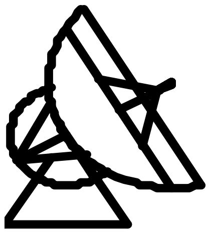
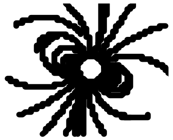
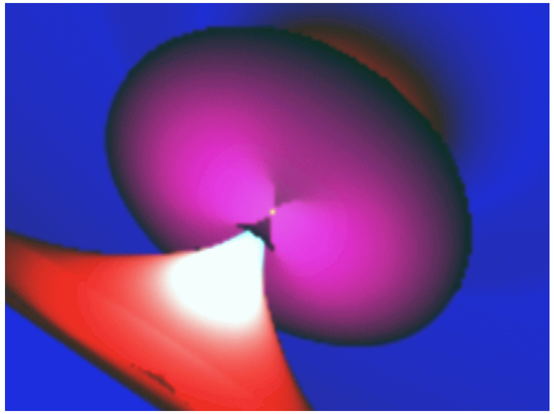






Resistivities in the Radioemission Region

A. Jessner (MPIfR)

J. Eilek (NMTech)

H. Lesch (LMU)

1. How can observations and plasmaphysics be reconciled?

2. Why are resistivities important?

3. What causes resistivity?

4. What are the typical magnitudes in the radio emission region?

5. Can one find a configuration that satisfies the constraints?

Observations and Plasmaphysics

Electric charges in the inner parts of the PSR magnetosphere move only along the field lines,-
their plasma frequency determines the lower frequency limits of effective plasma waves and instabilities.

n_e

$$\nu_{pl} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{q_e^2}{\varepsilon_0 \cdot \gamma \cdot m_e} \cdot \xi \cdot 2 \cdot \Omega \cdot \frac{B_0 \cdot \varepsilon_0}{q_e} \cdot \frac{r_{ns}^3}{R^3}}$$

angular dependence neglected and using

$$\xi = \frac{n}{n_{GJ}}$$

"Sturrock factor"

Depending on the emission process, the minimum observable frequency is

$$\nu_{min} = \frac{\gamma^{\alpha - \frac{1}{2}}}{2 \cdot \pi} \cdot \sqrt{\frac{q_e^2}{\varepsilon_0 \cdot m_e} \cdot \xi \cdot 2 \cdot \Omega \cdot \frac{B_0 \cdot \varepsilon_0}{q_e} \cdot \frac{r_{ns}^3}{R^3}}$$

α=1 for curvature radiation and α=2 for inverse compton scattering

Solving now for density and Lorentz factor we get a universal constraint for the emission height R , the Sturrock factor ξ and the Lorentz factor γ:

$$\xi \cdot \gamma^{2 \cdot \alpha - 1} = \frac{2 \cdot \pi^2 \cdot m_e \cdot \nu_{min}^2}{q_e \cdot r_{ns}^3 \cdot \Omega \cdot B_0} \cdot R^3 = 1.8 \cdot 10^{-3} \cdot \left(\frac{\nu_{min}}{100 \cdot MHz}\right)^2 \cdot \left(\frac{P}{s}\right) \cdot \left(\frac{10^{12} \cdot G}{B_0}\right) \cdot x^3$$

