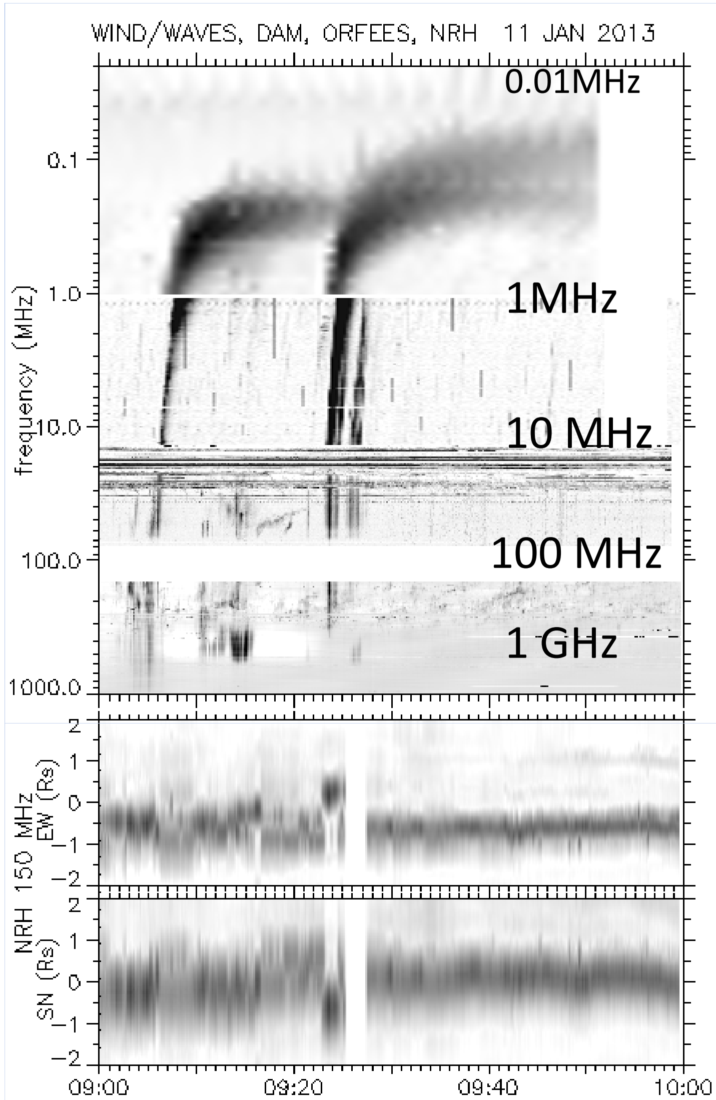


http://secchirh.obspm.fr

Observations of the active Sun in the MHZ to GHz range

Nicole Vilmer

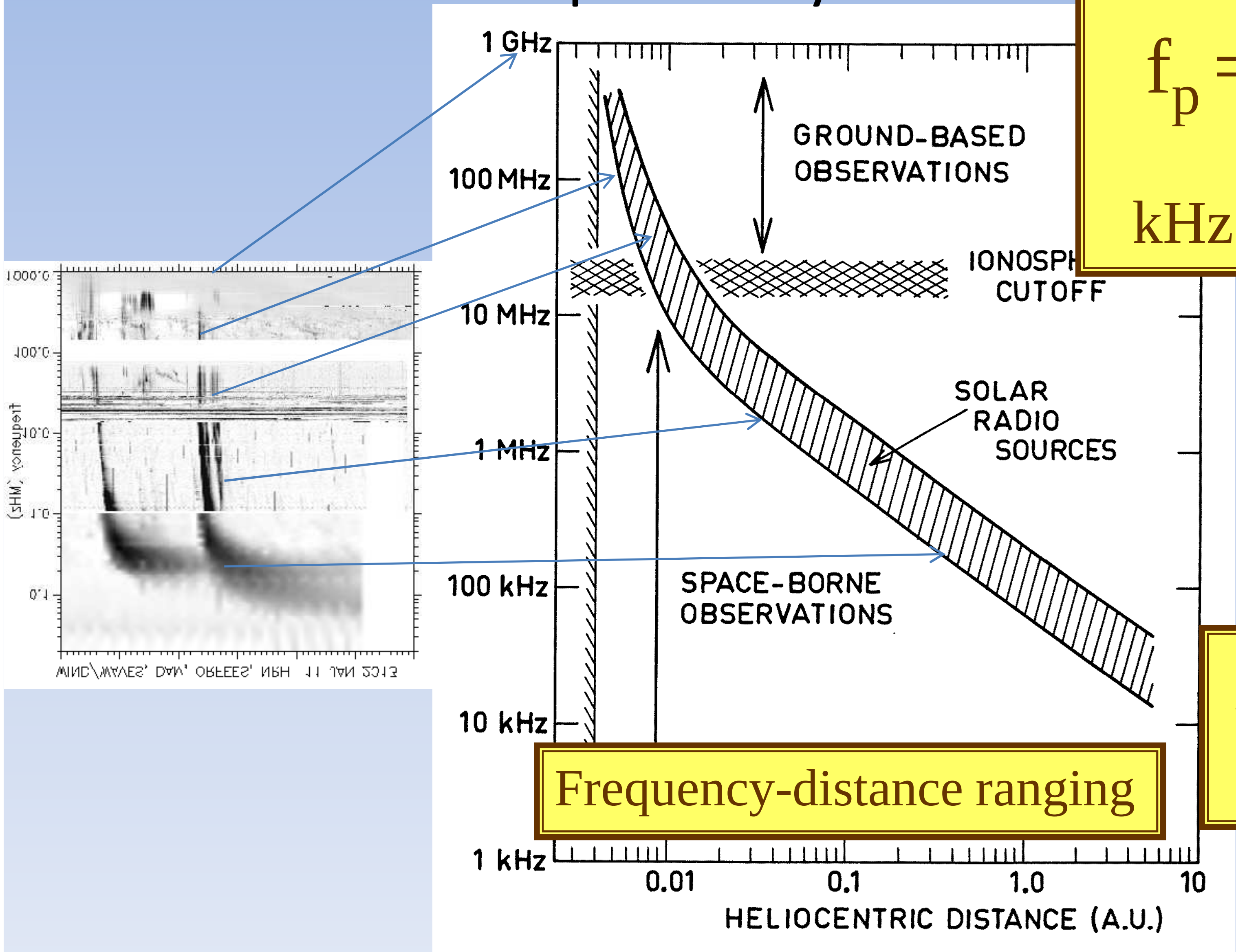
LESIA –Paris Observatory- CNRS- UPMC- Paris Diderot

l'Observatoire de Paris — LESIA

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Solar ALMA workshop ***14-17 January, 2013, Glasgow***

Radio emissions in the corona and the interplanetary medium



$$f_p = 9 \sqrt{N_e}$$

kHz $\quad cm^{-3}$

Frequency-distance ranging

in IP space

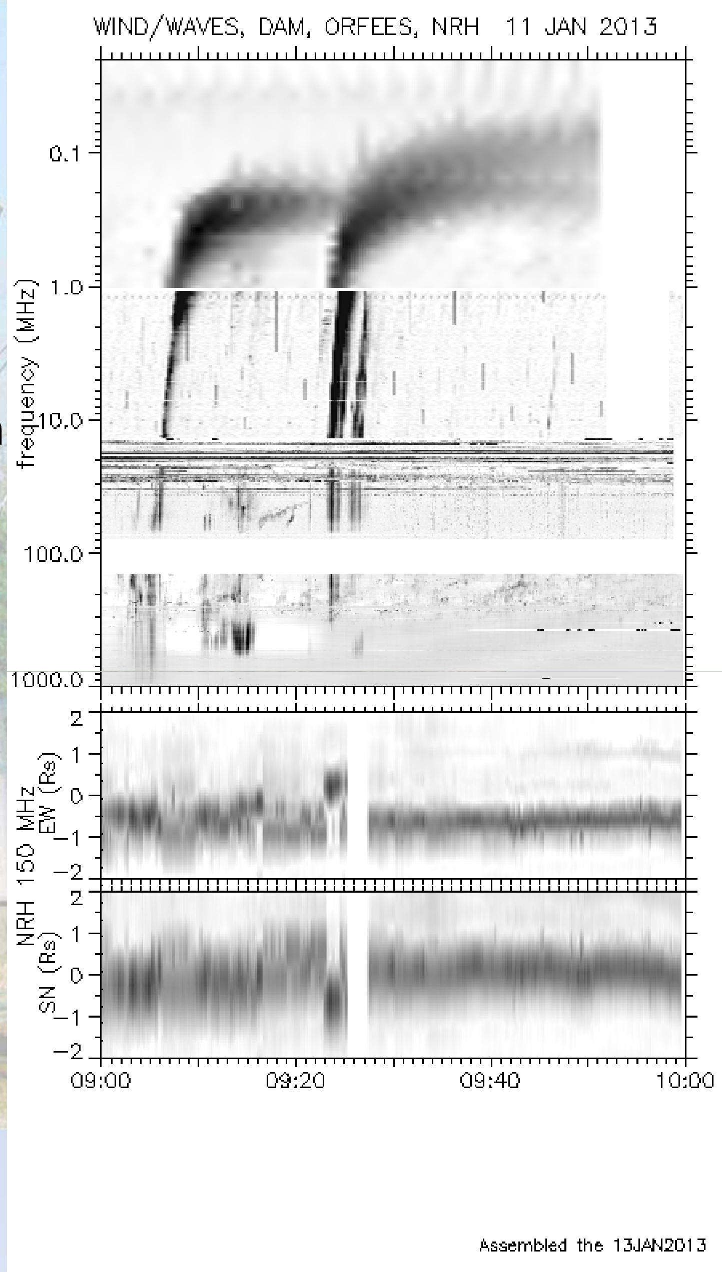
$f \approx R^{-1}$

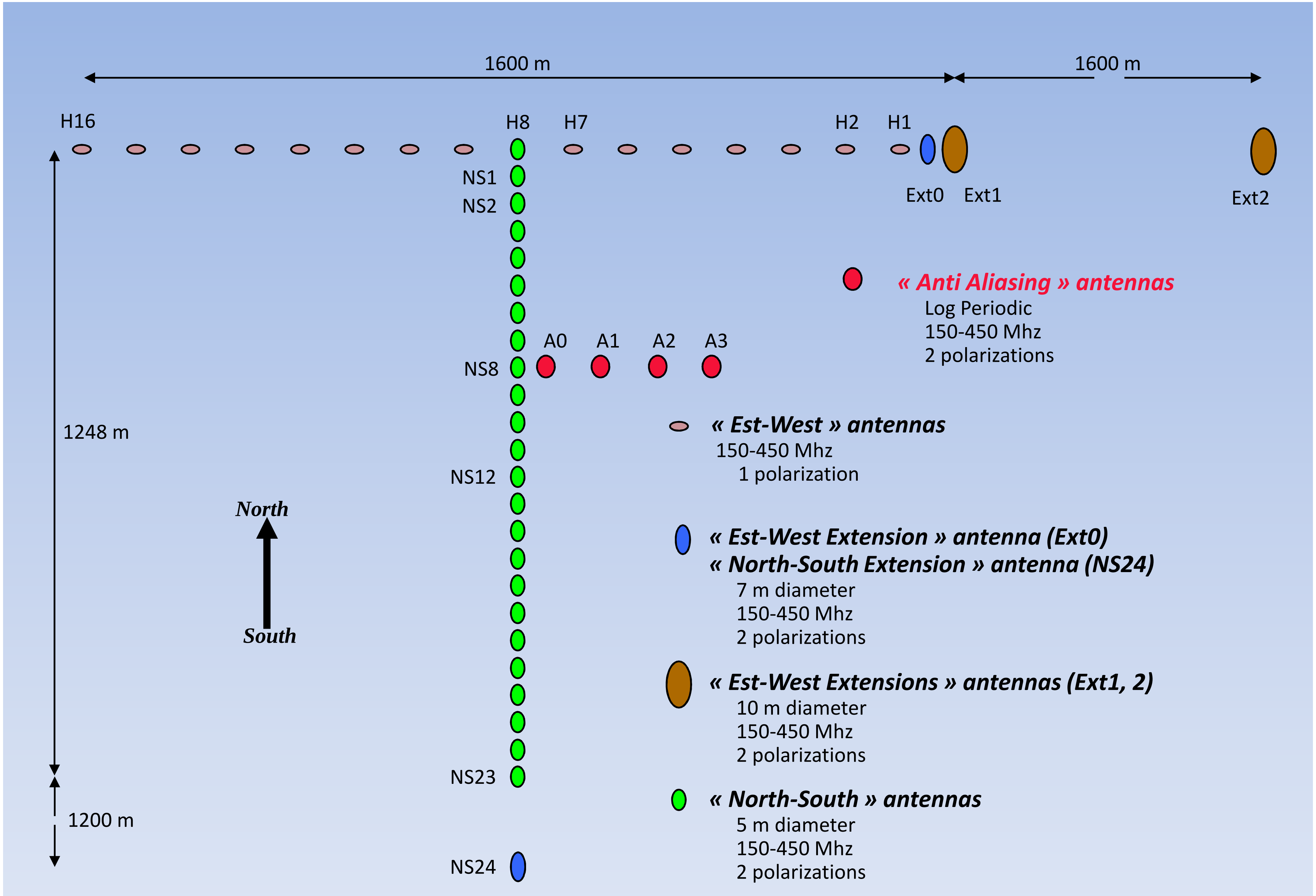
Nançay Radioheliograph (NRH)

General characteristics

- Frequency range: 150 - 450 MHz
- Baselines from 50 to 3200m (25 to 4,800 λ)
- 576 baselines (with some redundancies)
- Spatial resolution: ~4 to 0.3 arcmin (depending on frequency, declination, snapshot/synthesis)
- Full Sun
- Stokes I and V
- Time resolution: 5 ms* number of frequencies

