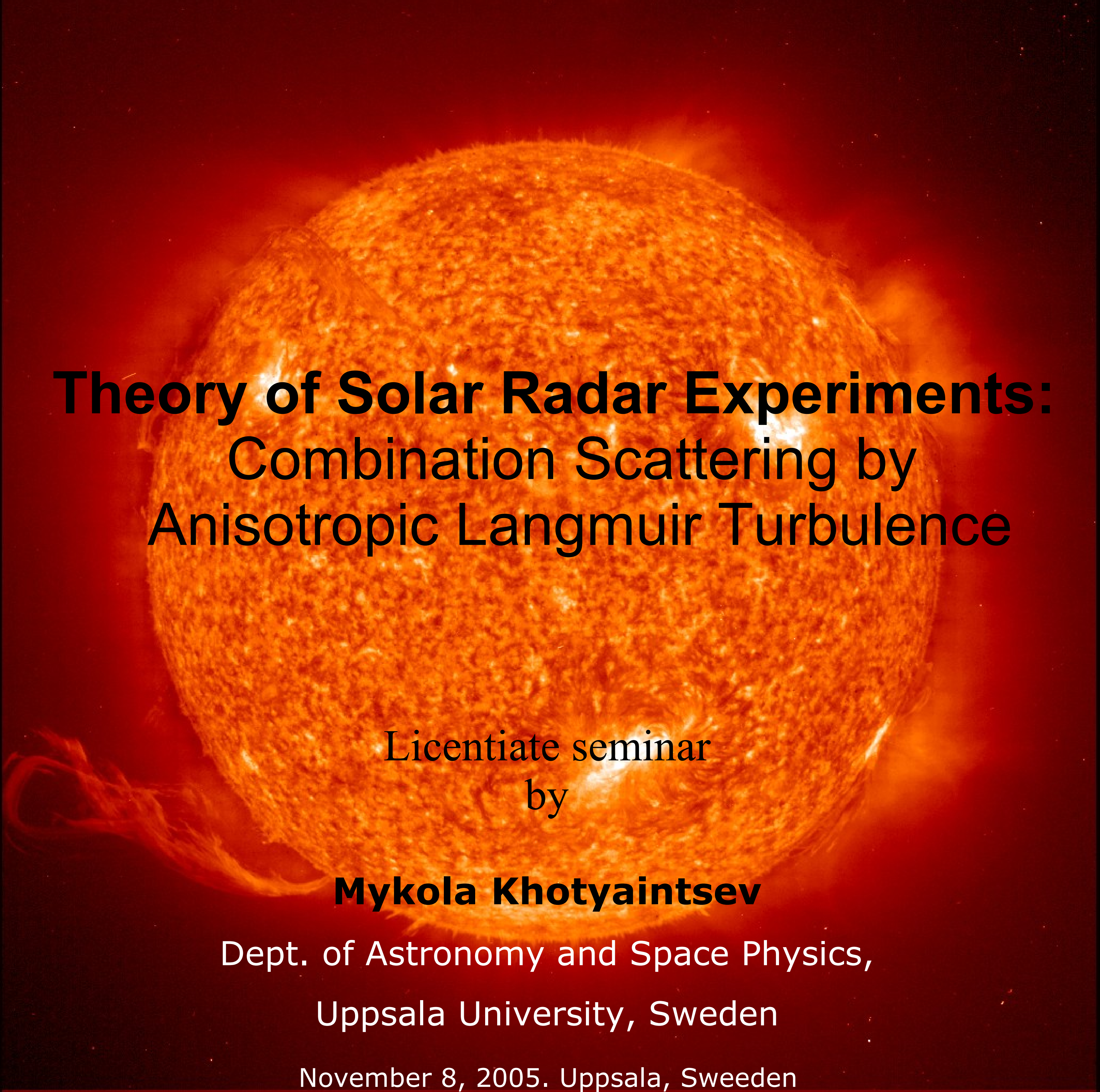

Theory of Solar Radar Experiments: Combination Scattering by Anisotropic Langmuir Turbulence

Licentiate seminar
by

Mykola Khotyaintsev

Dept. of Astronomy and Space Physics,

Uppsala University, Sweden

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Presentation outline

1. The Sun

- Overview
- Prominence, flares, and coronal mass ejections (CME's)
- Type III solar radio bursts

2. Solar radar experiments

- Overview
- Main experimental results

3. Theory of radar reflections from the Sun

- Specular reflection
- Volume scattering by density fluctuations
- Induced (combination) scattering by wave turbulence

4. Paper

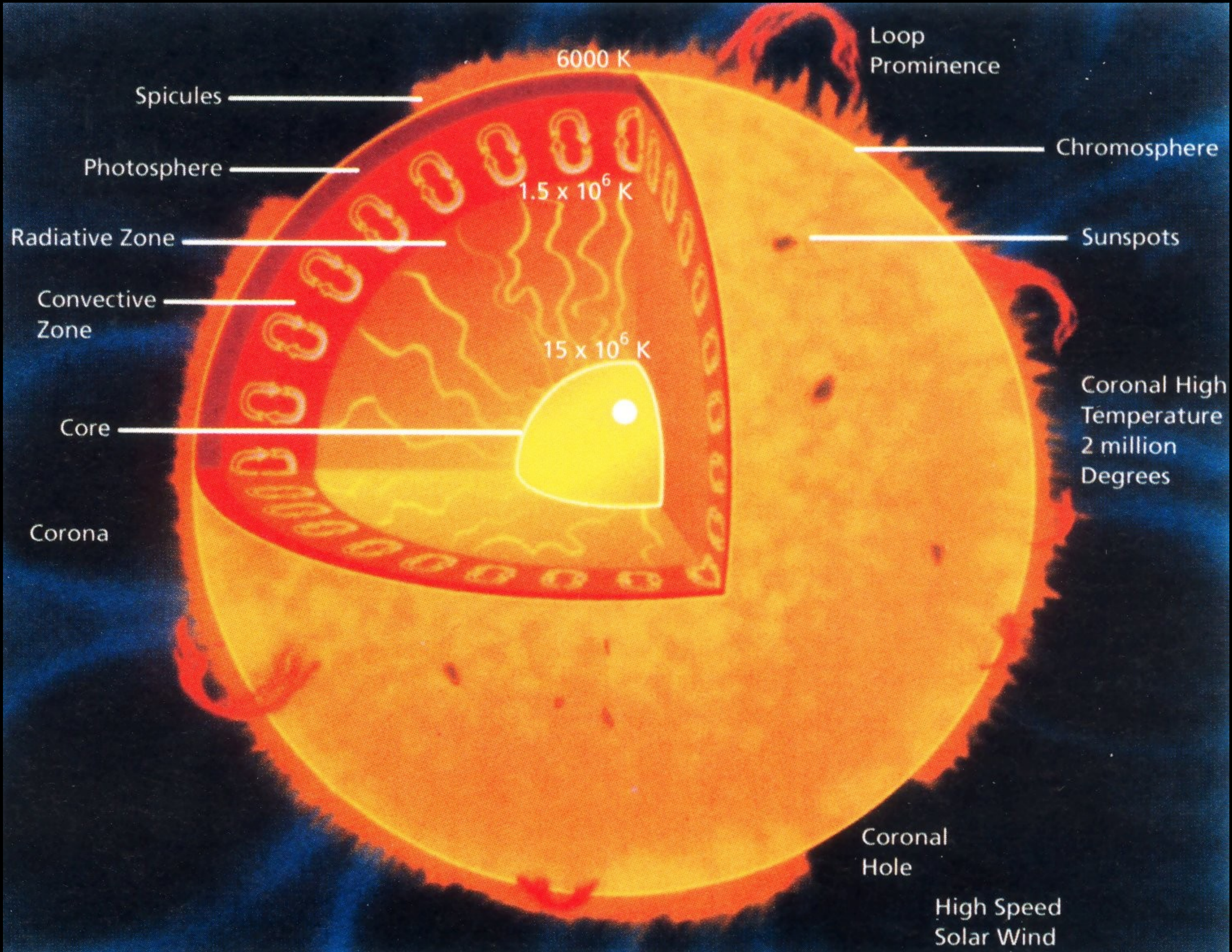
M.V. Khotyaintsev, V.N. Melnyk, Bo Thide' and O.O. Konovalenko
"Combination scattering by anisotropic Langmuir turbulence with application to solar radar experiments", *Solar Physics*, in press, 2005

