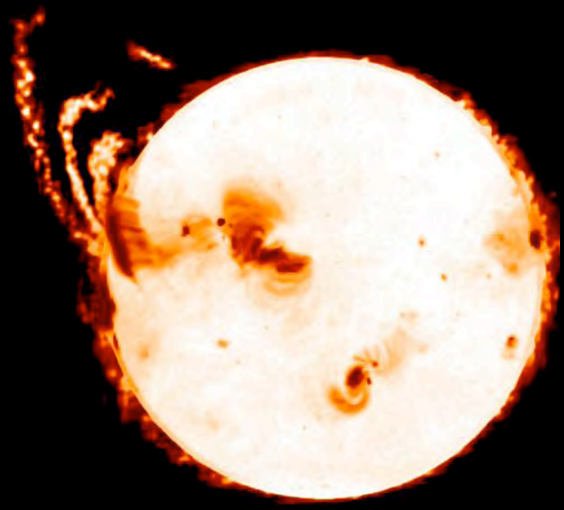
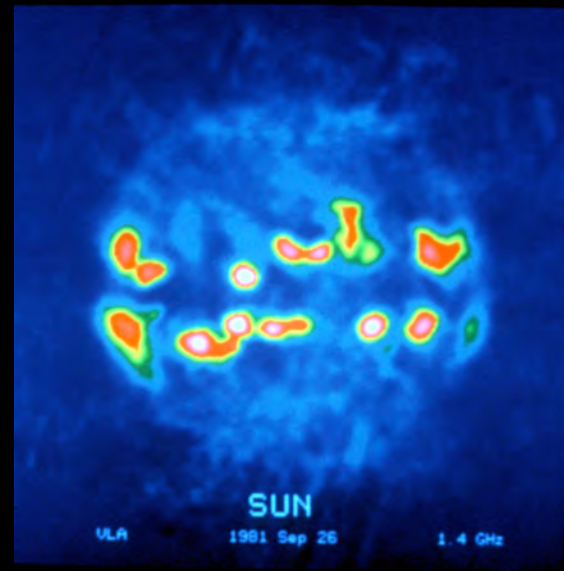
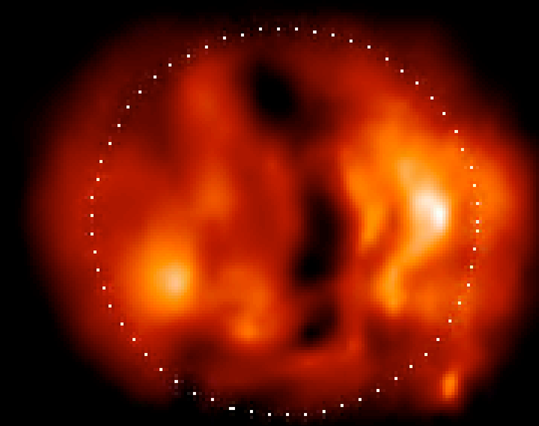


NoRH 17 GHz / 1.8 cm



VLA 1.4 GHz / 21 cm

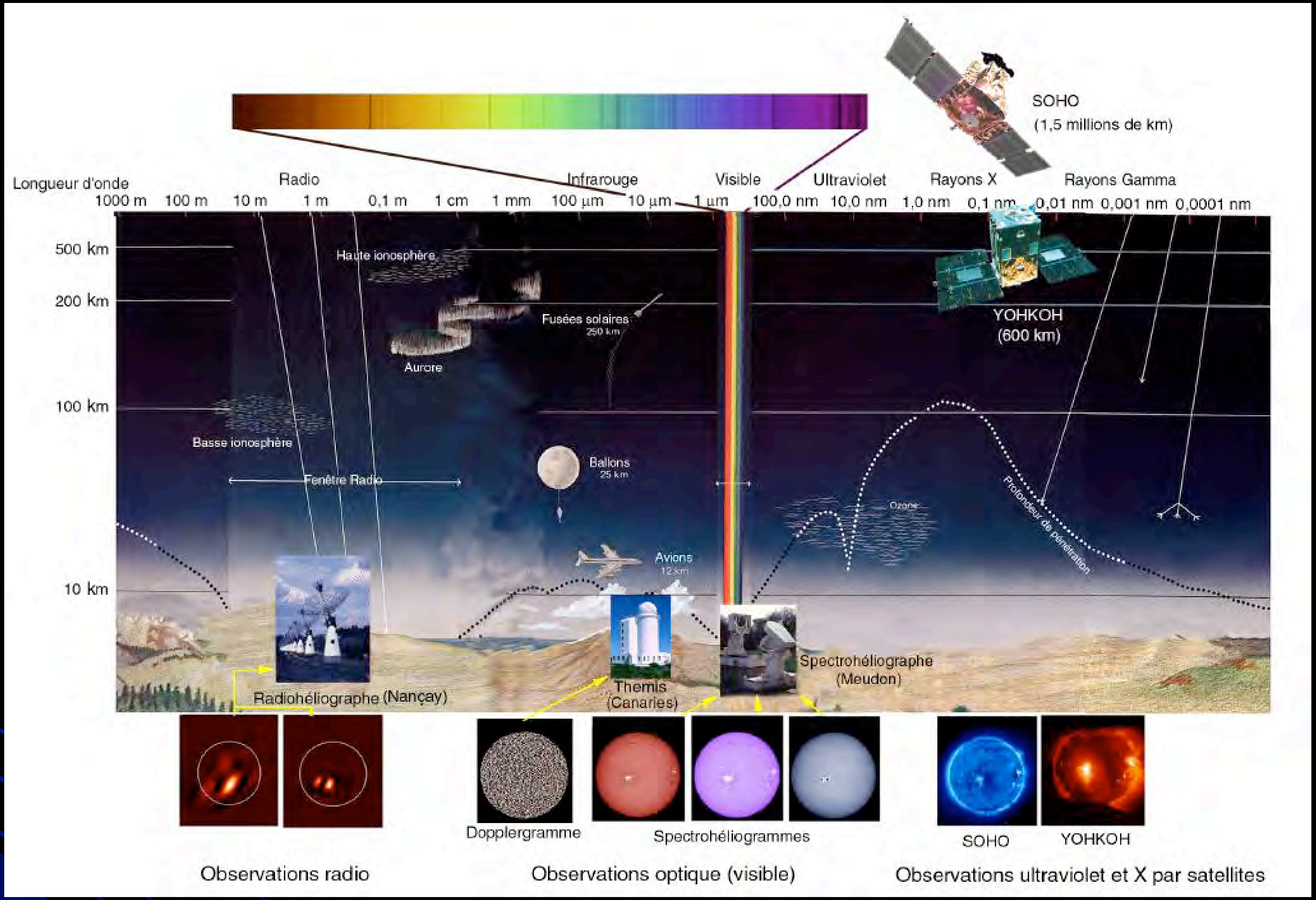


NRH 0.327 GHz / 91 cm

Solar Physics at Radio Wavelengths

N. Vilmer
with inputs from
J.L. Bougeret-K.L. Klein-M. Pick
LESIA
Paris Observatory

Ecole Radioastronomie Basses Fréquences Goutelas 05/06/07



Radio: from λ =1000m to λ= 0.1 mm
ν= 300 kHz to ν=3 Thz

Ground based observations
And space observations
At long wavelengths
And towards submm, far IR

Outline

- Basics of solar radioastronomy:
  - Instruments
  - Propagation of radio waves in the coronal plasma
  - where do radio emissions at different frequencies come from?
- Thermal emissions from the quiet Sun
- Non-thermal emissions from flares in the corona and in the IP medium:
  - Gyrosynchrotron emissions from high energy electrons
  - Coherent emissions from electron beams
  - Coherent emissions from shocks
- Radio signatures of CME's and ICME's
- Future of solar radio physics on ground (and in space)

- Total flux measurements:
- Spectrographs from ground based observatories
- Spatial information:

res = λ / D 1' with λ =1m $\Rightarrow$ D ~ 1km

need of interferometers not telescopes

In Europe solar radio astronomers are organized in CESRA

(Community of Solar Radio Astronomers)

Solar-dedicated radio interferometers: the present situation

Range	Image resolution	Time resolution	Spectral resolution
submm	Few ‘ SST (centroids)	1ms	212and405 GHz
mm	Few ‘’ NoRH	1s	17 and 34 GHz
cm	10’’ SSRT	50ms	Few % 1-18 GHz OVRO
dm/m	1’ NRH	125 ms	5-10 frequencies 150-450 MHz

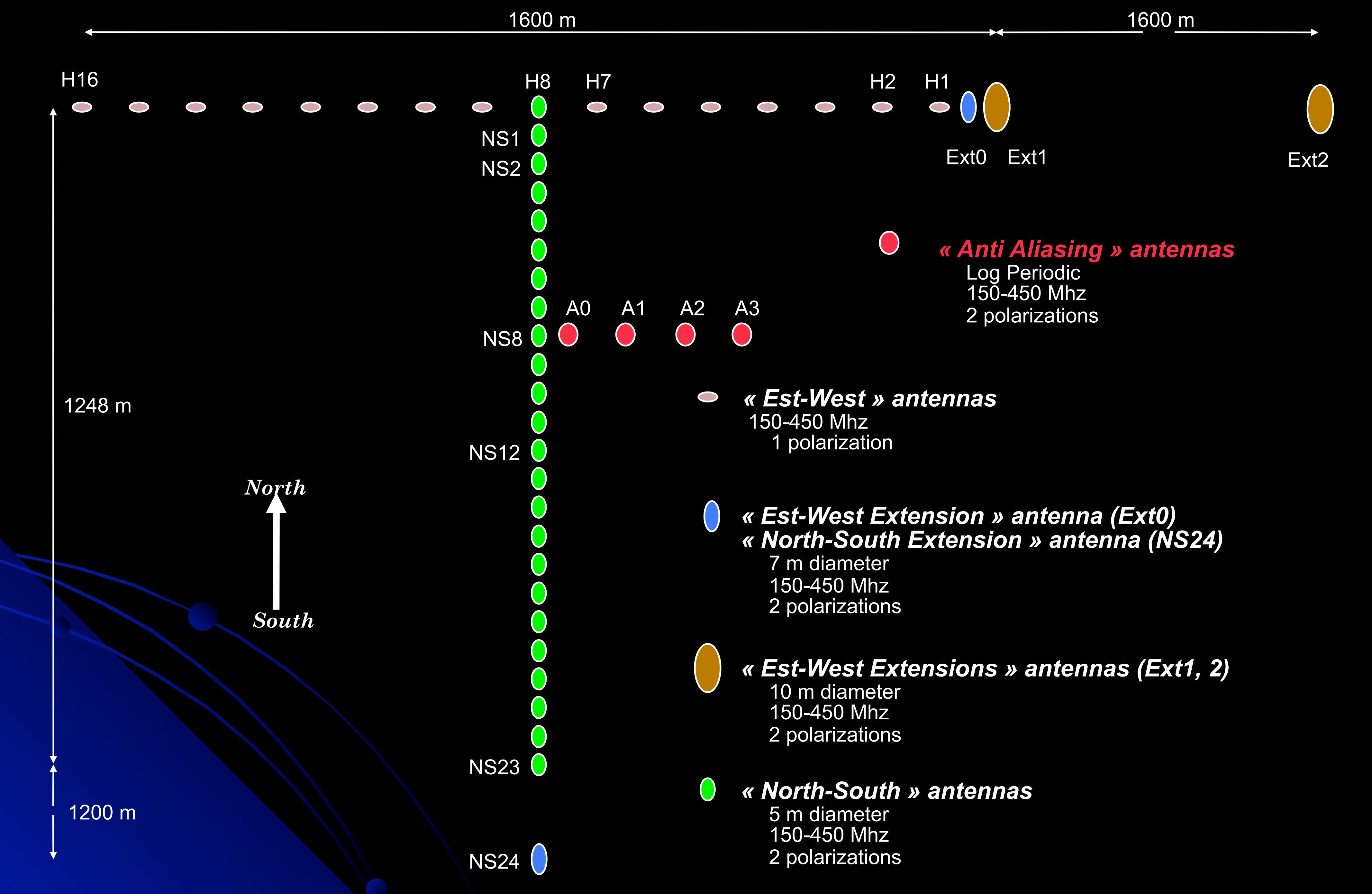
+ VLA , BIMA, GMRT…

Nançay Radioheliograph

- 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)
  - Field of view: from 3 to 0.5 degrees
  - Stokes I and V
  - Time resolution: 5 ms* number of frequencies

Nançay Radioheliograph

- General characteristics (cont.)
  - Bandwidth: 700 kHz
  - Dynamic: 45 db (power in that bandwidth)
  - Separate flux receivers set attenuators (time constant: 5 ms)
  - Multifrequency done by high speed (5ms) frequençy switching between 5 to 10 frequencies
  - Further integration gives standard mode: 8 Im./sec for 5 almost simultaneous frequencies.

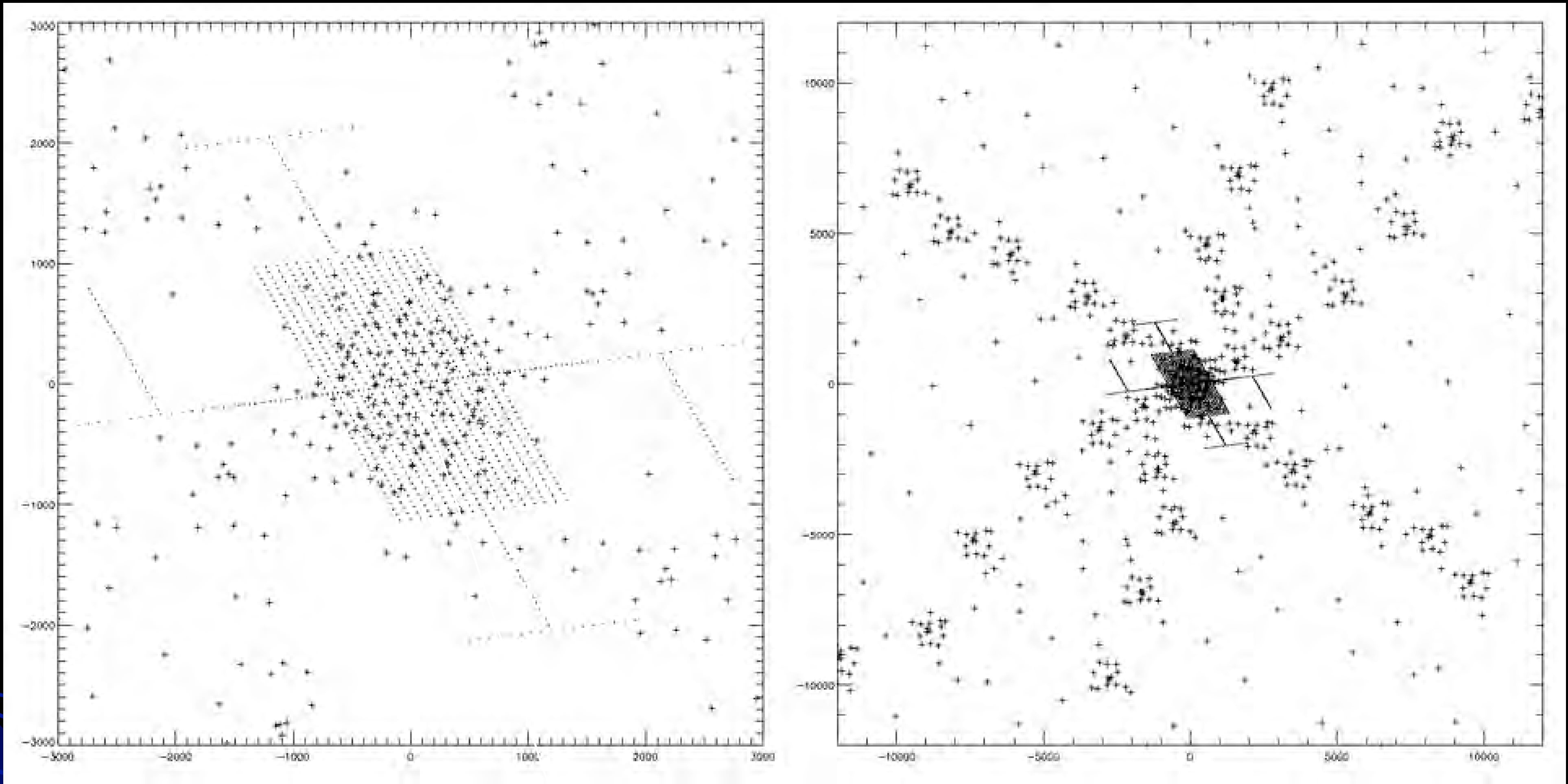


Nançay Radioheliograph array configuration

Nançay Radioheliograph: 5m antennas (north-south array)

Nançay Radioheliograph: East - west array flat antennas

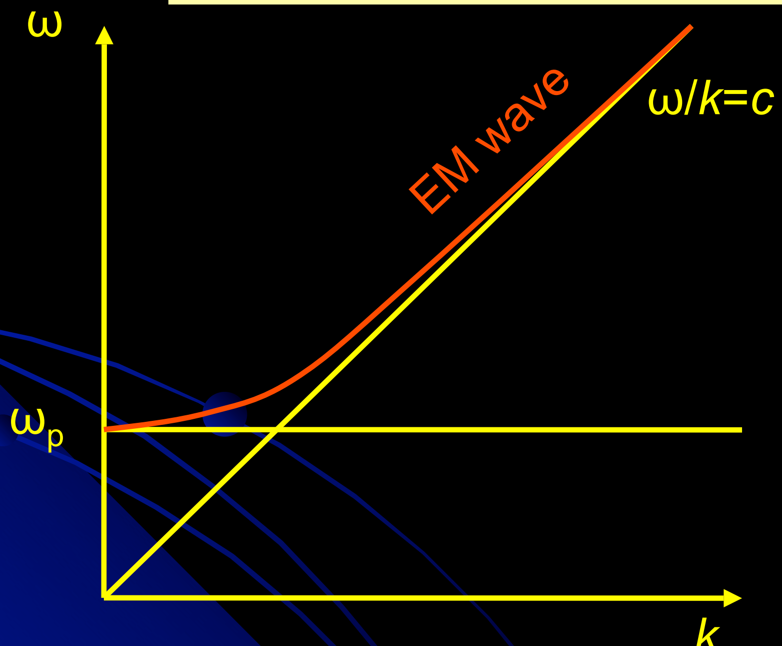
- Low gain antennas: (~wide band dipoles)
- Severe sensitivity limitation at high frequency
- One linear polarization



Uv plane for NRH + GMRT

High-frequency waves in a plasma : isotropic case (B=0)

$$\text{EM waves } n_\nu^2 = 1 - \frac{\nu_{pe}^2}{\nu^2}, \text{ where } \quad \nu_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \approx 9\sqrt{\frac{n_e}{1\ \mathrm{m}^{-3}}}\ [\mathrm{Hz}]$$



$$\text{Phase speed } \frac{\omega}{k} = c_\varphi = \frac{c}{n_\nu}$$

Radio waves propagate at $\nu > \nu_{pe}$.

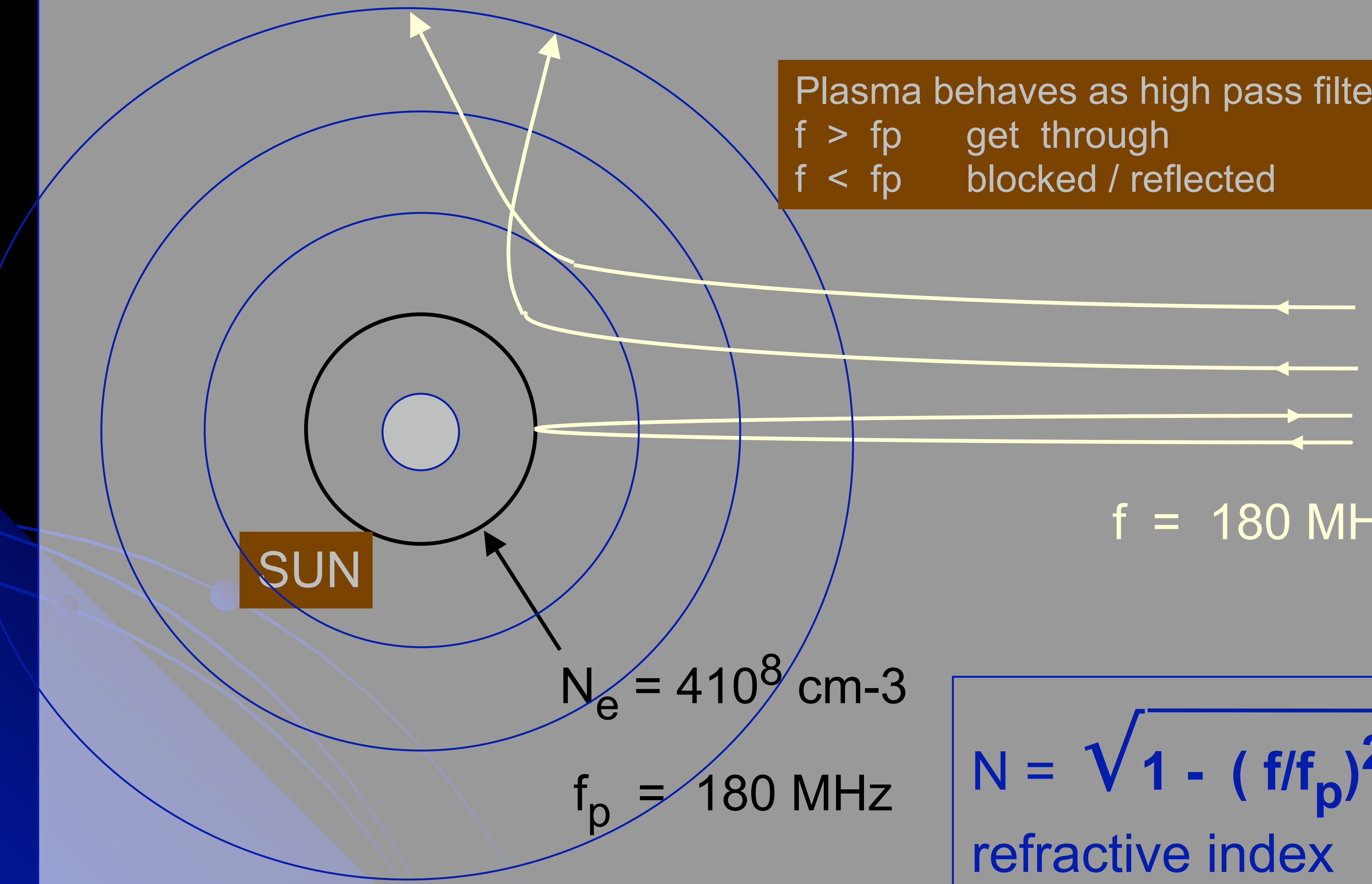
Earth's ionosphere : $\nu_{pe} \approx 9$ MHz (high-frequency limit)

IP space at 1 AU: $\nu_{pe} \approx 30$ kHz.

Plasma behaves as high pass filter:

f > fp get through

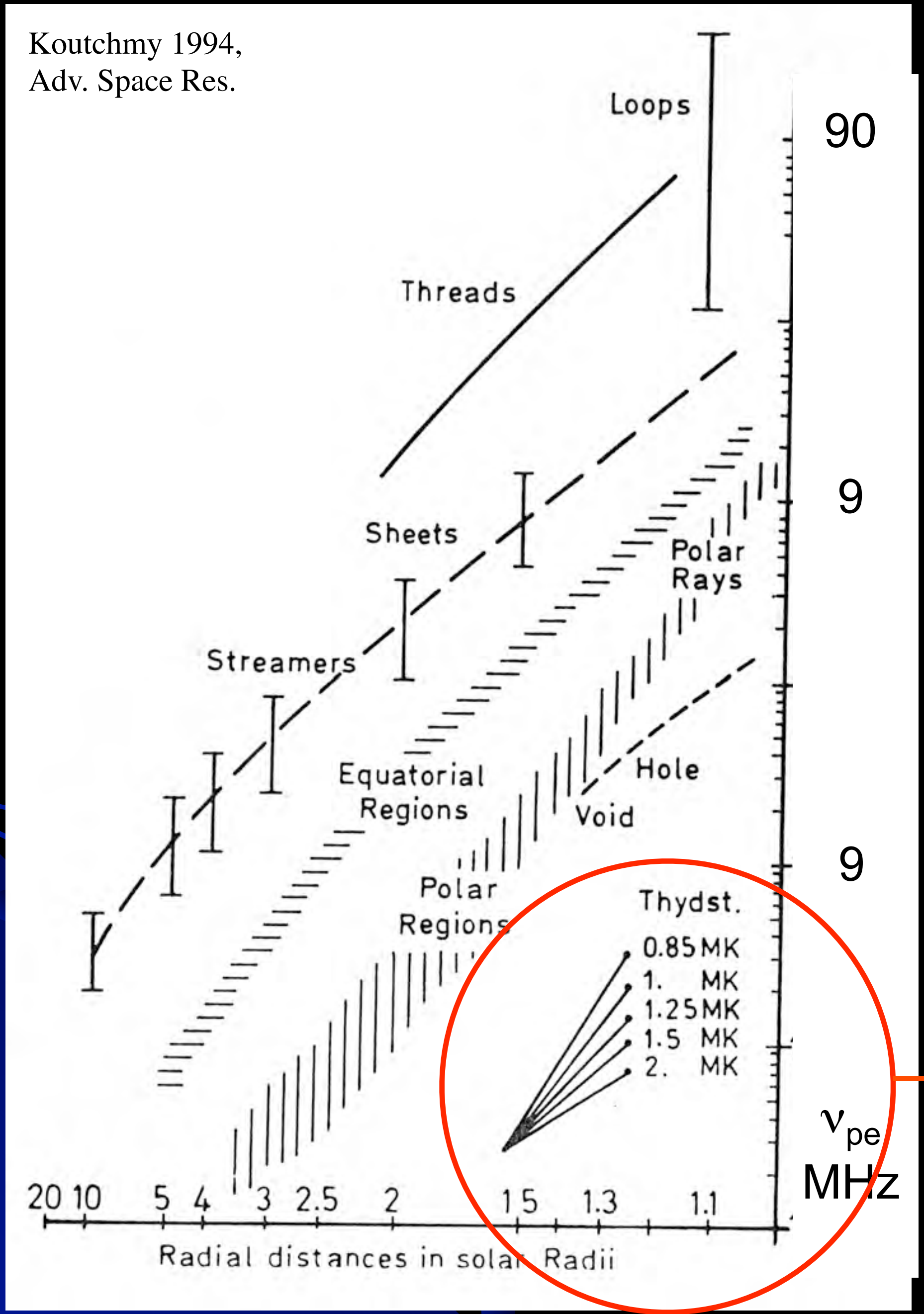
f < fp blocked / reflected



$$N = \sqrt{1 - (f/f_p)^2}$$

refractive index

Electron density in the corona

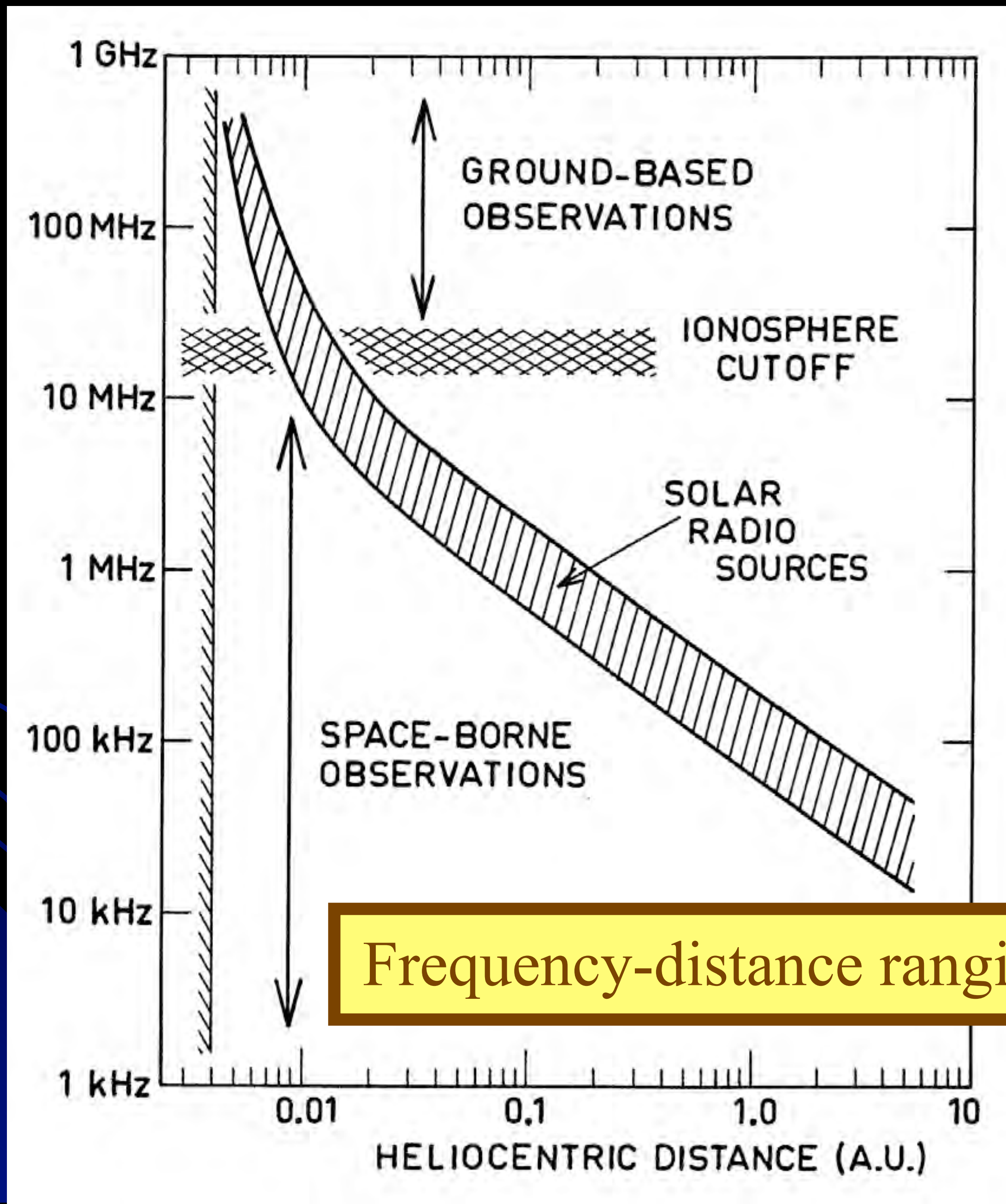


- Electron density profiles from white-light eclipse observations (Thomson scattering)
- Hydrostatic isothermal model (not too far from the surface, subsonic speeds):

$$n(r) = n_0 \exp\left(-\frac{R_0}{H_0}\left(1-\frac{R_0}{r}\right)\right)$$

$$H_0 = \frac{2KT}{m_p g_0}$$

Radio emissions in the corona and the interplanetary medium



Frequency-distance ranging

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

kHz cm^{-3}

in IP space

$$f \approx R^{-1}$$

Radio emissions from the inner heliosphere

Frequency distance ranging

	N_e (cm^{-3})	f_p
low corona	$\geq 10^8$	≥ 100 MHz
~ 10 $R_\odot$	$\sim 10^4$	~ 1 MHz
~ 30 $R_\odot$	$\sim 1.5\ 10^3$	~ 300 kHz
~ 1 AU	~ 10	~ 30 kHz

molecular absorption in Earth's atmosphere

Ground-based window

reflection/absorption in Earth's ionosphere

WAVELENGTH RANGE			FREQUENCY BAND
----------------	100 μ	--------------------	3 THz ----------
sub-millimetric			
----------------	1 mm	--------------------	300 GHz ----------
millimetric		EHF	Extremely High Frequency
----------------	1 cm	--------------------	30 GHz ----------
centimetric		SHF	Super High Frequency
----------------	10 cm	--------------------	3 GHz ----------
decimetric		UHF	Ultra High Frequency
----------------	1 m	--------------------	300 MHz ----------
metric		VHF	Very High Frequency
----------------	10 m	--------------------	30 MHz ----------
decametric		HF	High Frequency
----------------	100 m	--------------------	3 MHz ----------
hectometric		MF	Medium Freq uency
----------------	1 km	--------------------	300 kHz ----------
kilometric		LF	Low Frequency
----------------	10 km	--------------------	30 kHz ----------
		VLF	Very Low Frequency
----------------	100 km	--------------------	3 kHz ----------
		ULF	Ultra Low Frequency
----------------	1000 km	--------------------	300 Hz ----------

Chromosphere: lower, middle, upper

Coron a

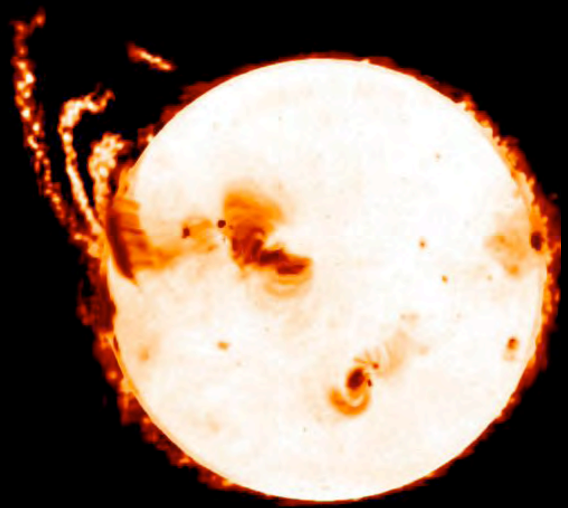
IP Medium

Observations of the solar corona at cm-m-λ : why ?

