Simulation of thermal sub-THz emission from solar flares

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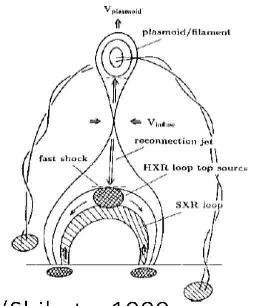
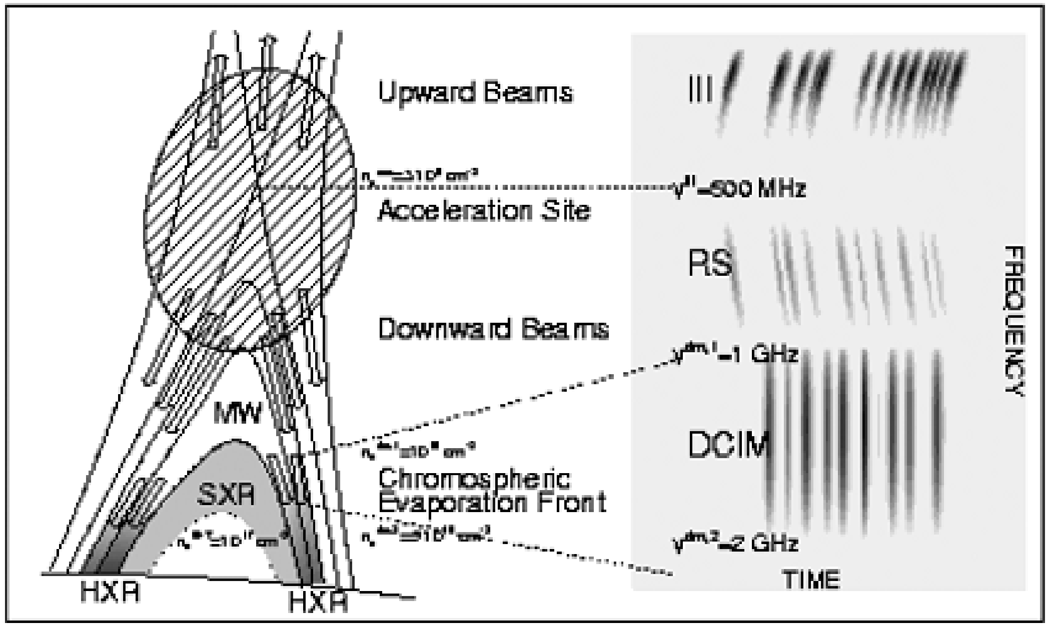
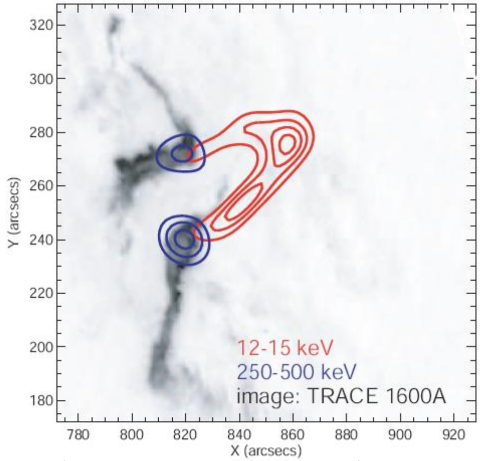
Sub-THz emission vs hard X-ray emission in solar flares



(Shibata, 1999; Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976)