For a "standard pulsar": ν=400 MHz, B=10^{12} G, P=0.5 s, x=50

For 0531+21 (Crab): ν=160 MHz, B=3.8 •10^{12} G, P=0.033 s, x_{LC}=157

→

ξγ = 1786

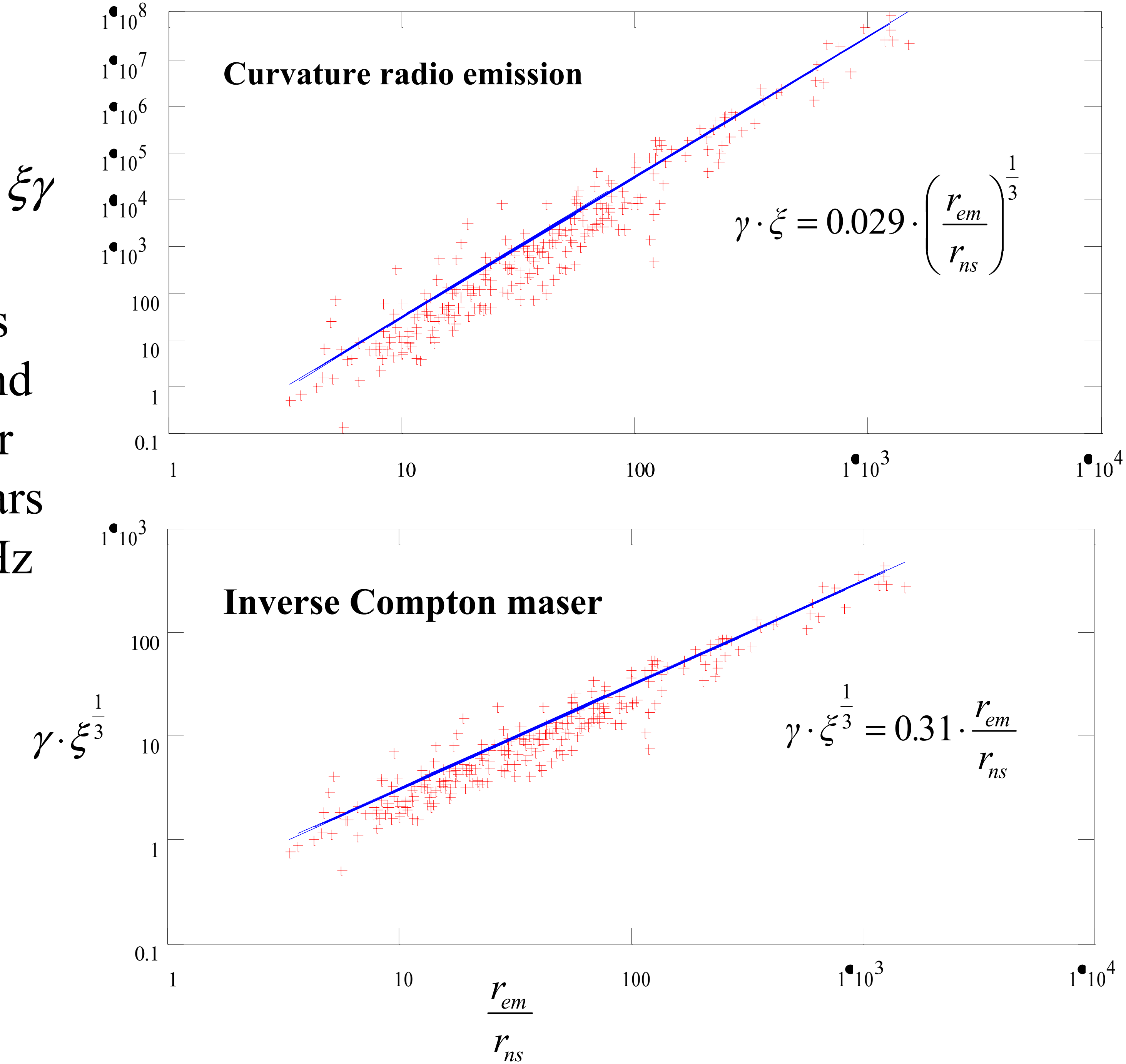
ξγ = 163

Kunzl, Lesch, Jessner, v. Hoensbroech
ApJ, 505, L139 (1998)

Standard (R&S-like) Models of the Pulsar Magnetosphere are not self-consistent!

Pair creation must not influence the density where radio waves are emitted
(and may not even happen! Jessner et. al. 2001, Eilek et. al. 1999**)**

Upper Limits on density and Lorentzfactor for 256 Pulsars at ν=400 MHz



The Observed Radio Luminosities are Dissipated Particle Energies!

Kramer, Xilouris, Jessner et. al. A&A 306, 867 (1996)   Taylor, Manchester, Lyne, ApJS, 88,529 (1993)

