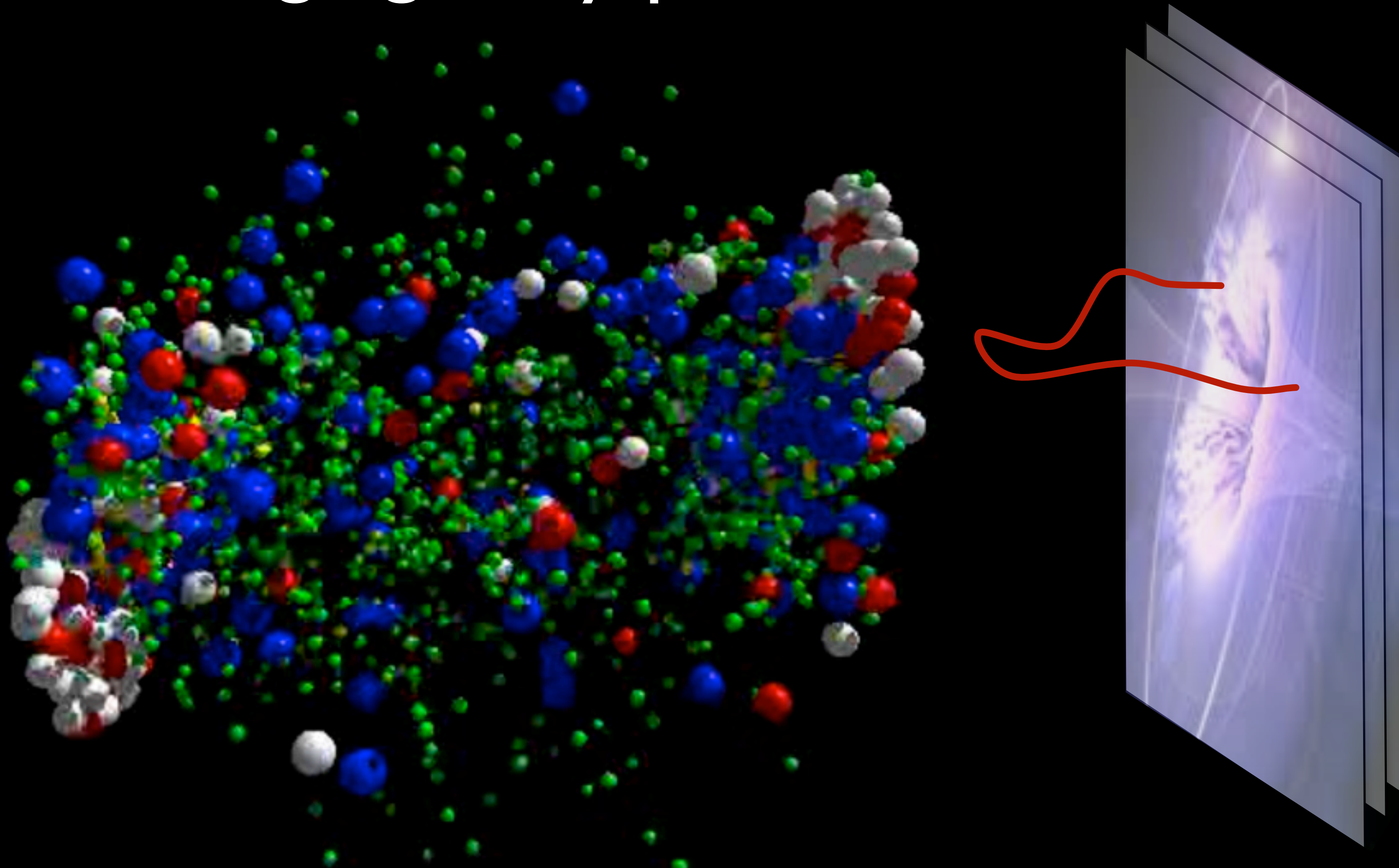
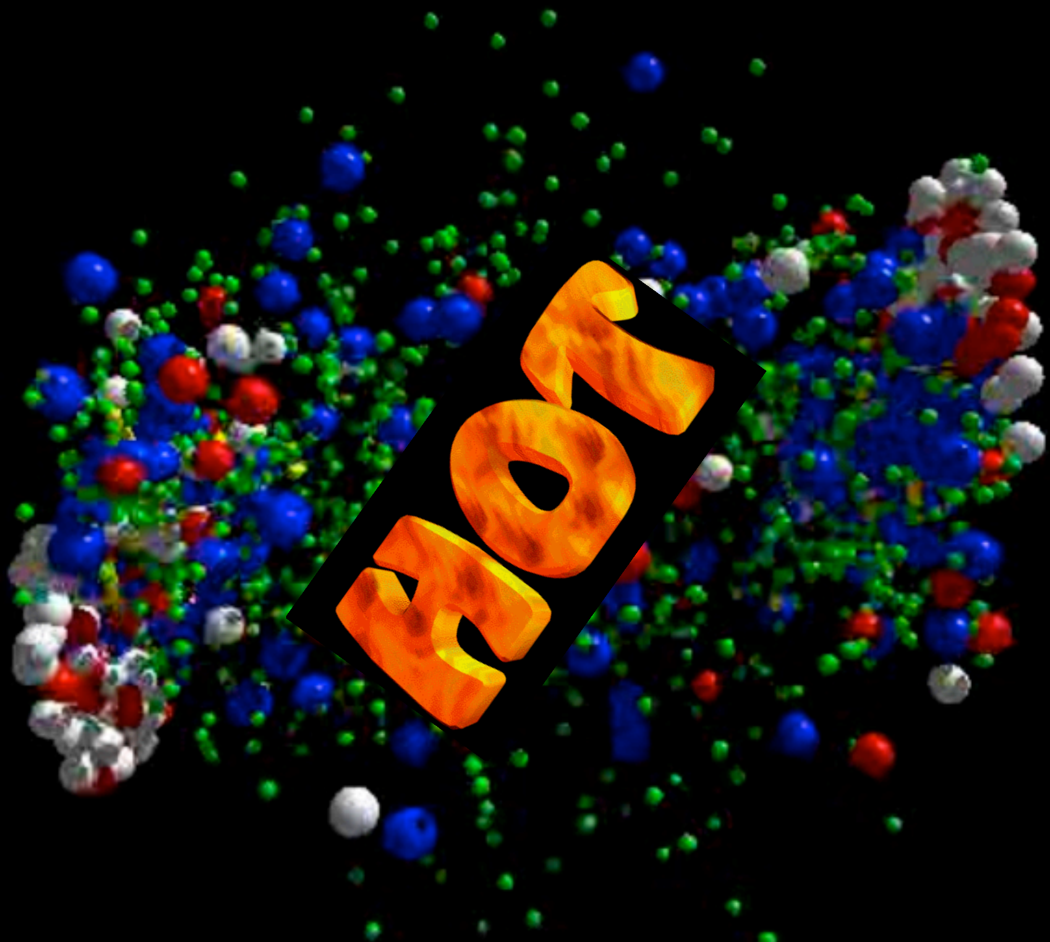
Quarks, Gluons and Black Holes

Gauge/gravity predictions for HIC



David Mateos
ICREA & University of Barcelona

Quarks + Gluons = Black Holes



David Mateos
ICREA & University of Barcelona

Plan

- All you need to know about:
  - Quantum ChromoDynamics.
  - String theory.
  - Why they should be related: Gauge/string duality.

- Illustrate with few results:
  - Equilibrium/Near equilibrium.

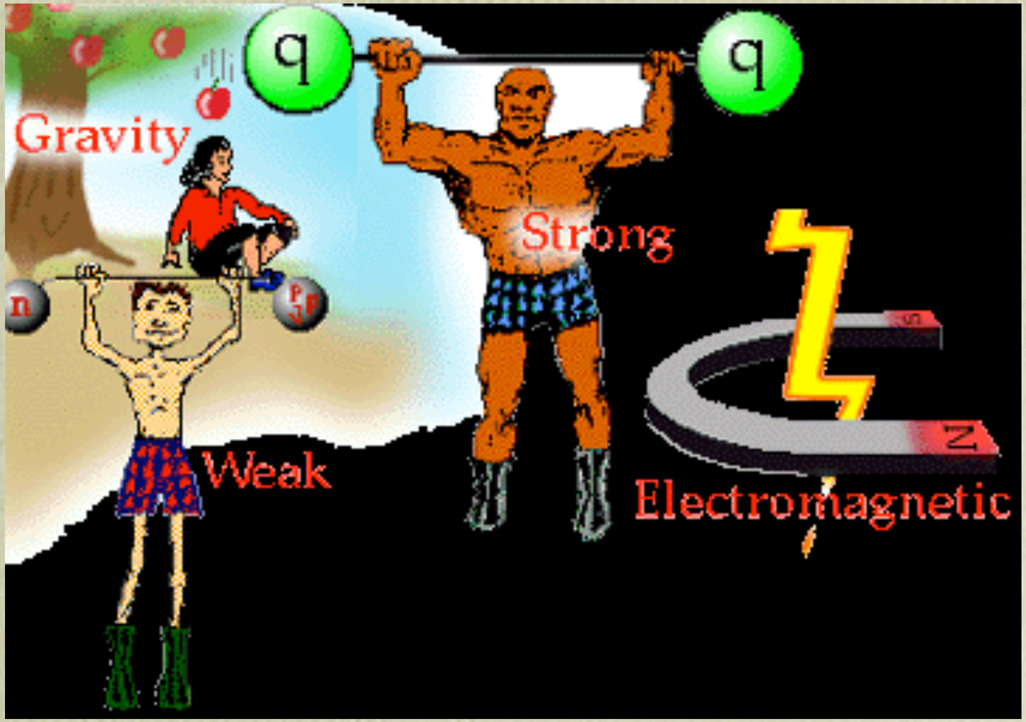
- Invitation for NR: Out of equilibrium.

  - For more information see:

Casalderrey-Solana, Liu, D.M., Rajagopal & Wiedemann
arXiv:1101.0618 [hep-th]

Quantum ChromoDynamics

Quantum ChromoDynamics...



... is the quantum theory of the strong nuclear force.

Quantum ChromoDynamics

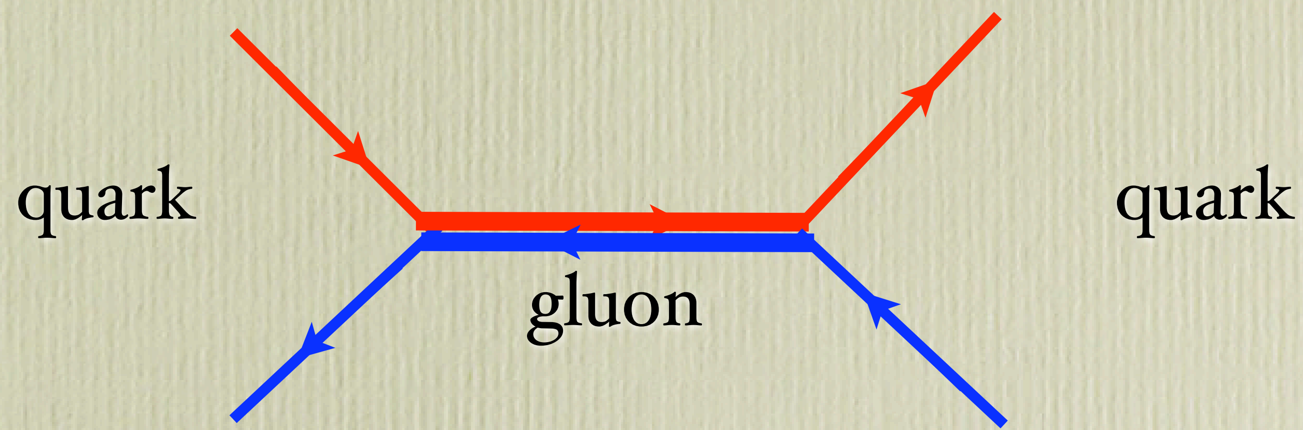
- Responsible for binding quarks inside mesons and baryons:

$\pi^0 , \pi^\pm , \ldots$

$p , n , \ldots$

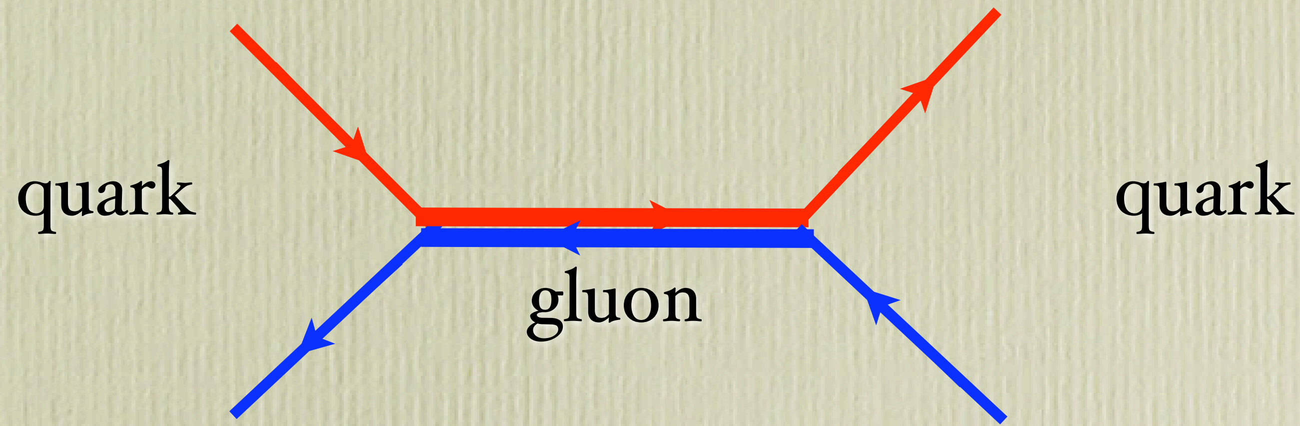
Quantum ChromoDynamics

- Quarks interact because they carry colour, which they exchange through gluons:



Quantum ChromoDynamics

- Quarks interact because they carry colour, which they exchange through gluons:

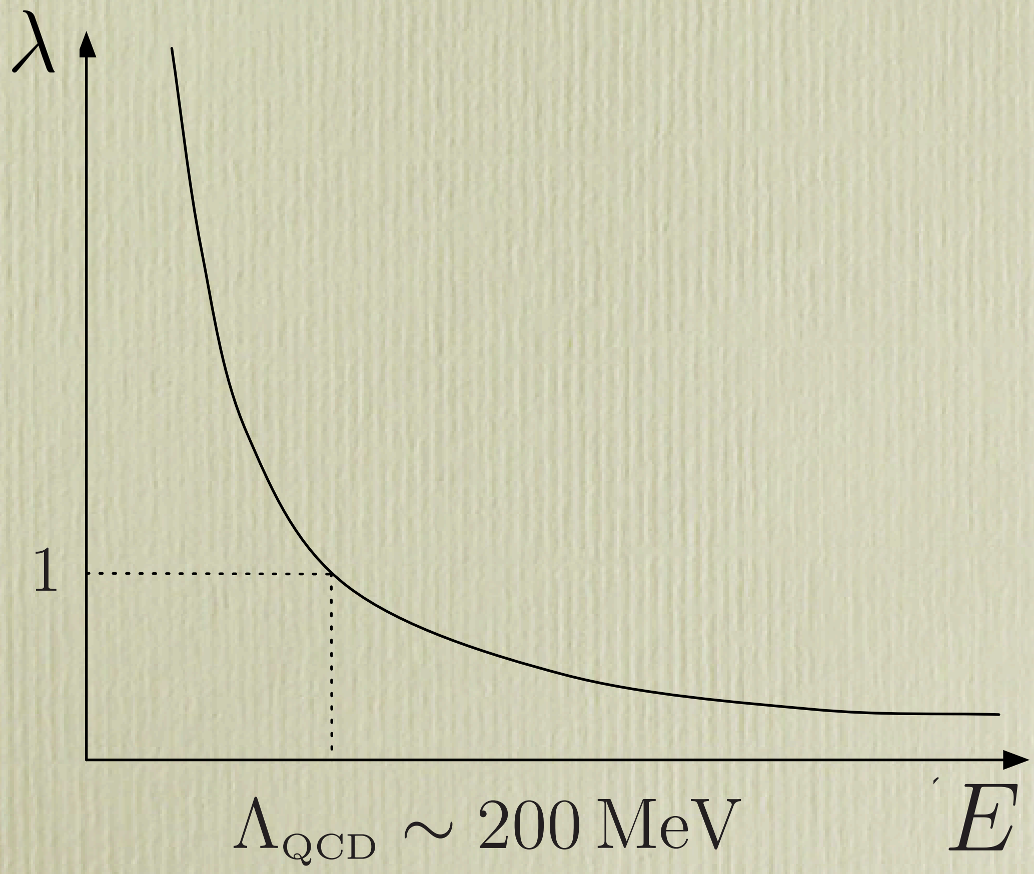


- Analogue of electric charge, but comes in $N_c = 3$ types:

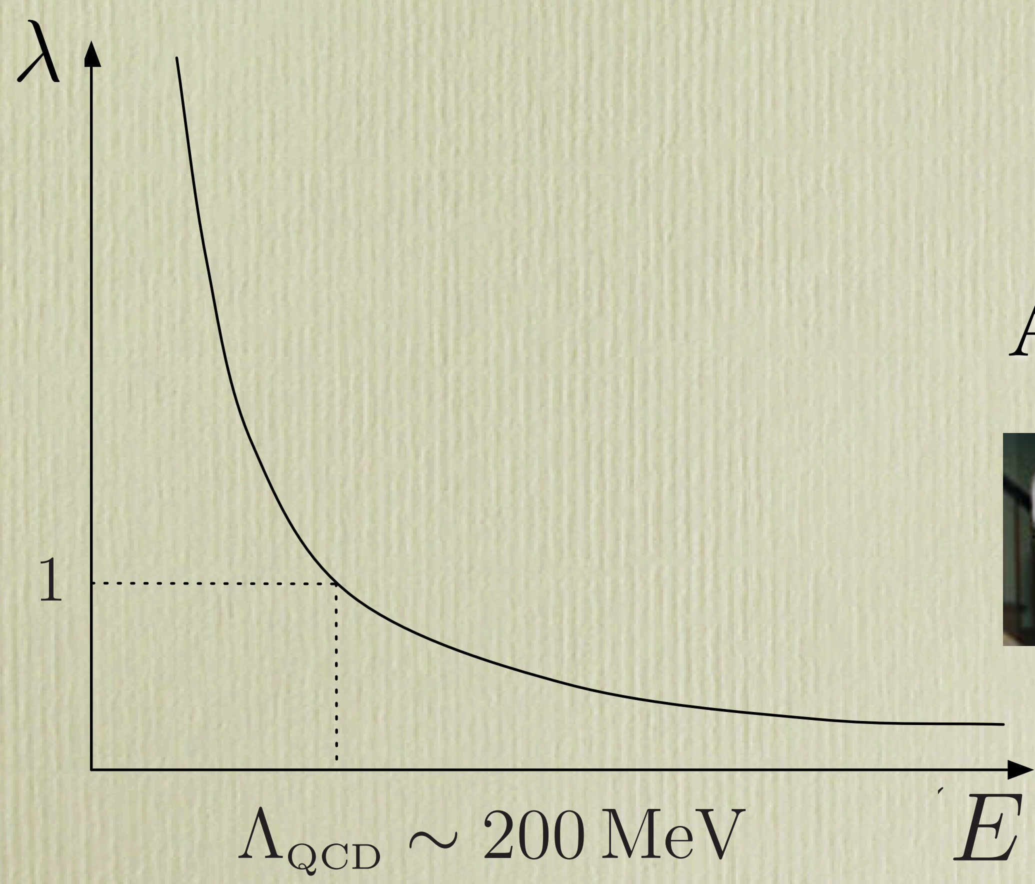
$$\{\, q,\ q,\ q \,\}$$

Why is QCD hard?