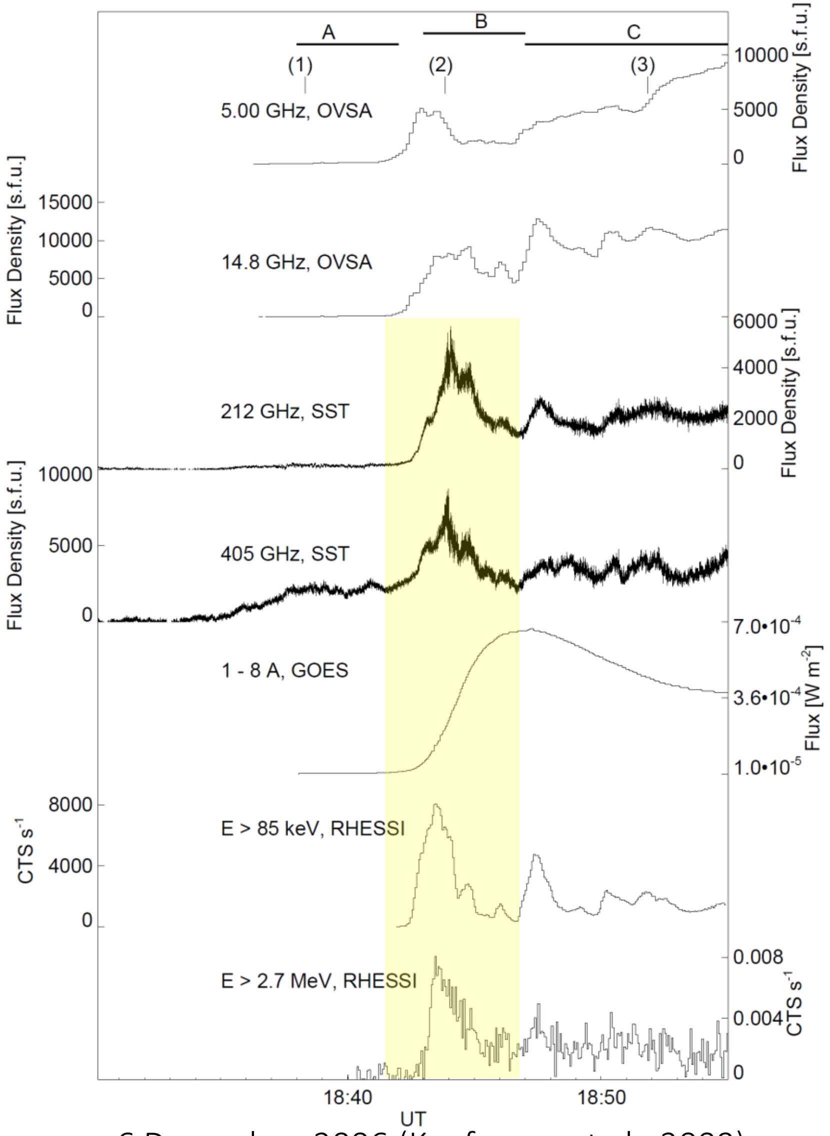
(Aschwanden, Benz,1997)



(Krucker et al., 2008)

Large fluxes at sub-THz frequencies & a correlation with HXRs

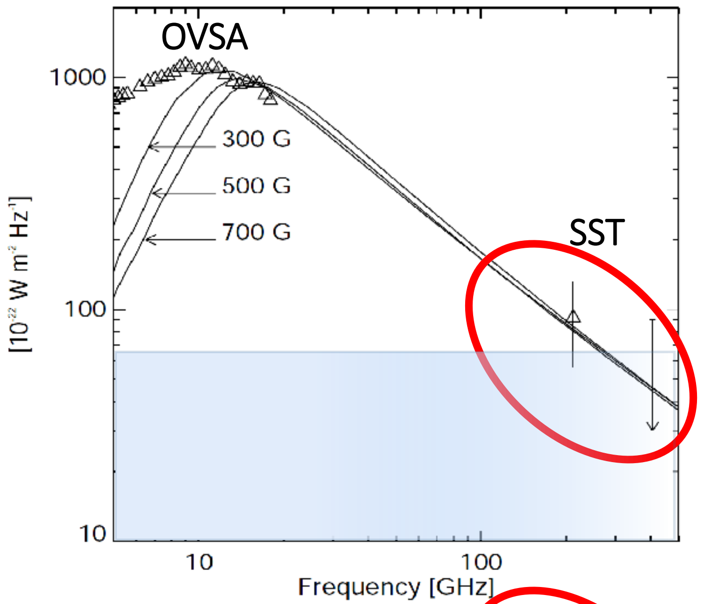
In many cases emission is associated with accelerated non-thermal electrons

