Radio AstronomyJargon

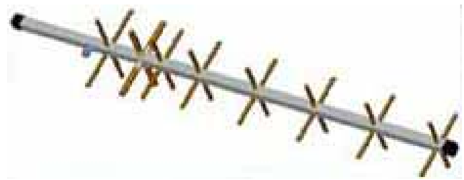
Al Wootten

- Basic radio astronomy
- Antenna fundamentals
- Types of antennas
- Antenna performance parameters

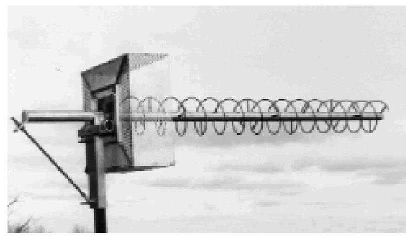
General Antenna Types

Wavelength > 1 m (approx) Wire Antennas

Dipole



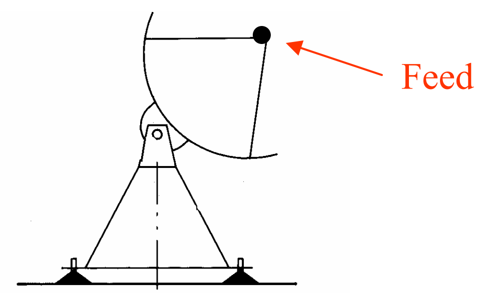
Yagi



Helix

or arrays of these

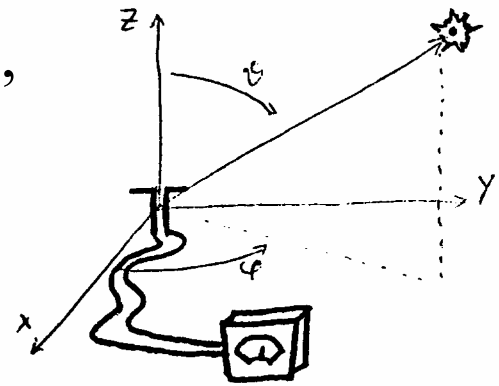
Wavelength < 1 m (approx) Reflector antennas



Wavelength = 1 m (approx) Hybrid antennas (wire reflectors or feeds)

Consider a simple radio telescope, two bent wires (dipole) attached to a meter, exposed to a point source a large distance away.

The meter responds to the presence of the source. We define $\boldsymbol{D}(\nu,\theta,\phi)$ = meter deflection, where θ and ϕ are the sky coordinates of the point source, and ν the frequency of observation.



For some orientation of source and dipole the meter deflection will be maximum. Define $\boldsymbol{D}_{max}(\nu,\theta,\phi) = \boldsymbol{D}(\nu,\theta_{\text{max}},\phi_{\text{max}})$ and

$$\frac{\boldsymbol{D}(\nu,\theta,\phi)}{\boldsymbol{D}_{max}(\nu,\theta,\phi)} = \boldsymbol{P}(\nu,\theta,\phi) < 1.$$

$\boldsymbol{P}(\nu,\theta,\phi)$ is the **Beam Pattern**

$\boldsymbol{P}(\nu,\theta,\phi)$ has a 'zeroth' moment: $\Omega_A = \iint_{\text{all sky}} \boldsymbol{P}(\nu,\theta,\phi)\, d\,\Omega$ where

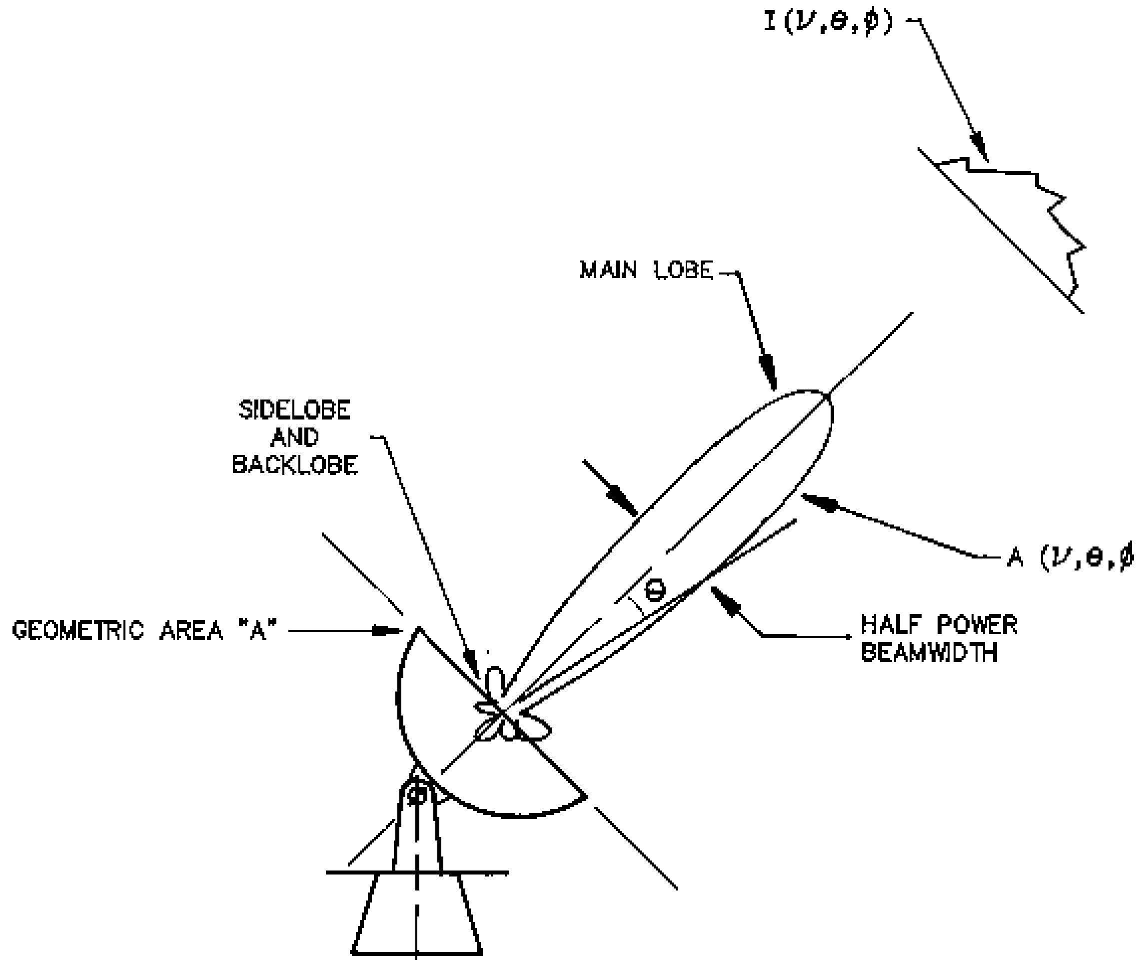
Ω_A is the **Beam solid angle**. Then define $D=4\pi/\,\Omega_A$ is the **Directivity or Gain** of the antenna. Generally, maximizing D is good, and to accomplish it we fashion cunningly shaped pieces of metal around the basic antenna.

100-meter Green Bank Telescope

GBT

Dedicated in 2000

BASIC ANTENNA FORMULAS



Effective collecting area $A(\nu,\theta,\phi)$ m^2

On-axis response $A_0 = \eta A$

η = aperture efficiency

Normalized pattern (primary beam)

$\boldsymbol{P}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$

Beam solid angle $\Omega_A = \iint_{\text{all sky}} \boldsymbol{P}(\nu,\theta,\phi)\, d\,\Omega$

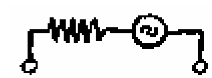
$A_0\, \Omega_A = \lambda^2$ Also **Main lobe solid angle** $\Omega_M = \iint \boldsymbol{P}(\nu,\theta,\phi)\, d\Omega$

and **Full Half Power Beamwidth** **'FWHP'**

$\eta_B = \Omega_M / \Omega_A < 1$ the Beam Efficiency

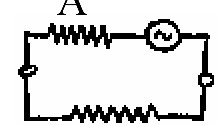
Reciprocity the power pattern of a transmitting antenna is identical to that of a receiving antenna. Suppose there are two identical antennas. In the transmitting antenna A we generate a current flow I_A we will measure a current flow I_B at antenna B and vice versa.

Now consider the antenna as an electrical system, equivalent to a source of fluctuating voltage V characterized by $\langle V^2 \rangle$ the mean square voltage, and some characteristic resistance.



Nyquist showed that a resistance R_A at a temperature T_A will produce a constant noise power per unit frequency interval. Therefore we define the fluctuating voltage in the antenna as arising from some characteristic temperature of its characteristic resistance:

$\langle V^2 \rangle = 4k\, T_A\, \Delta\nu\;\; R_A$



The power emitted into some frequency interval is

$P_{em} = \; k\, T_A\, \Delta\nu$

For a receiving antenna we connect a receiver (R_{LOAD}) and draw power $P_{LOAD} = \langle V^2 \rangle R_A/(R_A + R_{LOAD})^2$

The maximum power drawn is obtained by matching the receiver to the Antenna, which requires setting $R_A = R_{LOAD}$ and we find that
$P_{abs} = P_{LOAD}(max) = \langle V^2 \rangle R_A /(2 R_A^2)$.
Now, from reciprocity, identify the $\langle V^2 \rangle$ arising in the receiving antenna with the $\langle V^2 \rangle$ in the transmitting antenna and by Nyquist's law
$P_{abs} = k T_A \Delta\nu$.

We have identified the power stimulated in the antenna by the presence of a source with that obtained by heating the characteristic antenna resistance to some temperature T_A. This is the **Antenna Temperature**.

In reality, T_A refers to anything in the beam—source, sky, birds, etc. The noise power associated with T_A is combined with that from the receiver and what we actually measure is
$T_{SYS} = T_{LOAD} + T_A$, or **System Temperature** . In many cases, T_A is small compared to the other terms. Note that by cooling the receiver, we can make the load temperature, and the system temperature, smaller.

Radiometer Equation

Now $\langle V^2 \rangle$ is the mean sum of potentials arising from collisions among the thermally agitated electrons in the system. The number of collisions n_c will be proportional to the system temperature. To measure n_c we count collisions for a time. For a total of N counts, then the uncertainty in n_c will be:

$$\frac{\Delta n_c}{n_c} = \frac{1}{\sqrt{N}}$$

While the collisions are nearly instantaneous, the detector has a finite bandwidth $\Delta\nu$ and its response to an individual collision has a time constant, $1/\Delta\nu$. Therefore in an integration of τ seconds, one obtains $N = \Delta\nu\ \tau$ **independent** counts.

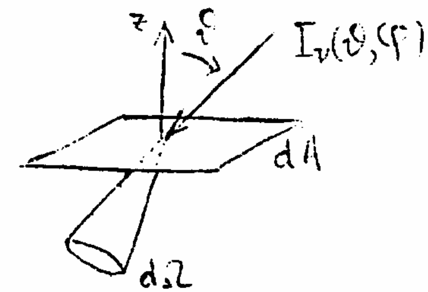
$$\frac{\Delta n_c}{n_c} \propto \frac{1}{\sqrt{\Delta\nu\tau}} \quad \text{or} \quad \Delta T_{sys} = \frac{K\,T_{sys}}{\sqrt{\Delta\nu\tau}}$$

the Radiometer Equation

Where K, near unity, depends on the receiver and the mode of observation.

Radiation, Intensity, Flux Density

Consider radiation incident upon the antenna, as represented by the specific intensity $I_\nu(\theta,\phi)$. Then the power passing through an area dA, directed into solid angle $d\,\Omega$ is:



$$dP_{incident} = I_\nu(\theta,\phi)\cos\theta\, dA\, d\,\Omega\, d\nu$$

And the total power incident upon the antenna is then:

$$P_{incident} = \int_\nu^{\nu+\Delta\nu} d\nu \int_{4\pi} d\,\Omega \int_{ant} dA \cos\theta\, I_\nu(\theta,\phi)$$

Where the source may be extended and its intensities may be added linearly. For $\Delta\nu$ small, I_ν is constant, and if we point the telescope at the source, $\cos\theta = 1$ so that

$P_{incident} = \Delta\nu \int_{4\pi} A\, I_\nu(\theta,\phi)\, d\,\Omega$ where A is the physical telescope area.