- Strength of interaction depends on energy:



Why is QCD hard?



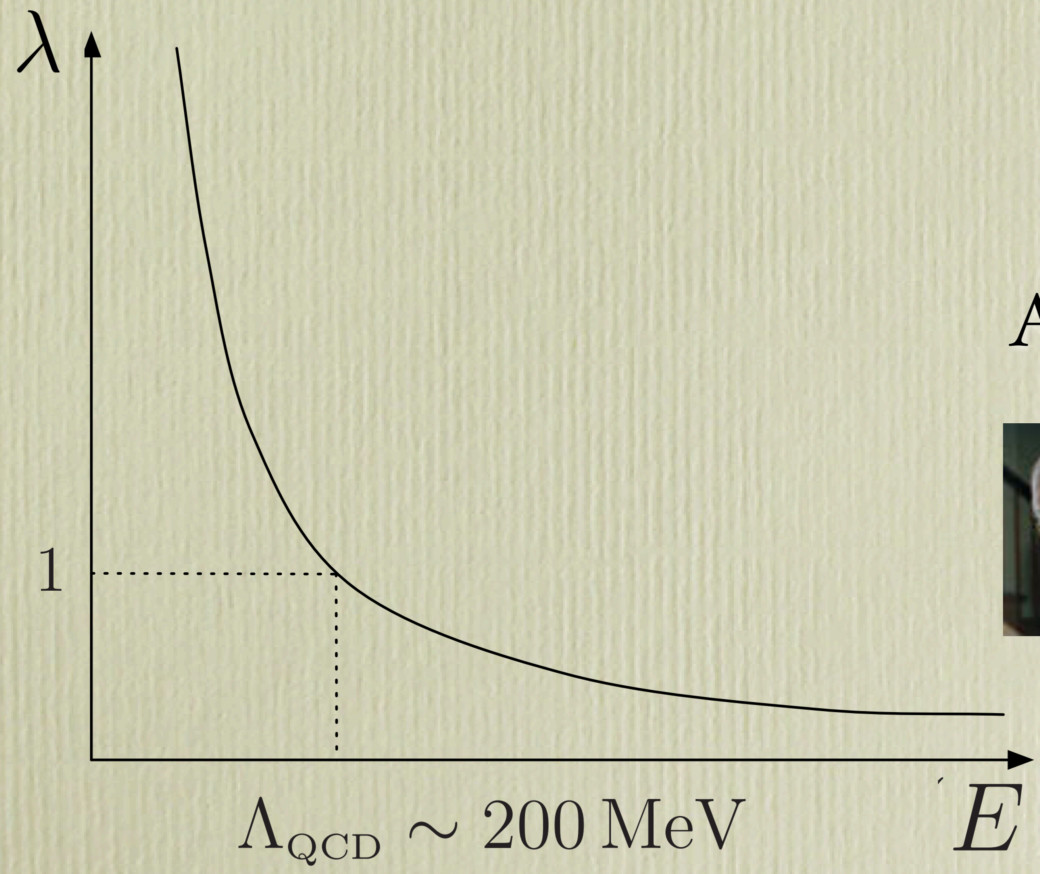
Asymptotic freedom

The Nobel Prize in Physics 2004

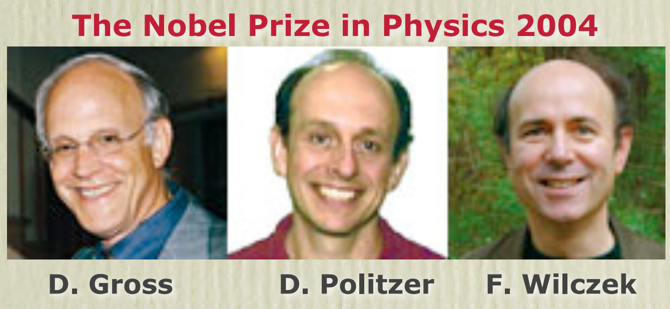
D. Gross D. Politzer F. Wilczek

Why is QCD hard?

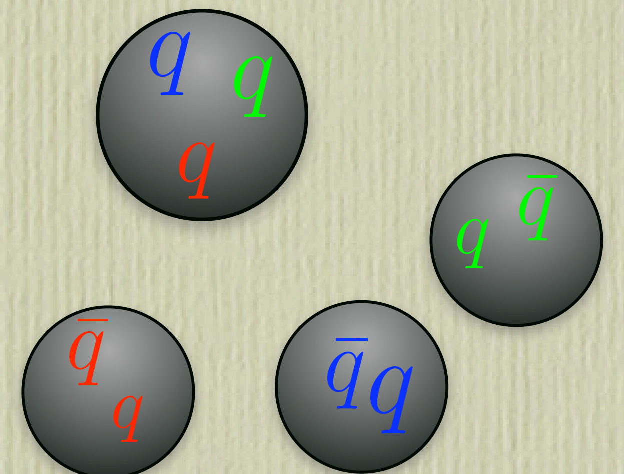
Strong coupling:
No truly systematic methods!



Asymptotic freedom

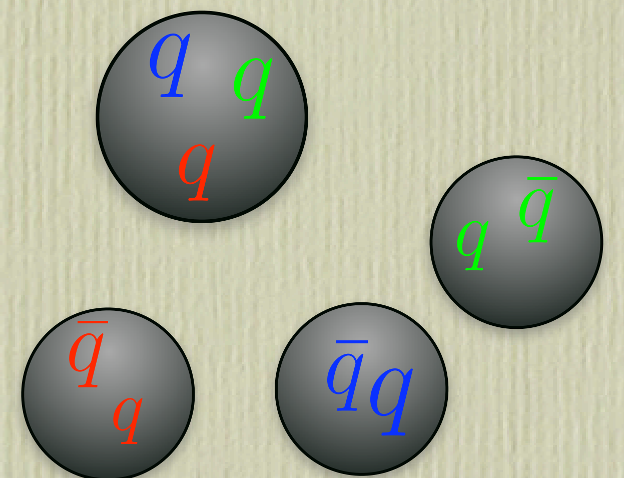


Confinement...



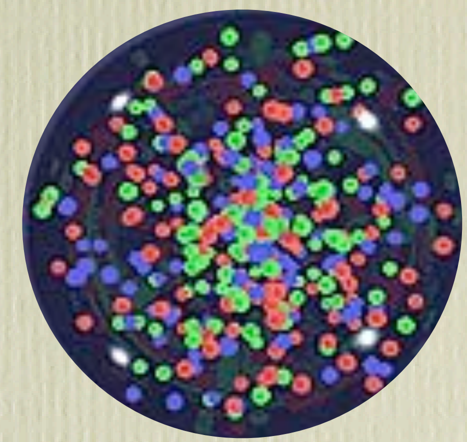
Mesons and baryons

Confinement and deconfinement



$\longrightarrow$

$T_c \sim 175\,\mathrm{MeV}$

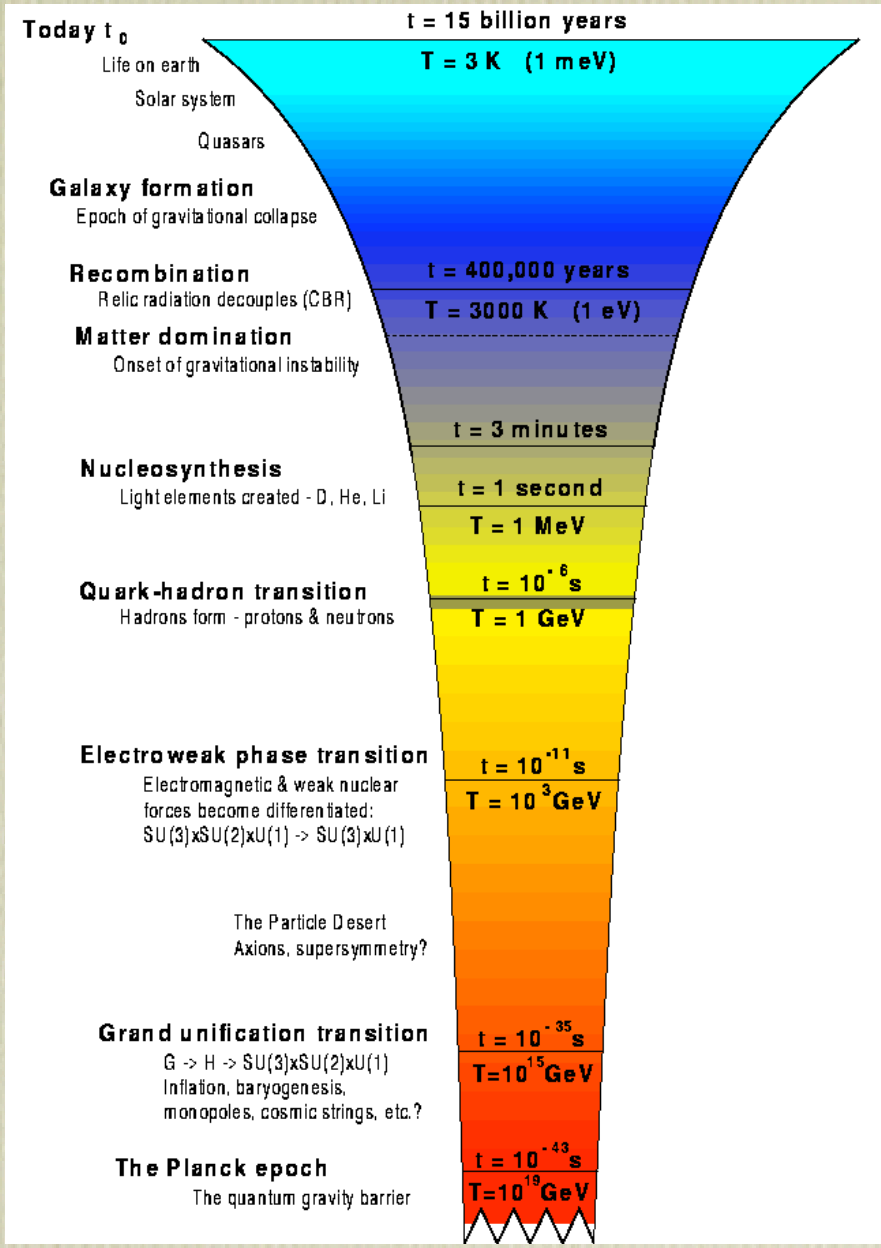


Mesons and baryons

Quark Gluon Plasma
(QGP)

The QGP

- This was realized in the hot, early Universe...



The QGP

... and is the only fundamental phase transition that can be recreated in a lab like RHIC or LHC!

QCD remains a challenge

- 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.

QCD remains a challenge

- 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.

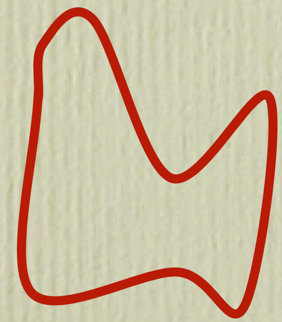
- A string reformulation might help.

- Topic of this talk with focus on QGP.

String Theory

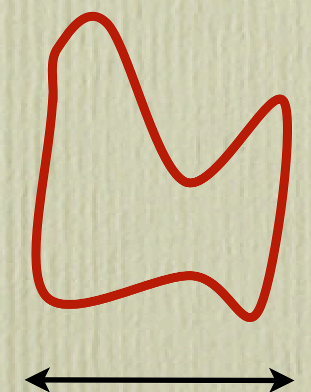
String theory

- Quantum theory of one-dimensional objects.

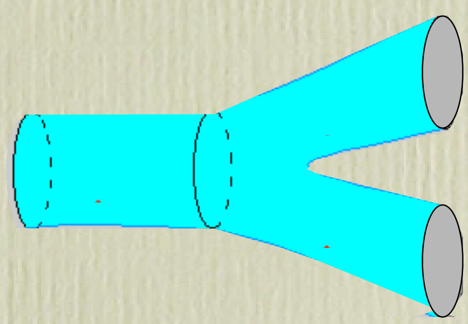


String theory

- Quantum theory of one-dimensional objects.
- Characterised by two parameters:



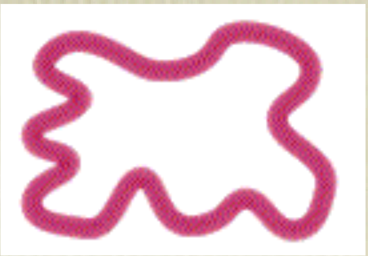
ℓ_s

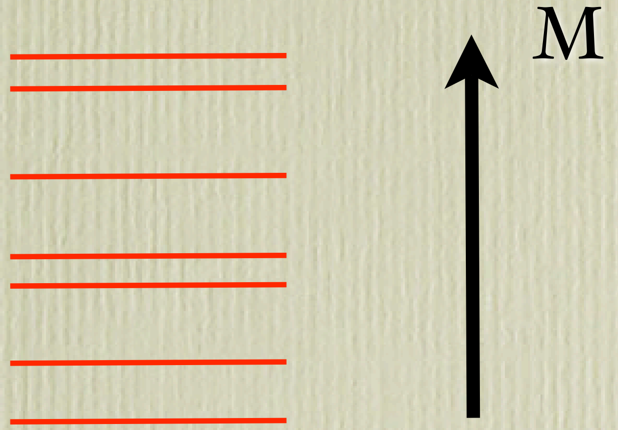


g_s

String theory

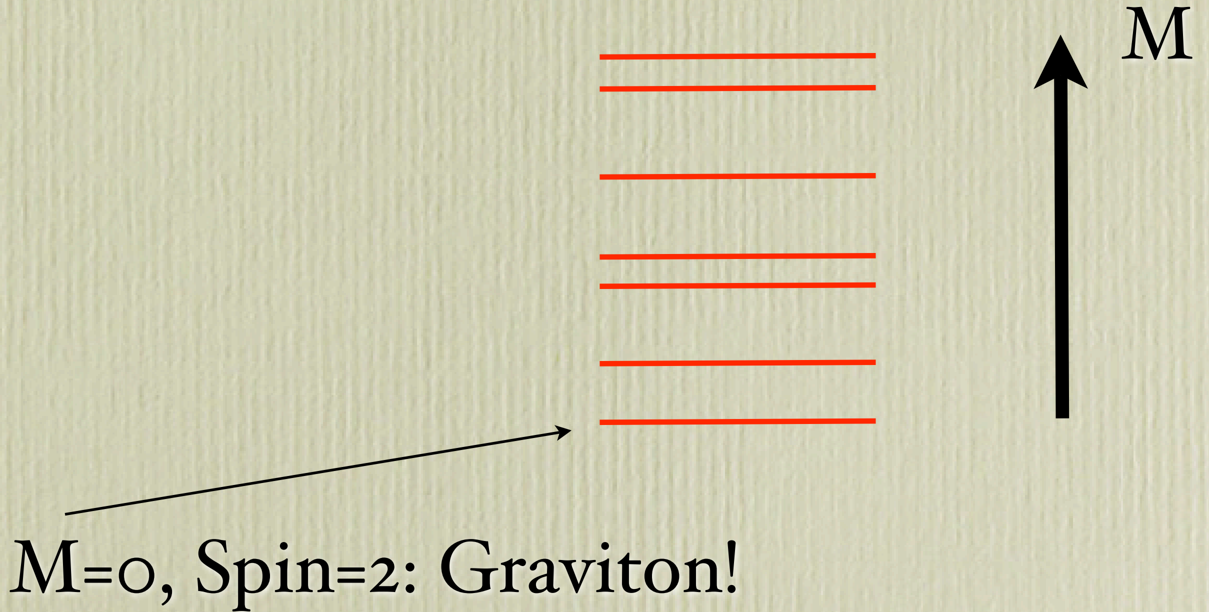
- Different vibration modes behave as particles of different masses and spins:





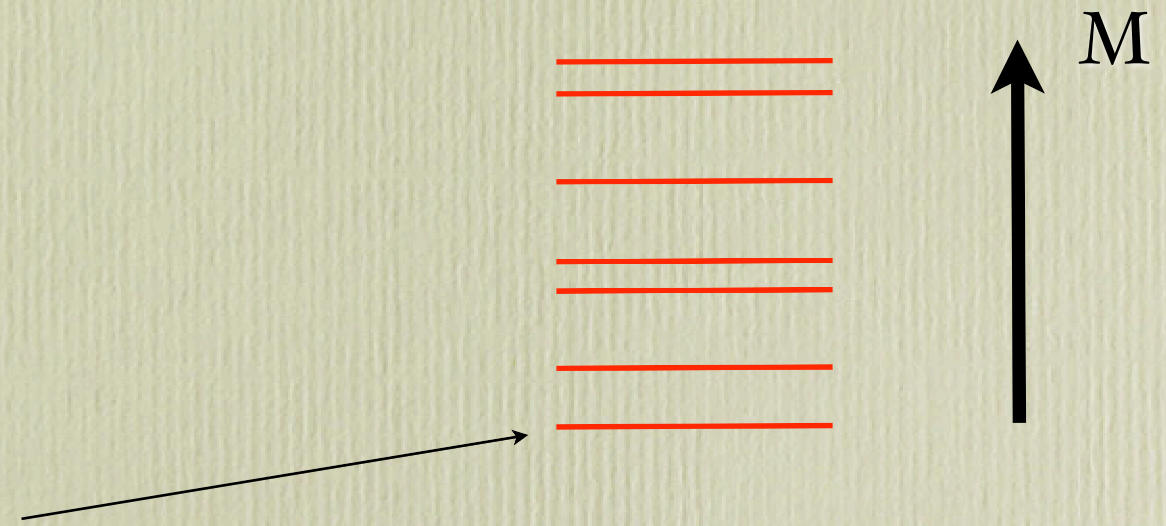
String theory

- Different vibration modes behave as particles of different masses and spins:

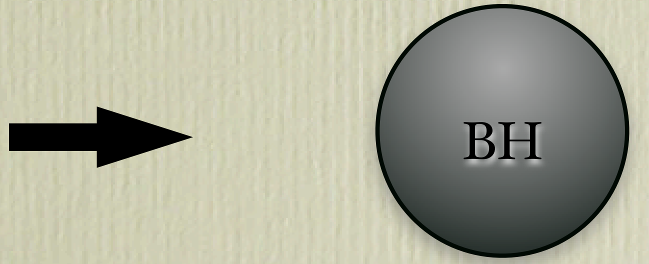


String theory

- Different vibration modes behave as particles of different masses and spins:

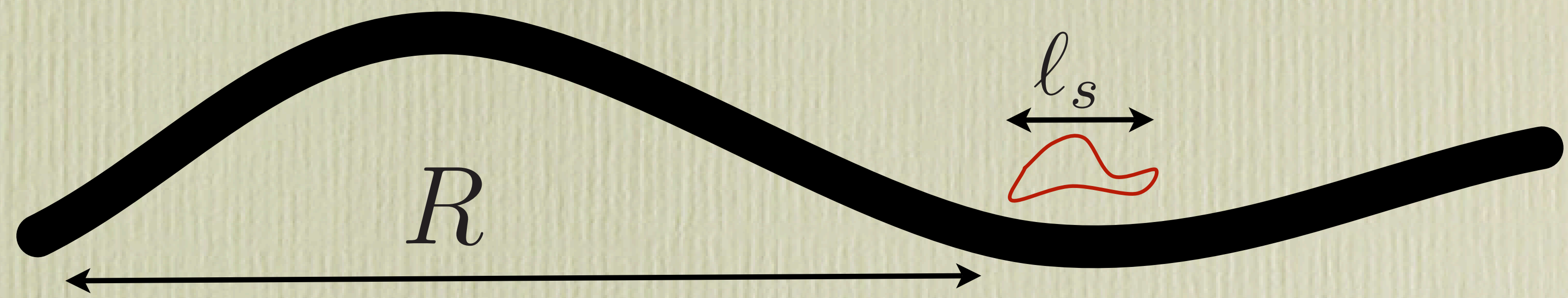


M=0, Spin=2: Graviton!



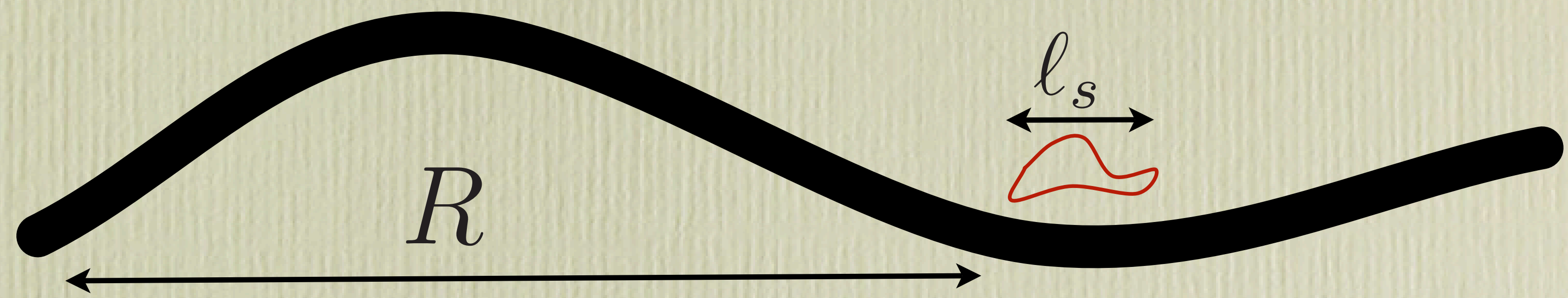
String theory

- Interested in strings propagating in curved space:



String theory

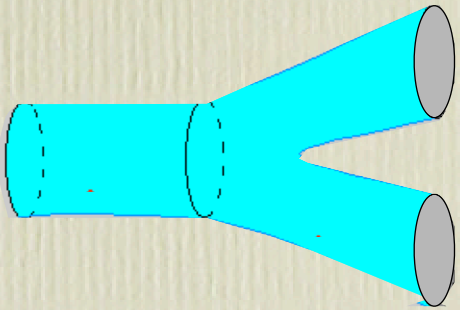
- Interested in strings propagating in curved space:

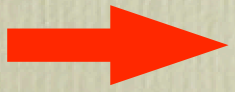


- Complicated theory, but simplifies dramatically if:

$\ell_s \ll R$: String behaves as a point.

$g_s \ll 1$: String does not split.



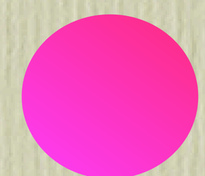
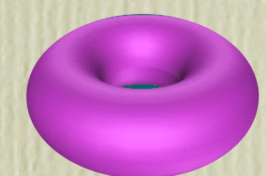

Classical supergravity.

Why and how should QCD and string theory be related

The gauge/string duality

- Large-N_c expansion:

't Hooft '74

 $+$  $+ \cdots$

$$g_s = \frac{1}{N_c}$$

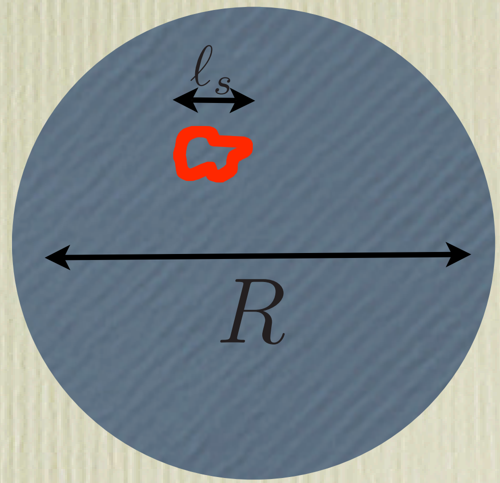
The gauge/string duality

- First concrete example:

Maldacena '97

$$\mathcal{N} = 4 \text{ SYM} \;\leftrightarrow\; \text{IIB on } AdS_5 \times S^5$$

$$g_s = \frac{1}{N_c} \quad , \quad R^4 = \lambda \ell_s^4$$



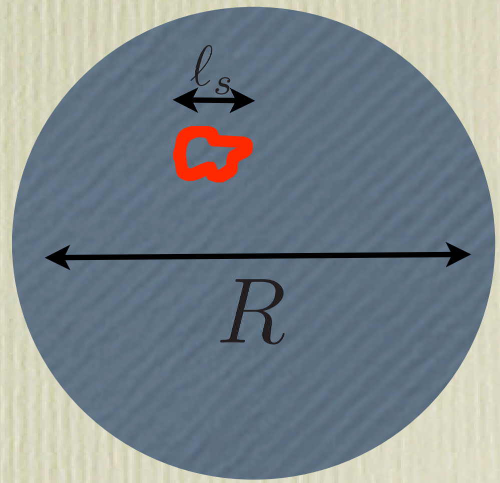
The gauge/string duality

- First concrete example:

Maldacena '97

$$\mathcal{N} = 4 \text{ SYM} \;\; \leftrightarrow \;\; \text{IIB on } AdS_5 \times S^5$$

$$g_s = \frac{1}{N_c} \quad , \quad R^4 = \lambda \ell_s^4$$



- Exact equivalence at *all* energies, N_c and $\lambda = g_{\rm YM}^2 N_c$!

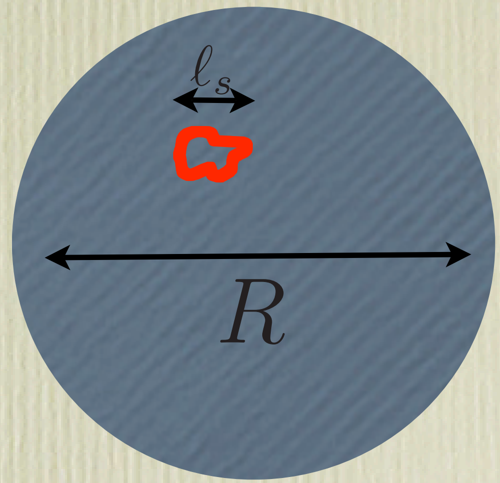
The gauge/string duality

- First concrete example:

Maldacena '97

$$\mathcal{N} = 4 \text{ SYM} \;\leftrightarrow\; \text{IIB on } AdS_5 \times S^5$$

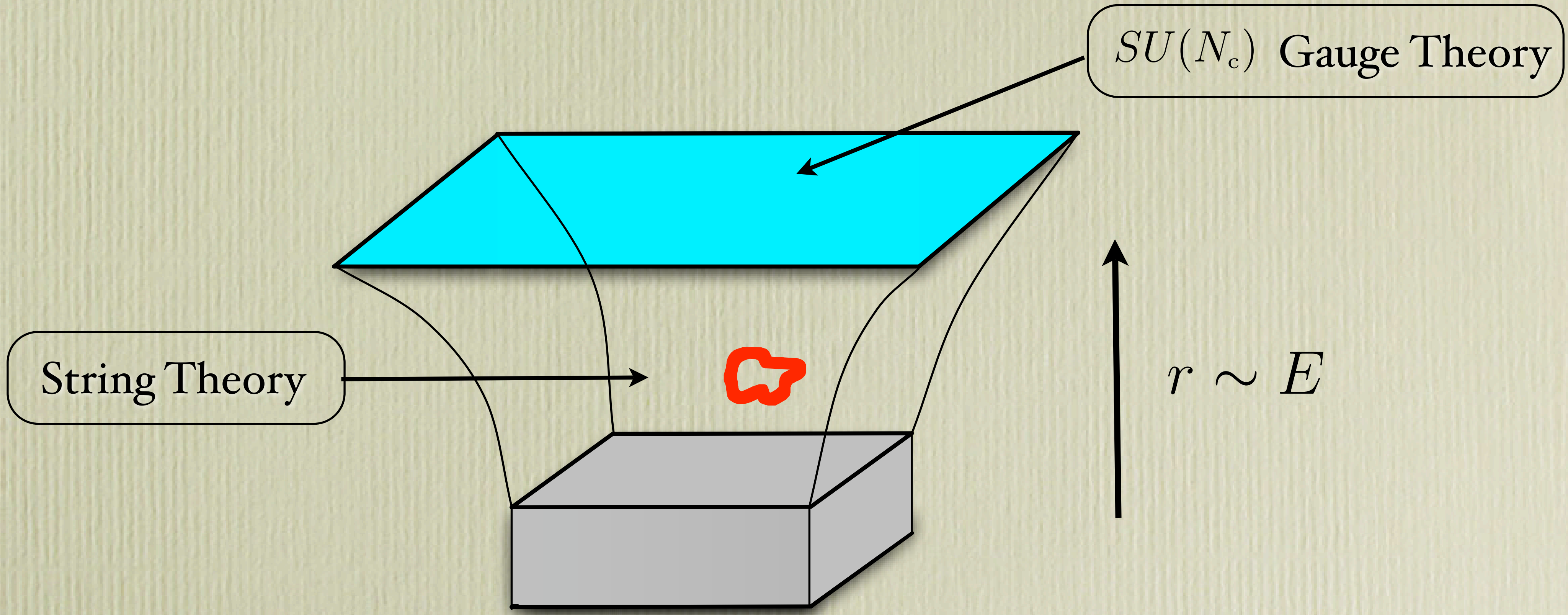
$$g_s = \frac{1}{N_c} \quad , \quad R^4 = \lambda \ell_s^4$$



- Exact equivalence at *all* energies, N_c and $\lambda = g_{YM}^2 N_c$!

- *Disclaimer:* Not proven but lots of evidence.

The duality is Holographic



From viewpoint of a *theorist*

- Duality is an extraordinary discovery:

$\boxed{\text{Quantum gravity}} = \boxed{\text{Ordinary QFT}}$

From viewpoint of a *theorist*

- Duality is an extraordinary discovery:

$$\boxed{\text{Quantum gravity}} = \boxed{\text{Ordinary QFT}}$$

- Unifying framework for diverse (and difficult) fields of physics: QGP, condensed matter, etc.

In terms of *applications* to QCD

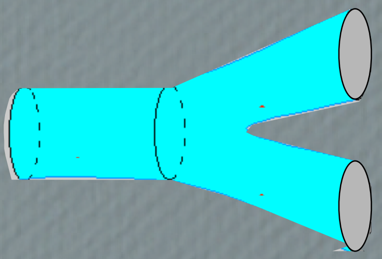
At present the duality has its own limitations

↓

Complementary tool

Limitations: Classical gravity requires

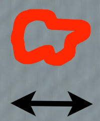
$$\boxed{N_c \longrightarrow \infty}$$



$$g_s \sim \frac{1}{N_c}$$

Suppresses quantum corrections.

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



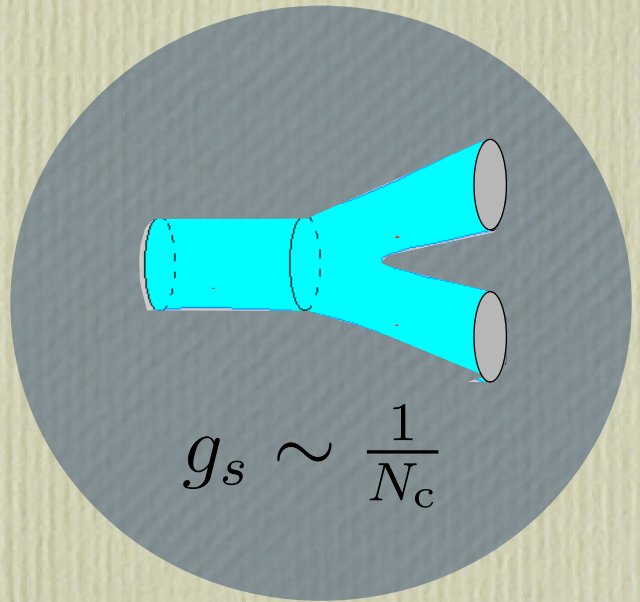
$$\ell_s \sim \frac{1}{\lambda^{1/4}}$$

Makes the string tiny.

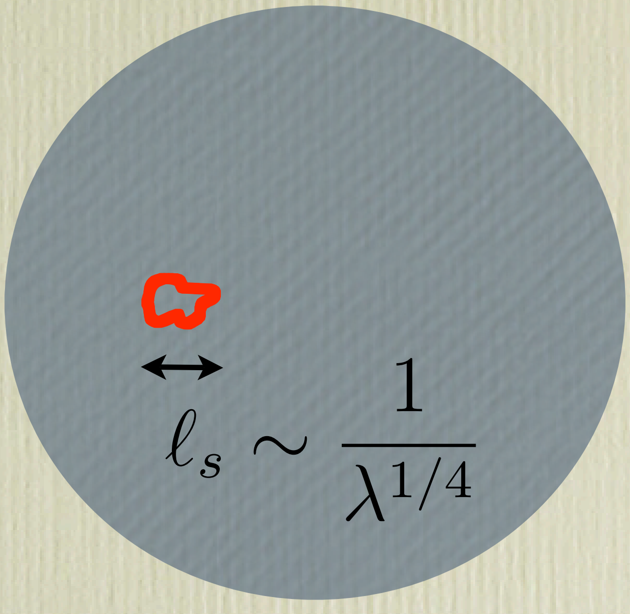
Limitations: Classical gravity requires

$$\boxed{N_\mathrm{c} \longrightarrow \infty}$$

$$\boxed{\lambda = g_{\mathrm{YM}}^2 N_\mathrm{c} \to \infty}$$



Suppresses quantum corrections.