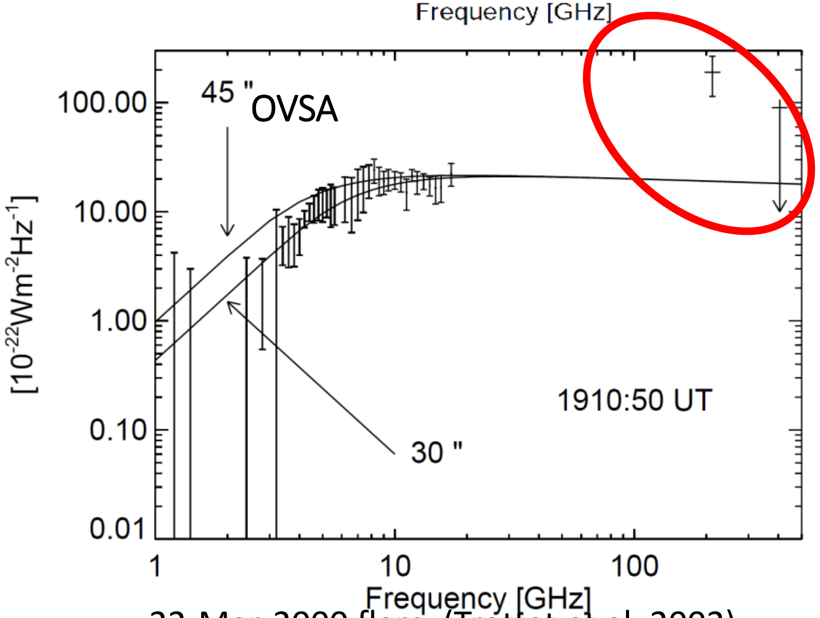


6 December, 2006 (Kaufmann et al., 2009)

Flare observations with sub-THz emission

Normal extension of microwave spectrum



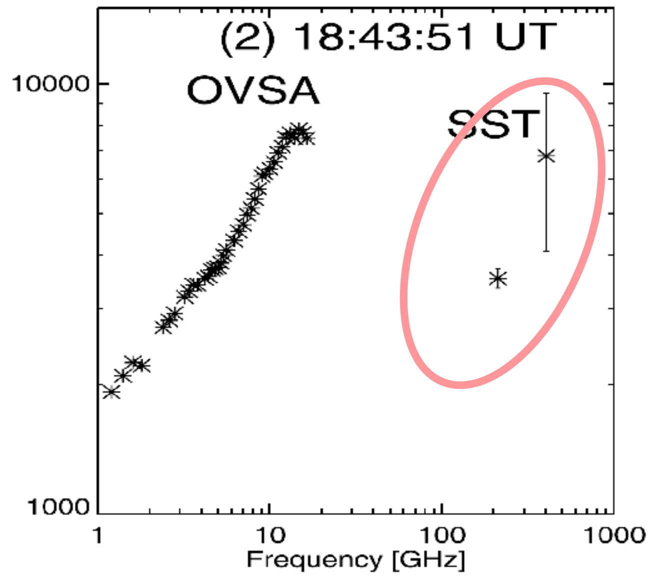


22-Mar-2000 flare (Trottet et al. 2002)

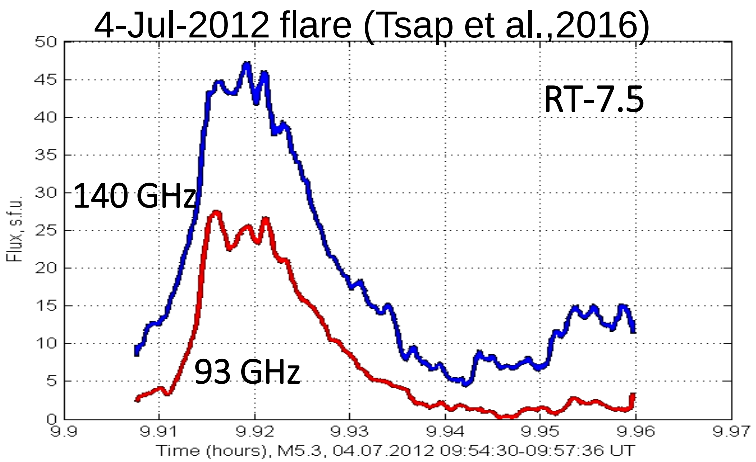
- Most events have a negative spectral slope between frequencies of 200 and 400 GHz (Kaufmann et al., 2004; Silva et al., 2007; Kaufmann et al., 2009)
- Flare emission is mostly gyro-synchrotron from power-law electrons (e.g. Dulk et al. 1979; Trottet et al 2002) with a source size of ~10” (typical size for millimeter sources, e.g. Raulin et al. 1999)

- Thermal component from hot coronal plasma gives rather small fluxes (e.g. Trottet et al. 2002; Tsap et al., 2016, 2018)

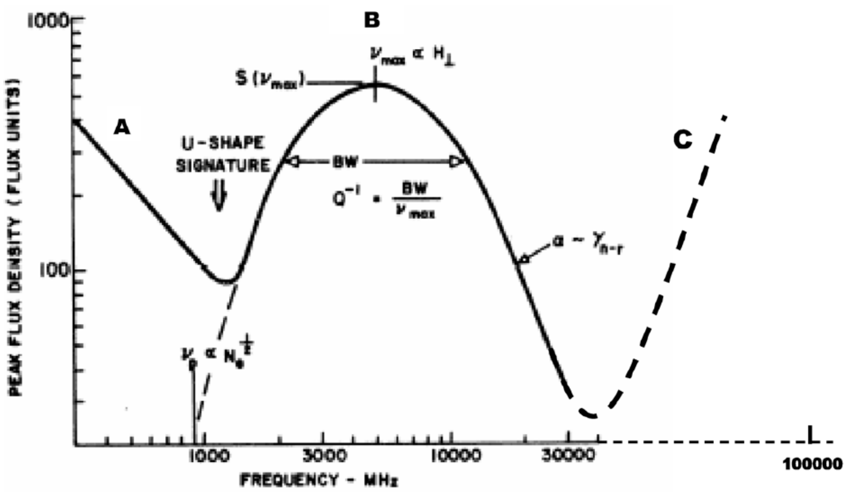
Flare observations with sub-THz emission



Microwave Spectrum+ Sub-THz- December 06, 2006 – 18:30UT (Adapted from Kaufmann etal, 2009 – *S.Phys. 255, 131*).



