Radio and mm astronomy

Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

16.10	*Introduction & Overview*	*(HL & HB)*
23.10	*Emission mechanisms, physics of radiation*	*(HB)*
30.10	*Telescopes – single-dishs*	*(HL)*
06.11	*Telescopes – interferometers*	*(HB)*
13.11	*Instruments – continuum radiation*	*(HL)*
20.11	**Instruments – line radiation**	**(HB)**
27.11	Continuous radiation (free-free, synchrotron, dust, CMB)	(HL)
04.12	Line radiation	(HB)
11.12	Radiation transfer	(HL)
18.12	Effelsberg Excursion	
	Christmas break	
08.01	Molecules and chemistry	(HL)
15.01	Physics and kinematics	(HB)
22.01	Applications	(HL)
29.01	Applications	(HB)
05.02	*last week, no lecture*	

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1213.html

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Topics today

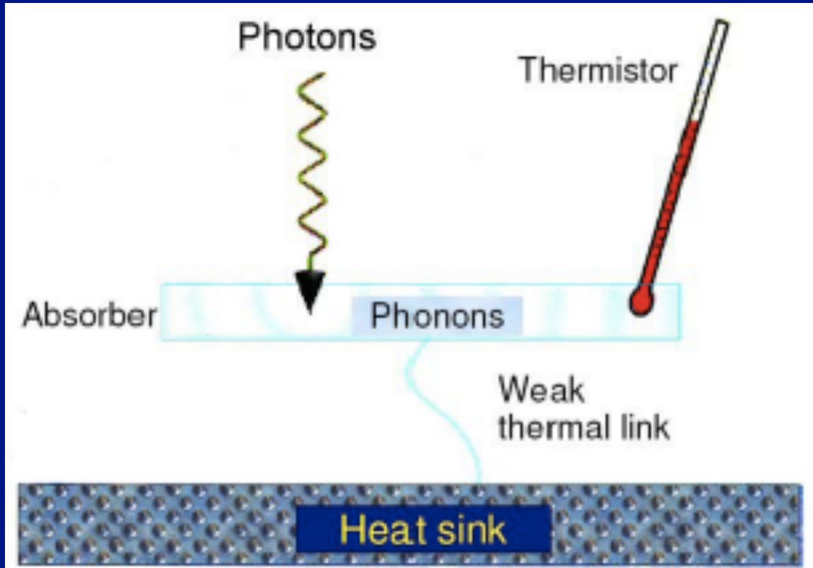
- Incoherent bolometers versus coherent line receivers, front ends and back ends
  - Basic principles
  - Front ends, heterodyne receivers

- Back ends
  - Correlator
  - FFTS
  - AOS
  - Interferometric cross correlators

- Polarization

- Applications

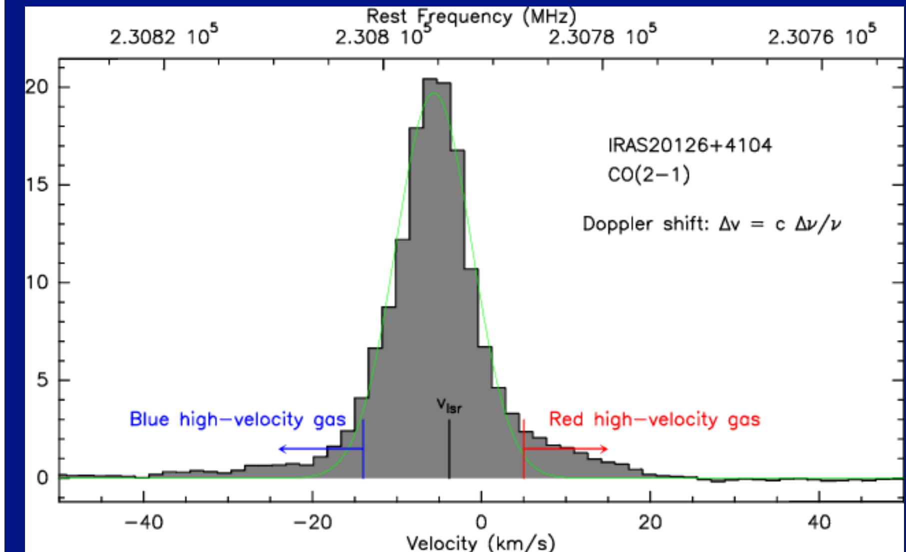
Incoherent bolometers and coherent line receivers



- Broad bandpasses, collect incoherently all photons

MAMBO at IRAM 30m

210GHz CO(2-1)@230GHz 290GHz

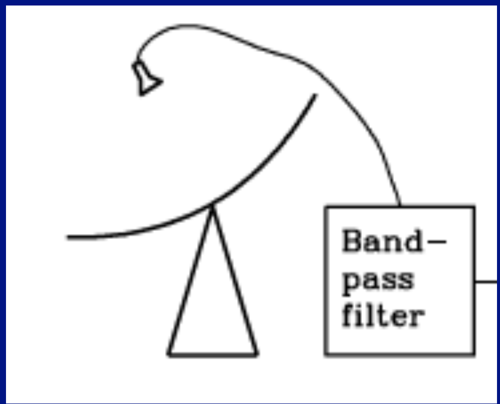


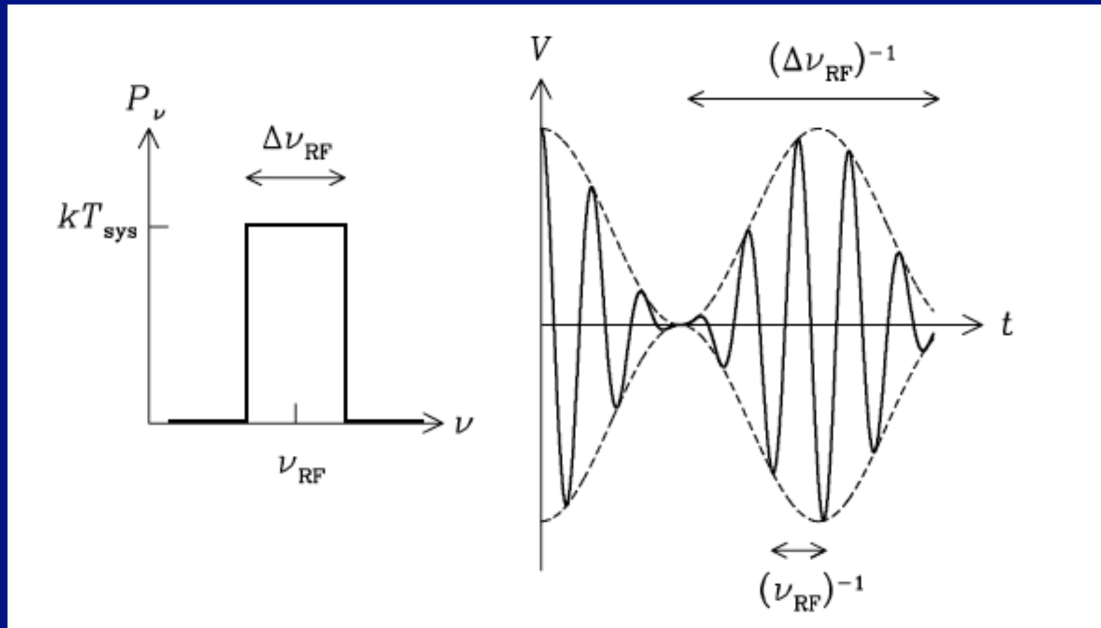
- Resolve the line information at high spectral resolution, wave information is preserved

- Differentiation of:
  front end → receiving signal
  back end → spectrally resolving it

Basic detection principles

Frequency- and time-domain are related via fourier transformation.

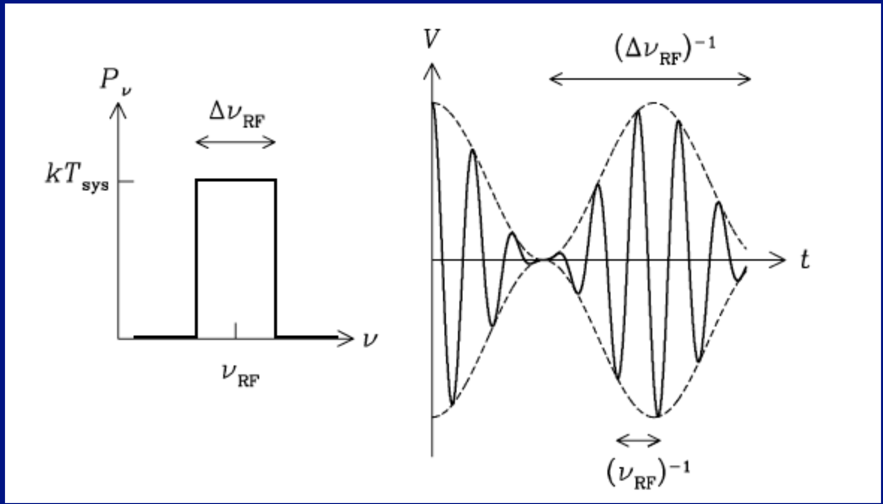


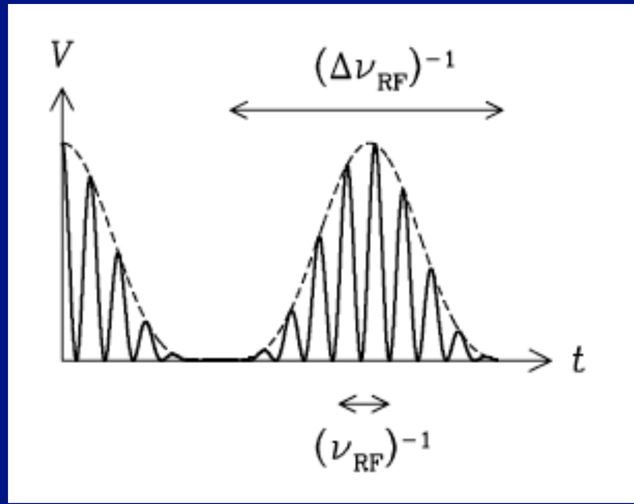


Output V of frequency filter proportional to $\cos(2\pi\nu_{RF})$

Amplitude envelope varies randomly on time scales: $\Delta t \approx (\Delta\nu_{RF})^{-1} > \nu_{RF}^{-1}$

Square law detector





$V_i \approx \cos(2\pi\nu_{RF})$ → $V_o \propto \cos^2(2\pi\nu_{RF}) \propto [1 + \cos(4\pi\nu_{RF})]/2$

Output signal (voltage) now proportional to input signal.

