Tracking of an electron beam through the solar corona with LOFAR

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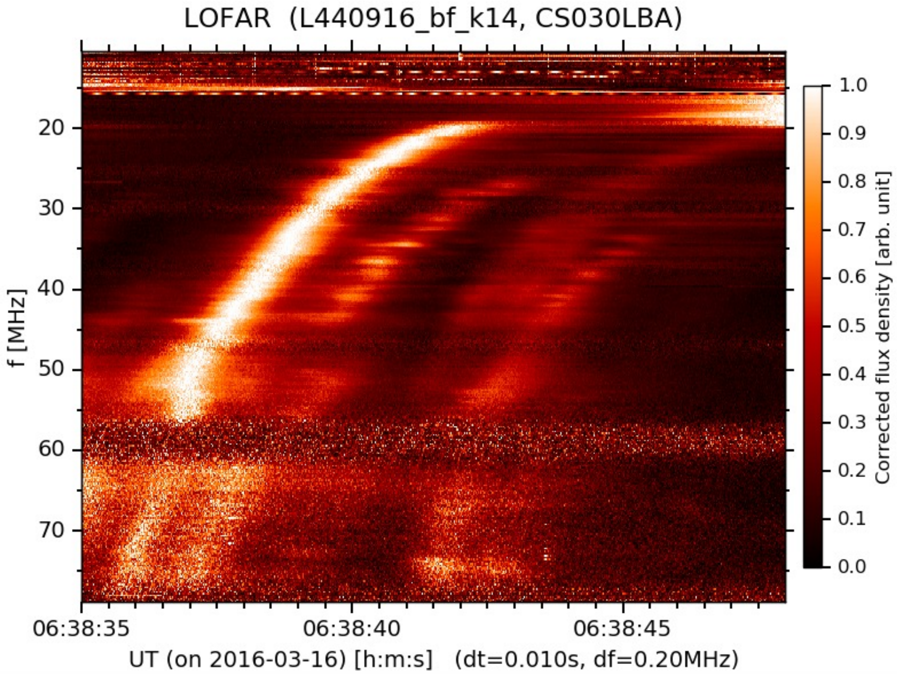
in collaboration with:

- LOFAR team at ASTRON
- core members of the solar KSP

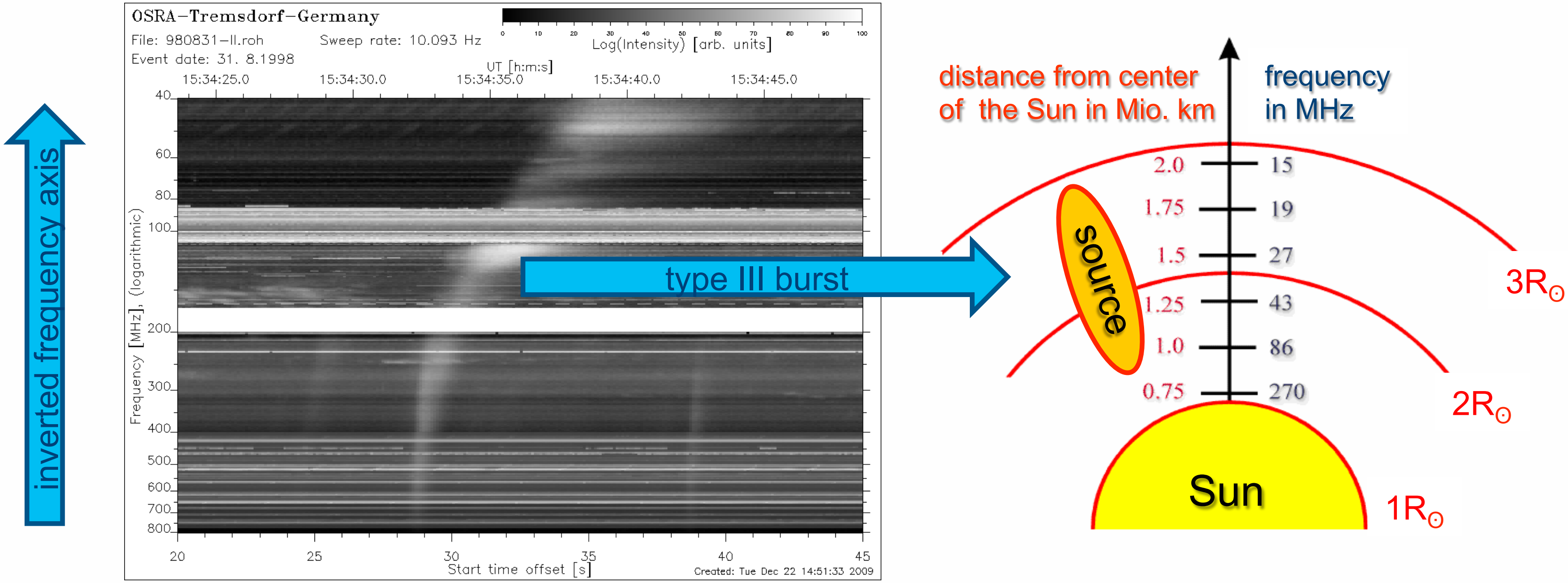


solar type III radio bursts:

