Overview of Radio Coronal Magnetography

OUTLINE (PART 1)

The uses and abuses of various emission mechanisms

- Thermal free-free radiation
- Thermal gyroresonance radiaton (SW)
- Nonthermal gyrosynchrotron radiation
- Radio bursts

OUTLINE (PART 2)

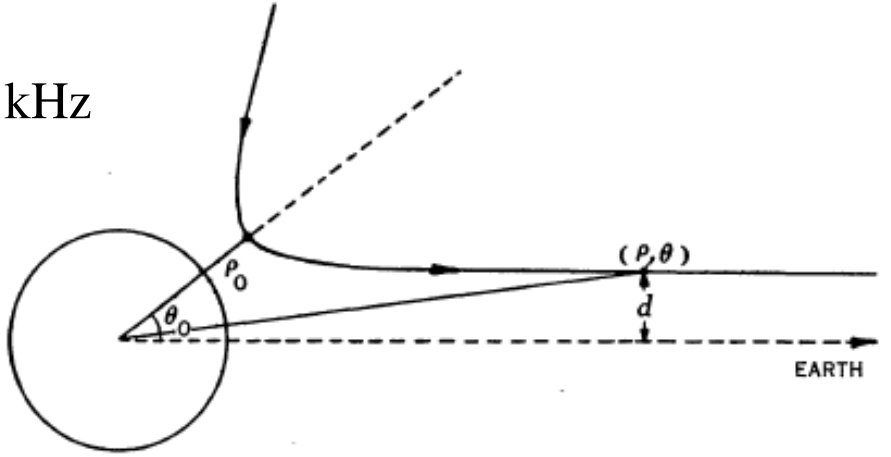
Propagation phenomena and related

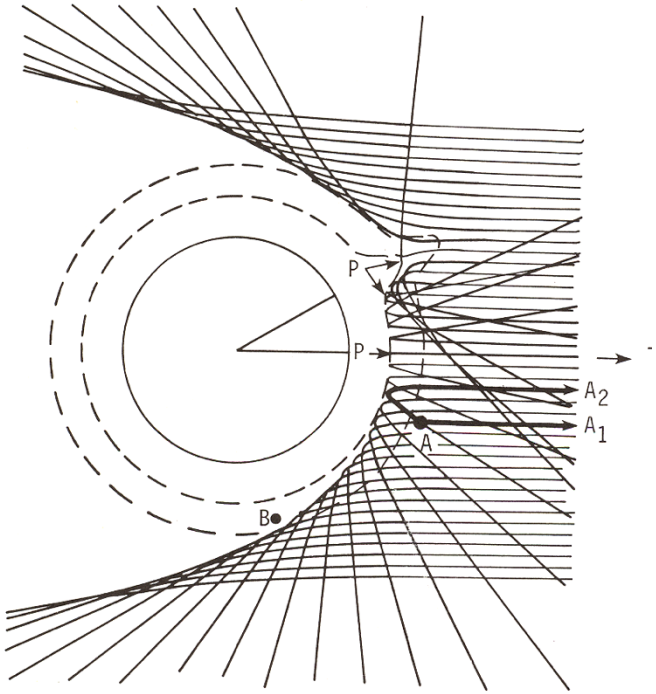
- Ray tracing
- Scattering phenomena
- Faraday rotation
- QT propagation

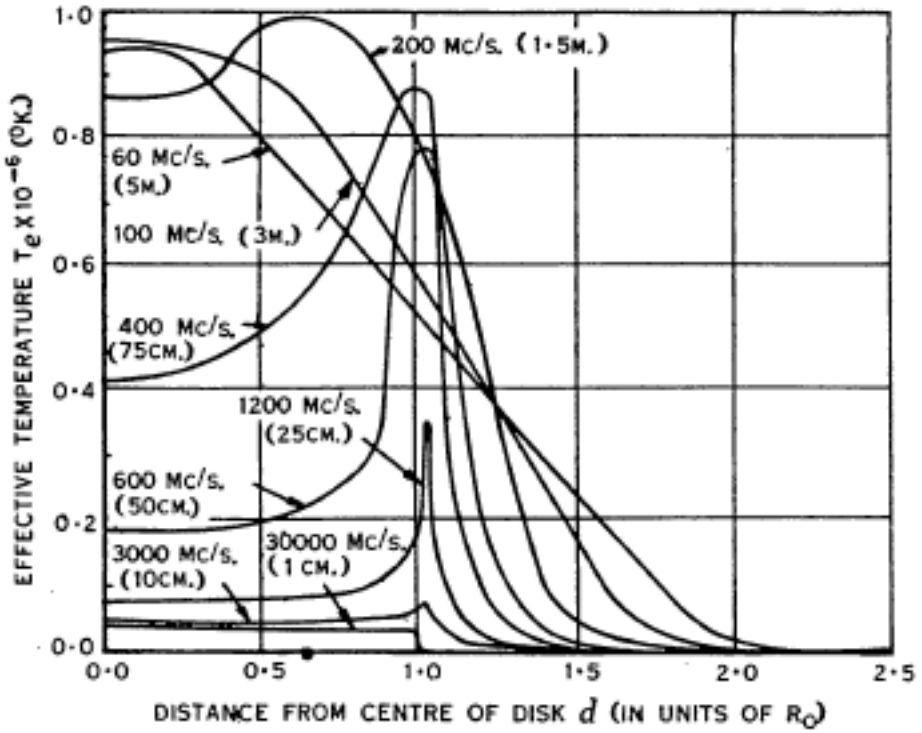
Smerd 1950

$$\mu = \left(1 - \frac{\nu^2}{\nu_{pe}^2}\right)^{1/2} \qquad \nu_{pe} = \sqrt{\frac{e^2 n_e}{\pi m_e}} \approx 9 n_e^{1/2} \text{ kHz}$$

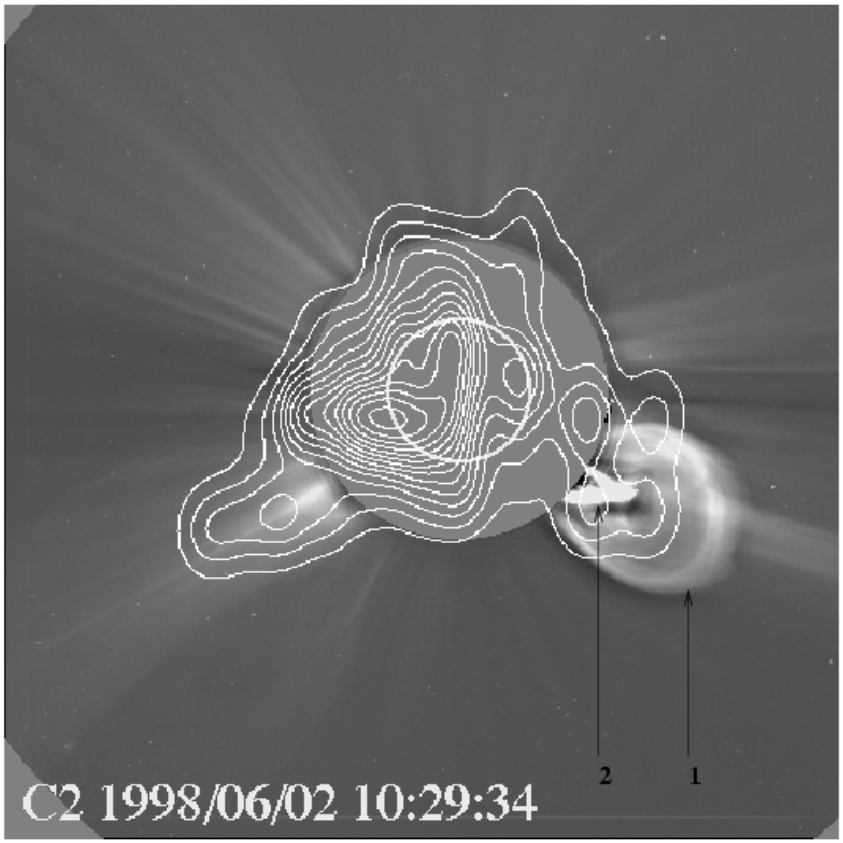
$$ds = \frac{R d\rho}{\sqrt{1 - d^2 / \mu^2 \rho^2}}$$

