Introduction to Radio Interferometry

Blake Ledger

Authors: Alison Peck, Jim Braatz, Toby Brown, Ashley Bemis, Sabrina Stierwalt

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

Main takeaways today

1. *Tune* your telescope frequency range depending on your science targets.
   - ALMA bands 3-10 span ~84-950 GHz (~3.5-0.3 mm).

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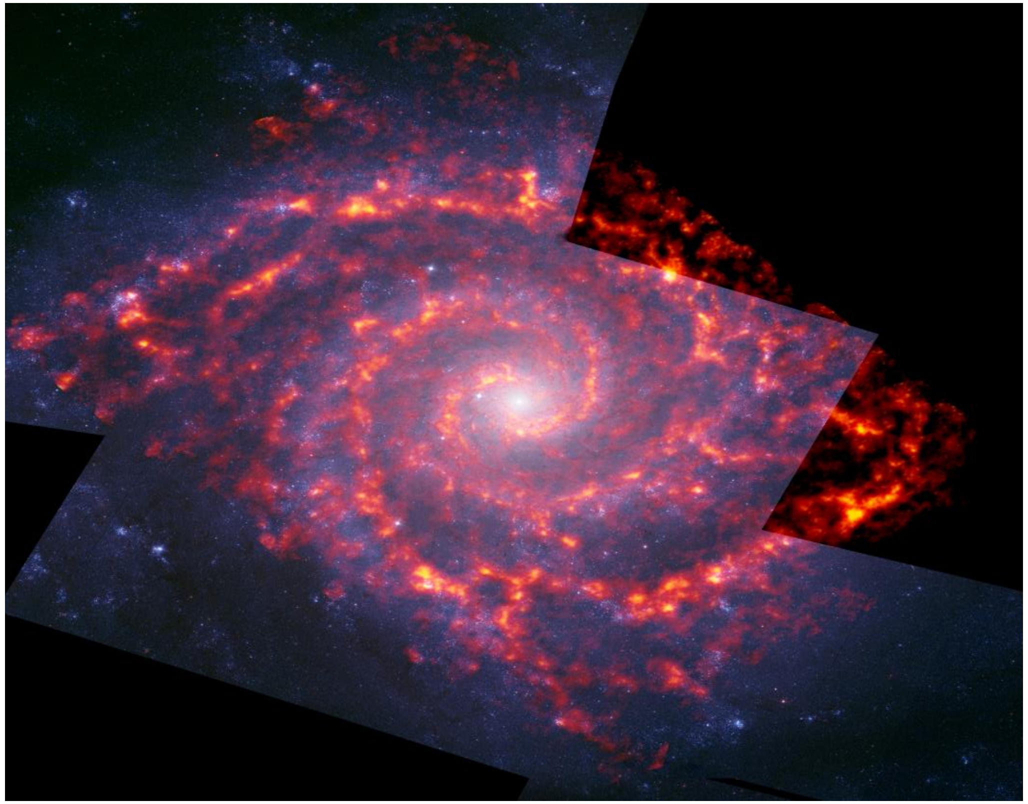

Star-forming clouds in NGC 628

- CO (1-0) emission

(~115 GHz in ALMA Band 3)

Credit: NRAO/AUI/NSF; B. Saxton

Main takeaways today

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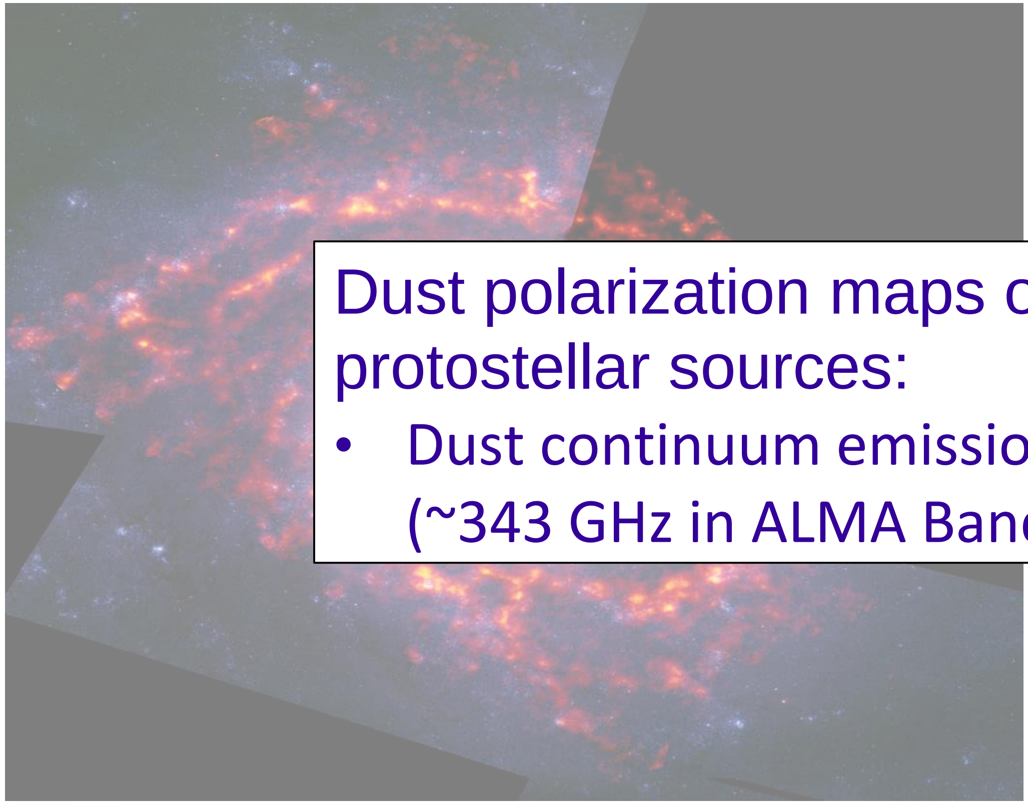
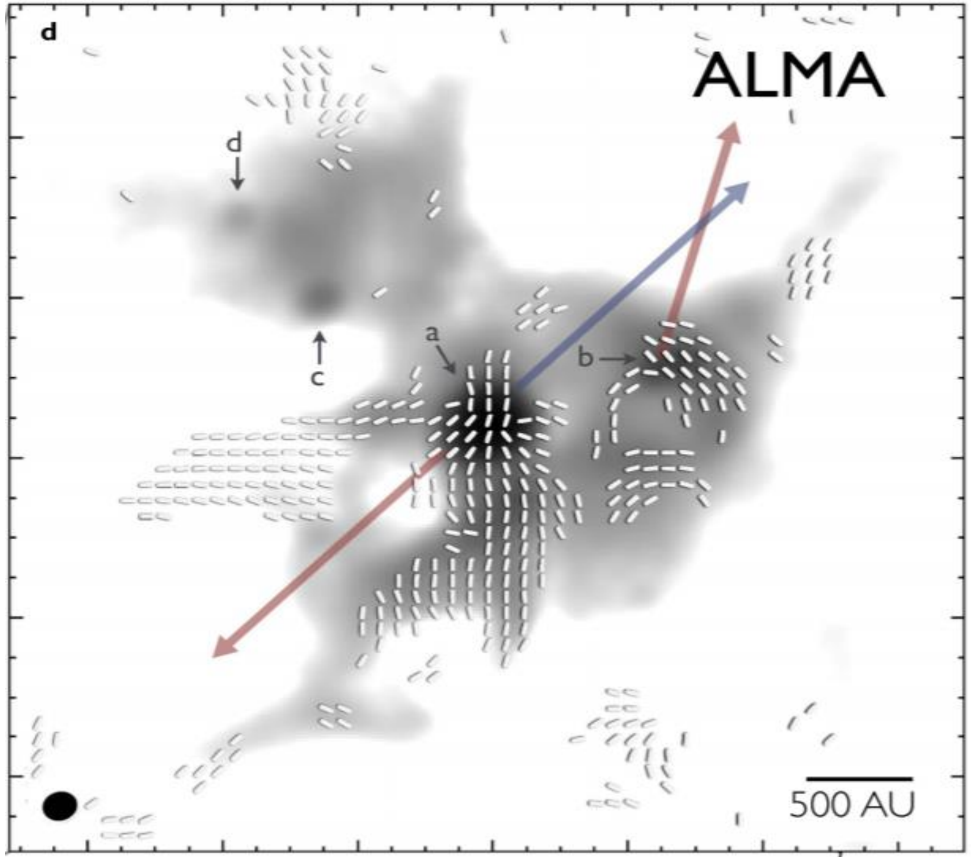


