AS5003: Contemporary Astrophysics

12/9/23

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Welcome to the moodle page of AS5003

This module comprises three parts:

Part 1: **Radio Interferometry and Imaging** by Dr Ian Czekala (ic95@st-andrews.ac.uk).
Part 2: **Historic Astronomy** by Dr Anne-Marie Weijmans (amw23@st-andrews.ac.uk).
Part 3: **Circumstellar disks** by Dr Paula S. Teixeira (psdvt@st-andrews.ac.uk)

Schedule:

Week	Tuesday 2pm room 222	Wednesday 12pm room 301	Friday 12pm room 222
0			
1	Part 1: Lecture	P1: Lecture	P1: Lecture
2	P1: Tutorial	P1: Lecture	P1: Lecture
3	P1: Lecture	P1: Lecture	P1: Tutorial
4	P1: Peer-supported study	Part 2: Workshop	P2: Lecture
5	P2: Lecture	P2: Lecture	P2: Tutorial
6		Independent Learning week	
7	P2: Lecture	P2: Lecture	P2: Lecture
8	P2: Tutorial	P2: Peer-supported study	Part 3: Lecture
9	P3: Lecture	P3: Lecture	P3: Lecture
10	P3: Lecture	P3: Lecture	P3: Lecture
11	P3: Lecture	P3: Lecture	P3: Peer-supported study
12	Part 1: Q&A	Part 2: Q&A	Part 3: Q&A

The module coordinator is Dr Anne-Marie Weijmans, office 334.

Class Times and Locations

Week	Tuesday 2pm room 222	Wednesday 12pm room 301	Friday 12pm room 222
0			
1	Part 1: Lecture	P1: Lecture	P1: Lecture
2	P1: Tutorial	P1: Lecture	P1: Lecture
3	P1: Lecture	P1: Lecture	P1: Tutorial
4	P1: Peer-supported study	Part 2: Workshop	P2: Lecture

Note different **times of day** and **different classrooms**

Tutorials

Week	Tuesday 2pm room 222	Wednesday 12pm room 301	Friday 12pm room 222
0			
1	Part 1: Lecture	P1: Lecture	P1: Lecture
2	P1: Tutorial	P1: Lecture	P1: Lecture
3	P1: Lecture	P1: Lecture	P1: Tutorial
4	P1: Peer-supported study	Part 2: Workshop	P2: Lecture

Now available on Moodle

Available at least one week before

Expectation that you will come to class with tutorials fully completed and ready for group discussion.

Additional Radio Resources

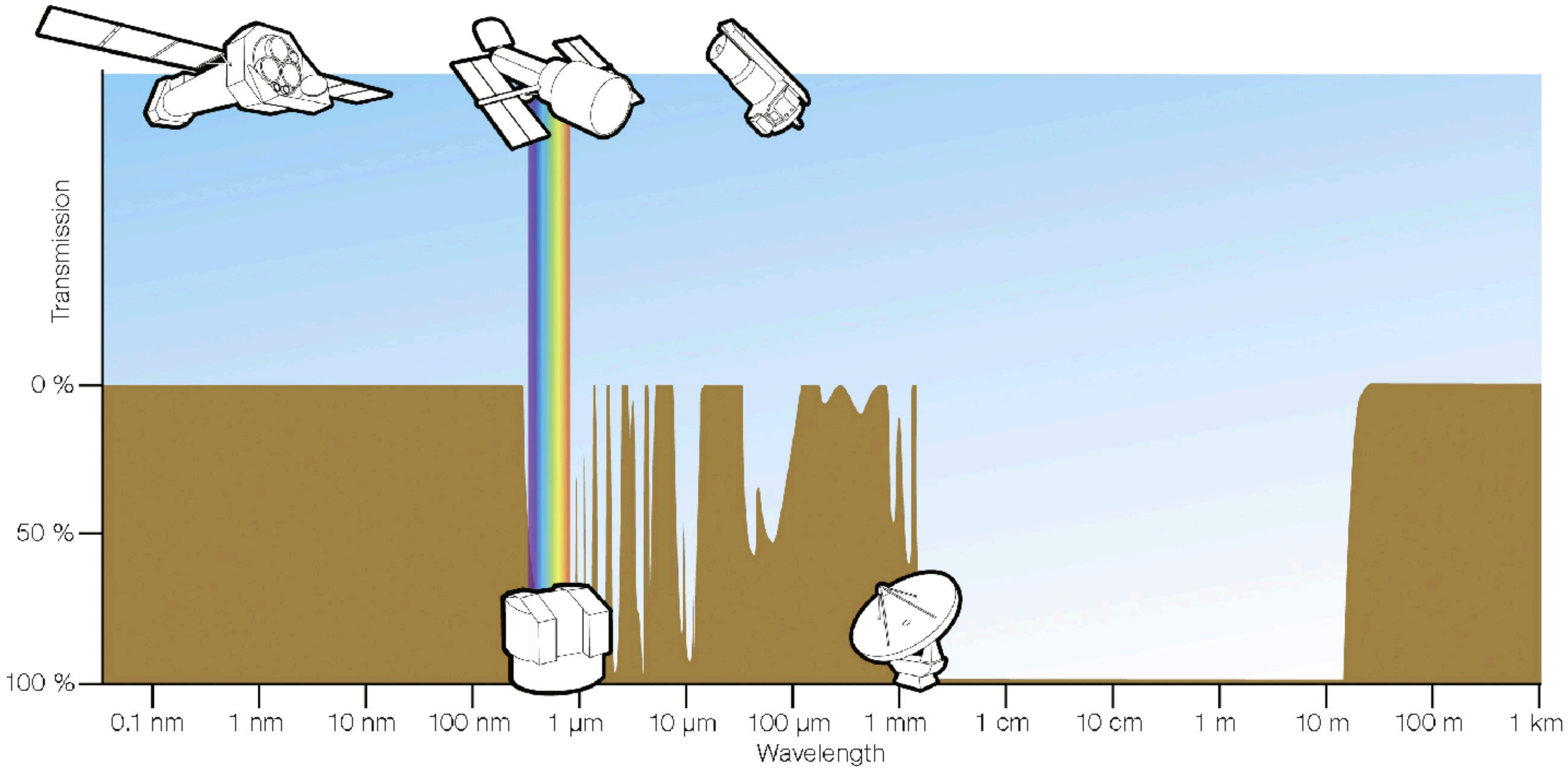
https://iancze.github.io/courses/as5003

Lectures

Lecture notes are provided as a courtesy and mainly serve to centralize figures and reference links. They are not a verbatim record of the material discussed in class (for that, use the recordings) nor are they an adequate substitution for paying attention during class lecture.

- 2023-09-12 | Introduction and Course Overview
- 2023-09-13 | The Fourier Transform I
- 2023-09-15 | The Fourier Transform II
- 2023-09-20 | Interferometry in Practice
- 2023-09-22 | 2D Interferometry, PSFs, Gridding, and Dirty Images
- 2023-09-26 | Image Plane Deconvolution (CLEAN)
- 2023-09-27 | Regularized Maximum Likelihood (RML)

Transmission of Earth's Atmosphere



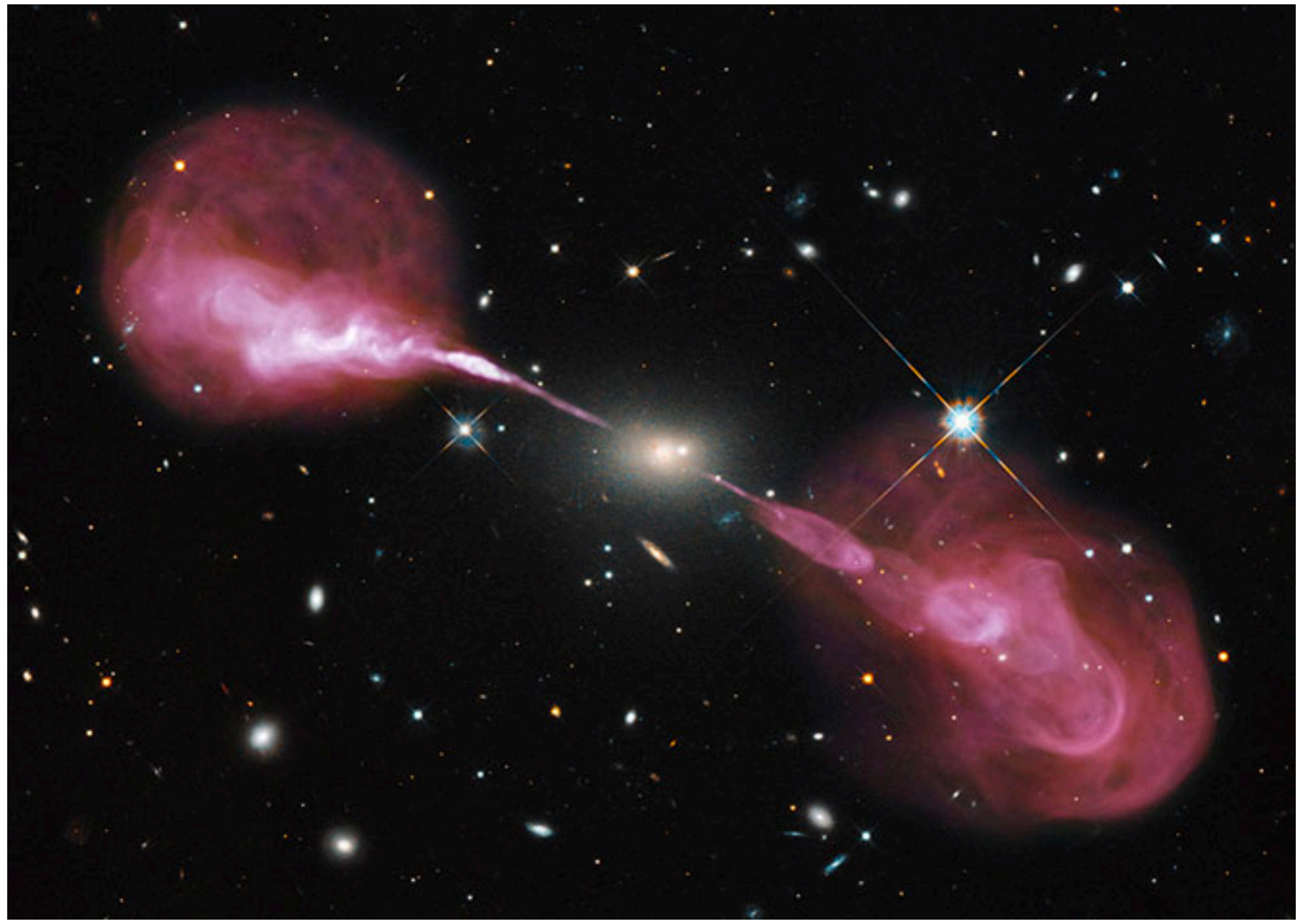
ESA/Hubble (F. Granato) and Essential Radio Astronomy.