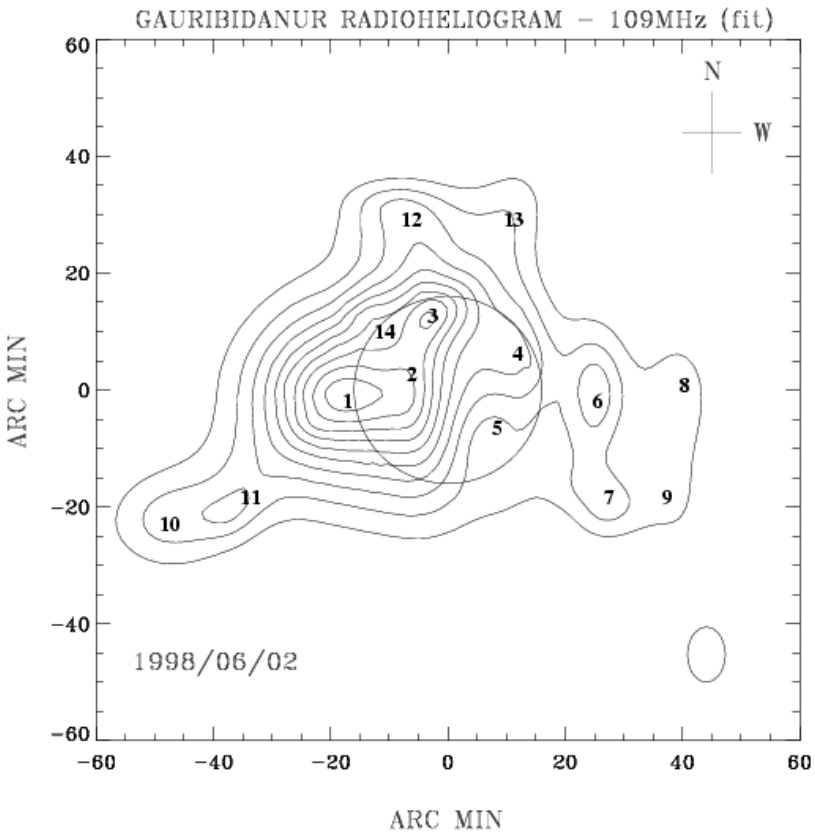






Gauribindanur RH: 109 MHz

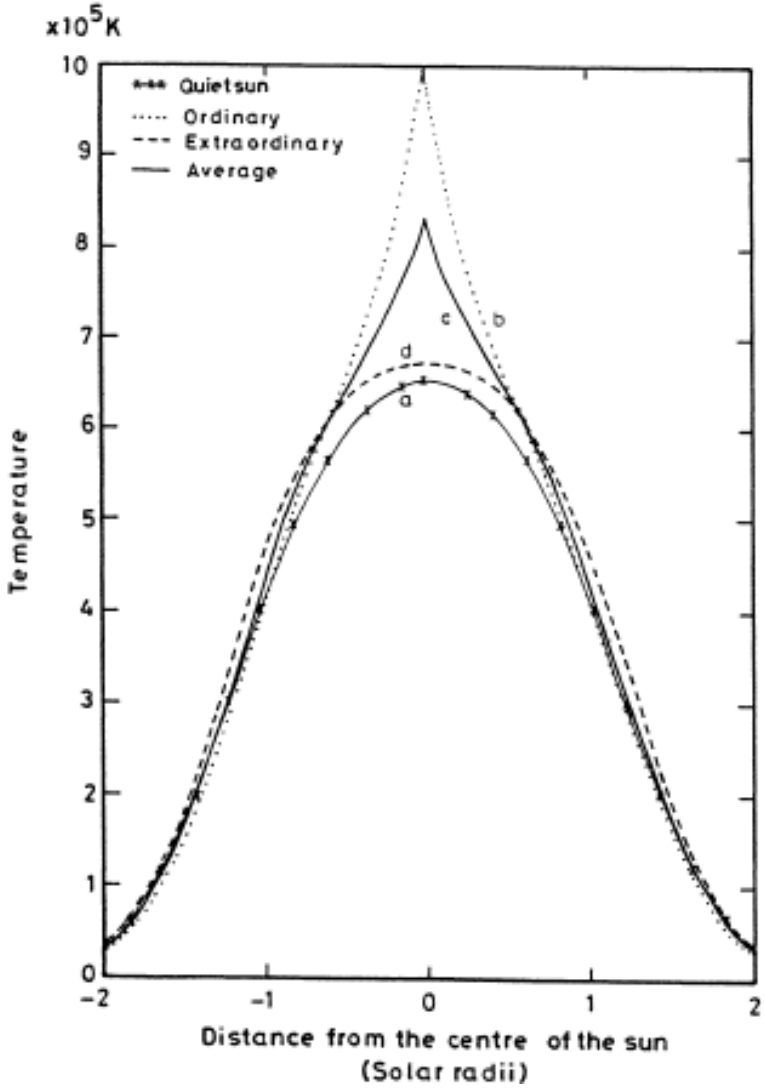


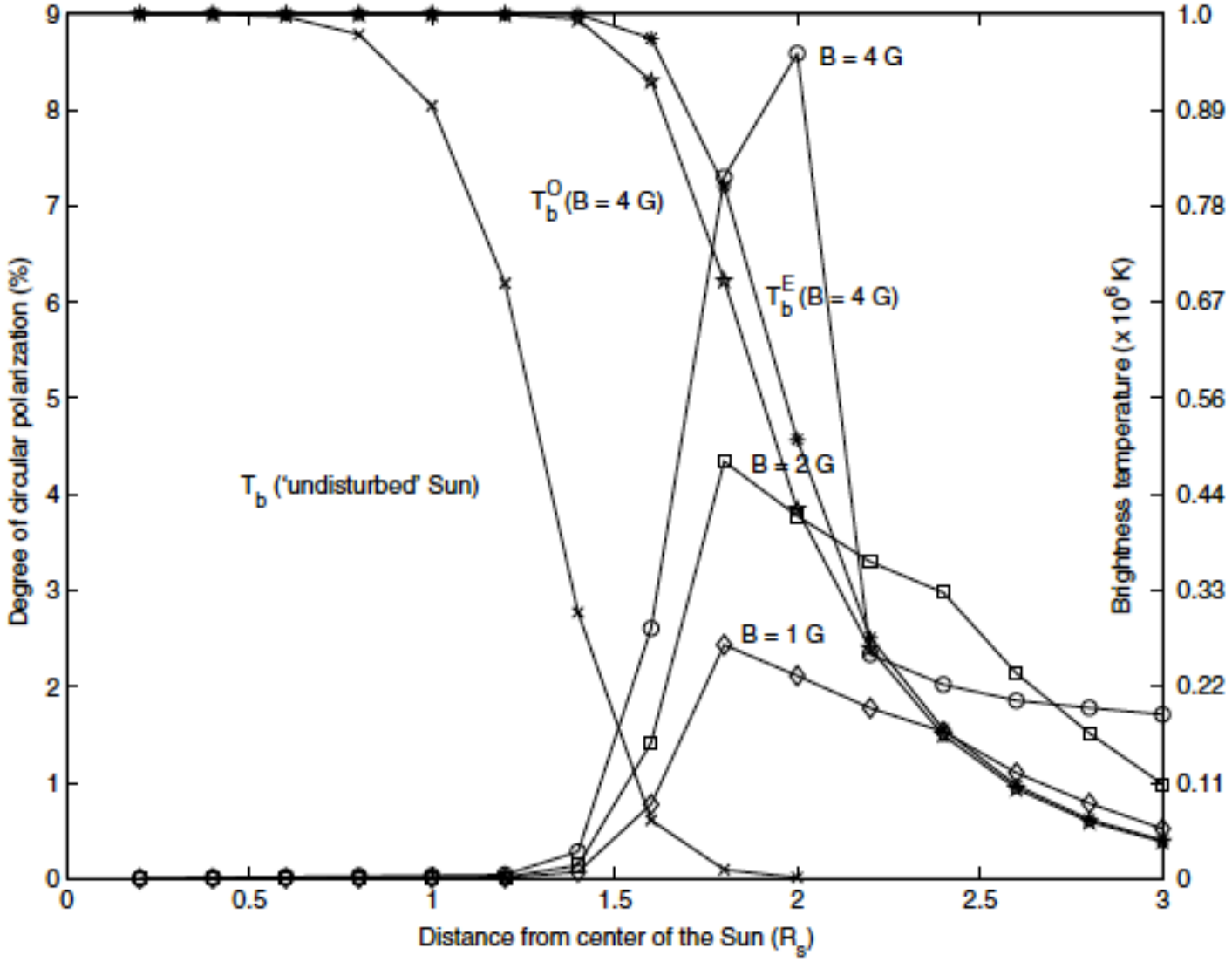


Kathiravan et al. 2002

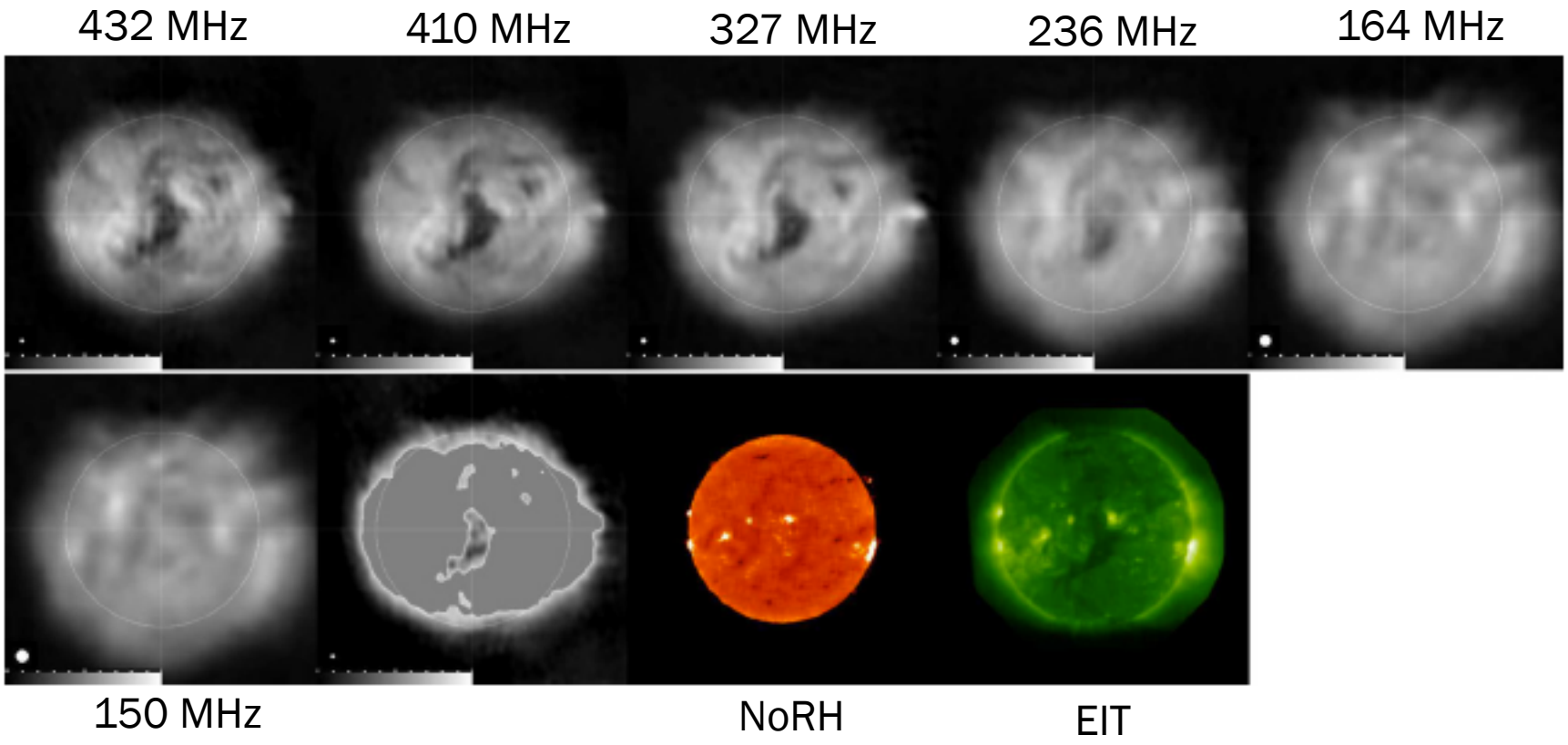
WHAT ABOUT THE MAGNETIC FIELD?

- Surprisingly little work has been done with ray-tracing codes to model the magnetized corona
- Golap & Sastry (1994) used Haselgrove's Equations (1955) to compute the radio brightness distribution of the Sun at 35 MHz in the presence of a radial magnetic field (DM78)
- Sastry (2009) subsequently explored streamer and CH structures, again using a radial field
- An area ripe for development!




Degree of circular polarization (%)
Brightness temperature (x 10^6 K)
Distance from center of the Sun (R_s)
B = 4 G
T_b^O (B = 4 G)
T_b^E (B = 4 G)
B = 2 G
B = 1 G
T_b ('undisturbed' Sun)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6
7
8
9
0
0.11
0.22
0.33
0.44
0.56
0.67
0.78
0.89
1.0

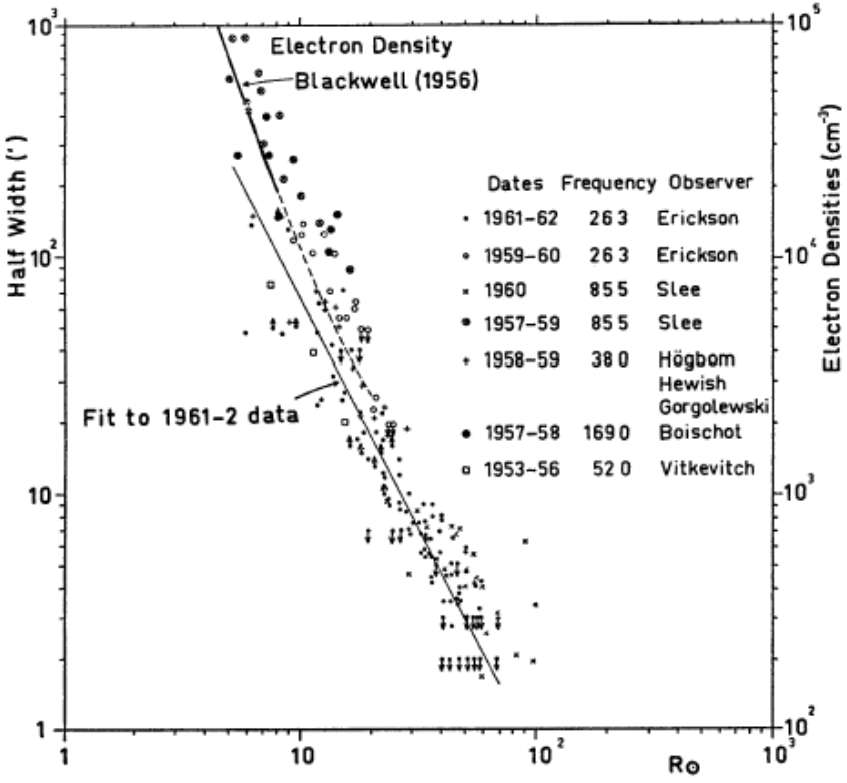
NRH: 2004 June 27



Mercier & Chambe 2009

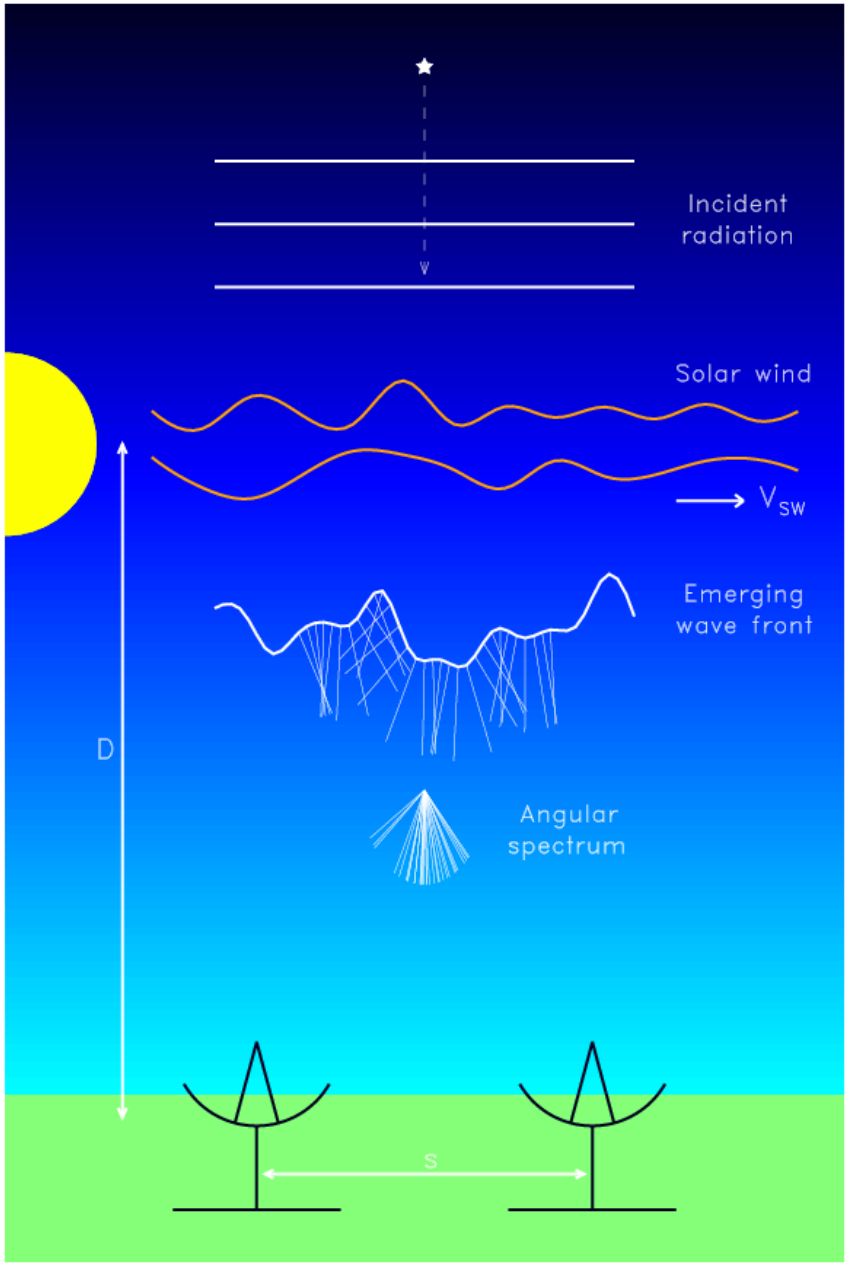
CORONAL SCATTERING

- Seminal work by Högbom (1959), Fokker (1965), Steinberg et al. (1971)
- Motivated by observations of:
  - Radio bursts a wavelengths
    - $\lambda > 1$m:
      - angular size
      - polarization
      - center-to-limb variation
- Angular broadening of cosmic sources viewed through the outer corona

