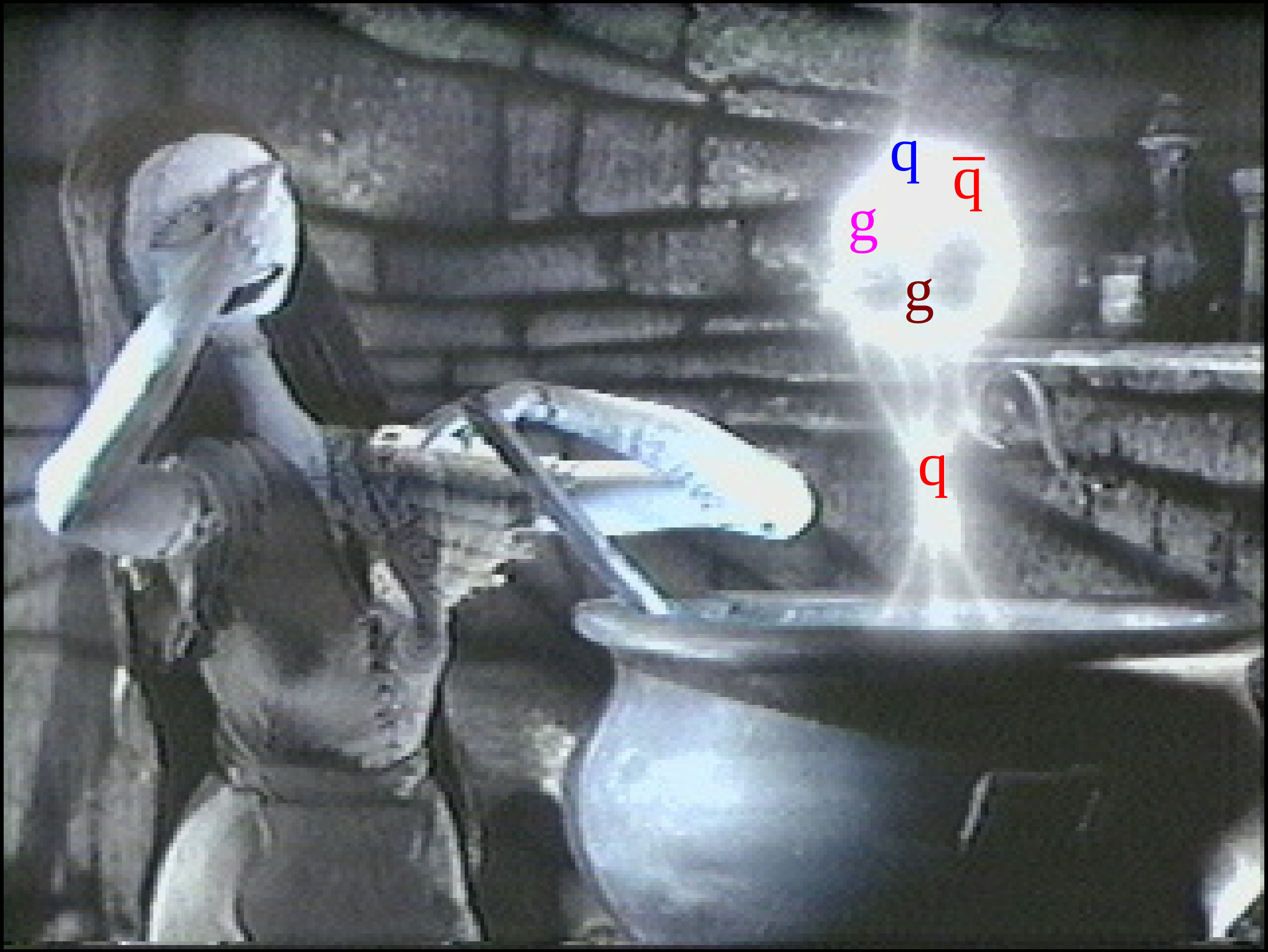
The Plasma Physics of Quark-Gluon Plasmas

(A Theorist's Perspective)



Peter Arnold, University of Virginia

First...

A brief summary of the field of plasma physics

(A particle theorist's perspective)

Plasma physics is complicated

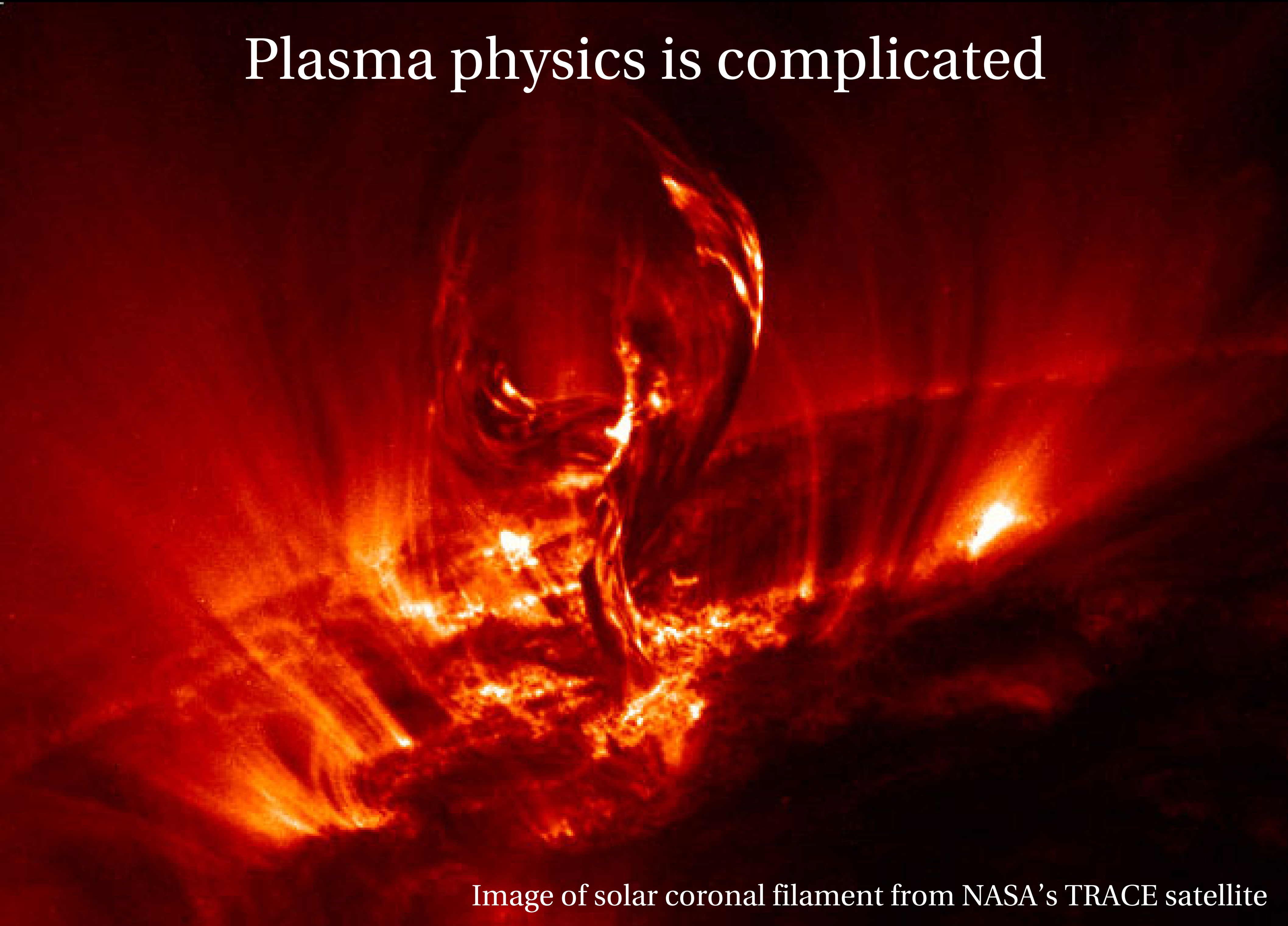
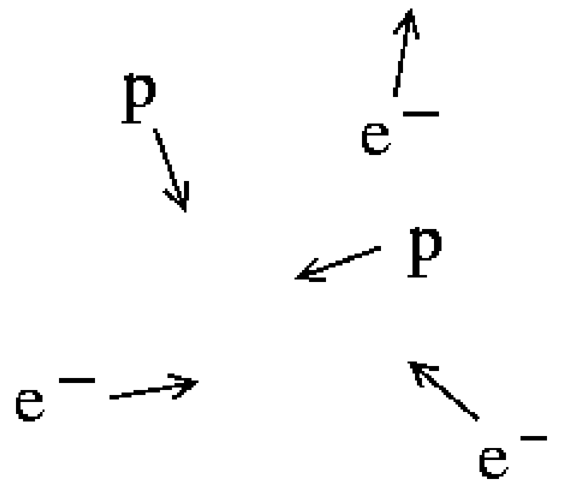
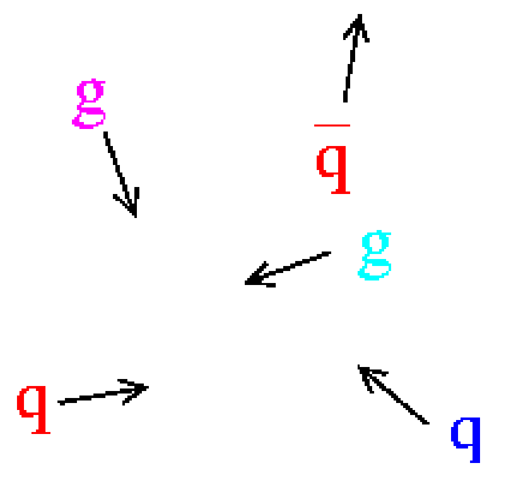


Image of solar coronal filament from NASA’s TRACE satellite plasma = gas of charged particles



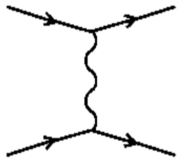
quark-gluon plasma:

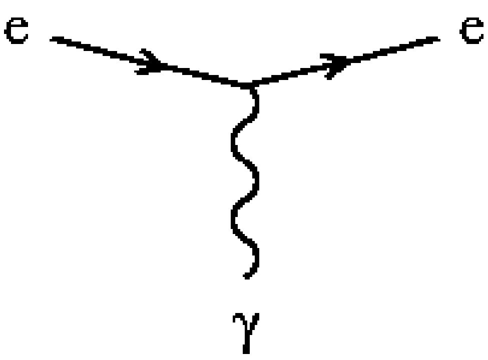
electromagnetism ⟷ color force

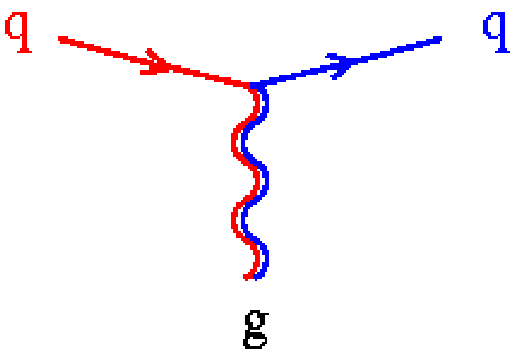


Similarity:

scattering

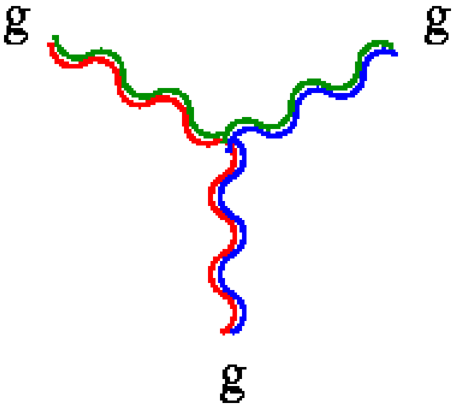






Minor difference: 1 photon 8 colors of gluon

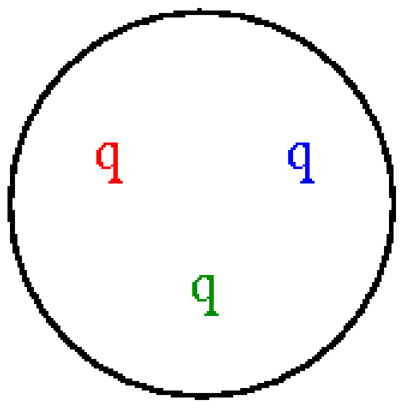
Major difference:



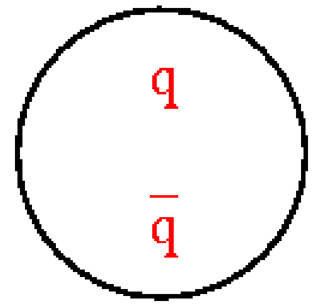
Familiar difference in T=0 physics:

No free quarks! (confinement into color-neutral objects)

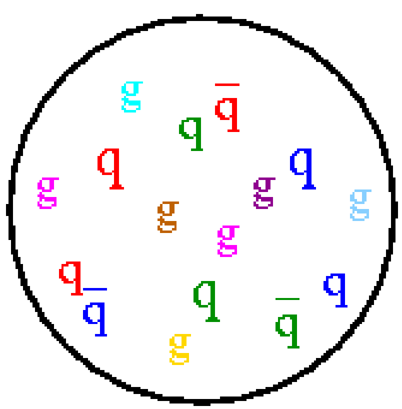
p , n

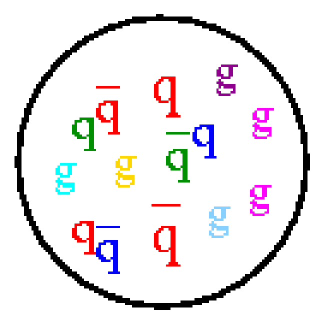


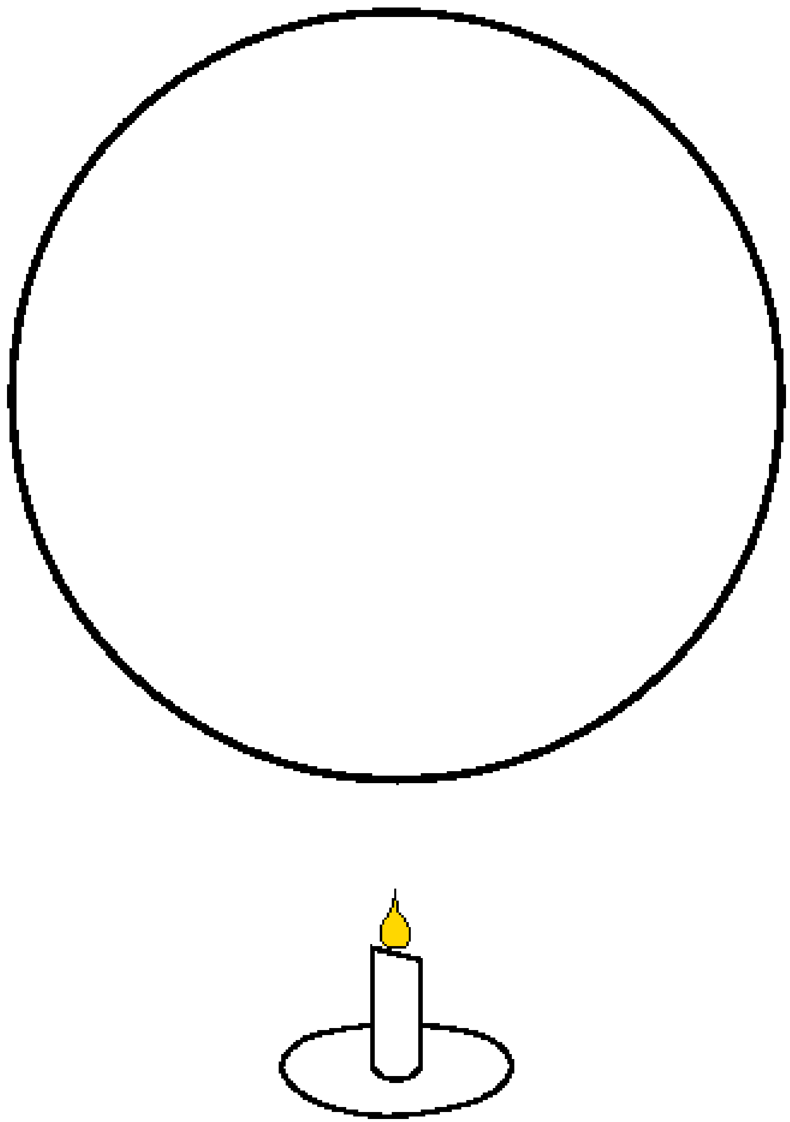
π



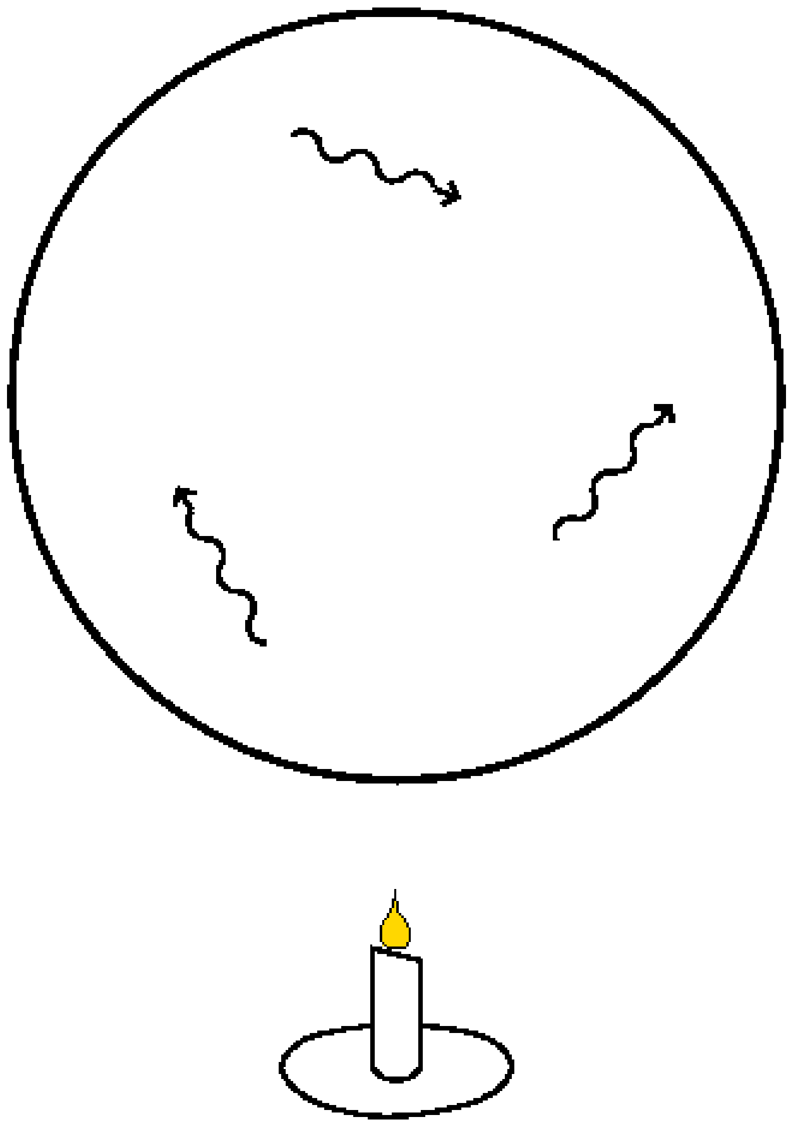
Note for later: lots of partons in hadrons if you resolve small distances (probe with high energies)