Emission Mechanisms

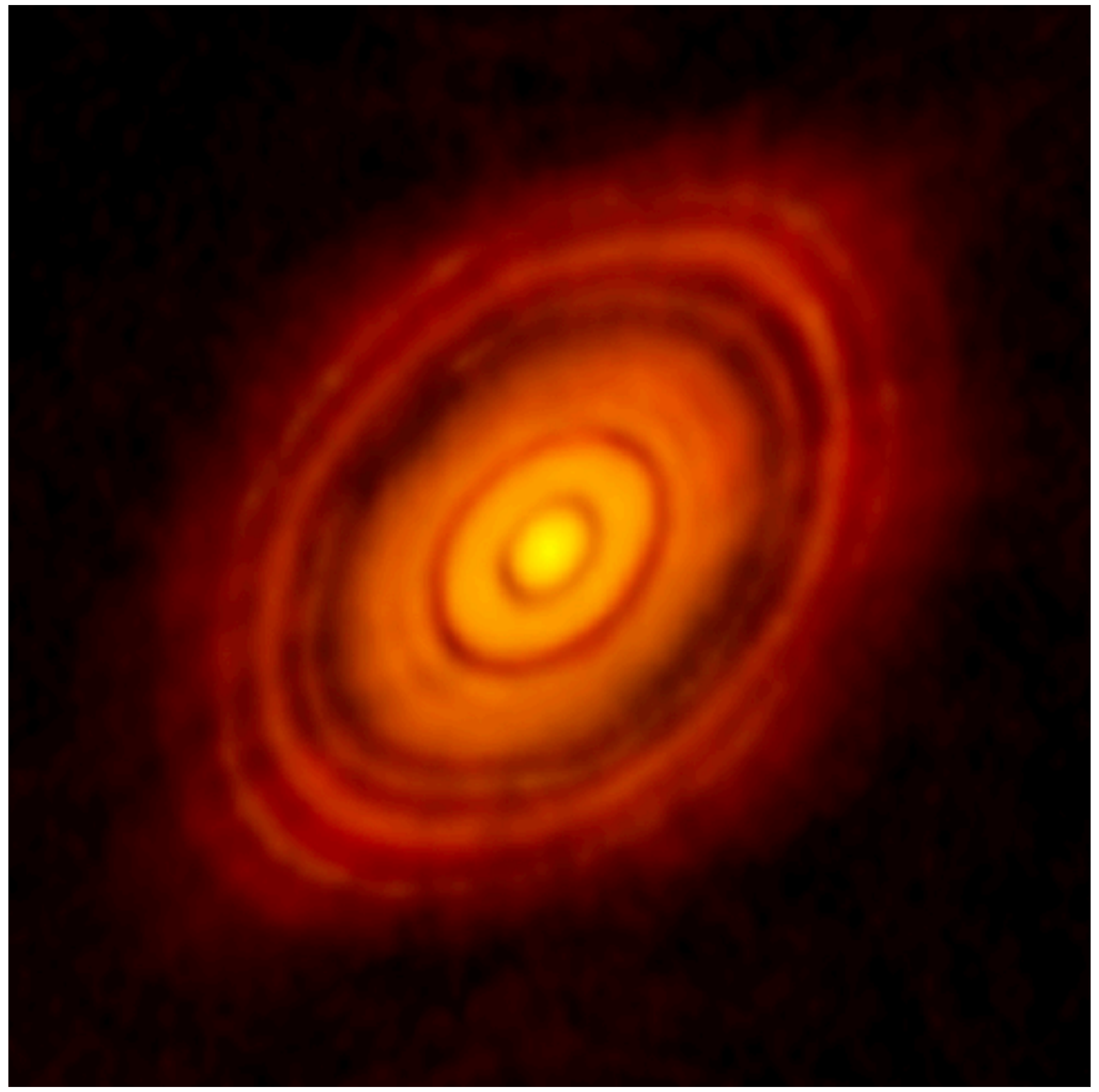
- Radio synchrotron (continuum), non-thermal emission from relativistic electrons in magnetic fields
- Bremsstrahlung (a.k.a. free-free) emission (continuum), thermal emission from ionized gas (H II regions)
- Thermal emission from cold ($<$ 100 K) media, like dust (continuum)
- Atomic hyperfine splitting (“21-cm” line corresponding to neutral hydrogen)
- Molecular emission lines, primarily from rotational transitions (e.g., CO $J = 2 - 1$)

Radio Astronomy Targets

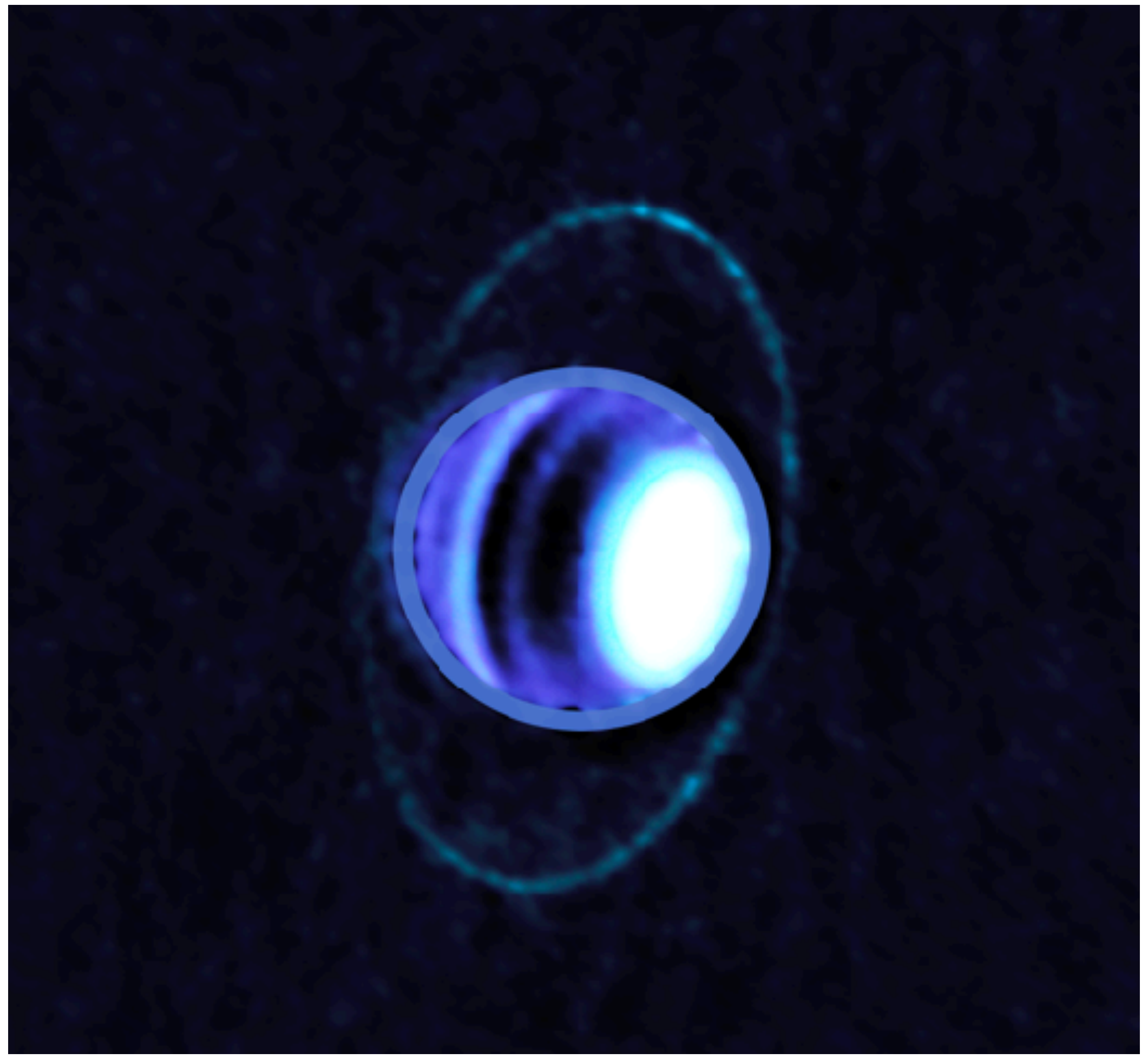
Radio jets from elliptical galaxy Hercules A



