Solar flares at submm wavelengths

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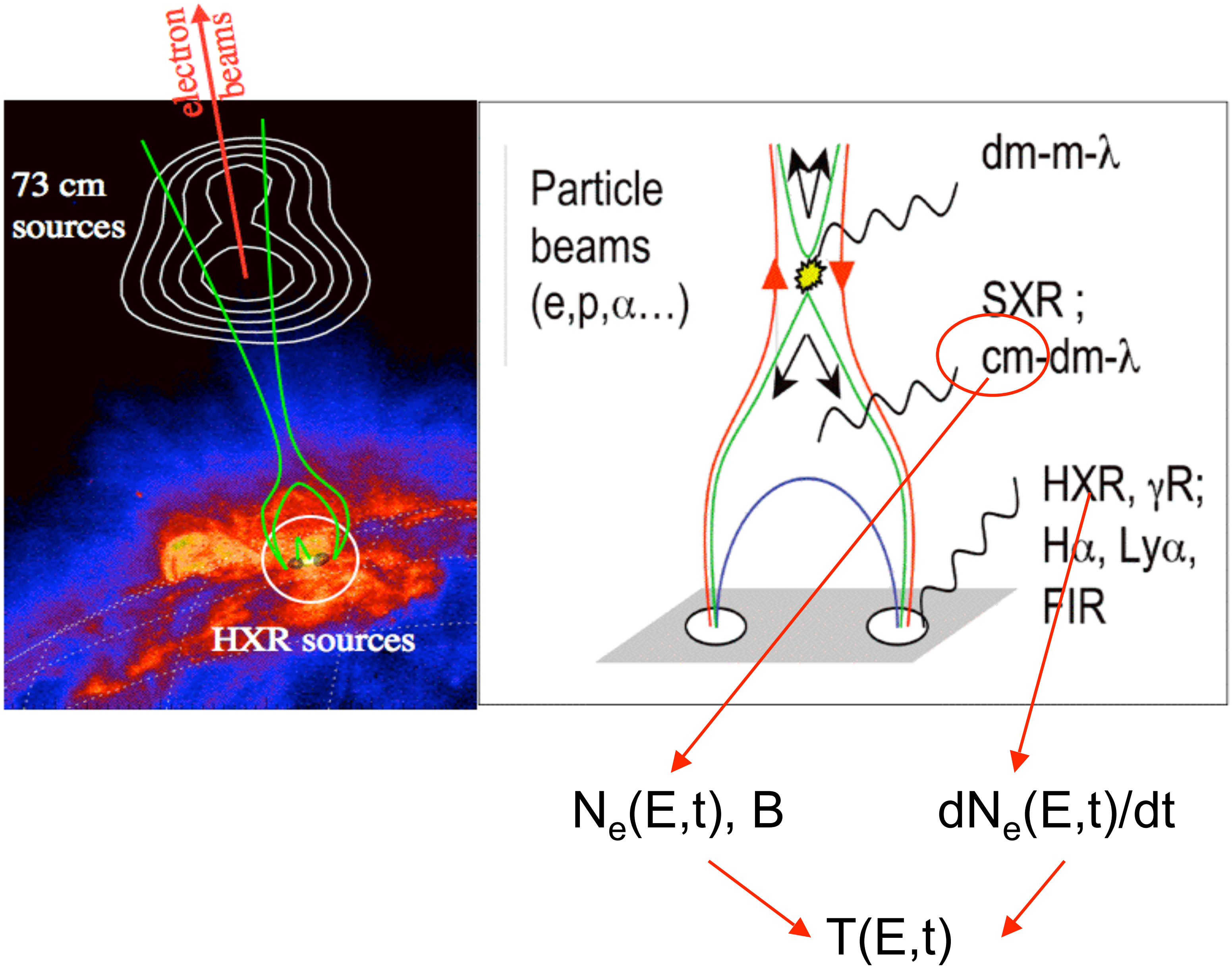
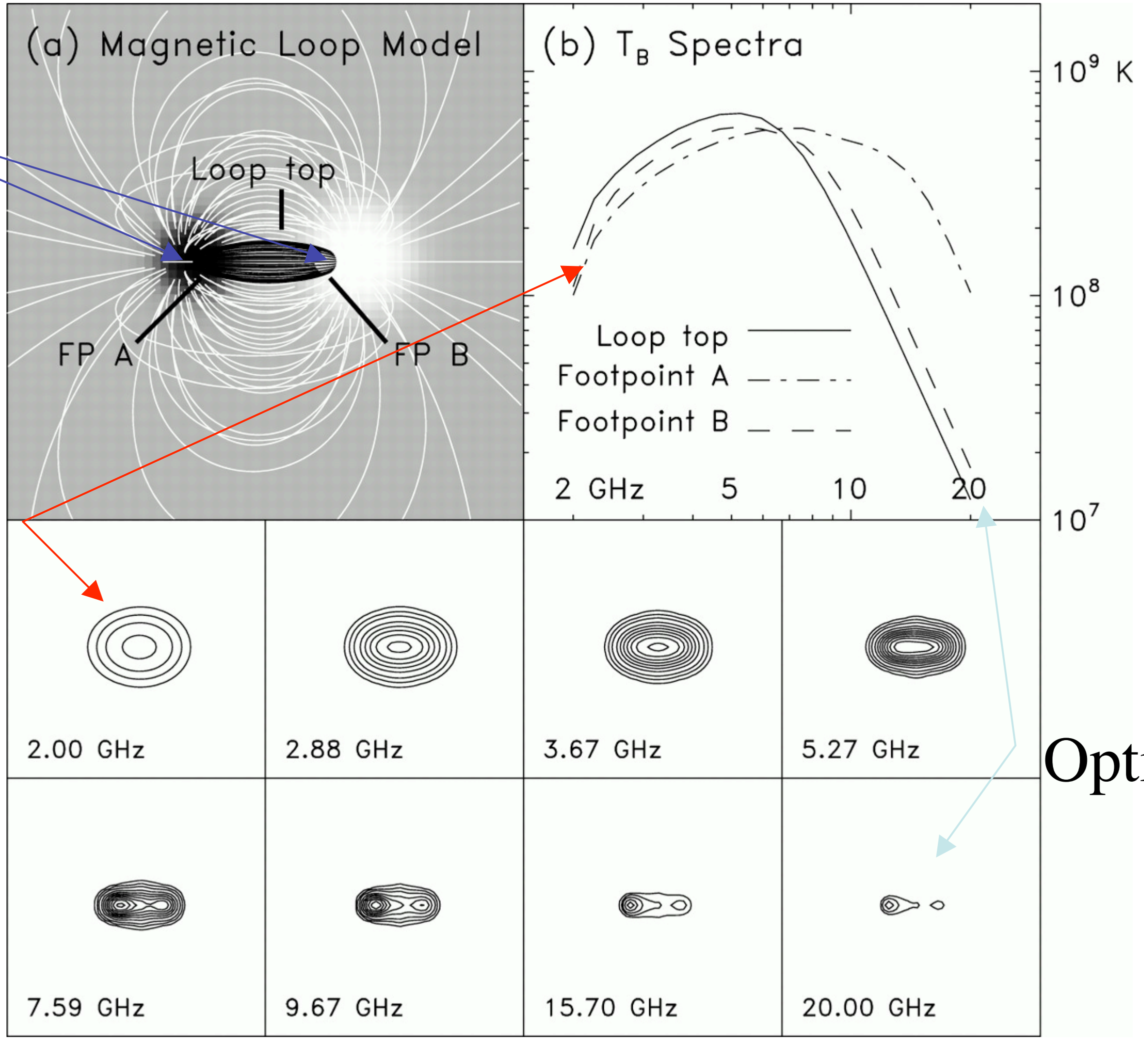
- Simple context for acceleration during flares
- Observations below and above 100 GHz
- Thermal emission
- (gyro)synchrotron emission from e^- and e^+


electron beams
73 cm sources
HXR sources
Particle beams (e,p,α…)
dm-m-λ
SXR ;
cm-dm-λ
HXR, γR;
Hα, Lyα,
FIR
$N_e(E,t)$, B
$dN_e(E,t)/dt$
T(E,t)

The Framework

HXR

Optically thick: loop top



Bastian, Benz, Gary 1998, ARAA

Optically thin: foot points

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

Radio Observations

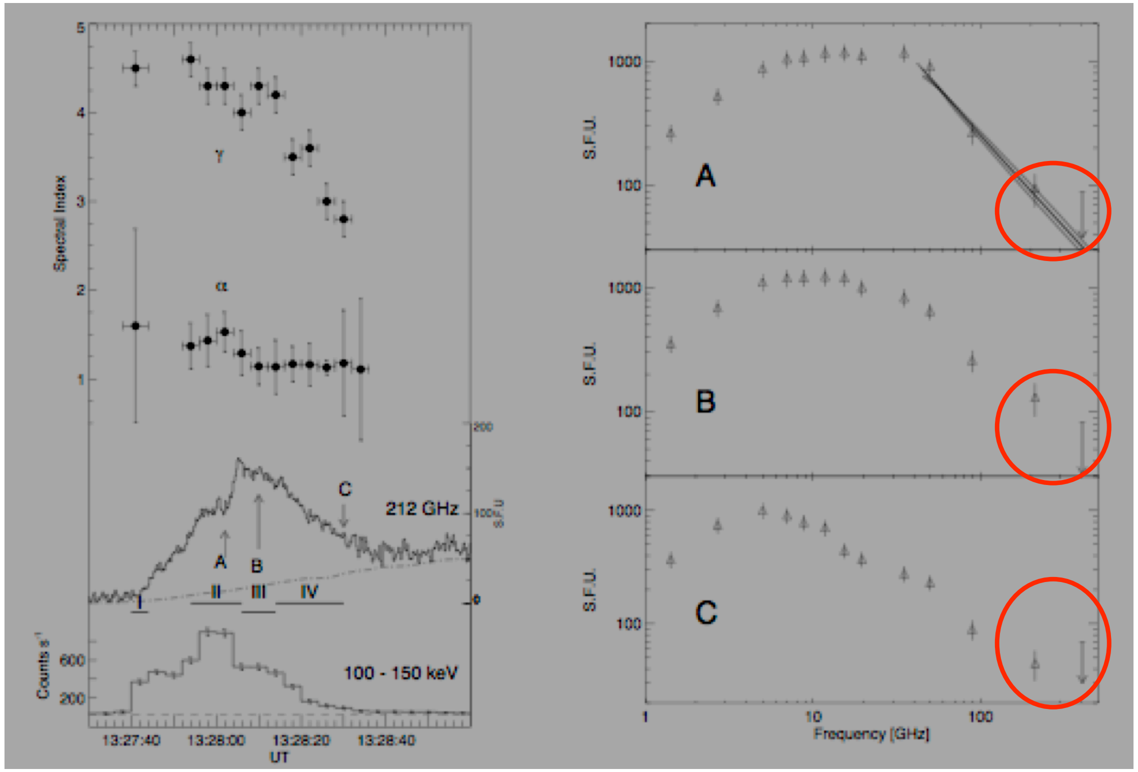
Before 2000: observations below 100 GHz

- Gyrosynchrotron radiation from flare accelerated electrons to mildly-relativistic energies
- Thermal emission