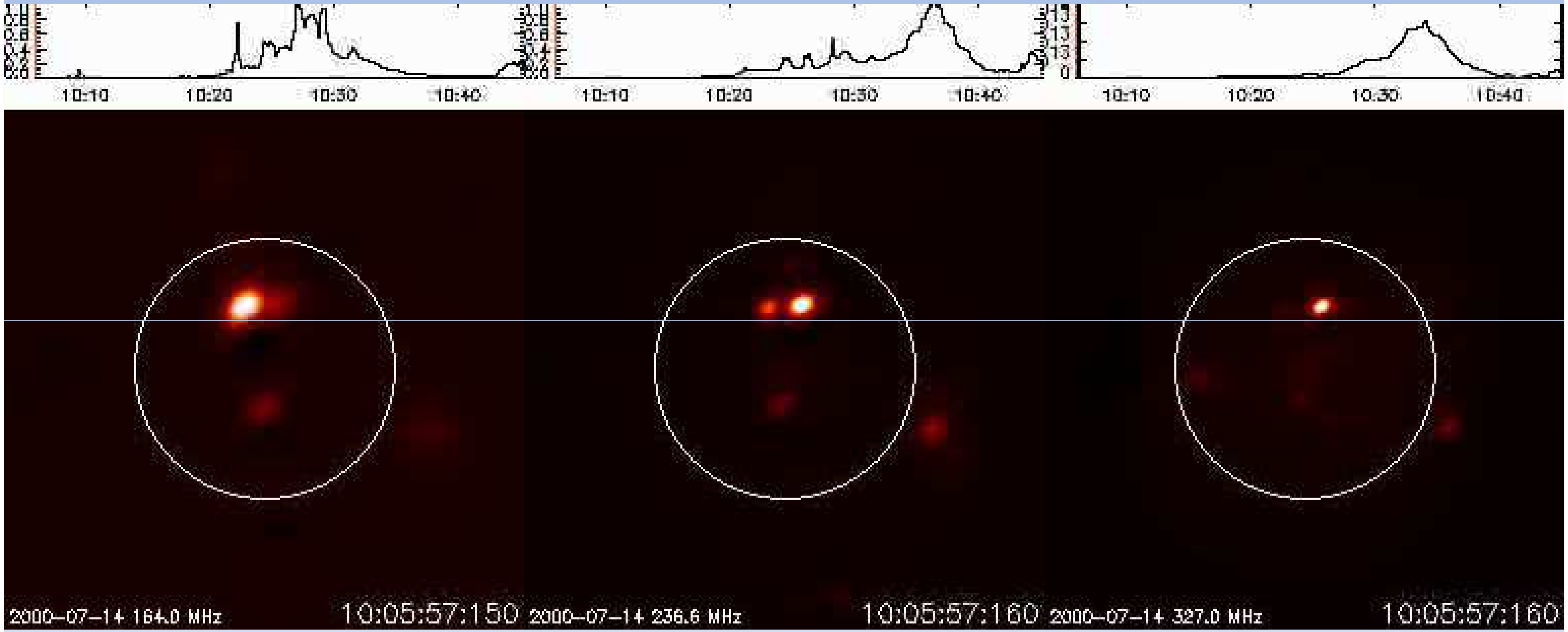
NRH





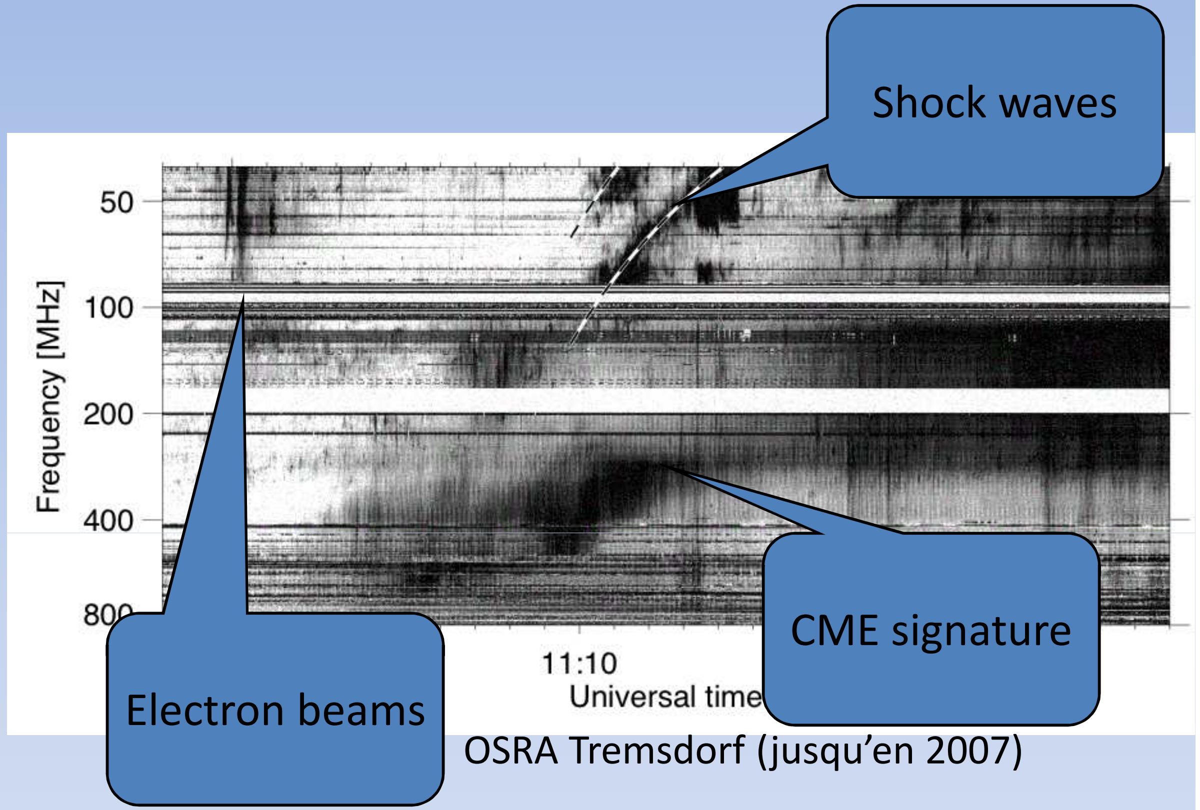
Nançay Radioheliograph array configuration

SOLAR ACTIVITY IN THE 100 MHZ RANGE



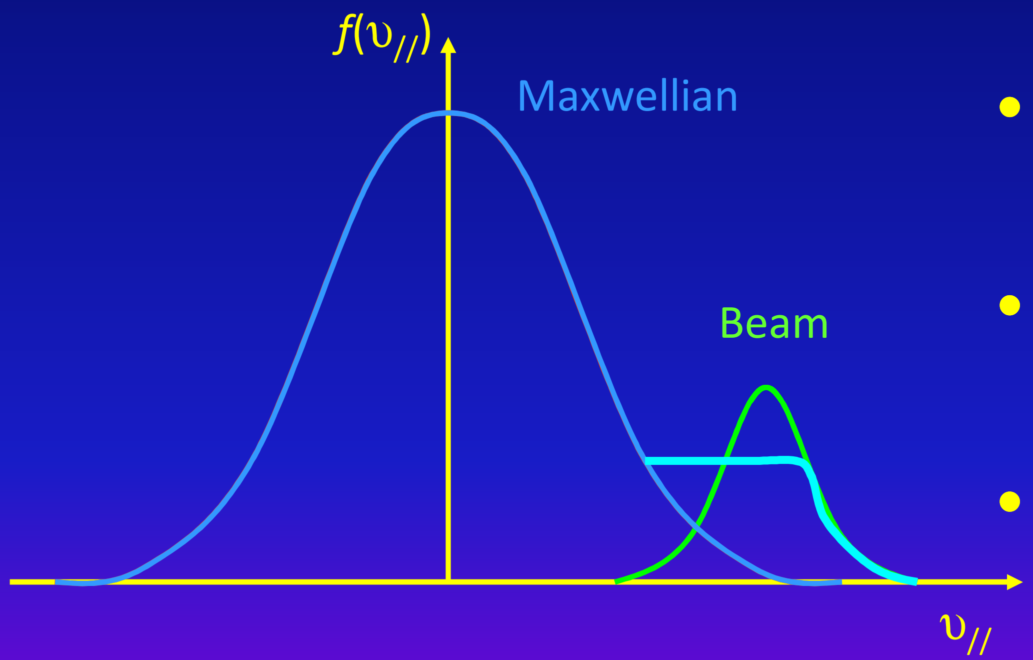
The Bastille Day Flare observed with the Nançay Radioheliograph (courtesy K.L. Klein)

Radio images and spectra



OSRA Tremsdorf (jusqu'en 2007)

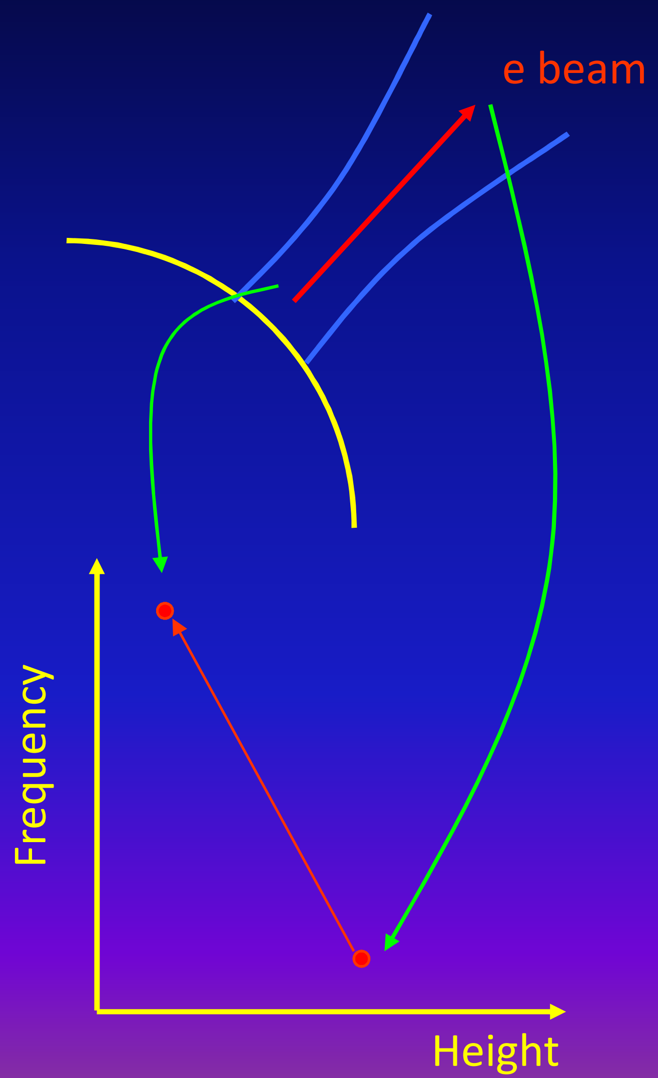
Radio emission from electron beams



- Beam generated by velocity dispersion
- “Bump in tail” instability
- $\partial f/\partial \upsilon_{//}>0$: growth of Langmuir waves
- Plateau (quasi-linear relaxation) ?

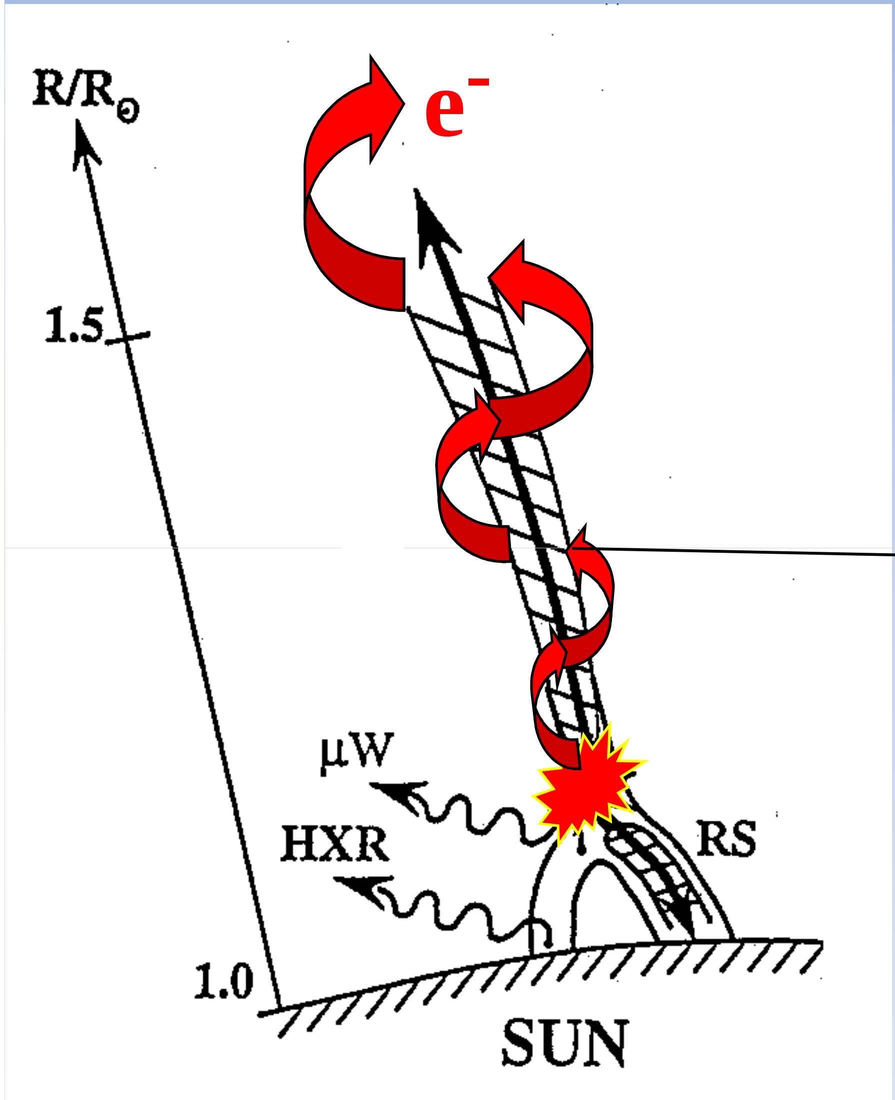
The Langmuir waves cannot escape from the plasma, but …

Electron beams and EM waves

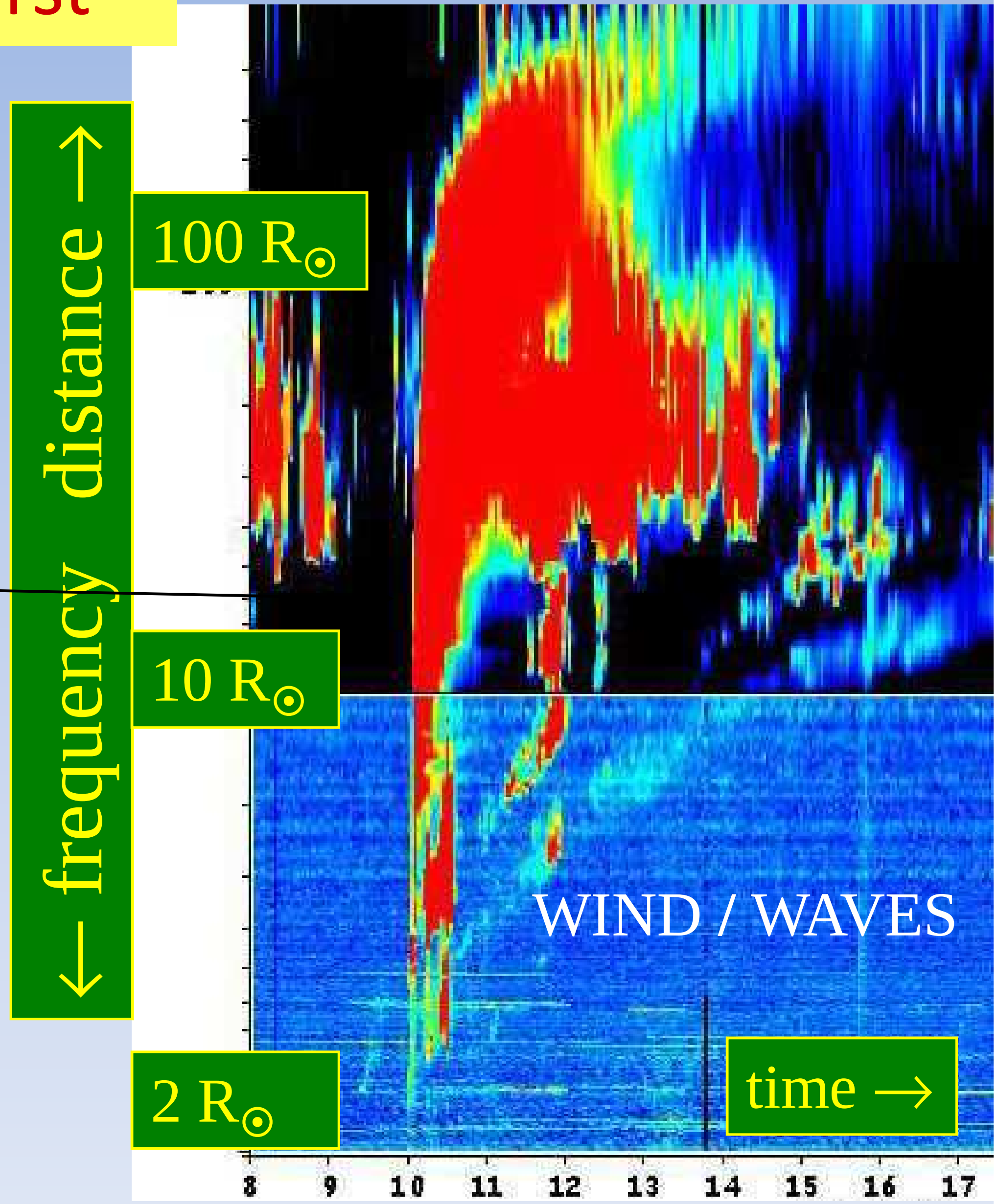


- Coupling of waves (L=Langmuir, T=transverse EM, S=ion-sound):
  - L+S$\longrightarrow$T (dominant in IP medium)
  - L+L$\longrightarrow$T (dominant in the corona)
- Conservation of $h\nu$:
  - $\nu_T = \nu_L + \nu_S \approx \nu_L \approx \nu_{pe}$ "fundamental"
  - $\nu_T = \nu_L + \nu_L = 2\nu_L \approx 2\nu_{pe}$ "harmonic"

