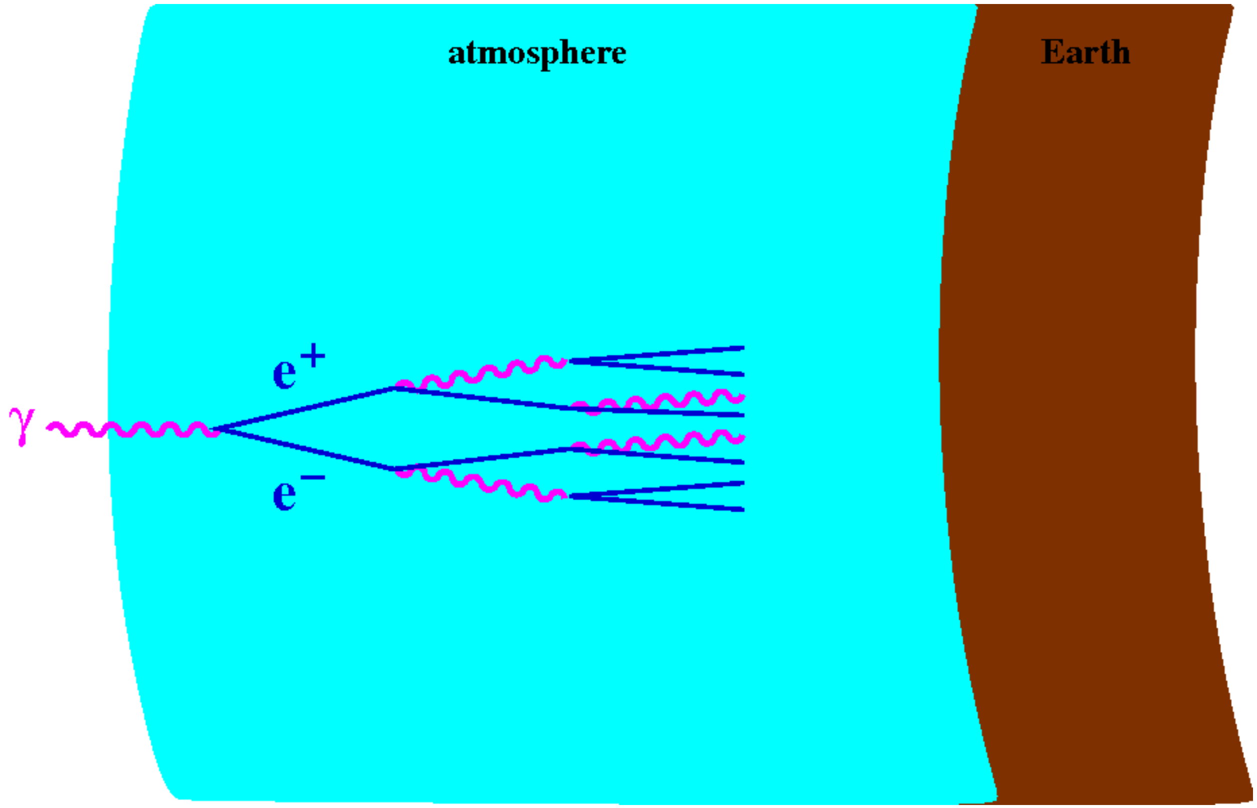
The Landau-Pomeranchuk-Migdal Effect
1953 – today

Cosmic Rays
to Quark-Gluon Plasmas
to String Theory

Peter Arnold
University of Virginia

Cosmic Ray Showering

High energy particles traveling through matter lose energy via successive bremsstrahlung and pair production:



[Oversimplification: Only electromagnetic shower shown.]

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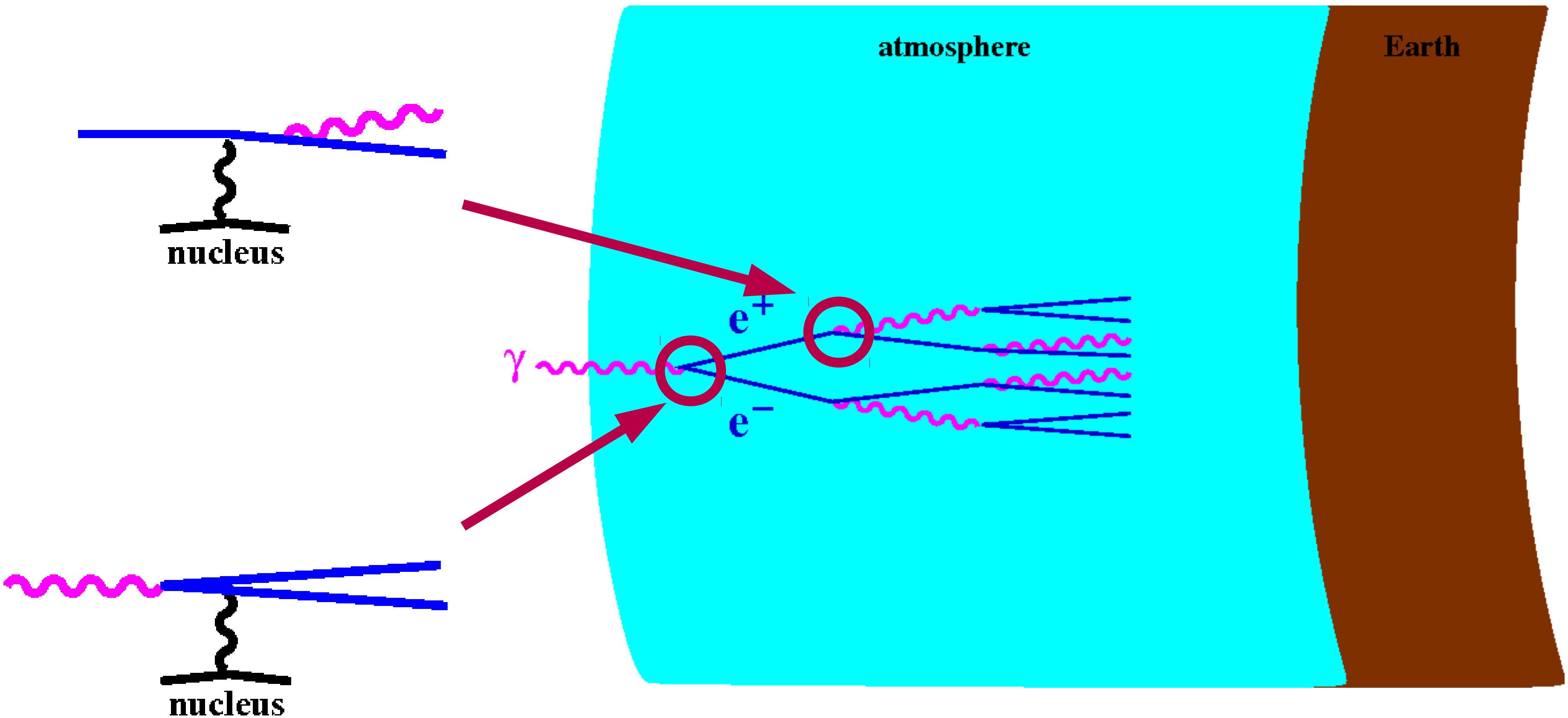

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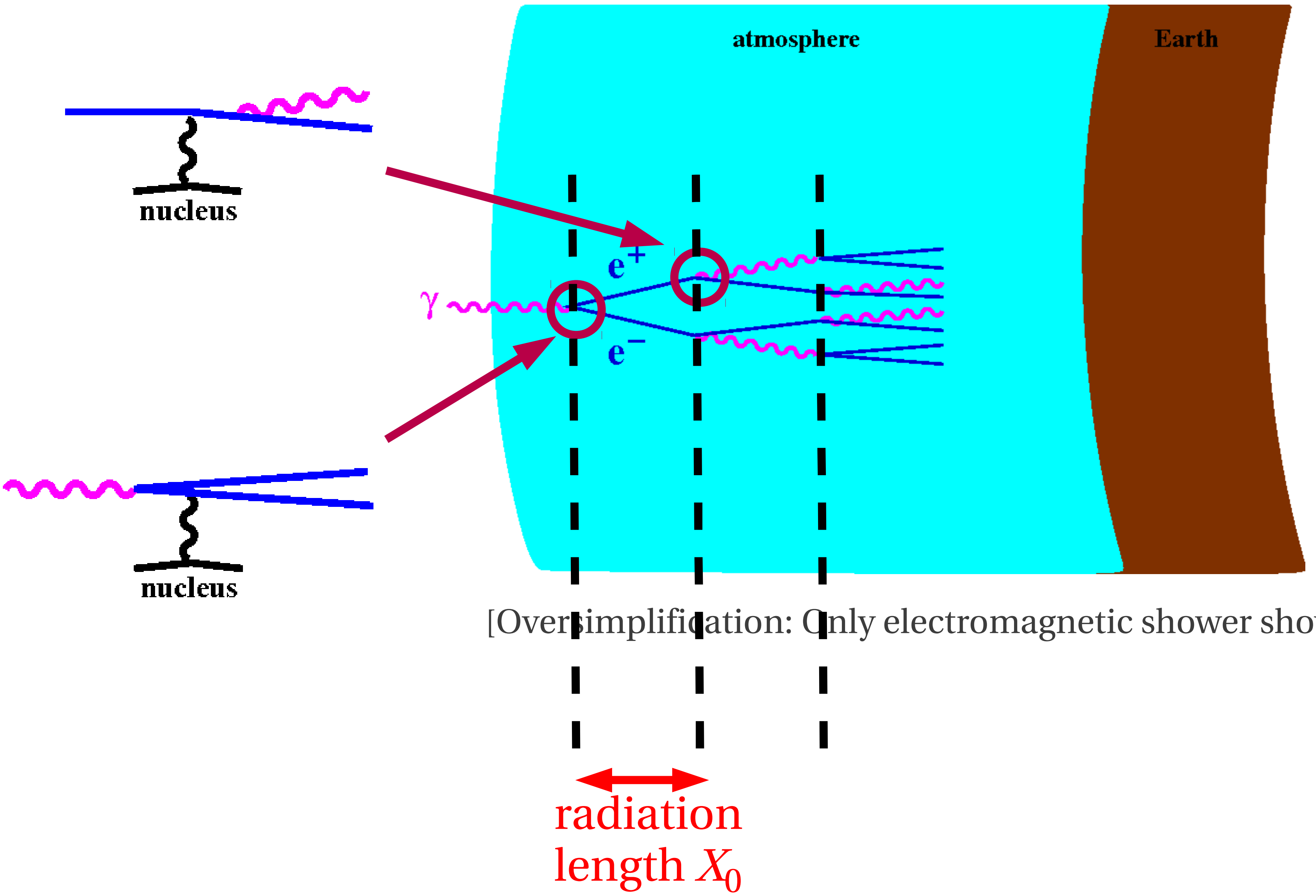


[Oversimplification: Only electromagnetic shower shown.]

Landau-Pomeranchuk-Migdal (LPM) effect

What is the LPM Effect?

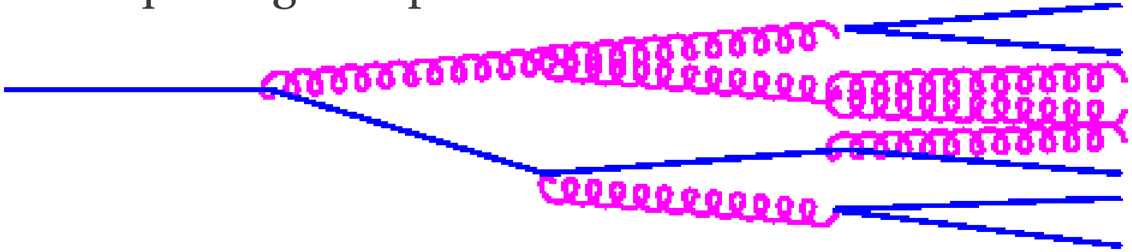
A coherence effect that complicates calculations of bremsstrahlung or pair production when a very high energy particle scatters from a medium.

Places it comes up in QED

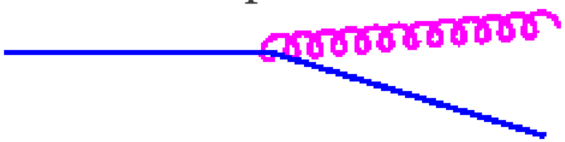
- Very high energy cosmic rays showering in the atmosphere.
- Certain beam dump experiments designed to measure the LPM effect.

Places it comes up in QCD

- Energy loss of high energy jets in a quark-gluon plasma.



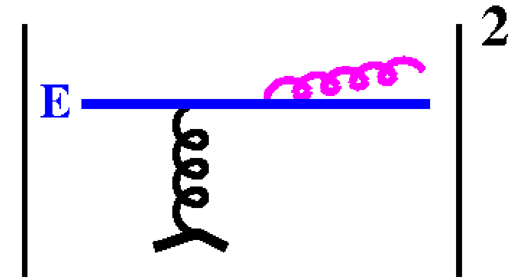
- Complete leading-order calculations of the viscosity and other transport coefficients of a weakly-coupled quark-gluon plasma.



- Coherence in high-energy, small-x scattering from a large nucleus: color glass condensate.

The LPM Effect

Naively

brem rate ~ $n \sigma v$ ~ (density of scatterers) $\times$  $\times\, c$

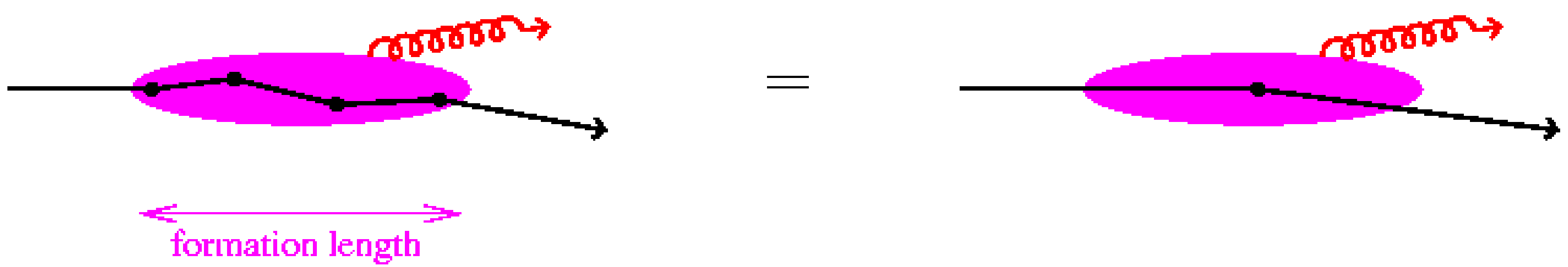
Result: high-energy brem rate independent of E.