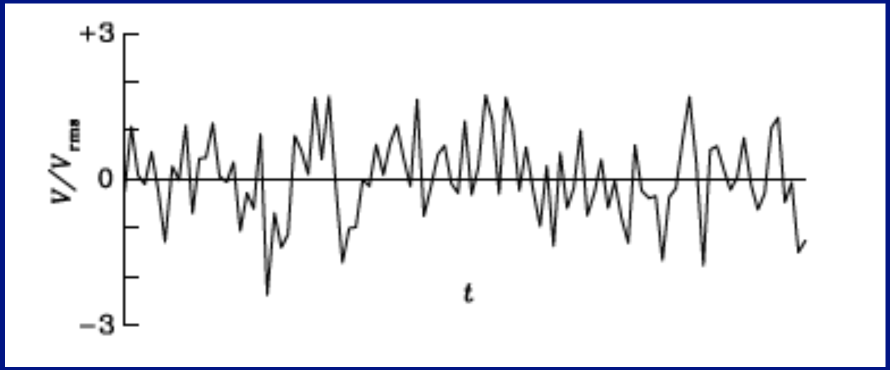
Both the rapidly varying components at frequencies $2\nu_{RF}$ and its envelope vary at time-scales shorter than variations of the expected sky signal.

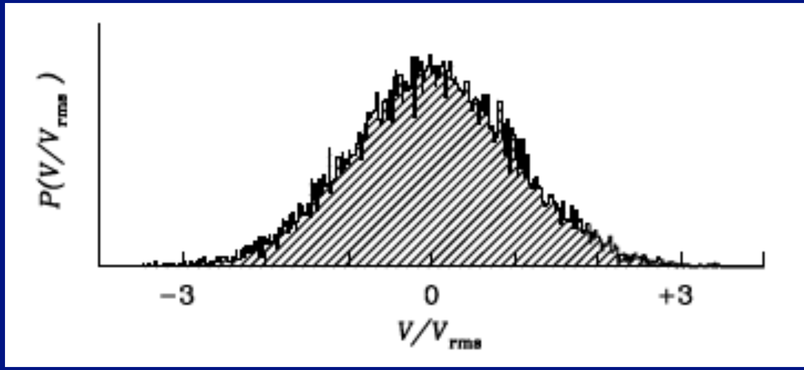
→ These rapid variations can be supressed by averaging/integration.

Time averages from integration

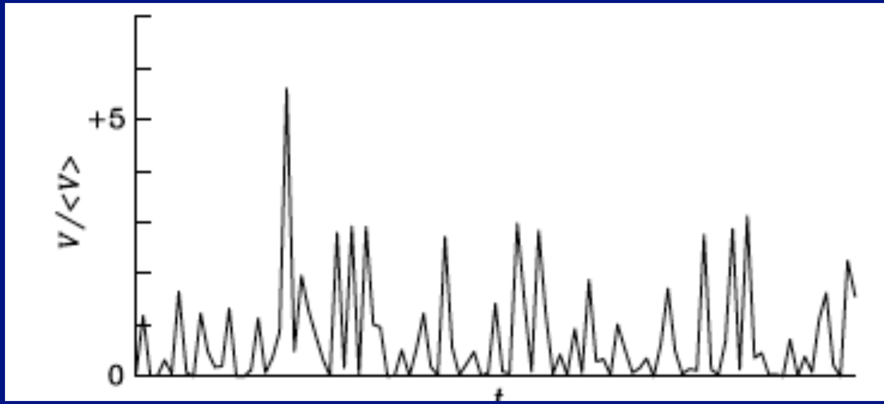
Before square law detector

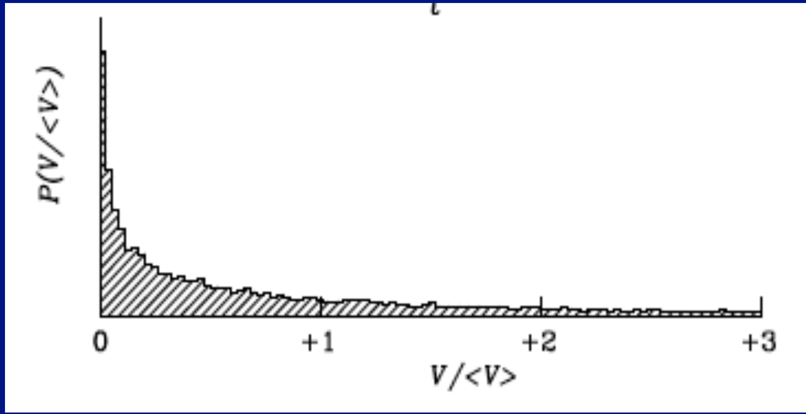
Times series (random noise example) Probability distribution





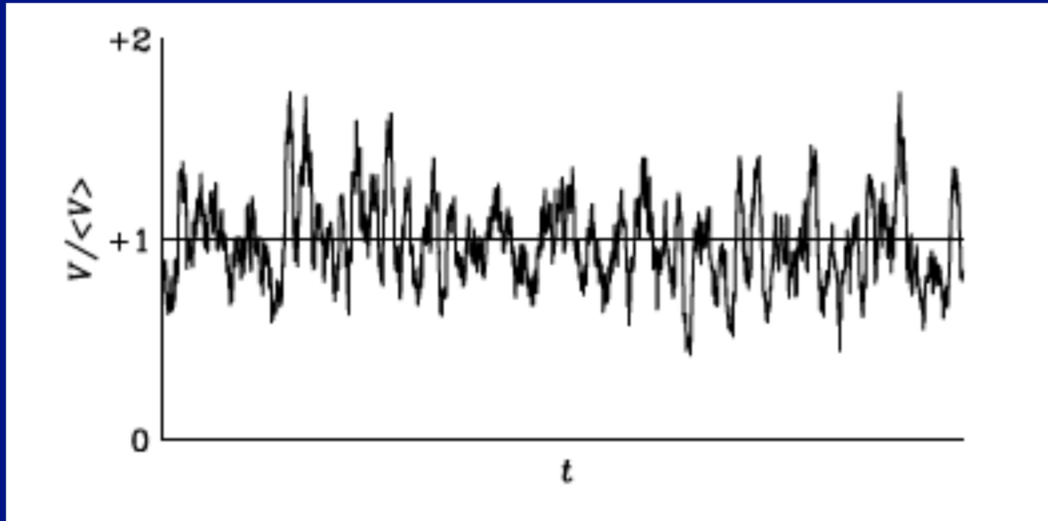
After square law detector

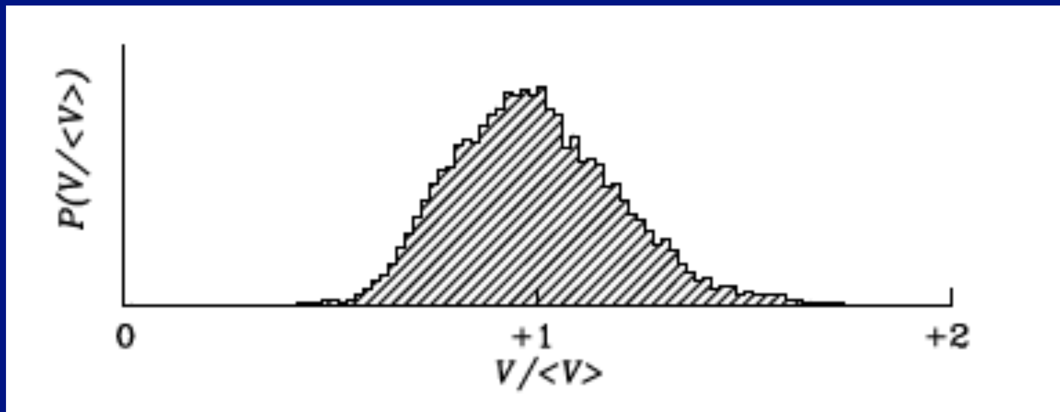




Time averages from integration

With a source signal > 0



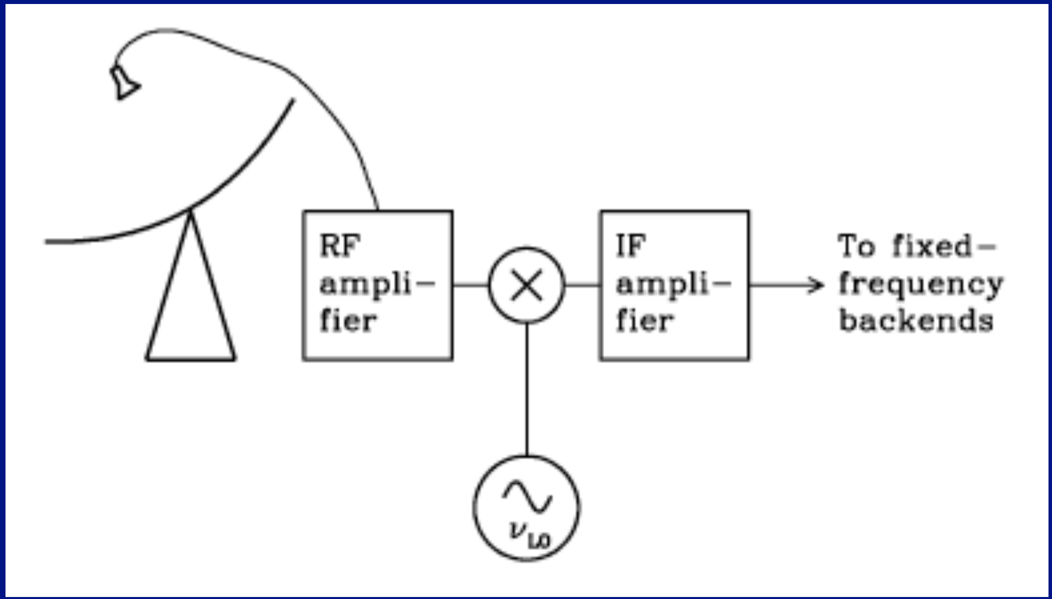


Radiometer equation

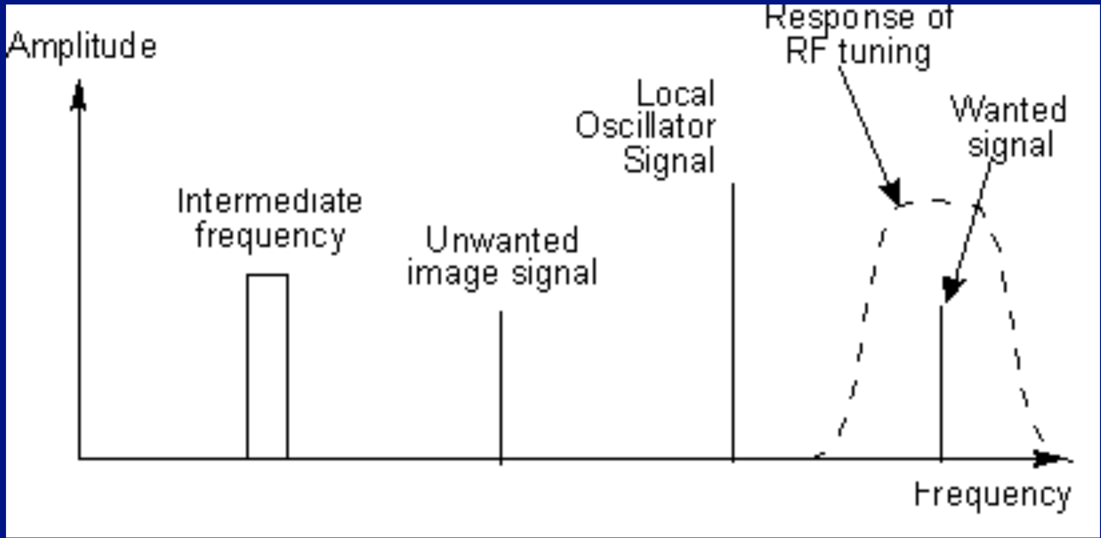
$$\sigma_{\mathrm{T}} \approx \frac{T_{\mathrm{sys}}}{\sqrt{\Delta\nu_{\mathrm{RF}}\tau}}$$

Heterodyne receiver I

- Signal processing at high frequencies technically very difficult and hence signal has to be down-converted to technically better accessible frequencies around a few GHz.
- "hetero dynamos" → the other force
- The receiver signal at frequency RF is mixed with a local osciallator LO to a lower frequency IF.