Motivation of solar radar experiments

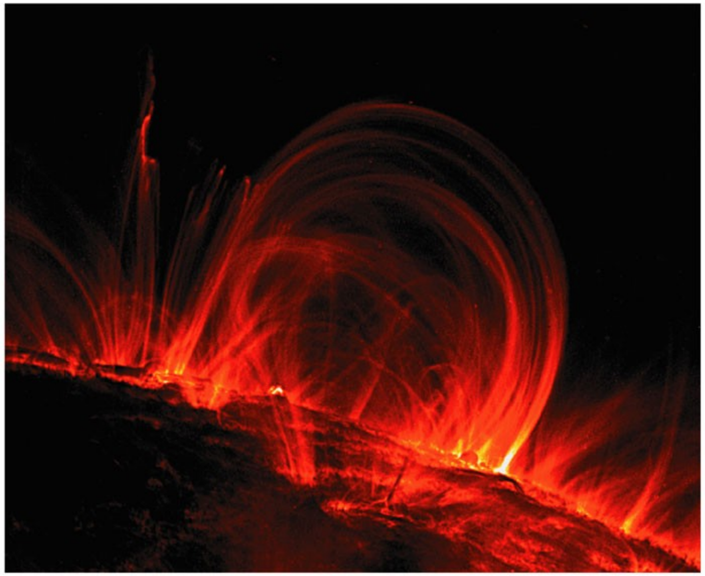
- radar is an additional tool for solar study
- to investigate dynamics of the solar corona
- solar wind acceleration
- coronal electron density profile
- magnetic field probing
- remote sensing of plasma wave turbulence
- detection of coronal mass ejections (CMEs)

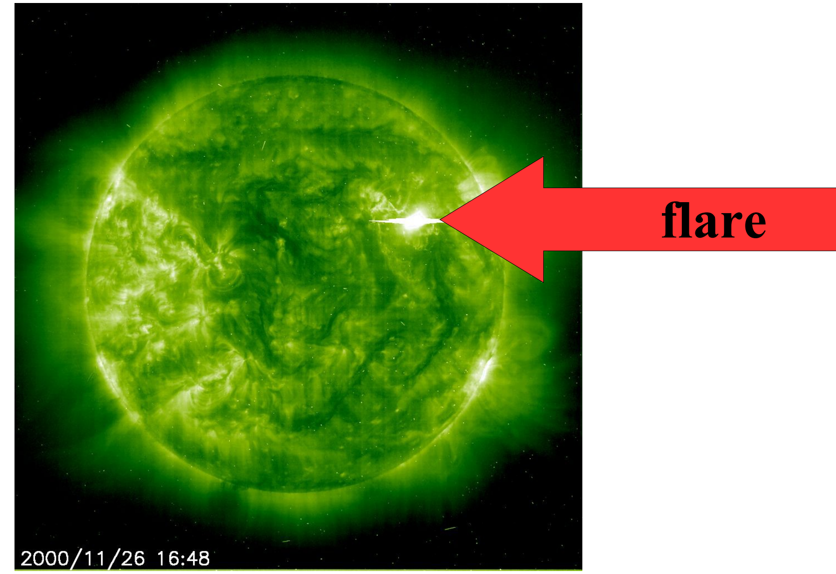
- recent experiment proposals by Thide' (2002), Coles (2004), Rodriguez (2004)