- radio signatures of electron beams in the corona
- LOFAR allows to track this beam
- example of
  electron-beam plasma interaction in space

→ **plasma physics**

Radio emission of type III bursts

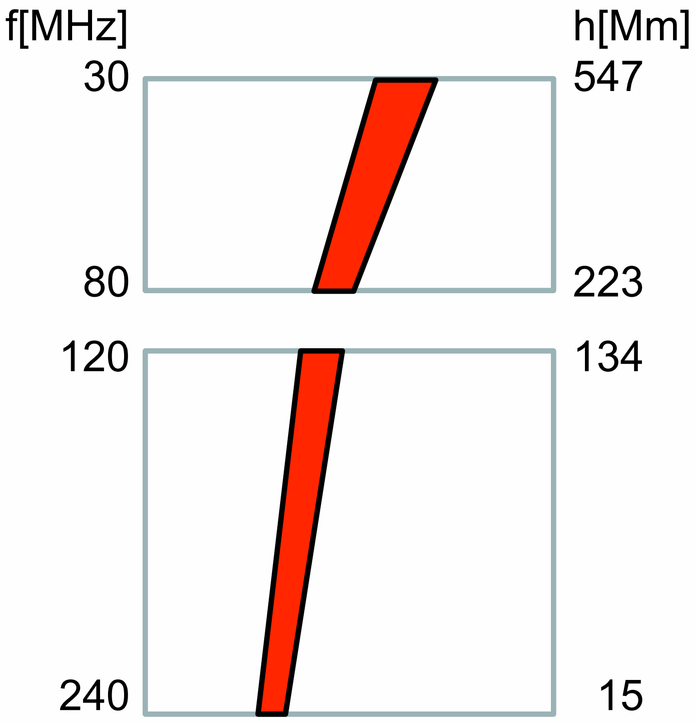


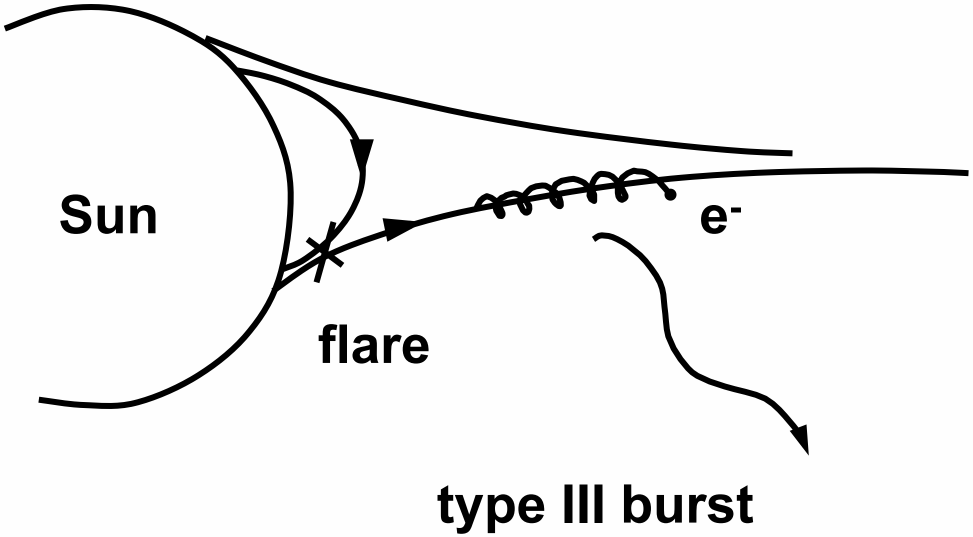
plasma emission
(no gyro emission)

$$f \approx n f_{pe} \quad \text{with} \quad f_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 N_e}{\varepsilon_0 m_e}}$$