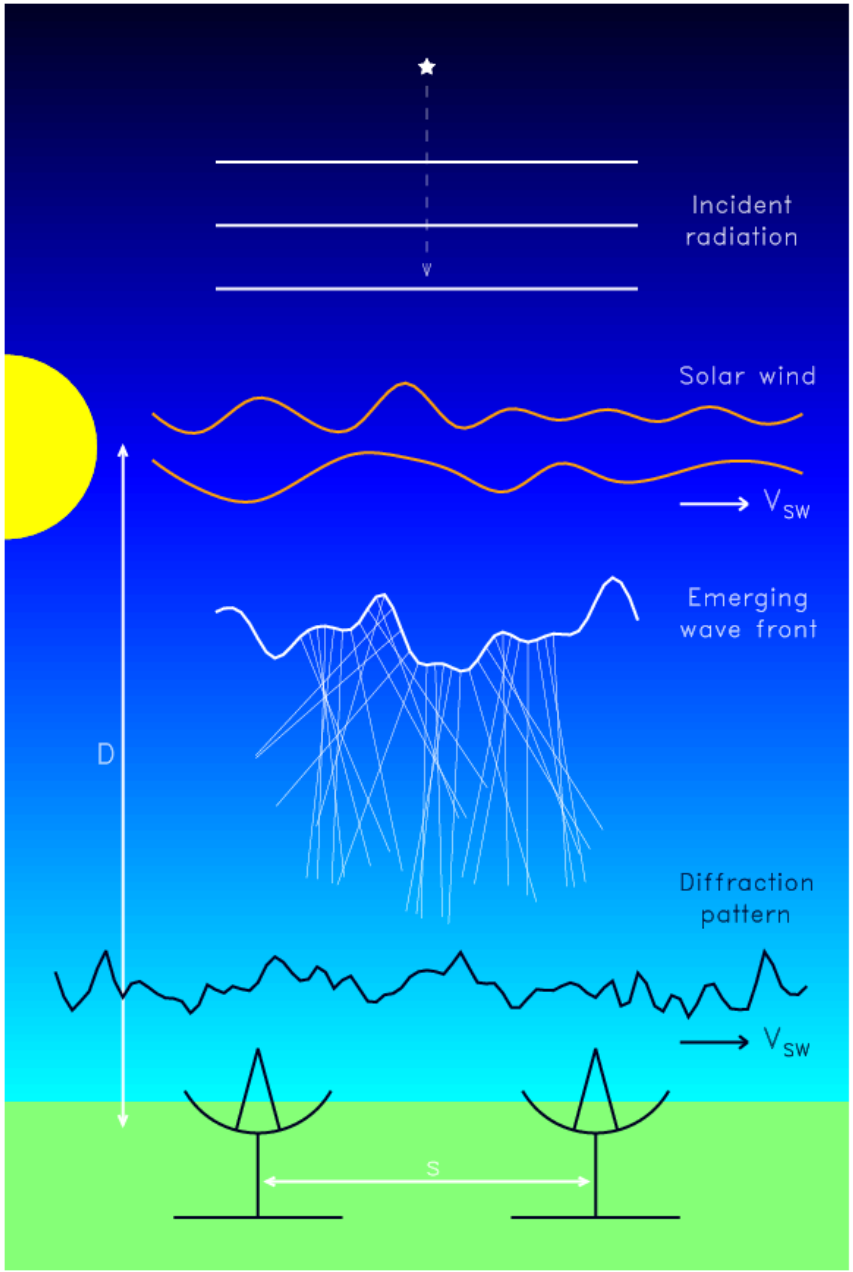


Erickson 1964

Angular broadening



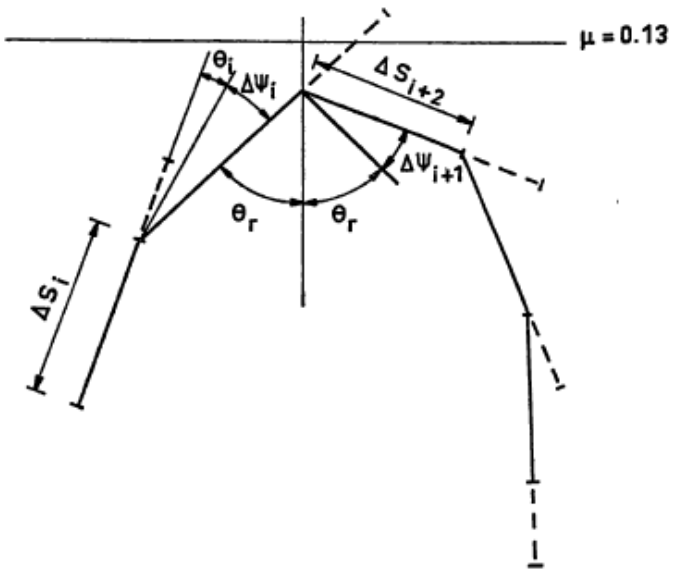
Scintillations



CORONAL SCATTERING

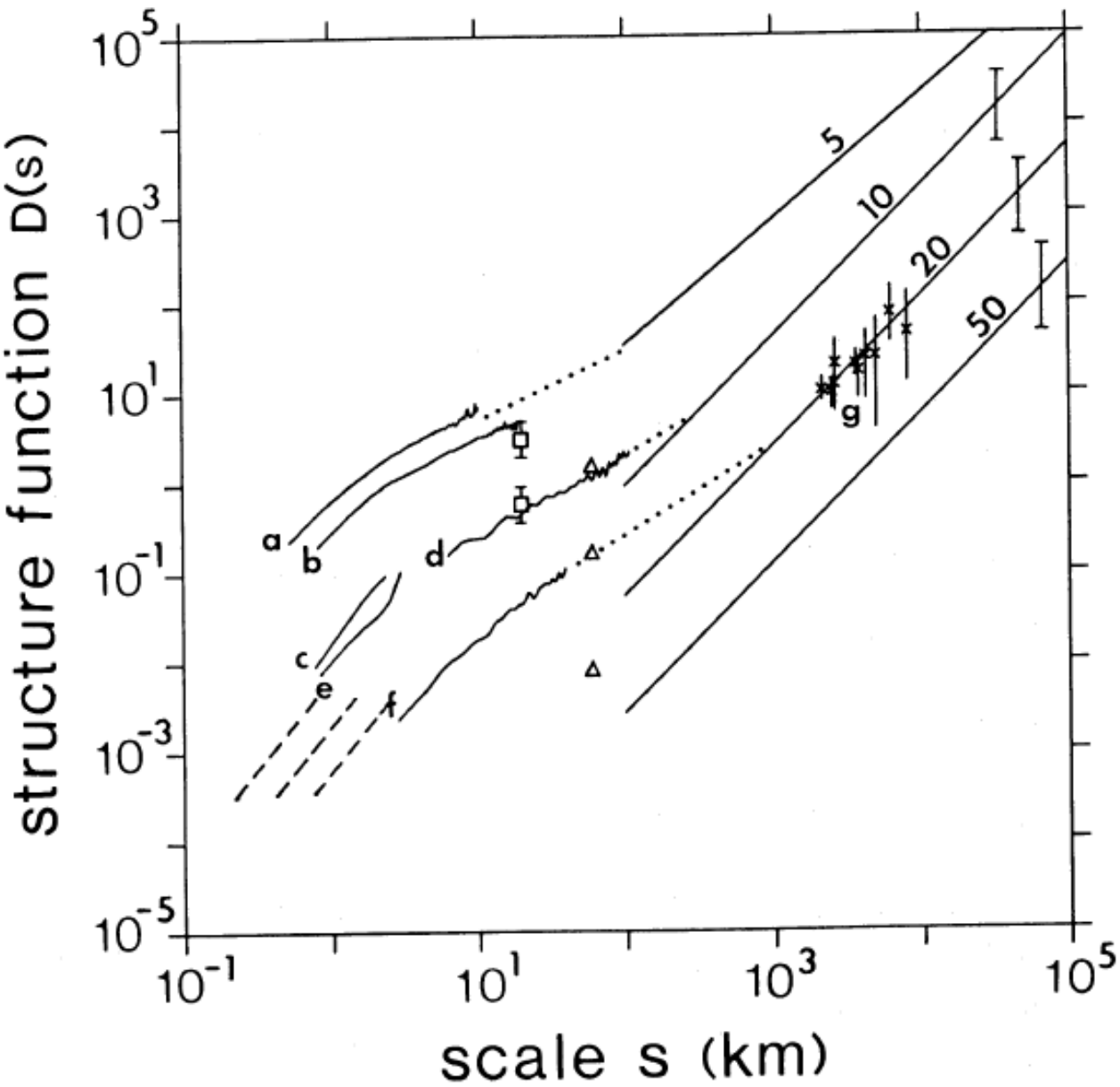
- Steinberg et al. (1971) performed ray-tracing calculations in a Newkirk corona with density inhomogeneities described by a Gaussian correlation function:

$$\left\langle \delta\mu(r_1)\delta\mu(r_2)\right\rangle = \left\langle -\delta\mu^2 \right\rangle \exp\left[-\frac{|r_1 - r_2|^2}{h^2}\right] \qquad h << \rho$$



$$\left\langle \delta\Psi^2 \right\rangle = \left\langle \delta\Omega^2 \right\rangle = 2\pi^{1/2} \int_{ray} \frac{\left\langle \delta\mu^2 \right\rangle}{\mu^2 h} dS$$

Concluded large scale refraction and scattering play a significant role in the propagation of radio waves in the corona.



Coles & Harmon 1989

SCATTERING AT CM AND DM WAVELENTHS

- Ignore large scale refraction
- An interferometric array measure the mutual coherence function of the electric field

$$\Gamma(s) = \frac{\langle E(r)E^*(r+s)\rangle}{\langle |E|^2\rangle}$$

- It is related to the *wave structure function D(s)* through

$$\Gamma(s) = \exp\,[-D(s)/2]$$

where $D(s) = \langle[\phi(r) - \phi(r+s)]^2\rangle$ and $\phi(r) = r_e \lambda \int n(r)dz$

- The spatial spectrum of electron density fluctuations $\Phi_n(\kappa)$ is the Fourier transform of the spatial correlation function of the electron density fluctuations.

SCATTERING AT CM AND DM WAVELENTHS

For a spatial spectrum $\Phi_n(\kappa) = C_n^2 \kappa^{-\alpha-2} \exp\left[-(\kappa l_0/2)^2\right]$ we have

$$\frac{\partial D(s,z)}{\partial z} = \frac{8\pi^2}{\alpha}\Gamma\left(1-\frac{\alpha}{2}\right)C_n^2(z) r_e^2 \lambda^2 \left(\frac{l_0}{2}\right)^{\alpha} \times \left\{ {}_1F_1\left[-\frac{\alpha}{2}, 1, -\left(\frac{s}{l_0}\right)^2\right] - 1 \right\}$$

In the limit that $s \ll l_0$, this becomes

$$\frac{\partial D(s,z)}{\partial z} = \frac{4\pi^2}{2^{\alpha}}\Gamma\left(1-\frac{\alpha}{2}\right)C_n^2(z) r_e^2 \lambda^2 l_0^{\alpha-2} s^2 \quad (s \ll l_0)$$

Which is true for spherical wave propagation:

$$D(s) = \int_0^L \frac{\partial D(s,z)}{\partial z}\, dz \quad \Rightarrow \quad D(s) = \int_0^L \frac{\partial D(sz/L,z)}{\partial z}\, dz$$

SCATTERING AT CM AND DM WAVELENTHS

Returning to the mutual coherence function it's seen that the angular width of a point source can be characterized by the scale s_o where $D(s_o)=1$ so that $\theta_c = (ks_o)^{-1}$ and $\theta_G = 2.35\theta_C$.

$$\Gamma(s) = \exp\left[-D(s)/2\right]$$

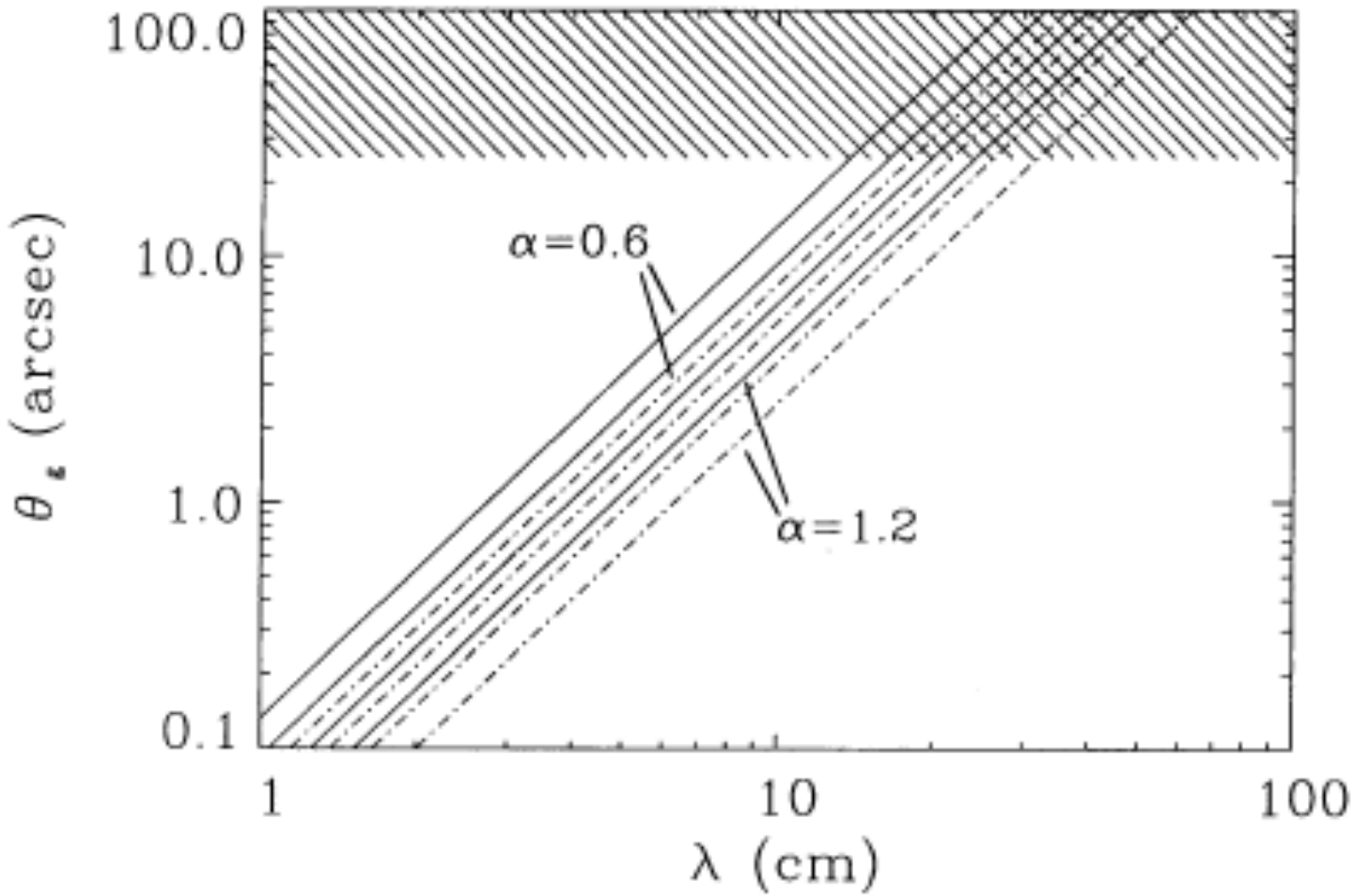
When observing an extended source in the absence of turbulence we have