Dust polarization maps of protostellar sources:

- Dust continuum emission (~343 GHz in ALMA Band 7)

Credit: NRAO/AUI/NSF; B. Saxton



Credit: Hull et al. 2017, APJ 847: 92

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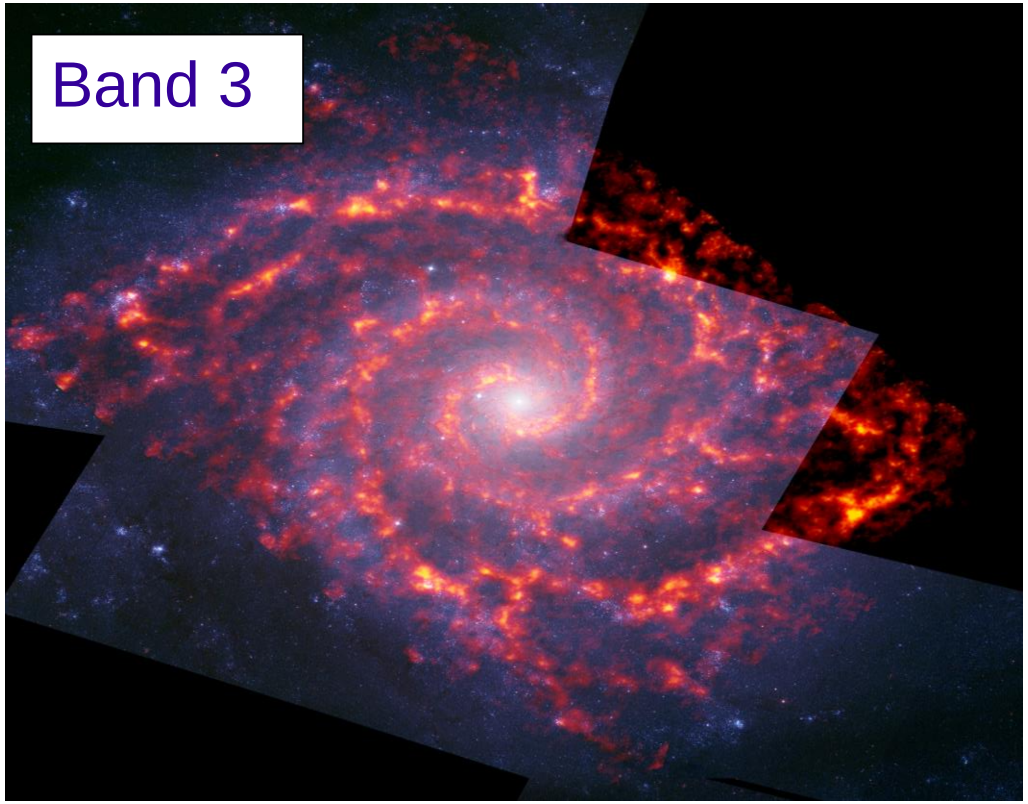

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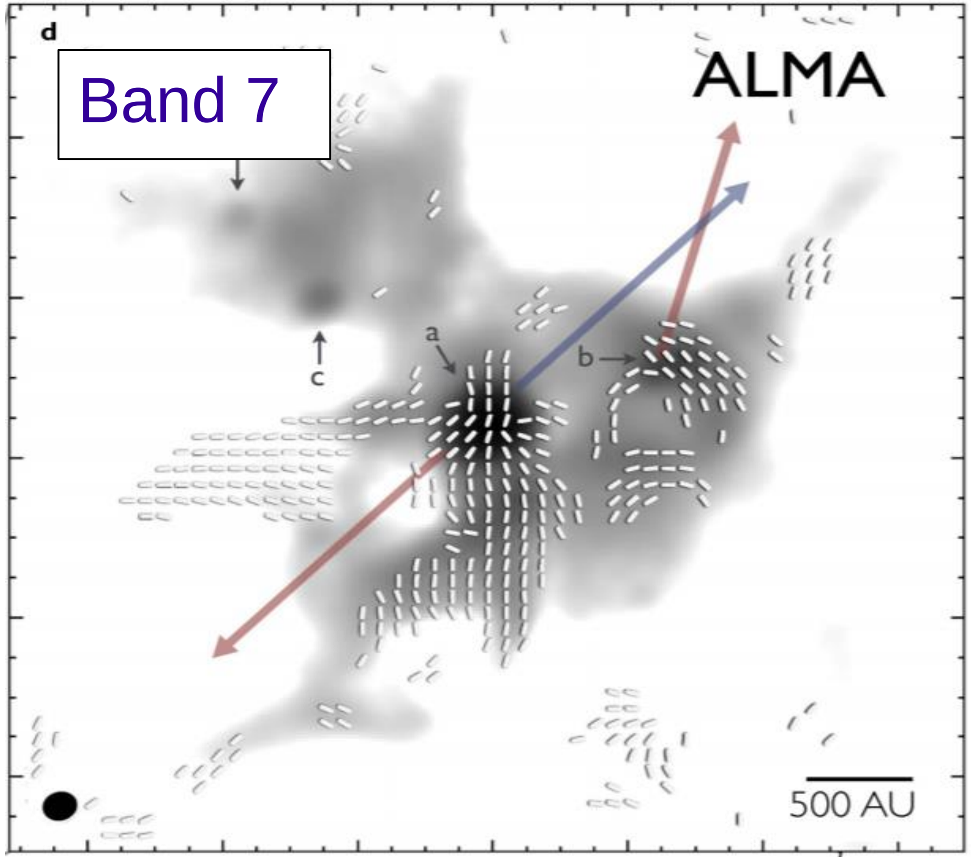