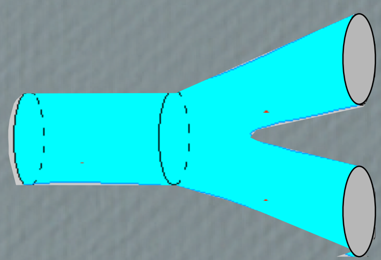
Makes the string tiny.

Technical difficulties, *not* fundamental limitations.

Limitations

$N_c \longrightarrow \infty$

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



$g_s \sim \frac{1}{N_c}$

$\ell_s \sim \frac{1}{\lambda^{1/4}}$

Suppresses quantum corrections.

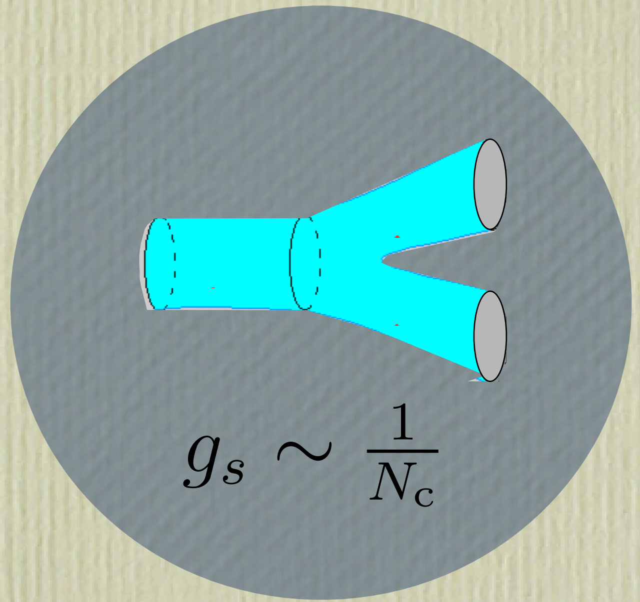
Makes the string tiny.

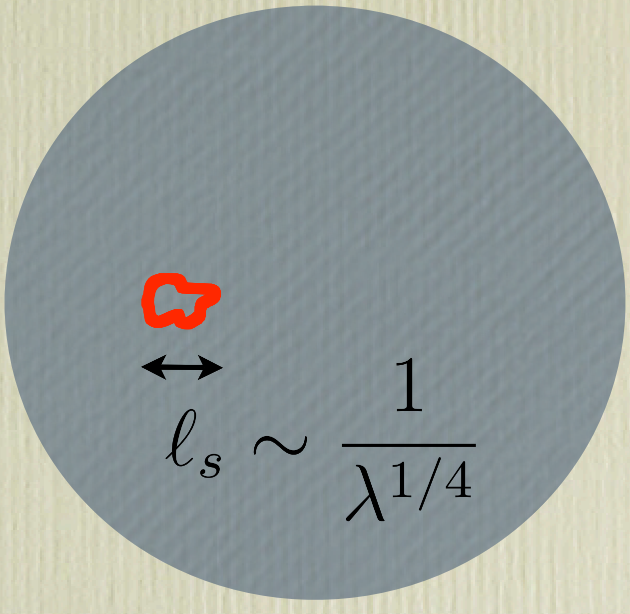
Solving large-N_c would be great progress!

Limitations

$$N_c \longrightarrow \infty$$

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





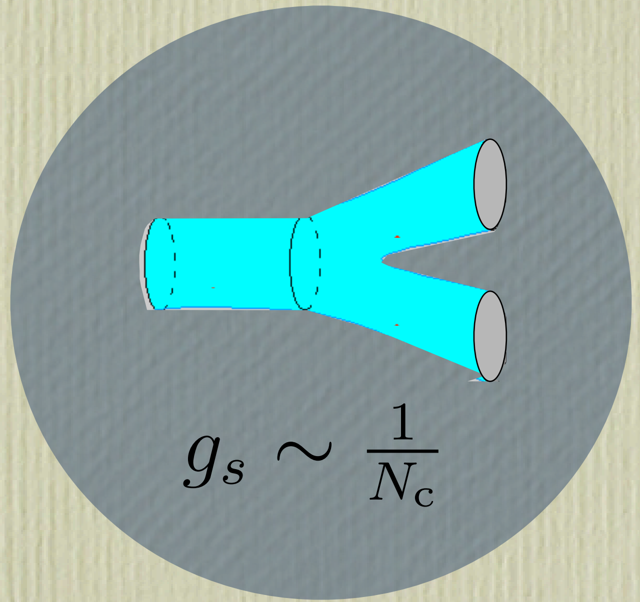
Suppresses quantum corrections.

Makes the string tiny.

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

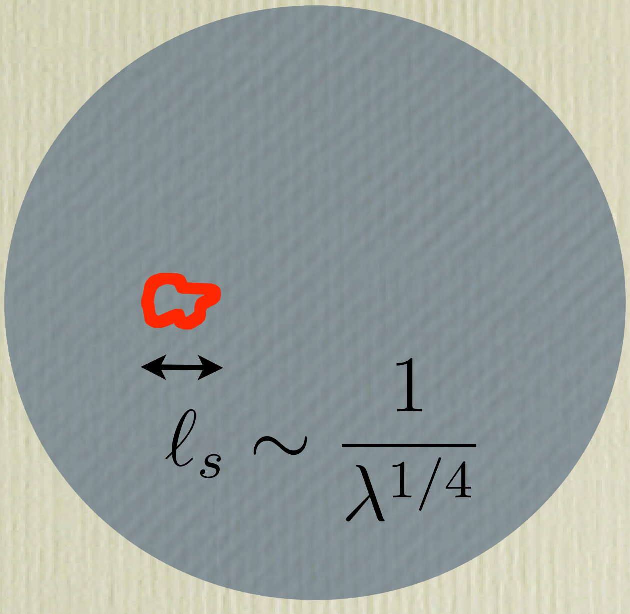
Limitations

$N_c \to \infty$



Suppresses quantum corrections.

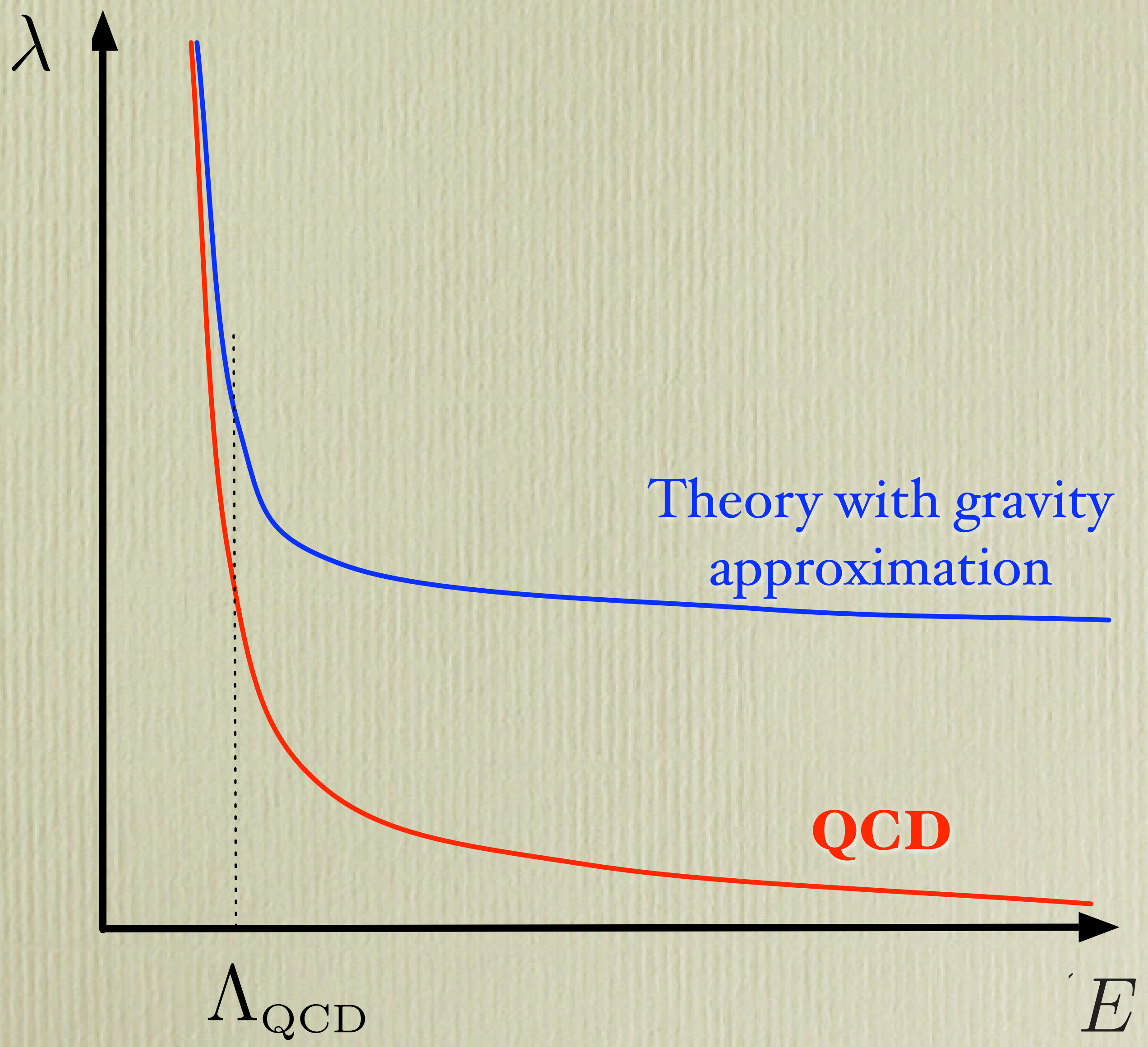
$\lambda = g_{\mathrm{YM}}^2 N_c \to \infty$



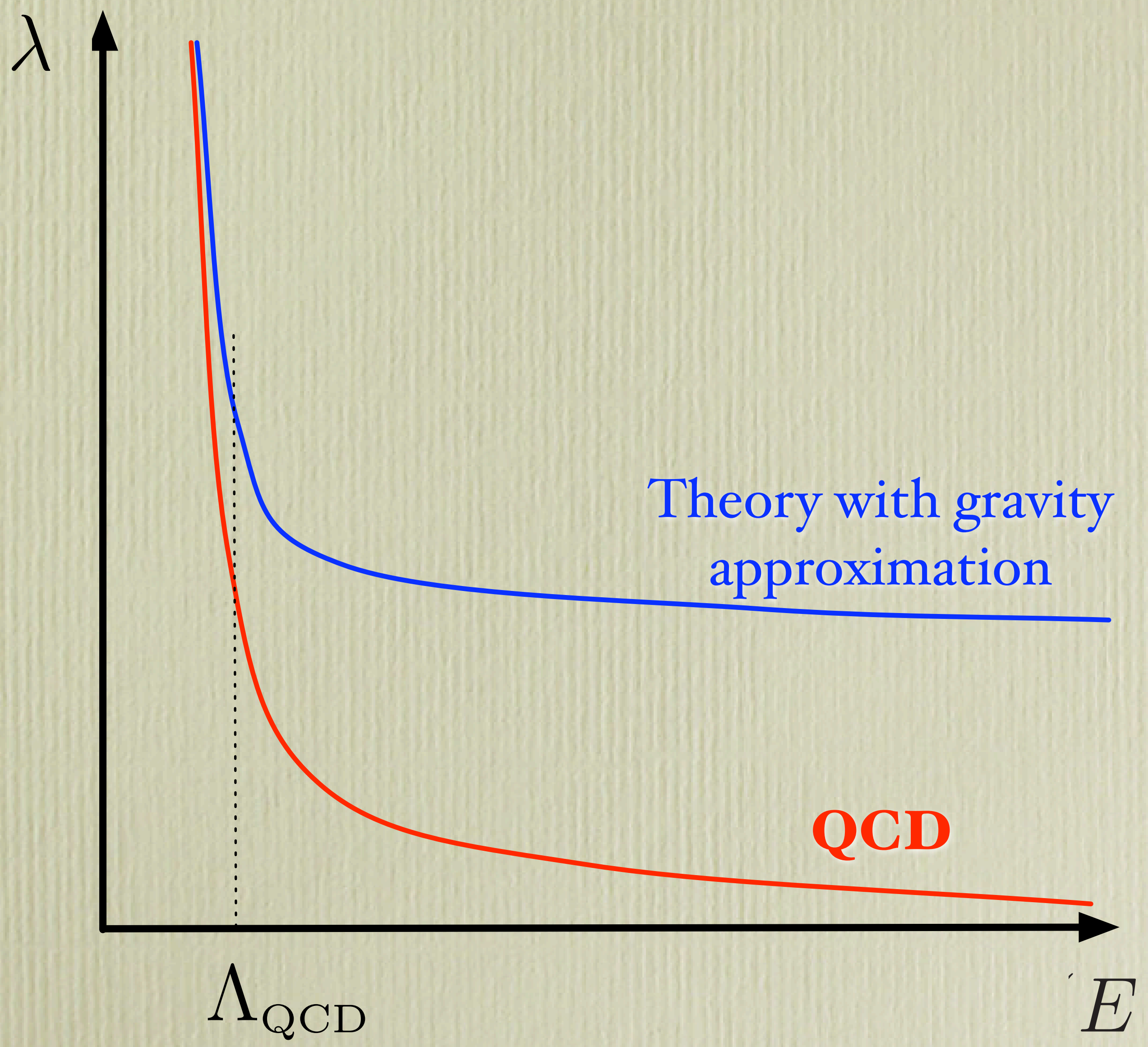
Makes the string tiny.

Strong coupling means *no* asymptotic freedom!

Limitations



Limitations



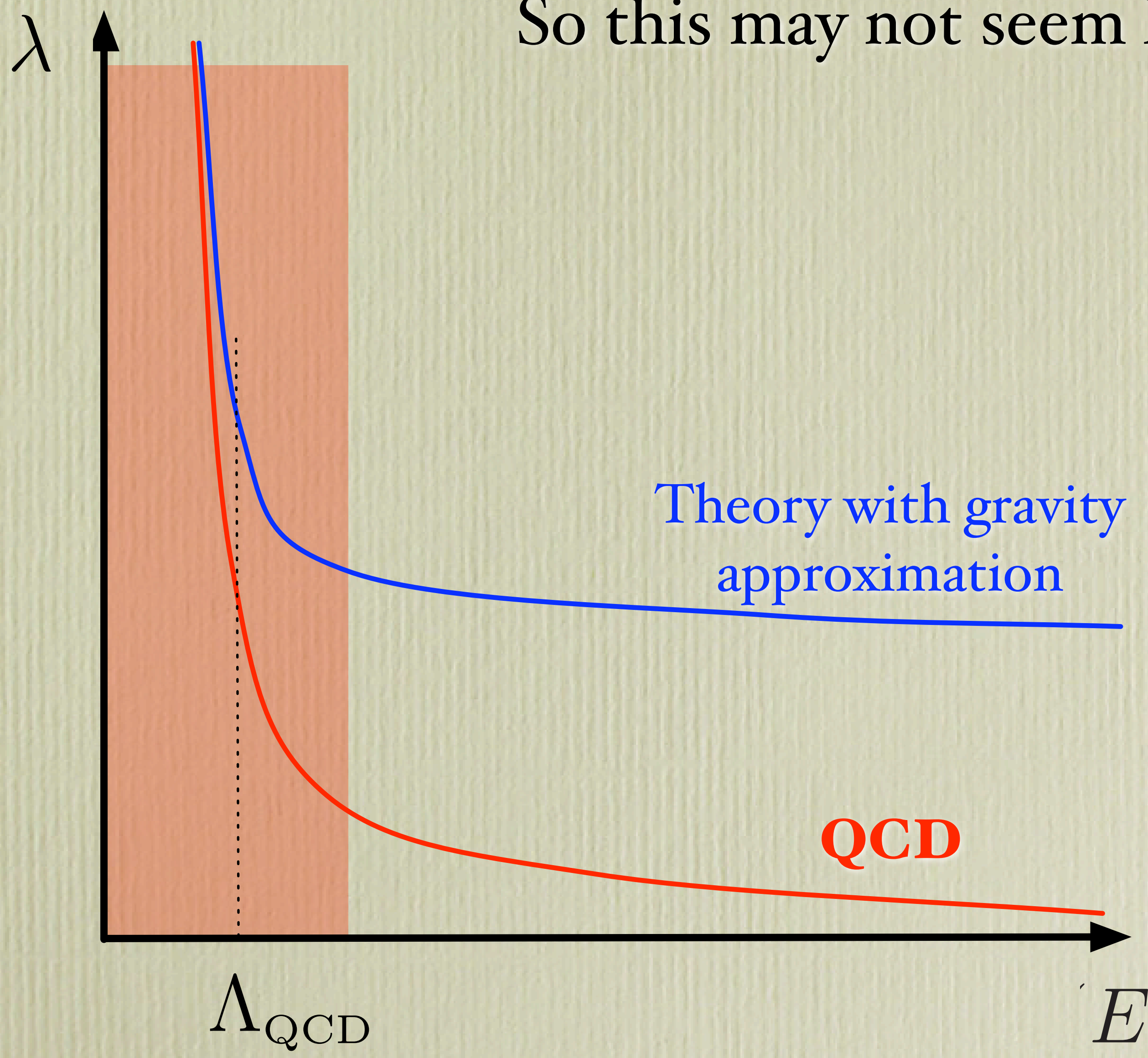
Need not be CFT!

AdS/CFT is a misnomer!