HL Tau protoplanetary disk



Uranus and its rings



quasars, gamma ray burst (GRB) afterglows, fast radio bursts (FRBs), pulsars, supernovae remnants, cosmic microwave background (CMB), galaxies, including molecules at high redshift sources, dust/interstellar medium, the Sun, planets (e.g., Jupiter, Uranus), protoplanetary disks, molecular clouds (molecular emission), black hole accretion disks (EHT), …, pretty much everything these days!

Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA). ALMA(ESO/NAOJ/NRAO); C. Brogan, B. Saxton (NRAO/AUI/NSF) ALMA (ESO/NAOJ/NRAO); E. Molter and I. de Pater.

Single Dish Radio Telescopes

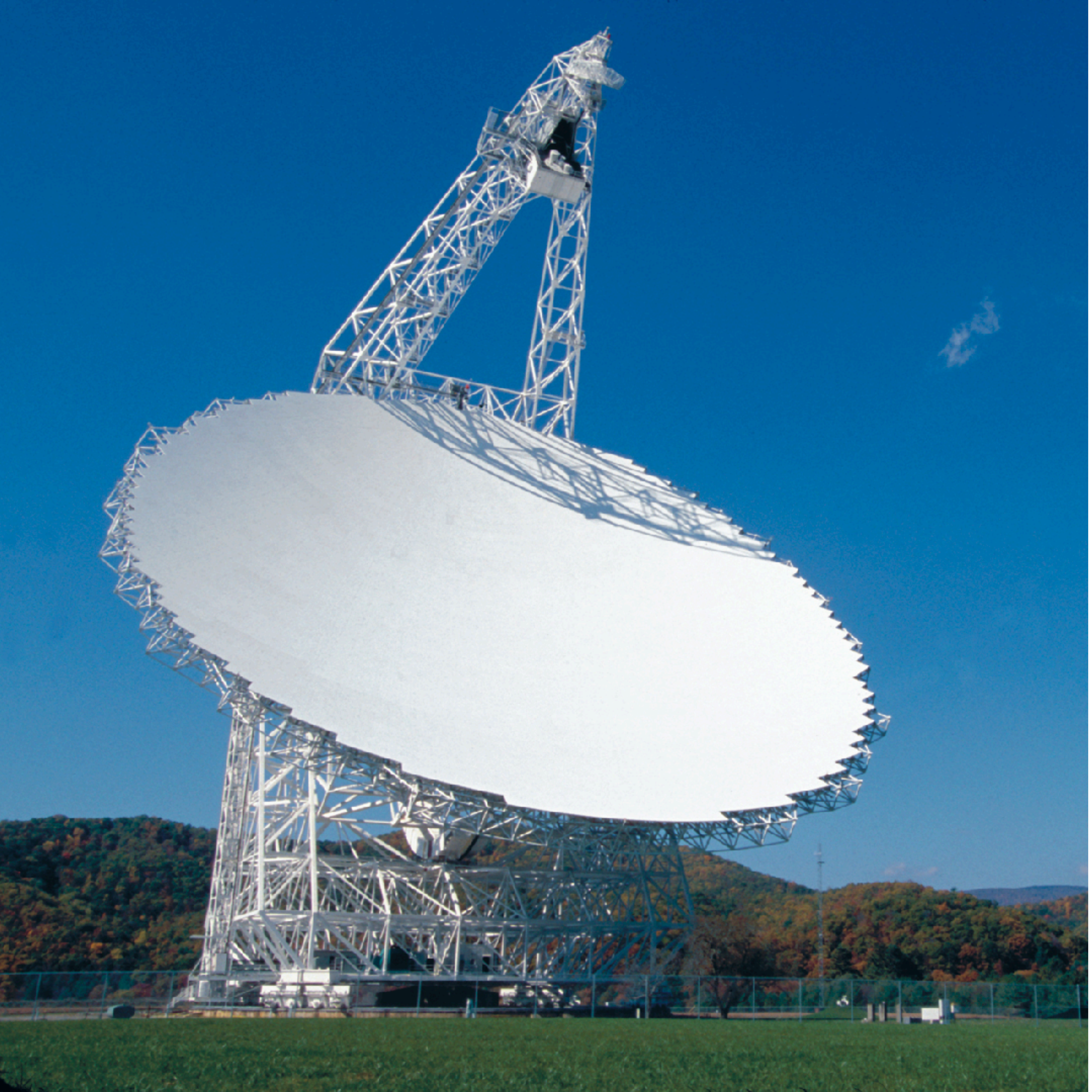
$$\theta \approx \frac{\lambda}{D}$$

still applies, but λ is much longer than you might be used to with optical telescopes.

Compared to an optical ($\lambda = 500\,\mathrm{nm}$) telescope the same size, a radio observation at $\lambda = 1\,\mathrm{cm}$

$$\frac{1\,\mathrm{cm}}{500\,\mathrm{nm}} = 20{,}000$$

worse resolution



The Green Bank Telescope (100m diameter) operates at radio wavelengths.

It is easier to build bigger telescopes at longer wavelengths, because surface tolerances need to be kept to

$$\sigma = \frac{\lambda_{\mathrm{min}}}{16}$$

NRAO/AUI/NSF

The IRAM 30m diameter telescope, which operates at sub-mm wavelengths. Credit: Wikipedia/ IRAM-gre

Single Dish Observations

The antenna “beam” is the power pattern as a function of direction.

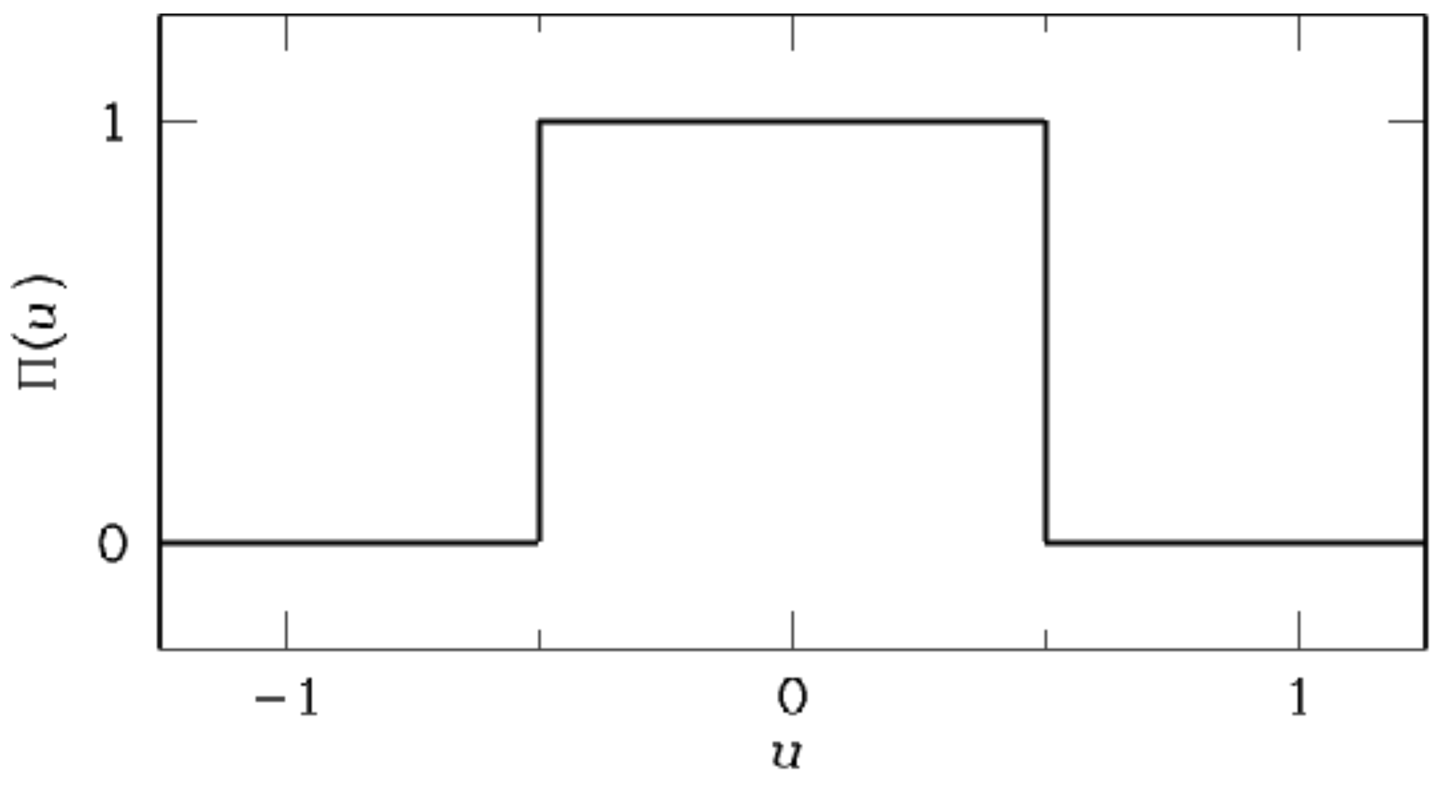
Reciprocity theorem:

the far-field electric field pattern is the Fourier Transform of the electric field illuminating the aperture of the telescope

