The Strange Physics of Nonabelian Plasmas

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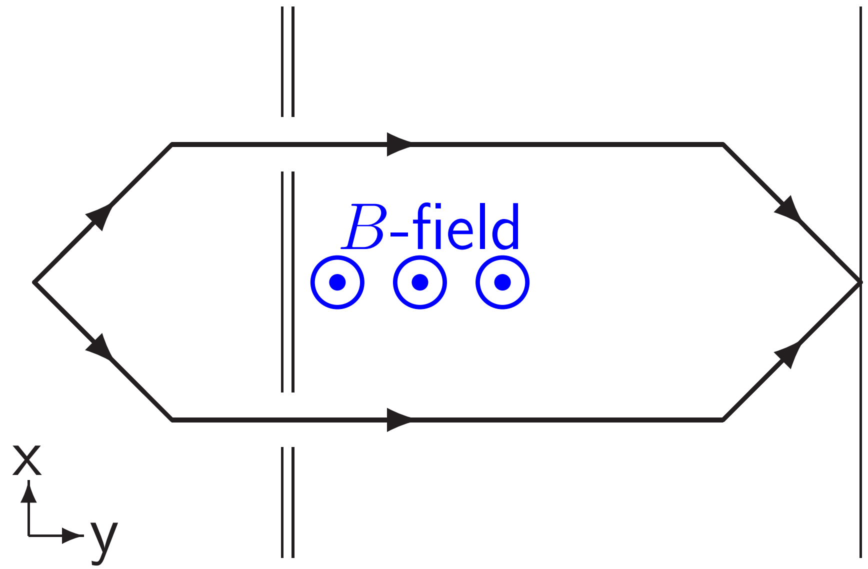
- Review: What does "Nonabelian" mean?
- Instability of a Uniform magnetic field
- Radiation and the LPM effect
- Plasma instabilities

My units: $c = 1$ and I write $\hbar$ where I think it's important

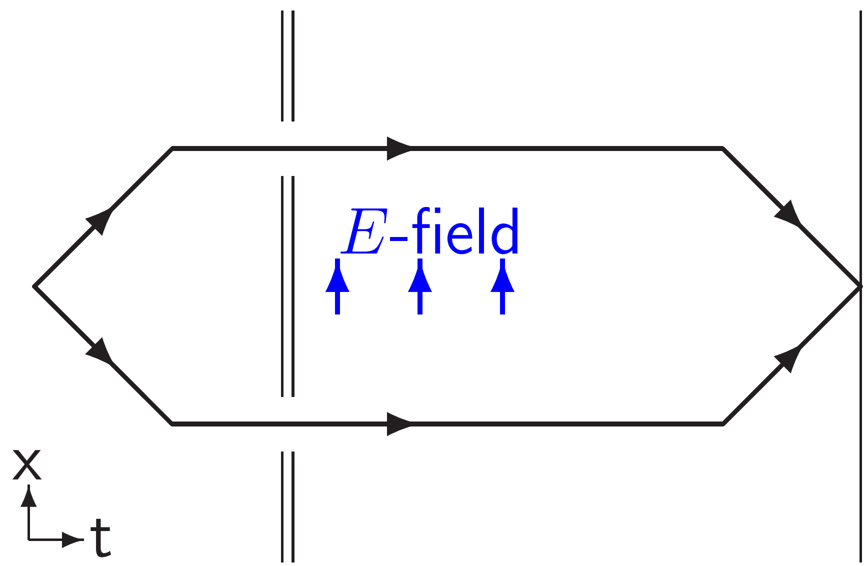
Aharonov-Bohm Effect



A charge following two paths which enclose some magnetic flux experience a phase difference.

Even if particle *never feels* B, phase shift shows up in interference phenomena when paths meet

Aharonov-Bohm for Electric Field



Paths which separate for some *time* and then meet pick up phase due to $\vec{E}$-field between them.
(Potential Φ difference $\Rightarrow e^{-iEt}$ difference)

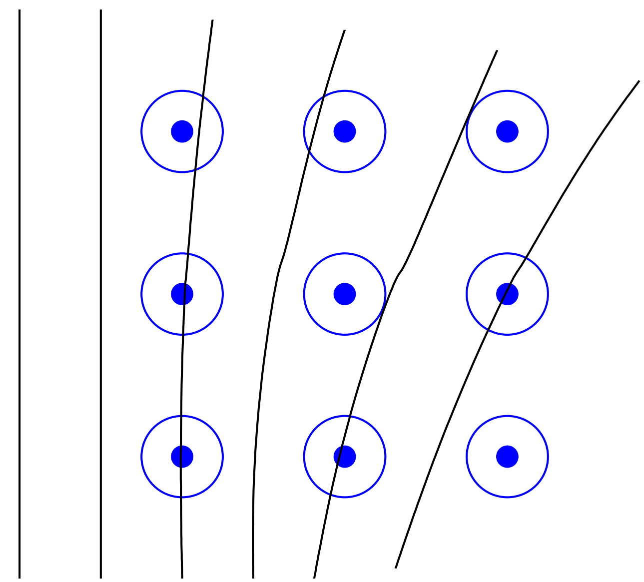
Phase manifests in interference effects JUST LIKE B-case.

E&M 4-Vector Potential *is* field to rotate phases!

$$\exp(i\theta_{\text{path}}) = \exp(i/\hbar)\int_{\text{path}} eA_\mu(x)dx^\mu \qquad A^\mu = (\Phi\ \vec{A})$$

Phase changes describe *all* physics caused by the field!

When wave moves through region *with* B field, phases distort wave-fronts and therefore direction of propagation



Direction change *is* Lorentz force law!

QCD: Rotations Instead of Phases

Quarks: like electrons but in three colors $[u_r\ u_g\ u_b]$

Eight fields (*gluon* rather than photon)
to control phases *and rotations*.

For rotations, order-of-operation MATTERS!

Color rotation changes current: Current not conserved.

To recover current conservation, gluons *must* interact!

Ampere's Law for Gluons

For gluon type "a" ($a = 1 \ldots 8$), Ampere's law is

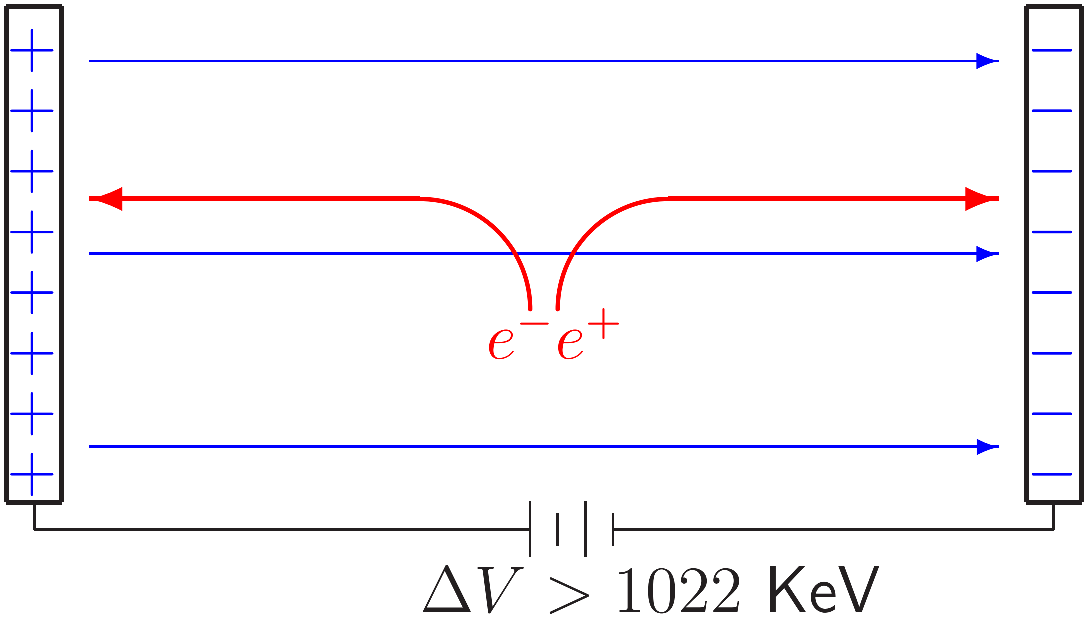
$$\vec{\nabla} \times \vec{B}_a - \partial_t \vec{E}_a = J_a - e f_{abc} (\vec{A}_b \times \vec{B}_c - \Phi_b \vec{E}_c)$$

with f_{abc} some (known, antisymmetric) constants.