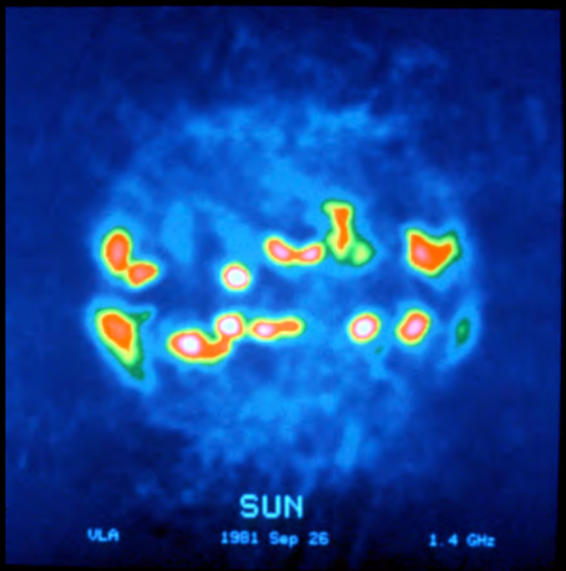
- Plasma diagnostics of the quiet corona (n_e, T, B) and of the nascent solar wind

- The Sun as a particle accelerator (high corona) :
  - « Quiet-time » non thermal e^--populations
  - e^- accelerated during flares, CME and at coronal shocks
  - Energetic particle propagation (corona, IP space)

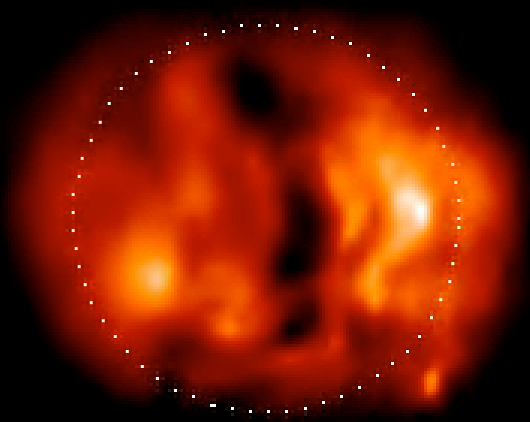
- Coronal magnetic topology, mass ejections (*CME)*, shocks



NoRH 17 GHz / 1.8 cm

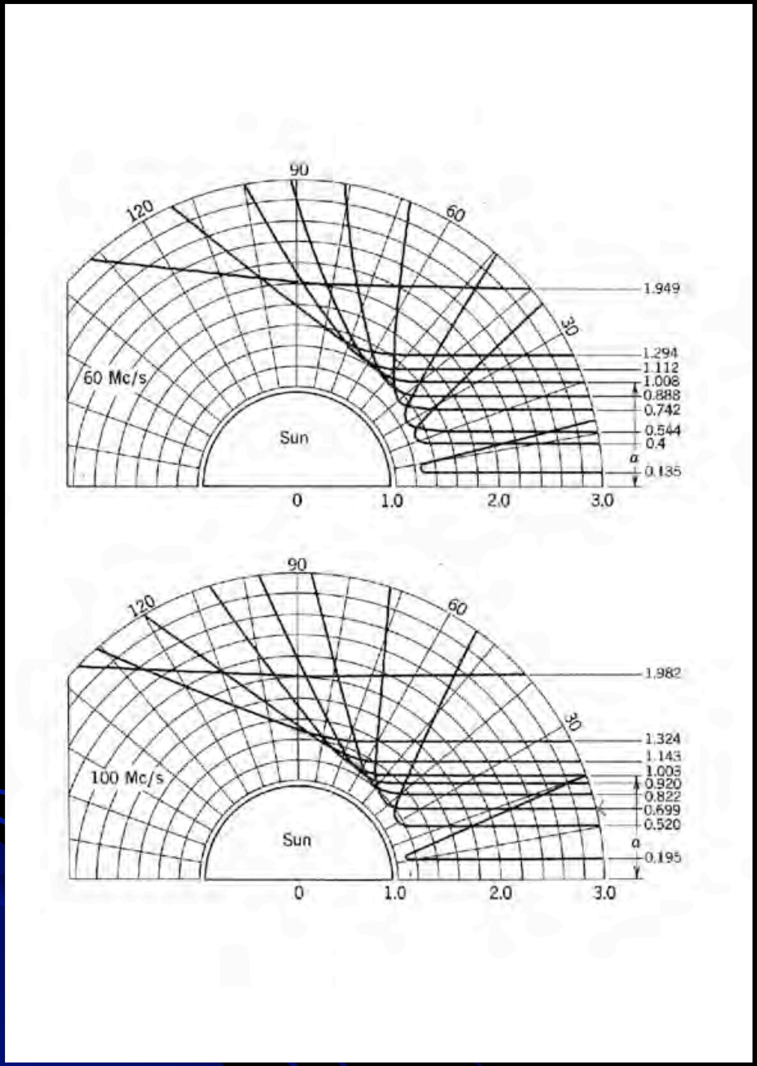


VLA 1.4 GHz / 21 cm

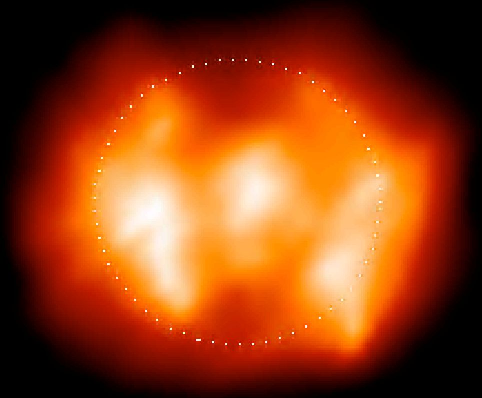


NRH 0.327 GHz / 91 cm

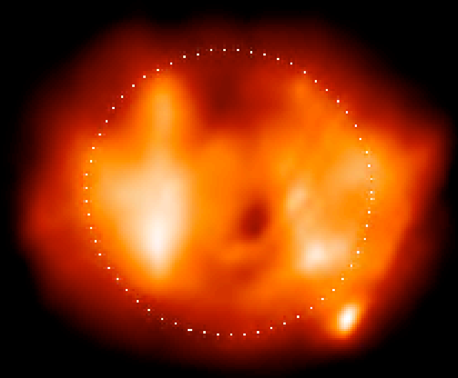
QUIET SUN at RADIO WAVELENGTHS



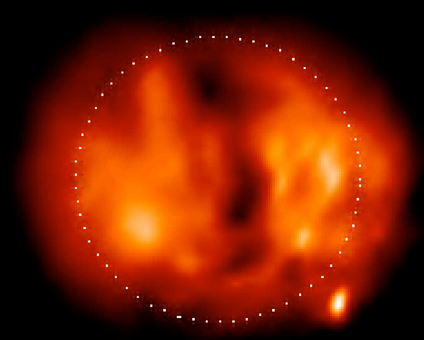
From Jaeger and westfold, (1949)



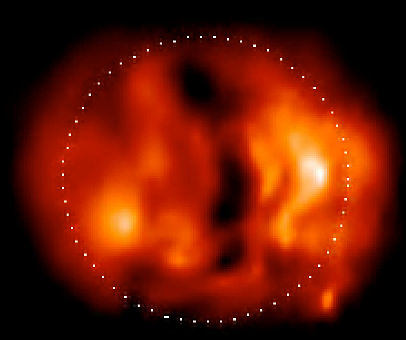
164 MHz



236 MHz

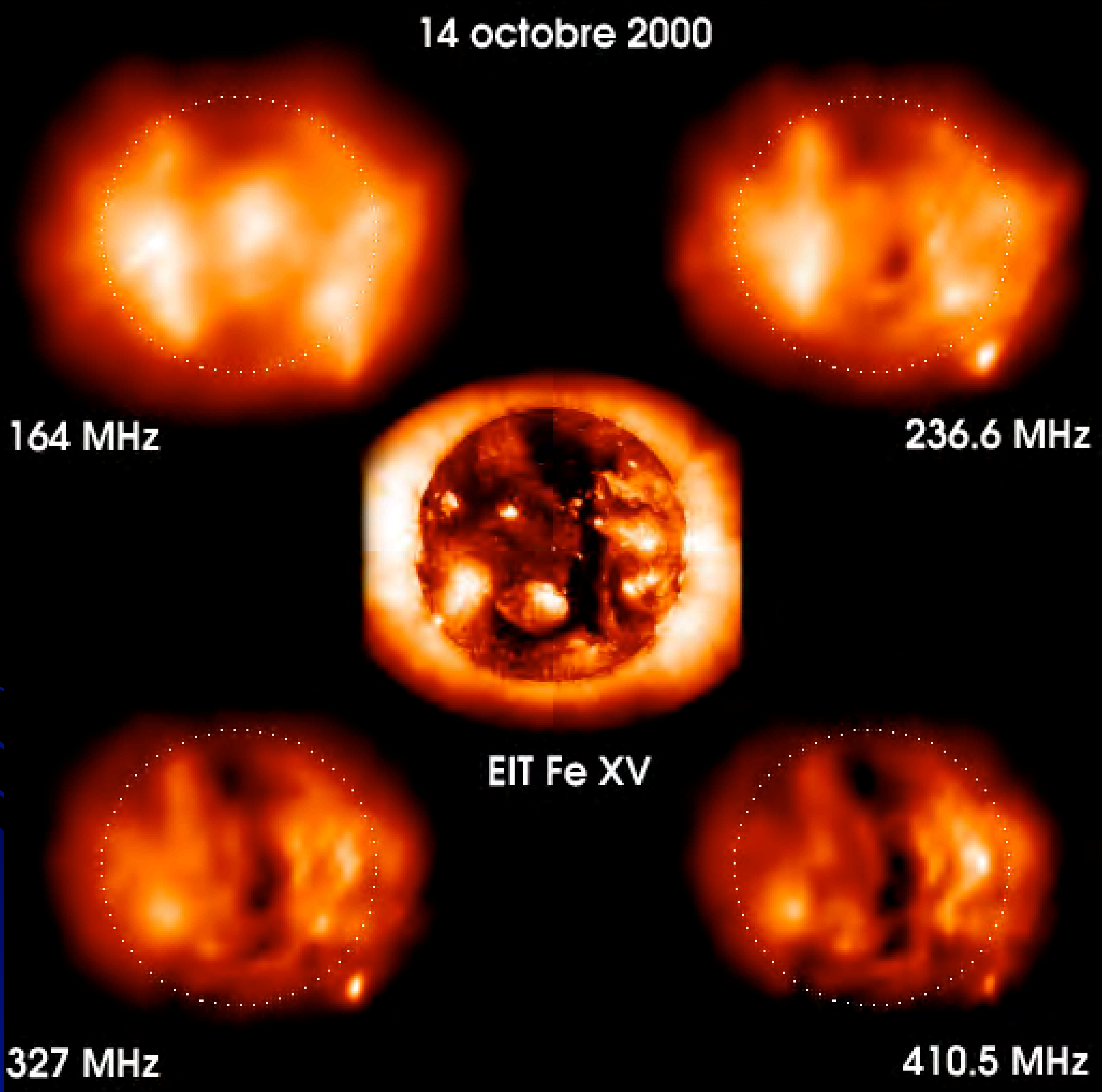


327 MHz

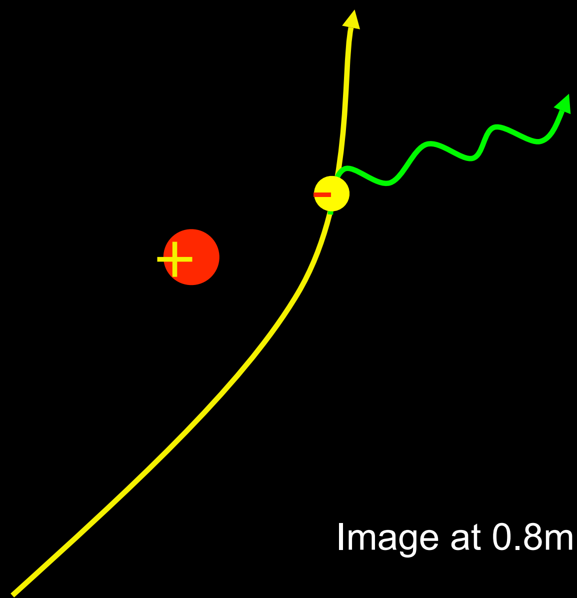


408 MHz

From C. Marque


14 octobre 2000
164 MHz
236.6 MHz
EIT Fe XV
327 MHz
410.5 MHz

Thermal bremsstrahlung from th… a



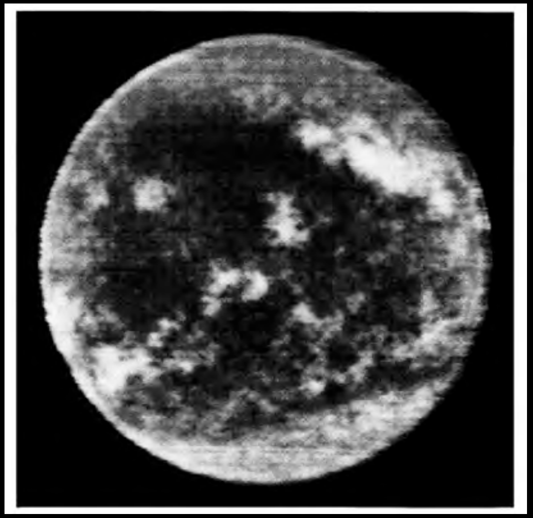
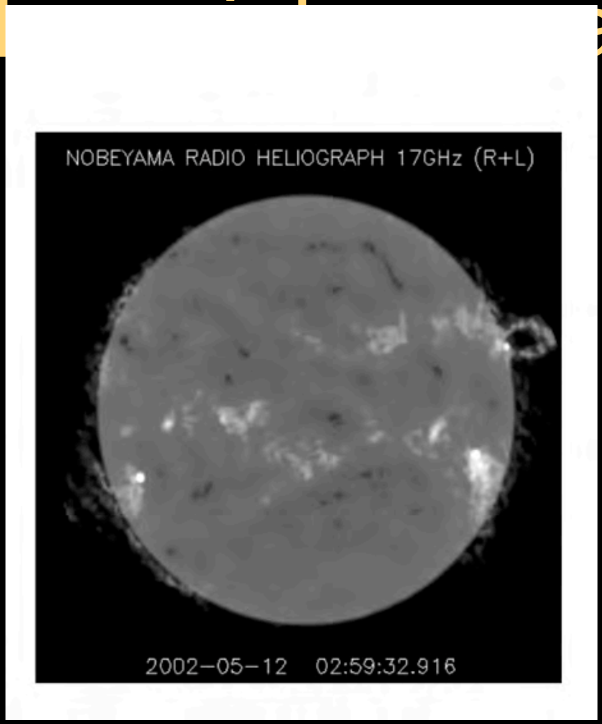
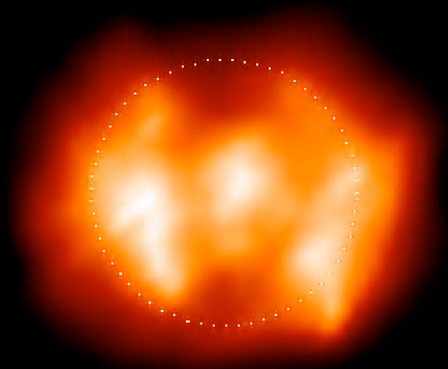


Image at 0.8mm (Caltech Submillimeter Observatory)
Bastian et al, 1993

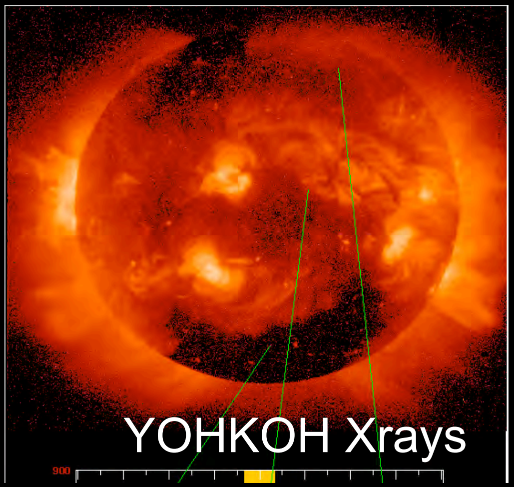


NoRH 17 GHz
(from Nakajima et al, 1994)

Acceleration of an e by a p :
- close encounter → XR,
- remote encounter → radio



NRH 164 MHz



YOHKOH Xrays

Radio Flux density ~ T and τ
Xray function EM and T

Radiative transport

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \qquad (d\tau_\nu = -\kappa_\nu ds)$$

Solution of the radiative transport equation :

$$I_\nu = I_0 e^{-\tau_{\nu 0}} + \int_0^{\tau_{\nu 0}} S_\nu e^{-\tau_\nu} d\tau_\nu = I_0 e^{-\tau_{\nu 0}} + S_\nu \left(1 - e^{-\tau_{\nu 0}}\right) = \begin{cases} S_\nu & (\tau_{\nu 0} >> 1) \\ I_0 \left(1 - \tau_{\nu 0}\right) + S_\nu \tau_{\nu 0} & (\tau_{\nu 0} << 1) \end{cases}$$

I_0 background radiation

Radio waves from a thermal plasma : Rayleigh-Jeans approximation

$$S_\nu = \frac{2KT\nu^2}{c^2}$$

Thermal radio emission

A useful quantity : brightness temperature

$$I_\nu = \frac{2KT_{b\nu}\nu^2}{c^2}$$

Thermal emission :

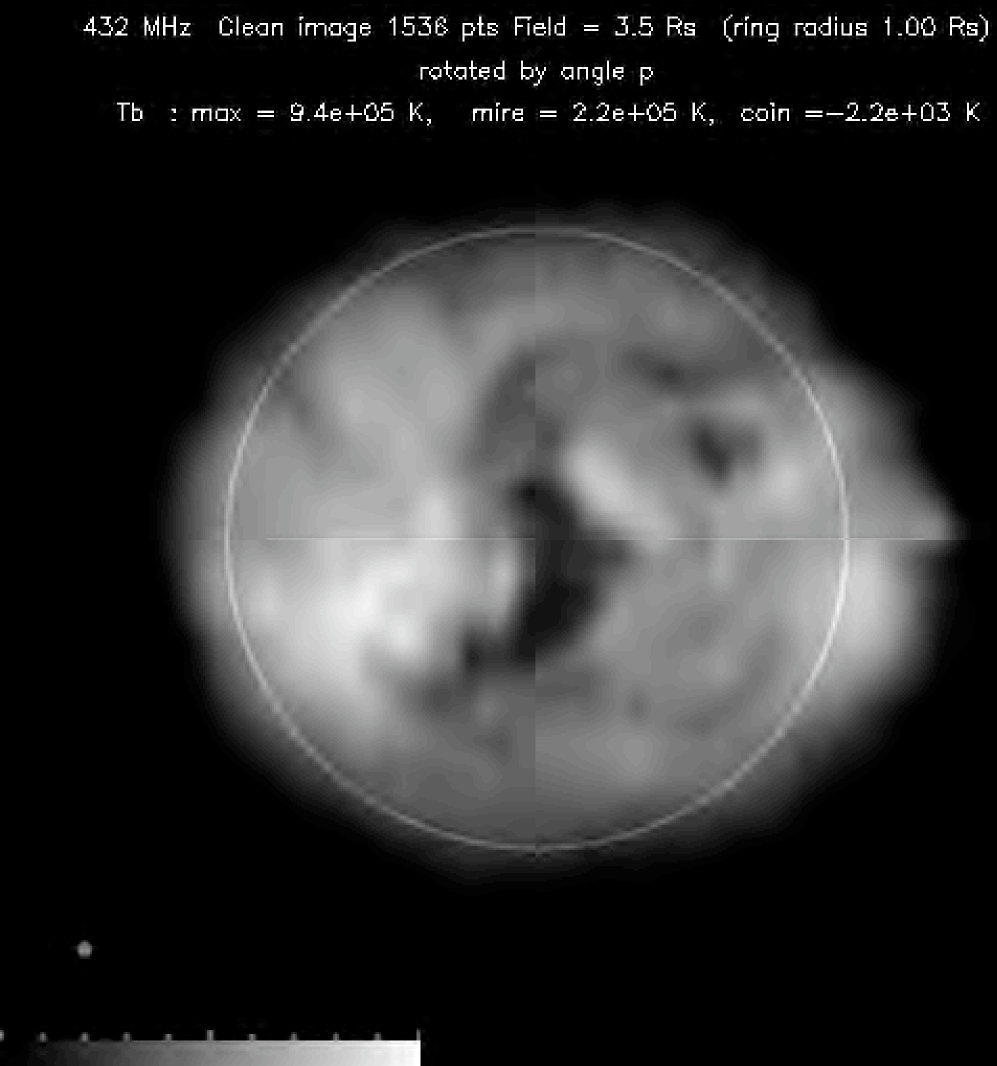
$$I_\nu = I_0 e^{-\tau_{\nu 0}} + \int_0^{\tau_{\nu 0}} S_\nu e^{-\tau_\nu} d\tau_\nu = I_0 e^{-\tau_{\nu 0}} + S_\nu \left(1 - e^{-\tau_{\nu 0}}\right)$$

In terms of the brightness temperature (I_0=0) :

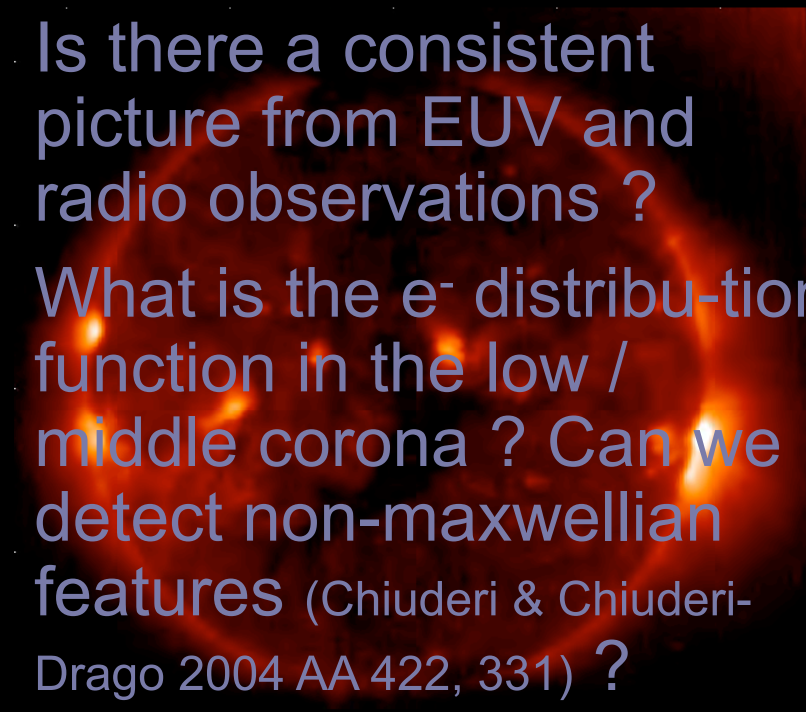
$$T_{b\nu} = T_e \left(1 - e^{-\tau_{\nu 0}}\right) \leq T_e$$

$$\tau_{\nu 0} : \frac{n_e^2 l}{T_e^{3/2} \nu^2}$$

Coronal plasma diagnostics : EUV and radio



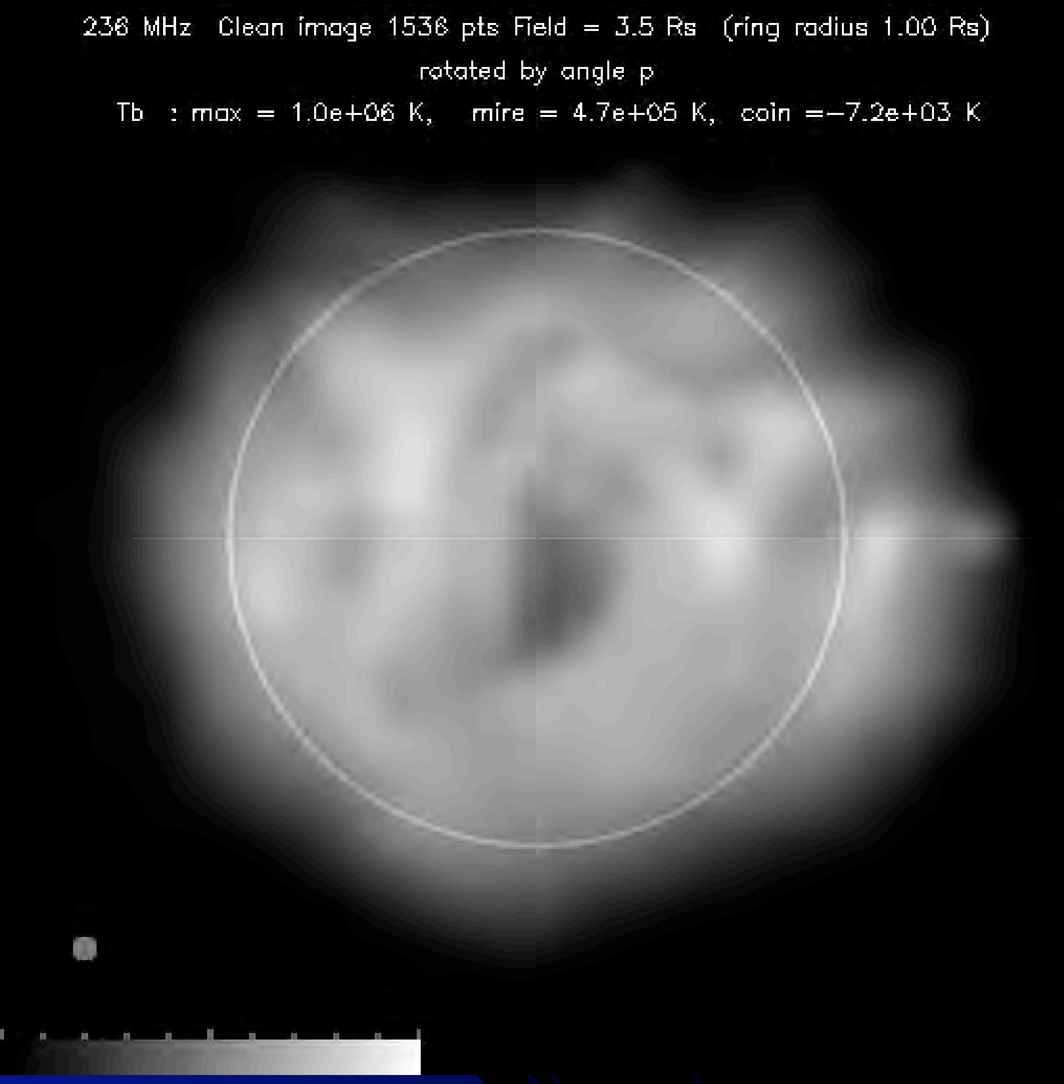
NRH (432 MHz): C. Mercier



- What is the density and temperature structure in the quiet corona ?
- Is there a consistent picture from EUV and radio observations ?
- What is the e^- distribu-tion function in the low / middle corona ? Can we detect non-maxwellian features (Chiuderi & Chiuderi-Drago 2004 AA 422, 331) ?