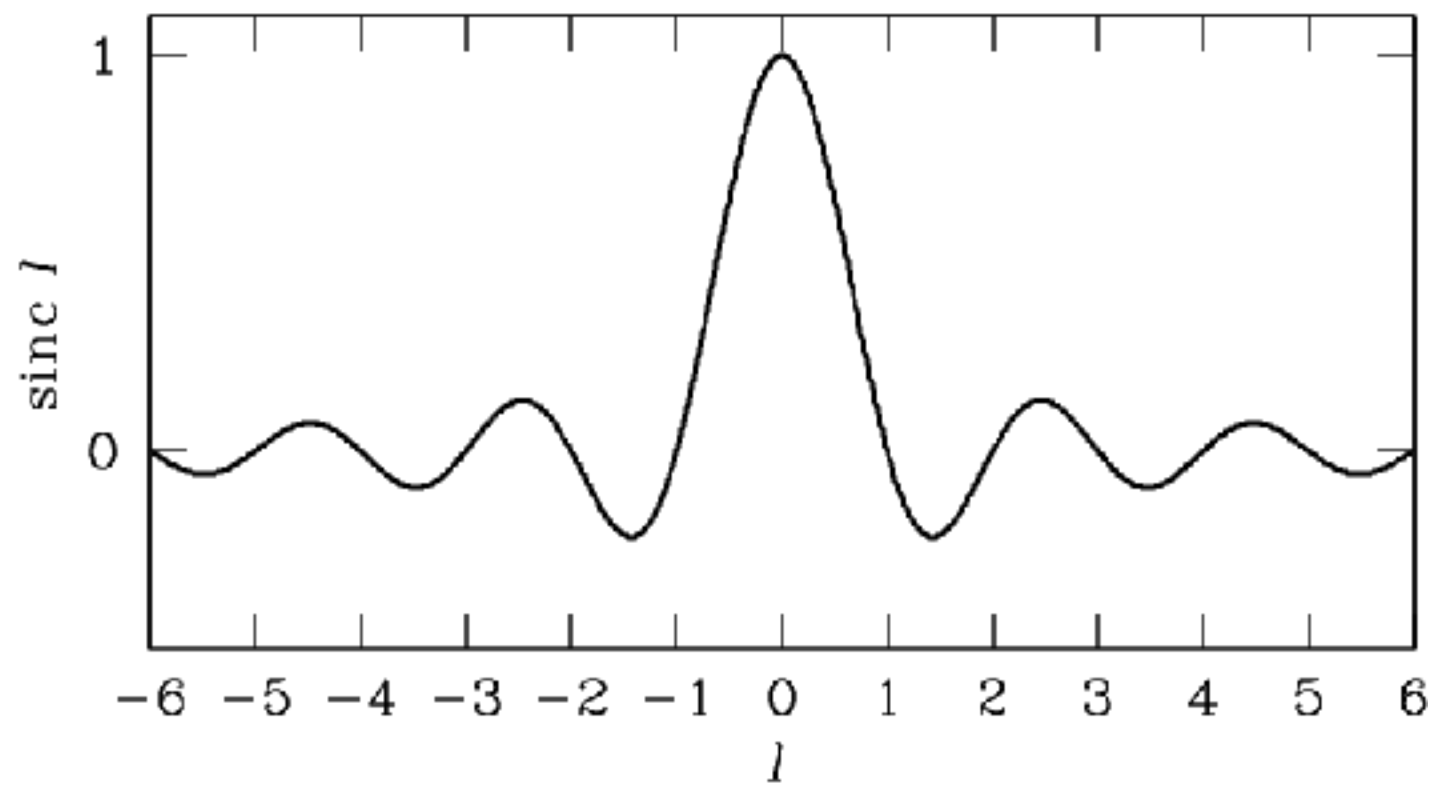
For large apertures, the nulls at $l = \pm 1, 2, \ldots$ appear at angles $\theta \sim \lambda/D, 2\lambda/D, \ldots$

In two dimensions, for a circular aperture, this is an Airy pattern.

