Title: Nuclear Theory/Heavy Ions 4

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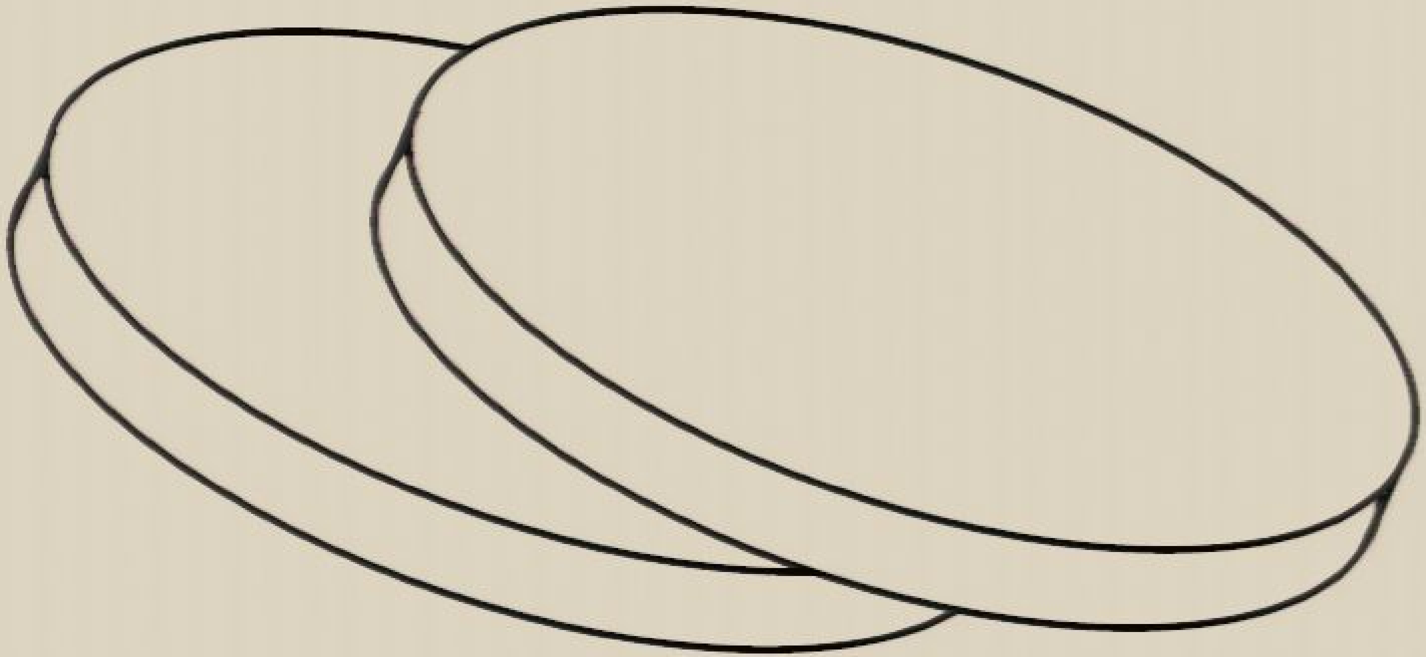
Abstract:

Plasma Instabilities in the QGP

Guy Moore: Arnold, Lenaghan, Yaffe
Mrówczyński, Strickland, Rebhan, Romatschke, Venugopalan, Dumitru, Nara, etc.

1. Heavy ion collisions
2. Physics of Weibel instability
3. Weibel instability in QCD
4. Saturation of the instability
5. Conclusions

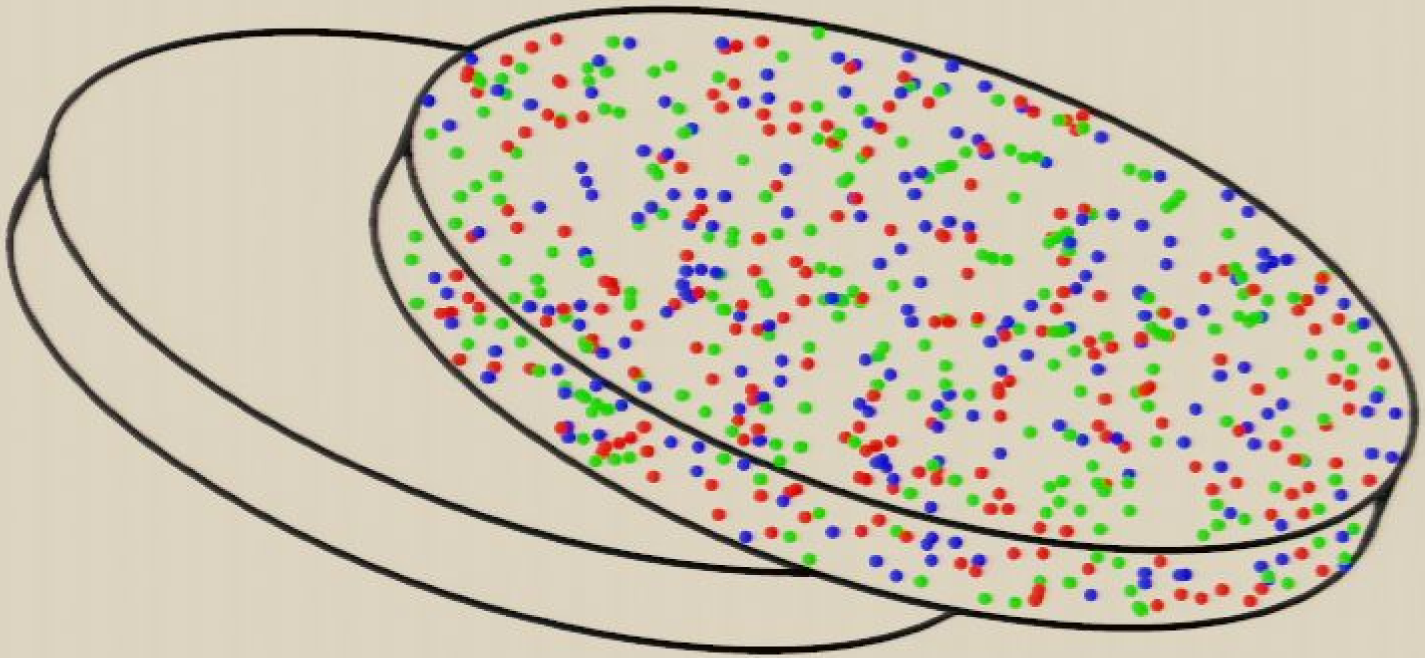
Just before collision



Lorentz contracted nuclei, striking with nonzero impact parameter

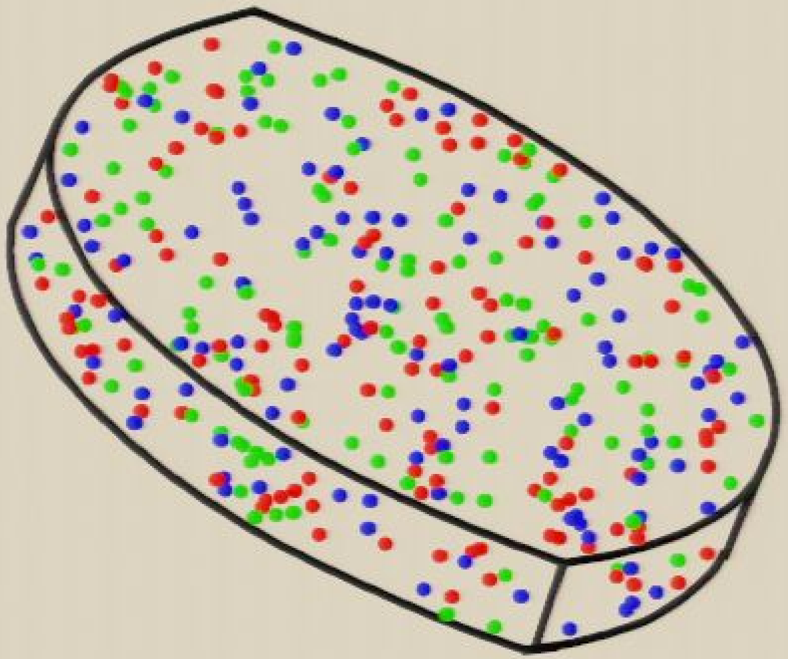
Heavy ion collisions

Each nucleus is ~ 200 p, n, each built of ~ 50 $q, \bar{q}, g$



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

Region where Collision Occurs:



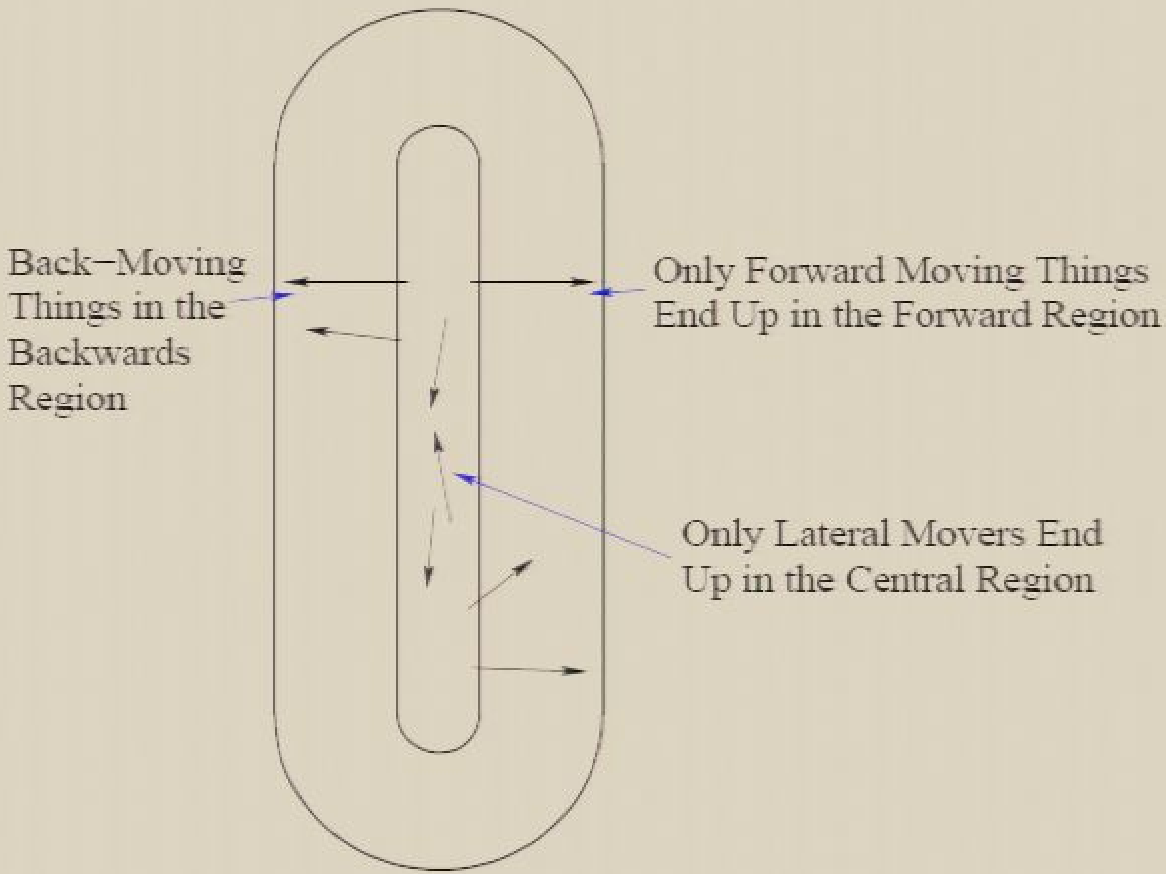
Irregular "flat almond" shaped overlap region:

Longer than it is wide, Wider than it is thick

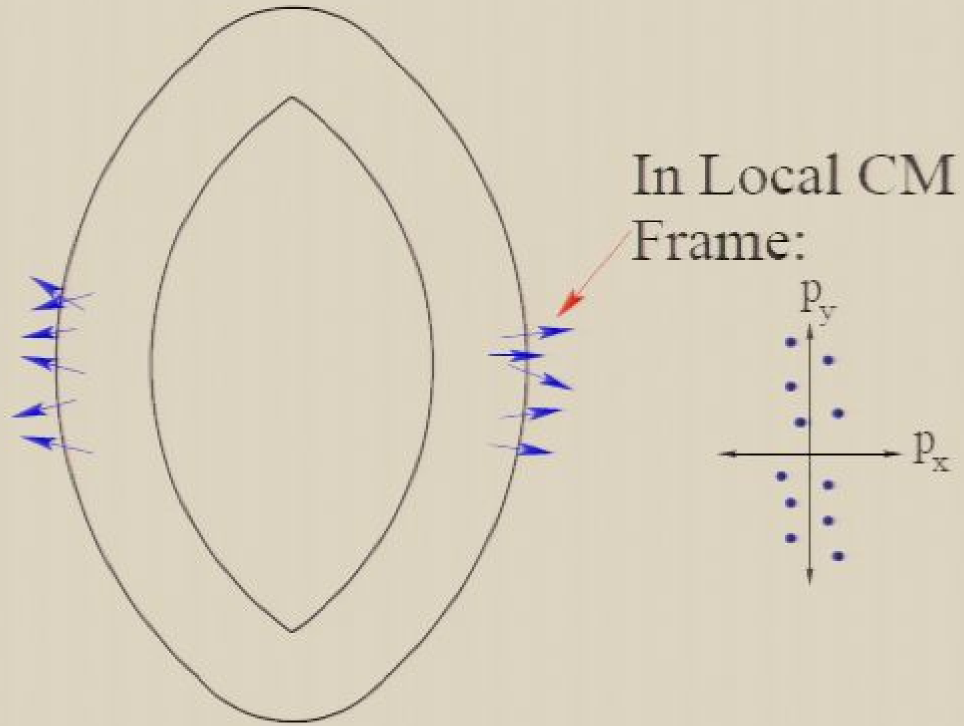
~ 2000 partons, p distribution azimuthally isotropic

Momentum Selection

Side-on view of the flat almond as it expands



Same is true in transverse plane

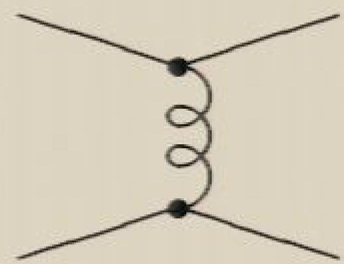


Free expansion: squeezed momentum distribution

Rescattering–Eliptic flow. Observed, nearly maximal!

Rescattering requires interactions.

Ordinary elastic scattering?



Appears to be too inefficient.
Molnar and Gyulassy, Nucl.Phys.A697:495-520,2002

Some strongly coupled physics? Possibly–just pleading ignorance

Misunderstood weak-coupling physics? Possible, read on.

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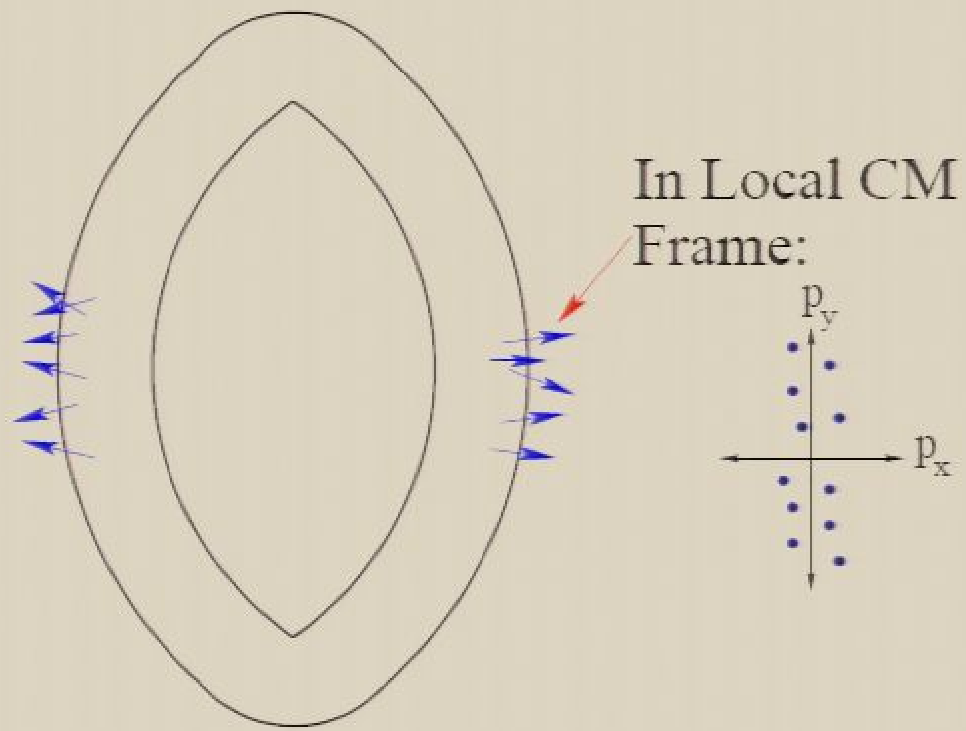

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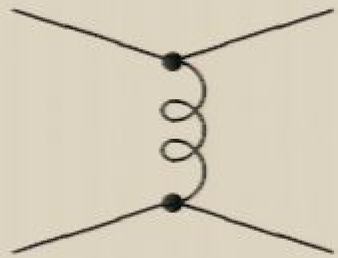

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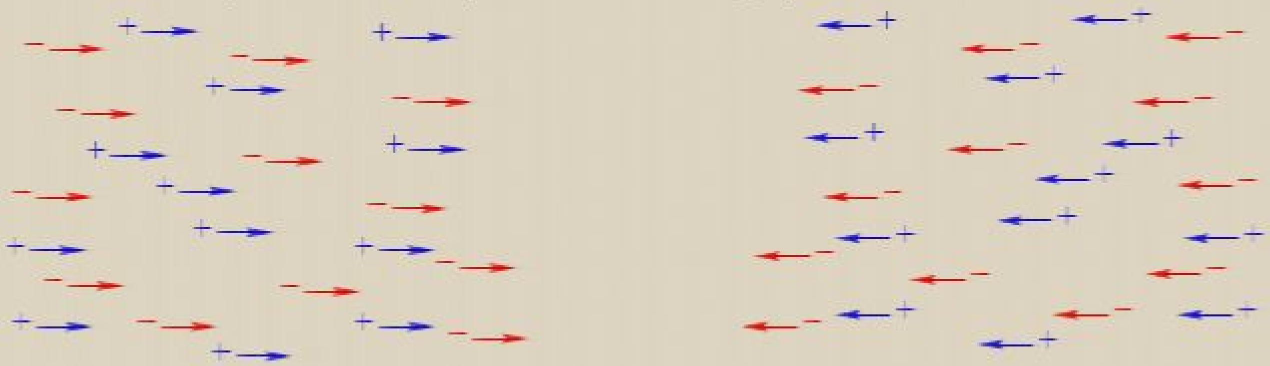
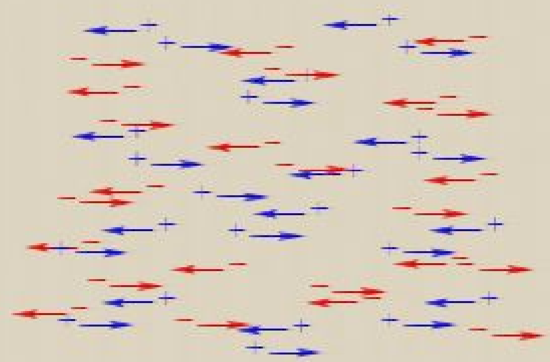
Anisotropic plasmas are unstable!

