Leibniz-Institut für Astrophysik Potsdam

LOFAR Observations of Energetic Electrons in the Sun's Atmosphere

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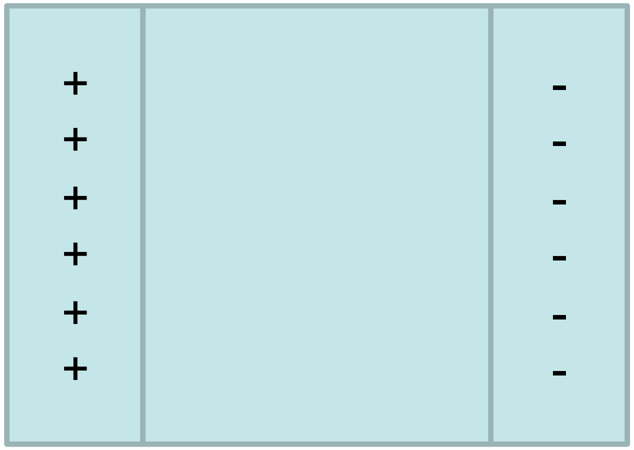
Plasma Emission

corona – fully ionized plasma



local charge separation
→ Langmuir waves

fundamental emission:

ω_R	=	ω_L	+	ω_{LF}
radio		Langmuir w.		LF plasma waves

harmonic emission:

ω_R	=	ω_L	+	ω_L
radio		Langmuir w.		