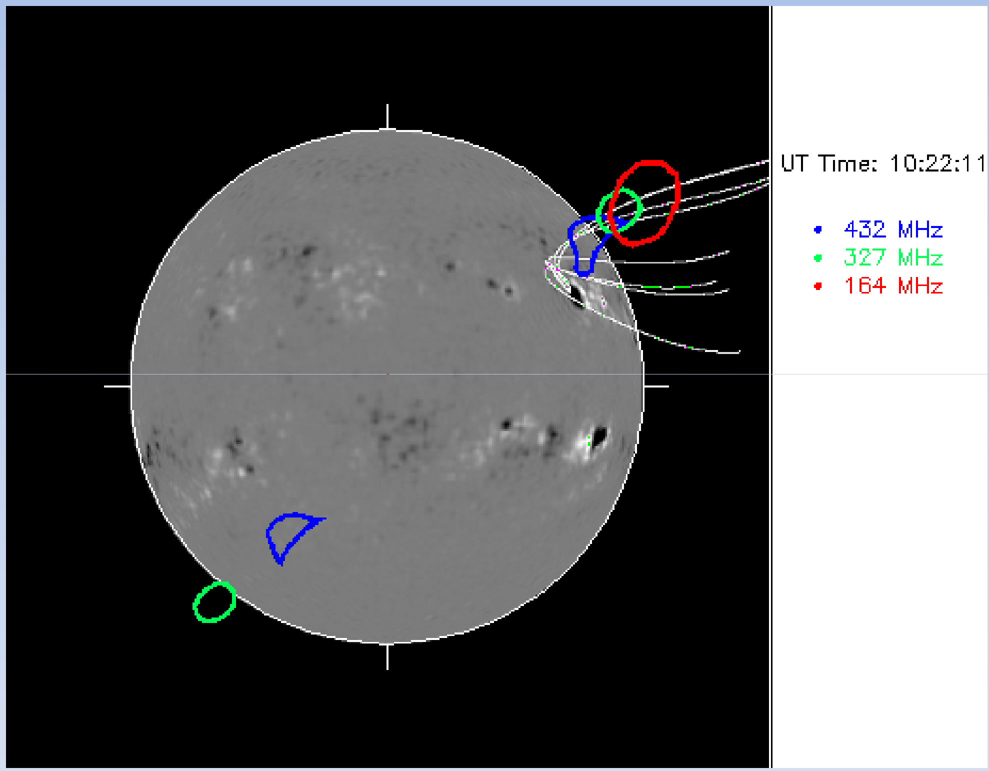
Type III radio burst

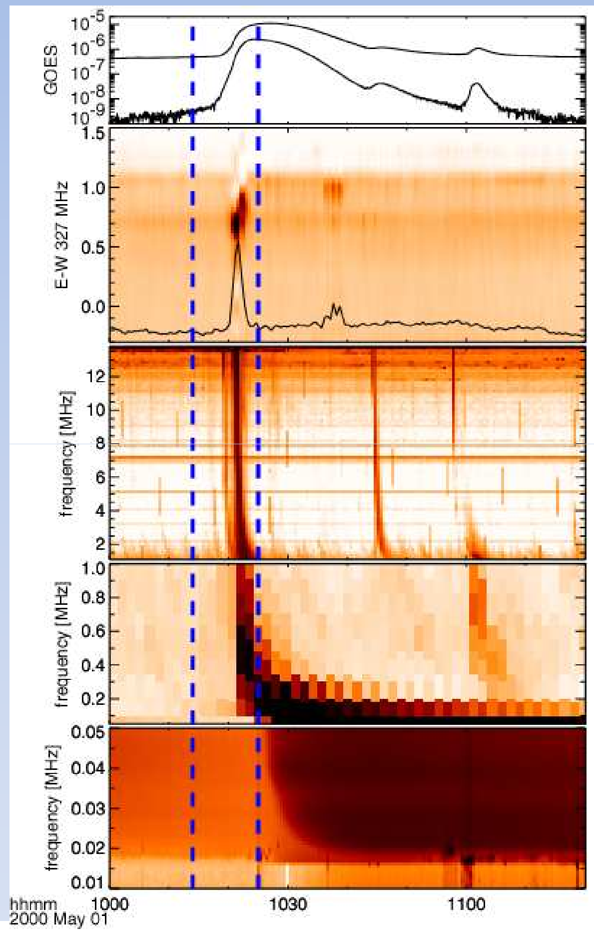


(adapted from Marcus Aschwanden)



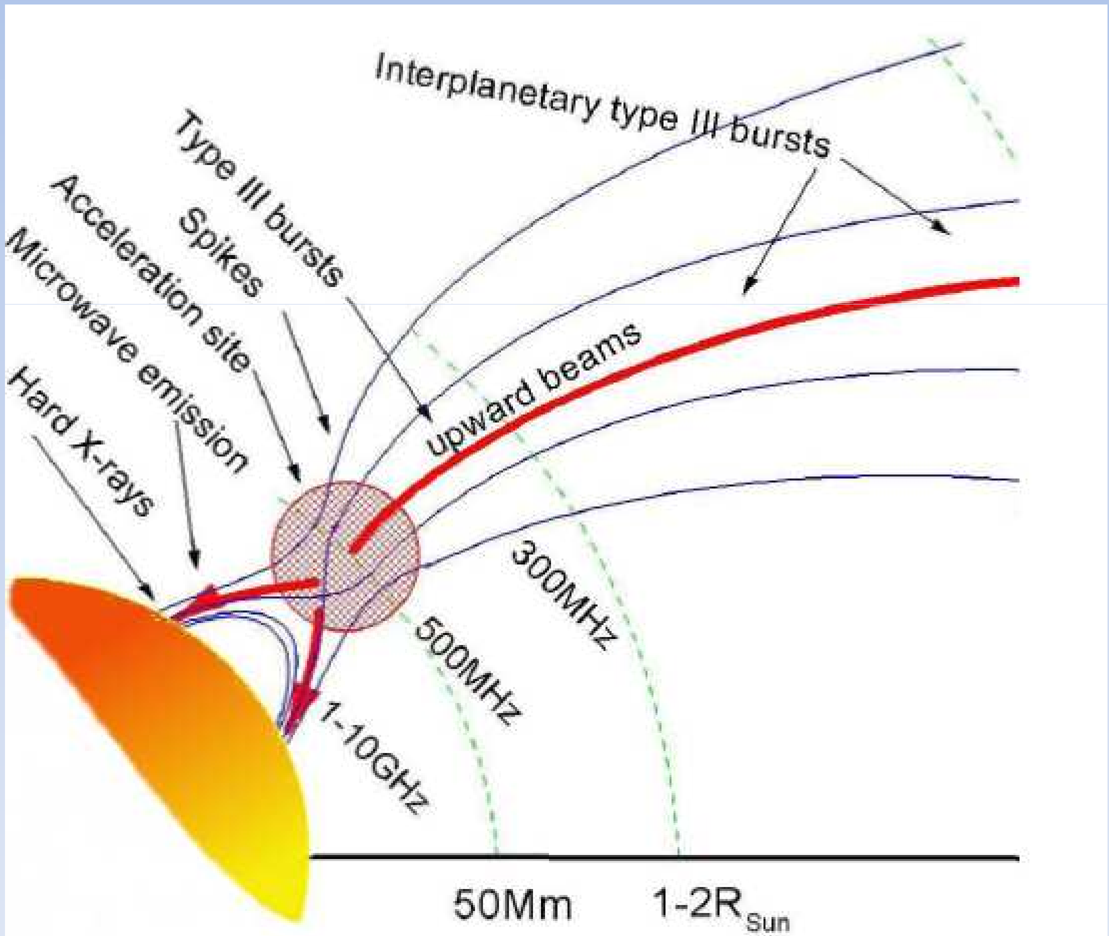
Propagation of electron beams in coronal magnetic flux tubes



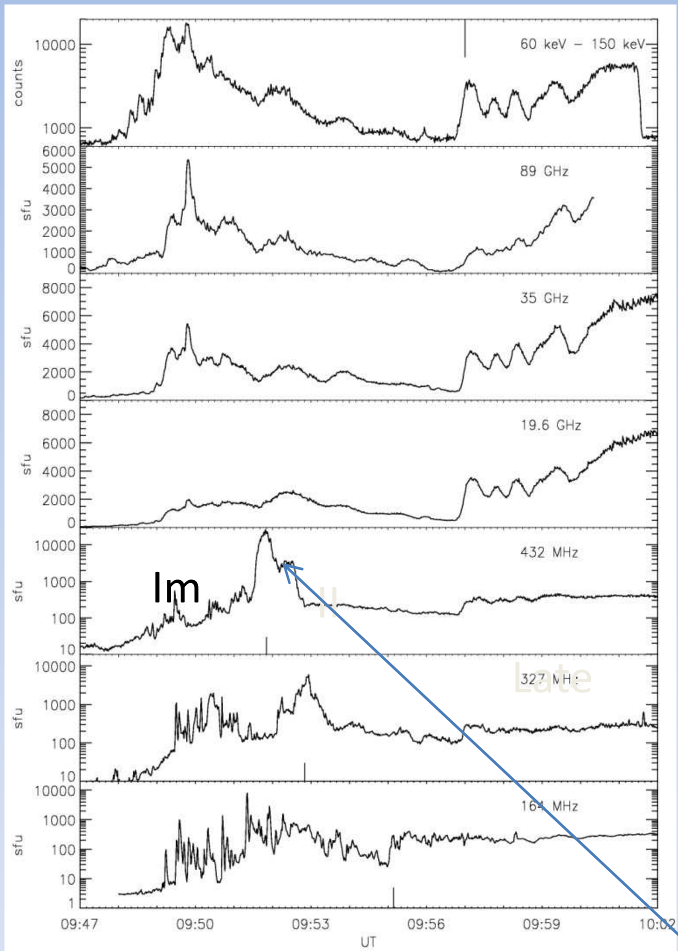


Electron beams in open magnetic flux tube inferred from PFSS model (Schrijver & DeRosa 2002, Solar Phys.; model available within SolarSoft).

Radio observations in the MHz-GHz range: input to the understanding of electron acceleration and propagation in the corona towards the interplanetary medium



Energetic Electrons in Solar Flares: Radio and X-ray Diagnostics



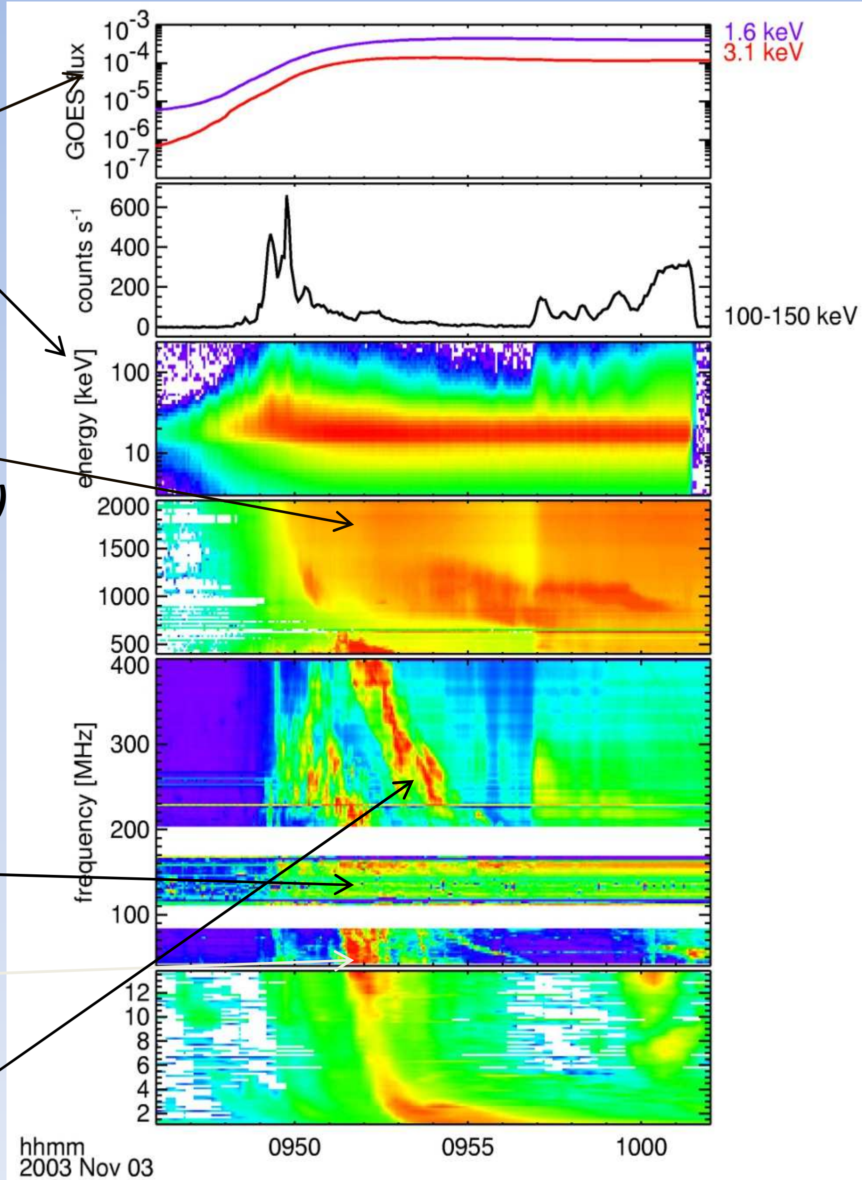
X-rays

Microwaves
Gyrosynchrotron
Emissions
$f_b(Hz) = 2.8\ 10^6\ B\ (G)$

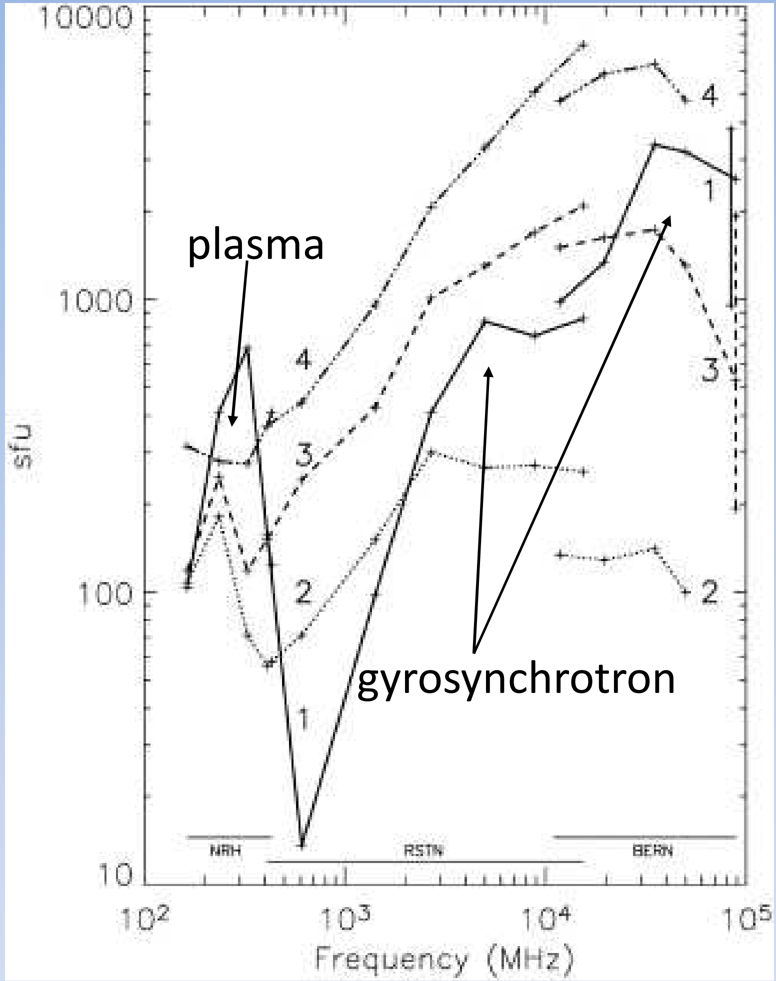
Meter waves
Plasma
emissions
$f_p(kHz) = 9\sqrt{n_e}\ cm^{-3}$

Type III
bursts
(electrons)

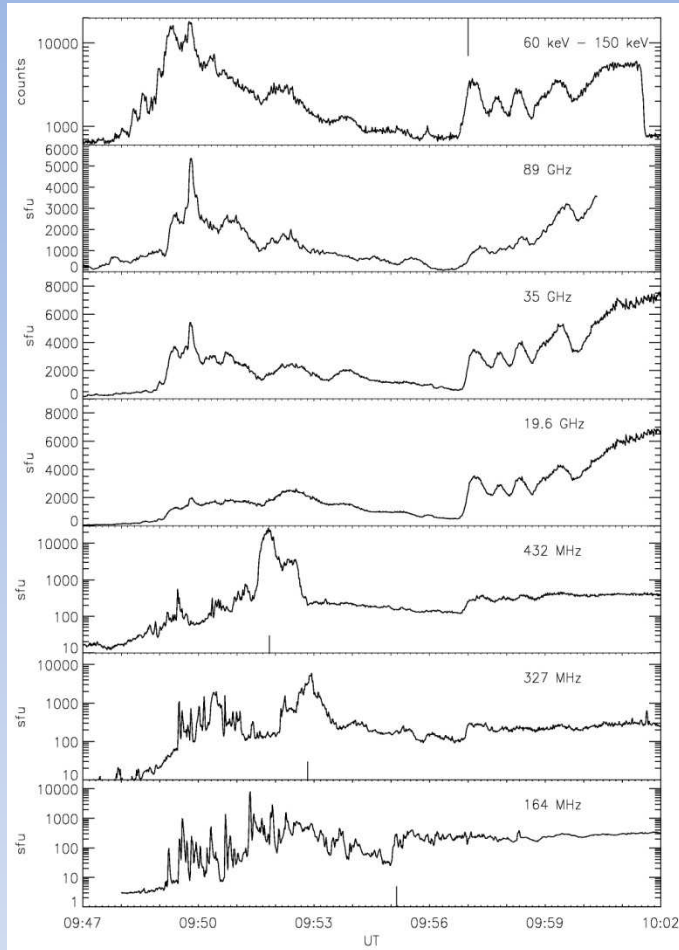
Type II burst
(shocks)



Dauphin et al., 2005
Dauphin, Vilmer, Krucker, 2006



s



Combined radio spectrum
1 first part
2 before modulations
3 four modulations to 09:59:50 UT
4 fifth modulation from 10:00:00 UT
Adjustment between NRH and RSTN at 410 MHz
No adjustement with Bern