Heterodyne receiver II



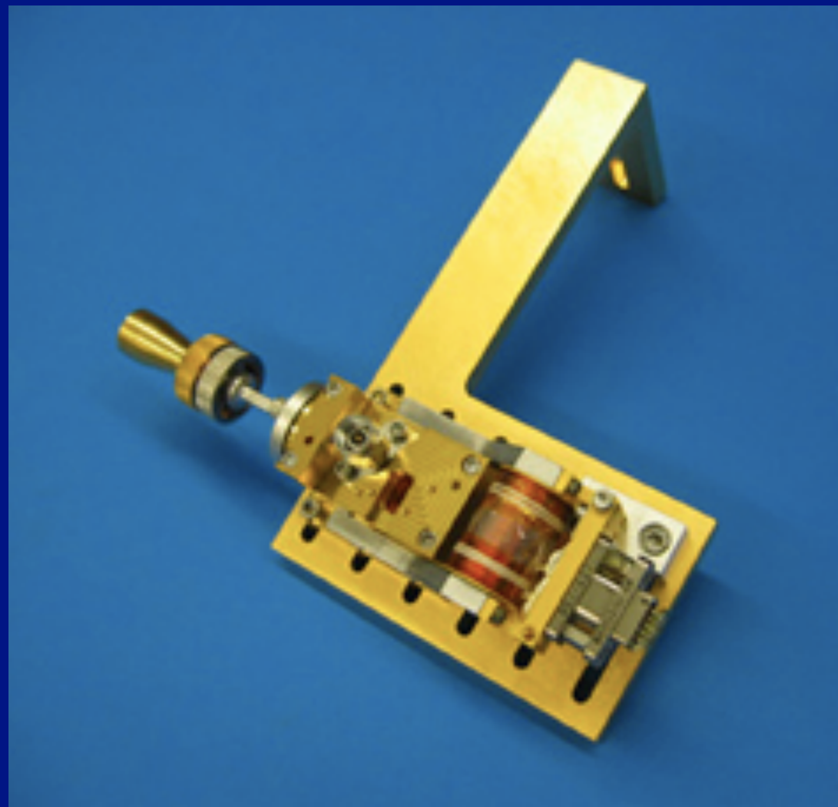
$$2\sin(2\pi\nu_{\rm LO}t)\times\sin(2\pi\nu_{\rm RF}t)=\cos[2\pi(\nu_{\rm LO}-\nu_{\rm RF})t]-\cos[2\pi(\nu_{\rm LO}+\nu_{\rm RF})t]$$

- The product of the receiver signal with the LO signal contains the sum and difference of the two signals → Signal and image sideband
- Sideband separation different technical issue.

- Advantages:
  - Further signal processing at low frequencies
  - Exact RF tuning can be done via LO tuning
  - Further spectroscopic processing can be done at fixed frequency.

Receiver examples

Parkes 21cm multi feed



180-280GHz receiver with horn

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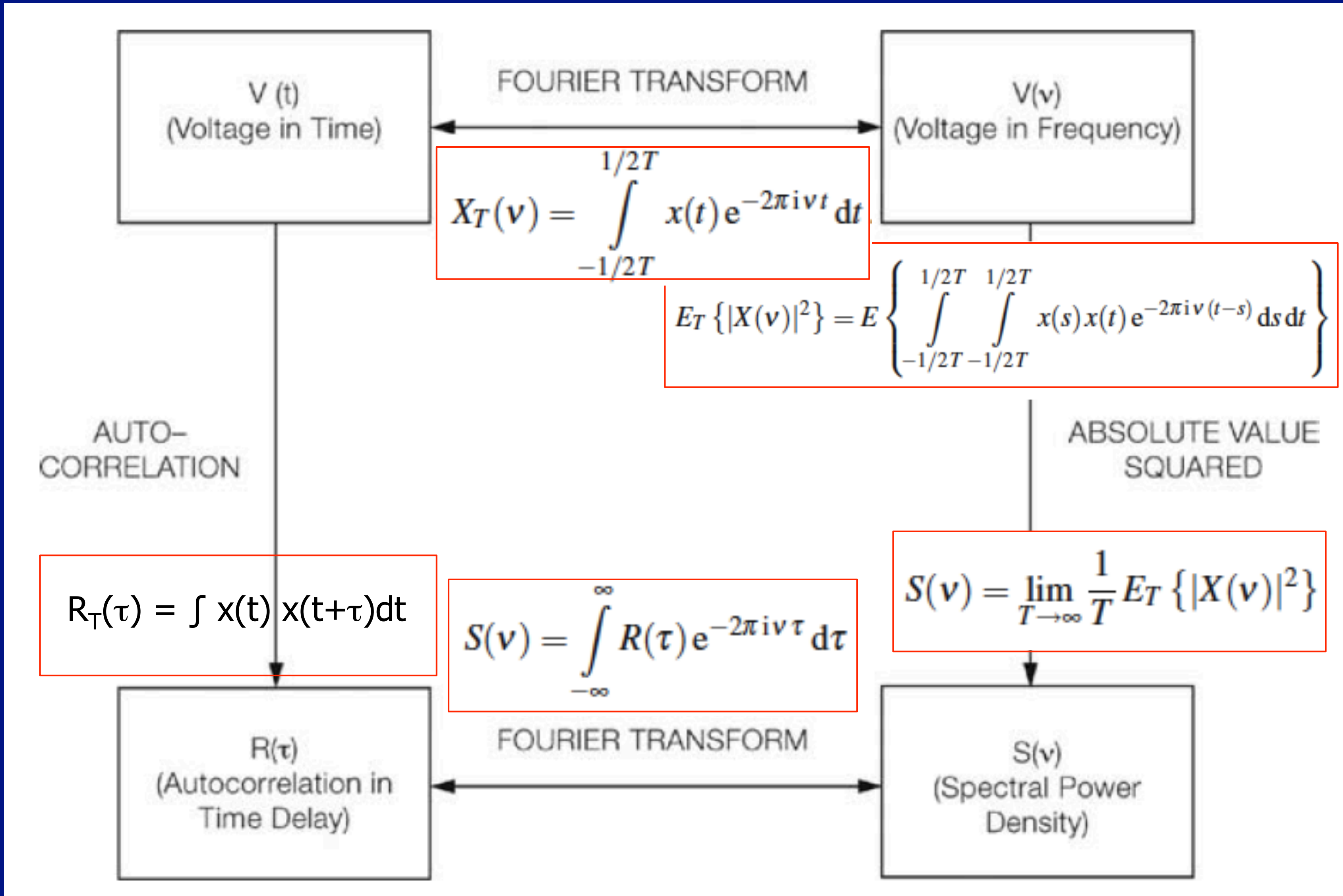
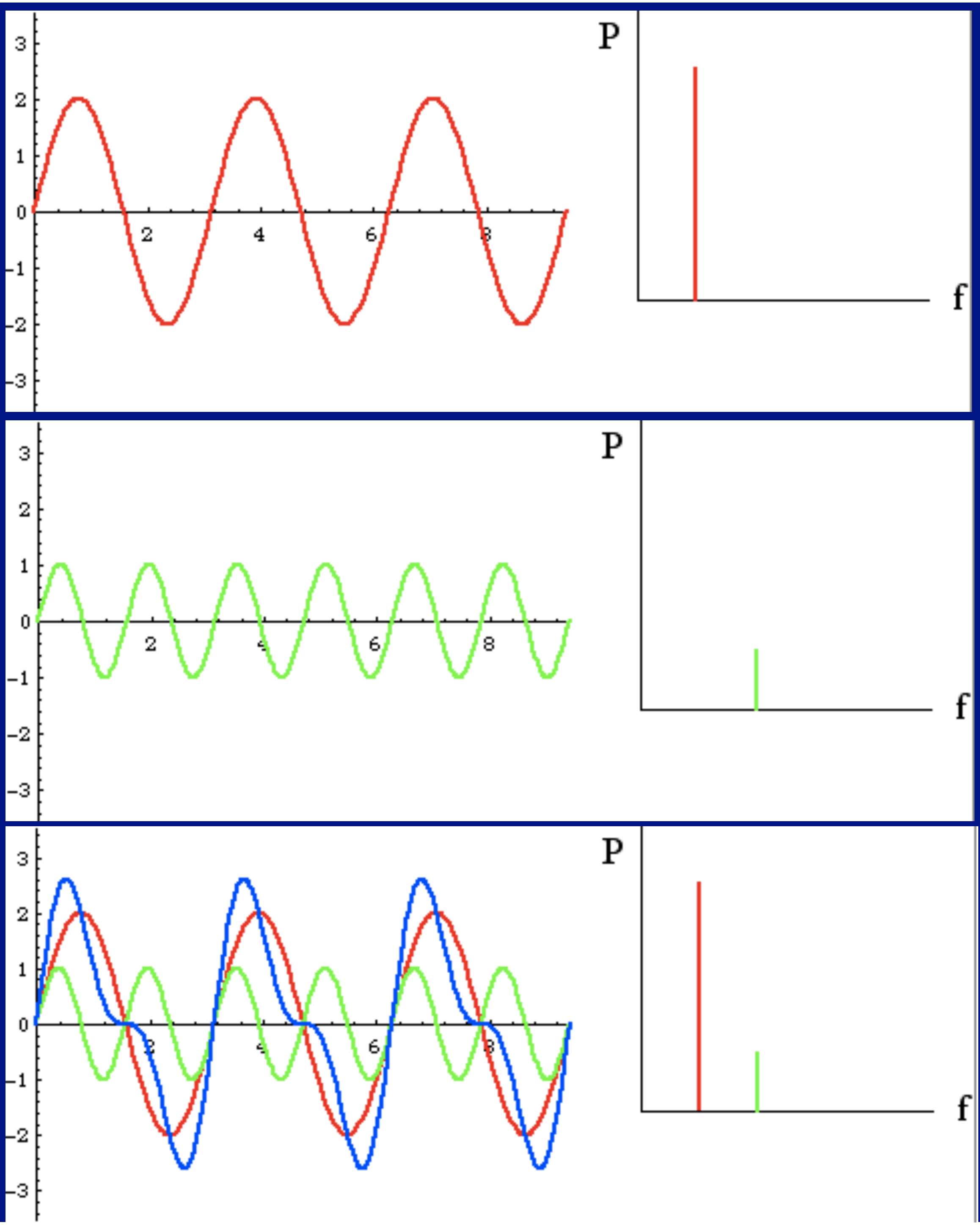
Fourier transform & autocorrelation spectrometer