$f_R = nf_{pe}$

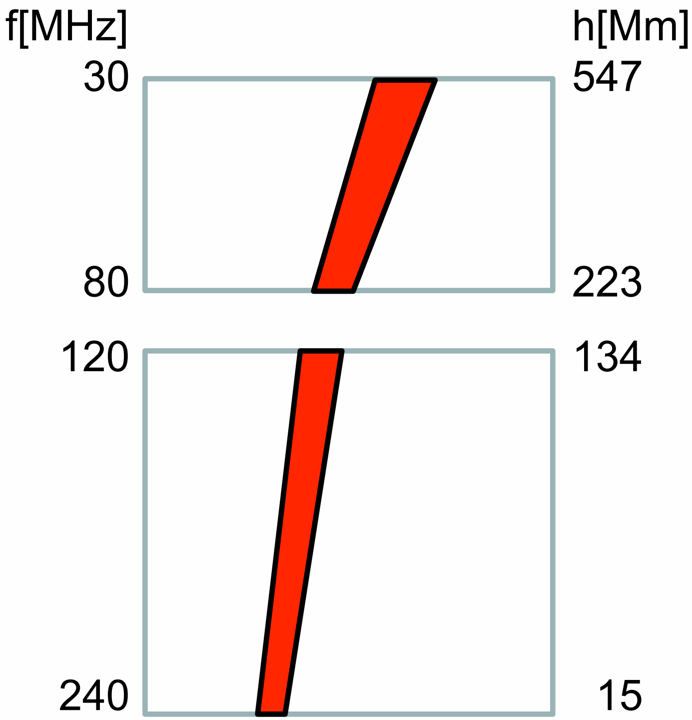
n=1: fundamental emission

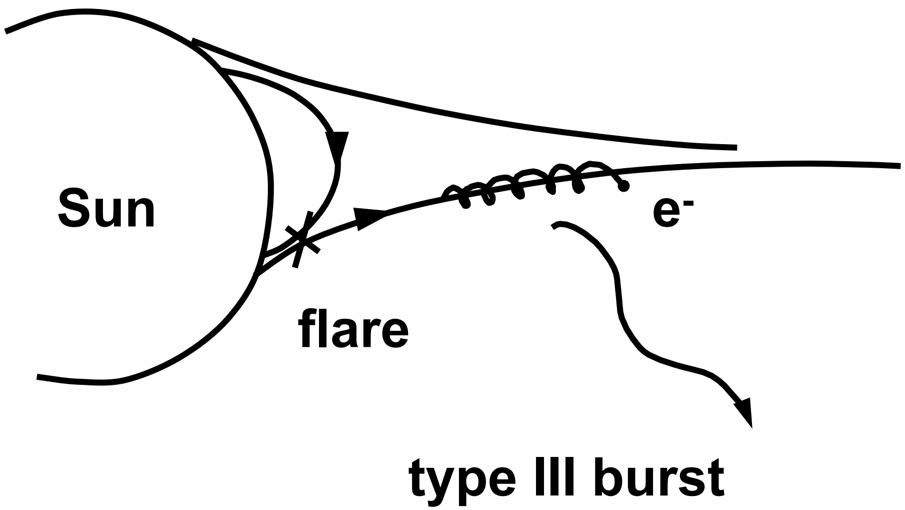
n=2: 1st harmonic emission

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 