Since 2000: observations in the 200-400 GHz range

- Solar Submillimeter Telescope (SST) 212 & 405 GHz at El Leoncito, Argentina (Kaufmann et al. 2000): multi-beam system at 212 GHz: information on the location and size of the emitting region
- **K**öln **O**bservatory for **S**ubmillimer and **M**illimeter **A**stronomy: 230 & 345 GHz (Lüthi et al. 2004a)
- **BE**rnese **M**ultibeam **RA**diometer for **K**osma: multibeam at 210 GHz (Lüthi et al. 2004b)

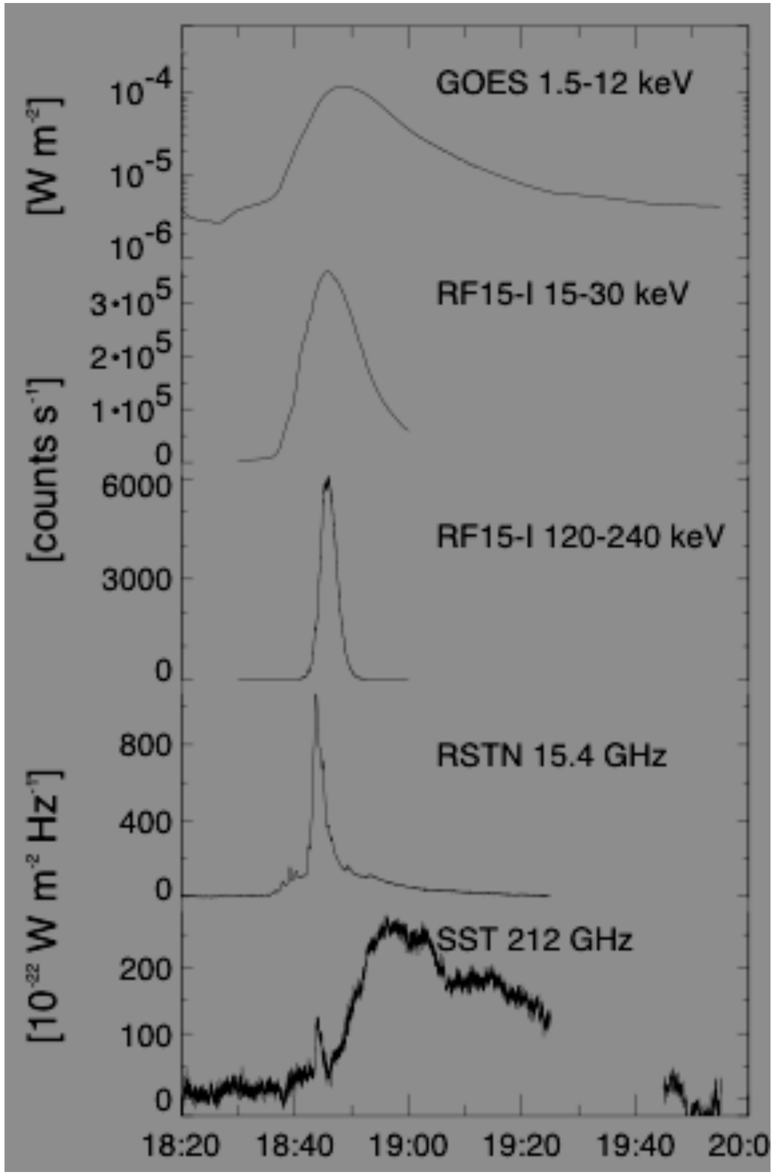
Synchrotron emission at $\lambda \leq 1$ mm (SST > 2000)

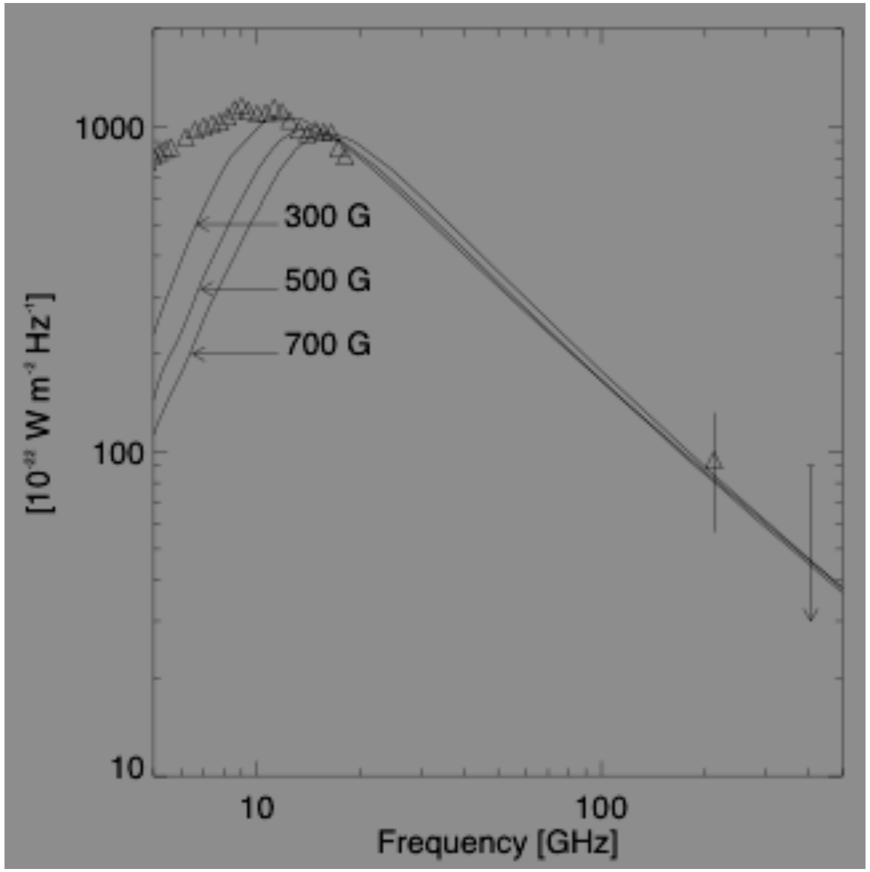


Giménez de Castro, Trottet, Kaufmann et al. 2009

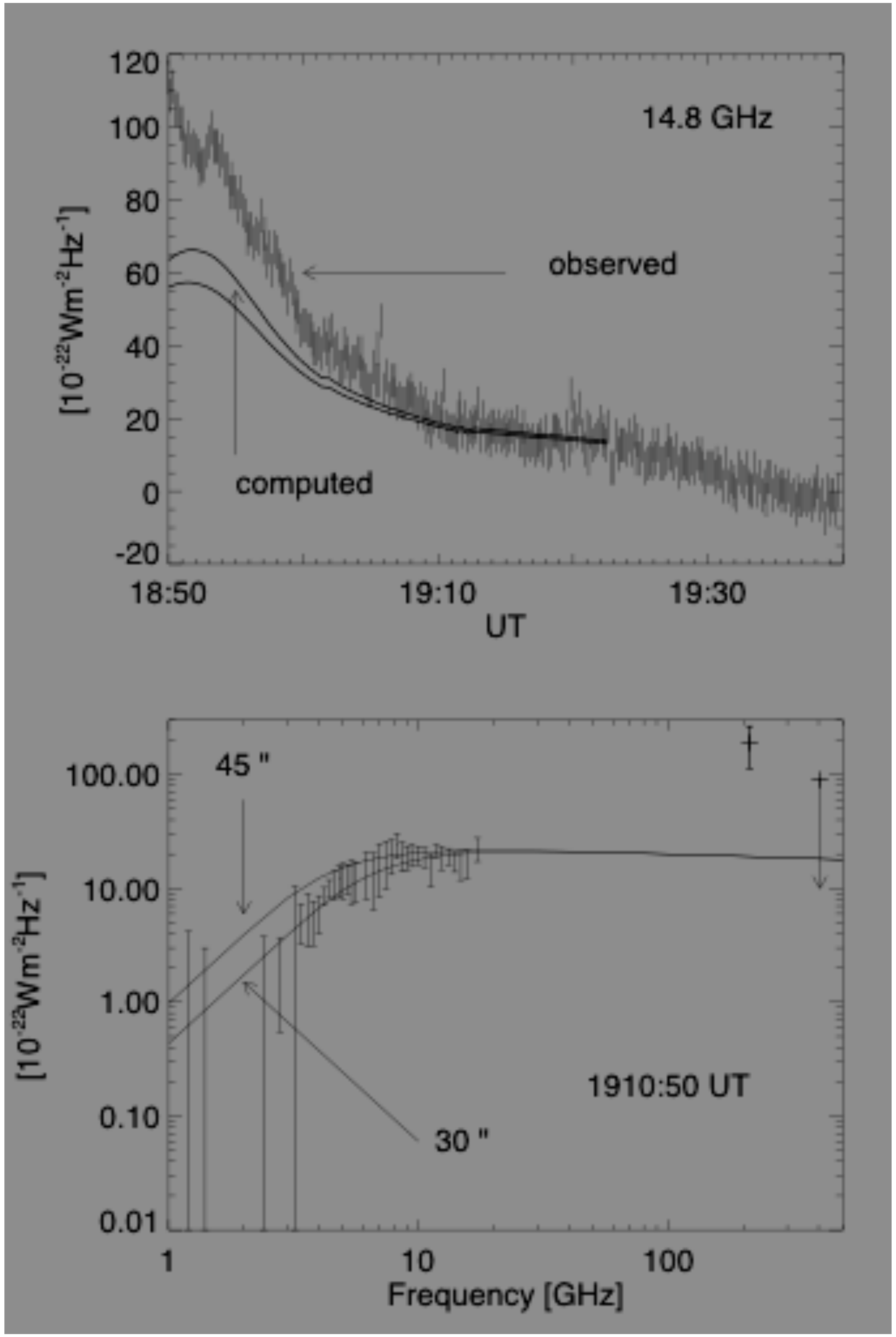
- X & cm-λ: typical of mw impulsive burst
- 212 GHz (SST):
- high frequency part of synchrotron spectrum;
- high energy part of e^- spectrum
- $\gamma_L^2 \approx \nu/\nu_{ce} \Rightarrow$ higher observing frequency $\Leftrightarrow$ greater energy of radiating e^-
- Radio diagnostics of relativistic e^- more sensitive than current X/γ diagnostics