Dauphin et al., 2005

Solar Flare Electron Acceleration

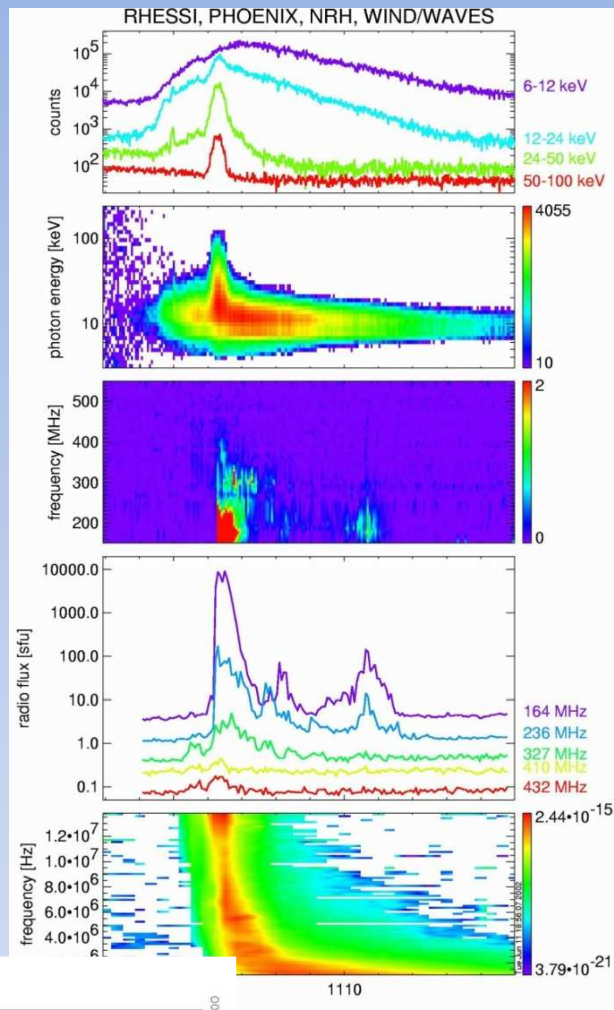
Standard picture

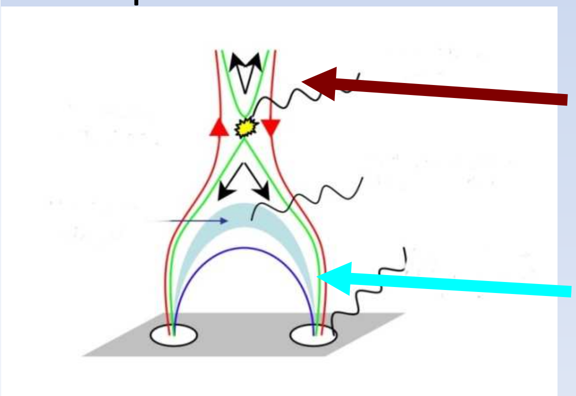
Electrons travelling downwards into the chromosphere radiate X-rays in dense ($n_e=10^{12}$ cm^{-3}) plasma via Bremsstrahlung. Detected X-rays are usually in the 6-100 keV energy range

Electrons travelling upwards can induce Langmuir waves which in turn produce coherent radio emission (type III) in the rarefied ($n_e<10^9$ cm^{-3}) coronal and interplanetary plasma. Detected radio frequencies are from around 400 MHz down to 2

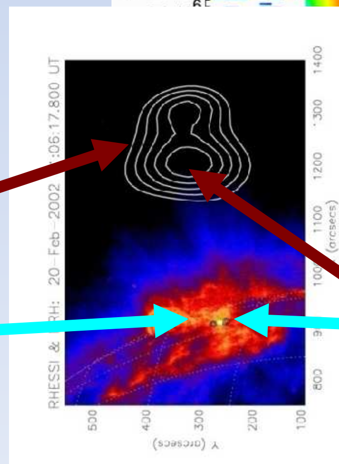
X-RAYS

RADIO





Standard picture:
Electron acceleration in the corona
Propagation both upwards and downwards.



Vilmer et al. 2002

NRH and RHESSI observations

HXR – Type III Statistical Connection

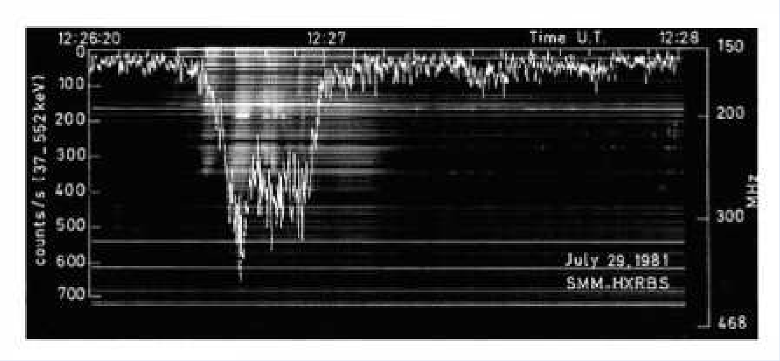
Simultaneous observation of hard X-ray (HXR) and metric/decimetric radio emission in solar flares: many studies since the 1970's (see e.g. Pick and Vilmer (2008) for a review).

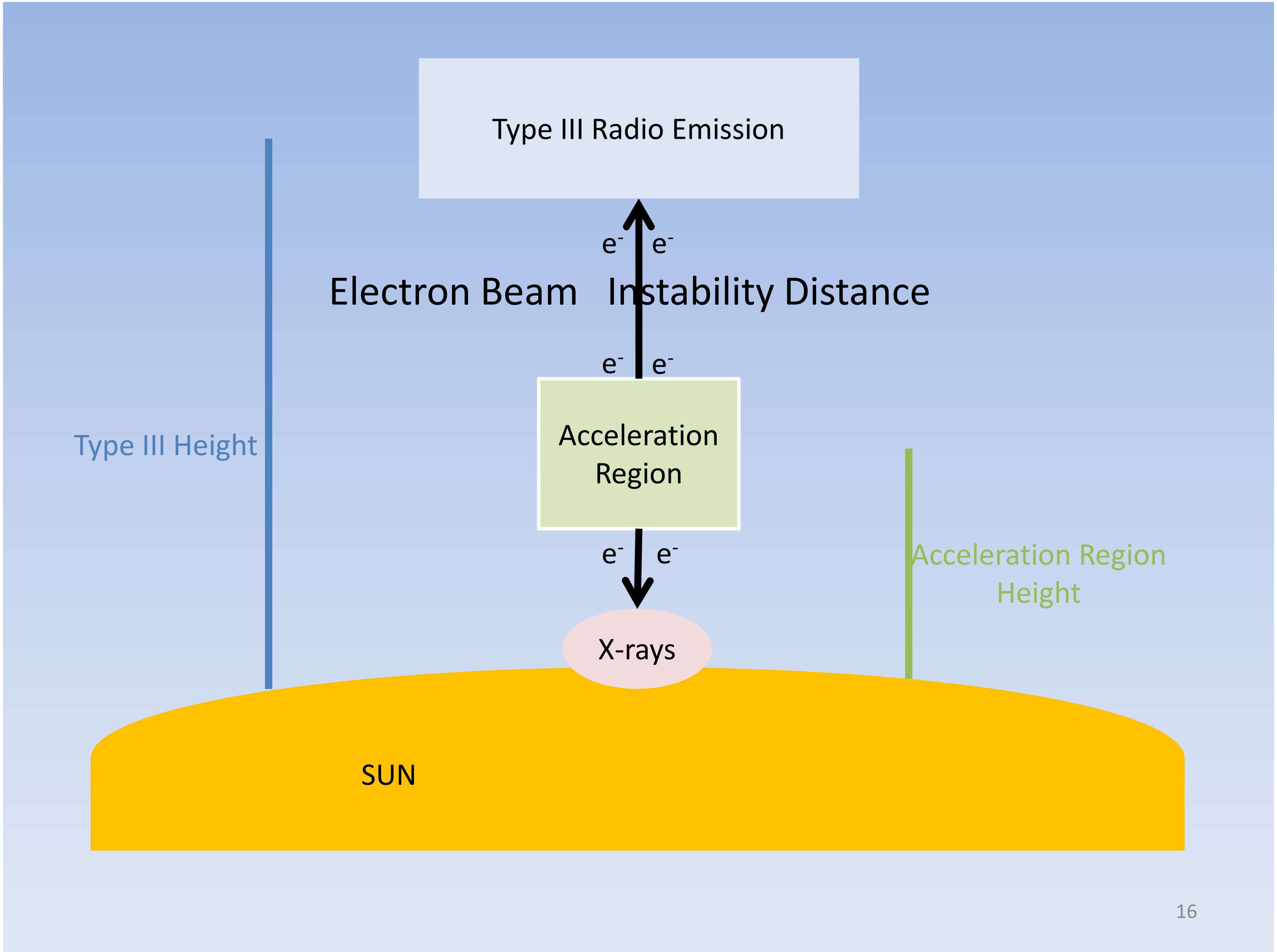
First studies by Kane (1972): good association between some HXR and type III radio emission, suggesting electrons can originate from a common acceleration site.

The first statistical study of HXRs and Type III emission was undertaken by Kane (1981):
The more intense the type III burst, the more likely it would be associated with a HXR flare. 3% of type III emission at metric wavelengths associated with HXRs.
The harder the X-ray spectral index, the more likely it is associated with a type III radio burst.

Events which have associated HXR and Type III radio emission tended to have higher radio starting frequencies.

The higher, the type III starting frequency, the stronger X-ray emission (Raoult et al., 1985)




Type III Radio Emission
e- e-
Electron Beam Instability Distance
e- e-
Type III Height
Acceleration Region
e- e-
Acceleration Region Height
X-rays
SUN

Electron Beam Energetics and TYPE III starting frequencies

The starting frequency of type III bursts can depend (amongst other parameters) on the spectral index of the electron beam [Reid, Vilmer, Kontar (2011); Reid, Kontar (2012)]

Initial electron beam

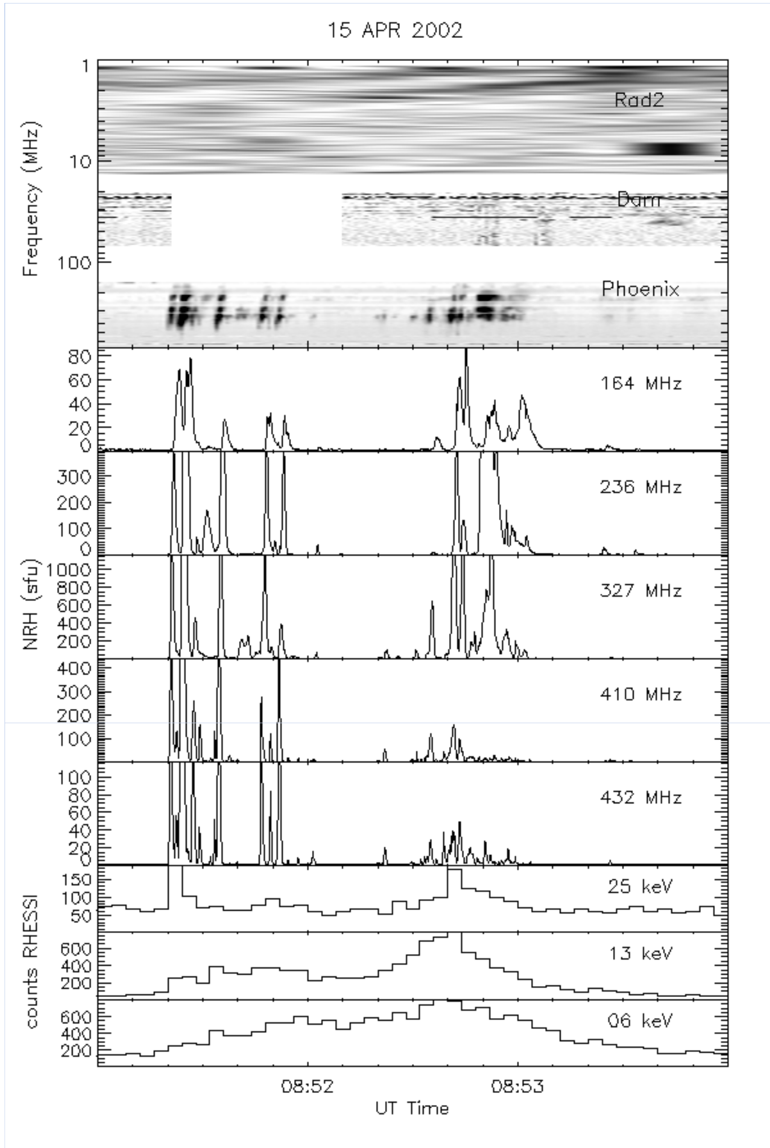
$$f_0(v, r, t=0) \propto v^{-\alpha} \exp\left(\frac{-|r|}{d}\right)$$

With propagation, the b eam generates Langmuir waves when t > 0 and growth is larger than the background plasma collisional absorption

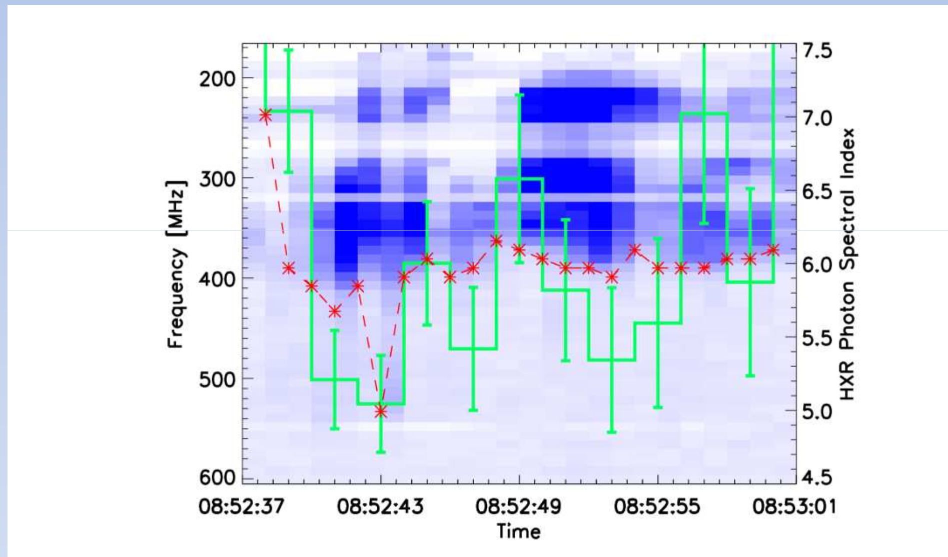
$$h_{typeIII} = d\alpha + h_{acceleration}$$

Spectral Index (in velocity space)

Spatial Size



Deducing the characteristics of acceleration region: height and size using combined radio and X-ray observations and numerical simulations (Reid, Vilmer, Kontar, 2011



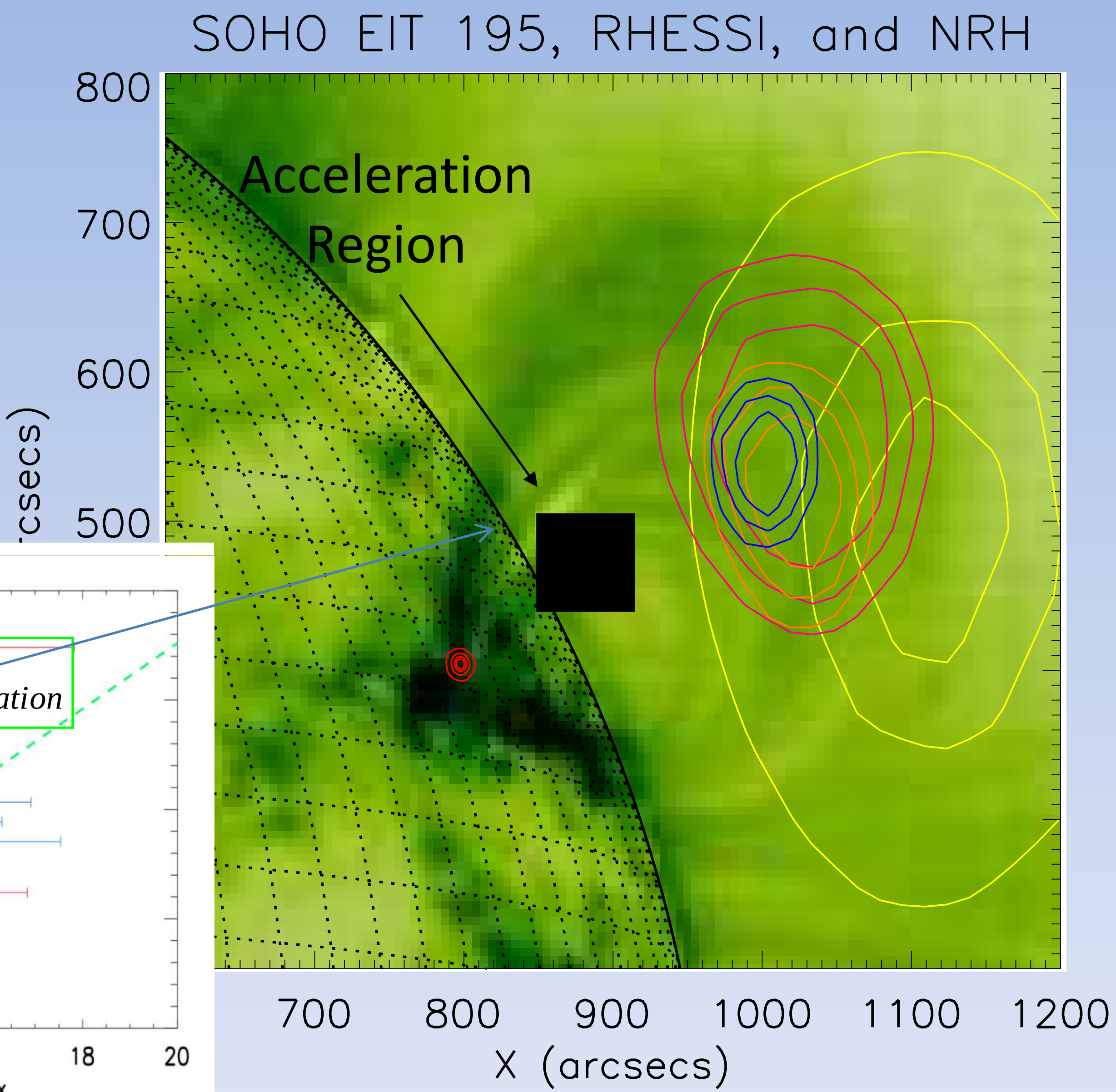
Starting frequency of the radio type III burst and HXR spectral index