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

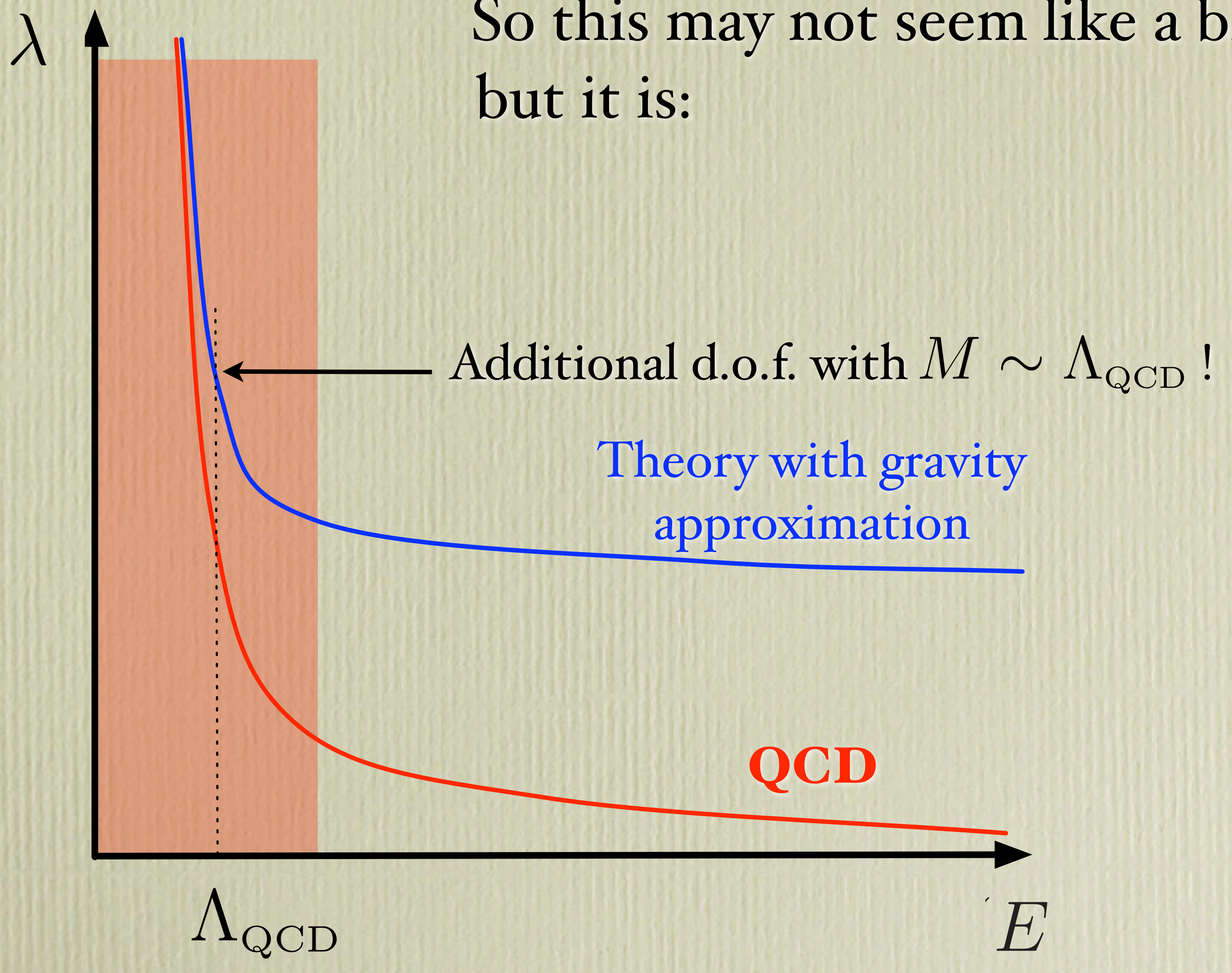
Limitations

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

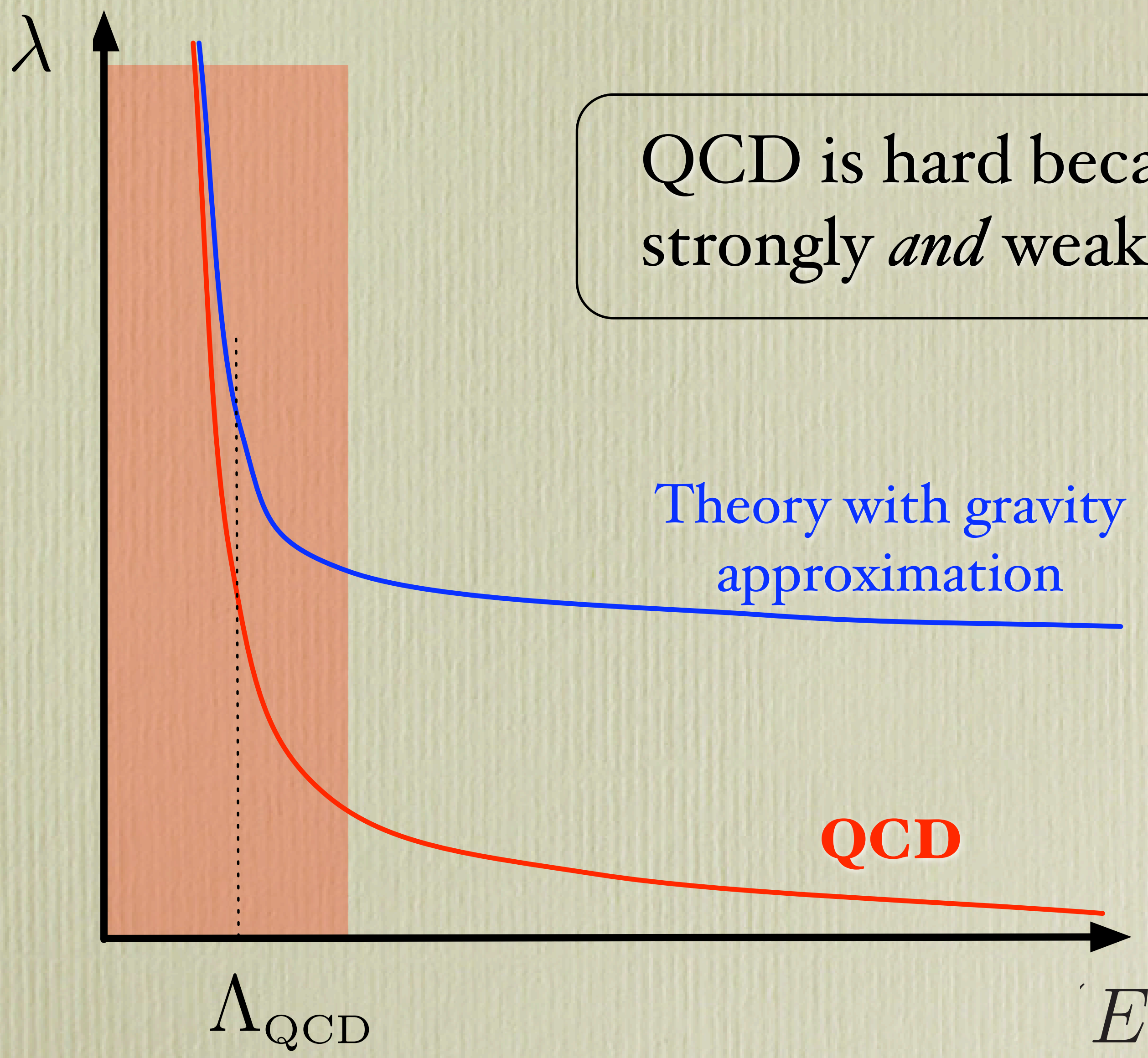


Limitations

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



Limitations



QCD is hard because it is *both* strongly *and* weakly coupled!

Therefore

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

Therefore

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

- However, *certain* results may be universal enough to apply to QCD in *certain* regimes:

    - Quantitative ballpark estimates.
    - Qualitative insights.

Therefore

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

- However, *certain* results may be universal enough to apply to QCD in *certain* regimes:

    - Quantitative ballpark estimates.
    - Qualitative insights.

- This can be extremely useful!

Illustration: A few results

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

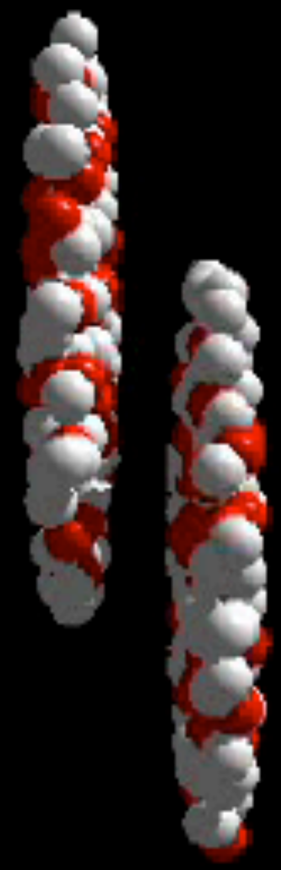
- It is the same for all non-Abelian plasmas with gravity dual in the limit $N_c \to \infty\,, \lambda \to \infty$.
    - Theories in different dimensions.
    - With or without quarks.
    - With or without chemical potential.
    - Etc.

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

- It is the same for all non-Abelian plasmas with gravity dual in the limit $N_c \to \infty\,,\, \lambda \to \infty$.
  - Theories in different dimensions.
  - With or without quarks.
  - With or without chemical potential.
  - Etc.
- In QCD we cannot calculate it but we can go to RHIC and LHC:



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

Results indicate strong coupling and $\frac{\eta}{s} \lesssim (2-3) \times \frac{1}{4\pi}$.

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

Results indicate strong coupling and $\dfrac{\eta}{s} \lesssim (2-3) \times \dfrac{1}{4\pi}$.

For water $\dfrac{\eta}{s} \sim 380 \times \dfrac{1}{4\pi}$.

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

Results indicate strong coupling and $\frac{\eta}{s} \lesssim (2-3) \times \frac{1}{4\pi}$.

For water $\frac{\eta}{s} \sim 380 \times \frac{1}{4\pi}$.

For liquid He $\frac{\eta}{s} \sim 9 \times \frac{1}{4\pi}$.

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

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policicastro, Son & Starinets '01
Kovtun, Son & Starinets '03

- Although in right ballpark, it could be off by 200-300% !

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

- Although in right ballpark, it could be off by 200-300% !
- Yet important because:
  - It teaches us that ratio *can* be "small" in sQGP.
  - It tells us what "*small*" means, e.g. results in HIC are quoted in units of $\frac{1}{4\pi}$.

A good quantitative example

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

- Although in right ballpark, it could be off by 200-300% !
- Yet important because:
  - It teaches us that ratio *can* be "small" in sQGP.
  - It tells us what "*small*" means, e.g. results in HIC are quoted in units of $\frac{1}{4\pi}$.
- $\frac{1}{4\pi}$ is *not* a lower bound in AdS/CFT!

Kats & Petrov '07
Mia, Dasgupta, Gale & Jeon '09
Buchel, Myers & Sinha '09

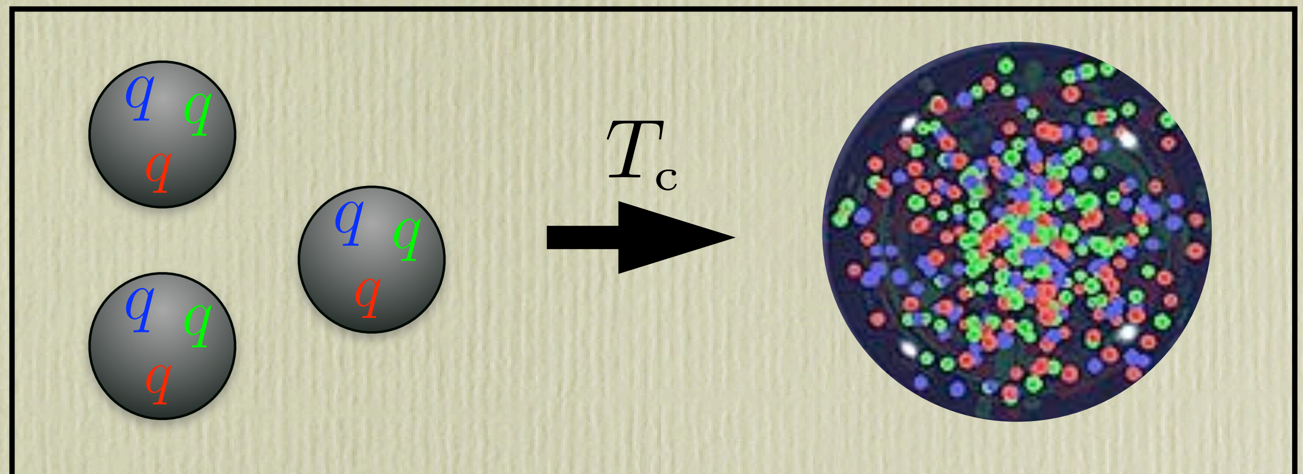
Strategy

Seek results based on universal features of the duality

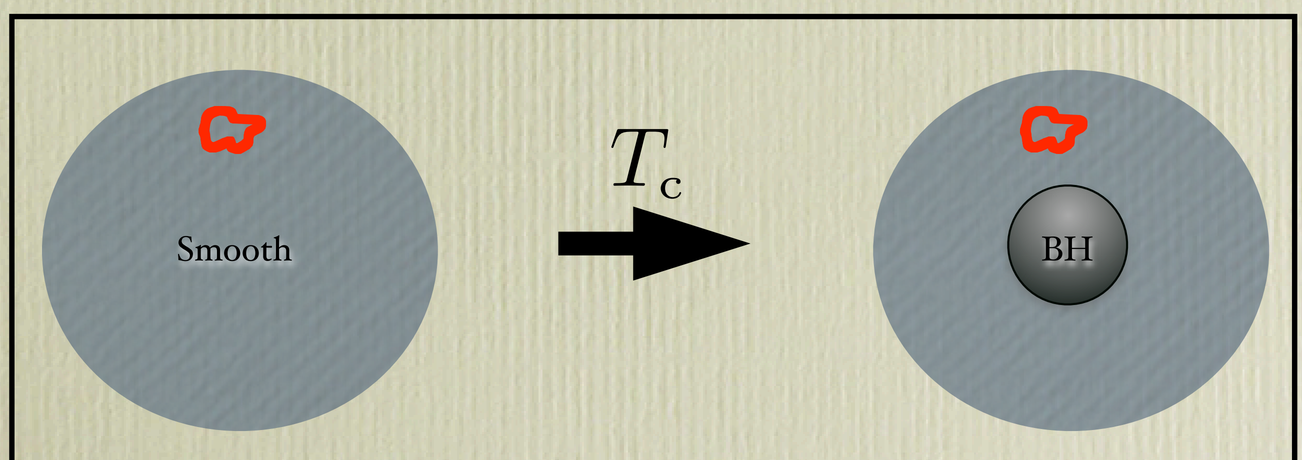
Deconfinement = Black Hole

Witten '98

Gauge



Gravity

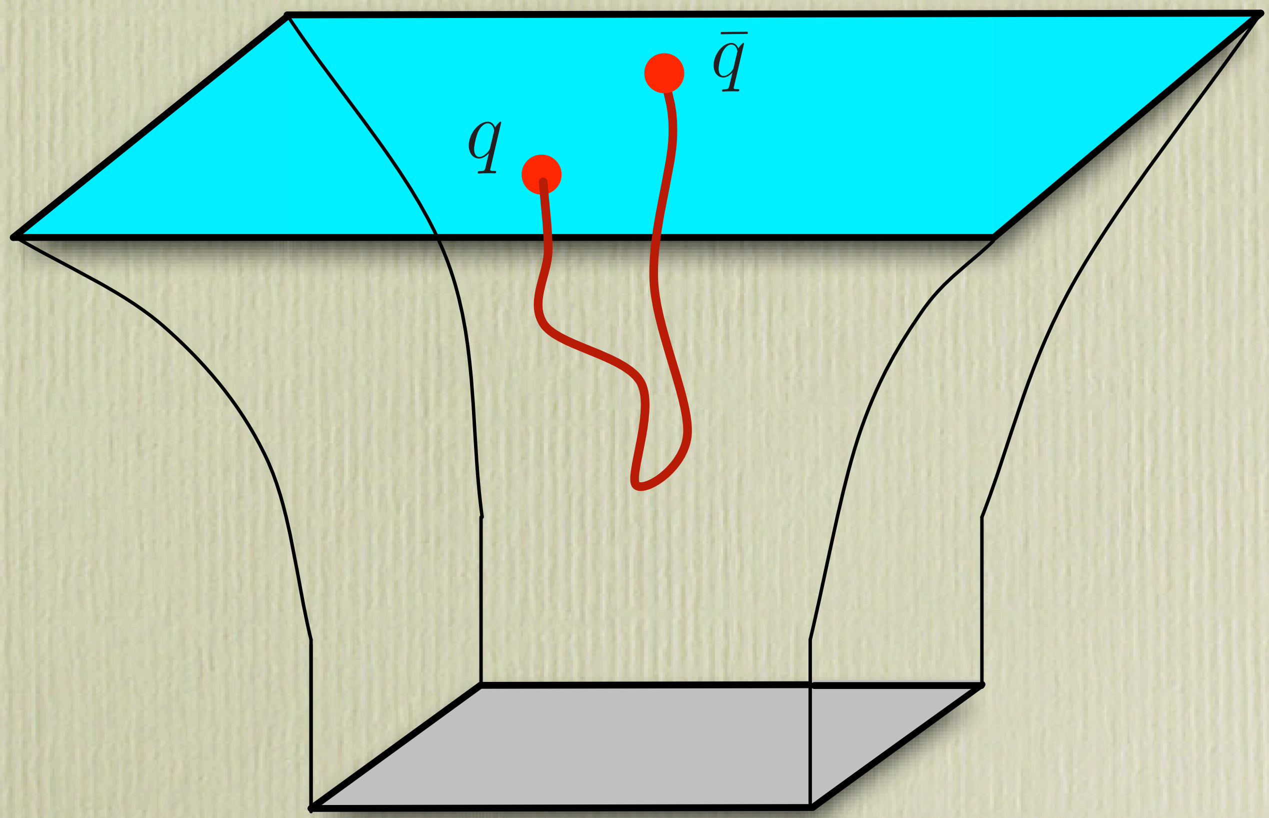


→ Universal:

