Radio Emission Relevant to Space Weather

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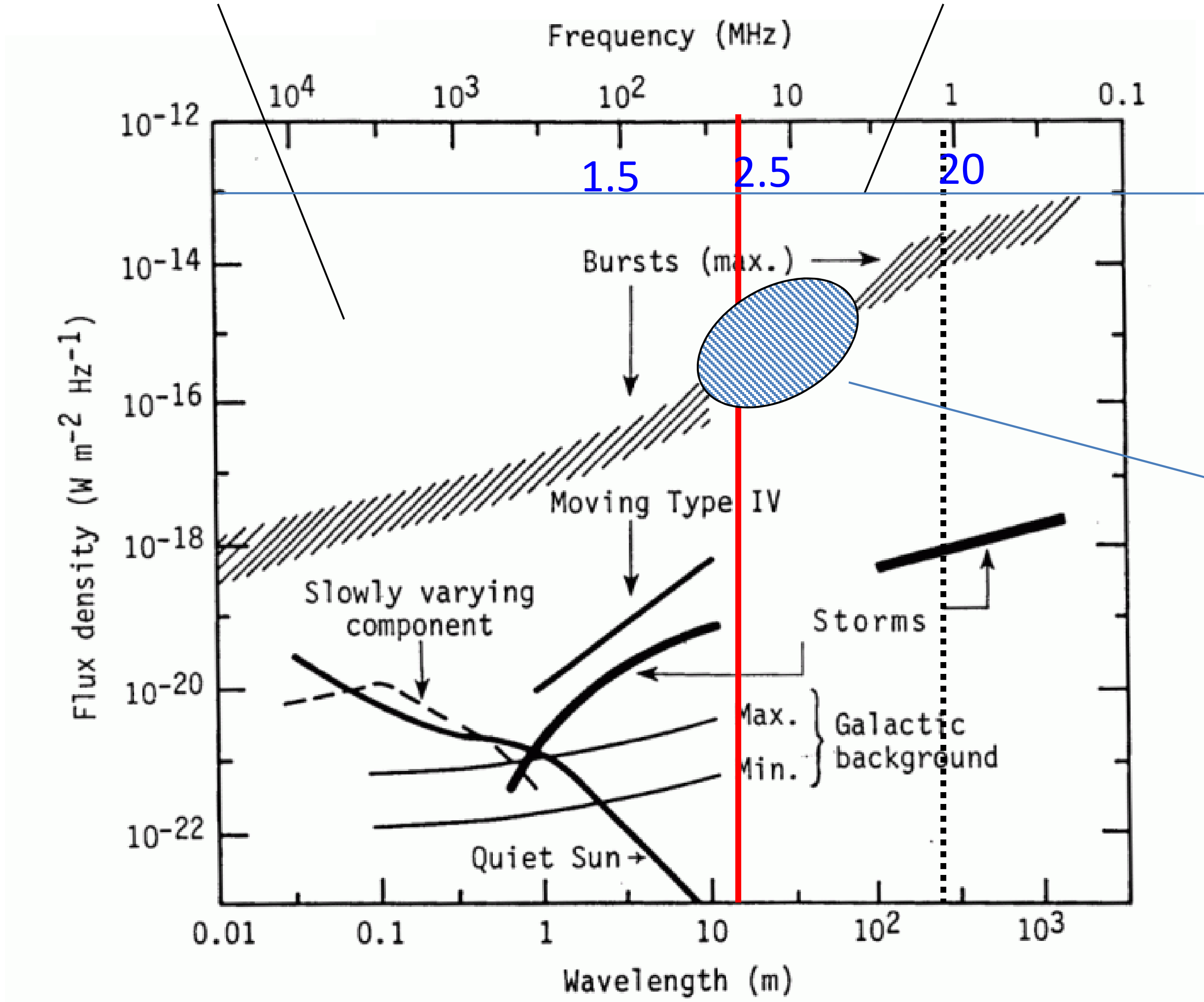
Radio Sky

Coronal:
Ground-based Obs.

Interplanetary
Space Obs.



Heliocentric Dist

Gap filled by Wind/WAVES

Flux densities of the quiet Sun (at sunspot minimum) and of large solar bursts of several types. Also shown is the range of the galactic background flux (20° beamwidth is assumed).

Type II, Type III bursts
Most intense

Radio spectrum is
less complex in the IP medium

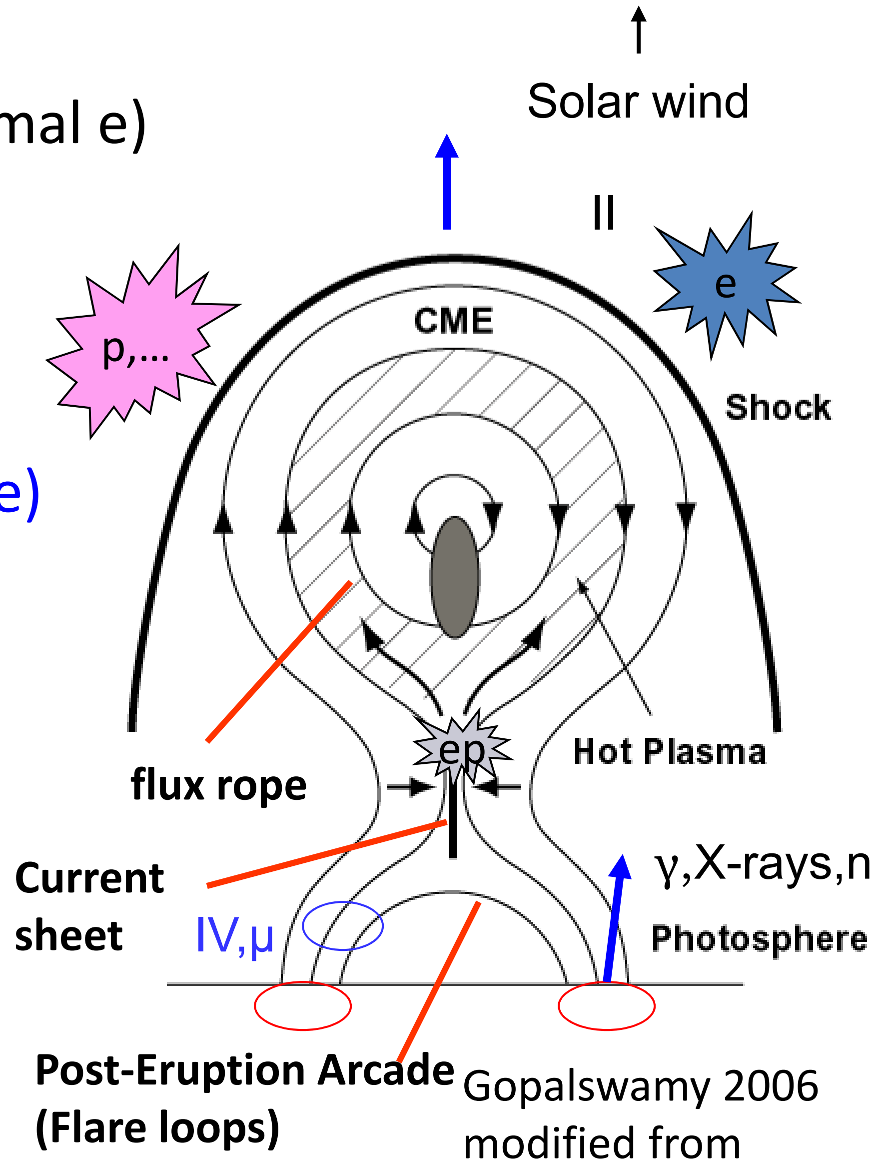
Nelson & Labrum, (1985)

Radio Bursts

- Type I bursts are due to evolution of active regions
- Type II radio bursts due to shocks
- Type III radio bursts due to electron beams
- Type IV bursts are due to electrons trapped in moving or stationary magnetic structures during an eruption
- Type V bursts are variants of type III bursts
- To study solar eruptions, one uses type II, Type III & Type IV
- Note that radio bursts are produced by energetic electrons, that need to be accelerated to keV energies
- Connection to particle acceleration → Space weather

CMEs and Radio Bursts

- Type I (Active region, nonthermal e)
- Type II (e from shocks)
- Type III (e along open B)
- Type IV (e in closed B structure)
- Type V (similar to Type III)

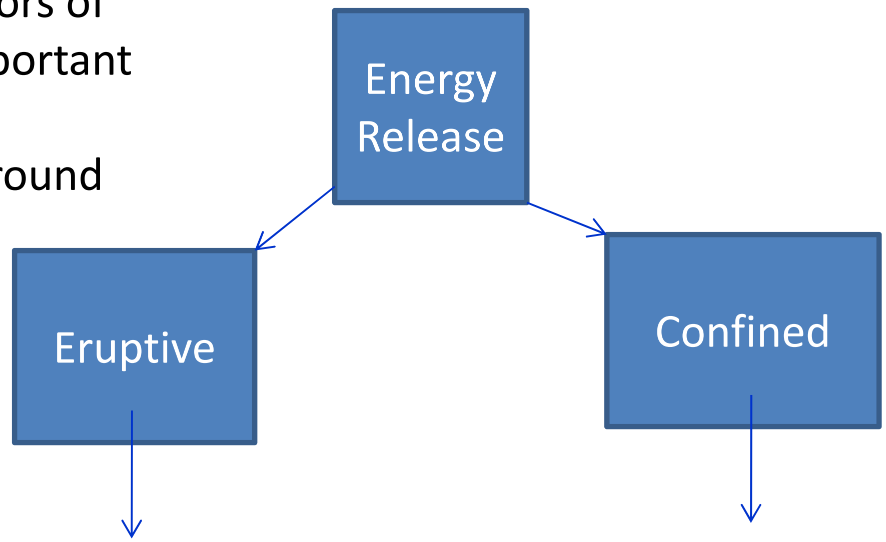


Gopalswamy 2006
modified from
Martens and Kuin 1989

Radio bursts are due to accelerated electrons propagating along open magnetic field lines
or trapped in closed field lines
→ Ions are simultaneously accelerated
→ good & immediate indicators of particle acceleration

Radio Bursts

Type II bursts are indicators of CME-driven shocks – important for space weather
Can be observed from ground (e.g. CALLISTO)



X-ray, Microwave bursts, γ-rays
(Sunward electrons, ions)
CME Shocks - Type II bursts
(outward electrons – type III, SEPs

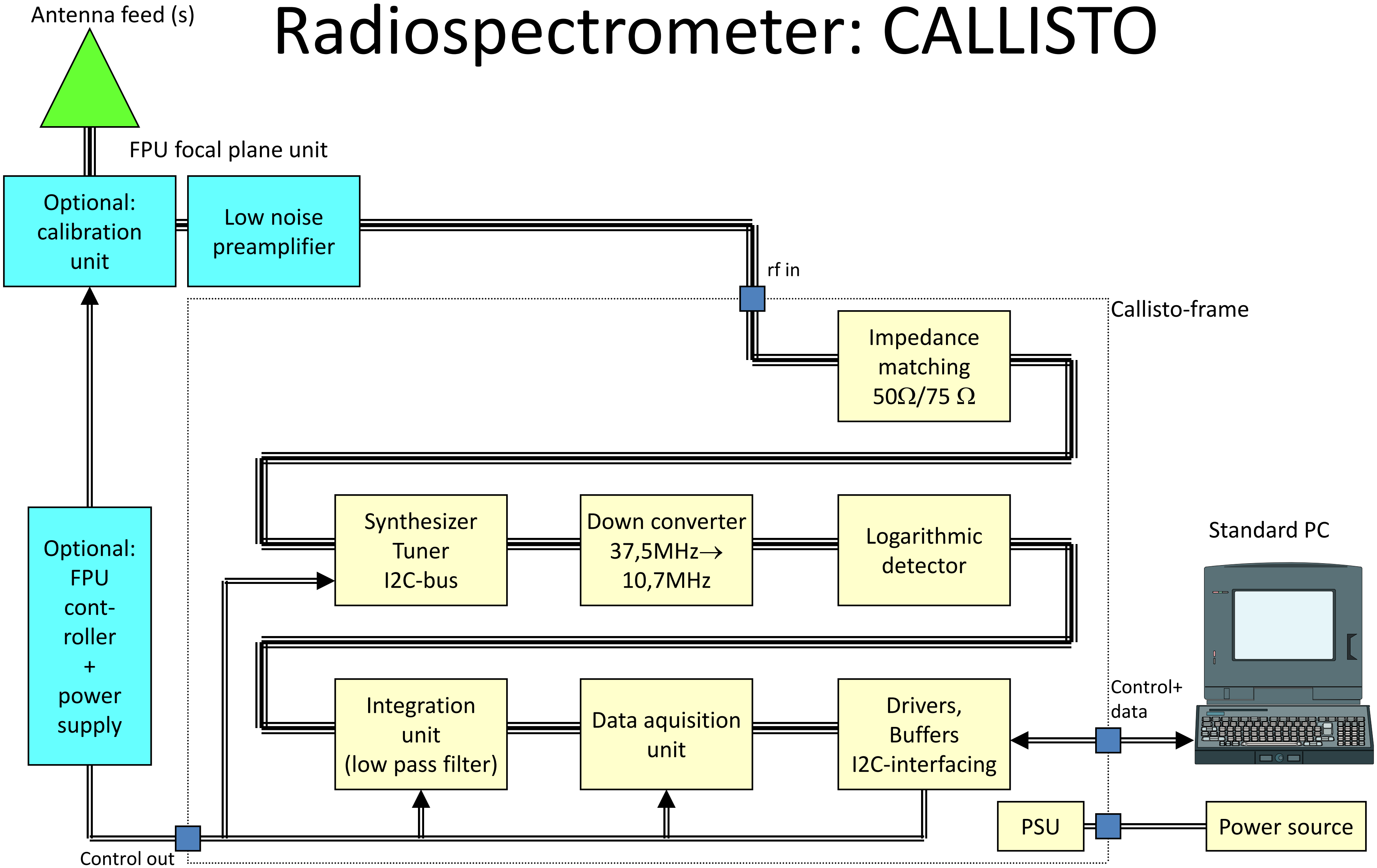
X-ray, Microwave bursts, γ-rays
(Sunward electrons, ions)

Radio bursts are due to accelerated electrons from ~1 keV to >1 MeV
Indicate acceleration of ions – important for space weather
Indicate shocks and CMEs – important for space weather (mag. storm)

CALLISTO

- CALLISTO is a Radio Spectrometer donated/manufactured at ETH Zurich: Dr. Christian Monstein
- Host institution provides Antenna, PC, internet, power
- Dr. Monstein sends the instrument to the host with instructions or installs in person
- At present, the CALLISTO network observes the Sun 24/h
- Data from all observatories available at a central location (Switzerland)

Radiospectrometer: CALLISTO



Control path
Signal path
Control- data link Callisto/Host-controller

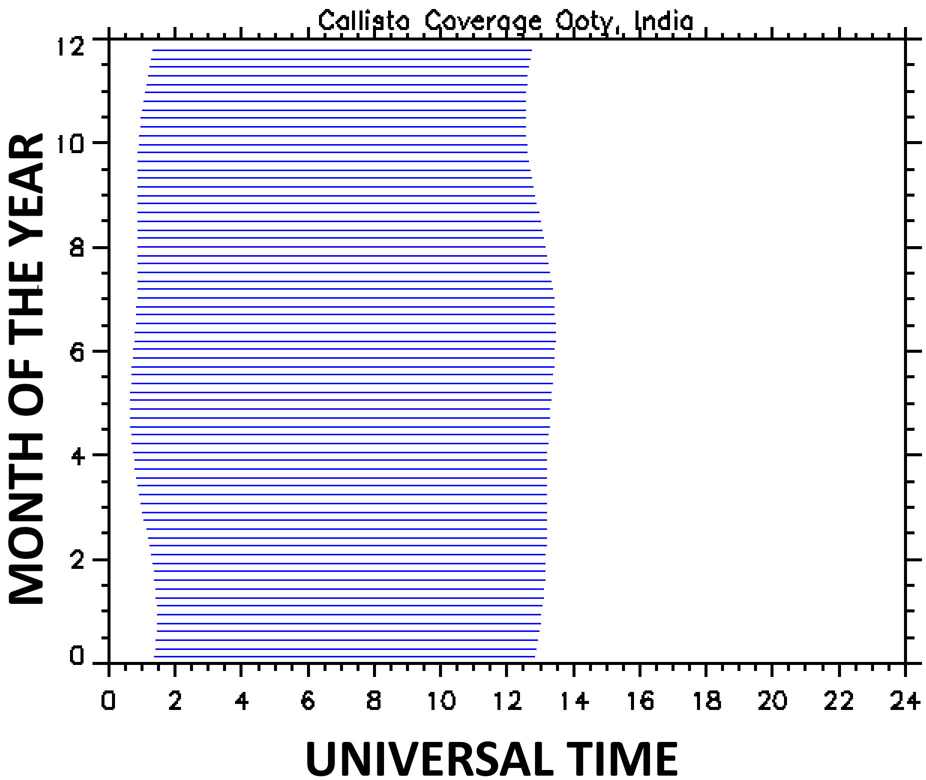
Frequencyrange: 50MHz...850MHz
Frequency resolution: 62,5KHz
Bandwidth: 280KHz
File: spectrometerV2.ppt, 2002-12-4, Monstein