PSR 0355+54

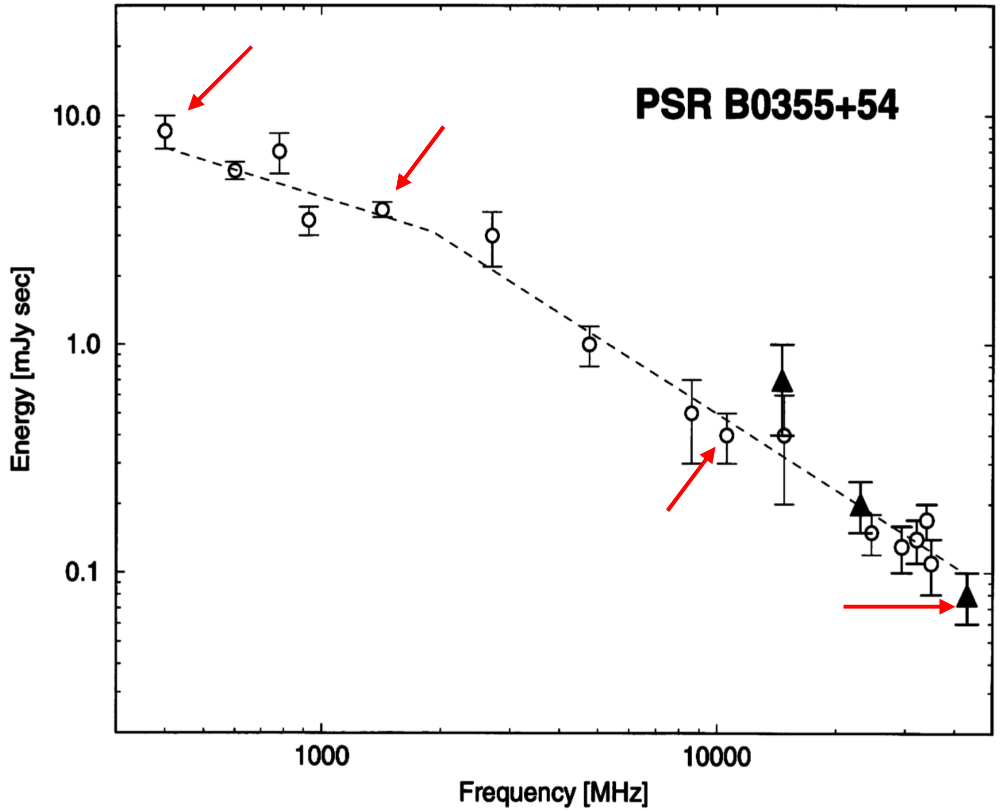
$\xi\gamma$

$L_{408} := 352.3 \cdot 10^{26} \cdot \frac{\text{erg}}{\text{s}} \longrightarrow 1250$

$L_{1400} := 143 \cdot 10^{26} \cdot \frac{\text{erg}}{\text{s}} \longrightarrow 507$

$L_{10GHz} := 13.3 \cdot 10^{26} \cdot \frac{\text{erg}}{\text{s}} \longrightarrow 47$

$L_{33GHz} := 5 \cdot 10^{26} \cdot \frac{\text{erg}}{\text{s}} \longrightarrow 18$