Problem

At very high energy,

probabilities of brem from successive scatterings no longer independent;

brem from several successive (small angle) collisions not very different from brem from one collision.



$$\textbf{formation length} \propto \sqrt{E}$$

Result: a reduction of the naive brem rate.

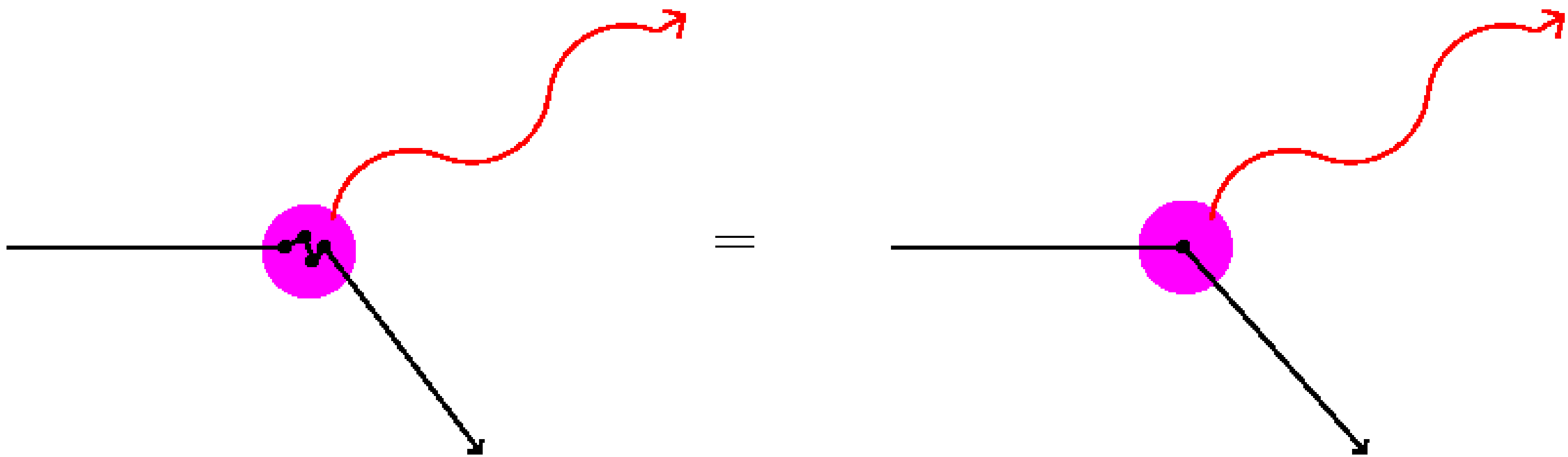
Example: stopping distance
(in a infinite medium)

If LPM effect ignored: stopping distance $\propto$ $\ln E$

Actual result (weak coupling): stopping distance $\propto$ $\left(\frac{E}{\ln E}\right)^{1/2}$

The LPM Effect (QED)

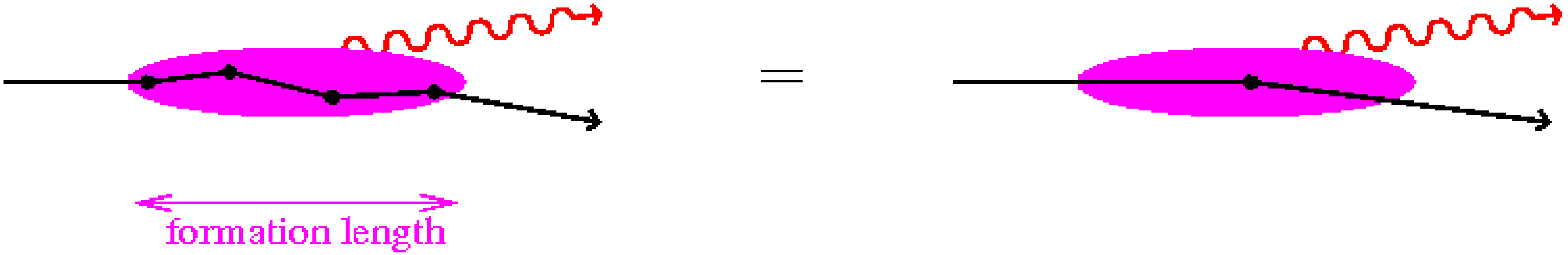
Warm-up: Recall that light cannot resolve details smaller than its wavelength.



[Photon emission from different scatterings have same phase → coherent.]

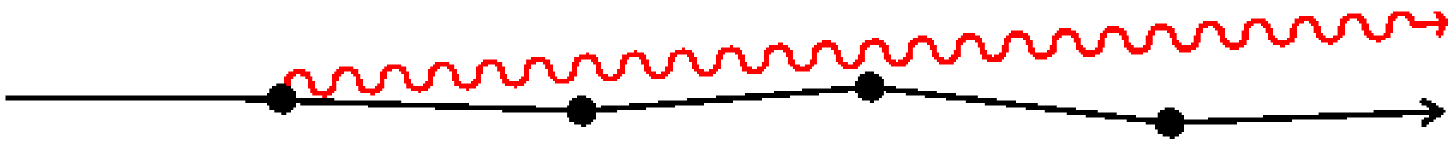
Now: Just Lorentz boost above picture by a lot!

The LPM Effect (QED)



Note: (1) **bigger E** requires bigger boost → more time dilation **→ longer formation length**
(2) big boost → this process is **very collinear.**

An alternative picture

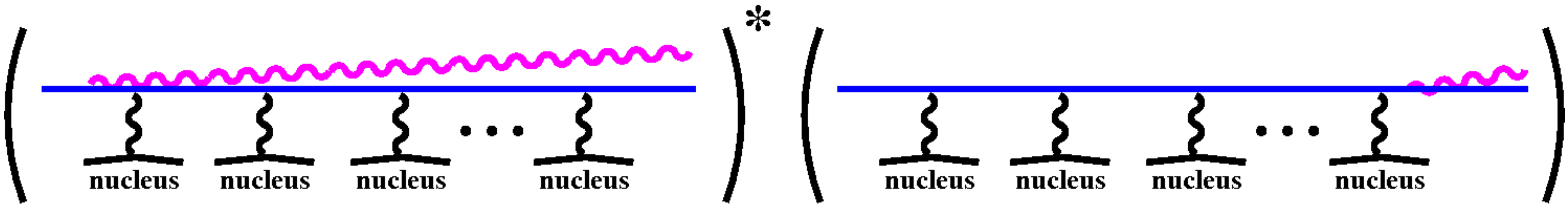


versus

Are these two possibilities in phase? Or does the interference average to zero?

IN PHASE if (i) everything is nearly collinear ✓
(ii) particle and photon have nearly same velocity ✓ (*speed of light*)

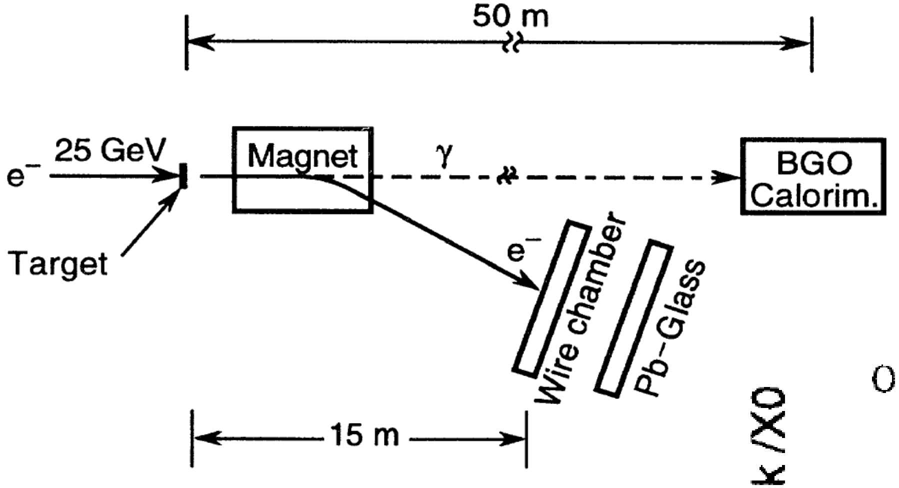
A real calculation involves...



soft photons: Can do a classical EM calculation (Landau+Pomeranchuk 1953)

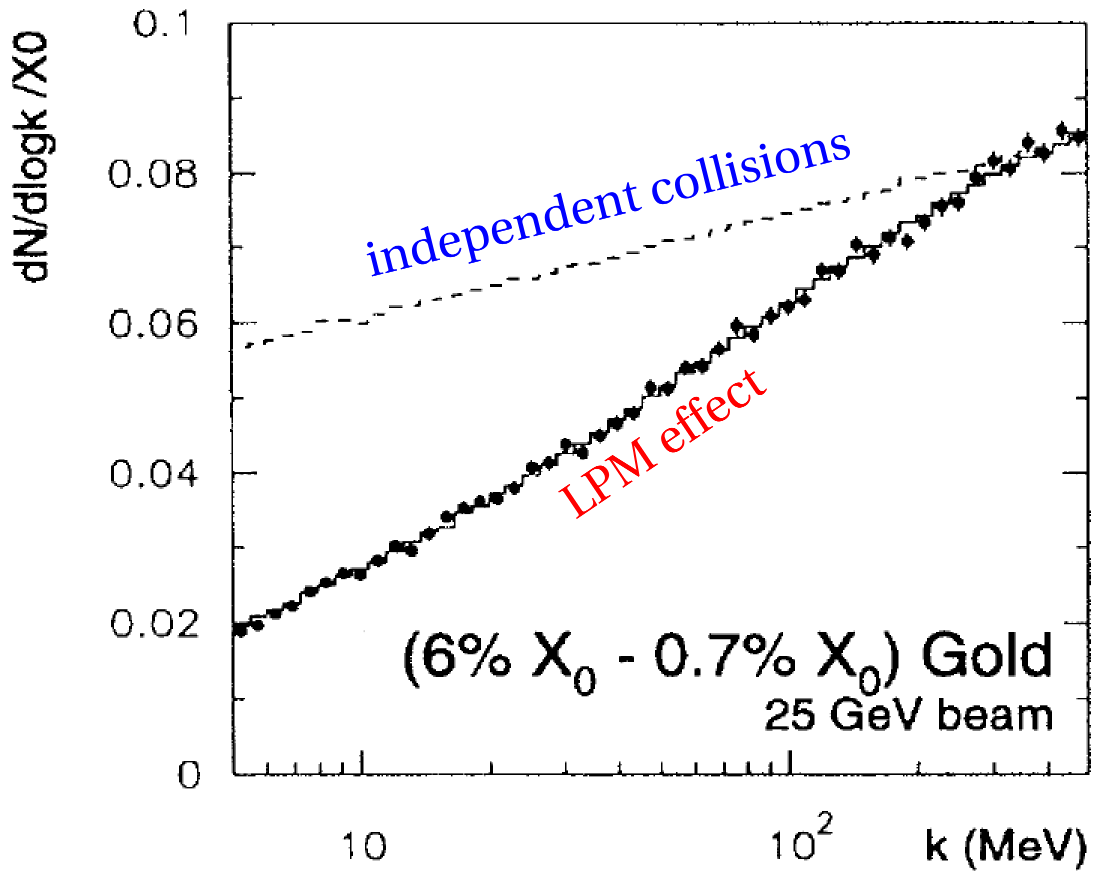
hard photons: Much trickier! (Migdal 1955)

Experimental Measurement of LPM (QED)