N_e: e^- number density
n=1: fundamental emission
n=2: 1st harmonic emission

Dynamic Radio Spectra

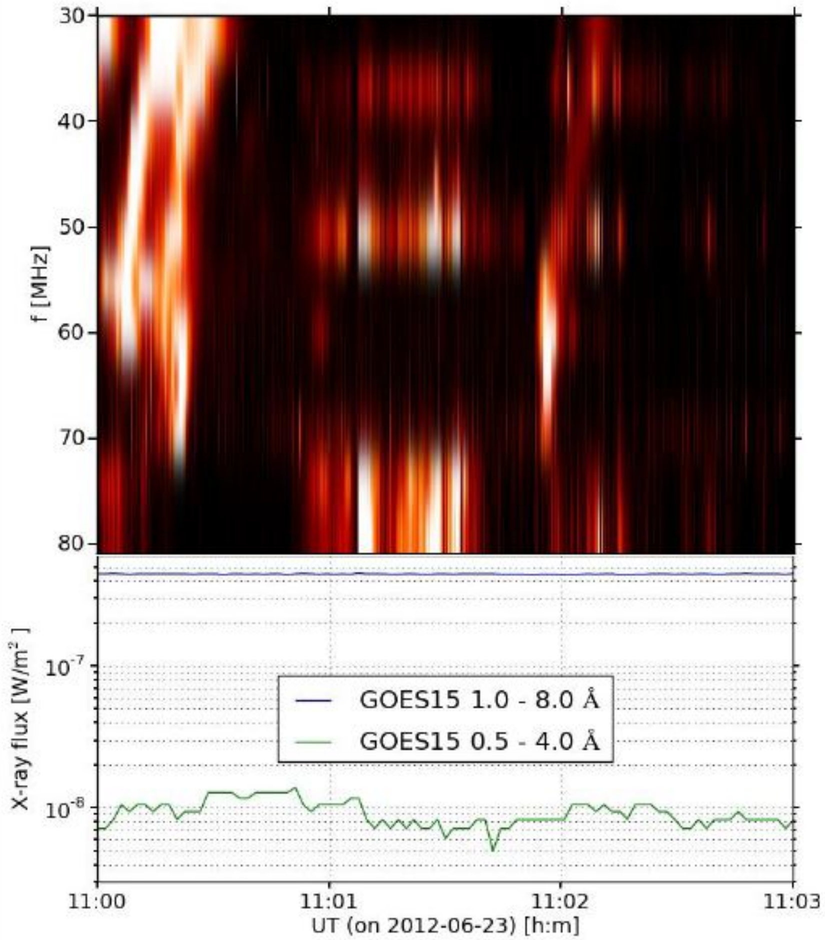




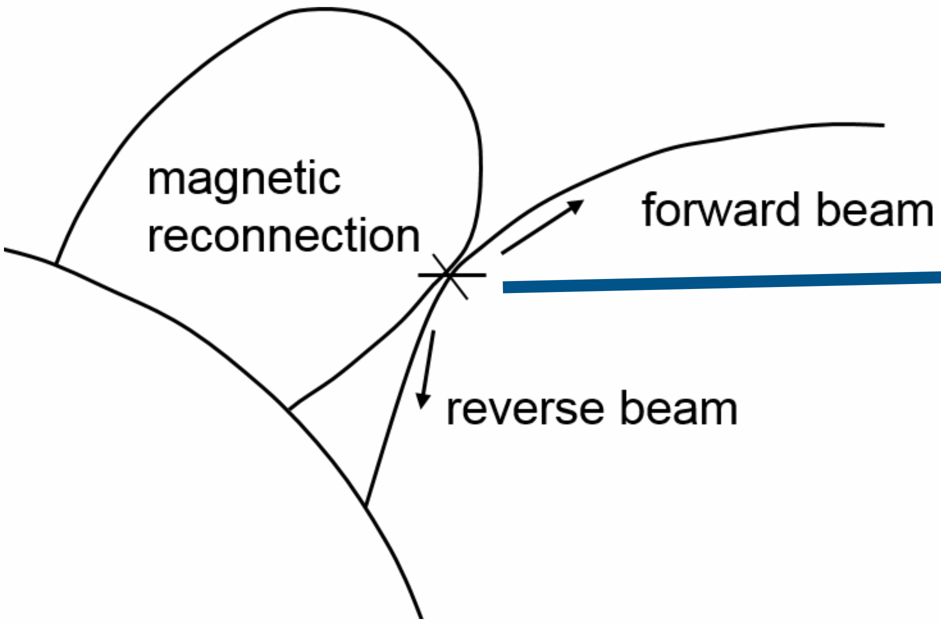
A type III burst is a radio signature of an electron beam initially generated at a flare. It travels along magnetic field lines through the corona and emits radio waves.
(Wild et al., 1952)