Besides "normal" current, there are "extra" currents caused by other gluon fields. Gluons have "color-charge"!

Photons are E&M fields, but they induce no current.
Gluons color-rotate in color-fields, and can make currents!
Profound effects for "macroscopic" fields.

Electric Fields and Vacuum Breakdown



Intense $\vec{E}$ fields can cause pair-production Vacuum Sparking

Efficient if $e\Delta\Phi > mc^2$ in a Compton length $l = \hbar/mc$,

or $ed\Phi/dx = |e\vec{E}| > m^2/(\hbar c)$. $(10^{18}V/m)$

Gluons are massless for same reason photons are.

Uniform color-E field *always* causes colored-vacuum sparking.

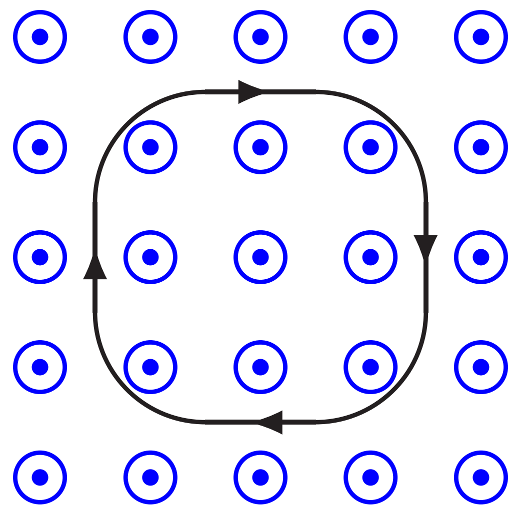
Nonuniform field: maximum potential $\Delta V = \lambda E/\pi$, with λ the field's wavelength.

Generated "charges" must have $\lambda_{\rm particle} < \lambda_{\vec{E}-\rm field}$ to "fit".

Vacuum "sparks" as soon as $E > 2\pi/(e\lambda^2)$.

But E&M would do this if there were massless charges.

Colored Magnetic Fields



In uniform B field, charges go in circles (Lamor orbits)

B-field doesn't change energy – but changes allowed states.

Wave function must match up around orbit $\Rightarrow$
transverse momentum quantized, $p_\perp^2 = (1 + 2n)eB$

Scalar (spinless) charges: energies are

$$E^2 = m^2 + (p_\perp^2 + p_z^2) = m^2 + p_z^2 + eB\,(2n+1)$$

Spin-$\frac{1}{2}$ charges: must add spin-magnetic energy

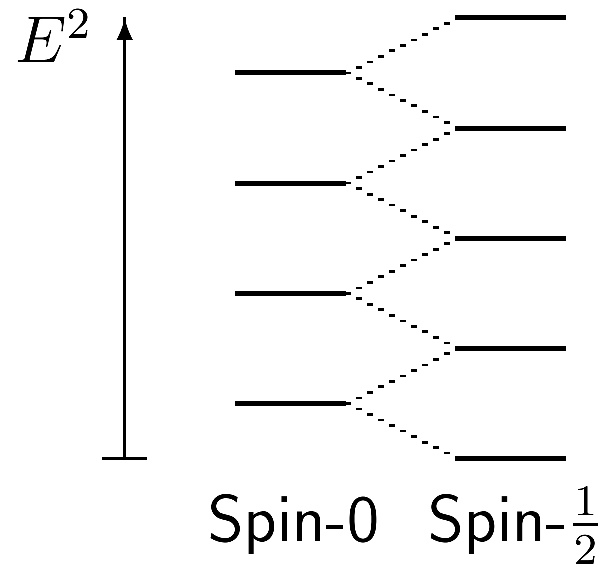
$$E^2 = m^2 + (p_\perp^2 + p_z^2) + 2e\vec{s}\cdot\vec{B} = m^2 + p_z^2 + (2n+1)\,eB \pm \frac{1}{2}(2eB)$$

Landau levels split.

For $p_z = 0$,

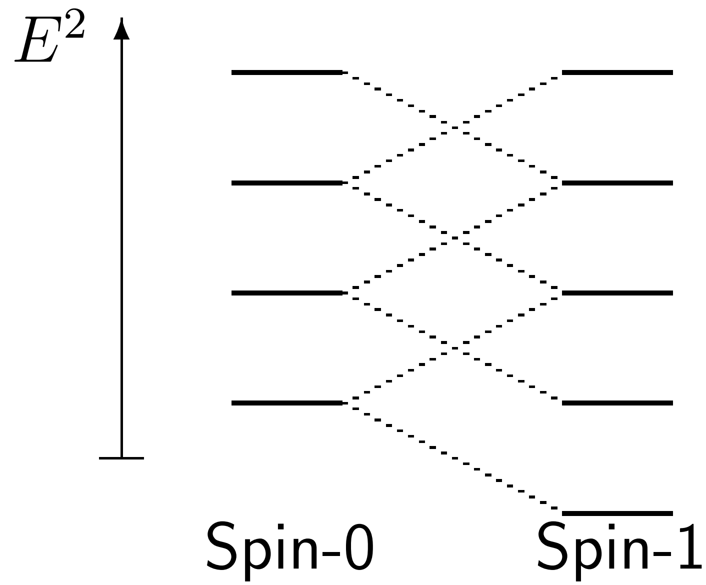
lowest level has

$E_{\rm kin} = 0$



Now consider spin-1 ($m^2 = 0!$)

$$E^2 = (p_\perp^2 + p_z^2) + 2e\vec{s}\cdot\vec{B} = p_z^2 + (2n+1)\,eB + (-1,0,1)2eB$$



Time-evolution: e^{-iEt}. If $E^2 < 0$, $E = \pm i\gamma$, evolution: $e^{\pm\gamma t}$

Uniform Color-$\vec{B}$ fields **Unstable!**

These energy shifts also modify zero-point energies.

Long story .... Summary: spin-0 or spin-$\frac{1}{2}$ means e^2 gets smaller at lower energies.
Spin-1 means e^2 gets *larger* at lower energies. Confinement.

Flip-side: at high energies, coupling e^2 is small in QCD.
Sufficient energy: "weakly" coupled For relativistic stuff, kinetic energy exceeds interaction energy, "nearly free" propagation.

Early in Universe, temperature was high ⇒ weak coupling
Maybe we can achieve energies in the lab where coupling also weak

QCD at Weak Couplings

Physics a lot like kinetic theory of gas/plasma:

- Nearly-free "particle"-like excitations fly around
- Sometimes they scatter
- In scattering, sometimes they radiate.

Some features turn out to be really different:

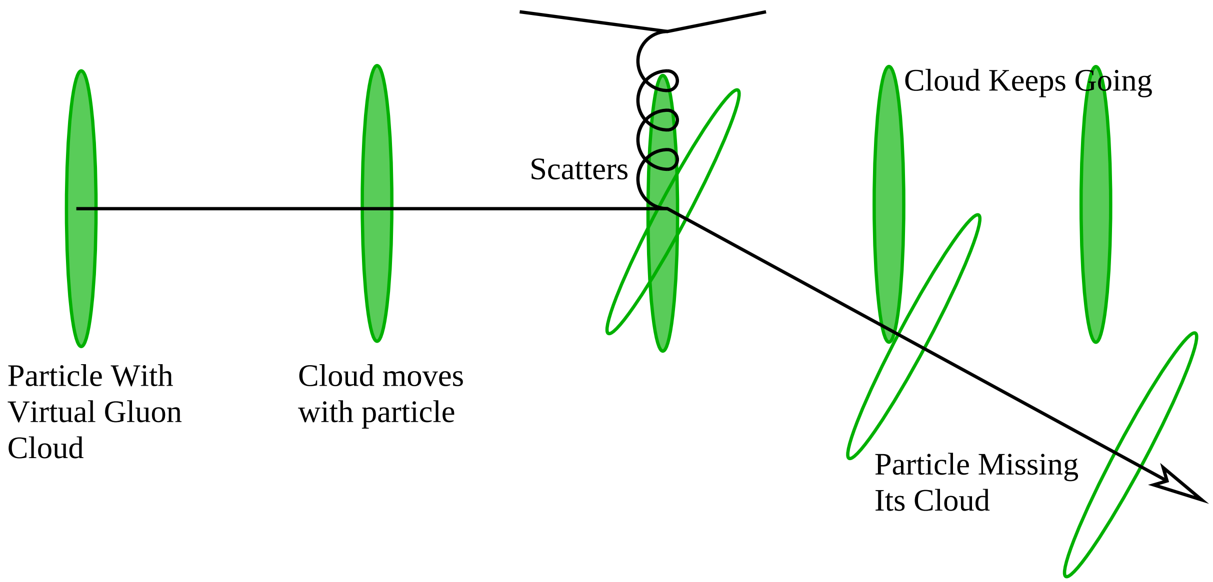
- Radiation can be suppressed by coherence effects – but very differently than in E&M
- Plasma instabilities. E&M has them too, but in QCD they behave differently!