N_e}{\varepsilon_0 m_e}}$$

plasma frequency

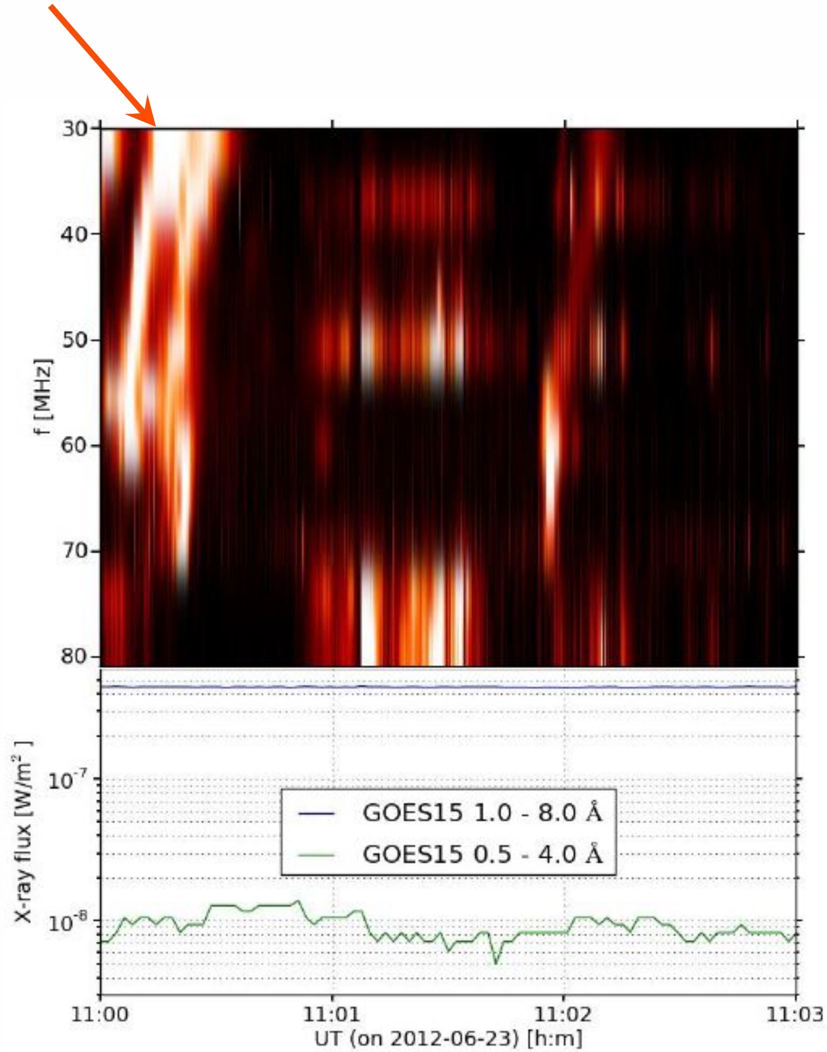
Solar Type III Radio Bursts





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