SXR : SXI (NOAA)

Coronal plasma diagnostics : EUV and radio



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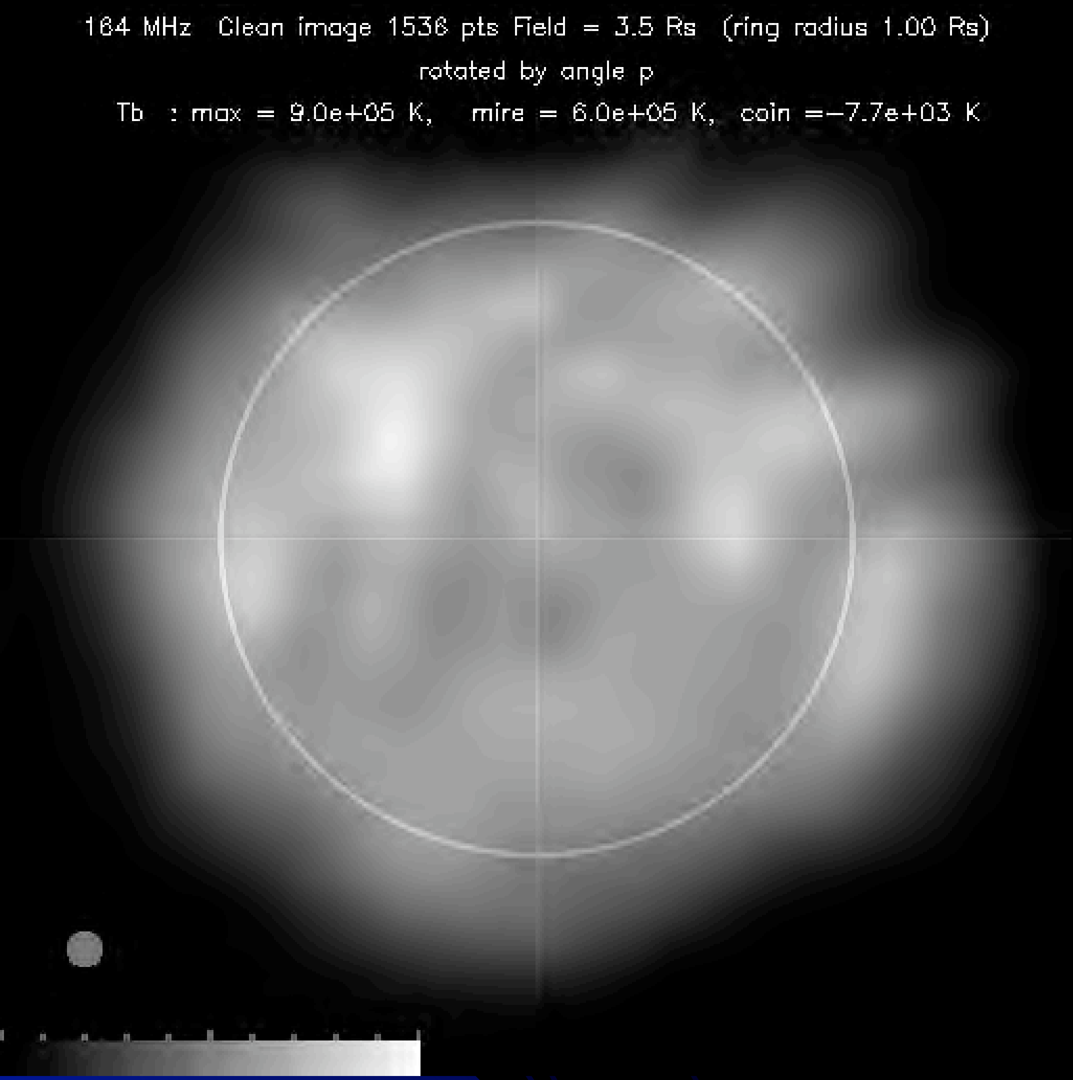
NRH (237 MHz): C. Mercier

Coronal plasma diagnostics : *EUV* and radio



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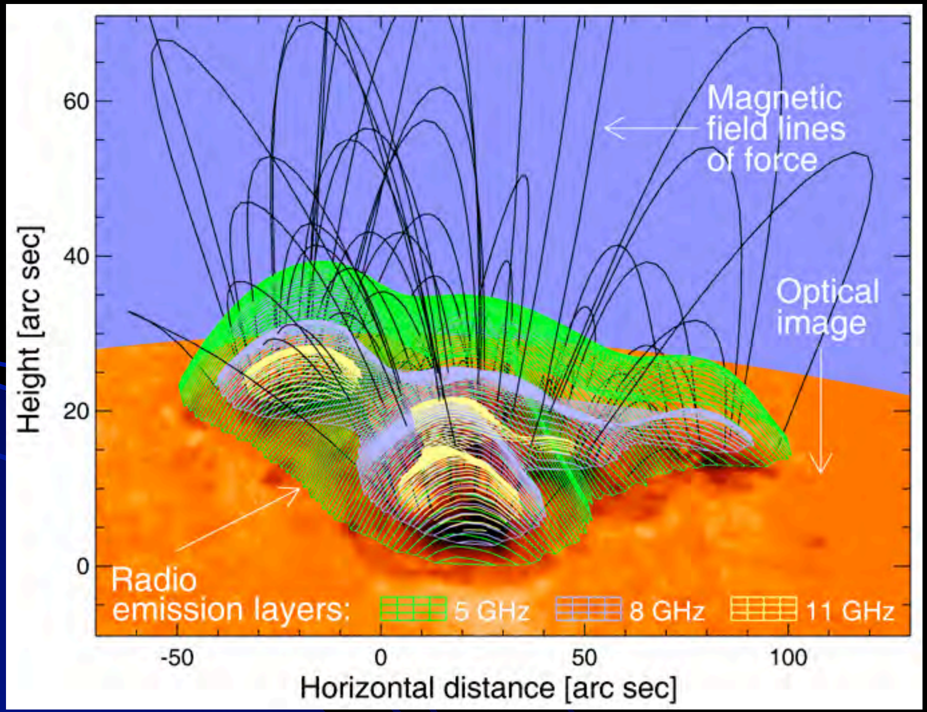
- What is the e^- distribu-tion function in the low / middle corona ? Can we detect non-maxwellian features (Chiuderi & Chiuderi-Drago 2004 AA 422, 331) ?

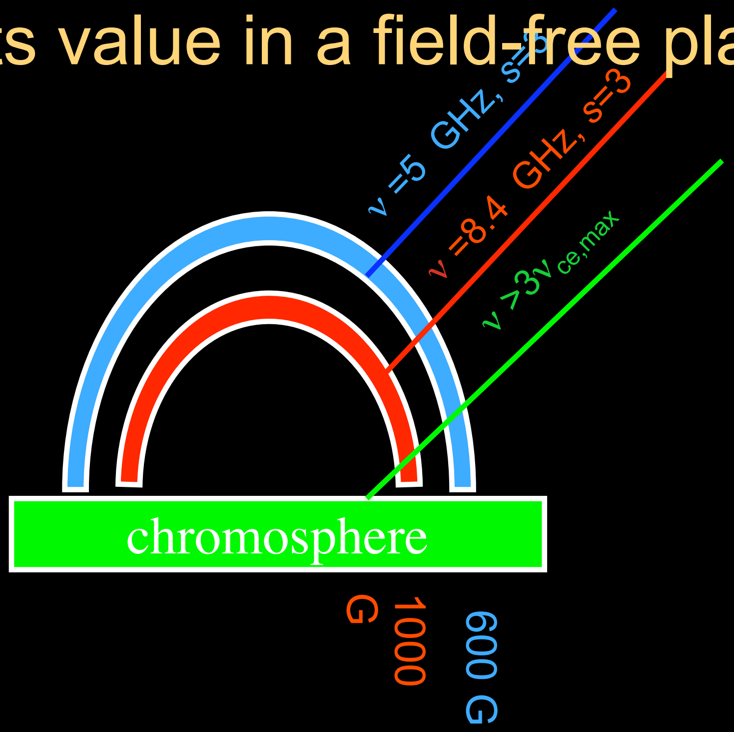
NRH (164 MHz): C. Mercier

Gyroresonance emission (thermal)

Emission of thermal electrons spiralling along B fields:
Enhancement of the opacity above its value in a field-free plasma :



From J. Lee



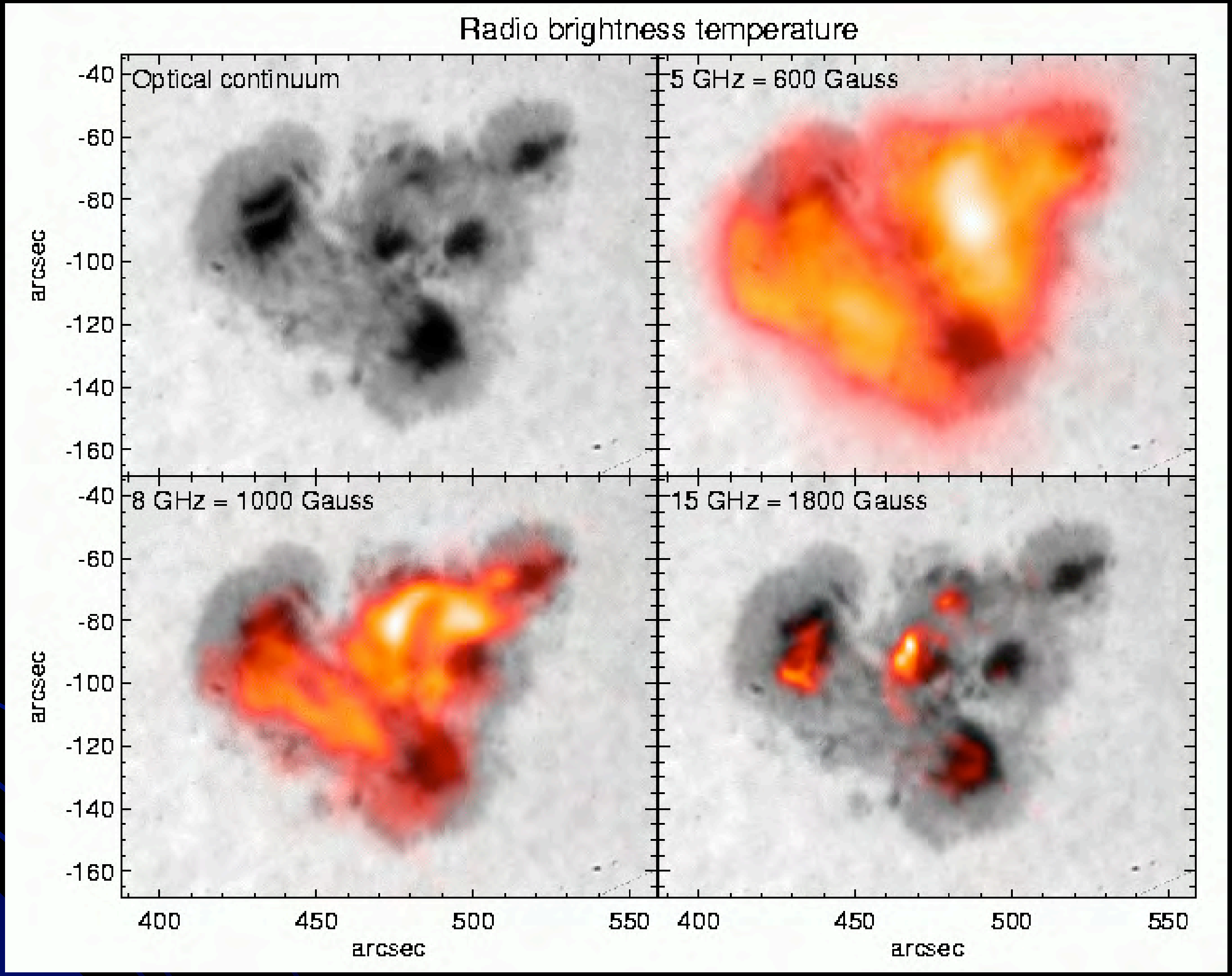
$\nu = s\nu_{ce}$ (s=2 … 4 for $T_e \approx 2 \times 10^6$ K)

= 5 GHz (6 cm) for s=3, B=600 G

Narrow resonant surface, ~100 km thick

Dominant radiation process above AR from 3 to 15 GHz

Gyroresonance emission

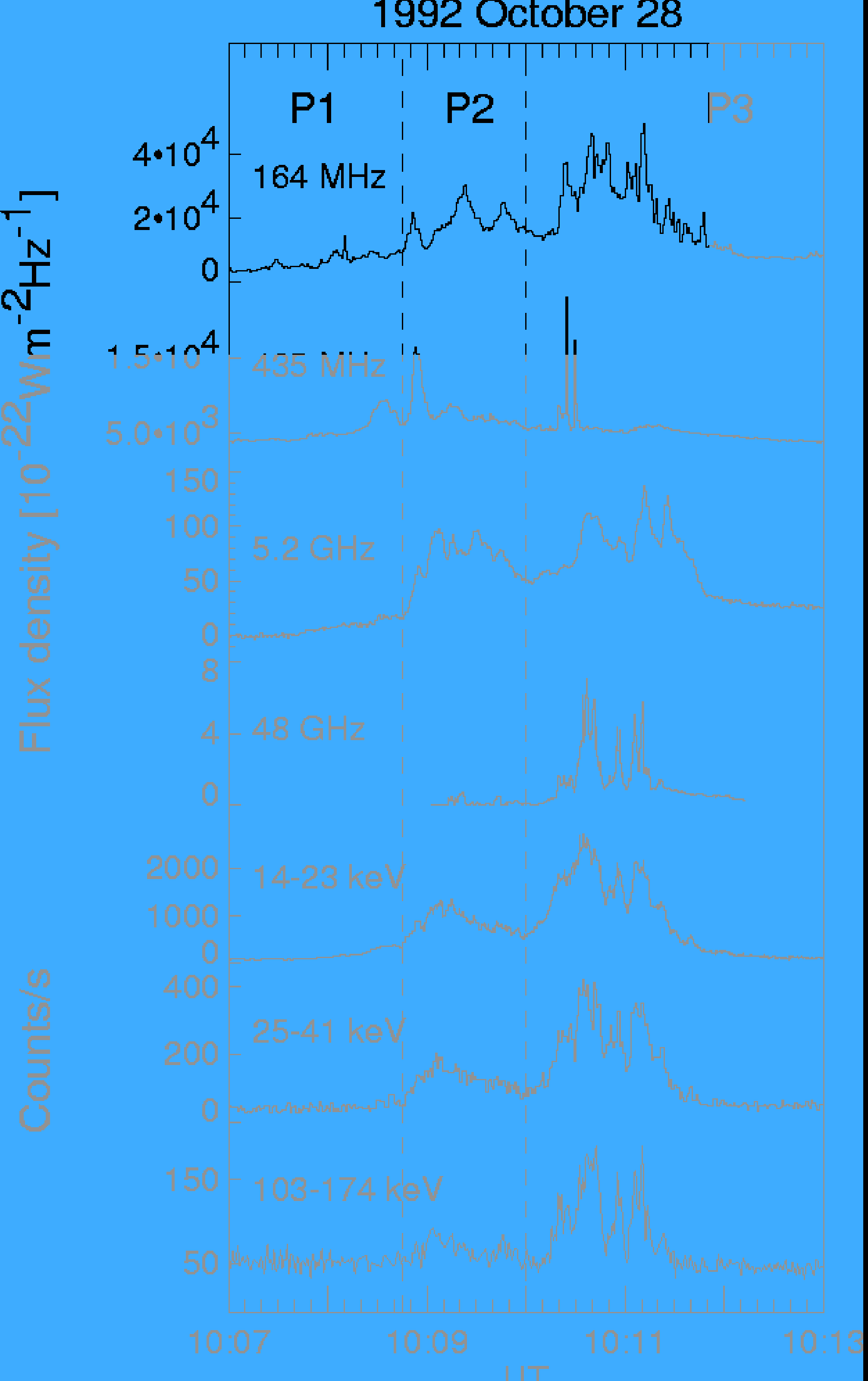


From
Lee et al., 1998

GR emission $\tau_{gr}>1$: *Tb* on iso-*B* surfaces($\nu = s\nu_{ce}$)
Above sunspots (high *B*)
Well-established technique at single ν: cf. Alissandrakis, Kundu, Lantos 1980, A&A 82, 30

Thermal emission from the solar corona: summary

- The corona emits bremsstrahlung at cm-to-m-λ (quiet corona), optically thin or thick.
- Coronal magnetic fields can be measured through gyroresonant emissions
- Perspective : Multi-frequency mapping of the Sun by the *Frequency Agile Solar Radiotelescope* (FASR).



Emissions radio métriques
Electrons non thermiques
Dans la couronne
Emissions plasmas

Emissions radio cm
Rayonnement gyroB ou synch
couronne

Emissions X dur
Rayonnement freinage électrons
chromosphère

Non Thermal Emissions from Flares

- 2 fundamental frequencies for radio solar physics:

Electron gyrofrequency:

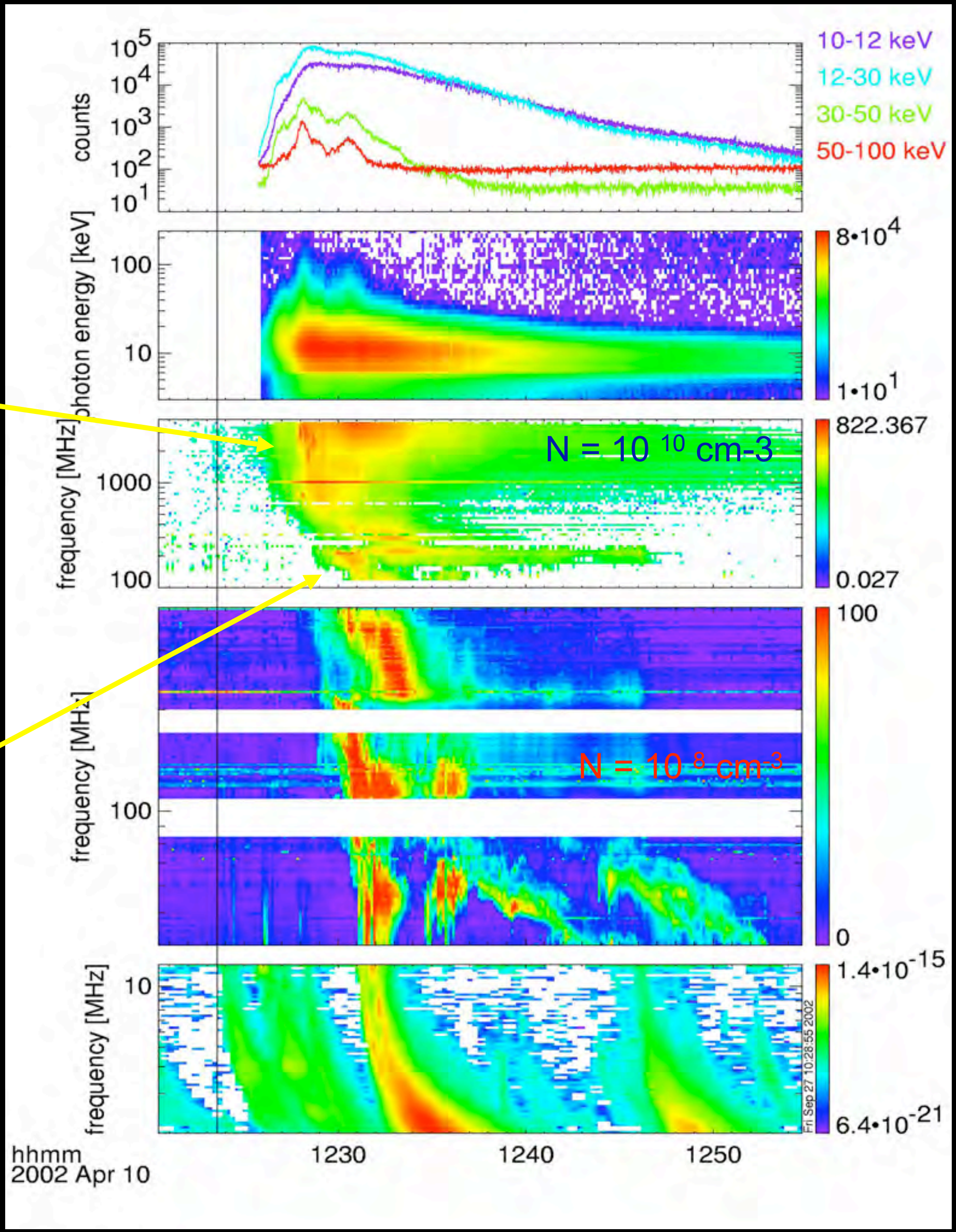
$f_b(Hz) = 2.8\ 10^6\ B\ (G)$

Plasma frequency

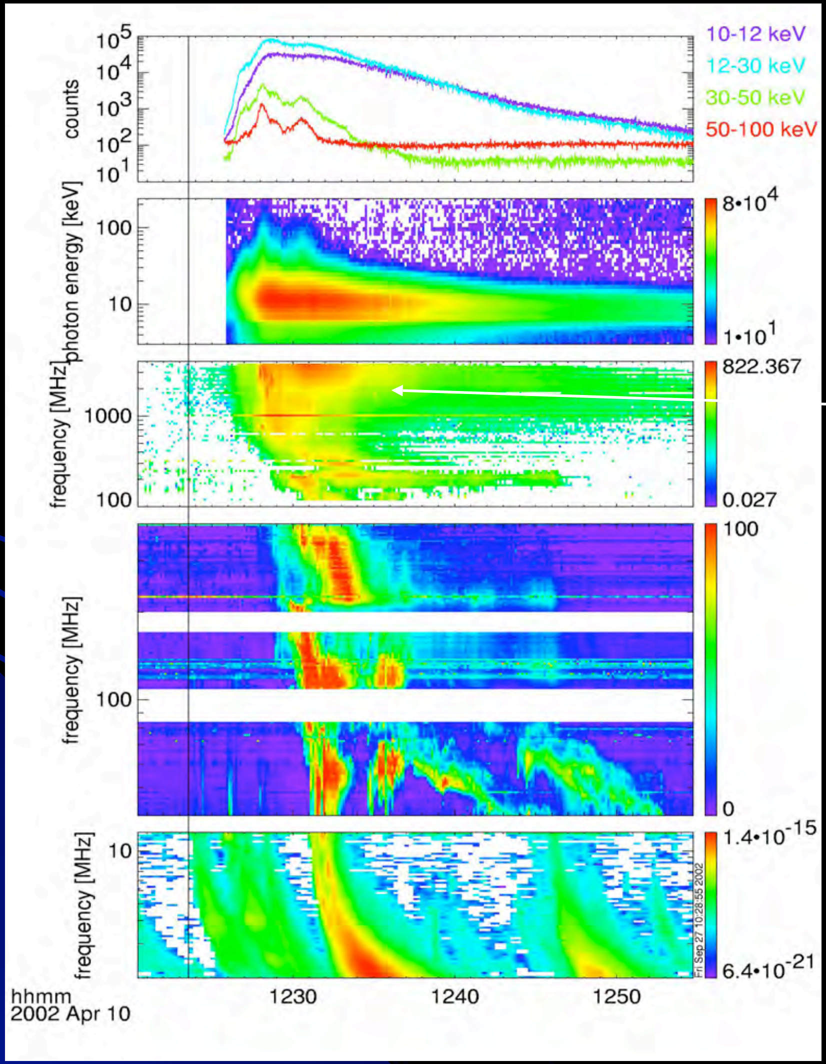
$f_p(kHz) = 9\sqrt{n_e}\ cm^{-3}$

frequency cutoff and emitting frequency

h



Non thermal emissions in solar flares:
Gyrosynchrotron emission from high-energy electrons



Gyrosynchrotron emission

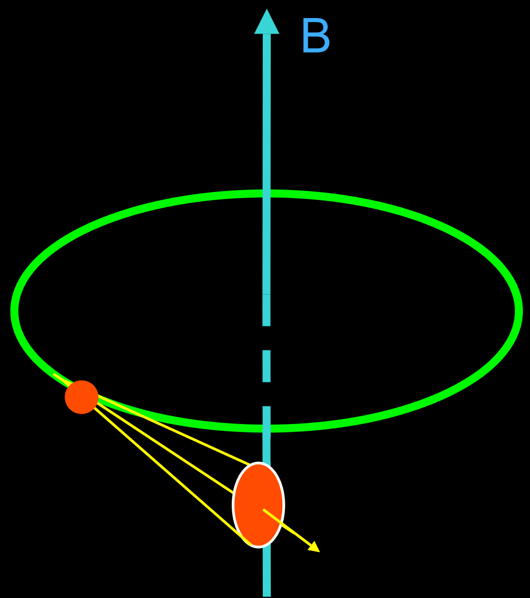
Rayonnement (gyro)synchrotron des électrons

- Rayonnement électrons spiralant autour des lignes de B
- Accélération centripète électron d'où rayonnement
- A énergie électrons croissante: gyromagnétique, synchrotron, gyrosynchrotron
- Puissance rayonnée $\propto \gamma^2$:

 fonction de B et énergie électron

- Observation si lobe émission dirigé vers l'observateur
- Plus la particule est énergétique, plus le spectre est large $\rightarrow$ continuum
- Gyrofréquence ν_B =eB/γm
- ν_B = 2.8B (kG)
- Cas solaire: B=1000G $\Rightarrow$ ν_B = 2.8 GHz

Gyromagnetic radiation (1)

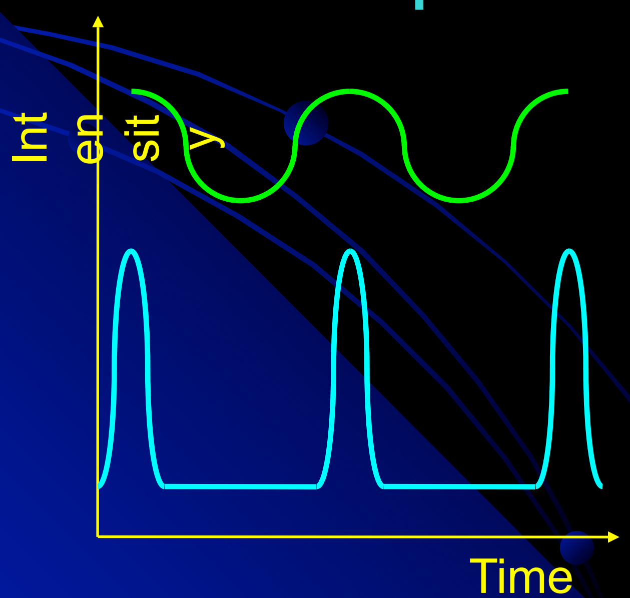


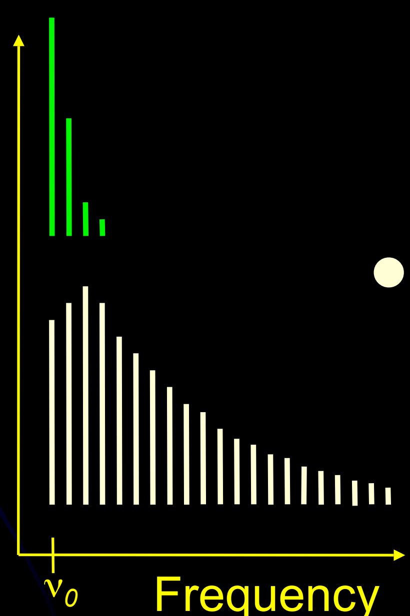
- Electron cyclotron frequency

$$\nu_{ce} = \frac{1}{2\pi}\frac{eB}{m_e} \approx$$

- Low speed electron (T=10^6 K) : cyclotron line (unobservable, since $\nu_{pe}>\nu_{ce}$) and low harmonics ($\nu=s\nu_0$, $\nu_0=\nu_{ce}$, s=1,2,3)
- relativistic e: $\nu_0=\nu_{ce}/\gamma$; beaming ⇒ high s, max. intensity at

$$\nu_c = \frac{3}{2}\gamma^2\nu_{ce}$$





Gyromagnetic radiation (2)

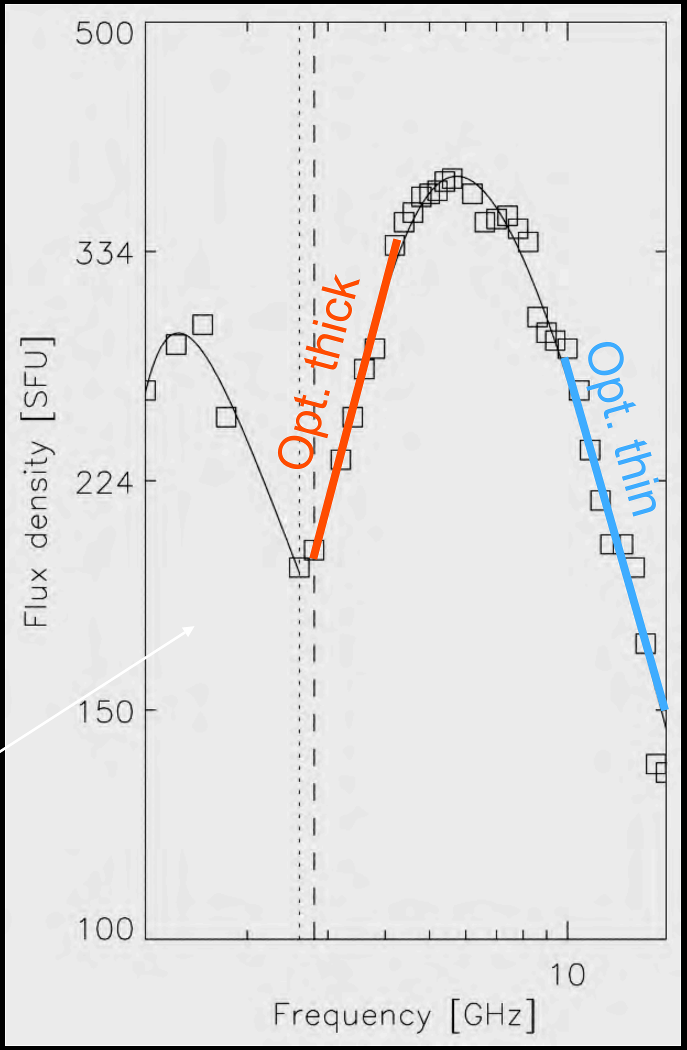
Emission but...