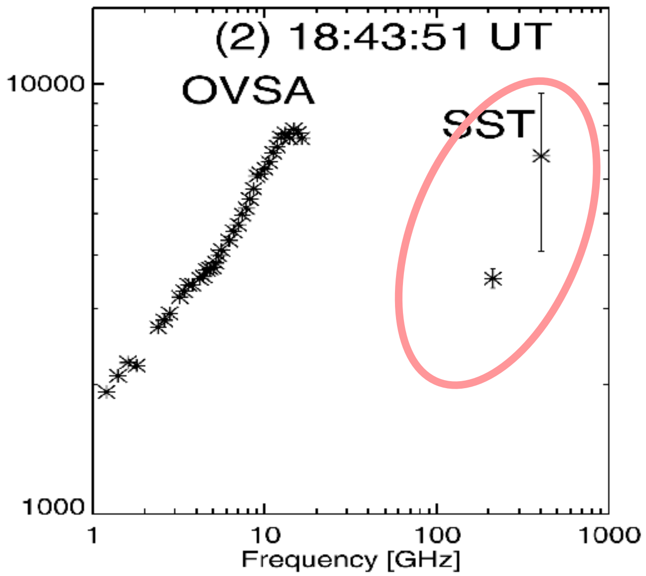
- But in some cases there is a positive spectral slope between frequencies of 200 and 400 GHz (Trottet et al., 2002; Raulin et al., 2004; Lüthi et al., 2004; Gimenez de Castro et al., 2009)



(Kaufmann et al., 2009; adapted from Castelli, 1972)

- “W-shaped” spectrum suggests existence of another emission mechanism at sub-THz frequency range

Proposed sub-THz emission mechanisms



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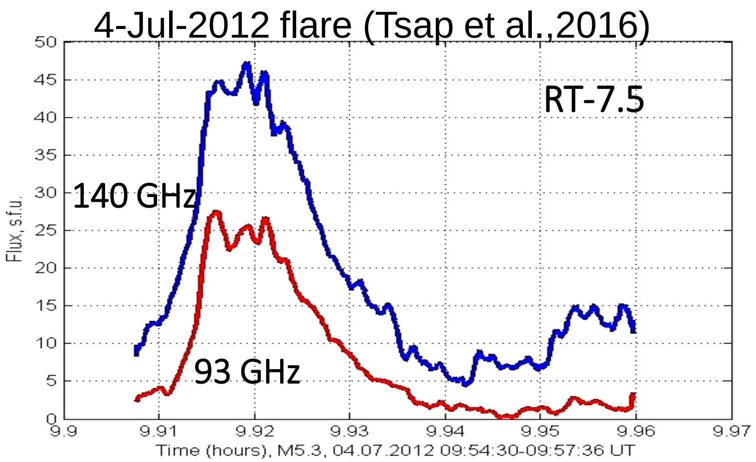
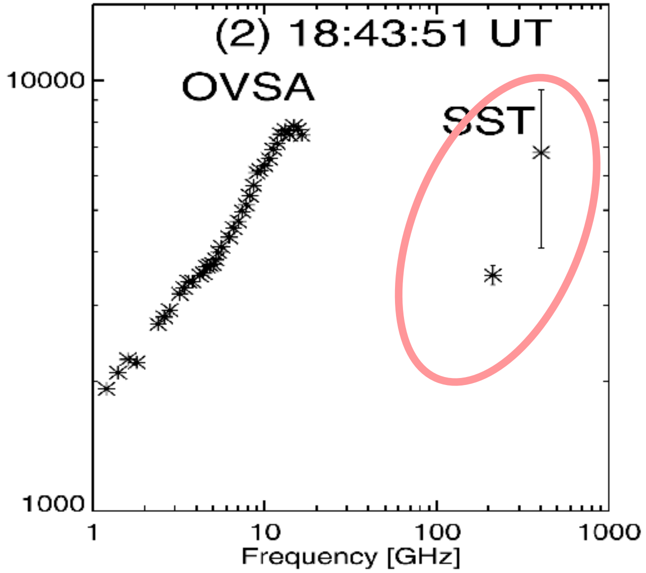