22 mars 2002





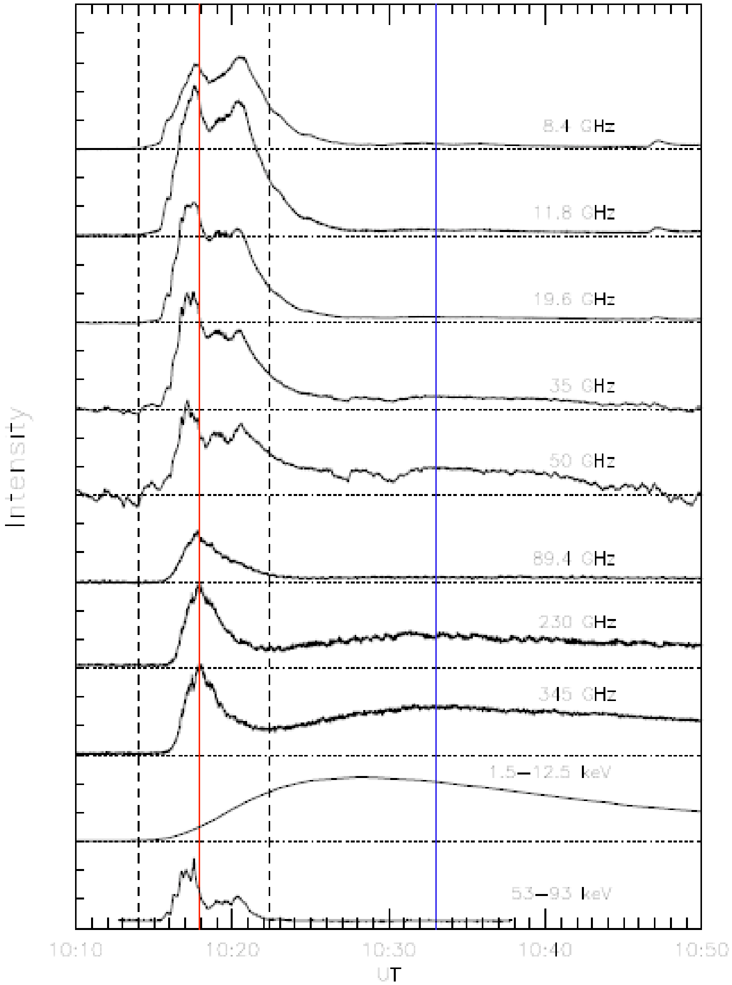
Trottet et al. 2002

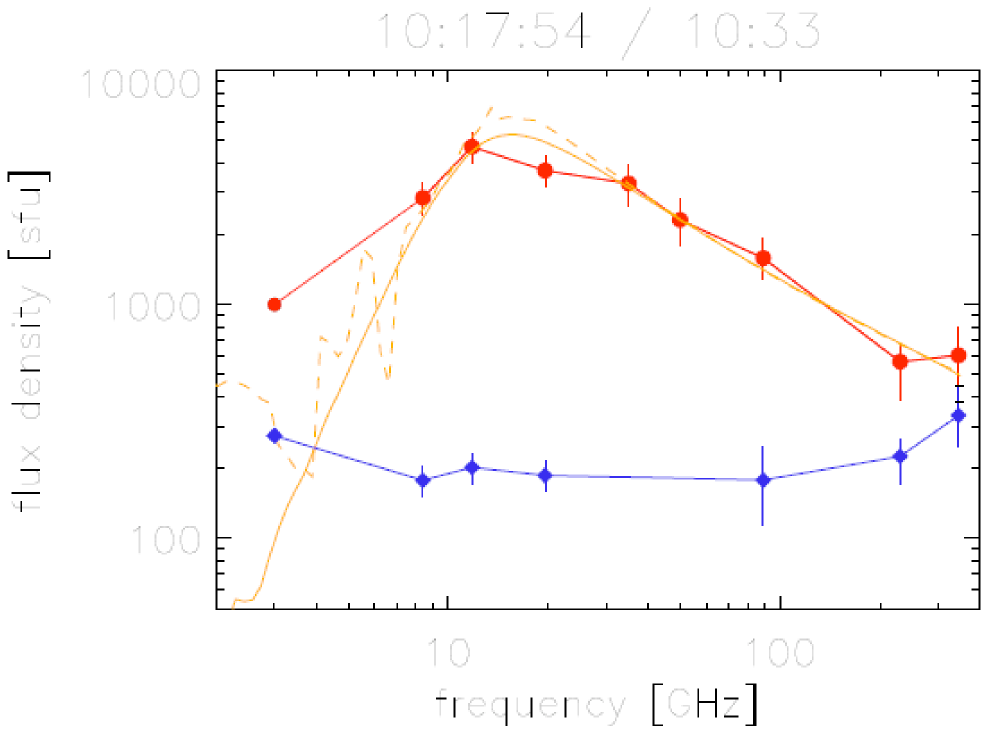


2002 March 22

Trottet et al. 2002

12.04.2001: First Observation of a Solar Flare in the Submm-range with KOSMA





Astronomy & Astrophysics, 415, 1123-1132, March 2004

2003 Nov 4

New spectral component

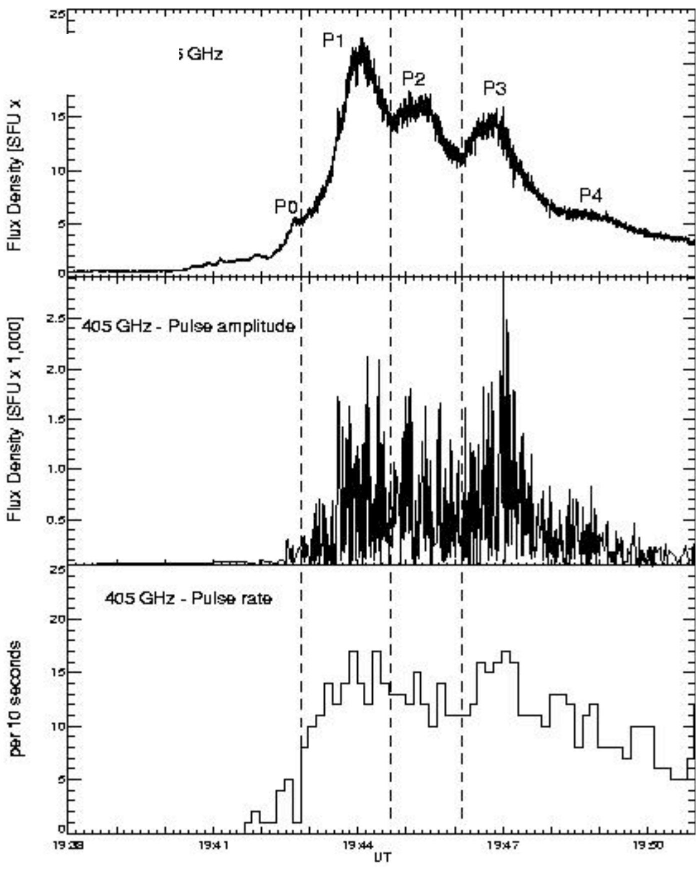


Figure 4

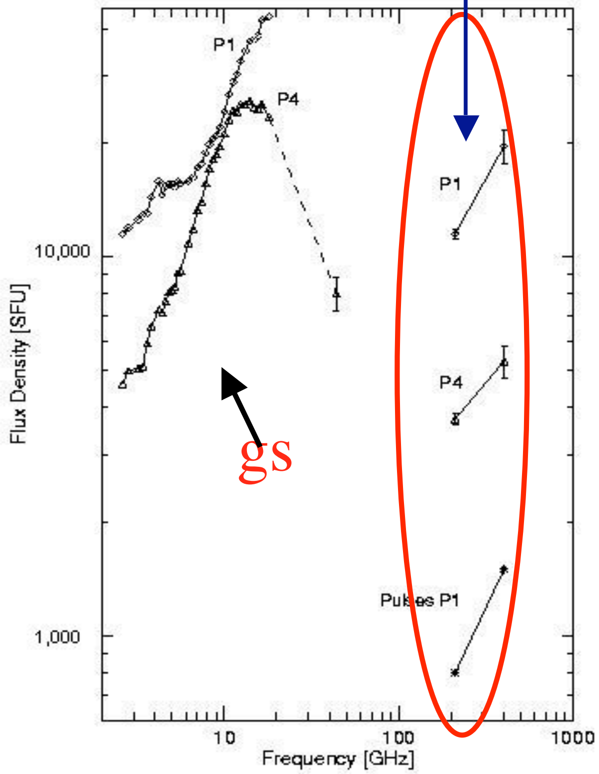
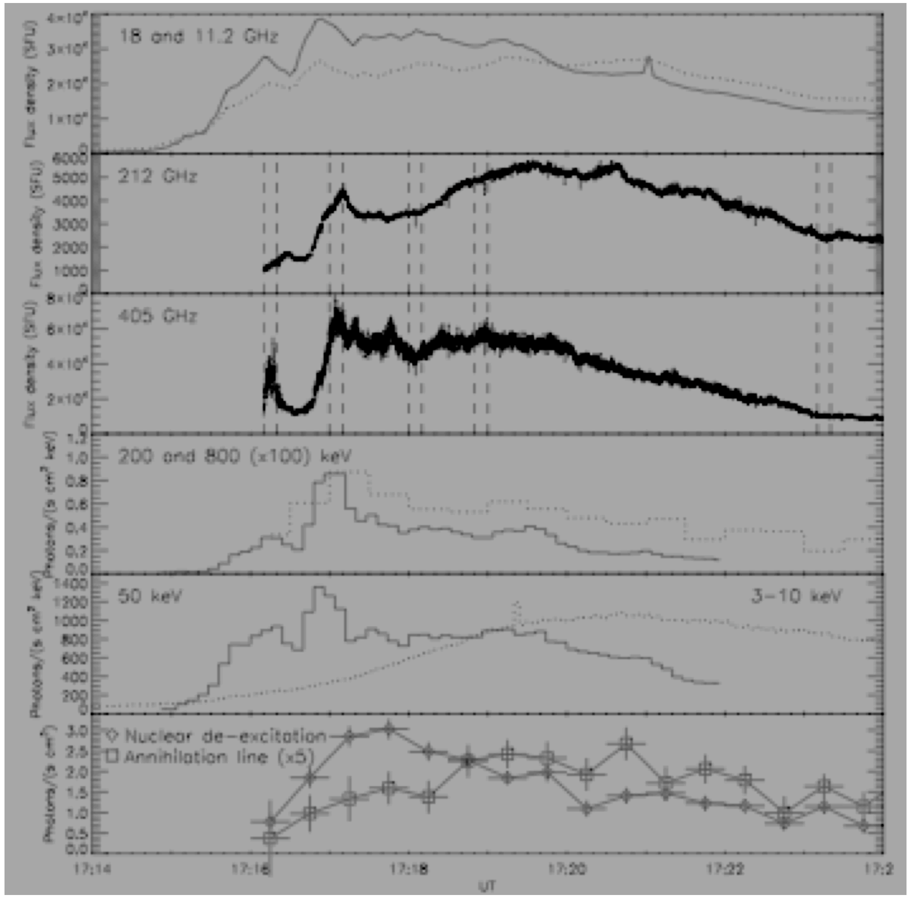