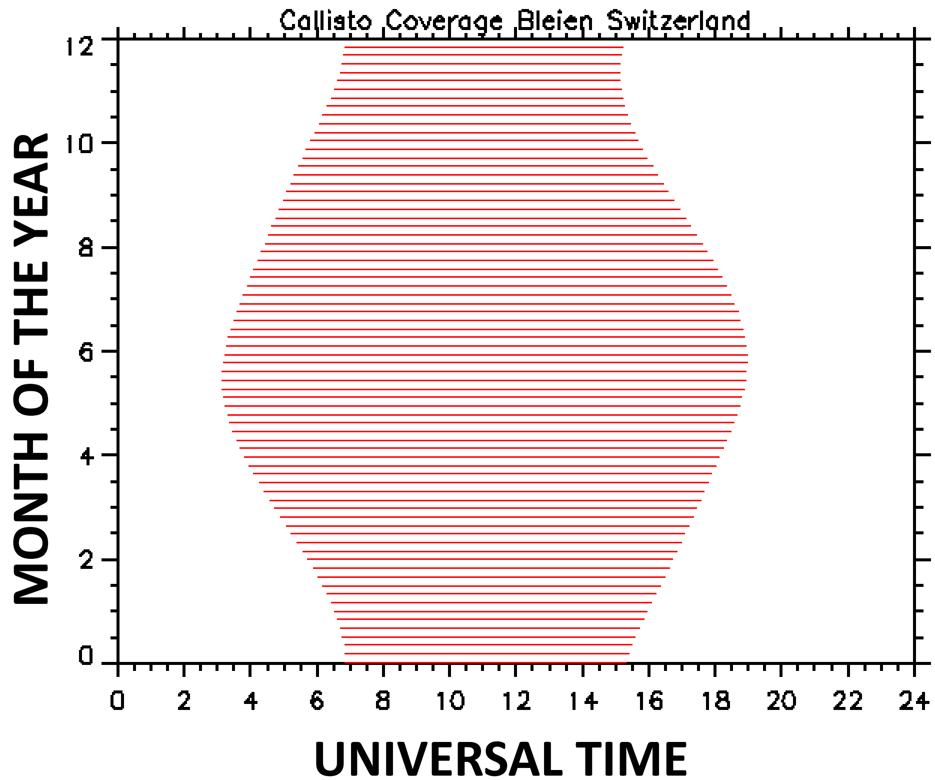
ISWI/CALLISTO

- Spectrometer Ooty/India operational
- Spectrometer Gauribidanur/India operational
- Spectrometer Badary/Irkustk/Russian Federation operational
- Spectrometer CINESPA/Costa Rica operational
- Spectrometer Unam, Mexico operational
- Spectrometer Switzerland 3 spectrometers (Bleien, Zurich and Freienbach) operational
- Spectrometer KASI Daejeon South Korea 2 spectrometers operational
- Spectrometer ROB/Humain operational
- … … … Austria, Germany
- In total, 36 spectrometers worldwide most of them operational
- More on the way: Ethiopia, Spain

CALLISTO Coverage of the Sun

courtesy: Monstein

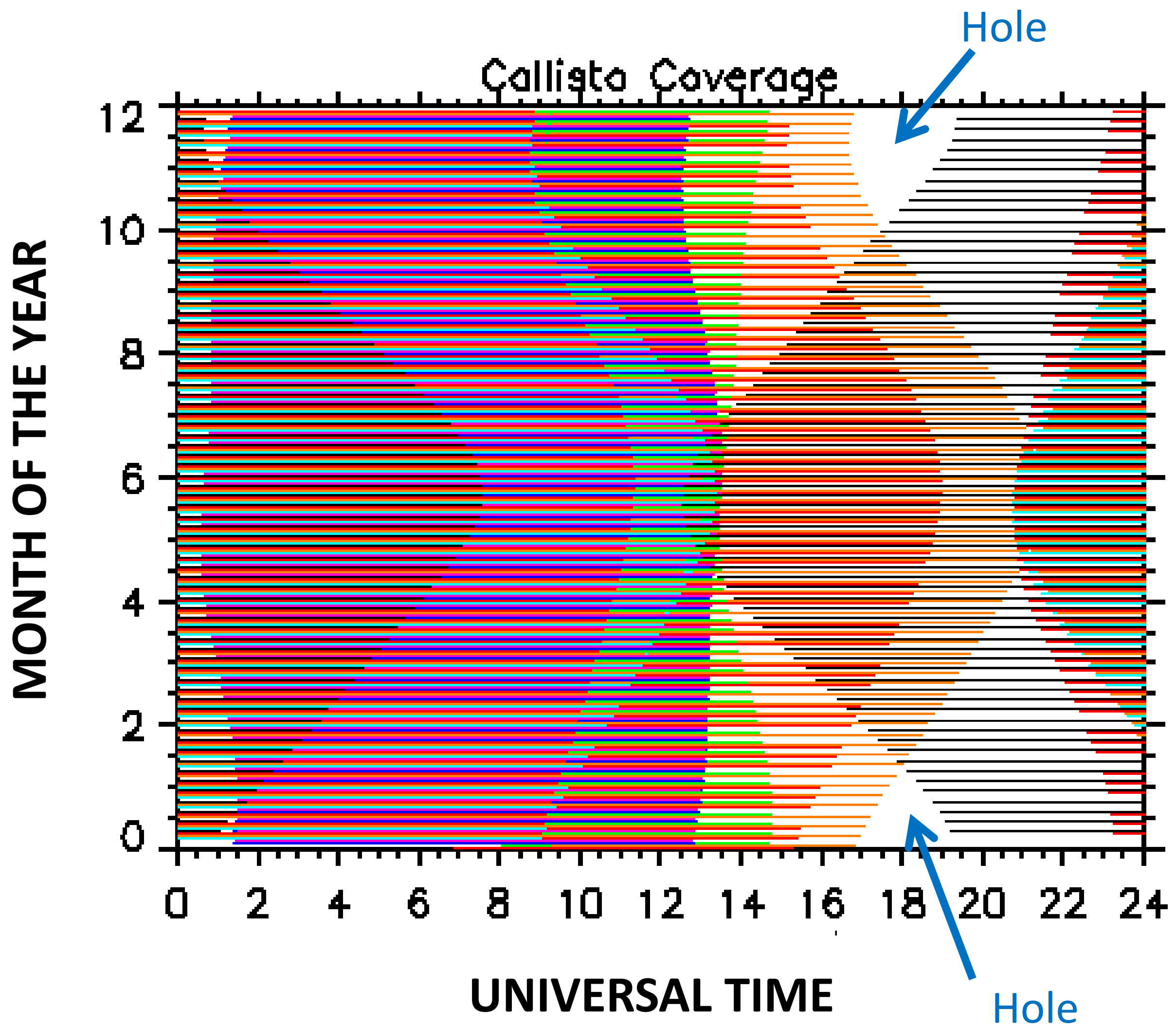




Low-latitude Station: Ooty, India
Uniform coverage throughout the year

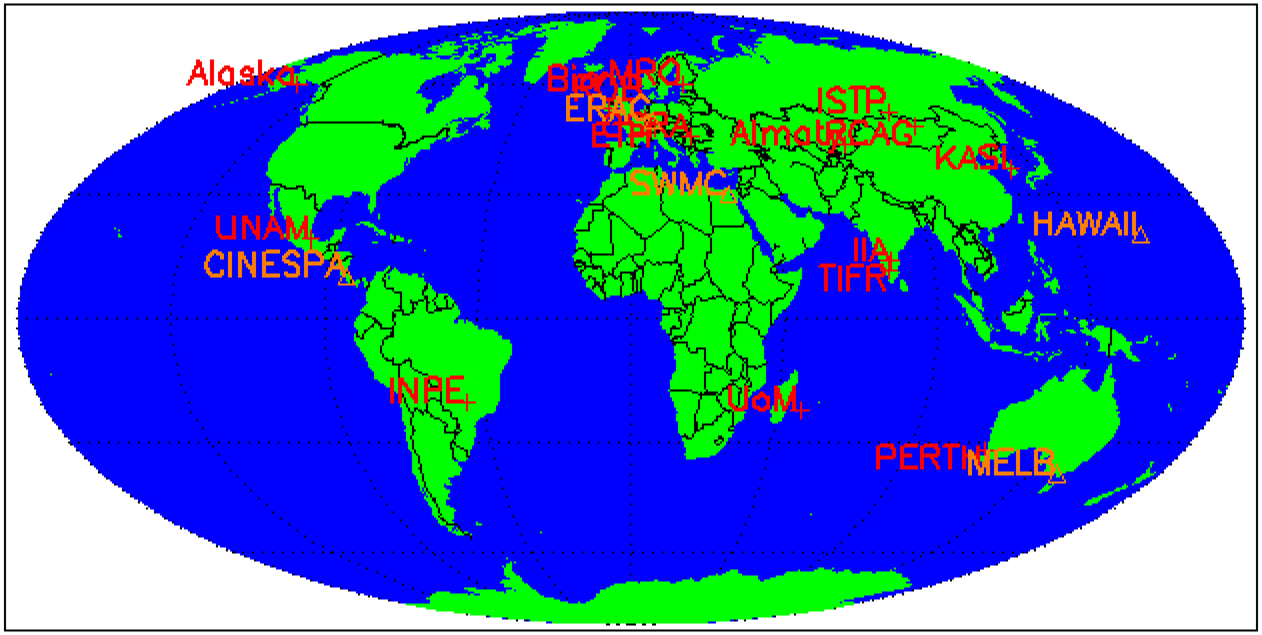
Mid-latitude Station: Bleien, Switzerland
More coverage during Summer months
Less coverage during Winter months

Current CALLISTO Coverage of the Sun



Data Access

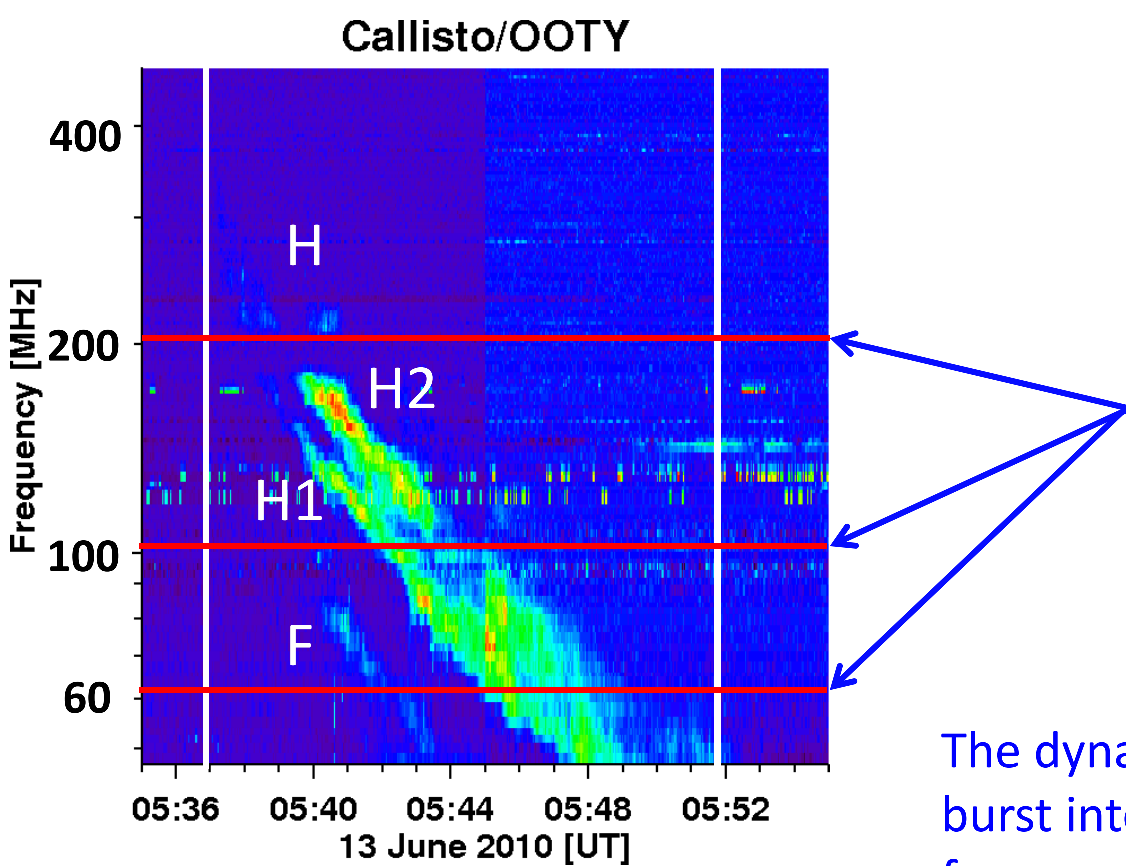
- Relevant links can be found here:
- http://e-callisto.org/
- All Data can be found here:
- http://soleil.i4ds.ch/solarradio/callistoQuicklooks/



Use CALLISTO Data!

- CALLISTO produces science quality data
- Detects tiny eruptions from the Sun
- CALLISTO data being utilized for a Indo-US project on solar eruptive events
- Need to identify a set of good instruments for continuous coverage over the whole frequency range
- CALLISTO is one of the success stories of ISWI instruments

Dynamic Spectrum from CALLISTO



The three frequencies used by Payne-Scott et al

Type II bursts are produced by shocks in the corona and IP medium

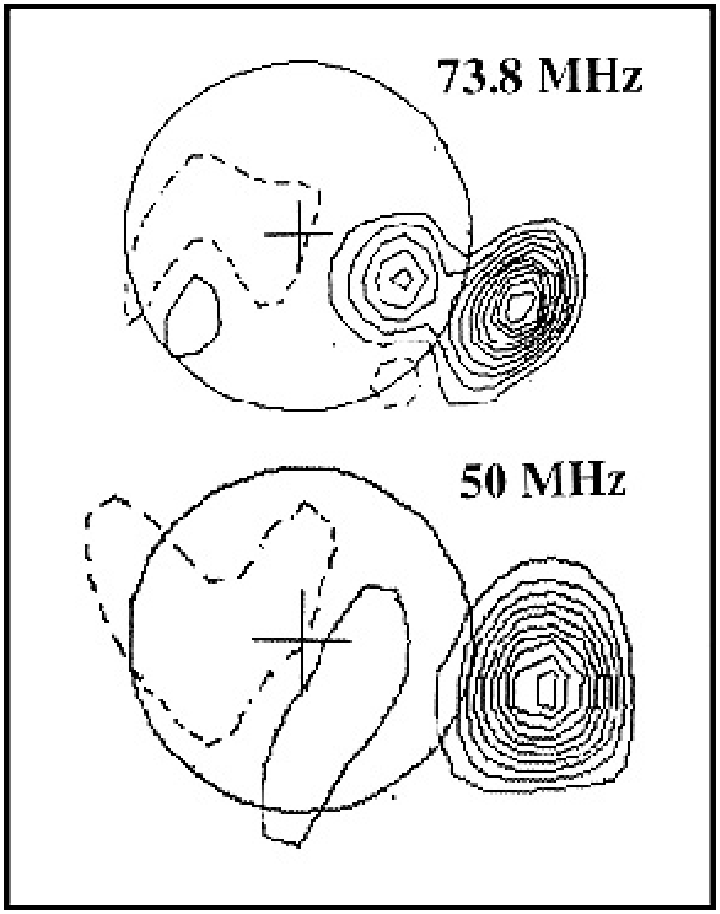
The dynamic spectrum shows the burst intensity variation in the frequency – time plot
Type II burst with fundamental-harmonic structure (F-H) and band splitting (H1,H2)

Type II bursts

- Shock origin confirmed by in situ observations of shock, radio burst, plasma waves in the vicinity of Wind spacecraft
- Shock source was thought to be flare blast waves and/or coronal mass ejections (CMEs)
- SOHO observations showed that type II bursts occur only in association with CMEs
- Type II bursts are indicators of shock-driving CMEs

Radio Observations

Type II burst from Clark Lake



Gopalswamy, 2000

- Mainly spectra:

- RSTN, CALLISTO, HiRAS, Potsdam, IZMIRAN, Nancay, … (ground based)

- Wind/WAVES, STEREO/WAVES (space)

- Imaging: only from ground:

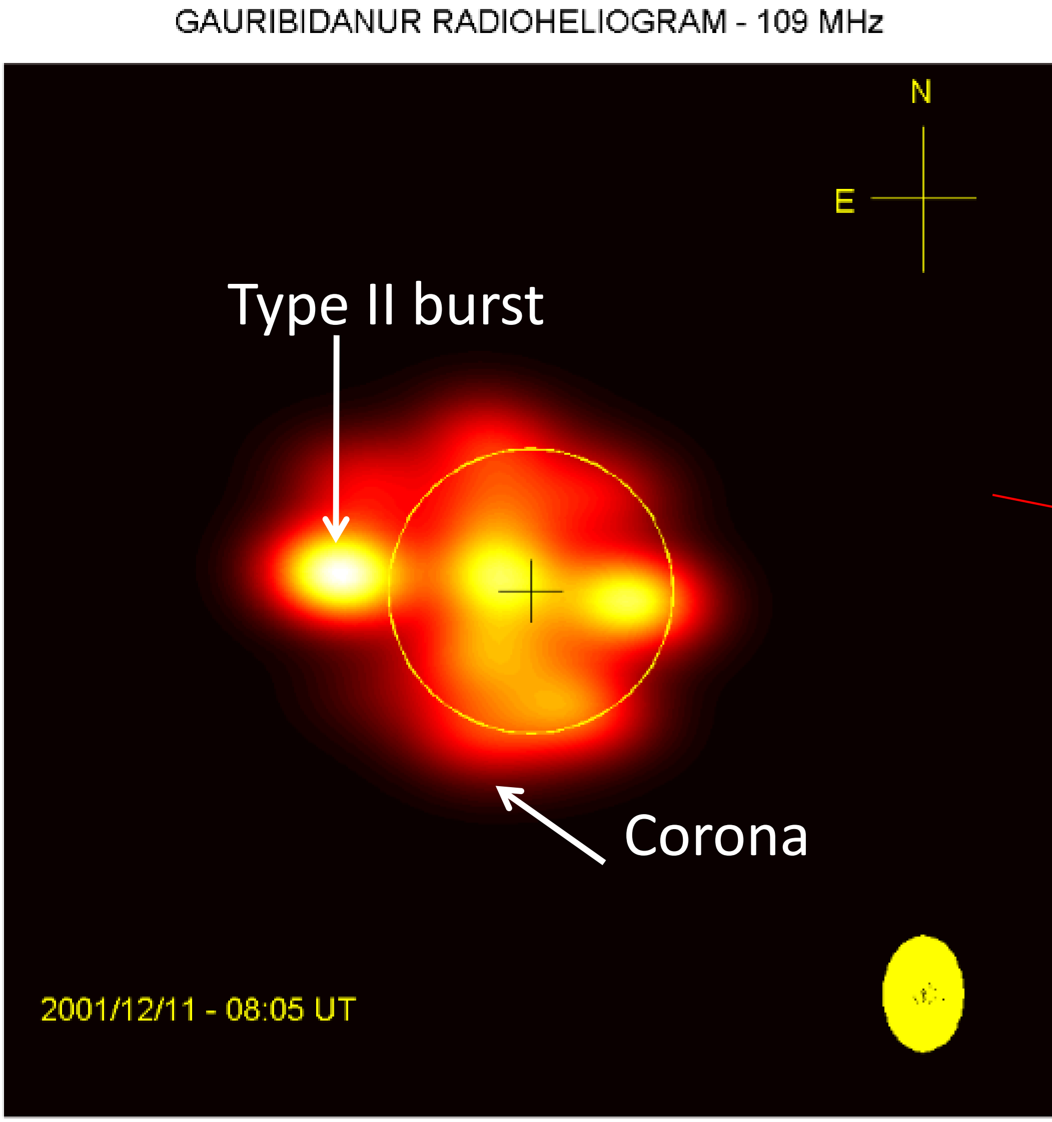
- Gauribidanur Radioheliograph (India)

-Nancay Radioheliograph (France)

-Murchison Widefield Array (Australia), LOFAR (Netherlands)

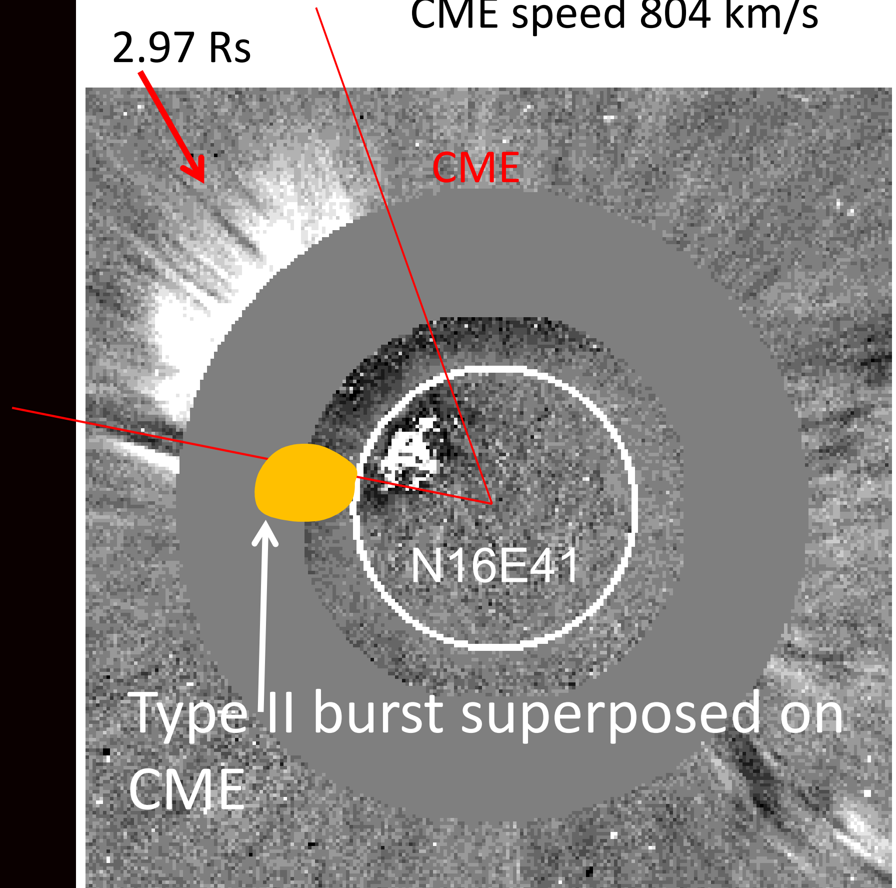
RSTN, CALLISTO have 24 – hour coverage

Imaging is best, but expensive



011211 POTS 0803.0 0836 II 2 40X 170U

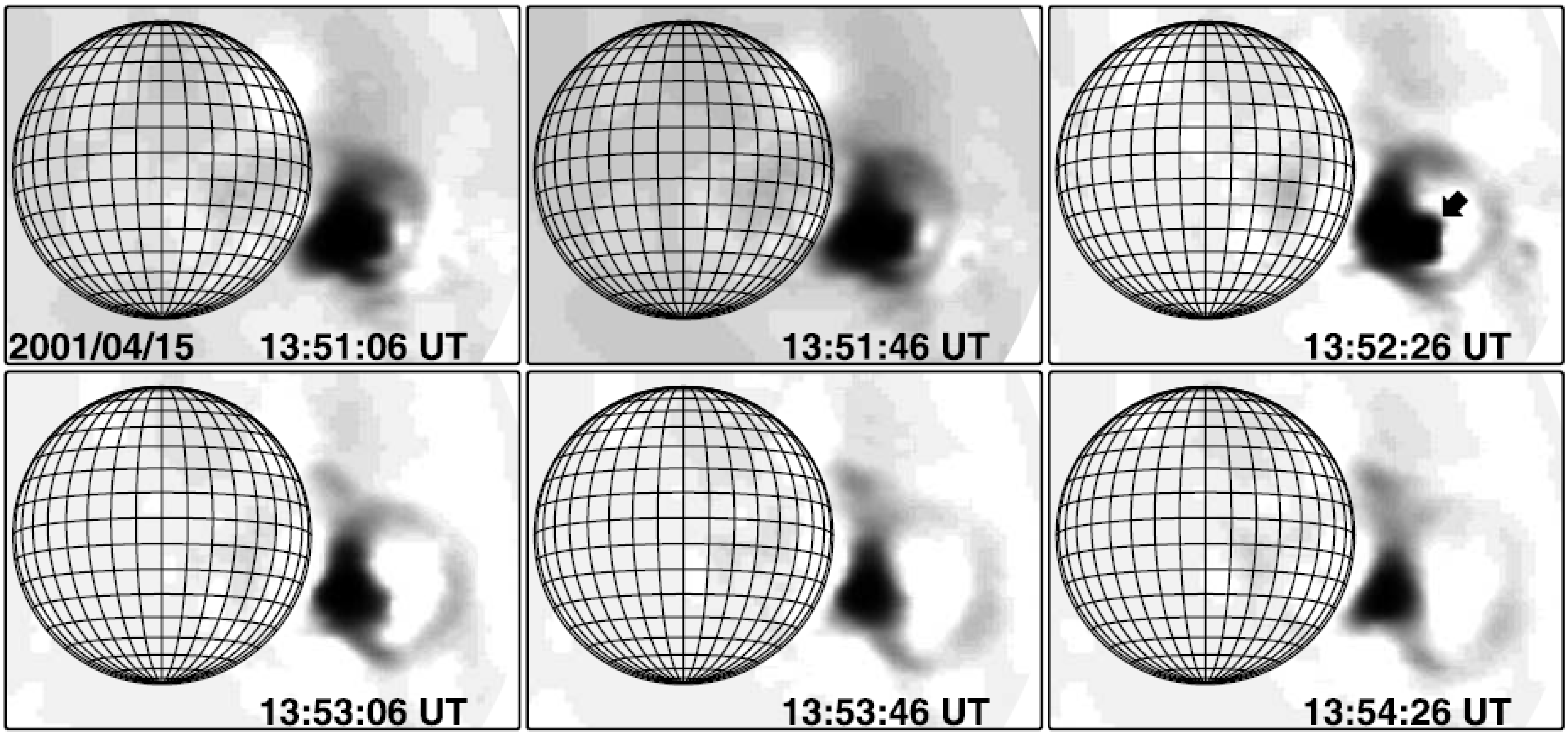
CME onset 08:02 UT
CME speed 804 km/s



Imaging tells that the type II is from the flank of the CME. We cannot get this information from spectra

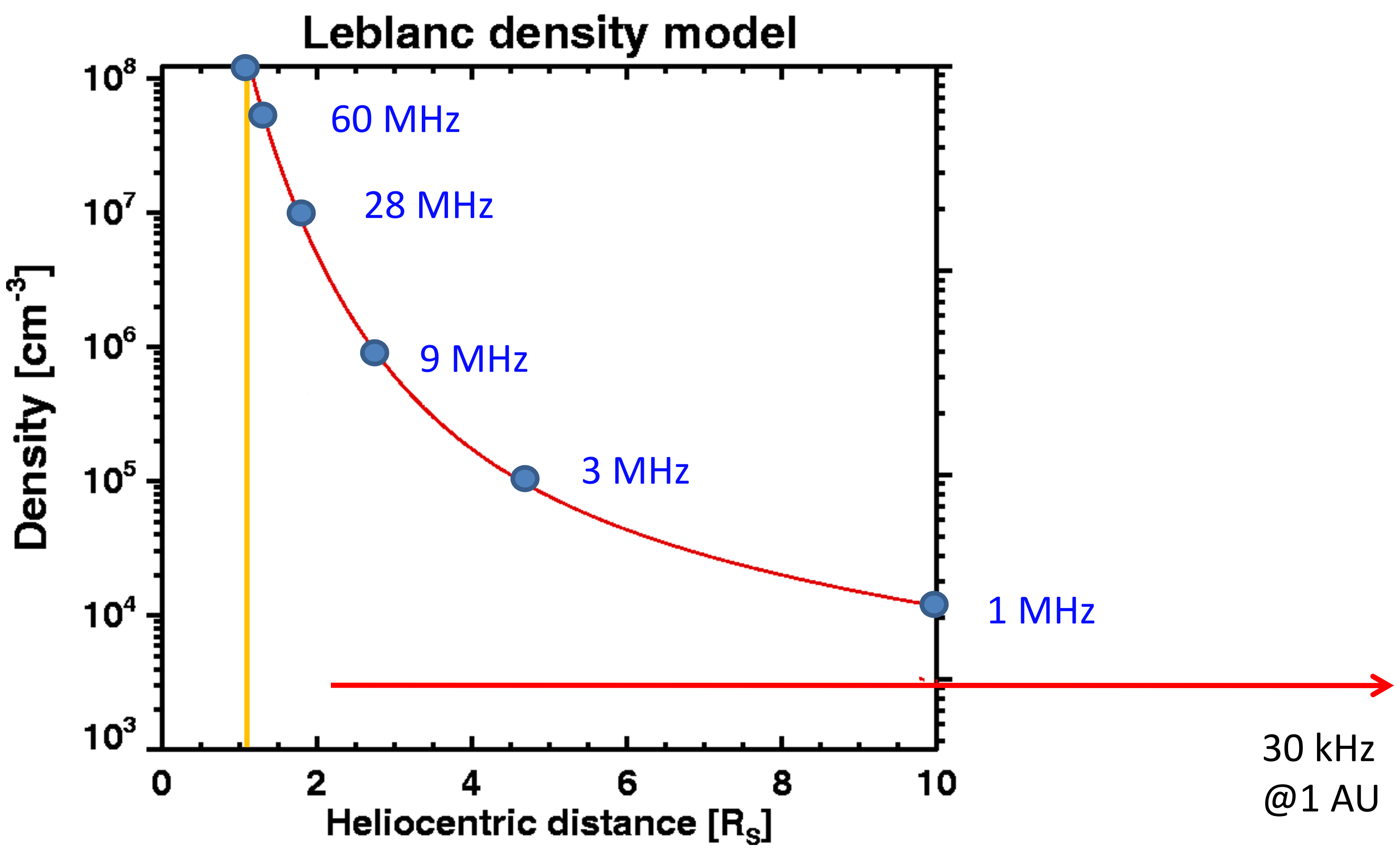
Spectra vs. Imaging

Radio images made by the Nancay Radioheliograph showing a radio bursts moving out. The burst is due to energetic electrons trapped in CME magnetic structures.
However, the spectra are very useful in understanding the properties of the shock and the medium in which the shock propagates.



Maia et al. 2007

Density decrease in the corona → drift of radio emission in dynamic spectra



1 Rs = 700,000 km. Earth at 214 Rs.

Plasma frequency = $9 \times 10^{-3} n^{1/2}$ MHz

Emission Frequency Tells the Heliocentric Distance

	N_e (cm^{-3})	f_p
low corona	$\geq 10^8$	$\geq$ 100 MHz
~ 10 $R_\odot$	~ 10^4	~ 1 MHz
~ 30 $R_\odot$	~ 1.5 10^3	~ 350 kHz
~ 1 AU	~ 10	~ 30 kHz

Emission frequency f = plasma frequency f_p or $2f_p$

How to get the shock speed?