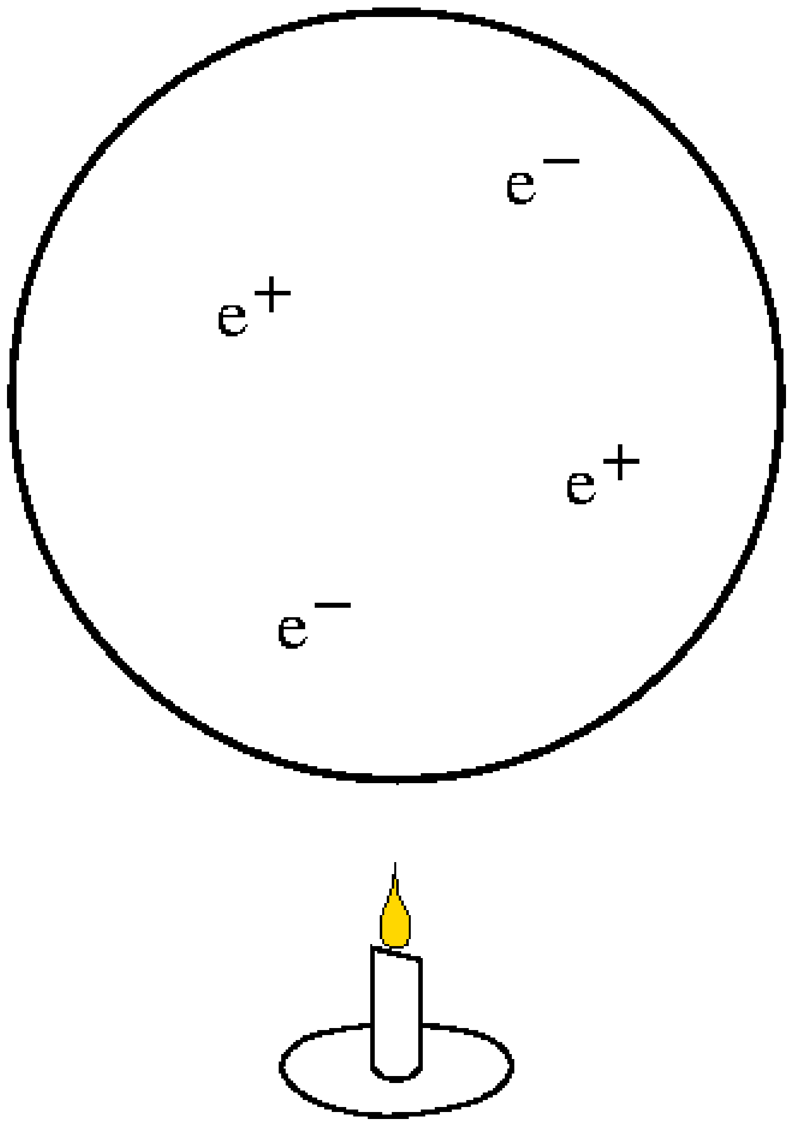


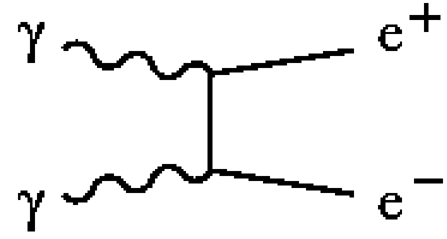


blackbody radiation



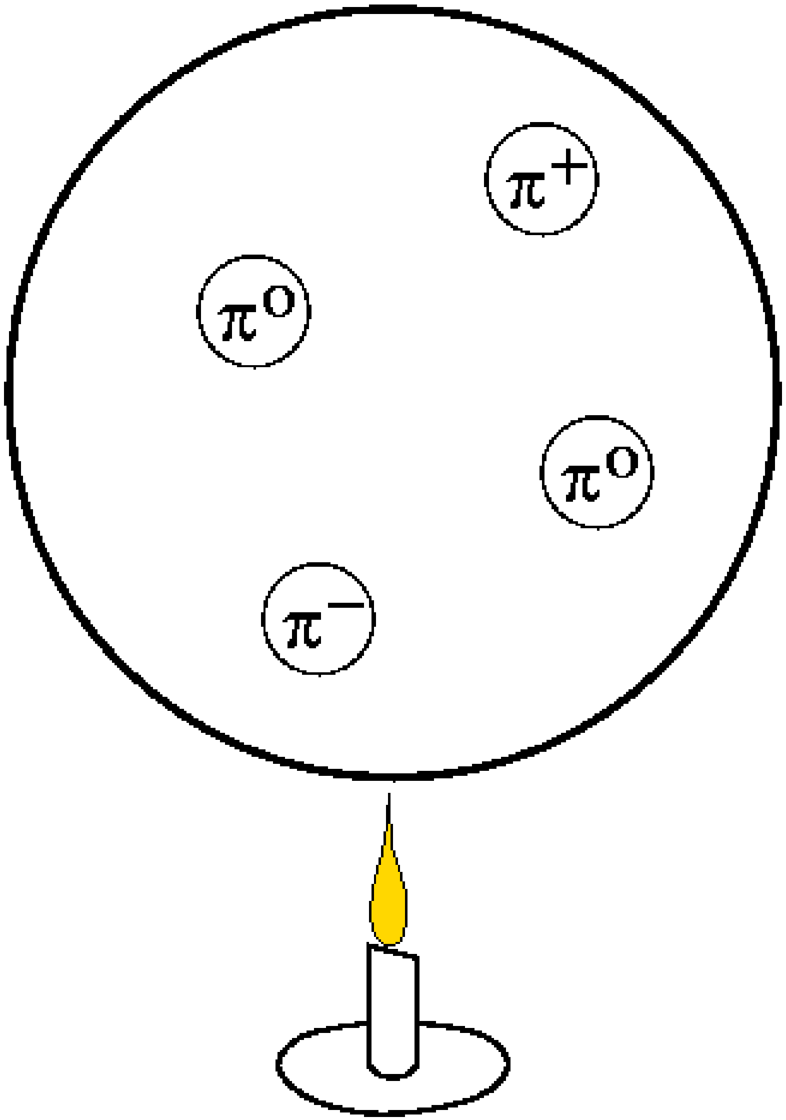
$k_B T \sim 0.5$ MeV

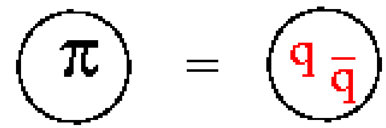




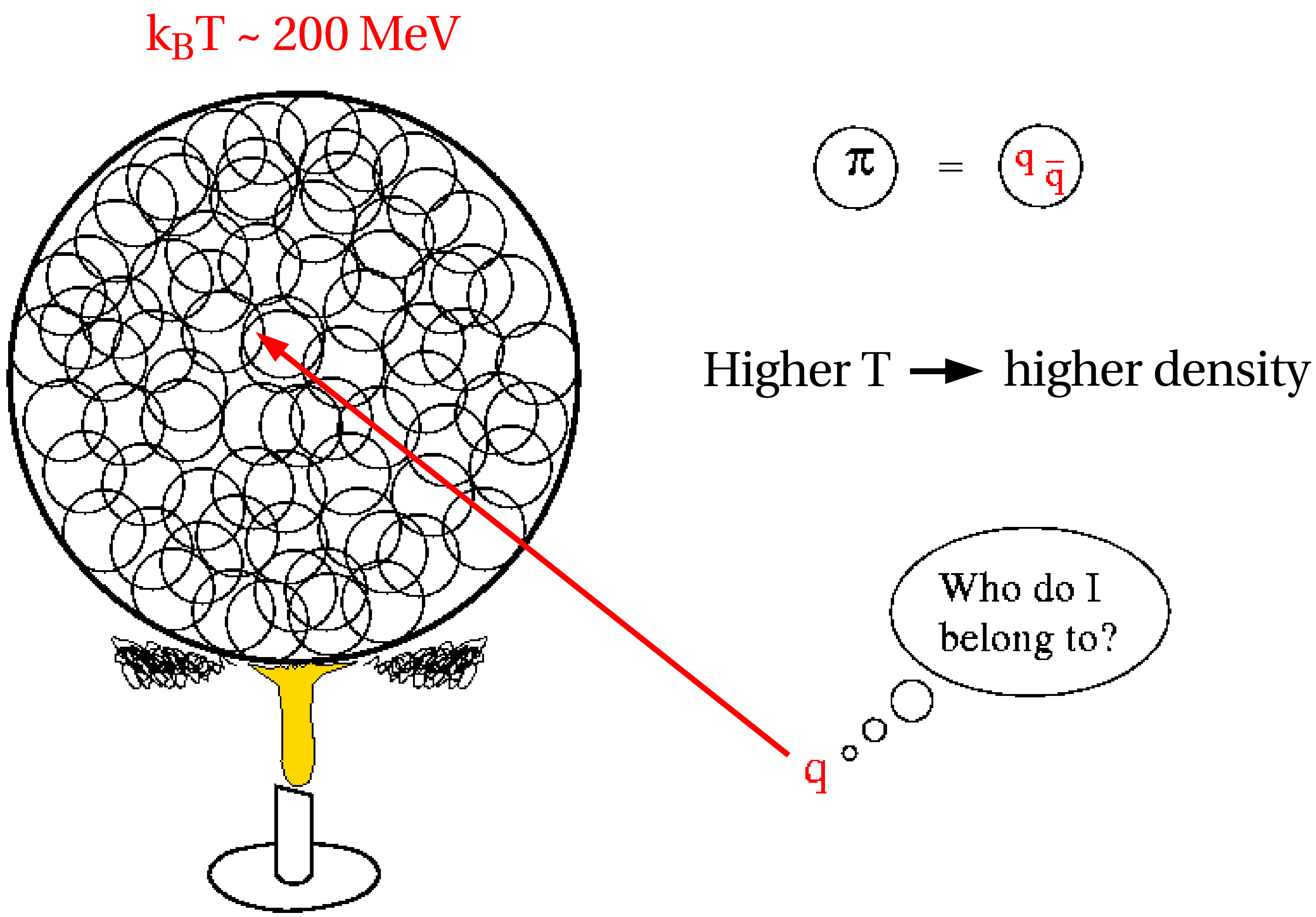
$$\gamma\,\gamma \rightleftharpoons e^+ e^-$$

$k_B T \sim 50$ MeV



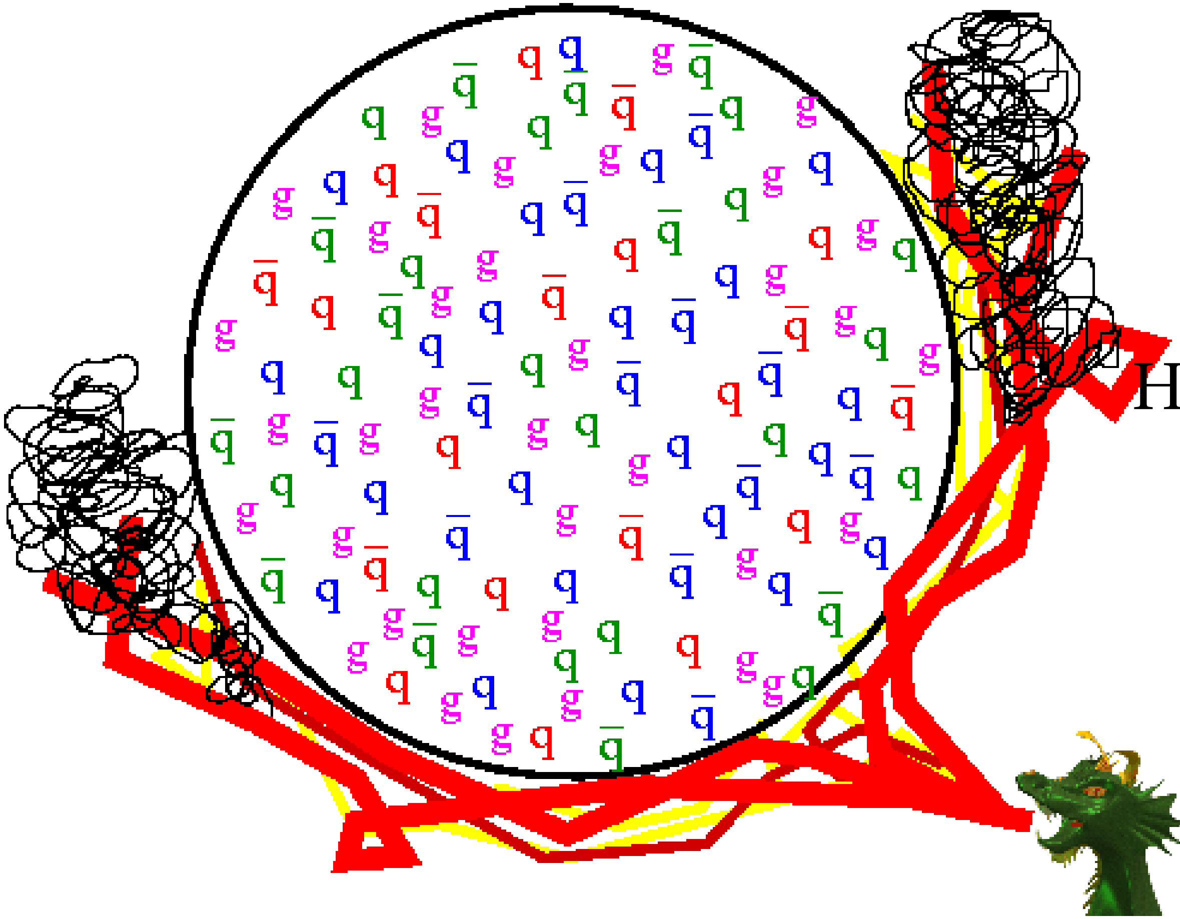


Higher T → higher density



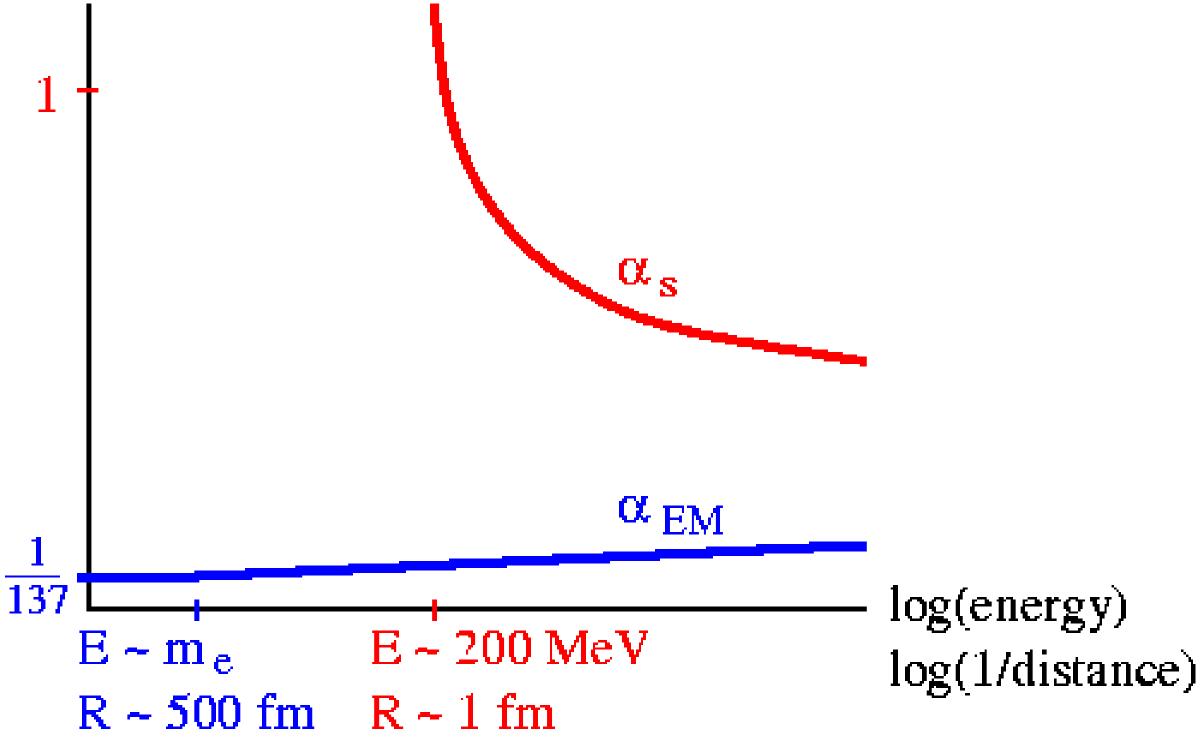
$k_B T \sim 200$ MeV
π = $q\,\bar{q}$
Higher T → higher density
Who do I belong to?
q