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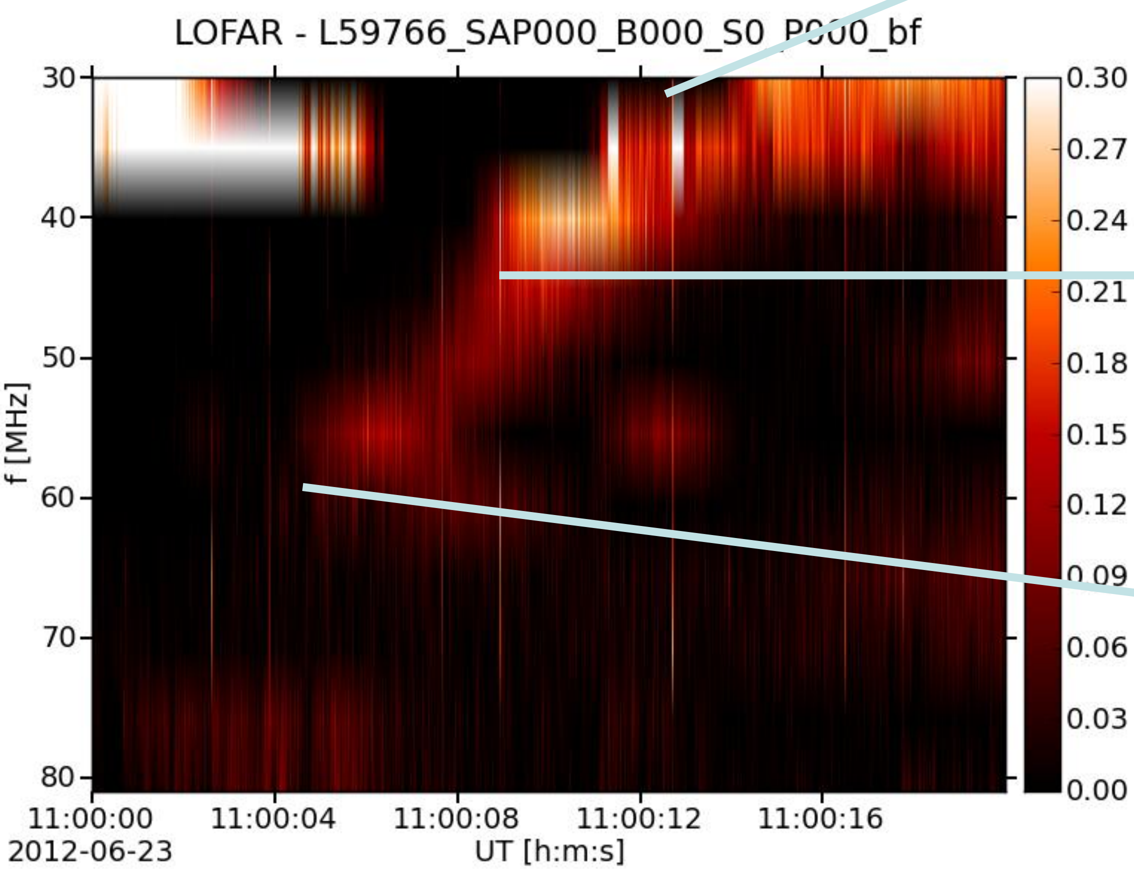
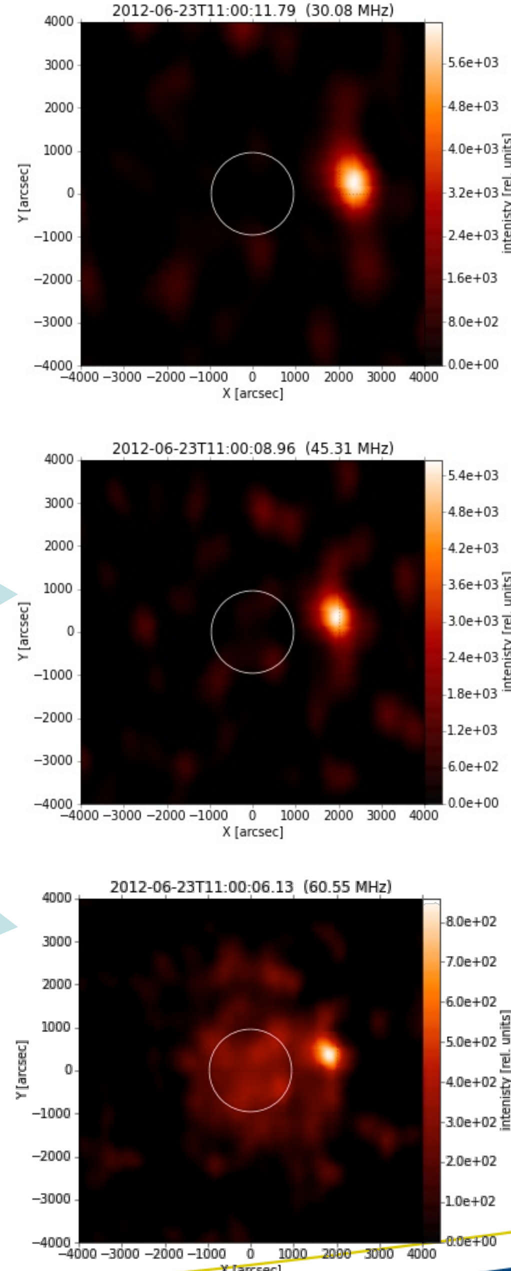
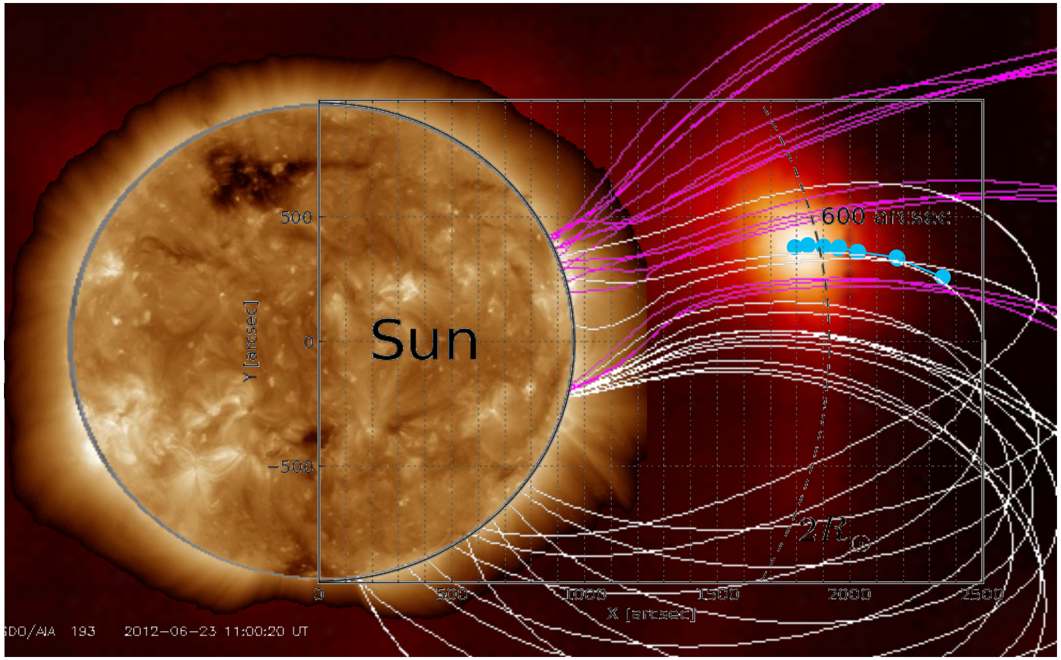
Solar Type III Burst II