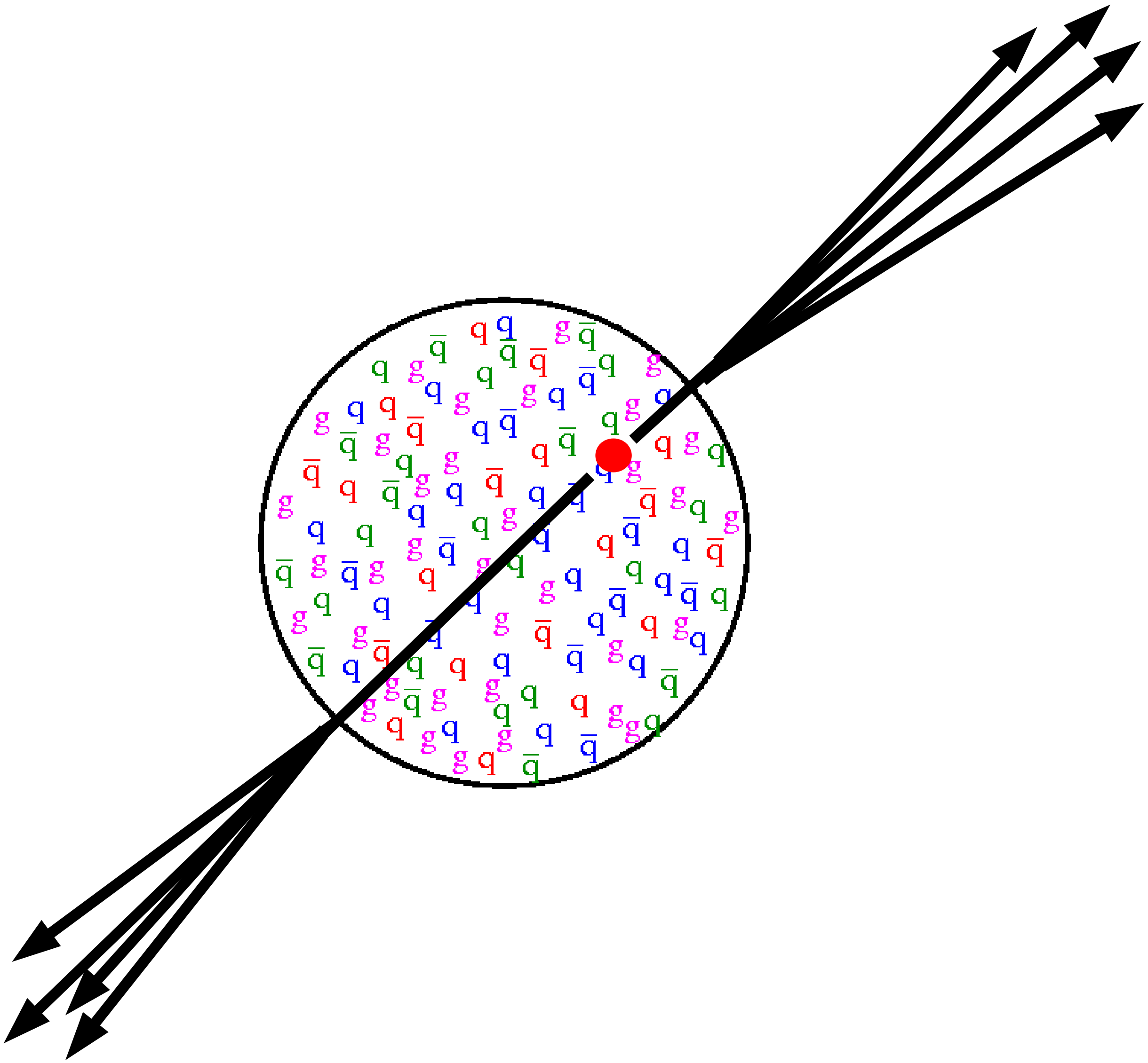


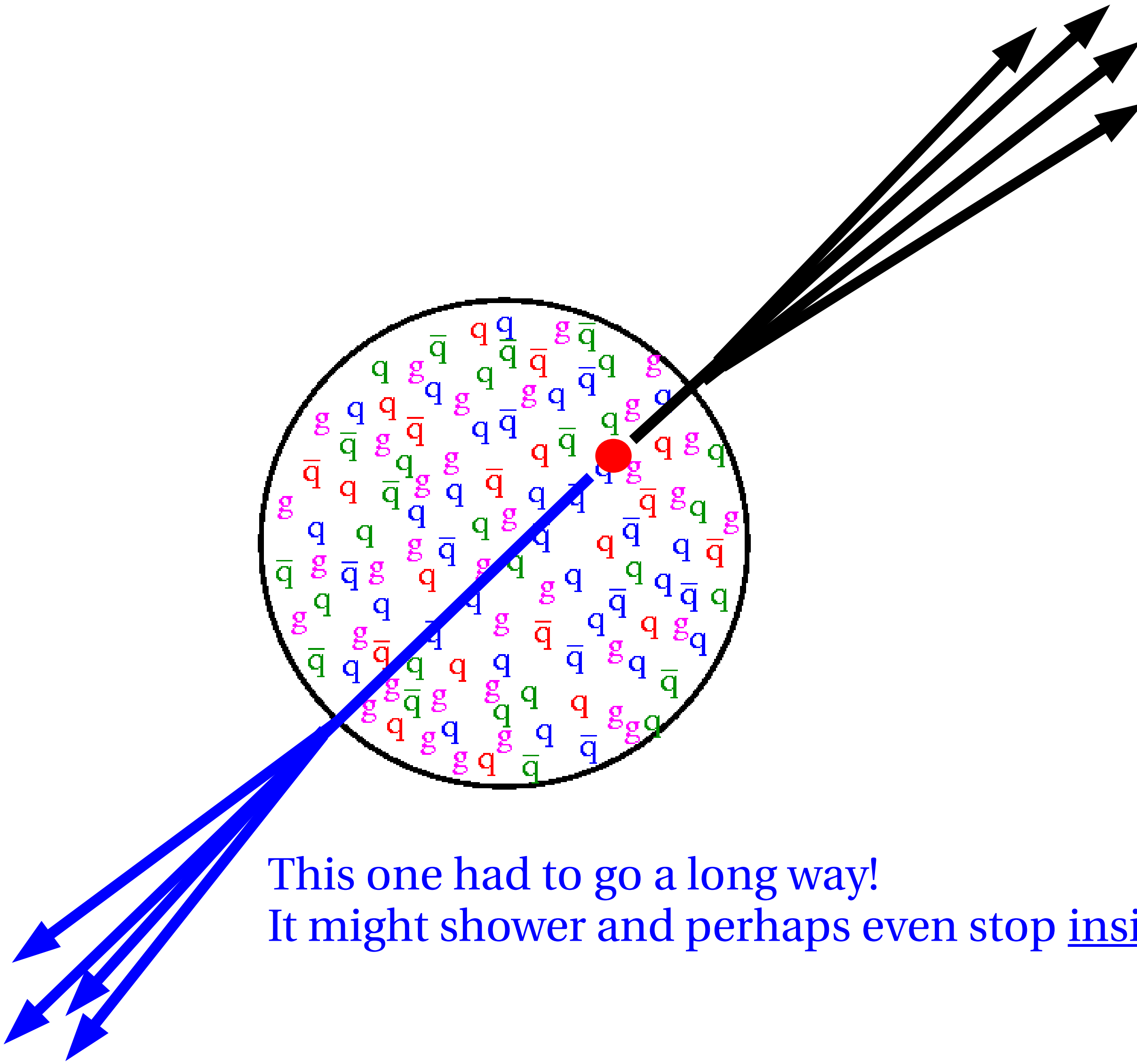
SLAC E-146

Phys. Rev. Lett. **75** (1995) 2949.

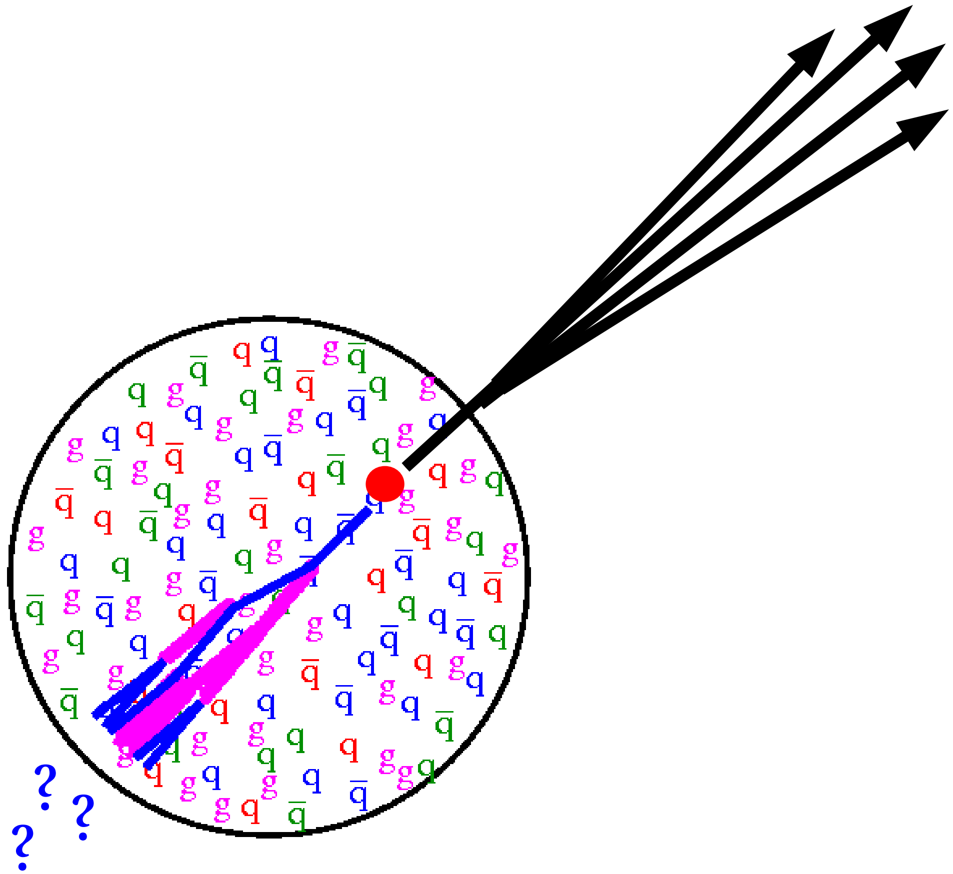


Jet Quenching in Quark-Gluon Plasmas





This one had to go a long way!
It might shower and perhaps even stop <u>inside</u> the medium.



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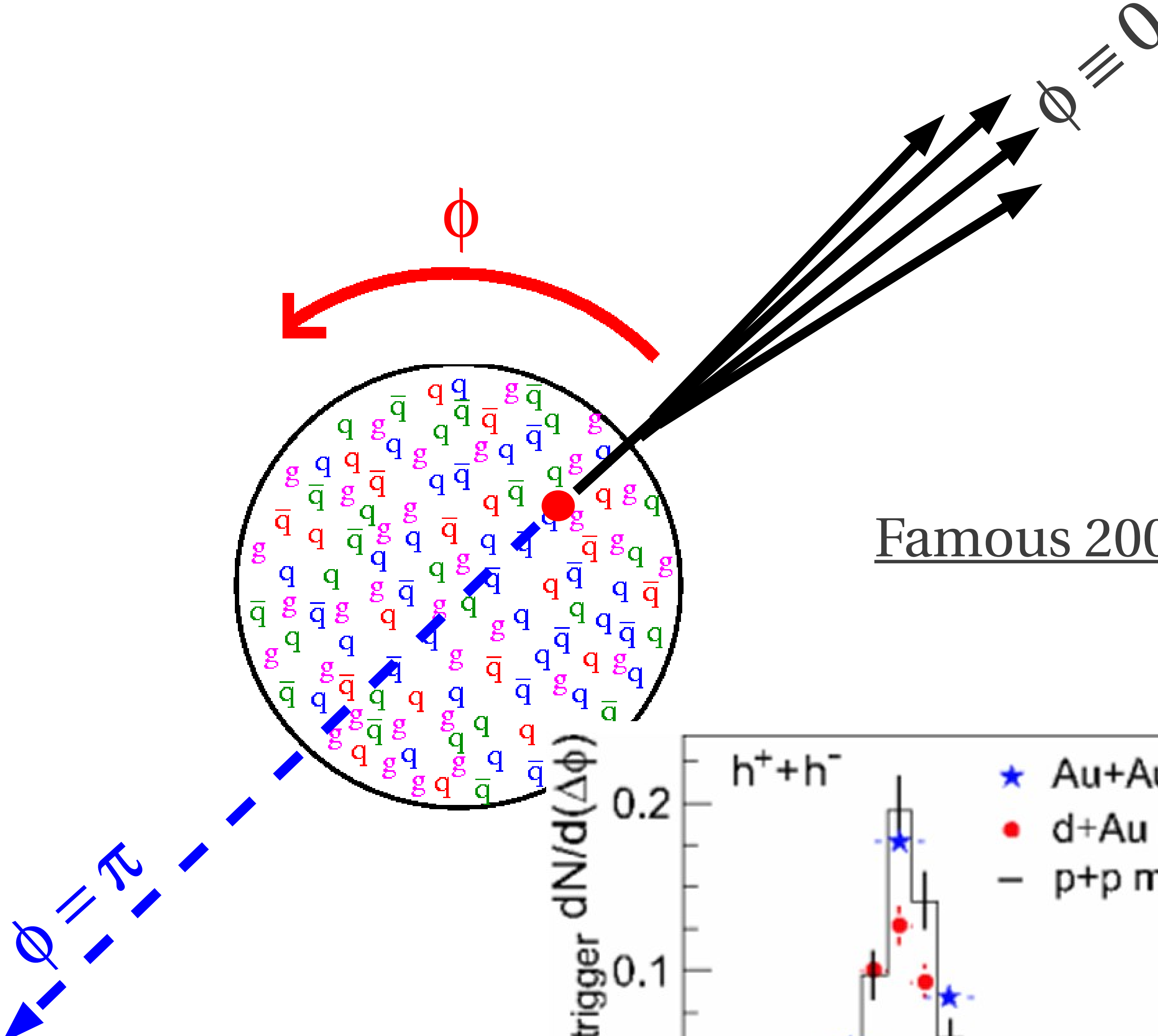
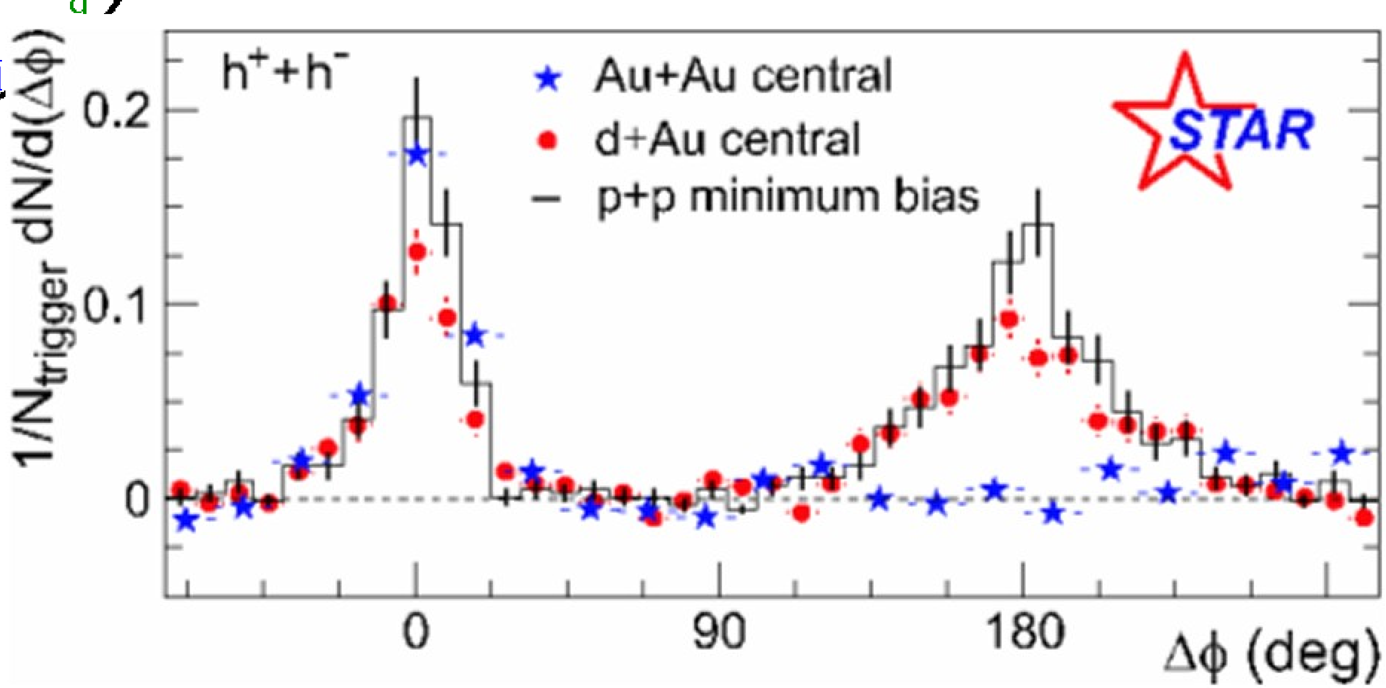
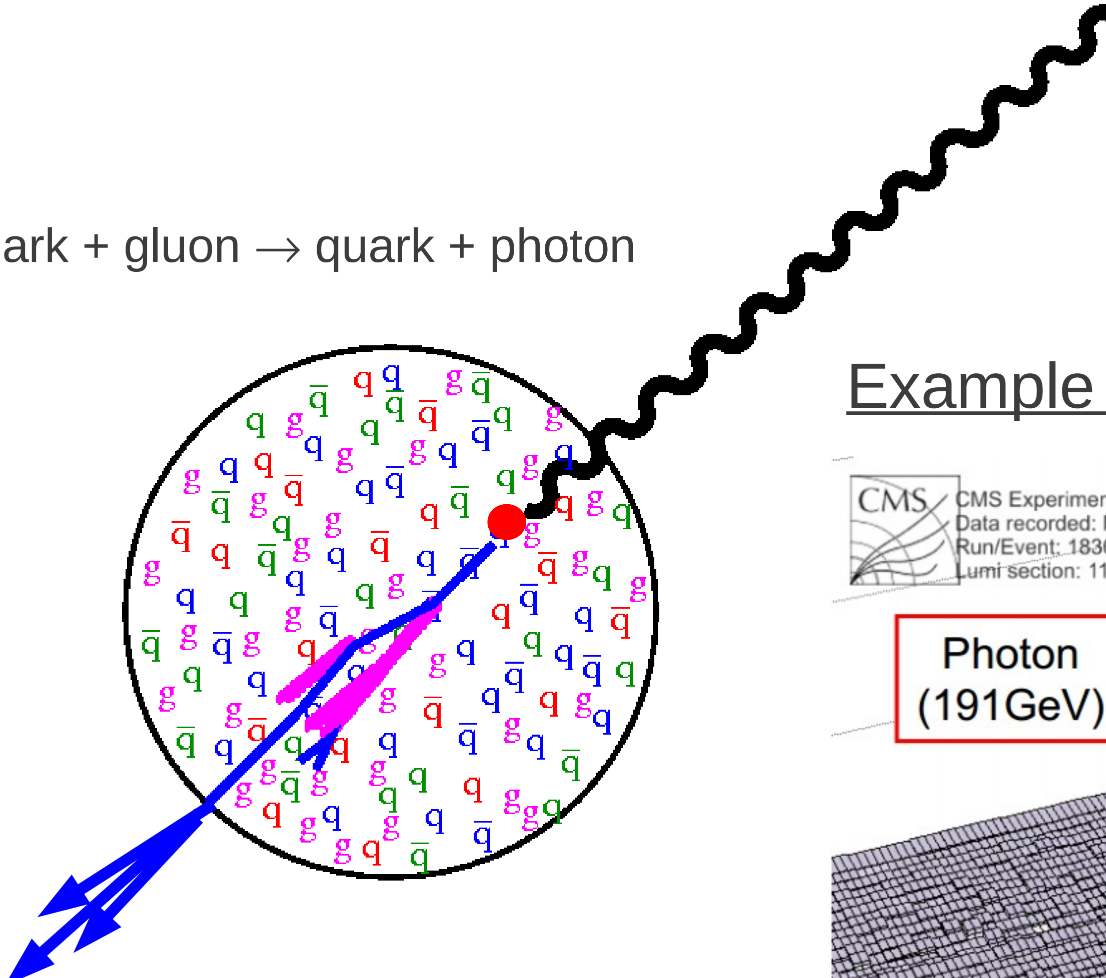