Also absorption: optically thick part of the spectrum:

- free-free absorption: absorption by thermal electrons
- self absorption by gyrosynchrotron non-thermal electrons

Effect of background thermal plasma (Razin suppression)

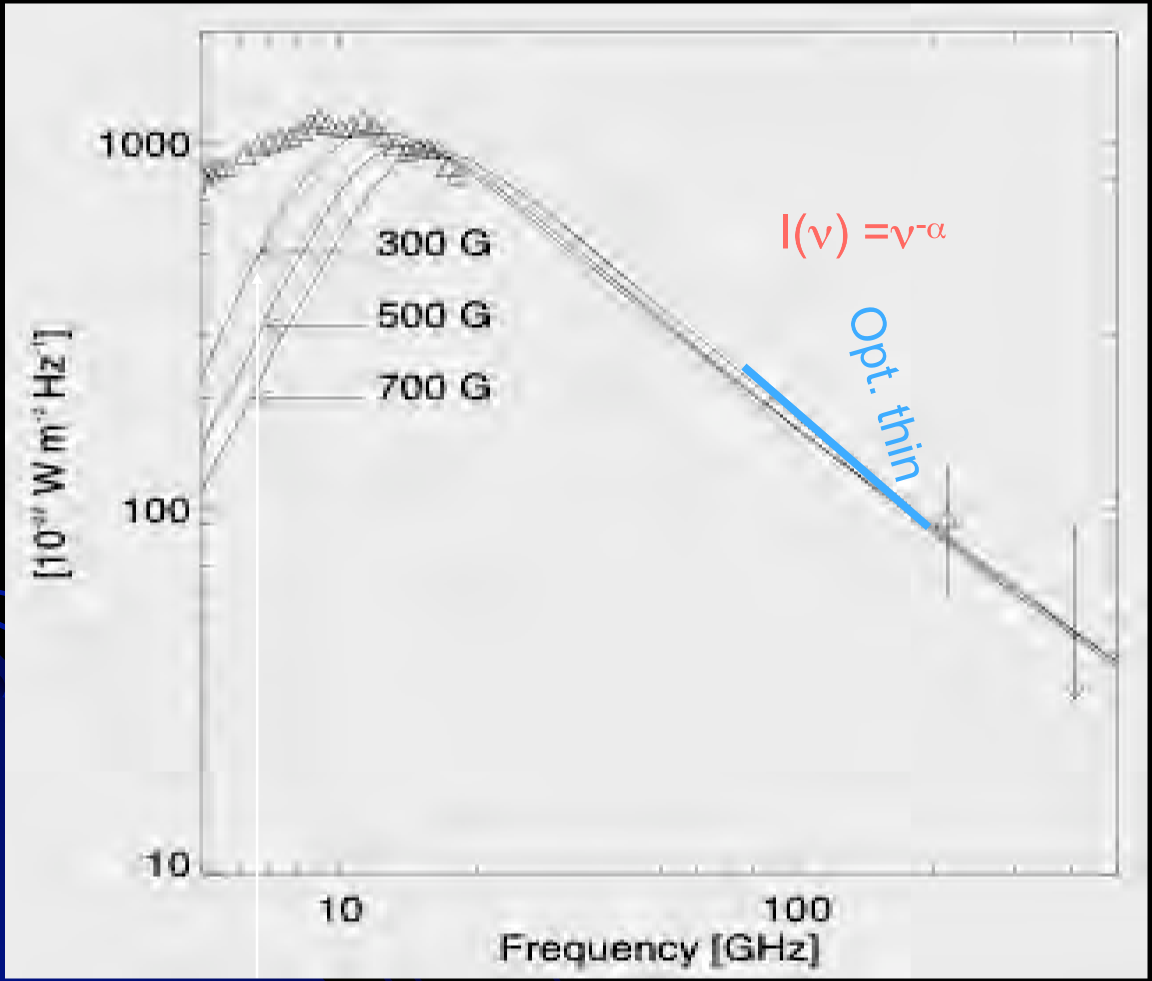
For practical cases (electron distribution as a fct of energy and pitch angle) the spectrum is continuous



Observations : Owens Valley,

Nita, Gary, Lee 2004, ApJ 605, 528

Gyromagnetic radiation (3)



Radiation for an isotropic electron distribution in a uniform B field
$N(E) \approx E^{-\delta}$

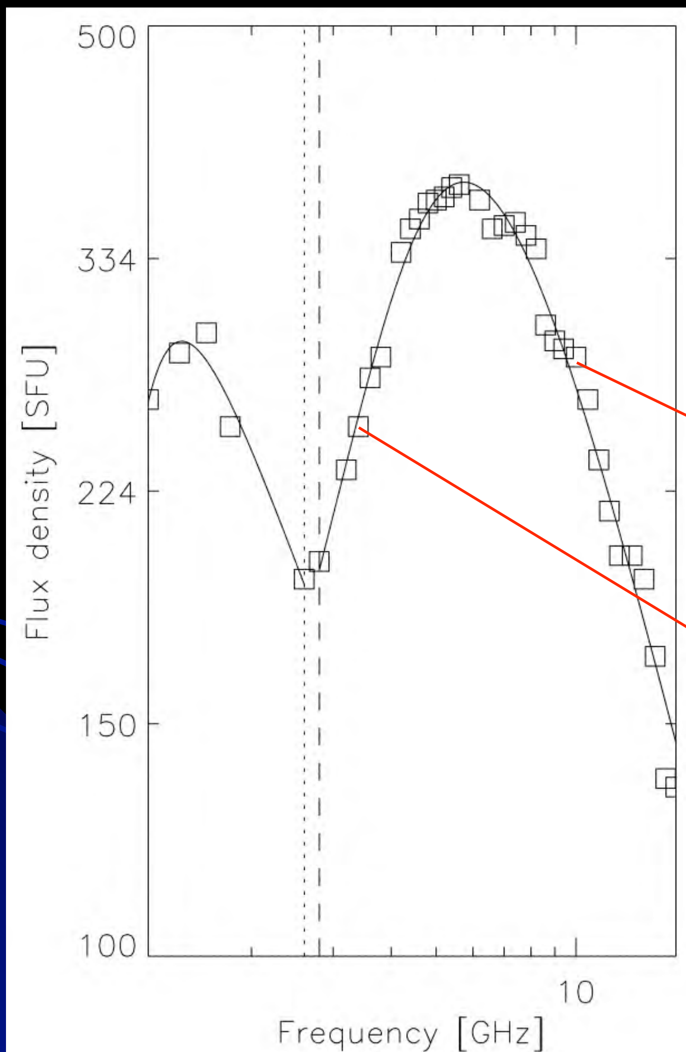
Optically thin part:
Slope linked to the spectral index of the electrons:

$-1.22+0.9\delta$ for mildly relativistic electrons

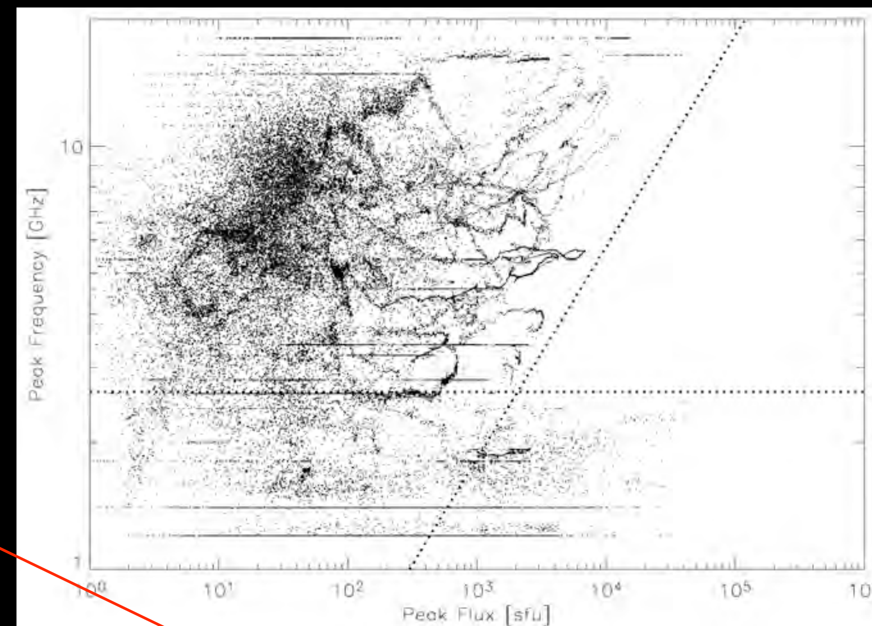
$0.5(\delta-1)$ for relativistic electrons

Optically thick part: $2.52 + 0.08\delta$
Flatter spectra: non uniform B
Steeper spectra: Razin suppression

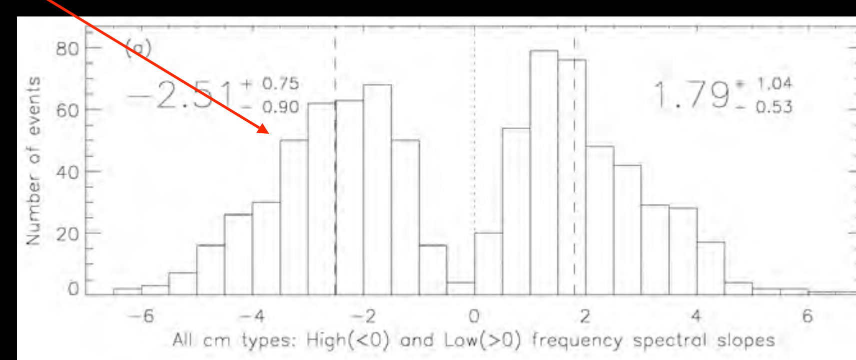
Gyromagnetic emission (4)



From Nita et al, 2004)



Correlation of peak frequency and of peak flux



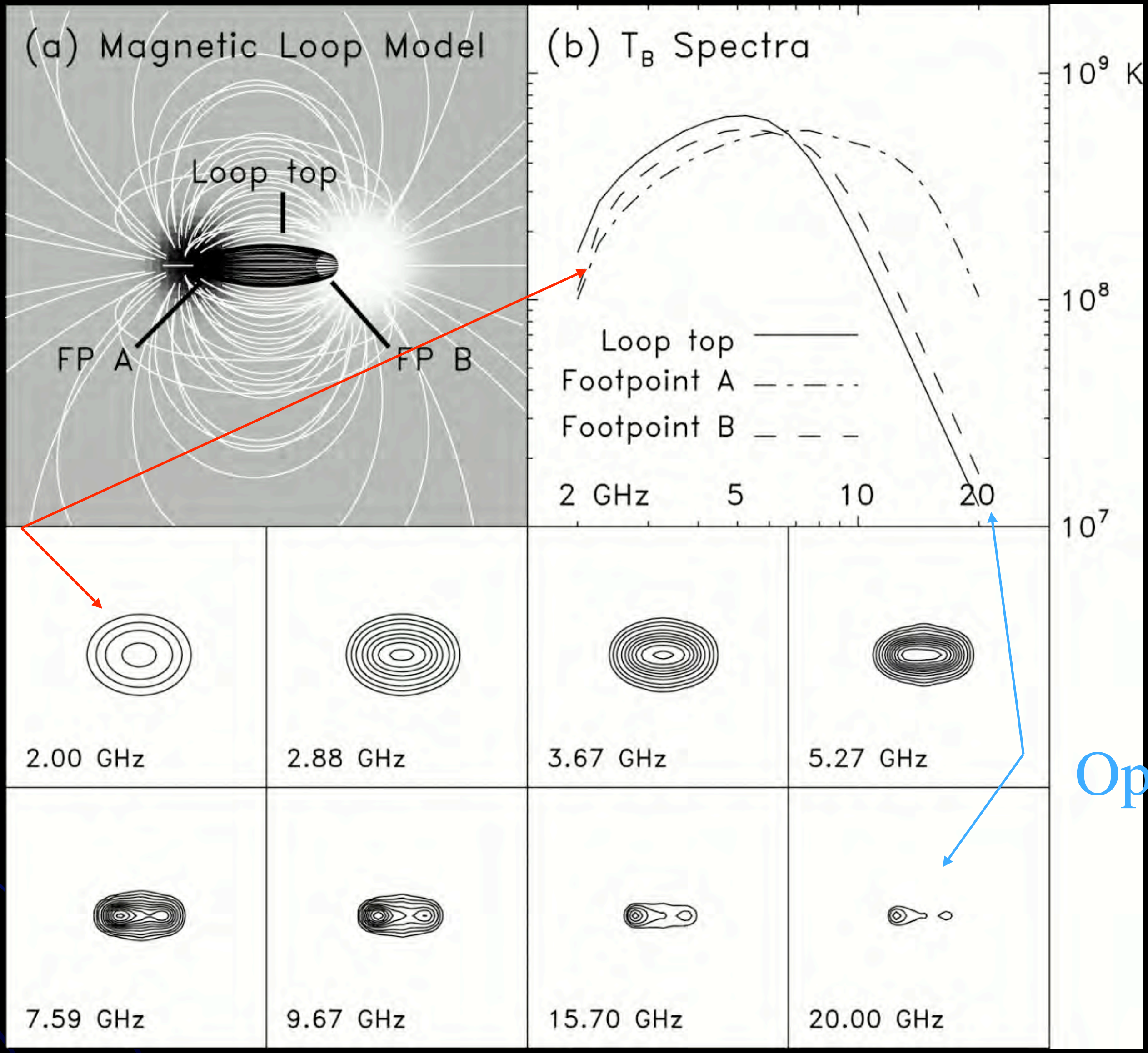
412 events

A gyrosynchrotron model source

A : 1000G 5 ”

B   500G 7.1”

Optically thick: loop top

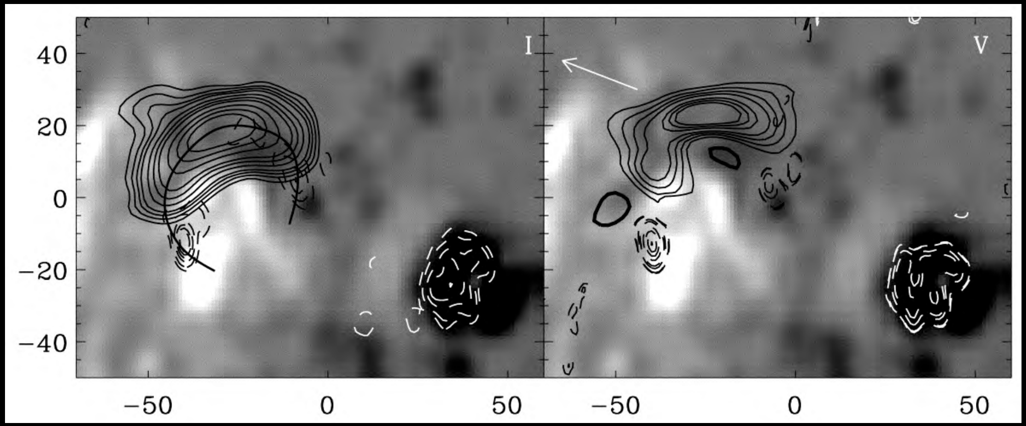


Bastian, Benz, Gary 1998, ARAA

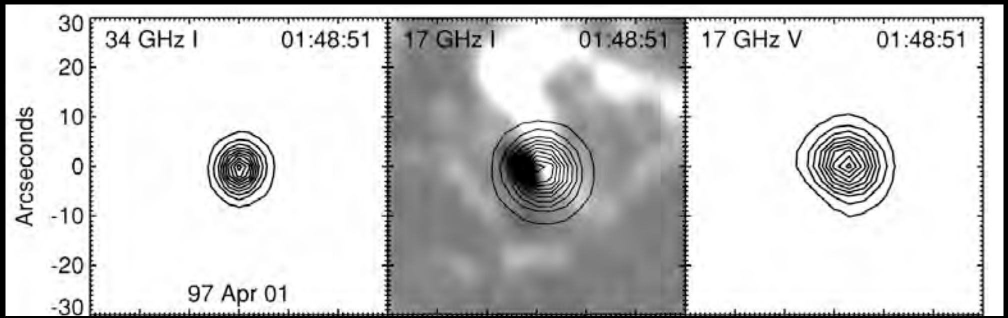
Optically thin: foot points

More detailed models:
Preka-Papadema & Alissandrakis AA 139, 507; 1988 AA 191, 365: 1992 AA 257, 307
Klein & Trottet 1984, AA 141, 67

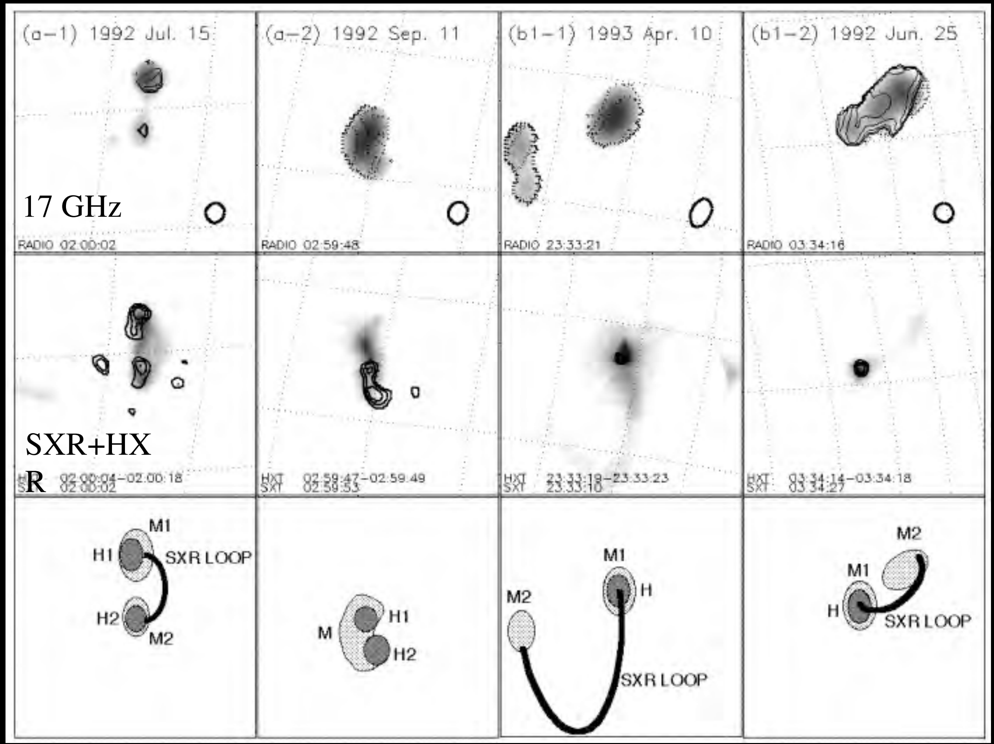
Microwave source morphologies



Loop (LF) + footpoints (HF):
Nindos et al. 2000, ApJ 533, 1053



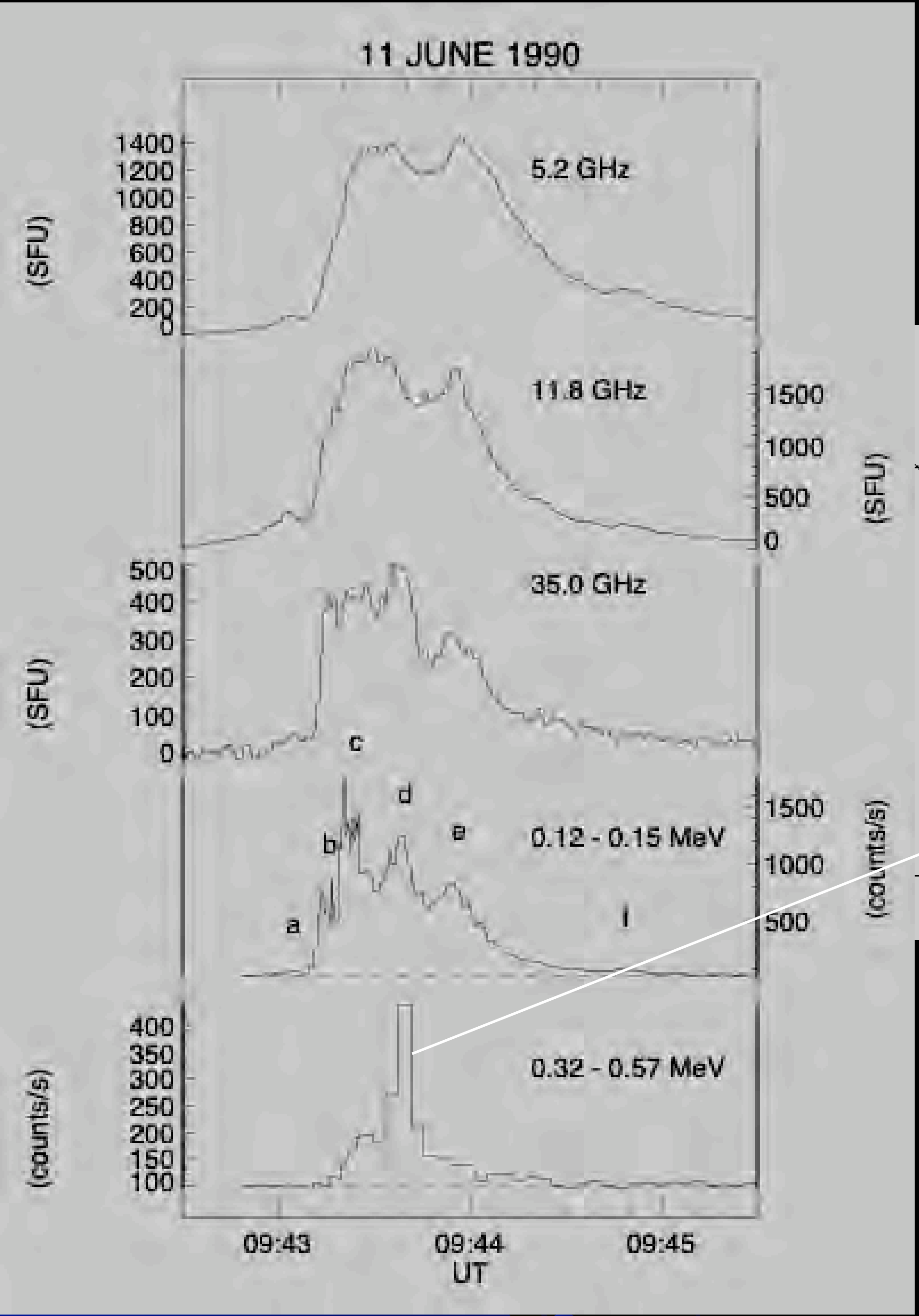
Compact loop :
Kundu et al. 2001, ApJ 547, 1090

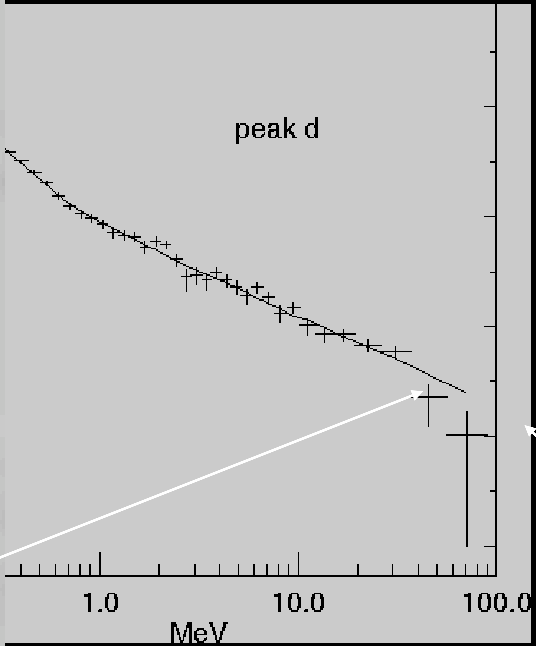


Multiple sources :
- footpoints (cospatial 17 GHz, HXR)
- compact or extended loops

Nishio et al. 1997, ApJ 489, 976
Hanaoka 1996, 1997, Solar Phys.

Relationship between HXR and cm emitting electrons?



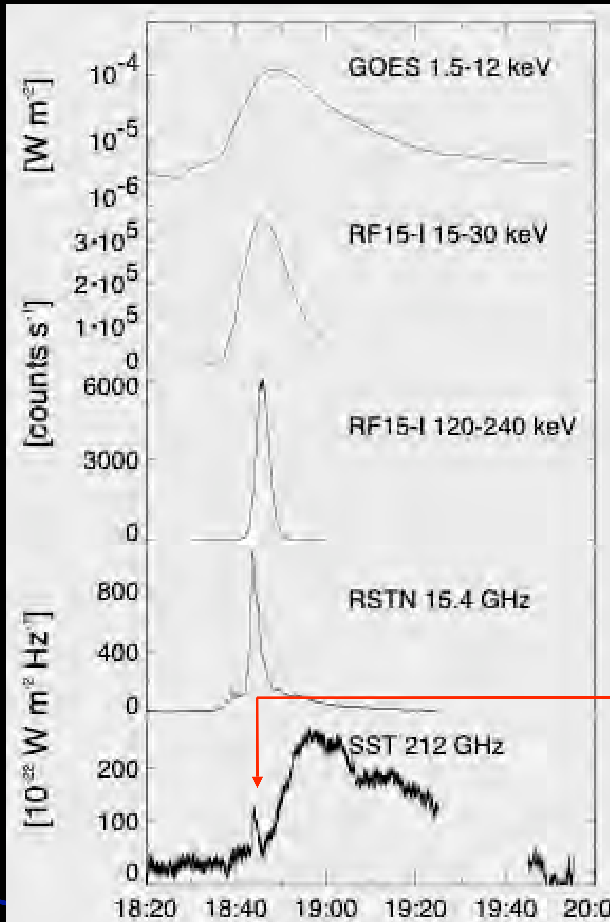


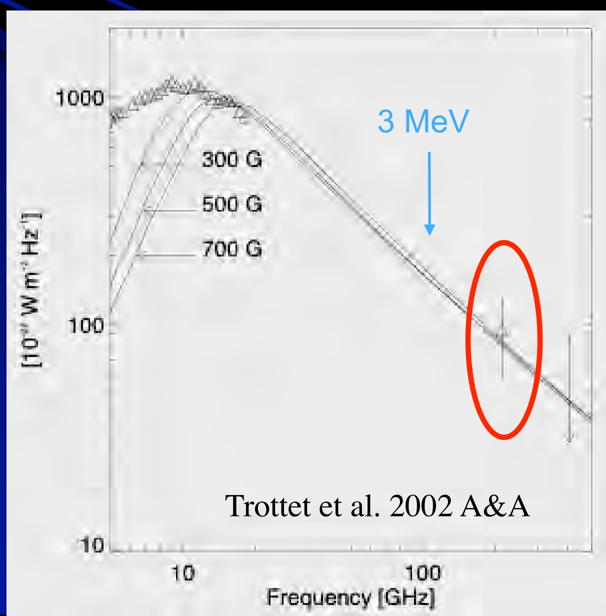
PHEBUS/GRANAT observations

α= radio spectral index
35 to 11.8 GHz

Peak d
- from HXR/GR
α = 2.7 for E<Eb
α = 1.2 for E>Eb
observed
α = 1.3

PHEBUS& Bern
Trottet et al (1998)





Trottet et al. 2002 A&A

Relativistic electrons at the Sun

- Solar radio burst : impulsive electron acceleration on second - time scale
- ν=212 GHz (SST[1]): synchrotron emission from relativistic e⁻ :

$$\nu \approx \tfrac{3}{2}\gamma^2 \nu_{ce}$$

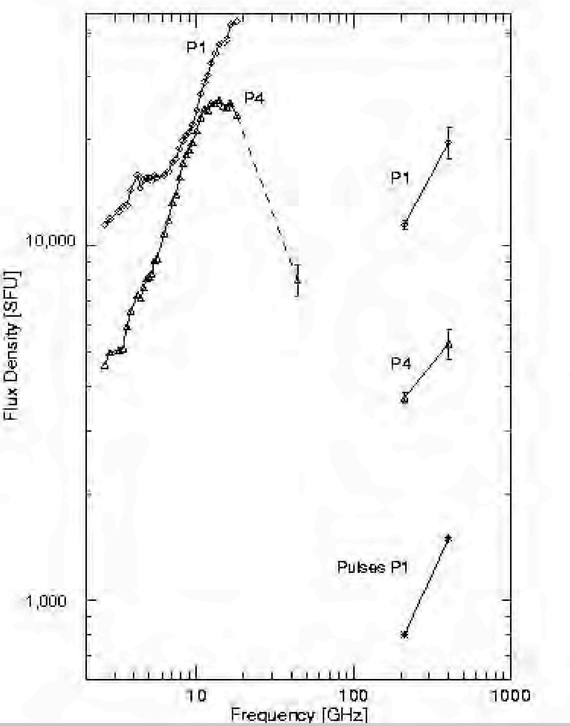
- Slope of the microwave spectrum :

$$\propto \nu^{-(\delta-1)/2} \text{ pour } N(E)dE \propto E^{-\delta}dE$$

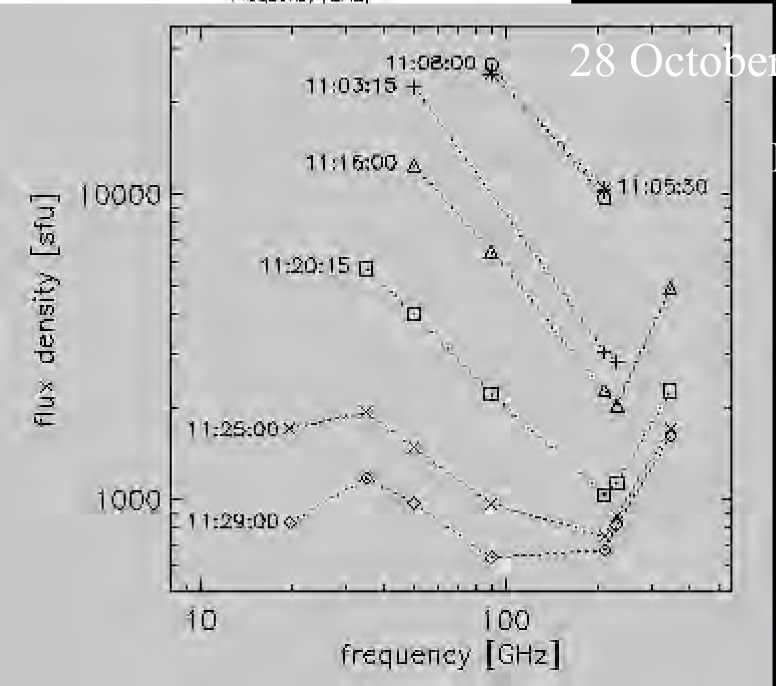
- Consistent with e-spectrum inferred fromgamma-ray bremsstrahlung (hν> 300 keV; Trottet et al. 1998 AA 334, 1099)

(1) Univ. Mackenzie Sao Paulo

BUT A New Spectral component above 200 GHz???



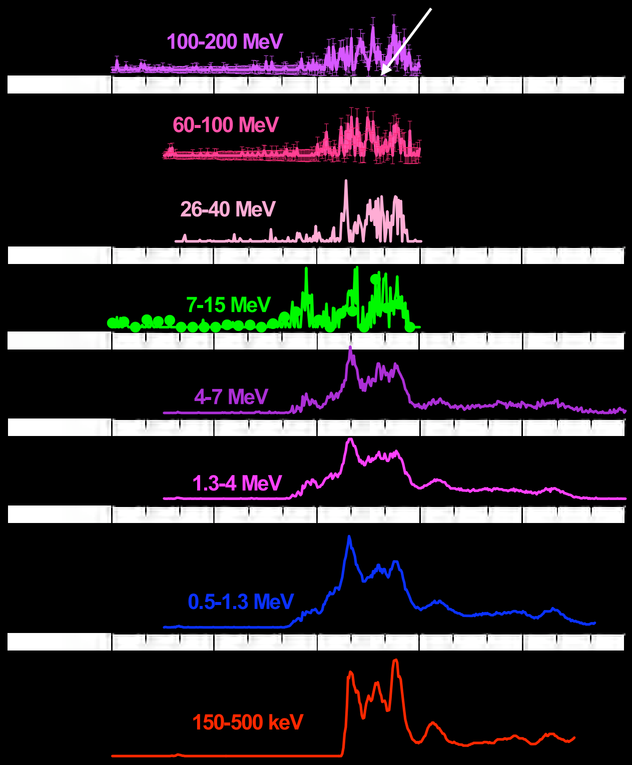
04/11/03
Kauffmann et al, 2004



28 October 2003

Lüthi et al, 2004

Pion decay radiation?



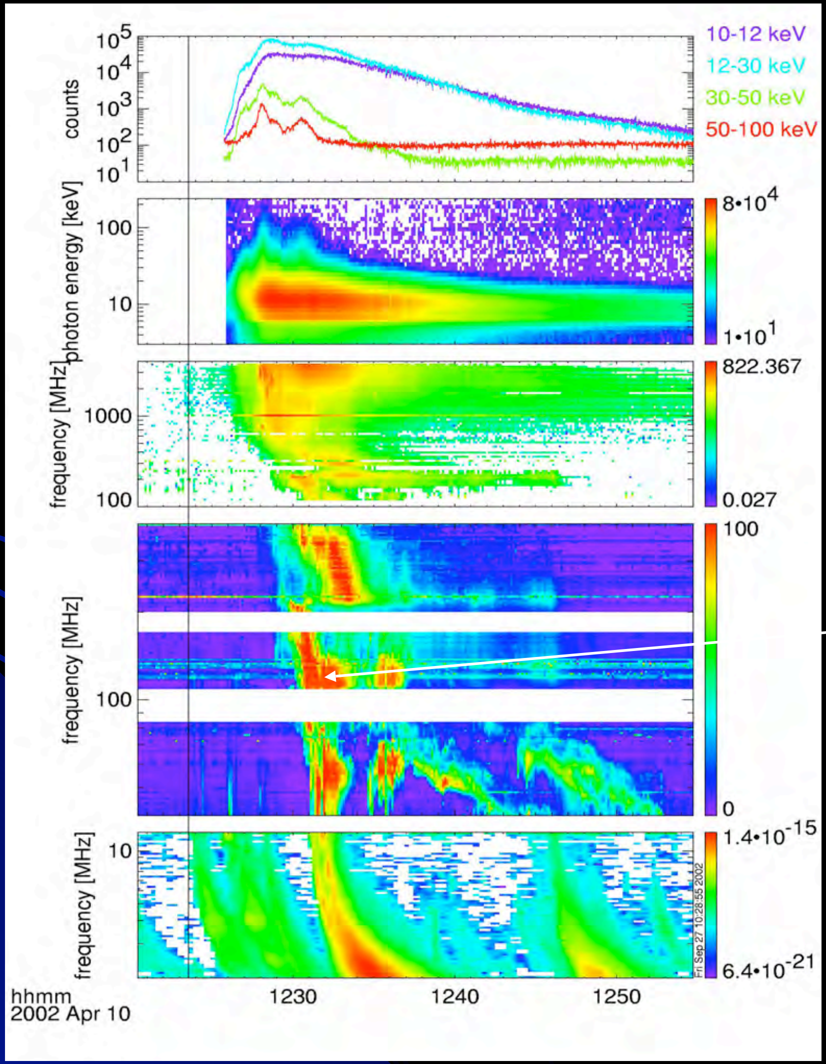
Myagkova et al, 2004

BUT for both flares > 60 MeV (pion decay?) emission observed by SONG/CORONAS

Possible origin: gyrosynchrotron from positrons from charged pion decay??
Coherent emission??(Kaufmann and Raulin, 2006)

Observations at even higher frequencies DESIR/SMESE??