Simplest example: Interpenetrating plasmas





What happens?

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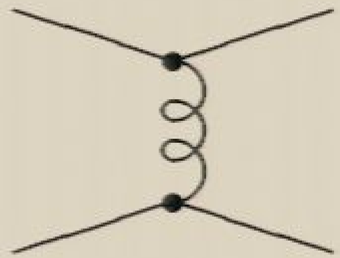

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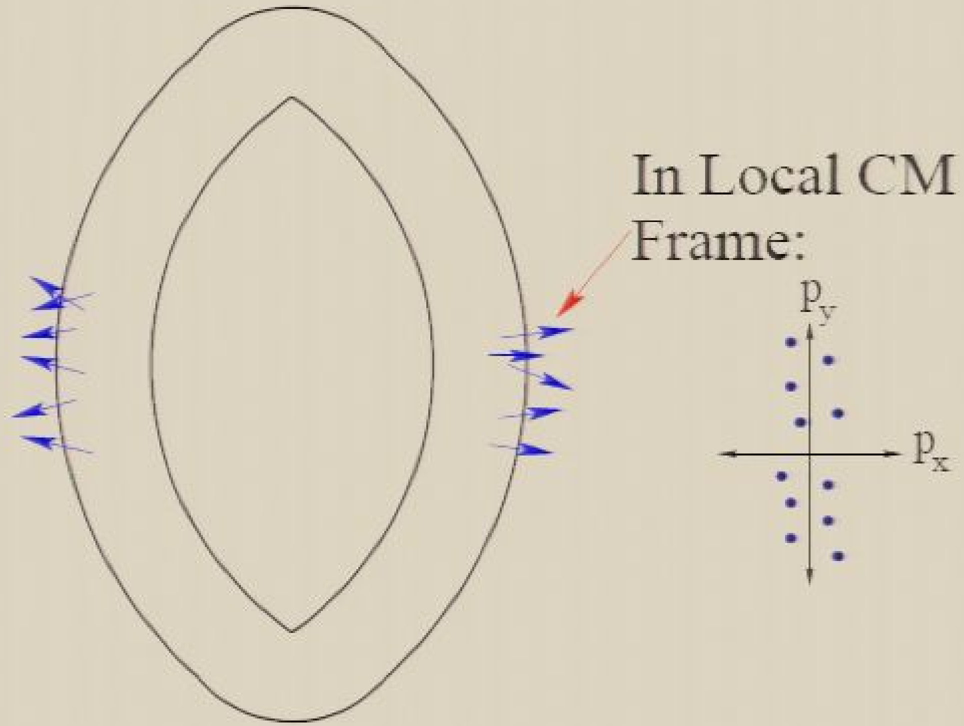

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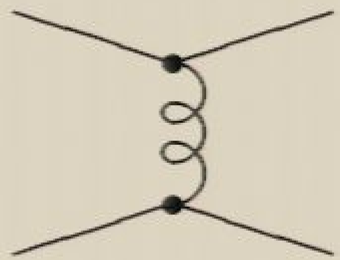

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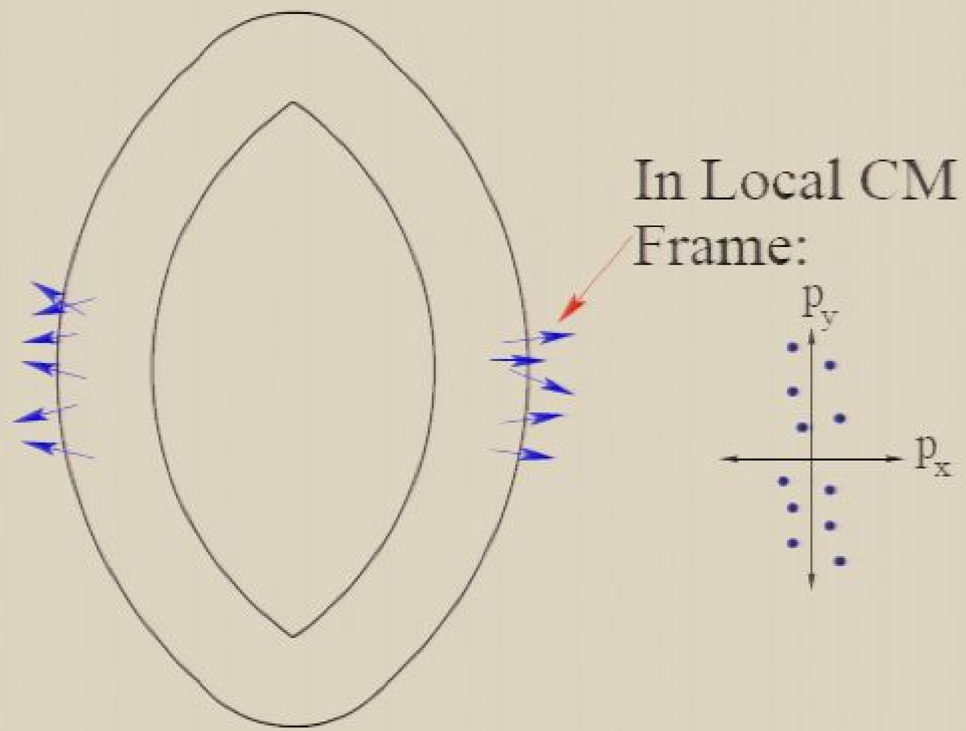

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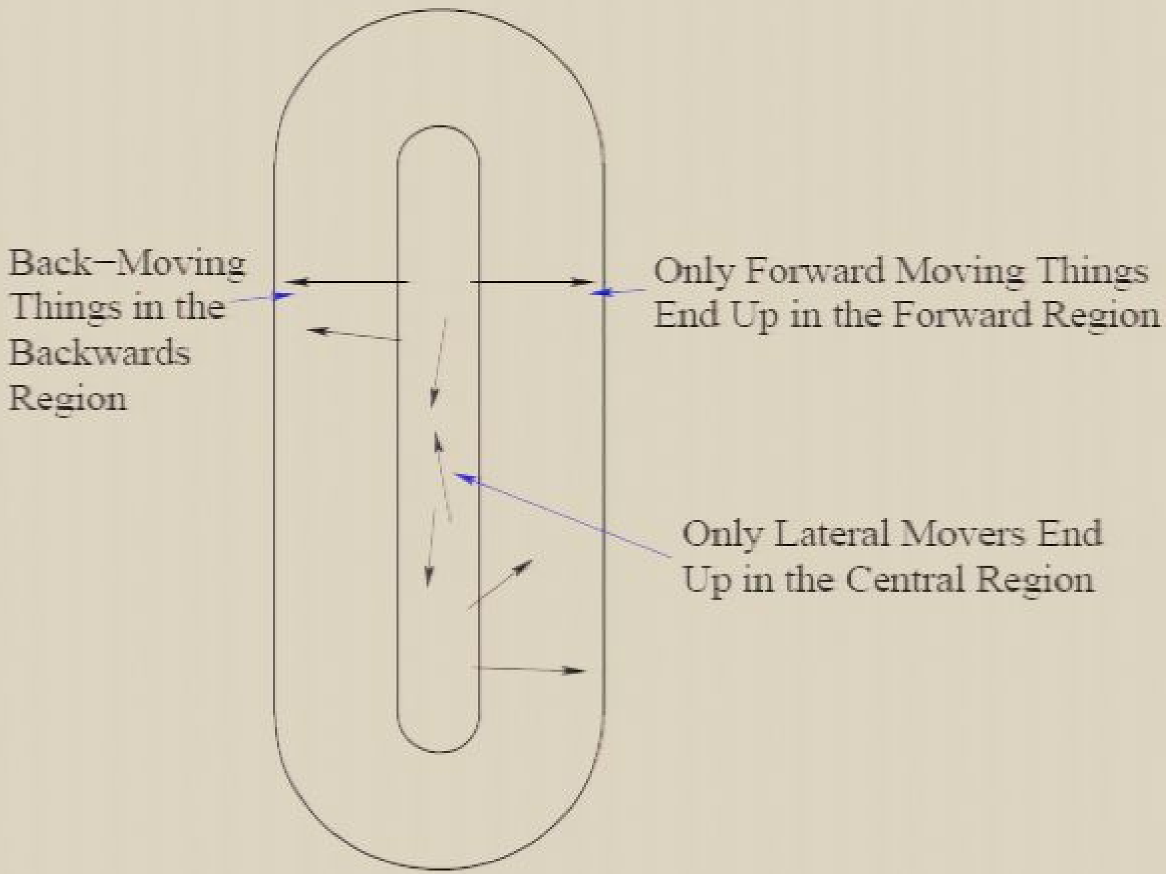

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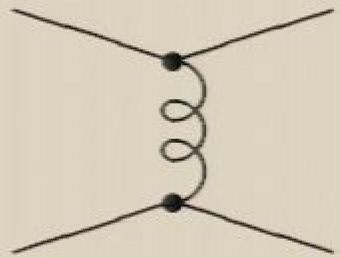