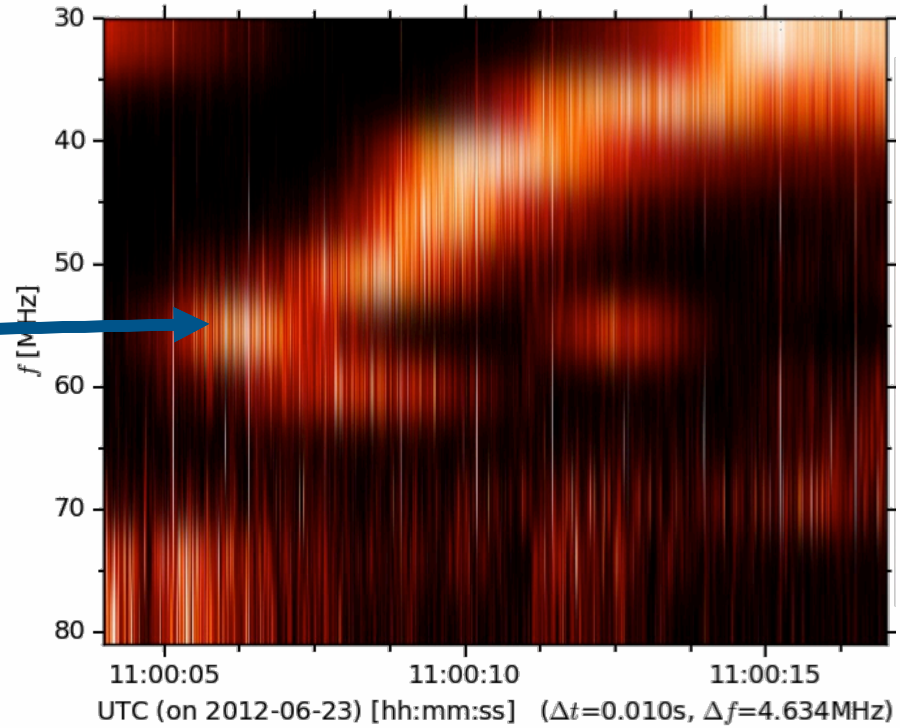
Solar Type III Radio Burst Observed with LOFAR I

During LOFAR's commissioning phase, several type III bursts were observed on March 26, 2012.



Solar Type III Radio Burst Observed with LOFAR II

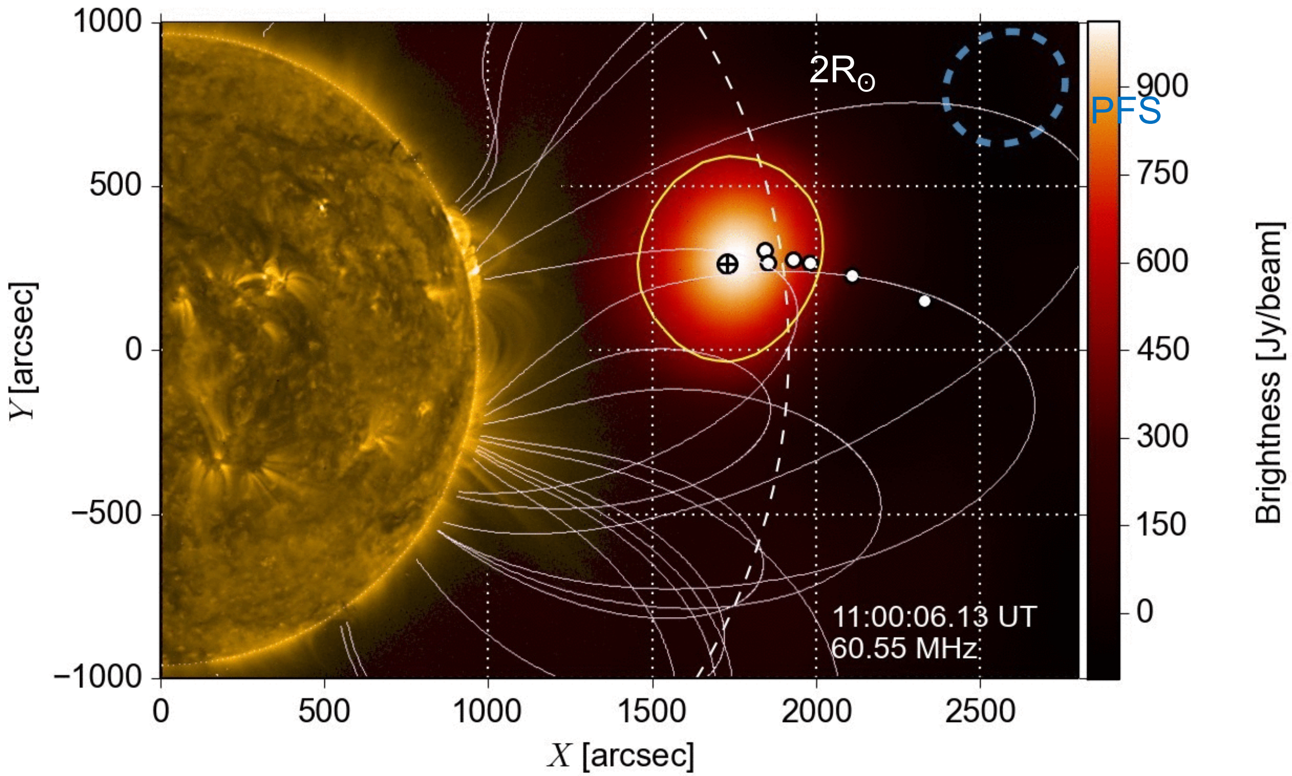




With LOFAR we can immediately look into the primary acceleration site.

It is not possible with other instruments working in other spectral ranges.