$k_B T >> 200$ MeV



Higher T → higher density

Also: Asymptotic Freedom



$$\alpha \equiv \frac{e^2}{4\pi\hbar c}$$

Higher temperature → smaller coupling α_s

Ideal gas

2 polarizations

photons: $\varepsilon = 2\,\frac{\pi^2}{30}\,T^4$

π^0 , π^+ , π^- (spin 0)

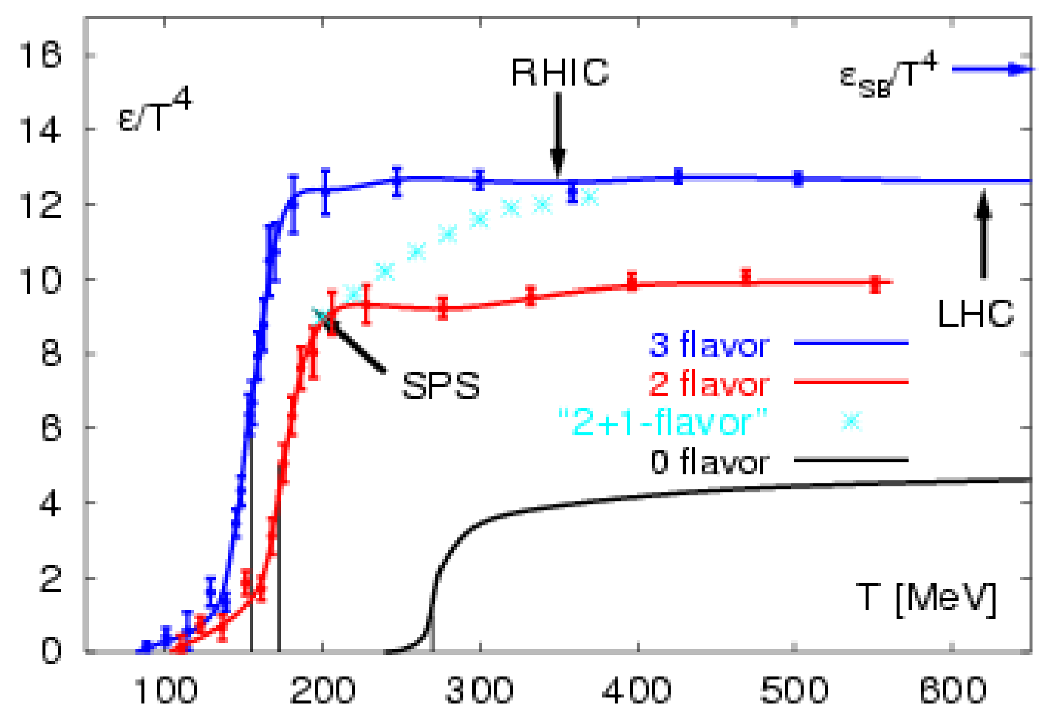
massless pions: $\varepsilon = 3\,\frac{\pi^2}{30}\,T^4 \simeq T^4$

units: $\hbar = c = k_B = 1$

quark-gluon plasma with u,d,s: $\varepsilon = 47.5\,\frac{\pi^2}{30}\,T^4 \simeq 16\,T^4$

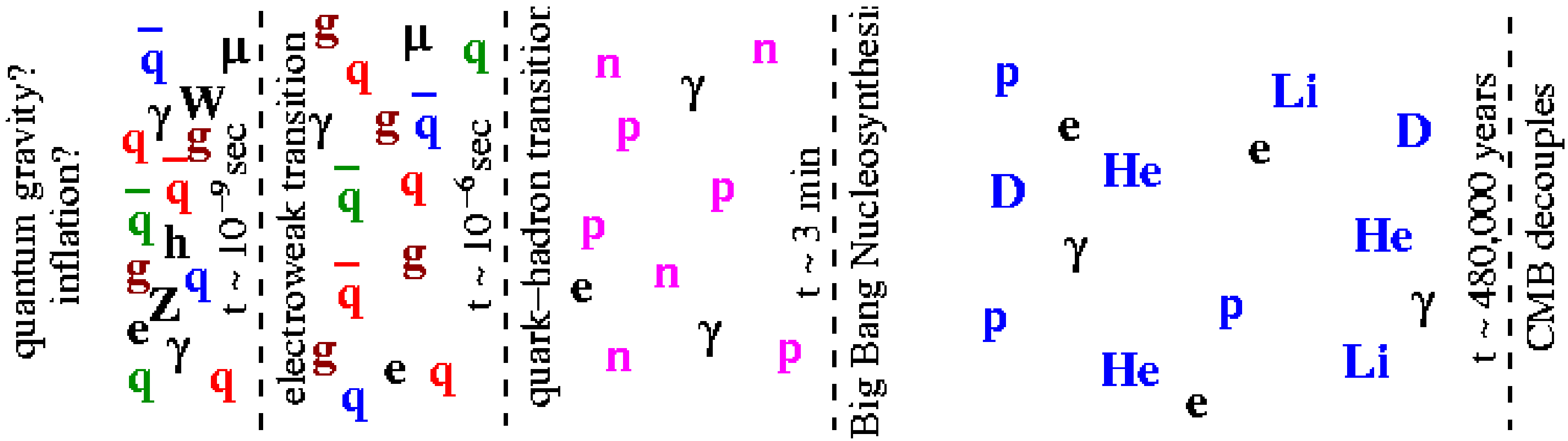
(u,d,s) (3 colors) (2 spins)
+ anti-quarks + gluons (8 colors) (2 polarizations)

Lattice data
(courtesy F. Karsch)



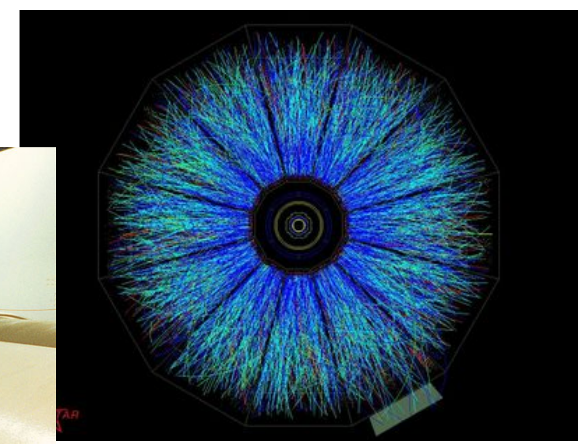
Where to find a QGP?

The Early Universe $t < 10^{-6}$ sec

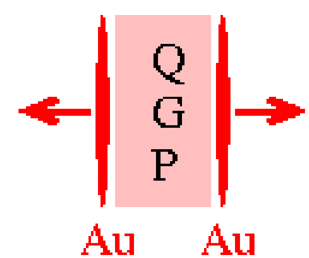


Heavy Ion Collisions

RHIC

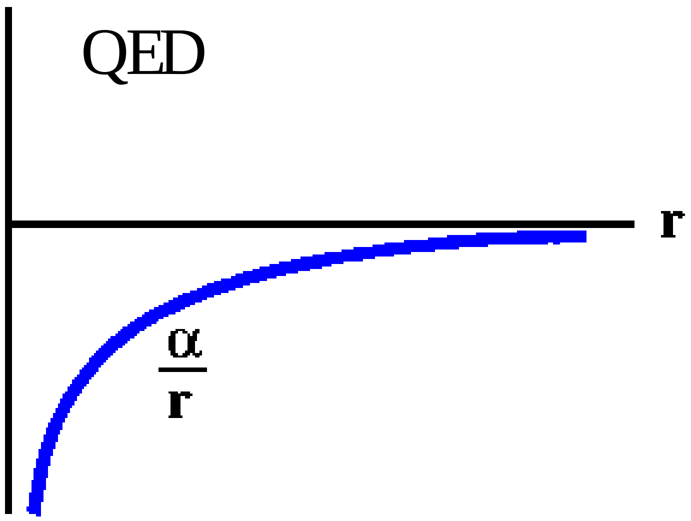


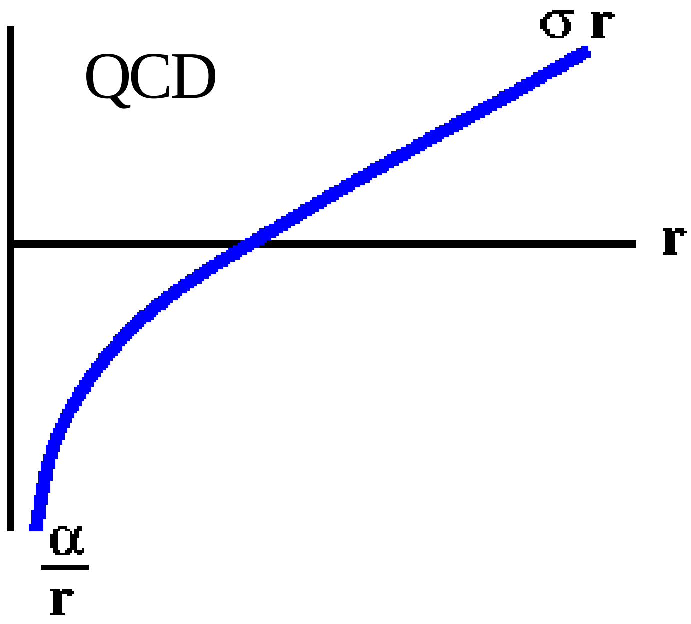
Au: v = 0.99995 c
E ~ 100 GeV per nucleon



Deconfinement as Debye Screening

Potential energy between 2 charges in vacuum

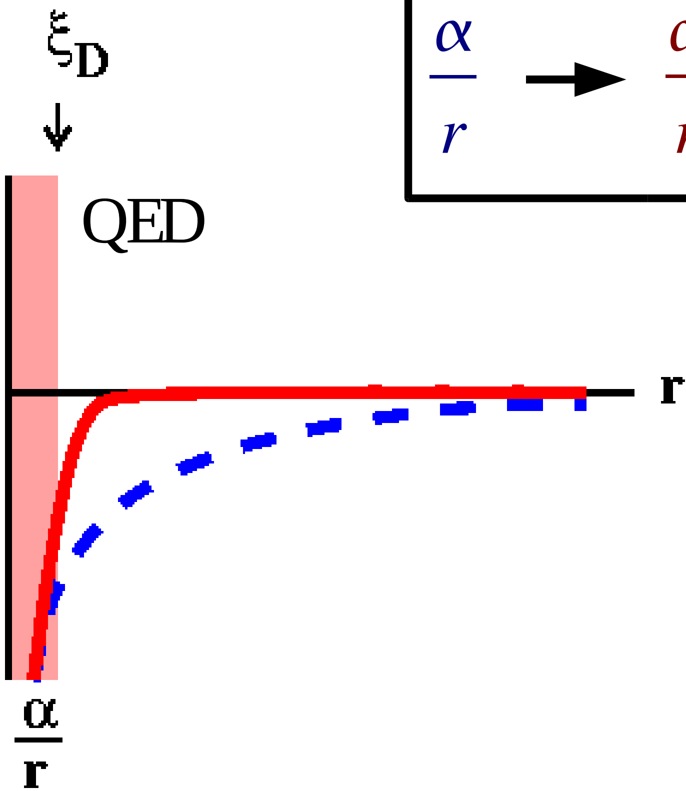


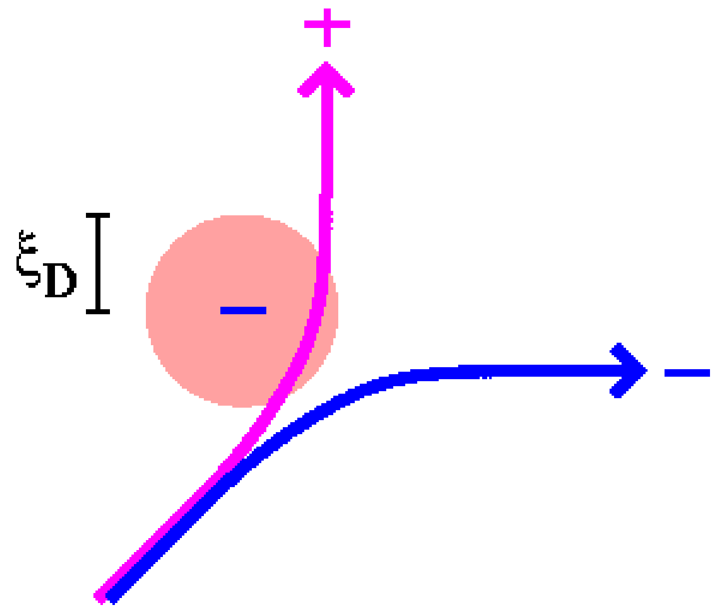


Deconfinement as Debye Screening

In a medium with free charges:

$$\frac{\alpha}{r} \longrightarrow \frac{\alpha}{r}\, e^{-r/\xi_D}$$





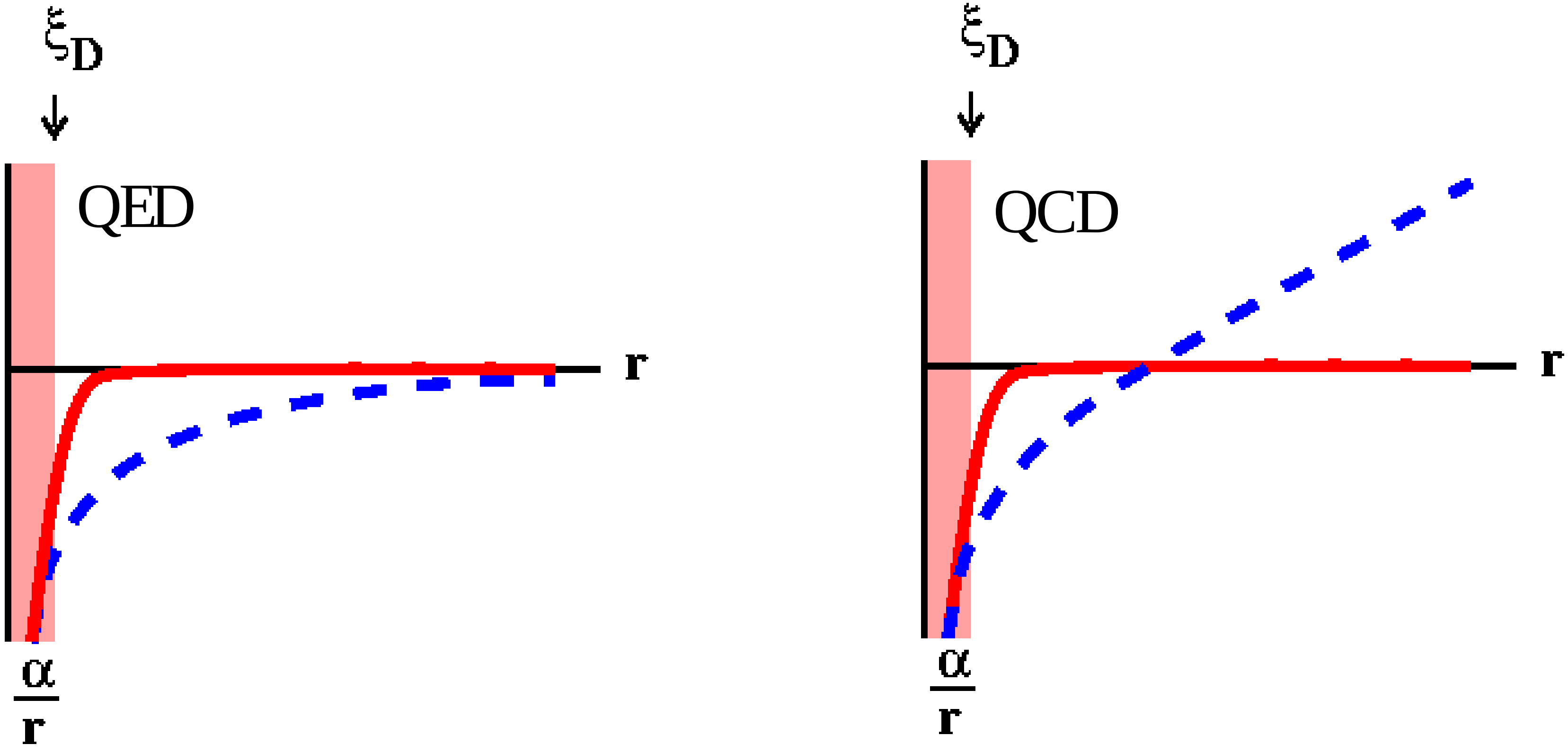
Debye screening length: $\xi_D \sim \left(\frac{T}{e^2 n}\right)^{1/2}$

ultra-relativistic: $n \sim T^3 \longrightarrow \xi_D \sim \frac{1}{eT}$

Higher temperature → smaller Debye radius

Deconfinement as Debye Screening

In a medium with free charges:



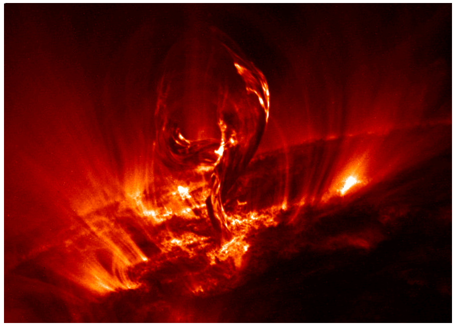
Higher temperature → smaller Debye radius

The Debye effect screens electric fields. In contrast:

Magnetic fields are <u>not</u> screened in a plasma.