The structure of the Sun

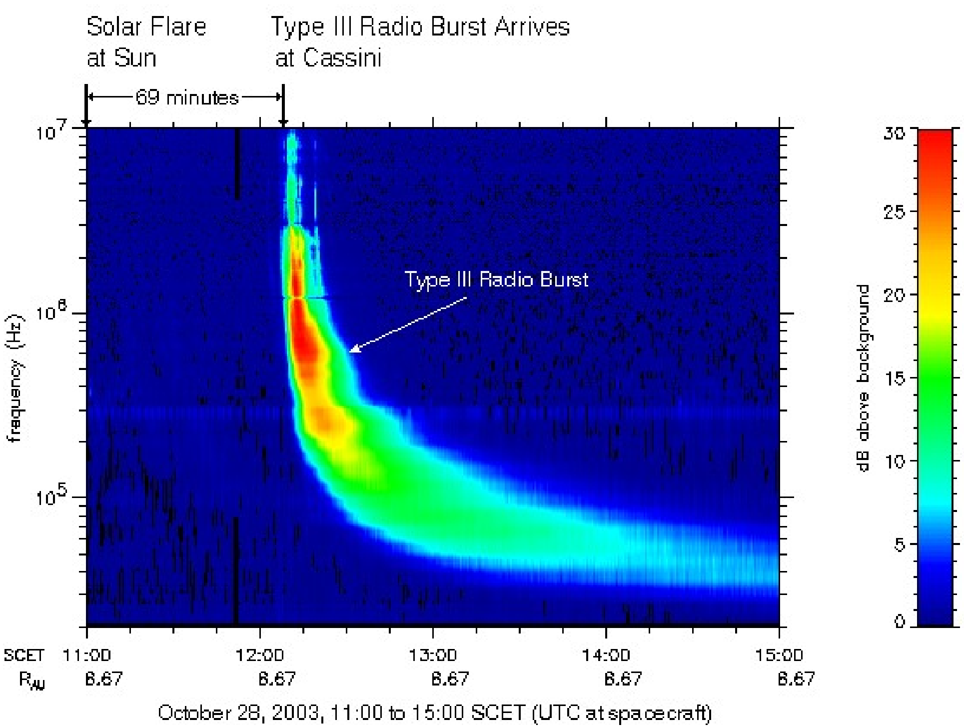


Prominences, flares and type III radio bursts





X-ray observation with the EIT on SOHO



Type III solar burst

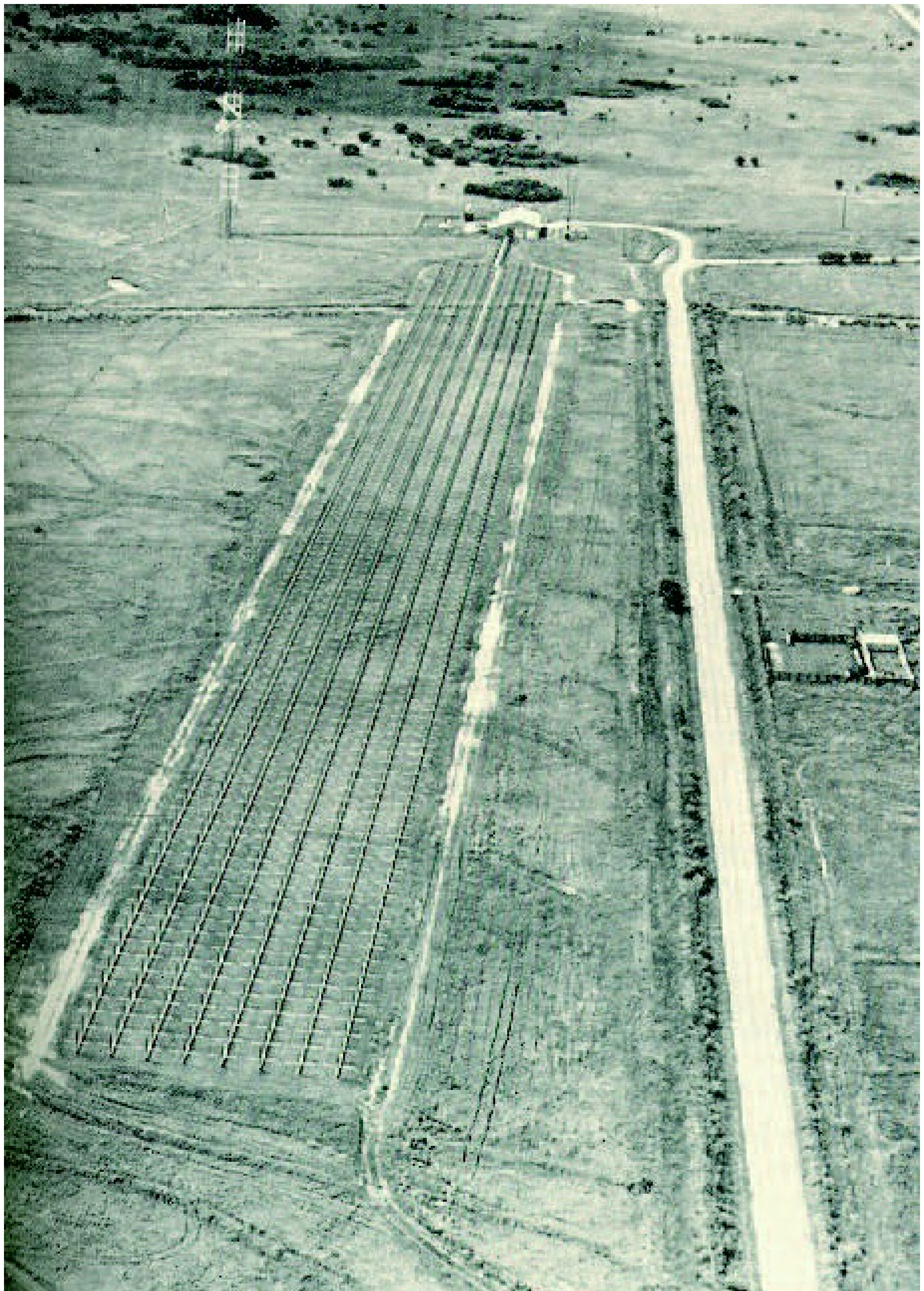
- are associated with solar flares
- attributed to beams of electrons with velocities v = 0.2 – 0.6 c
- generate Langmuir turbulence
- radiation is emitted at the local plasma frequency => density probe

Solar radar experiments

RADAR = RAdio Detection And Ranging

- 1940s – first radar studies of space objects (the moon)
- 1959 – first solar radar experiment at 25 MHz by a Stanford group
- 1961-1969 – daily experiments at 38 MHz by an MIT group at El Campo, Texas
- 1977 and 1978 an attempt to observe scatter from Langmuir waves in the corona using a **2380 MHz**, transmitter at Arecibo
  no echo observed most likely because of the **too high frequency** used
- 1996-1998 – experiment at **9 MHz** at the Russian Sura transmitter and the Ukrainian UTR-2 radio telescope
  no echo observed because of the too **low frequency** used

The El Campo solar radar experiment



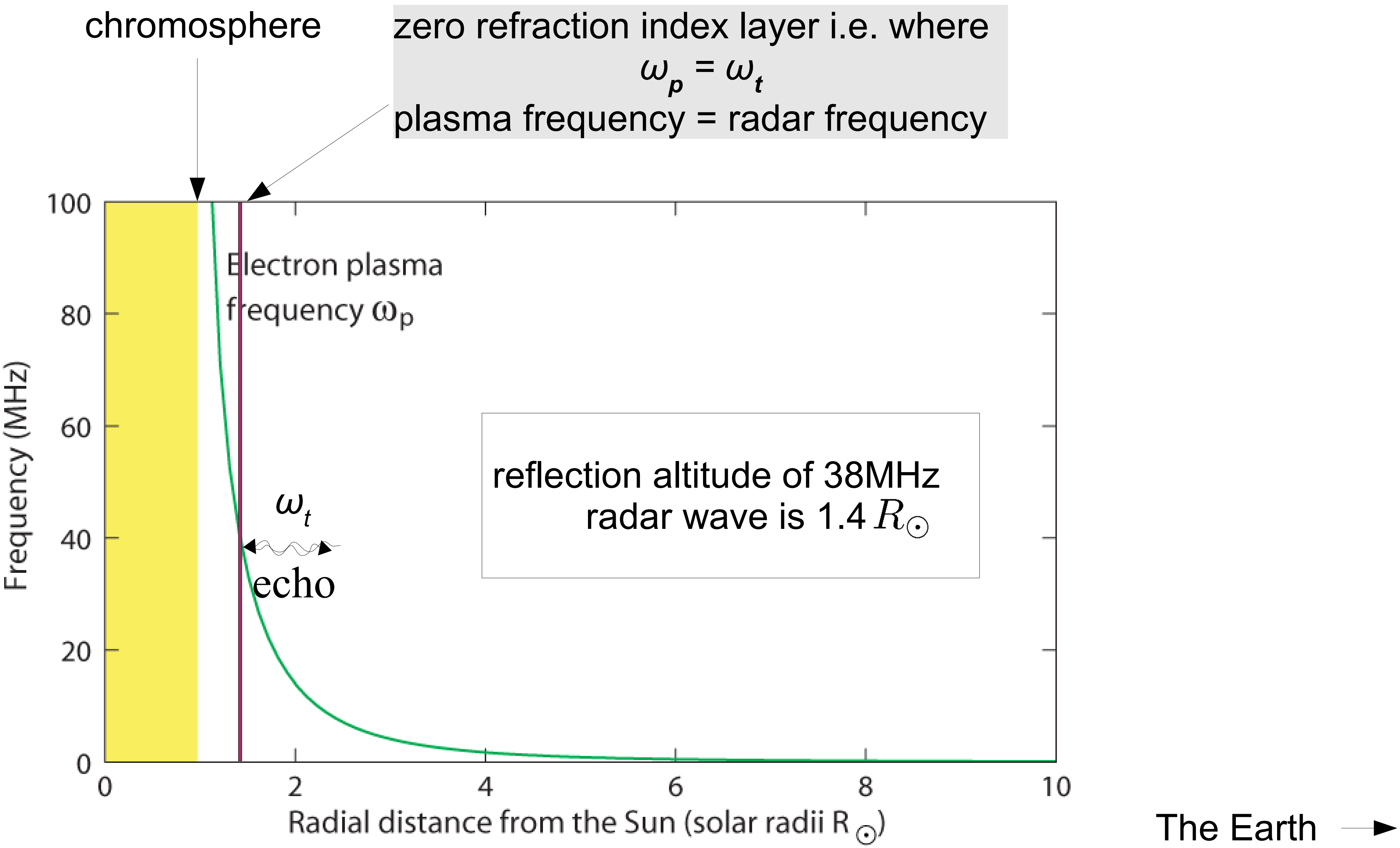
Operating frequency:	38.25 MHz
Total power:	500 kW
Beam size:	1° x 6°
Size of the Sun:	0.5°
Gain:	32-36 dB
Eff. radiated power:	1300 MW