Famous 2003 result from RHIC !

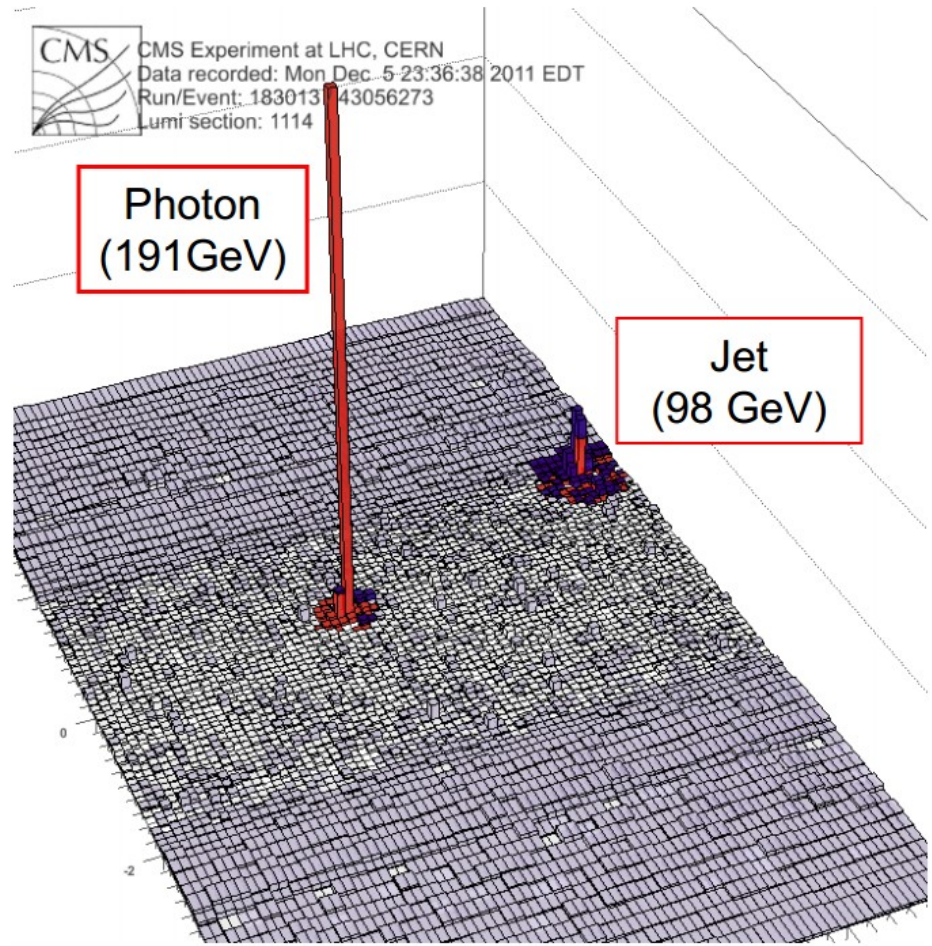
PRL 91 (2003) 072304



quark + gluon → quark + photon



Example of a 2011 event from CMS

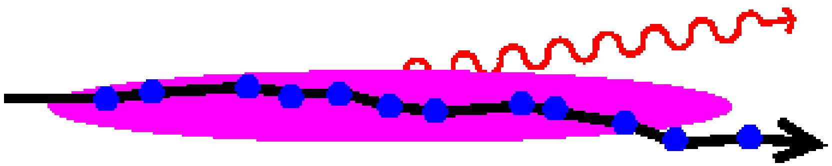


[from CMS highlights talk at Quark Matter 2012]

The LPM Effect (QCD)

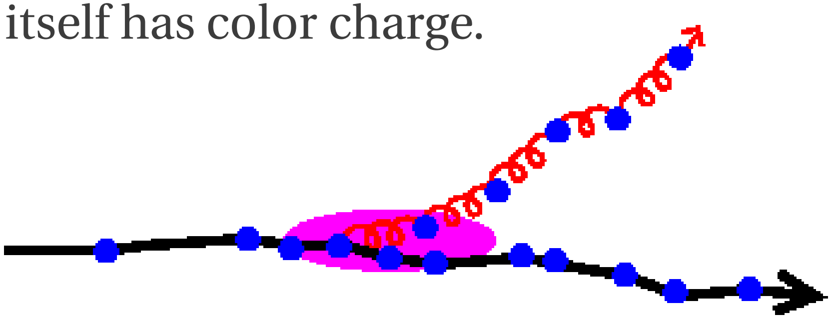
Basic formalism worked out in the 1990s by BDMPS-Z
(with ongoing caveats about how to apply it to realistic experimental situations).

Qualitative difference from QED: The brem gluon itself has color charge.



photon brem

vs.



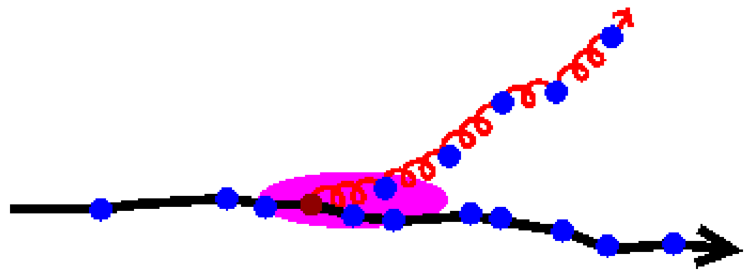
gluon brem

Parametrically, still gives rise to a rate suppression that grows like $E^{1/2}$.

stopping distance $\propto$ $\boldsymbol{E^{1/2}}$

One of the Caveats

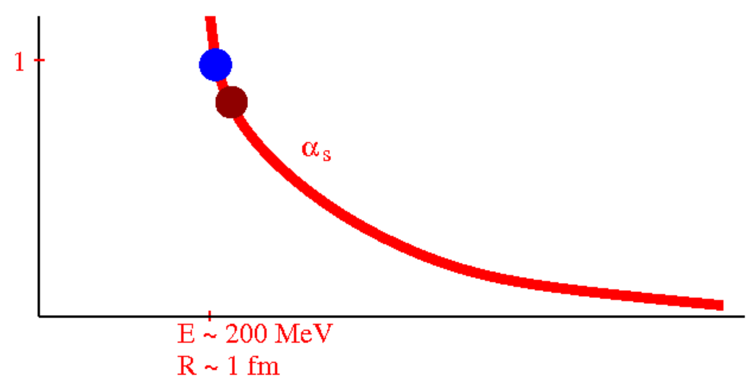
A picture like



implicitly assumes that it makes sense to talk about individual quarks and gluons.

Talking about individual quanta makes sense for **weakly**-coupled systems, but not so much for strongly-coupled systems.

Complication: QCD interaction strength depends on scale.

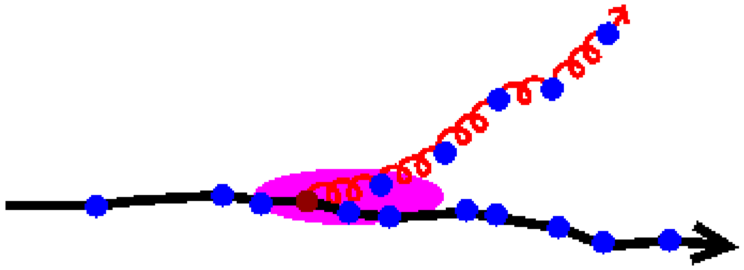


● ~ $\alpha_s(T)$

● ~ $\alpha_s(Q_\perp)$ ~ $\alpha_s(\,(\hat{q}\,E)^{1/4}\,)$

One of the Caveats

A picture like



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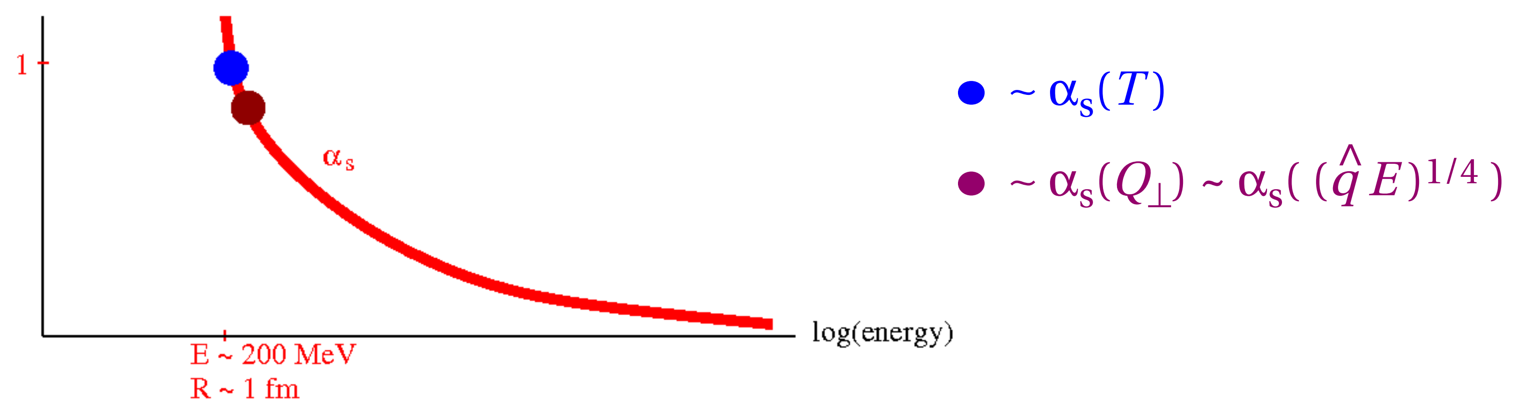


Basic theory question:

How robust is conclusion that stopping distance $\propto E^{1/2}$?

Applied String Theory

also referred to as, variously,

Applied Holography
Gauge-String Duality
Gauge-Gravity Duality
the AdS/CFT correspondence

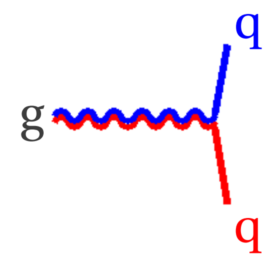
Basic theory question:

How robust is conclusion that stopping distance $\propto E^{1/2}$?

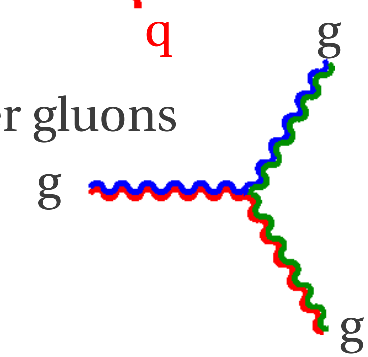
So far, too hard to study theoretically in QCD iteslf.
But we can study robustness by looking at theories similar to QCD that *can* be solved.