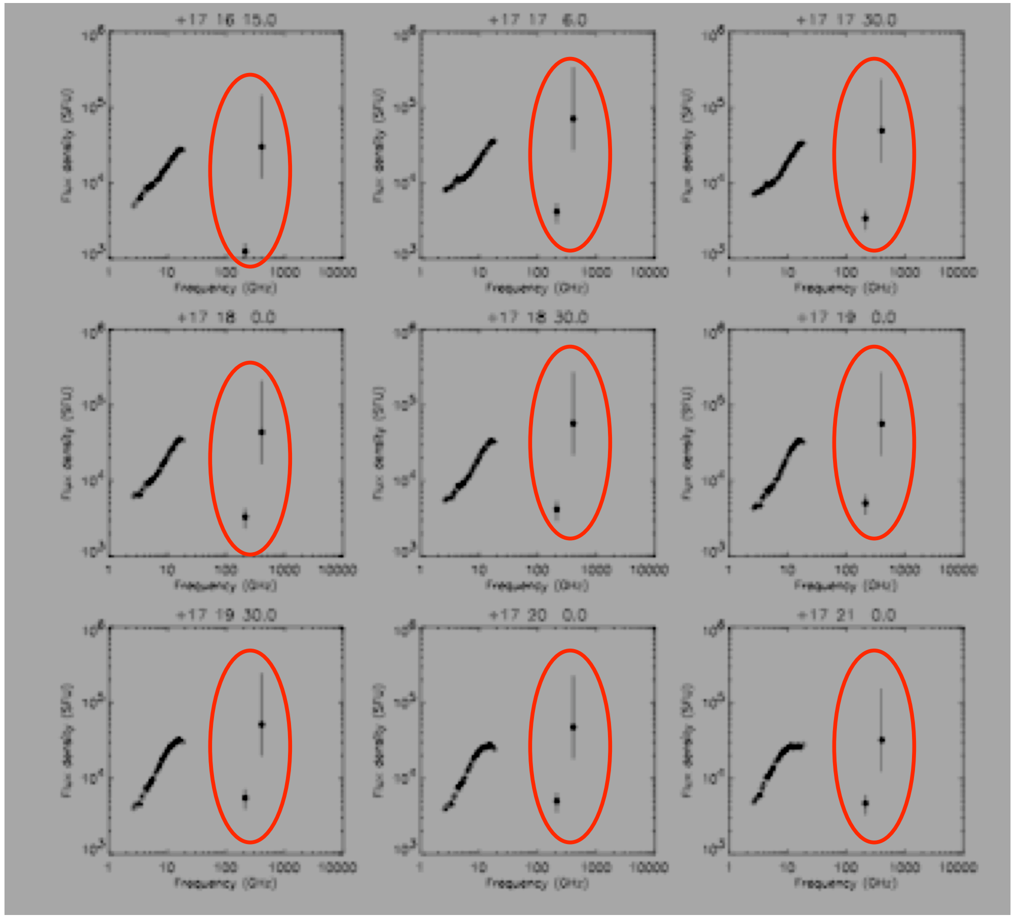
Figure 3

Flux density increases with ν in the sub-THz region

Kaufmann Raulin, de Castro et al. 2004

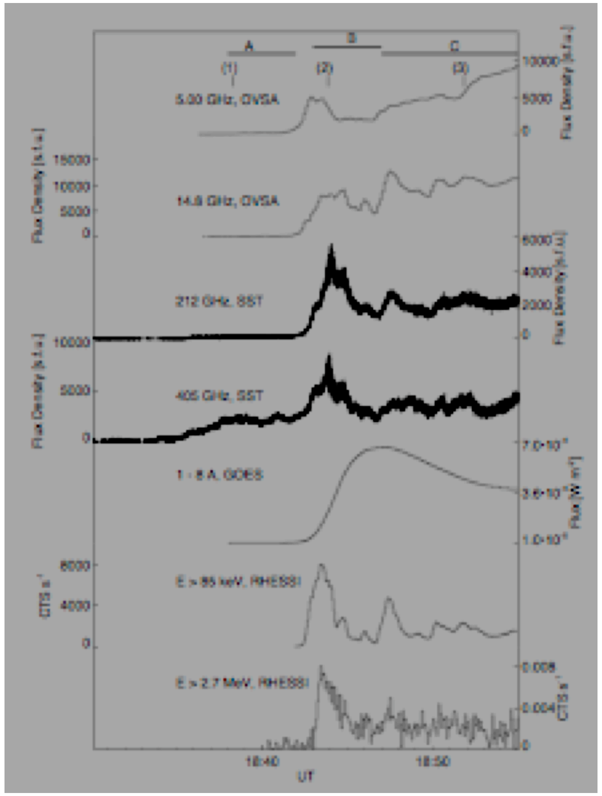
2003 Nov 2

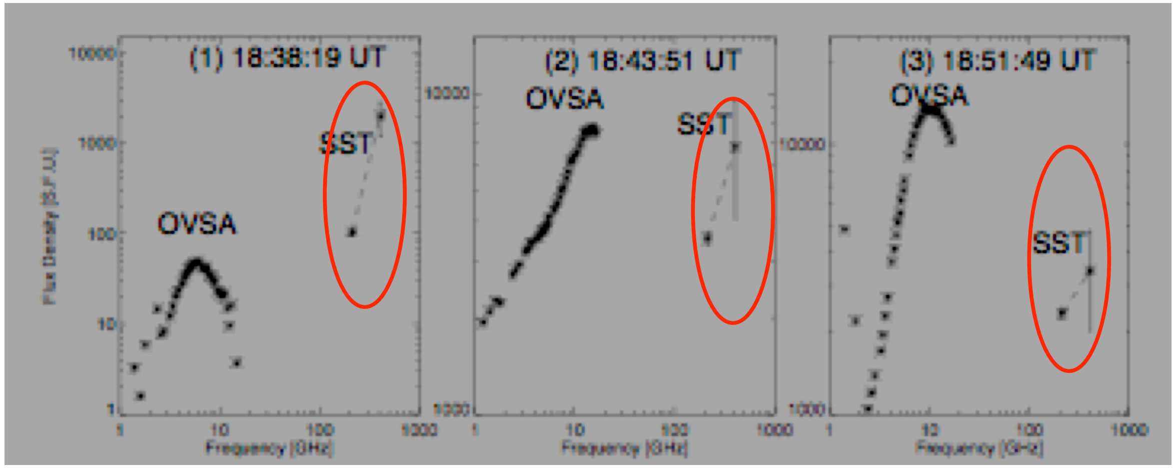




Silva, Share, Murphy et al. 2007

6 déc 2006





Kaufmann, Trottet, de Castro et al. 2009

Modeling of the sub-THz spectrum

- Optically thick free-free emission (thermal)
- Synchrotron emission from electrons (non-thermal)
- Synchrotron emission from positrons (non-thermal)
- Other mechanisms: See Eduard

Observations

	10/28/03 Lüthi et al. 2004	11/02/03 Silva et al. 2007	11/04/03 Kaufmann et al.2004	12/06/06 Kaufmann et al.2009
212/210 GHz flux density (sfu)	10^4	$4.5\ 10^3$	10^4	$3.8\ 10^3$
405 GHz flux density (sfu)		$7\ 10^4$	$2\ 10^4$	$7\ 10^3$
T_{max} * ($\times 10^6$ °K)	25	26	> 32	25
EM_{max} * ($\times 10^{49}$ cm^{-3})	81	35	> 82	30

* From GOES: EM < 10^{51} cm^{-3}, T ~ 2-3 10^7 K

Free-free thermal emission

Ambient medium

- Electronic density: N_e
- Temperature: T

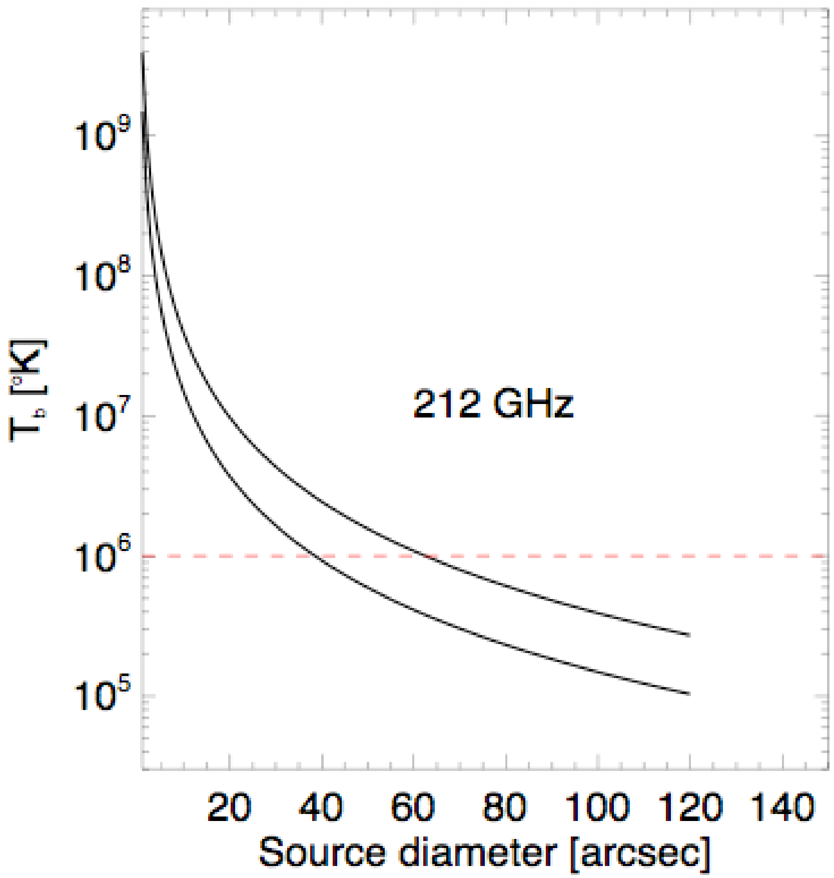
Radio emitting region

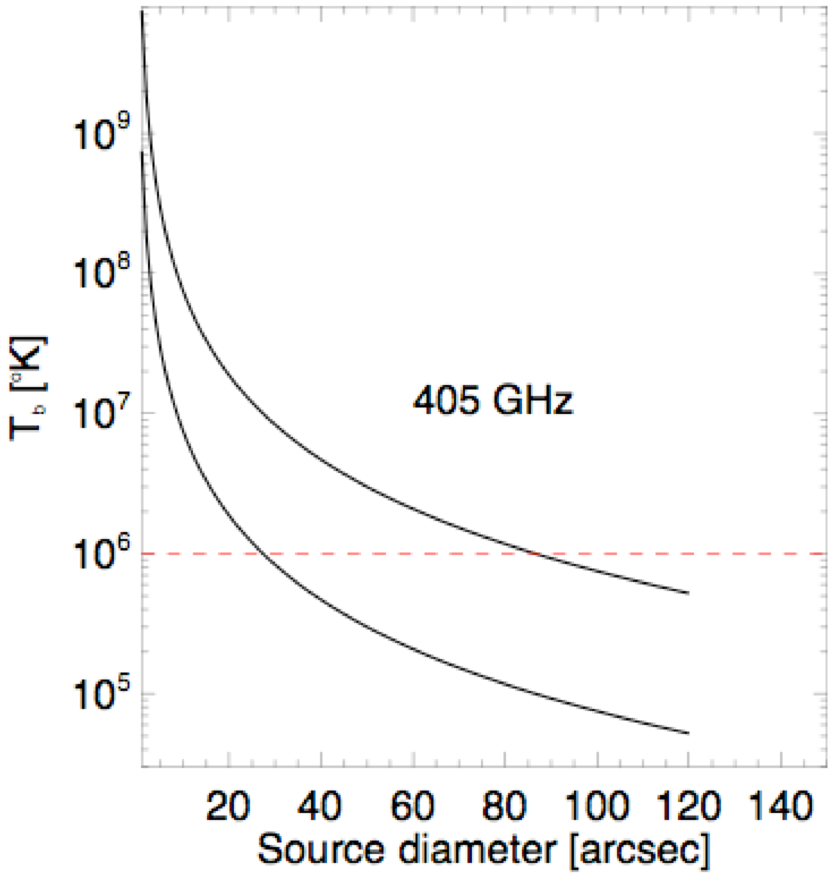
- Projected source diameter: D_s(“) or d_s(cm)
- Source size along the line of sight: H_s (“) or h_s (cm)
- Flux density at a few frequencies: S (sfu)