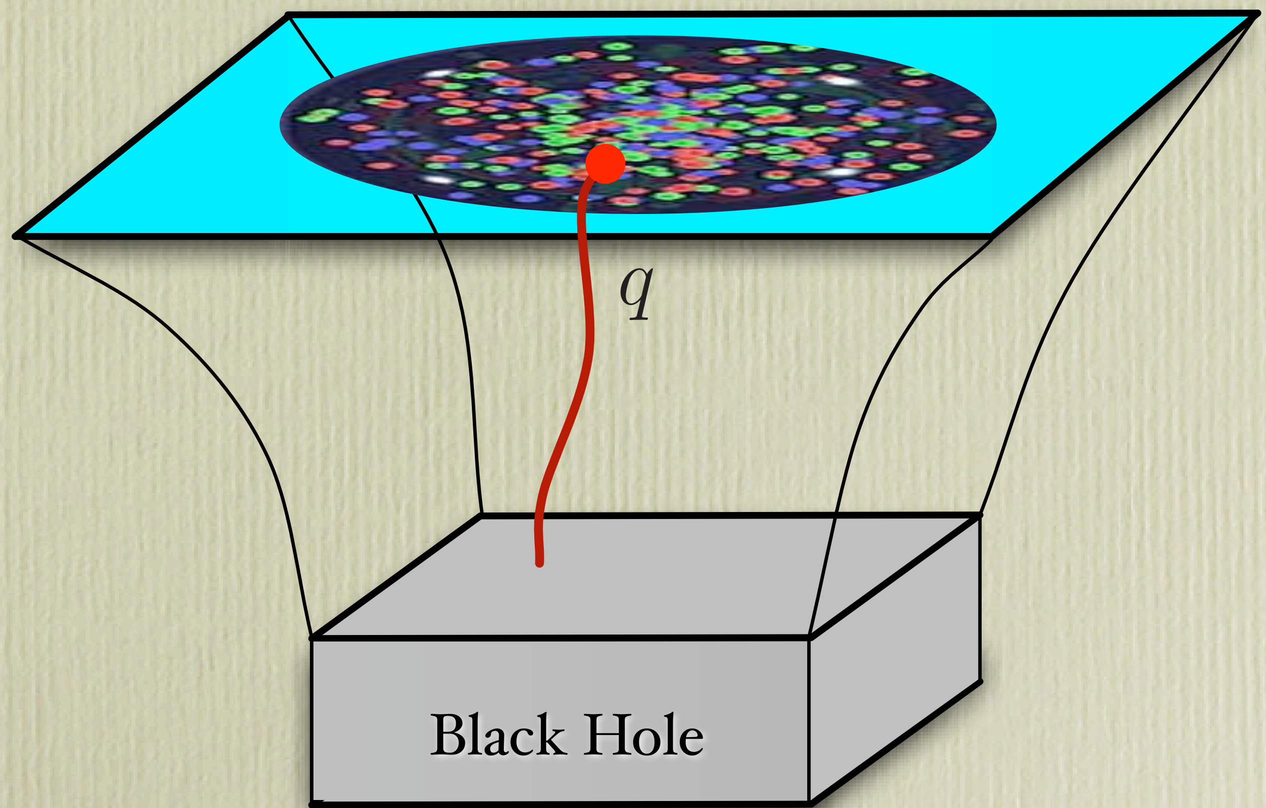
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Policastro, Son & Starinets '01
Kovtun, Son & Starinets '03

Confinement

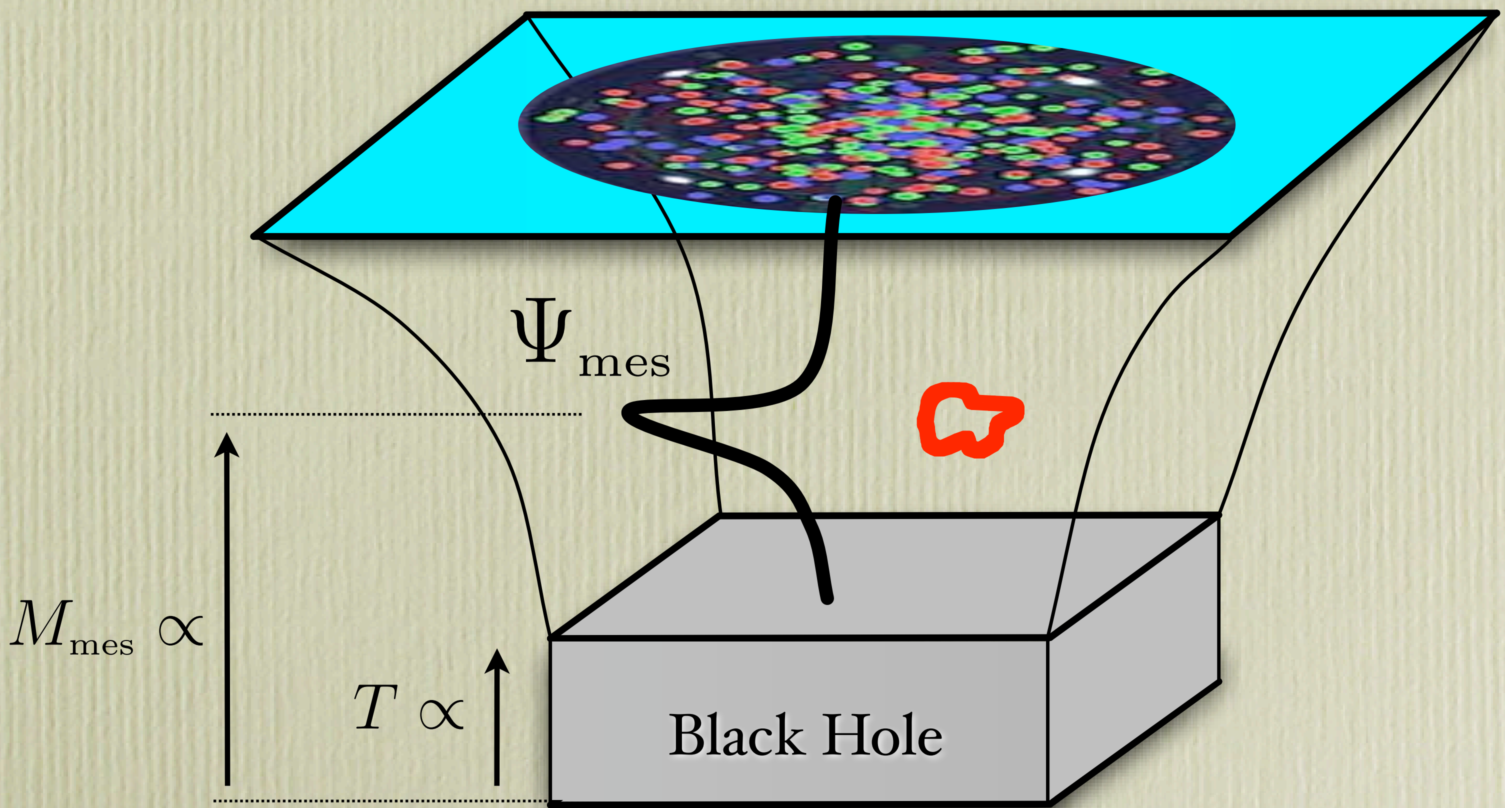


Deconfinement



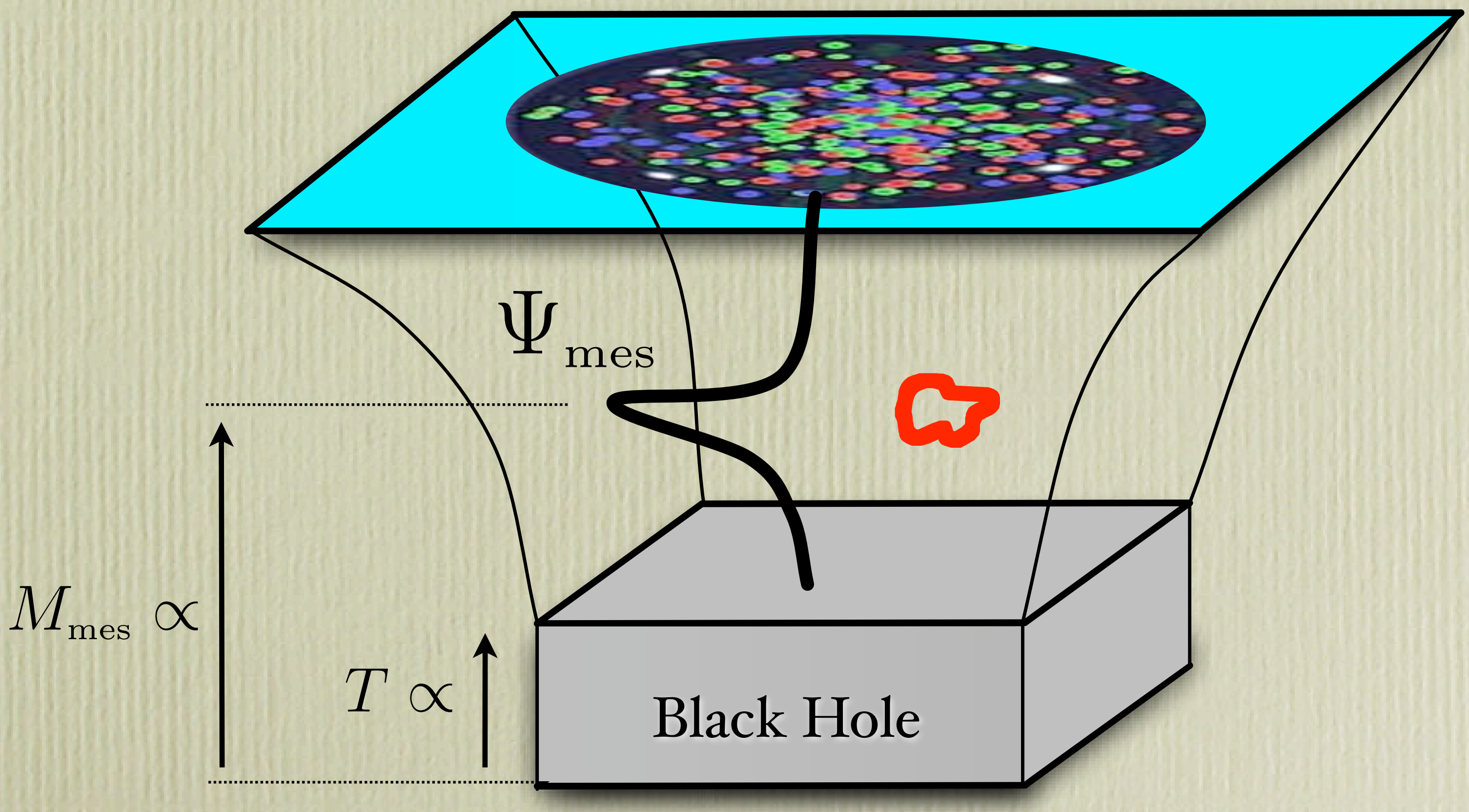
Heavy mesons survive deconfinement

D.M., Myers & Thomson ‘ 06
Hoyos-Badajoz, Landsteiner & Montero ’06
Babington, Erdmenger, Guralnik & Kirsch ’03
Kruczenski, D.M., Myers & Winters ’03
Kirsch ‘04



Heavy mesons survive deconfinement

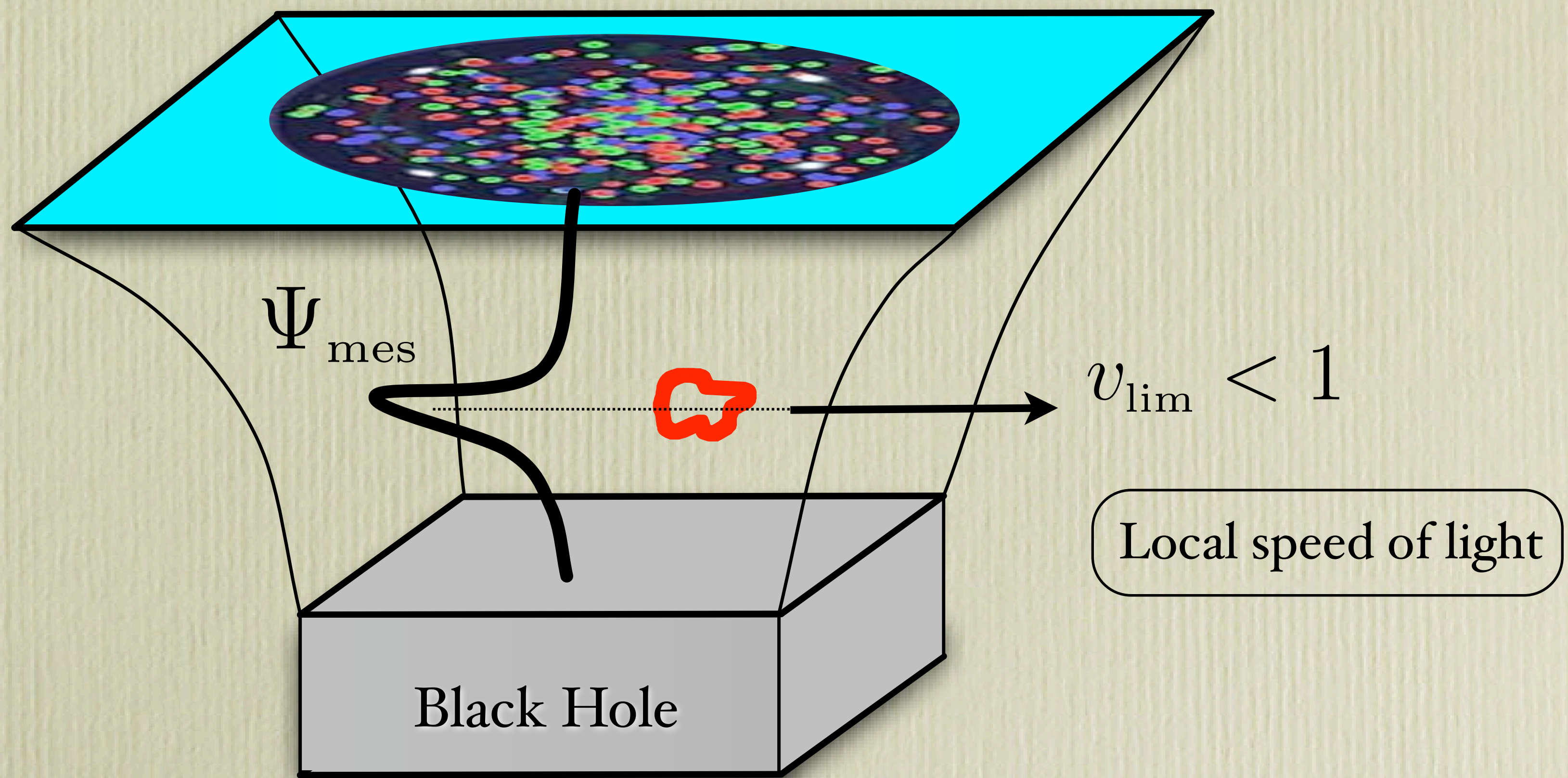
D.M., Myers & Thomson ' 06
Hoyos-Badajoz, Landsteiner & Montero '06
Babington, Erdmenger, Guralnik & Kirsch '03
Kruczenski, D.M., Myers & Winters '03
Kirsch '04



