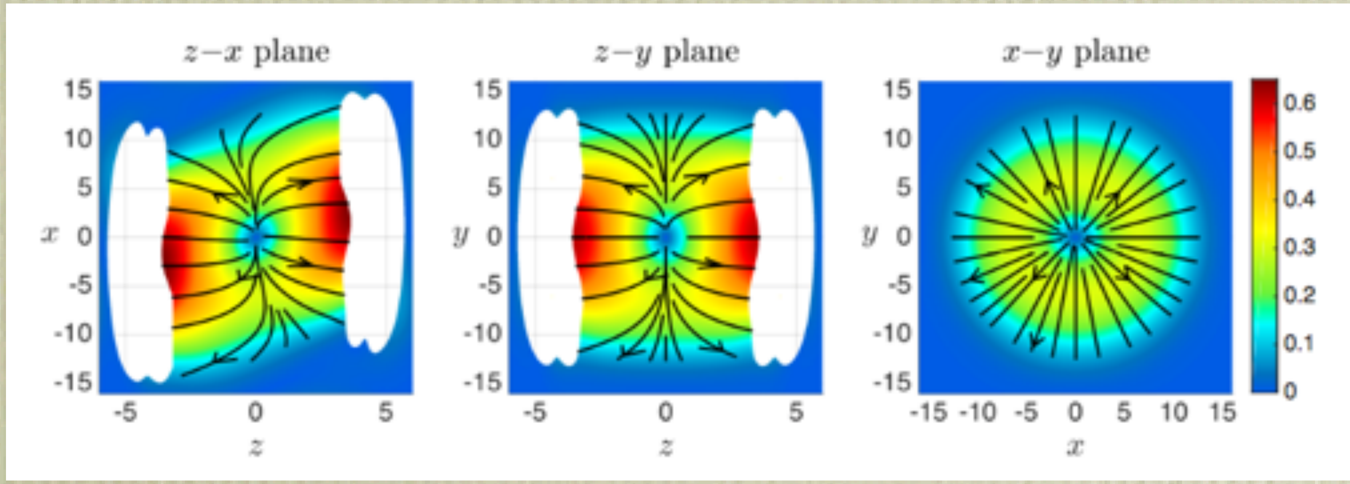
Gravitational waves

Off-centre collisions of finite nuclei

Chesler & Yaffe ’15



See development of transverse flow.

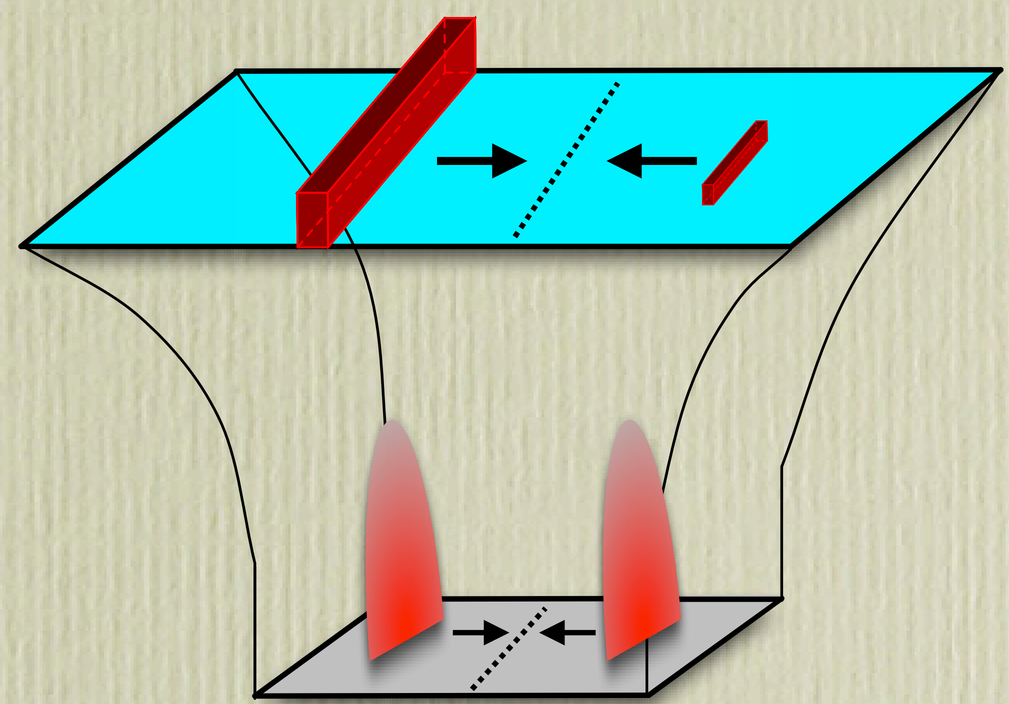


But essentially no elliptic flow.
(perhaps due to transverse Gaussians).

p+A collisions and the smallest drops of QGP

Chesler '15

Infinite vs finite brick



Gravitational waves

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

Thank you.