

Conclusions

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# Scattering length of relativistic particles in aperiodic fluctuations

Anne Stockem

Ruhr-University Bochum, Theoretical Space and Astrophysics



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# Outline



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Motivation

Particle/Field

The Filamentation Instability

Conclusions

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# Outline

### Motivation:

• AF: Magnetic field generation

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# Outline

### **Motivation:**

- AF: Magnetic field generation
- Origin of magnetic fields

Scattering length

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### Motivation:

- AF: Magnetic field generation
- Origin of magnetic fields
- Many applications in Space and Astrophysics

### Solar eruption:

Outline



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### Motivation:

- AF: Magnetic field generation
- Origin of magnetic fields
- Many applications in Space and Astrophysics
- Reduction of instabilities

# Solar eruption:

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### Motivation:

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# Solar eruption:

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### Motivation:

- AF: Magnetic field generation
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- Reduction of instabilities

# Solar eruption:

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### Scattering length:



### **Condition:**

- Instability
- Interaction: Particles/Field

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### Motivation:

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# Solar eruption:

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### Scattering length:



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### Condition:

- Instability
- Interaction: Particles/Field

• Inside the system?!



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Scattering length

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### Motivation:

- AF: Magnetic field generation
- Origin of magnetic fields
- Many applications in Space and Astrophysics
- Reduction of instabilities

# Solar eruption:

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### Scattering length:



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### Condition:

- Instability
- Interaction: Particles/Field
- Inside the system?!

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• Scattering length



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# The Physical Principle

### Linear phase:



• Counterstreaming particles

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# The Physical Principle

### Linear phase:



- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_u(x,t) = B_u(t) \mathrm{e}^{ikx}$



length

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Instability

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# The Physical Principle

### Linear phase:



- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_u(x,t) = B_u(t) \mathrm{e}^{ikx}$
- Lorentz force  $\mathbf{F}_L = q\mathbf{v} \times \mathbf{B}$



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# The Physical Principle

- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_y(x,t) = B_y(t) {\rm e}^{ikx}$
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# The Physical Principle

- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_y(x,t) = B_y(t) \mathrm{e}^{\imath k x}$
- Lorentz force  $\mathbf{F}_L = q \mathbf{v} \times \mathbf{B}$
- Charge separation
- Right hand rule: amplification of  $B_y$



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# The Physical Principle

- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_y(x,t) = B_y(t) \mathrm{e}^{\imath k x}$
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### **RUHR-UNIVERSITÄT BOCHUM**

# The Physical Principle

- Counterstreaming particles
- Magnetic field fluctuation  $\delta B_y(x,t) = B_y(t) \mathrm{e}^{\imath k x}$
- Lorentz force  $\mathbf{F}_L = q\mathbf{v} imes \mathbf{B}$
- Charge separation
- Right hand rule: amplification of  $B_y$

### Non-linear phase:



- Biot-Savart interaction
- Merging of the current filaments

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# Interaction between Particles and Field

Scattering length	1. Case:	
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1. Case:

•  $\lambda \ll L$ 

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# Interaction between Particles and Field

No interaction:

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1. Case:

•  $\lambda \ll L$ 

Particle leaves the system

before being scattered

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# Interaction between Particles and Field

### No interaction:



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No interaction:

# Interaction between Particles and Field

### 1. Case:

- $\lambda \not\ll L$
- Particle leaves the system before being scattered
- No instability



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•  $\lambda \not\ll L$ • Particle

1. Case:

- Particle leaves the system before being scattered
- No instability

2. Case:

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# Interaction between Particles and Field

### No interaction:



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Case:
 λ ≪ L

1. Case:

•  $\lambda \ll L$ 

No instability

Particle leaves the system

before being scattered

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# Interaction between Particles and Field

# No interaction:

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# Interaction between Particles and Field

### 1. Case:

- $\lambda \not\ll L$
- Particle leaves the system before being scattered
- No instability

### 2. Case:

- $\lambda \ll L$
- Interaction inside the system



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No interaction:

### Interaction:





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# Interaction between Particles and Field

### 1. Case:

- $\lambda \not\ll L$
- Particle leaves the system before being scattered
- No instability