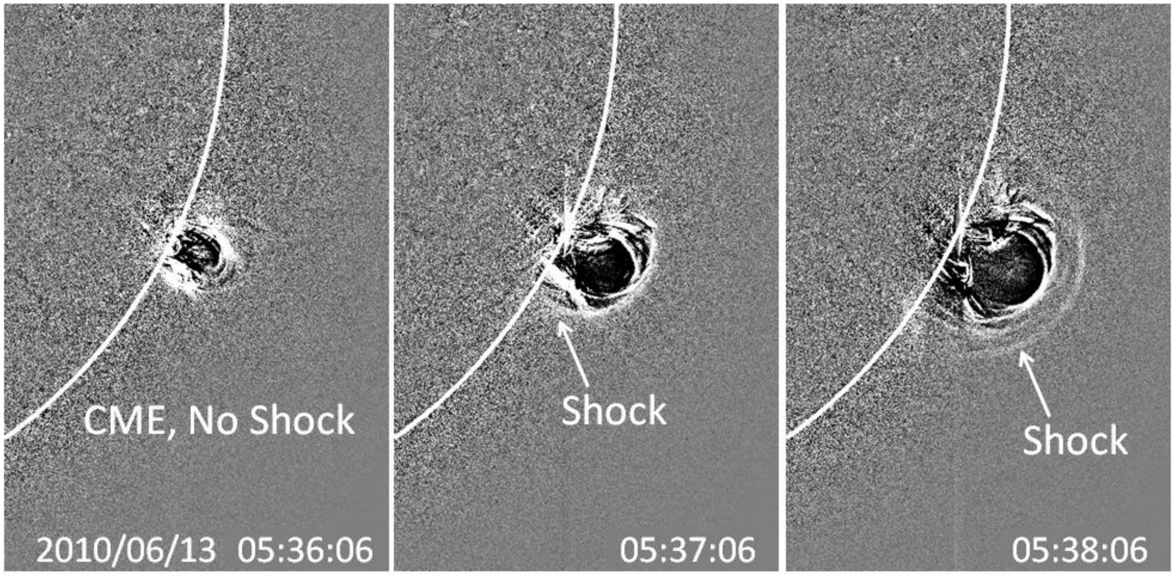
- $f = 9 \times 10^{-3} n^{1/2}$ MHz plasma frequency (emission takes place at this frequency or its harmonic)
- $df/dt = (df/dr)(dr/dt) = (V/2)\, f\, n^{-1} (dn/dr)$ using the relation between f and n; V is the shock speed (dr/dt)
- $(1/f)\, df/dt = (V/2L)$, with $L = |(1/n) dn/dr|^{-1}$

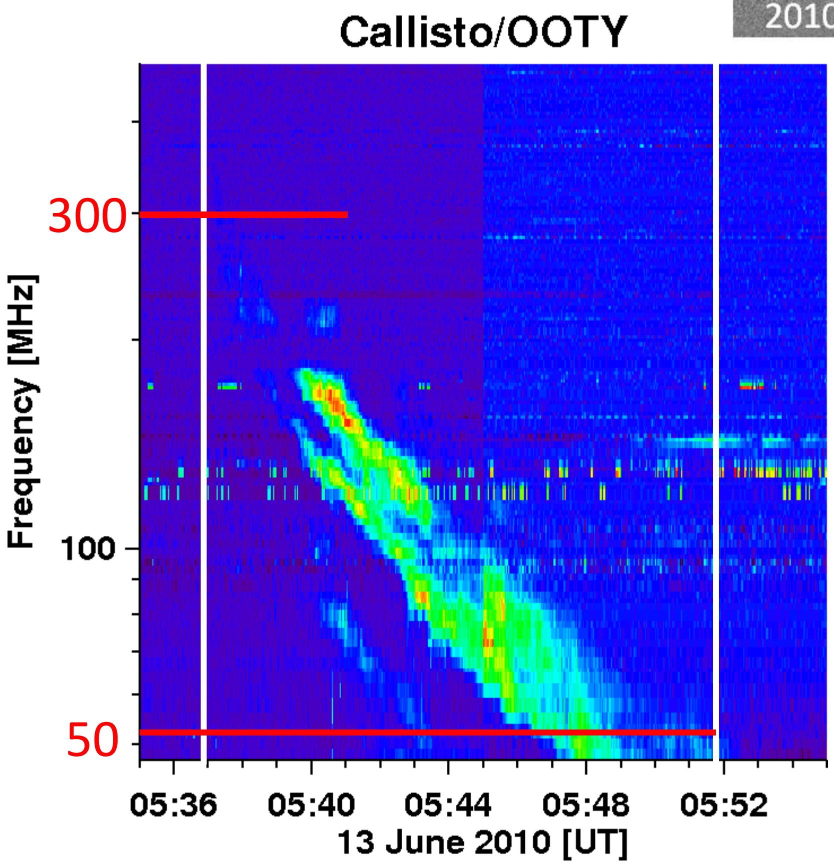
From the dynamic spectrum

From the density model
e.g Newkirk model
Saito Model
...

- $V = 2L. (1/f)\, df/dt$

Shock Source: coronal mass ejections





Solar Dynamics Observatory (EUV 193 Å)

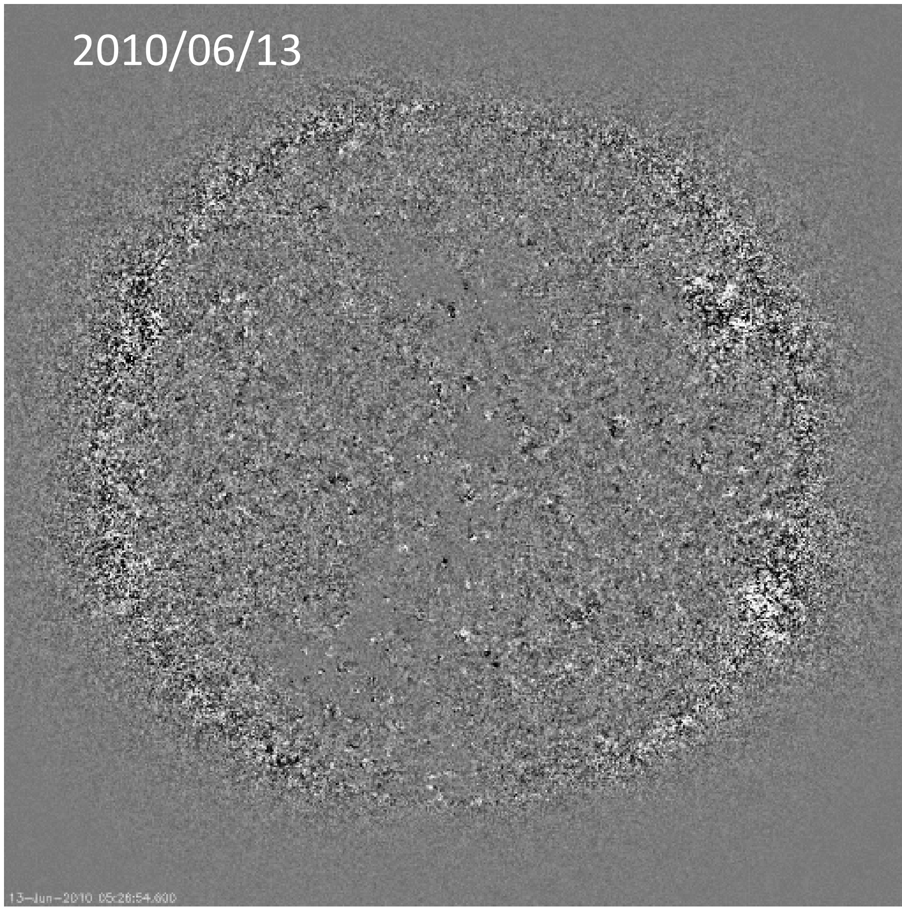
Type II burst starts exactly at the time the shock appears in the corona at 1.2 Rs (this is the leading edge method)

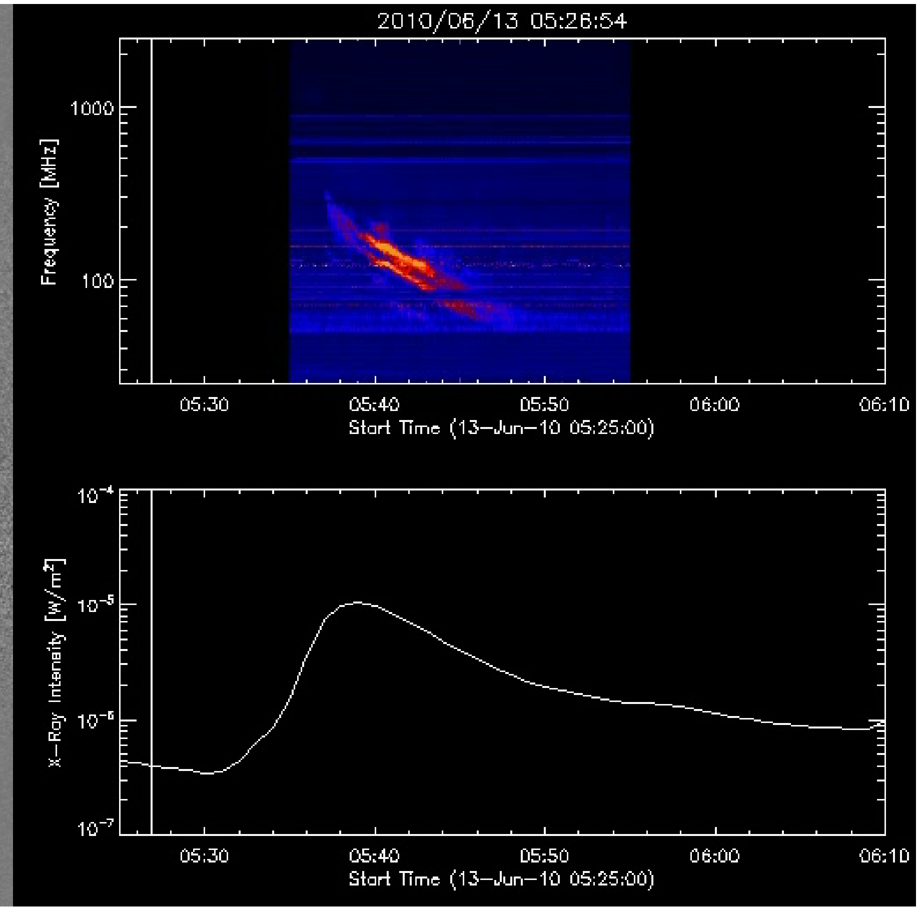
We can probe the coronal medium as well as the shock structure by combining type II and EUV/coronagraph observations

df/dt = 0.28 MHz/s; (1/f)df/dt = (0.28/175) s^{-1}

V = 600 km/s; L = 189,000 km

Where does the shock form? Or What is the shock/CME height when the type II bursts starts?





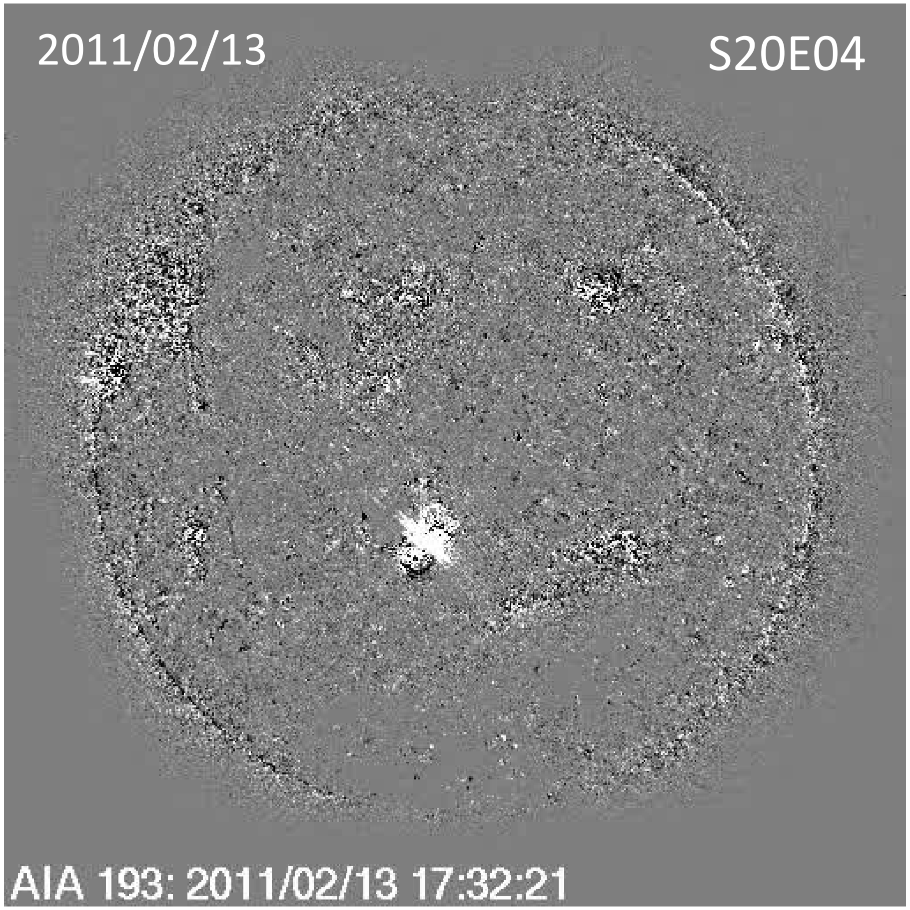
CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs

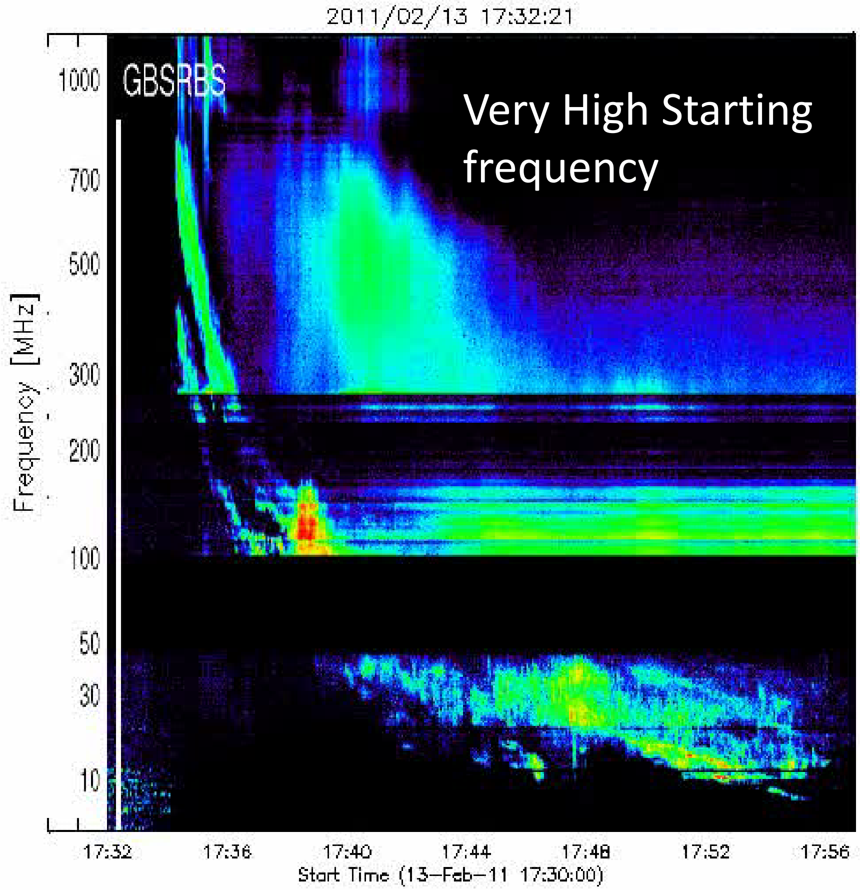
f_p = 150 MHz → n_p =2.8x10^8 cm^{-3}

Gopalswamy et al., 2012 ApJ

Wave Diameter Method:

The shock is hemispherical around the CME, so the shock height above the surface is half of Wave Diameter