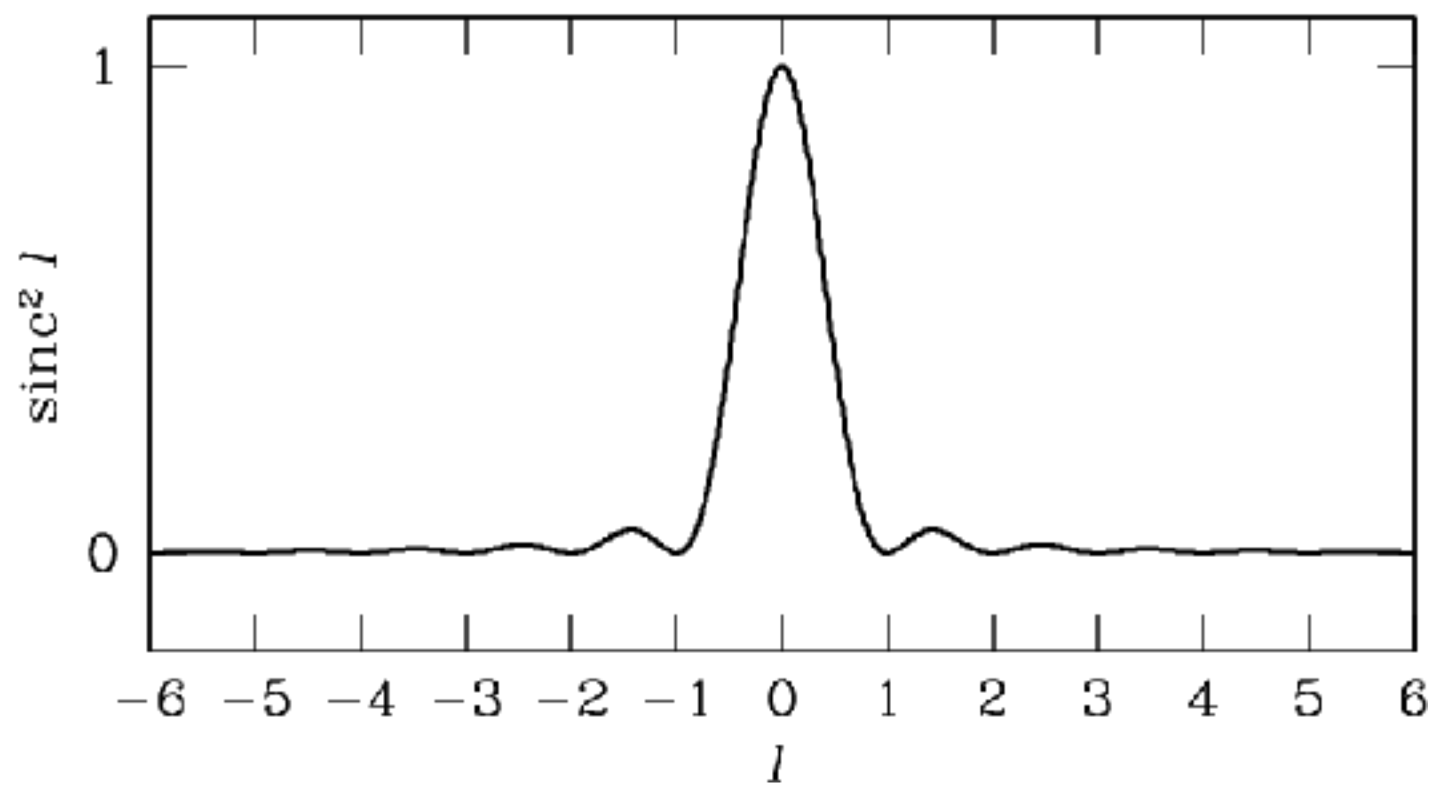
Uniformly illuminated aperture



Electric field pattern of antenna as a function of direction



Power pattern of antenna, as function of direction



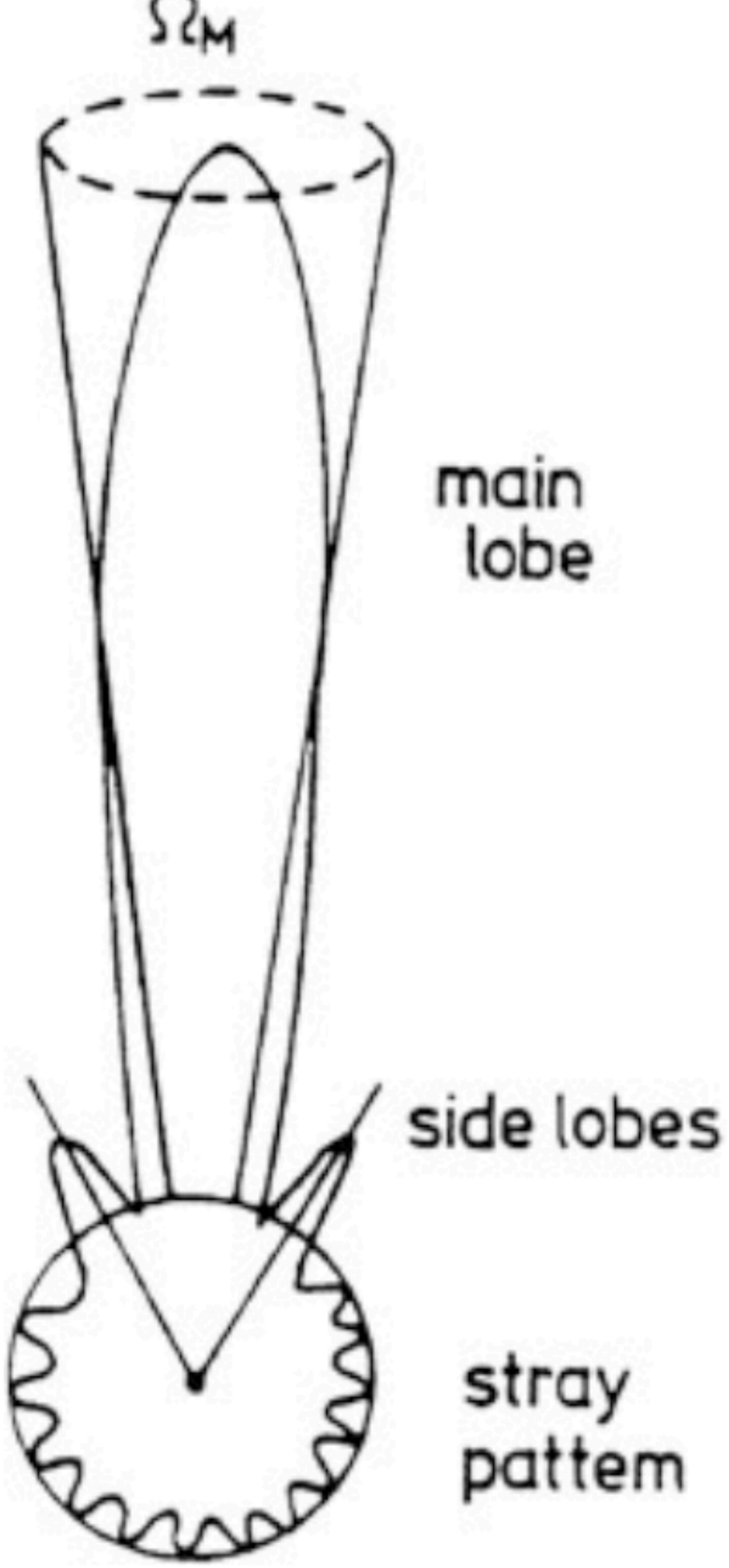
Essential Radio Astronomy

Single Dish Observations

A beam power pattern in polar coordinates: antenna can pick up power from “sidelobes” at range of angles. Antennas w/ secondary reflectors + supports can be contaminated with reflected “ground” radiation

You can conceptualise most single-dish telescopes as single-pixel devices: to make a map of the sky, you would need to raster scan the telescope across the region of interest, reading out antenna temperature as a function of RA, Dec.

Some advanced instruments may have an array of “feeds” in a focal plane (mirroring a set of “pixels”), but this is still a small number compared to a typical CCD (e.g., 25 or 36 compared to 2046^2).



Tools of Radio Astronomy

Image Units

What are the units of the sky, and the images we make of it?

Most useful quantity from radiative transfer is I_ν.

This is the *specific intensity* of radiation, and you can think of it as the energy carried along by an infinitesimal "bundle" of rays