J/Ψ → $T_{\rm diss} \sim 1.6 - 2.1 T_c$

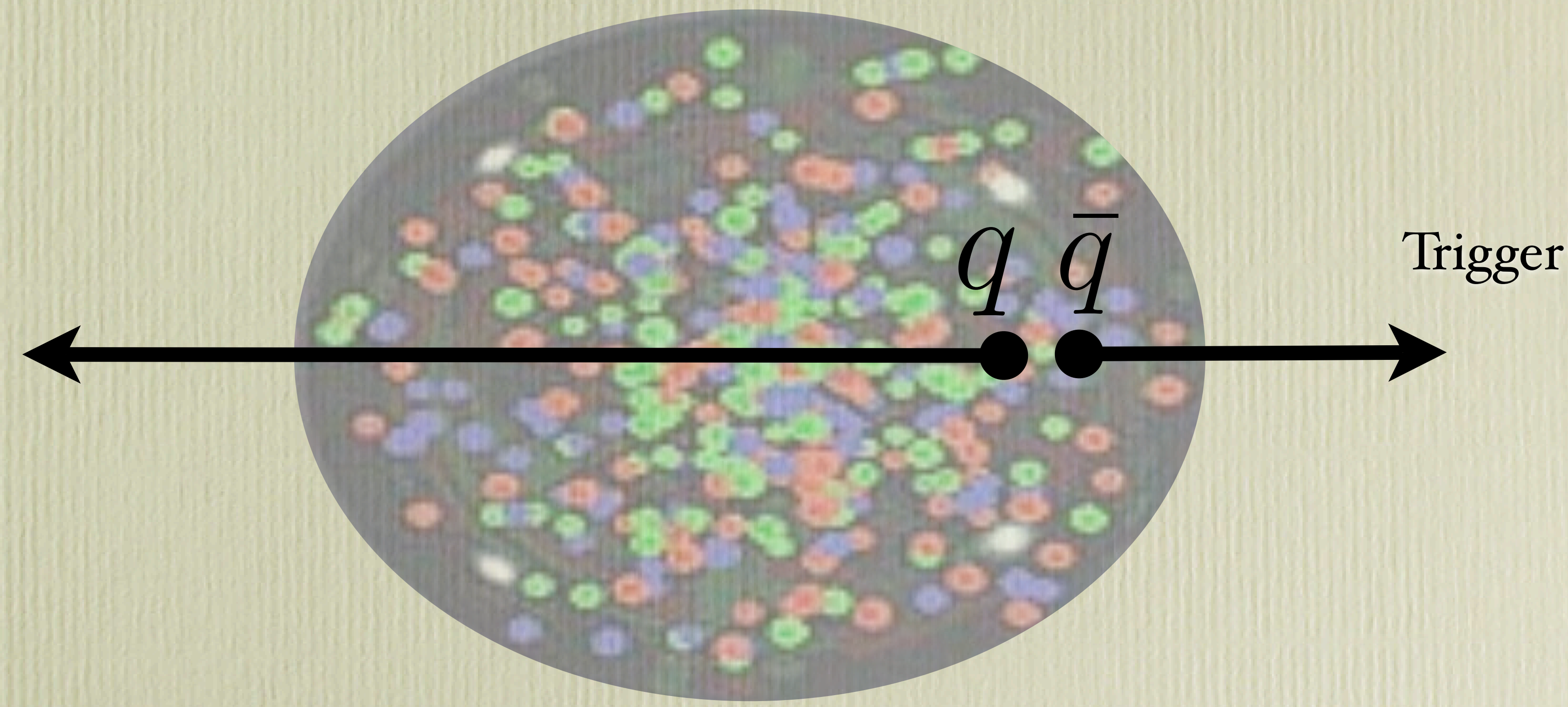
Mesons limiting velocity

D.M., Myers & Thomson '07
Ejaz, Faulkner, Liu, Rajagopal & Wiedemann '07



Cherenkov quark energy loss

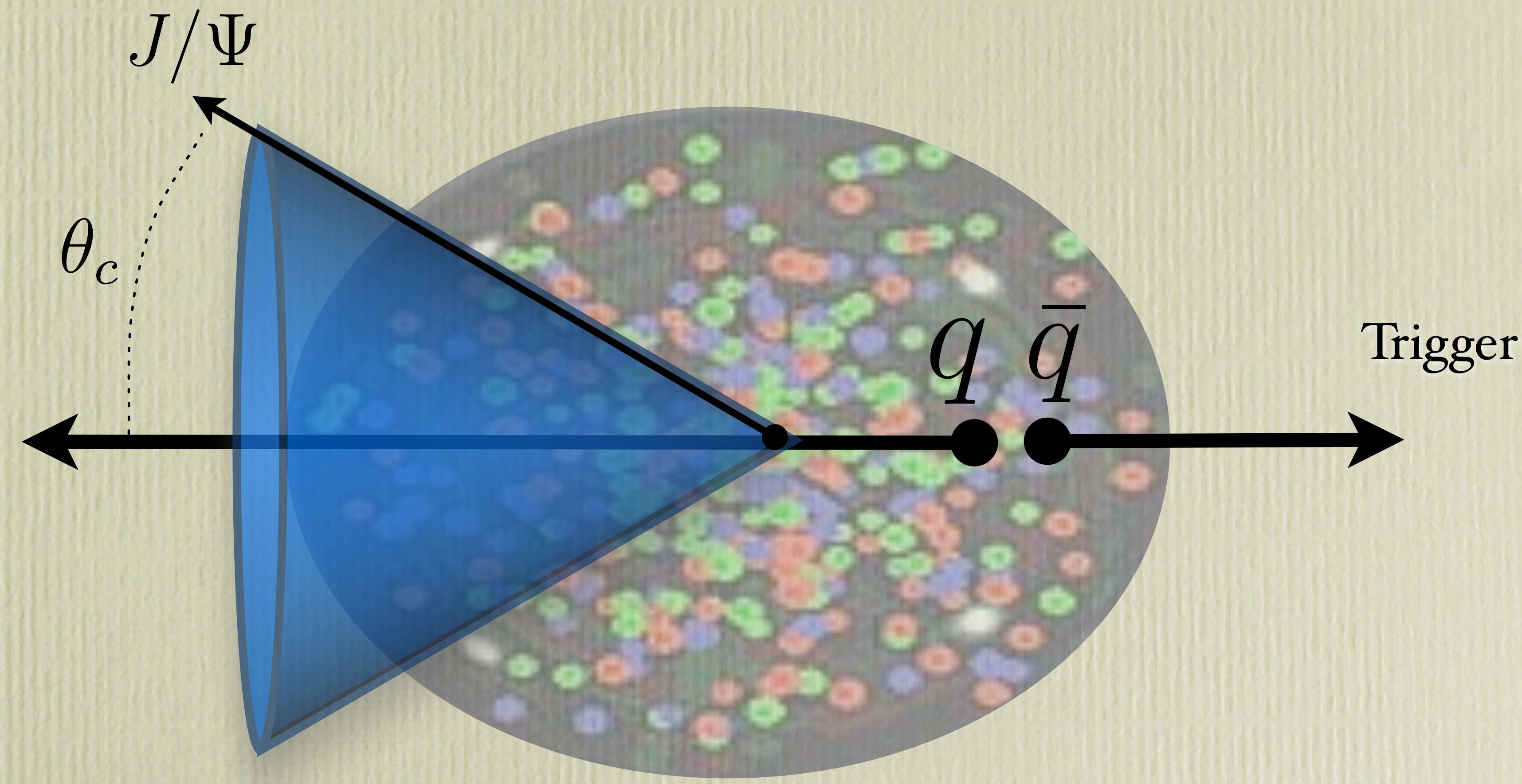
Casalderrey-Solana, Fernandez & D.M. ’10



$$\boxed{v_q > v_{\lim}}$$

Cherenkov quark energy loss

Casalderrey-Solana, Fernandez & D.M. '10

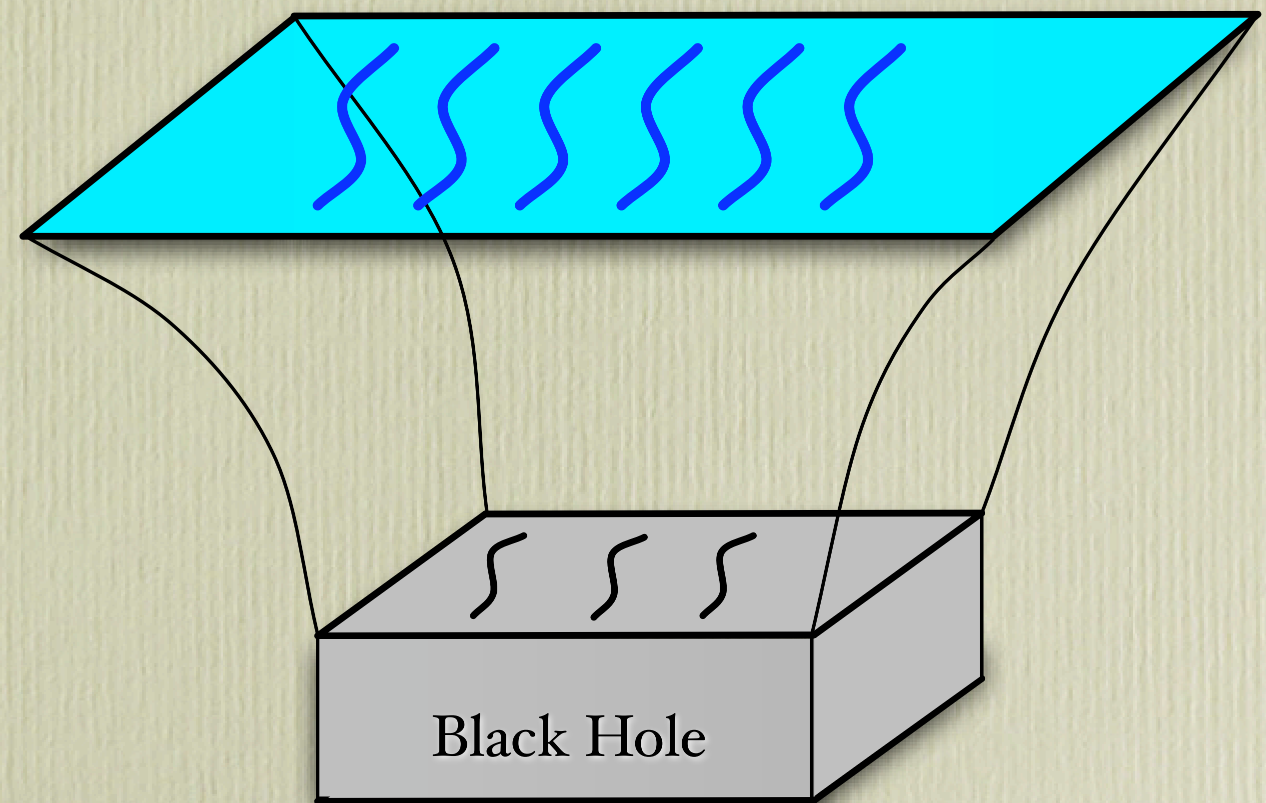


$$\cos\theta_c = \frac{v_{\rm lim}}{v_q} \lesssim 70^0$$

$$\frac{dE}{dx} \approx 2 - 8 \text{ GeV/fm}$$

All-order hydrodyanmics from gravity

Bhattacharyya, Hubeny, Minwalla & Rangamani '08



Invitation for NR:
Out of equilibrium

Out of equilibrium

Out of equilibrium QFT

$$\Updownarrow$$

Classical Dynamical GR in AdS

Out of equilibrium

Out of equilibrium QFT

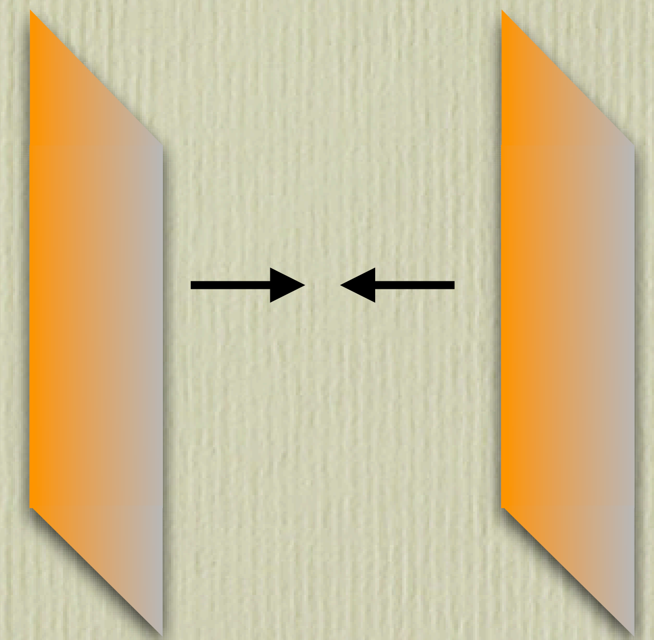
Classical Dynamical GR in AdS

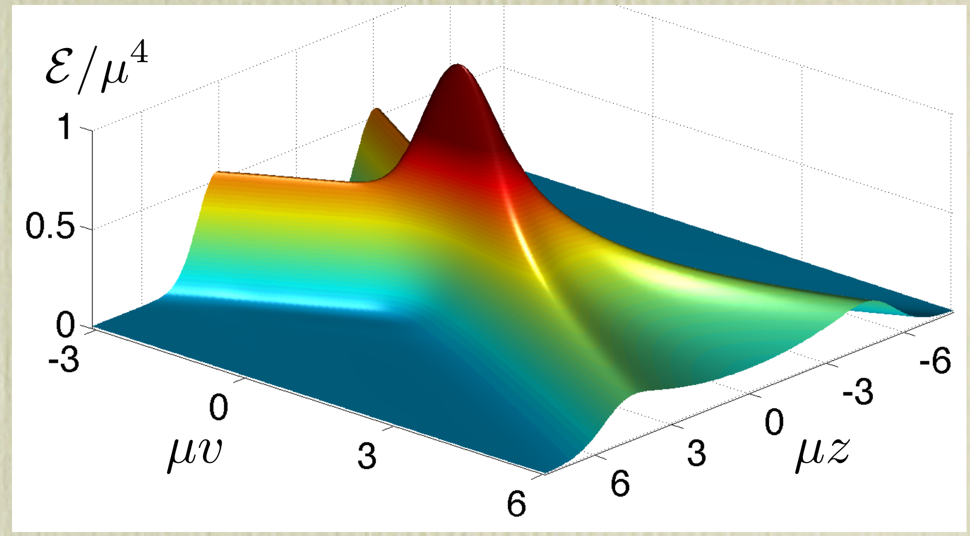
Don't let boundary conditions stop you!

Time dependence & thermalization

Chesler & Yaffe '10

- Collide two infinite sheets of energy in N=4 ⟶ d=2+1 in AdS

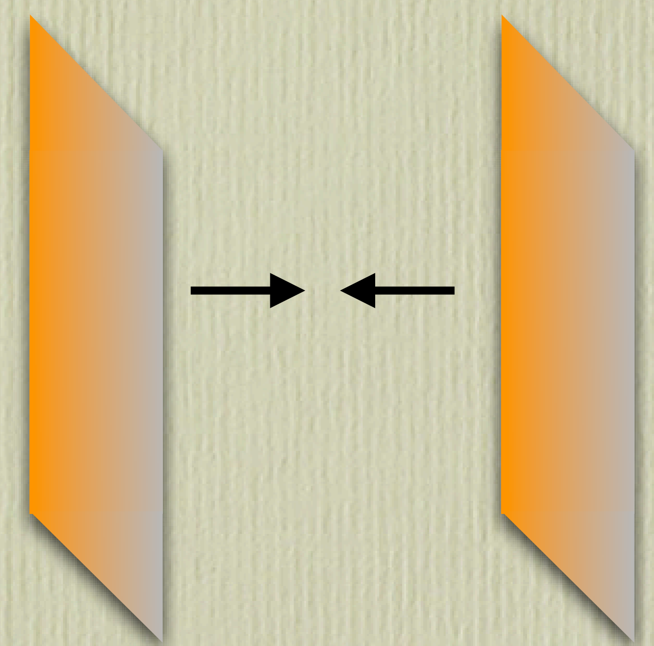


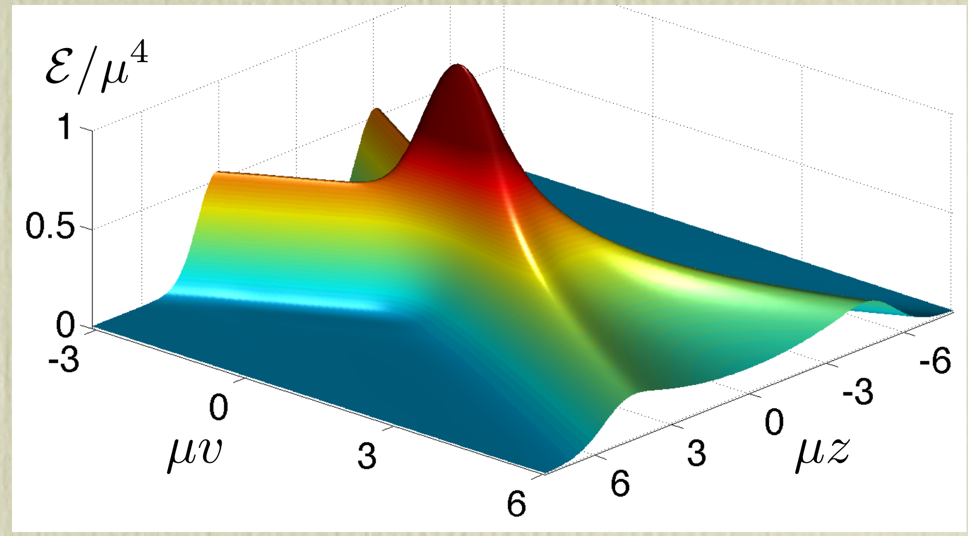


Time dependence & thermalization

Chesler & Yaffe '10

- Collide two infinite sheets of energy in N=4 ⟶ d=2+1 in AdS





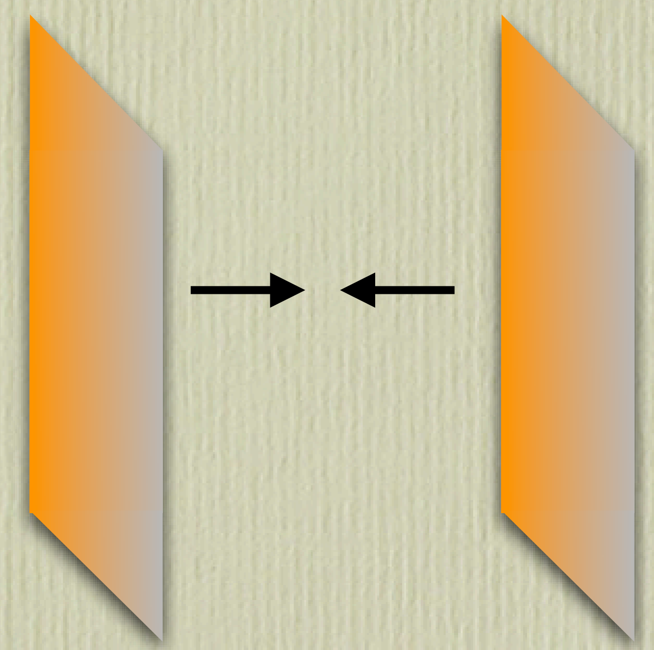
Insight:

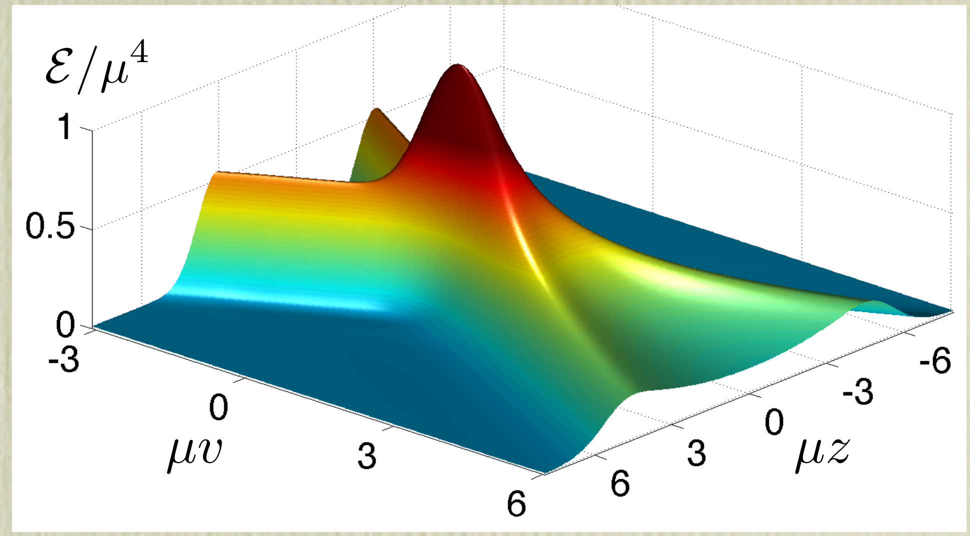
- Short thermalization time ~ 0.3 fm.