Operation mode:

16 min. of transmission followed by
16 min. of reception

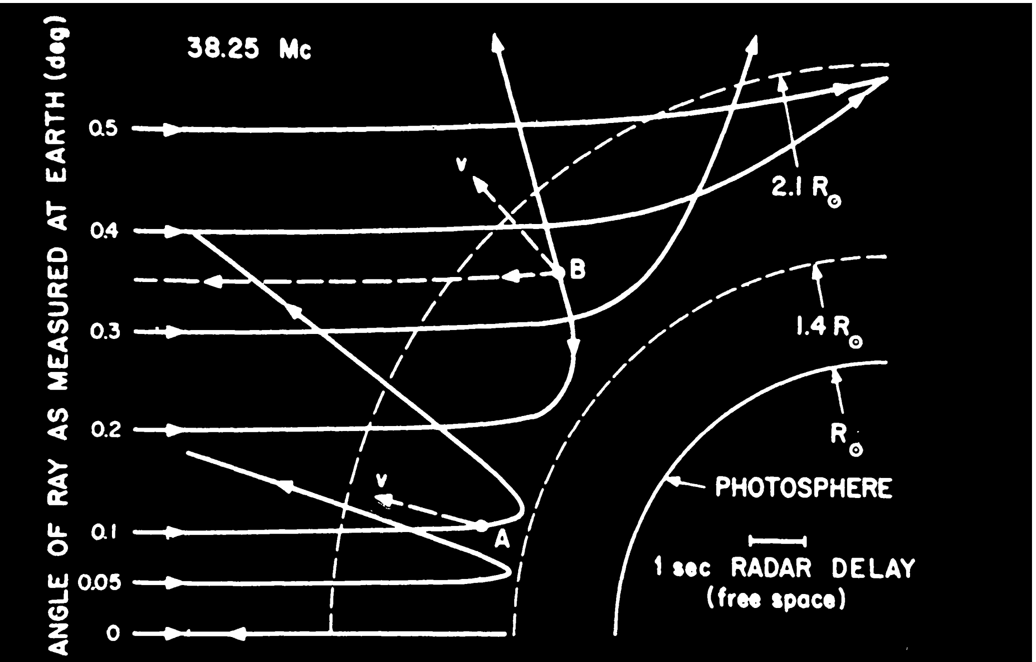
light travels from the Sun
to the Earth in 8 min

Theory: specular reflection of a radio wave the corona (1D)



Specular reflection from the spherically-symmetric corona

Ray paths at 38 MHz in the corona



Computed ray paths at 38 MHz; reflections are assumed to occur against the irregularities moving between 1.4 $R_\odot$ and 2.1 $R_\odot$ (James, 1964).

- reflection occurs from the layer with the zero refracting index, i.e. where

  $$\omega_p = \omega_t$$

  plasma frequency = radar frequency
- reflection from a r**ough** sphere
- collisional absorption

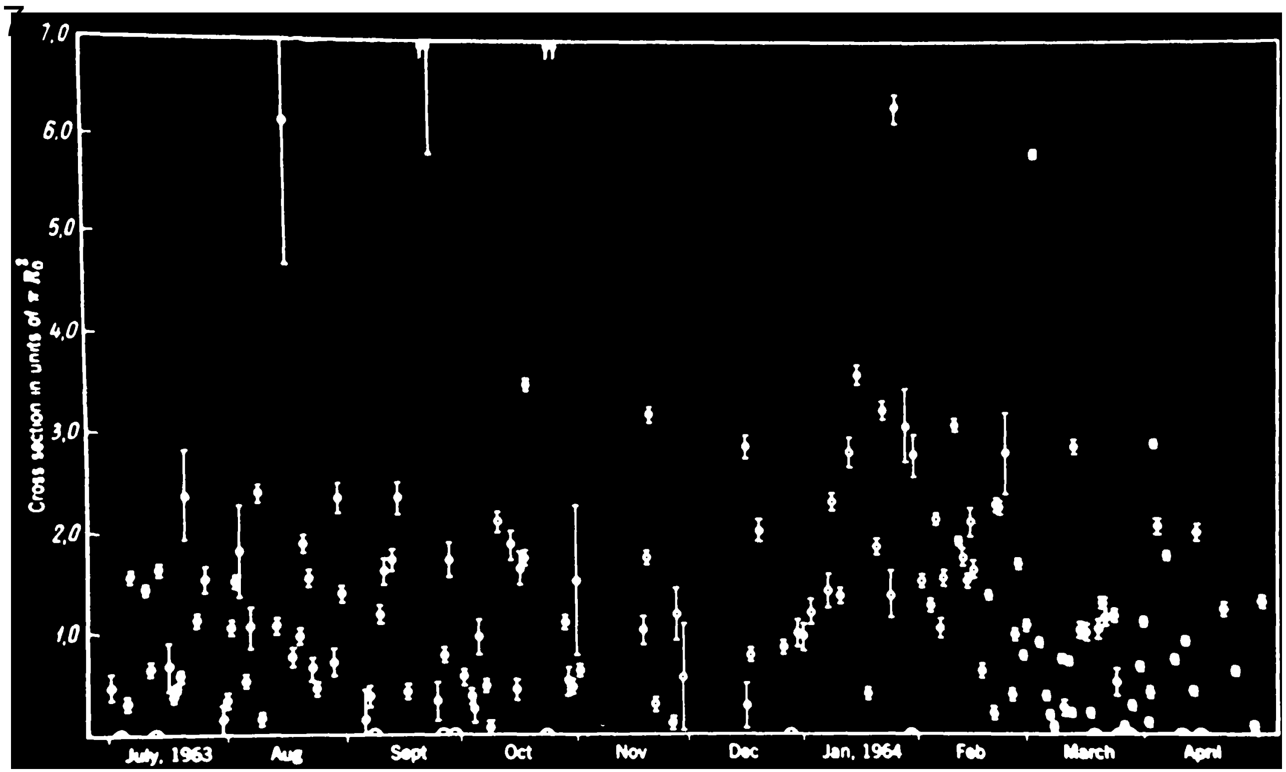
Volume scattering by large-scale (L >> λ) density irregularities