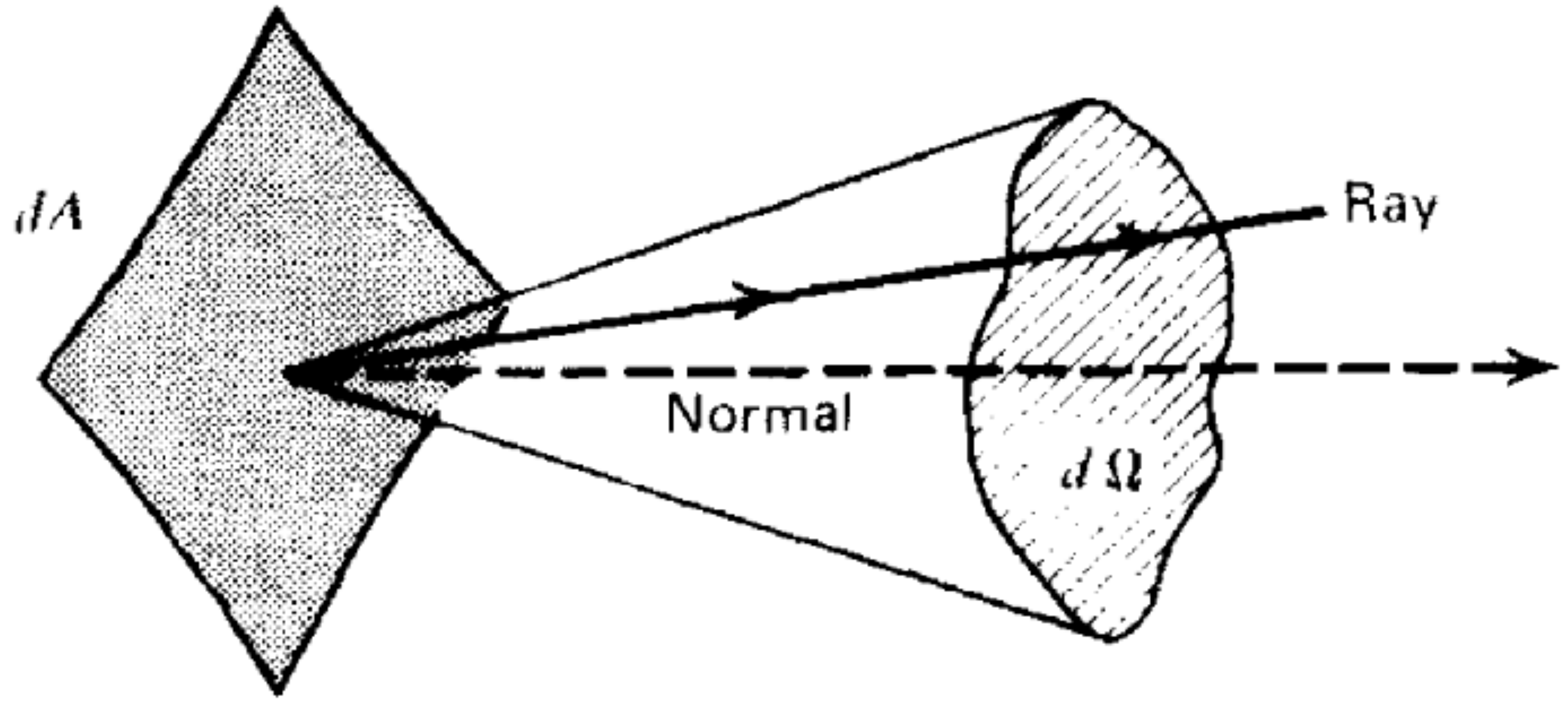


Figure 1.2 **Geometry for normally incident rays.**

Radiative Processes, Figure 1.2

specific intensity I_ν

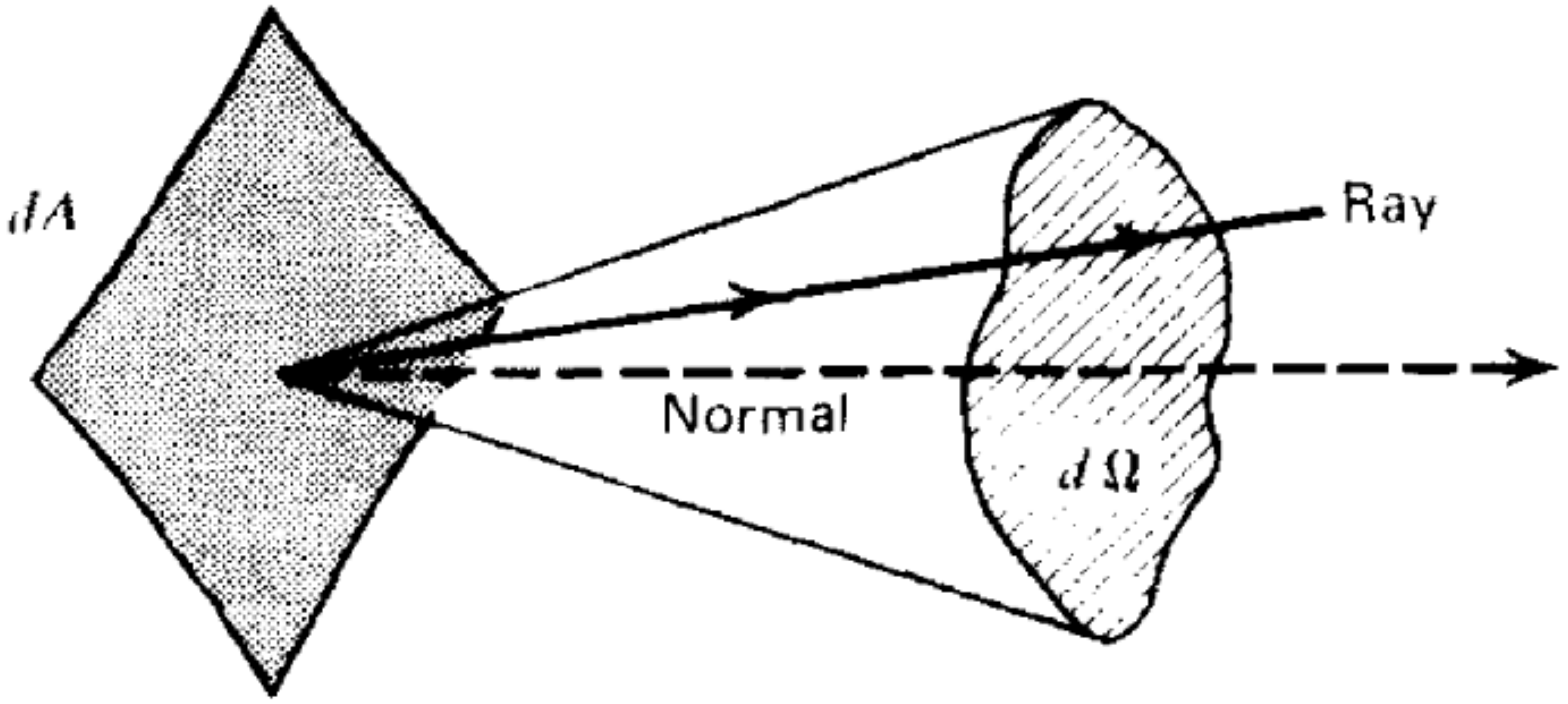


Figure 1.2 Geometry for normally incident rays.

- $\mathrm{d}A$ is infinitesimal patch of area
- $\overrightarrow{\Omega}$ is a direction vector normal to that patch of area
- $\mathrm{d}\Omega$ is a differential solid angle surrounding that vector

$$(\,\mathrm{d}\Omega = \mathrm{d}\phi \sin\theta \mathrm{d}\theta\,)$$

units $\quad$ $\text{energy (time)}^{-1}\ \text{(area)}^{-1}\ \text{(solid angle)}^{-1}\ \text{(frequency)}^{-1}$

CGS $\quad$ $\text{ergs s}^{-1}\ \text{cm}^{-2}\ \text{ster}^{-1}\ \text{Hz}^{-1}$

non-astronomy settings use “spectral intensity” for I_ν,
integrated over all frequencies, get I “radiant intensity”

Radiative Processes, Figure 1.2

specific intensity I_ν

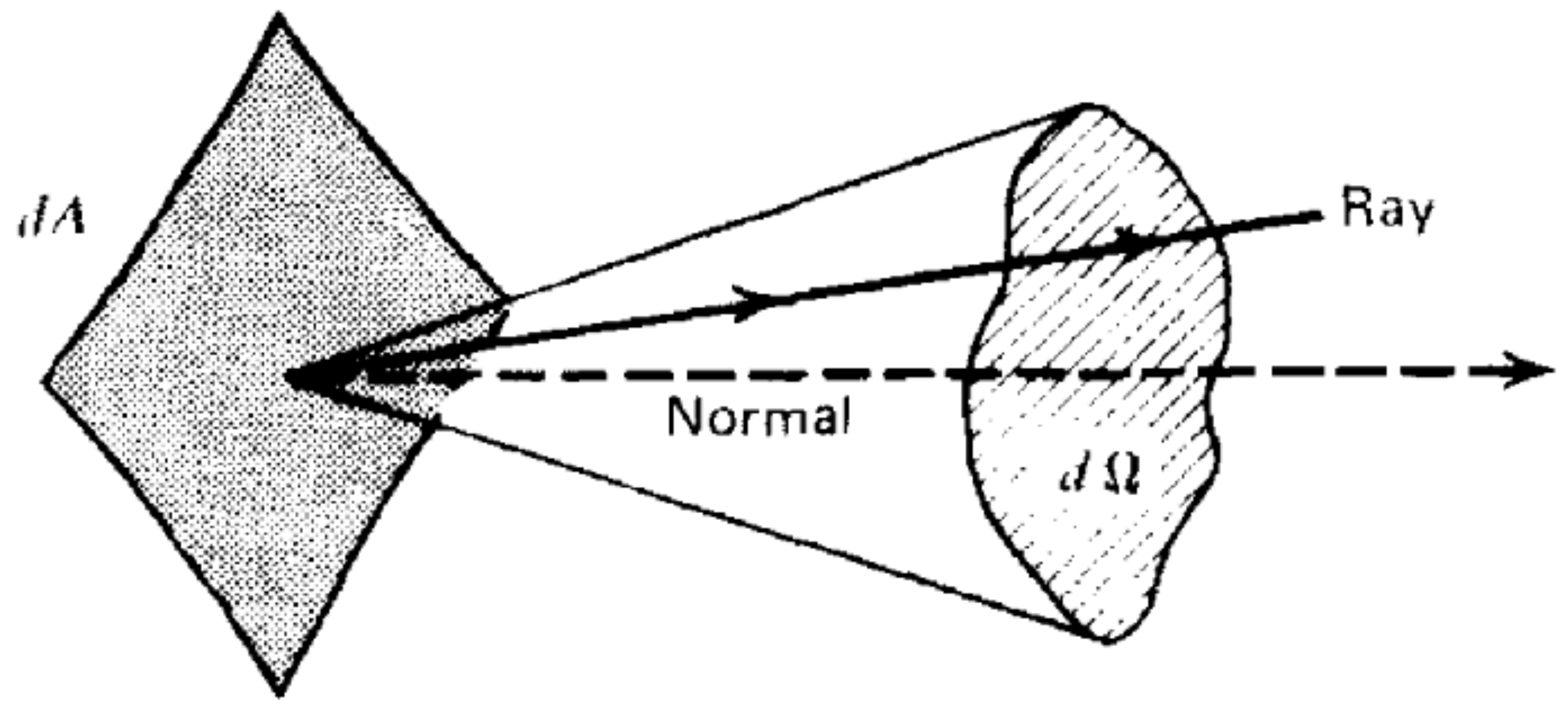


Figure 1.2 Geometry for normally incident rays.