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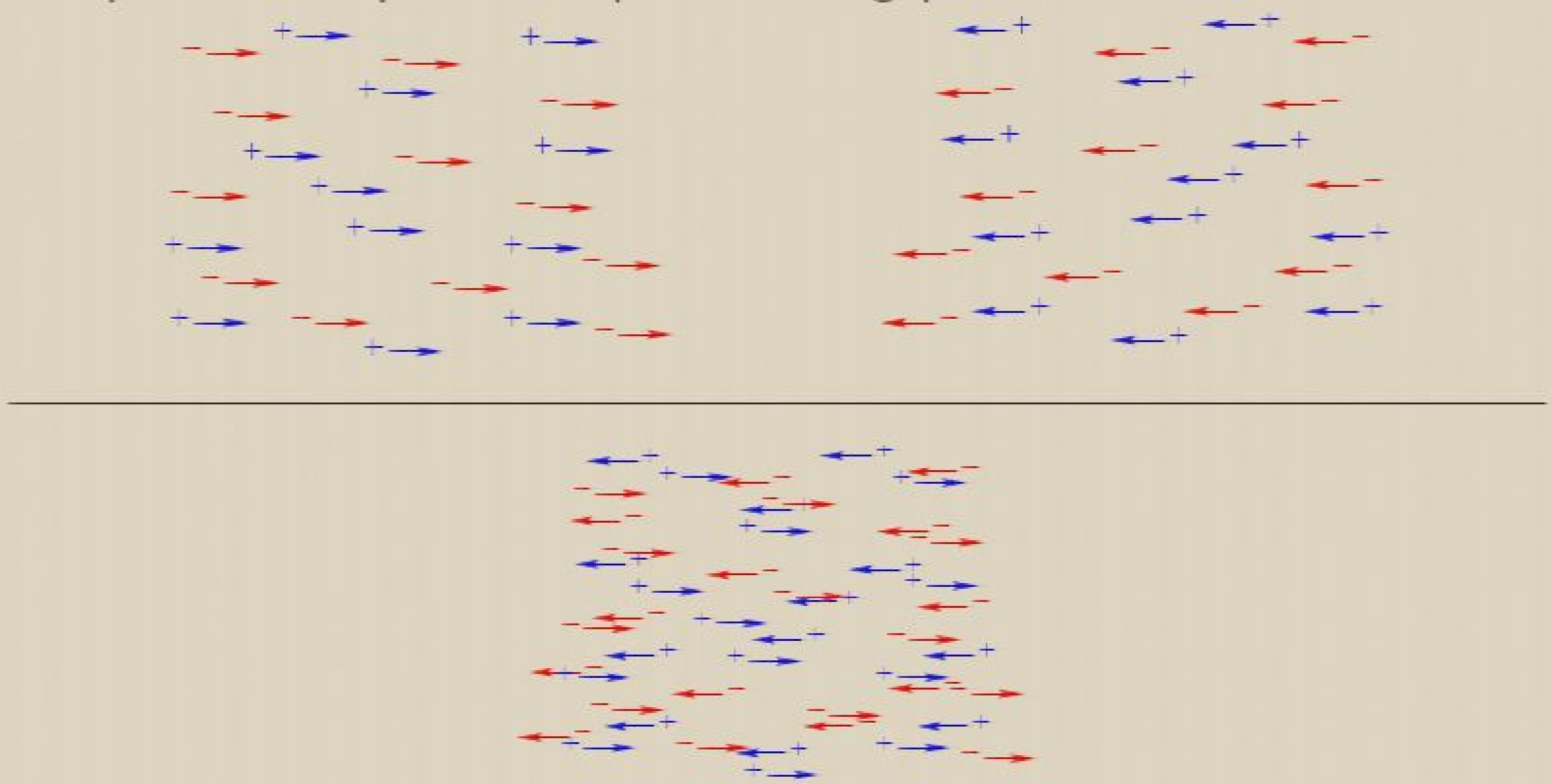
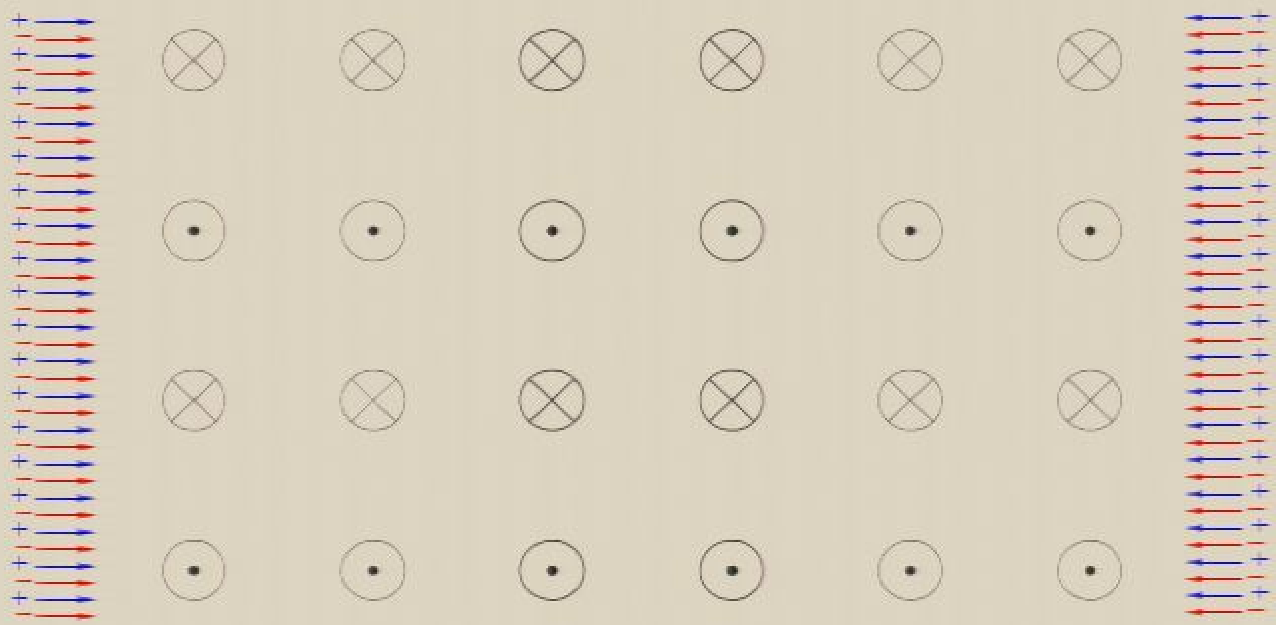


What happens?

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?

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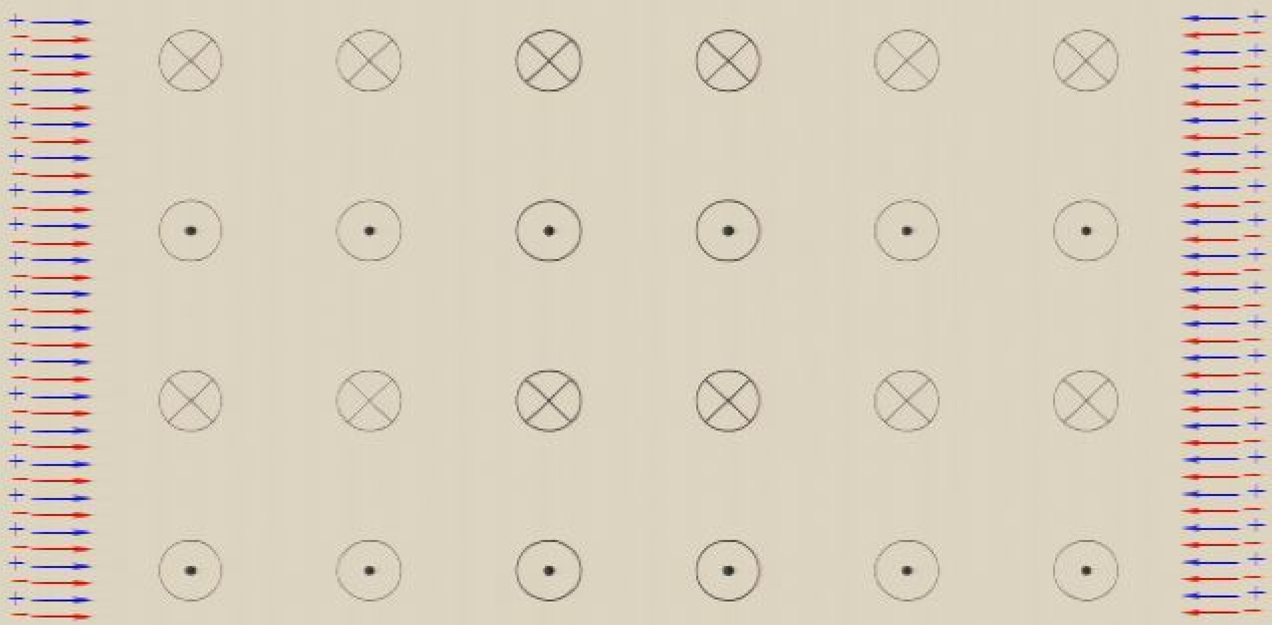
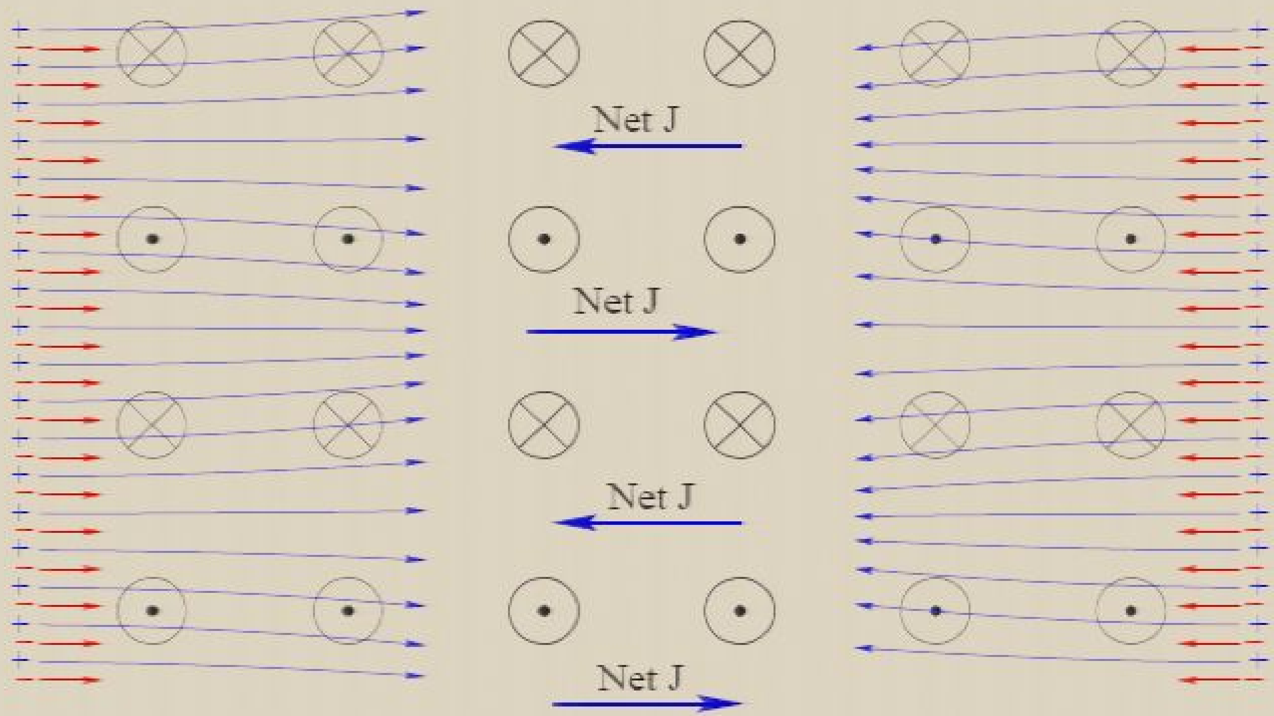