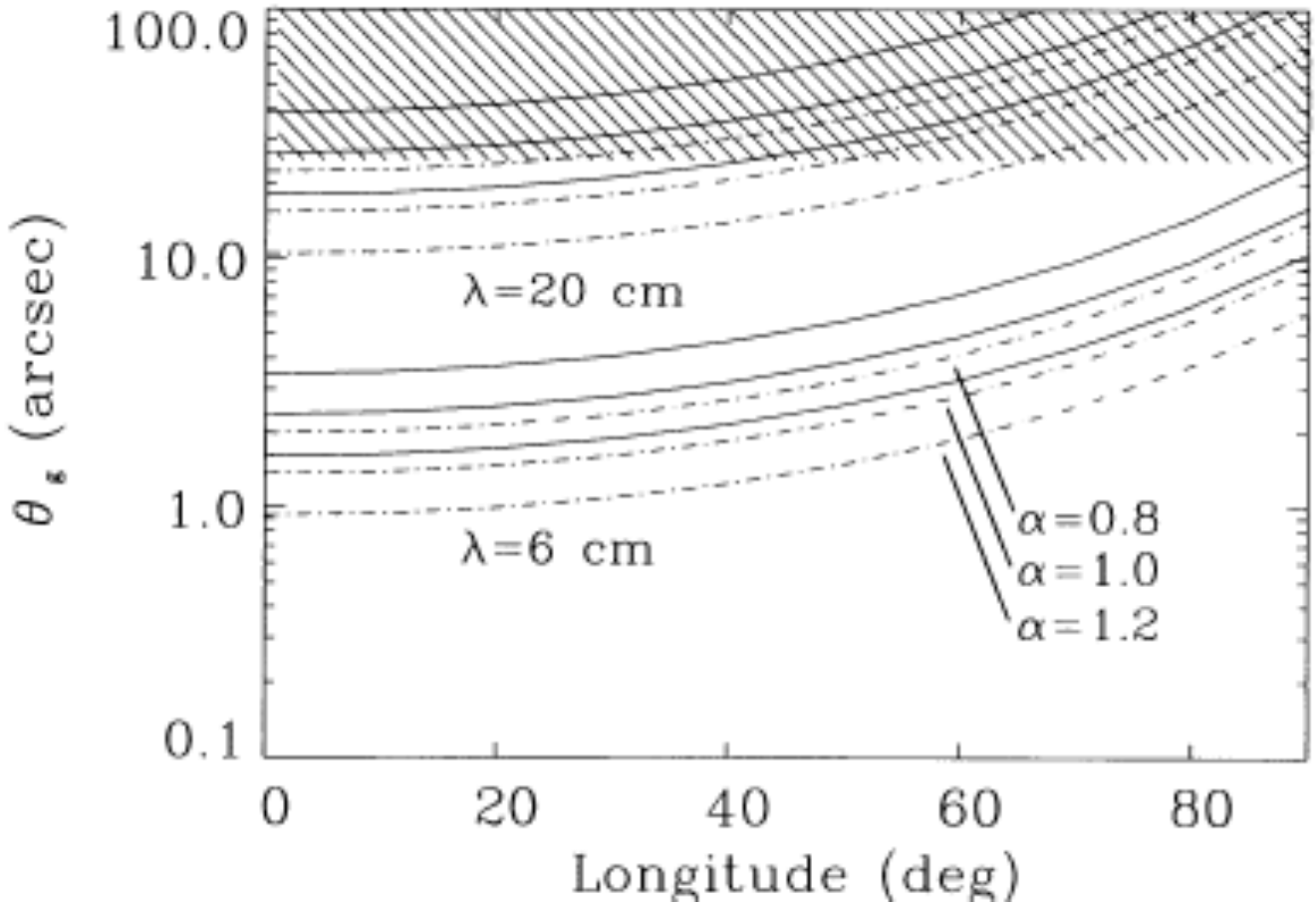
$$\Gamma(s) = V(s)$$

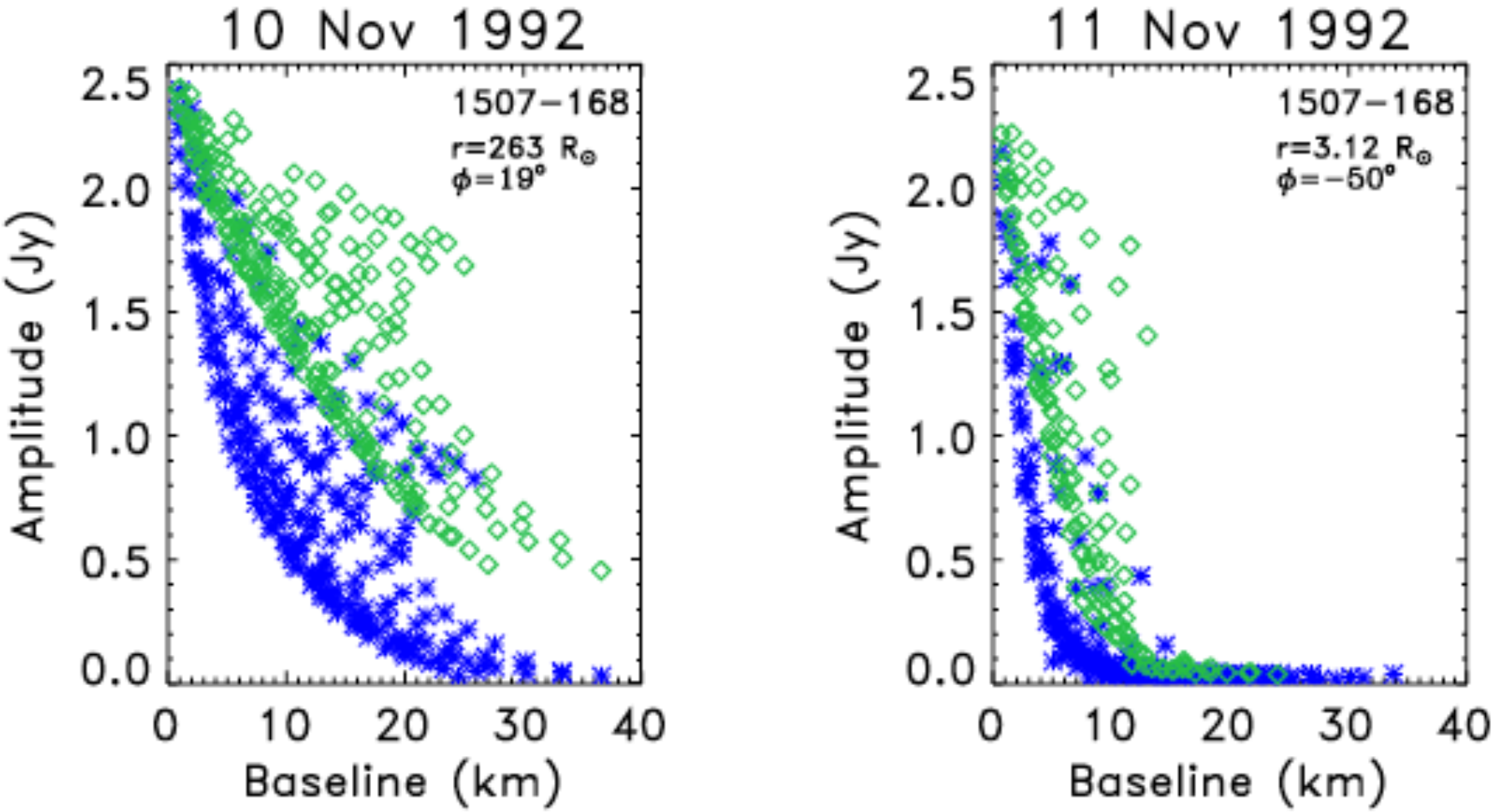
and when a turbulent medium lies between the source and the observer

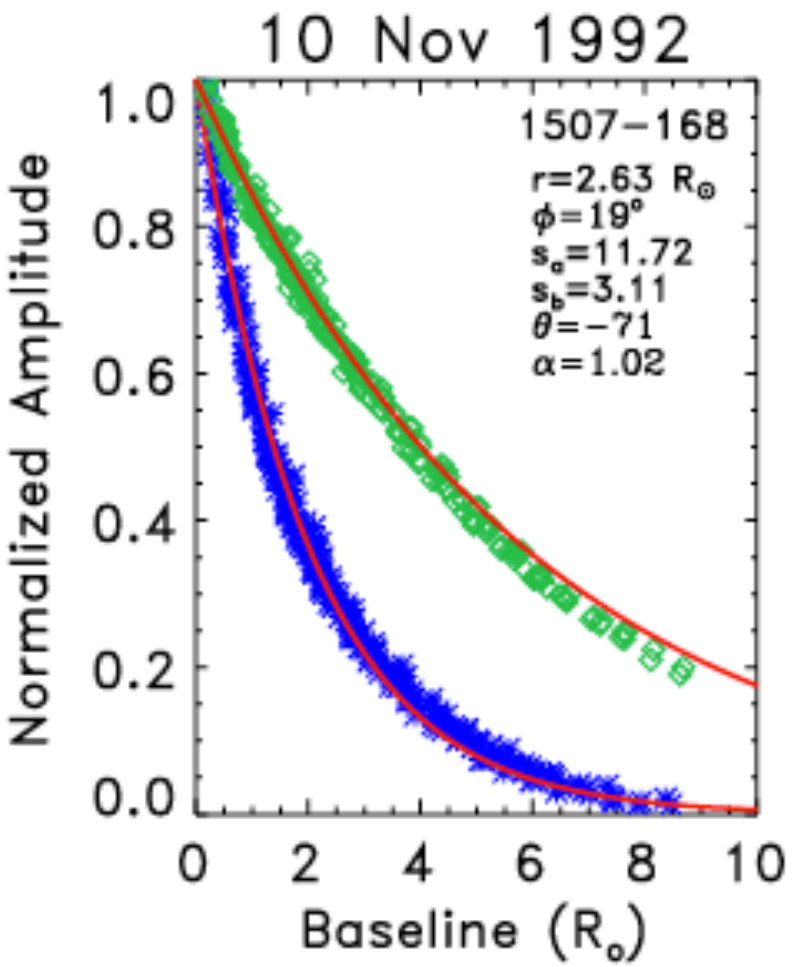
$$\Gamma(s) = V(s)\exp\left[-D(s)/2\right]$$

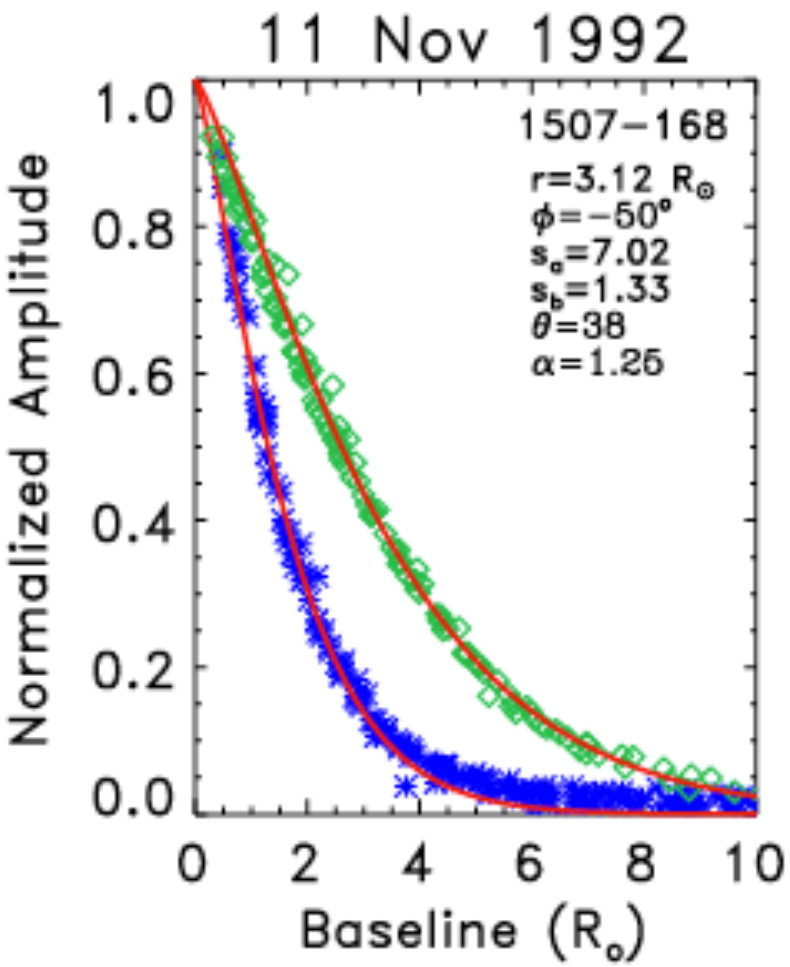
i.e, the image of the source is convolved with a Gaussian angular broadening function.

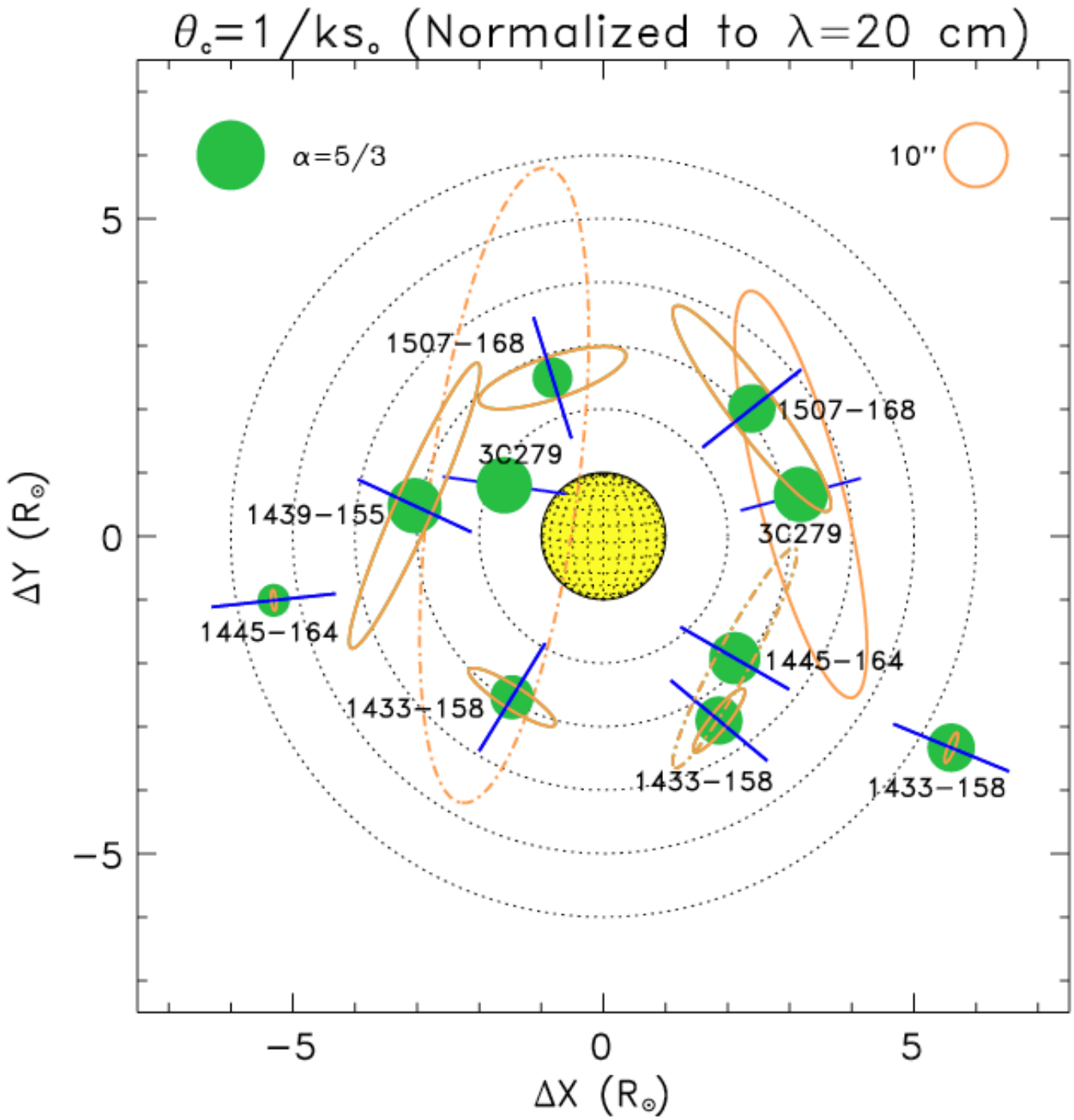

100.0
10.0
1.0
0.1
θ_s (arcsec)
α=0.6
α=1.2
1
10
100
λ (cm)


100.0
10.0
1.0
0.1
θ_s (arcsec)
λ=20 cm
λ=6 cm
α=0.8
α=1.0
α=1.2
0
20
40
60
80
Longitude (deg)

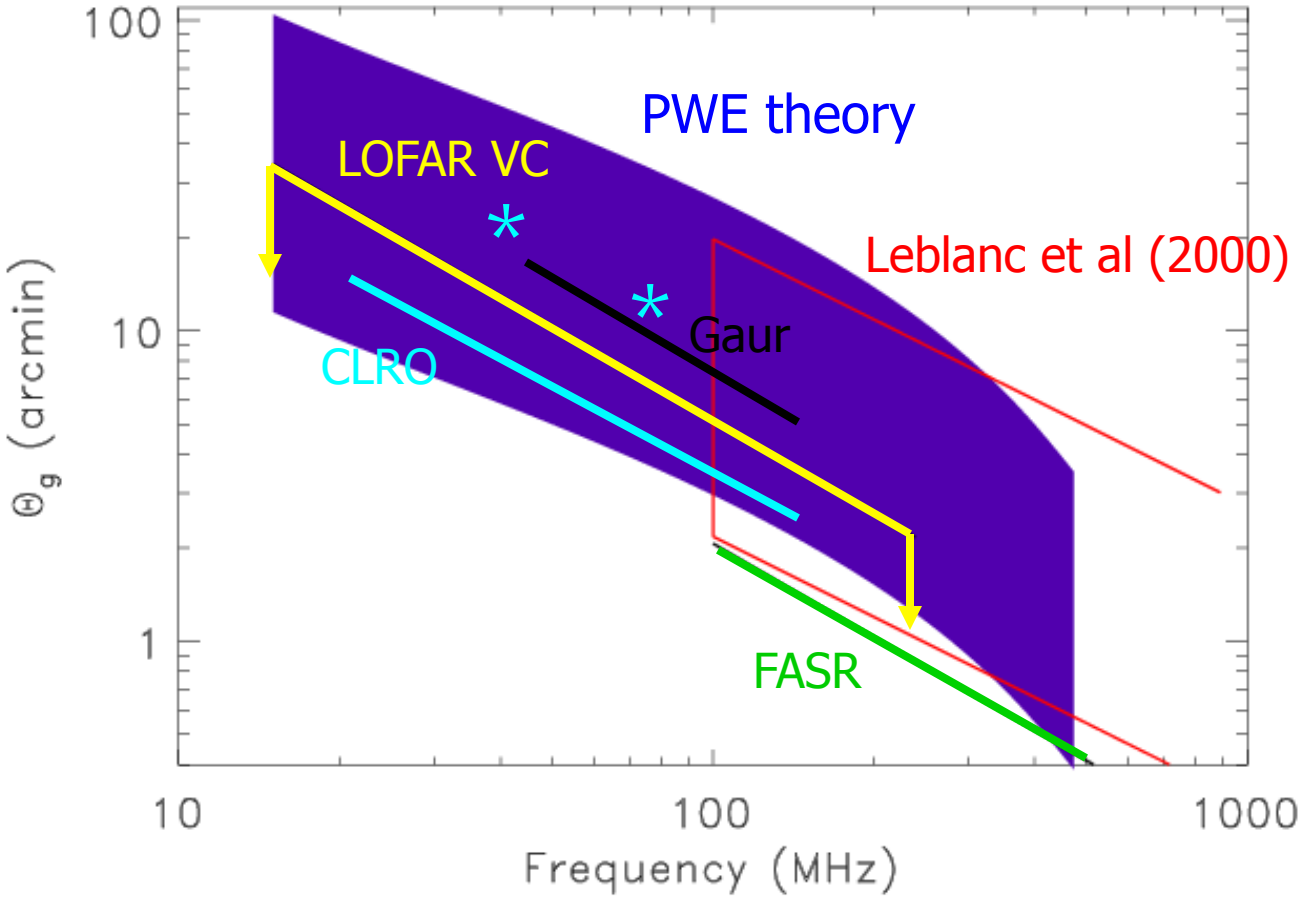

10 Nov 1992
1507−168
r=263 R⊙
ϕ=19°
Amplitude (Jy)
Baseline (km)
0.0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40
11 Nov 1992
1507−168
r=3.12 R⊙
ϕ=−50°
Amplitude (Jy)
Baseline (km)