So

QED: magnetic forces are still long range

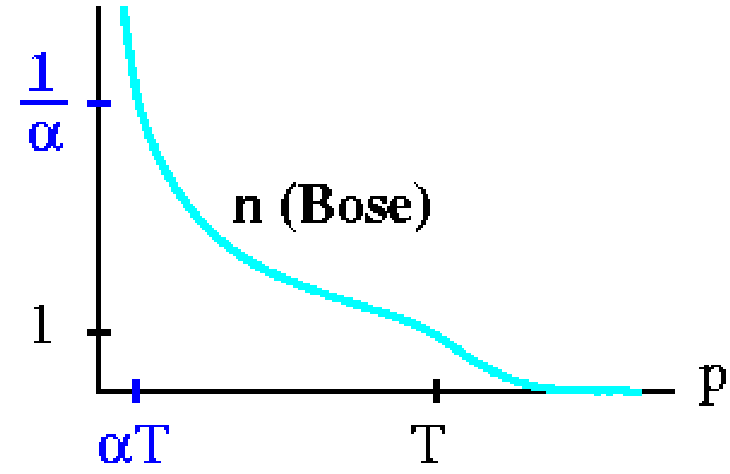


QCD: could there be confinement of colored currents?

→ no long range colored B fields?

Version for particle theorists: Do spatial Wilson loops still have area-law behavior?

YES, and at very short distances too!



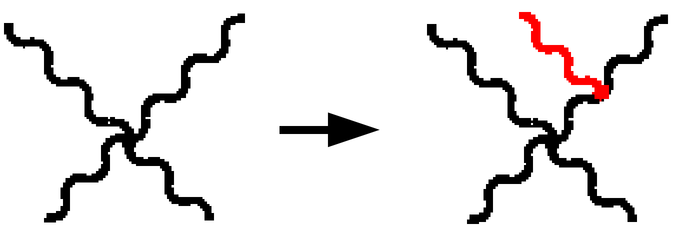
$$n_{\text{Bose}} = \frac{1}{e^{\beta E} - 1} \rightarrow \frac{T}{E} \quad \text{as} \quad E \rightarrow 0$$

For massless bosons,

$$E \sim p \sim \alpha T \quad \longrightarrow \quad n_{\text{Bose}} \sim \frac{1}{\alpha}$$

Photons don't directly interact with each other, but gluons do.

Result: Perturbation theory breaks down for gluons with $p \sim \alpha T$.



costs $|e|^2 \sim \alpha$ for extra interaction

$n_{\text{Bose}} \sim \dfrac{1}{\alpha}$ for density of extra gluons

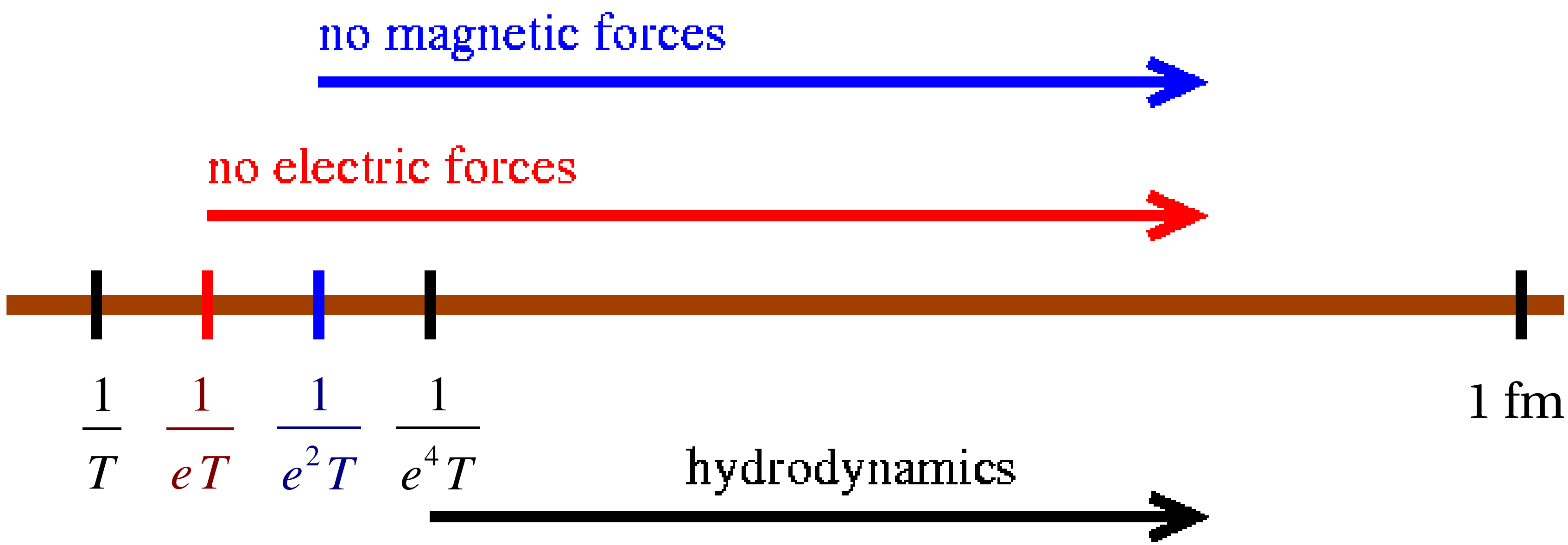
1 total

Summary

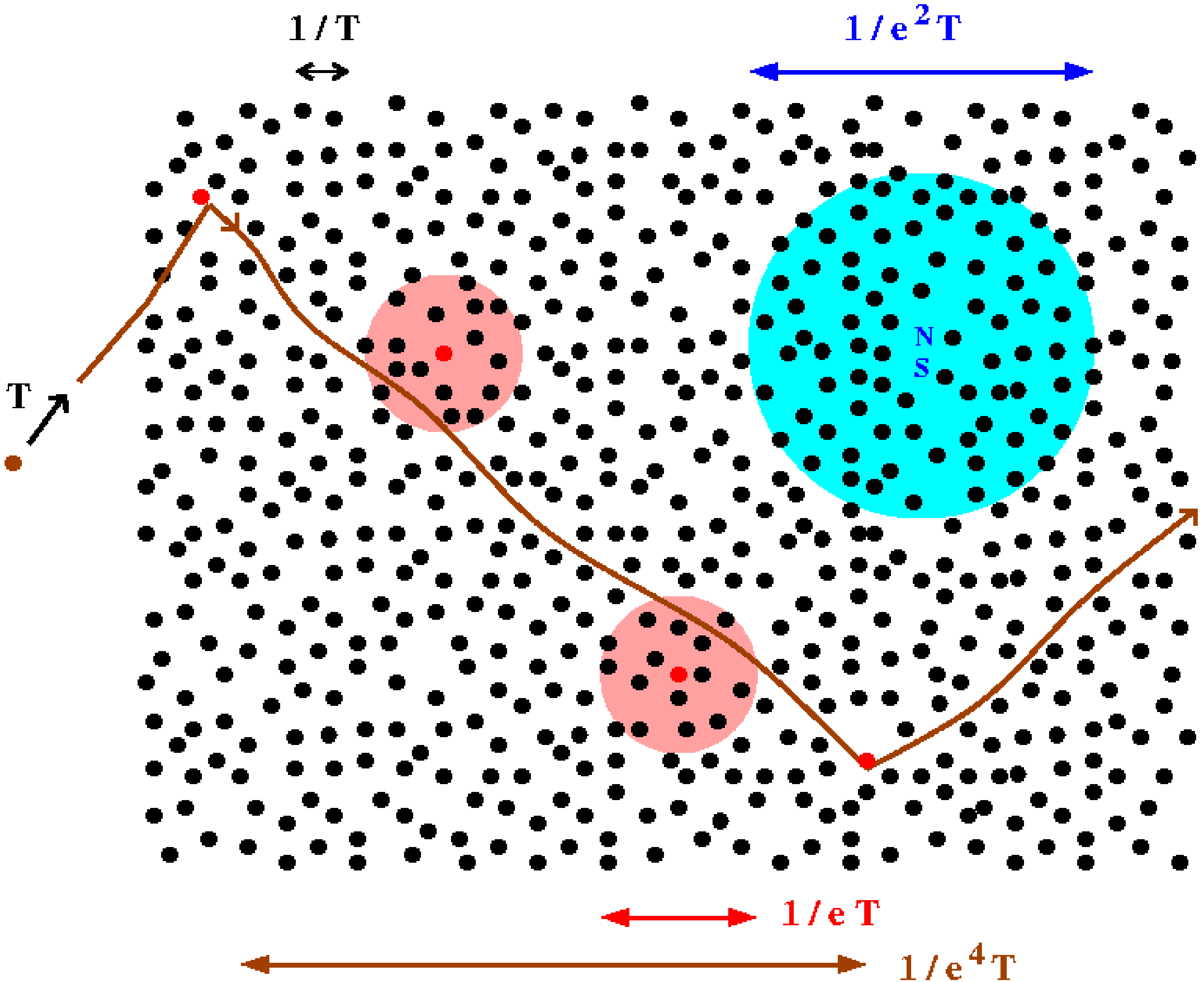
Note: "e" means "g_S" here

electric screening at $\xi_D \sim \dfrac{1}{eT}$ → no charge confinement

no traditional magnetic screening → current confinement at $\dfrac{1}{e^2 T}$



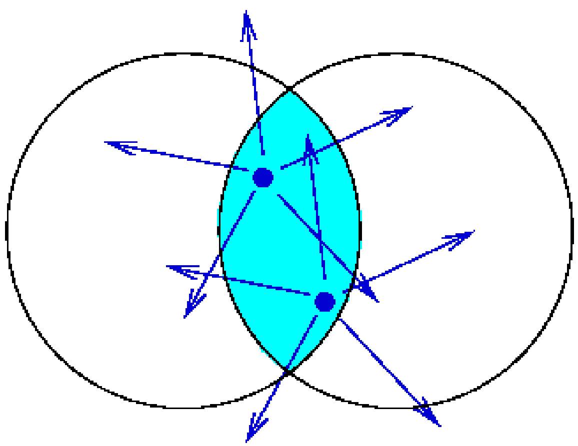
Long distance physics is hydrodynamics, not colored MHD.

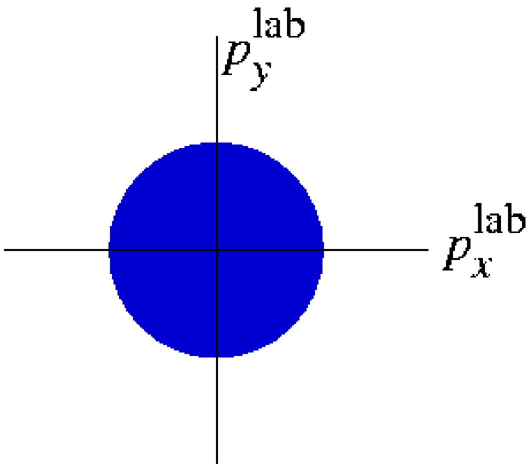

1 / T
1 / e²T
T
N
S
1 / e T
1 / e⁴T

Is there no "interesting" plasma physics in a quark-gluon plasma?

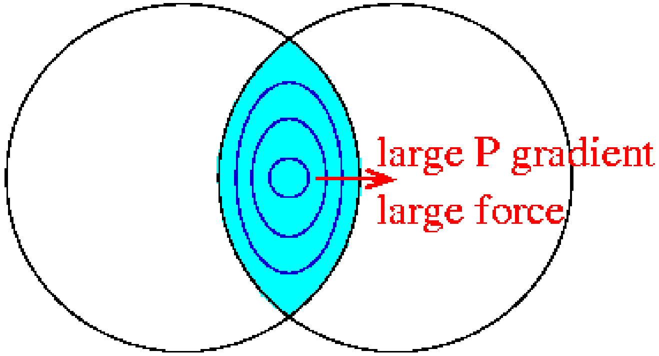
QGP hydrodynamics

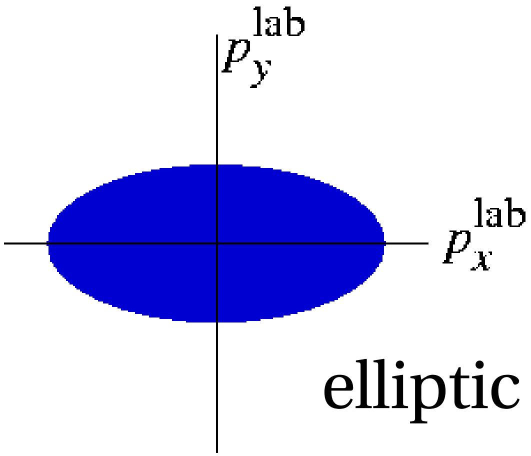
Independent collisions: mean free path >> anything





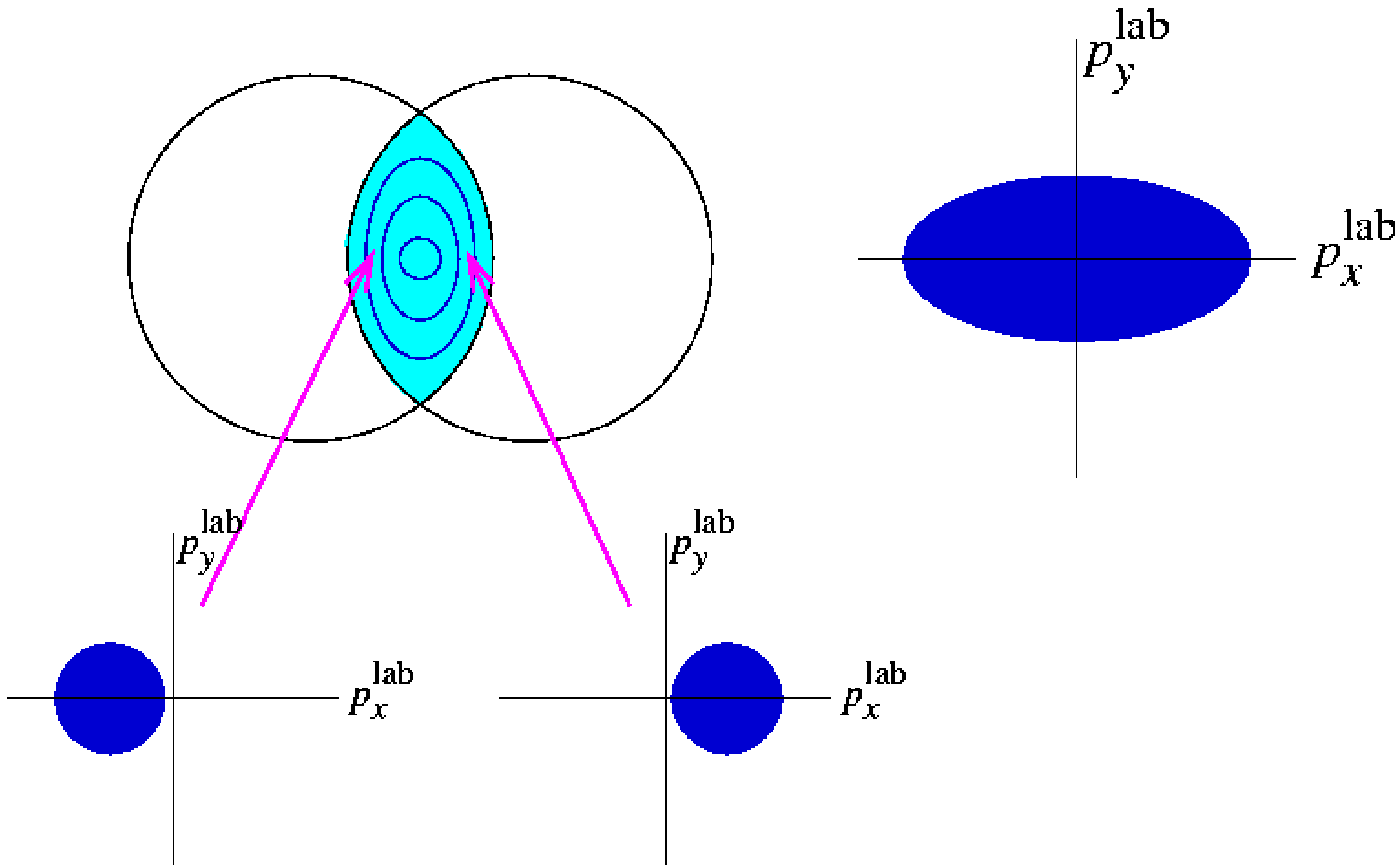
Hydrodynamics: mean free path << whatever





elliptic flow

Hydrodynamics usually associated with fluids in *local equilibrium*.