Radiation Induced by Scattering

As in E&M, a moving charge carries E&M fields with it.

Scatter: fields "don't know" no instantaneous propagation of information

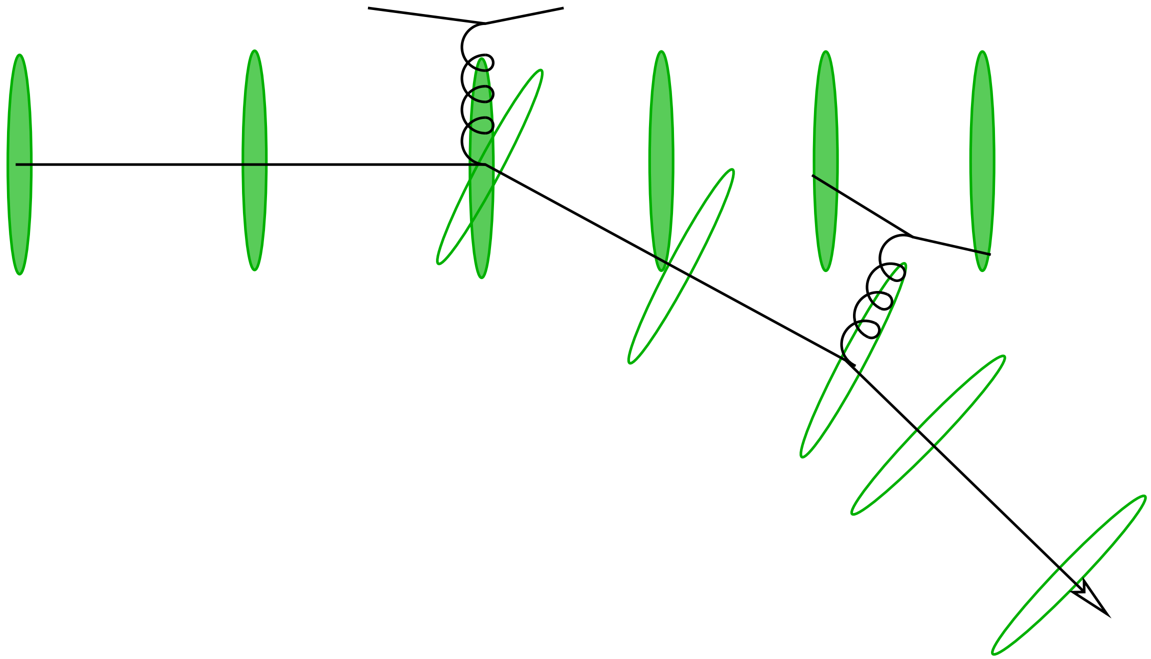
so part of fields continue to fly in straight line!



Also emits along new direction: from "missing" E&M fields

The LPM Effect

Takes time for E&M fields to re-form. Scattering before re-formation does not create new emission



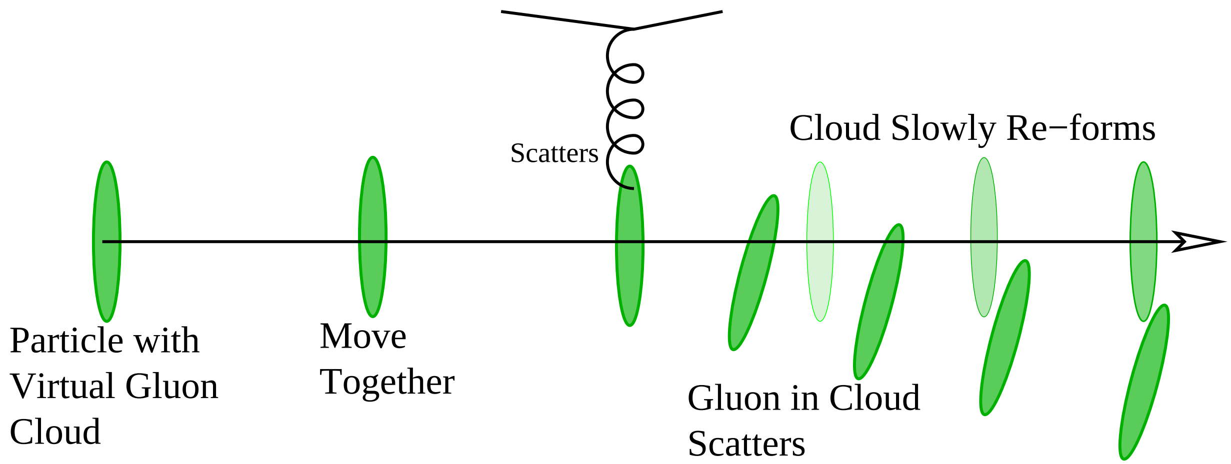
t for E&M to re-form $= t$ for rad., charge to separate.

Non-relativistic: radiation moves faster than charge.

Ultra-Relativistic: only happens because of angle difference.

E&M: most suppression for small-θ, low-energy emission.
Experimentally verified in experiments at SLAC

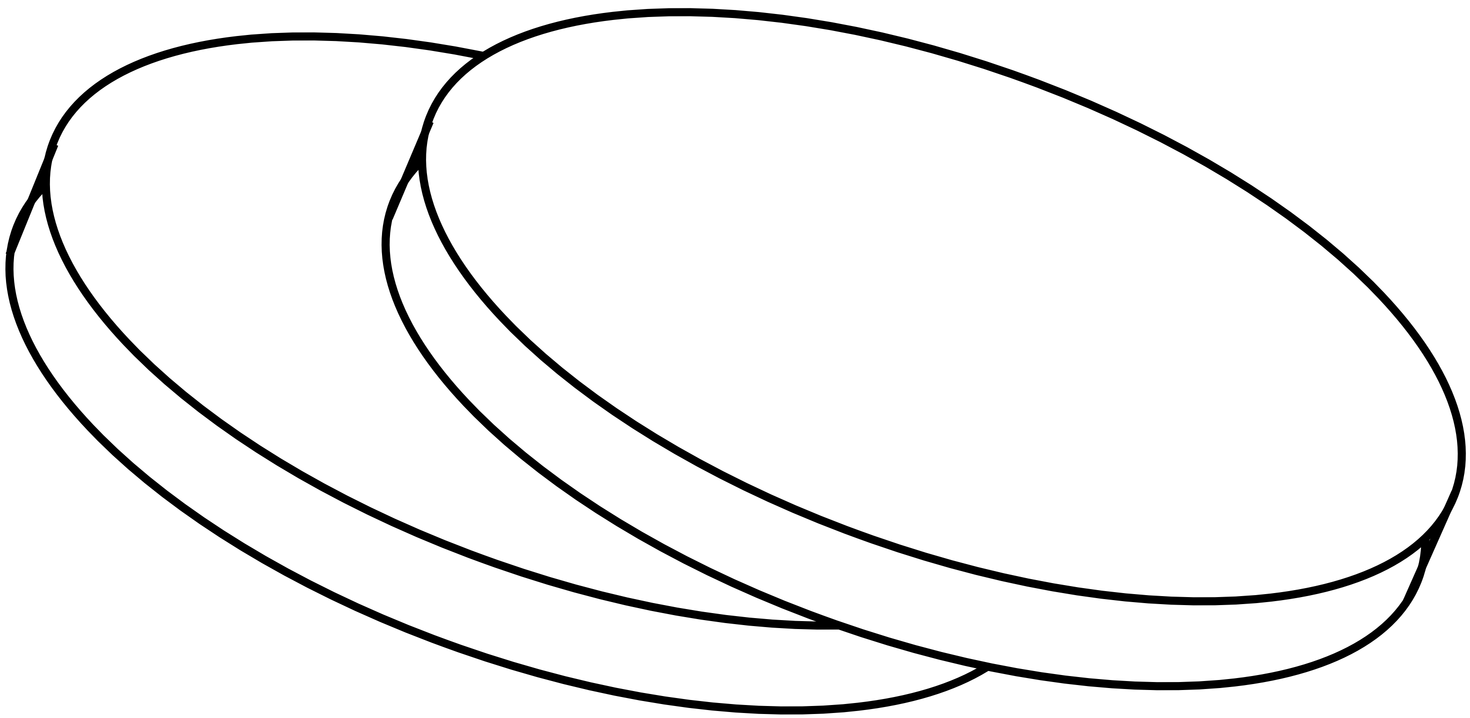
QCD: The charge (quark) can scatter – like E&M.
OR the E&M-like field itself can scatter!