Input time series from front end



Spectral output



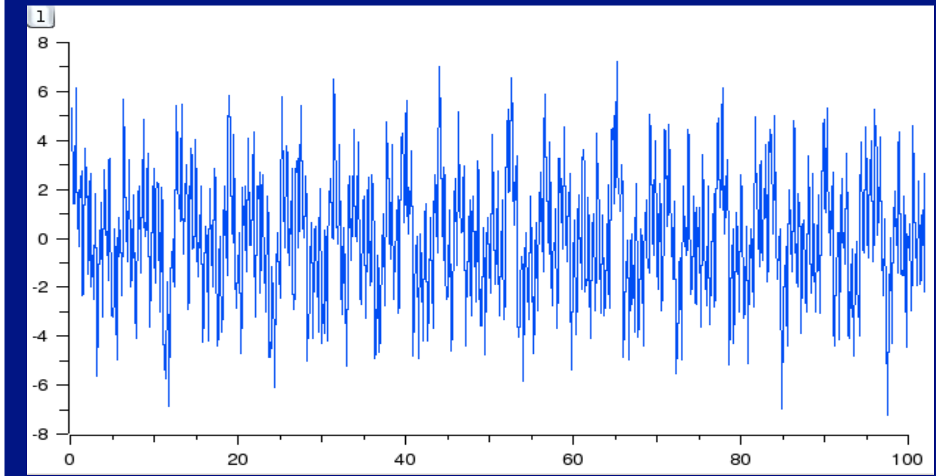
Power spectra I

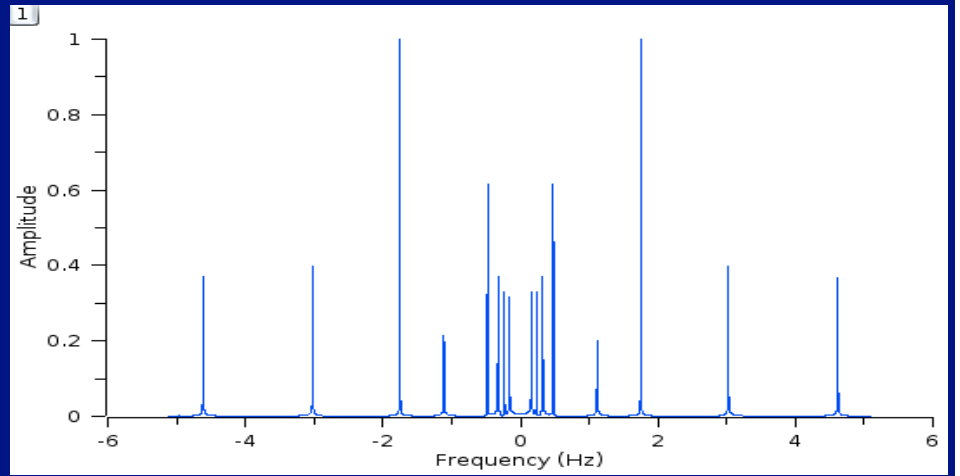
Technically for a long time doing the FFT was much more time consuming than the autocorrelation.

Therefore, one did many autocorrelation, averaged over time and then did the FFT.

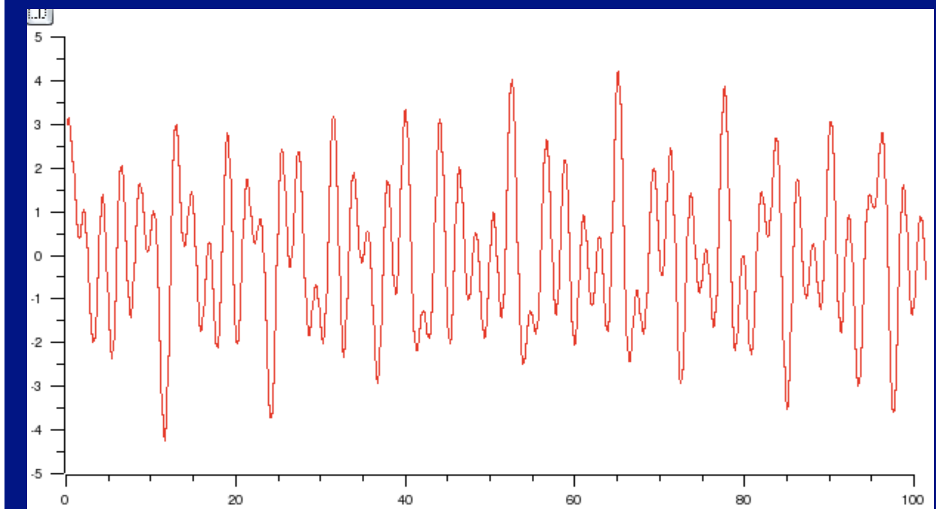
Today, FFT is easily and cheap technical feasible as well.

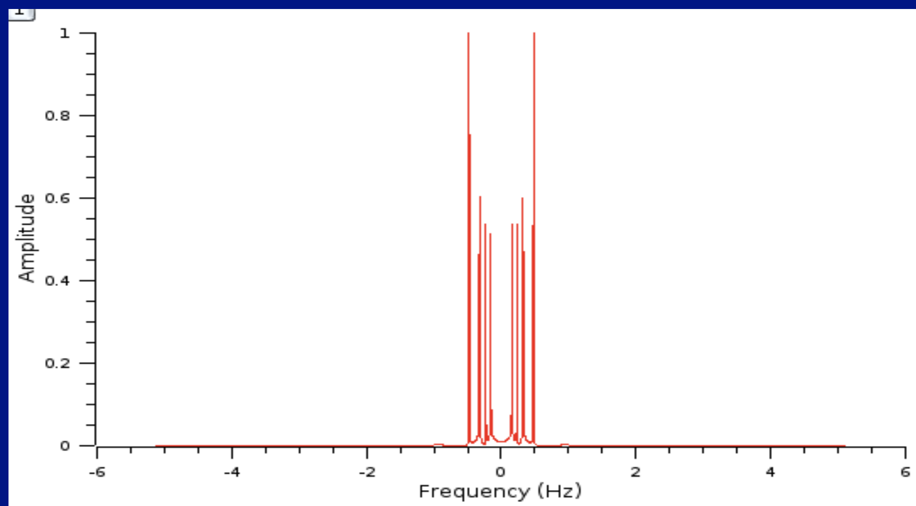
Power spectra II



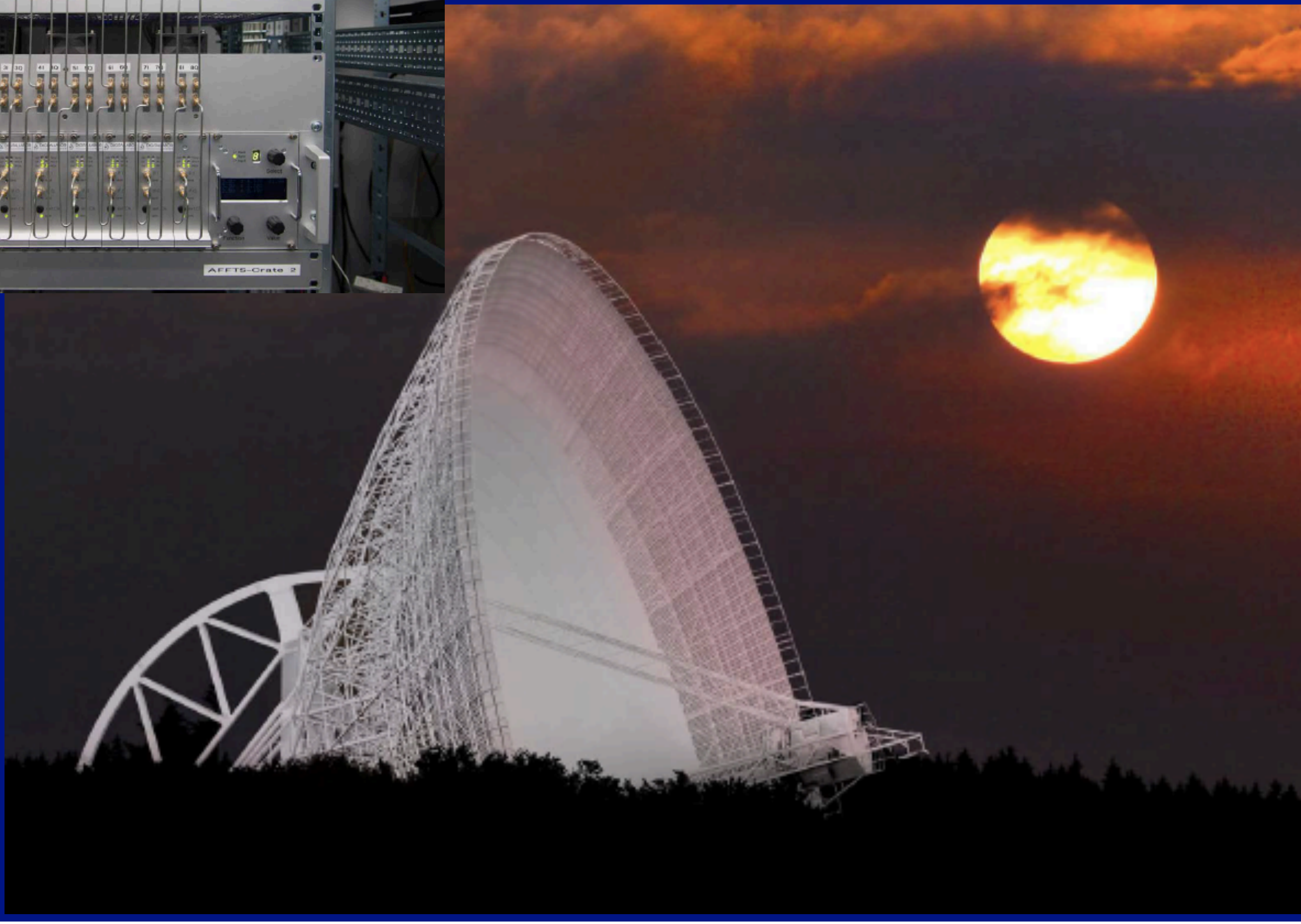


Time series → Spectrum

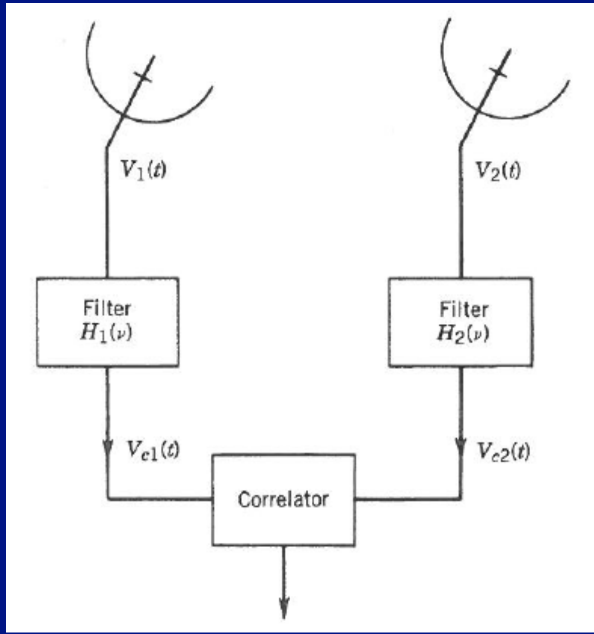




Effelsberg FTS



Cross correlation for interferometers



$$V_1(t) \star V_2(t) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} V_1(t) V_2^*(t-\tau)\, dt$$

with: $V_{2-}(t) = V_2(-t)$

Express as convolution:

$$V_1(t) \star V_2(t) = \lim_{T\to\infty} \frac{1}{2T} \int_{-\infty}^{\infty} V_1(t) V_{2-}^*(\tau - t)\, dt = V_1(t) * V_{2-}^*(t)$$