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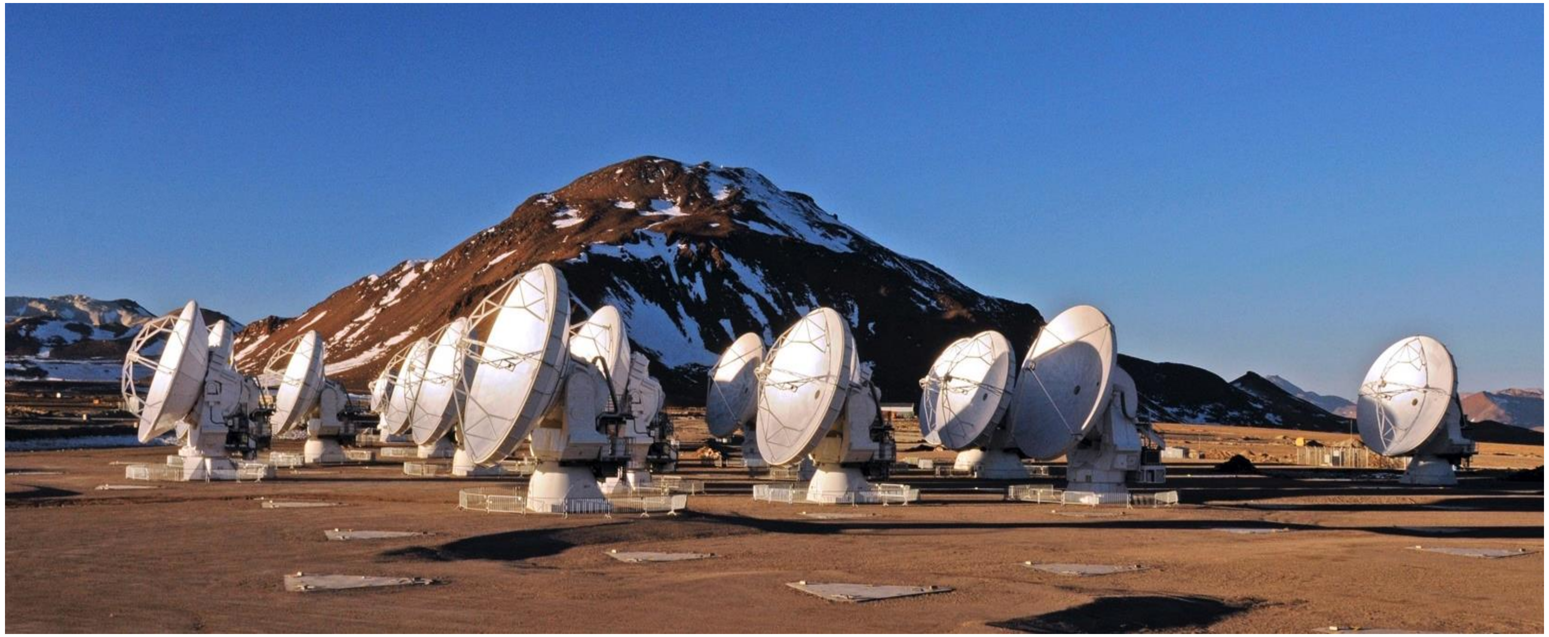
Main takeaways today

1. *Tune* your telescope frequency range depending on your science targets.
   - ALMA bands 3-10 span ~84-950 GHz (~3.5-0.3 mm).

2. Choose the ALMA configuration based on the angular resolution that you would like to achieve in your observations.
   - be aware of which *scales* we are limited to
   - be aware of the *configuration* schedule and if your *target* is visible during that time



Resolution of Observations

Angular resolution for most telescopes is ~ λ/D

D is the diameter of the telescope and λ is the wavelength of observation

For the Hubble Space Telescope:

λ ~ 1um / D of 2.4m = resolution ~ 0.13"

To reach that resolution at λ ~1mm, we would need a 2 km-diameter dish!

Instead, we use arrays of smaller dishes to achieve the same high angular resolution at radio frequencies

This is interferometry!

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Characteristic Angular Scales

Angular resolution of telescope array:

~ λ/B_{max} (B_{max} = longest baseline)

Maximum angular scale:

~ λ/B_{min} (B_{min} = shortest distance between antennas)

Field of view (FOV):

~ λ/D (D = antenna diameter)

*Sources more extended than the FOV can be observed using multiple pointing centers in a mosaic

An interferometer is sensitive to a range of angular sizes: $\lambda/B_{max} < \theta < \lambda/B_{min}$

What Are Visibilities?

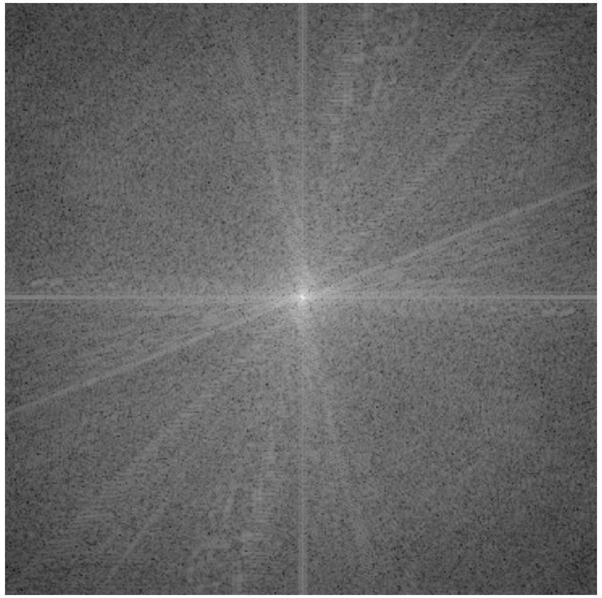
Each V(u,v) contains information on T(x,y) everywhere

Each V(u,v) is a complex quantity

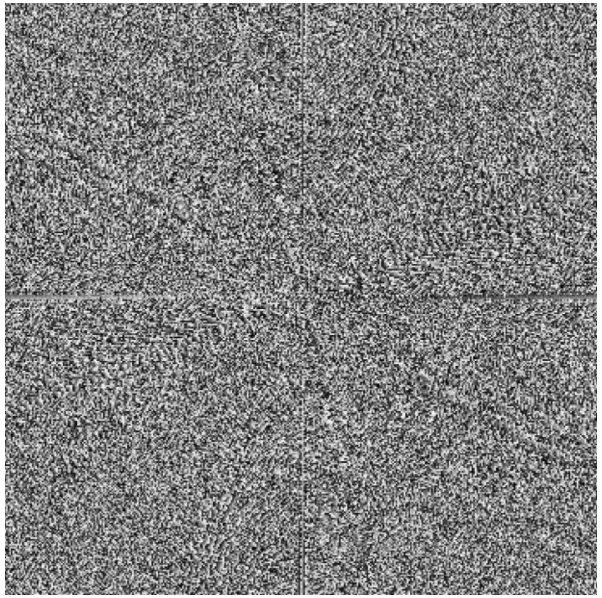
Expressed as (real, imaginary) or (amplitude, phase)

T(x,y)

FT →



V(u,v) amplitude



V(u,v) phase

Basics of Aperture Synthesis

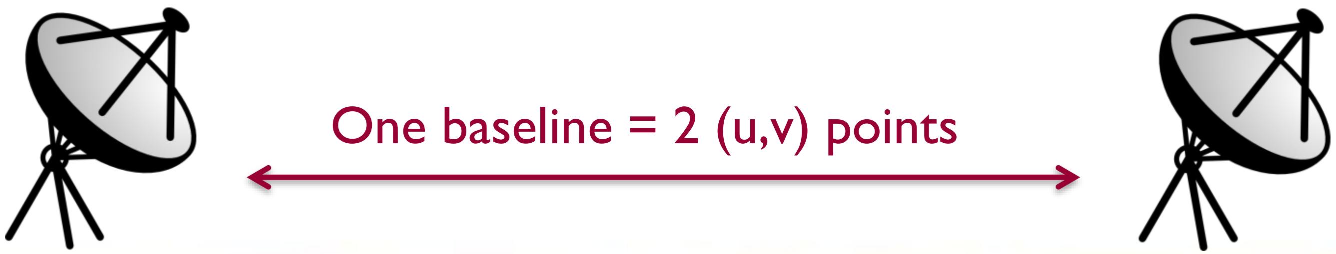
Idea: Sample V(u,v) at an enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{max}, v_{max})

One pair of antennas = one baseline

For **N antennas**, we get **N(N-1) samples** at a time

How do we fill in the rest of the (u,v) plane?