$A_e(\theta,\phi) = A_e\, \boldsymbol{P}(\theta,\phi)$ and A_e is the effective area of the telescope.

$\eta_A = A_e/A$ is the aperture efficiency of the telescope. Also,

$S_\nu = \iint d\,\Omega\, I_\nu(\theta,\phi)$ is the flux density of the source.

Of course, $P_{incident}$ and $P_{absorbed}$ are usually not equal. Often, a receiver is sensitive to only one polarization of the incoming energy and $P_{absorbed} = 0.5\ \Delta\nu\ A_e\ S_\nu$ and so using the relation $\lambda^2 = A_e\,\Omega_A$ (cf. Kraus' *Radio Astronomy* Chapter 6, esp 6-2 & 6-7). Then

$D = 4\pi\ A_e/\ \lambda^2$

$T_A = \lambda^2/2k\,\Omega_A \iint_{4\pi} d\,\Omega\ P(\theta,\phi)\ I_\nu(\theta,\phi)$ a good statement of our measurement.

Now, for a blackbody,

$I_\nu = 2h\nu^3/c^2\ (e^{h\nu/kT_B}-1)^{-1}$ and for $h\nu \ll kT_B$ then $I_\nu \approx 2kT_B/\ \lambda^2$

Or $J(T_B) \equiv \lambda^2 I_\nu/2k$ the Radiation Temperature

Or, since $h\nu \ll kT_B$ generally holds for centimeter frequencies,

$T_B \equiv \lambda^2 I_\nu/2k$ the Brightness Temperature

Beware that at millimeter wavelengths this is not true and

$T_B = h\nu/k\ (e^{h\nu/kT_B}-1)^{-1}$

Now we have $T_A = 1/\Omega_A \iint_{4\pi} d\,\Omega\ P(\theta,\phi)\ T_B(\theta,\phi)$. For a source smaller that the beam, we have

$T_A = \Omega_S/\Omega_M\ T_B$ where Ω_S/Ω_M is called the dilution factor.For a larger source, $T_A = \Omega_M/\ \Omega_A\ T_B = \eta_B\ T_B$; η_B is called the Beam efficiency.

Equation of Transfer

$dI_\nu = j_\nu\, ds - k_\nu I_\nu\, ds$ where j_ν and k_ν are volume emission and absorption coefficients, which depend upon physical conditions along the line of sight, ds. Then

$dI_\nu / ds = j_\nu - k_\nu I_\nu$ and defining optical depth $\tau = k_\nu\, ds$

$dI_\nu / d\tau = j_\nu / k_\nu - I_\nu$ which we can integrate from τ_1 to τ_2

$$I_\nu(\tau_2) = I_\nu(\tau_1) e^{-(\tau 2 - \tau 1)} + \int_{\tau 1}^{\tau 2} d\tau_\nu\, (j_\nu / k_\nu) e^{-(\tau_2 - \tau_\nu)}$$

Define $\tau_1 = 0$, $J(T_B) = \lambda^2 I_\nu / 2k$, and $J(T_S) = \lambda^2 / 2k\, (j_\nu / k_\nu)$ where

T_S is the Source Radiation Temperature. Then

$$T_B(\tau_2) = T_B(0) e^{-\tau 2} + \int_{0}^{\tau 2} T_S(\tau) e^{-(\tau_2 - \tau_\nu)}\, d\tau$$

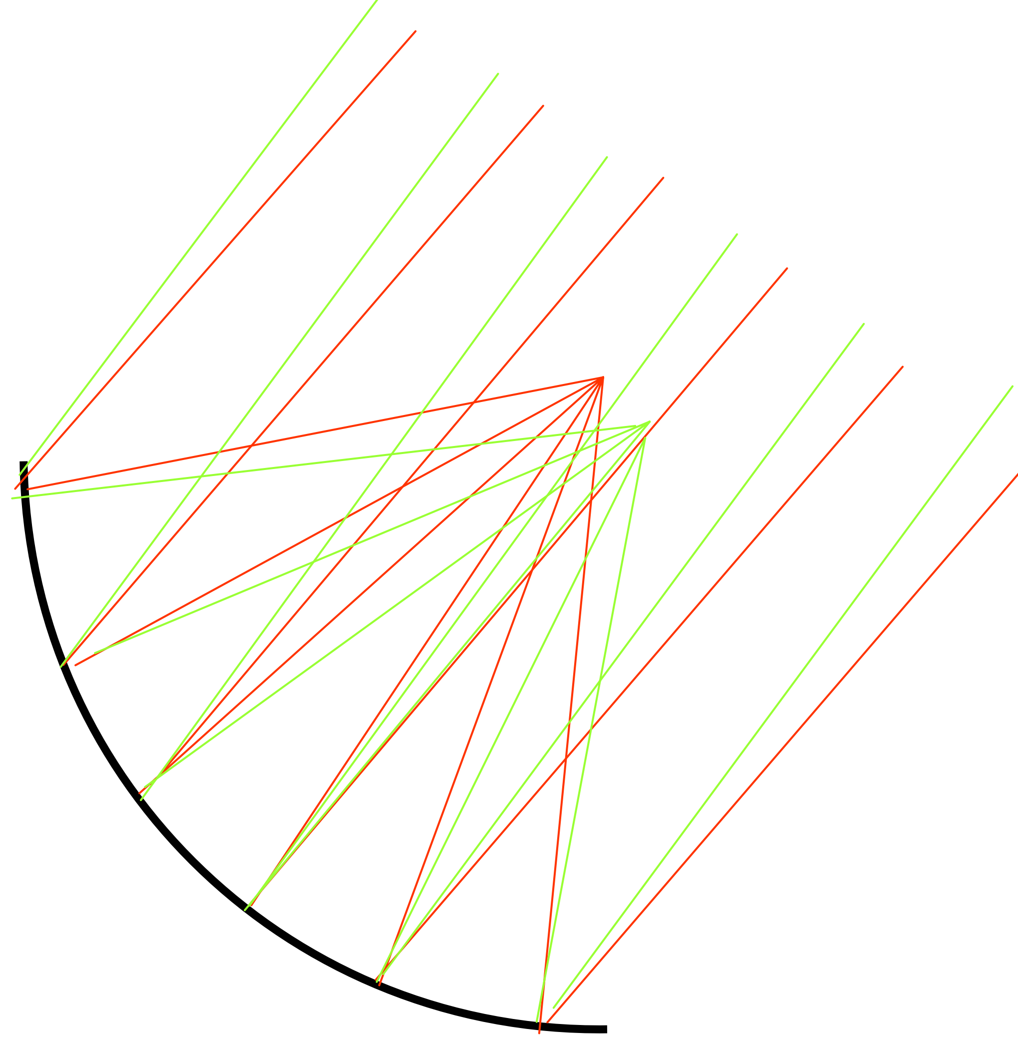
j_ν / k_ν is the Source Function and may be uniform along the path—that is, $T_S(\tau)$=constant. If so, then

$T_B(\tau_2) = T_B(0)\, e^{-\tau 2} + T_S(1 - e^{-\tau_2})$

For $\tau_2 \gg 1$ then $T_B(\tau_2) \approx T_S$ (optically thick)

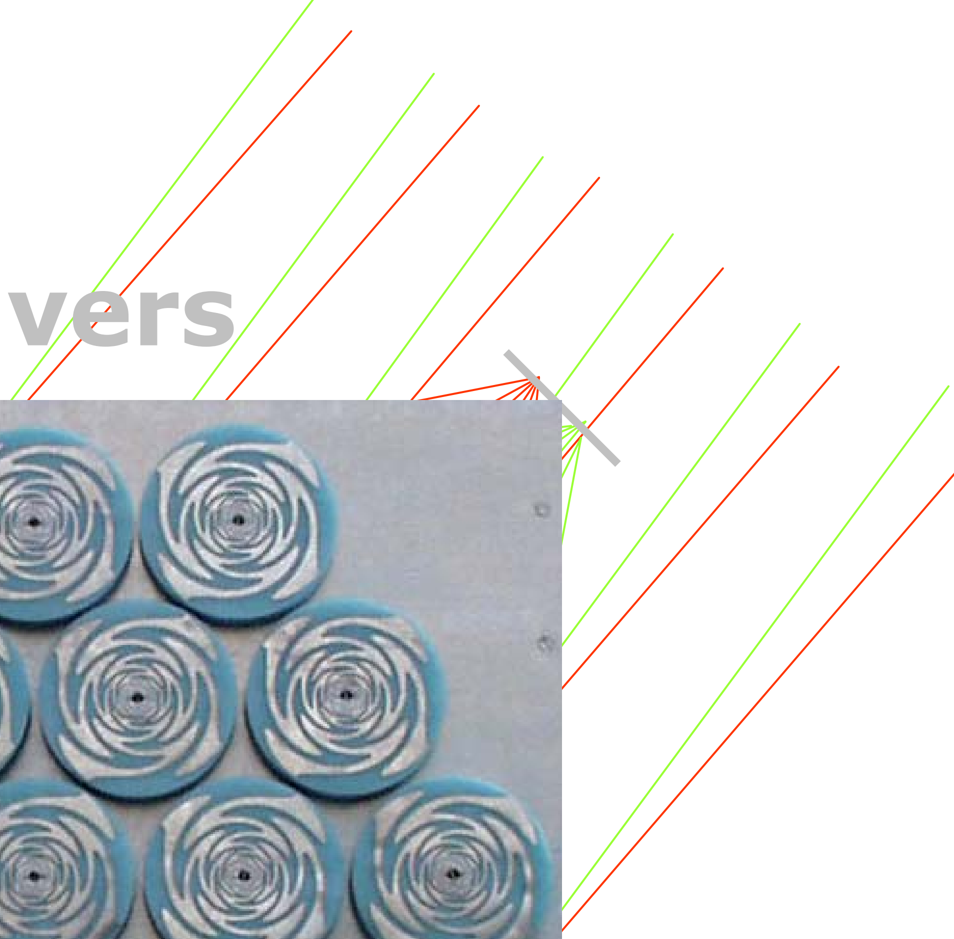
And $\tau_2 \ll 1$ then $T_B(\tau_2) \approx T_B(0) + T_S\, \tau_2$ (optically thin)