Brightness temperature

$$T_b(°K) = \frac{Sc^2}{2k_B\nu^2\Omega_s}; T_b = T_e \quad for \quad \tau_{ff} >> 1$$

$$\Omega_s = \frac{\pi d_s^2}{4R^2}(str)$$





$$\tau_{ff} \approx \xi \frac{N_e{}^2 h_s}{T^{3/2}\nu^2}$$

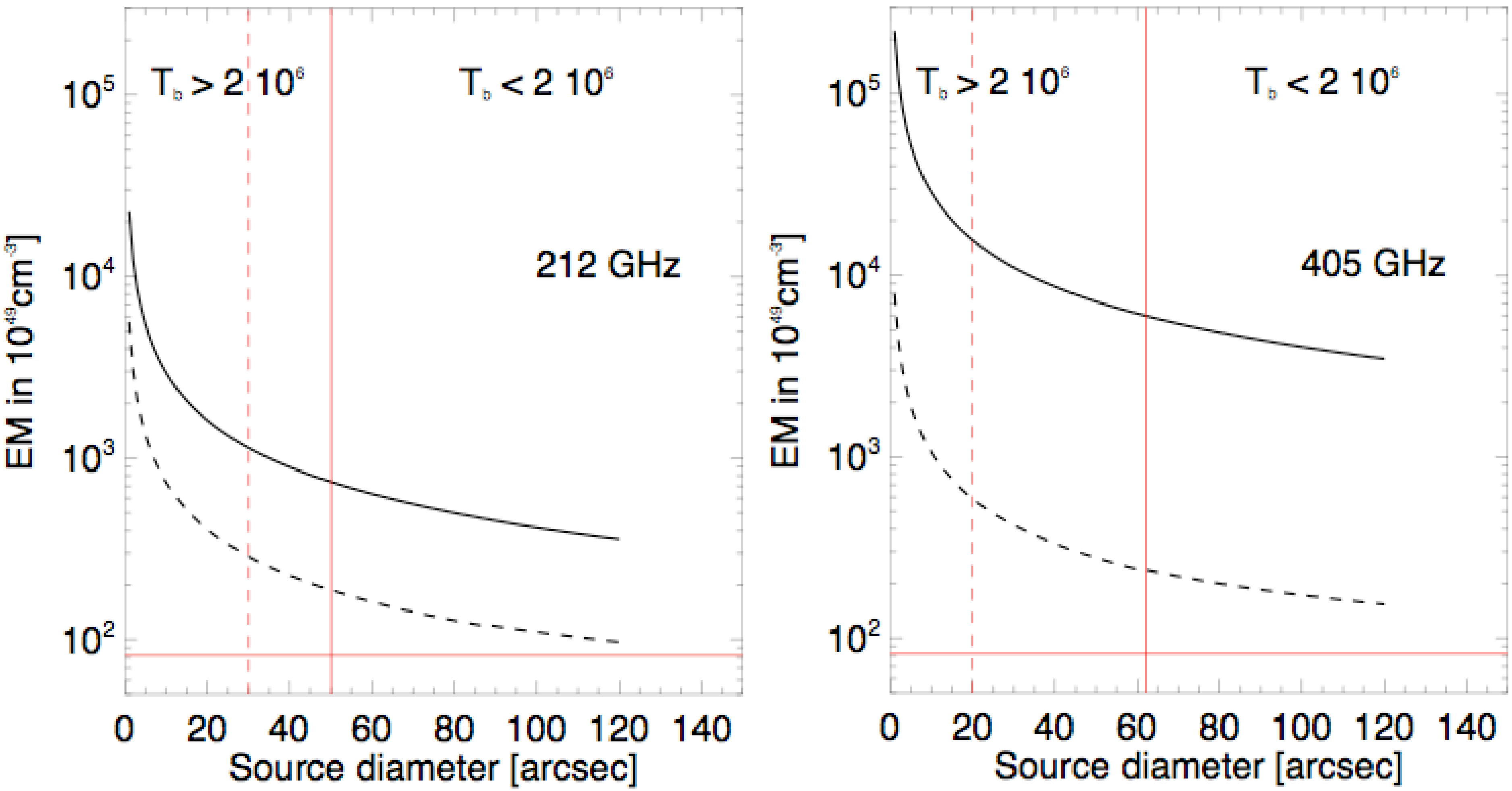
$$\xi = 9.78 \times 10^{-3} \times \left(24.5 + \ln(T) - \ln(\nu)\right) \; for\, T \geq 2 \times 10^5\, K$$

$$\xi = 9.78 \times 10^{-3} \times \left(18.2 + \ln\left(T^{3/2}\right) - \ln(\nu)\right) \; for\, T < 2 \times 10^5\, K$$

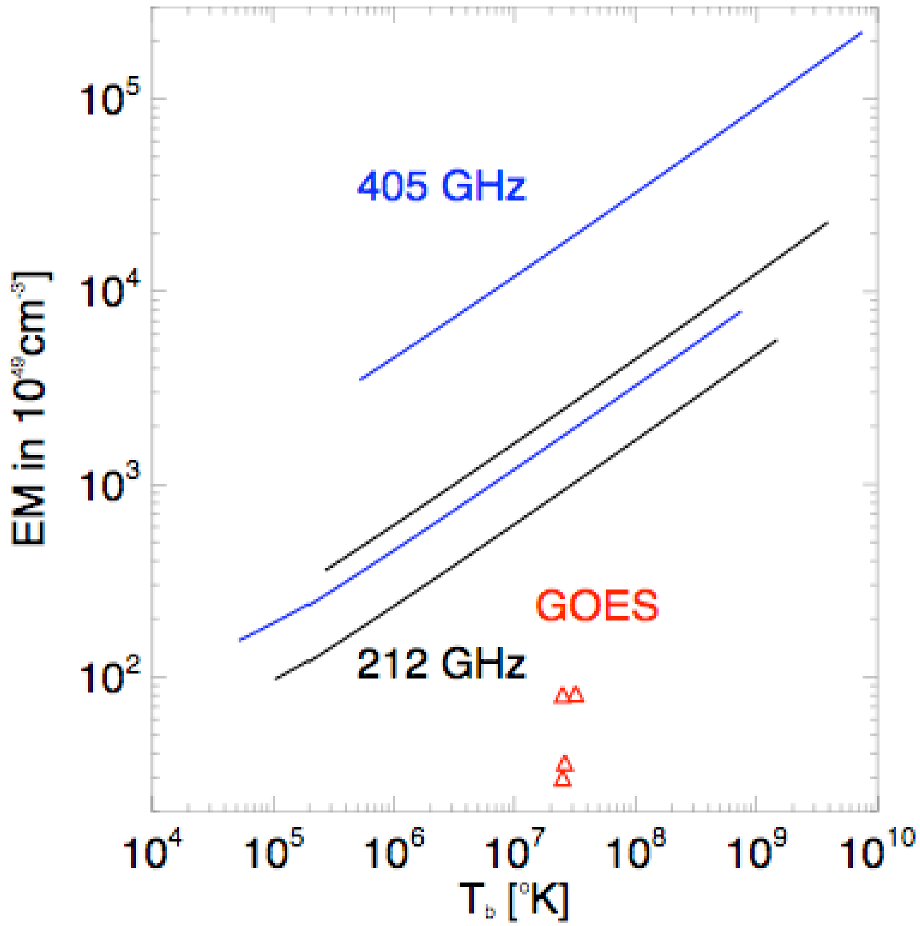
$$\tau_{ff} >> 1 \Rightarrow T = T_b$$

$$N_e\,(cm^{-3}) >> \left(\frac{T^{3/2}\nu^2}{\xi h_s}\right)^{1/2}$$

$$EM\,(cm^{-3}) = N_e{}^2 V_s = \frac{\pi}{4} N_e{}^2 d_s{}^2 h_s >> \frac{\pi T^{3/2}\nu^2}{4\xi} d_s{}^2$$



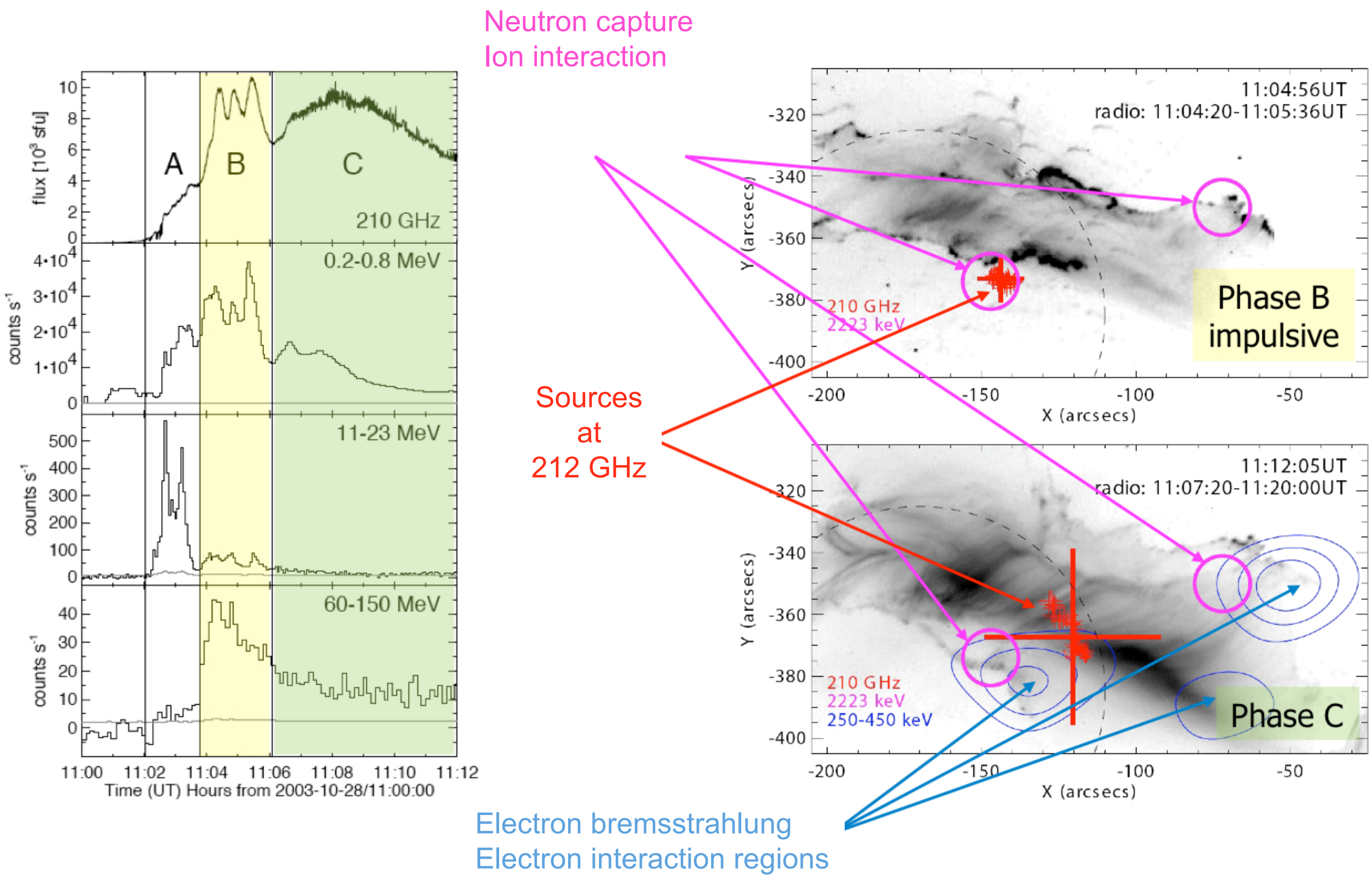
T_b > 2 10^6
T_b < 2 10^6
212 GHz
405 GHz
EM in 10^49 cm^-3
10^2
10^3
10^4
10^5
0
20
40
60
80
100
120
140
Source diameter [arcsec]