Solar Type III Radio Burst Observed with LOFAR III



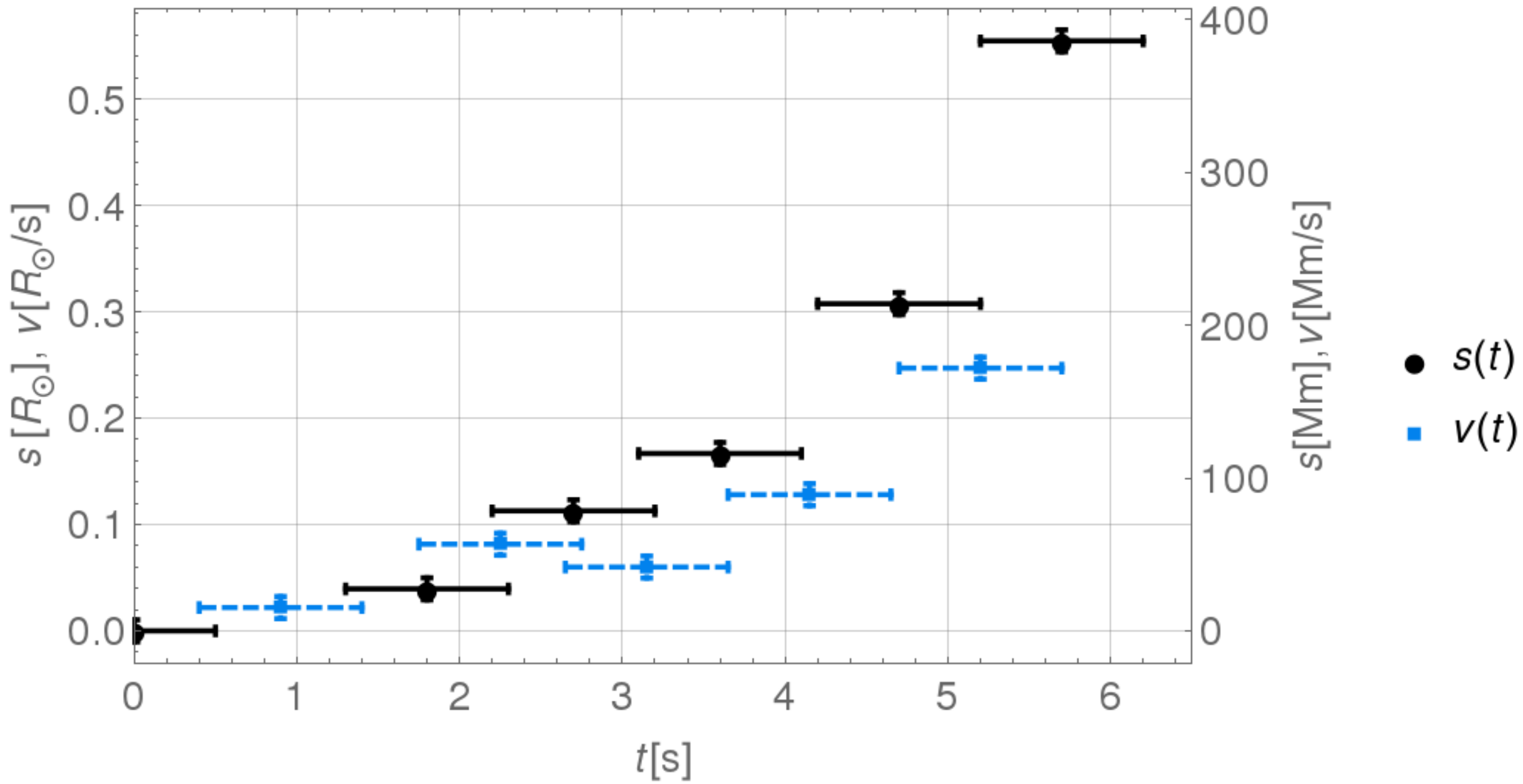
FWHM source width from Gaussian fit

f [MHz]	major axis	minor axis
60.5	11.0'	10.2'
55.5	8.7'	6.7'
50.4	11.3'	7.3'
45.3	12.2'	7.5'
40.2	15.2'	8.2'
35.2	16.6'	9.2'
30.1	21.7'	10.5'

– extrapolation of photosphere magnetic field into the corona (Potential-Field Source-Surface method *(Schrijver & De Rosa, 2003)*)

Propagation along the coronal magnetic field lines

Propagation velocity



velocity increases → since no large scale E-field → propagation effect

Electron-Beam Plasma Interaction I

AIP

An electron beam excites Langmuir waves which convert into escaping radio waves *(Melrose 1985).*

invitial distribution of an electron beam:

$$f_{beam}(V,s,t=0) \sim e^{-(V-V_b)^2/2v_w^2} \text{ x } e^{-s^2/2d^2}$$

The evolution can be described by a force-free Vlasor equation: $0 = \frac{\partial f}{\partial t} + V \cdot \frac{\partial f}{\partial s}$

solution: $f_{beam} \propto e^{-(V-V_b)^2/2v_w^2} \text{ x } e^{-(s-Vt)^2/2d^2} = e^{-W(V)/2}$

$$W(V) = \frac{\left(1+\frac{v_w^2 t^2}{d^2}\right)}{v_w^2} \cdot \left[V - V_{beam}\right]^2 + \frac{1}{d^2} \cdot \frac{(s-V_b t)^2}{\left(1+\frac{v_w^2 t^2}{d^2}\right)} \quad \text{with} \quad V_{beam} = \frac{\left(V_b + \frac{v_w^2 st}{d^2}\right)}{\left(1+\frac{v_w^2 t^2}{d^2}\right)}$$