Single Antenna



R.D. Ekers

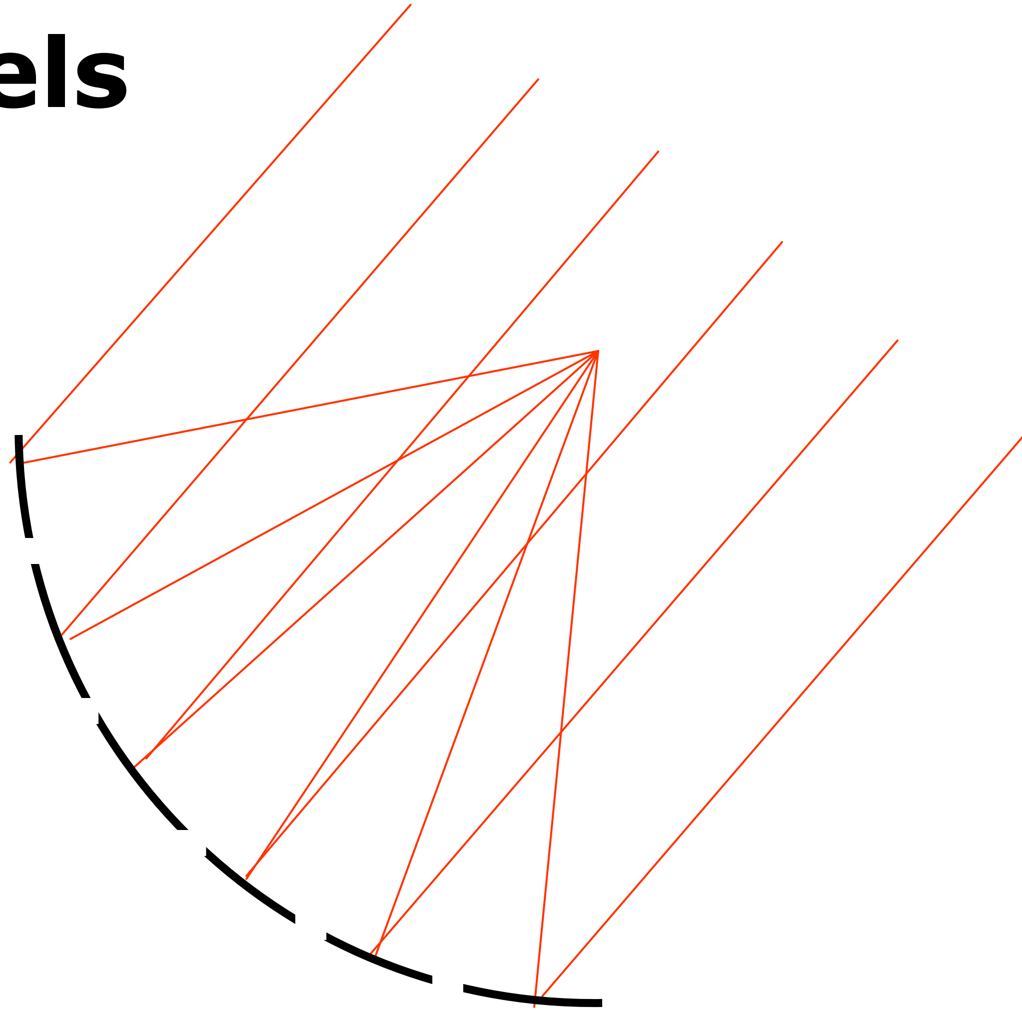
Single Antenna
+
Focal Plane Receivers



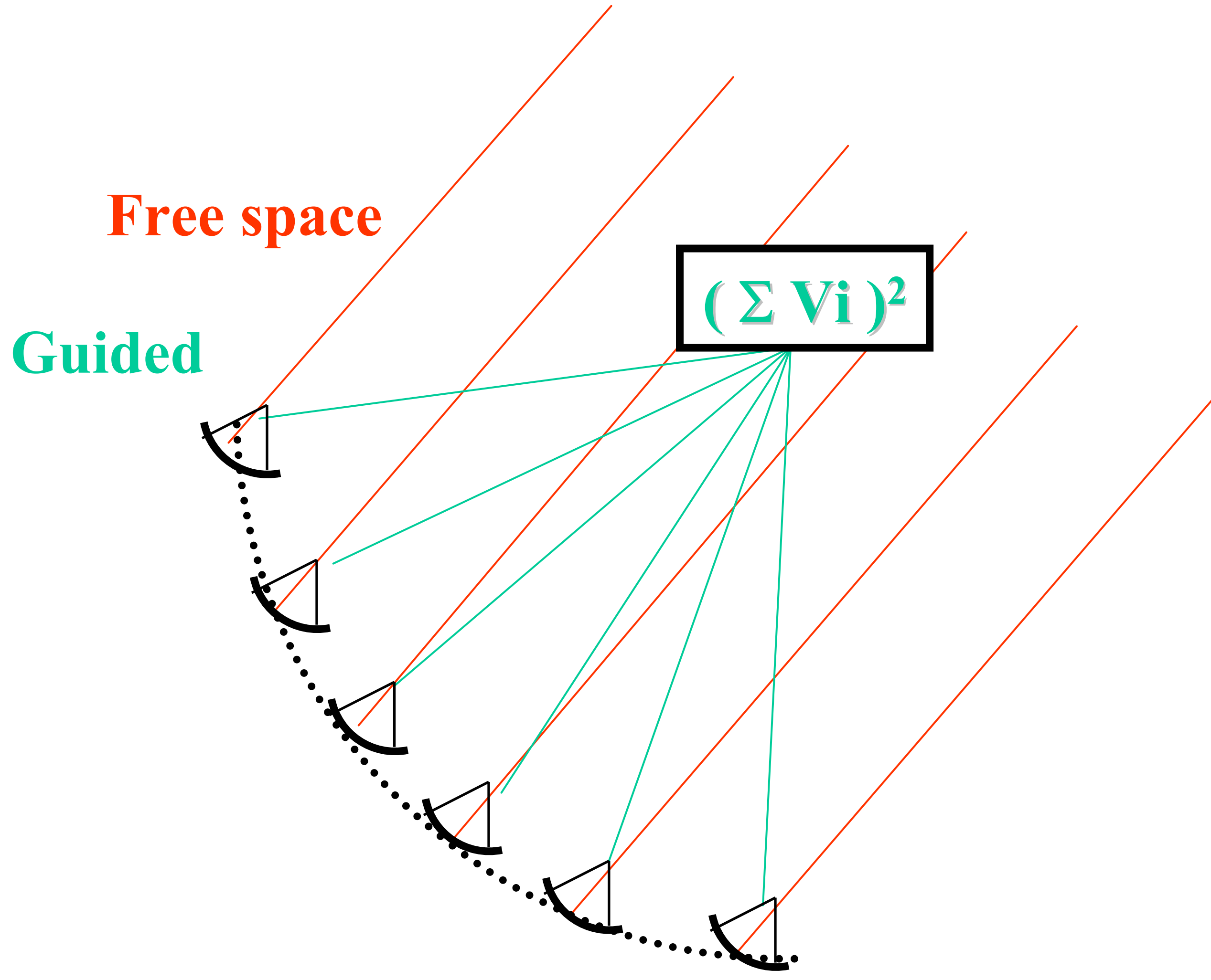
R.D. Ekers

Single Antenna Made of Many Panels

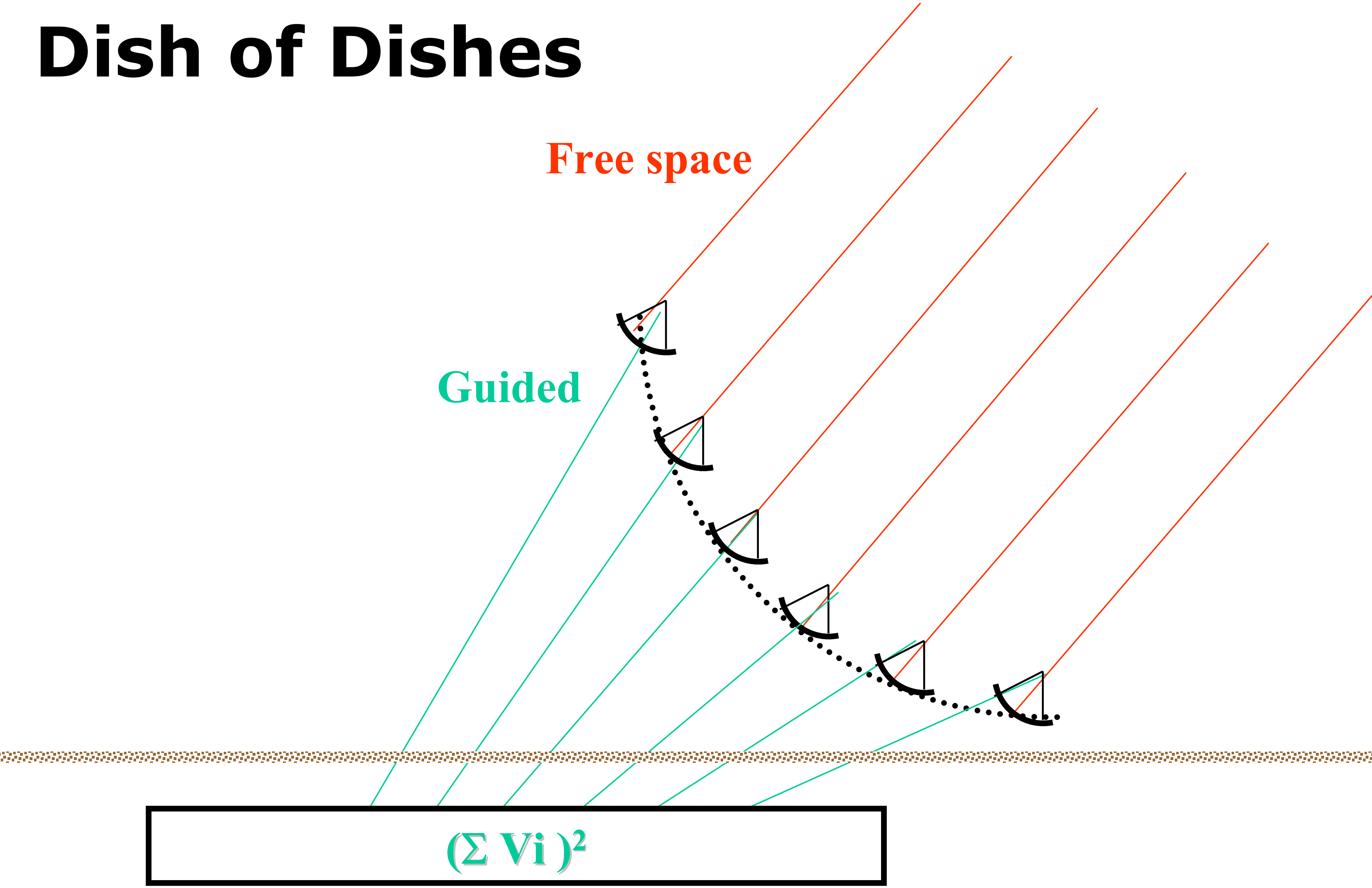
Antenna of Panels



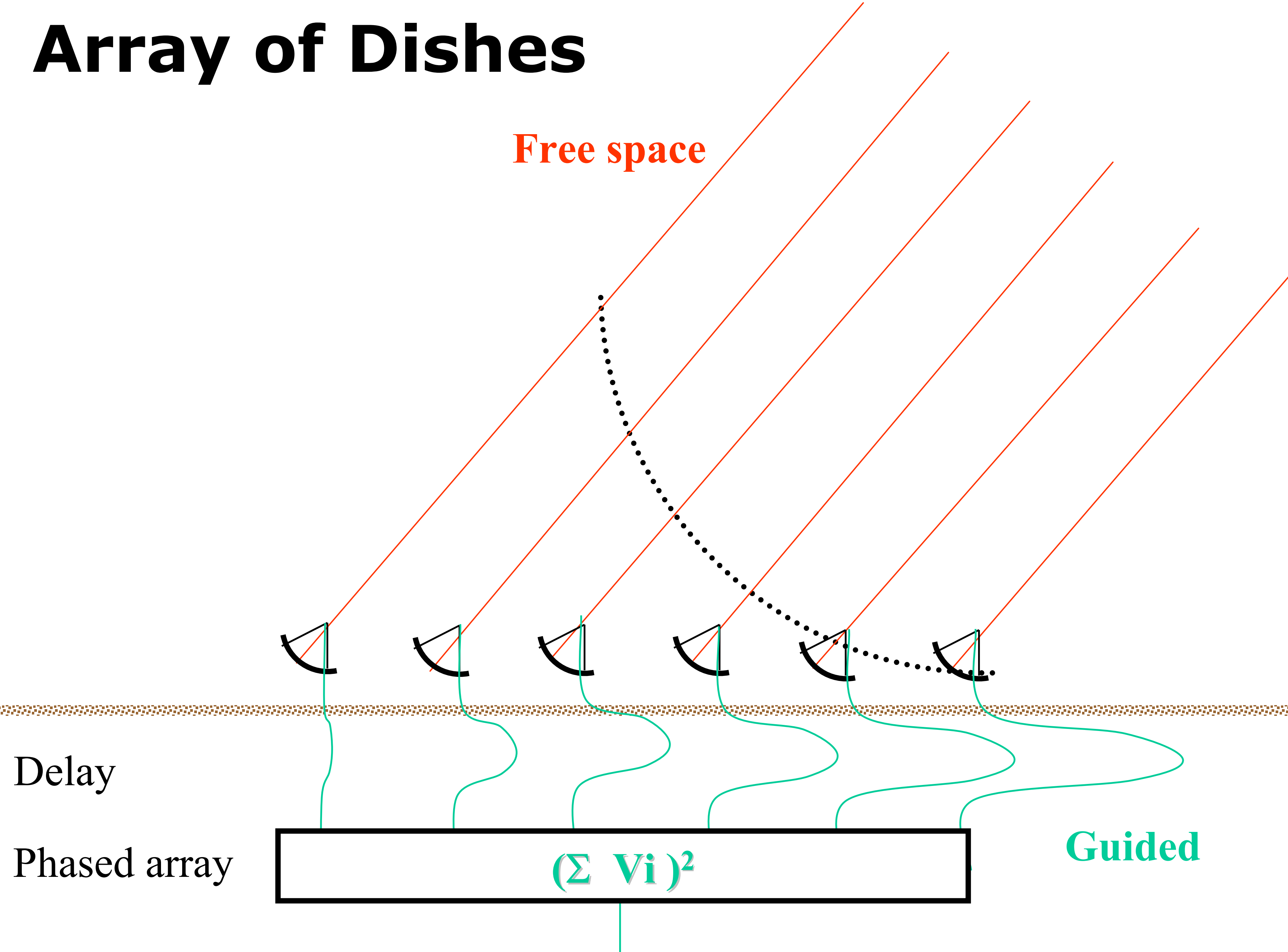
Antenna of Antennas



Dish of Dishes

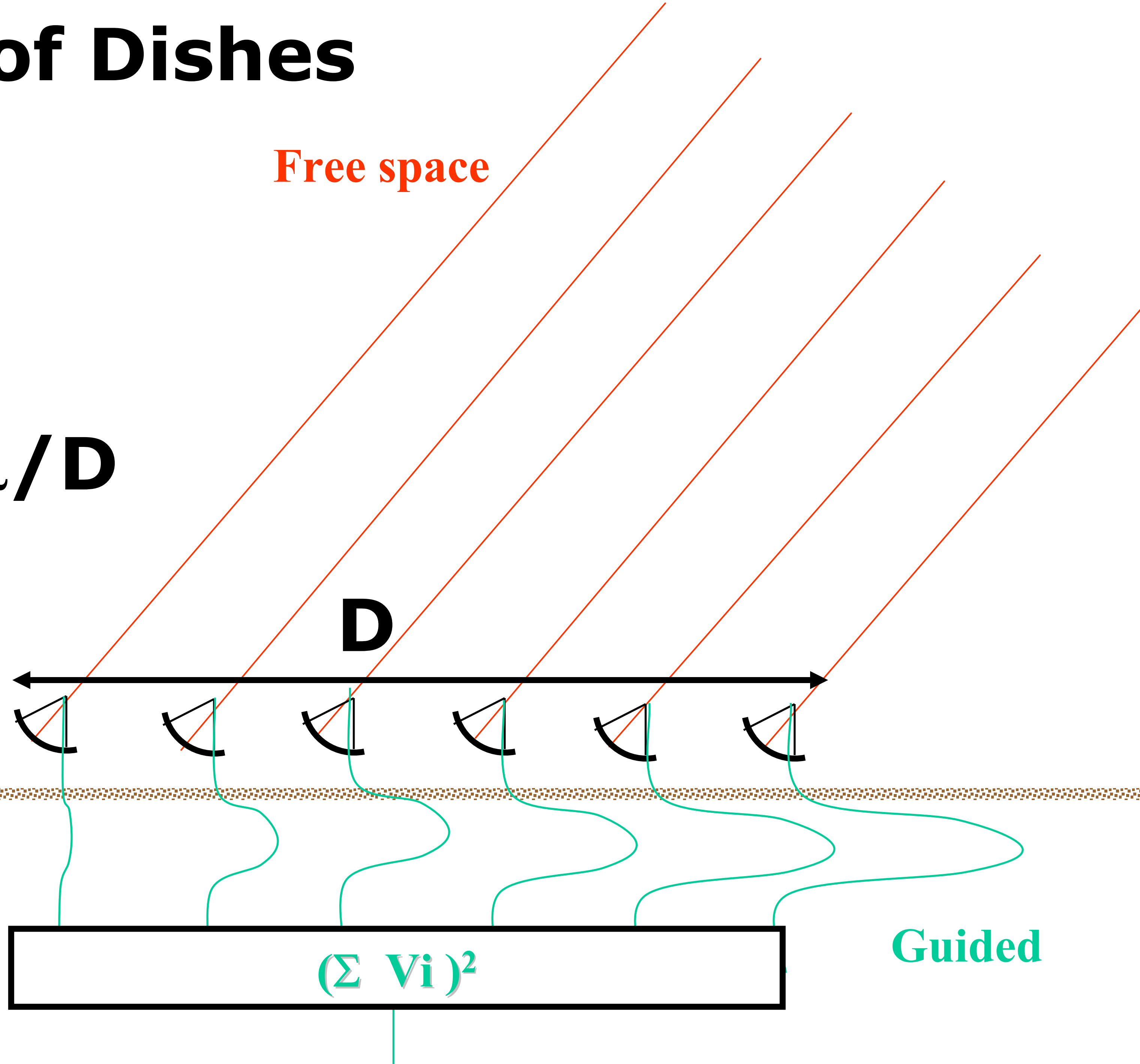


Array of Dishes



Array of Dishes

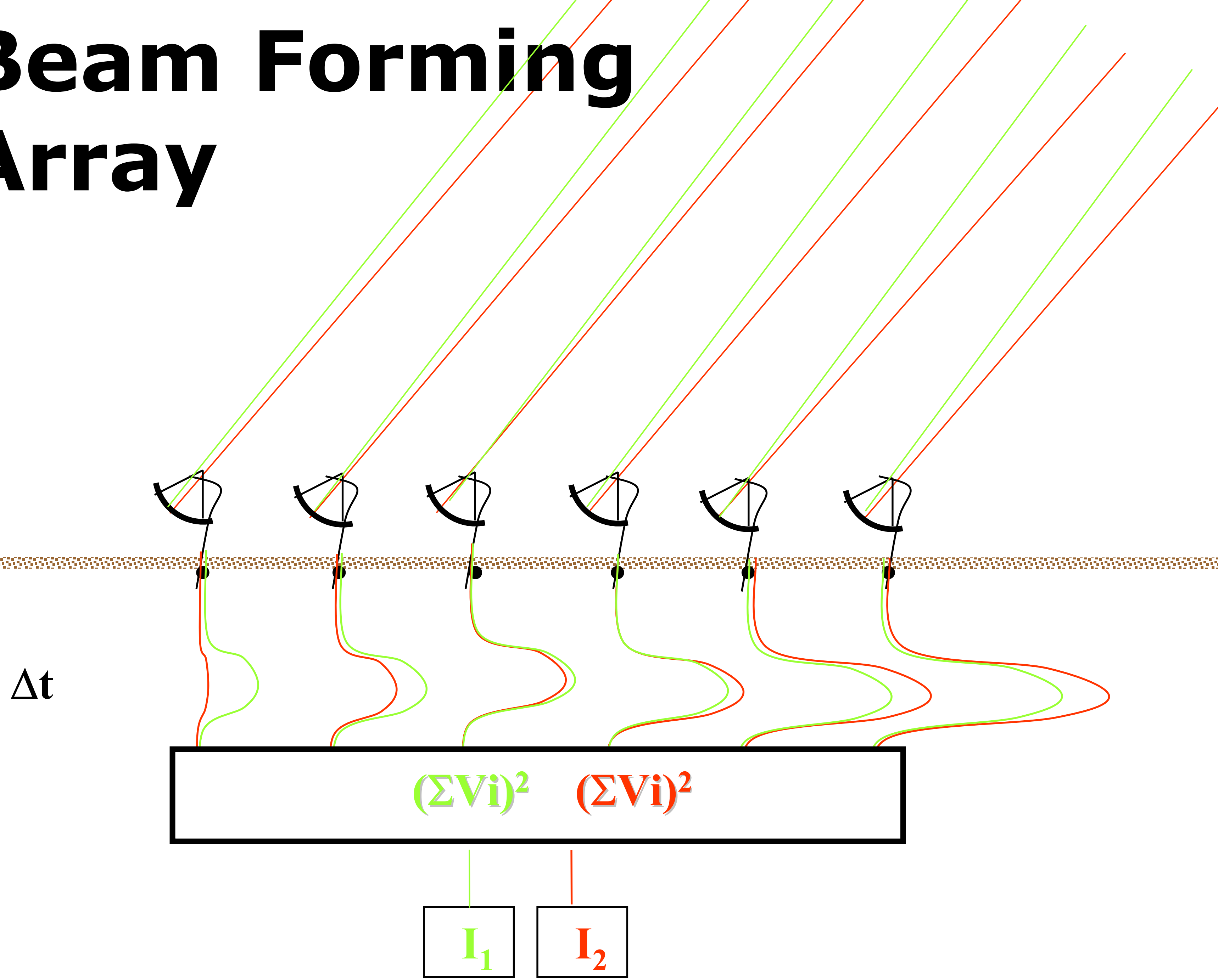
$$\Delta\Theta = \lambda / D$$



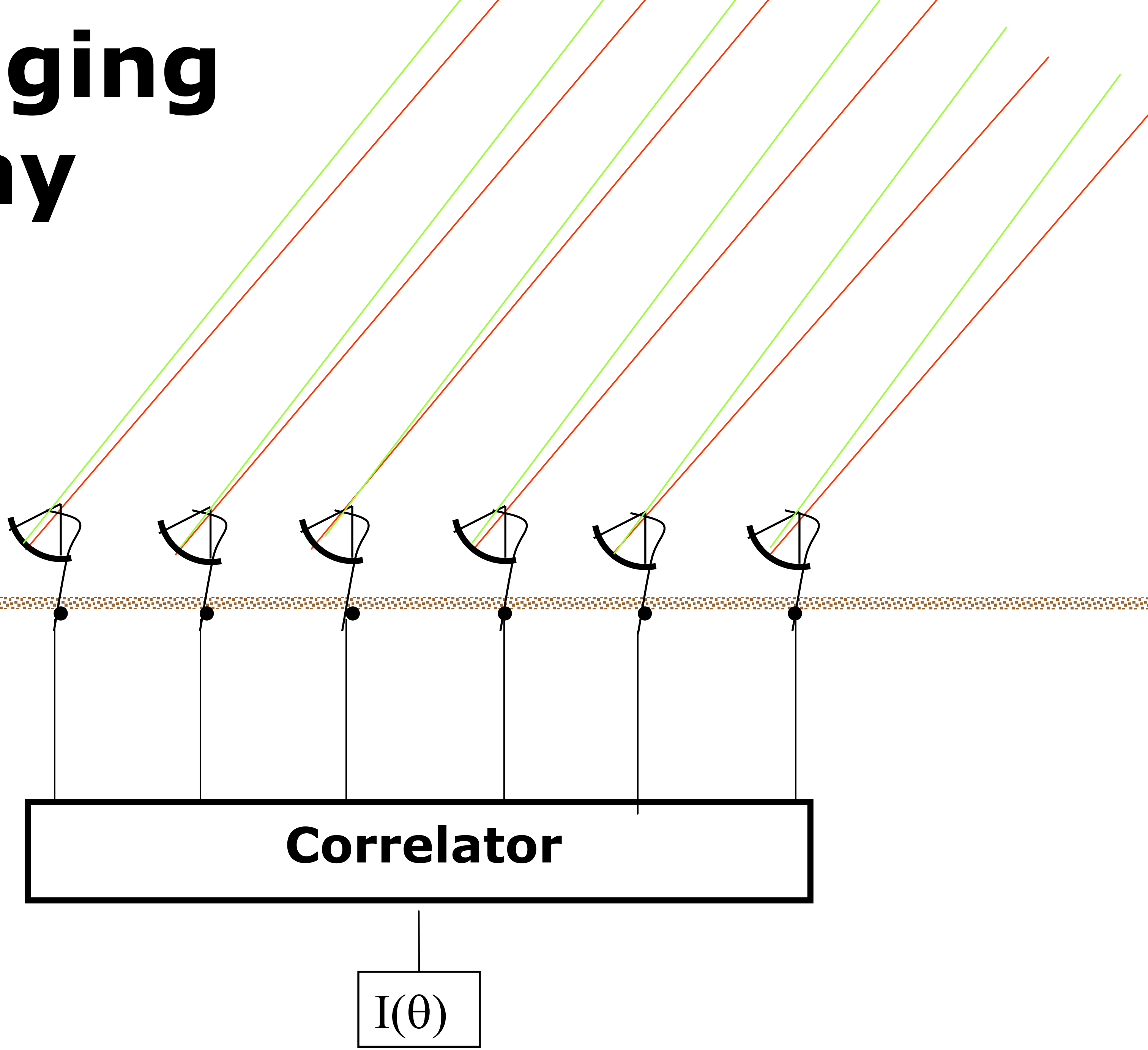
Delay

Phased array

Beam Forming Array



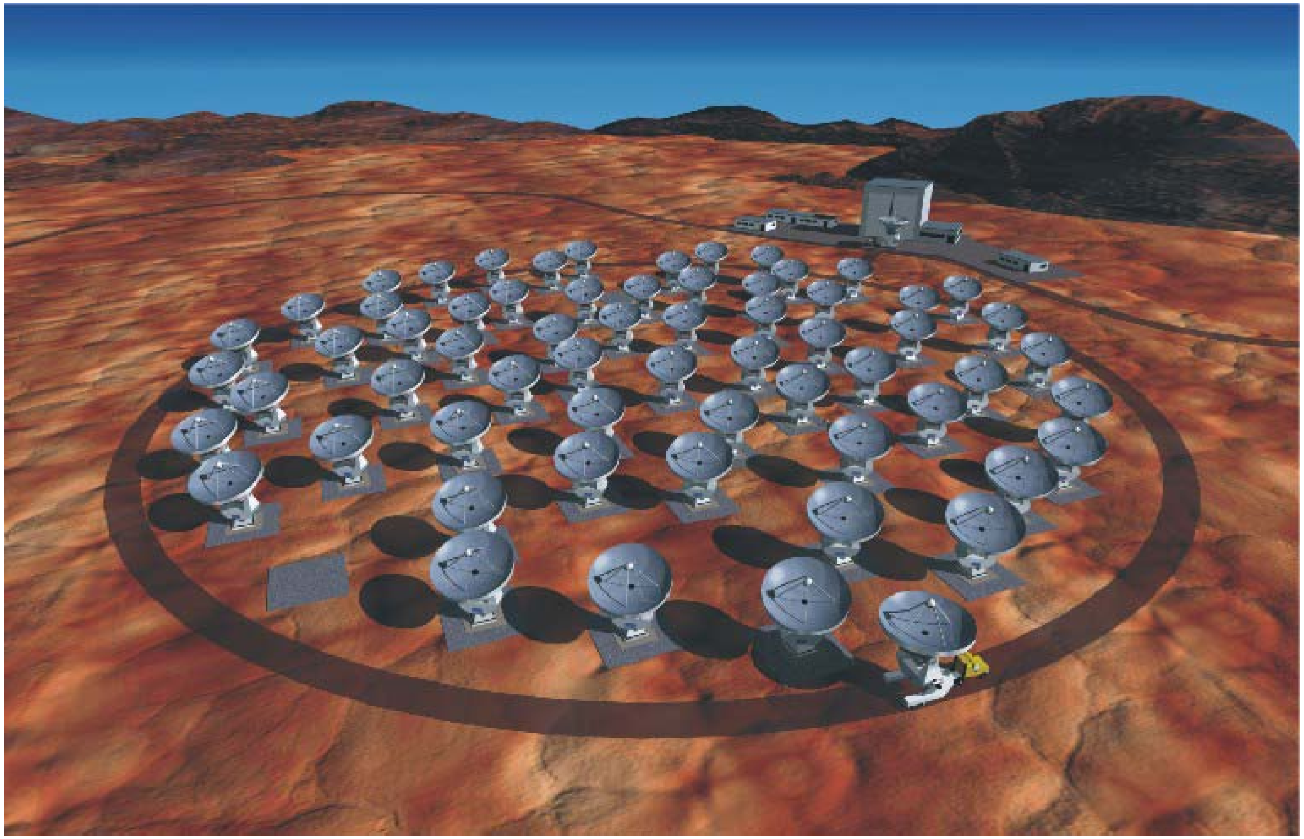
Imaging Array



The Very Large Array - VLA

Dedicated in 1980

ALMA at Chajnantor



Radio Astronomy Examples

Jupiter – a disk about 1 arcminute (1') in diameter, most of its radiation is re-emitted solar radiation, with some derived from gravitational contraction; the temperature of its disk is about T_B ~200 K is the . $T_B \equiv$ Brightness Temperature. For a perfect telescope with a beam with size 1' or less the antenna temperature will approximate this—recall that for a source smaller that the beam, we have