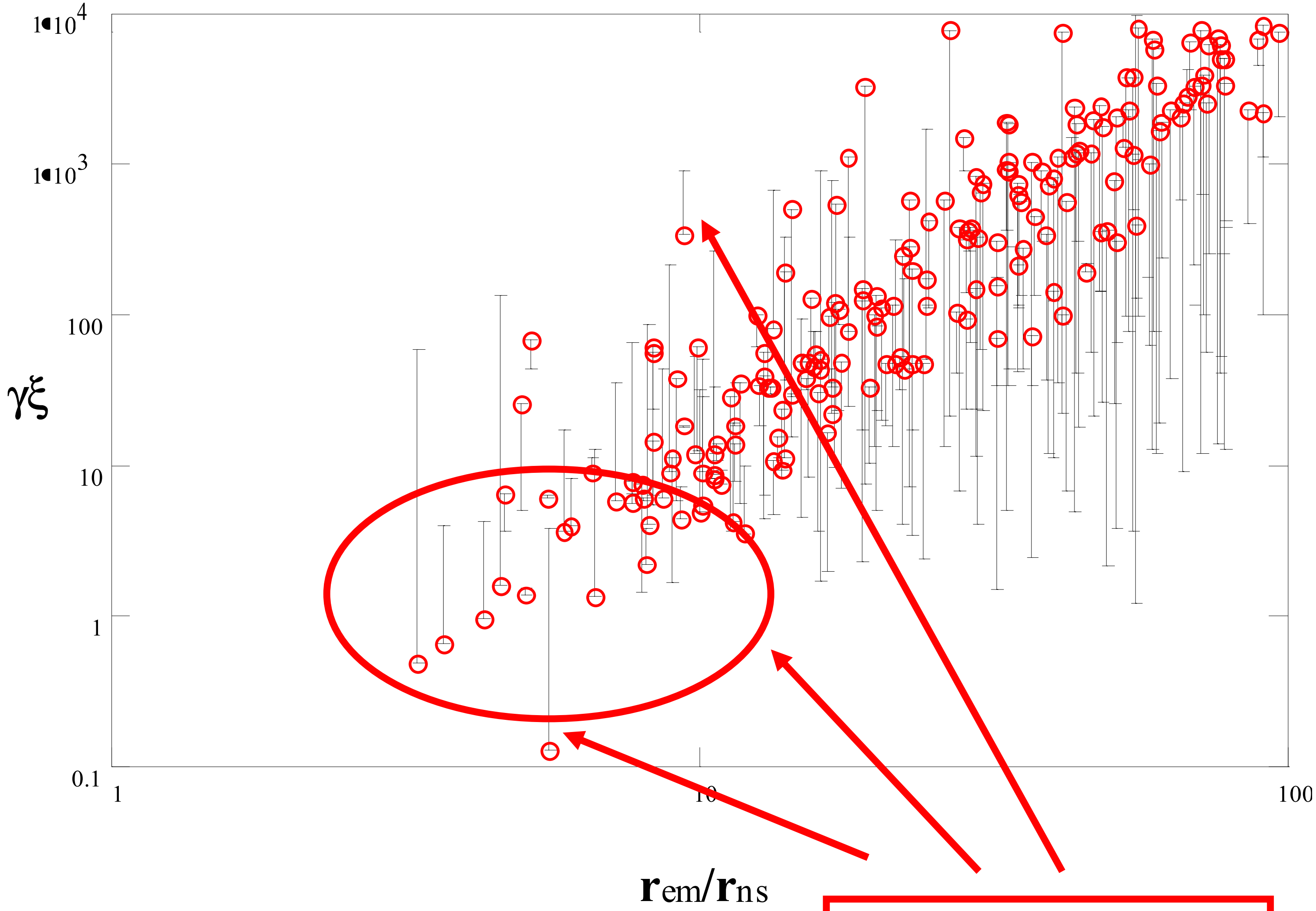


These are minimum estimates as the width of the beam could be greater!

$$\xi\gamma = \frac{L}{n_{GJ} \cdot m_e c^2 \cdot A_{cap} \cdot c}$$

Permitted and required Lorentzfactors for 256 PSRs at ν=400MHz

Red circles: Maximum permitted for curvature radiation mechanisms



With inv. Compton *all* PSRs would have

$$\gamma \cdot \xi\big|_{rad} > \gamma \cdot \xi\big|_{\max}$$

Radio observations present us with a dilemma:

low particle energies $\gamma < 10^2$

and densities around n_{GJ} $\xi \sim 1$

? prevail in the radio emission zone,- ?

because low ν radiation has to escape!

But for the radio luminosities we need $\xi\gamma > 1000$

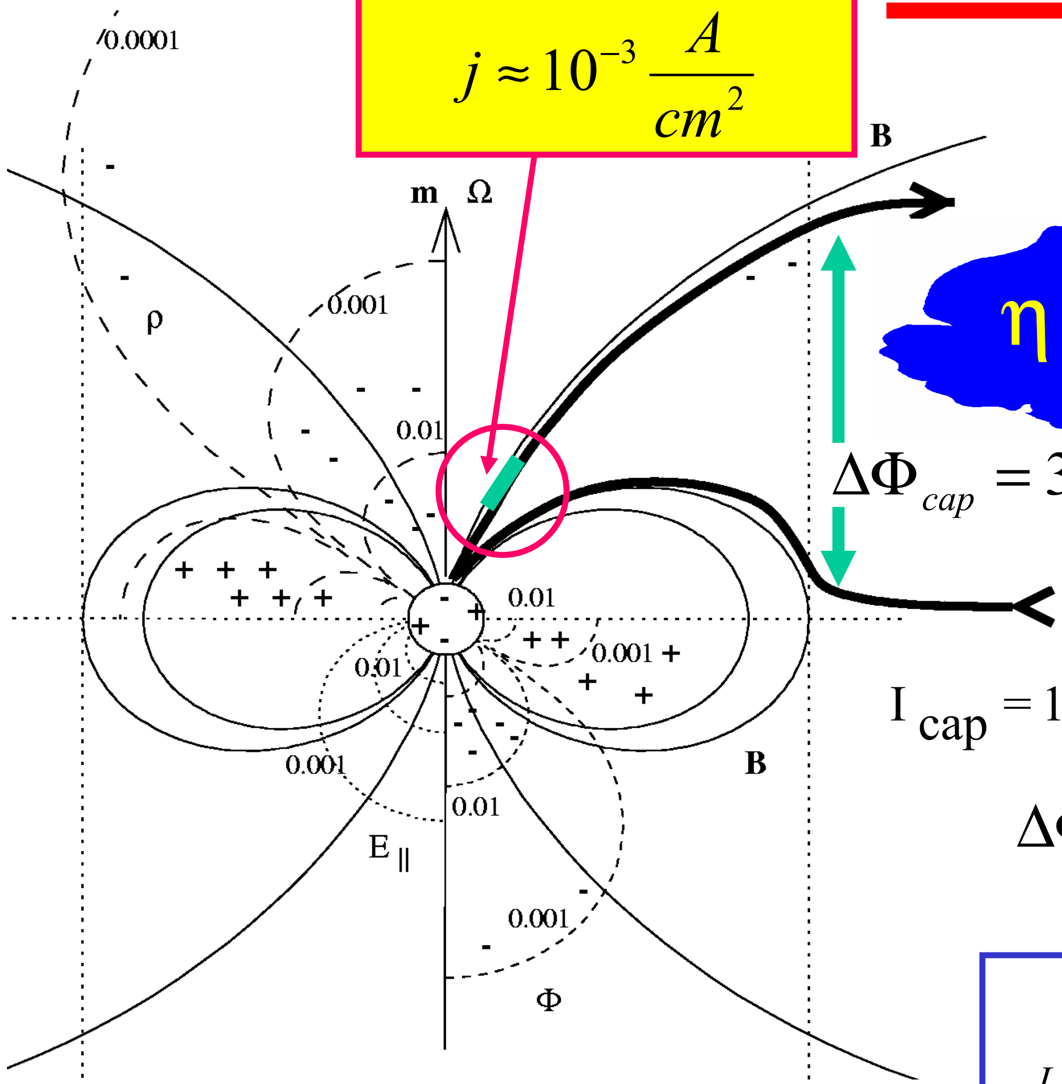
We have to find a model that fits the observations without any violation of plasma physics !