Cross-section $S \approx 1.5\,\pi R_\odot^{\,2}$

Solar cross-sections detected with the El Campo radar

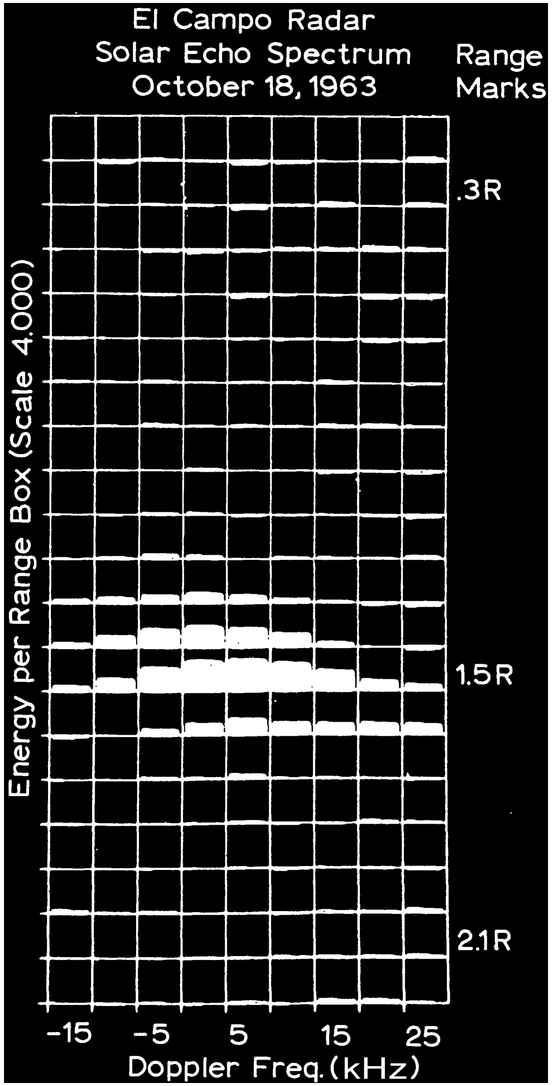
- Cross-sections observed are in the range 0 < *S* < 800 $\pi R_{\odot}^{2}$
- The majority of cross-section *S* = 0 - 4 $\pi R_{\odot}^{2}$

Cross-sections in units of $\pi R_{\odot}^{2}$

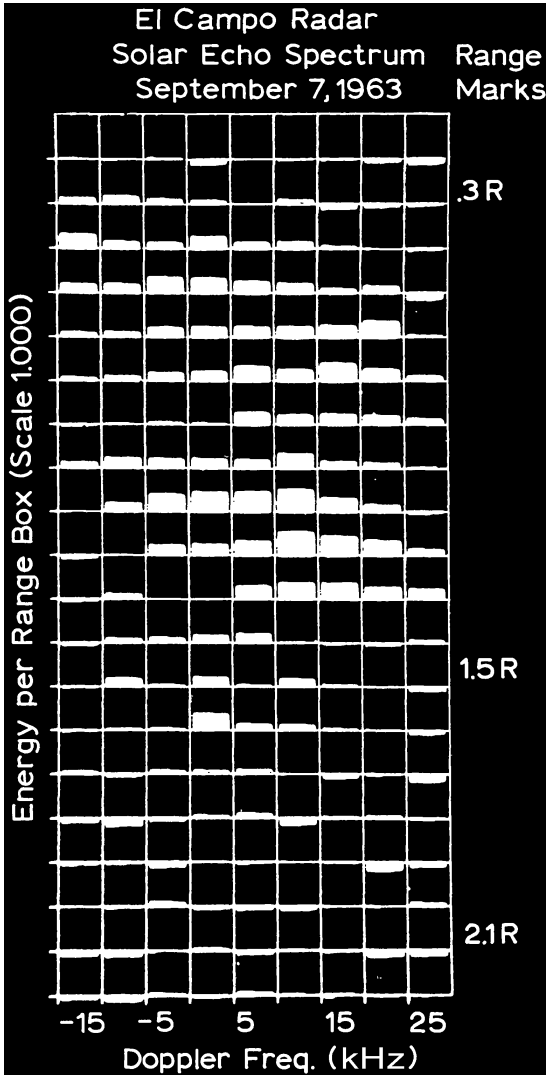


July, 1963 – April, 1964

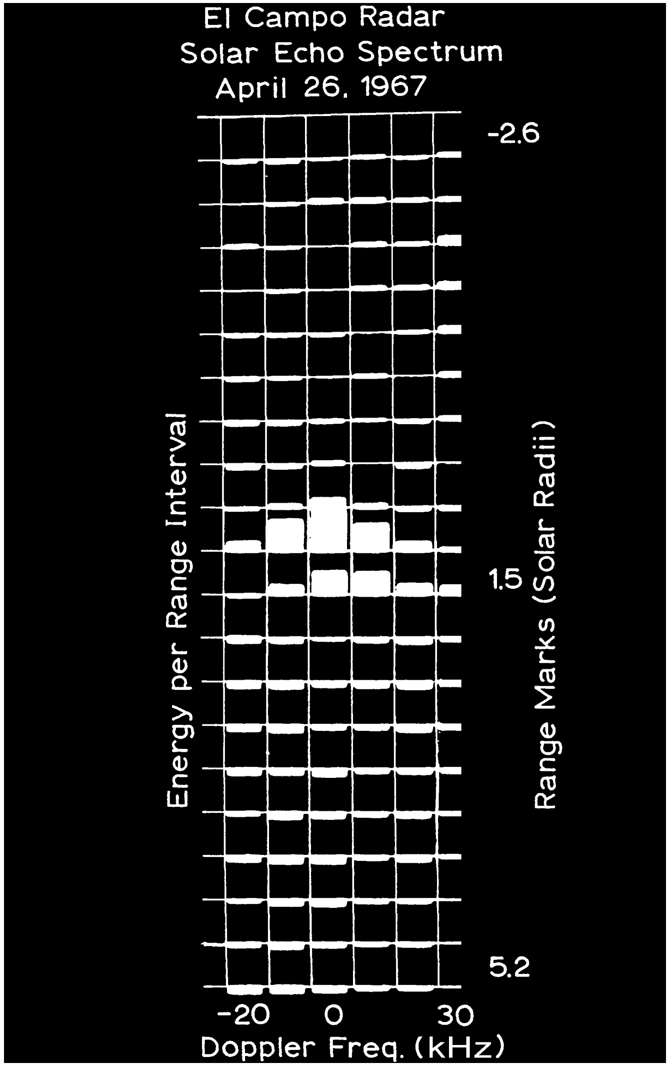
El Campo radar echo spectrum



Type A (70%)