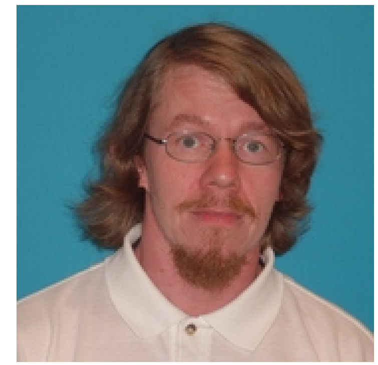


Distributions are isotropic in local fluid rest frames.

How well does hydrodynamics do?

Groups studying flow successfully model many aspects of heavy-ion collisions with ideal hydrodynamics.

Pasi Huovinen



But it requires hydrodynamical behavior to set in fairly early.
Some like like to quote: $t = 0.6$ fm/c

Phenomenological question: Is $t = 0.6$ fm/c reasonable?

Can a quark-gluon plasma reach local equilibrium in a time of order 0.6 fm/c?

Thermalization

Question:

What is the (local) thermalization time for QGPs in heavy ion collisions?

A simpler question:

What is it for arbitrarily high energy collisions, where $\alpha_s << 1$?

A much simpler question:

How does that time depend on α_s?

$$t_{\mathrm{eq}} \sim \frac{\alpha_s^{-??}}{\text{momentum scale}}$$

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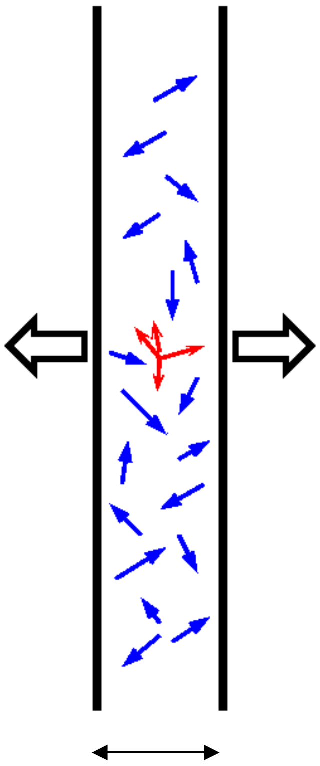
"Bottom-up thermalization" predicted **??** **= 13/5**
(Baier, Mueller, Schiff, and Son)

Bottom-Up Thermalization

(Baier, Mueller, Schiff, Son '00)

Starting point

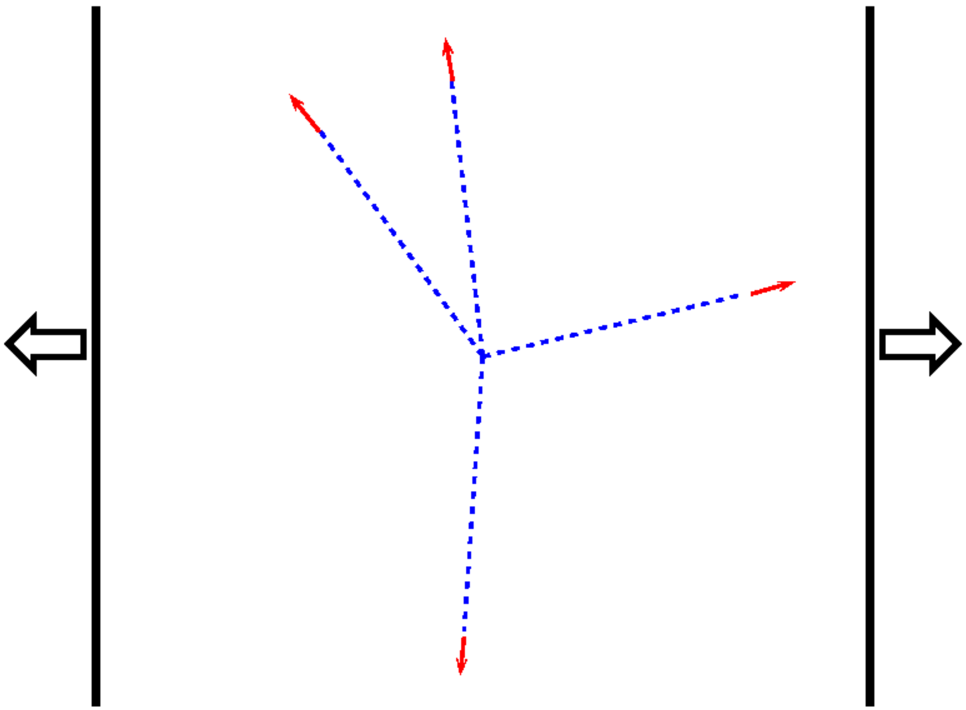


System expands
→ density decreases
→ more perturbative

Bottom-Up Thermalization

(Baier, Mueller, Schiff, Son '00)

Later, if interactions ignored

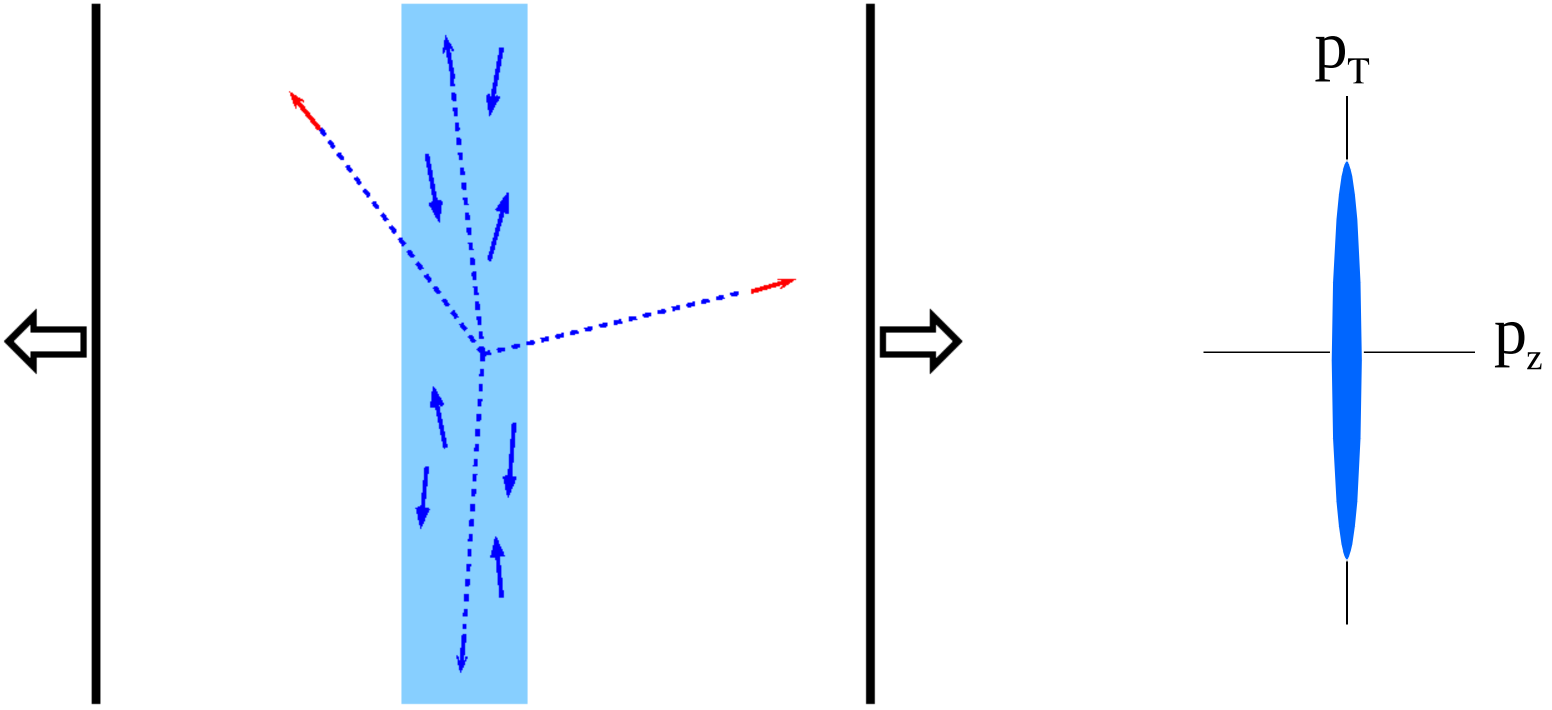


$\Delta z \sim v_z \, t$

Bottom-Up Thermalization

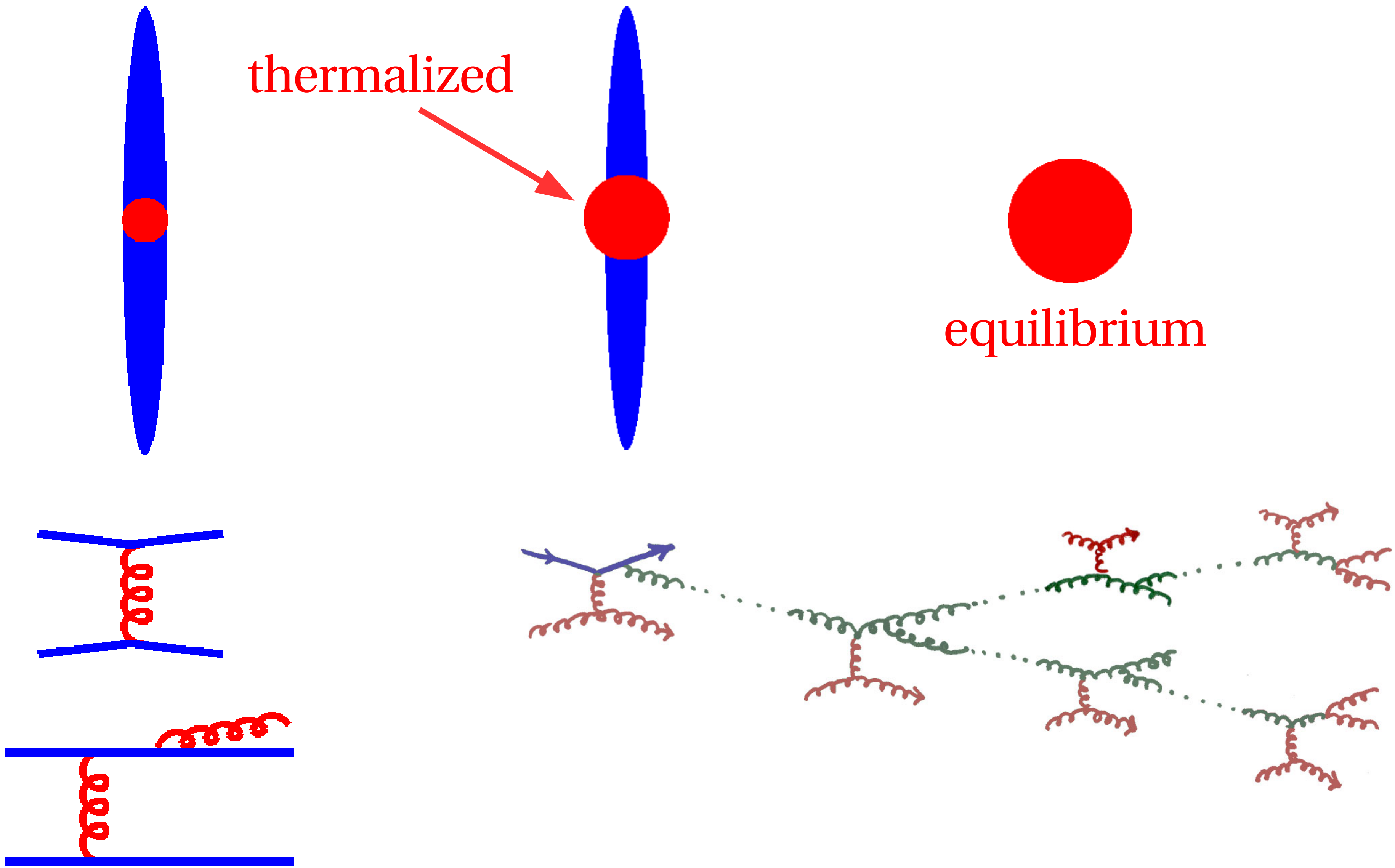
(Baier, Mueller, Schiff, Son '00)

Later, if interactions ignored



Bottom-Up Thermalization

(Baier, Mueller, Schiff, Son '00)



So what's the problem?

Plasma physics is complicated

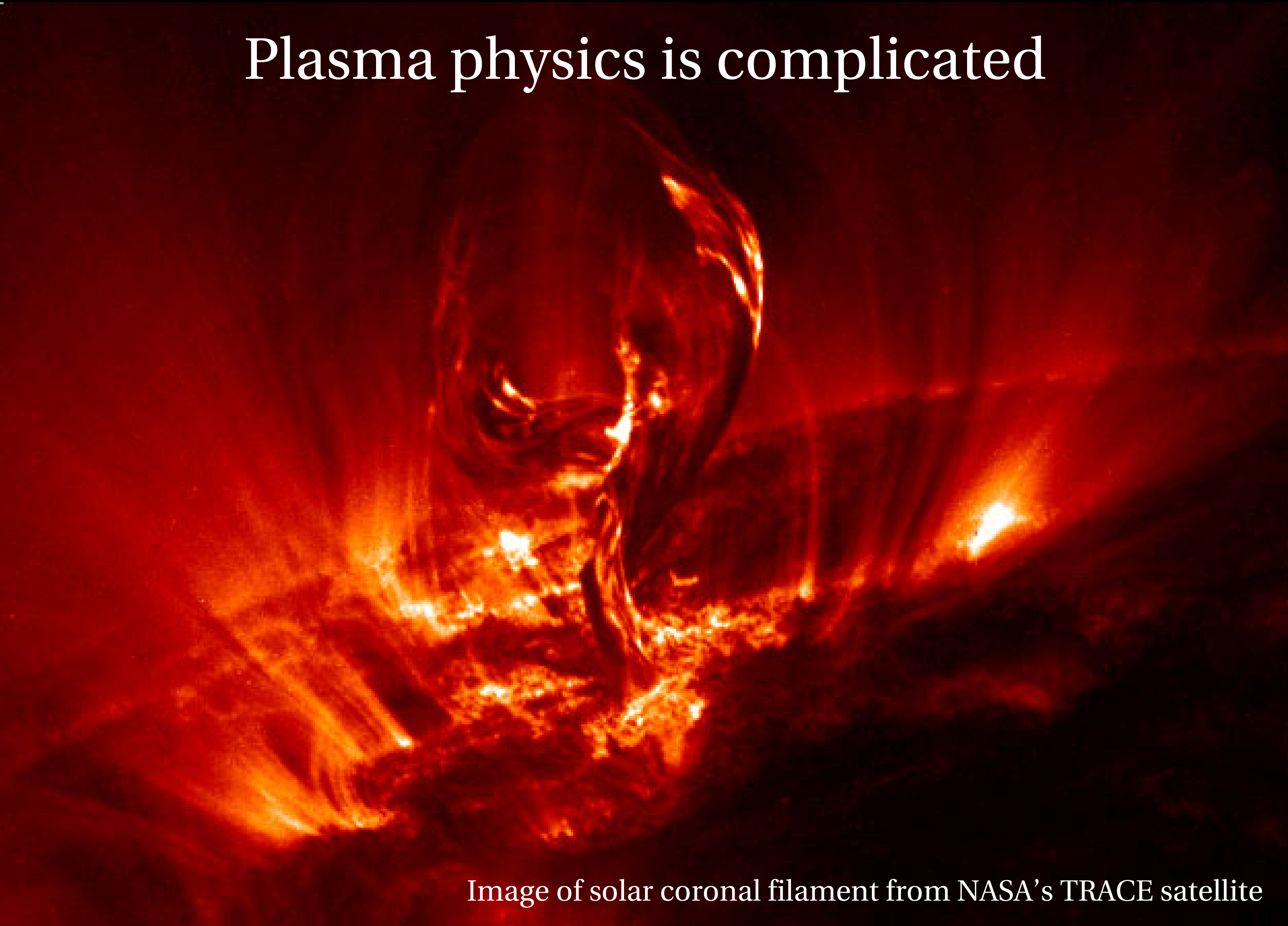
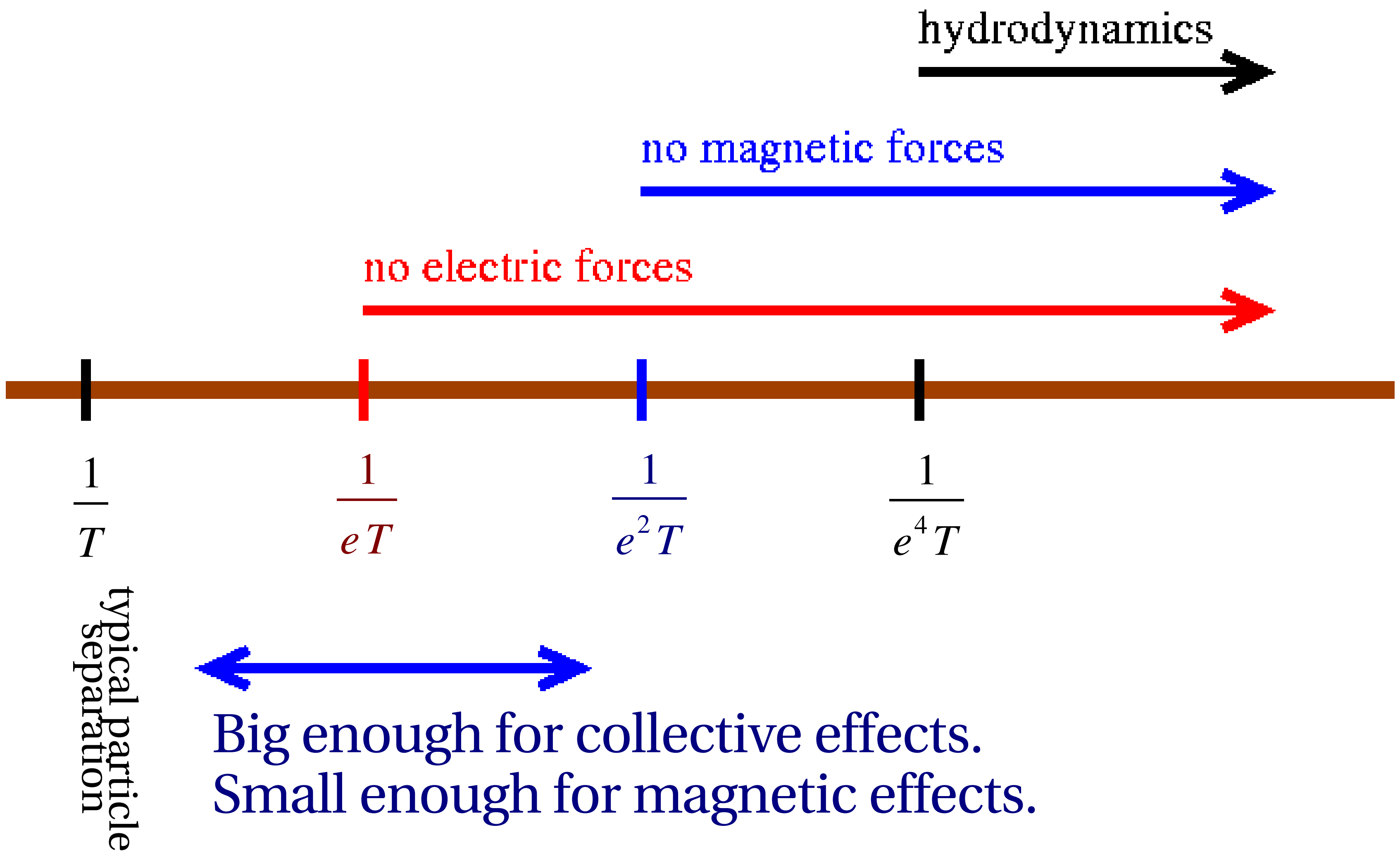