Convolution theorem: →

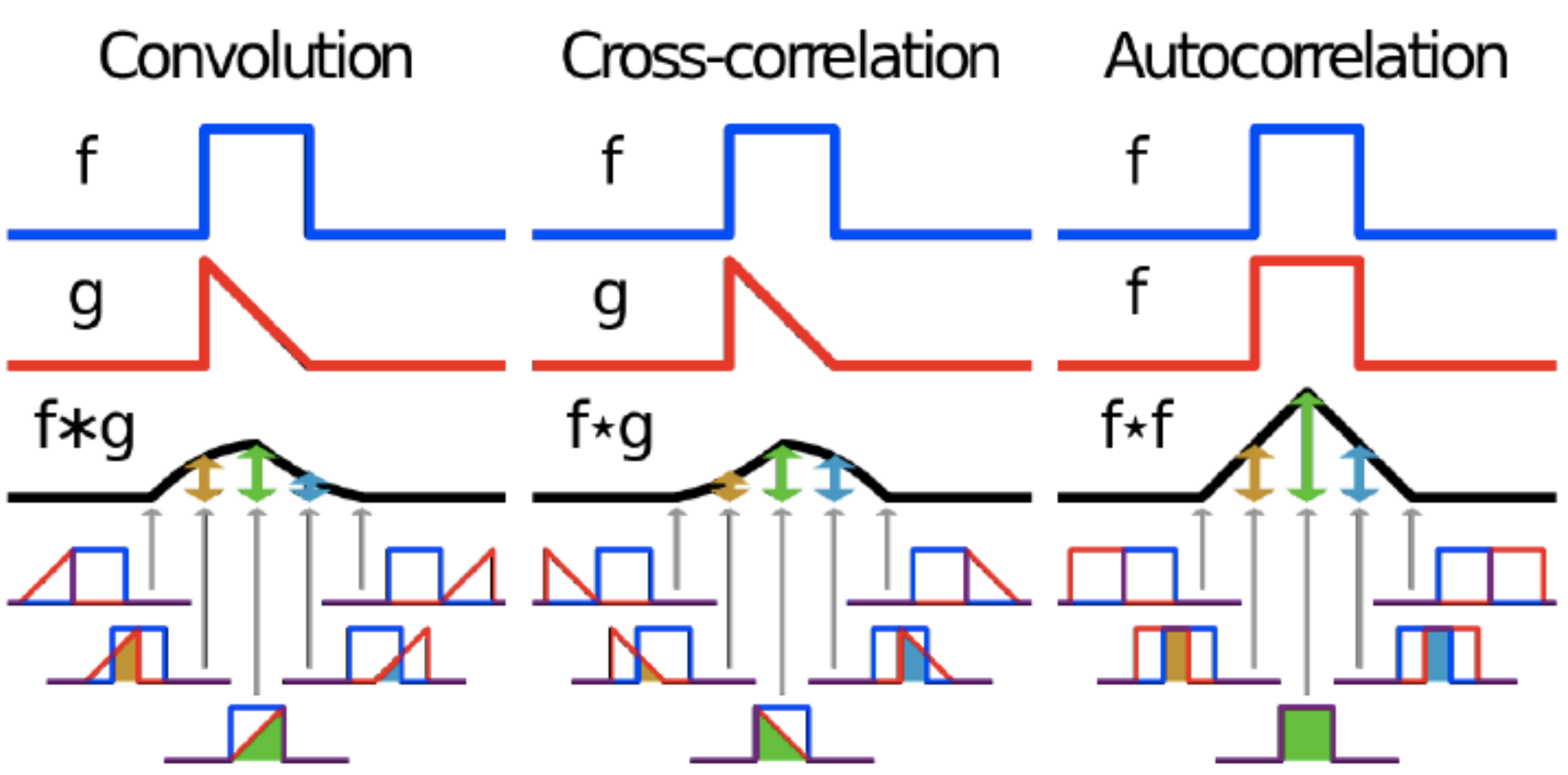
$$V_1(t) \star V_2(t) \rightleftharpoons \widehat{V}_1(\nu) \widehat{V}_2^*(\nu)$$

With Fourier transformation:

$V_1(t) \rightleftharpoons \widehat{V}_1(\nu)$

$V_{2-}^*(t) \rightleftharpoons \widehat{V}_2^*(\nu)$

Convolution and Correlation



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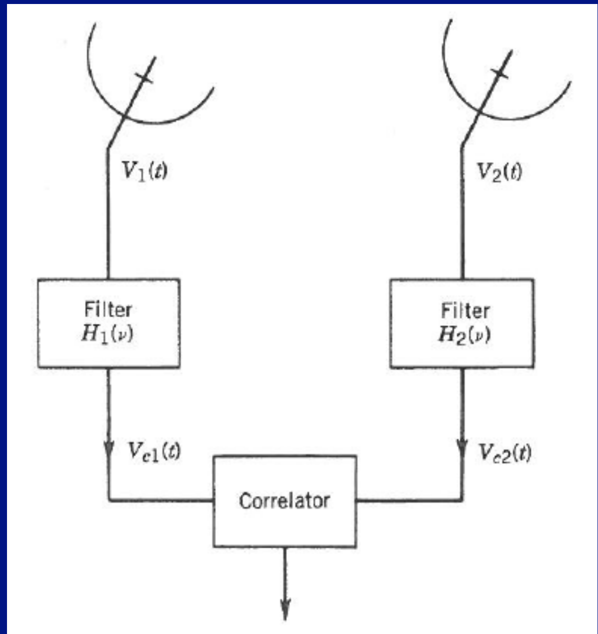

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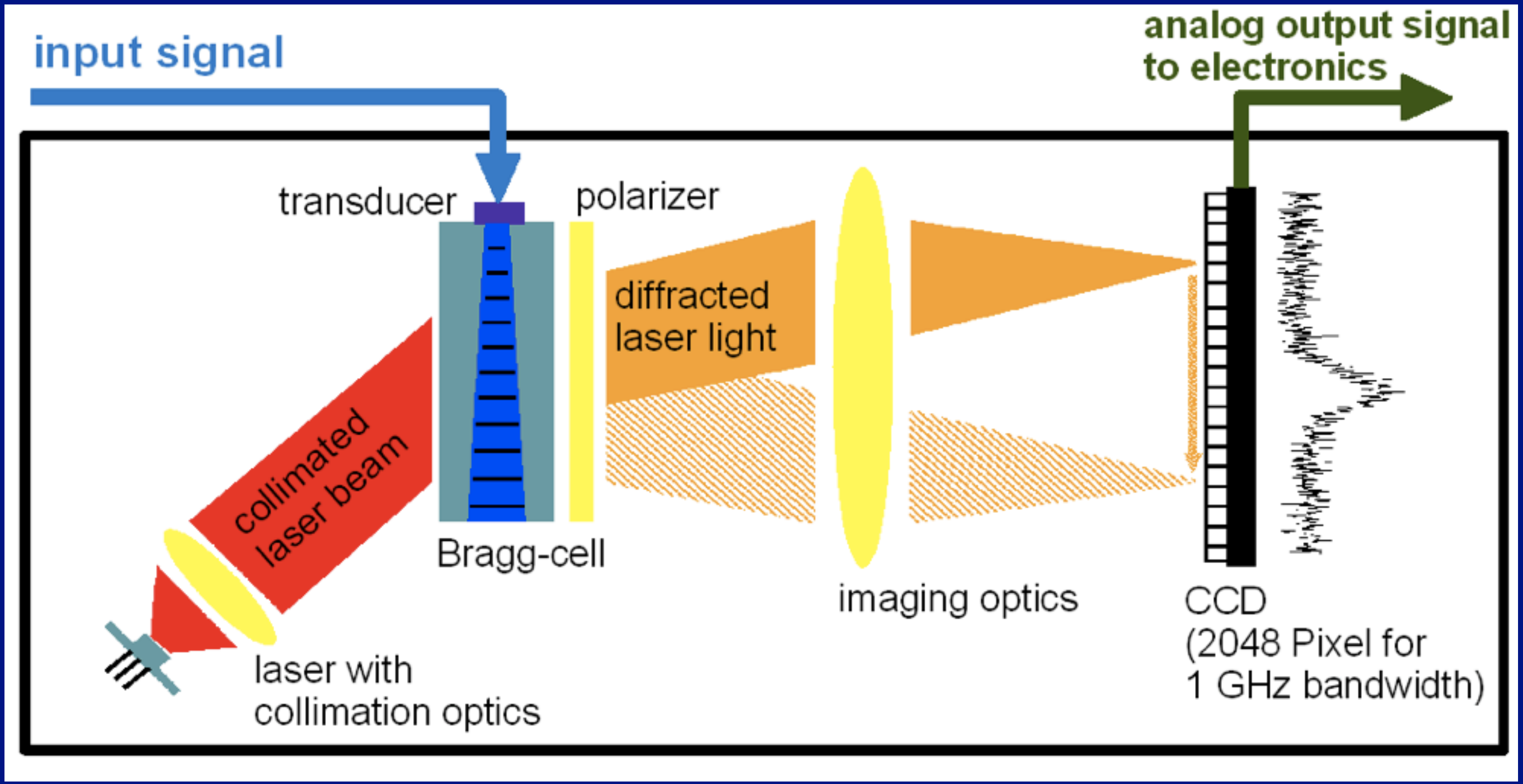
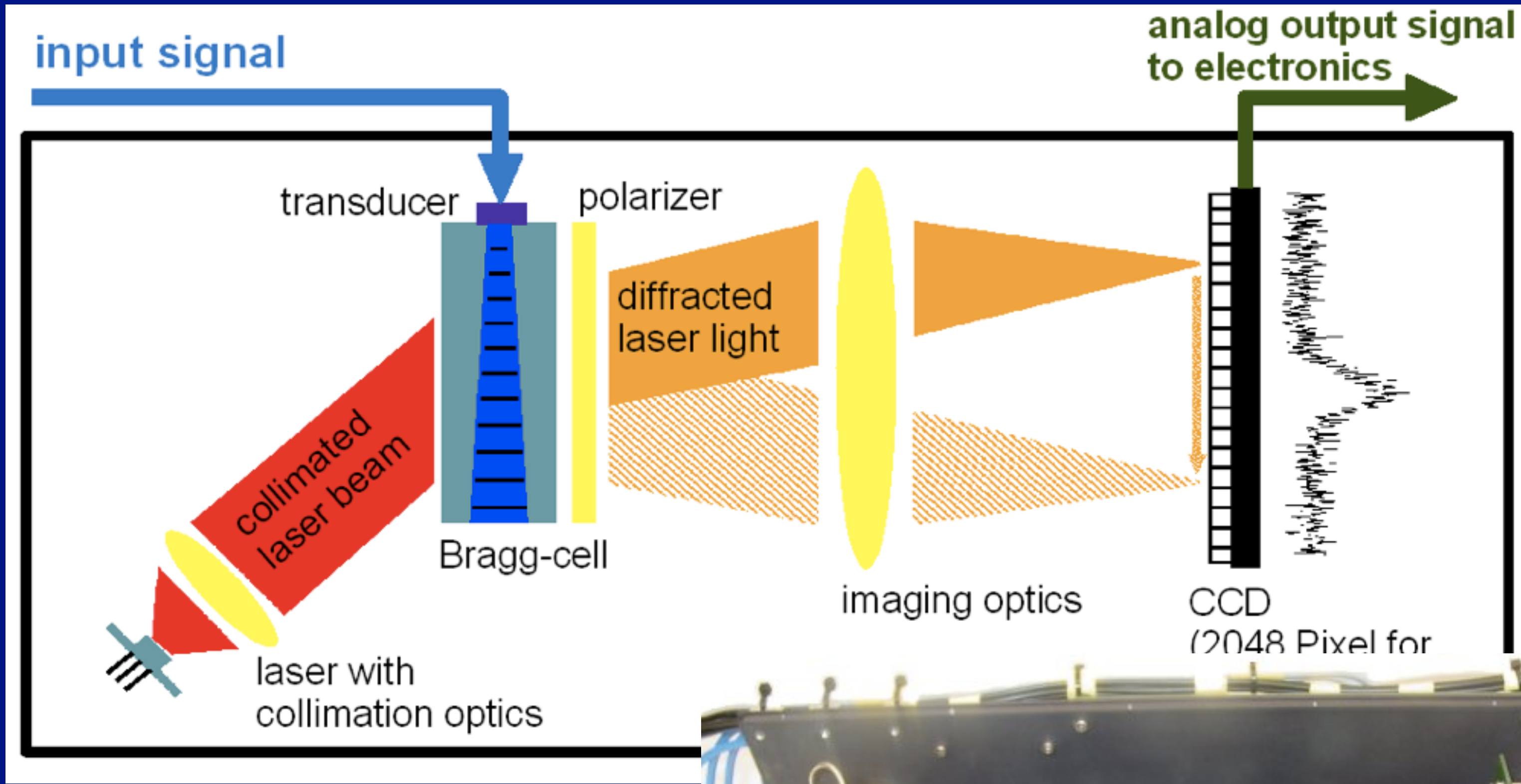
ALMA correlator