Resistivities are Local Quantities that Determine the Global Current

$$\Delta\Phi_{radio} \approx 3.4 \cdot 10^{7} V$$

$$j \approx 10^{-3} \frac{A}{cm^2}$$

$$\eta_{radio} \cong \frac{\Delta\Phi}{j \cdot \Delta r} \approx 16 \cdot \Omega m$$



Fields of an aligned Rotator

η ??

$$\Delta\Phi_{cap} = 3 \cdot 10^{13} V$$

$$R_{PSR} = 9 \cdot 10^{5} \cdot R_{radio}$$

$$I_{cap} = 1.484 \cdot 10^{12} \cdot A$$

$$\Delta\Phi_{cap} \cdot I_{cap} = 4.5 \cdot 10^{25} W \approx L_{spin-down}$$

Quantities for PSR 2021+51

$L_{radio} = 5 \cdot 10^{19} W$ $\Lambda_{rad} := 150 \cdot km$ $x_{em} = 75$

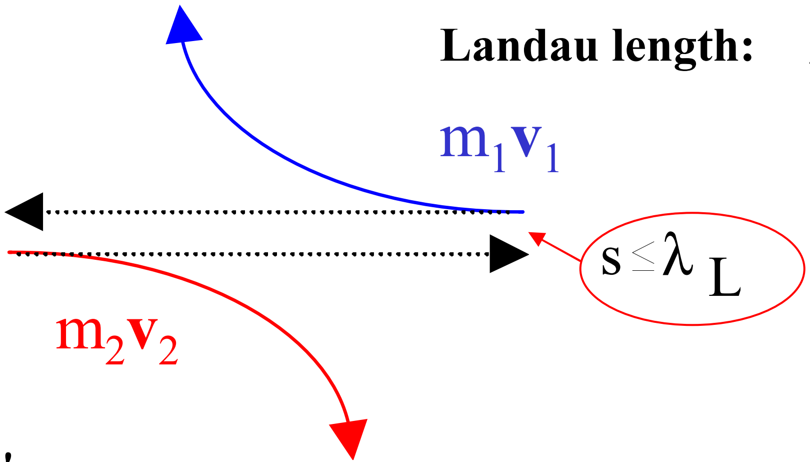
Dissipation corresponds to Resistivity !

Individual particle interactions:

Interparticle distance: $\lambda_n := n_e^{-\frac{1}{3}}$ **= 0.015 cm**

Landau length: $\lambda_L = 5.57 \cdot 10^{-9} \cdot \mathrm{cm}$

3-D Collisions:
(thermalisation)