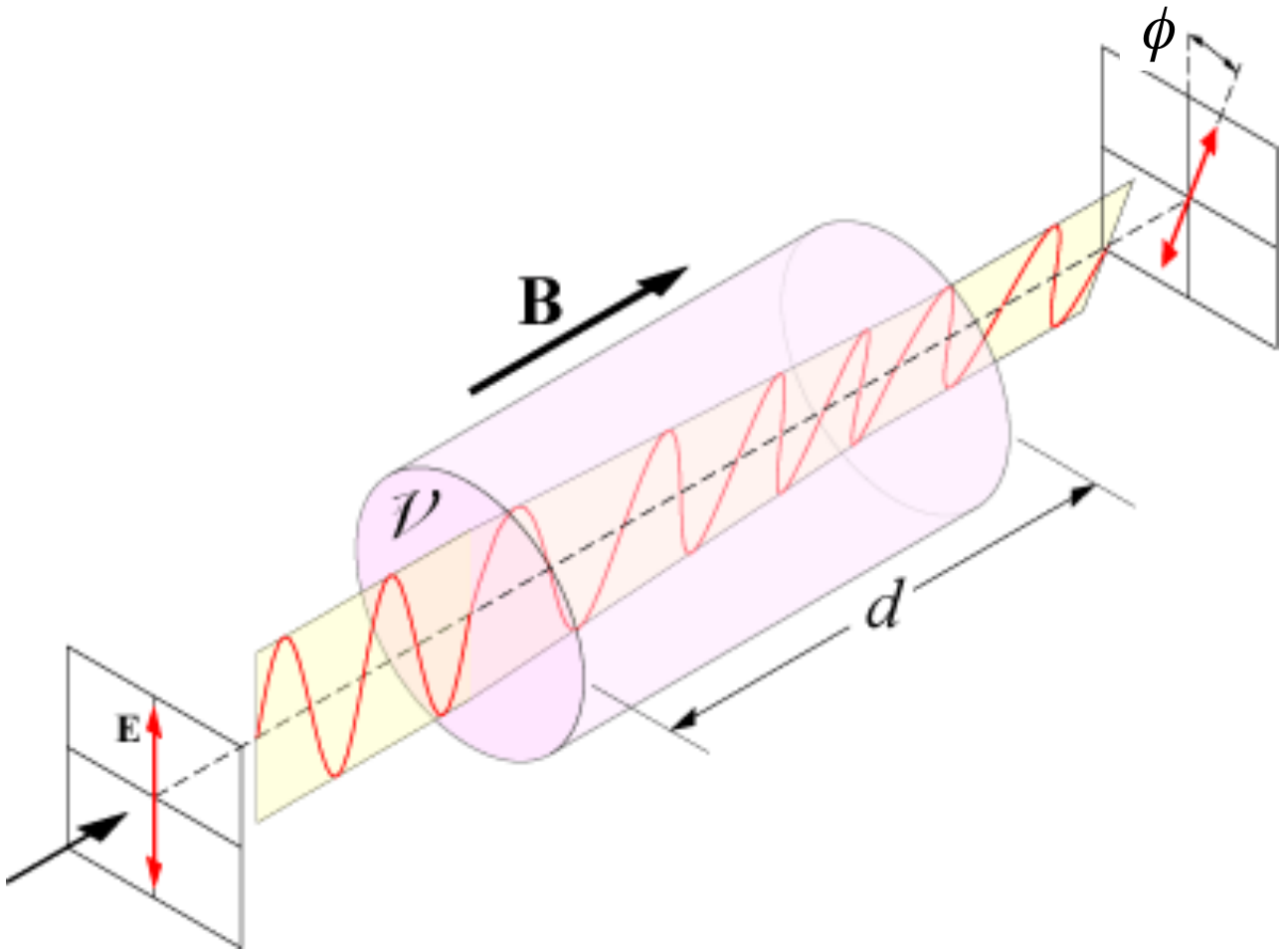

10 Nov 1992
1507−168
r=2.63 R⊙
ϕ=19°
s_a=11.72
s_b=3.11
θ=−71
α=1.02
Normalized Amplitude
Baseline (R⊙)
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10

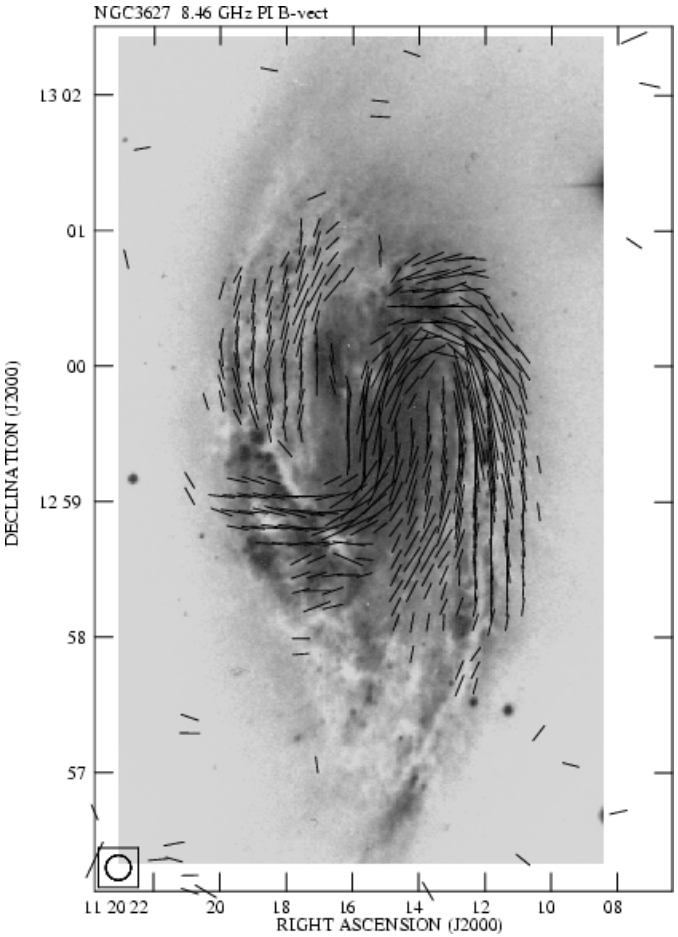

11 Nov 1992
1507−168
r=3.12 R⊙
ϕ=−50°
s_a=7.02
s_b=1.33
θ=38
α=1.25
Normalized Amplitude
Baseline (R⊙)
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10


θc=1/ksₒ (Normalized to λ=20 cm)
α=5/3
10″
1507−168
3C279
1439−155
1445−164
1433−158
1507−168
3C279
1445−164
1433−158
1433−158
5
0
−5
ΔY (R⊙)
−5
0
5
ΔX (R⊙)

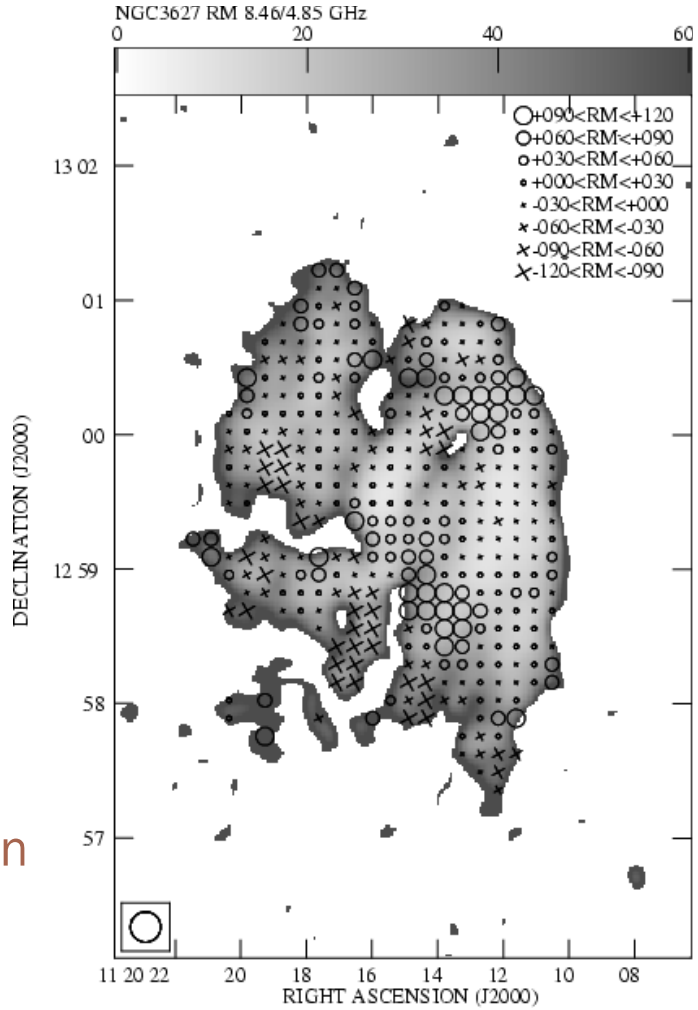
Angular broadening of solar radio sources by coronal turbulence




ϕ
B
V
d
E

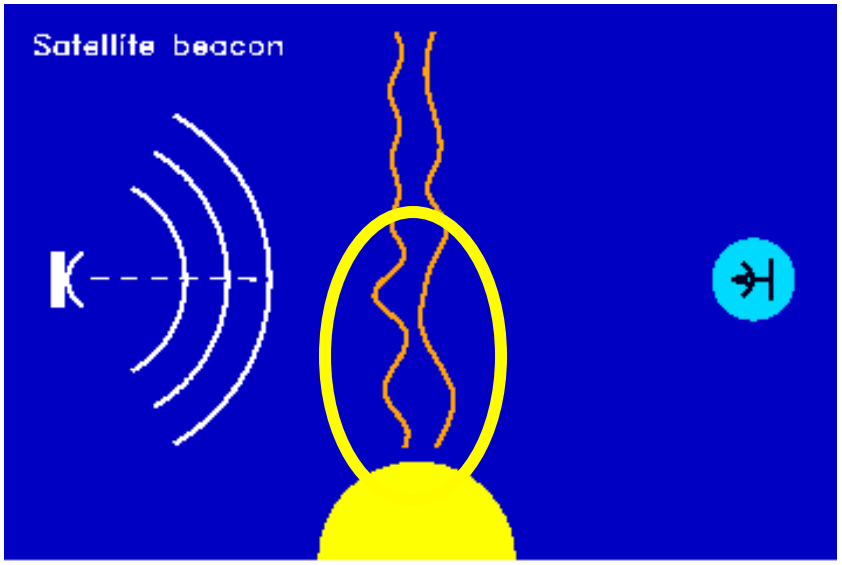


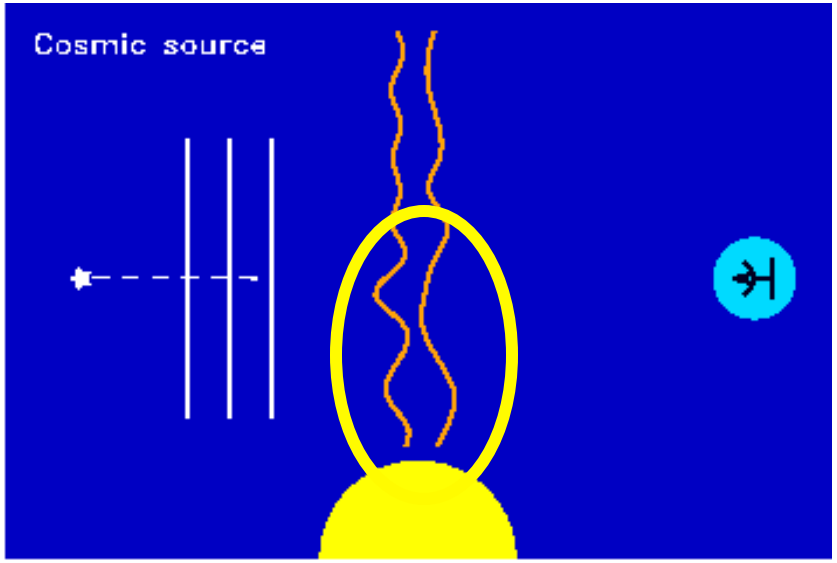
VLA 8.4 GHz map of NGC3627 with magnetic field vectors superposed.



Map of Faraday rotation between 8.4 and 4.9 GHz

Soida et al. 2001





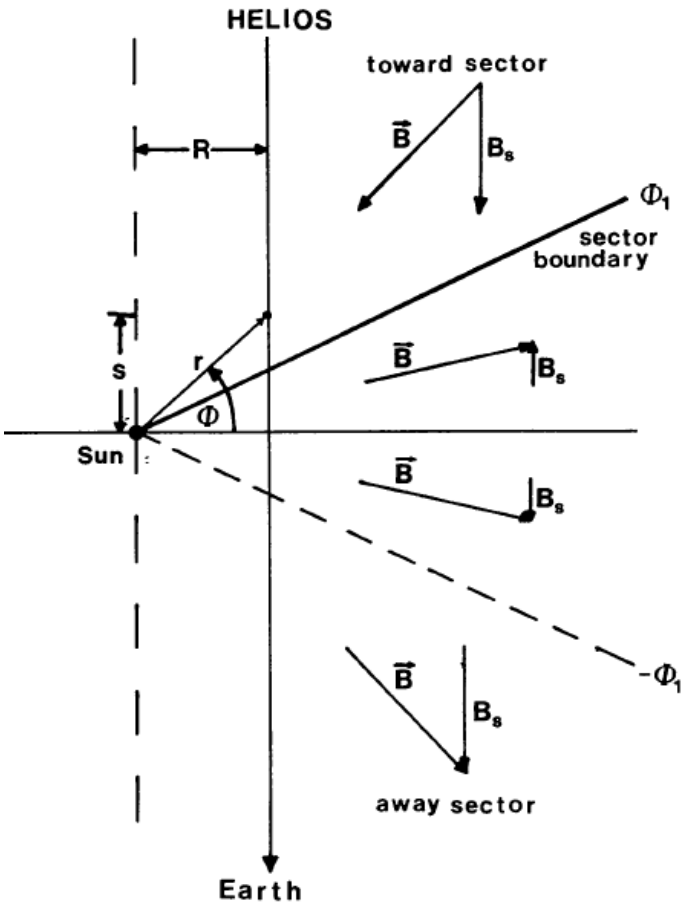
The position angle of a linearly polarized signal passing through a magnetized plasma is