### 2. Case:

- $\lambda \ll L$
- Interaction inside the system
- Instability possible



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No interaction:

### Interaction:



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# Interaction between Particles and Field

### 1. Case:

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### 2. Case:

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### **Consequences:**

### No interaction:

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### Interaction:



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# Interaction between Particles and Field

### 1. Case:

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- Particle leaves the system before being scattered
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### 2. Case:

- $\lambda \ll L$
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- Instability possible

### **Consequences:**

• Calculation of  $\lambda$ 

### No interaction:

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### Interaction:





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# Interaction between Particles and Field

### 1. Case:

- $\lambda \not\ll L$
- Particle leaves the system before being scattered
- No instability

### 2. Case:

- $\lambda \ll L$
- Interaction inside the system
- Instability possible

### Consequences:

- Calculation of  $\lambda$
- Appropriate model is necessary!



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No interaction:

### Interaction:





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# The Scattering Length

Parallel mean free path length:

$$\lambda_{\parallel} = \frac{3v}{8} \int_{-1}^{1} d\mu \, \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}$$

Jokipii (1966); Hasselmann and Wibberenz (1968); Earl (1974)

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# The Scattering Length

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Jokipii (1966); Hasselmann and Wibberenz (1968); Earl (1974)

### Diffusion coefficient:

$$D_{\mu\mu}(\mu) = const. \quad \int_{k_{min}}^{\infty} dk_{\perp} \int_{0}^{\infty} ds \, \mathrm{e}^{\Gamma(k_{\perp})s} \, f(k_{\perp}, \mu, s)$$

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# The Scattering Length

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### Damping rate:

Assumption:  $\Gamma(k_{\perp}) = c \, l_e^{r-1} \, k_{\perp}^r$  Chang et al. (2008)

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Scattering length

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### **Thermal particles:**

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• r = 1:  $\frac{\lambda_{\parallel}}{L} \approx \frac{8.18 \cdot 10^{-20}}{n_{-3}L_1^2} \left(\frac{m}{m_e}\right)^{\frac{3}{2}} \theta^{-\frac{1}{2}}$ 

$$r = 3:$$

$$\frac{\lambda_{\parallel}}{L} \approx \frac{3.84 \cdot 10^{-3}}{n_{-3}^{1/6} L_1^{1/3}} \left(\frac{m}{m_e}\right)^{\frac{7}{12}} \theta^{\frac{5}{12}}$$

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### Thermal particles:

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### Scattering length:



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### Thermal particles:

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### Scattering length:



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### Highly relativistic particles:

• 
$$r = 1$$
:  
 $\frac{\lambda_{\parallel}}{L} \approx \frac{8.65 \cdot 10^{-23}}{n_8 L_{15}^2} \frac{m}{m_e} \gamma$ 

• 
$$r = 3$$
:  
 $\frac{\lambda_{\parallel}}{L} \approx \frac{3.08 \cdot 10^{-3}}{n_8^{1/6} L_{15}^{1/3}} \frac{m}{m_e} \gamma$ 

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### Thermal particles:

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### Scattering length:



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### **Scattering length:**



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# Influence of an Ambient Magnetic Field

Geometry:

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# Influence of an Ambient Magnetic Field

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### Interpretation:

• Magnetic field fluctuations  $\delta {f B} \perp {f e}_{{f z}}$ 

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# Influence of an Ambient Magnetic Field

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### Interpretation:

- Magnetic field fluctuations  $\delta {f B} \perp {f e}_{{f z}}$
- $\bullet$  Ambient field  $\mathbf{B_0} \parallel \mathbf{e_z}$



# Influence of an Ambient Magnetic Field

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### Interpretation:

- Magnetic field fluctuations  $\delta {f B} \perp {f e}_{{f z}}$
- $\bullet$  Ambient field  $\mathbf{B_0} \parallel \mathbf{e_z}$

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• Charge separation slows down



# Influence of an Ambient Magnetic Field

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### Interpretation:

- Magnetic field fluctuations  $\delta \mathbf{B} \perp \mathbf{e_z}$
- $\bullet$  Ambient field  $\mathbf{B_0} \parallel \mathbf{e_z}$
- Charge separation slows down
- Particle confinement for  $B_0 \geq B_c$