- Optically thick thermal free-free emission (Silva et al. 2007; Fleishman & Kontar, 2010)
- Gyro-synchrotron emission:
  - from a compact source with a large magnetic field $B >$ 2000 G (Kaufmann and Raulin 2006; Fleishman & Kontar, 2010)
  - due to absorption in an optically thick thermal plasma (Morgachev et al., 2017)
  - Razin effect in a dense plasma (Melnikov et al. 2012)
- Plasma mechanism (Zaitsev et al., 2013)
- Cherenkov radiation from chromospheric layers (Fleishman and Kontar, 2010)
- Synchrotron mechanism of emission from positrons (Trottet et al., 2004)
- Inverse Compton effect (Kaufmann et al., 1986)
- Emission from short-wavelength Langmuir turbulence (Fleishman & Kontar, 2010)

Proposed sub-THz emission mechanisms



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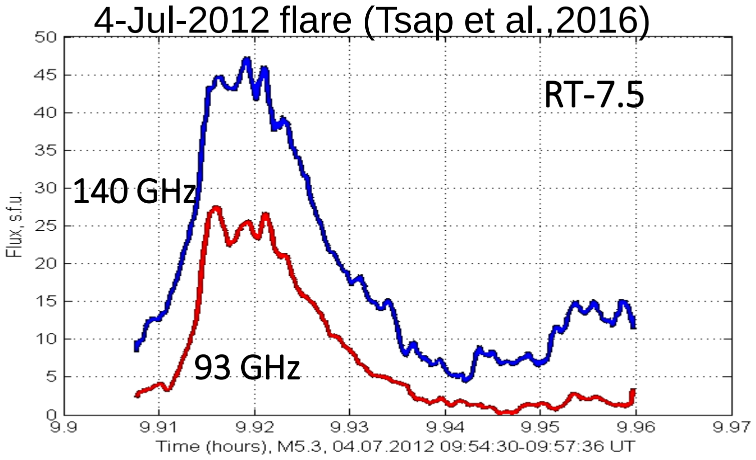