Solar Type III Burst III

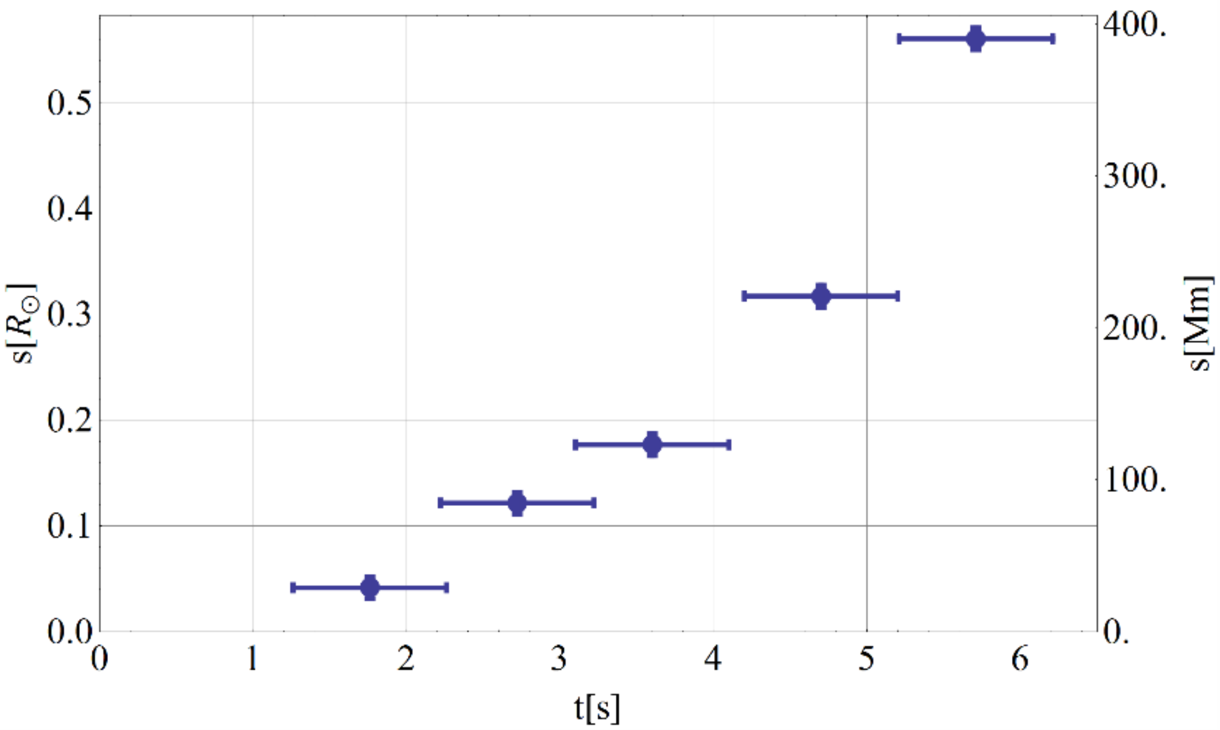


The photospheric magnetic field was extrapolated using the Potential-Field Source-Surface (PFSS) method provided by the SolarSoft program package. *(Schrijver & De Rosa, 2003)*

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

Solar Type III Bursts IV

path-time behaviour of the radio source



$s = a\,t^2$ with $a = 10.5$ Mm/s^2

Beam Plasma Interaction I

velocity distribution function: $f = f_{background} + f_{beam}$

at $t = 0$: $$f_{beam} \sim e^{-(V-V_b)^2/2v_{th,b}^2} \times e^{-s^2/2d^2}$$

V_b = beam velocity
$v_{th,\,b}$ = width of the beam
d = acceleration length

spatio-temporal evolution:

$$0 = \frac{\partial f}{\partial t} + V\frac{\partial f}{\partial s} \quad \rightarrow \quad f(V,s,t) = f(V, s - Vt, t = 0)$$