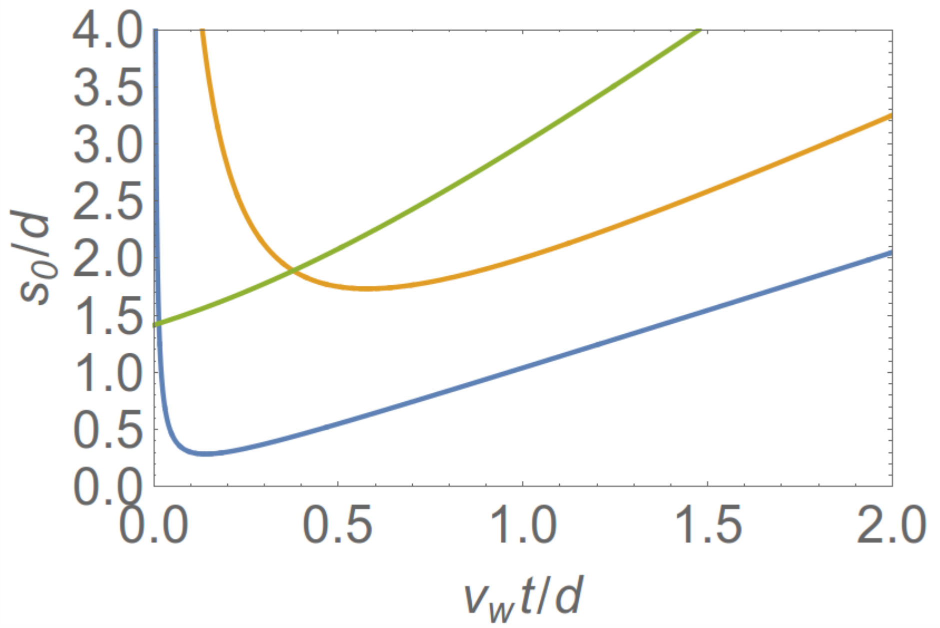
Note: For $V_b = 0$; i.e. no initial beam distribution, an electron beam develops due to the spatio-temporal evolution of the distribution function. Then, the beam is formed by different parts of the electron ensemble at different positions and times.

Electron-Beam Plasma Interaction II

at $V = V_{beam}$:

$$s_0(t) = V\,t + \frac{d^2}{v_w^2}\cdot\frac{(V - V_b)}{t} < s_{max}(t) = V_b t + d\cdot\sqrt{2\left(1 + \frac{v_w^2 t^2}{d^2}\right)}$$

- pure electron beam: $V = V_b$, $\rightarrow$ $s_0\,(t) = V_b \cdot t$



The observed path-time diagram can be reproduced by an electron ensemble of different velocities and its resulting velocity dispersion.

(Mann et al., 2017, A&A, subm.)