- Optically thick thermal free-free emission (Silva et al. 2007; Fleishman & Kontar, 2010)
- Gyro-synchrotron emission:
  - from a compact source with a large magnetic field $B >$ 2000 G ... r, 2010)
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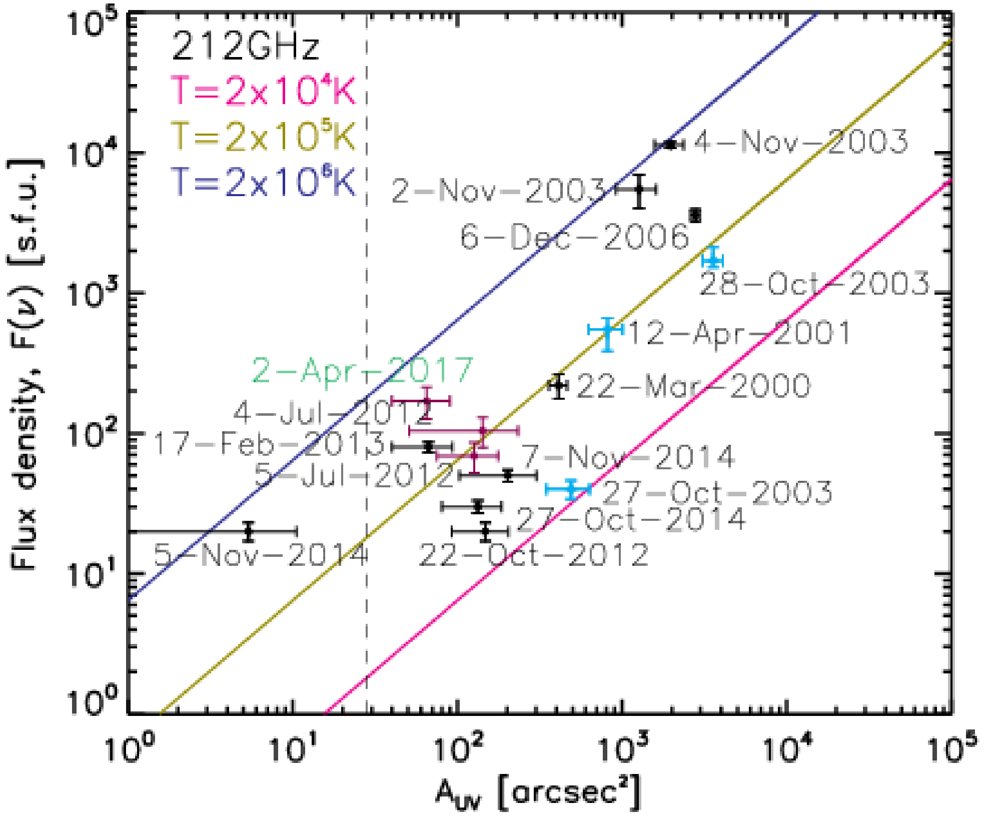
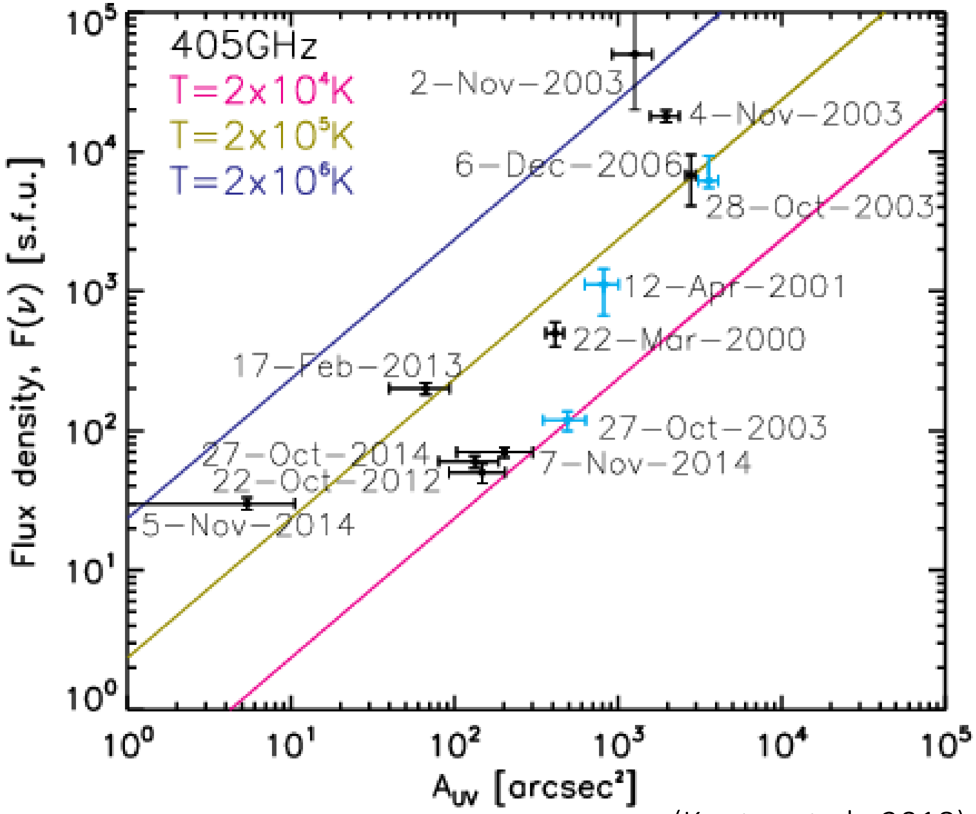
  - ... 2)
-
- **The proposed models have several assumed conditions and suffer from a lack of observational support, thus they cannot be verified observationally**
- Cherenkov radiation from chromospheric layers (Fleishman and Kontar, 2010)
- Synchrotron mechanism of emission from positrons (Trottet et al., 2004)
- Inverse Compton effect (Kaufmann et al., 1986)
- Emission from short-wavelength Langmuir turbulence (Fleishman & Kontar, 2010)

UV flare ribbon areas vs the sub-THz radio flux (Kontar et al., 2018)





(Kontar et al., 2018)

- Large sub-THz fluxes correspond to large UV areas
- Spectral index between 200 and 400 GHz δ <2
- All radio fluxes at 200-400 GHz frequency range can be explained by the radiation of an optically thick source with a plasma temperature between 2×10^4 K and 2×10^6 K, which characterizes the chromosphere and transition region
- Numerical simulation is needed