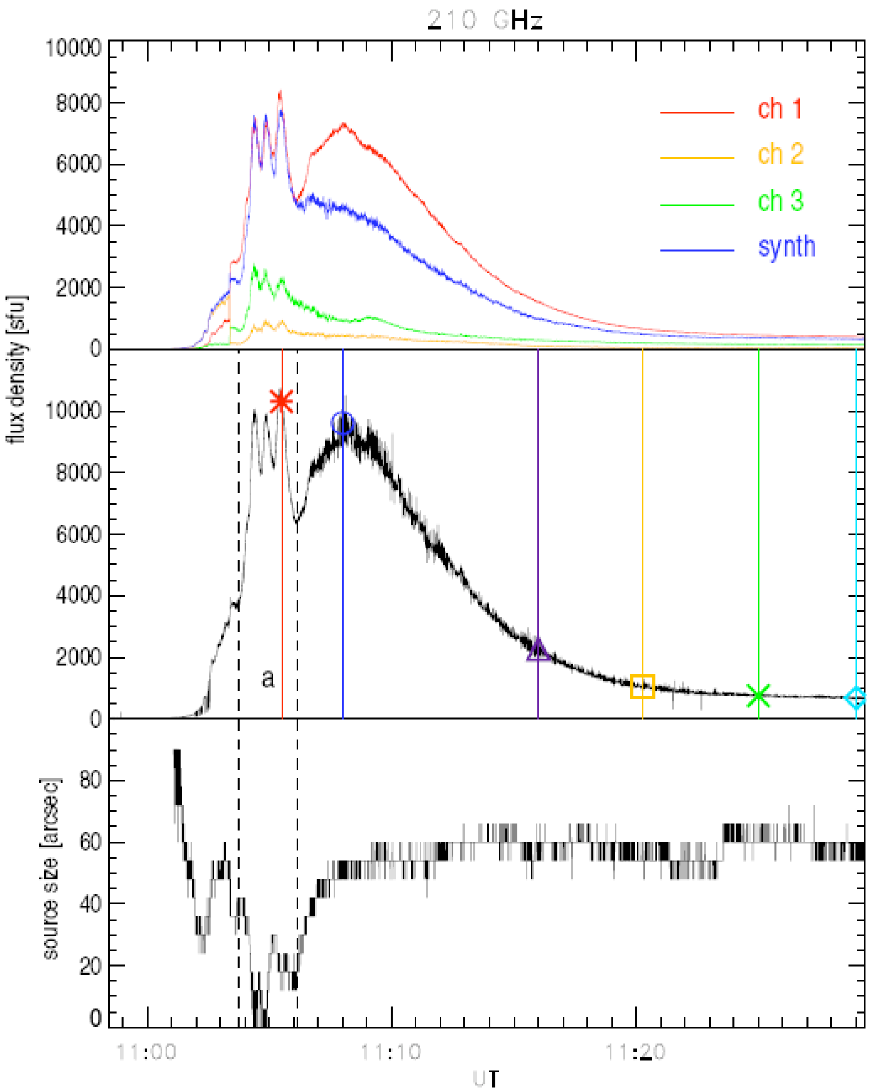


Summary:

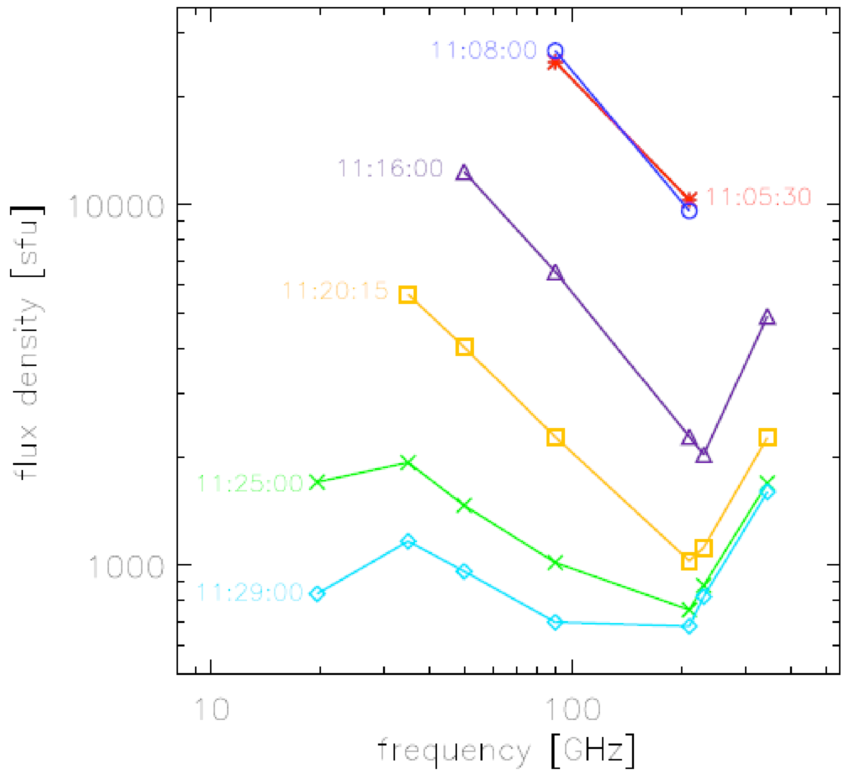
Free-free emission only from rather large sources (D_s > 40”). This is the case for the extended phase of the 28 Oct 2003 event

28 Oct 2003 (Trottet et al. 2008)





Interval C



T. Lüthi et al., A&A, **420**, *361–370, 2004*

Thick free-free at 345 GHz: $N_e^{amb} > 10^{11}$ cm^{-3}, $T^{amb} \sim 0.2$ MK,
Trottet et al. 2008
E content > 10^{30} erg << total int. irradiance $(6\pm3)10^{32}$ erg
Kopp et al. 2005

Synchrotron during C

- Similar index for electrons derived from > 0.7 MeV GR and from the slope of the optically thin radio spectrum ~ 3.2

- < 20% HXR/GR from Corona N_{amb} 10^{11} cm^{-3} (from RHESSI thermal) ⇒ $N_e(> 1 MeV) < 10^{33}$

PARAMETERS OF 210 GHz RADIO-EMITTING REGION DURING THE GRADUAL EMISSION

B (G)	N_e (>1 MeV) (10^{33})	E_{char} (MeV)	Δt (s)	τ_{coll} (s)	τ_{syn} (s)
50	60	20	400	530	4900
100	15	15	100	380	1700
200	4	10	27	270	570
300	1.5	9	10	230	300
400	0.75	8	5	200	190
500	0.5	7	3	180	130
700	0.25	6	1.5	150	80
1000	0.1	5	0.7	130	40

Interval B

Optically thick free-free at 210 GHz requires:

- T ~ 3.5 10^7 K ~ T from GOES
- EM >> 8 10^{52} cm^{-3} >> EM from GOES (10^{51} cm^{-3})
- N_e^{amb} ~ >> 2 10^{13} cm^{-3}

Synchrotron

Ambient medium

- N_e (cm^{-3})
- T (°K)
- B (G)