The particular theory I'm going to focus on

q q q

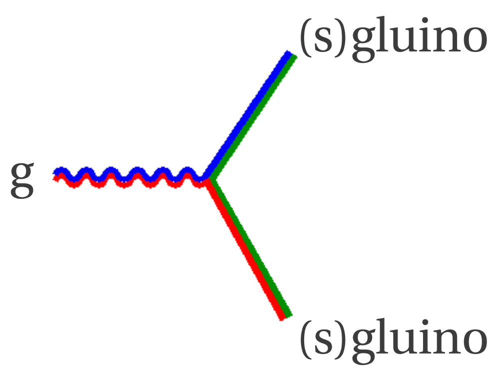


1. Start with QCD
2. Increase the number of colors from $N_c = 3$ to $N_c \to \infty$.
3. For simplicity of discussion , throw away quarks and just consider gluons (but we could have kept them if we wanted)



4. Add lots of supersymmetry

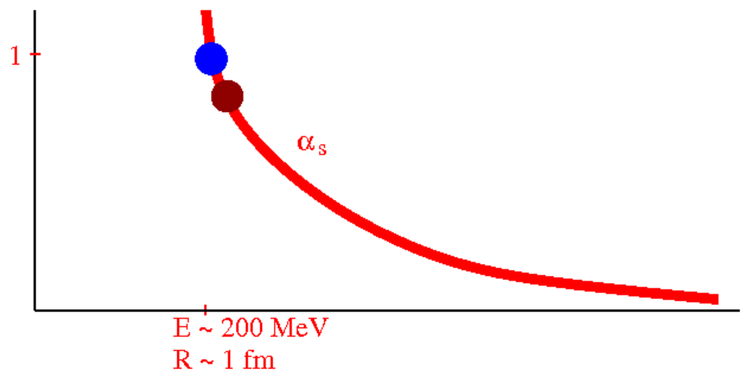
gluons	spin 1
gluinos	spin ½
sgluinos	spin 0



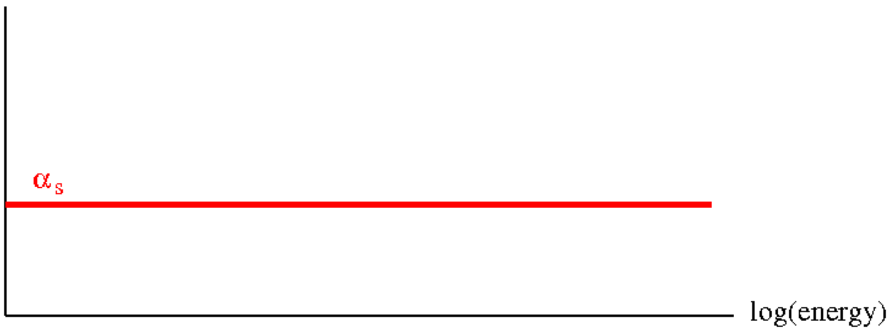
“large-N_c $\mathcal{N}$=4 Super-Yang-Mills (SYM) theory”

At zero temperature, this theory does not behave much like QCD

QCD



$\mathcal{N}$=4 SYM



confining!

scale invariant!

no scales $\rightarrow$ no confinement

[Note: value of α_s can be set to whatever you want to study.]

But a QCD plasma is very similar to a SYM plasma (at weak coupling)

Units: $\hbar = c = 1$

Debye screening length $\sim \dfrac{\#}{\alpha_s^{1/2} T}$

Plasma frequency $\sim \# \alpha_s^{1/2} T$

Correlation length of color magnetic fields $\sim \dfrac{\#}{\alpha_s T}$

Shear viscosity $\sim \dfrac{\# T^3}{\alpha_s^2 \ln \frac{1}{\alpha_s}}$

Stopping distance $\sim \dfrac{\# E^{1/2}}{\alpha_s^2 T^{3/2} \ln^{1/2}(E/T)}$

etc.

SYM is a good theorist playground for studying *lots* of things, (including the robustness of "stopping distance $\propto E^{1/2}$") because

(large-N_c $\mathcal{N}$=4) SYM can <u>also</u> be solved at strong coupling!

Gauge-Gravity Duality
(the AdS/CFT correspondence)

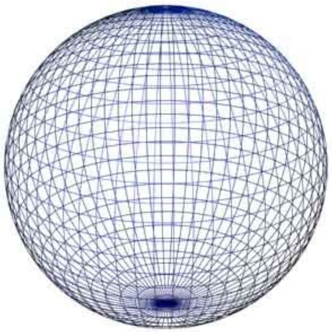
Quantum Field Theory	a theory of classical waves
3+1 dimensional space+time	4+1 dimensional space+time
no gravity (flat space)	a curved spacetime (General Relativity)
$\mathcal{N}$=4 SYM a conformal field theory (CFT)	the spacetime is Anti-deSitter space (AdS)
large N_c	can ignore quantum effects
strong coupling	General Relativity instead of non-perturbative string theory

Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

A flavor of a thought #1

If the theories are the same, the symmetries of the 3+1 field theory should be the same as those of the 4+1 curved spacetime...

isometries



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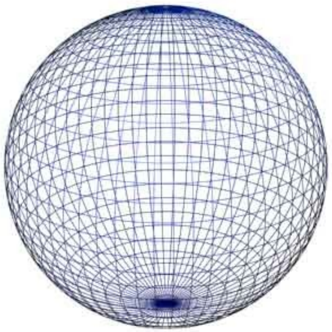
symmetries

translations

rotations

Lorentz boosts

isometries



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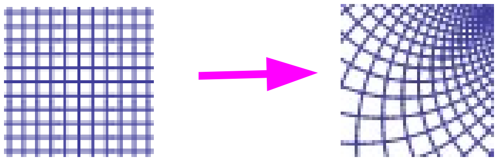
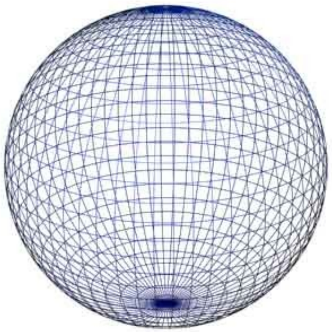
scaling transformation

conformal transformations



isometries



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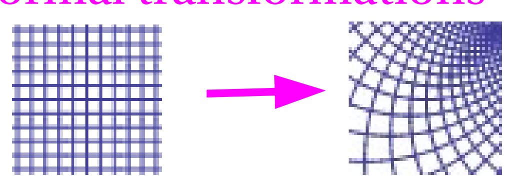

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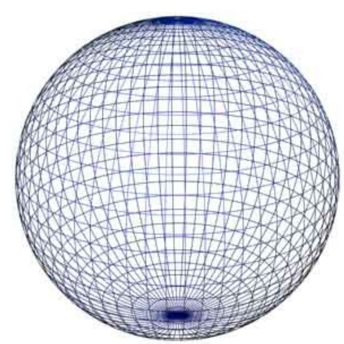
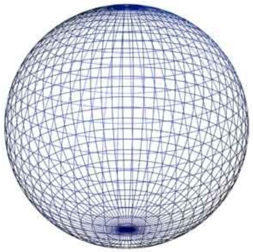
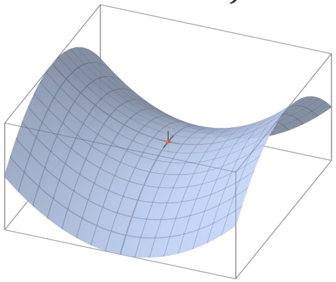


symmetry group of 3+1 dim CFT = isometry group of 4+1 dim AdS

What is AdS?

1.  = a picture of a 2-dimensional surface called the “2-sphere”

2. Now instead think of a 5-sphere (if the goal is to work our way to 4+1 dim AdS)



3. Now imagine the surface instead has negative curvature everywhere
   (like a saddle except that every point has to look the same!)
   Unlike the sphere, this space has infinite size.

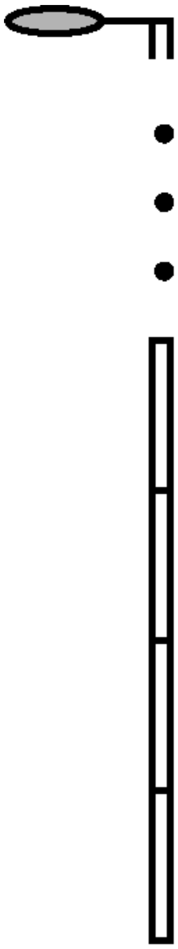
4. Finally, trade one of the five spatial dimensions for a time dimension.

Irrelevant connection to cosmology:

If our universe had nothing in it but the cosmological constant, it would be a 3+1 dim. deSitter spacetime.
If the cosmological case were negative instead of positive, it would be a 3+1 dim. anti-deSitter spacetime,

Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

A flavor of a thought #2



An infinitely high tower of meter sticks with a mirror on top.

Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

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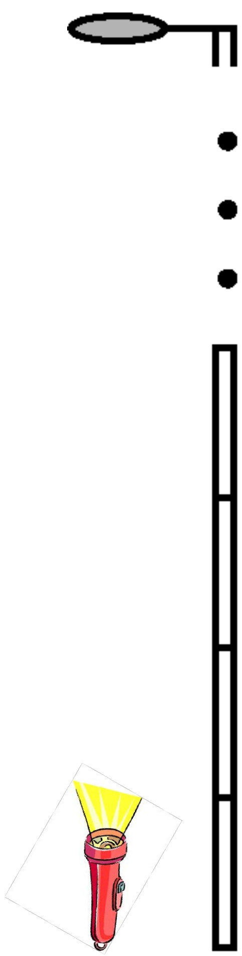
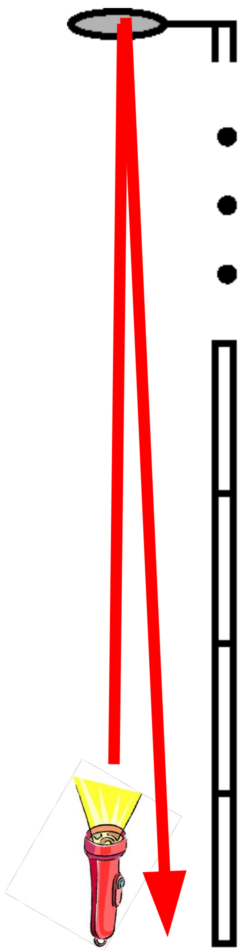


An infinitely high tower of meter sticks with a mirror on top.

Shine a light up from the bottom.

Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

A flavor of a thought #2



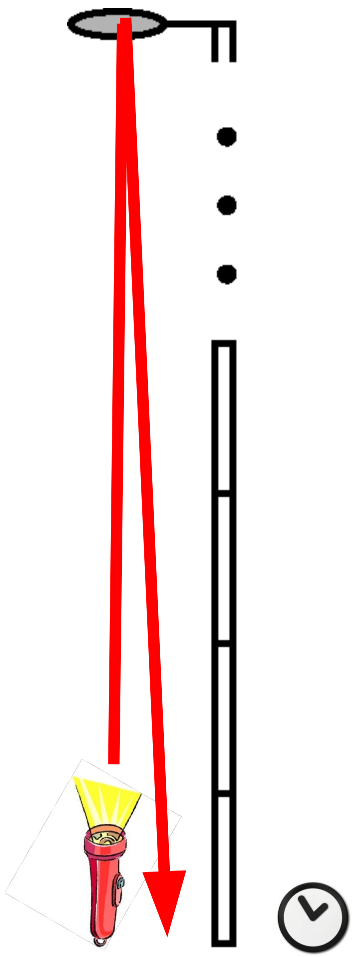
An infinitely high tower of meter sticks with a mirror on top.

Shine a light up from the bottom.

In AdS, the light returns in finite time!

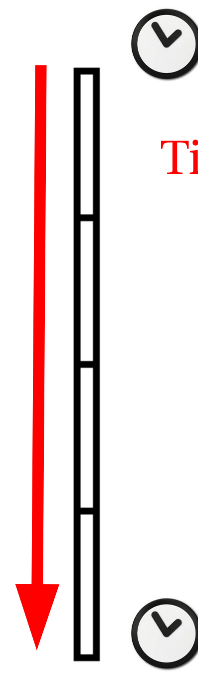
Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

A flavor of a thought #2



How??

Think Pound and Rebka in 1959

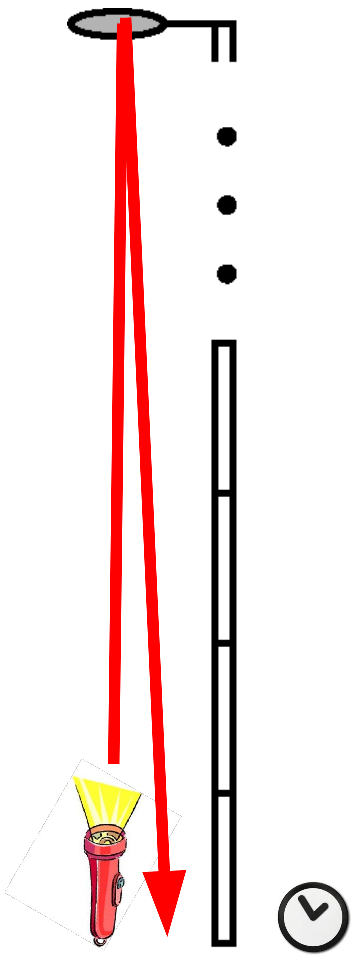


Time runs fast at top relative to bottom!

In AdS, there's significant gravity everywhere, and time justs goes faster and faster as you go up and up.

Why would a 3+1 dim. theory be equivalent to a 4+1 dim. theory?

A flavor of a thought #2



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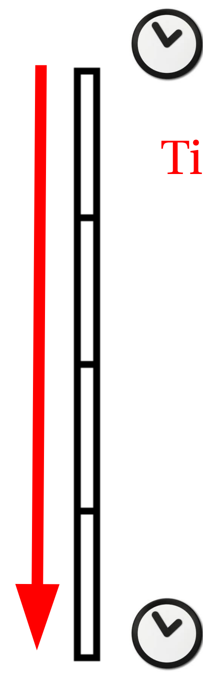

Time runs fast at top relative to bottom!

In AdS, there's significant gravity everywhere, and time justs goes faster and faster as you go up and up.

Upshot: What's happening at ∞ in AdS is not decoupled.