I_ν is mind-bending to think about. It is a *function* of

- 3D space $\vec{x}$
- direction $\overrightarrow{\Omega}$
- frequency ν

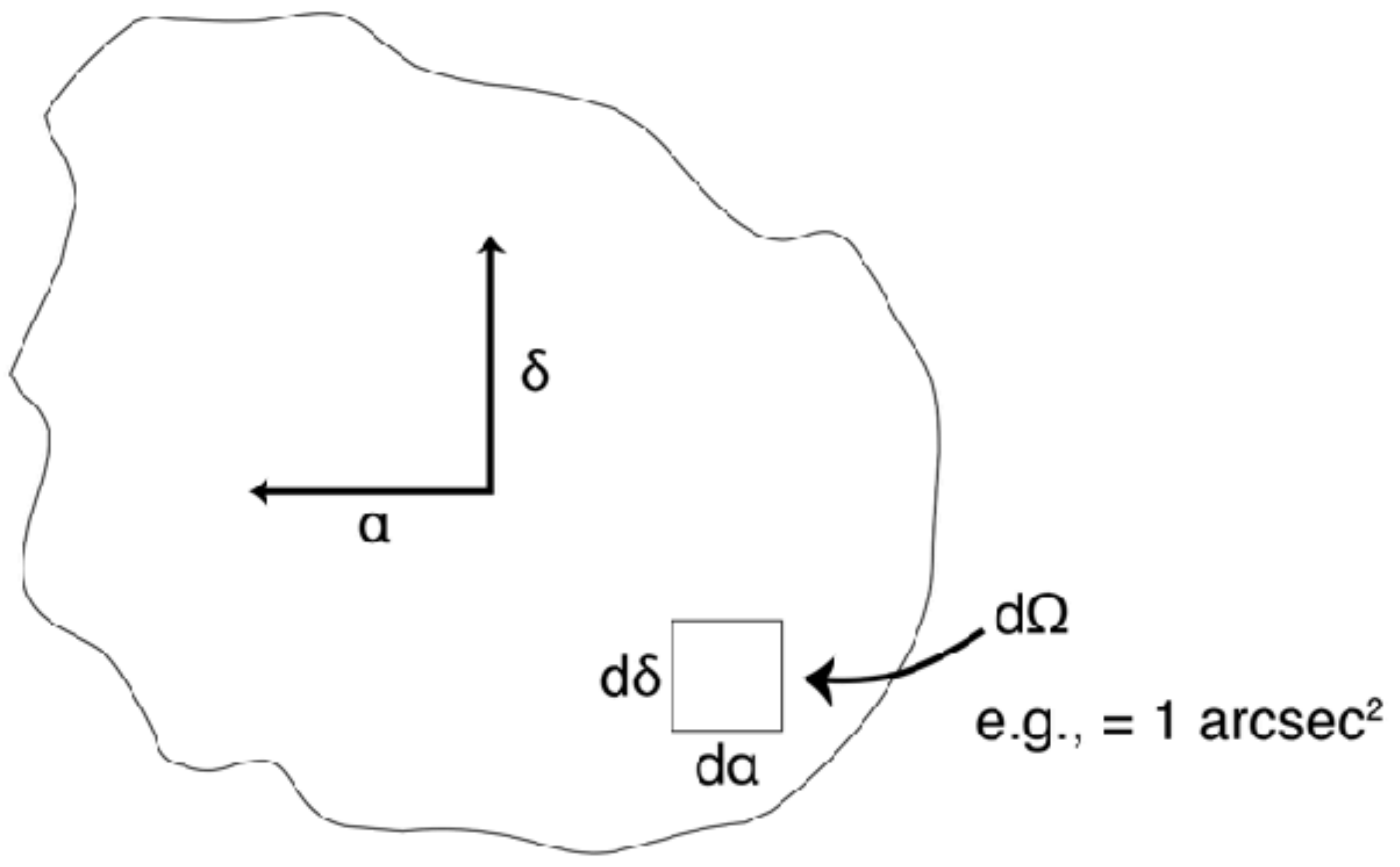
I_ν itself is *not* a vector quantity. It is a scalar field that is a function of vector quantities $I_\nu(\vec{x}, \overrightarrow{\Omega})$

Radiative Processes, Figure 1.2

Astrophysical observations

Observations are (usually) from the Earth, looking at the night sky. Rather than $I_\nu(\vec{x}, \overrightarrow{\Omega})$ we talk about direction on the celestial sphere, $I_\nu(\alpha, \delta)$.

Images have the same units because they are representations of specific intensity. It's very common to refer to $I_\nu(\alpha, \delta)$ as *surface brightness.*



A solid angle describes an area on a unit sphere (e.g., the sky), the area itself need not be circular

Flux

$$F_\nu = \int I_\nu \cos\theta \mathrm{d}\Omega$$

Intensity passing through some differential area $\mathrm{d}A$, lowered by the effective angle

$$\mathrm{ergs\ s^{-1}\ cm^{-2}\ Hz^{-1}}$$

Most sources produce significantly less energy in radio waves compared to higher frequency bands, and so the raw CGS unit can be quite cumbersome.

To make this easier, astronomers use a unit called the “Jansky,” which is defined as

$$1\ \mathrm{Jy} = 10^{-23}\ \mathrm{ergs\ s^{-1}\ cm^{-2}\ Hz^{-1}}$$

Bright radio sources would have fluxes of ~1 to ~1,000 Jy at radio frequencies, though modern instrumentation is much more sensitive. Measurements of μJy are common at sub-mm wavelengths.

Specific Intensity for Radio Sources?

Reintroduce the “per solid angle” to the Jy unit,

$$\mathrm{Jy\,arcsec^{-2}}$$

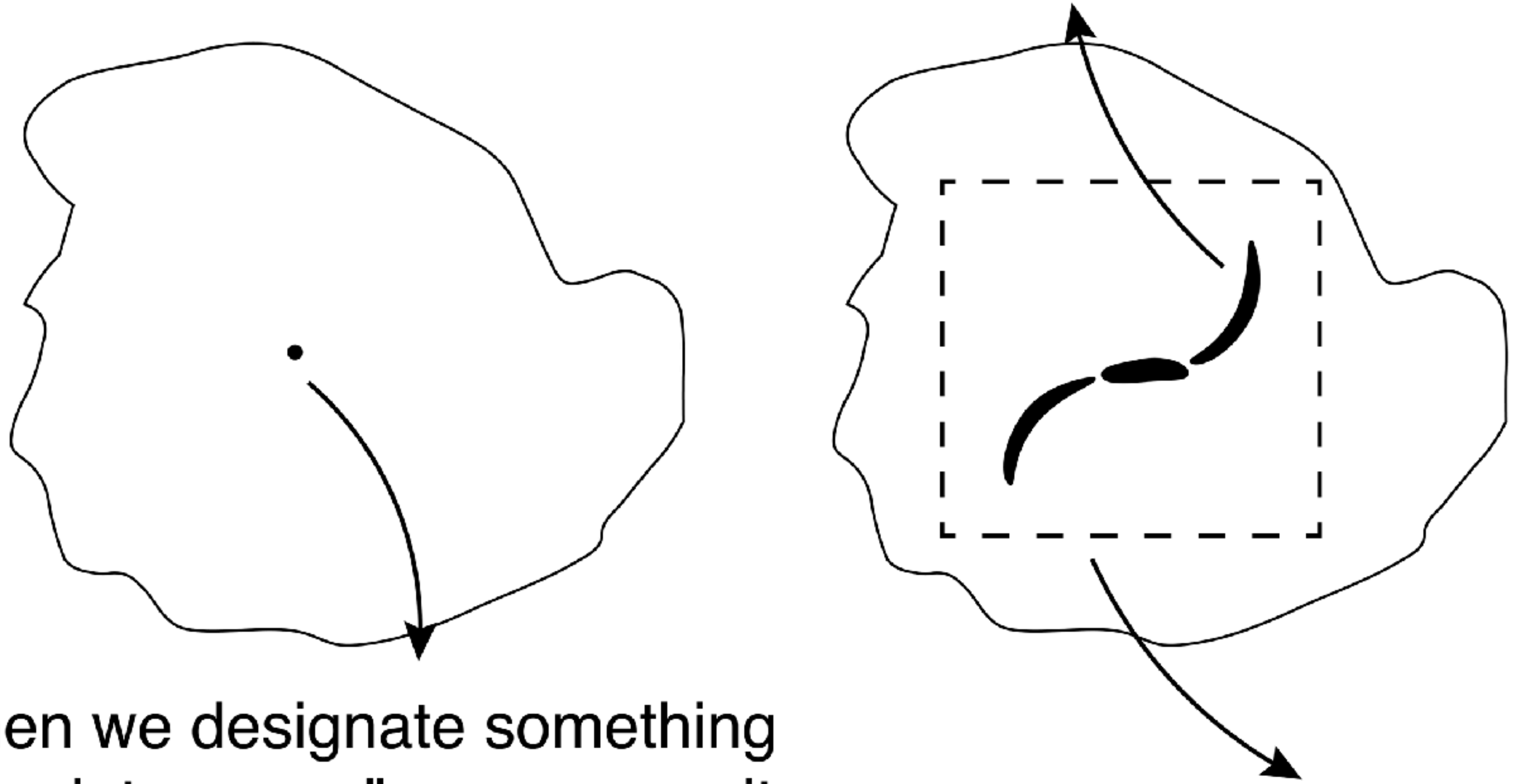
Other surface brightness units include:

- Jy “per beam,” an (observation-dependent) way to measure solid angle
- $\mathrm{mag\,arcsec^{-2}}$ (optical)
- $\mathrm{MJy\,sr^{-1}}$ (infrared)

Questions for review

- What is the name of I_ν, and what are its units?
- What is the name of F_ν, and what are its units?
- Is a Jansky a unit for I_ν or F_ν?
- If we made an astronomical observation of a “point source,” would we report I_ν or F_ν?
- What about for a spatially resolved source?

represent resolved
source as $I_\nu(\alpha,\delta)$



when we designate something
a “point source,” we assume it
has no (resolvable) spatial
extent, so only F_ν is relevant

extract F_ν by summing
within aperture

Brightness Temperature, T_B: *the temperature such that a blackbody would emit with the observed specific intensity*

Caution: one needs to be very careful of the *context* when using brightness temperature

"Classic" Radio Astronomy Definition

$$T_B \equiv \frac{c^2}{2k}\frac{1}{\nu^2}I_\nu$$

Rayleigh-Jeans approximation assumed *regardless* of whether it's physically applicable