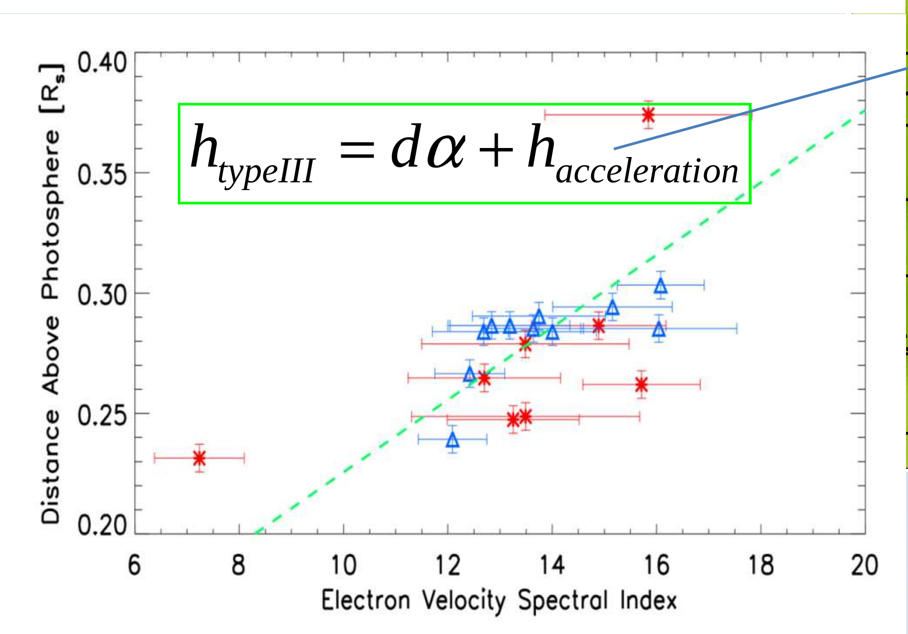
Propagation of an electron beam accelerated at height H and with a spatial beam width of d,

Langmuir waves are expected to grow at distance $r = h_{typeIII} - h_{acceleration}$

Linked to the parameters of the accelerated electrrons and the properties of the acceleration site

Reid, Vilmer, Kontar, 2011





H =50 Mm d=10 Mm

HXR – Type III Statistical Connection

Hamilton et al (1990) : statistical analysis using SMM (X) and BLEN, WEIS,TRIESTE (R)
No correlation between the peaks of the X-ray and type IIIs.
[But a statistical dependence]

Aschwanden et al. 1995: 31% of HXR associated with Type III around 300 MHz

More recent surveys by Benz et al. 2005;2007 combining RHESSI HXR observations and radio observations by PHOENIX-2 (4 GHz-100 MHz)
-Xray flares with GOES class > C5
-All types of coherent emissions
-All flares associated with some form of coherent emission
- Classic meter wave type III bursts associated with 33% of HXR flares
-Only in 4% the only emission
-No coherent emission observed for 17% of the flares below 100 MHz
-But for some of them emission below 100 MHz

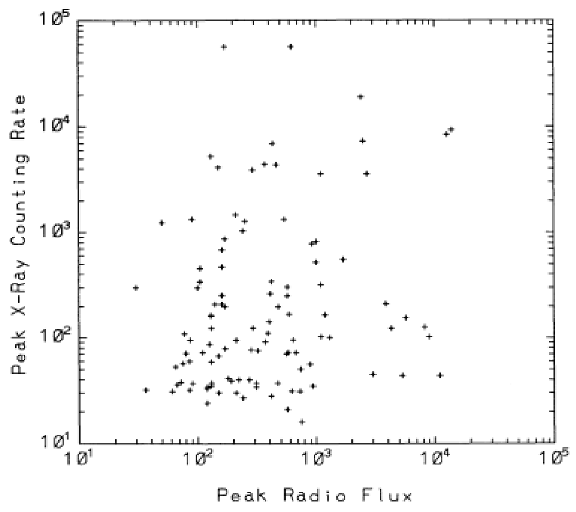


FIG. 1.—Distribution of the correlated events in the R-X plane

Hamilton et al., 1990

HXR – Type III Statistical Connection

SOME RESULTS FROM RECENT STUDIES

-Re-examine the link between HXR emissions and type III emissions in the decimeter/ meter range (>100 MHz)

-Systematic study of the extension of the type III emission at lower frequencies (<100 MHz) in the higher corona towards the interplanetary medium

-Study of the « morphology » of the X-ray and radio sources combining spatially resolved HXR and radio observations (tracing the magnetic connection between the solar surface and the corona towards the interplanetary medium).

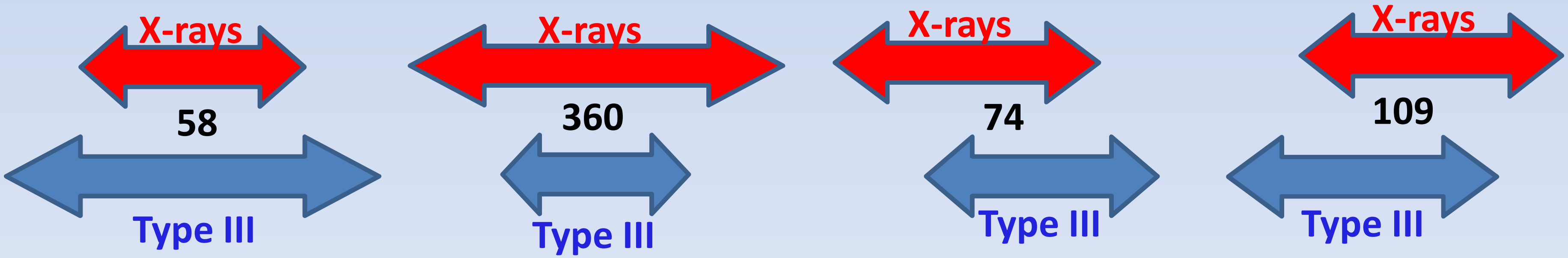
Radio and X-ray Events

A systematic work in progress from **2002 to 2011**

Start from the list of RHESSI flares. Automatic detection in the **6-12 keV** band.
http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt

And the list of type III bursts observed with PHOENIX-2 in the **4 GHZ-100 MHz** between 2002 and 2009 and BLEN7M in the **900-100 MHz** range between 2010 and 2011. Between 08-16 UT (also for combination with NRH data).
http://soleil.i4ds.ch/solarradio/data/BurstLists/1998-2010_Benz/
http://soleil.i4ds.ch/solarradio/data/BurstLists/2010-yyyy_Monstein/

18,206 X-ray flares and **1,959** solitary groups of type III radio bursts
Consider only events with the following morphologies: total: **601** events



Radio and X-ray Events

We created spectra using different instruments.
RADIO: PHOENIX 2 / BLEN7M
Decametre Array (DAM)
Wind/Waves (RAD2)

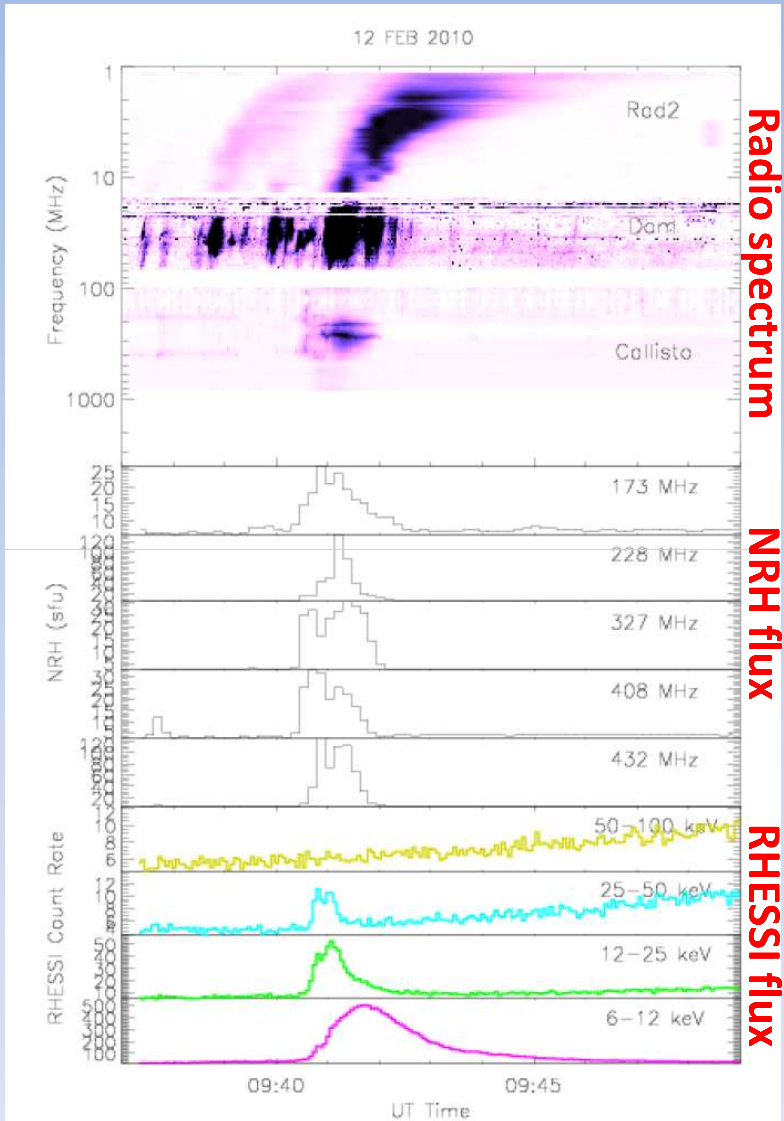
RADIO flux: Nançay Radioheliograph
XRAY flux: RHESSI

Automatic detection is great but far from perfect!
Many false positives that have to be removed.

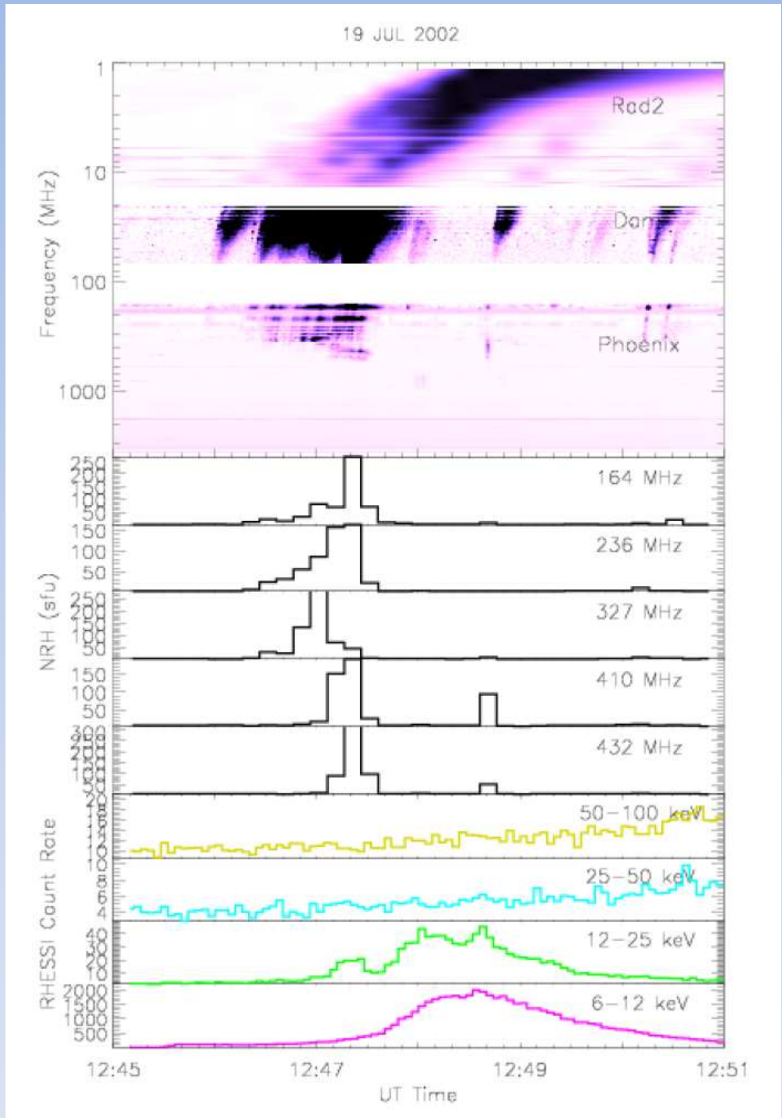
We went through all of the 601 events and removed the events which had problems (bad data, duplicated events, RHESSI night time etc). We were left with **378 events**.

Flares are less intense than Benz et al 2005, 07

Between 2002 – 2007, the GOES class is M=13%, C=53%, B=34%



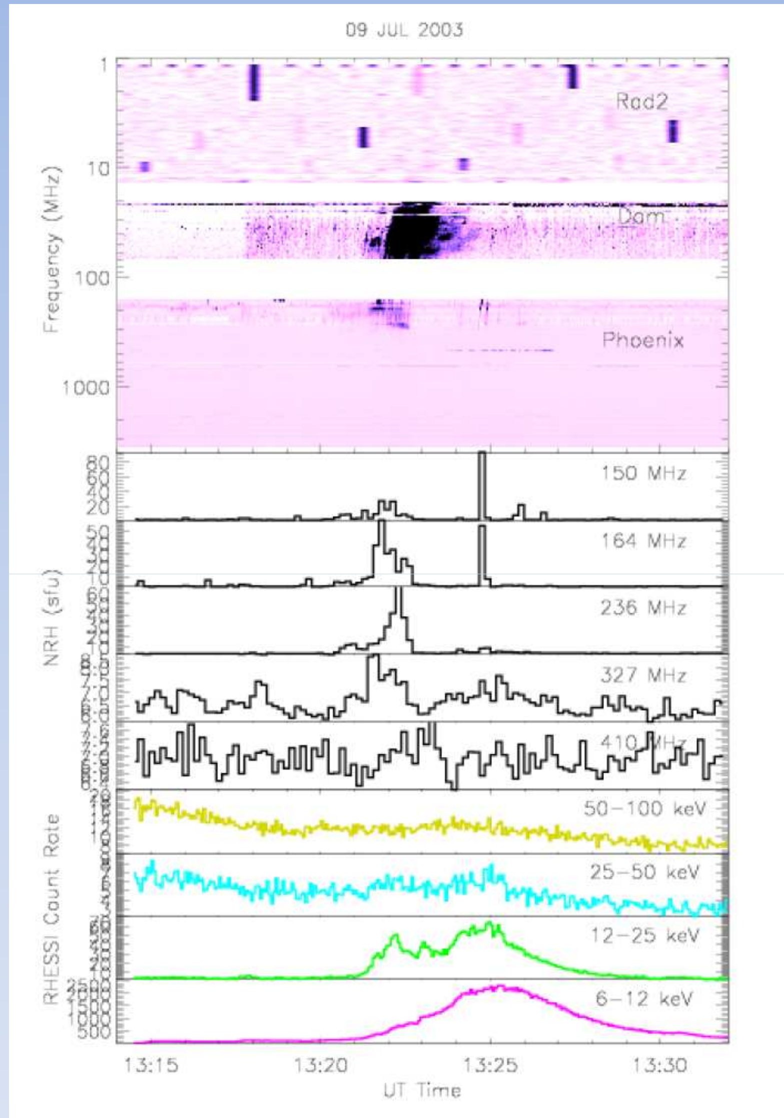
Radio and X-ray Events



Radio spectrum

NRH flux

RHESSI flux



Overlap of type III and X-ray emissions but the peaks are not simultaneous.

Some type III burst do not go to interplanetary medium

Some statistics on Starting Frequencies

For the 378 events between 2002 – 2011 we have, we found that 321 of them showed associated X-ray and type III emission after a visual inspection.