1. Earth's rotation
2. Reconfigure physical layout of N antennas



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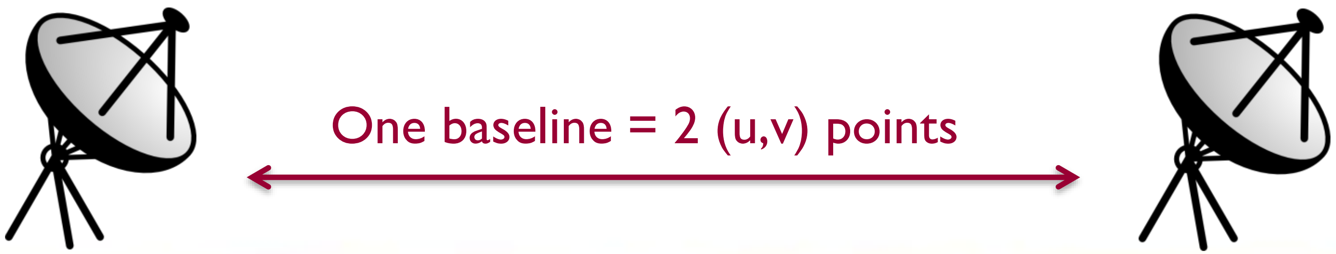
Then, V(u,v) gives T(x,y) everywhere after a FT



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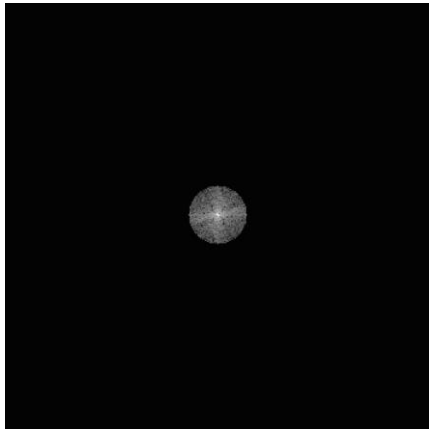
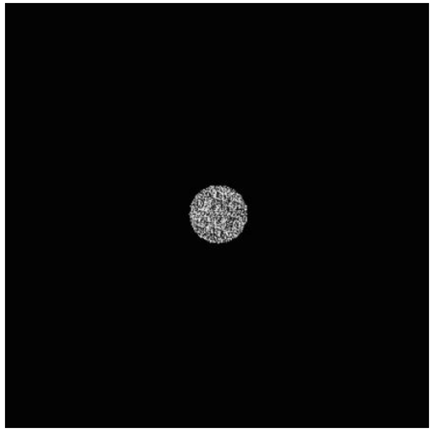
Implications of (u,v) Coverage

What does it mean if our (u,v) coverage is not complete?

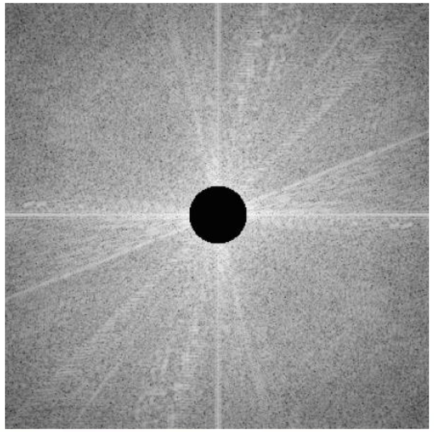
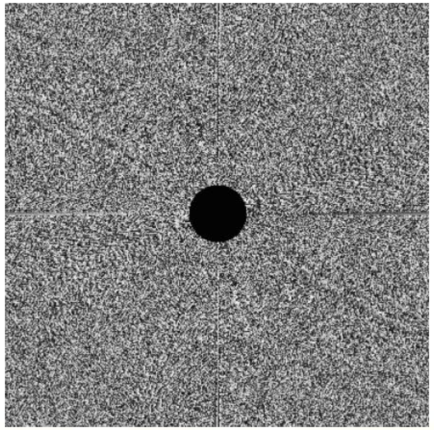
V(u,v) amplitude | V(u,v) phase | T(x,y)

Missing High Spatial Frequencies

FT →

Missing Low Spatial Frequencies

FT →

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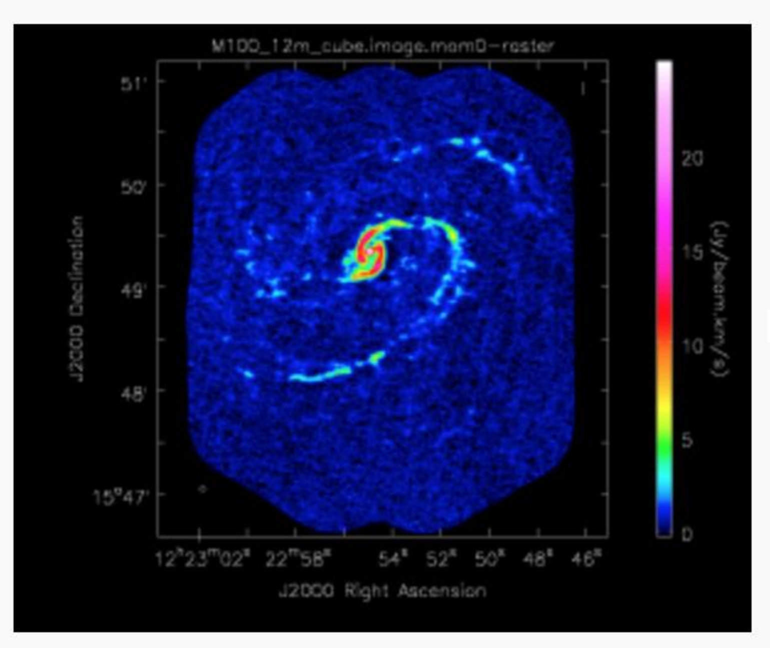
Characteristic Angular Scales: M100

ALMA 12m



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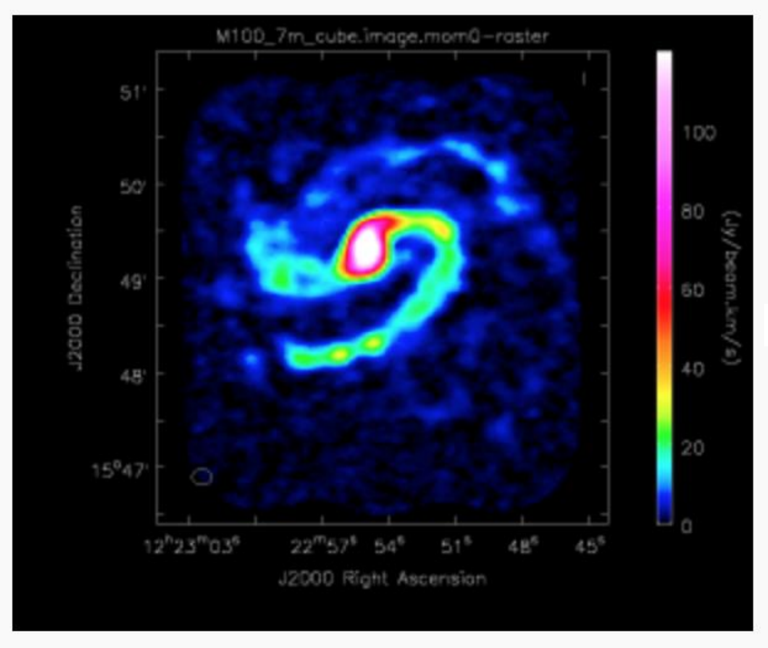
ACA 7m