T_B and I_ν are linearly related

Physics-oriented definition

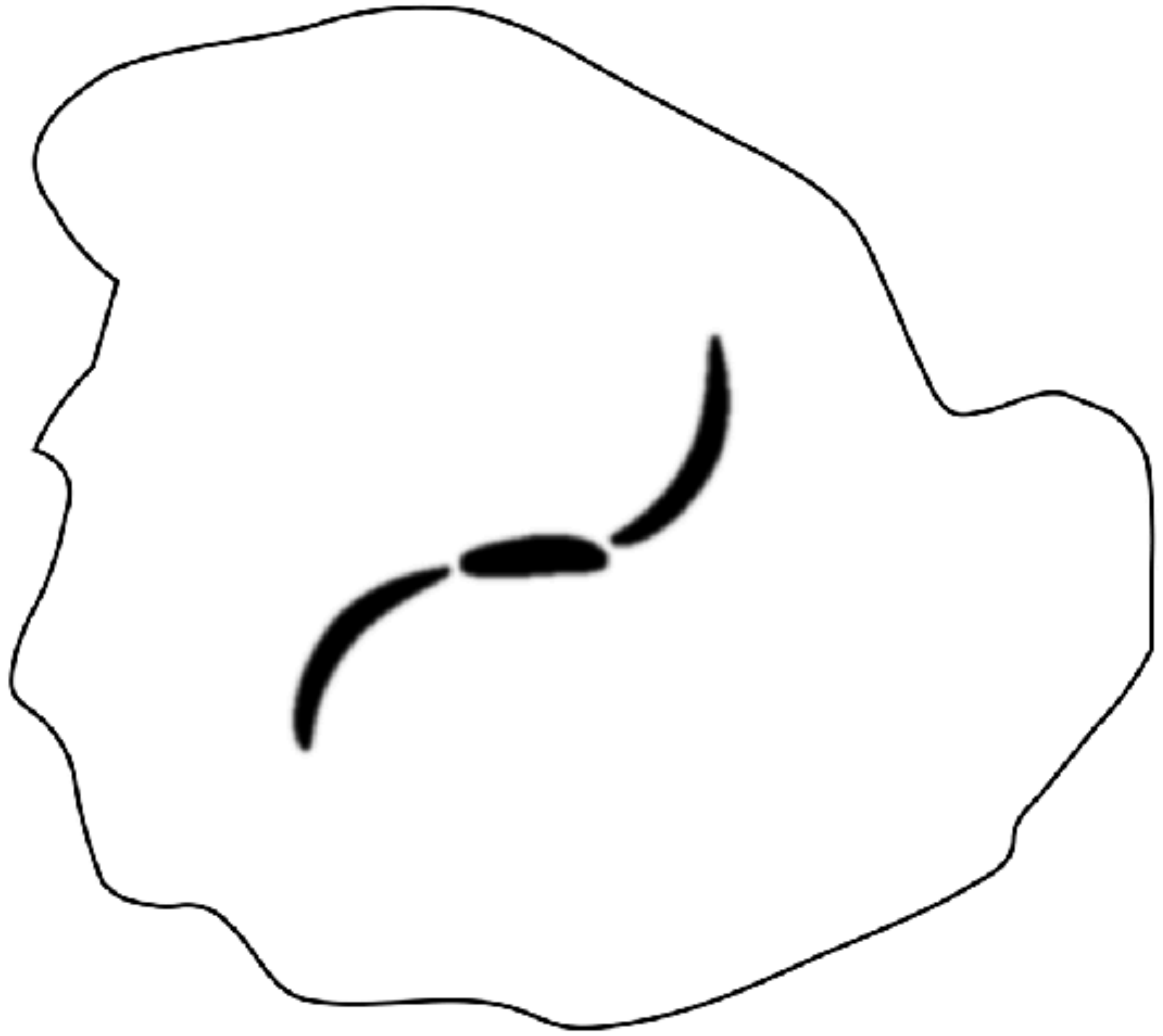
$$T_B \equiv \frac{h\nu/k}{\ln[1 + 2h\nu^3/c^2 I_\nu]}$$

Uses full Planck formulation

Temperature matches source if in LTE

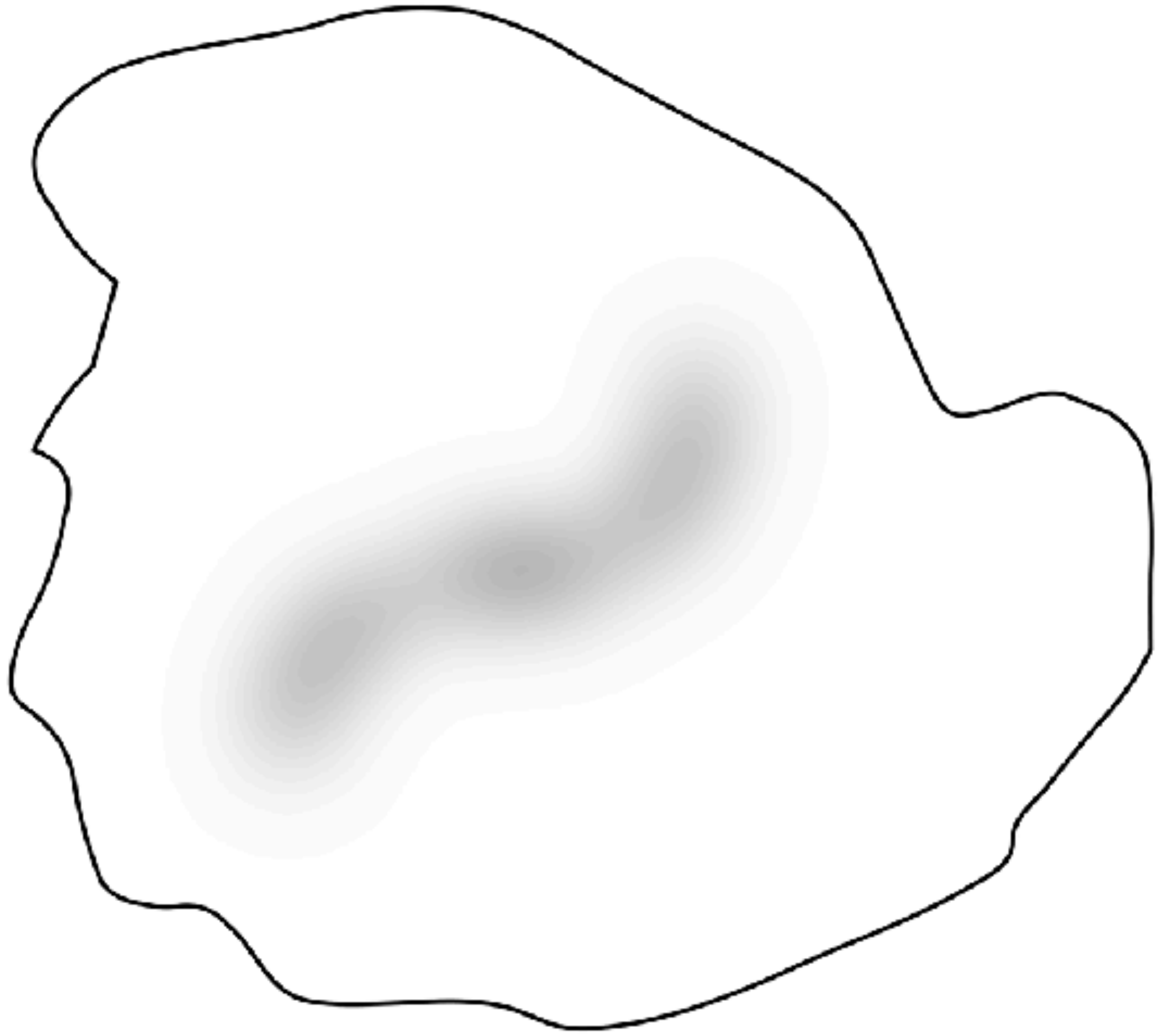
Observations and Beam Dilution

“sufficiently” resolved



resolution of observations: ·

inadequately resolved
and beam diluted



resolution of observations:

if the source is not adequately resolved, observed T_B can be an unfaithful proxy for actual T, even if the source is in LTE

Leads to inaccurate inference of astrophysical properties

Introduction to Interferometric Arrays

The Atacama Large (Sub)millimeter Array (ALMA). 66 antennas operating at sub-millimeter wavelengths. The largest antennas in the array are only 12m in diameter, yet through interferometry, the array is able to obtain far higher spatial resolution than the largest single-dish antennas.

Credit: NRAO/ESO/NAOJ/JAO

The Very Large Array (VLA), located in Socorro, NM. Credit: NRAO

One antenna at the Eastern end of the Very Long Baseline Array (VLBA), St. Croix, U.S. Virgin Islands. Credit: Cumulus Clouds

The NOEMA, located in the French Alps on the Plateau du Bure. Credit: IRAM/Rebus

The Submillimeter Array (SMA), located on Mauna Kea, Hawaii. Credit: I. Czekala