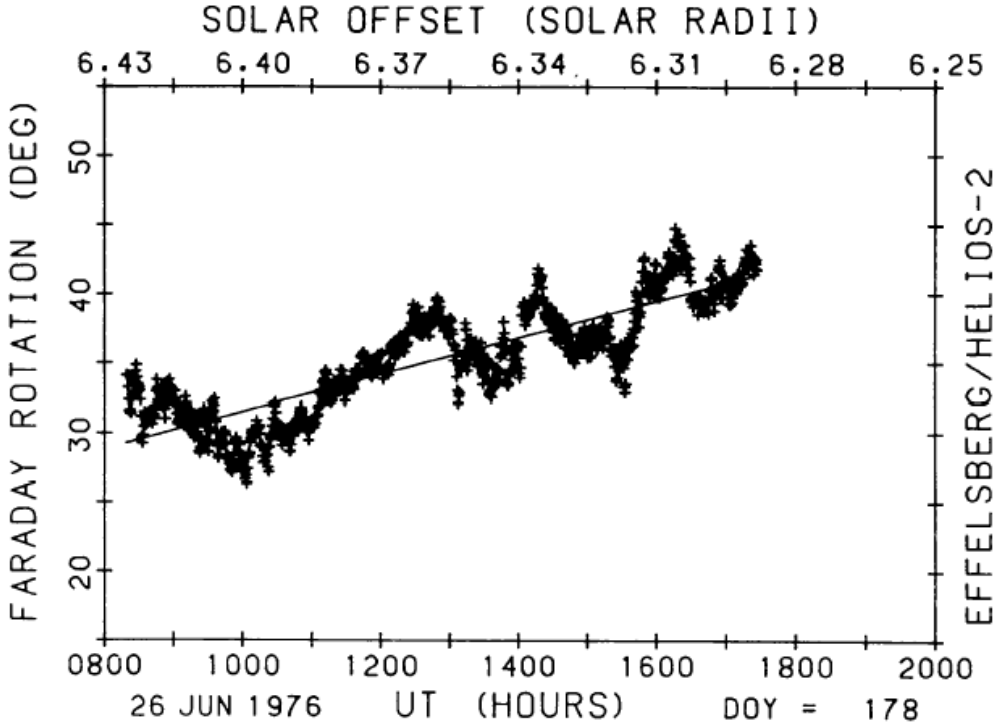
$$\phi \propto \lambda^2 \int n_e B_l ds$$

The passage of a transient (e.g., CME) perturbs the ambient electron number density and magnetic field - ϕ is therefore also perturbed as

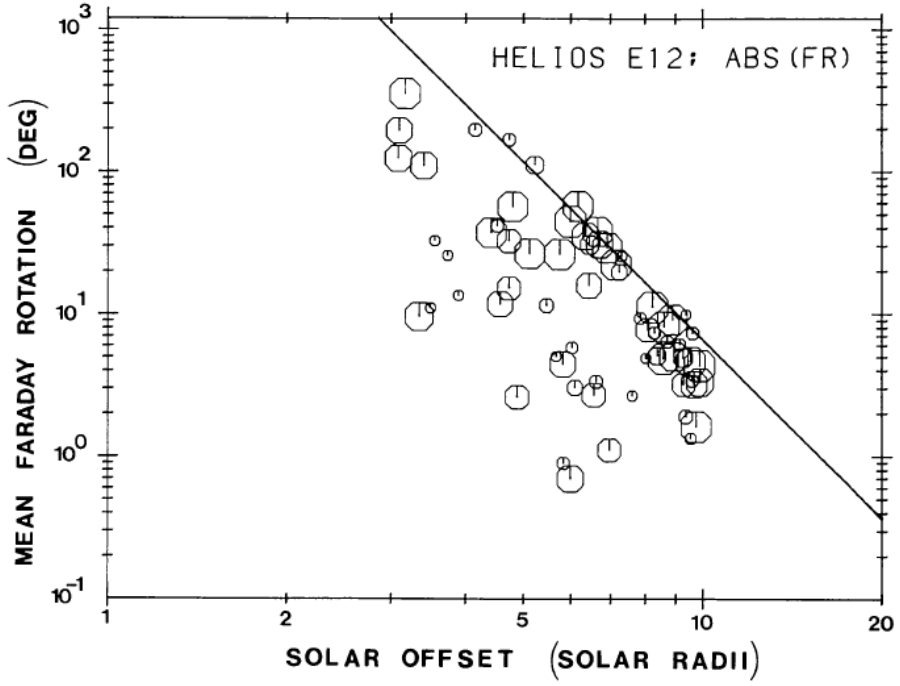
$$\Delta\phi \propto \lambda^2 \int n_e^{tr} B_l^{tr} ds$$

If an estimate of n_e^{CME} may be determined using white light coronagraphs, allowing an estimate of the mean longitudinal magnetic field to be derived.

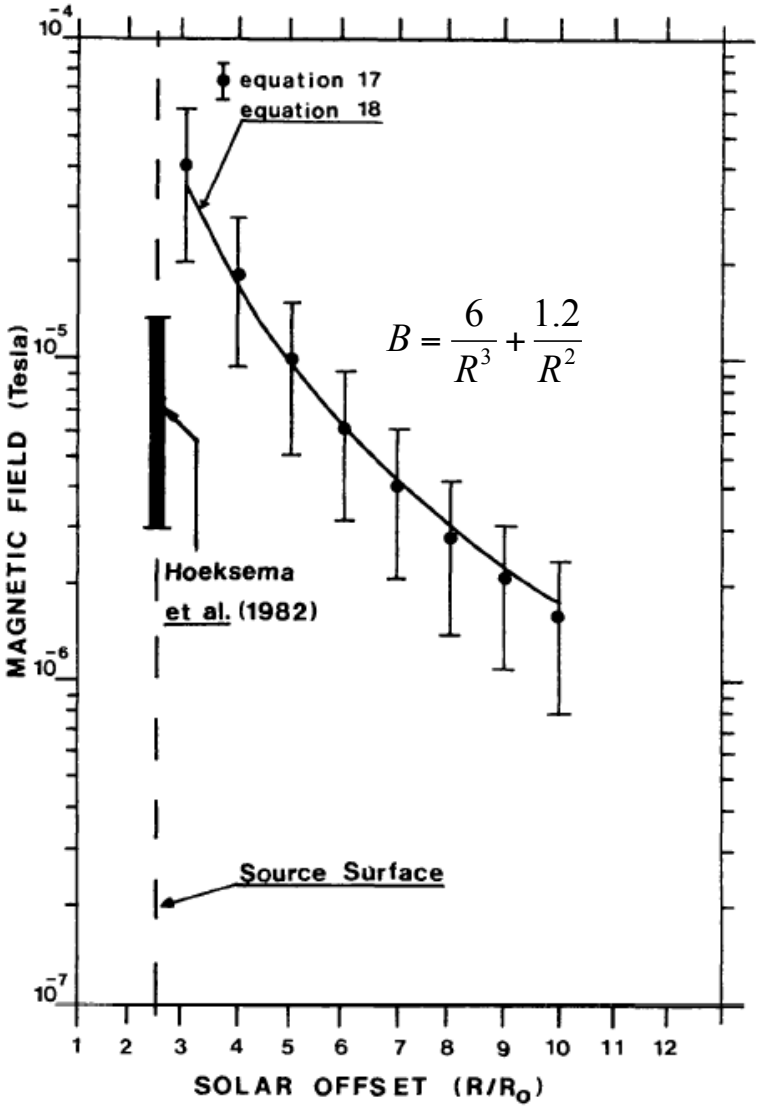




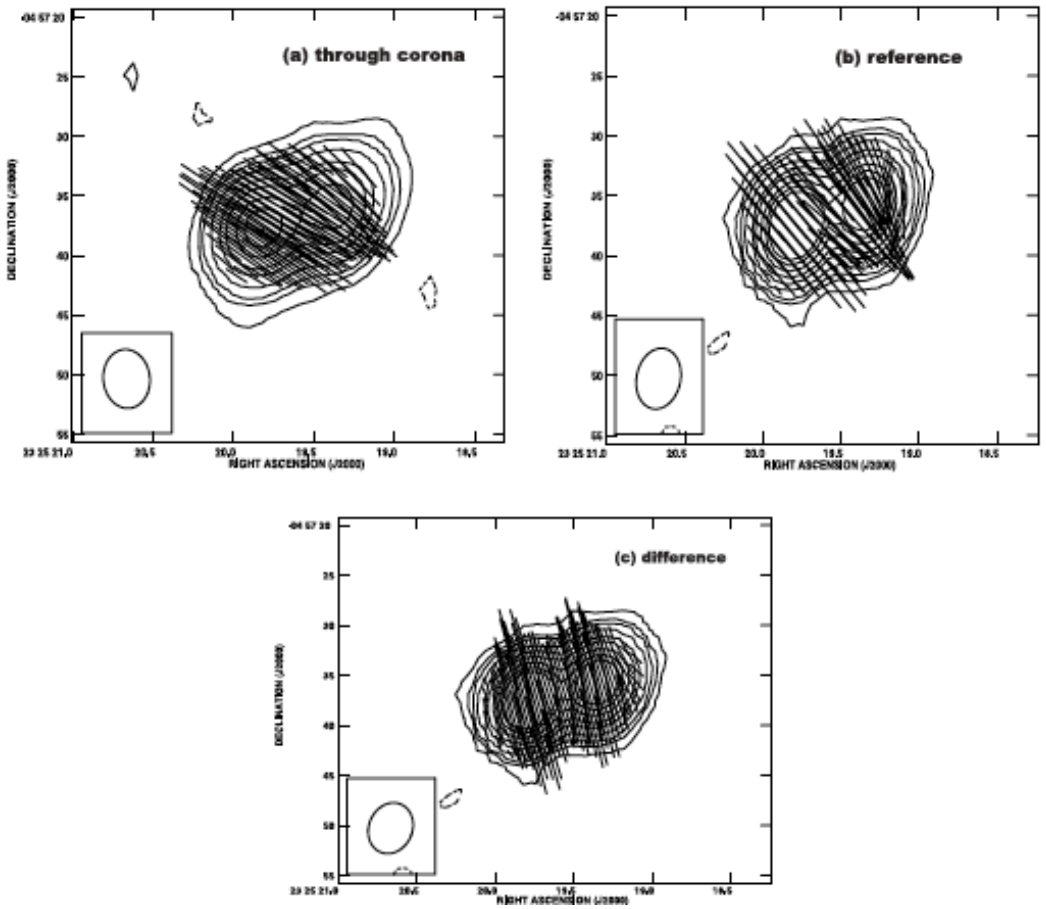
Patzöld et al. (1987)

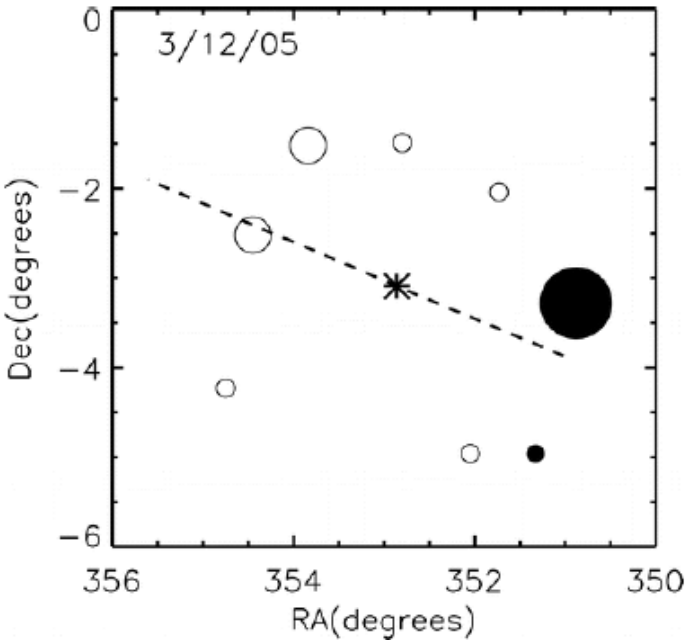


Faraday rotation measurements using a radio beacon on Helios



Patzöld et al. (1987)





Forward fitting needed to disentangle B from n_e.

Ingleby et al 2007

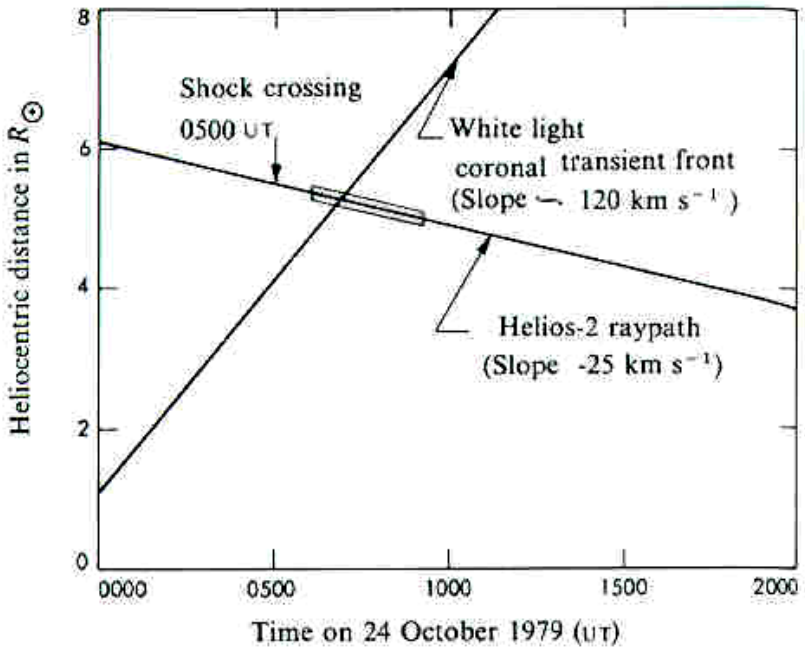


Fig. 2 Height–time profiles for the Helios-2 raypath and Solwind white light coronal front measurements. The cross-hatched region indicates the possible range of intersections between the Helios-2 raypath and the white light transient front allowing for the 120± 120 km s^{-1} uncertainty in the measured transient speed.

Observation of spectral broadening as a result of propagation through a CME.

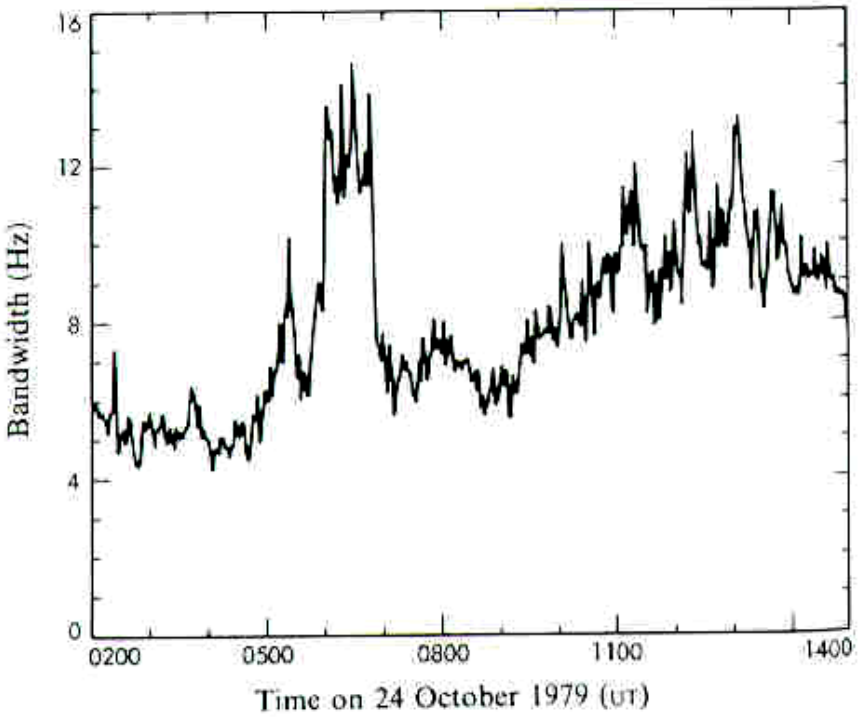
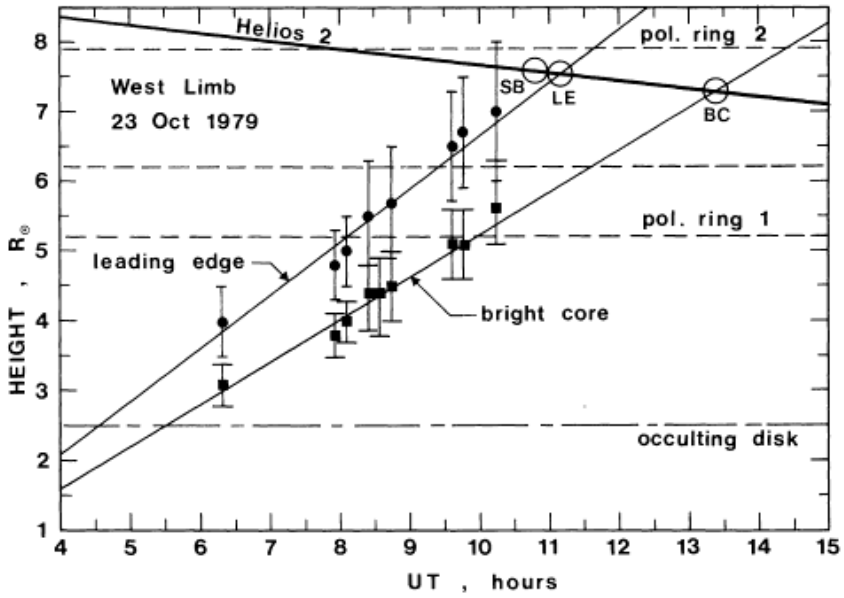


Fig. 3 Time history of Helios-2 2.3-GHz spectral broadening bandwidth BW.