$\nu_{coll} = 0.011 \cdot s^{-1}$

$$\eta_{coll} := \frac{m_e \cdot \nu_{coll}}{q_e^2 \cdot n_e}$$

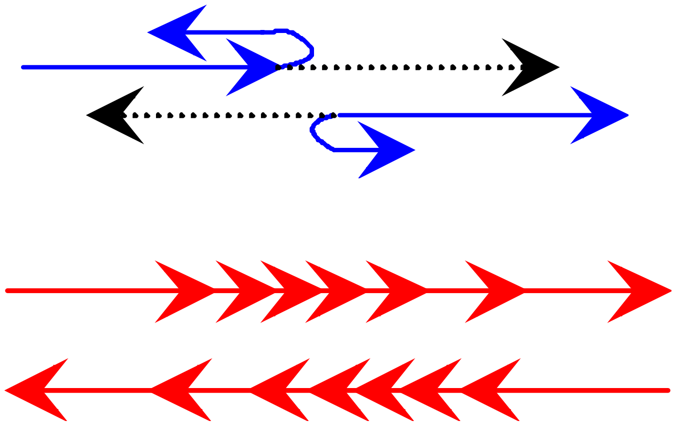
$\eta_{coll} = 1.3 \cdot 10^{-6} \cdot \mathrm{Ohm} \cdot \mathrm{m}$

$$L_{coll} = 10^{-7} \cdot L_{radio}$$

$\eta_{Hg} = 1 \cdot 10^{-6} \cdot \mathrm{Ohm} \cdot \mathrm{m}$

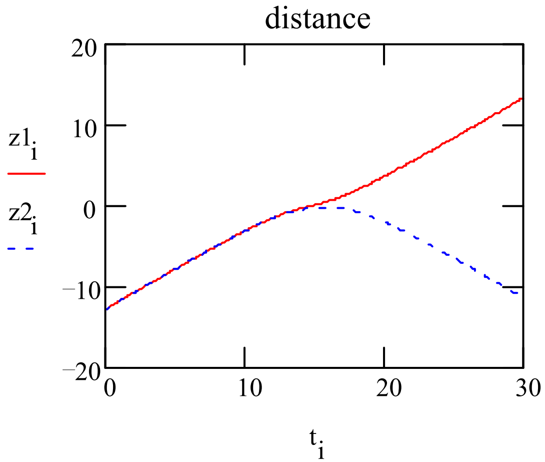
But the magnetic field constrains particle movement and enforces an additional symmetry!

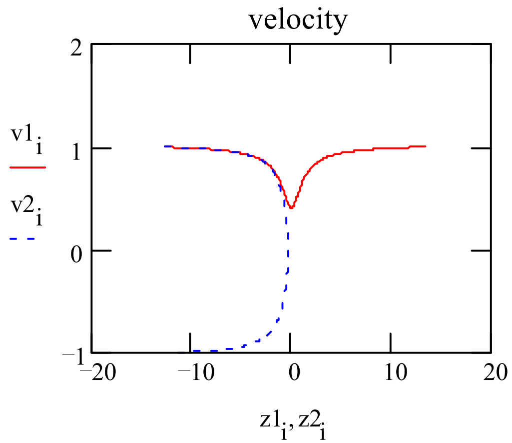
1-D collisions:



$s \leq \lambda_L$

$s \geq \lambda_L$





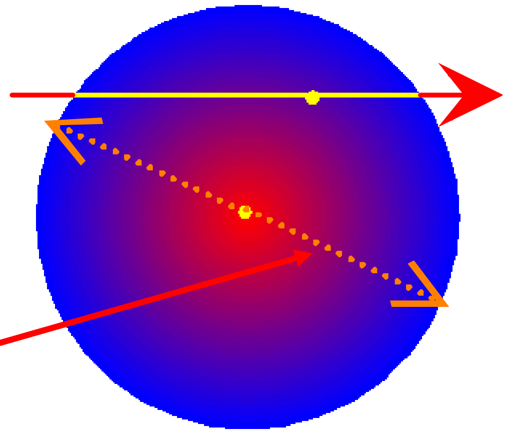
For particles of the similar mass:

Particle momenta are either preserved or just swapped!

η_{coll}=0 for high B fields !

Collective Effects are important in a Plasma !

The shielding (Debye)-length



$$\lambda_D := \sqrt{\frac{\varepsilon_0 \cdot k \cdot T_e}{q_e^2 \cdot n_e}}$$ **= 7 cm**

determines the range of el.mag. Interactions.

$$n_e \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{\lambda_D}{2}\right)^3 = 5.209 \cdot 10^7$$

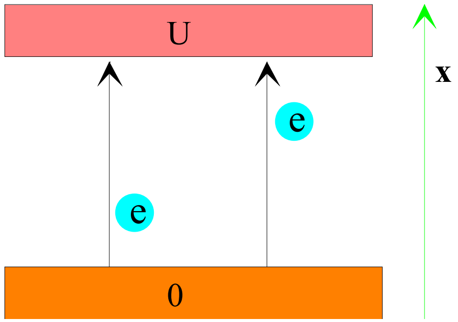
particles interact within a Debye sphere via electrostatic (Langmuir) waves

Their effect is certainly not small:

$$\eta_D = 2.8 \cdot \mathrm{Ohm} \cdot \mathrm{m}$$

$$L_{el.} \approx 0.3 L_{radio}$$

Even „empty“ space has a resistivity!