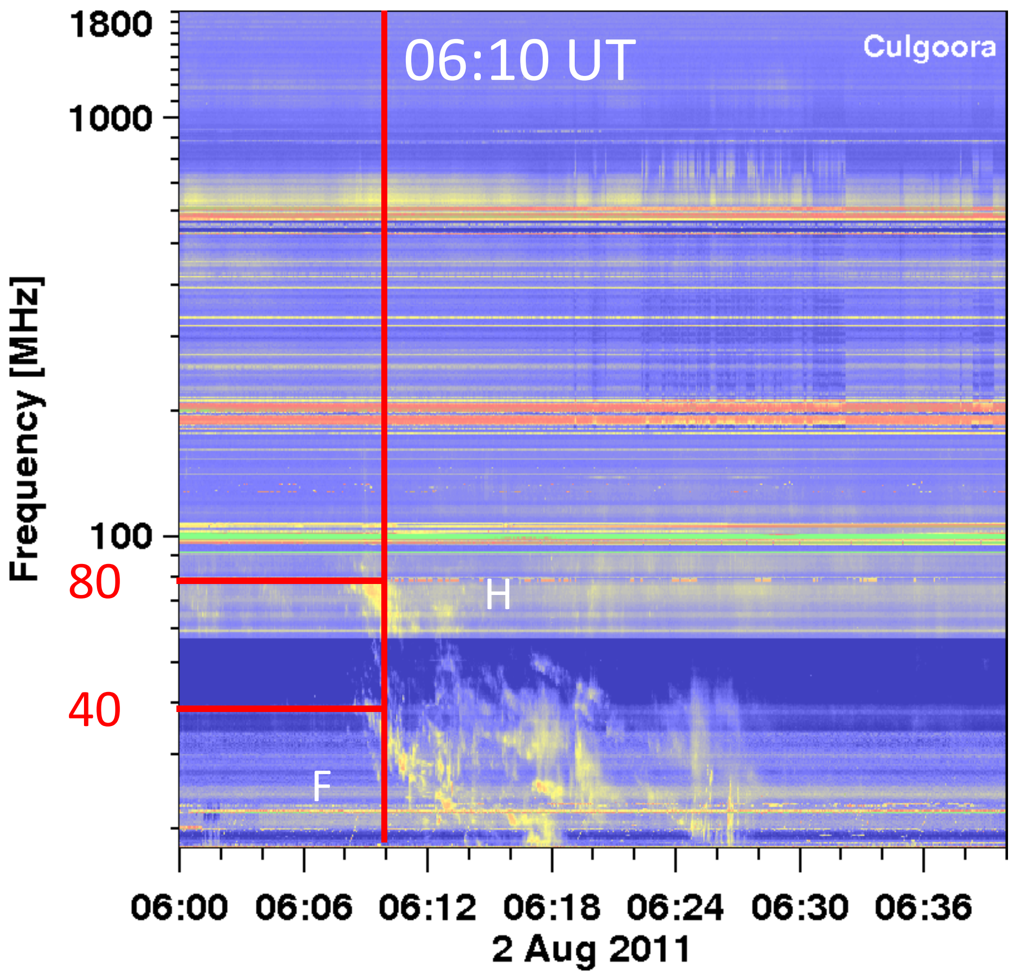


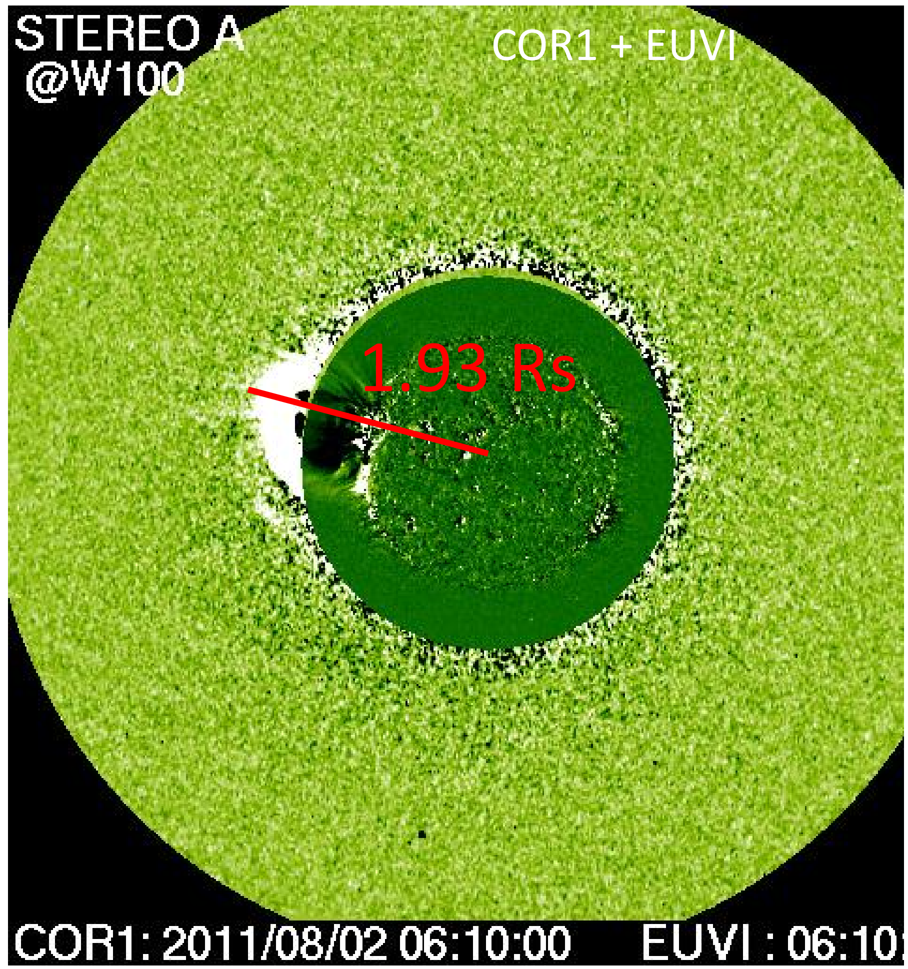


AIA wave radius @ type II onset = 0.14 Rs = Shock height in EUVI

400 MHz → $n_p = 1.98\text{x}10^9\ cm^{-3}$

Leading Edge Method applied to White-light Data: CME already in the coronagraph FOV when type II occurs

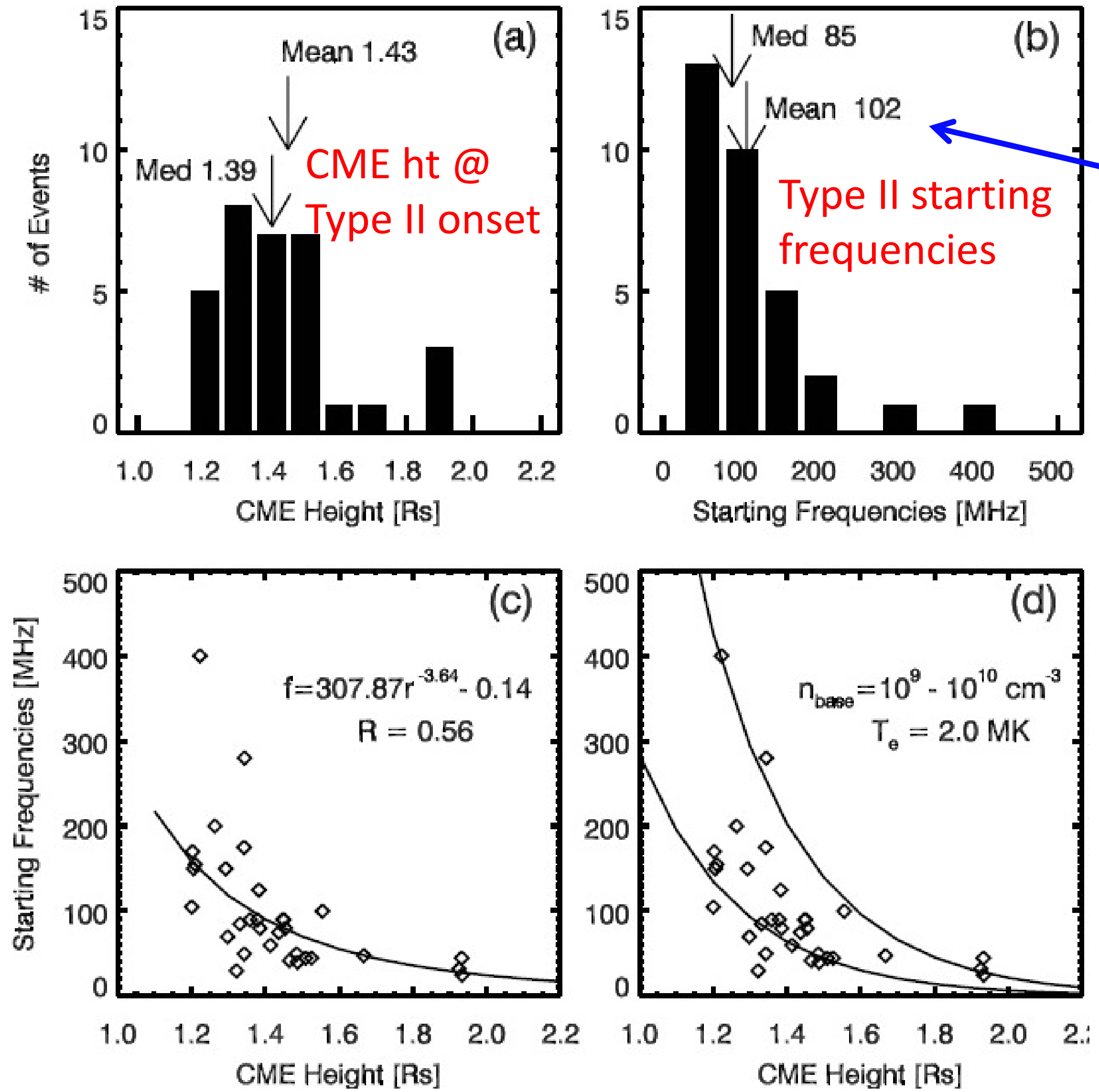




fp = 40 MHz → 1.98×10^{7} cm^{-3} Shock formation height is large: 1.93 Rs

Where in the Corona do shocks form? Statistics

32 Type II bursts
STEREO CMEs



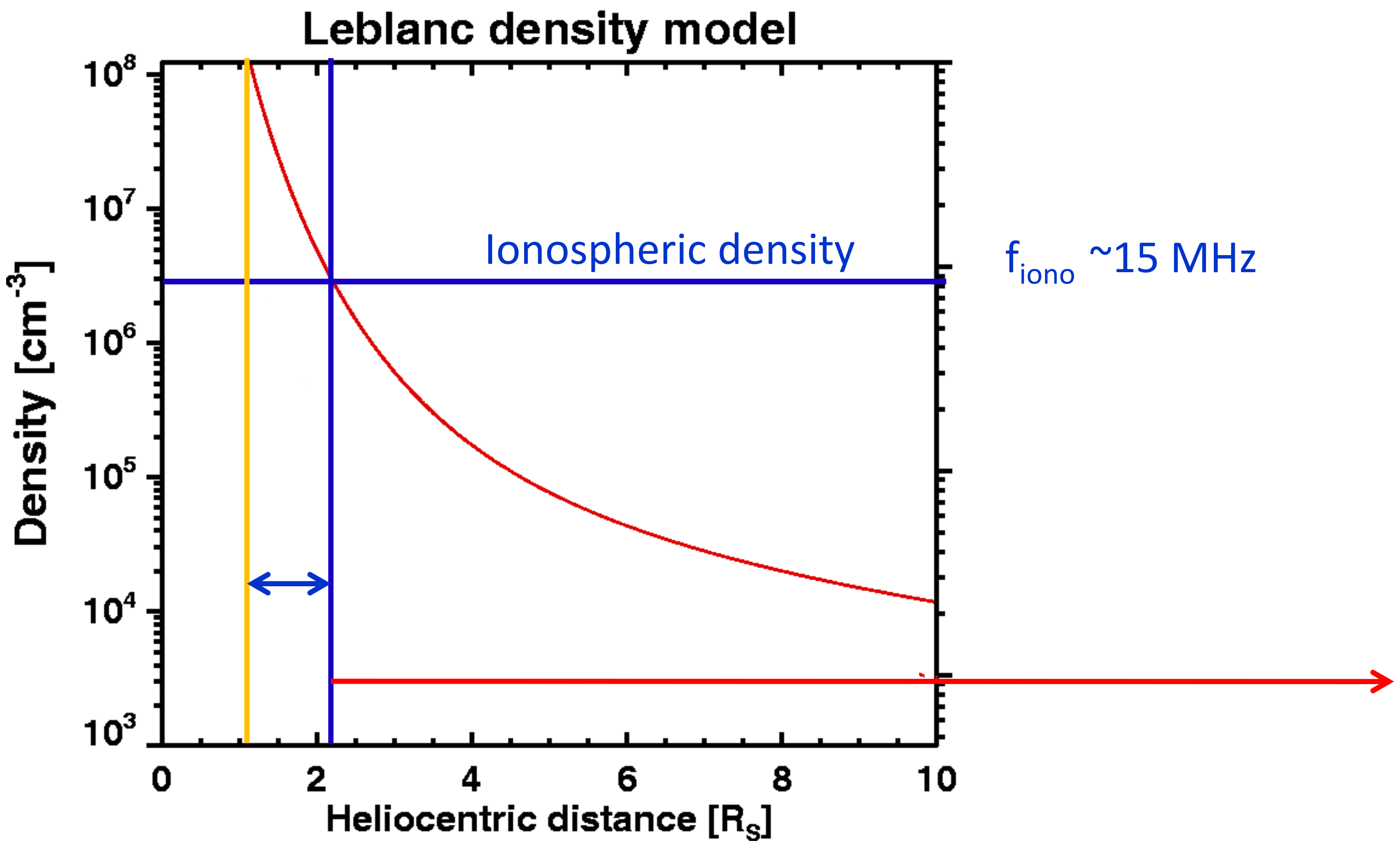
$n = 1.2 \times 10^8\ cm^{-3}$

Type II heights indicate overall density decline with height

model: exponential fall off of n with a hydrostatic scale height

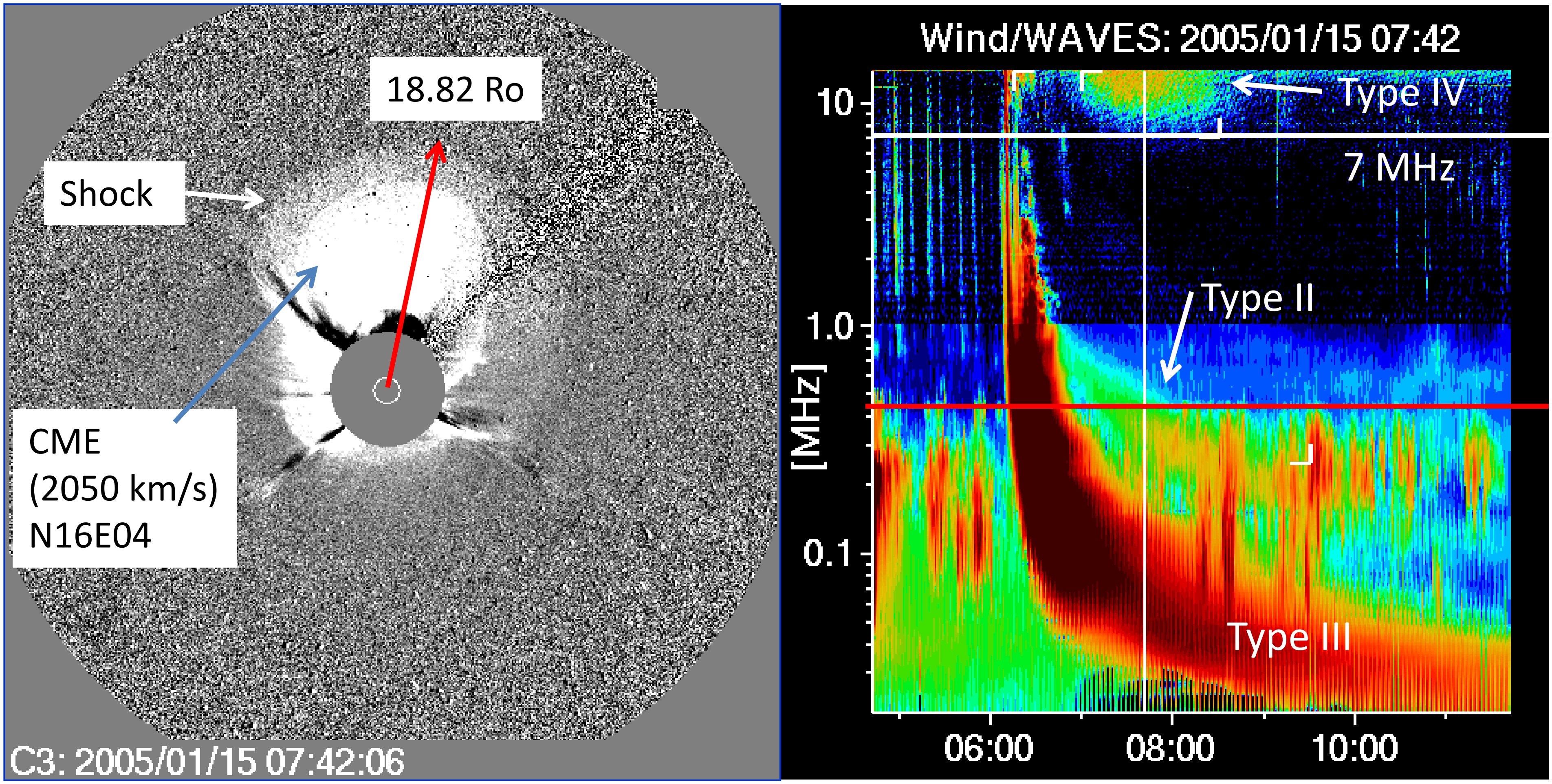
Gopalswamy et al. 2013 AdSR

Coronal density = Ionospheric density at 2 Rs



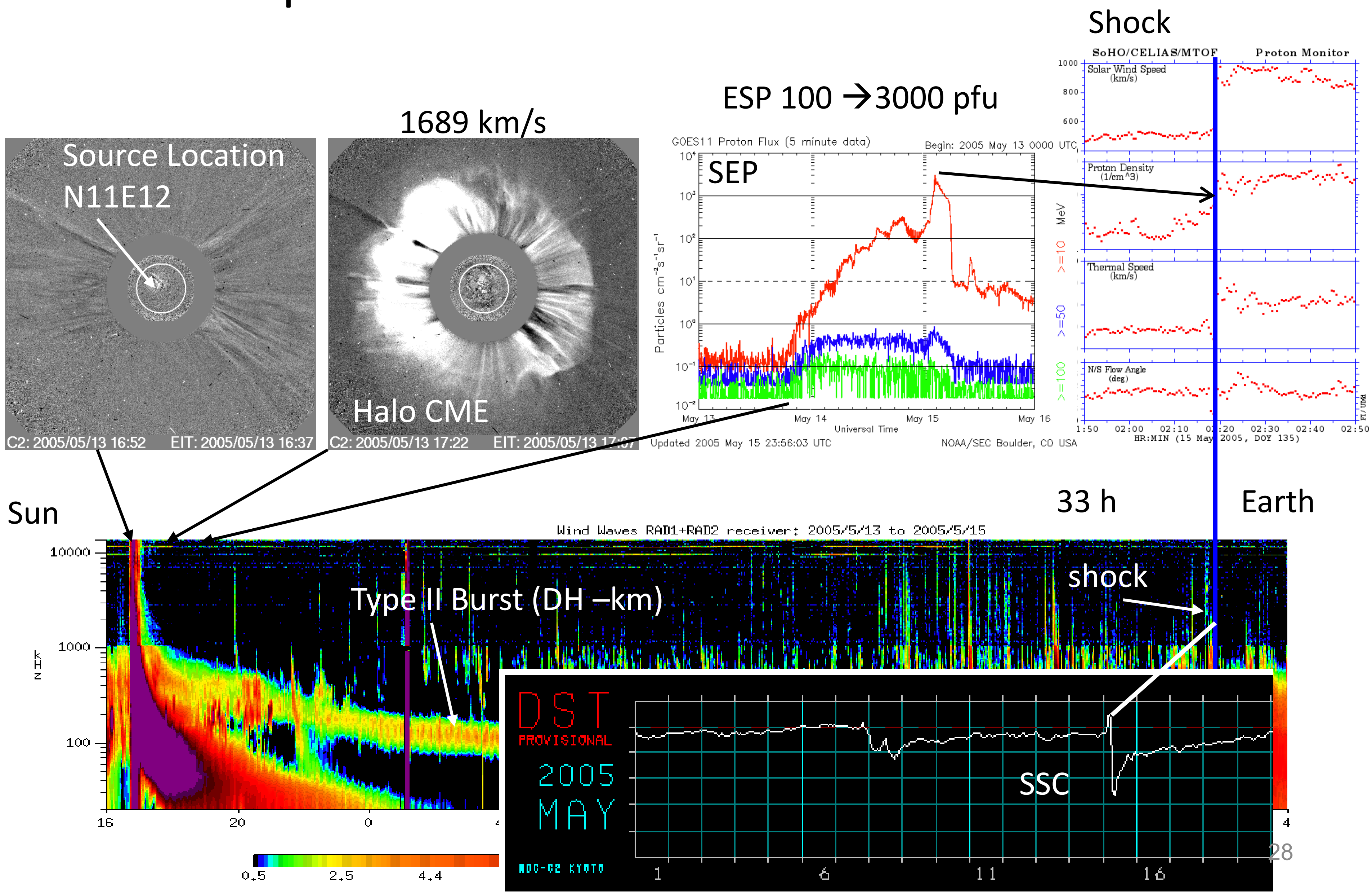
f < f_{iono} cannot reach Earth → go above the ionosphere to observe disturbances beyond 2 Rs (i.e., type II bursts below 15 MHz)