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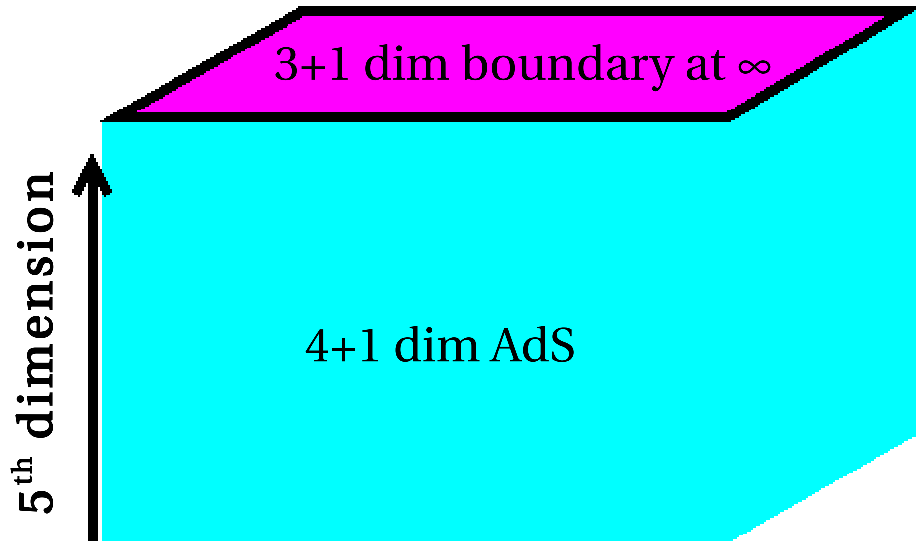
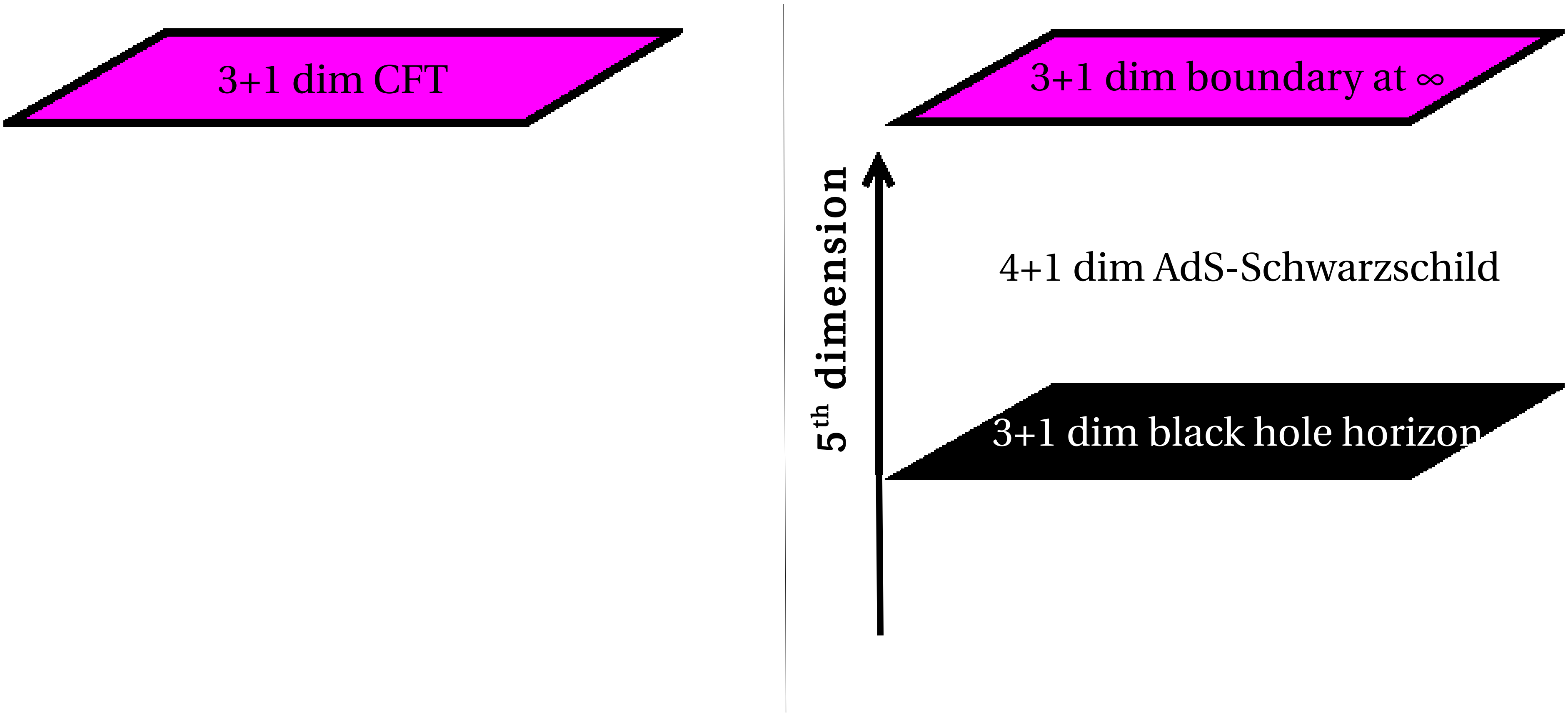
A flavor of a thought #2



Q: How to study the theory at finite temperature?
A: Put a <u>black hole</u> in on the gravity side.



temperature for QFT = Hawking temp. of black hole

Defining Stopping Distance

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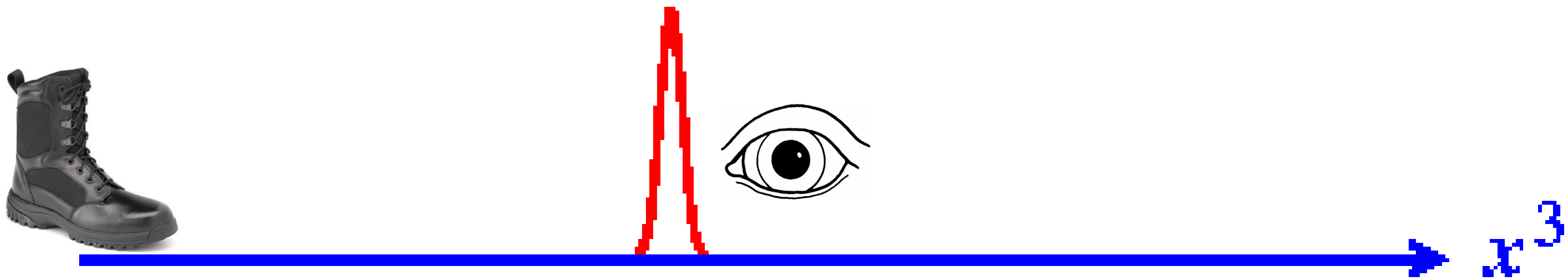

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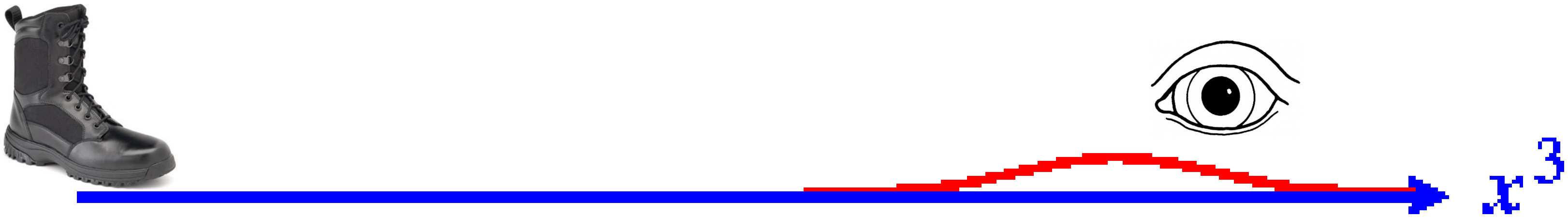
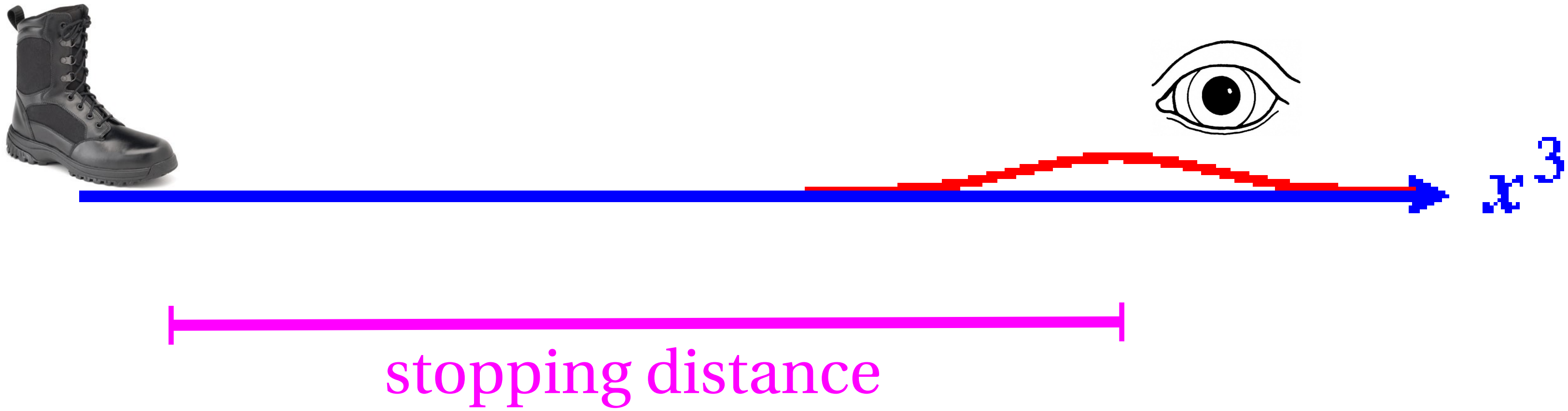
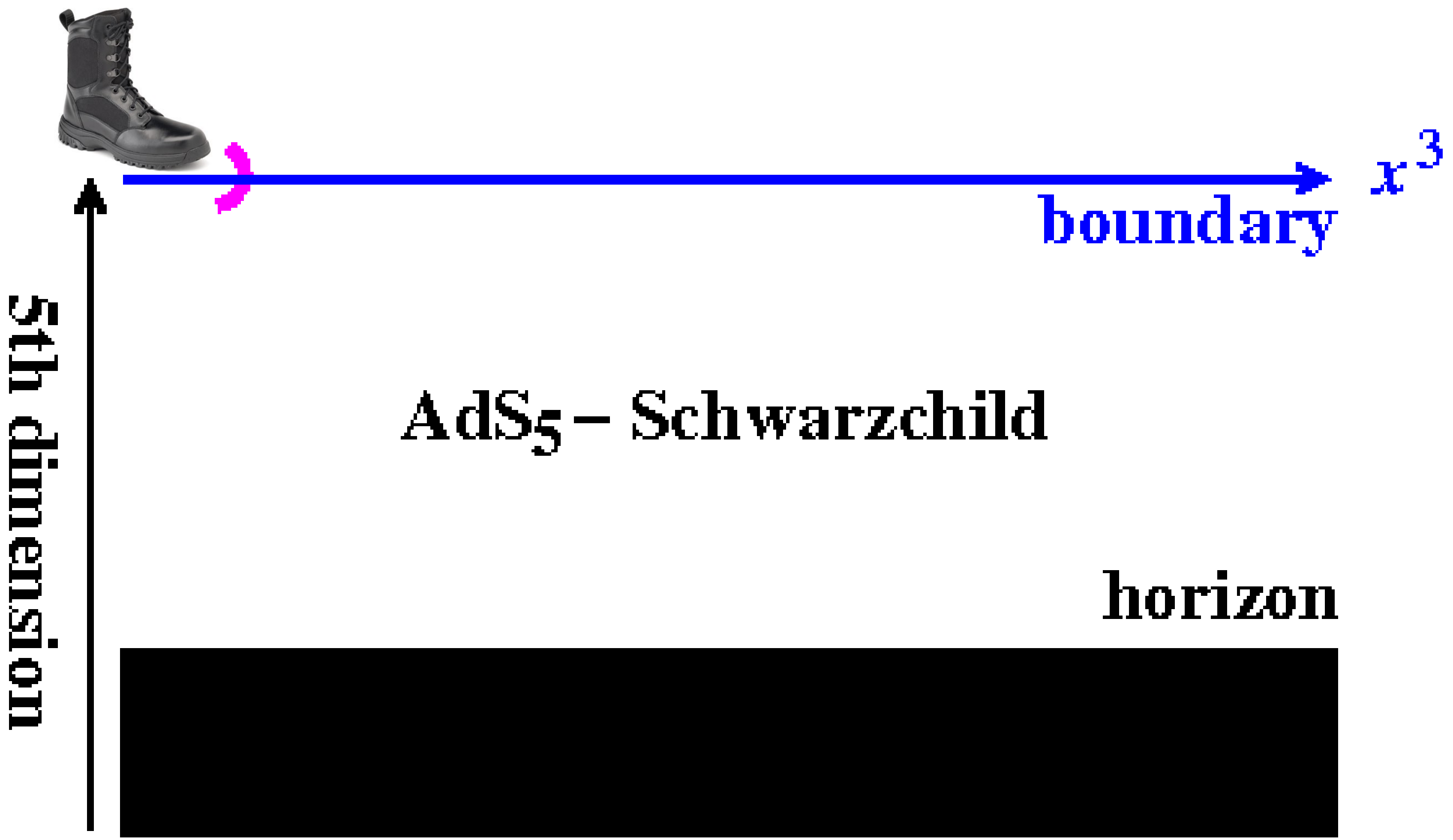