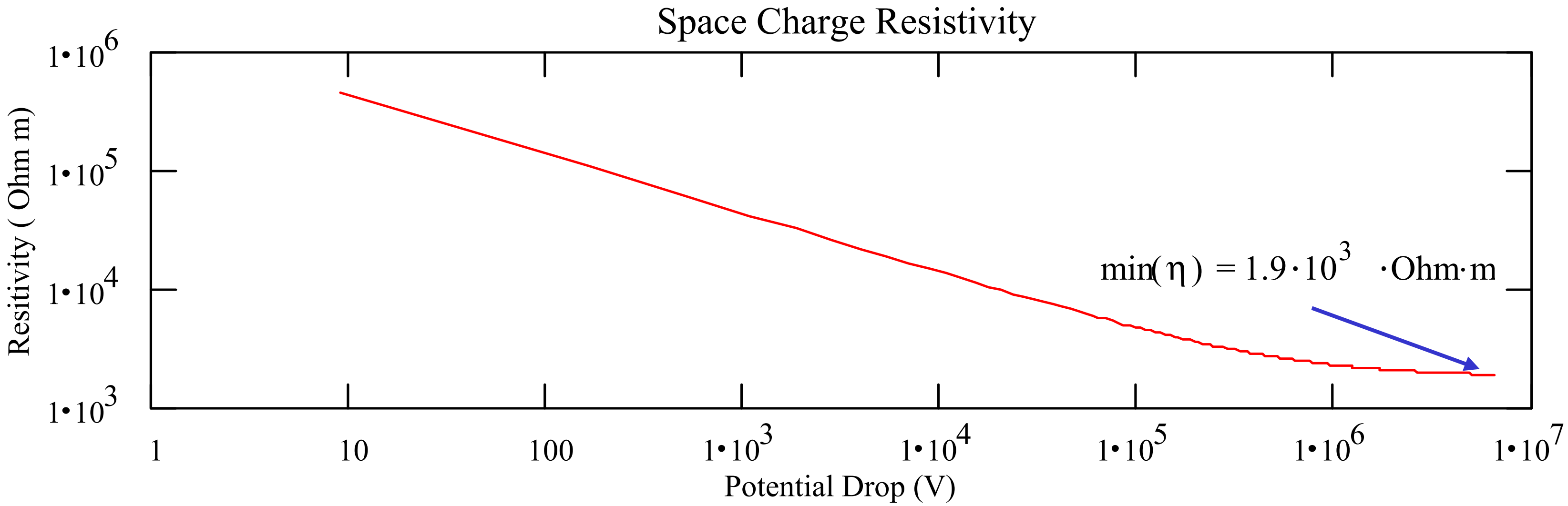


$U << 511\ kV$

$$j_{CL} = 7\cdot 10^{-10}\cdot\left(\frac{x}{m}\right)^{-2}\cdot\left(\frac{U}{V}\right)^{\frac{3}{2}}\cdot\frac{A}{cm^2} \qquad \eta_{CL} \cong 1.4\cdot 10^{5}\cdot\left(\frac{x}{m}\right)\cdot\left(\frac{U}{V}\right)^{-\frac{1}{2}}\cdot Ohm\ m$$