Using the Phoenix 2 spectrometer (2002 – 2007)

194 events from 254 had a good association between the Hard X-rays and the type III radio emission (3.8 to 1)

If the starting frequency > 1 GHz, ratio is 6.5 to 1
If the starting frequency < 1 GHz, ratio is 2.3 to 1
For starting frequency > 1 GHz and ending frequency < 400 MHz , ratio 8.75 to 1

Associated HXR TYPEIII (308): Mean Starting Frequency of **1597 MHz** (no obs above 4 GHz)
Non Associated TYPE III (1638): Mean Starting Frequency of **995 MHz**

We find that radio bursts which start at high frequencies are more likely to be associated with X-ray emission. **More dense, more energetic electron beams?**

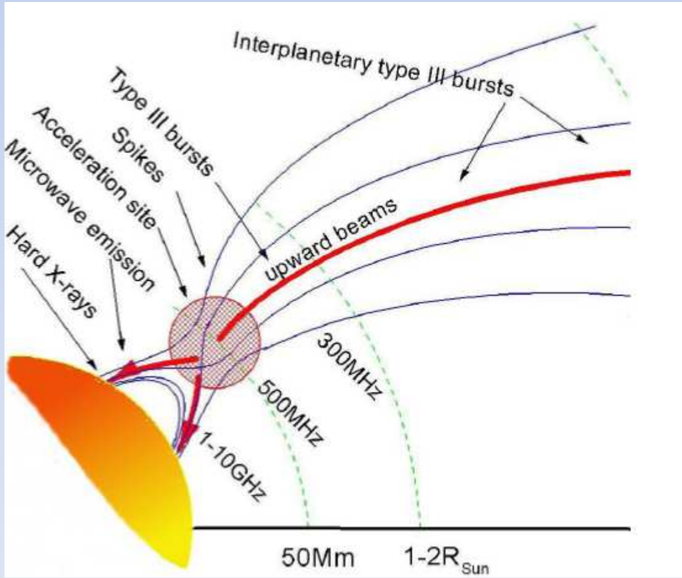
Better connection to the middle corona?

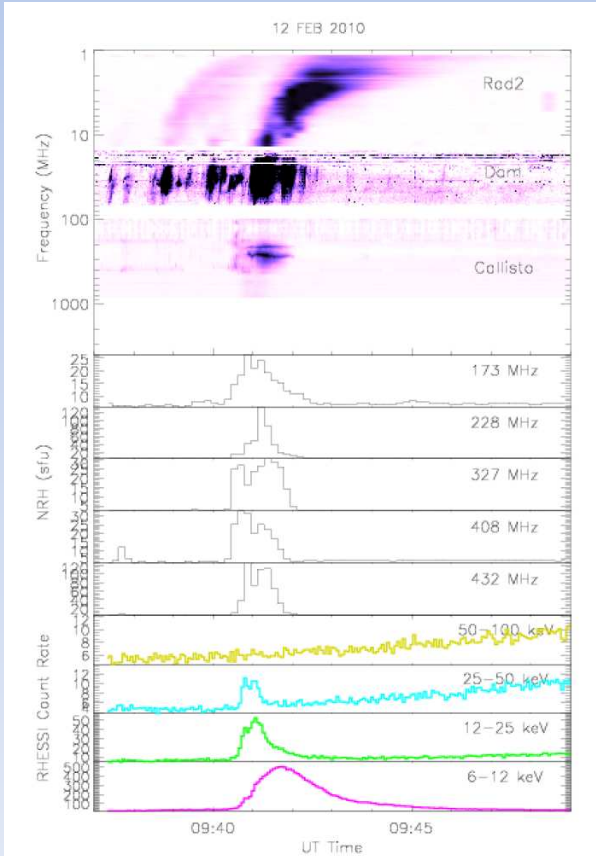
Some statistics on the extension towards interplanetary Type IIIs

Interplanetary type III bursts:

174 of the 321 events had strong emission in RAD2, 14-1 MHz. (>50 %)

Among these events, 63% had significant HXR emission in 25-50 keV
29% were observed at 12-25 keV but not 25-50 keV
8% had the highest HXR emission in 6-12 keV





Peaks of X-ray and Radio events

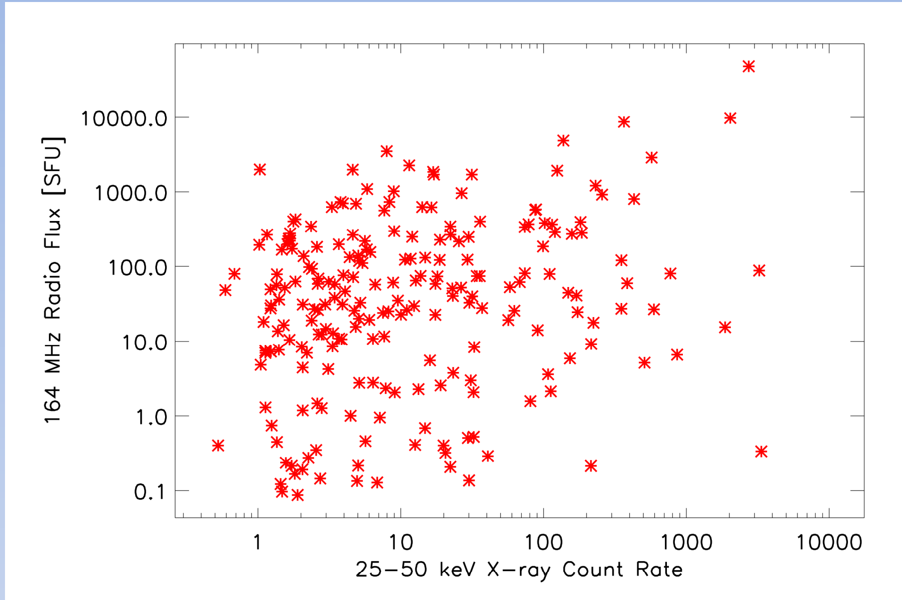
Peak count rate of the X-ray emission and
peak flux of the type III emission (background subtracted).

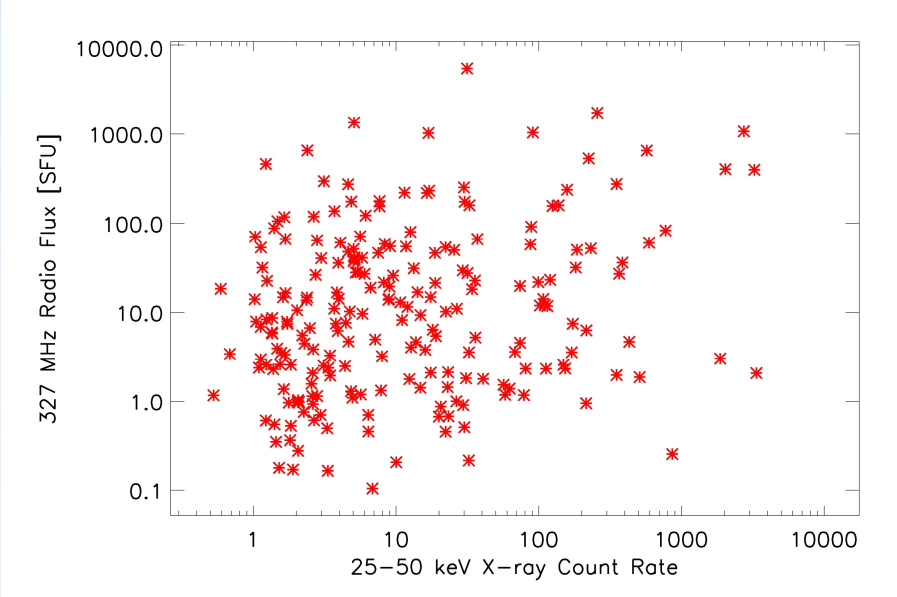
We found **NO** correlation between the peak flux of any radio frequencies with any of the X-ray energy channels.

These results agree with Hamilton et al 1990.

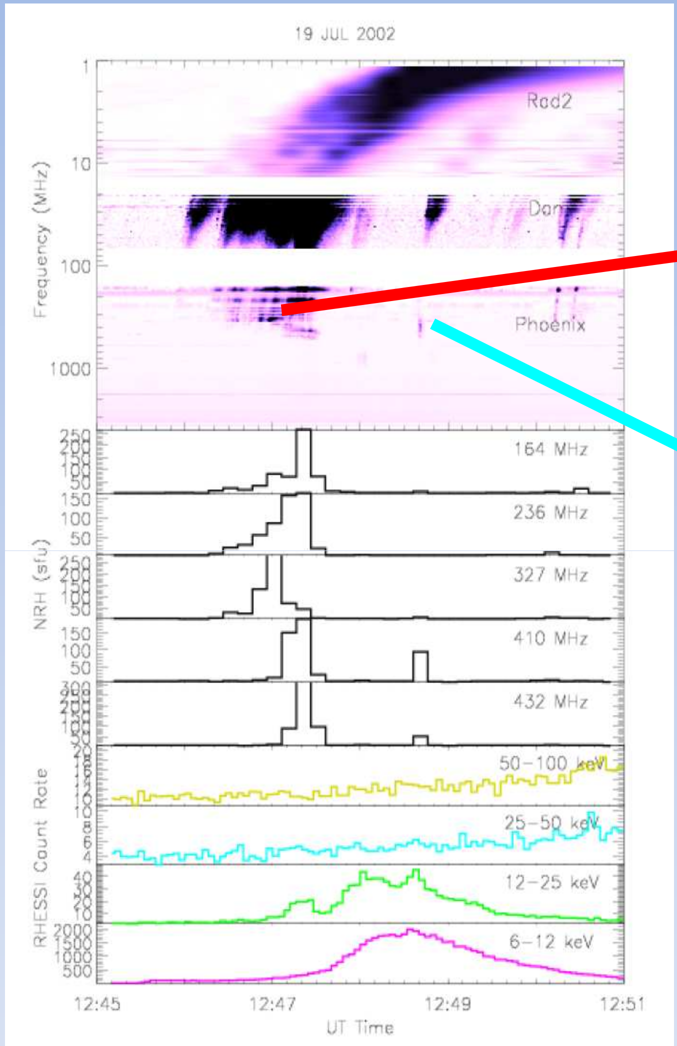
The lack of correlation is expected considering the nonlinear processes that generate the type III emission.

Reid , Vilmer in preparation





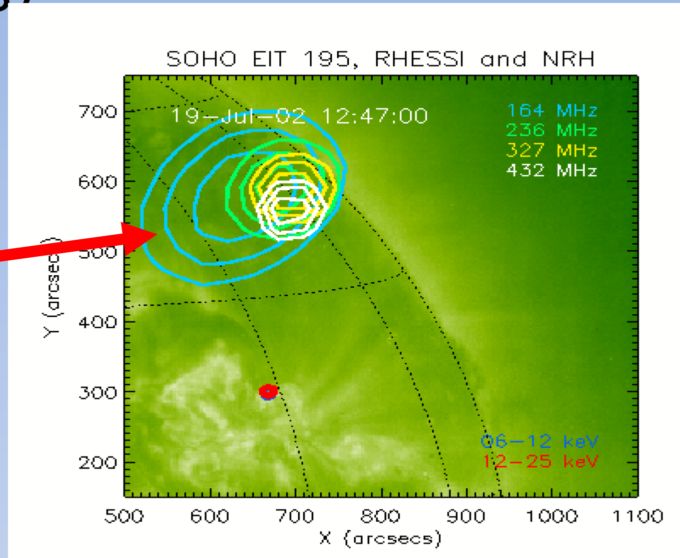
Flare Morphology

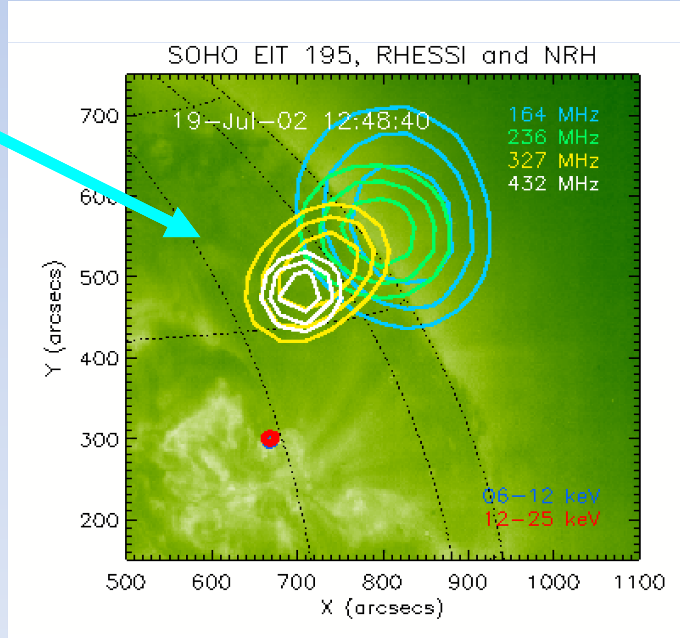


The standard flare model is very simplified. The reality is more complicated

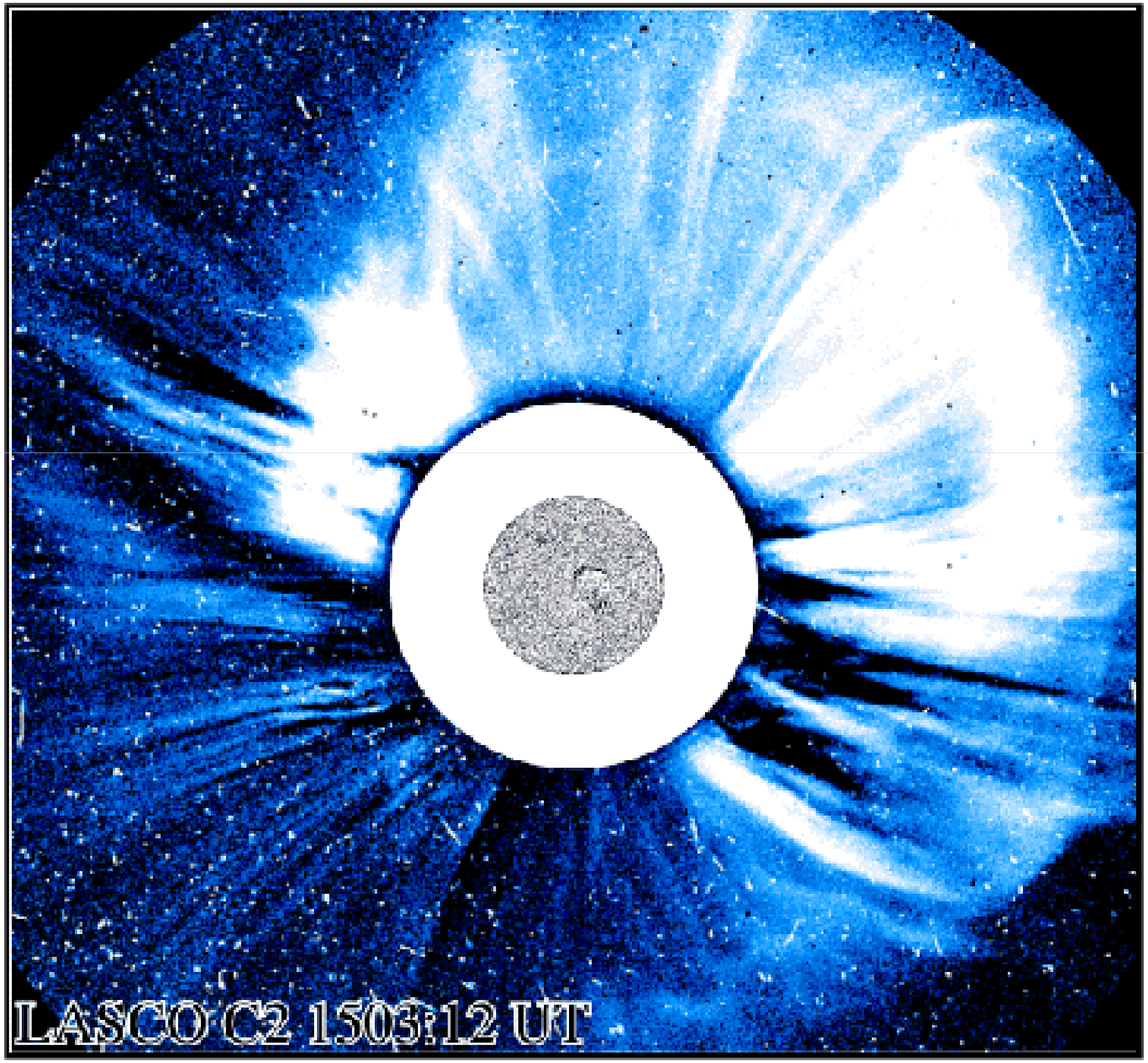
Particles can be injected into different magnetic structures during the course of a flare.

This can influence whether the electron beam makes it into interplanetary space.