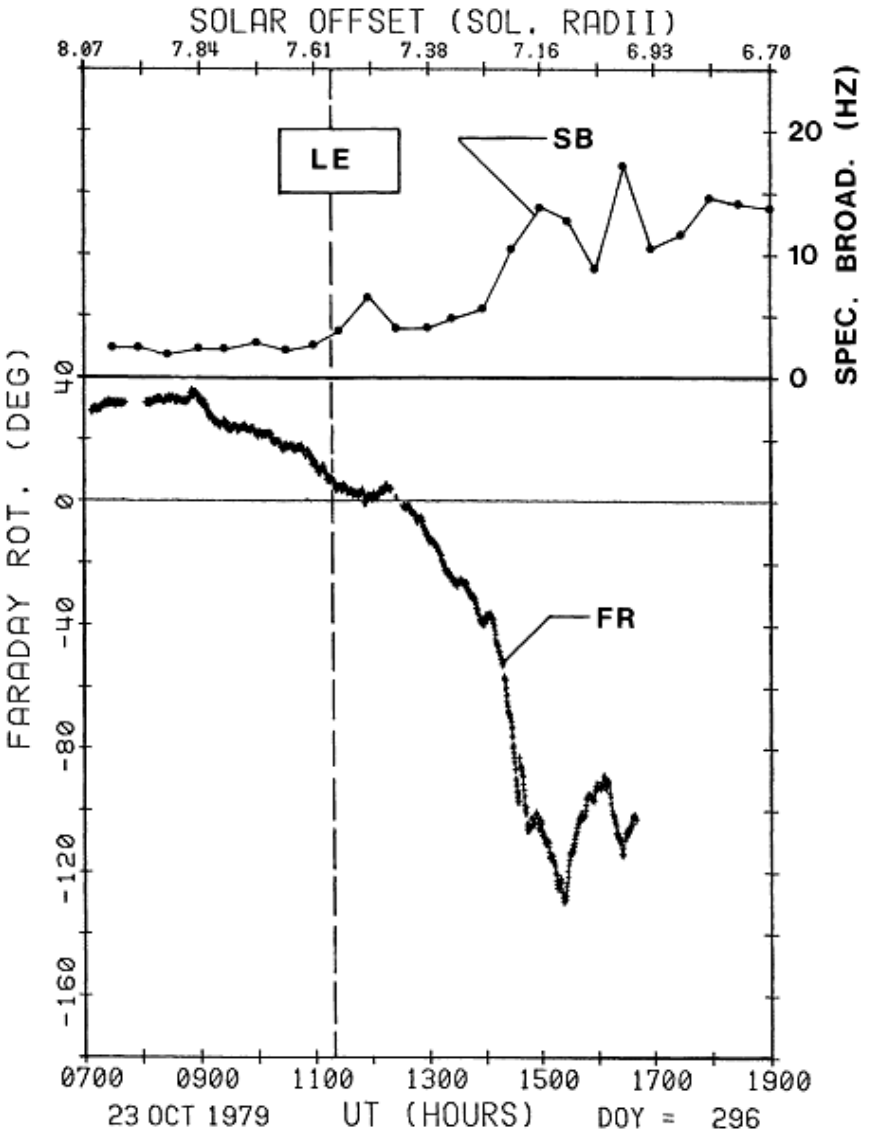
$$\Delta\nu \sim \sigma_{ne} V_p$$

from Woo *et al.* 1982



A total of 5 CMEs were observed. There was a one-to-one correspondence between SB and FR perturbations.

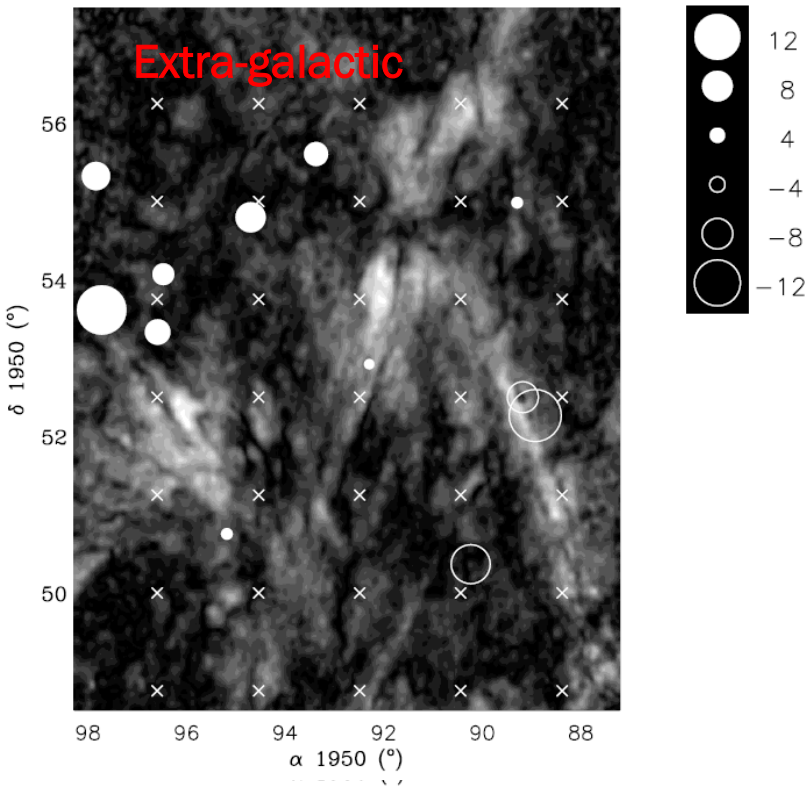
Mean longitudinal magnetic fields ranged between 10-100 mG, normalized to a radial distance of 2.5 solar radii.



FR SOURCES

HOW MANY SOURCES AT OUR FREQUENCIES?

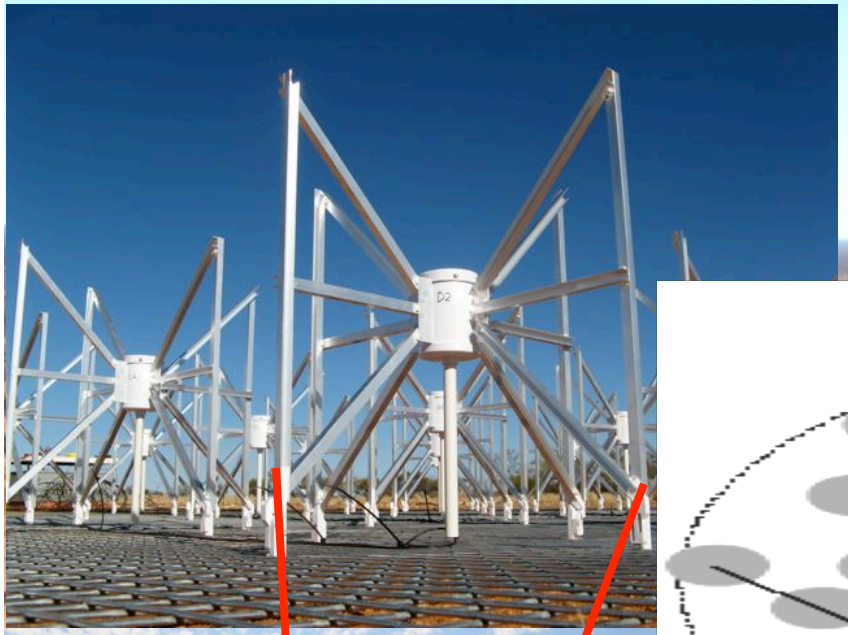
Near Auriga constellation

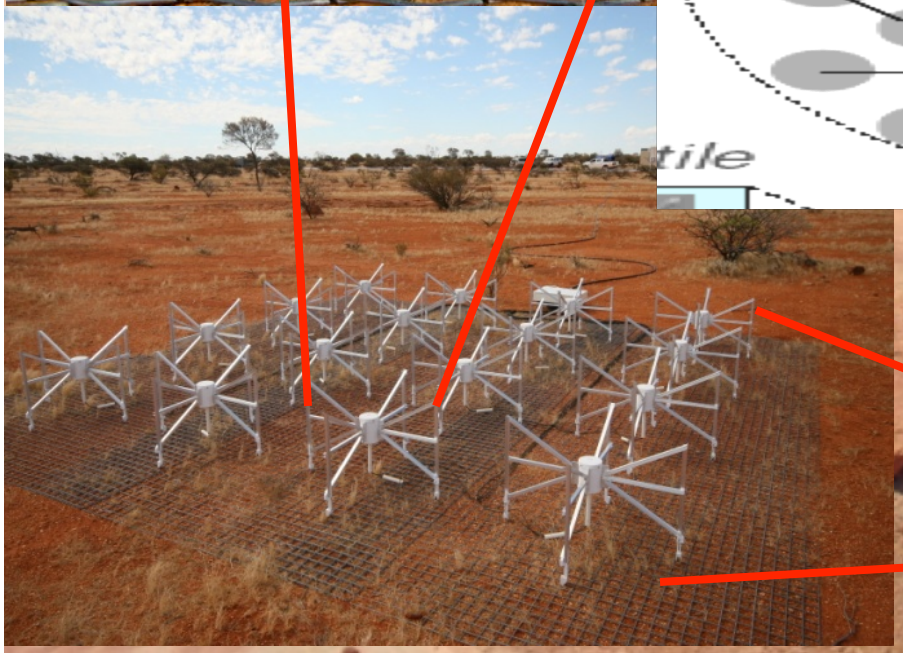


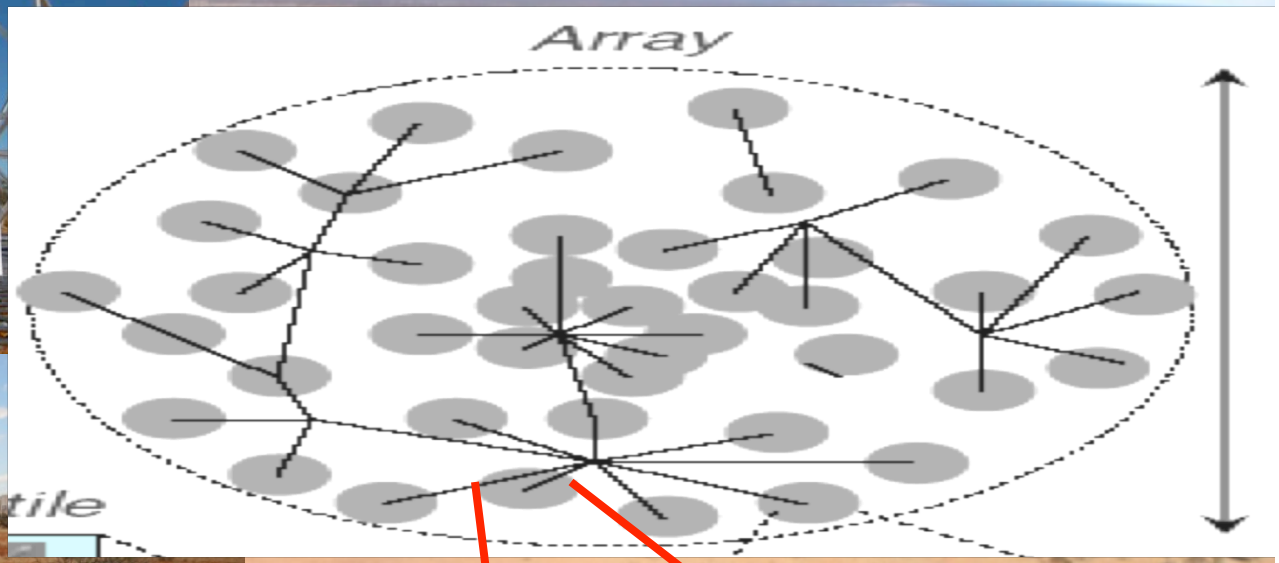
- Polarization tends to decrease with frequency
- Westerbork Northern Sky Survey at 327 MHz
- One extragalactic source ~ 2 square degrees
- RM of several hundred sources detectable in five minute integration
- Potential to use diffuse galactic emission as well