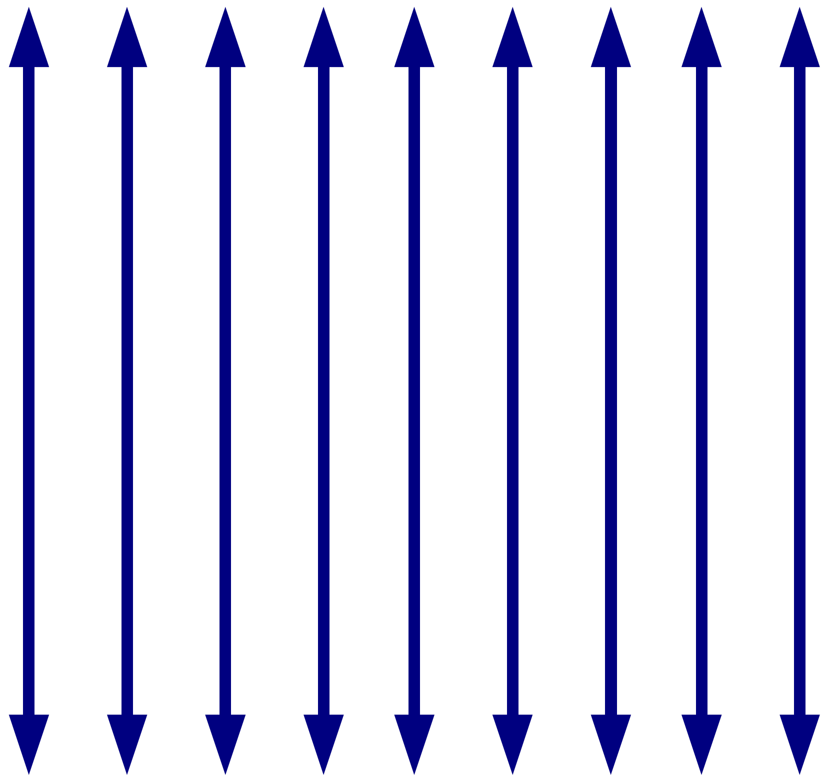
Image of solar coronal filament from NASA’s TRACE satellite

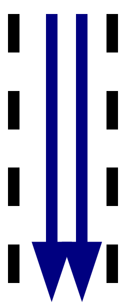
A Window for Interesting Collective Effects



Big enough for collective effects.
Small enough for magnetic effects.

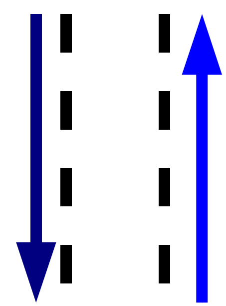
The Weibel (or filamentation) instability



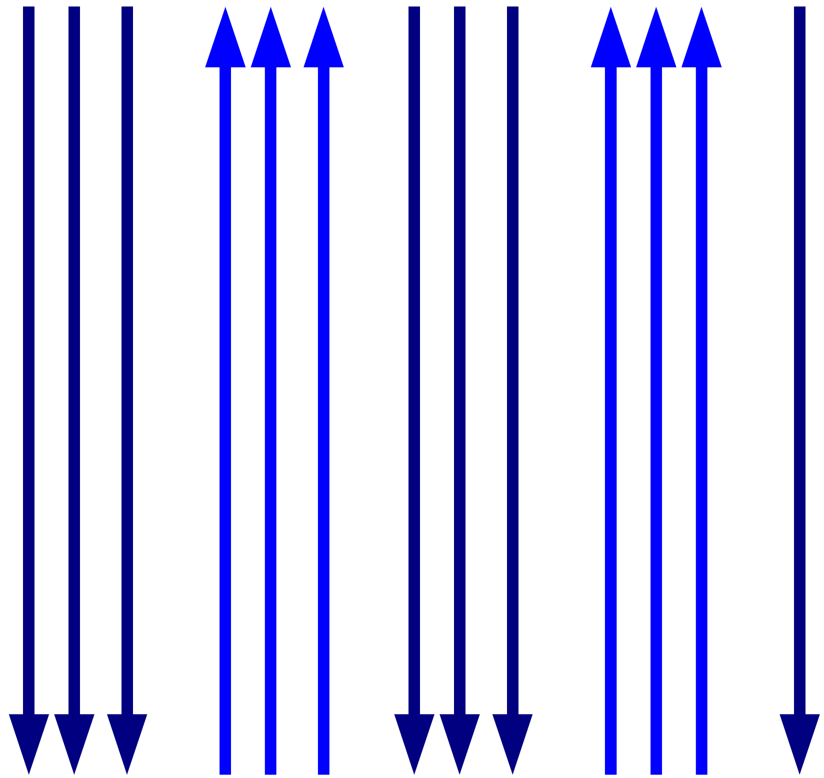


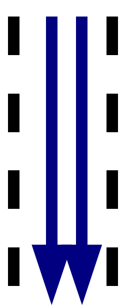
Parallel currents attract

Opposite currents repel



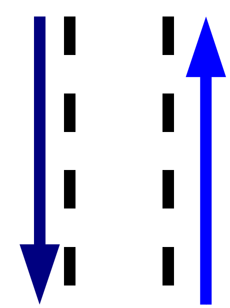
The Weibel (or filamentation) instability



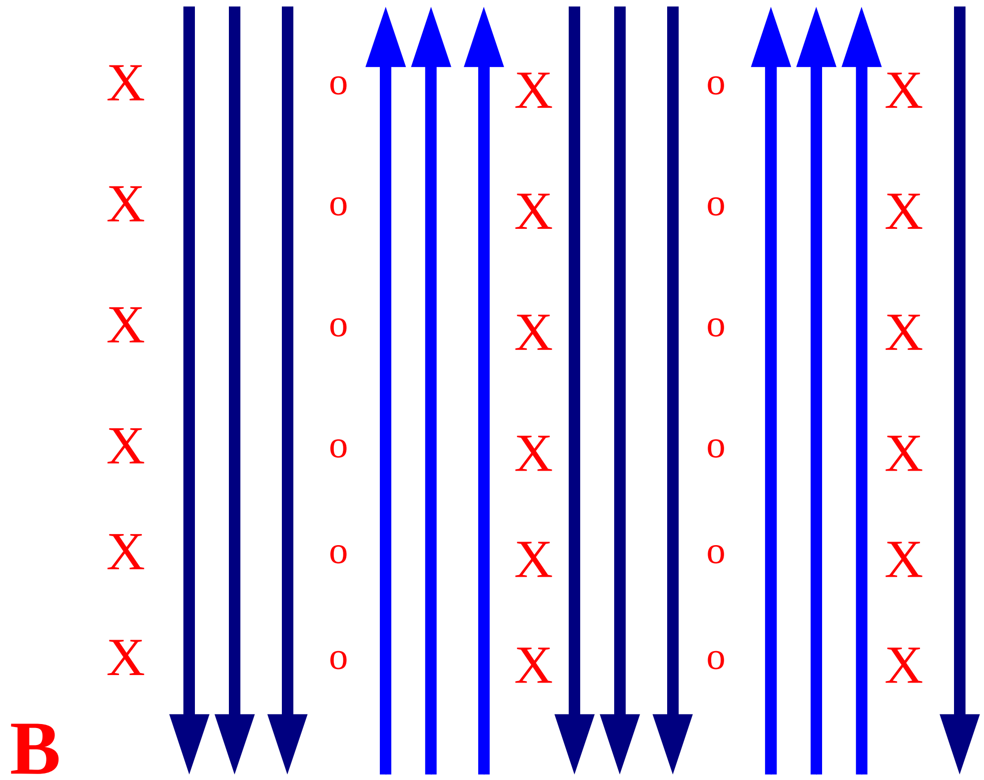


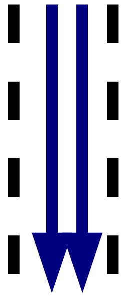
Parallel currents
attract

Opposite currents
repel



The Weibel (or filamentation) instability





Parallel currents attract

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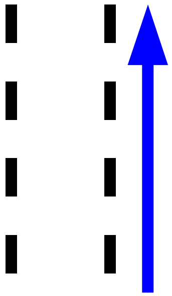
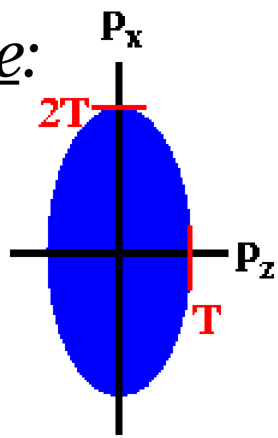
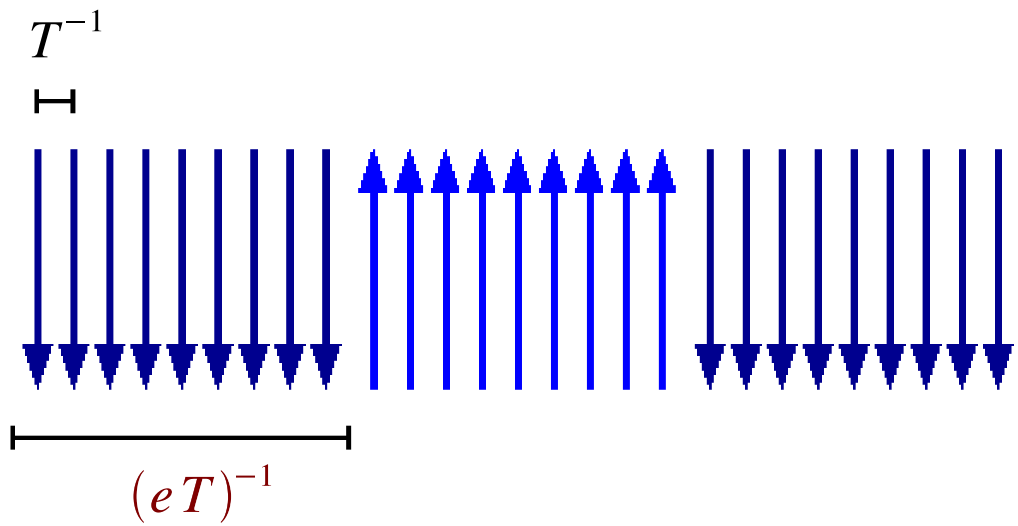


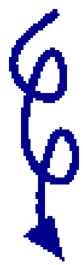
Weibel instability occurs when velocity distribution is anisotropic.

<u>*Example*</u>:





In relativistic QED, would grow until



$\frac{1}{T}$ — typical particle separation

$\frac{1}{eT}$ — Weibel instability

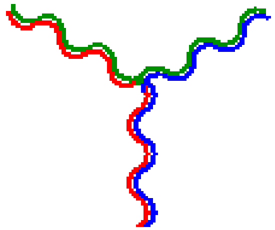
$\frac{1}{e^2 T}$

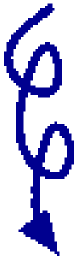
$\frac{1}{e^4 T}$ — randomization via individual 2 --> 2 collisions

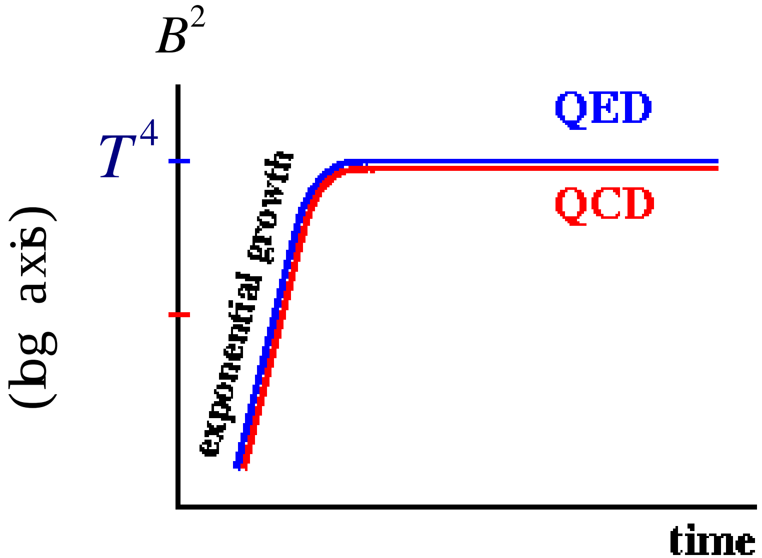
Instabilities
→ fast randomization

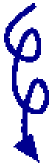
Except ...

Colored magnetic fields can interact with *each other*!

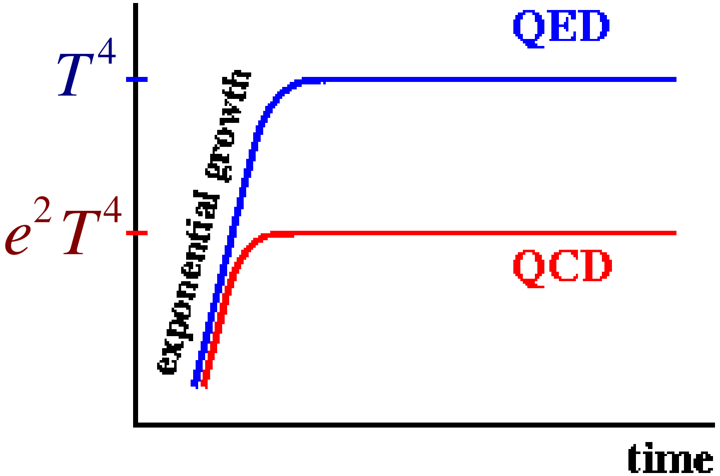


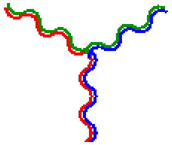
Can this stop instability growth before  ?



growth until 

<u>or</u>



growth limited by  ?

The Vlasov Equations

Traditional QED Plasmas

Describe particles by classical phase space density $f(p,x,t)$.
Describe EM fields by classical gauge fields $A_\mu(x,t)$.

$$\partial_t f + v \cdot \nabla_x f + e(E + v \times B) \cdot \nabla_p f = 0$$ Collisionless Boltzmann eq.