Non thermal emissions in solar flares:
Coherent emission from non-thermal electrons



Coherent emissions from electrons

Coherent and incoherent radio emissions

Thermal emission : $$T_b = T_e \left(1 - e^{-\tau_\nu}\right) \leq T_e$$

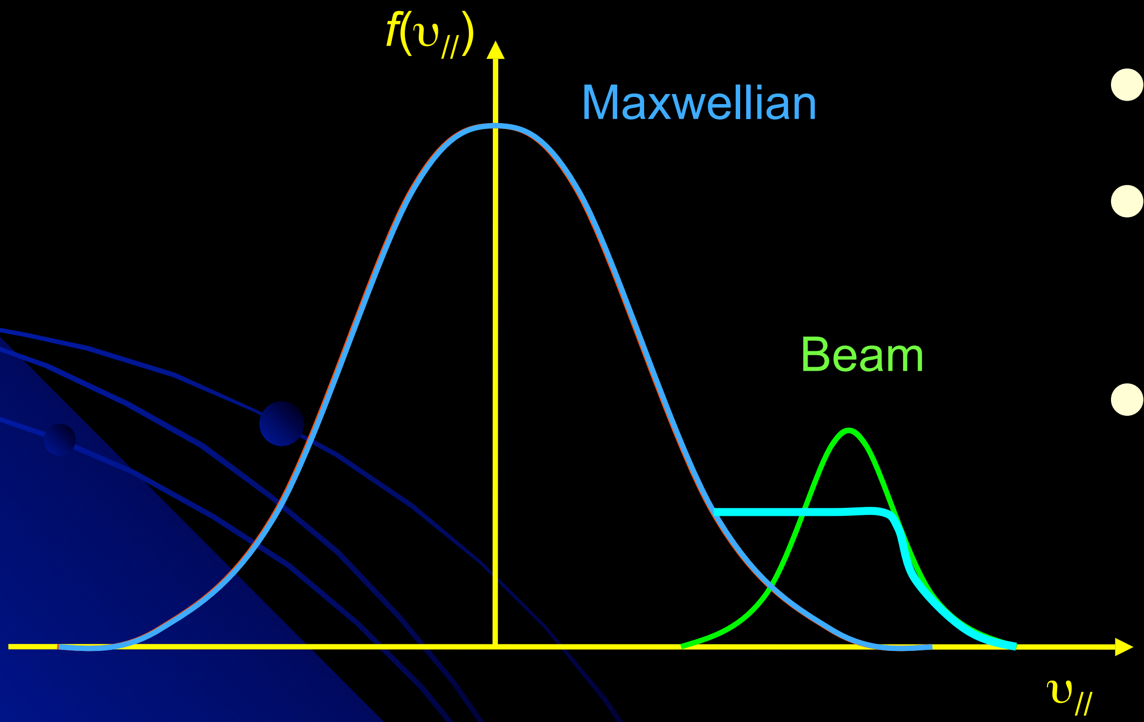
Incoherent emission :

$$KT_b \leq (\gamma - 1) m_e c^2 \Rightarrow T_b \leq 5 \times 10^9 (\gamma - 1) \text{ [K]}$$

Coherent emission from non thermal electrons required if brightness temperature is higher

⇒Non linear conversion of electron energy to plasma waves

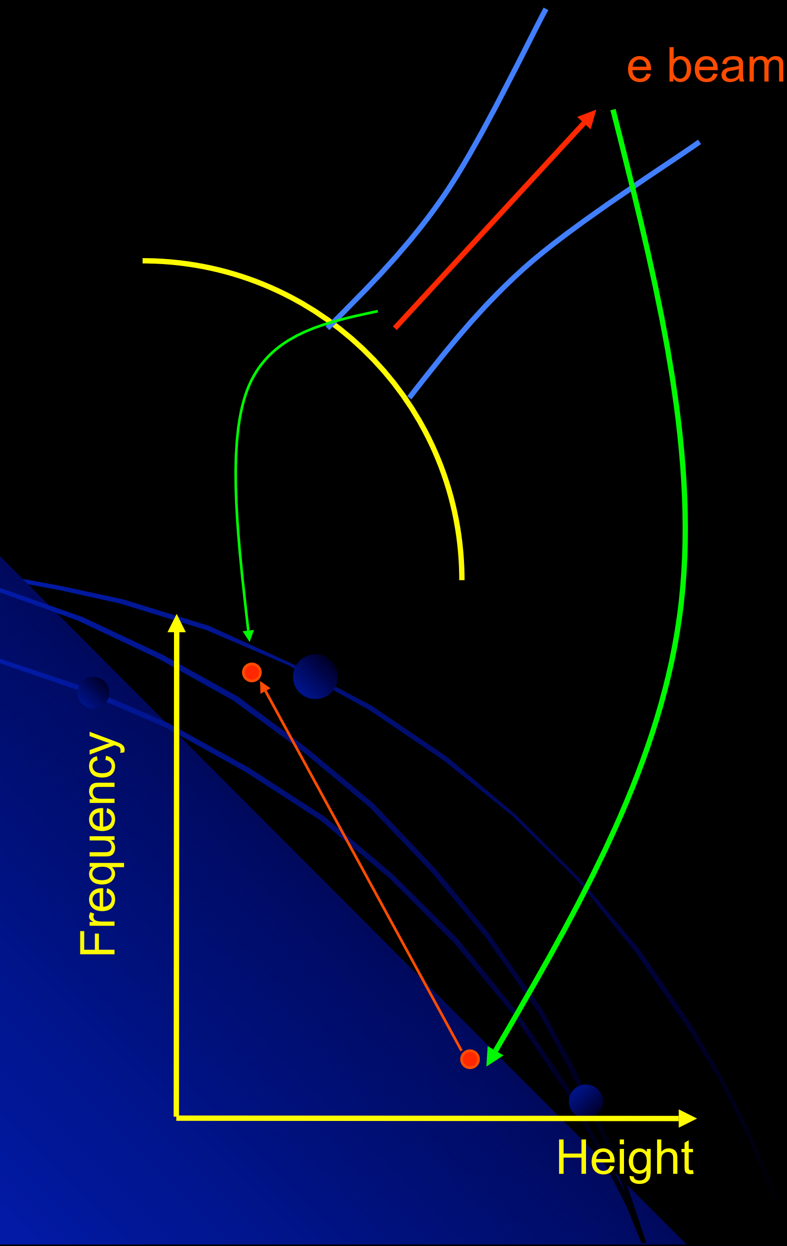
An example: radio emission from electron beams



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

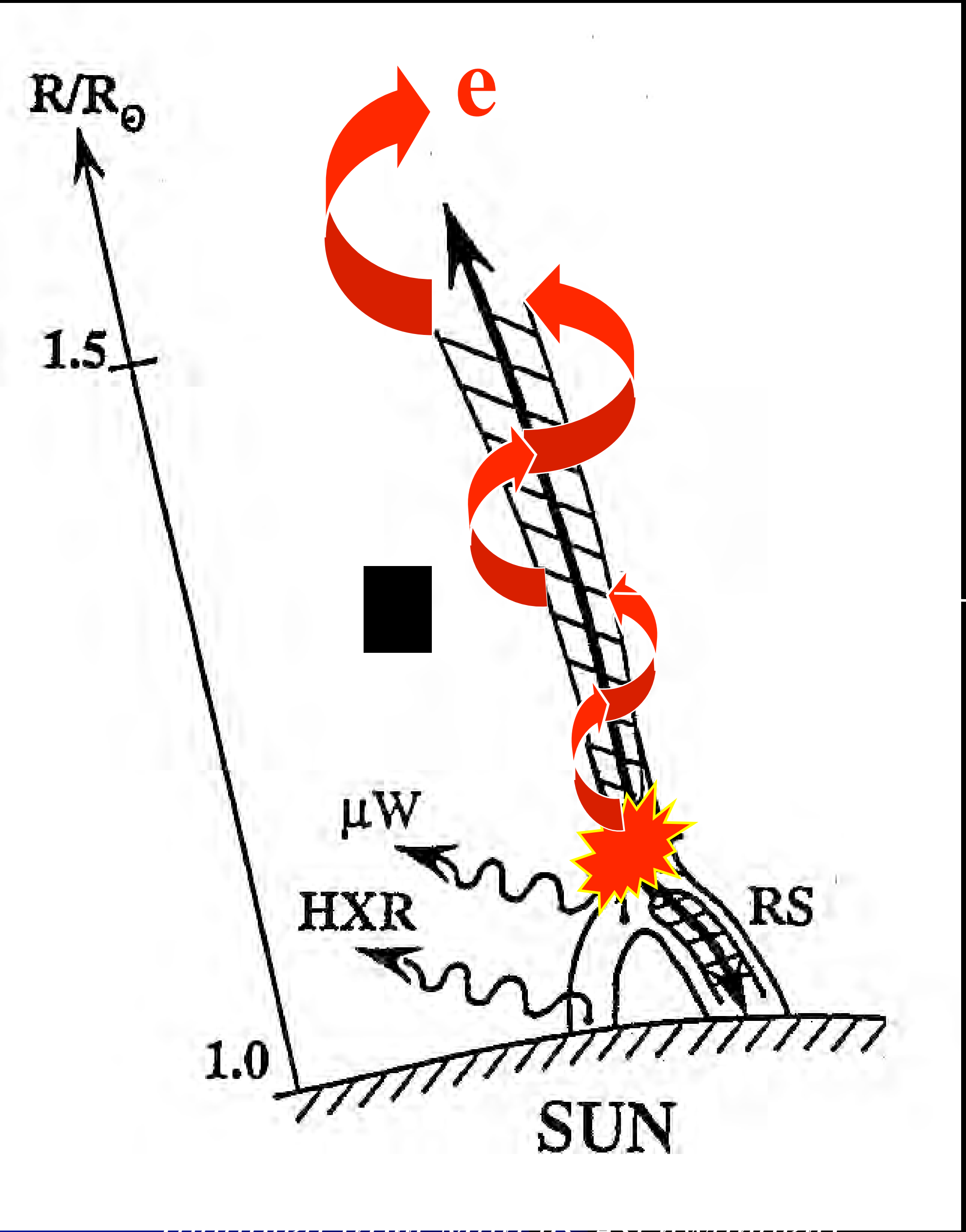
The Langmuir waves cannot escape from the plasma, but …

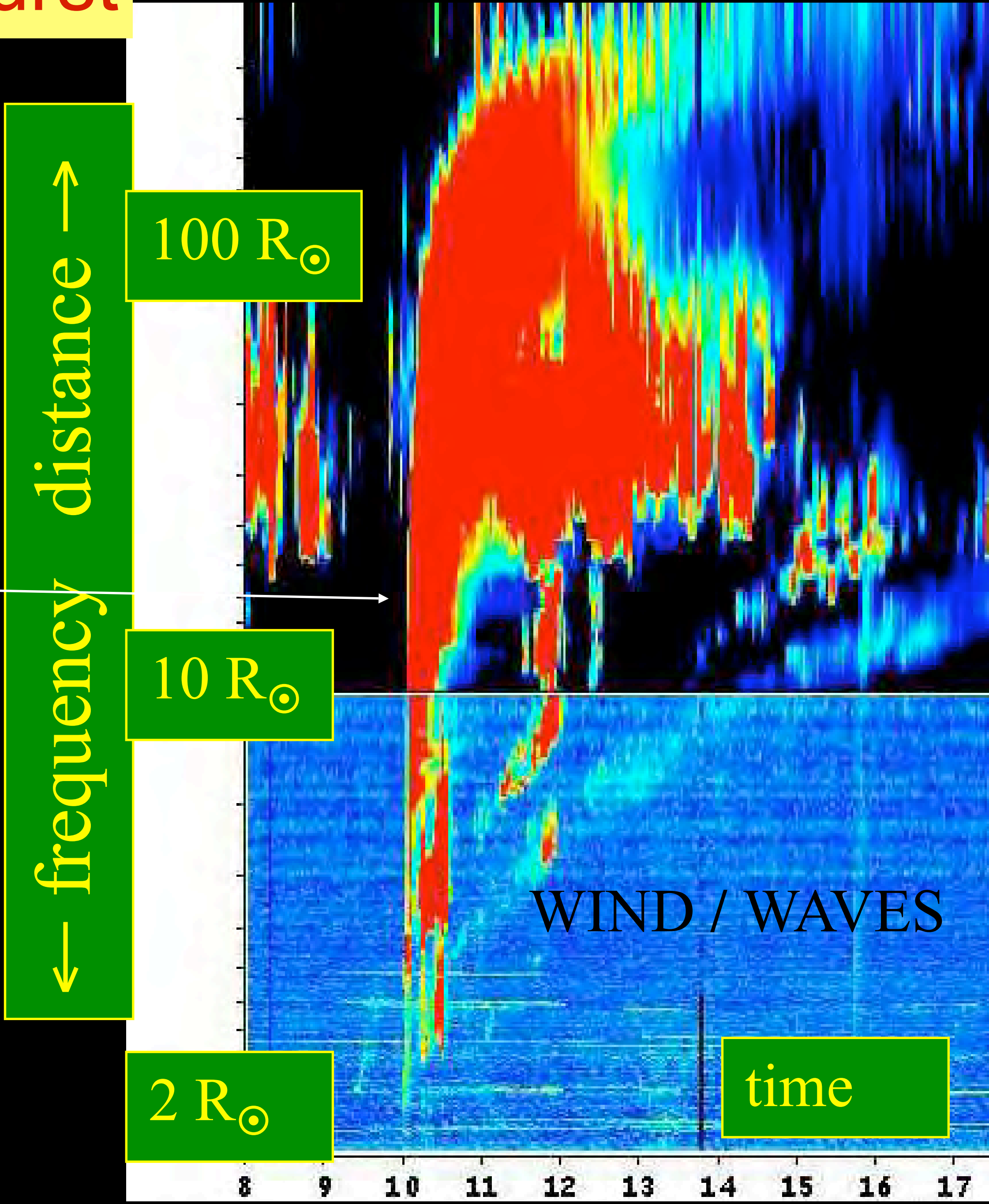
Electron beams and EM waves



- Coupling of waves (L=Langmuir, T=transverse EM, S=ion-sound):
  - L+S→T (dominant in IP medium)
  - L+L→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"

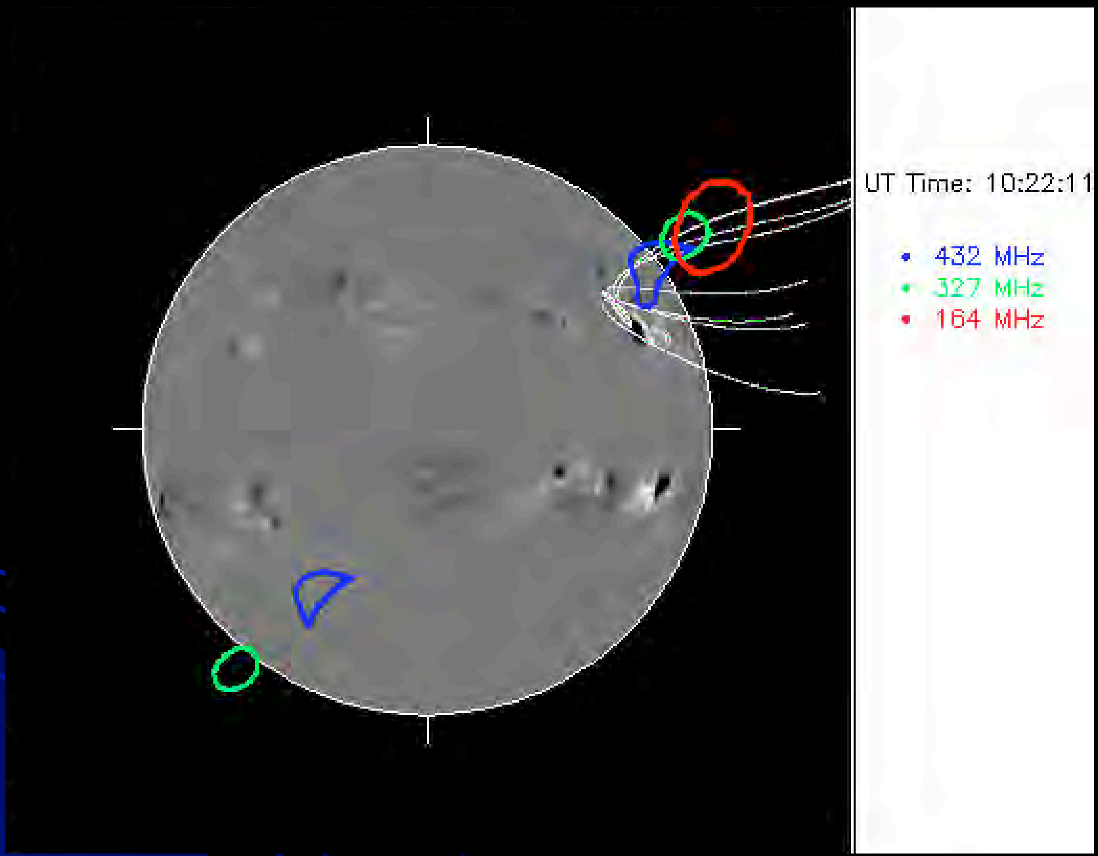
Type III radio burst

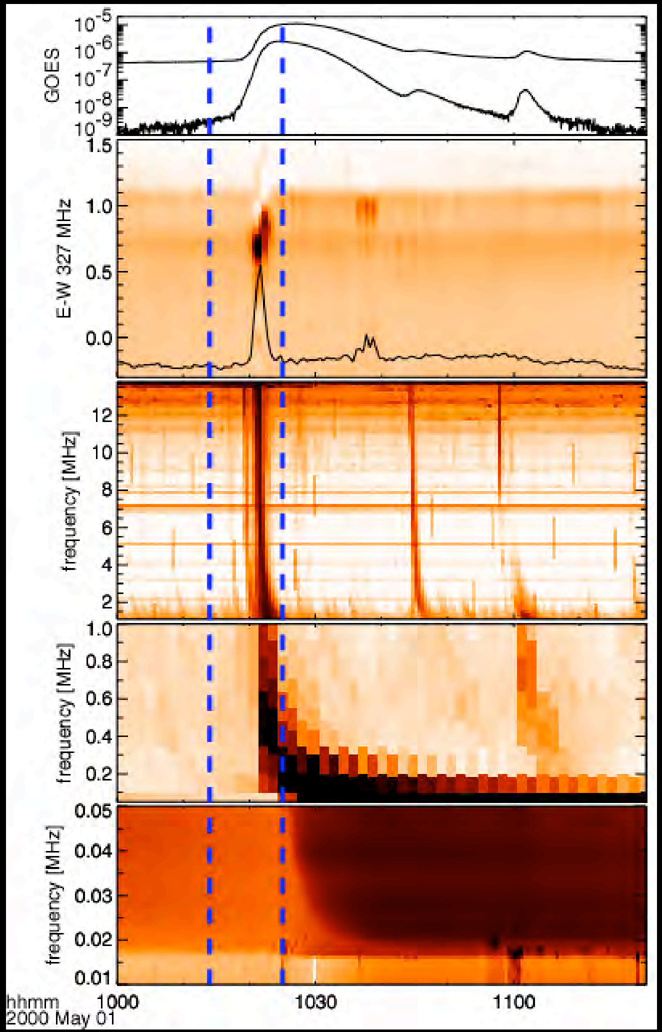




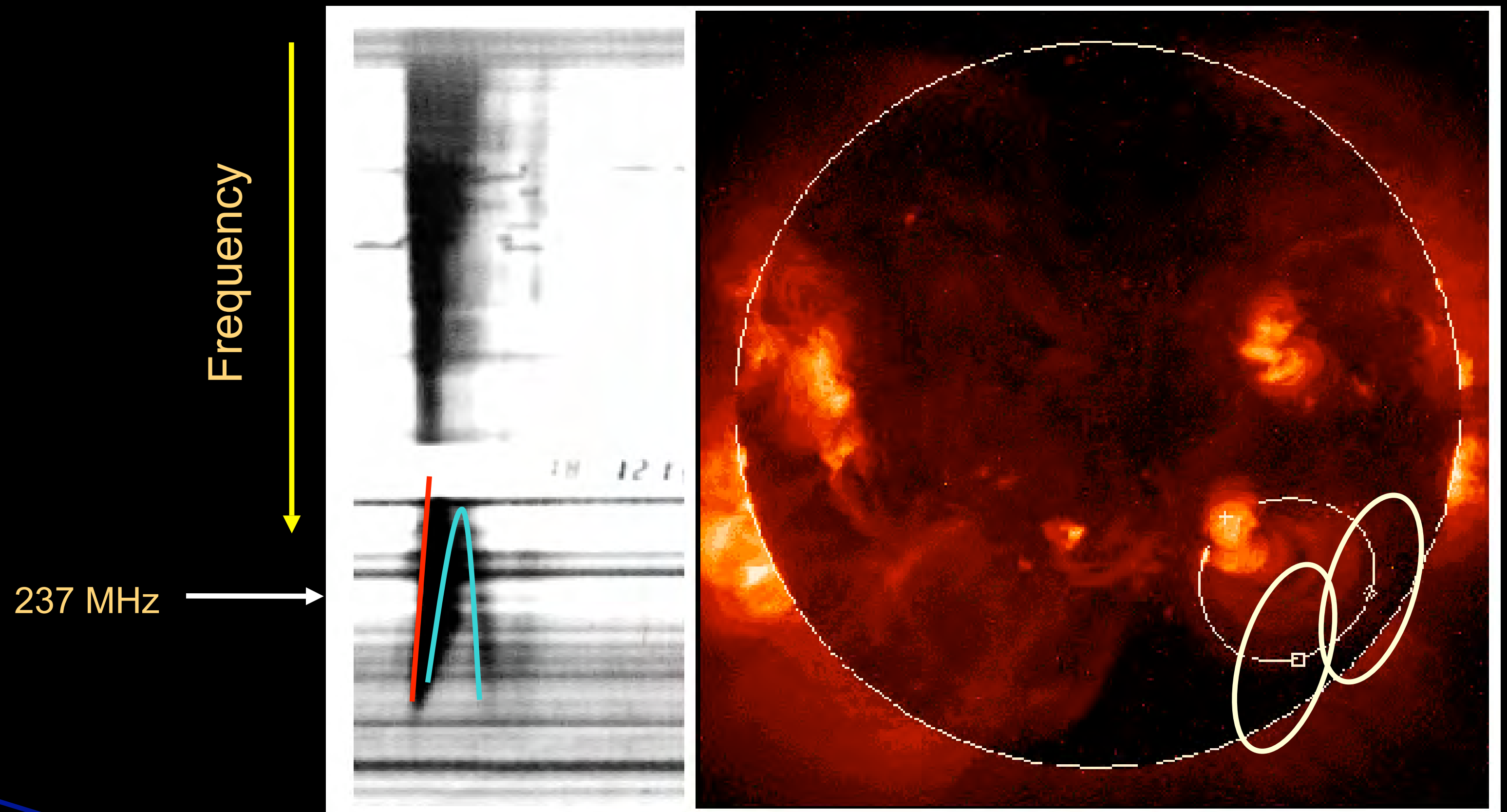
(adapted from Markus Aschwanden)

Propagation of electron beams in coronal magnetic flux tubes





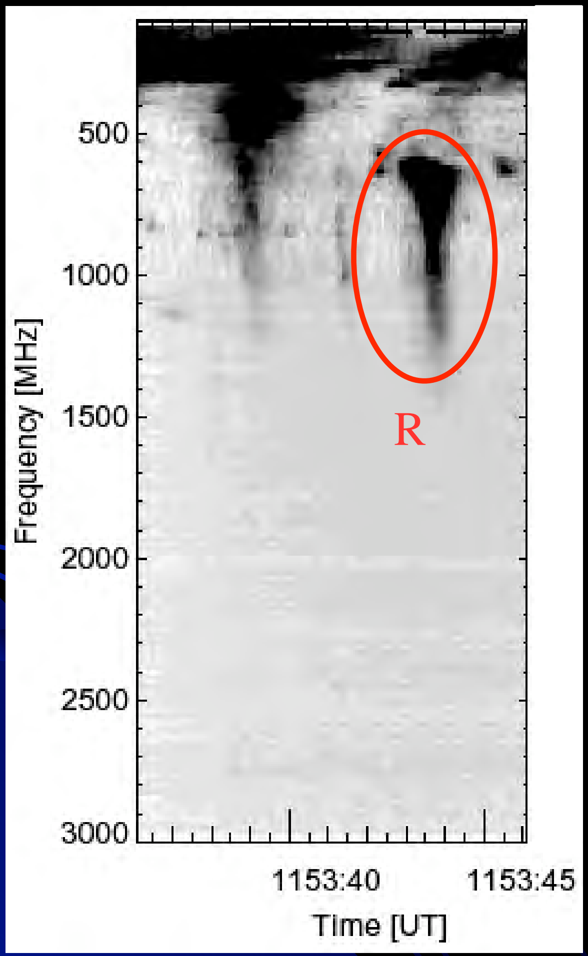
Electron beams in open magnetic flux tube inferred from PFSS model (Schrijver & DeRosa 2002, Solar Phys.; model available within SolarSoft). Electrons reach the *Wind* spacecraft (Langmuir waves).



Tremsdorf Yohkoh/SXT & Radiohéliographe Nançay

- Type III burst (e beam low → high corona) followed by type U (beam guided along a magnetic loop).
- Distance between U sources at ν =237 MHz / travel time ⇒ speed ~ 0,23 c (E=14 keV >> E_{th}≅100 eV)

Acceleration sites during impulsive flares : bidirectional beams



Aschwanden & Benz 1997, ApJ 480, 825

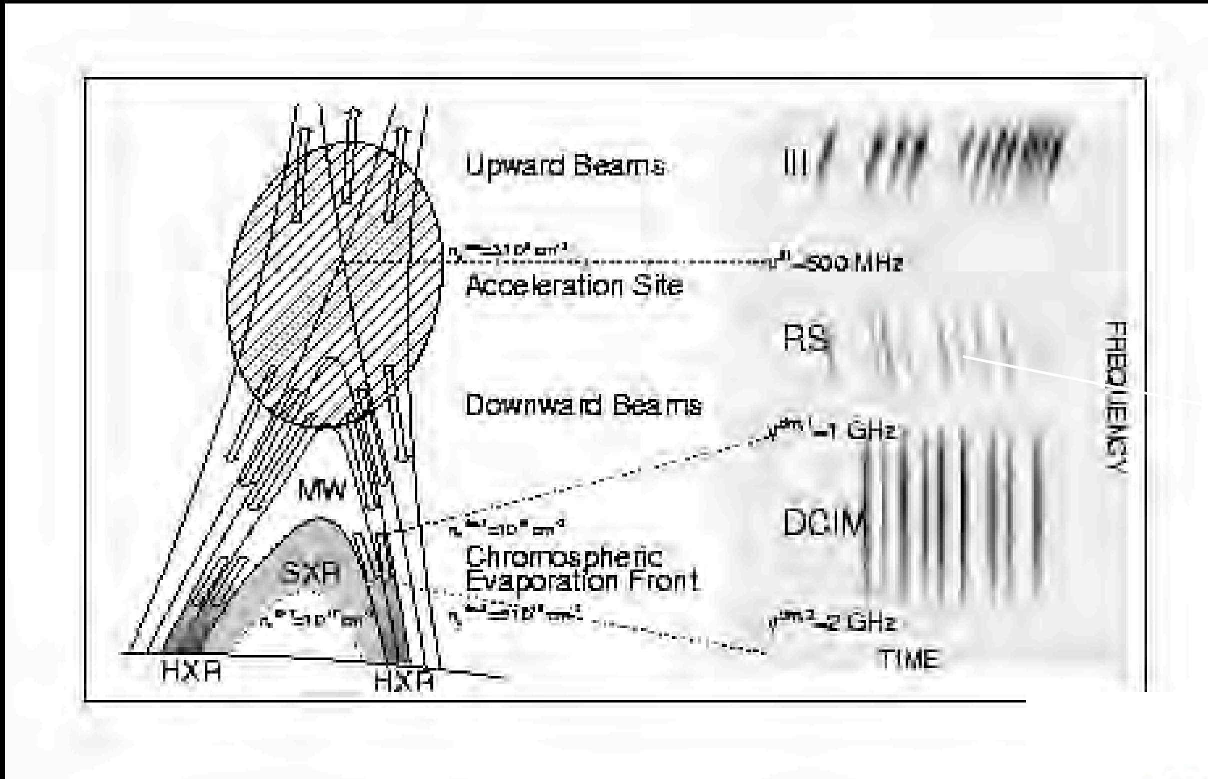
Type III & RS bursts (« reverse slope ») as tracers of upward & downward propagating e^- beams: density of the acceleration region

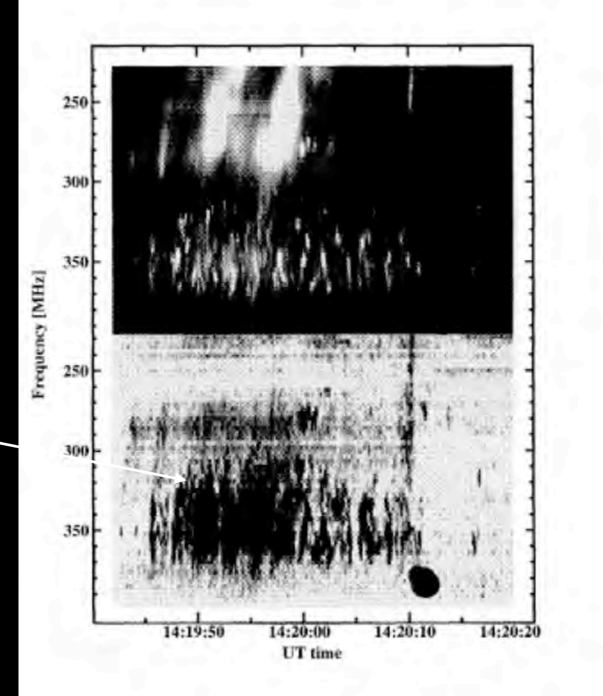
$$n_e \approx (0.6\text{-}10) \times 10^9 \text{ cm}^{-3}.$$

Scatter in individual flares: distributed sites of acceleration.

Time scale of acceleration $\leq$ 1 s.

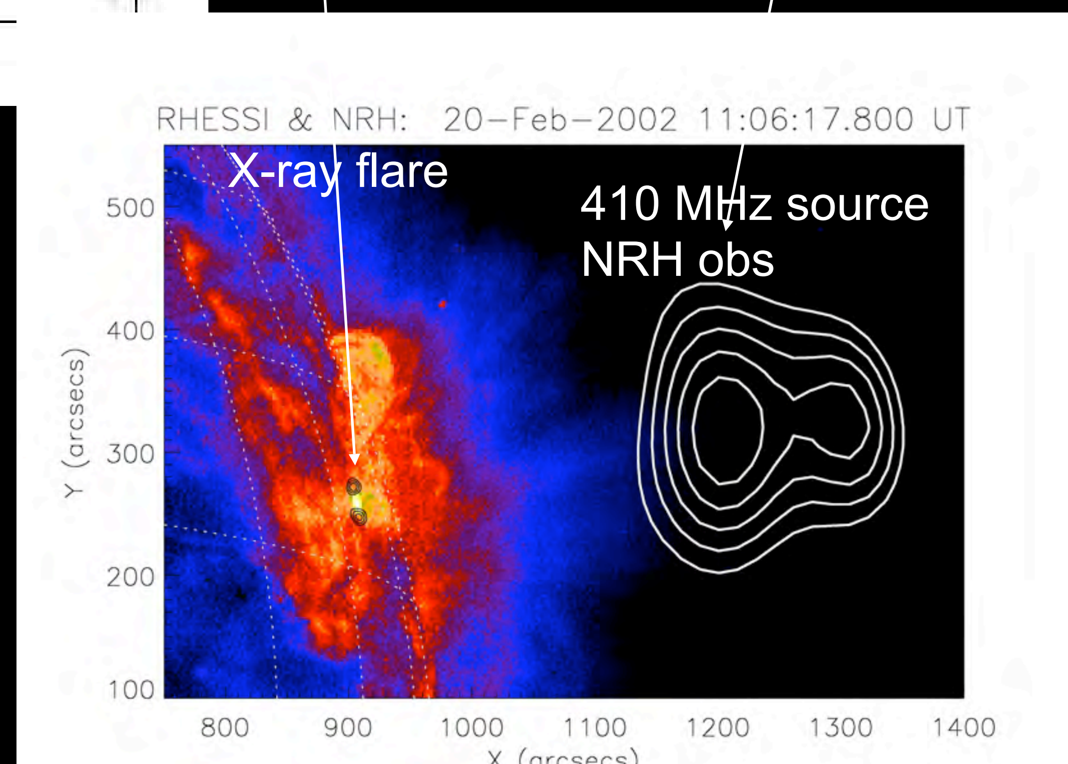
(see Aschwanden 2002, Spa. Sci. Rev. 101, 1).