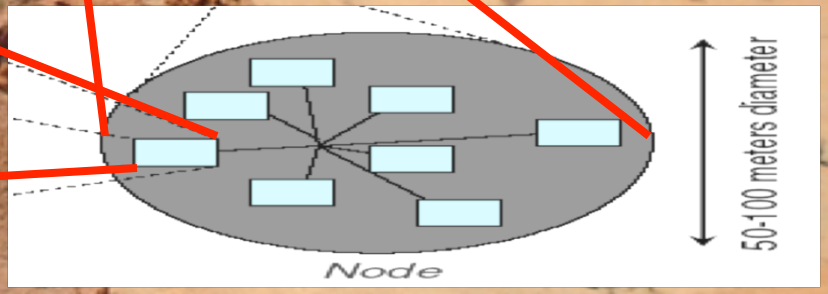
Haverkorn, 2003

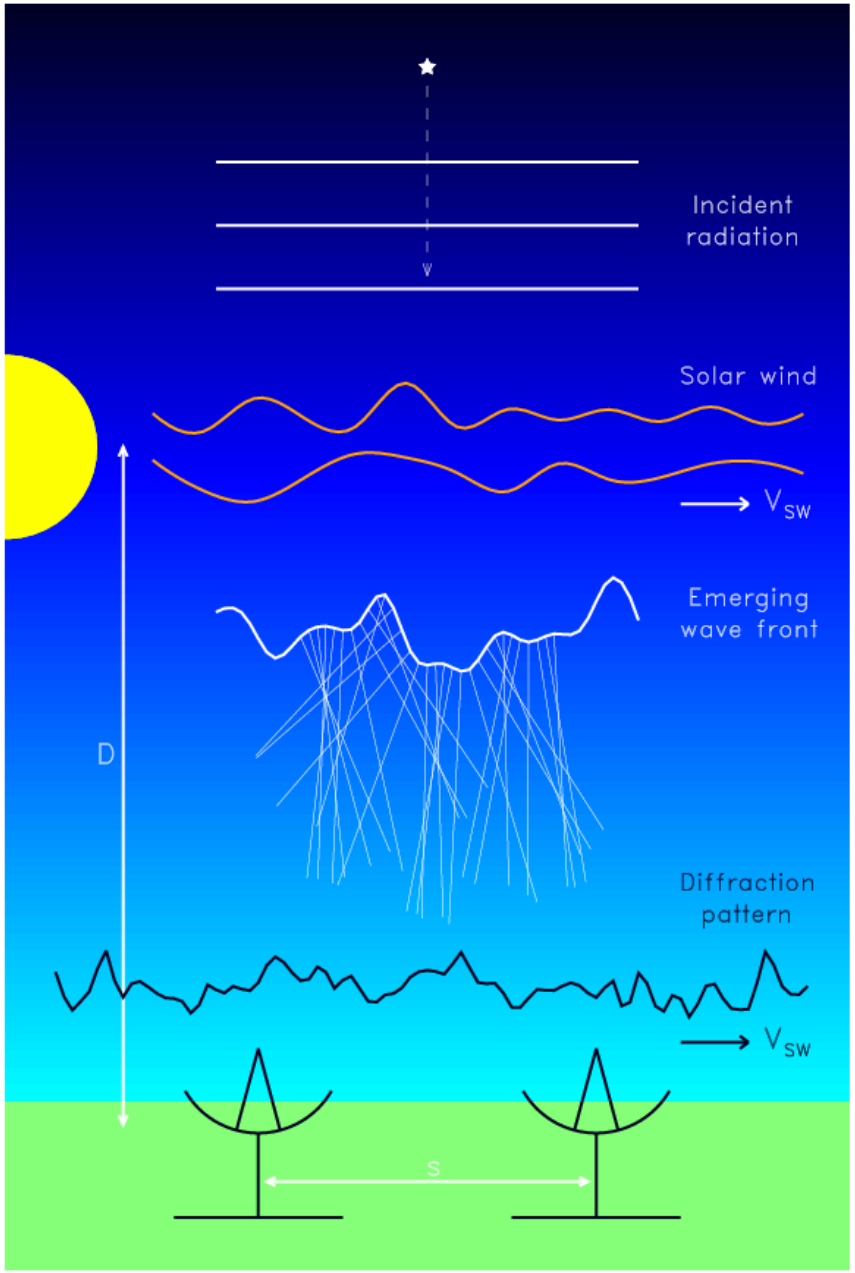
Currently building out from 32 tile demonstrator to 128 tiles



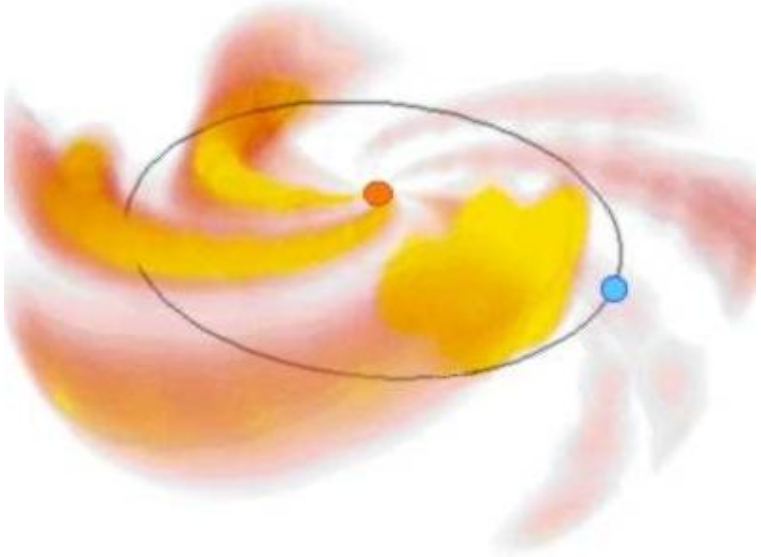






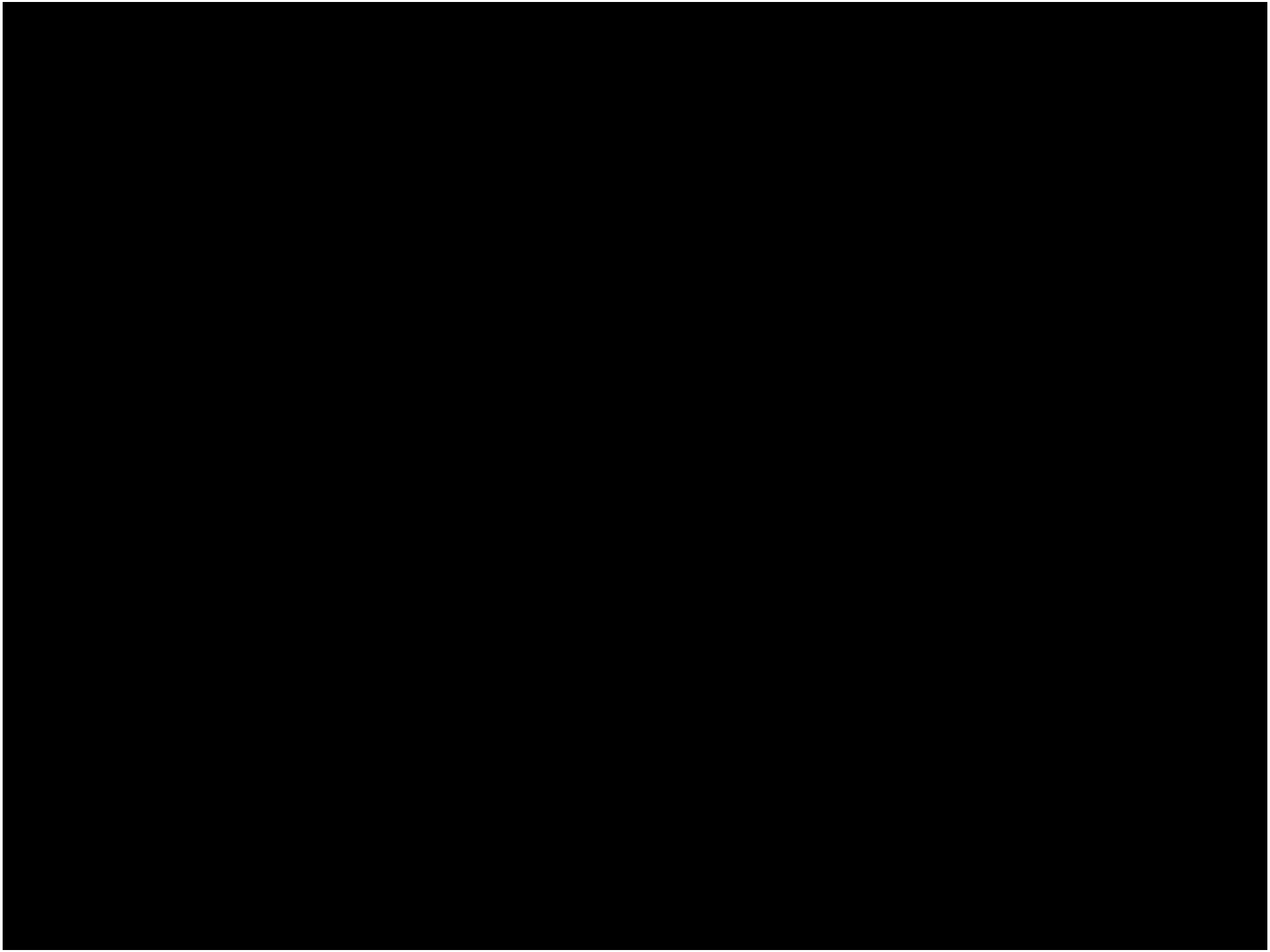


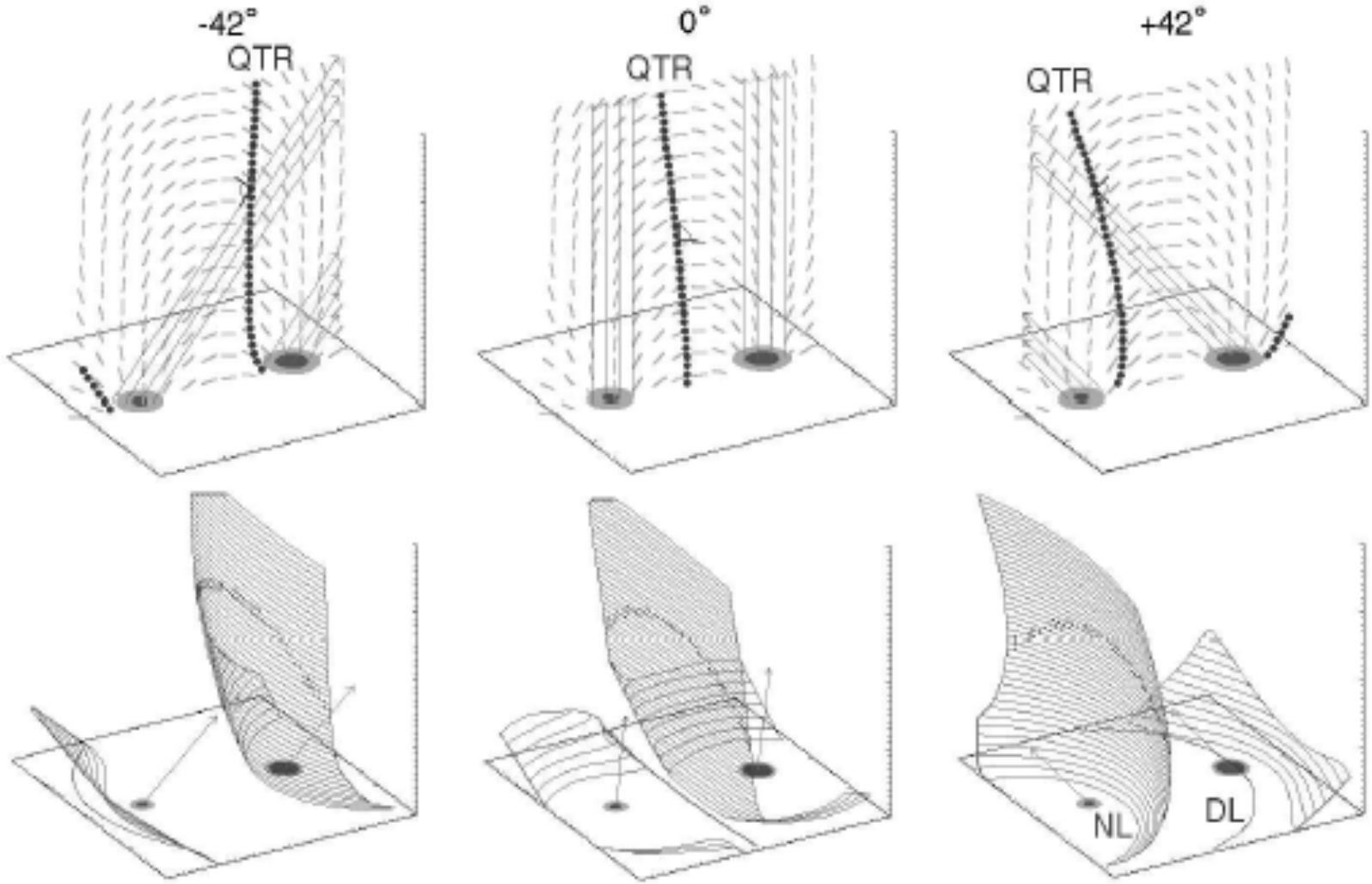
Tomographic reconstruction of recurrent structures in the inner heliosphere using observations of inter-planetary scintillation (IPS).



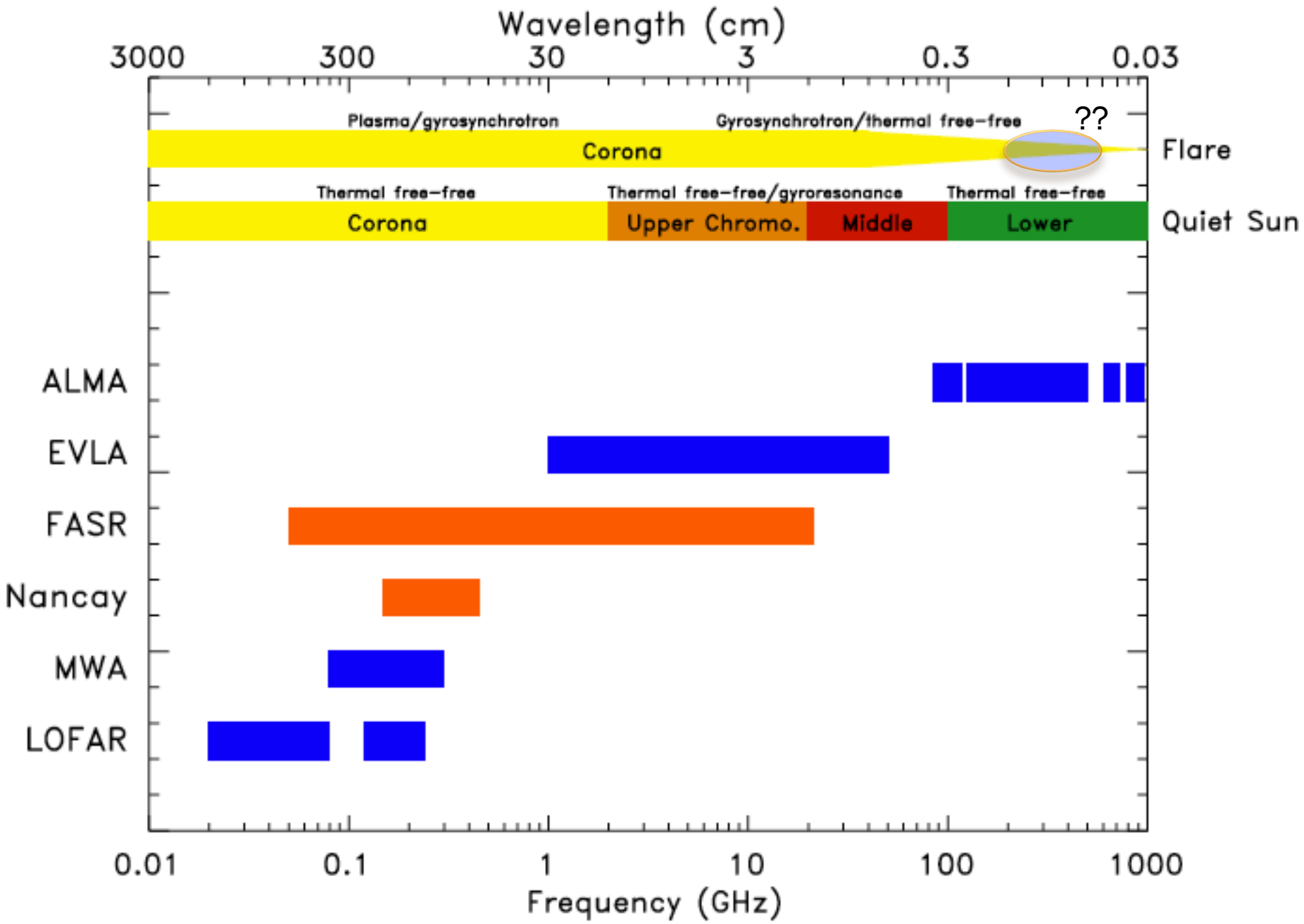
LOFAR could provide much more comprehensive maps at higher angular resolution.

Jackson et al. 2001





Ryabov 2003


Wavelength (cm)
3000
300
30
3
0.3
0.03
Plasma/gyrosynchrotron
Gyrosynchrotron/thermal free-free
??
Corona
Flare
Thermal free-free
Thermal free-free/gyroresonance
Thermal free-free
Corona
Upper Chromo.
Middle
Lower
Quiet Sun
ALMA
EVLA
FASR
Nancay
MWA
LOFAR
0.01
0.1
1
10
100
1000
Frequency (GHz)