$$f_{beam} \sim e^{-(V-V_b)^2/2v_{th,b}^2} \times e^{-(s-Vt)^2/2d^2}$$

Beam Plasma Interaction II

normalization: $u = V/v_{th,\,b}$

$u_b = V_b/v_{th,\,b}$

$\xi = s/d$

$\tau = v_{th,\,b}\, t/d$

$$f_{beam} \sim e^{-E(u)/2}$$

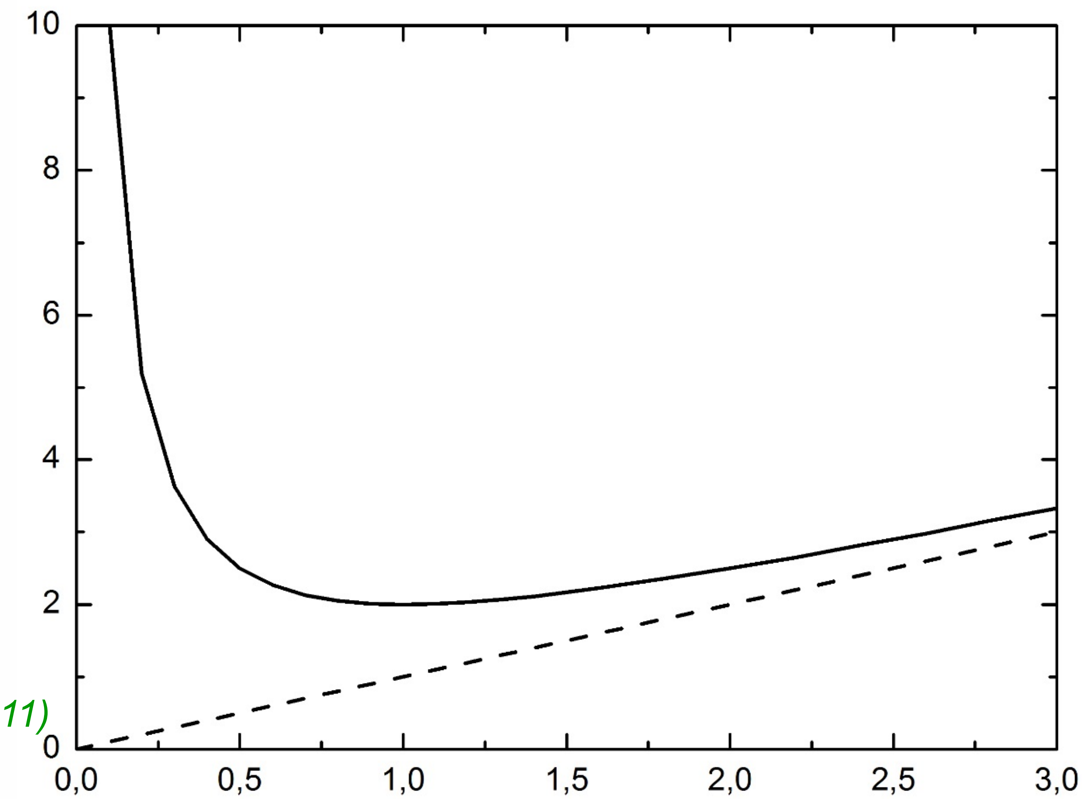
with $E(u) = (u - u_b)^2 + (\xi - u\tau)^2$

beam plasma instability:

$$\frac{\partial f_{beam}}{\partial u} > 0$$ *(see e.g. Reid et al., 2011)*

$$\xi > \xi_0(\tau) = \frac{(u - u_b)}{\tau} + u\tau$$

if $u \approx u_b \quad \rightarrow \quad \xi_0(\tau) = u_b\,\tau$



For a pure beam, $\xi_0\ (\tau)$ is a straight line!

Beam Plasma Interaction III

now $u_b = 0$:

$$\xi_0(\tau) = u^2 \frac{(1+\tau^2)}{\tau}$$

It has a minimum at $\tau_{min} = 1$ and $\xi_{min} = \xi_0(\tau = 1) = 2u$

$$\Delta\xi = \xi_0(\tau) - \xi_{min} = u\frac{(\tau-1)^2}{\tau}$$

If the highly energetic electrons establish a broad distribution, then $\xi_0(\tau)$ behaves near ξ_{min} as a parabolic function as observed by LOFAR.