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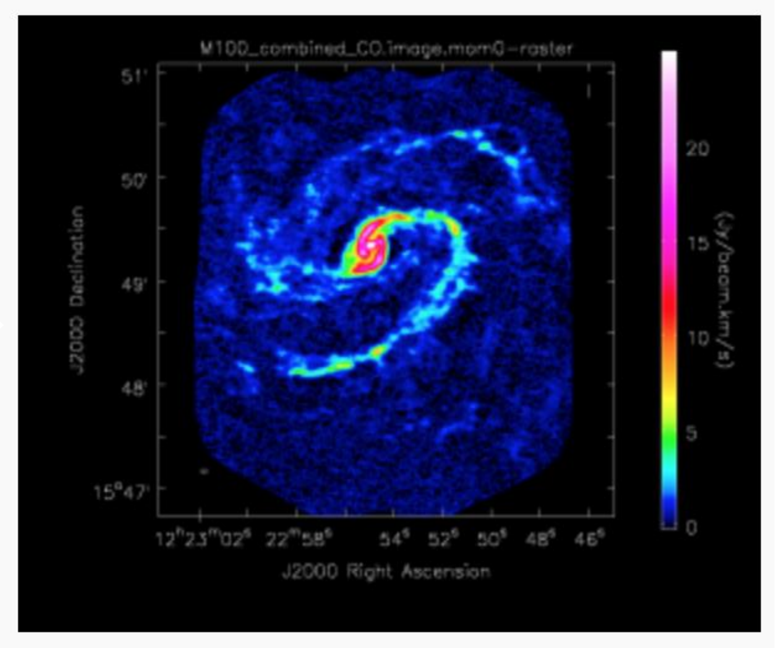
Combined



ALMA 12m shows smaller spatial scales (denser, clumpier emission)
ACA 7m data shows larger spatial scales (diffuse, extended emission)

To get both — you need a combined image!

Interferometry: Spatial Scales

- The **sensitivity** is given by the number of antennas times their area
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam) ($\sim\lambda/D$)
- The **resolution** is given by the largest distance between antennas (called the synthesized beam) ($\sim\lambda/B_{max}$)
- The **largest angular scale** that can be imaged is given by the shortest distance between antennas ($\sim\lambda/B_{min}$)

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Angular Scales — A Proposal Tip!

Interferometers act as spatial filters - shorter baselines are sensitive to larger targets

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Config.									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.735	0.52	0.389
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C-2	θ_{res} (arcsec)	2.30	1.53	1.24	0.999	0.666	0.499	0.353	0.264
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.9	3.47	2.59
C-3	θ_{res} (arcsec)	1.42	0.943	0.765	0.615	0.41	0.308	0.218	0.163
	θ_{MRS} (arcsec)	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C-4	θ_{res} (arcsec)	0.918	0.612	0.496	0.399	0.266	0.2	0.141	0.106
	θ_{MRS} (arcsec)	11.2	7.5	6.08	4.89	3.26	2.44	1.73	1.29
C-5	θ_{res} (arcsec)	0.545	0.363	0.295	0.237	0.158	0.118	0.0838	0.0626
	θ_{MRS} (arcsec)	6.7	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C-6	θ_{res} (arcsec)	0.306	0.204	0.165	0.133	0.0887	0.0665	0.0471	0.0352
	θ_{MRS} (arcsec)	4.11	2.74	2.22	1.78	1.19	0.892	0.632	0.472
C-7	θ_{res} (arcsec)	0.211	0.141	0.114	0.0917	0.0612	0.0459	0.0325	0.0243
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From the ALMA Cycle 8 Proposal Guide

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θ_{MRS}: maximum resolvable scale

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Angular Scales — A Proposal Tip!

Interferometers act as spatial filters - shorter baselines are sensitive to larger targets, so remember …

θ_{MRS}: maximum resolvable scale

θ_{res}: limiting resolution

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From the ALMA Cycle 8 Proposal Guide

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i.e. Configuration C-4, Band 6

θ_{res}: 0.399"

θ_{MRS}: 4.89"

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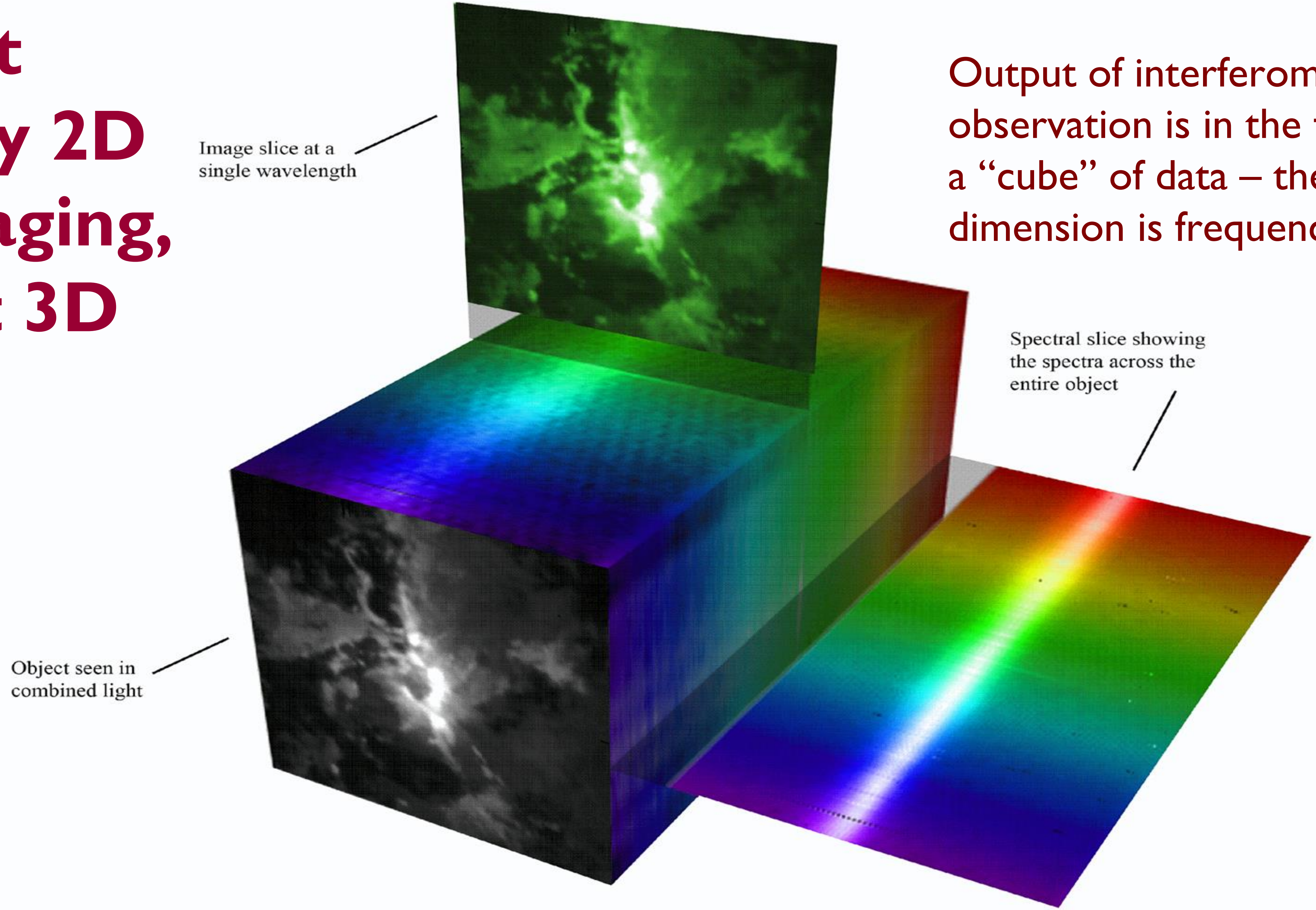
From the ALMA Cycle 8 Proposal Guide

Not only 2D imaging, but 3D

Output of interferometric observation is in the form of a "cube" of data – the third dimension is frequency.