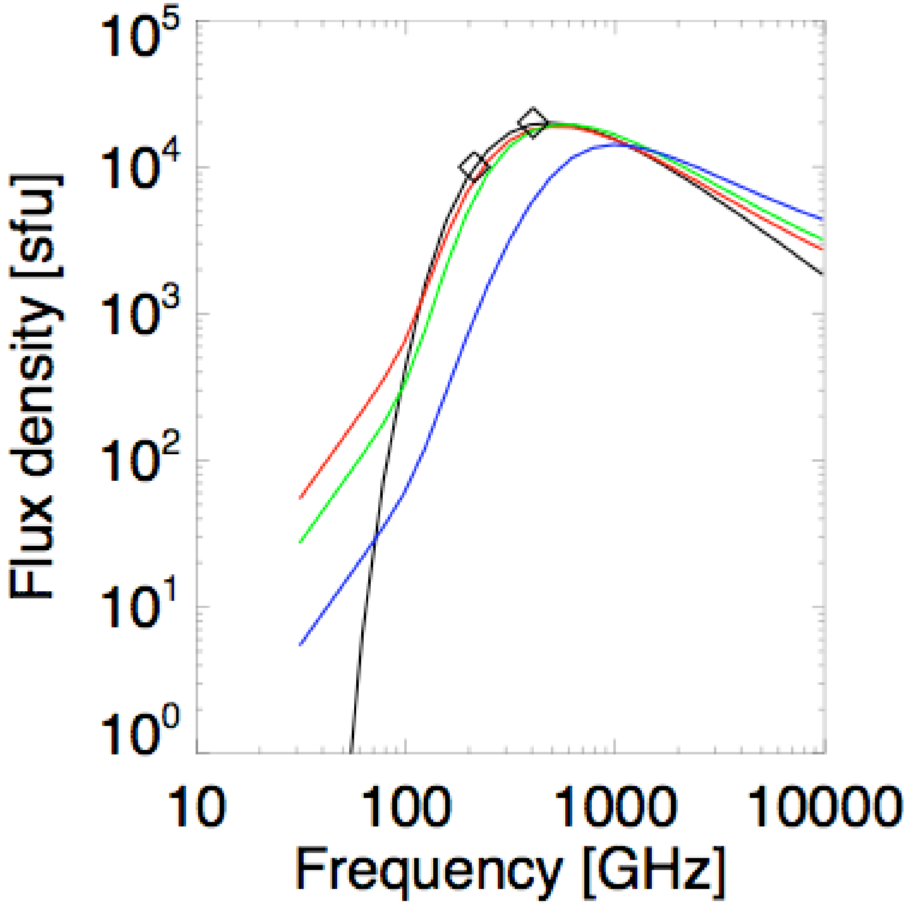
Radiating particles

- Nature (electrons, positrons)
- Energy spectrum
- Pitch angle distribution

Radio emitting region

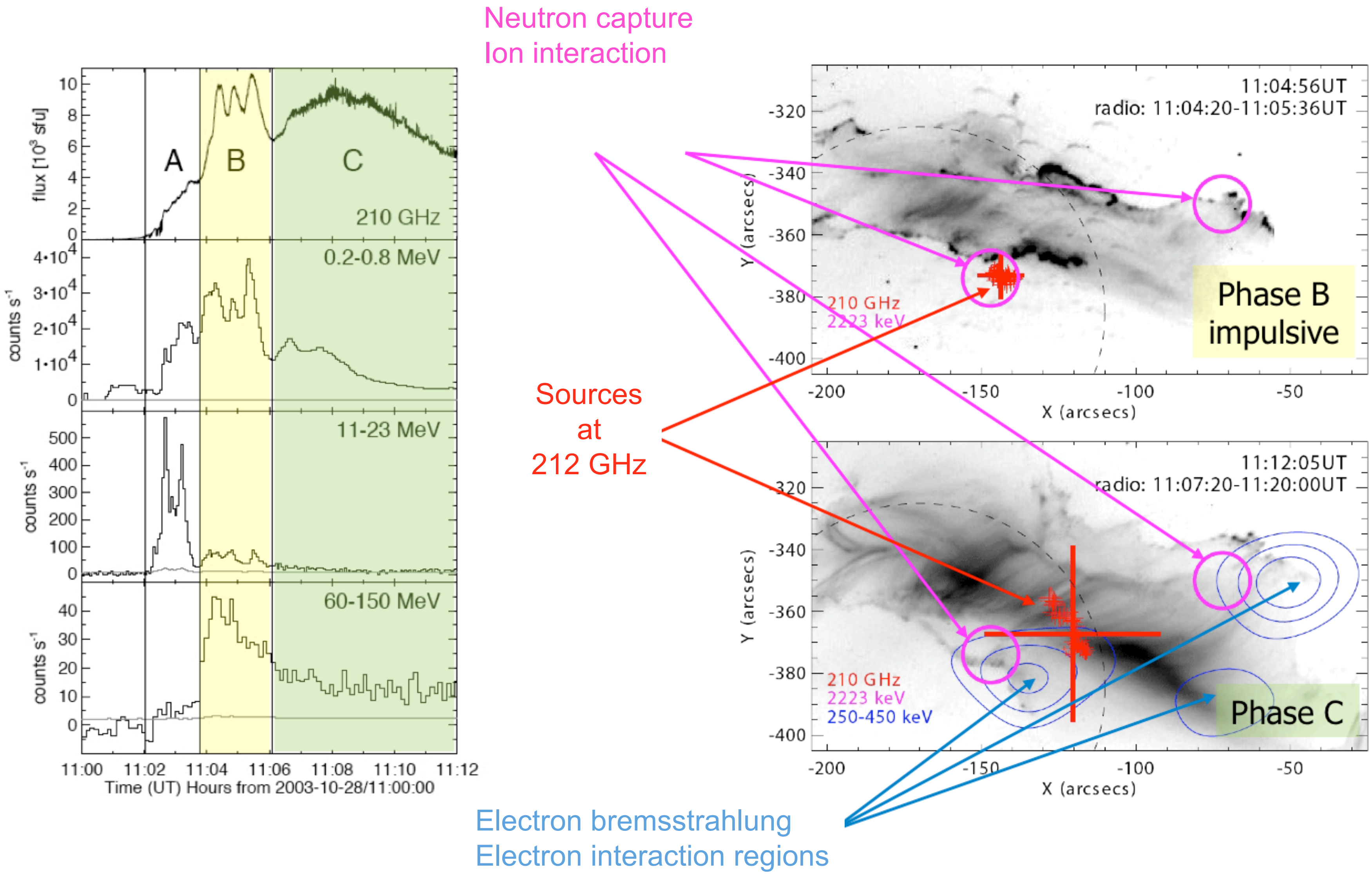
- D_s (d_s), H_s (h_s), S as a function of ν_{obs}

Razin suppression
for electrons

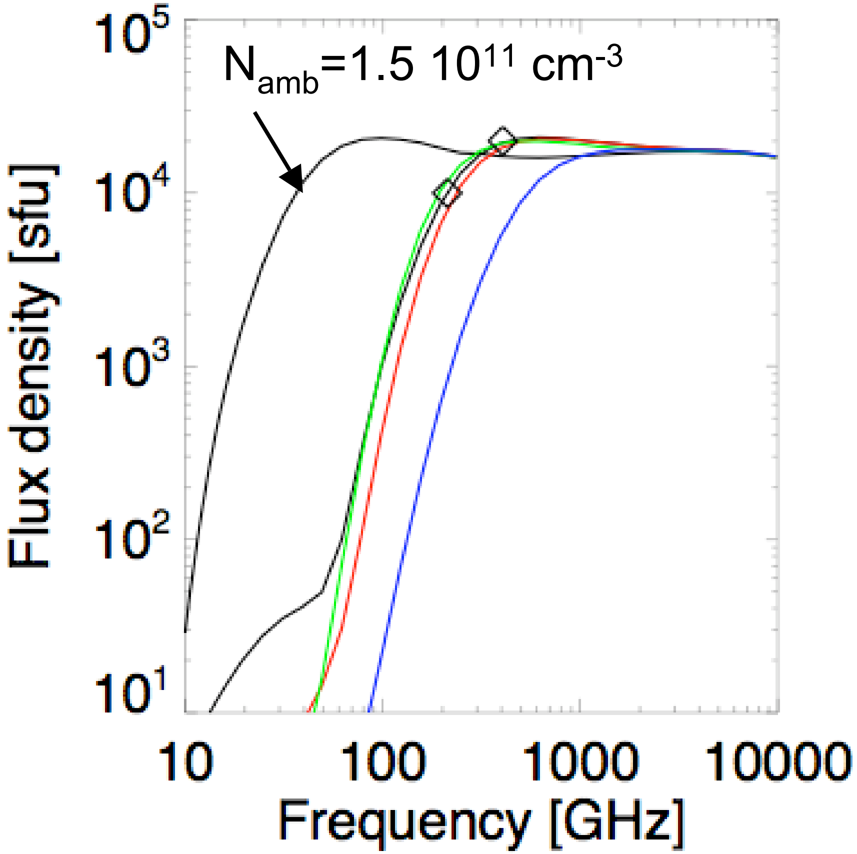


D_s = 10''
H_s = 1''
B=700 G
N_e=8 10^{12} cm^{-3}
ν_p = 25 GHz
ν_R = 220 GHz ~20 N_e/B
δ=3
N(>1 MeV)= 3.5 10^{33}
No free-free (black)
T (°K) = 10^7 (red),
5 10^6 (green)
10^6 (blue)
EM ~ 2 10^{51} cm^{-3}

28 Oct 2003 (Trottet et al. 2008)



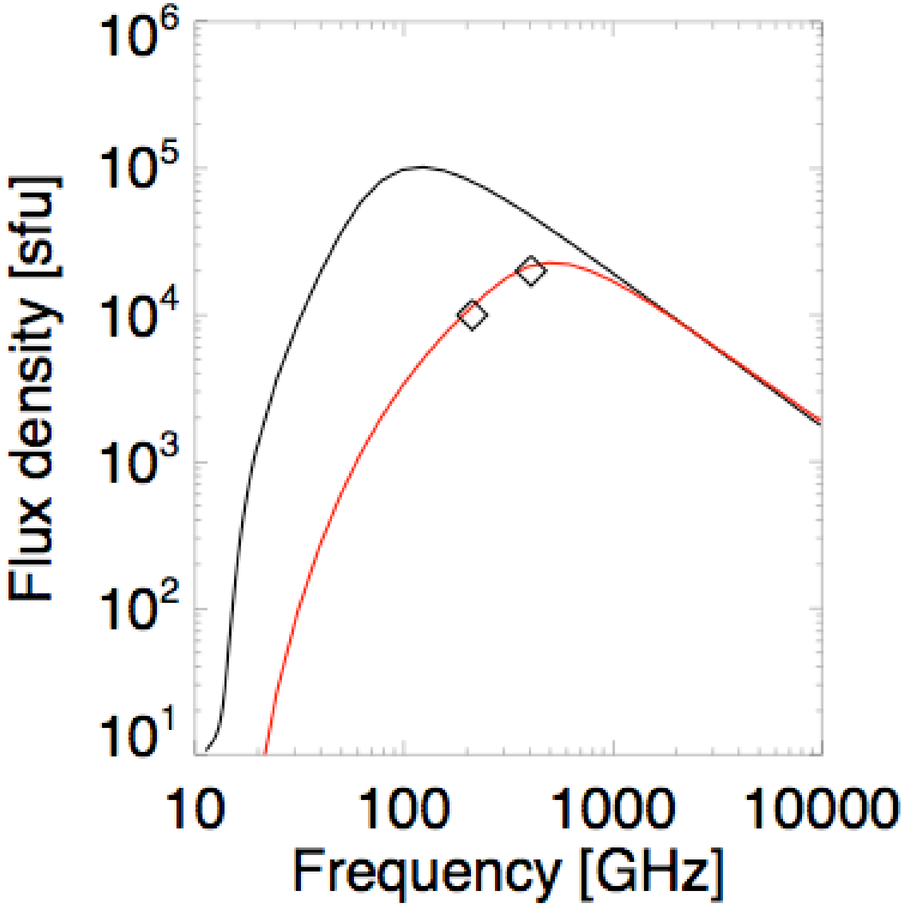
Razin suppression
+ free-free for positrons



D_s = 10'', H_s = 1''
B=700 G
N_e= 1.5 10^{12} cm^{-3}
ν_p = 11 GHz
ν_R = 41 GHz
N_{pos}/Mev= 6 10^{29}
between 12 and 100 MeV

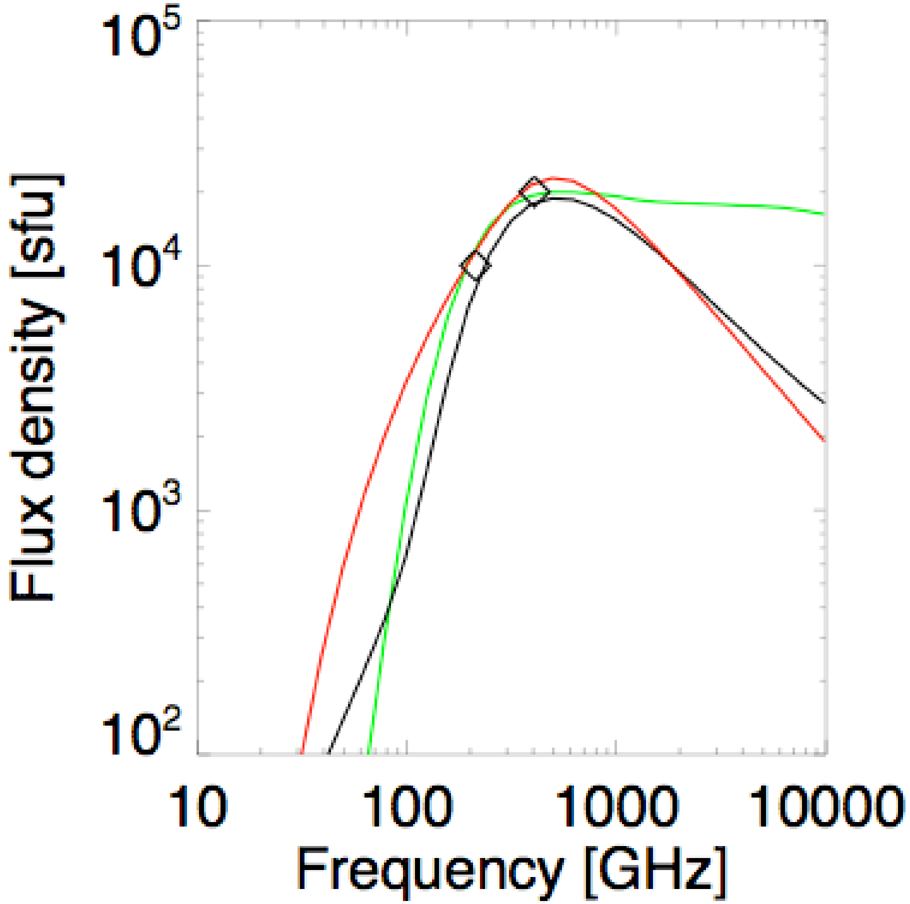
T(°K) = 10^7 (black)
10^6 (red)
5 10^5 (green)
10^5 (blue)
EM ~ 7 10^{49} cm^{-3}
N_{tot} 5 10^{31} =>
> 5 10^{32} >200 MeV p