Low-k gluons move away at bigger θ. Faster separation
Less suppression. Opposite energy dependence as E&M!

Application: Heavy ion collisions

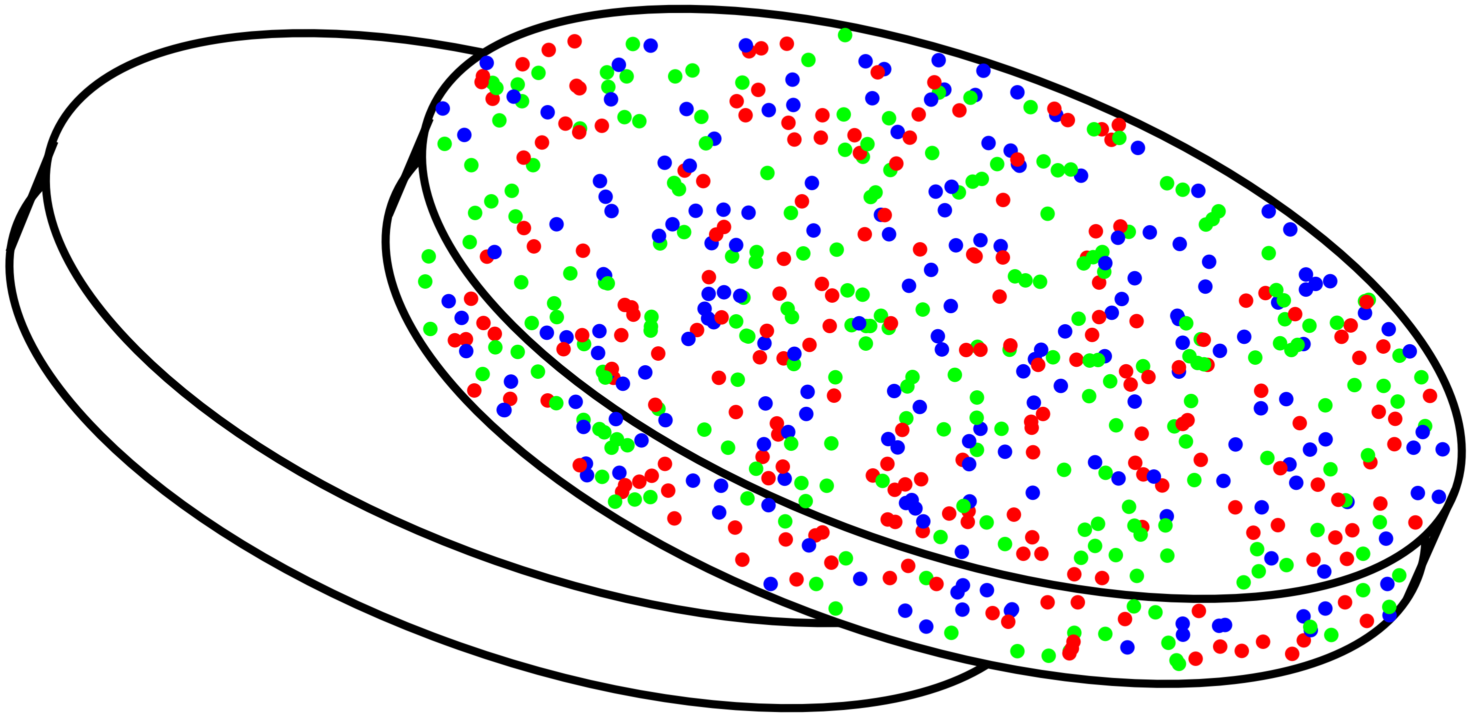
Accelerate two heavy nuclei to high energy, slam together.



Just before: Lorentz contracted nuclei

Application: Heavy ion collisions

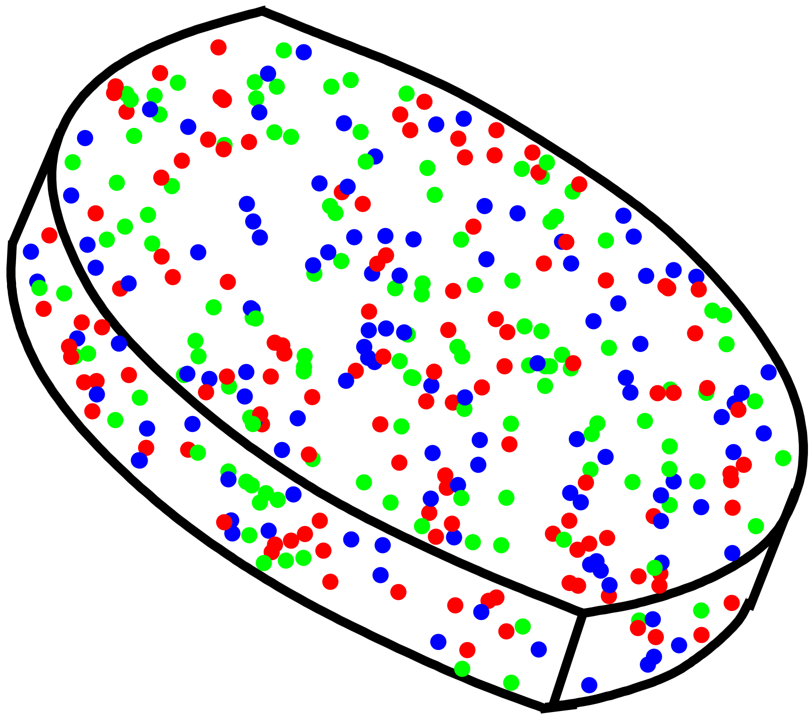
Collide nuclei: $\sim 200\ p, n$, each built of $\sim 50\ q, \bar{q}, g$



It is the $q, \bar{q}, g$ which scatter.

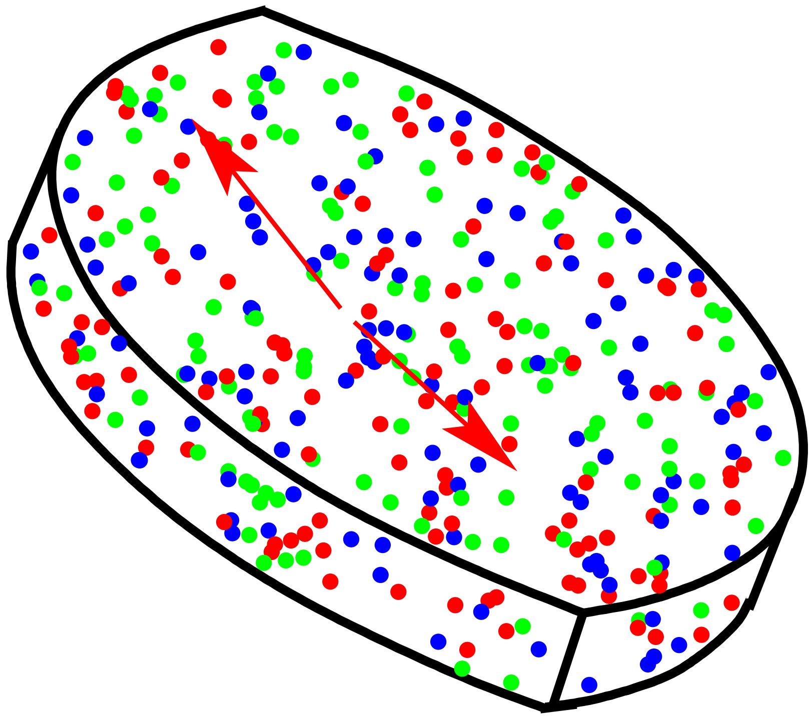
After the scattering:

"Flat almond" shaped region of $q, \bar{q}, g$ which scattered.