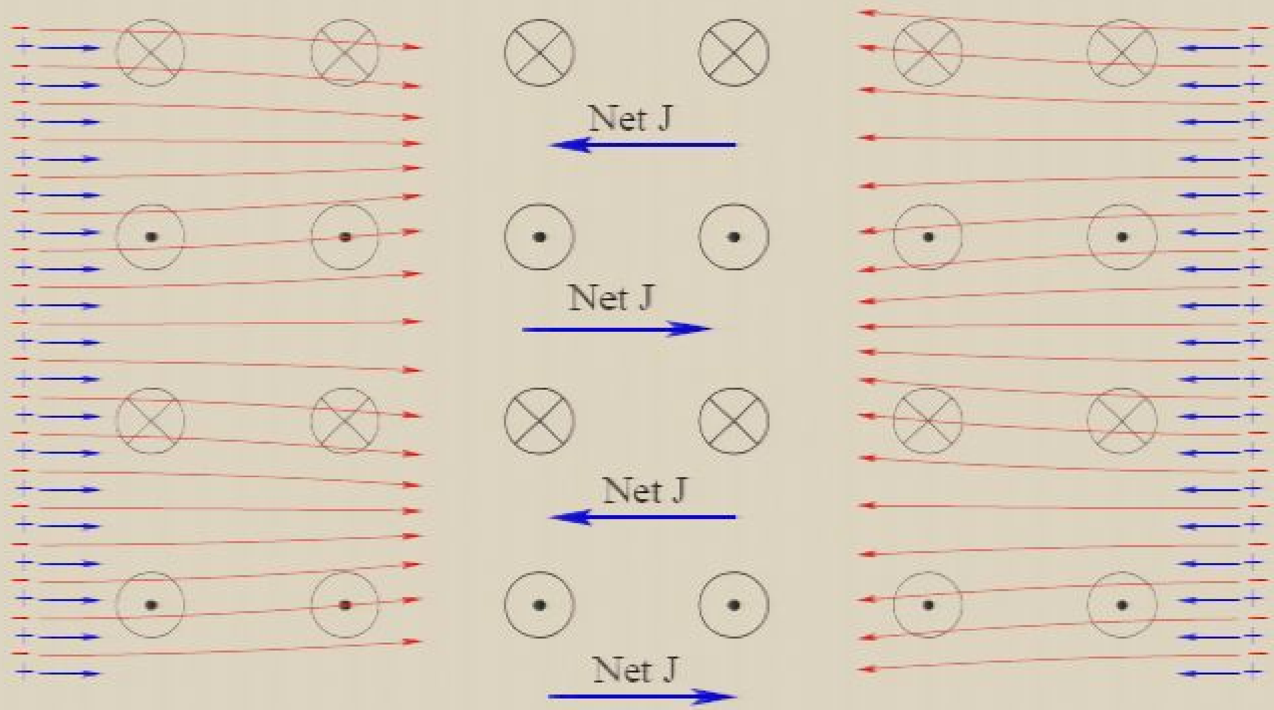
How do the particles deflect?

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.

How fast is Weibel instability?

Weibel instability is a kind of "plasma screening."

Gauge fields of wavenumber k bend particles, $F = gv \times B$

$$\delta p \sim g\frac{B}{k} \sim gA$$

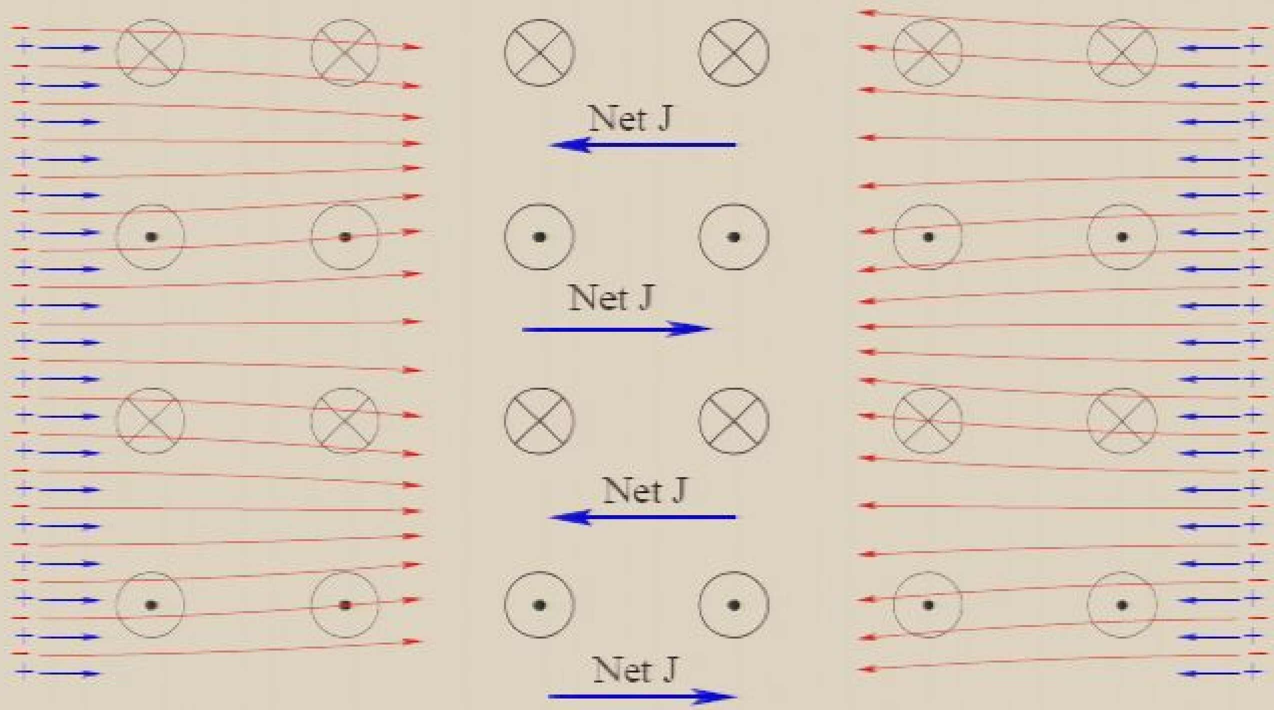
inducing a current $j \sim n\delta p/p$ which is important if

$$\nabla \times B \sim gj \quad \Rightarrow \quad k^2 A \sim gj \sim \frac{g^2 n}{p} A \quad \Rightarrow \quad k \sim g\sqrt{\frac{n}{p}} \quad (\text{think } gT)$$

Exponentiation time is $\sim g\sqrt{n/p}$ ("gT")

Fast! Faster than scattering ("$g^4 T$")

Negative charges:



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Fast! Faster than scattering ("$g^4 T$")

Kinetic theory approach

Assume $\alpha_s \ll 1$.

Guarantees imperfect scattering–anisotropy

Also: provides scale separation into "hard" and "soft"

- Hard fields–large momentum. Dominate energy density. Anisotropic. Act near-ballistically. Responsible for instability
- Soft fields–long wavelength. Small energy but large occupancy. Some grow unstably. Classical field approximation is valid.

Permits Vlasov treatment (particles in background field).