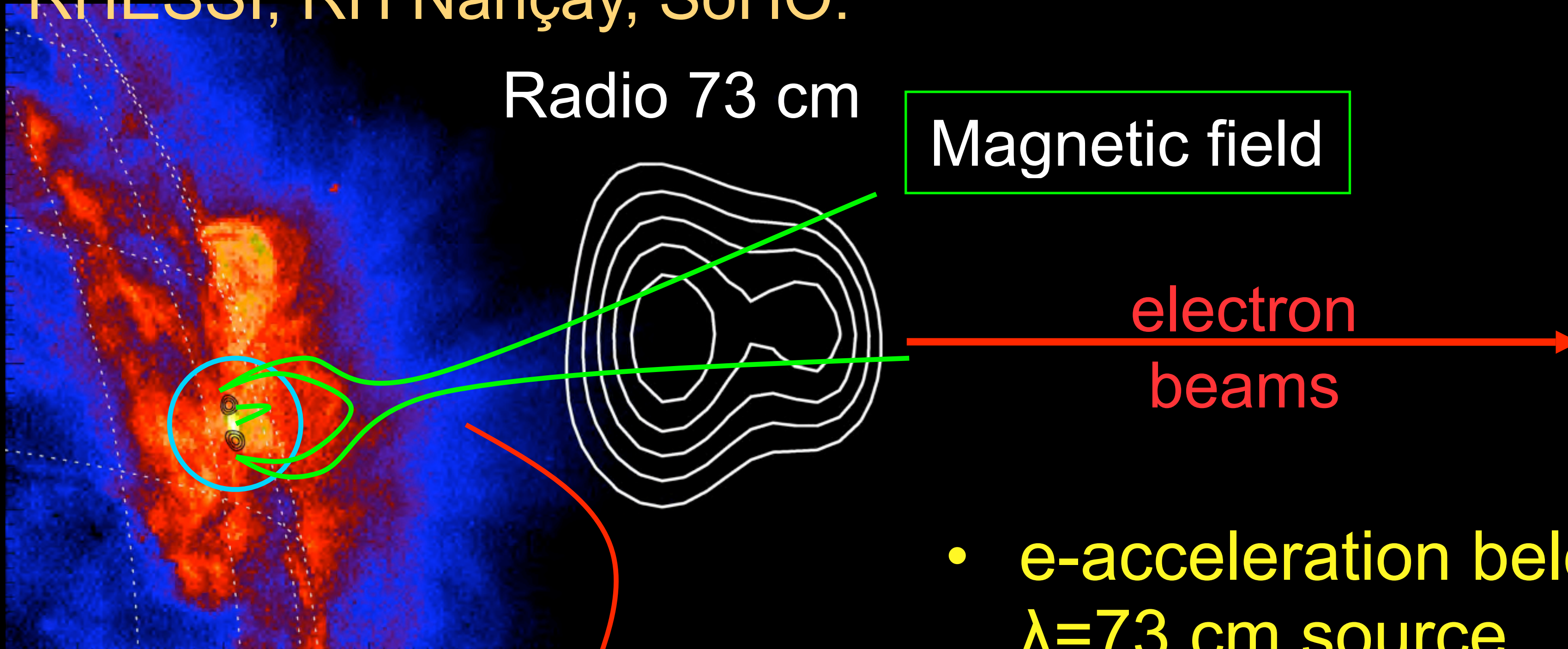
from Aschwanden & Benz 1997

Benz et al, 1996

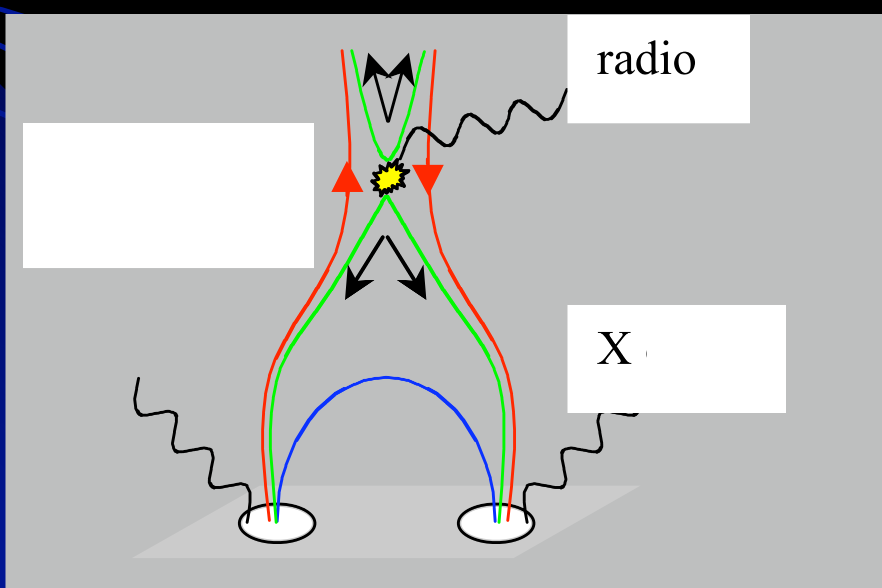


From Vilmer et al, 2002

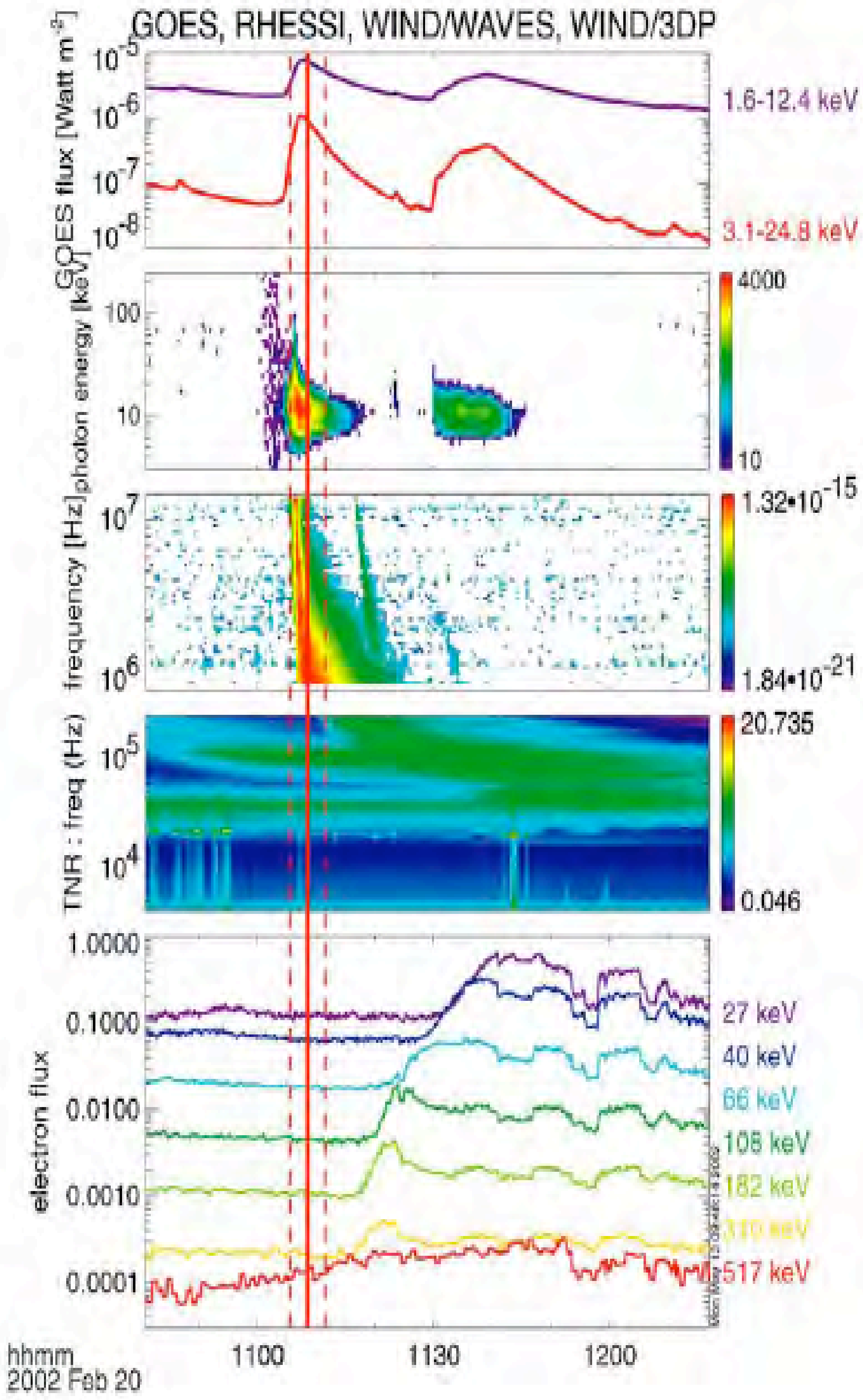
RHESSI, RH Nançay, SoHO:



XR

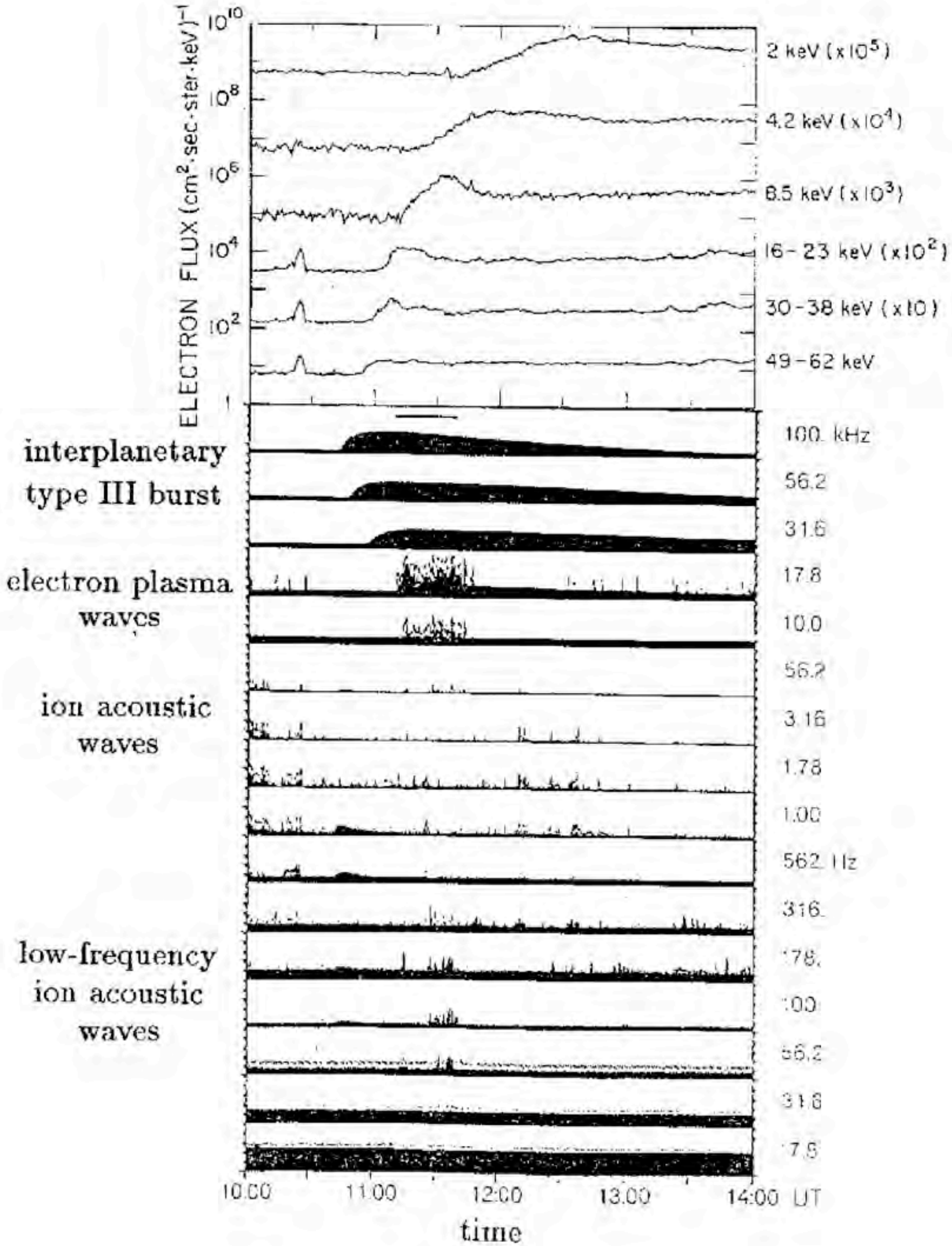


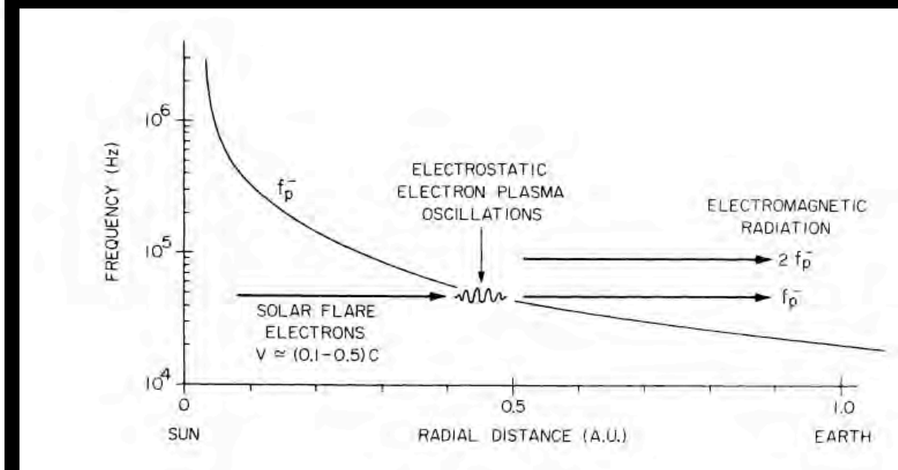
- e-acceleration below λ=73 cm source.
- Upward (radio) and downward (HXR) propagation
- Artist's (?) view of the acceleration region



Electron beams in the interplanetary medium

Electron beams in the interplanetary medium

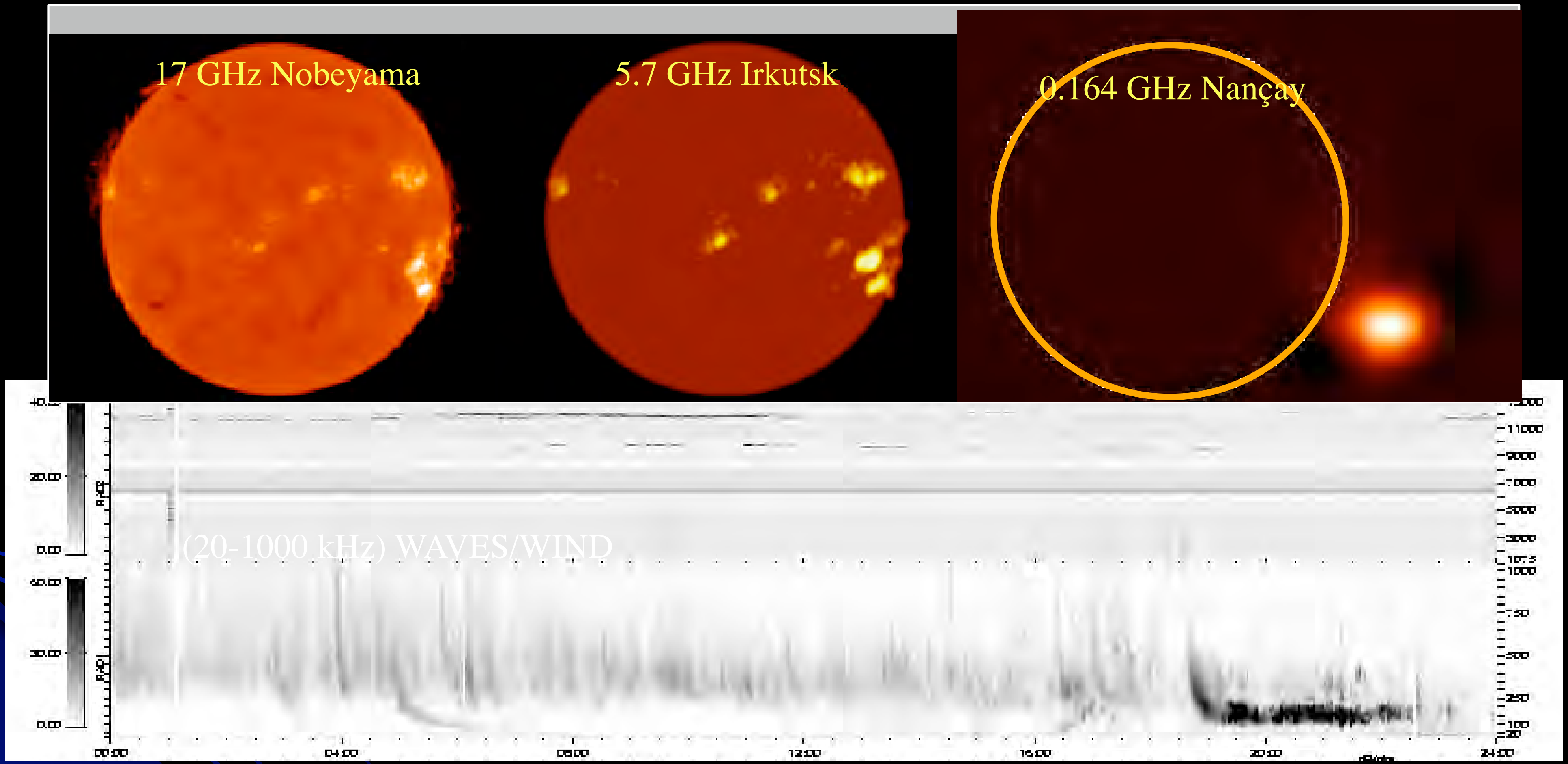




Lin et al, 1986

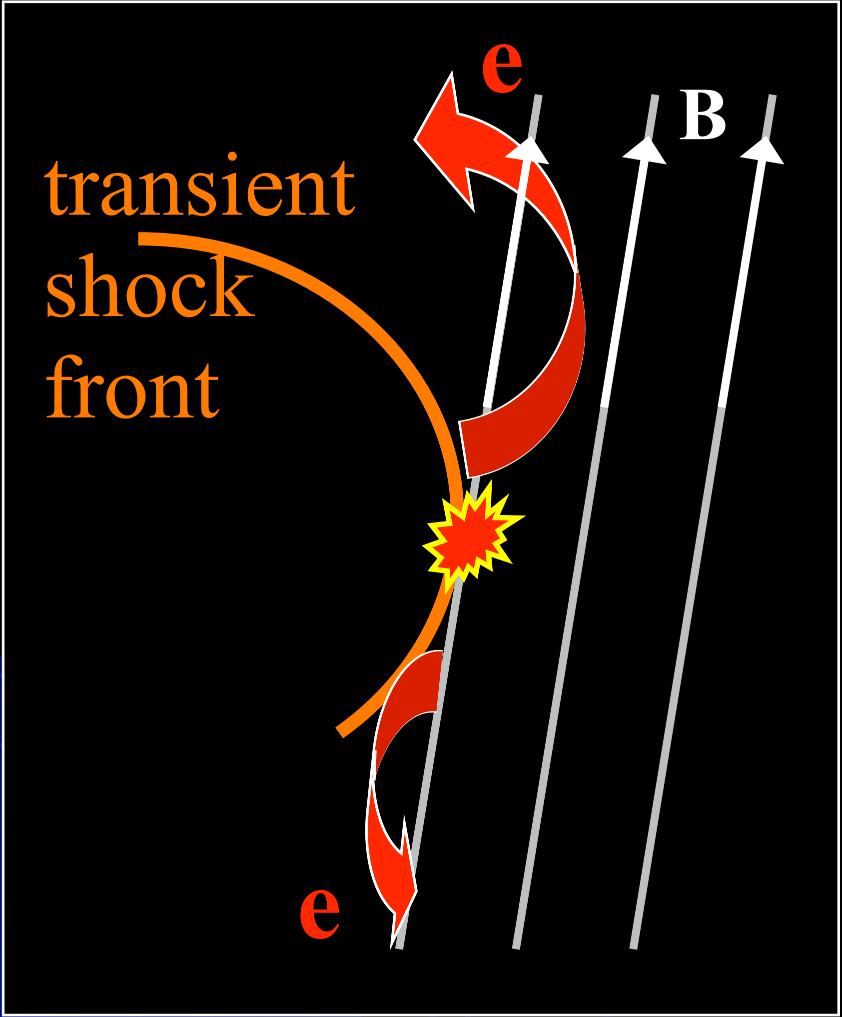
L+S⇒T

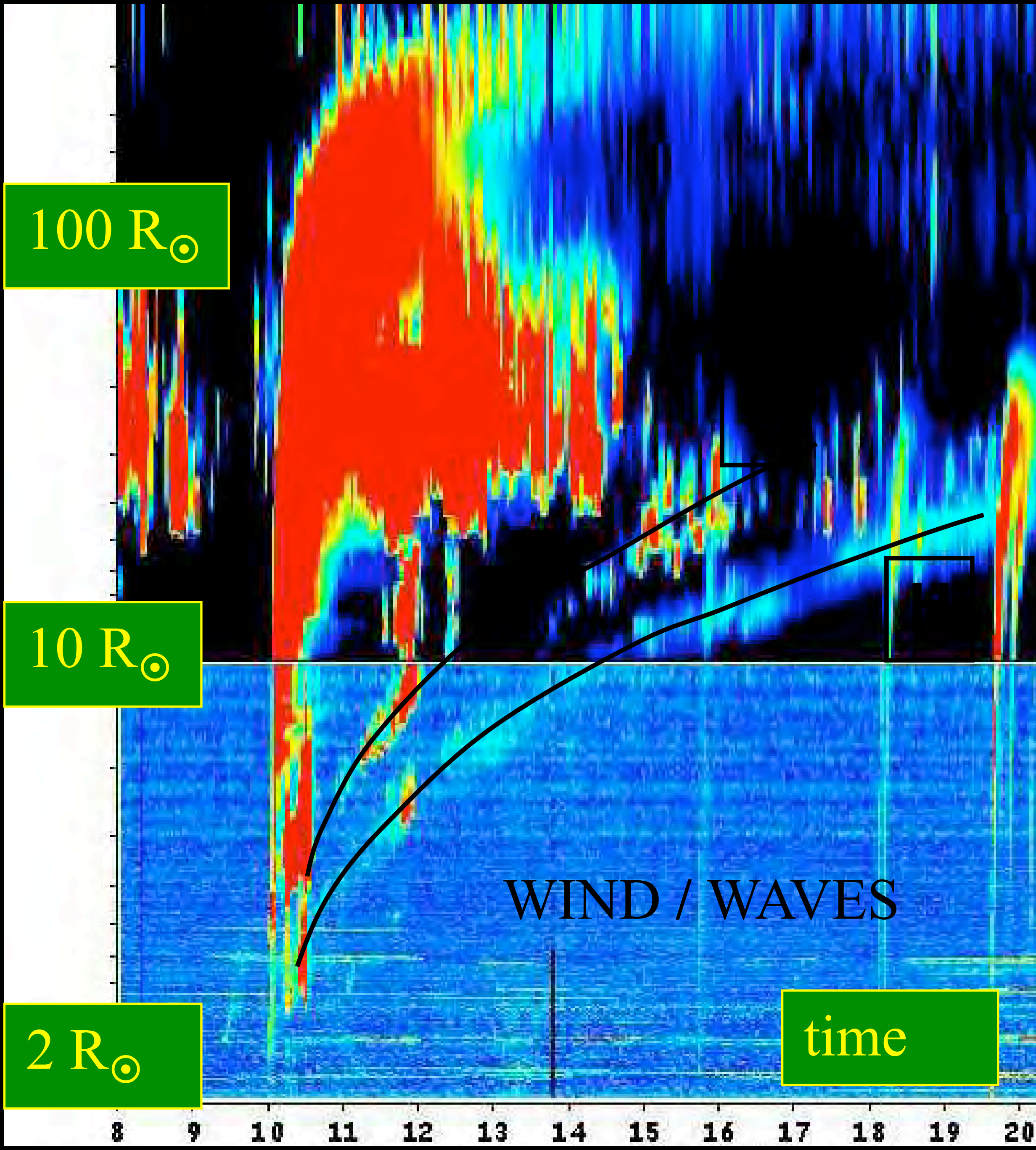
Mapping non thermal radio sources outside flares



- Non thermal e^- (some keV) in/above non-flaring *AR*. Multi-λ mapping : Where ? Trajectories? Circular polar : *B*.
- Origin of nonmaxwellian e^- populations in *IP* space ?

Type II radio burst





Slowly drifting emission lanes : slower exciter than type III

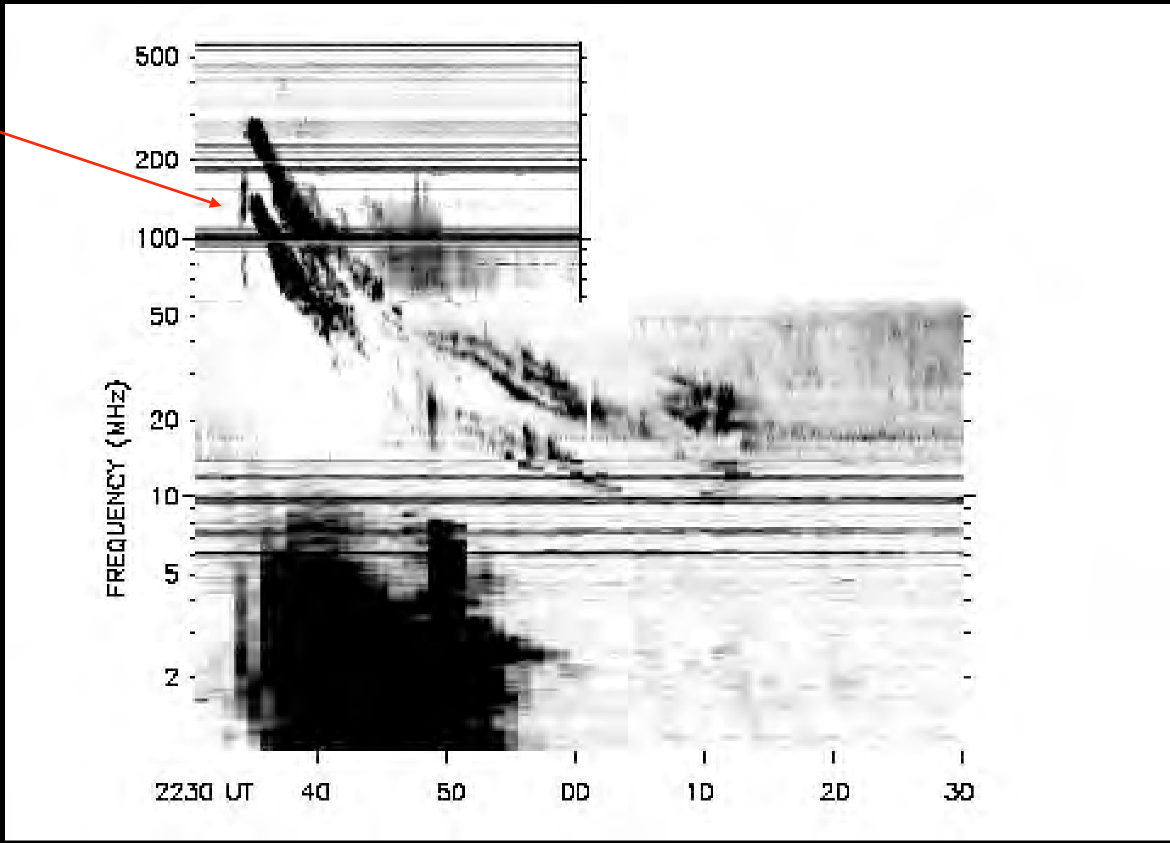
Typical speeds some hundreds – 2000 km/s (shock wave)

Fundamental / harmonic structure of the spectrum

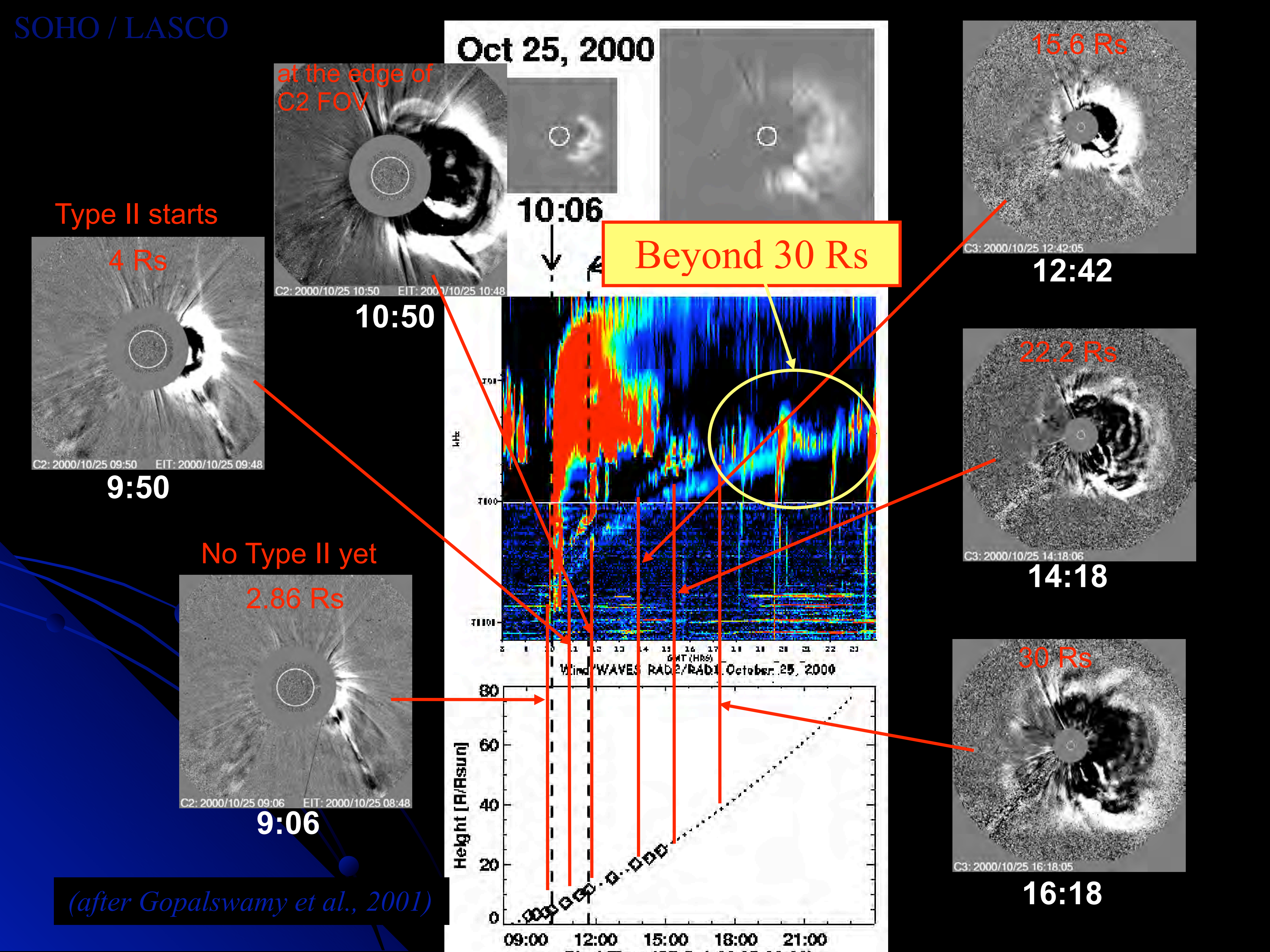
Metric and IP type II bursts

- Metric type II bursts associated with flares and generally vanish before reaching the high corona (blast waves) but still controversial (see a few examples of driven shocks in the corona)
- IP type II bursts believed to be CME driven shocks formed above 1 solar radius
- No continuous spectrum