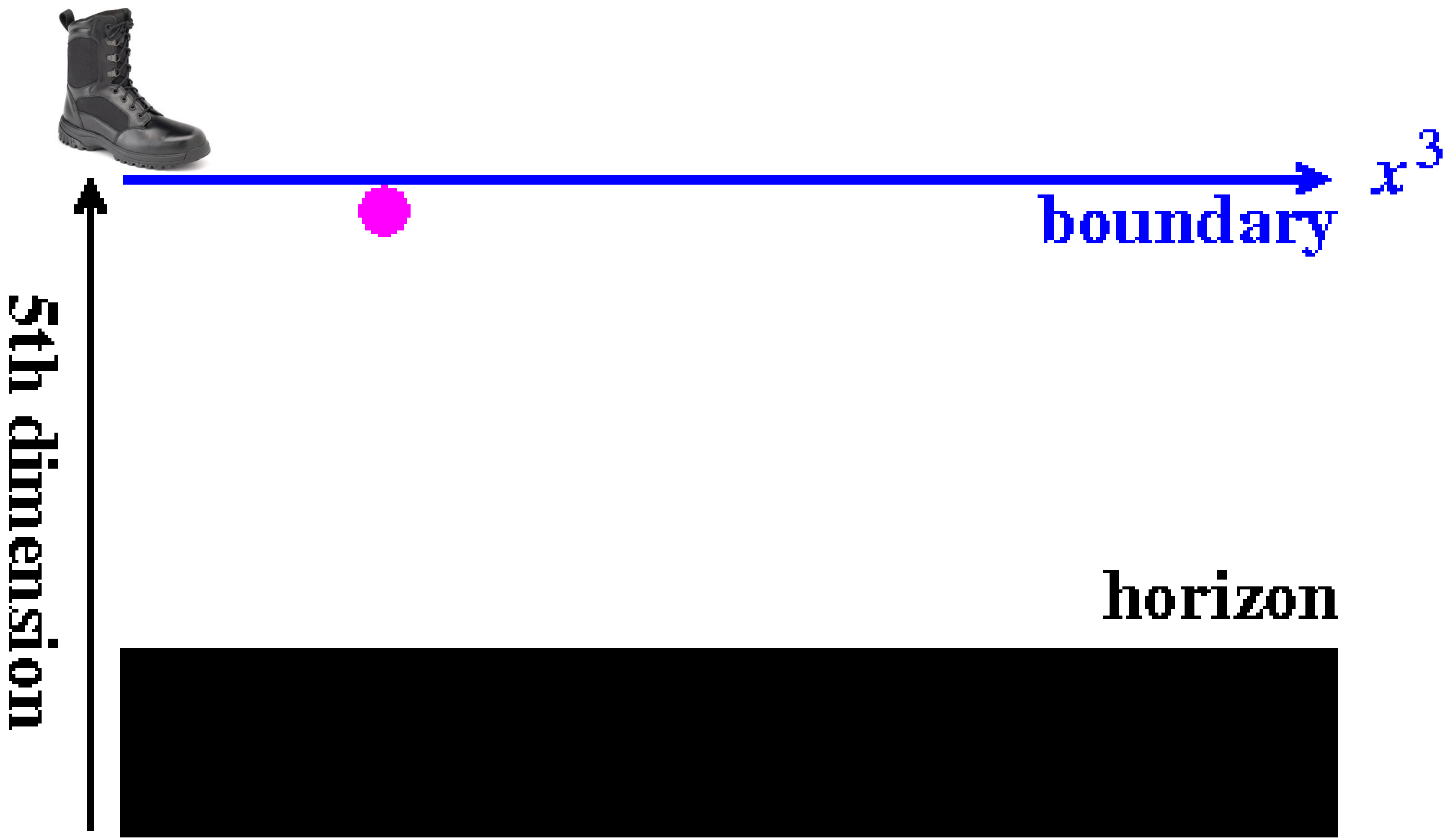
Defining Stopping Distance



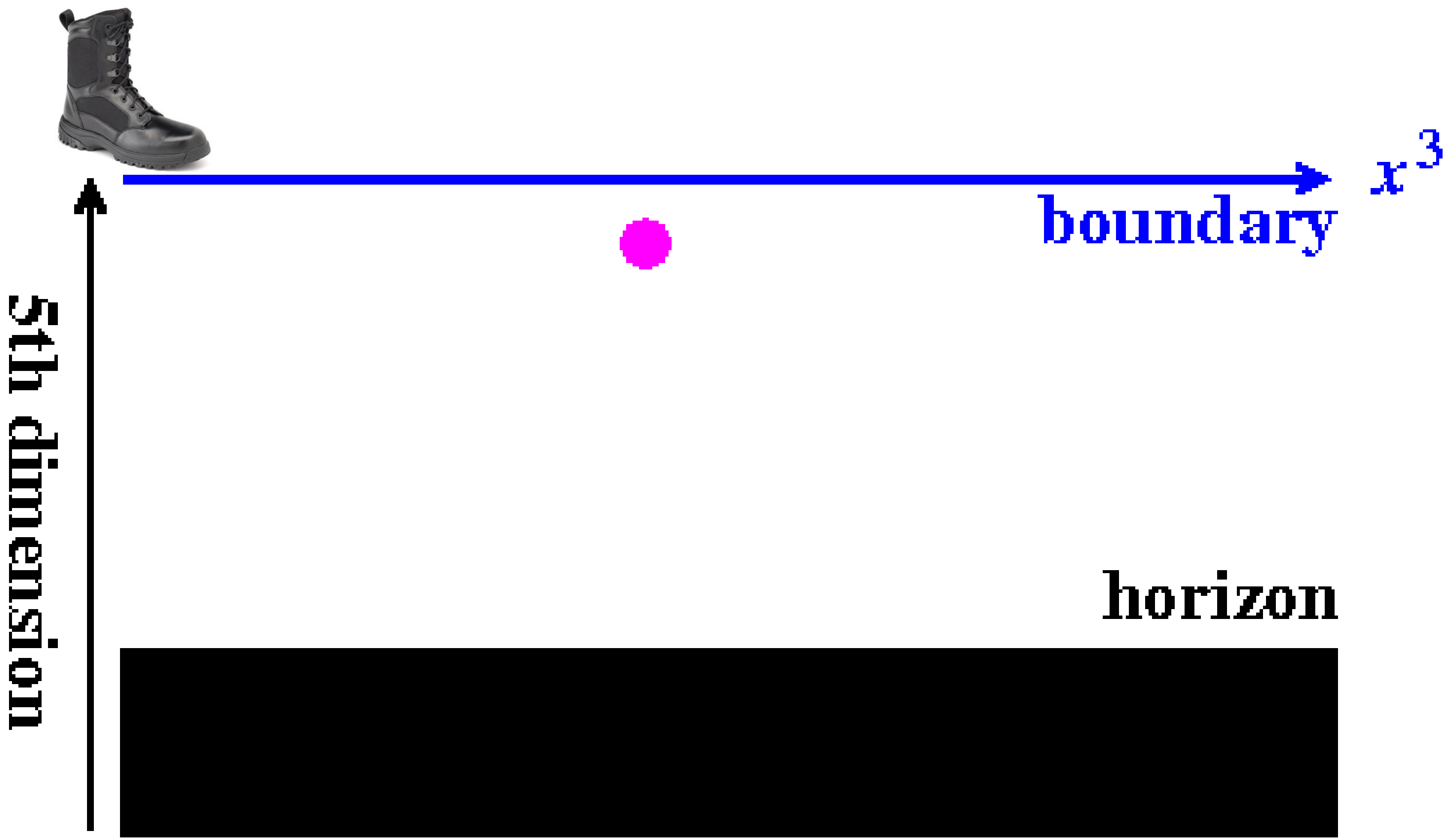
Stopping Distance using AdS/CFT



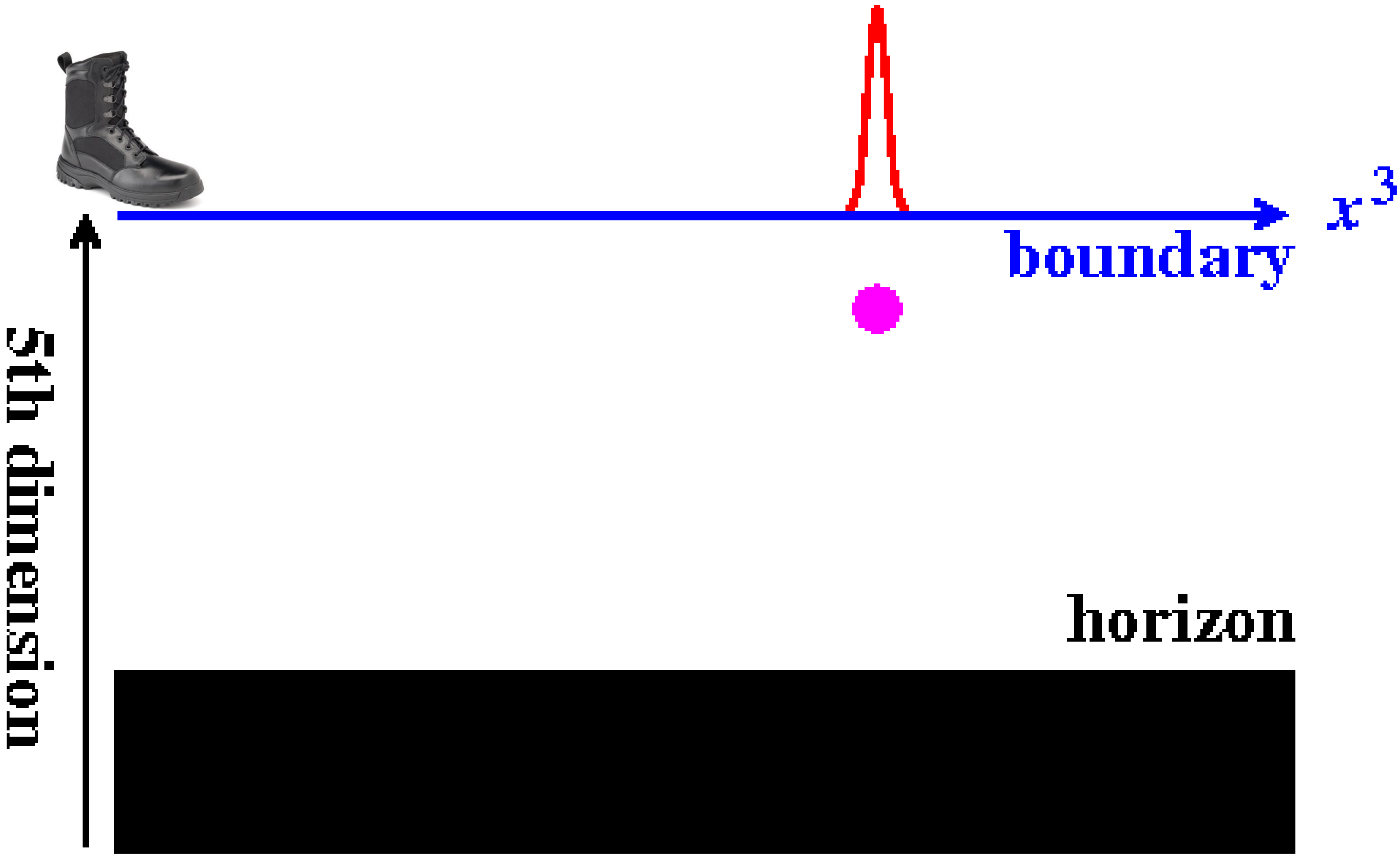
Stopping Distance using AdS/CFT



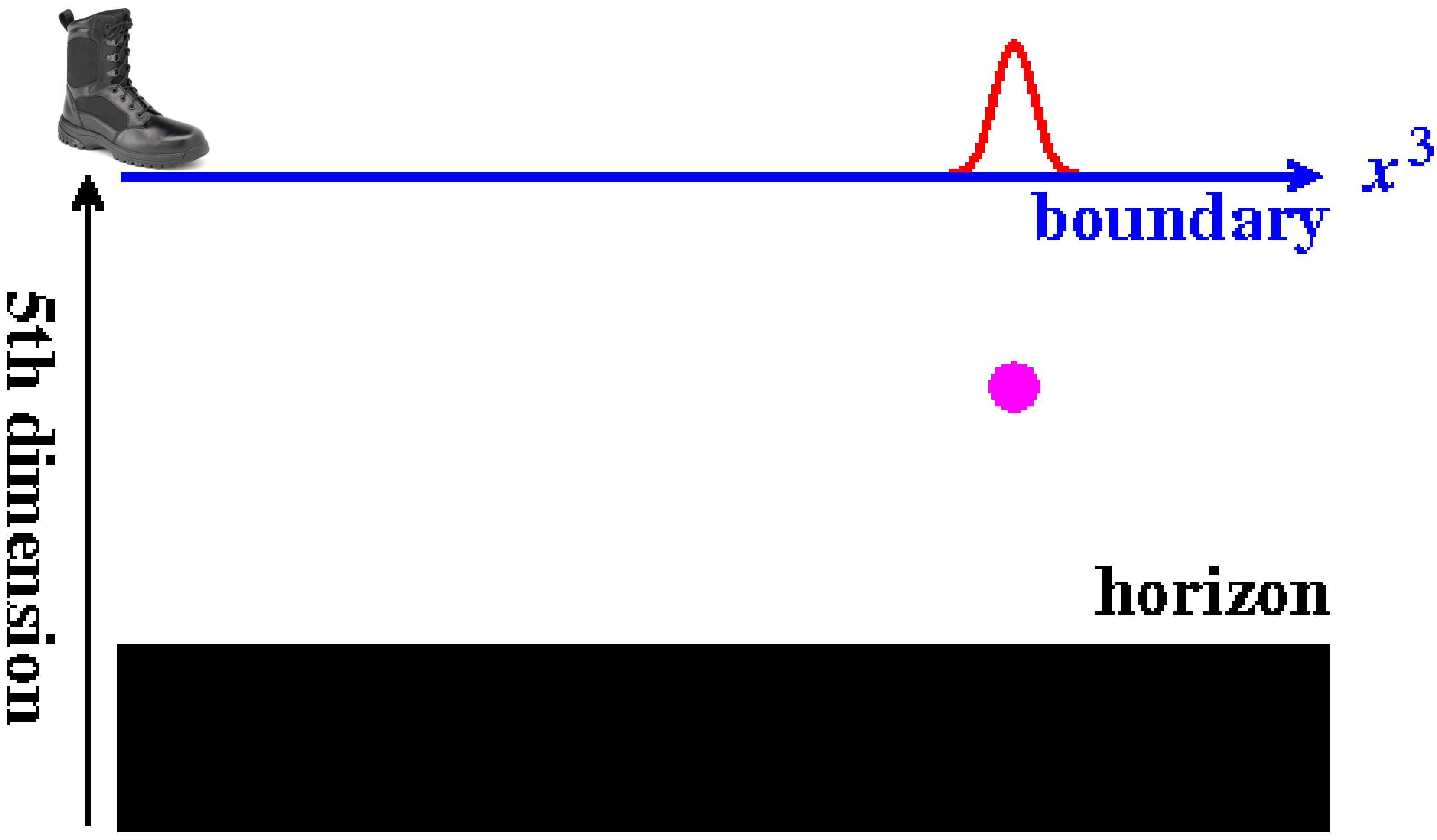
Stopping Distance using AdS/CFT



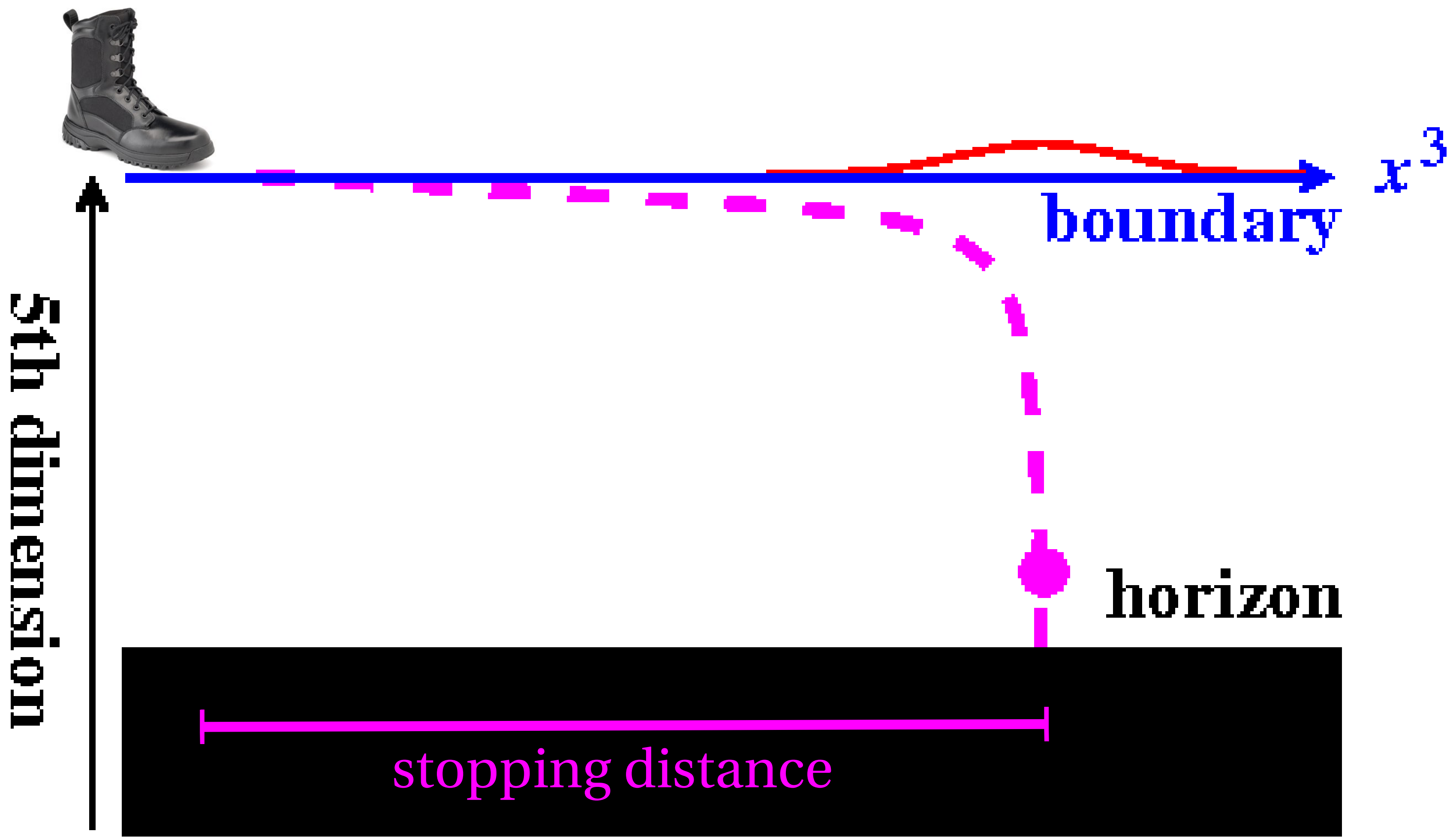
Stopping Distance using AdS/CFT



Stopping Distance using AdS/CFT



Stopping Distance using AdS/CFT



Results

weak coupling: stopping distance $\propto E^{1/2}$

strong coupling: stopping distance $\propto E^{1/3}$

[Gubser, Gollota, Pufu, Rocha; Hatta, Iancu, Mueller; Chesler, Jensen, Karch, Yaffe (2008)]

What did we learn?

1) A point specific to the field

One should look for corrections to the LPM energy dependence

$$\text{stopping distance} \propto E^{1/2} + \dots$$

in real QCD, even if the relevant coupling for high-energy jets is not BIG with a capital "B"

2) A general point about the nature of theoretical research

One of many cases where basic, curiosity-driven research into theory (e.g. string theory, supergravity in weird curved spacetimes, …) yielded insights in unanticipated applications.

What I personally have been doing lately
(w/ Diana Vaman, Phil Szepietwoski, Gabriel Wong)

When I said

strong coupling: stopping distance $\propto E^{1/3}$