Acousto-Optical Spectrometer (AOS)



- The RF (IF) signal from the receiver creates an acoustic wave in piezoelectrical transducer (Bragg-cell).
- This wave modulates the refractive index and induces a phase grating.
- The Bragg-cell is illuminated by a collimated laser beam. The angular dispersion of the diffracted light represents a true image of the RF-spectrum according to the amplitude and wavelengths of the acoustic waves in the crystal.
- The spectrum is detected by using a single linear diode array (CCD), which is placed in the focal plane of an imaging optics.

Acousto-Optical Spectrometer (AOS)



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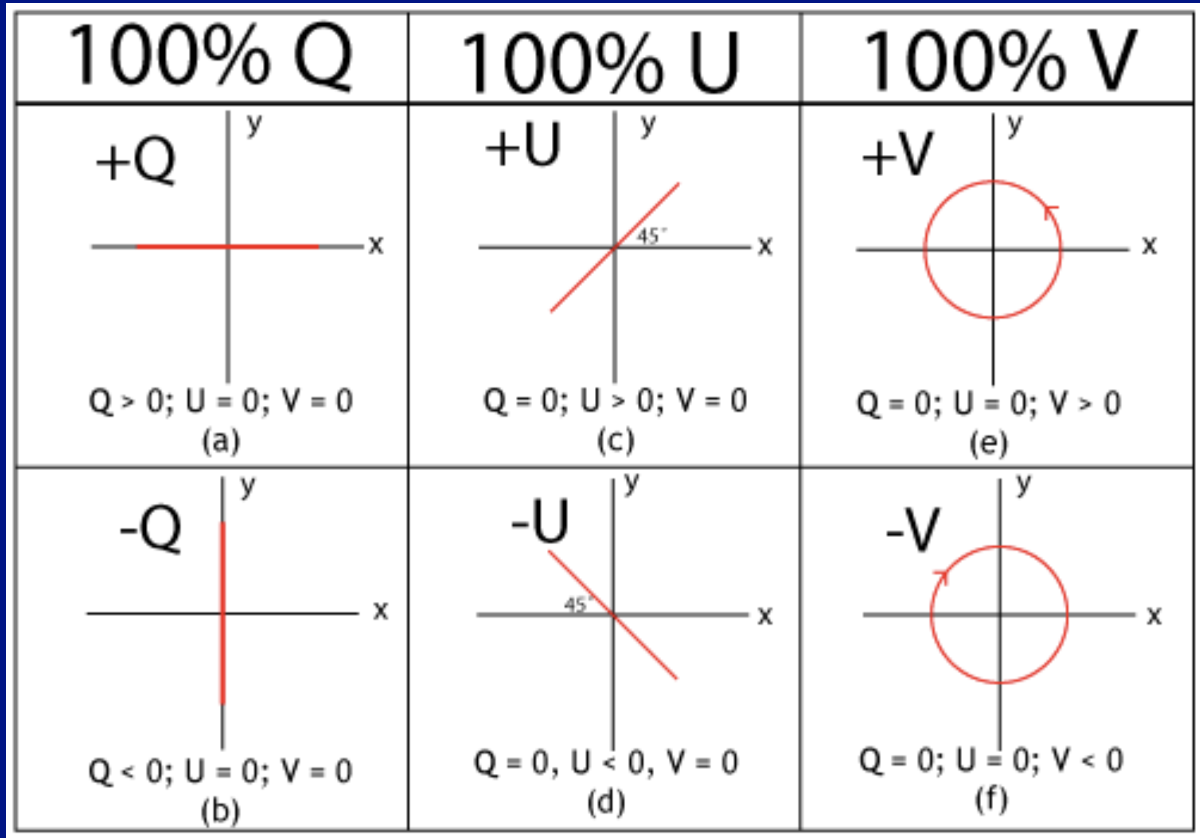
Polarization and Stokes parameters I



Linear description:

$S_0 = I = E_x^2 + E_y^2$ total intensity

$S_1 = Q = E_x^2 - E_y^2$ linear polarization

$S_2 = U = 2E_xE_y \cos\delta$ linear polarization

$S_3 = V = 2E_xE_y \sin\delta$ circular polarization

Circular description

$S_0 = I = E_l^2 + E_r^2$

$S_1 = Q = 2E_lE_r \cos\delta$

$S_2 = U = 2E_lE_r \sin\delta$

$S_3 = V = E_l^2 - E_r^2$

δ: relative phase between two orthognal waves

Polarization and Stokes parameters II

Degree of polarization:

$$P_{tot} = \frac{\sqrt{U^2 + Q^2 + V^2}}{I} \qquad P_{lin} = \frac{\sqrt{U^2 + Q^2}}{I} \qquad P_{circ} = \frac{V}{I}$$

Important for example because:

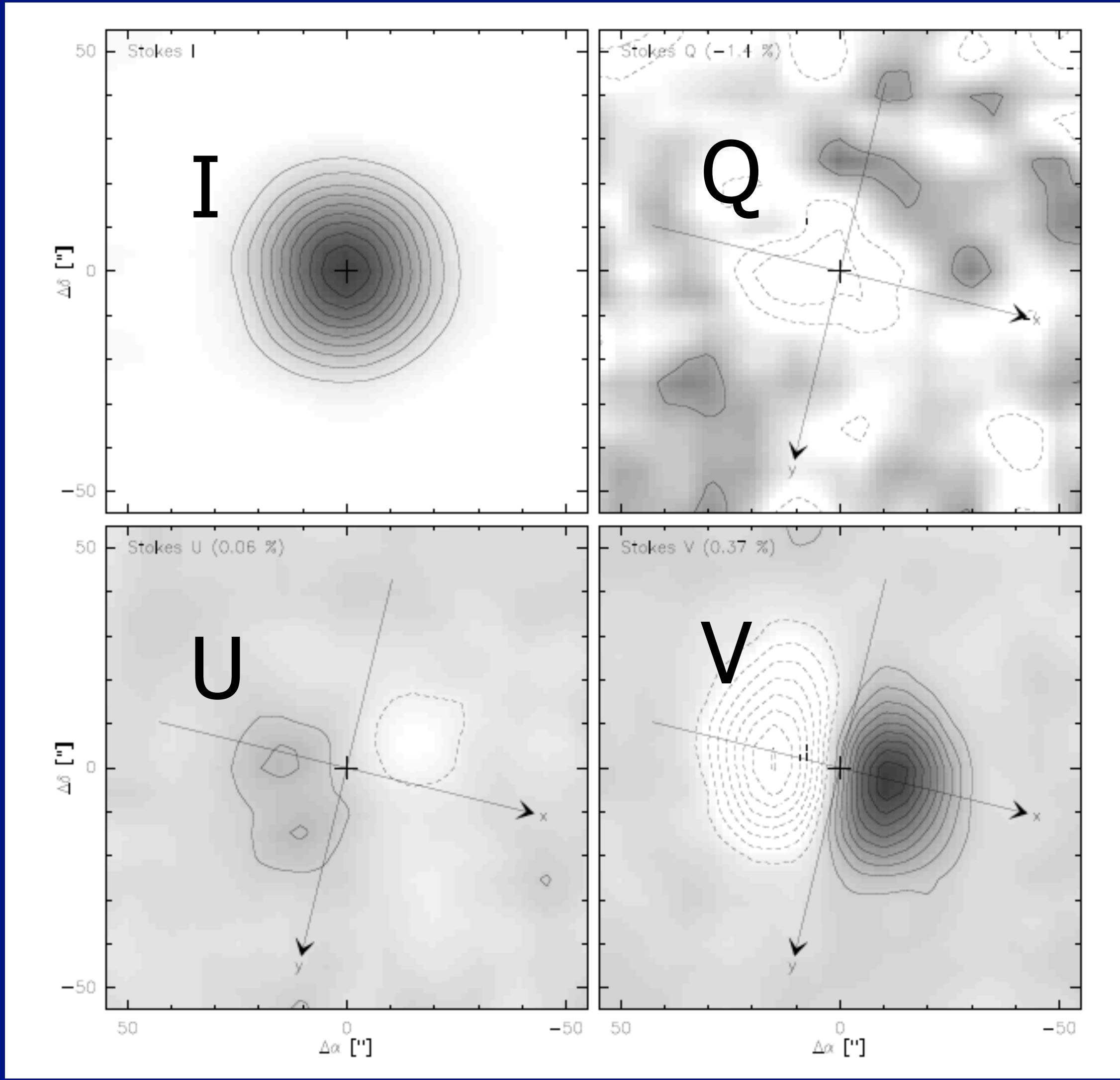
- Synchrotron radiation is polarized → magnetic field
- Dust emission can be polarized → magnetic field
- Polarization also results from Zeeman measurements