$T_A = \Omega_S / \Omega_M \, T_B$ where Ω_S / Ω_M is called the dilution factor.For a larger source, $T_A = \Omega_M / \Omega_A \, T_B = \boldsymbol{\eta_B} \, T_B$; $\boldsymbol{\eta_B}$ is called the Beam efficiency.

Take, typically, $\boldsymbol{\eta_B}$=60%. Now recall that for a blackbody,

$I_\nu = 2h\nu^3/c^2 \, (e^{h\nu/kT_B} - 1)^{-1}$ and for $h\nu \ll kT_B$ then $I_\nu \approx 2kT_B / \lambda^2$

So $S_\nu = \iint d\,\Omega \, I_\nu(\theta,\phi)$ is the flux density of the source.

$S_\nu \approx 2kT_B \, d\,\Omega / \lambda^2$. So we know how bright Jupiter is, how long does it take to detect it with various telescopes at various wavelengths? We need to know the sensitivity, **System Temperature** and the sensitivity of our system from the Radiometer Equation $\Delta T_{sys} = \dfrac{K \, T_{sys}}{\sqrt{\Delta\nu \, \tau}}$

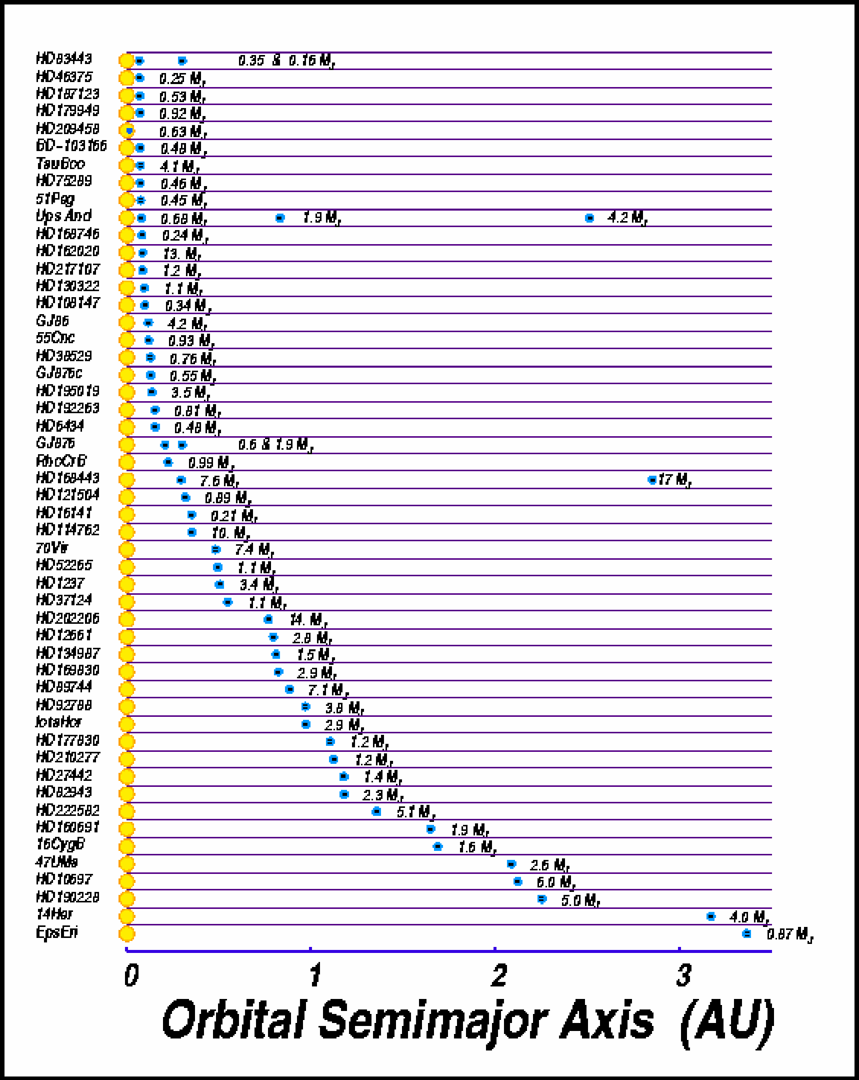
Then at λ=1cm, for Jupiter,