Type B: echo is coming from different altitudes



Extreme case of type B spectrum

- experimental results could not be explained by the specular reflection theory

Induced (combination) scattering by a wave turbulence

- corona contains areas of localized plasma wave turbulence:
  Langmuir (*l*) and ion-sound (*s*)
- echo signal may be formed due to resonant interaction of the radar wave with the waves of the turbulence (induced scattering)

DECAY **($t \rightarrow l + t'$)**

COALESCENCE **($t + l \rightarrow t'$)**

resonant conditions

Decay:

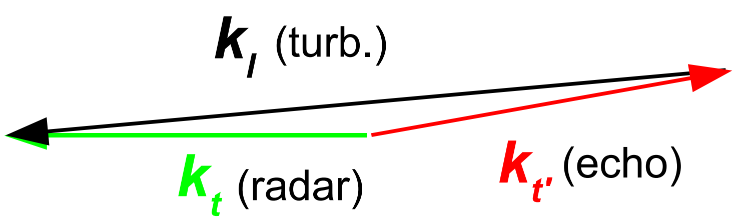
$$\omega_t = \omega_l + \omega_{t'}$$

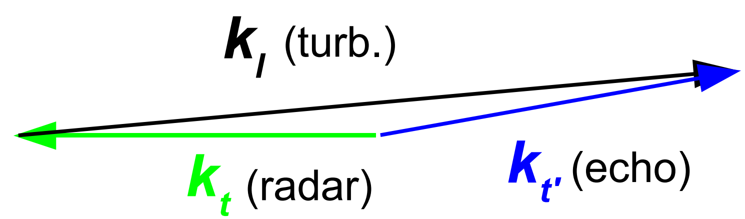
$$\mathbf{k}_t = \mathbf{k}_l + \mathbf{k}_{t'}$$

Coalescence:

$$\omega_t + \omega_l = \omega_{t'}$$

$$\mathbf{k}_t + \mathbf{k}_l = \mathbf{k}_{t'}$$





- radar wave ω_t is scattered into two satellites:

  $\omega_t - \omega_l$ (red-shifted) and $\omega_t + \omega_l$ (blue-shifted)

- qualitative description is given by **the kinetic wave equation** (Tsytovich, 1970)

Paper : Combination scattering by anisotropic Langmuir turbulence with application to solar radar experiments

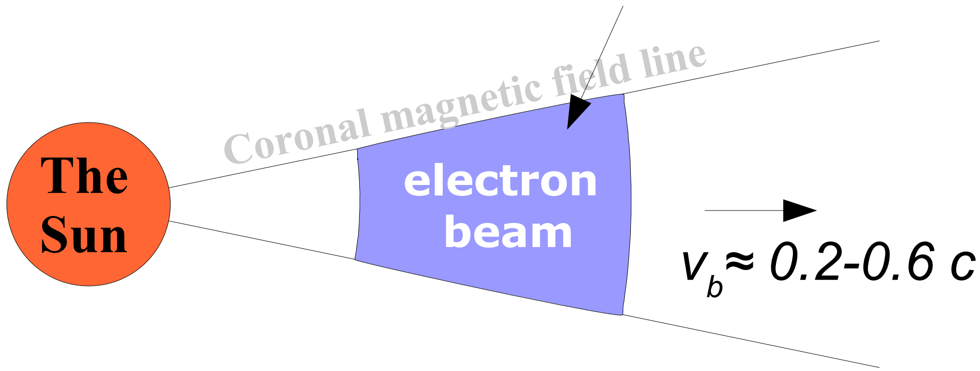
Motivation

- can radar echoes come from type III burst turbulence?
- properties of the echo and what can we derive from them?
- to give hints for future radar experiments: transmitting freq., receiving bandwidth, etc.

- We assume existence of a Langmuir turbulence generated by type III electrons (*l*)
- Existence of the radar wave (*t*)
- Induced scattering process in a weak turbulence limit
- Focus on backscattering

What is a type III solar burst?

Beam instability => Langmuir turbulence



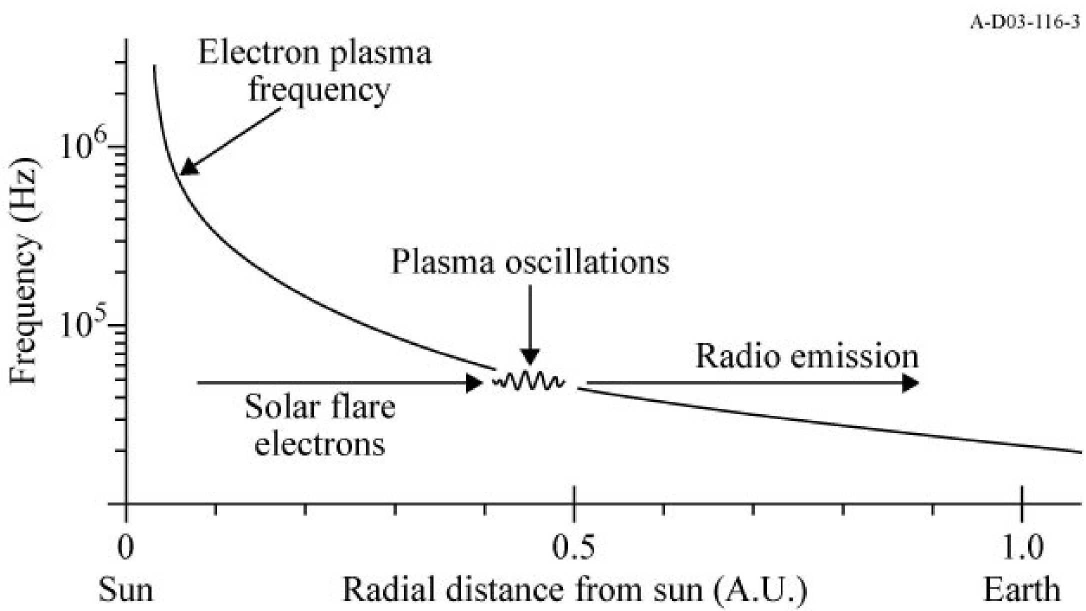
Radiation generation:

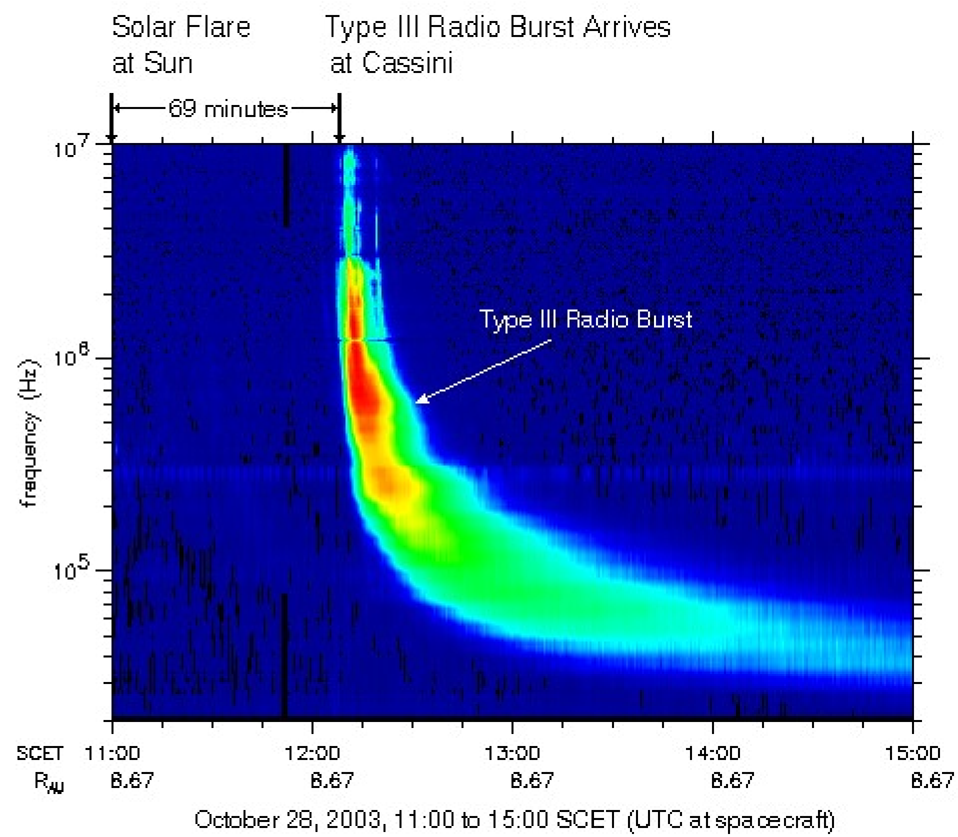
1) $l \rightarrow l' + s$ (*s* – ion-sound)
2) $l + s \rightarrow t$

t' t

echo $\omega_l >> \omega_s$ => $\omega_t \approx \omega_p$

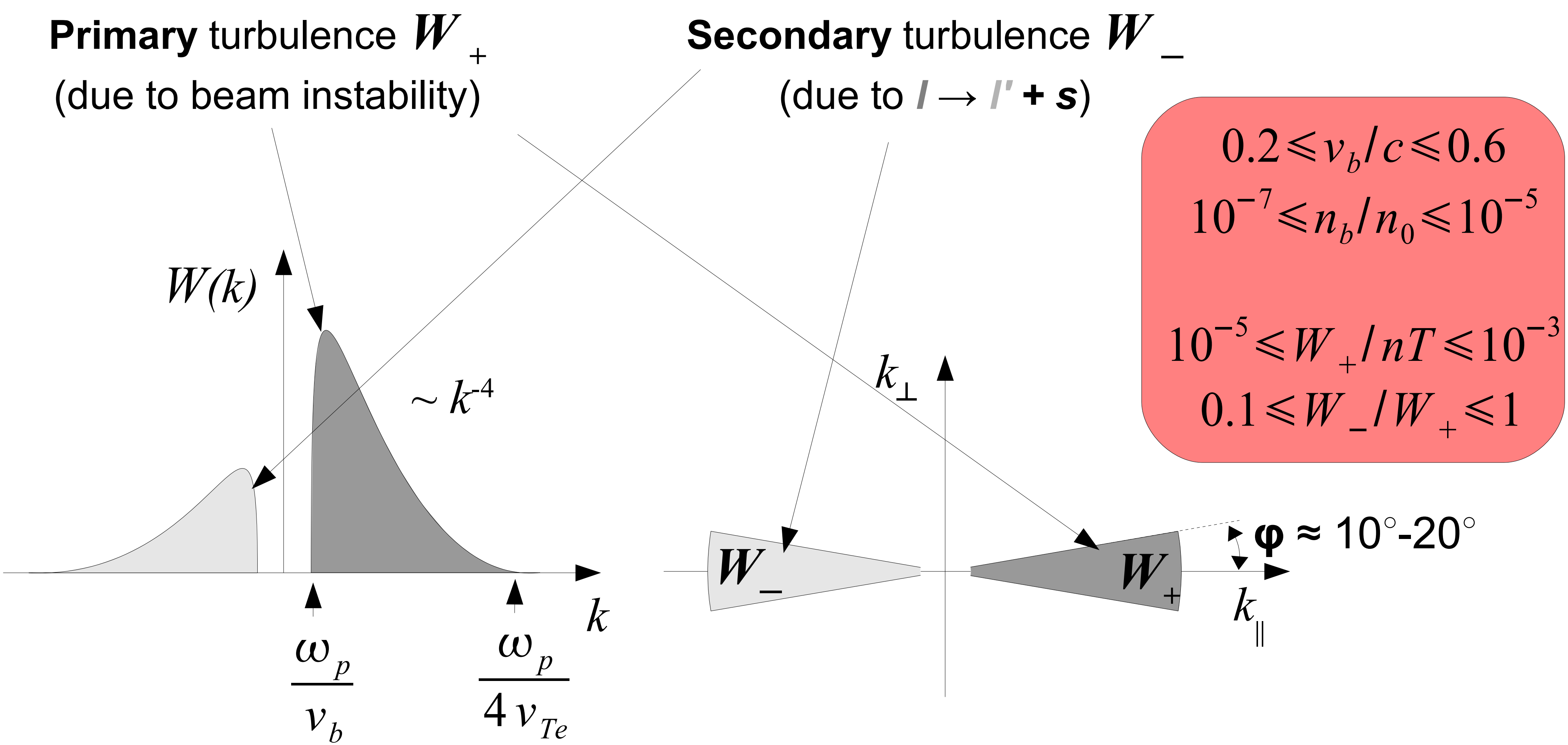
(radiation at plasma frequency) radar





Langmuir turbulence spectral energy density W(k)

Mel'nik et. al. (1999)



$$0.2 \leqslant v_b / c \leqslant 0.6$$

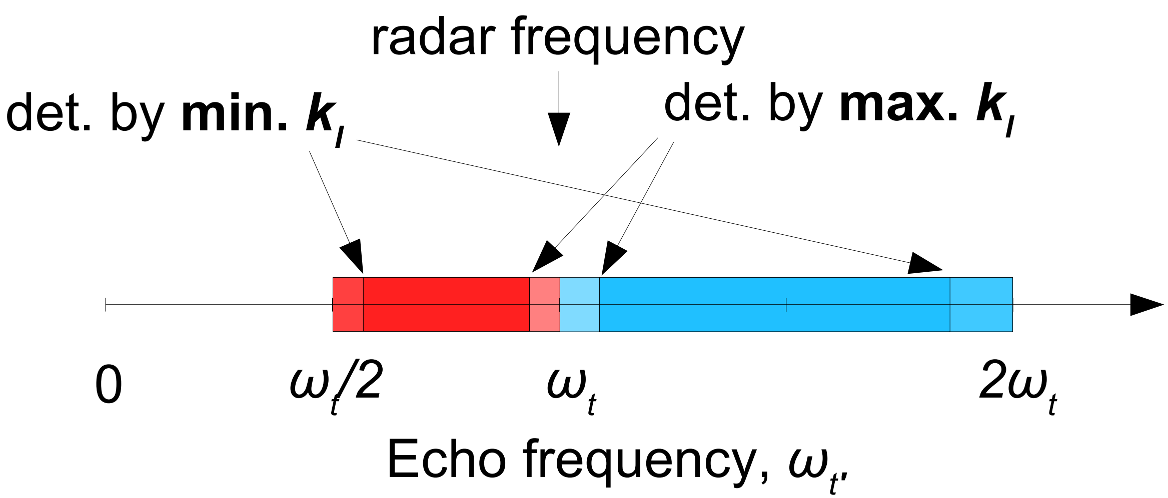
$$10^{-7} \leqslant n_b / n_0 \leqslant 10^{-5}$$