Signed, Sealed, Delivered (Data by ALMA)

- Data delivered after passing Quality Assurance (QA)
- Download data from *Archive Query* and *Request Handler* tools on the ALMA Science Portal
- Delivered data include:
    - Fully calibrated data ("Measurement Set")
    - Calibration tables and diagnostics
    - Preliminary images (better products may be possible with more careful continuum identification & cleaning)

See Sections 11, 12, 14, and Appendix C of ALMA Technical Handbook for details

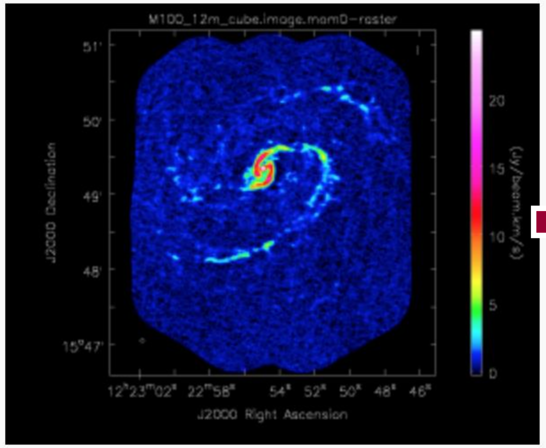
Summary of takeaways

1. ***Tune* your telescope frequency range depending on your science targets.**

- ALMA bands 3-10 span ~84-950 GHz (~3.5-0.3 mm)

2. **Choose the ALMA configuration based on the angular resolution that you would like to achieve in your observations.**

- Maximum resolvable scale set by the smallest baseline (θ_{MRS} limiting)
- Angular resolution set by the largest baseline (θ_{res} limiting)



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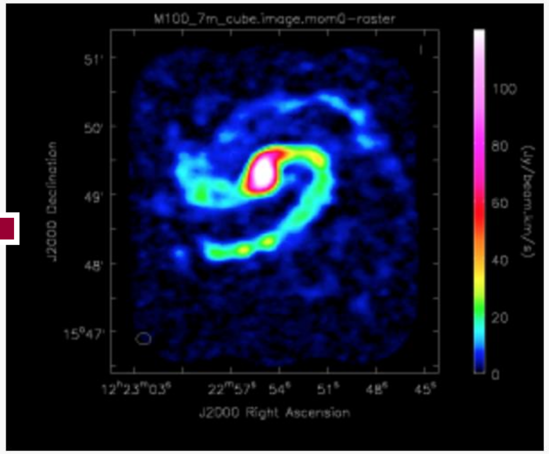

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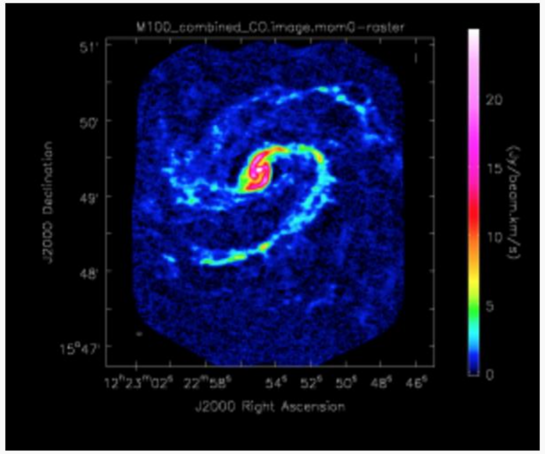

Good Future References

Thompson, A.R., Moran, J.M., Swensen, G.W. 2017 "Interferometry and Synthesis in Radio Astronomy", 3rd edition (Springer)

http://www.springer.com/us/book/9783319444291

Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 "Synthesis Imaging in Radio Astronomy" (San Francisco: ASP)

www.aoc.nrao.edu/events/synthesis

IRAM Interferometry School proceedings

www.iram.fr/IRAMFR/IS/IS2008/archive.html

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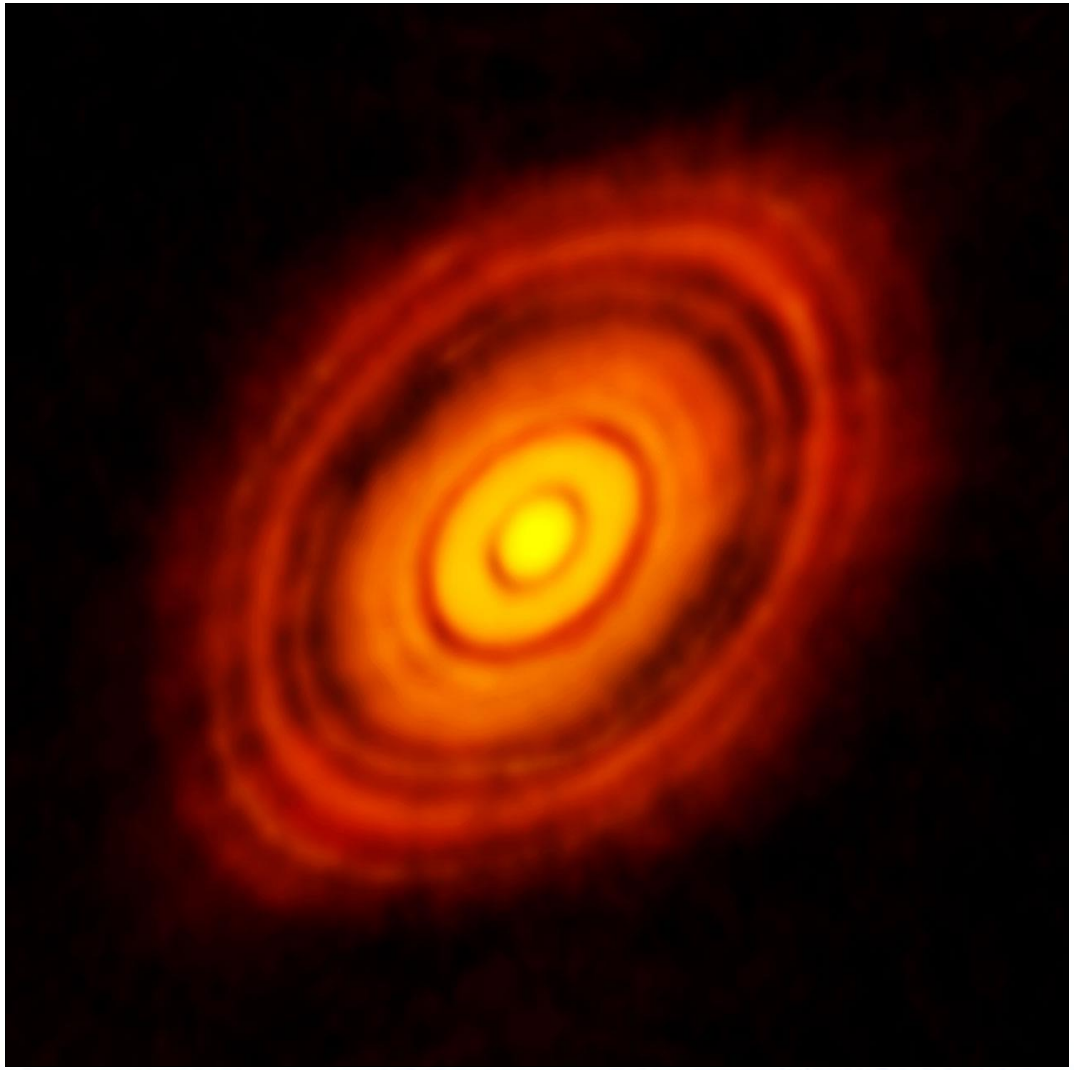
Extras