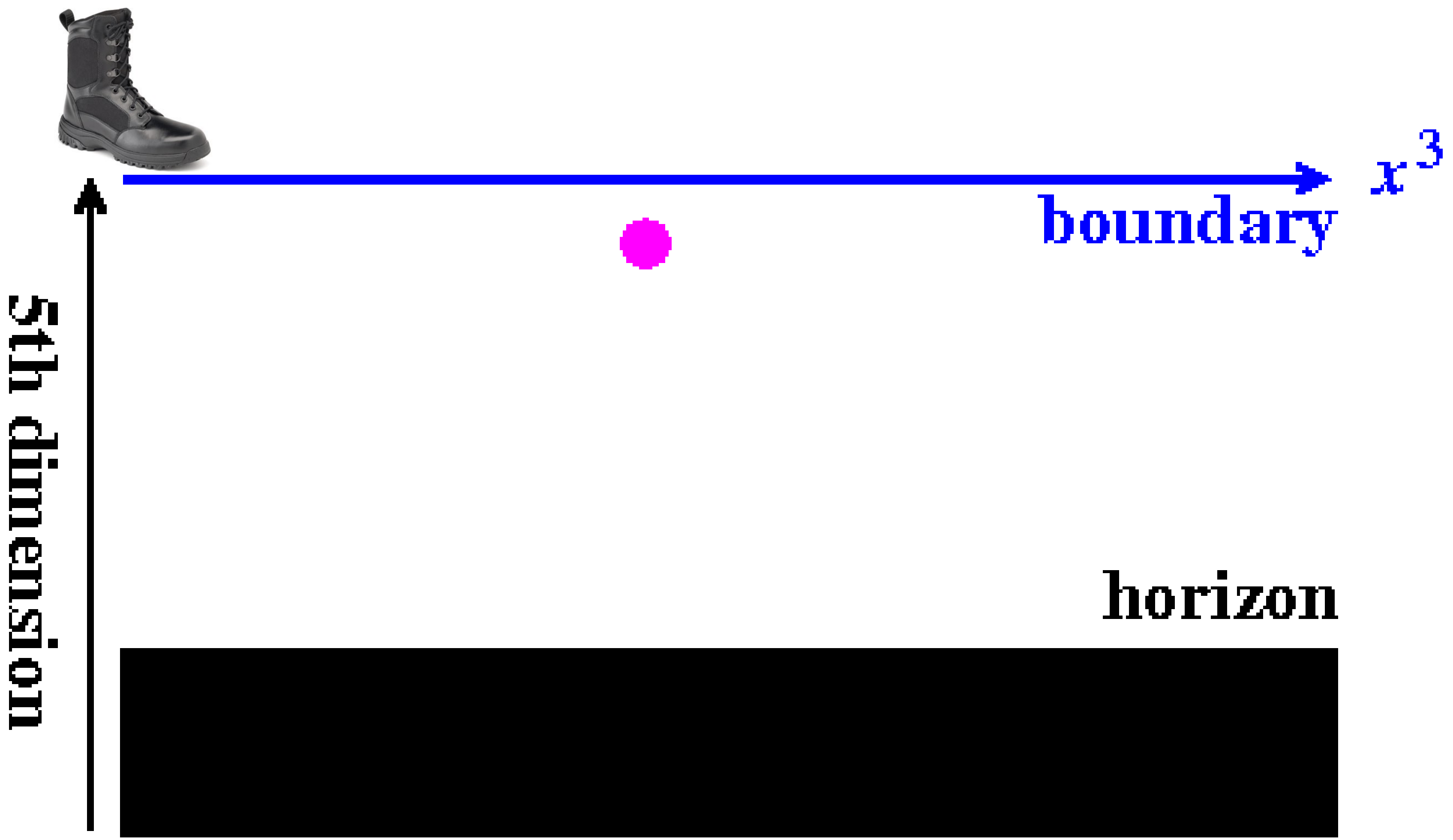
strong really meant coupling $\to \infty$.

But is this really the high energy behavior if, instead, coupling = large but finite ?
What happens if, for example,

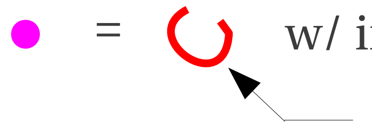
$$E \gg T\sqrt{\text{coupling}}\,,$$

which you really can't explore in any calculation that takes coupling = ∞.

Reminder



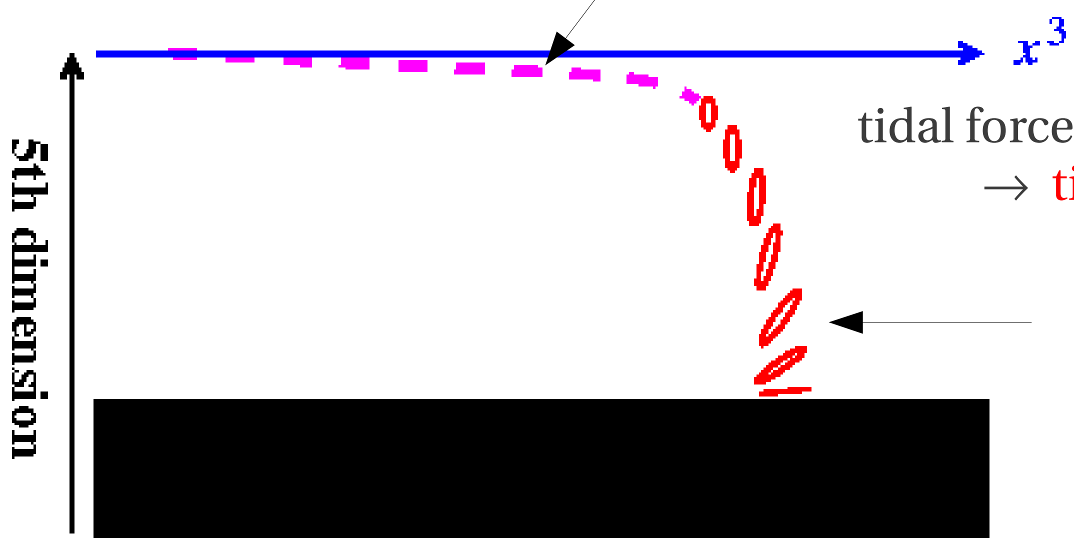
But really



w/ internal degrees of freedom in ground state

proper size ~ (string tension)$^{-1/2}$

quanta are quantum string loops



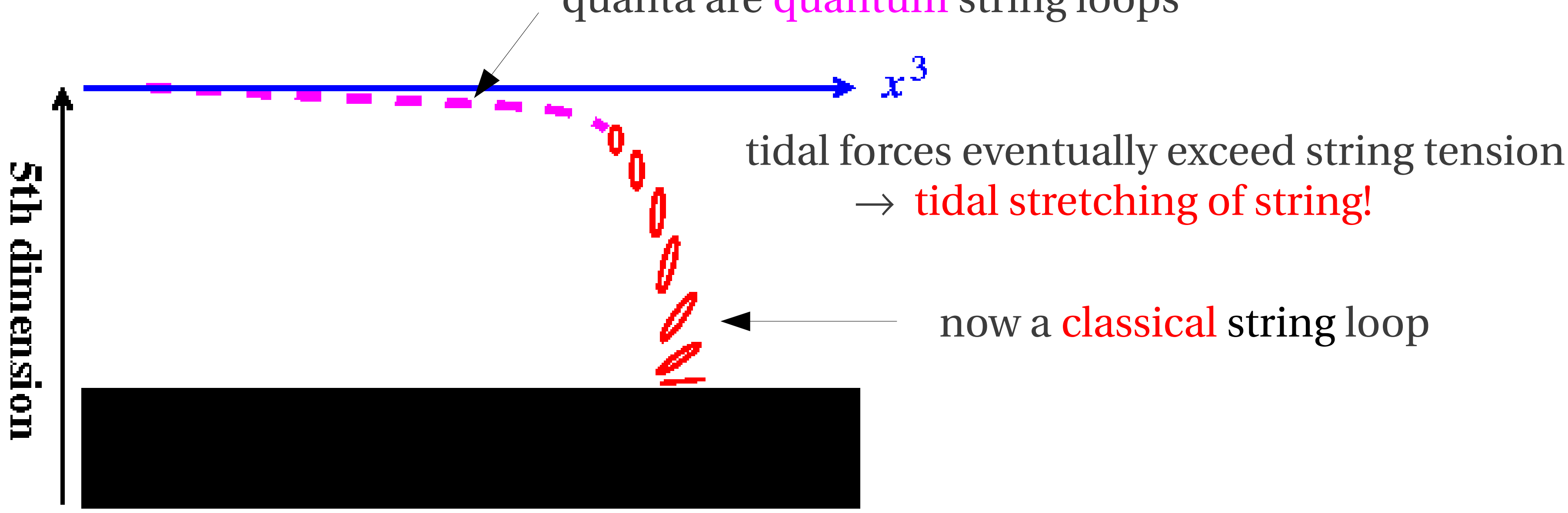
tidal forces eventually exceed string tension
→ tidal stretching of string!

now a classical string loop

But really

w/ internal degrees of freedom in ground state

proper size ~ (string tension)$^{-1/2}$



Result

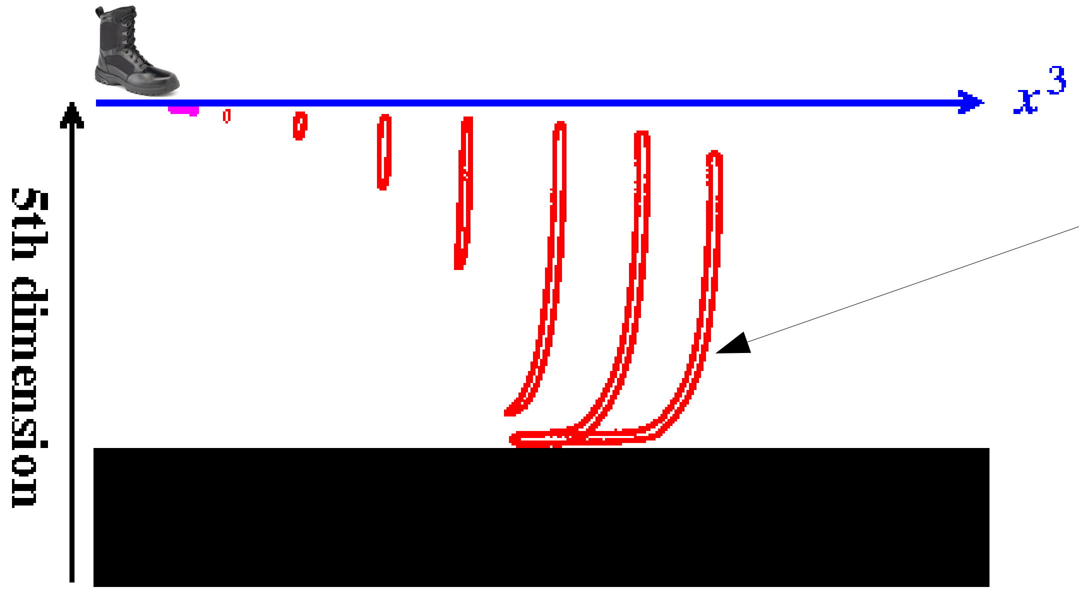
Interesting stuff, but does not change the following:

strong but finite coupling: maximum stopping distance $\propto E^{1/3}$

A quick aside for those who follow AdS/CFT jet stuff

Q: What happens if you adjust the “kick” (virtuality) that creates the jet so that it stops earlier than the maximum stopping distance?

A: It's possible to get the following:



trailing, classical, folded string loop

like those studied by
Gubser, Gollota, Pufu

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