Between m and km type II bursts

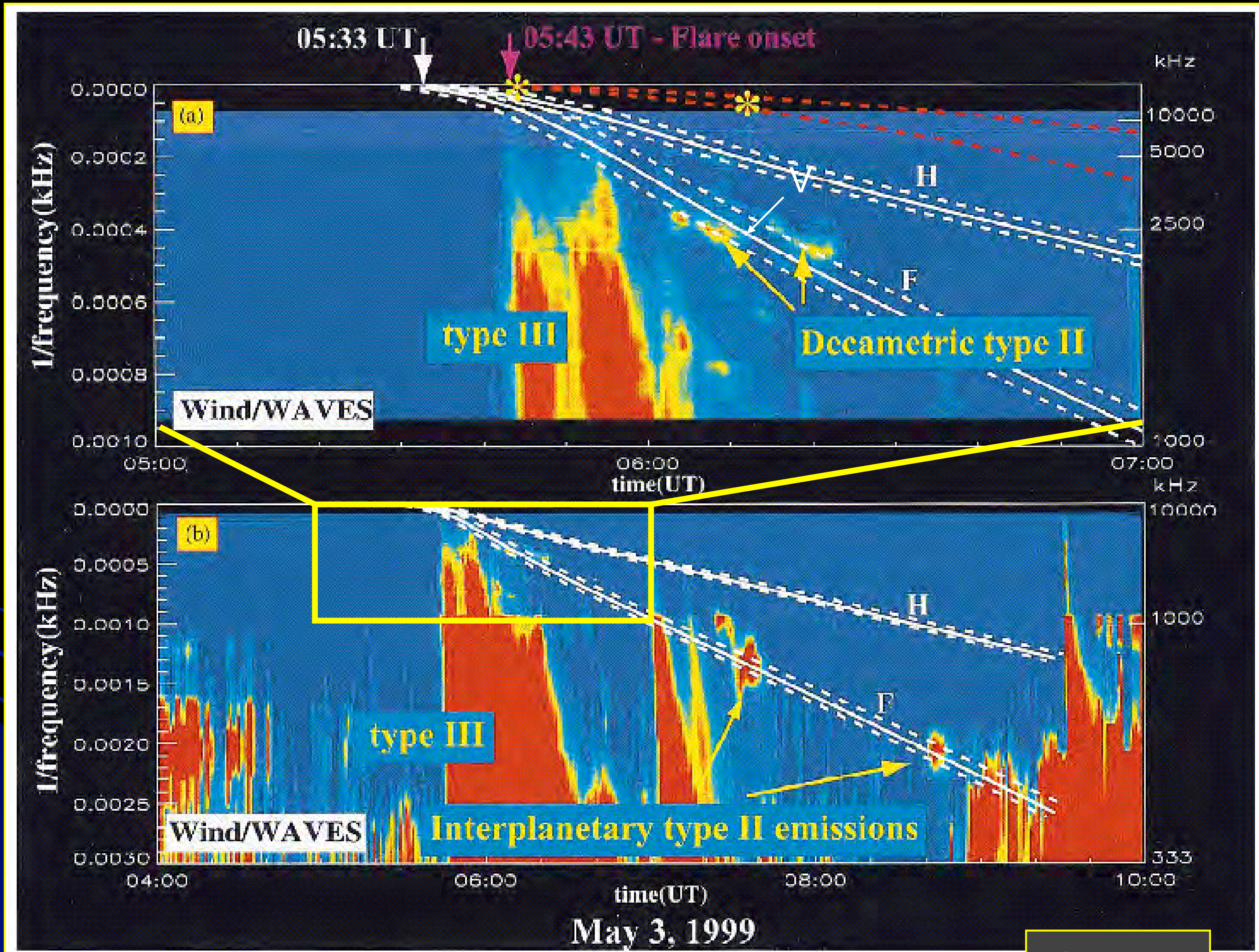


Cane and Erickson (2005)
Example of metric type II burst from 300 to 10 MHz


SOHO / LASCO
Oct 25, 2000
10:06
at the edge of
C2 FOV
C2: 2000/10/25 10:50 EIT: 2000/10/25 10:48
10:50
Type II starts
4 Rs
C2: 2000/10/25 09:50 EIT: 2000/10/25 09:48
9:50
No Type II yet
2.86 Rs
C2: 2000/10/25 09:06 EIT: 2000/10/25 08:48
9:06
Beyond 30 Rs
GMT (HRS)
Wind/WAVES RAD2/RAD1 October 25, 2000
Height [R/Rsun]
80
60
40
20
0
09:00
12:00
15:00
18:00
21:00
15.6 Rs
C3: 2000/10/25 12:42:05
12:42
22.2 Rs
C3: 2000/10/25 14:18:06
14:18
30 Rs
C3: 2000/10/25 16:18:05
16:18
(after Gopalswamy et al., 2001)

tracking shock waves from the Sun to 1 AU

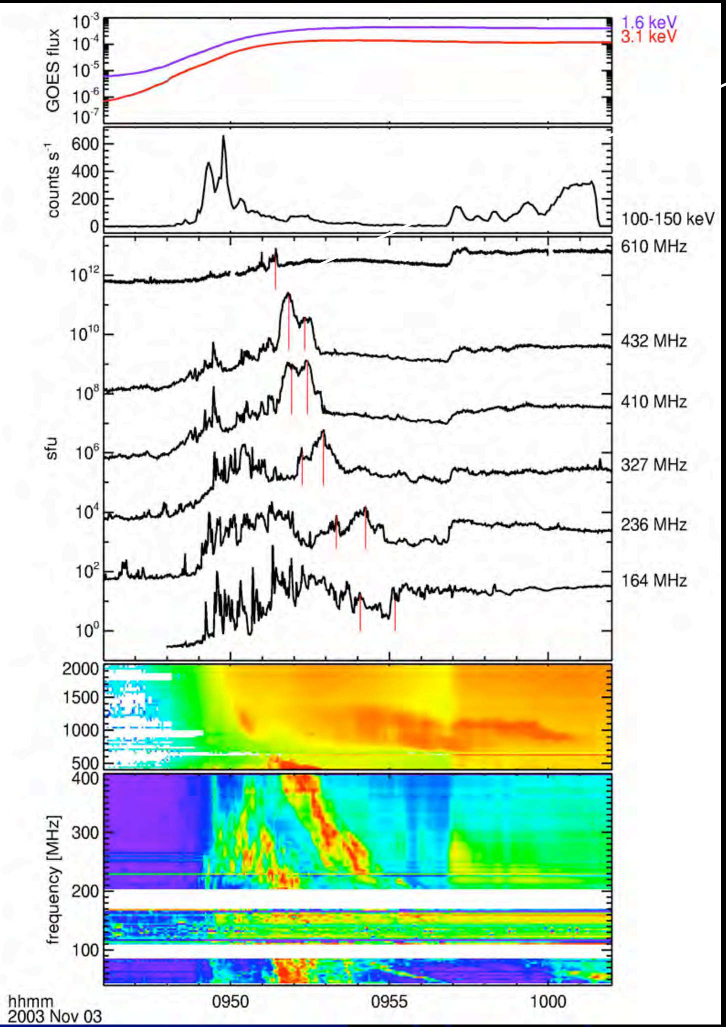
← distance frequecy →



time →

(Reiner et al., 1999)

Origin of the metric type II burst



Metric type II emission starting at 610 MHz (high frequency)

In the high corona: two scenario: blast wave or wave driven by a plasma motion

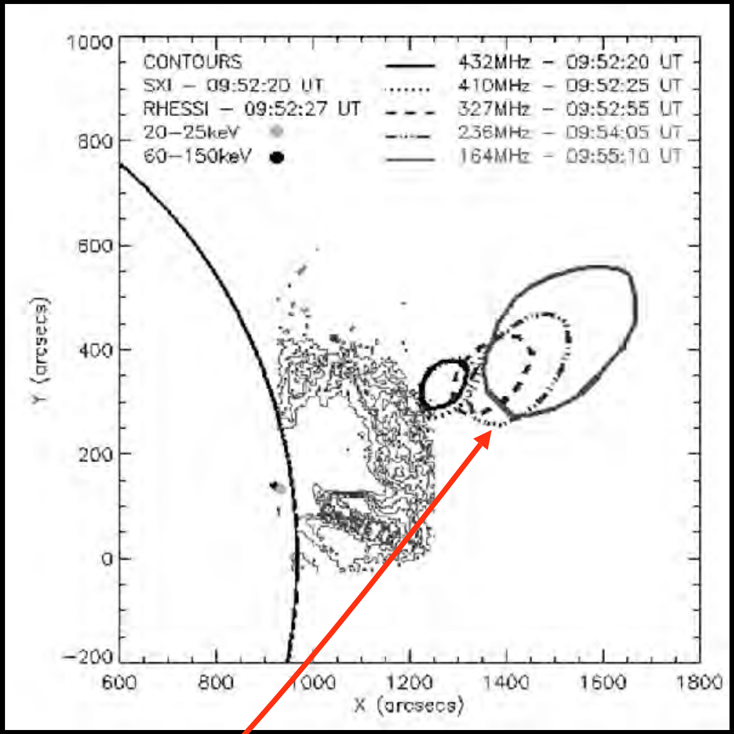
A few observations of X-ray "ejecta" associated with meter type II burst (Klein et al, 1999, Gopalswamy et, 1997, Dauphin et al, 2006)

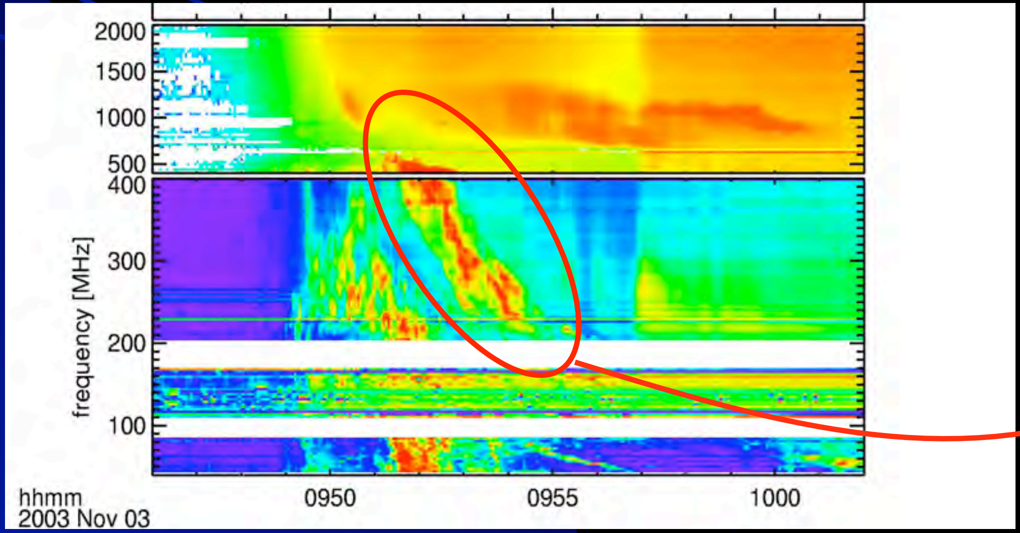
Dauphin et al, (2006)

Mapping coronal shock waves

- Radio emission most direct evidence of coronal shocks
- Occurs with different kinds of other bursts (gyrosynch, plasma) : complex spectra

SXI 09:52:20 UT NRH (432 MHz)

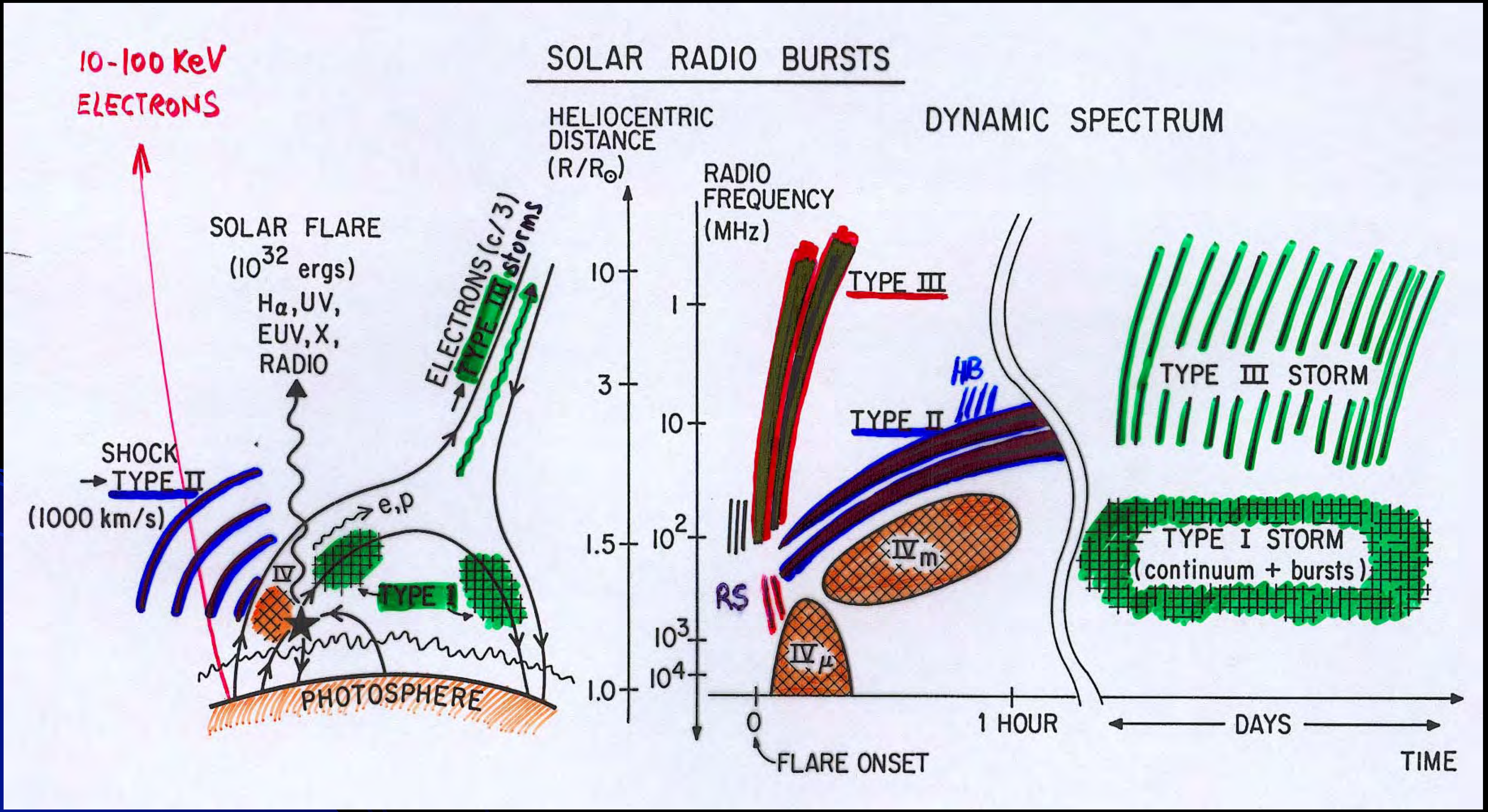


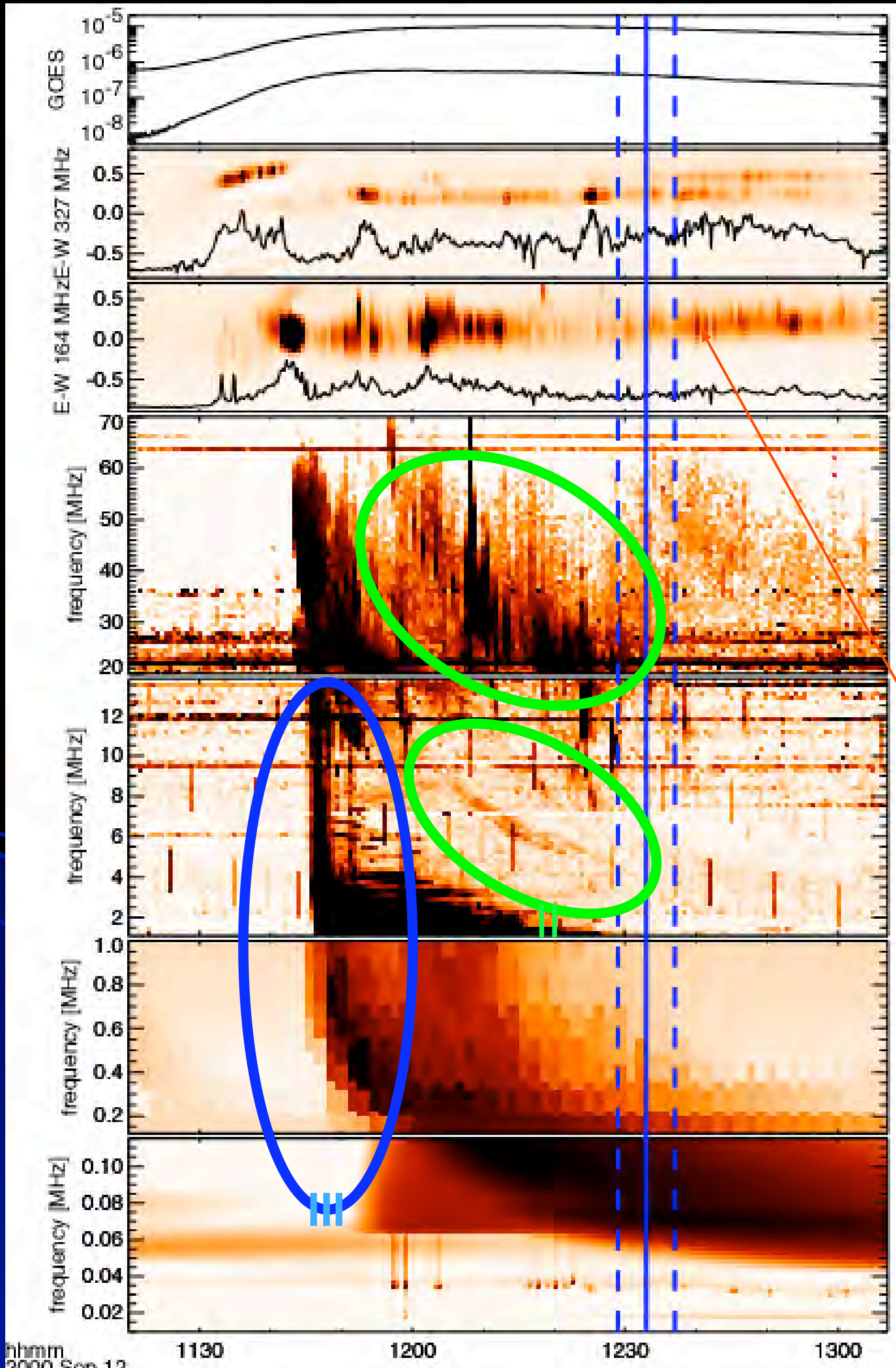


Where do shocks develop ? How are they related with *CME*, where are they located w/r to the white-light signature of a *CME* (front ? flanks ?) ? Piston-driven ? Blast ?

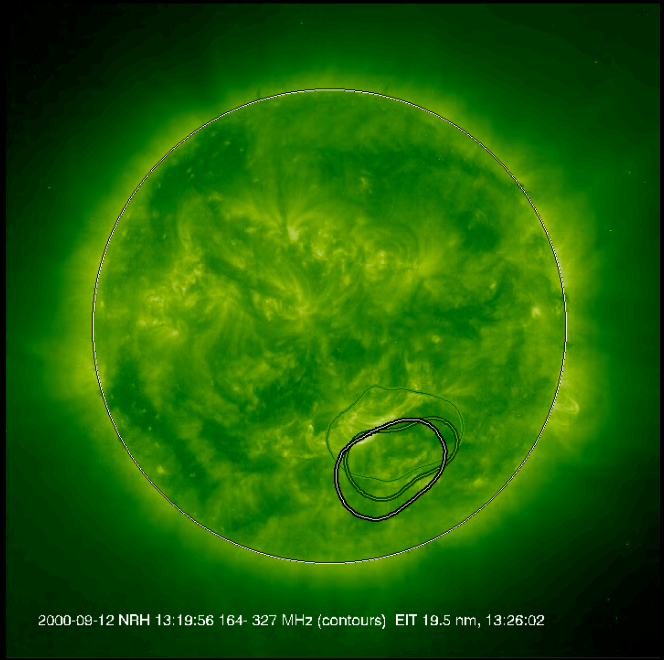
Dauphin et al. 2006 AA

Idealized sketch of a complete radio event





Time-extended e⁻ acceleration in the corona



Filament eruption + post-flare loops; type IV radio emission (long & broadband) above former filament position, at places where flare loops develop (aftermath of CME, current sheet ?)

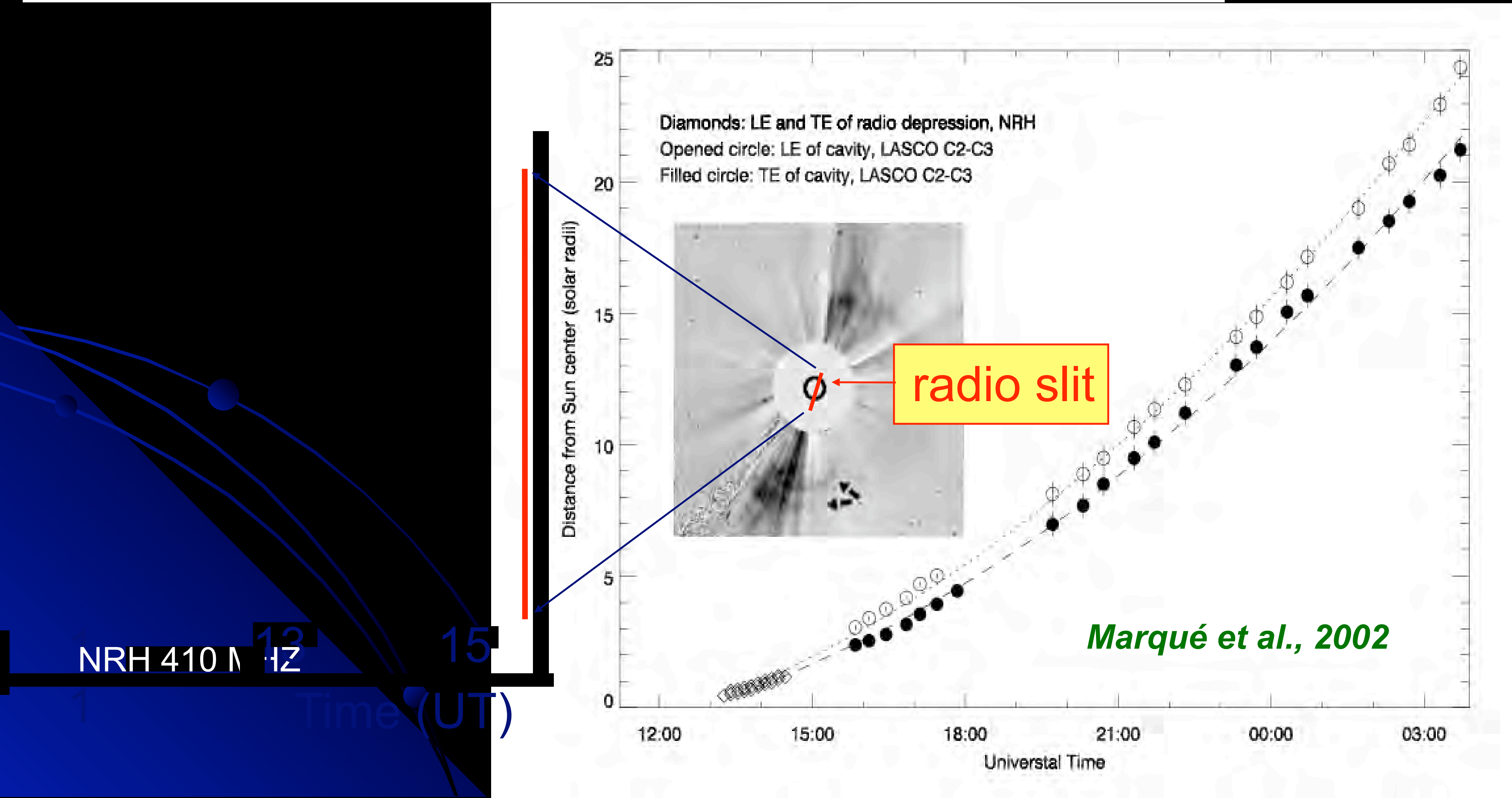
Klein, Krucker, Trottet, Hoang, 2005

Radio signatures of CME's and ICME's

- CMEs are the main drivers of interplanetary and geomagnetic disturbances ⇒ space weather
- Radio observations: signatures of CME development on both the solar disk and corona out to a few radii and with a high cadence

Transient RADIO DEPRESSIONS: filament and percursor to the white light cavity

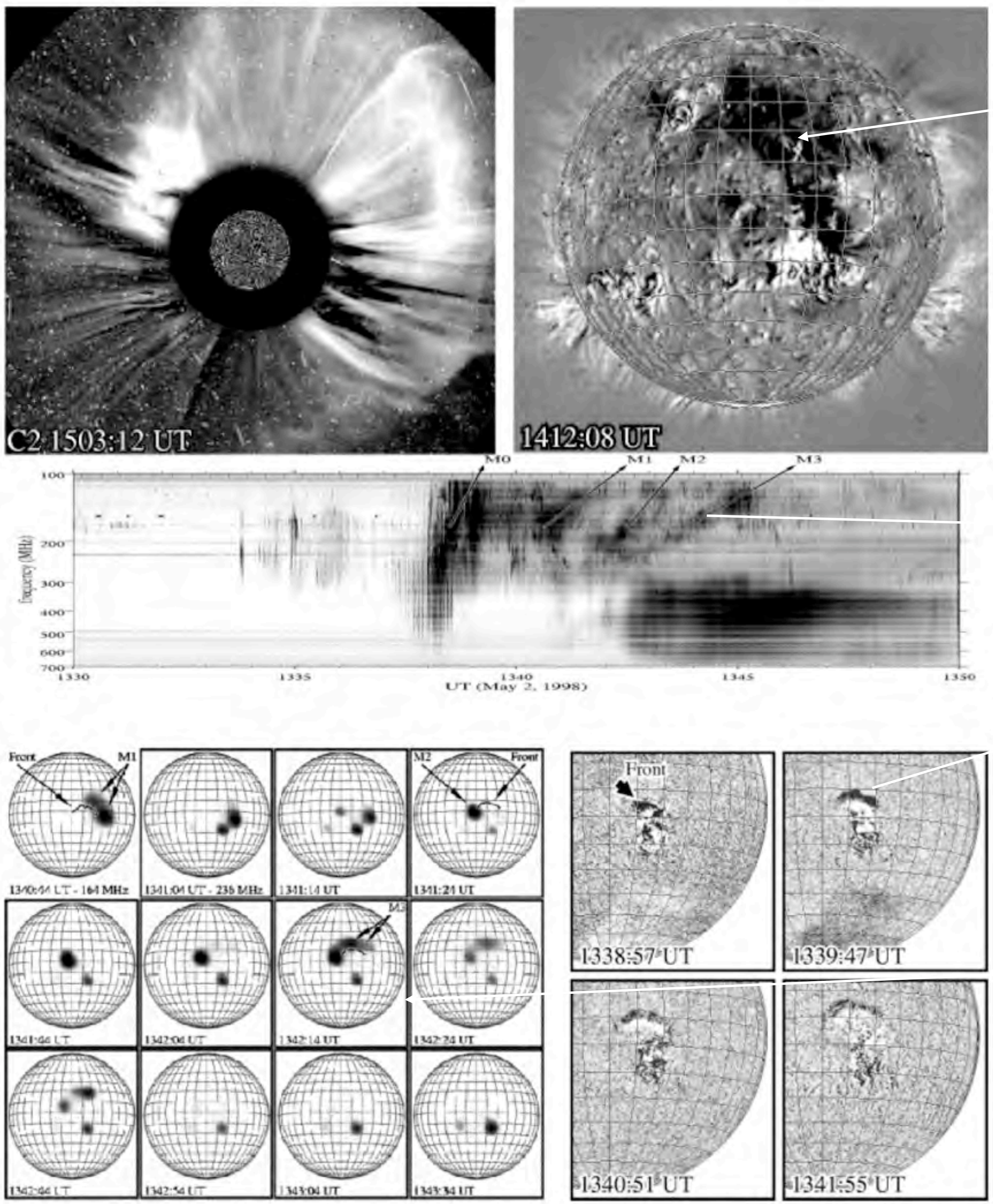
- Continuity between radio depression and CME CAVITY
- Radio: on-disk and limb observations
- Traces the motion at low altitude
- Link between EIT and LASCO



Flare/CME events: lift-off and angular spread in the corona

From Maia et al, 1999

Successive magnetic
Interactions at larger
Distances from the flare site
Corresponding to speeds
$\approx$ 1000 km/s



EIT dimming and halo CME's

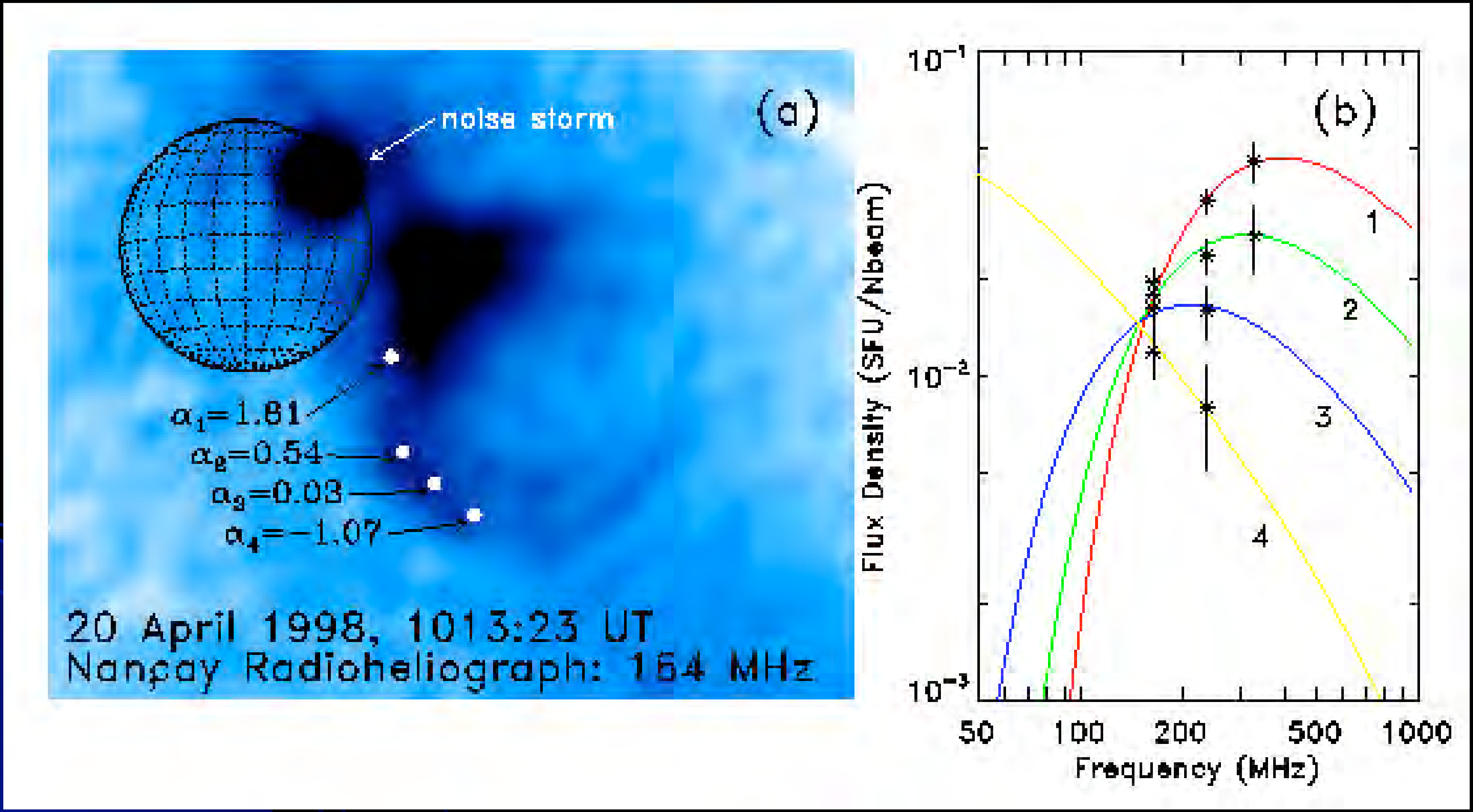
Type II like emissions

Hα Moreton waves

Radio images at 164 and 236 MHz

Pohjolainen et al, 2001

DIRECT RADIO CME IMAGING



Radio loops behind the CME front
Gyrosynchrotron emissions from non thermal electrons

Bastian et al. (2001)

Mapping *CME* loops : relativistic electrons

- Synchrotron radiation from relativistic e^-
- Where / when are they accelerated ?