$S_\nu \approx 2kT_B \, d\,\Omega / \lambda^2 = 2(1.38\text{x}10^{-23})(200)\,(8.46\text{x}10^{-08})/(.01)^2$
$S_\nu \approx 4.67 \text{ x } 10^{-26}\ \text{Wm}^{-2}\ \text{Hz}^{-1}\ \text{sr}^{-1}$ = 467 Jansky (Jy). At λ=3mm, $S_\nu \approx$ 5189 Jy and at λ=0.3mm $S_\nu \approx$ 518900 Jy. Note that as long as the source fills the beam, T_B remains constant, while S_ν increases with decreasing wavelength, as it follows the long-wavelength tail of the Planck blackbody function.

Beware that at millimeter wavelengths $h\nu \ll kT_B$ this is not true and $T_B = h\nu/k\,(e^{h\nu/kT_B}-1)^{-1}$ so this approximation fails into the submillimeter!

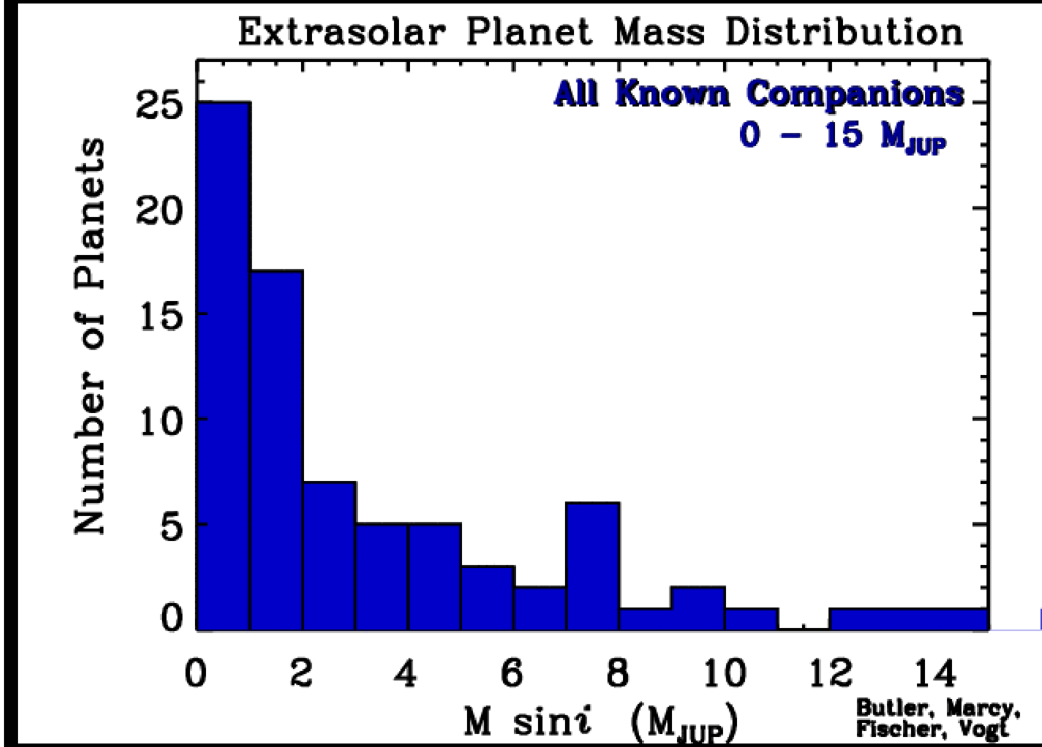
Now let's assume $T_{sys} = T_{rx}$ = 50K, resonable at 1cm, ignoring the atmosphere. Let's integrate for 1 second, and for a bandwidth what is reasonable??? Say 50 MHz to be conservative, though $\Delta\nu/\nu$=30% for a state-of-the-art high frequency receiver. Then for K=2 (position switching) we have ΔT_{sys} = 0.014 K—a signal-to-noise ratio of 8600 in one second!