In practice, many observatories observe two polarizations, for example, the IRAM 30m telescope has two orthogonally linearly polarized receivers. Combining these components accordingly one can derive all 4 Stokes parameters

For example: Vector multiplication $\mathbf{E_x} \cdot \mathbf{E_y} = E_x E_y \cos \delta$

→ introducing a phase shift of 90 deg, one gets circular Stokes V

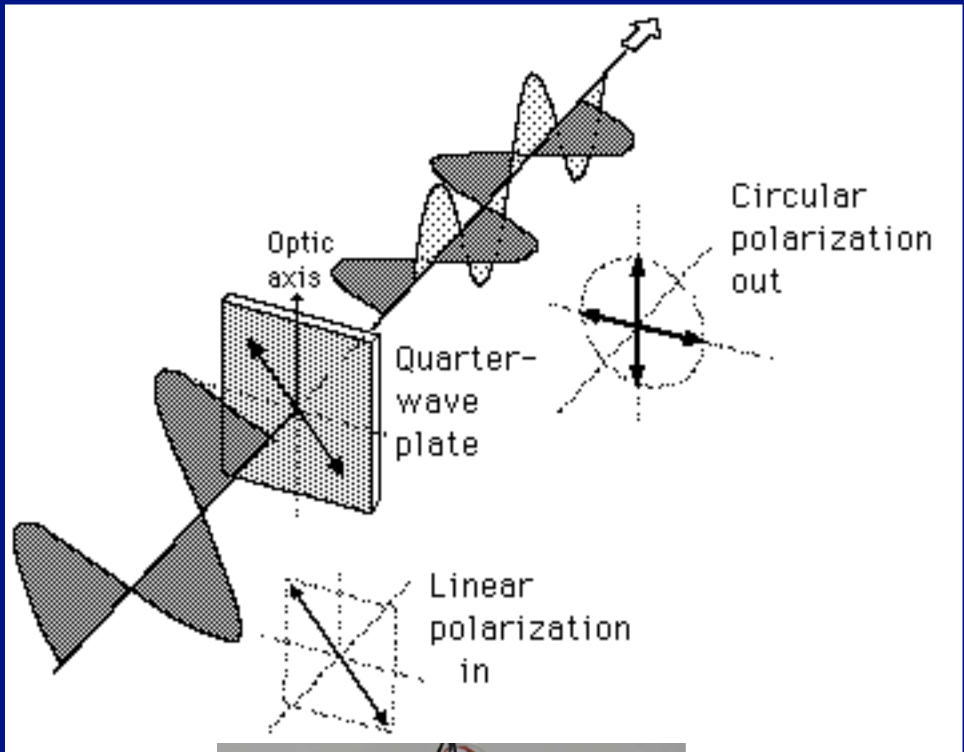
Caveat: instrumental polarization



Instrumental polarization usually sum of primary mirror, optical path, receiver contributions...

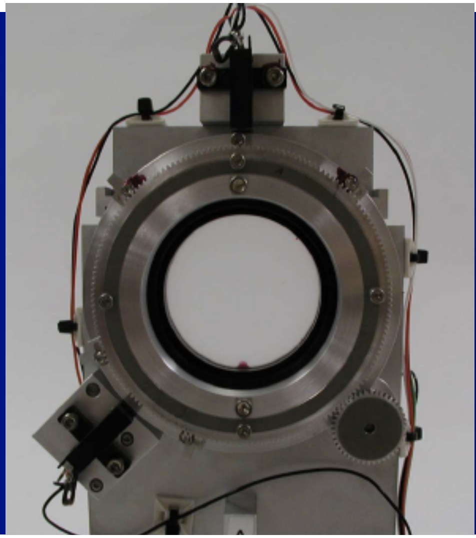
Stokes beam maps of the 30m at 86GHz (Wiesemeyer et al. 2009)

Quarter wave plates



A quarter-wave plate is an anisotropic optical element that introduces a quarter wavelength phase delay between orthogonal linear polarizations. When oriented at 45 deg to incident linear polarization, pure circular polarization is output.

By rotating the plate by 90 deg, left- and right-handed polarization can be produced.



At Submillimeter Array (SMA) only single linearly polarized receiver. Introducing quarter-wave plates in a "Walsh cycle" producing left- and right-handed polarization allows to re-construct all Stokes parameters.

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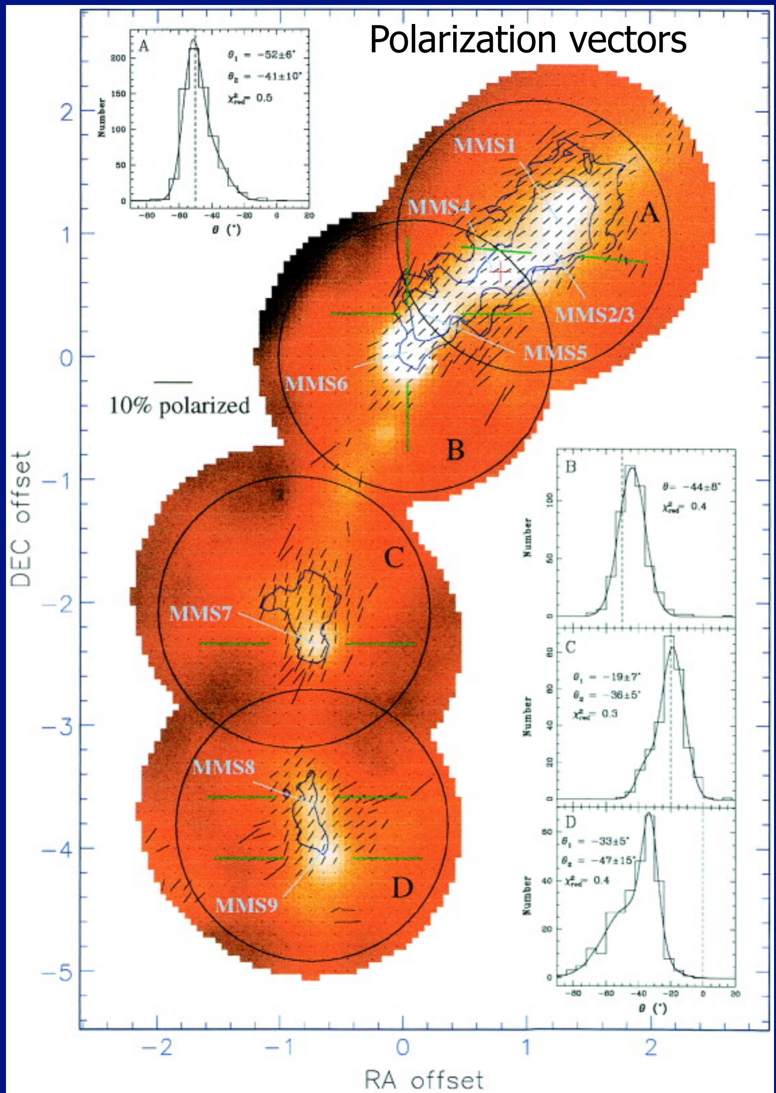
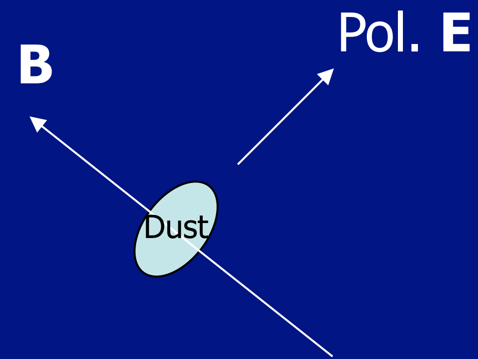
Dust polarization and magnetic fields



Polarized submm continuum emission

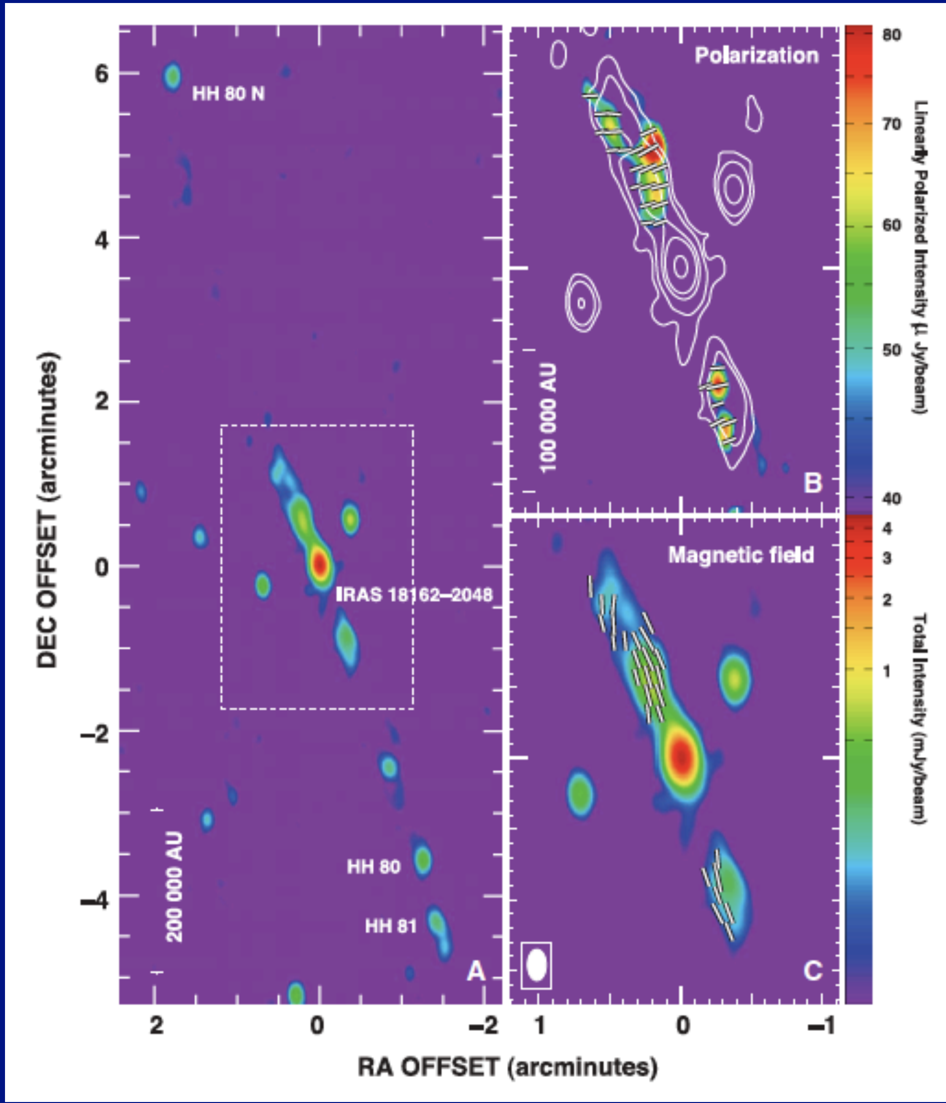
In contrast, thermal dust emission at (sub)mm wavelengths perpendicular to magnetic field!