Three Types of low-frequency bursts that can be observed only from space: type III, type II, type IV

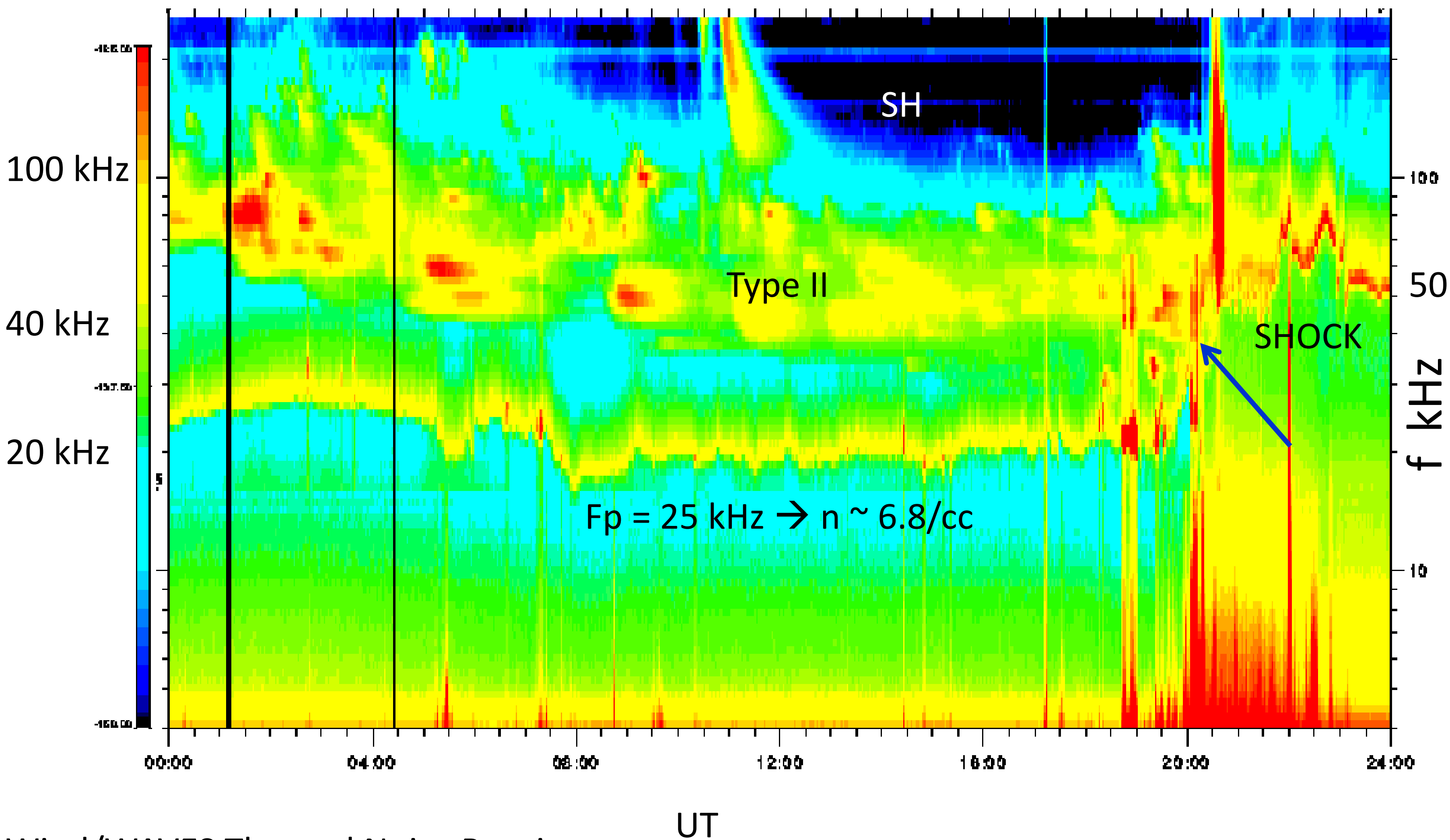


When the shock is at a distance of 18.82 Rs, the Type II burst occurs at 450 kHz as observed by the WAVES experiment on board Wind (n = 2450/cc)

A CME with Type II, SEP event & Shock at 1-AU: Radio helps track CMEs from the Sun to earth

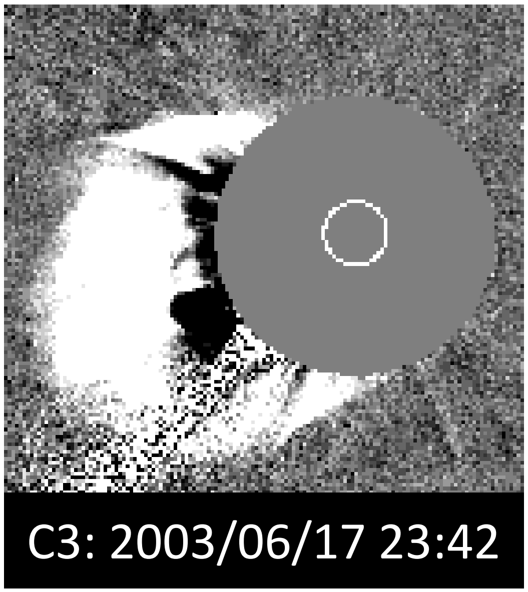


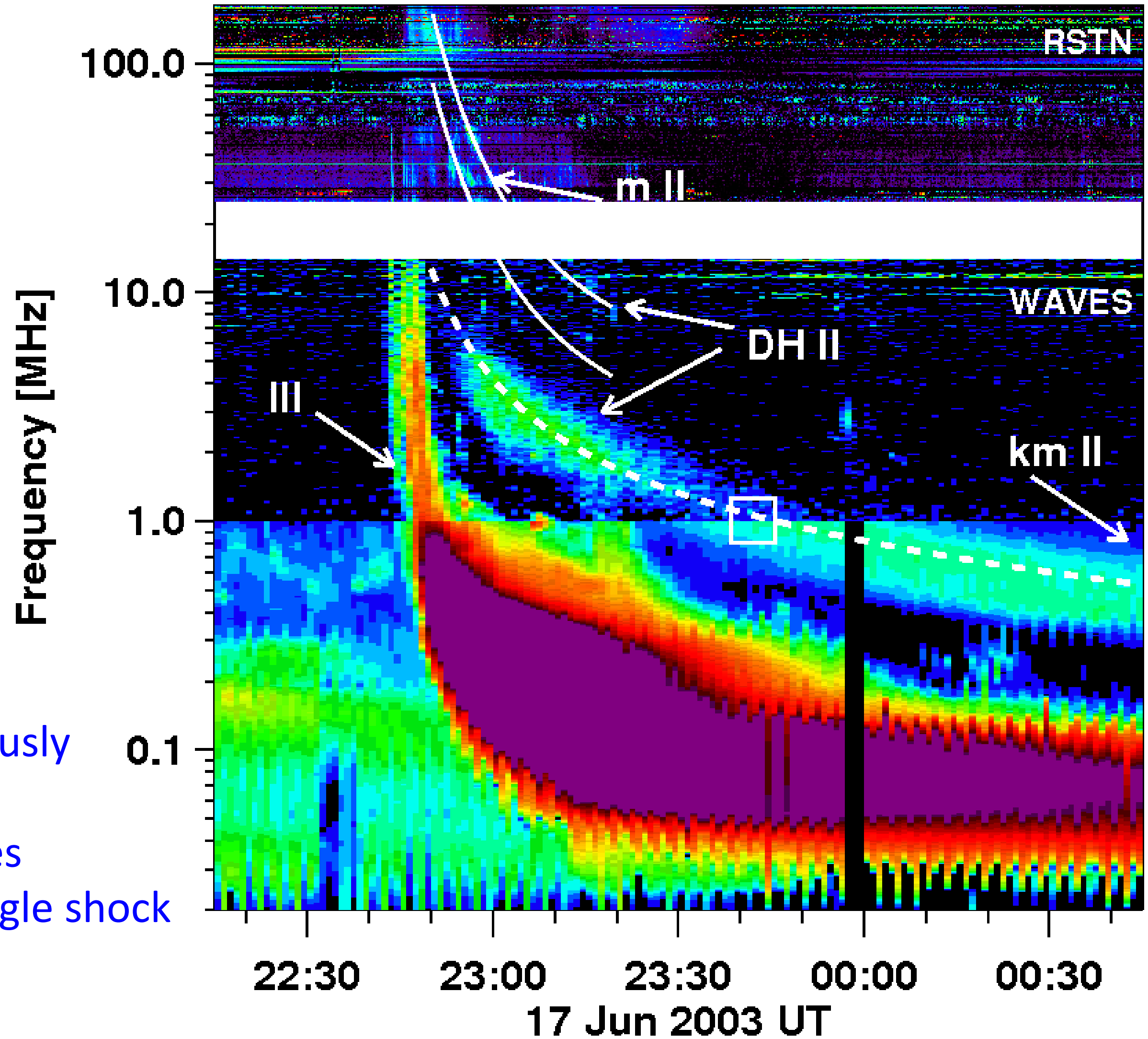
Shock, Type II, & Langmuir Wave at Wind Spacecraft



Wind/WAVES Thermal Noise Receiver

Type II burst at low & high frequencies appearing simultaneously



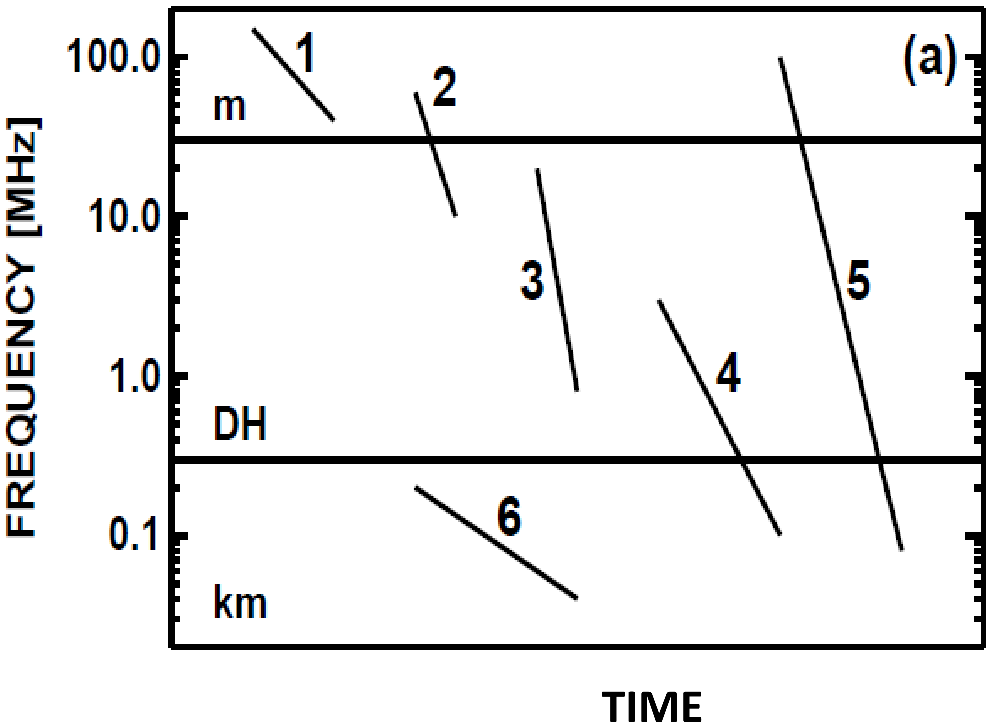


Curved shock crossing low and high-density regions simultaneously
→ different shock speeds,
→ different Alfven speed profiles
→ Different drift rates, but a single shock
Flank & Nose?

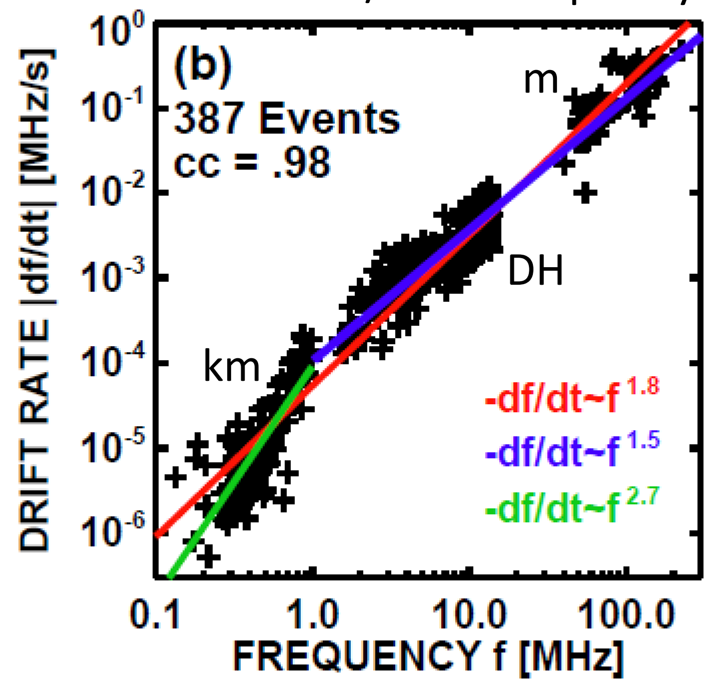
m = metric; DH = Decameter-hectometric

Type II Burst Related to CME-driven Shock

Schematic dynamic spectra showing type II freq. range



drift rate df/dt vs. frequency f



Observed wavelength ranges of type II bursts

1,6: 600 km/s; 2,3,4: 1000 km/s; 4, 5: 1500 km/s (CME speed)