Wow! Jupiter is bright! Can we see Jupiter around another star???

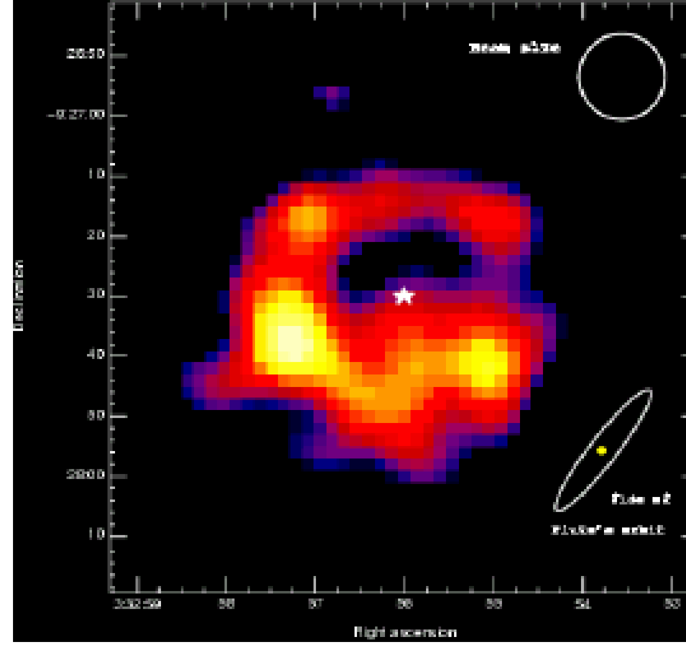
Once we dreamed… now we can detect them!



Radial velocity surveys are sensitive to ~Jupiter/Saturn mass planets.



Epsilon Eridani a nearby star with planets AND a dusty debris disk…



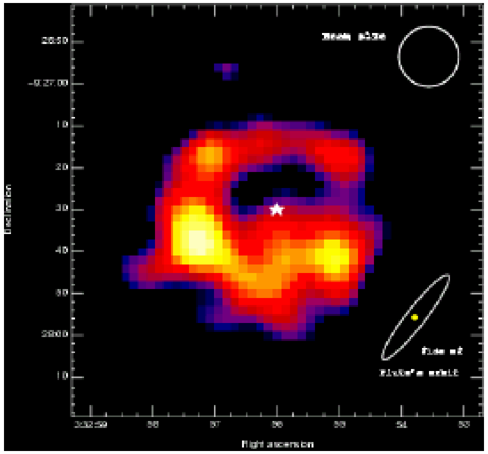
$S_\nu \approx 2kT_B \, d\,\Omega / \lambda^2$ where $d\,\Omega$ is the solid angle, and Jupiter filled the beam. Jupiter's radius is 70,000,000 m. In the previous slide we saw that Epsilon Eridani had a Jovian sized planet at a distance of 3.3AU from its solar-type stellar host, so its brightness temperature is probably similar. Epsilon Eridani lies at 3.2 pc = 10^{17} m, so approximately $S_{EpEri} = \pi\,(7\text{x}10^7 \text{ m}/ 10^{17} \text{ m})^2 \, S_{Jupiter} = 10^{-7}$ Jy even at 3mm! Even at 0.3mm, this planet only provides a few microJy. Or, in terms of brightness temperature, $T_A = \boldsymbol{\eta_B}\, T_B \approx \Omega_{EpEri} / \Omega_M \, T_B \approx 10^{-18}\, T_B$! Clearly we win by making the beam as small as possible but even for ALMA this would take many many weeks!

But wait a minute…what about the dust disk in the last slide????

The problem is the beam-filling factor—for an extended disk (and a 100 AU solar system at that distance is about 30”), even for very low masses, current instruments can detect about a lunar mass of *extended cold* dust (say 50K), but with resolution of only 8” in the submillimeter region, or ~1” in the millimeter.

- Extended sources are easier—protoplanets or dust disks best
- Cooler objects easier than hot objects, to some limits
- Resolution is the key—confusion (the dust disk as ~1mJy of flux, hence 1000 times the signal!)
- From the emissivity of the dust, we can measure the mass of dust directly.

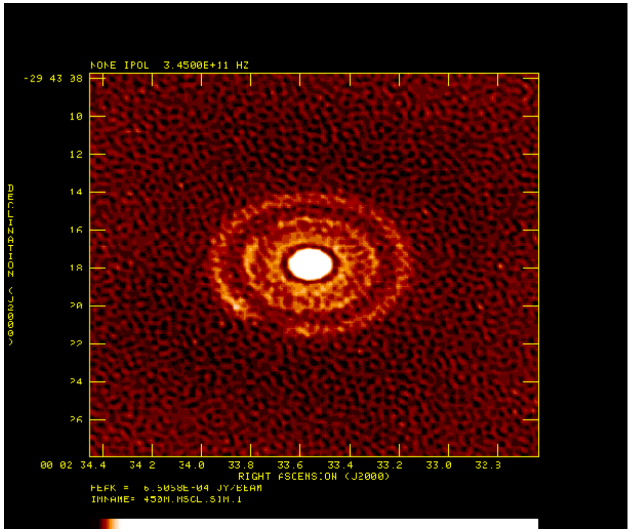
ε Eridani JCMT

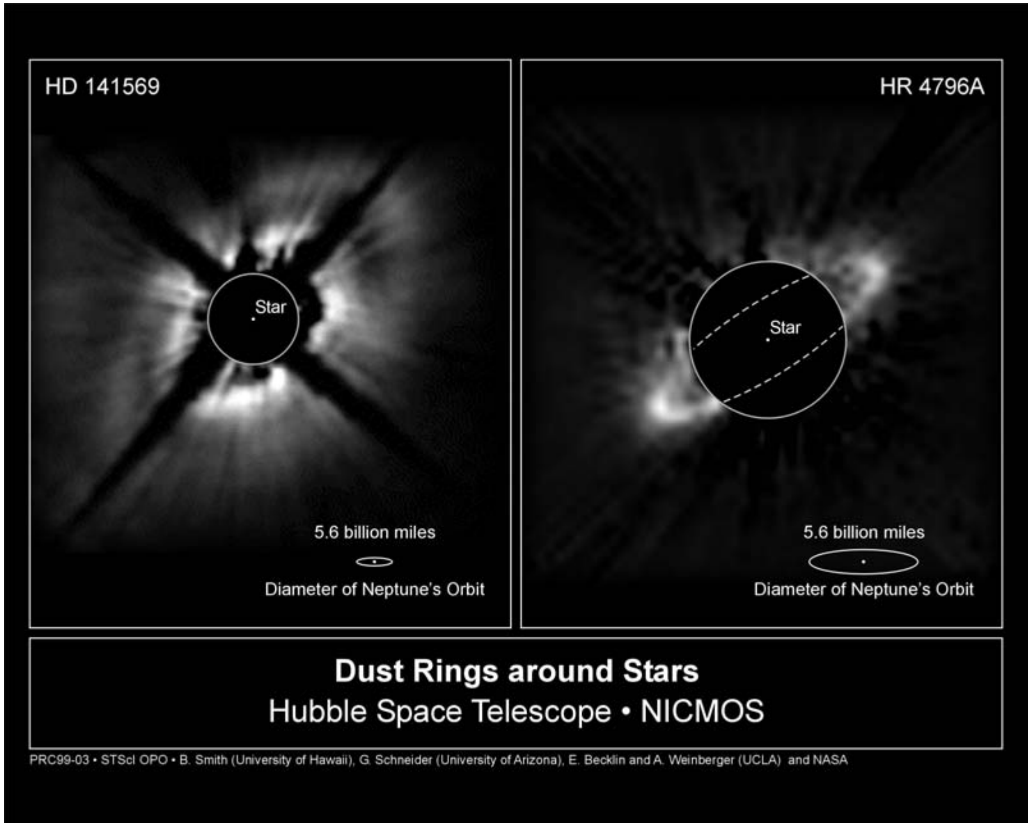


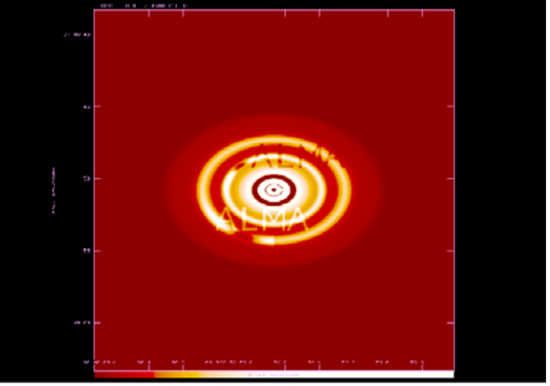
Present mm-wave cameras provide only a few pixels, ALMA imaging will rival HST.