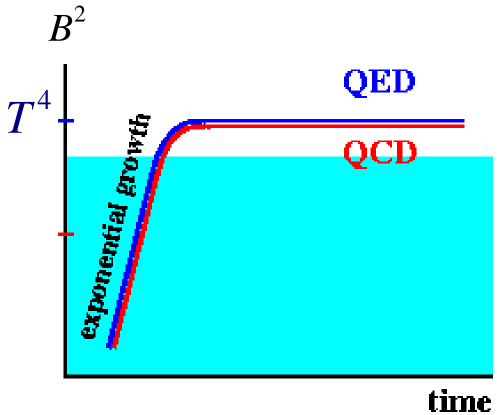
$$\partial_\mu F^{\mu\nu} = j^\nu = \int_p e\, v^\nu f$$ Maxwell's eqs.

QCD Plasmas

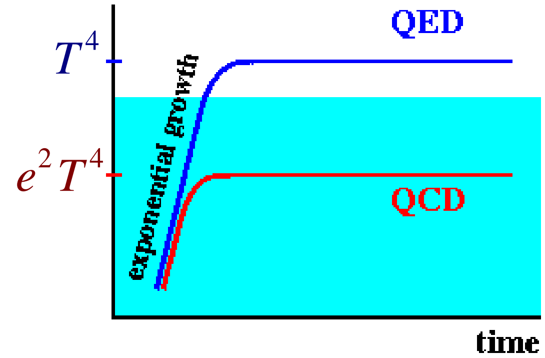
$f(p,x,t)$ becomes a color density matrix.

$\partial_t \rightarrow \partial_t - i e A_0$ and $\nabla_x \rightarrow \nabla_x - i e \mathbf{A}$ above.

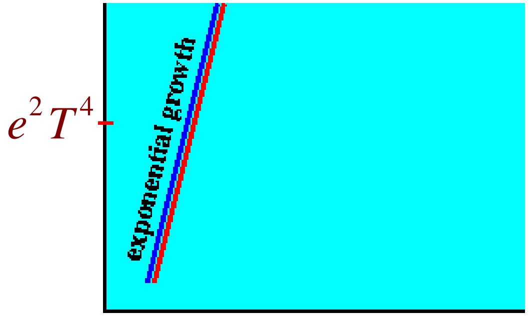
Can cleanly study shaded region of



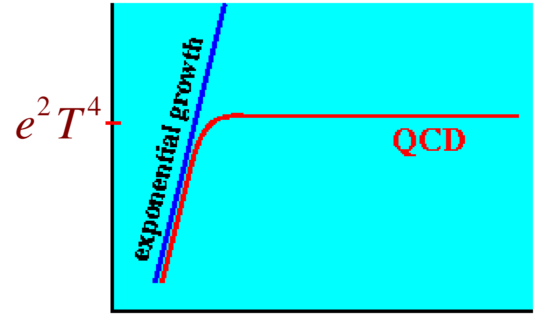
vs.



by writing $f = f_o + \delta f$ and linearizing in δf :

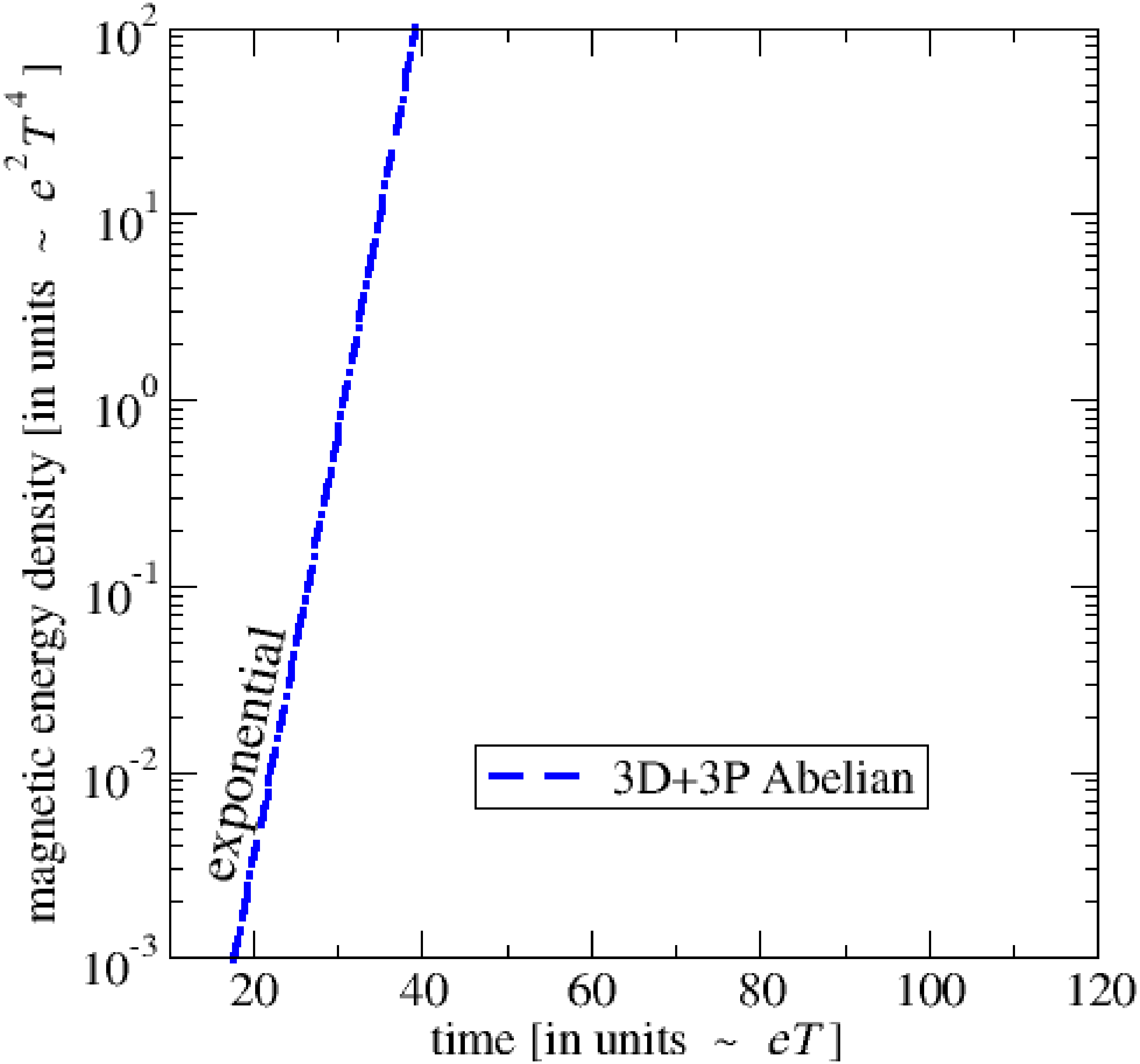


vs.

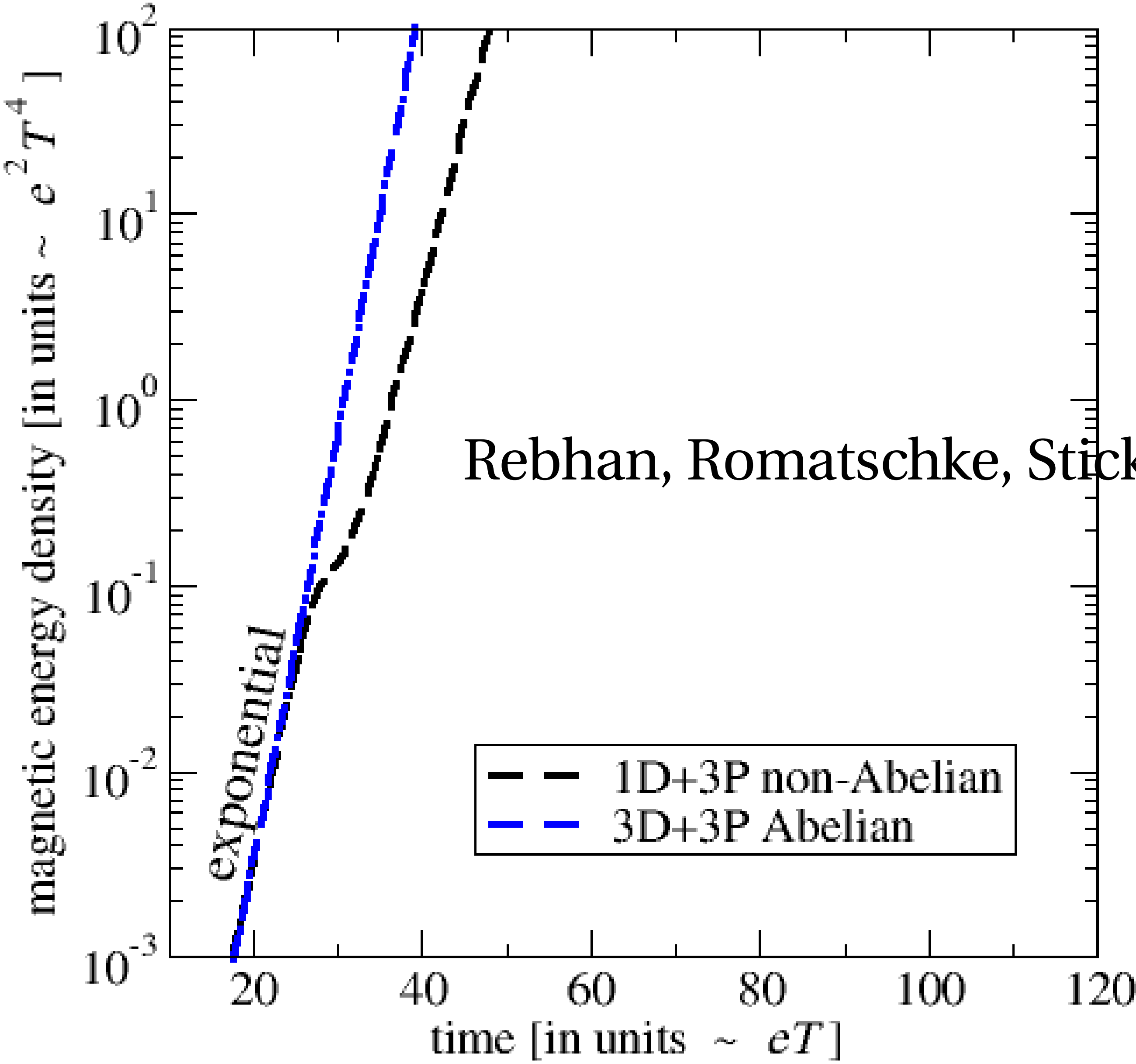


<u>Numerical Simulations</u>:

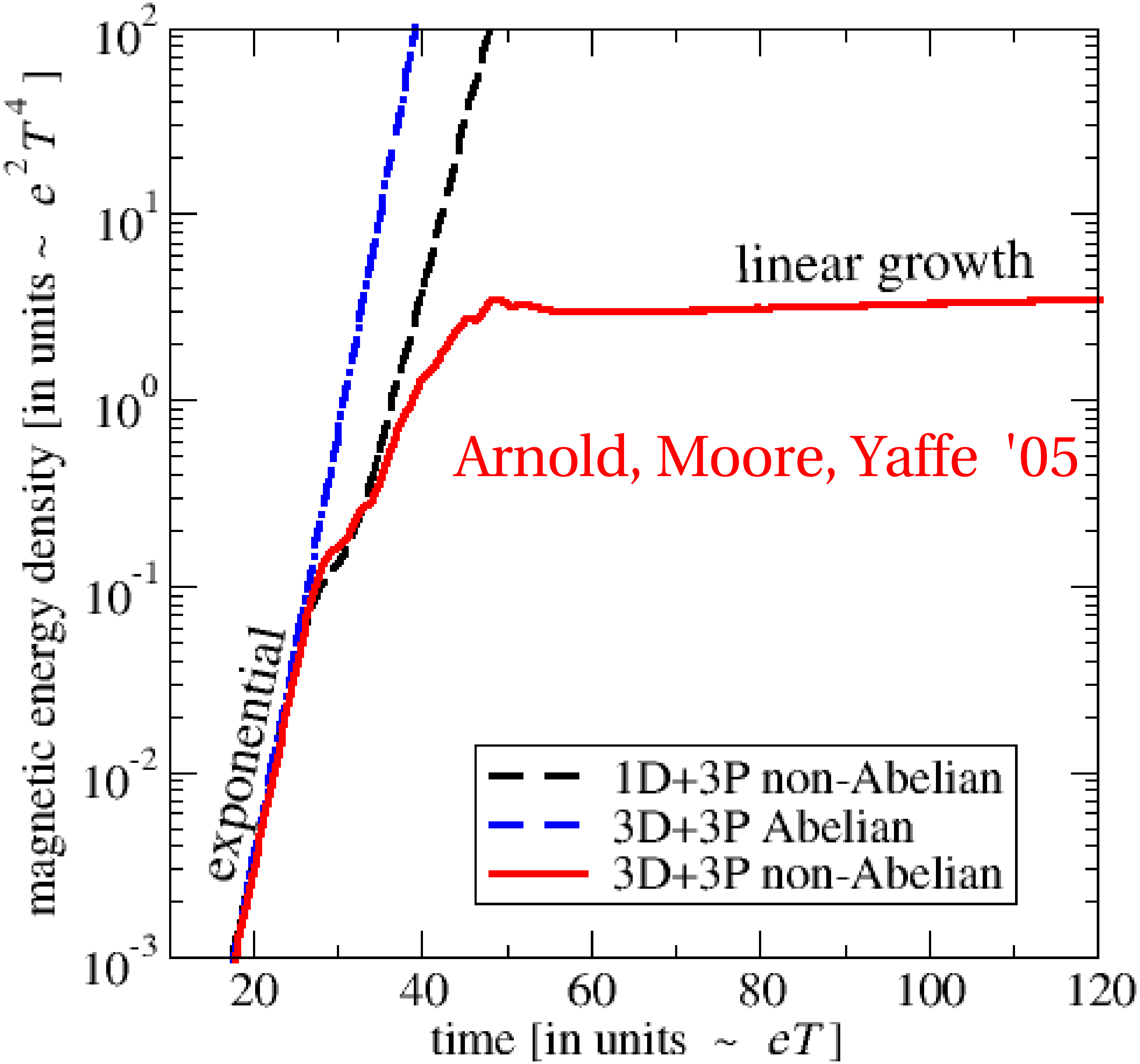
Treat x as a lattice (lattice gauge theory).
Discretize p.
Evolve classical QCD Vlasov equations in time.



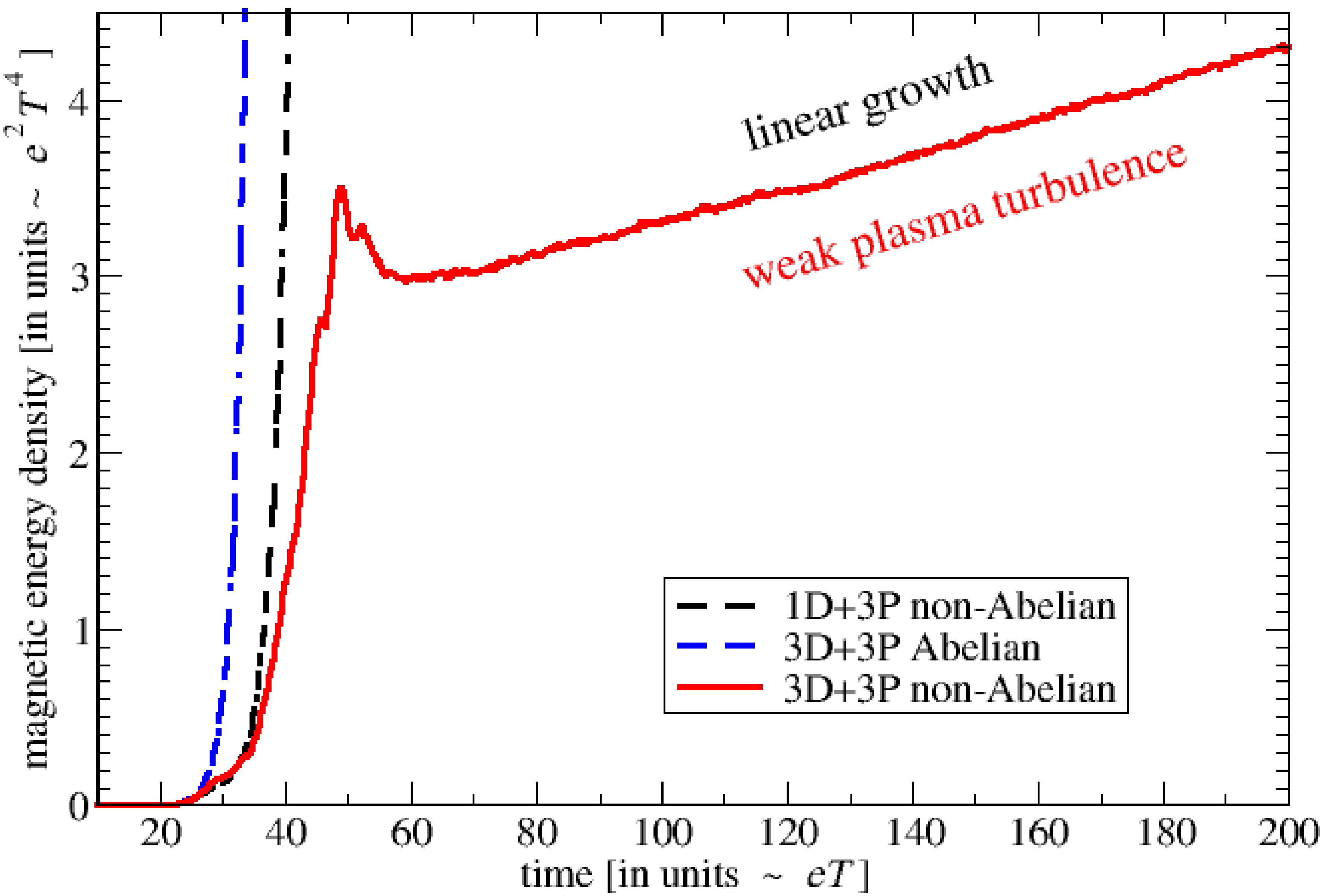
magnetic energy density [in units ~ e^2T^4]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
40
60
80
100
120
time [in units ~ eT]
exponential
3D+3P Abelian