$df/dt \sim f^{\varepsilon}$

$n \sim r^{-\alpha}$ $f \sim r^{-\alpha/2}$

$V \sim r^{-\beta}$

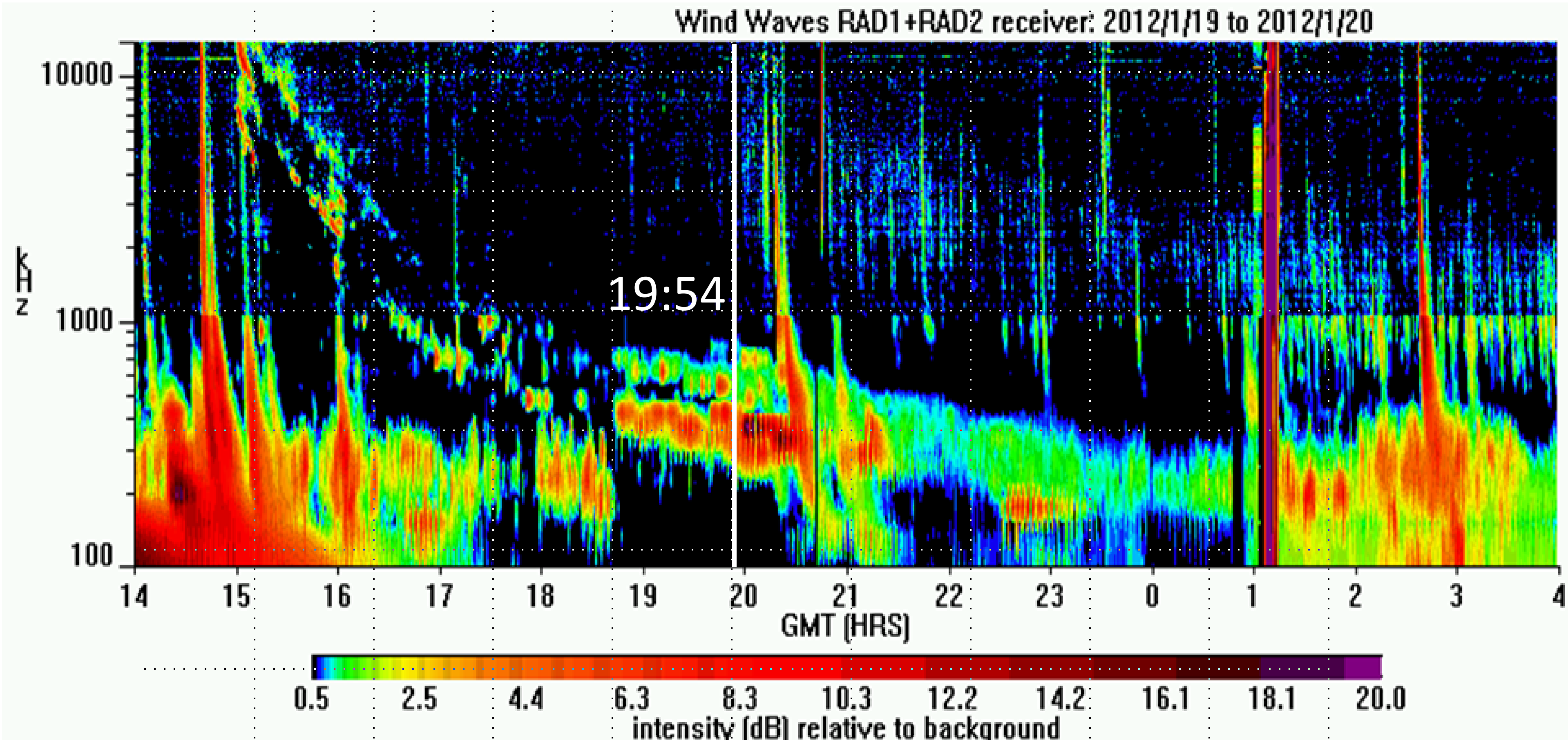
$\varepsilon = (\alpha + 2\beta + 2)/\alpha$

Inner corona: α ~6; for $\varepsilon = 1.07$, $\beta = -\ 0.79$ (CME still accelerating)

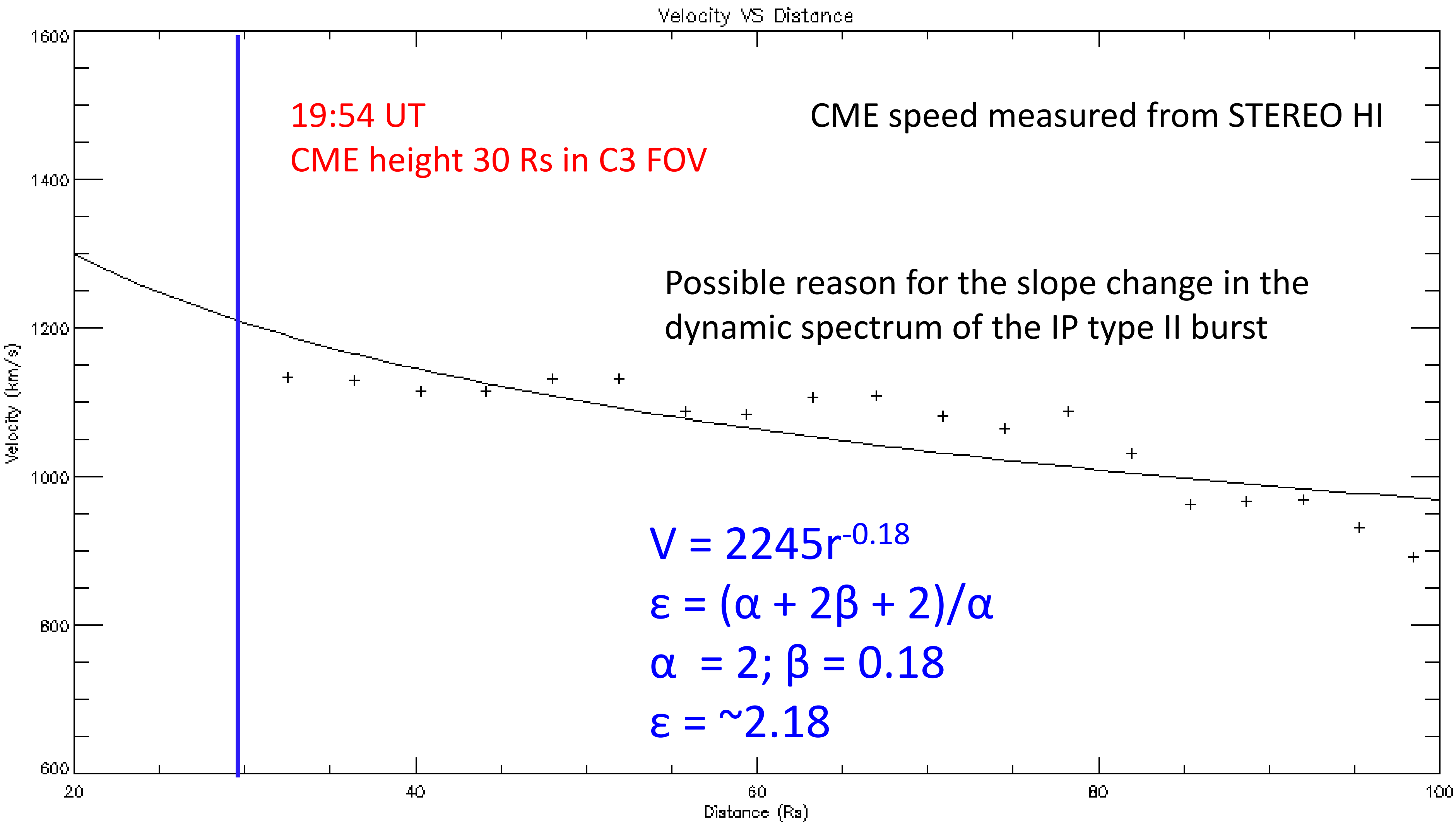
Outer corona: α ~4; for $\varepsilon = 1.5$, $\beta = 0$ (CME attained constant speed)

IP medium: α ~2; for $\varepsilon = 2.7$, $\beta = +0.7$ (CME decelerates due to drag)

Example: 2012/01/19 Type II

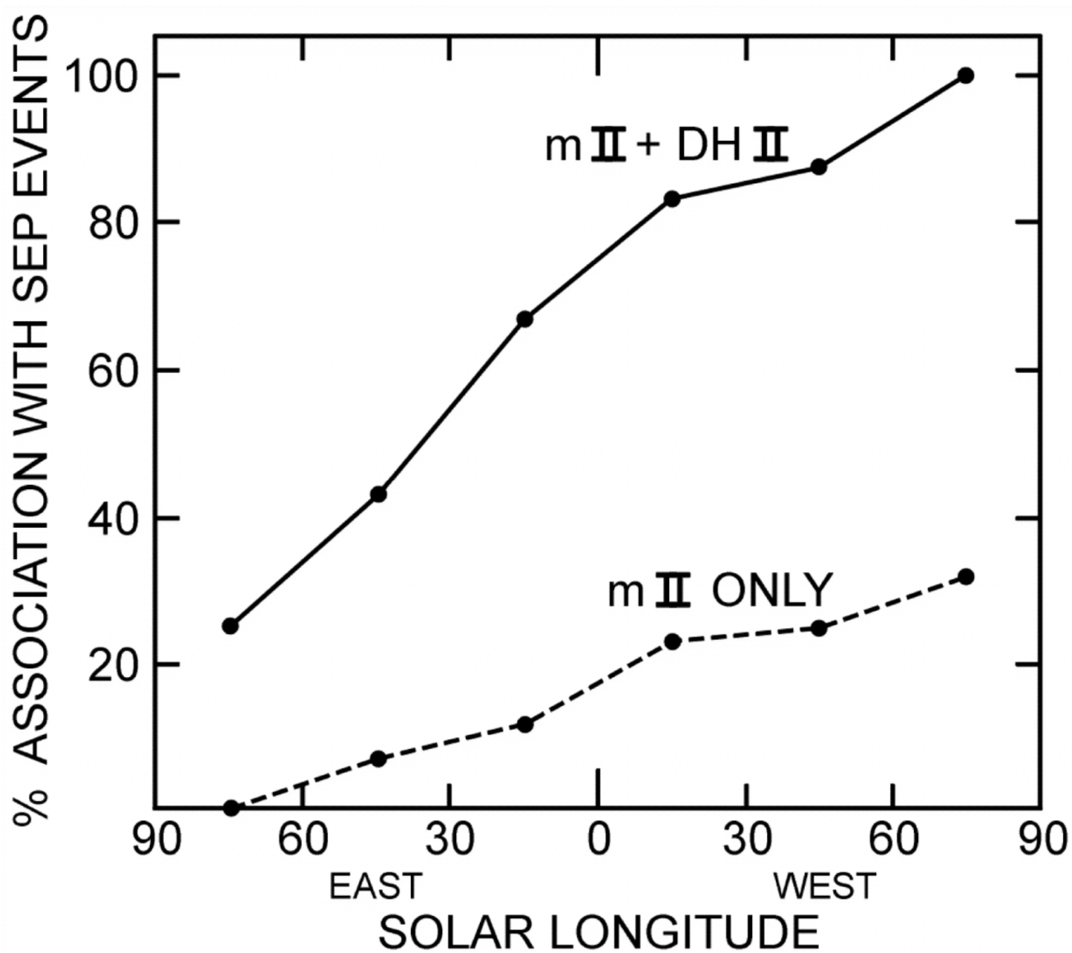


Speed Evolution in HI 1 FOV

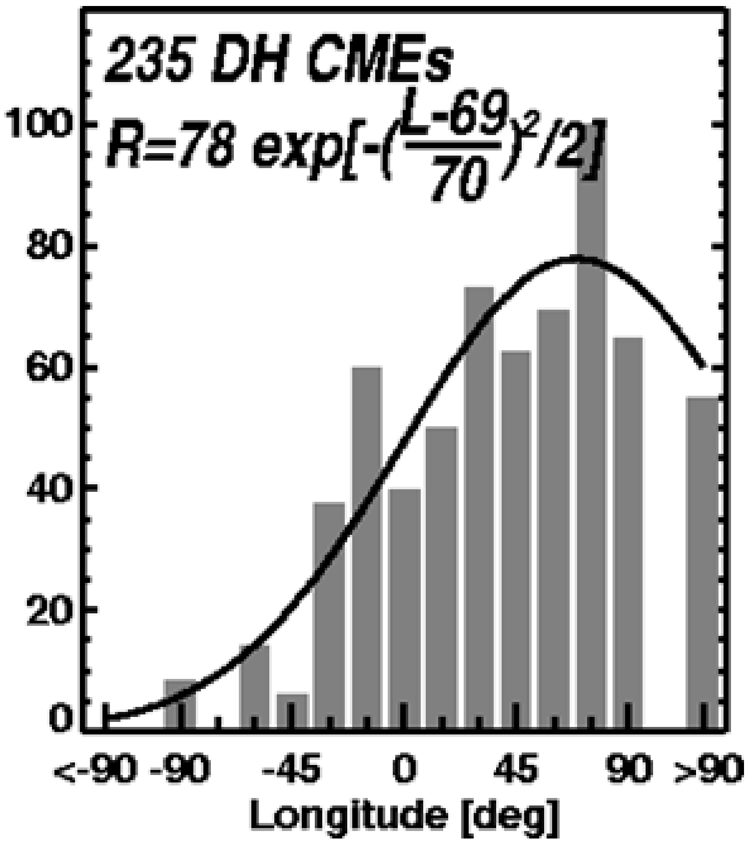


Type II Bursts and SEP Events

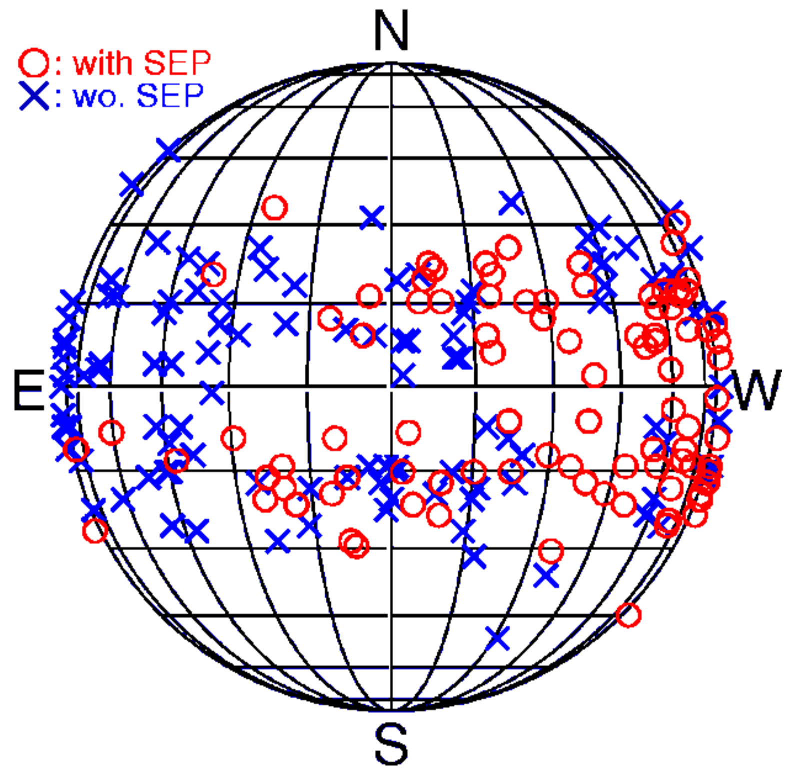
SEP association higher when type II occurs at metric and longer wavelengths



What Fraction of Radio-loud CMEs Produce SEPs?