x10

ALMA Simulation

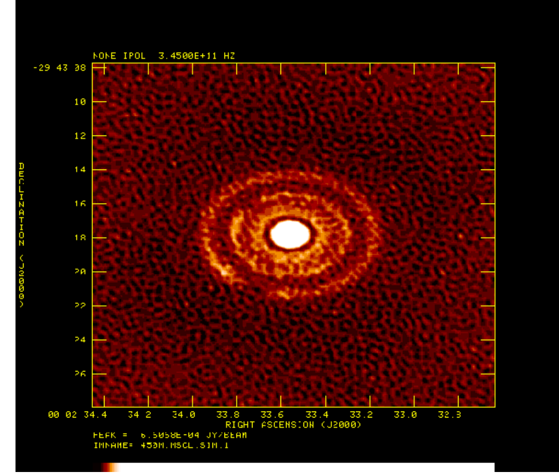






AIPS User 1134 MUNDY DEBRIS DISK

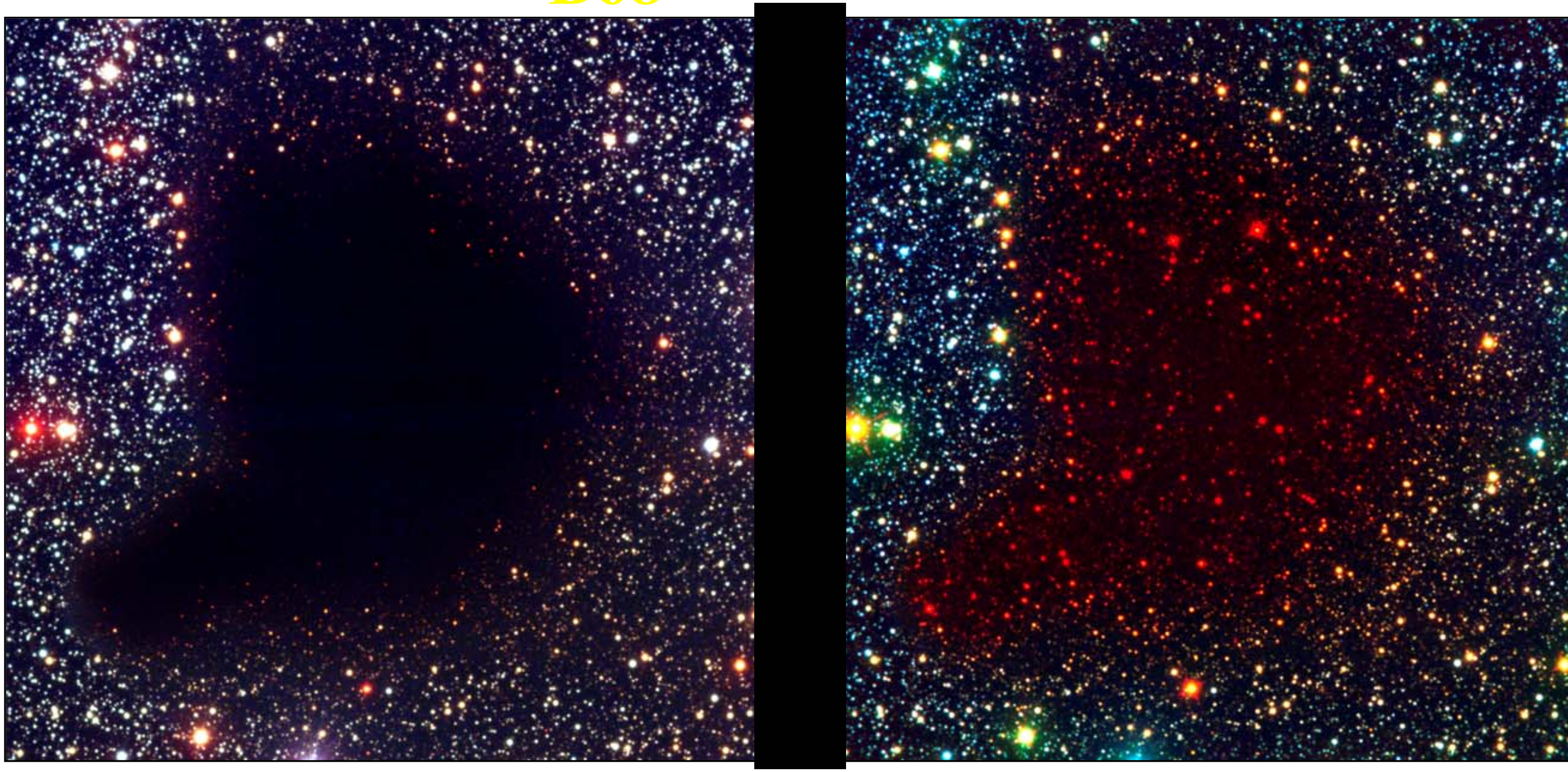
Debris Disks



- These provide a challenge to ALMA imaging because:
  - They are faint about nearby stars – 1mJy is about half a lunar mass at 12 pc
  - They are extended about nearby stars—several fields of view at 12 pc for instance
  - They emit most strongly in the submillimeter, where imaging is the greatest challenge.
- But they can provide best evidence for planetary

Optical **Infrared**

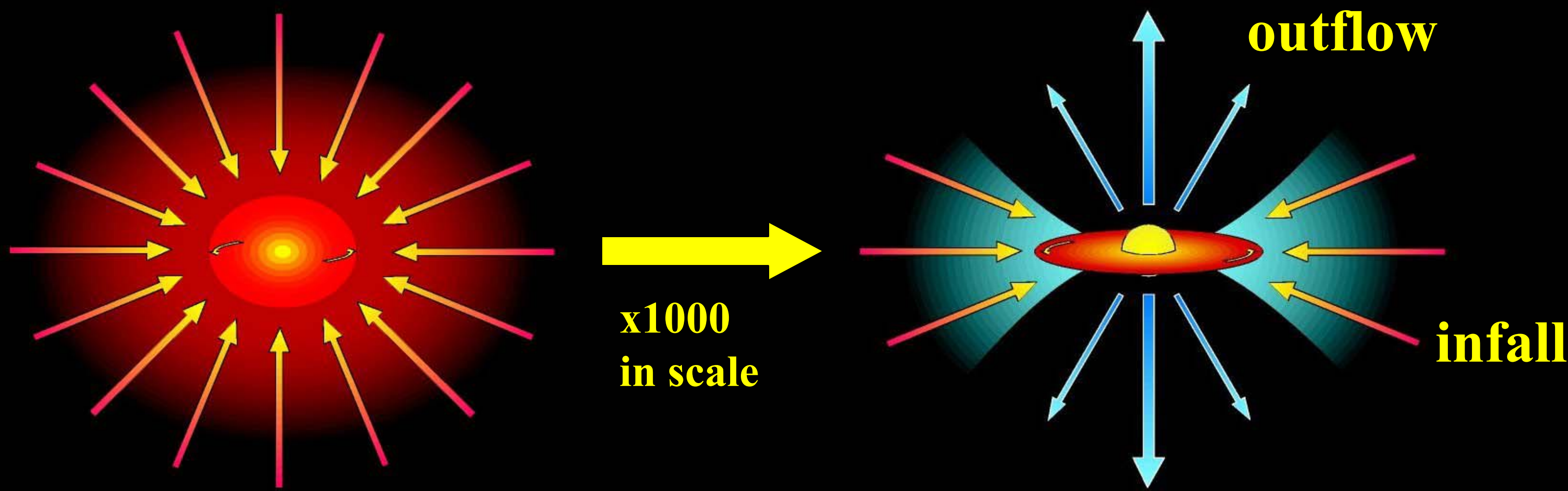
B68



Alves et al. 2001

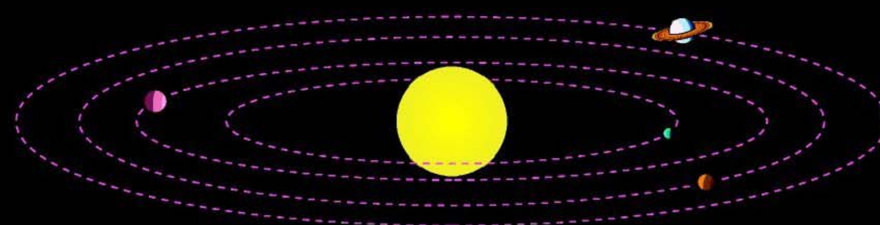
Using trace molecules, mm-wave astronomy can probe these regions directly.

How are single stars created?



Cloud collapse **Rotating disk**

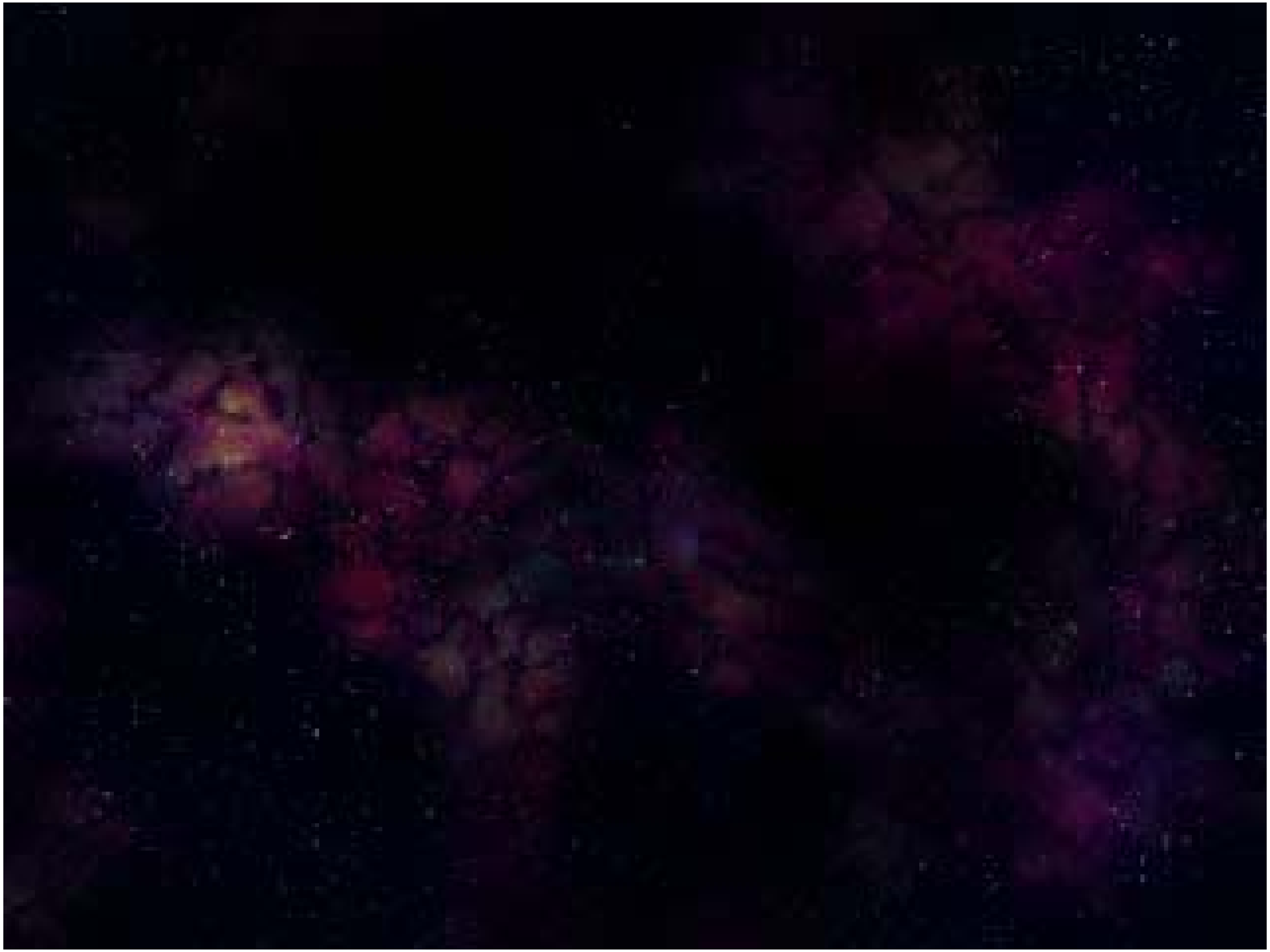
Planet formation



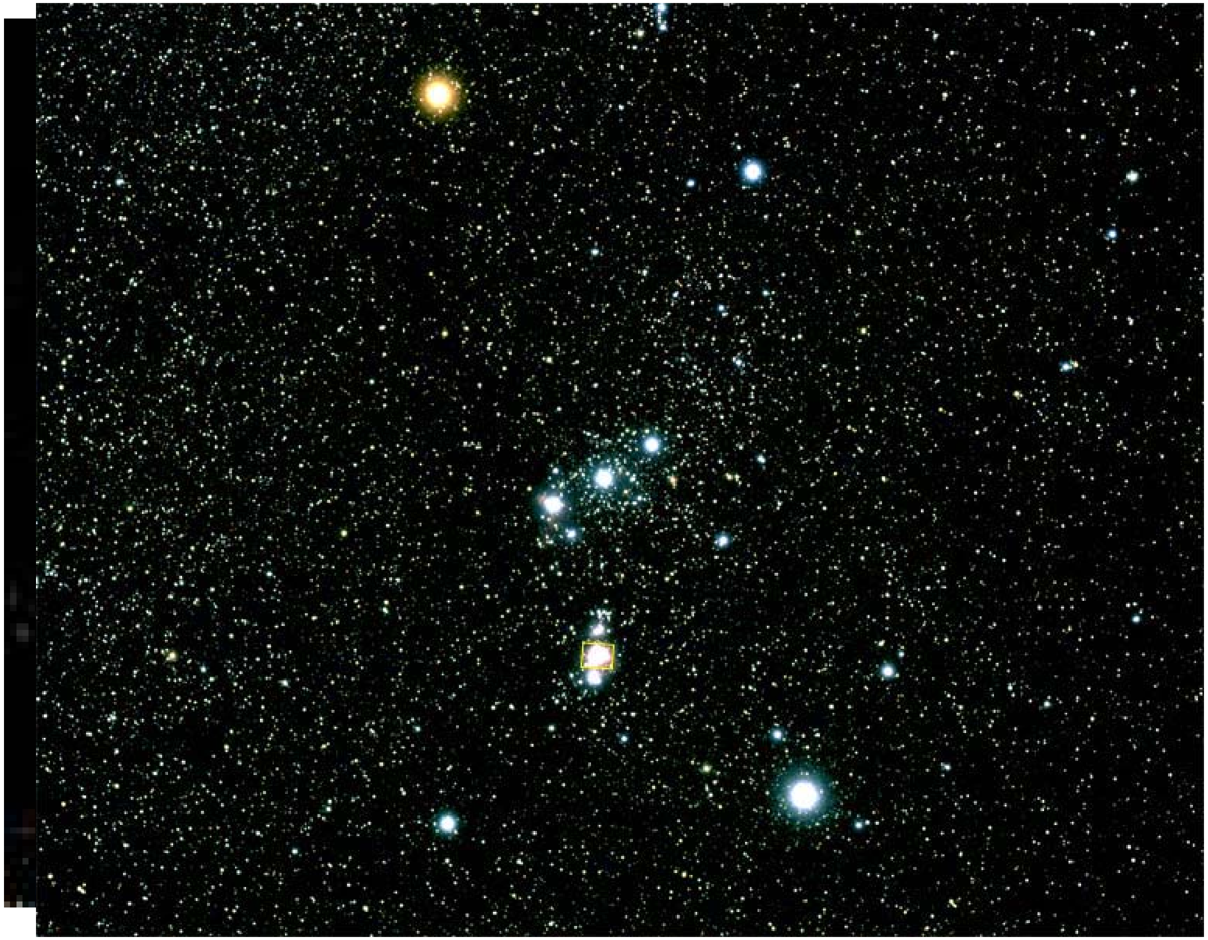
Mature solar system

Scenario largely from indirect tracers.