What can you observe?

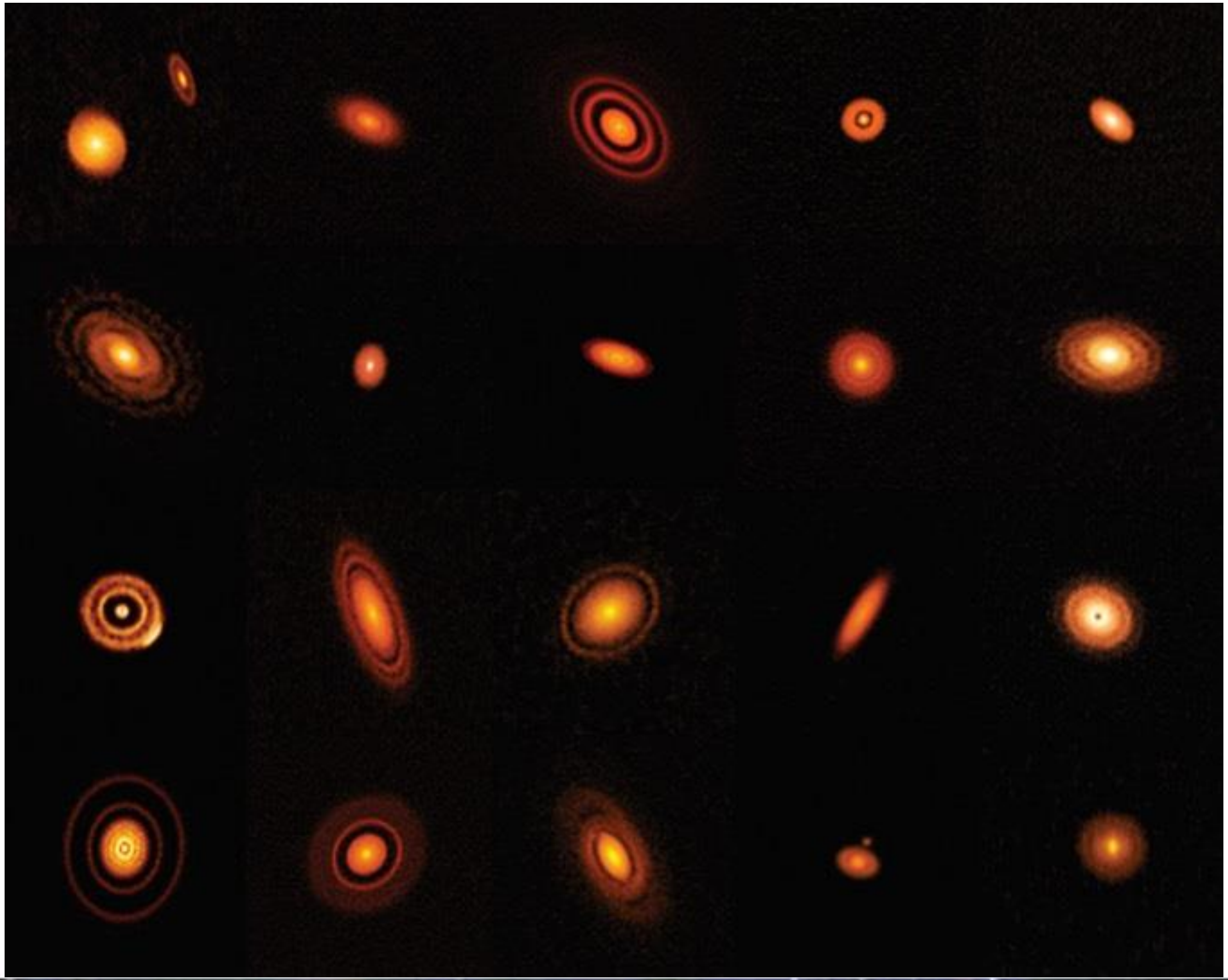
Protoplanetary discs like this one around HL Tauri!



Credit: ALMA (NRAO/ESO/NAOJ)

What can you observe?

A Protoplanetary Zoo!



Credit: ALMA (NRAO/ESO/NAOJ)

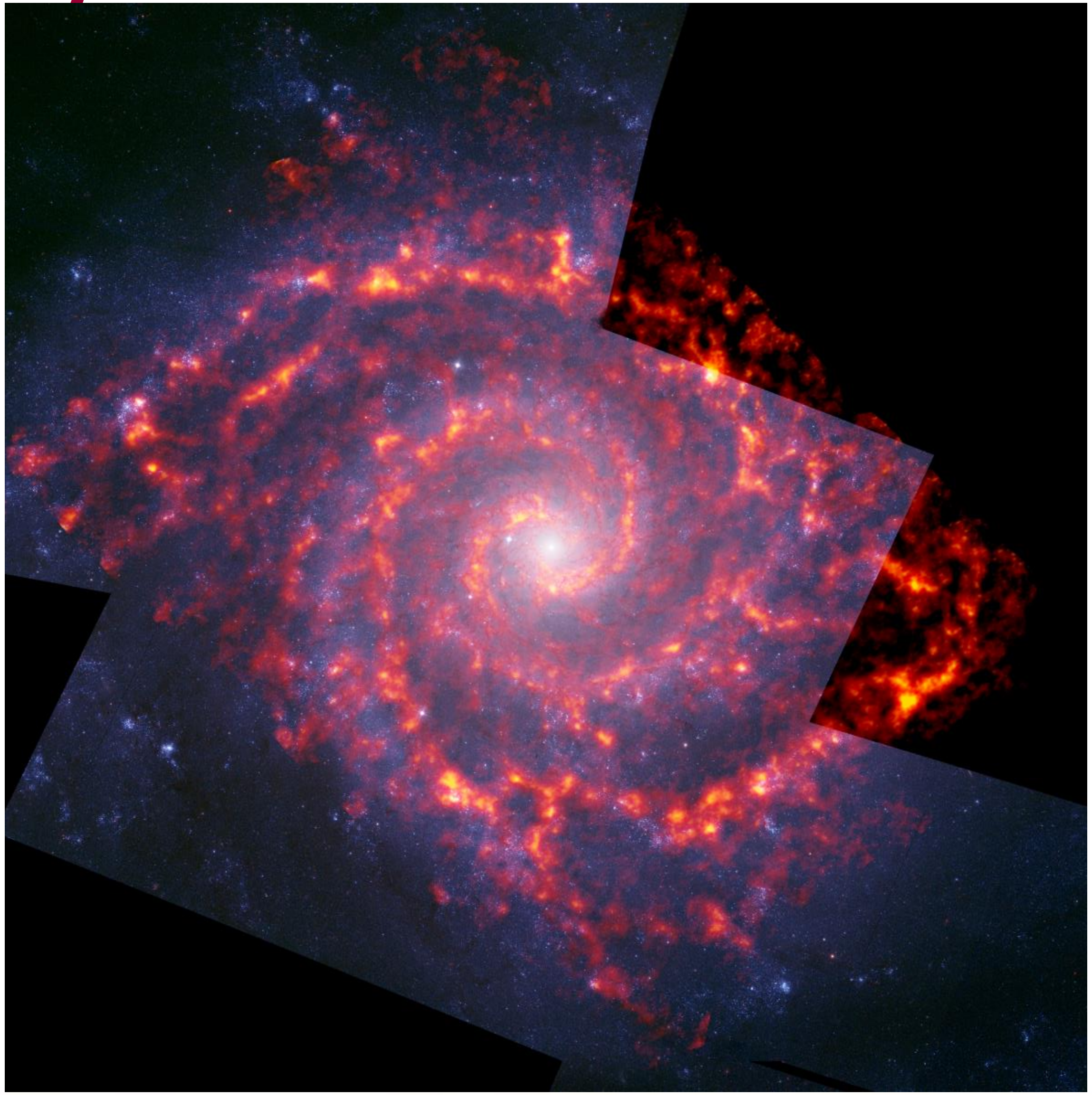
What can you observe?