$U >> 511\ kV$ →

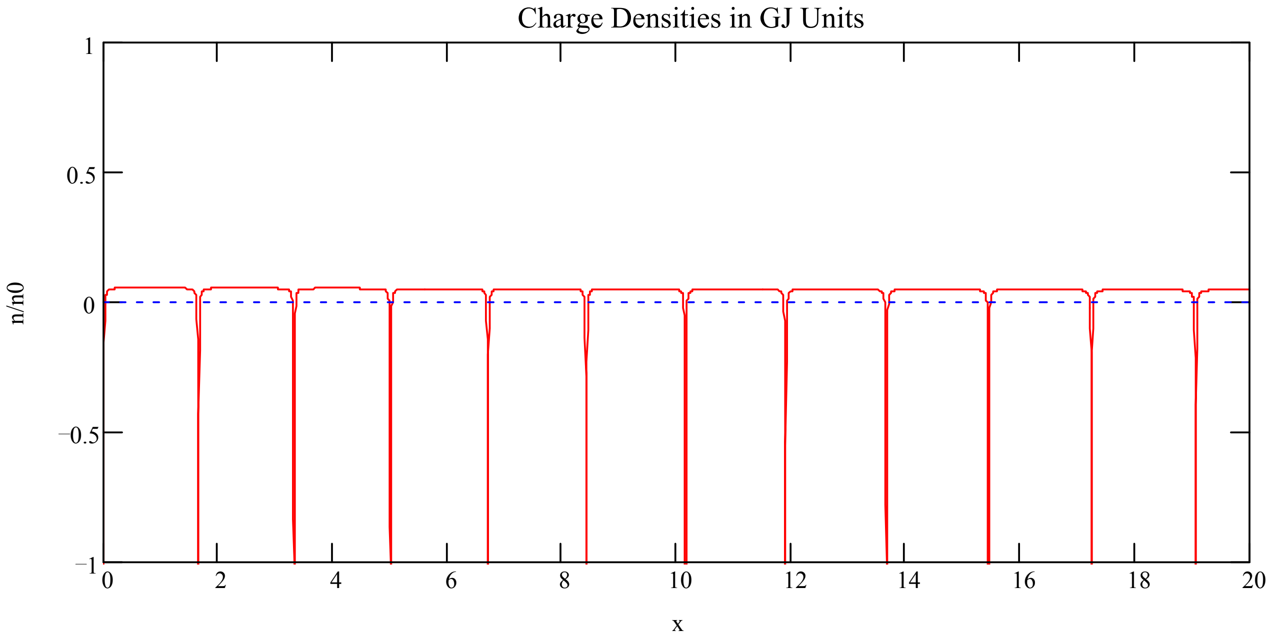
$$j_{CL} = 5.3\cdot 10^{3}\cdot\frac{A}{cm^2} \qquad \eta_{CL} \cong 188\ \cdot\left(\tfrac{x}{m}\right)\cdot Ohm\ m$$



over $\frac{c}{\omega_p} = 9.8\cdot m$

$\omega_p = 3.1\cdot 10^{7}\ \cdot s^{-1}$

What happens if the injected current exceeds the space charge limits?



Such currents oscillate strongly, involving mildly relativistic potentials and strong density modulations.

These oscillations are common in diodes with overcritical currents

Discovery: **Pierce (1940);**

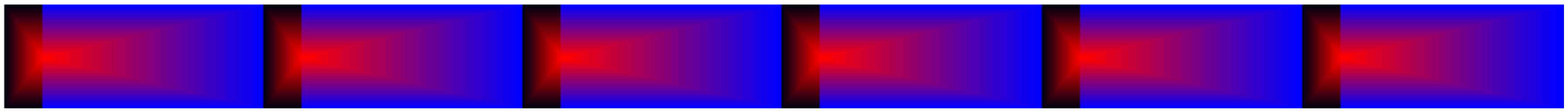
Analytical treatment: **Mestel, Wang & Westfold; Shibata;**

Numerical experiments: **Eilek; Schopper & Lesch; Jessner**

Anomalous Resistivity from Strong Density Modulations

A heuristic estimate of dissipation in the radio emission region:

Length of dissipation region $\Lambda_{rad} := 150 \cdot km$



Number of mini-gaps $N_{CL} := 70$

Length of acceleration region (mini-gap) $\lambda_{CL} := \dfrac{c}{\omega_p}$ $\quad \lambda_{CL} = 9.8 \cdot m$ $\quad \dfrac{\Lambda_{rad}}{N_{CL}} = 2.1 \cdot 10^{3} \cdot m$

δγ in gap:

$$\frac{\Phi_{rad} - n_e \cdot q_e \cdot c \cdot \eta_D \cdot \left(\Lambda_{rad} - N_{CL} \cdot \lambda_{CL}\right)}{N_{CL}} \cdot \frac{q_e}{m_e \cdot c^2} = 0.78$$

Langmuir losses in between two gaps:

$$\frac{n_e \cdot q_e \cdot c \cdot \eta_D \cdot \left(\Lambda_{rad} - N_{CL} \cdot \lambda_{CL}\right)}{N_{CL}} \cdot \frac{q_e}{m_e \cdot c^2} = 0.16$$

Total dissipated Lorentz factor: $\Delta\gamma = 65.9$ $\Longleftrightarrow$ $\dfrac{L_{rad}}{A_{cap} \cdot n_{GJ} \cdot m_e \cdot c^3}$

Conclusions

- **Estimates of local resisitivities can provide important clues on how the magnetospheric current system operates.**
- **Given the correct initial parameters, it is possible to obtain a self-consistent description of the radio emission region that will not violate the observed constraints!**