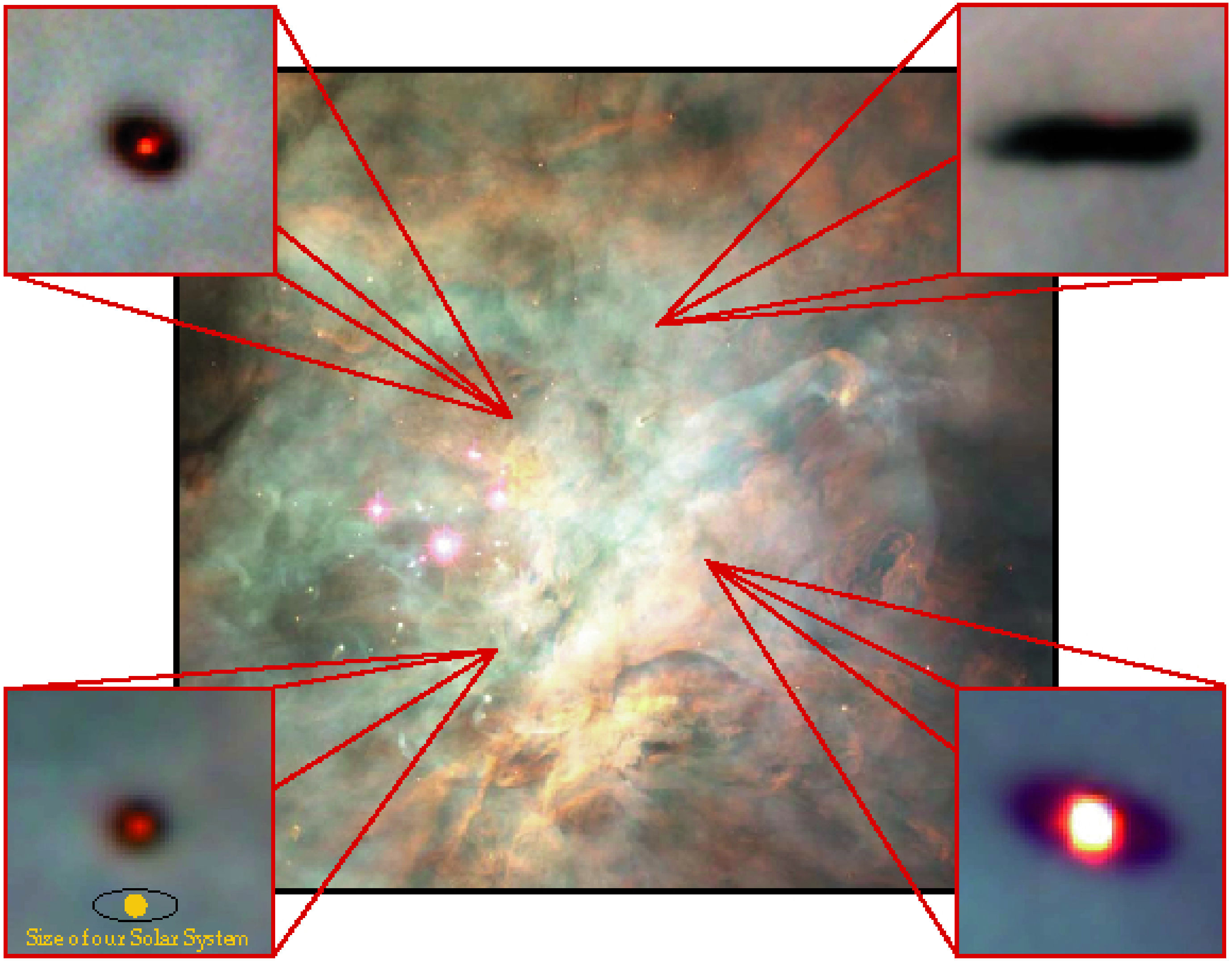
Adapted from McCaughrean



5 Astronomical Units (AU = Earth-Sun Distance)



How large are these disks in Orion?

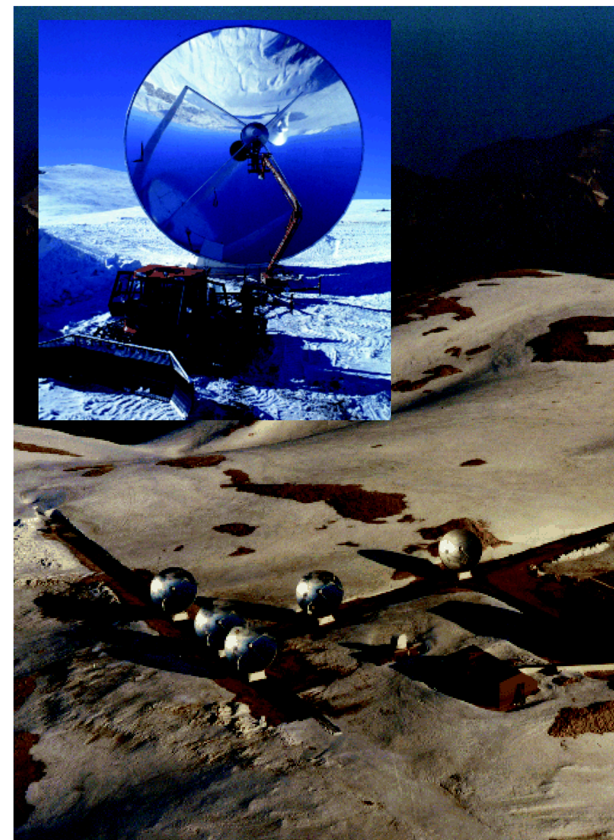


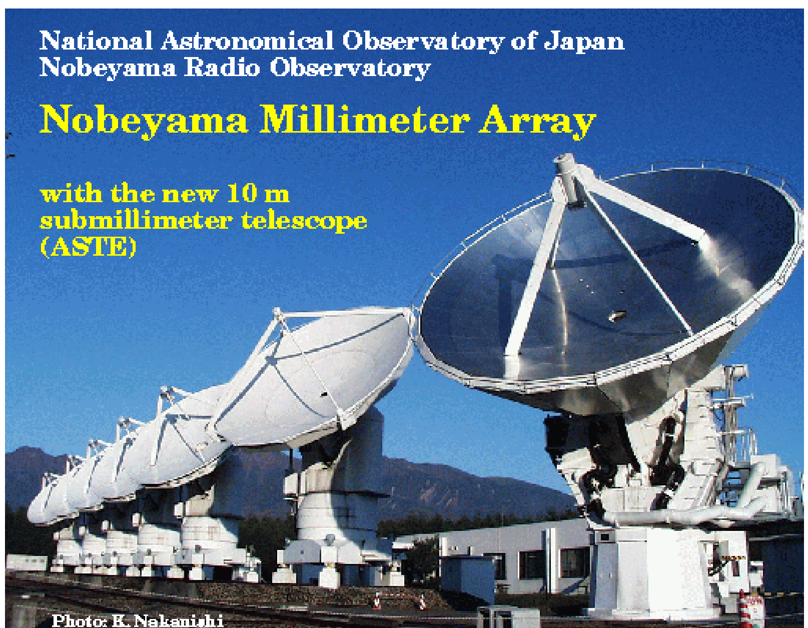
About 2x Sun-Pluto, or 1-2’’ on the sky.

SUBARU imaging @ λ = 1 mm ⇒ D > 1 km!

CARMA = OVRO + BIMA

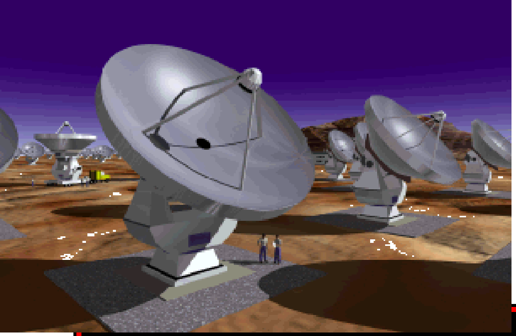
Plateau de Bure

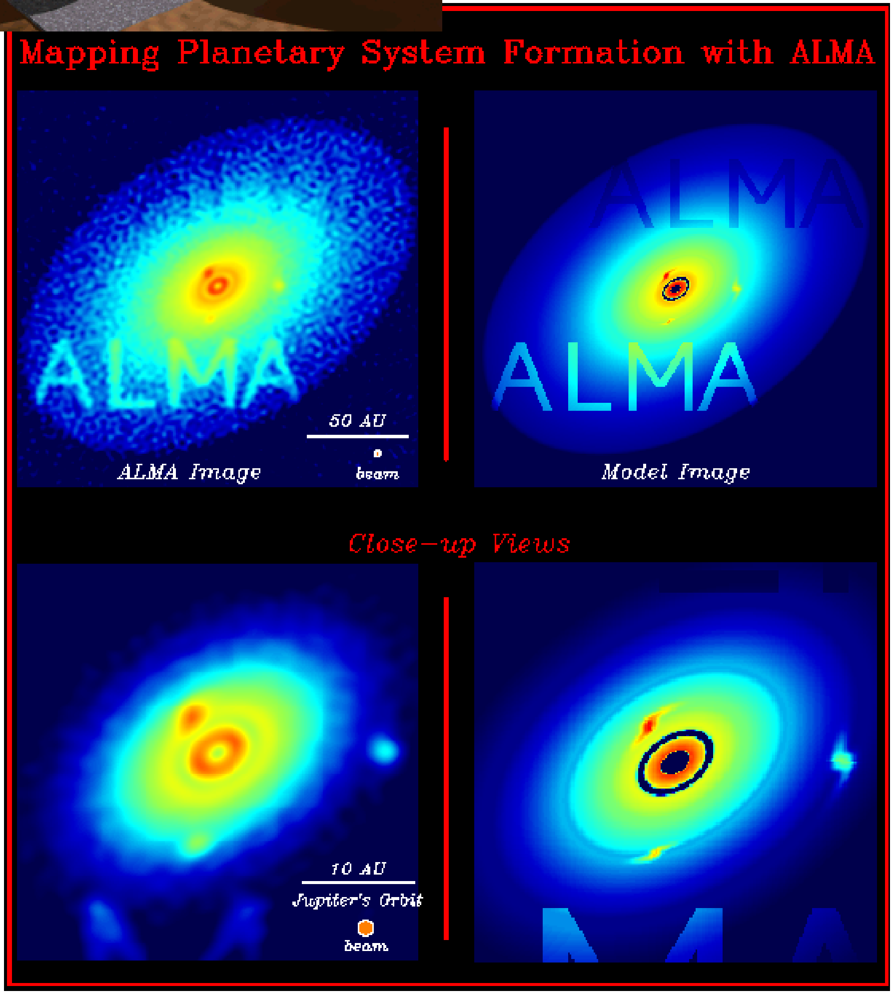




Current arrays are small and situated at relatively low elevations.

Protoplanet Formation





- Disks are observed about young stars, but with poor resolution
- ALMA will provide the resolution and the sensitivity to detect condensations, the cores of future giant planets
- As the planets grow, they clear gaps and inner holes in the disks
- On the right are models of this process, and on the left simulations of ALMA's view showing that condensations, gaps and holes are readily distinguished