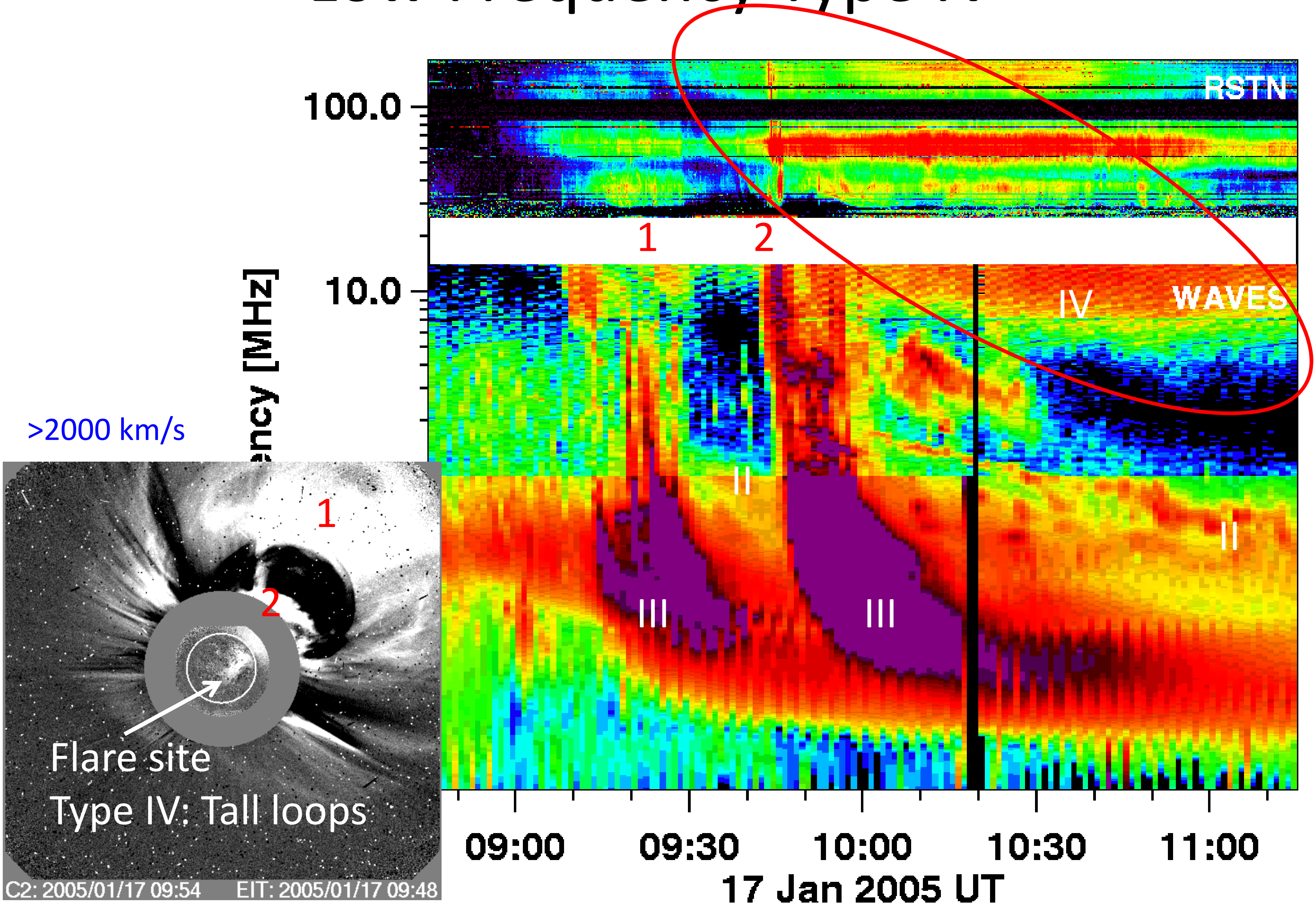


Sources of CMEs associated with DH type II bursts



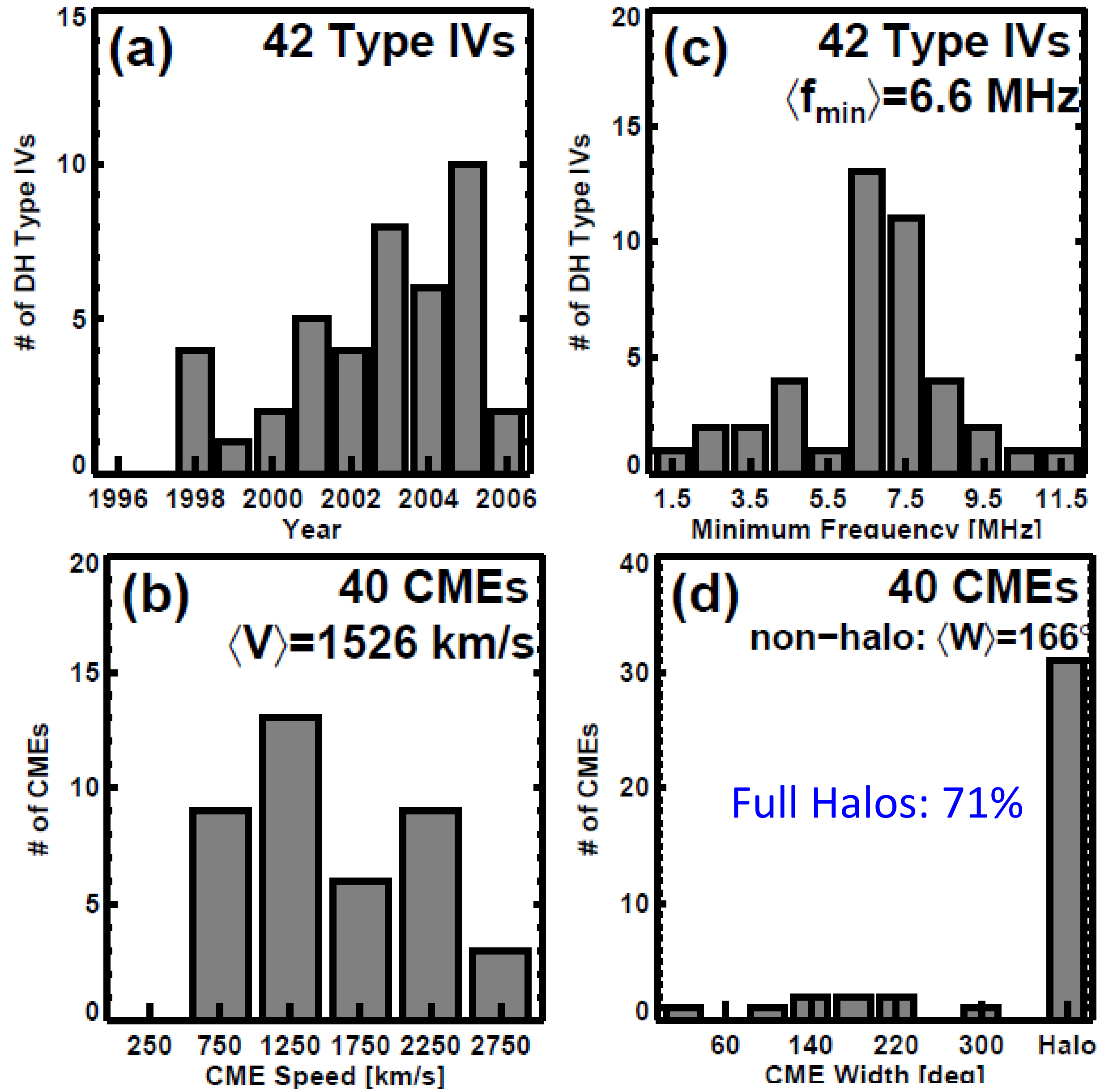
Answer: About 50% because magnetic connectivity needed for SEPs, not for EM radiation

Low Frequency Type IV



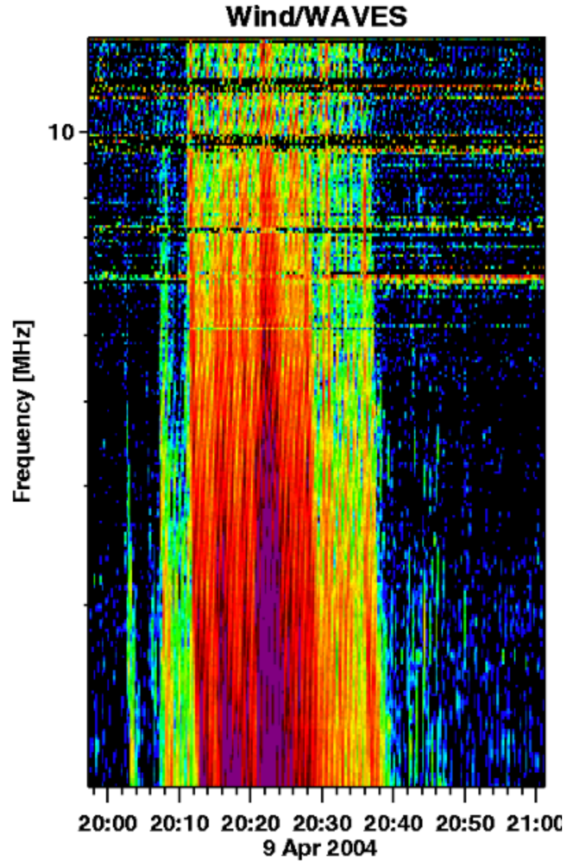
Type IV Bursts

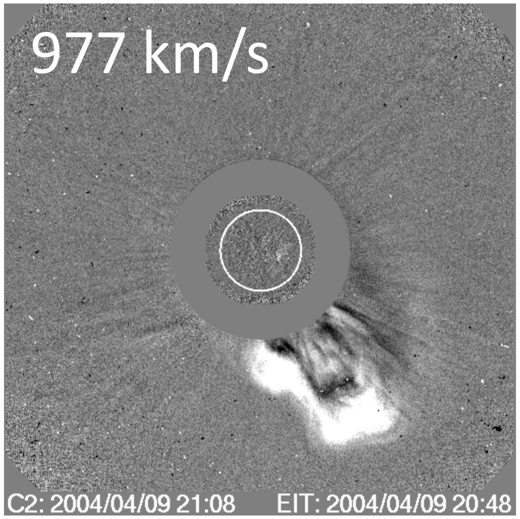
- Rarest of the three burst types – only 42 in solar cycle 23
- DH Type IV bursts are continuation of metric type IV bursts down to ~ 2 MHz
- Loops up to a height of 4-5 Rs (derived from the minimum frequency of ~3 MHz)
- Associated with energetic CMEs – similar to Type II/SEP associated CMEs
- Some big SEP events do not have LF type IV



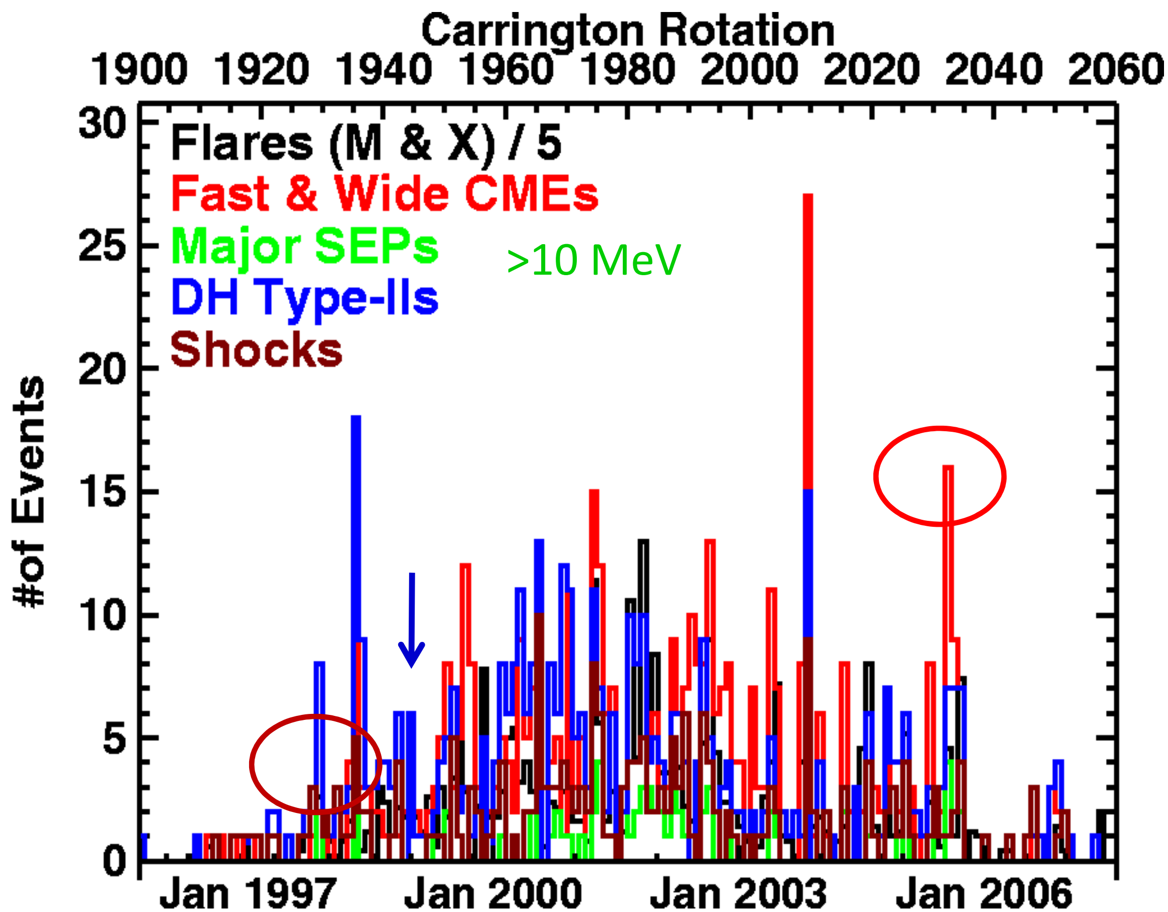
CME-associated Type III Bursts

- Long-duration, low-frequency type III bursts initially thought to be due to shock acceleration (Cane et al., 1981); but now believed to be due to flare reconnection (MacDowall et al., 1987; Reiner et al., 1999; 2000).
- Presence of a fast CME is essential for their occurrence (Gopalswamy et al., 2000); the shock origin is not completely ruled out (Bougeret et al., 1998; Dulk et al., 2000)
- Type III bursts lasting for ≥ 20 min seem to be linked to SEP events (Cane et al. 2002; MacDowall et al., 2003; 2009) : Flare origin for SEPs?
- Cliver and Ling (2009): type III intensity did not distinguish between impulsive (flare) and gradual (CME) SEP events.
- The presence of a complex long-duration, low-frequency type III burst is not a sufficient condition for SEPs (Gopalswamy & Mäkelä, 2010, 2011)





CME-driven Shocks, SEPs, Type IIs: Close Physical Relationship



Fast: CME speed ≥ 900 km/s; CME width ≥ 60 degrees

- The numbers are similar within a factor of 2, except for flares.
- DH type II and FW CMEs have roughly the same number
- # SEP events ~ half the # DH type II bursts
- Some FW CMEs are radio quiet
- Some slow CMEs have DH type II and SEPs
- Some IP shocks are radio quiet

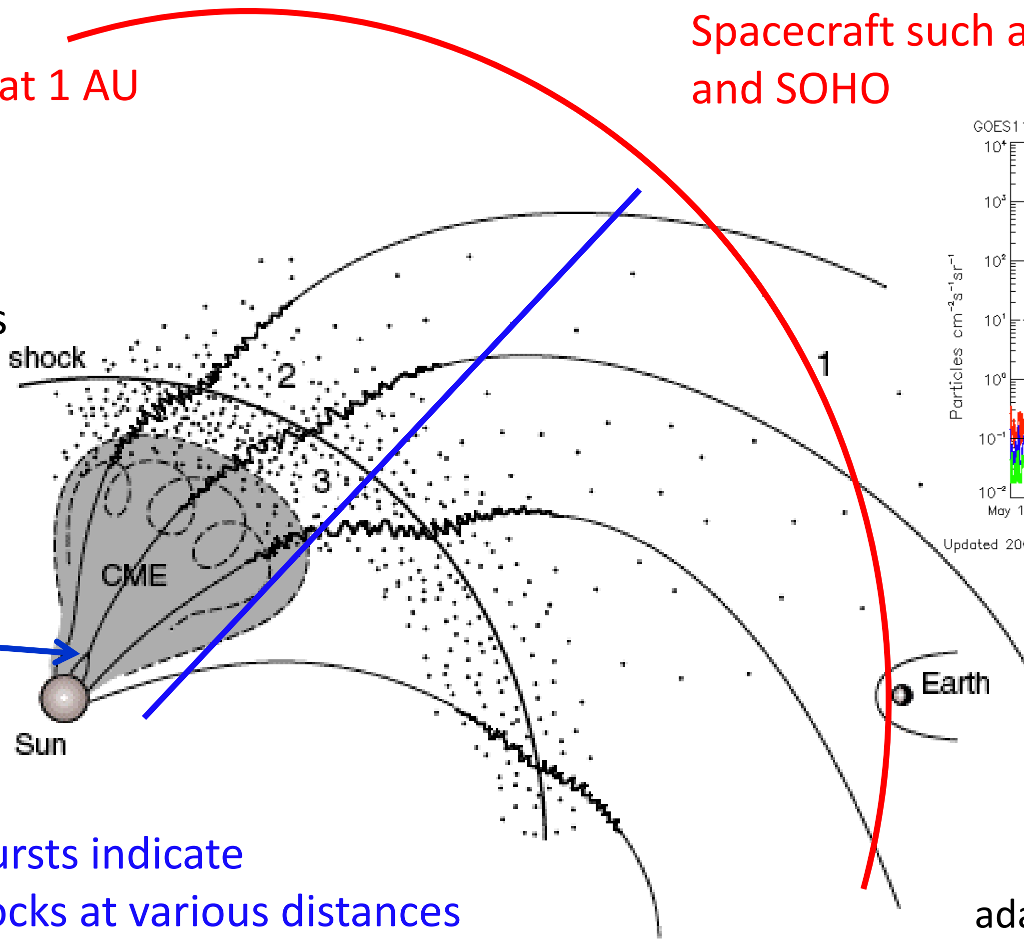
CME, Flare, Shock, Type II, SEP – All Closely Related

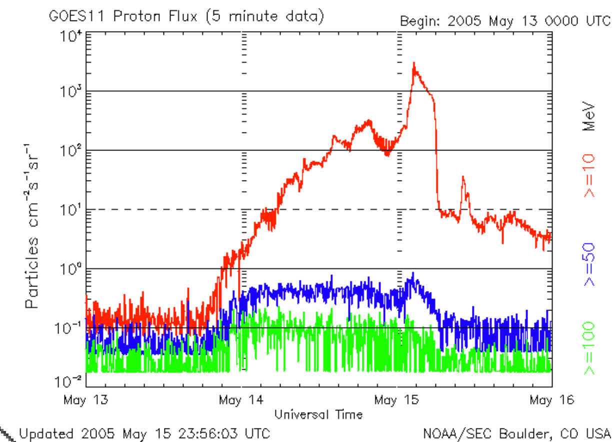
IP shocks detected in situ by
Spacecraft such as Wind, ACE
and SOHO

shock at 1 AU

Shocks accelerate
electrons and ions

Type III bursts are
due to electrons
from flares





Type II Radio Bursts indicate
CME-driven shocks at various distances
from the Sun (emitted by accelerated electrons)

adapted from Lee 1997

Shocks studied using type II bursts, CMEs, and in-situ plasmag observations

Summary

- Radio technique is very useful for solar terrestrial relationship (CMEs, shocks, electron beams)
- The CALLISTO instrument is an ISWI instrument currently deployed in many countries providing 24-h coverage of the Sun