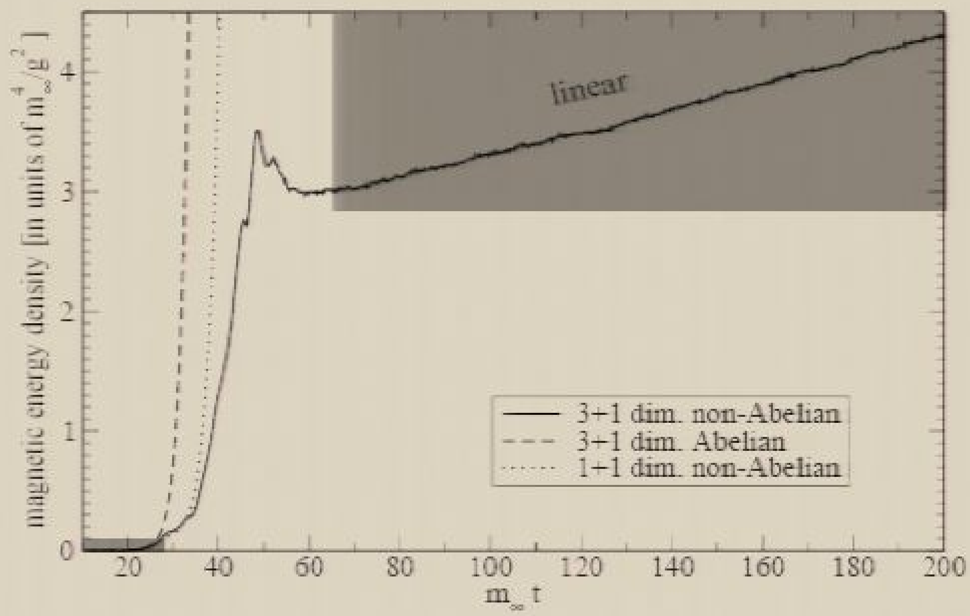
Define $W^a(x,\vec{v})$: mean color of particles going in $\vec{v}$ direction at point x.

$$\begin{aligned} D_t W^a(x,\vec{v}) &= -\vec{v}\cdot\vec{D}W^a(x,\vec{v}) + m_\infty^2 \text{ Source} \\ \text{Source} &= 2\Omega(\mathbf{v})\vec{v}\cdot\vec{E} - \vec{E}\cdot\frac{\partial}{\partial\vec{v}}\Omega(\mathbf{v}) - F_{ij}v_i\frac{\partial\Omega(\mathbf{v})}{\partial v_j} \\ D_\mu F^{\nu\mu} &= J^\nu = \int_{\mathbf{v}} v^\nu\, W(\mathbf{v}) \end{aligned}$$

$\Omega(\mathbf{v})$ = angle dependence of anisotropic p distribution of (color neutral) bulk of particles.

Put on lattice: must also discretize $\vec{v}$ space. Spherical harmonics, with $l_{\max}$ cutoff. SU(2) for simplicity.

If gauge fields start with small fluctuations:



first: exponential growth. Fields get nonperturbatively large. Switches to linear growth in energy.

Time scales: exp. time shorter than system age.

all the time spent in the linear growth part.

Concentrate on nonperturbative linear part

Why linear growth?

Because there are several unstable modes, growing at once

- Different colors
- Different k vectors

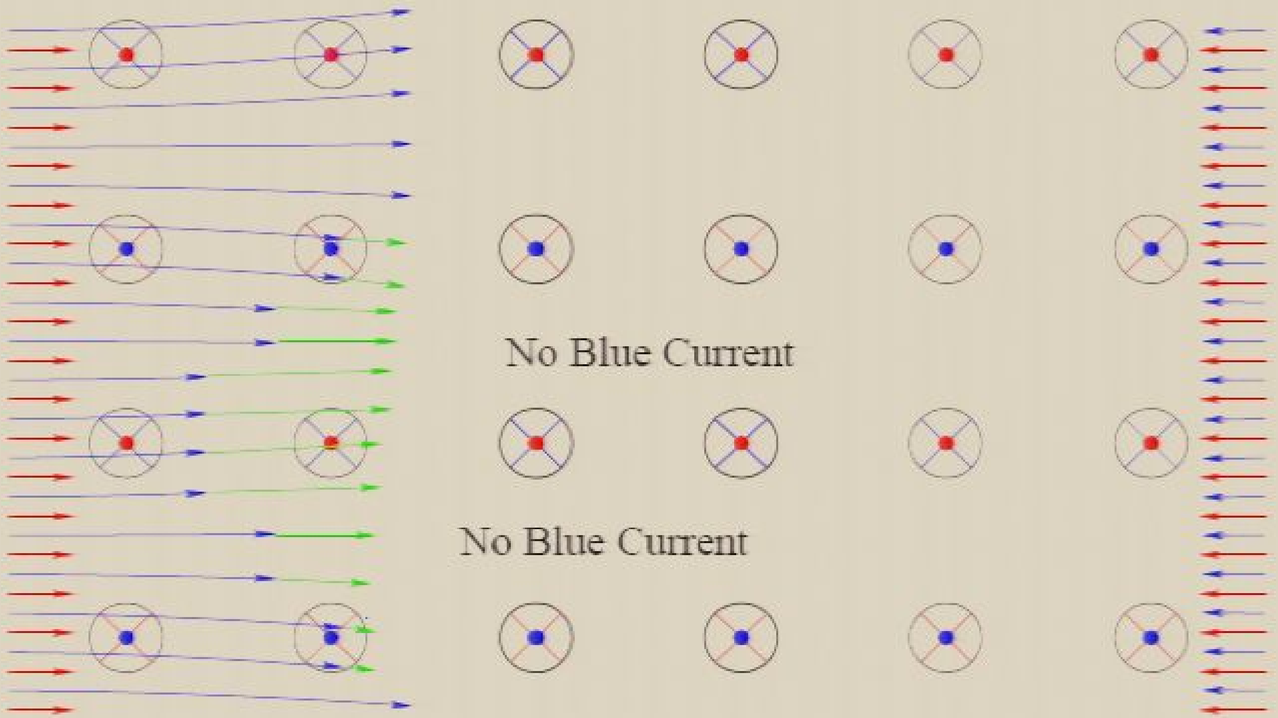
Modes interfere with each others' growth:

- A field color-rotates currents needed for other modes' growth
- Nonabelian interaction: soft k "scatter," moving energy into stable k wave-vectors.

Soft fields *stop* growing. Energy gain is at larger k.

Color rotation

Suppose another field, not shown, causes colors to rotate:



Current does not support B. Growth stops/is inhibited

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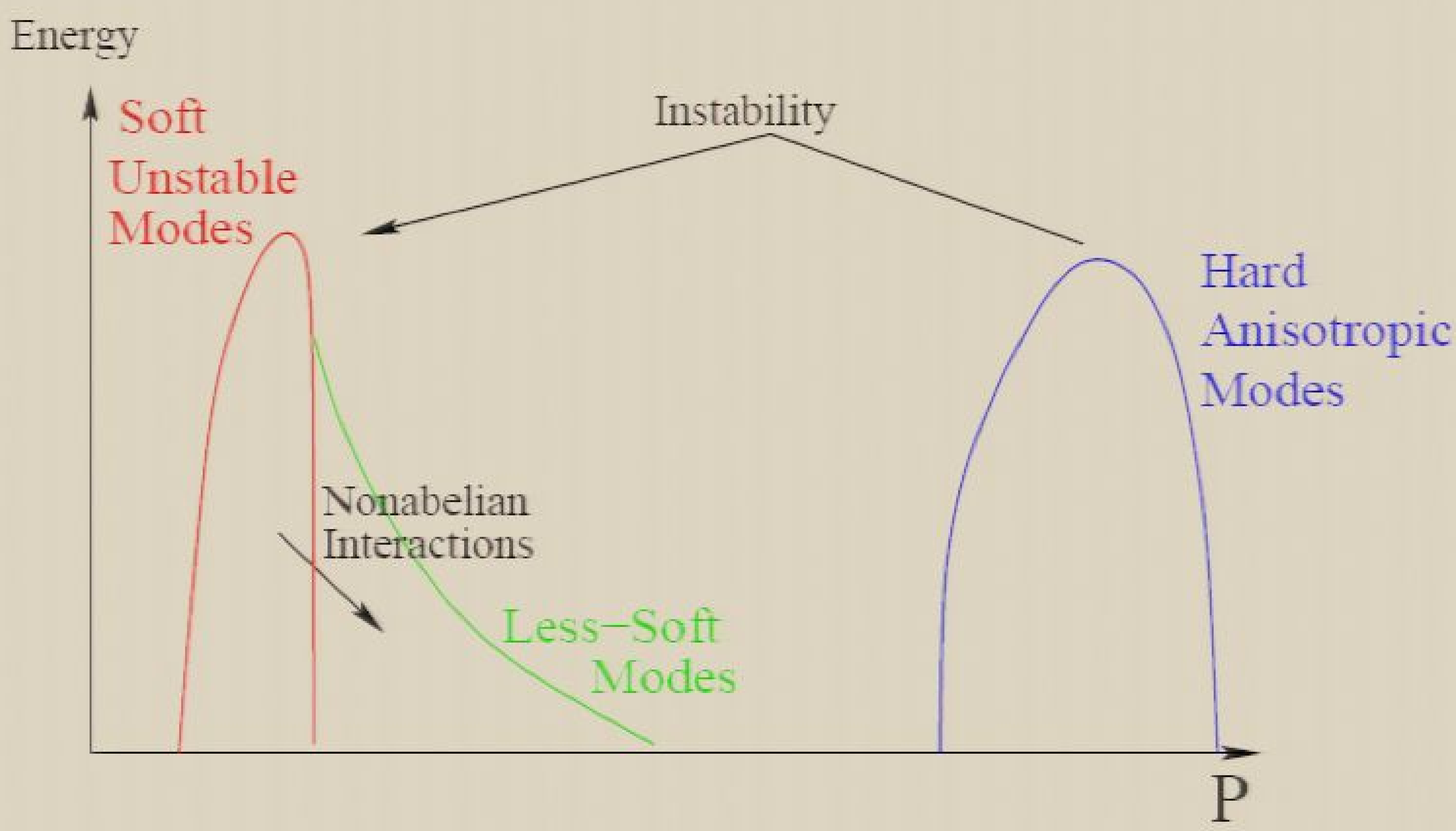
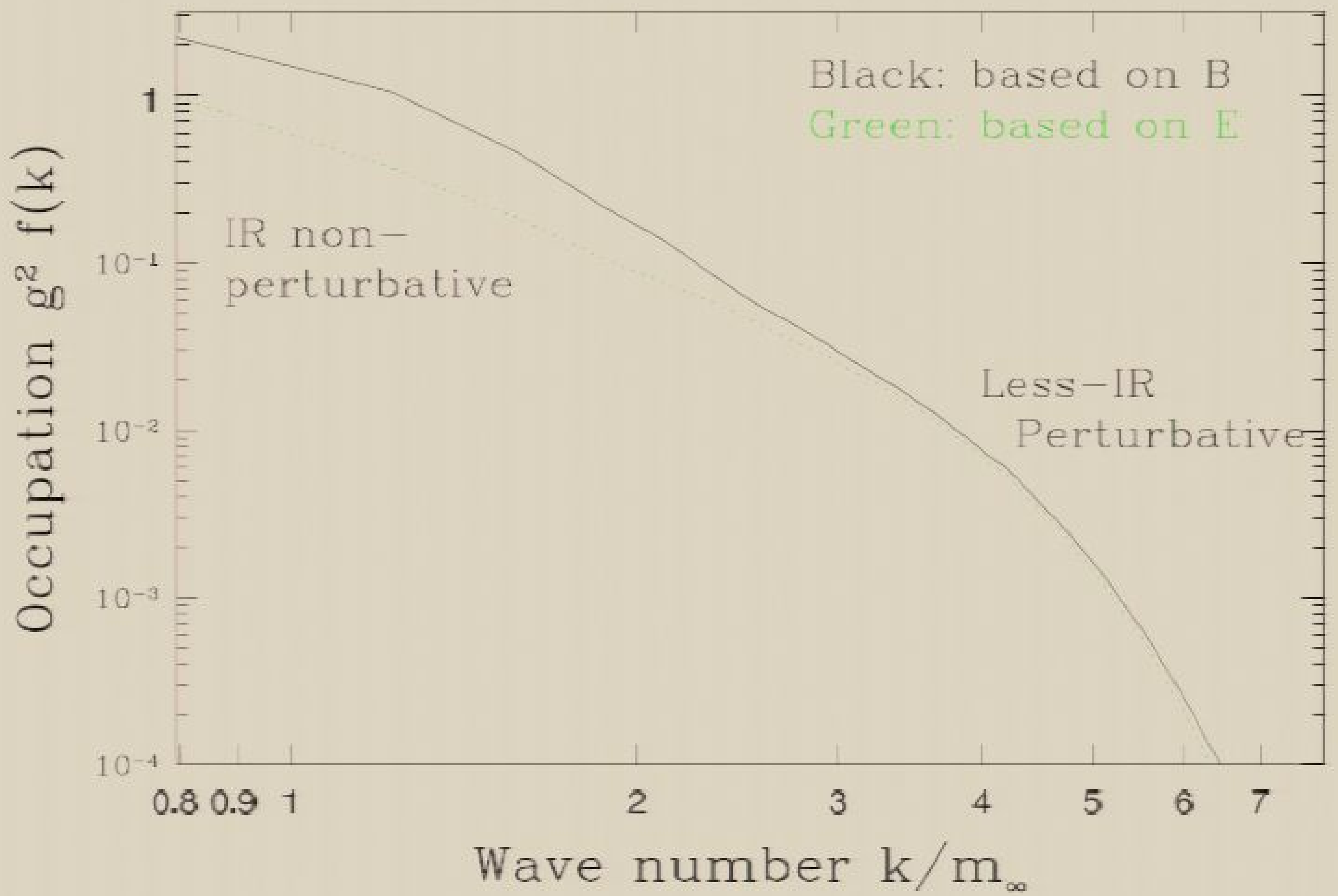
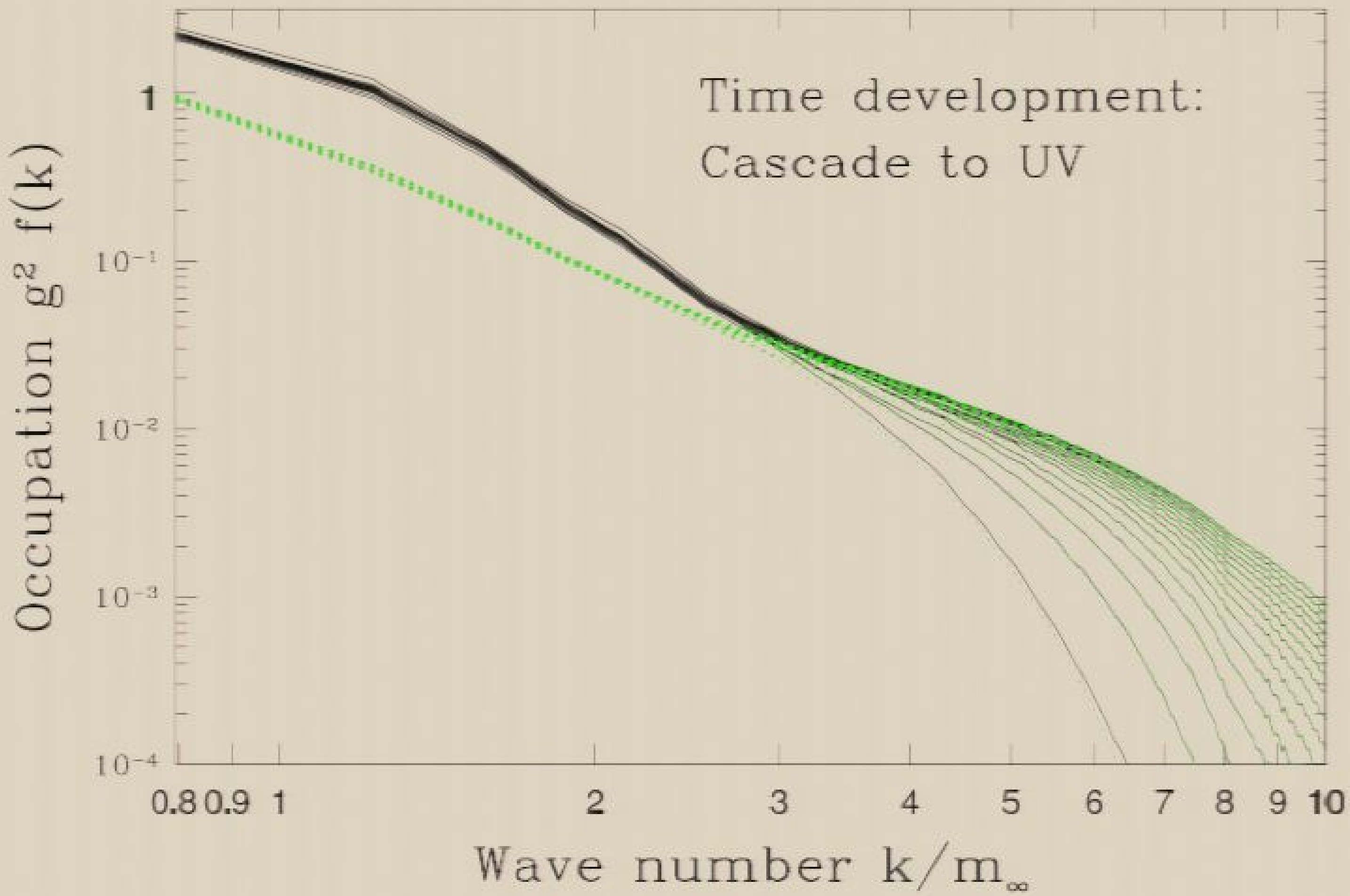
Instability pumps soft modes. Nonabelian interaction cascades energy into less-soft modes.