Free-free absorption for electrons



D_s = 10''
H_s = 1''
B=700 G
$N_e = 1.5\ 10^{12}\ cm^{-3}$
ν_p = 11 GHz
ν_R = 41 GHz
δ=3
N(>1 MeV)= $3.5\ 10^{33}$
T (°K) = 10^7 (black)
$1.5\ 10^5$ (red)
EM ~ $7\ 10^{49}$ (cm^{-3})

Summary on synchrotron emission



Positrons (green)

Too large numbers of > 200 MeV protons

Electrons+Razin (black)

High N_{amb} (~8 10^{12} cm^{-3} for B=700 G) => T_{amb} > 5 10^6 K to get $\tau_{ff} < 1$

High EM

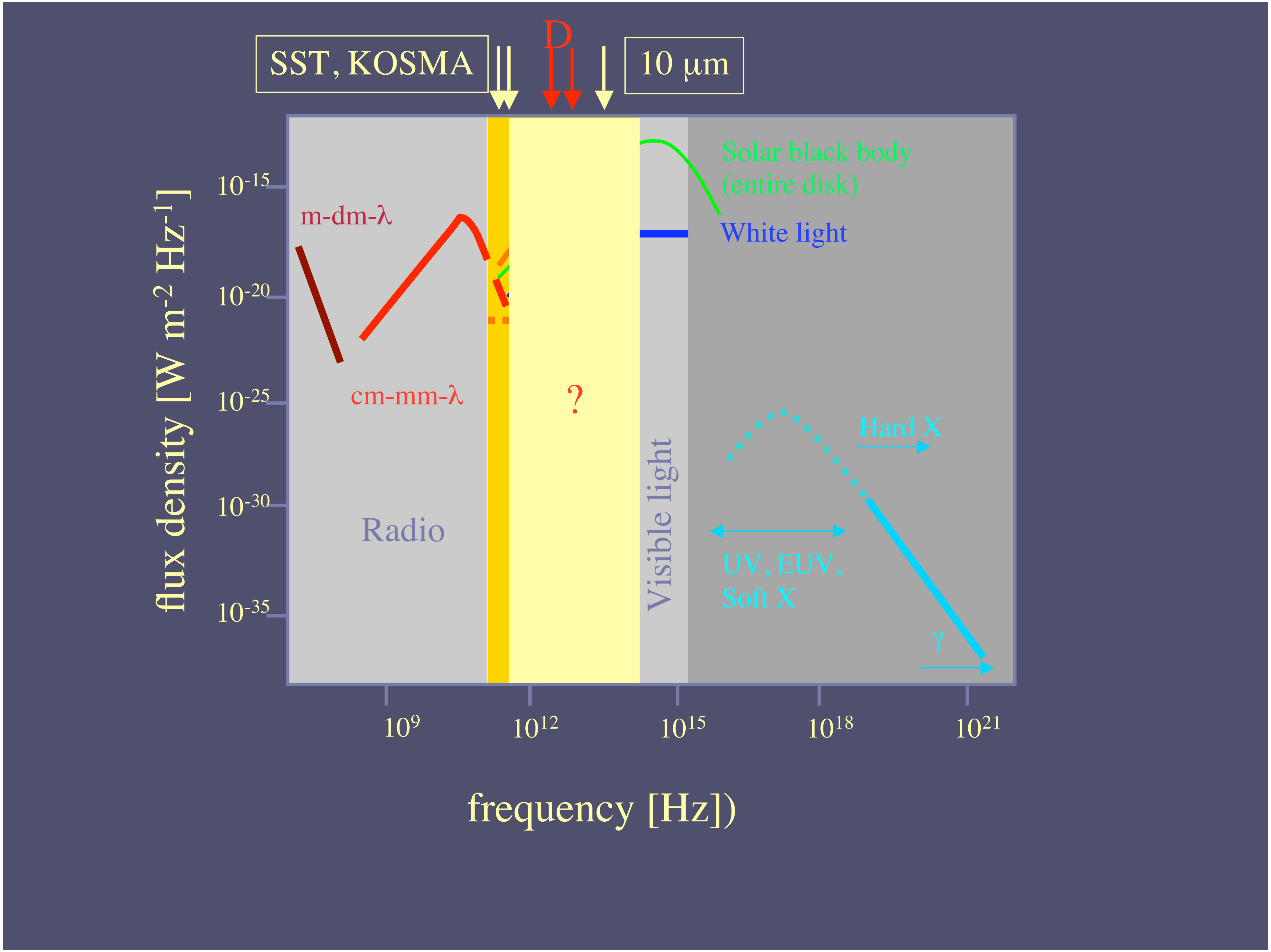
Electrons+free-free (red)

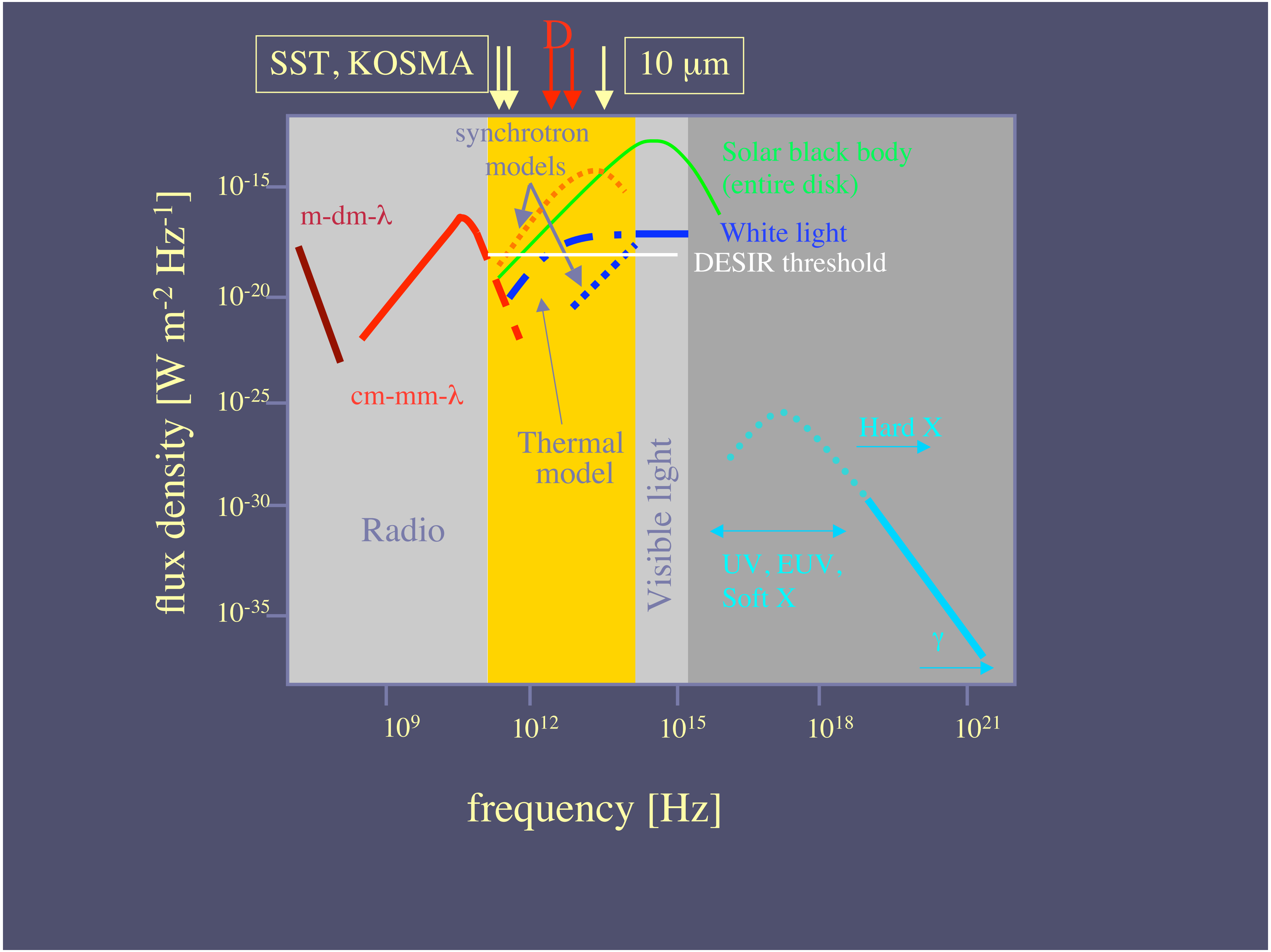
- N_{amb} ~ 1-2 10^{12} cm^{-3} to get
- ν_R < 50 GHz
- Small EM
- low T (few 10^5 K and lower)

Sub-THz emission process ?

Summary of discussions at an ISSI workshop held in Bern (Nov 2009)
S. Krucker et al.

free-free	known mechanism rising spectrum	Not viable for compact sources Fast time variations (?)
Electron synchrotron	known mechanism rising spectrum (razin or absorption) fast time variations	'extreme' parameters needed to reproduce observations
Positron synchrotron	time and space coincidence with γ-ray observations fast time variations	not enough positrons (as derived from gamma-ray observations)
Vavilov-Cherenkov	rising spectrum large fluxes rapid variations	dielectric properties of chromosphere not known (i.e. refractive index could be smaller)
Bunching	association with GHz emission	THz emission attributed to electron synchrotron (see above) setup of bunching is unclear coronal microwave sources difficult to explain
Plasma emission	correlation with γ-rays low number of particles needed	needs high densities and collisions should therefore be important not otherwise observed above 8 GHz
Diffusive radiation	Rising spectrum	Origin of high levels of long-wavelength Langmuir waves
Thermal Gyrosynchrotron	Rising spectrum	Extreme parameters Associated thermal hard X-ray emission not observed
Synchrotron Maser	Low number of particles needed	
Inverse Compton	association with GHz emission	not enough primary photons


SST, KOSMA
D
10 µm
flux density [W m-2 Hz-1]
10-15
10-20
10-25
10-30
10-35
m-dm-λ
cm-mm-λ
Radio
?
Visible light
Solar black body
(entire disk)
White light
Hard X
UV, EUV,
Soft X
γ
10^9
10^12
10^15
10^18
10^21
frequency [Hz])



SST, KOSMA
D
10 µm
synchrotron
models
Solar black body
(entire disk)
m-dm-λ
White light
DESIR threshold
cm-mm-λ
Thermal
model
Visible light
Hard X
Radio
UV, EUV,
Soft X
γ
10-15
10-20
10-25
10-30
10-35
flux density [W m-2 Hz-1]
10^9
10^12
10^15
10^18
10^21
frequency [Hz]