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

SoHO/LASCO

Radio emissions from the corona and the

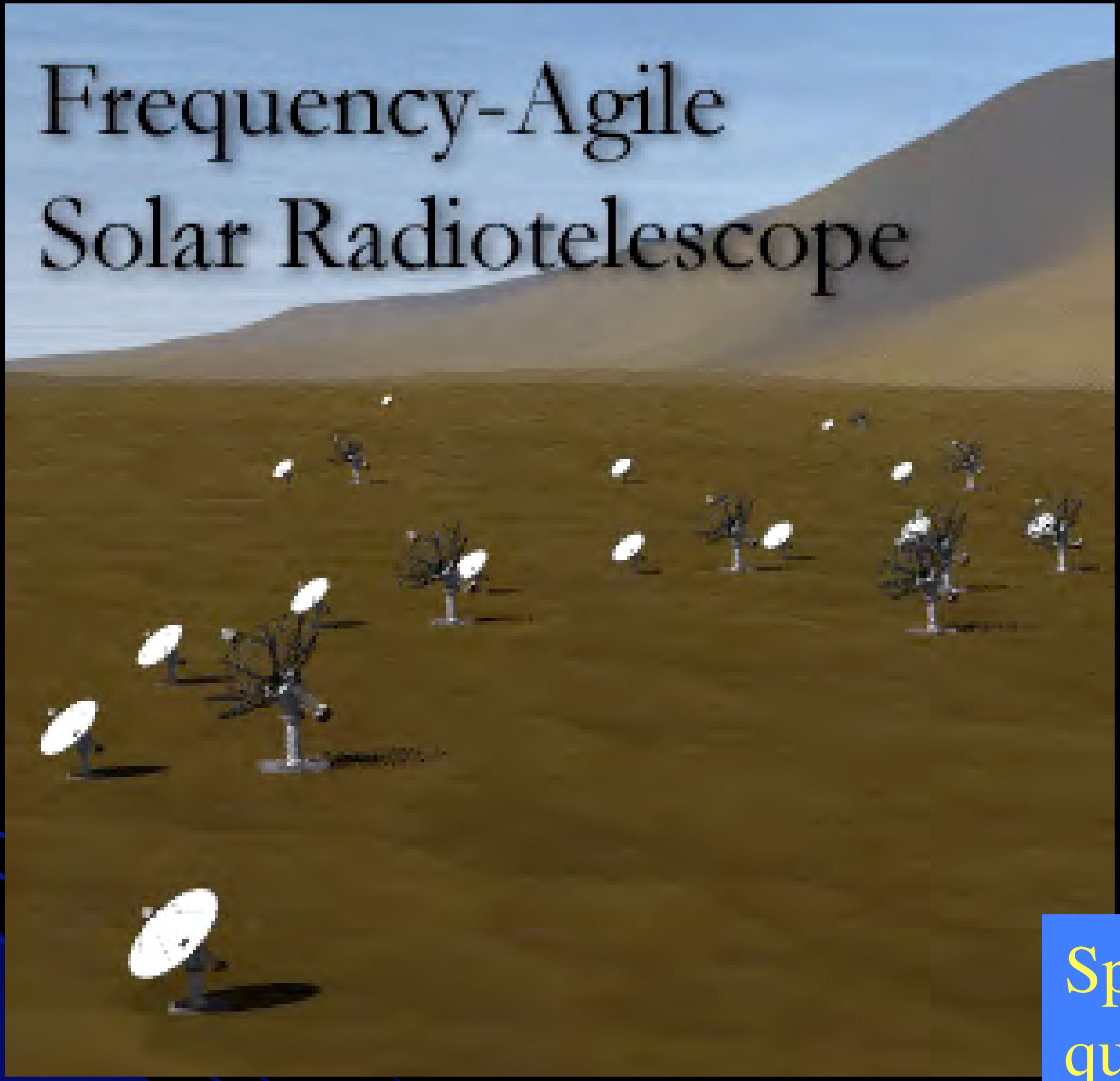
- Radio traces **energetic electrons and phenomena**
- Radio **proves** the existence of a **shock** and provides unique information on its **formation and evolution**
- Radio traces **fast**, **broad** shocks (CMEs, V> 500 km/s)
- Radio can yield the **shock velocity**
- Radio traces the acceleration of **high energy electrons at shock front**
- Radio at best for disturbances **moving towards the observer**

What to do next on ground?

- Towards imaging spectroscopy in the domains already imaged
  FASR (Frequency Agile Solar Radio Telescope) (0.1-30 GHz)
  (20” at 1 GHz)

- Imaging spectroscopy in frequency ranges never imaged
  FASR (Frequency Agile Solar Radio Telescope)
  LOFAR (Low Frequency Array)
  ALMA (Atacama Large Millimeter Array) (several bands 31 GHz-950GHz)
  (0.015”-1.4 ”at 1mm i.e. at 300 GHz)

- Opening new windows of radio observations
  toward submm –far IR domain
  extension of SST to 850 GHz and near IR
  in space : DESIR on SMESE (Chinese/French project) 2 and 8.6 THz
  35 and 150 μ
  Far IR



- Quasi-continuous coverage 30 GHz-100 MHz
- High time resolution (<1 s)
- Firsts :
  - mapping of the coronal magnetic field in AR
  - Localisation of bursts in the (0.5-1.5) GHz range, acceleration region during flares

Spectral imaging of the quiet, active & eruptive Sun, from the chromosphere to $1\ R_\odot$

FASR FREQUENCY-AGILE SOLAR RADIOTELESCOPE

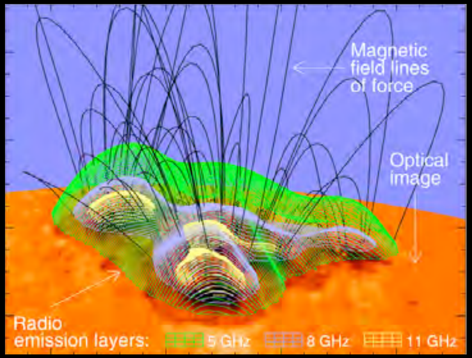
FASR FREQUENCY-AGILE SOLAR RADIOTELESCOPE

SPECTRO-IMAGEUR RADIO large bande dédié solaire

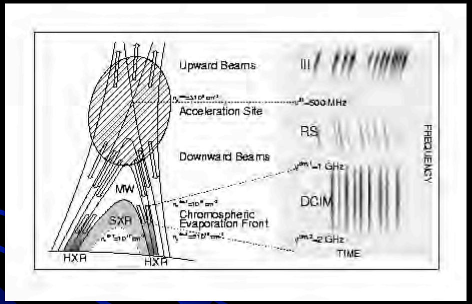
largeGamme de fréquence	~0.1 – 30 GHz
Résolution spectrale	1%, 0.1 – 3 GHz 3%, 3 – 30 GHz
Résolution temporelle	<0.1 s, 0.1 – 3 GHz <1 s, 0.3 – 30 GHz
Nombre d'antennes	~100 (5000 bases)
Taille des antennes	D = 3 – 5 m
Polarisation	~0.1 - 3 GHz, IV/QU 3 – 30 GHz, IV/QU
Résolution angulaire	$20/\nu_{GHz}$ arcsec
Champ de vue	$19/(D\nu_{GHz})$ deg

Why?

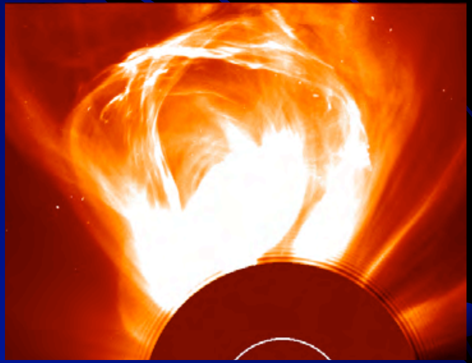
FASR Key Science



- Nature & Evolution of Coronal Magnetic Fields
  - Measurement of coronal magnetic fields
  - Temporal & spatial evolution of fields
  - Role of electric currents in corona
  - Coronal seismology



- Physics of Flares
  - Energy release
  - Plasma heating
  - Electron acceleration and transport
  - Origin of SEPs



- Drivers of Space Weather
  - Birth & acceleration of CMEs
  - Prominence eruptions
  - Origin of SEPs
  - Fast solar wind streams

FASR Specifications

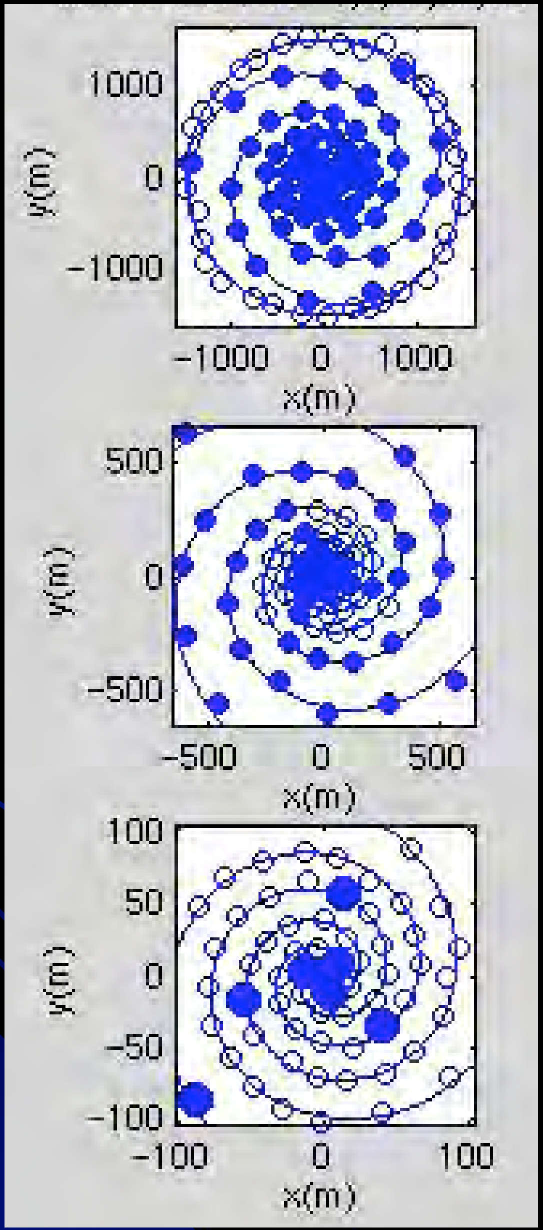
FASR A: ~3-30 GHz

FASR B: ~0.3-3 GHz

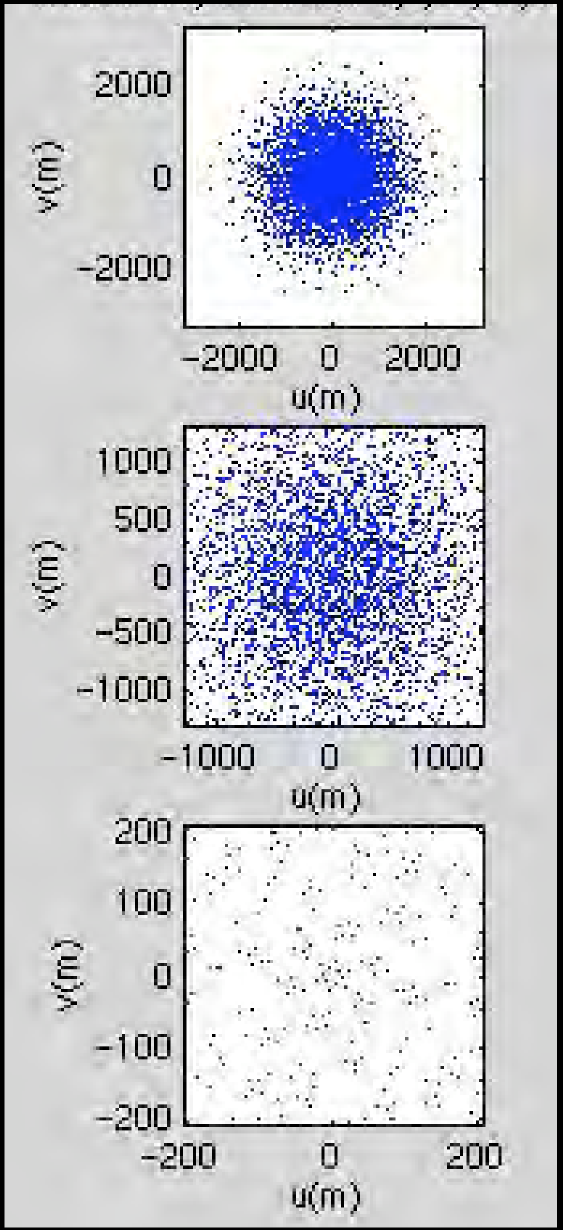
FASR C: ~30-300 MHz

Frequency range	30 MHz - 30 GHz
Frequency resolution	A, C: 1% B: 0.1%,
Time resolution	A, C: 100 ms B: 10 ms
Number antennas	A: ~100 (4950 baselines) B: ~80 (3160) C: ~60 (1770)
Size antennas	A: 2 m B: 6 m C: LPDA or similar
Polarization	Stokes IV(QU)
Angular resolution	$20/\nu_9$ arcsec
Footprint	~6 km
Field of View	>0.5 deg

Log spiral



1000
0
-1000
y(m)
-1000 0 1000
x(m)
500
0
-500
y(m)
-500 0 500
x(m)
100
50
0
-50
-100
y(m)
-100 0 100
x(m)



2000
0
-2000
v(m)
-2000 0 2000
u(m)
1000
500
0
-500
-1000
v(m)
-1000 0 1000
u(m)
200
100
0
-100
-200
v(m)
-200 0 200
u(m)

LOFAR:
Low Frequency Array

2000-1 : LOFAR project
ASTRON (NL), NRL + MIT/Haystack (USA)
• Interferometer / Phased array : core + stations,
106 m2, ∅ > 400 km

• Wide-field (several °) high-resolution (1-10")
imagery / multi-beam (8)
• Multi-frequency (10-240 MHz),
Not dedicated to solar physics

2004-5: LOFAR funded in NL, with NL site (Astron
Dwingeloo ,H.Falcke
à reorganization of LOFAR consortium,
descope (A~0.2×106 m2, ∅ ~100 km)

Operations start 2007
Full operation 2008?
European expansion :
- remote stations
- science centers
- funding (FP7…)
- enhanced scientific collaboration…
Associate members of LOFAR consortium :
Sweden (LOIS),Germany (GLOW) … UK ? France ?
Italy ? Poland ?

What can *LOFAR* bring to solar studies ?

LOFAR can be a very useful tool for studying transient proces-ses in the high corona related with flares and *CME*, provided :

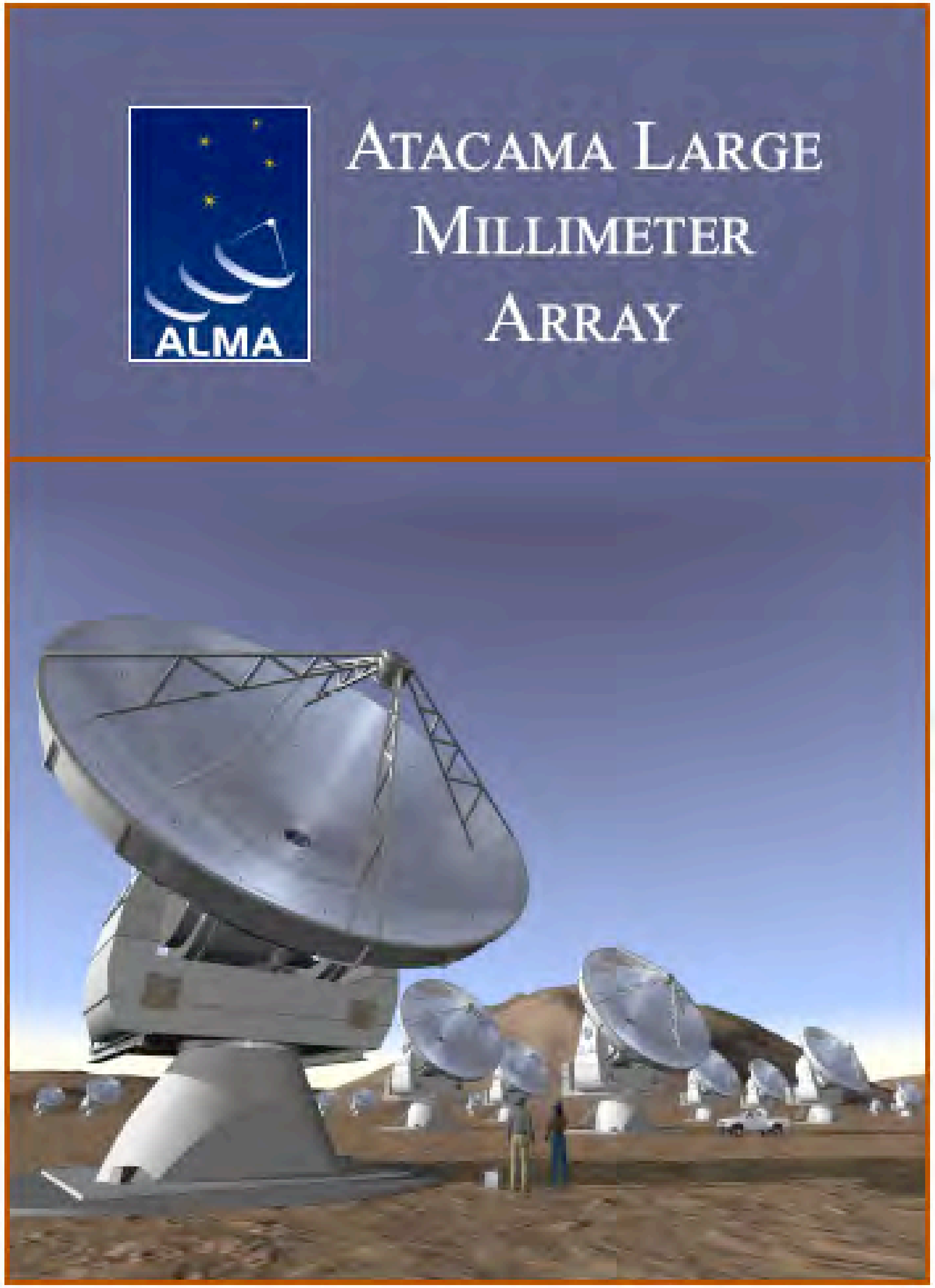
- Dedicated solar mode / long term observations
- Mapping with high dynamic range ($>10^4$)
- Multi-frequency mapping with sub-second cadence
- Ionospheric corrections including changes during flares

LOFAR will need complementary observations:

- Simultaneous spectral coverage (whole Sun, dm-hm-λ)
- Radio imaging at higher frequencies (relationship high corona - active region / primary flare signatures / *CME* origin)
- Coronographic observations (*STEREO* …)

Limitations to solar radio imaging at m-λ

- Spatial resolution limited by propagation effects :
  - Corona : scattering $\Rightarrow$ broadening
    - Modelling : apparent source sizes ~ 5′ at 100 MHz (Bastian)
    - Observation : no structure <60″ (236 MHz, NRH - GMRT)
    - Baselines < 10 km needed for solar observations
  - Ionosphere : (unpredictable) gravity waves, esp. in winter, ray deviation $\sim\nu^{-2}$
    - Apparent shifts of source centroids
    - Image distorsion, possible destruction (focussing)
    - Variable due to flare-produced EUV & XR (large flares)
- Imaging at ν<60 (?) MHz may be difficult



Specifications

		Large Array	Compact Array
Array	Number of Antennas	up to 64	12 (7 m) + 4 (12 m)
	Total Collecting Area	up to 7240 m^2	460 + 450 m^2
	Angular Resolution	0.02" (λ /1 mm)(10 km/baseline)	5.7" (λ /1 mm)
	Continuous Zoom	150 - 18500 m	
Antennas	Diameter	12 m	7 m, 12 m
	Surface Precision	<25 μm	<20μm, <25 μm
	Offset Pointing	<0.6"	<0.6"
Correlator	Baselines	2016	120
	Bandwidth	16 GHz per baseline	16 GHz per baseline
	Spectral Channels	4096	4096

Receiver Bands

Band Number	Frequency Range (GHz)	Wavelength (mm)	Instantaneous Bandwidth (GHz)
1	31.3 - 45.0	6.7 - 9.6	1 × 8
2	67 - 90	3.3 - 4.5	1 × 8
3	84 - 116	2.6 - 3.6	2 × 4
4	125 - 163	1.8 - 2.4	2 × 4
5	163 - 211	1.4 - 1.8	2 × 4
6	211 - 275	1.1 - 1.4	1 × 8
7	275 - 373	0.8 - 1.1	2 × 4
8	385 - 500	0.6 - 0.8	2 × 8
9	602 - 720	0.4 - 0.5	2 × 8
10	787 - 950	0.3 - 0.4	2 × 8

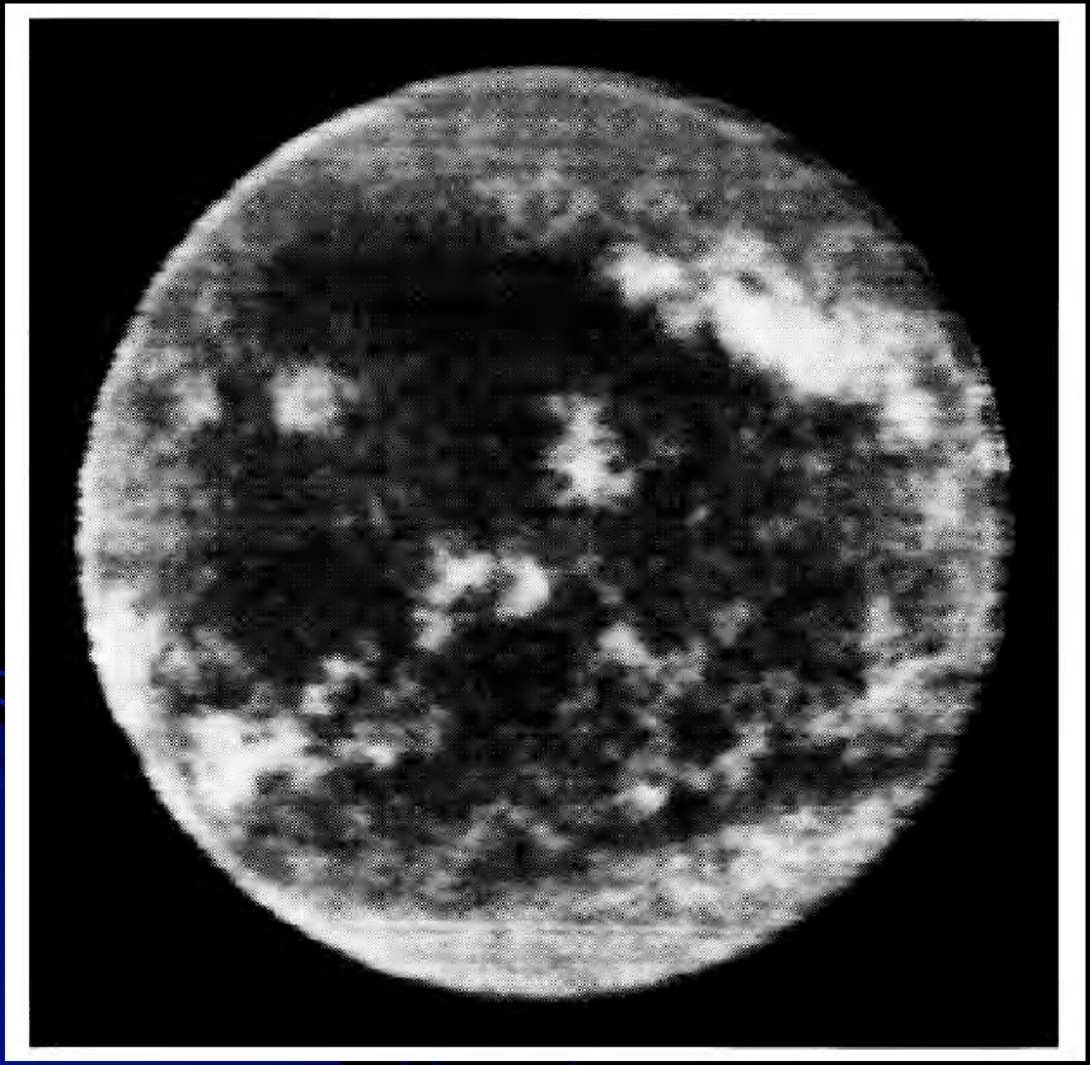
(Bands in bold font will be available at first light)

Not solar dedicated

Limited field of view (21’’ at 1mm!)

but new solar radio
Physics!!

ALMA and the Sun!



- Structure and dynamics of the solar chromosphere (oscillations)

Flux density ~ T

-Formation and disruption of Filaments and prominences

-Flares (need to be very lucky…)

-Detection and exploitation of radio recombination lines…

BUT needs
Calibration of the antenna when looking at the sun
Calibration of the time variable contribution of the sky

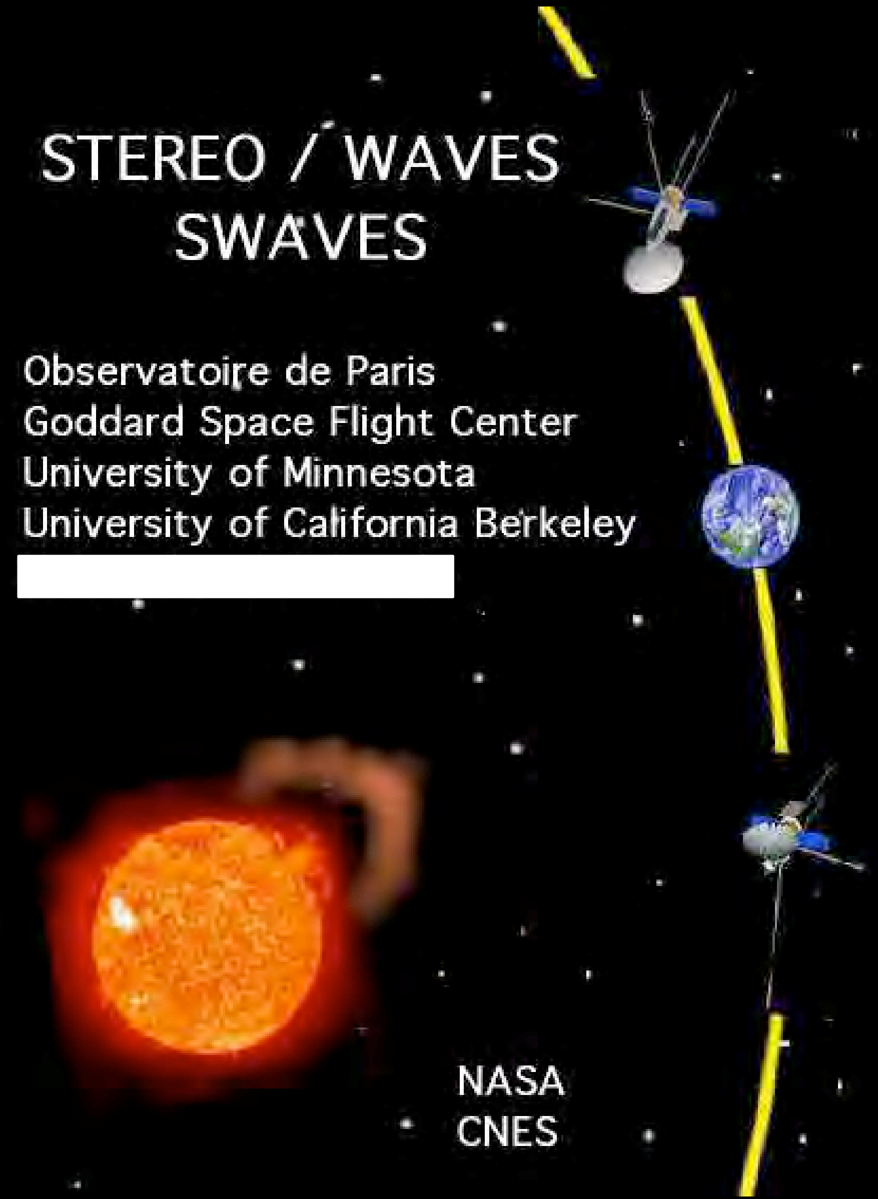
Image at 0.8mm (Caltech Submillimeter Observatory)
Bastian et al, 1993

Requirements for solar radio imaging

- A highly variable and unpredictable radio source :
  - VLA, NRH+GMRT : limited usefulness of campaigns
  - « alert » modes preclude studies of impulsive bursts and initial phases of flare activity (but : data buffer ?)
  - ⇒ Dedicated long-term observations at high time resolution
  - ⇒ The best being dedicated interferometers
- Spectrum : no lines, but structured features covering wide frequency range
  - ⇒ Imaging over wide frequency range
  - ⇒ The best being imaging spectroscopy

What to do next in space:

- Track and probe CME driven shocks from the corona to 1 AU
- Map the structure of radio shocks and of flare electron beams
- Probe density and structure of the IP medium before and after a CME
- Understand radio emission and beam pattern of radio bursts
- Measure electron density and temperature of filament material in clouds



http://www-lep.gsfc.nasa.gov/swaves/swaves.html