Few thousand. random velocities. Quark-Gluon Plasma

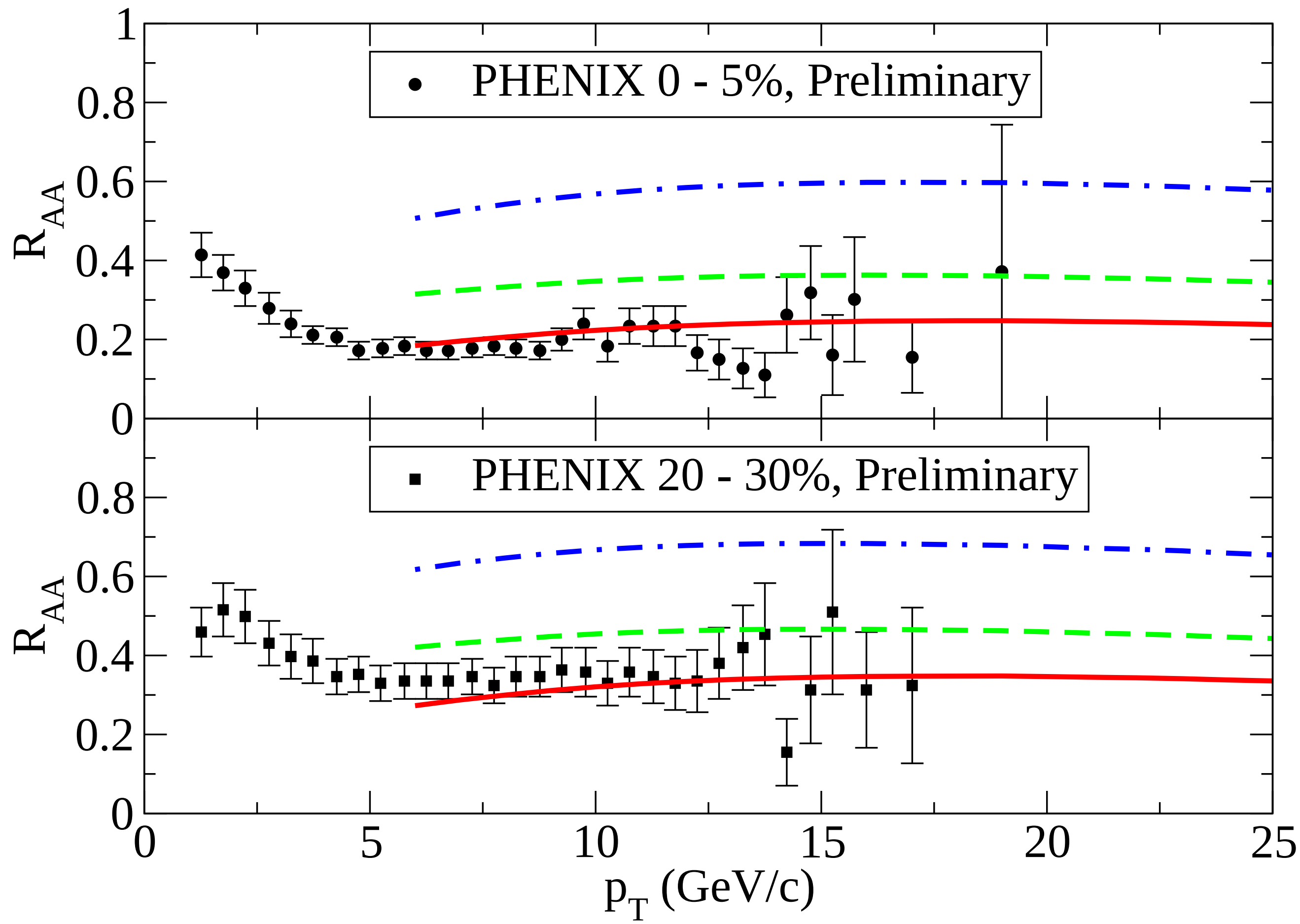
Sometimes high-energy quark/gluon "born" into QGP



Escape from plasma gives info about plasma (*tomography*)

if we understand how plasma makes it radiate!

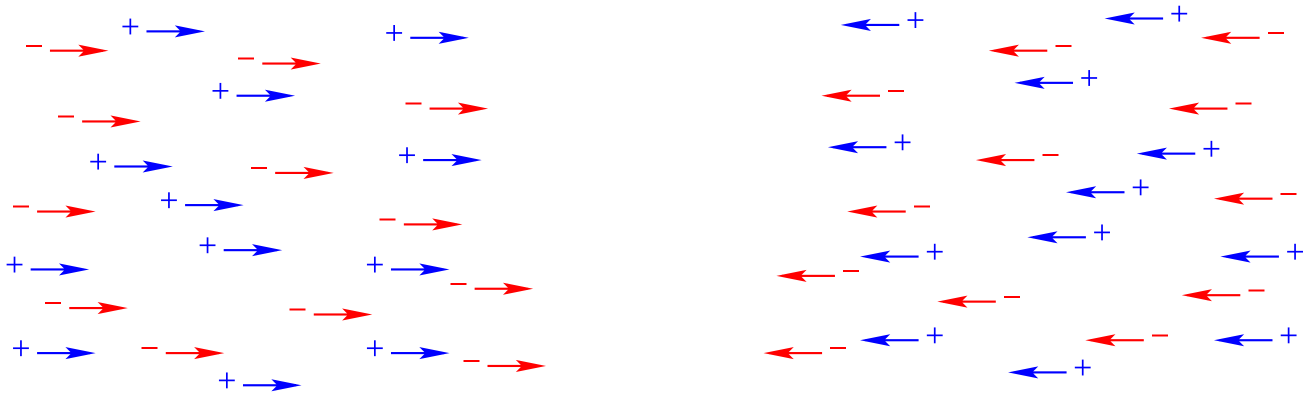
Work with McGill group on jet energy loss



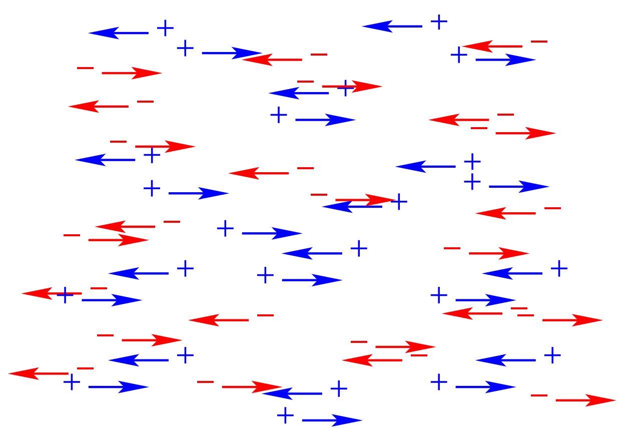
Inclusion gives a good description of the energy dependence of energy loss for these high-energy probes.

Plasma instabilities: E&M Vs. QCD

Suppose two streams of plasma collide:



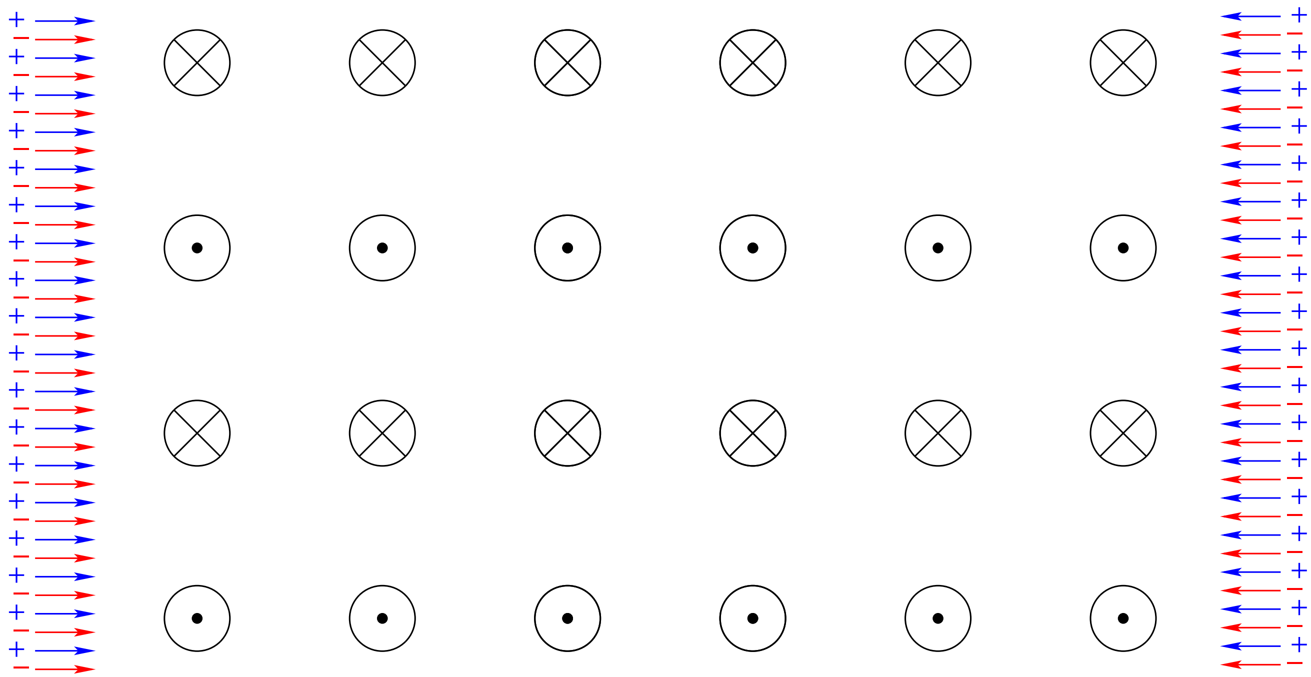
becomes



what happens?

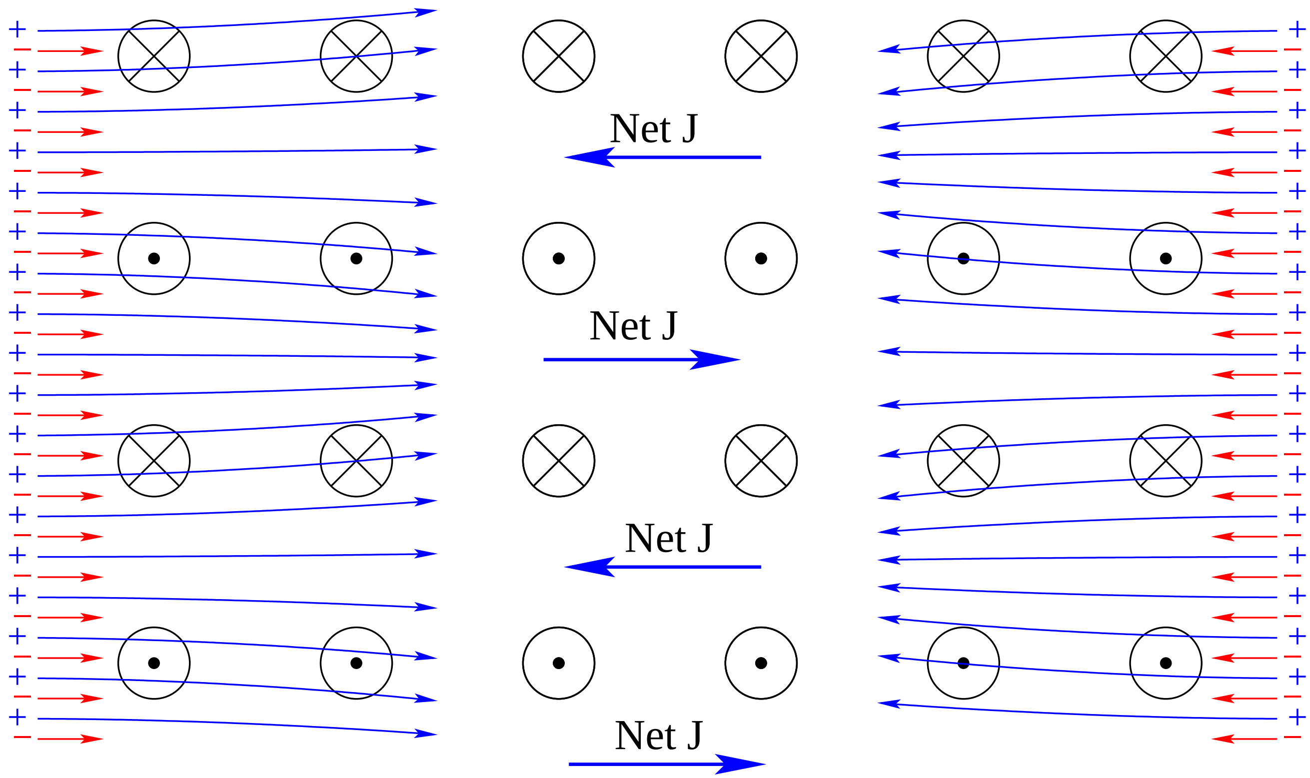
Magnetic field growth!

Consider the effects of a seed magnetic field $\hat{B} \cdot \hat{p} = 0$ and $\hat{k} \cdot \hat{p} = 0$



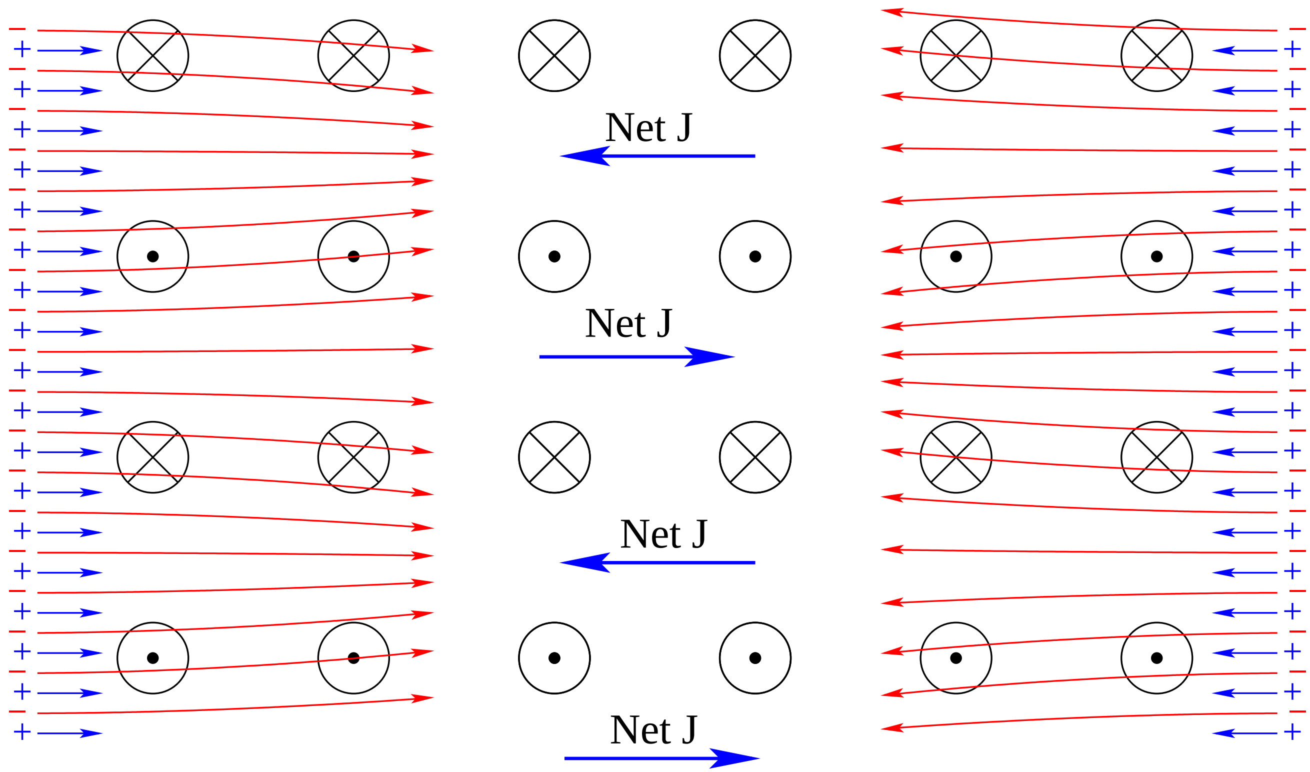
How do the particles deflect?

Positive charges:



No net ρ. Net current is induced as indicated.