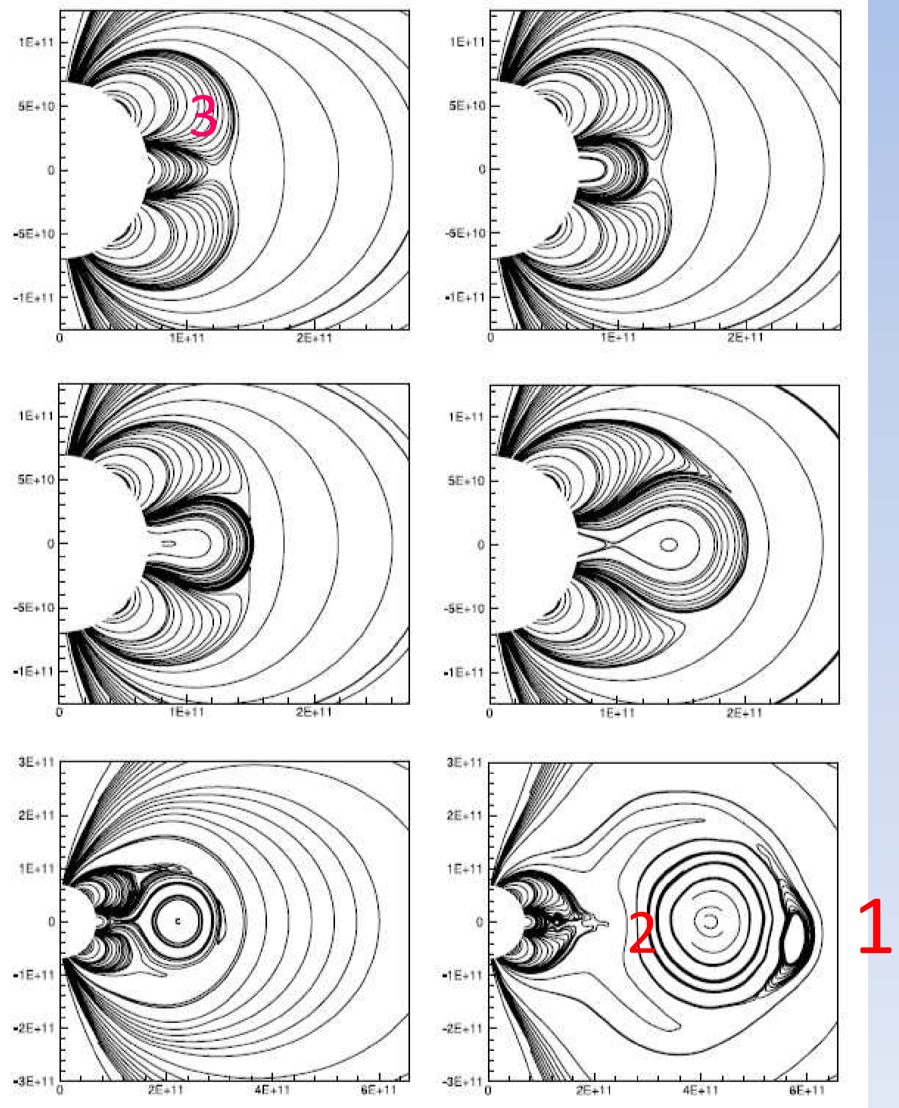




Radio observations in the MHz-GHz range: input to the understanding of CME developments



Where are the acceleration sites in the corona?



From Mac Neice et al., 2004
Snapshots of selected field lines from the numerical simulation of the break-out model for Coronal Mass Ejections
Where are the possible acceleration sites??

Related to the shock wave?? (1)
In the reconnection sheet forming below the CME?? (2)
In the interaction regions during the evolution of The magnetic features at different scales?? (3)

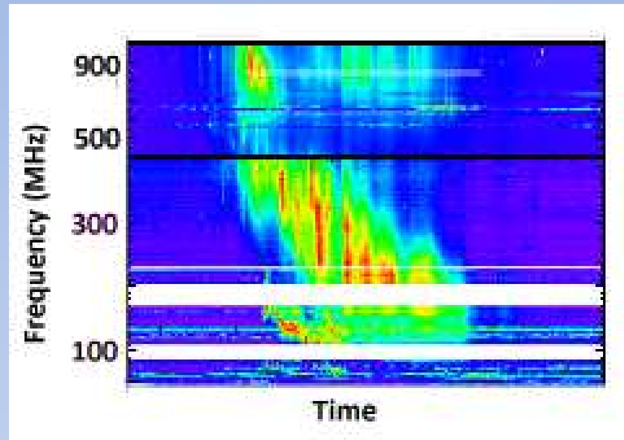
INPUT OF RADIO IMAGES…

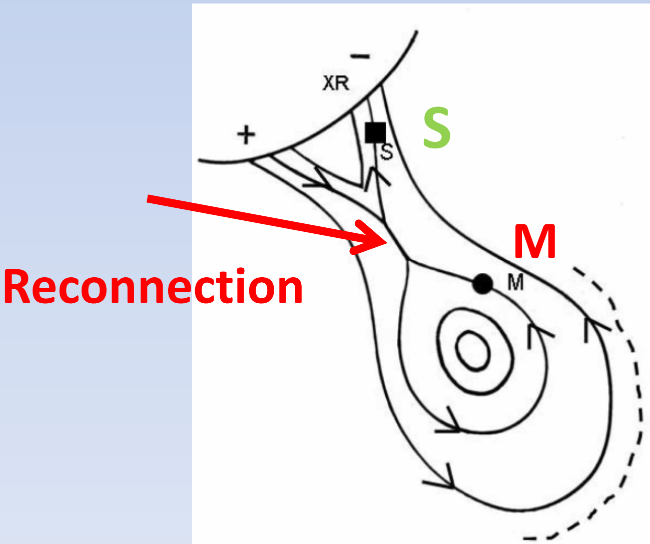
Electron acceleration in current Sheets in flares and CMEs

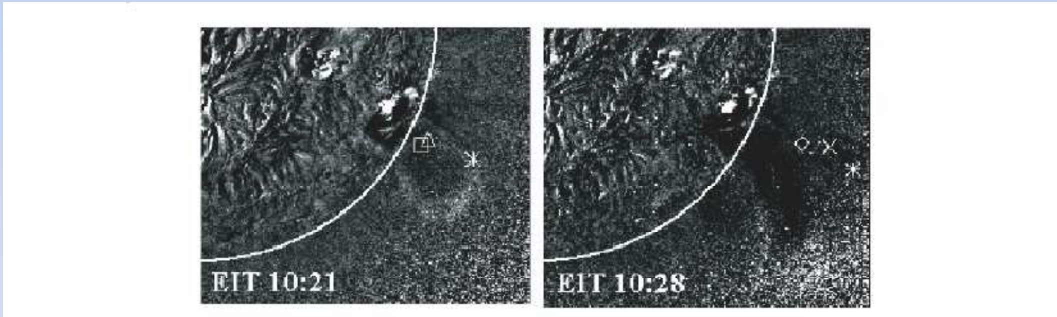
Evidence from Spectrography

Kliem, et al. 2000,
Karlicky et al., 2002, 2004

Quasi periodic episodes
from magnetic reconnection in CS



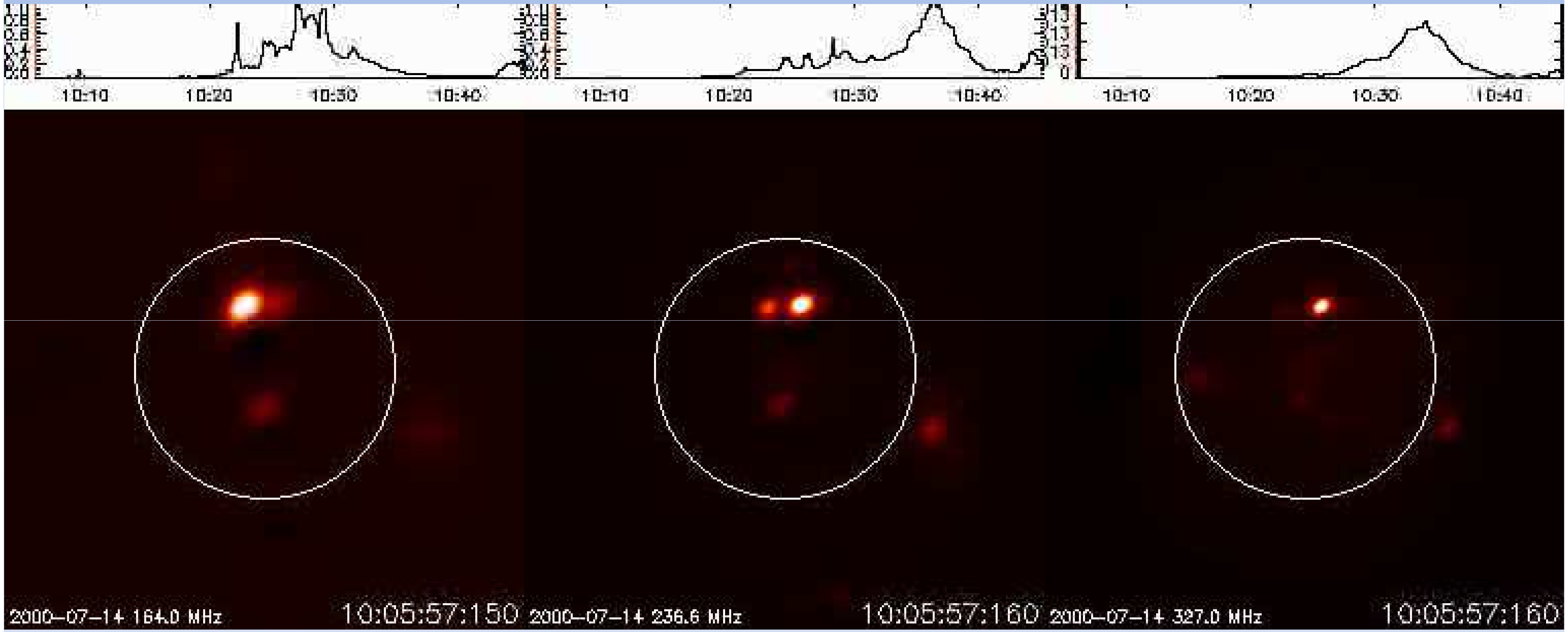




Multifrequency imaging

Pick, Démoulin et al., 2005

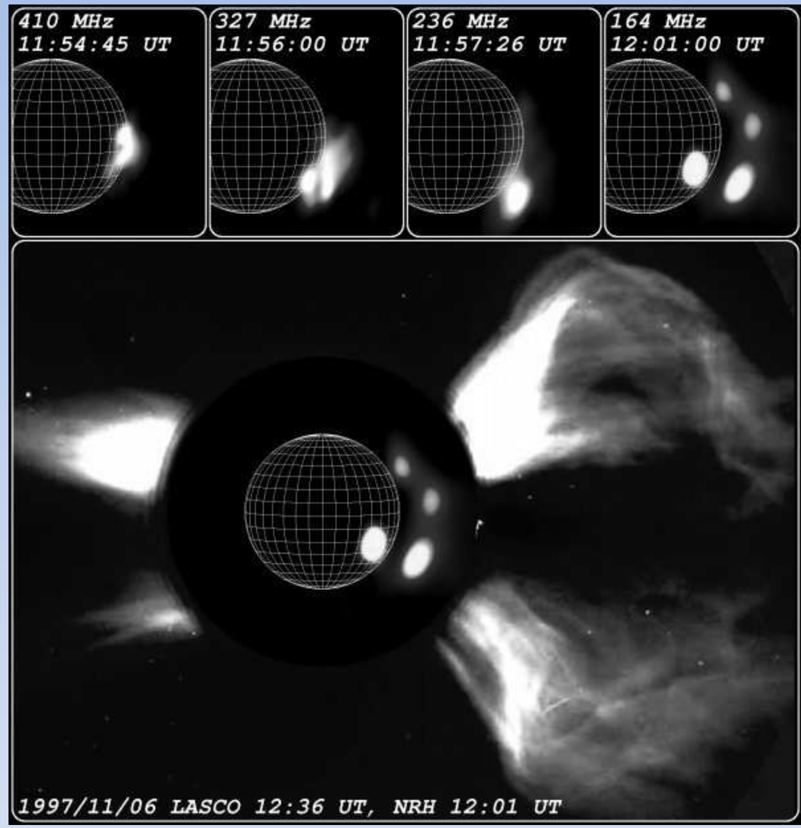
SOLAR ACTIVITY IN THE 100 MHZ RANGE



The Bastille Day Flare observed with the Nançay Radioheliograph (courtesy K.L. Klein)

Electron acceleration related to CME lift-off

Electron acceleration in successive magnetic
interactions at larger distances from the flare
Note the comparable extent of the radio
source
and of the CME.

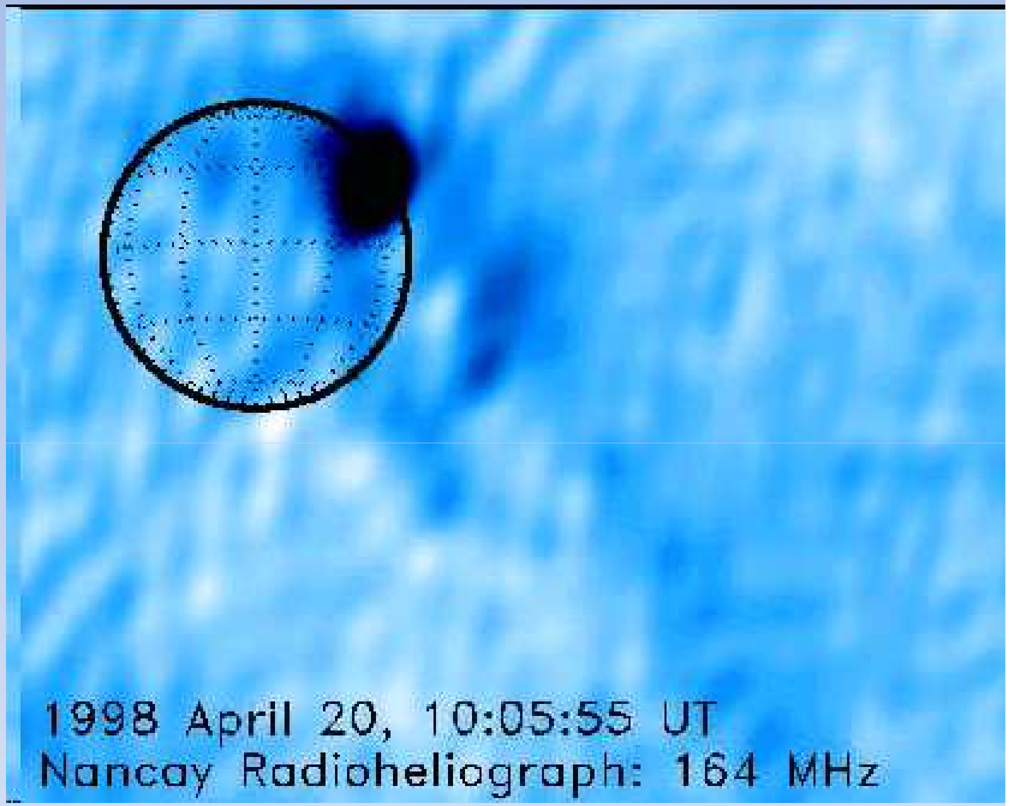


Maia et al., 1999

White light and radio CMEs

- Synchrotron radiation from relativistic e^-
- **Loops (3-4 Rs) illuminated by synchrotron emission from relativistic electrons**

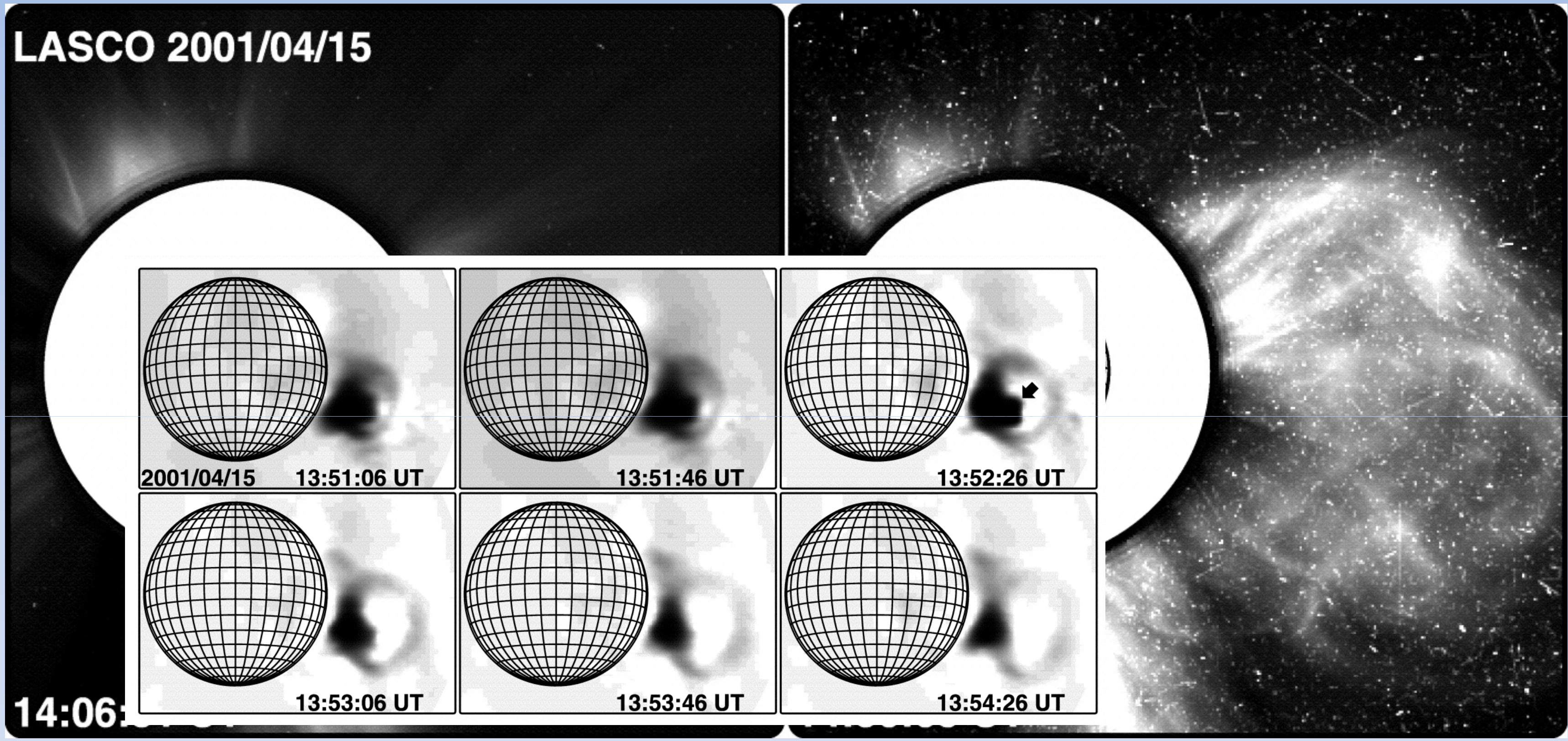
- Where / when are they accelerated ?