Furthermore

$$E(u) = (1+\tau^2)\left[u - \frac{\xi\tau}{(1+\tau^2)}\right]^2 + \frac{\xi^2}{(1+\tau^2)}$$ at $u = u_{beam}$ $$E(u) = u_{beam}^2 \cdot \frac{(1+\tau^2)}{\tau^2}$$

Owing to the spatio-temporal evolution a beam like distribution is established with

a beam velocity $u_{beam} = \dfrac{\xi\tau}{(1+\tau^2)}$ and a width $\dfrac{1}{\sqrt{1+\tau^2}}$

Discussion

with $\tau = 1 + \Delta\tau$

$$\Delta\xi = u\,\frac{(\Delta\tau)^2}{(1+\Delta\tau)}$$

$$s = V\,\frac{v_{th,b}}{d}\cdot t^2$$

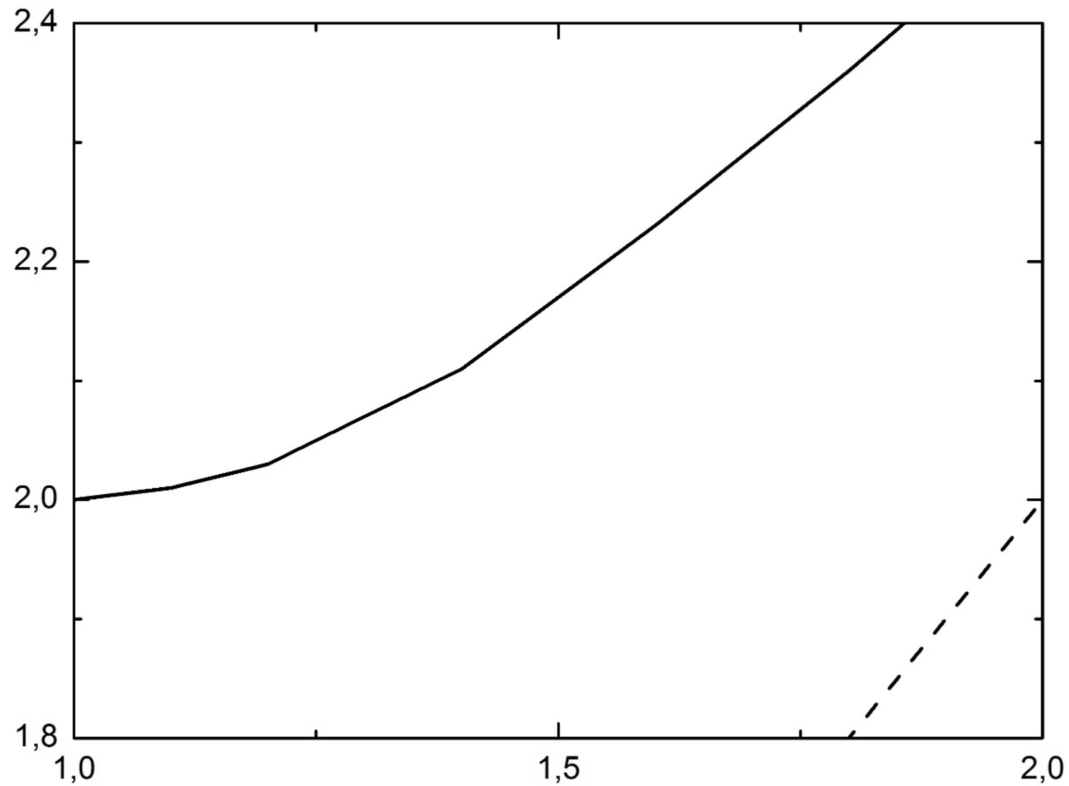
$$a = V\,\frac{v_{th,b}}{d}$$

identifying

$t = 5.71$ with $\tau = 0.6$

then: $v_{th,b}/d = 0.12\ s^{-1}$

and V = 100 Mm/s = c/3



Conclusions

In the framework of LOFAR's commissioning phase, we demonstrated:

- The solar imaging pipeline works well.
- LOFAR can really work as a ***dynamic spectroscopic radio imager*** of the Sun
  (→ LOFAR opens a new window, indeed.)
- 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)*
- Solar type III radio bursts are generated by a broad electron distribution and **not** by an pure electron beam.

Thank you for your attention!

This work was done
in collaboration
with the solar KSP and
LOFAR/ASTRON team