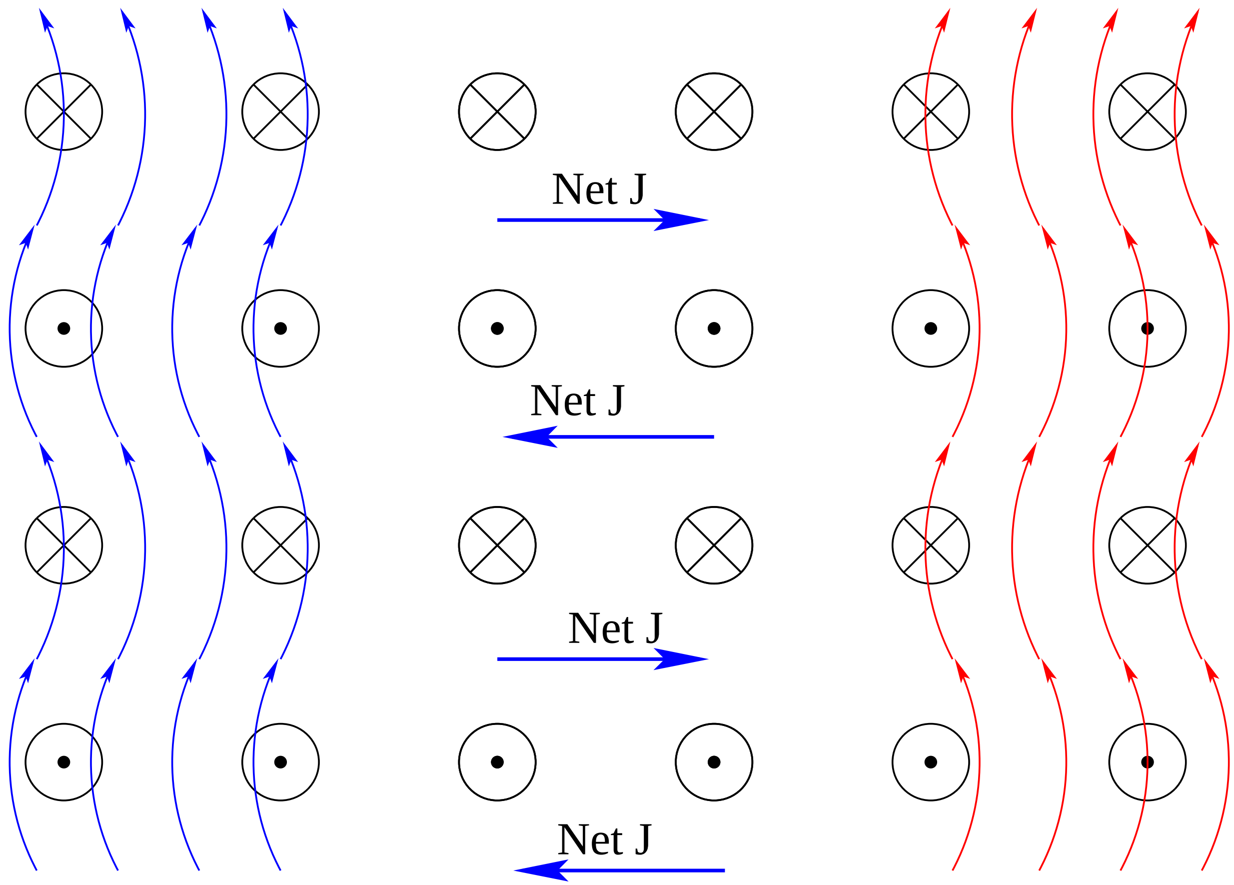
Negative charges:



Induced B *adds* to seed B. Exponential Weibel instability

Linearized analysis: B grows until bending angles become large.

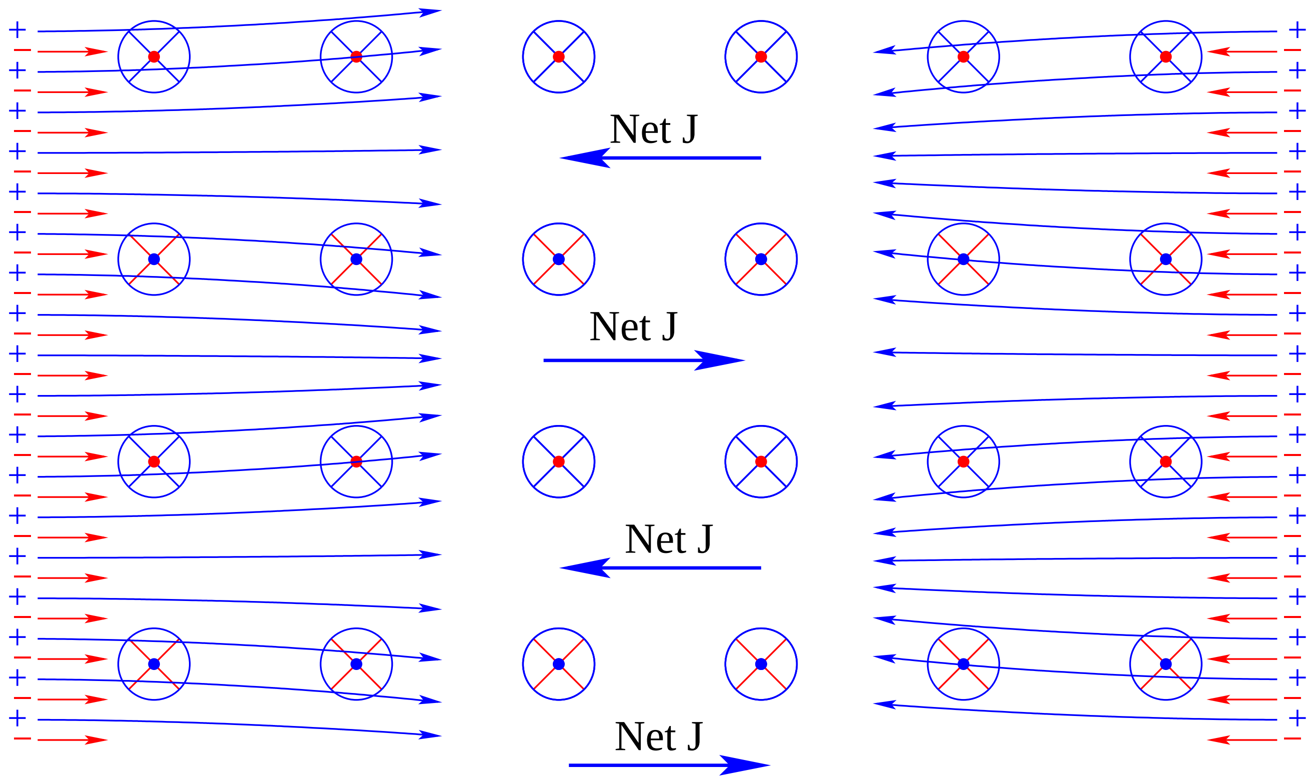
Don't panic. Isotropic system: B stable:



Particles in other directions stabilize B field.

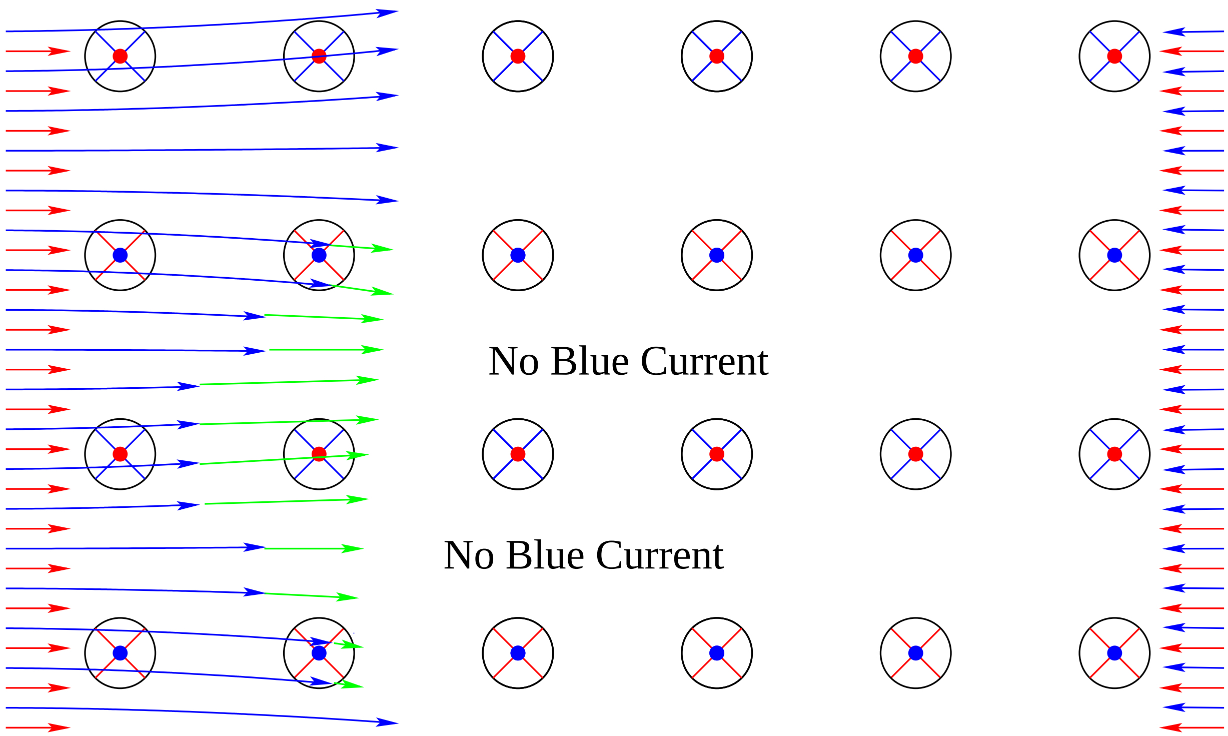
Thermodynamic argument: isotropic: B cannot grow. Aniso: B can.