Rebhan, Romatschke, Stickland '04

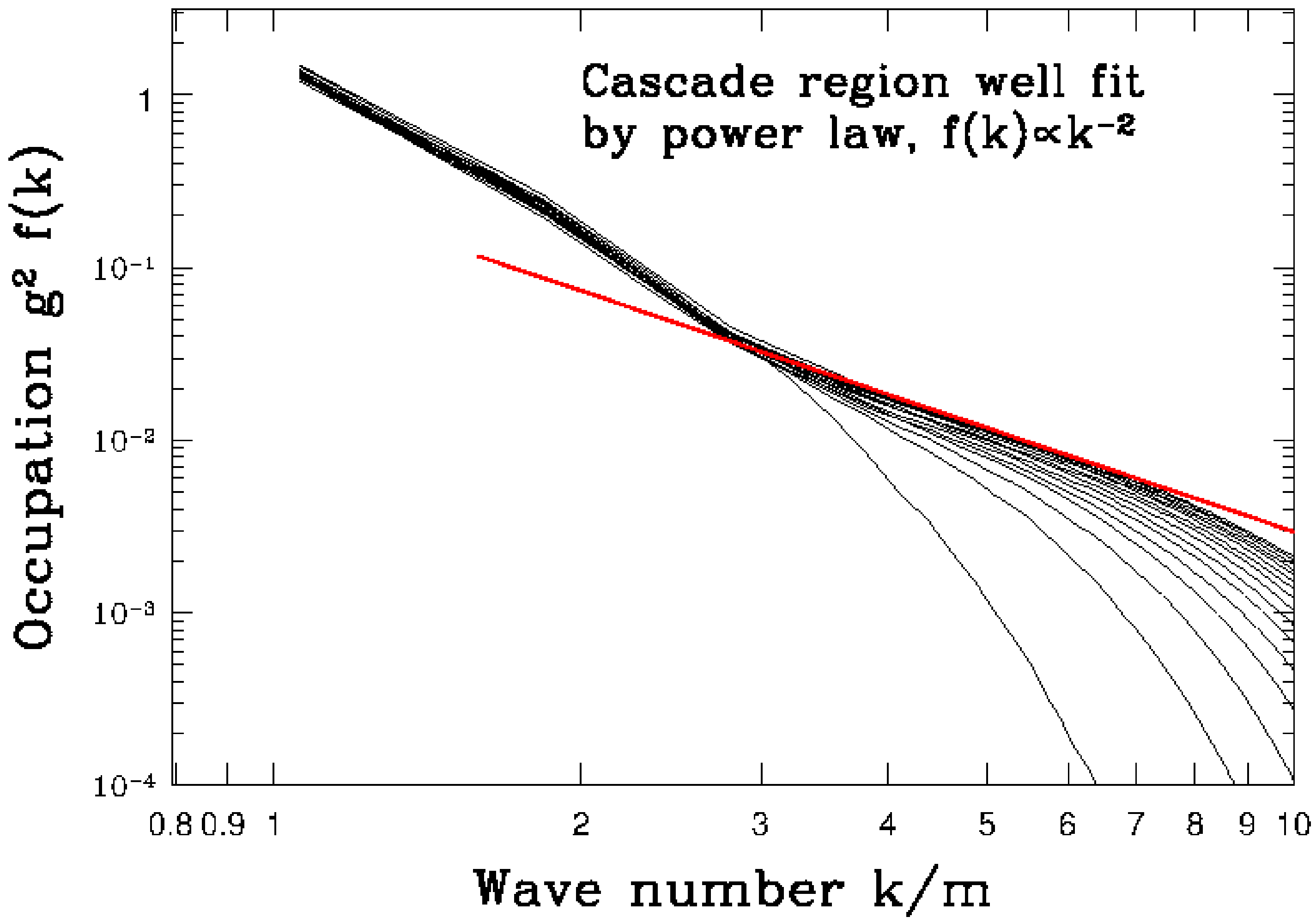


linear growth
Arnold, Moore, Yaffe '05
exponential
1D+3P non-Abelian
3D+3P Abelian
3D+3P non-Abelian
magnetic energy density [in units ~ $e^2 T^4$]
time [in units ~ eT]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
20
40
60
80
100
120

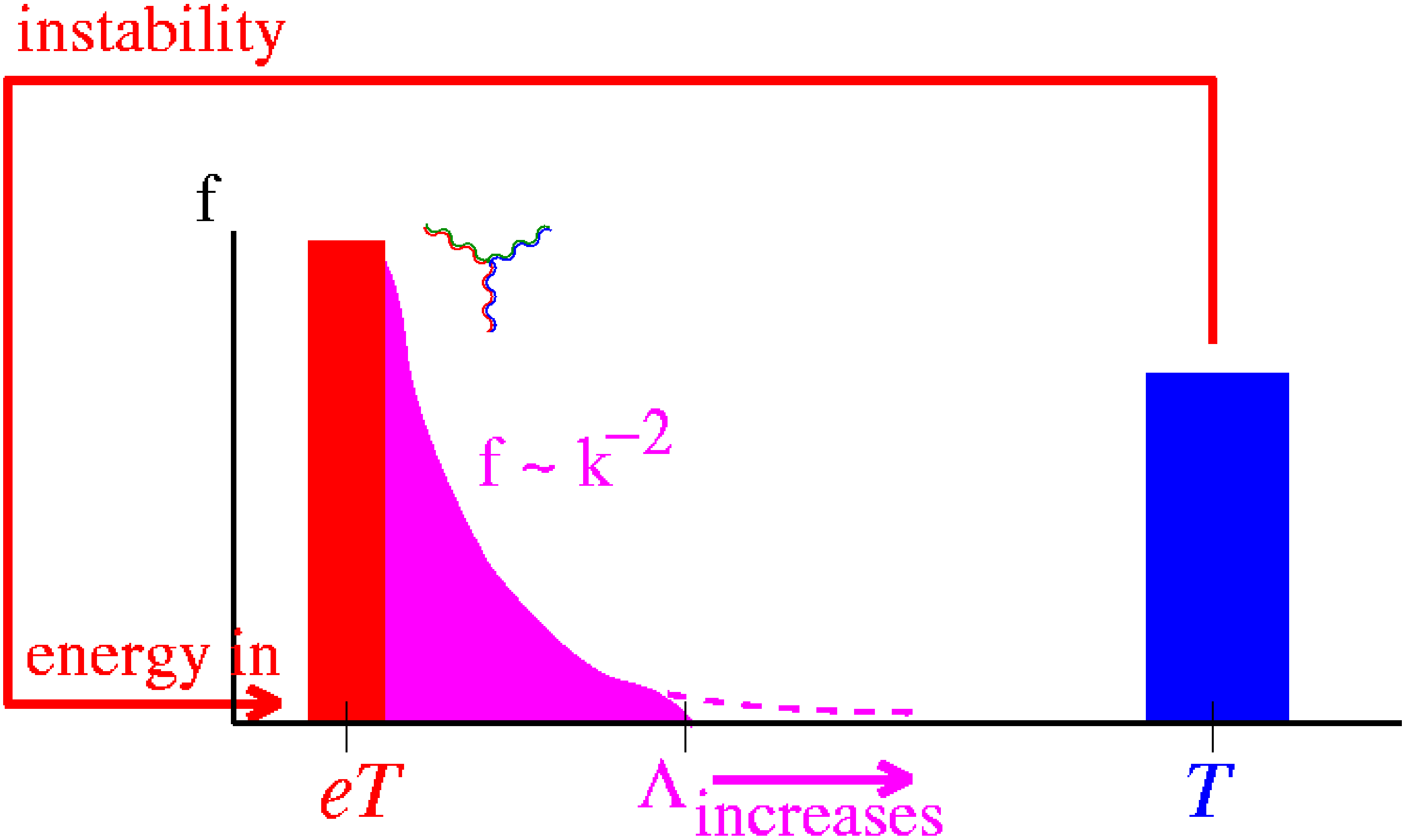


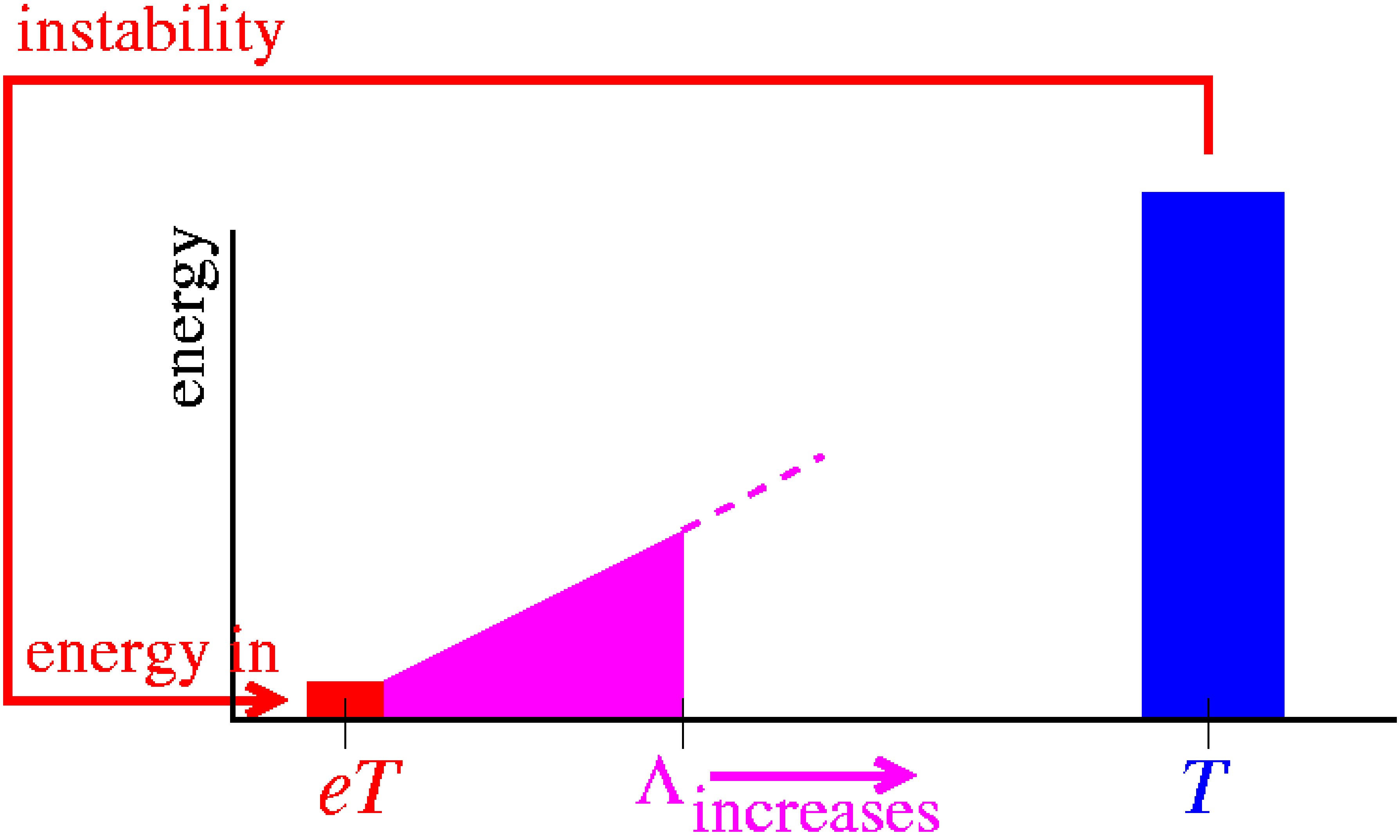
linear growth
weak plasma turbulence
1D+3P non-Abelian
3D+3P Abelian
3D+3P non-Abelian
magnetic energy density [in units ~ e^2T^4]
time [in units ~ eT]
0
1
2
3
4
20
40
60
80
100
120
140
160
180
200

Coulomb gauge spectra



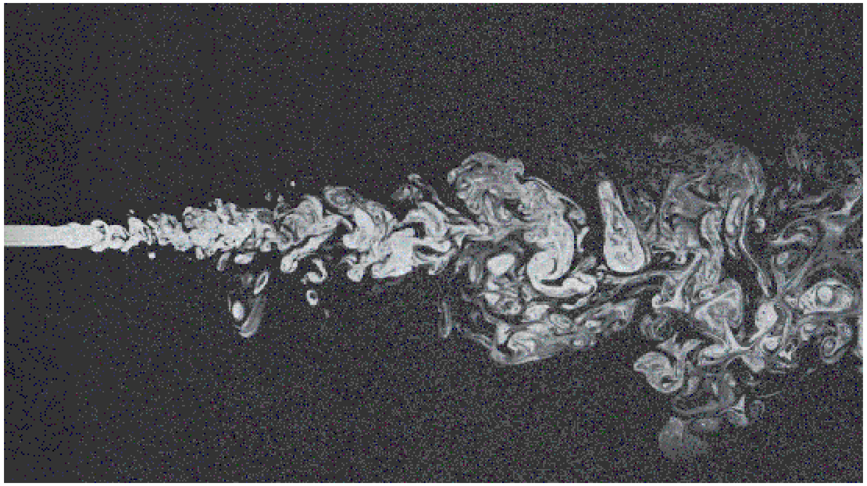
Arnold & Moore


instability
f
f ~ k^{-2}
energy in
eT
Λ increases
T


instability
energy
energy in
eT
Λ
increases
T

Examples of energy cascades

Turbulence in hydrodynamics



Big whirls make little whirls
which feed on their velocity;
Little whirls make lesser whirls,
and so on to viscosity.

L.F.G. Richardson

Kolmogorov spectrum: $(\text{energy})_k \sim k^{-5/3}$

Applications in Particle Physics

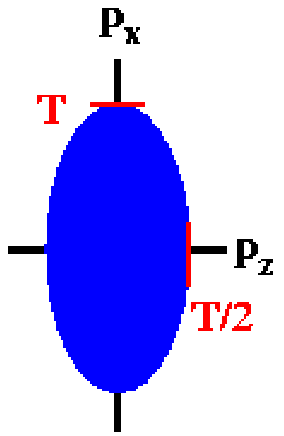
Thermalization after inflation in the early Universe.

So what's the answer?

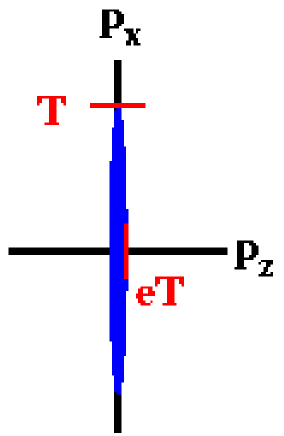
$$t_{eq} \sim \frac{\alpha_s^{-??}}{\text{momentum scale}}$$

Problem:

So far, only understood the case of moderate anisotropy,



But early stages of super-high-energy heavy ion collisions would initially generate parametrically **extreme** anisotropy, *e.g.*

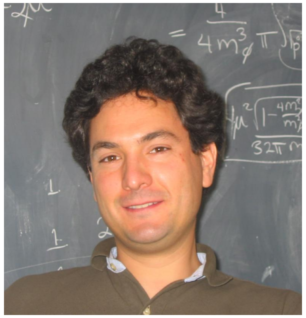


Summary

- There is interesting plasma physics in quark-gluon plasmas, but it behaves differently than in traditional plasmas.

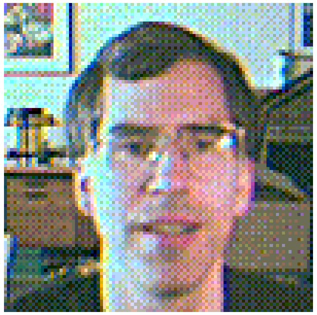
- Because of this interesting plasma physics, theorists have more work to do to understand quark-gluon plasma equilibration <u>even</u> at the weak couplings of arbitrarily high energy collisions.

My collaborators:

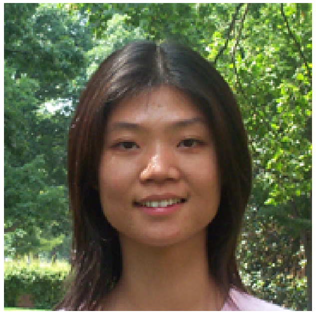


Guy Moore
(McGill)

Jonathan Lenaghan
(Physical Review)



Larry Yaffe
(U. Washington)



Po-shan Leang
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Caglar Dogan
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