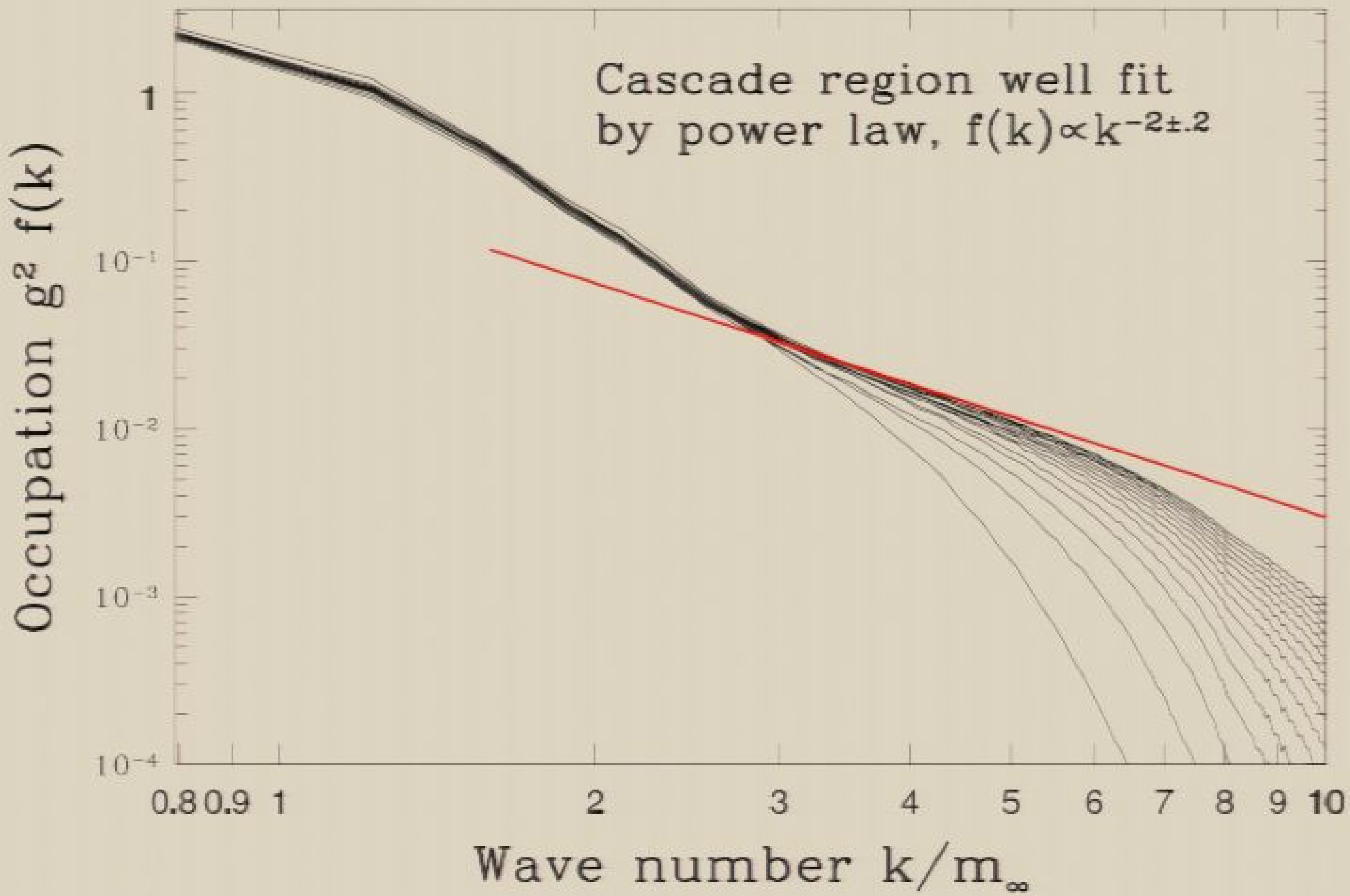
Coulomb gauge power spectrum: Initially



Time development of Coulomb gauge spectrum



Power-law behavior with moving cutoff



Conclusions

- Anisotropy $\longrightarrow$ plasma instability
- Instability cut off by nonabelian effects
- Lattice treatment is possible
- Energy feeds into a gauge field cascade

Most pressing problems:

- understanding large anisotropy cascade
- (irr)relevance to scattering and flow
- quantitative question of (un?)importance of instability

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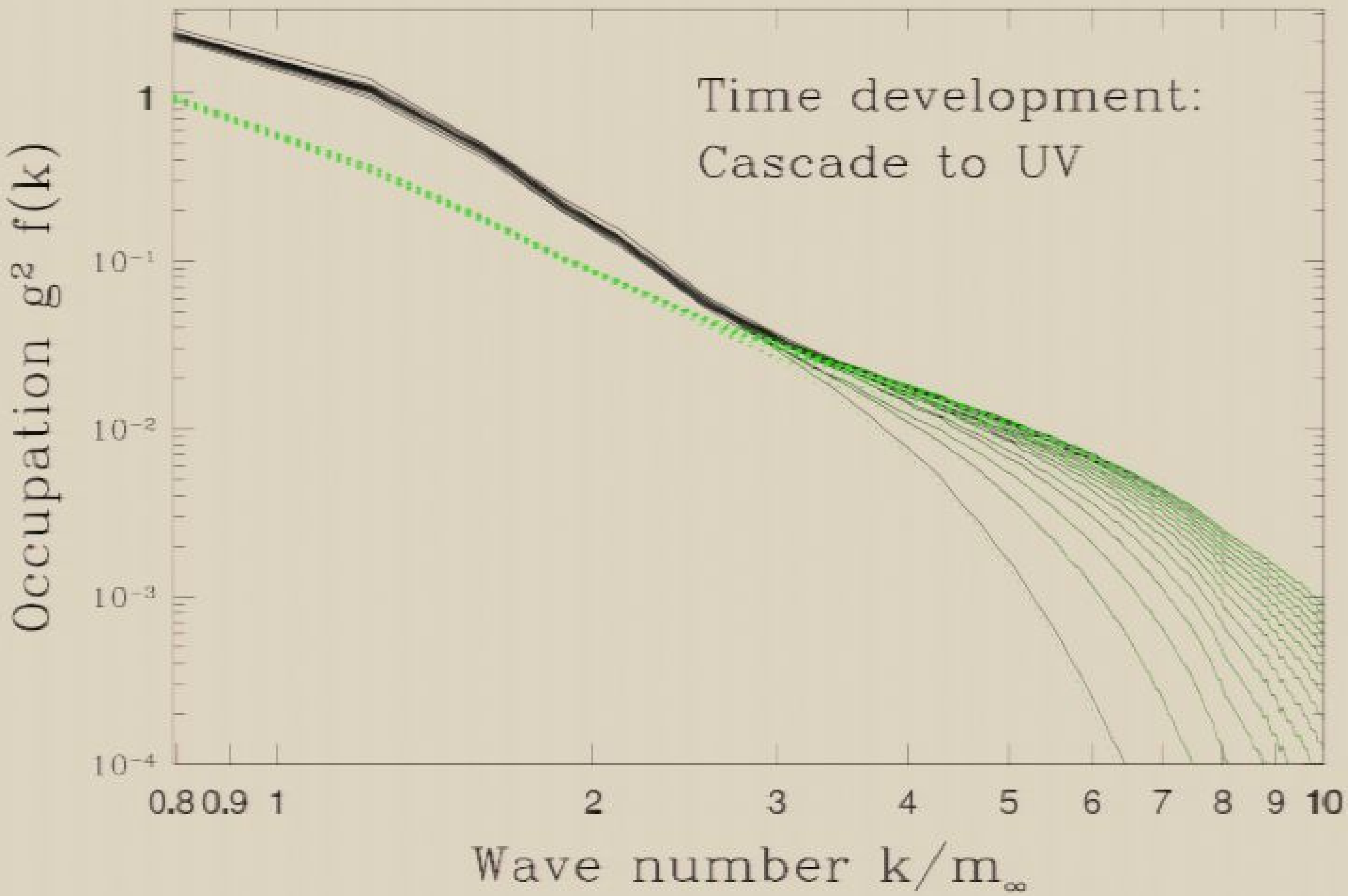

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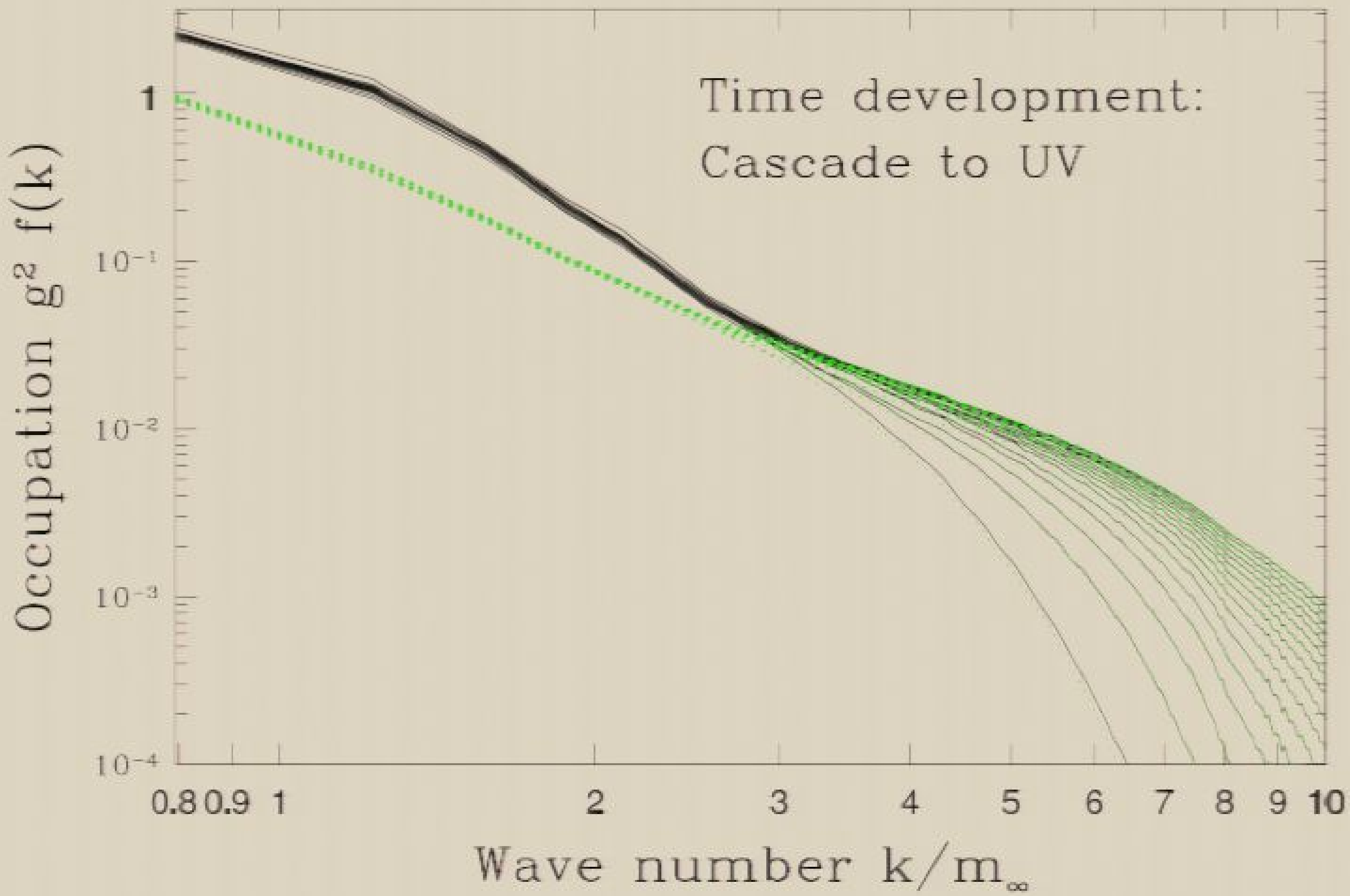

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Things still to do

Do instabilities have any relevance?

- Understand startup time–are instabilities just too late?
- Compare "kicks" on hard modes to hard-hard scattering
- Understand induced bremsstrahlung by hard modes–energy loss?
- Changes to jet observables?