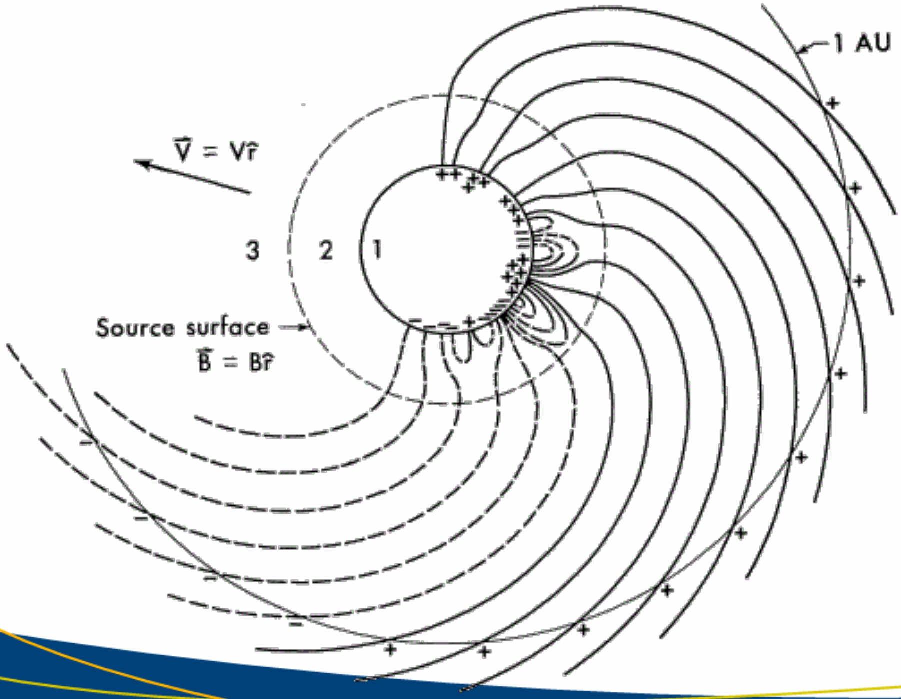
Conclusions

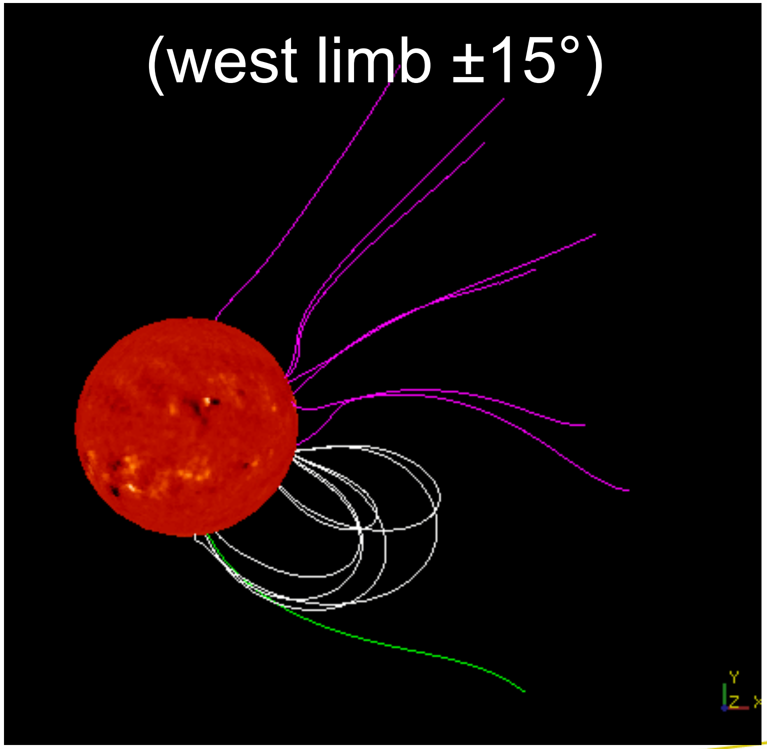
- LOFAR can really work as a ***dynamic spectroscopic radio imager*** of the Sun
  (→ LOFAR opens a new window, indeed.)
- The solar imaging pipeline works well.
- LOFAR confirms, that solar type III radio bursts are really generated by beams of energetic electrons travelling along magnetic field lines.
  (see also *Klein et al. 2008)*
- **With LOFAR, processes associated with energetic electrons** (e.g. fast motions of electrons) **can be observed in the corona as never possible with other instruments** (e.g. in the visible and X-ray range).

Thank you for your attention !

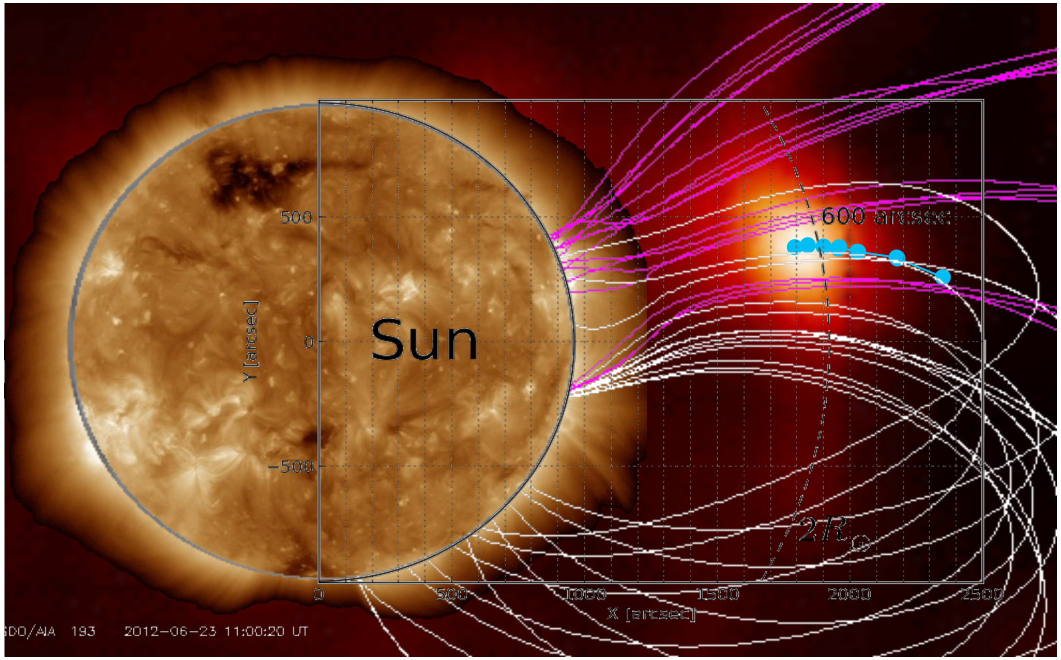
The solar magnetic field

- *Potential-field source-surface* (PFSS) method
  - Package for the Solarsoft IDL library by Schrijver & De Rosa 2003
  - *B*-field from SDO/HMI