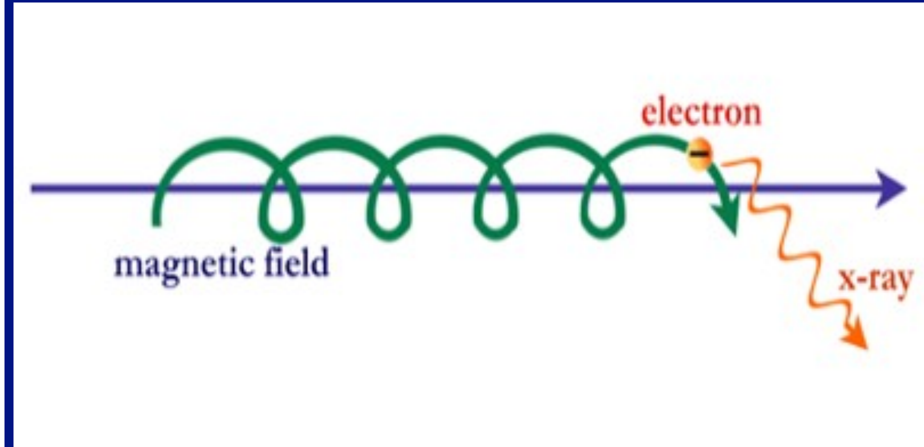


Molecular filaments can collapse along their magnetic field lines.

Matthews & Wilson 2000

A polarized synchrotron jet



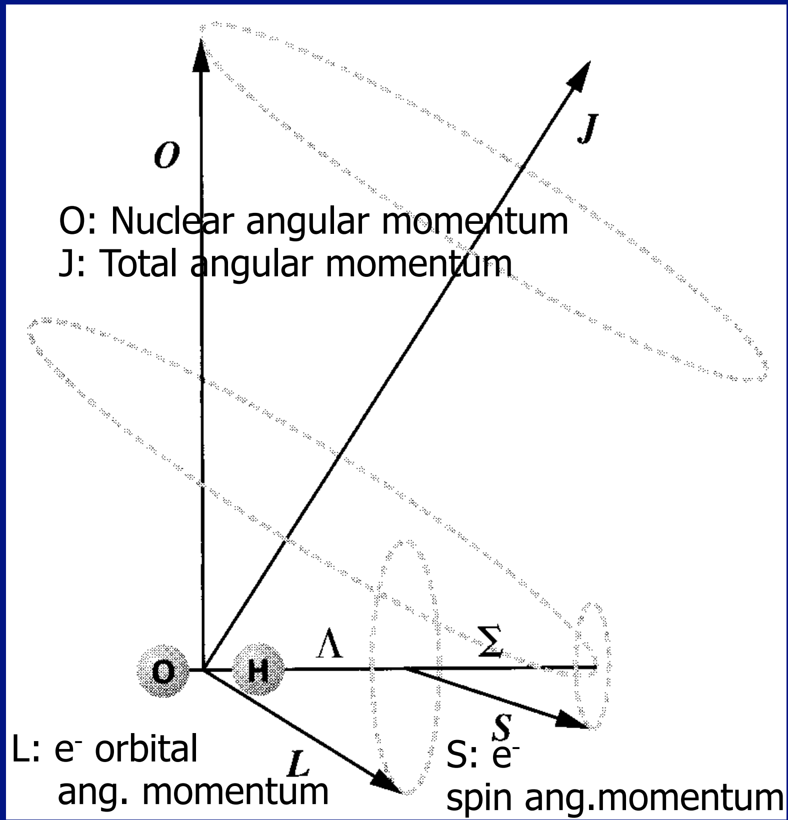


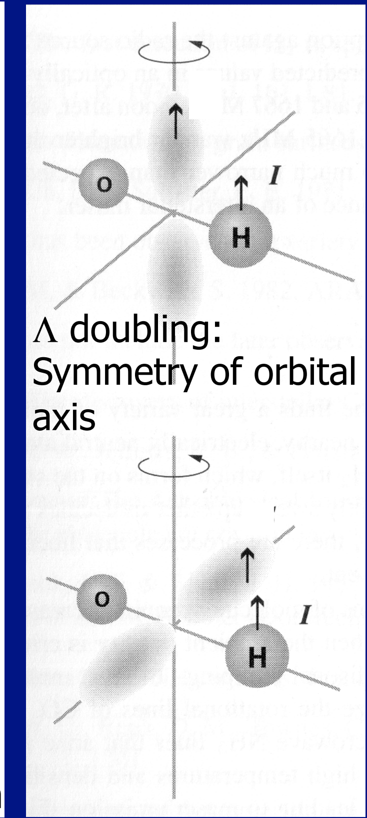
→ Linearly polarized synchrotron emisssion.

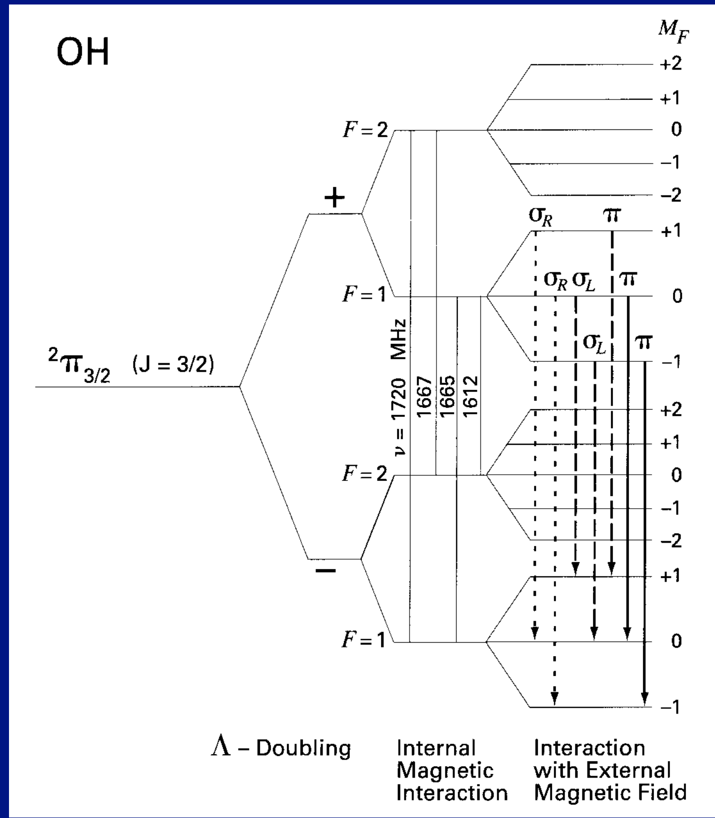
Direction of polarization again perpendicular to magnetic field.

Carrasco-Gonzales et al. 2010

The Zeeman effect and magnetic fields I

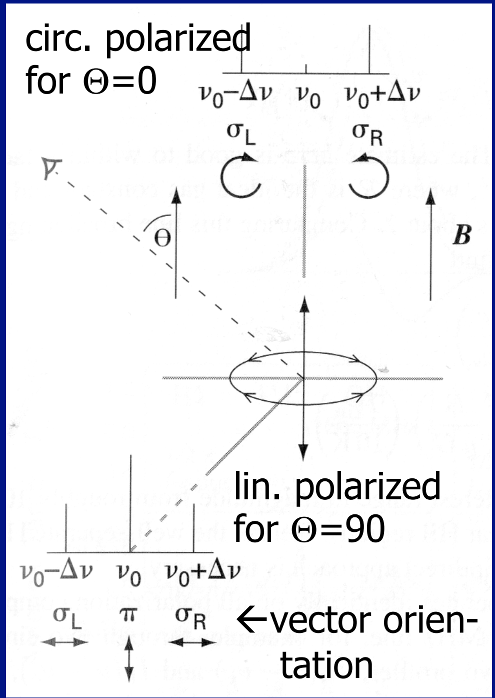


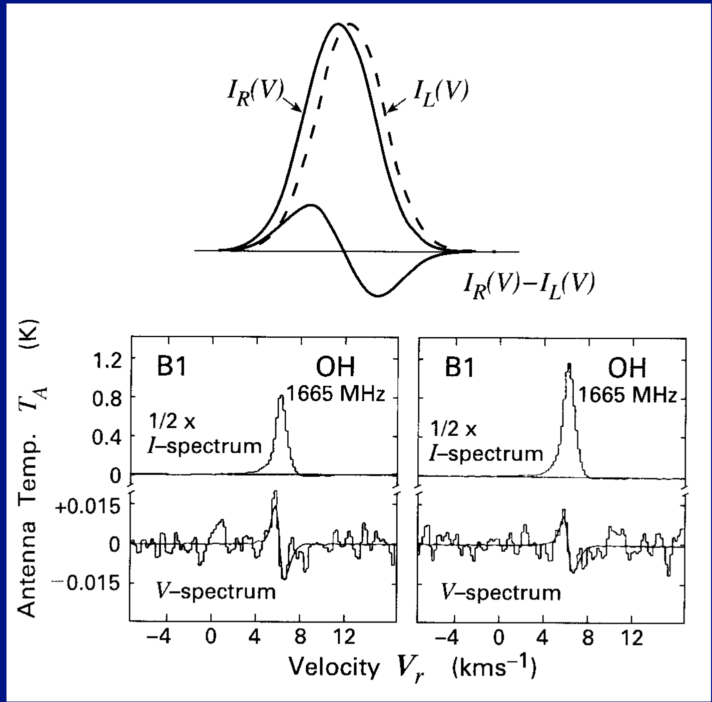




- OH is a free radical with one unpaired free electron and hence non-zero electronic angular momentum. Highly reactive in lab, but can survive in space.
– Λ doubling, which is caused by symmetry difference of the e⁻ orbital with respect to the rotation axis, produces energy splitting.
- Interaction between spins of e⁻ and H nucleus causes additional magnetic hyperfine splitting.
- And external magnetic fields then produces the Zeeman splitting.

The Zeeman effect and magnetic fields II





$\Delta\nu_{mag}$ ~ B usually of the order a few 10 μG

←Subtraction of left- from right-handed circ. pol. results in Stokes-V spec.

- Magnetic energy E_{mag} = **μ B** depends on relative orientations of magnetic moment **μ** and external field **B**.
- Analysis results in Zeeman splitting of $\Delta\nu_{mag}$ = (b/2) B (b: constant)
- Orientation between **B** and line of sight causes different polarization properties, Θ=0 (l.o.s) circular pol., Θ=90 lin. pol., in reality elliptical polarization.
- Thermal line broadening complicates matter: $\Delta\nu_{mag}/\Delta\nu_{therm} \sim 10^{-3}$B(μG)
  → Hence, one measures two polarizations differentially. One is only senstive to the B component along the line of sight.

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Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

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