QCD: take charge colors literally, make B Blue-Antired:



QCD B fields also grow exponentially *if small*.

QCD: eight B-type fields. All are unstable, all grow. Consider blue-antired. When blue-antigreen gets big, my blue charges turn to something else:



Currents no longer “feed” B, cutting off growth.

Particle-and-field simulations confirm this picture.

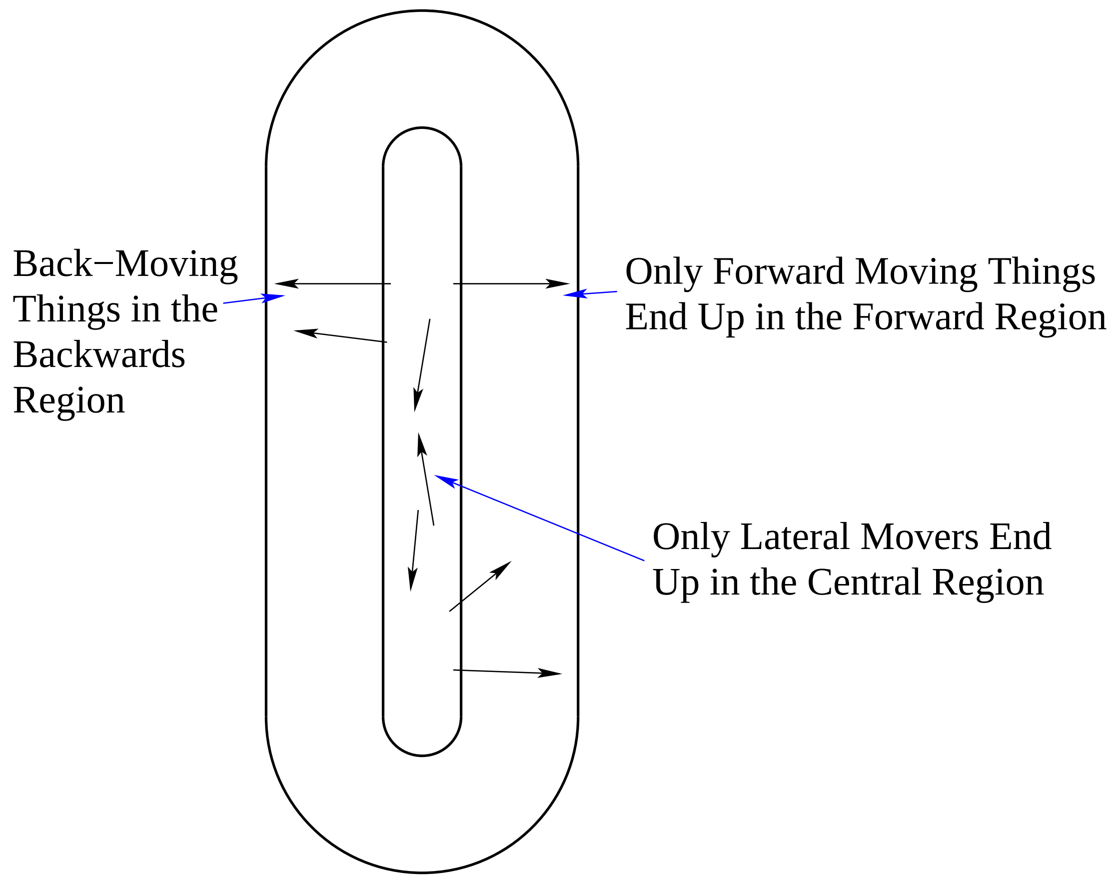
Work with Arnold and Yaffe

E&M: anisotropic plasmas have B grow until bending angles get large. Then physics of B-re-organization.

QCD: anisotropic plasmas have B grow, to (smaller) size where color-randomization efficient. Then B size quasi-stationary. B dominate physics by repeated small-angle scattering.

Application: early dynamics

Initially thin "pancake" expands sideways

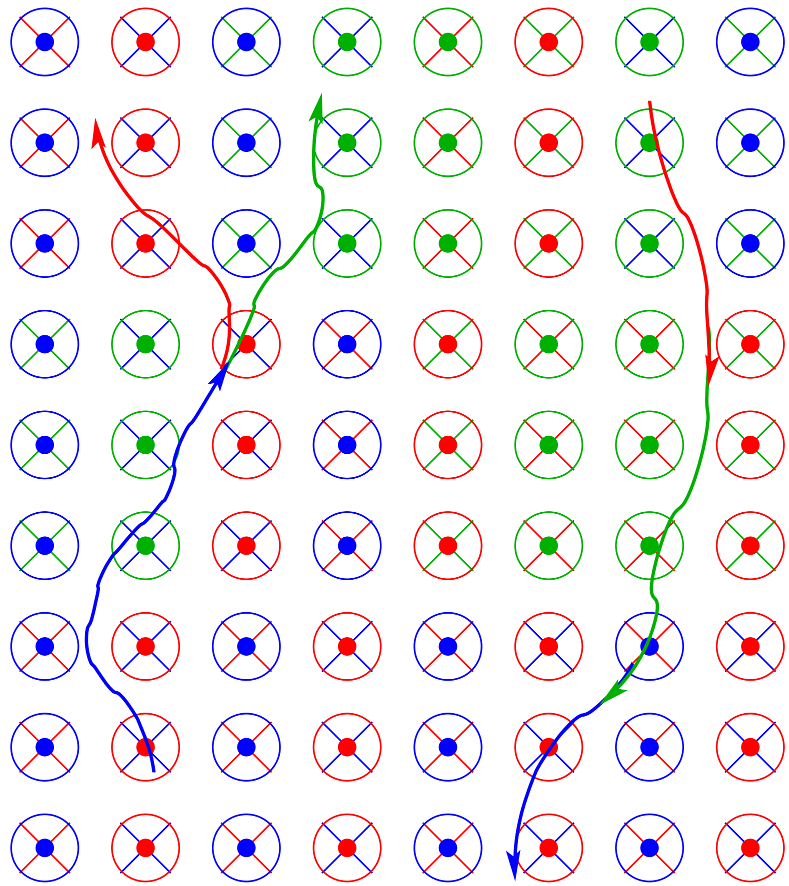


Leads to highly *anisotropic* plasma

Plasma instabilities should be everywhere!

Quark-Gluon Plasma whould be patchwork of B fields

High-momentum "particles" move through B-fields, bending and occasionally radiating



These B fields should dominate dynamics.

Physics fairly complicated:

- B fields cause Angle change
- B fields cause (Bremsstrahlung) radiation
- Radiated fields *also* anisotropic.
  They cause their own plasma instabilities

Recently (arXiv:1107.5050, arXiv:1108.4684)
we presented complete *parametric* treatment Kurkela&Moore

Current goal: quantitative estimates.

Conclusions

Nonabelian plasmas are *a lot like* E&M plasmas, *but*

- Uniform Magnetic fields are Unstable!
- Coupling shrinks with energy, opposite of E&M
- Radiation, Suppression of Bremsstrahlung is different
- Plasma instabilities are different –
  different physics limits their growth

Putting this together into a picture of formation (thermalization) and behavior of Quark-Gluon Plasma is *an interesting challenge.*