Time dependence & thermalization

Chesler & Yaffe ‘10

- Collide two infinite sheets of energy in N=4 ⟶ d=2+1 in AdS





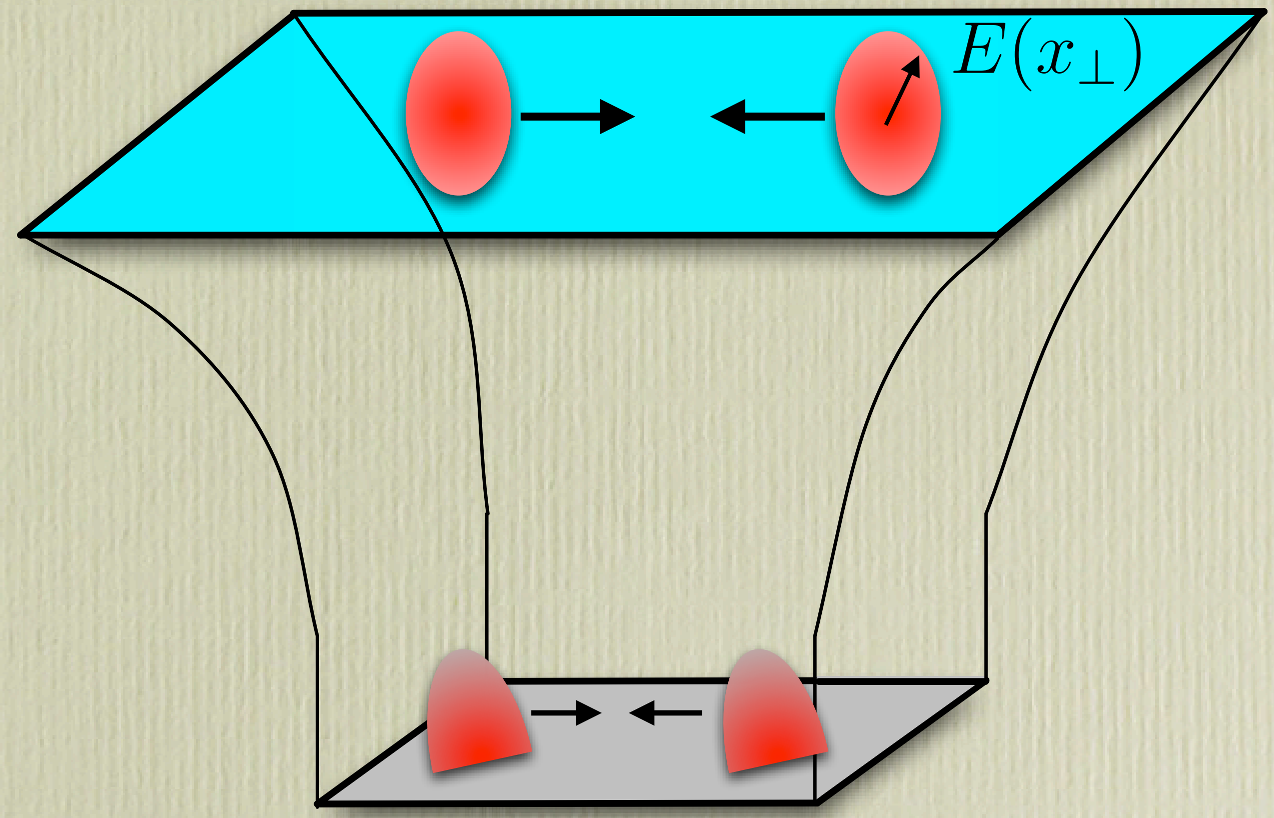
Insight:

- Short thermalization time ~ 0.3 fm.

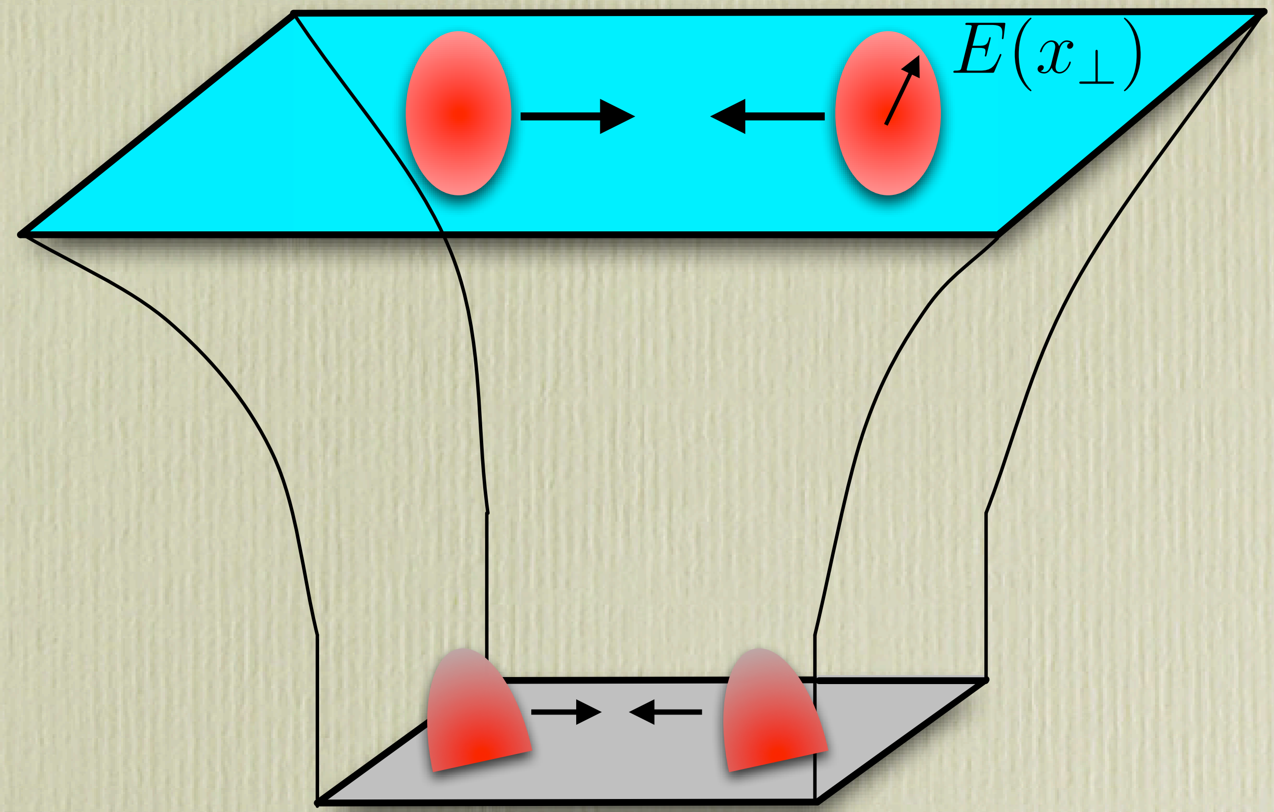
Caveats:

- Only numerical ball-park.
- Thermalization could occur via weak-coupling mechanism.

- Generalize to two discs in confining geometry:



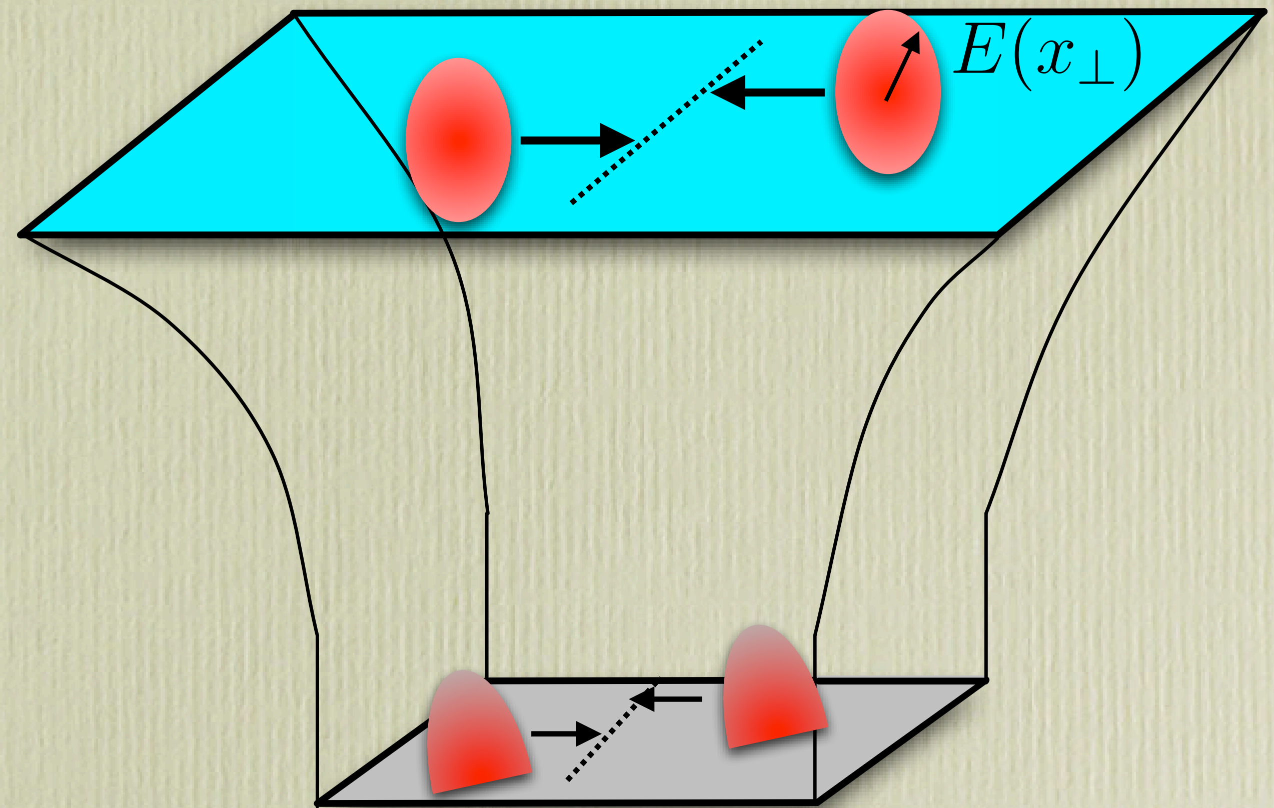
- Generalize to two discs in confining geometry:



Head-on: d=3+1 in AdS

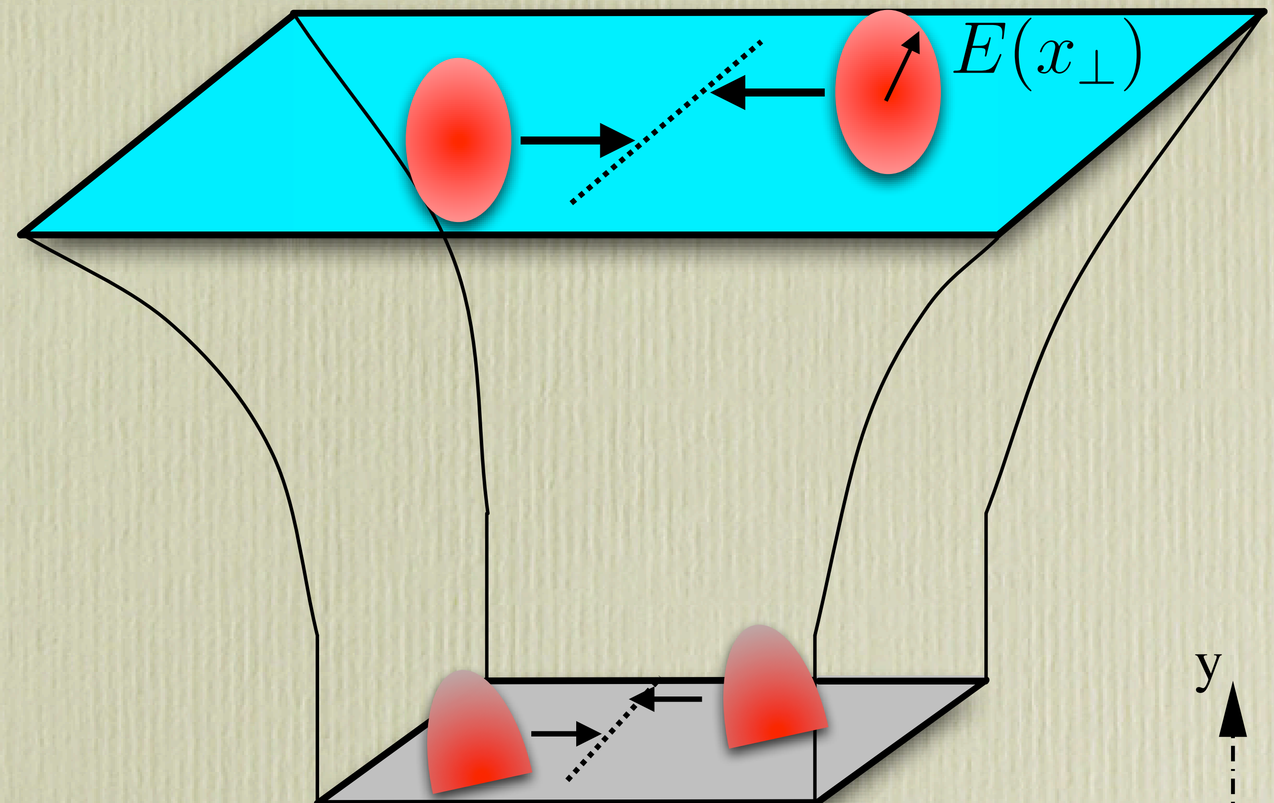
- How does the profile at thermalization depend on initial profile?

- Generalize to two discs in confining geometry:



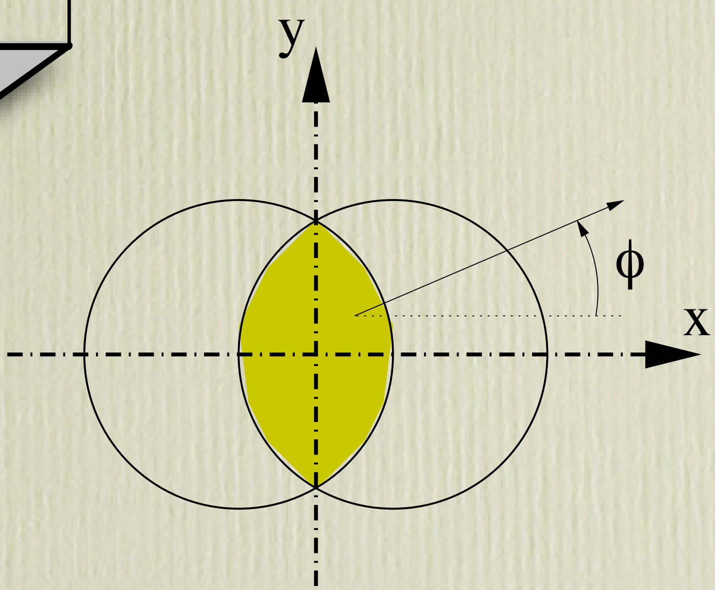
Finite impact parameter: d=4+1 in AdS

- Generalize to two discs in confining geometry:



Finite impact parameter: d=4+1 in AdS

- Include elliptic flow.



Conclusions

- Gauge/String duality is not a *precision* tool for sQGP, but it provides solvable models.

Conclusions

- Gauge/String duality is not a *precision* tool for sQGP, but it provides solvable models.

- Sometimes these may offer valuable insights into problems difficult (or impossible) to analyze by other methods.

Conclusions

- Gauge/String duality is not a *precision* tool for sQGP, but it provides solvable models.

- Sometimes these may offer valuable insights into problems difficult (or impossible) to analyze by other methods.

- Many of these problems require “just” solving classical Einstein equations in AdS.

Conclusions

- Gauge/String duality is not a *precision* tool for sQGP, but it provides solvable models.

- Sometimes these may offer valuable insights into problems difficult (or impossible) to analyze by other methods.

- Many of these problems require “just” solving classical Einstein equations in AdS.

Let’s sit down and talk !

Thank you.