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# Influence of an Ambient Magnetic Field

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- Particle confinement for  $B_0 \geq B_c$

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### **Consequences:**

• Growth rate is reduced



# Influence of an Ambient Magnetic Field

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### Interpretation:

- Magnetic field fluctuations  $\delta \mathbf{B} \perp \mathbf{e_z}$
- $\bullet$  Ambient field  $\mathbf{B_0} \parallel \mathbf{e_z}$
- Charge separation slows down
- Particle confinement for  $B_0 \ge B_c$

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### **Consequences:**

- Growth rate is reduced
- No amplification for  $B_0 \ge B_c$



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# Analytical Results of the FI

### Additional assumption:

Cold plasma approach: T = 0



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### **Analytics:**

• Aperiodic fluctuations:  $\delta B_{\perp} \propto e^{i \mathbf{k} \cdot \mathbf{x} + \sigma t}$  RUHR-UNIVERSITÄT BOCHUM

# Analytical Results of the FI

# Additional assumption:

Cold plasma approach: T = 0





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# Analytical Results of the FI

### Additional assumption:

Cold plasma approach: T = 0

### **Analytics:**

- Aperiodic fluctuations:  $\delta B_{\perp} \propto {\rm e}^{i{f k}\cdot{f x}+\sigma t}$
- Maximum growth rate:  $\sqrt{0^2 0^2}$

$$\sigma_{max} = \sqrt{\Omega_{max}^2 - \Omega^2}$$

### Linear growth rate:

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# Analytics:

• Aperiodic fluctuations:  $\delta B_{\perp} \propto e^{i \mathbf{k} \cdot \mathbf{x} + \sigma t}$ 

• Maximum growth rate:  $\sigma_{max} = \sqrt{\Omega_{max}^2 - \Omega^2}$ 

$$\Omega_{max} = \omega_p U / \sqrt{\gamma} e^{i \omega_p T}$$
$$\Omega = e B_0 / m$$

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### Additional assumption:

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### Linear growth rate:





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# Analytical Results of the FI

### Additional assumption:

Cold plasma approach: T = 0

### Analytics:

- Aperiodic fluctuations:  $\delta B_{\perp} \propto {\rm e}^{i{f k}\cdot{f x}+\sigma t}$
- Maximum growth rate:  $\sigma_{max} = \sqrt{\Omega_{max}^2 - \Omega^2}$
- No growth for  $B_0 \ge B_c$

$$\begin{split} \Omega_{max} &= \omega_p U / \sqrt{\gamma} c \\ \Omega &= e B_0 / m \end{split}$$

### Linear growth rate:

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# The Energy Densities

### Magnetic energy density:



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# The Energy Densities

### Magnetic energy density:



**Electric energy density:** 



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# The Energy Densities

### Magnetic energy density:



### **Electric energy density:**



### **Results:**

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• Same amplification level independent of  $B_0$ 





- Same amplification level independent of  $B_0$
- $\epsilon_B$ : Growth for  $B_0 = B_c$



- Same amplification level independent of  $B_0$
- $\epsilon_B$ : Growth for  $B_0 = B_c$
- Non-linear effect





- Same amplification level independent of  $B_0$
- $\epsilon_B$ : Growth for  $B_0 = B_c$
- Non-linear effect
- Amplification of  $\epsilon_E$  starts later





### Perpendicular component:



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### Perpendicular component:



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### Perpendicular component:



### Parallel component:



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### Perpendicular component:



### Parallel component:



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3 x 3

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### **Comparison:**

- Strong perpendicular component has developed
- Amplification of  $B_{\parallel}$ : temperature effect

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# Conclusions

• Aperiodic fluctuations

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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field

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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field



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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field
- Scattering length



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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field
- Scattering length
- Appropriate model



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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field
- Scattering length
- Appropriate model
- Physical principle of the B-generation process



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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field
- Scattering length
- Appropriate model
- Physical principle of the B-generation process
- Analytics PIC simulations

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# Conclusions

- Aperiodic fluctuations
- Instability generating a magnetic field
- Interaction between particles and field
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- Appropriate model
- Physical principle of the B-generation process
- Analytics PIC simulations

### Thanks for your attention!