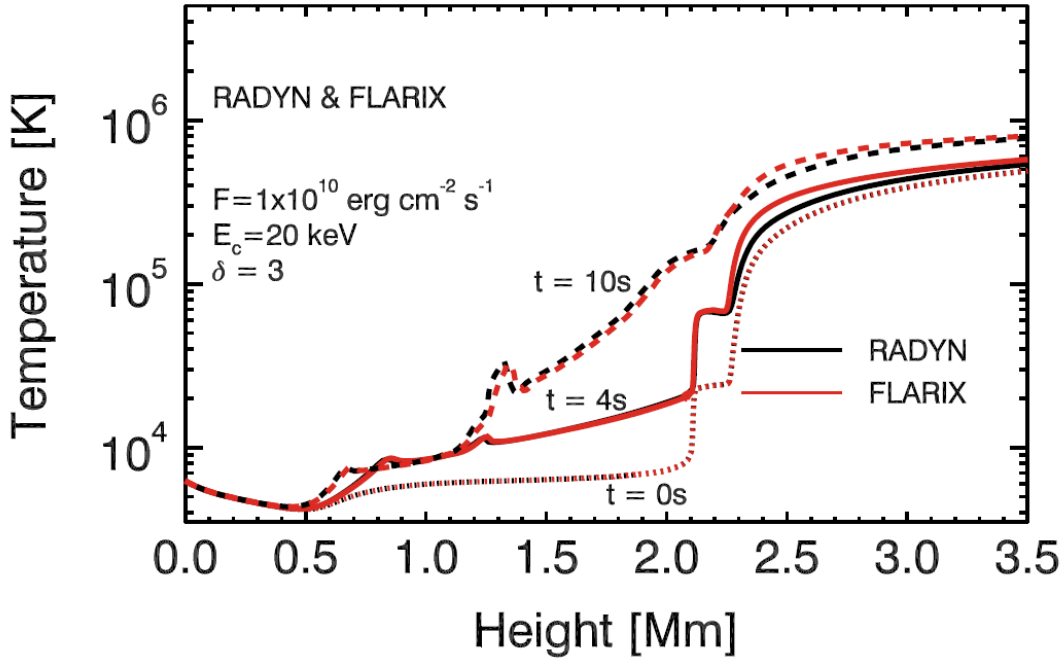
Numerical codes: FLARIX и RADYN (Kašparova et al., 2009; 2019)

FLARIX (Varady et al. 2010) и **RADYN** (Carlsson & Stein, 1997)

- RHD codes which couple the hydrodynamic equations to the non-LTE 1D radiative transfer and time-dependent non-equilibriumatomic level population equations, for elements important for chromospheric energy balance
- Describe the response of an unperturbed solar atmosphere VAL-C to a beam of non-thermal electrons

- There are differences in approaches (Fokker-Planck VS test particles); different initial flare atmosphere; radiation losses; RADYN considers H, He & Ca, with Mg also sometimes included, whereas FLARIX considers H, Ca, and Mg; etc...

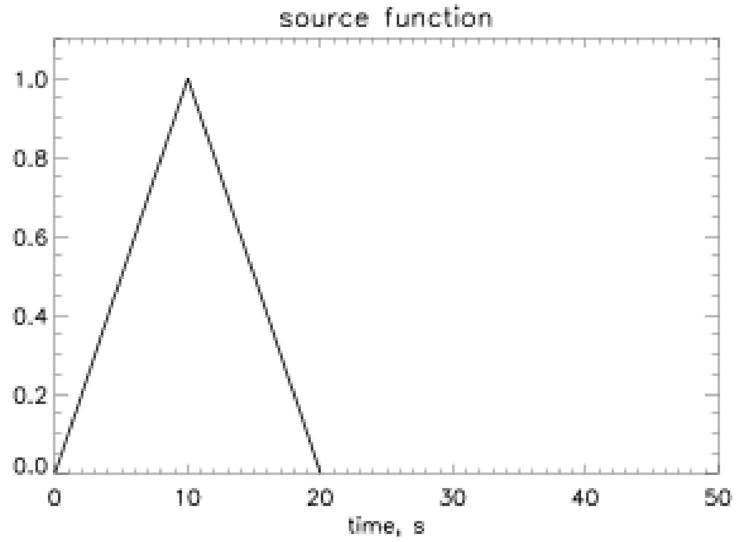
(Kerr & Polito, ISSI proposal, 2019)



Modeling: FLARIX и RADYN

Initial parameters:

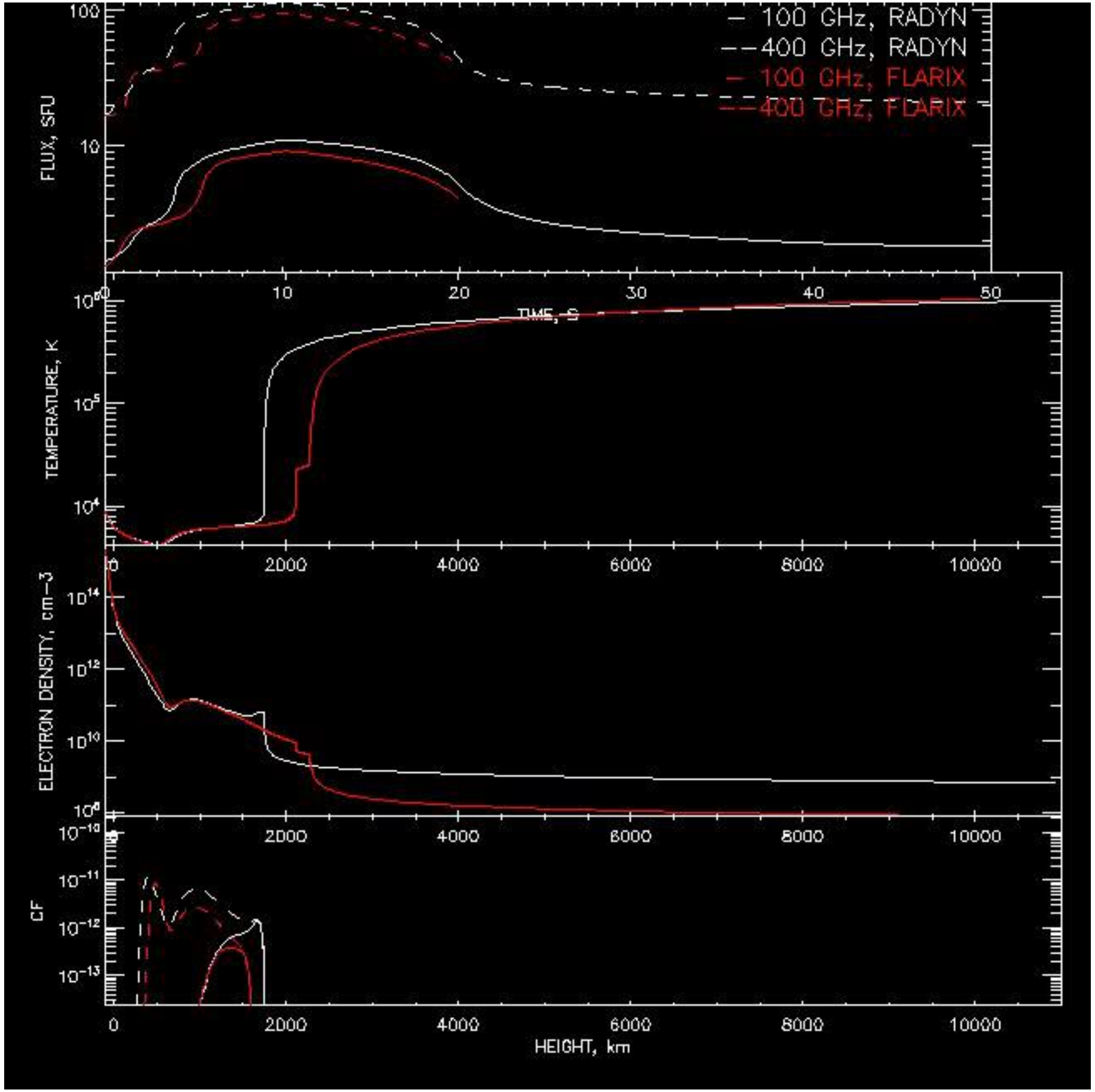
- Initial atmosphere VAL-C (Vernazza, Avrett, and Loeser, 1981)
- Nonthermal electron flux in the form of a triangular pulse
- Parameters of the electron beam:
    - spectral index $\delta=3$;
    - cutoff energy $E_c=20$ keV;
    - total energy of electrons $F_e=10^{11}$ erg$\times$s$^{-1}\times$cm^{-2}



- Each model contains distributions of plasma parameters (temperature T, electron density n_e, degree of ionization, etc.) with height over a time interval of 50 sec. with a time step of 0.1 sec
- Using the model height dependences of the temperature and electron number density at each time, we can calculate the intensity of its thermal bremsstrahlung at height H at frequencies ν equal to 100 and 400 GHz

*Model №37 based on RADYN is taken from F-CHROMA solar flare model database (https://www.fchroma.org)

Results Comparison



- Nonthermal electron flux in the form of a triangular pulse with duration of 20 sec
  - spectral index δ=3
  - cutoff energy E_c=20 keV
  - total energy of electrons $F_e=10^{11}$ erg×s^{-1}×cm^{-2}
- Contribution Function

$$CF(h) = \eta_\nu(h)\exp\left(-\int_h^H k_\nu dh\right)$$

- The total radiation flux

$$F_\nu(h) = \frac{S}{R^2}\int_0^h CF(h')dh'.$$

Conclusions

1) The time evolution of thermal bremsstrahlung in the sub-terahertz range was calculated for the RADYN & FLARIX models.
2) The maxima of the pulse and millimeter emission coincide. The characteristic heights of the formation of sub-THz emission vary over a wide range. The main contribution to the sub-THz emission is made by plasma with a temperature of 0.01 - 0.1 MK.
3) The regions of formation of sub-THz emission in the RADYN & FLARIX models differ by less than 100 km. The difference in the radiation flux does not exceed 15%.
4) The information about formation of sub-THz emission along with new ALMA observations will help us to understand the origin of sub-THz emission in solar flares.