$$10^{-5} \leqslant W_+ / nT \leqslant 10^{-3}$$

$$0.1 \leqslant W_- / W_+ \leqslant 1$$

Echo frequency

- echo frequency shift $|\Delta\omega| = |\omega_{t'} - \omega_t| \approx \omega_p$ (plasma frequency)
- $\Delta\omega < 0$ (decay) $\Delta\omega > 0$ (coalescence)
- echo frequencies lie in a limited range



minimal $|\Delta\omega|$ is determined by **max. k_l** of turbulence spectrum

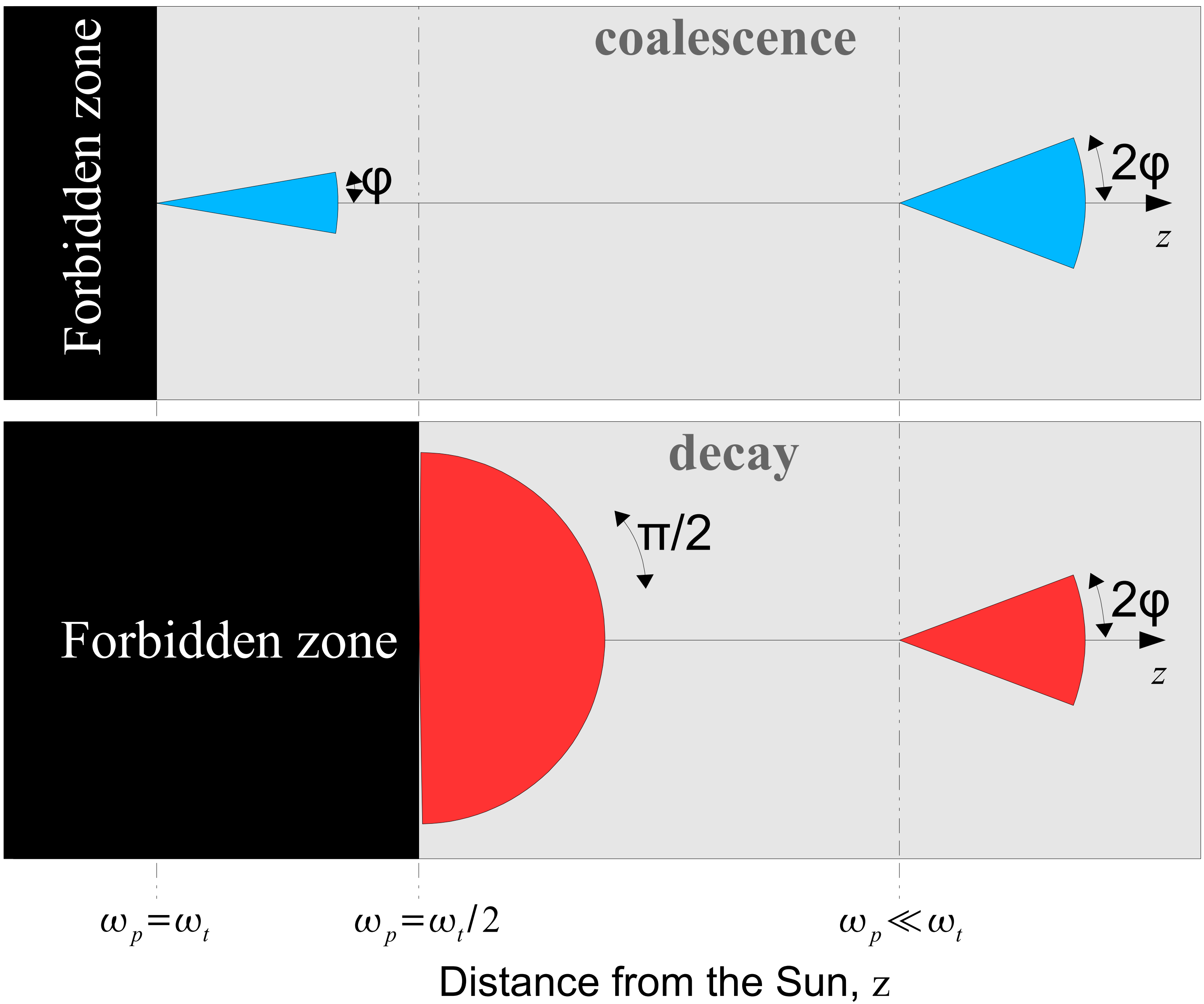
maximal $|\Delta\omega|$ is determined by **min. k_l** (beam velocity)

- echoes with $\Delta\omega > 0$ are due to scattering by the **primary** turbulence W_+
- echoes with $\Delta\omega < 0$ are due to scattering by the **secondary** turbulence W_-

- turbulence **anisotropy** => scattering by $\Delta k \ll k$

Echo angular spread

φ - angular spread of Langmuir waves



Efficiency of the scattering process

- The kinetic wave equation *(Tsytovich, 1970)* for the intensity of the incident radar wave $\mathbf{W}^{t}_{kt}$ may be simplified to the radiation transfer equation

$$\frac{dW^{t}_{k_t}}{dz} = -[\mu_+(z) + \mu_-(z)]\,W^{t}_{k_t}$$

μ_+ and μ_- are coeff. of attenuation of the radar wave due to scattering

- obtained analytical expressions for μ_+ and μ_- show:

decay is most efficient at $\omega_p \approx \omega_t / 2$

coal. is most efficient at $\omega_p \approx \omega_t$

- the scattering process is "optically thick" ($\tau = \int_{z1}^{z2} \mu_+ + \mu_- \, dz \geqslant 1$) for $W \geq 10^{-5}\, n\kappa T$

- μ_+ and μ_-, angular characteristics of scattered signal → spectrum of echo

Summary of the paper

- Studied the process of scattering of a radar beam by an anisotropic Langmuir turbulence
- Showed, that the frequency of radar echo is within a limited frequency range
- Angular spread of blue-shifted and red-shifted echo differ dramatically
- Decay and coalescence are most efficient at alt. of $\omega_p \approx \omega_t/2$ and ω_t
- Obtained estimates of an echo spectrum
- Minimum turbulence level needed for a reflection is $W \approx 10^{-5}\, nT$
- Radar experiments may be used to study the spectrum of the beam-generated Langmuir turbulence

Summary and outlook

- Solar radar can be a useful tool for solar studies
- There is a need in new radar experiments
- There is a need in further development of theory
- Future work: theory of radar reflections from CMEs