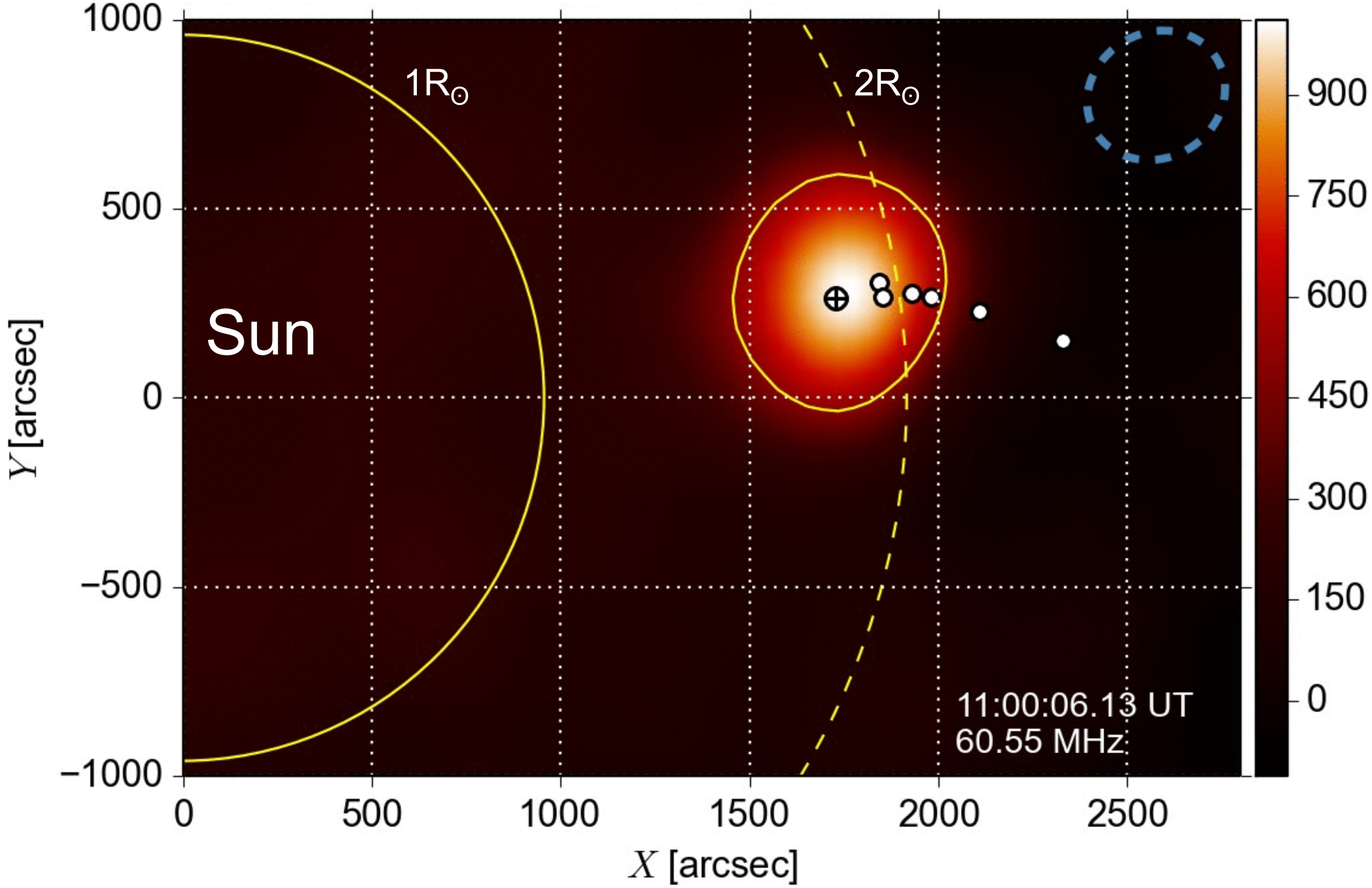
Solar Type III Burst III



The photospheric magnetic field was extrapolated using the Potential-Field Source-Surface (PFSS) method provided by the SolarSoft program package. *(Schrijver & De Rosa, 2003)*

LOFAR confirms that type III bursts are generated by electron beams propagating along (closed) magnetic field lines.

New LOFAR Type III burst images



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- Propagation path in high time and frequency resolution
- Source size increases with distance to Sun