Bastian, Pick, Kerdraon, Maia, Vourlidas, 2001, ApJ 558, L65

SoHO/LASCO

Energetic electrons in the corona and injection in the IP space during a large SEP event



Maia et al 2007 ApJ 660, 874 : large SEP event of 2001 April 15

- Nançay RH : synchrotron radiation of relativistic electrons (≥1 MeV) in CME-related loops, while CME still occulted
- Energetic electrons accelerated in the aftermath of CME (post-CME current sheets?)

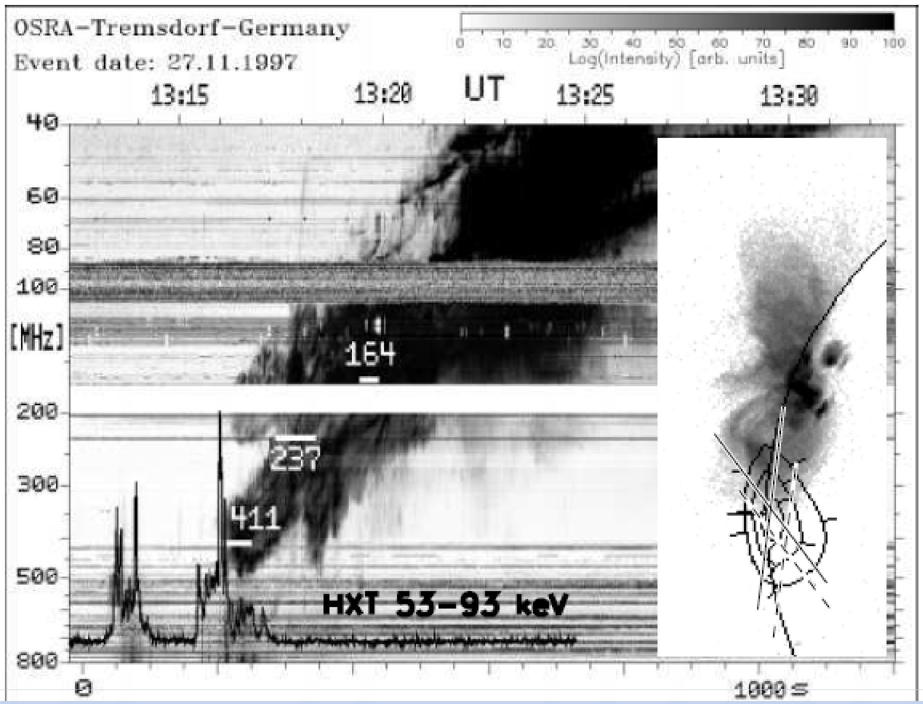
- Coronal type II bursts: signature of MHD shock waves (Wild & Smerd, 1972; Mann, 1995; Cairns 2011,…)

- **Origin of the coronal shock wave?**
- *Flare blast wave*
- *Piston driven shock driven by eruptive magnetoplasma structure*

- *A lot of discussions(Aurass 1997; Cliver et al., 1999; Vrsnak & Cliver 2008,…)*

- *Need to study the relative positions of radio type II sources and eruptive plasma*

- *But very few observations of type II bursts starting at high enough frequencies to compare positions of radio type II sources (e.g. with the NRH) with the positions of eruptive plasmas (seen in X-ray, EUV)*

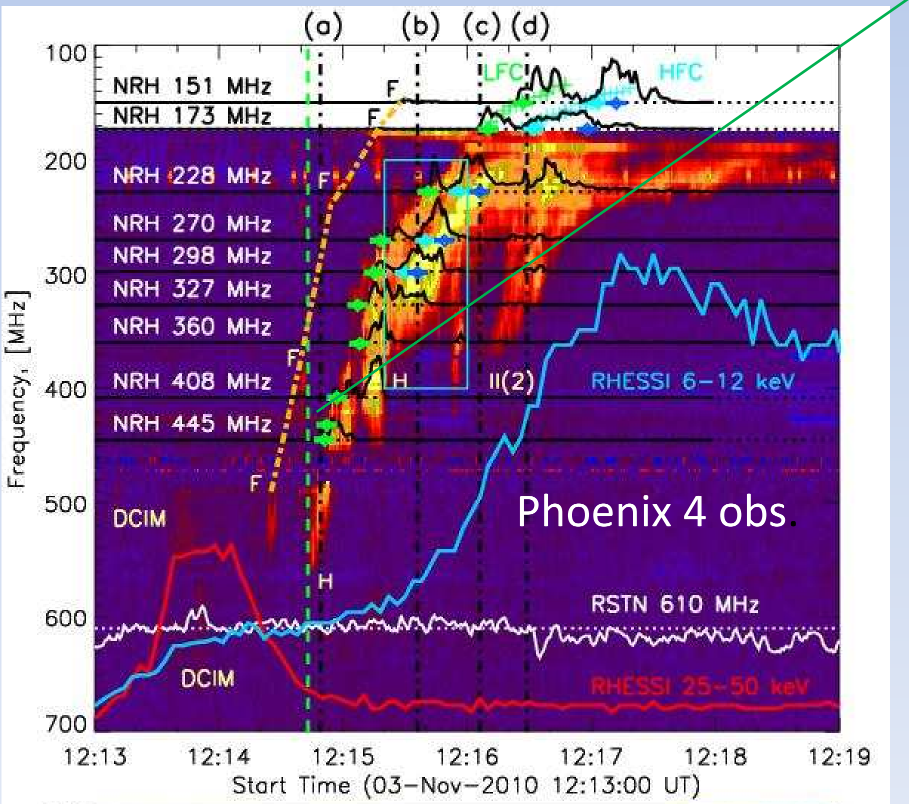


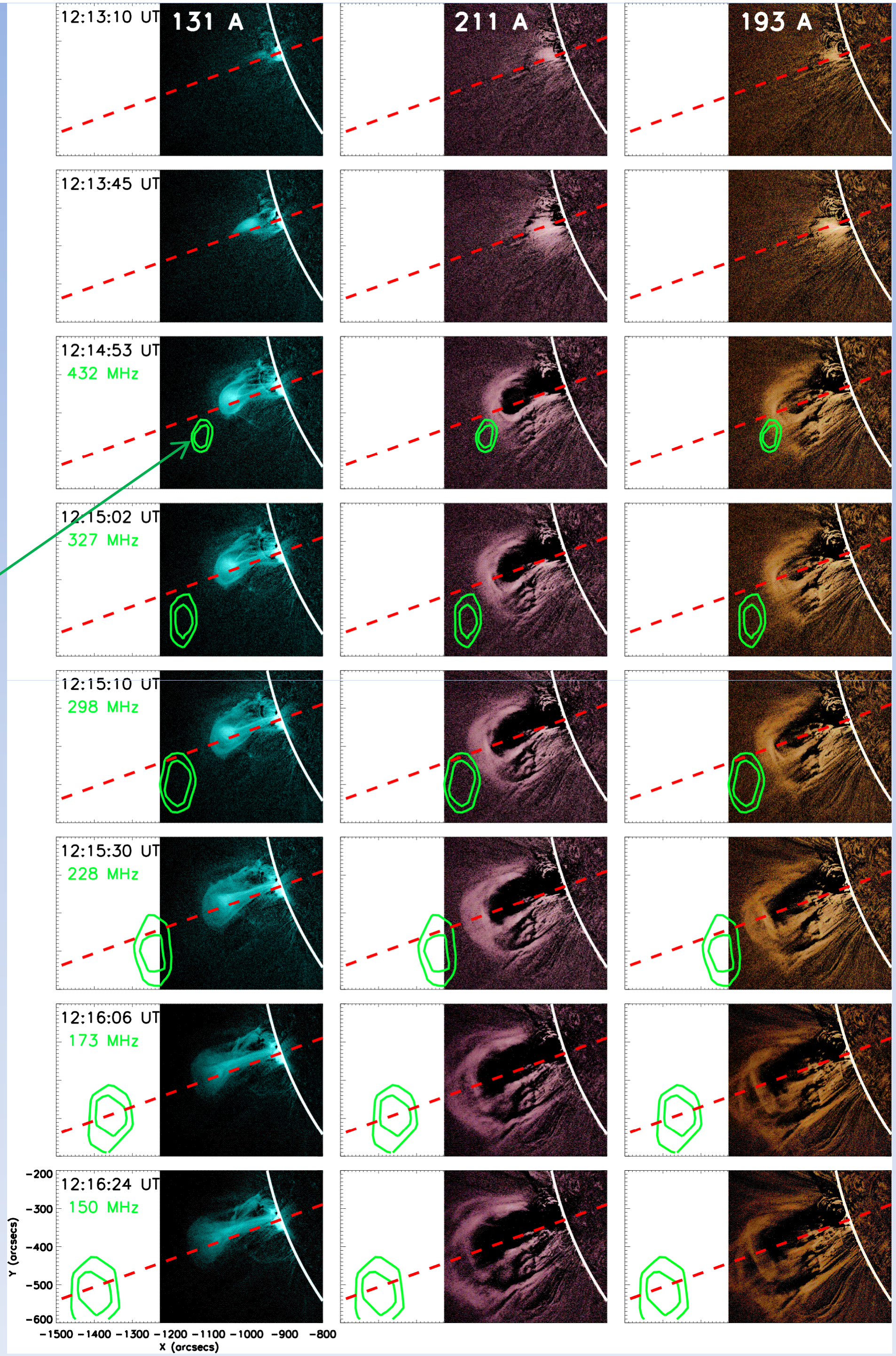
Klein et al., 1999

A few studied cases
Gopalswamy et al., 1997;
Klein et al., 1999; Dauphin et al., 2006

Type II burst and eruptive plasma

Mostly harmonic emission
Start at 561 MHz
Observations with the NRH at 10 frequencies
Position of the radio type source at the time of its first appearance
Source at 432 MHz above the LE of hot plasma
Increase of the distance between the LE and the type II positions at lower frequencies
(Zimovets , Vilmer et al., 2012)





Concluding remarks

- **Input of Joint spectral and Imaging observations at high temporal cadence in the MHz to GHZ range**
- Radio traces **energetic electrons**

➢ **Link between the corona and interplanetary medium**

➢ **Electron acceleration in current sheets**

➢ **Electron acceleration in regions of field line interaction**

➢ **Electron acceleration in connection with shock waves**

What to do next on ground in the MHz-GHz Range?

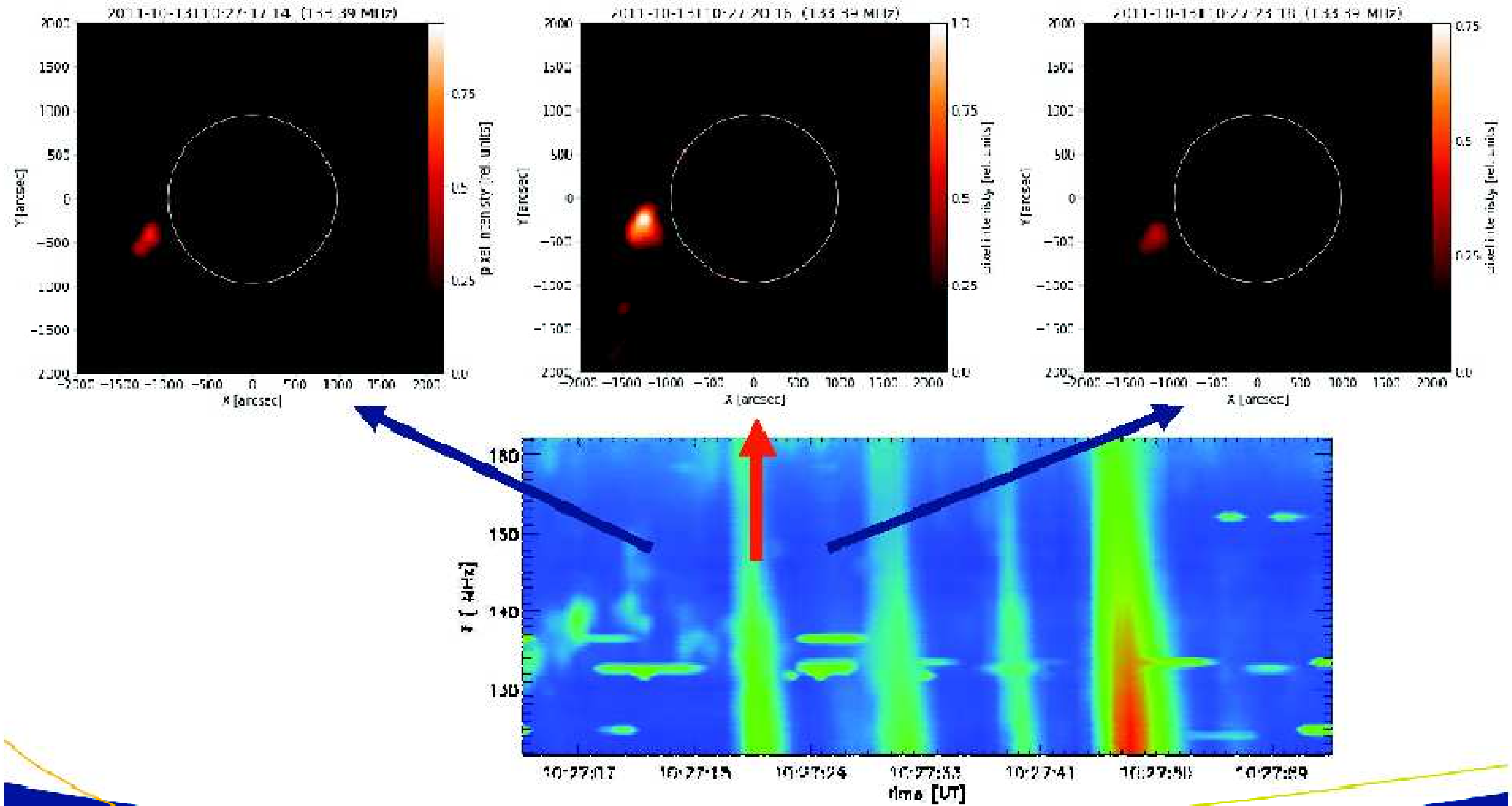
CSRH (Chinese Spectral Radioheliograph**) (**0.4-15 GHz)
(50-1.3’’ 1 GHz)

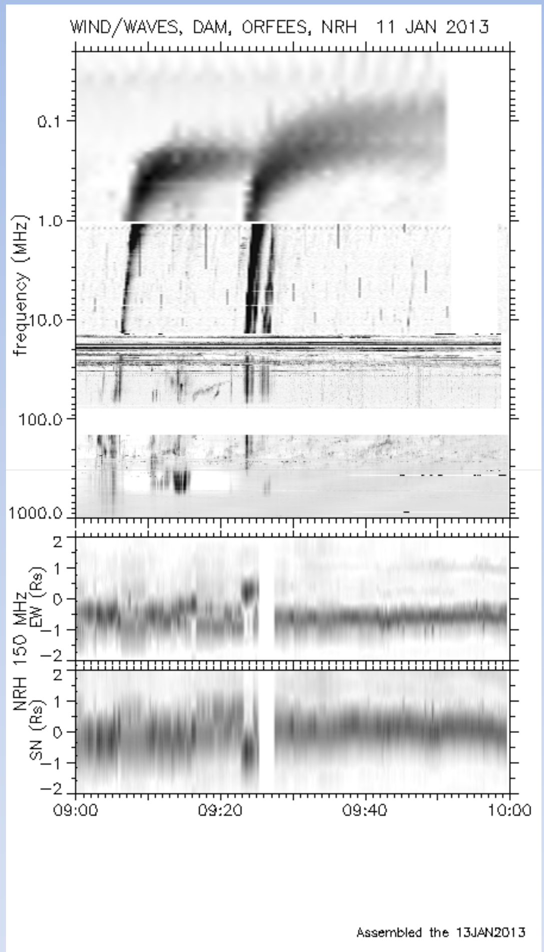
LOFAR (Low Frequency Array**) 30**-80 MHz & 120-240 MHz
MWA, (Murchison Widefield Array) 80-300 MHz

FASR Frequency Agile Solar Radio Radio Telescope (0.1-30 GHz)
(20’’ at 1 GHz)

Complementary to ALMA
ALMA (Atacama Large Millimeter Array) (several bands 31 GHz-950GHz)
(0.015’’-1.4 ’’at 1mm i.e. at 300 GHz)

Solar Type III Radio Bursts I




WIND/WAVES, DAM, ORFEES, NRH 11 JAN 2013
frequency (MHz)
0.1
1.0
10.0
100.0
1000.0
NRH 150 MHz
EW (Rs)
SN (Rs)
2
1
0
−1
−2
09:00
09:20
09:40
10:00
Assembled the 13JAN2013

Thanks!