A Star, Sprinkled with Salt

Credit: NRAO/AUI/NSF; S. Dagnello

What can you observe?

Star-forming clouds in NGC 628



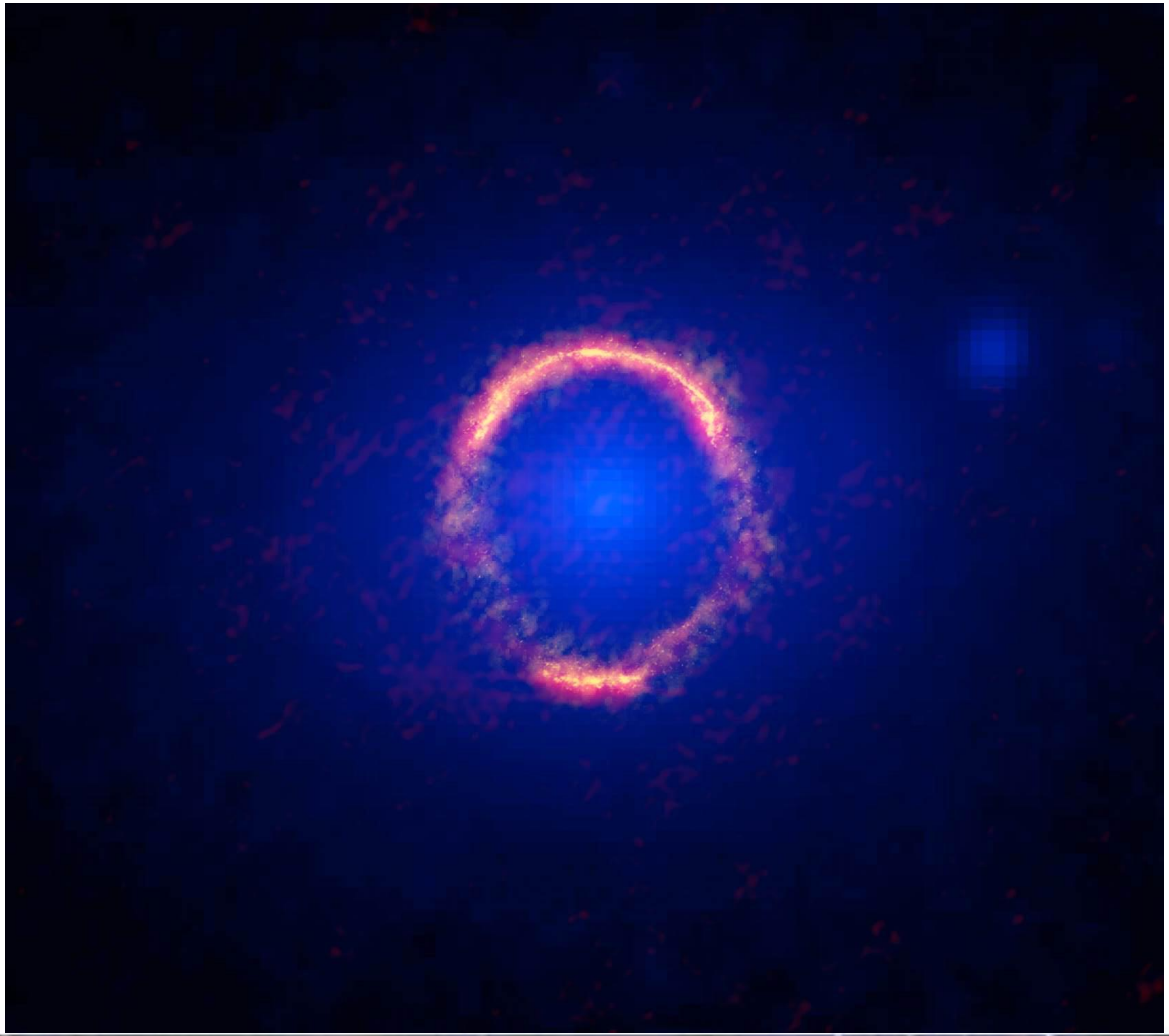
Credit: NRAO/AUI/NSF; B. Saxton

What can you observe?

We can observe a broad range of molecular lines

What can we observe?

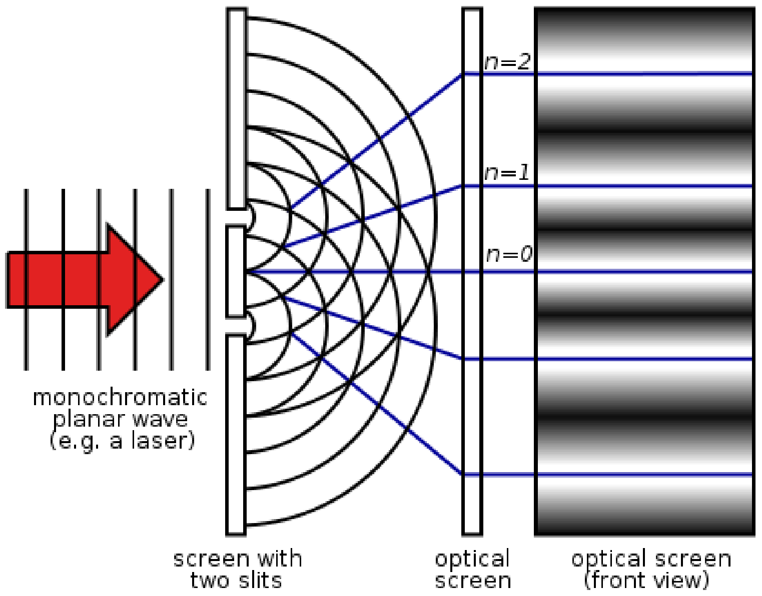
Gravitational lensing of high-z galaxies



Credit: ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF; NASA/ESA Hubble, T. Hunter (NRAO).

What is an interferometer?

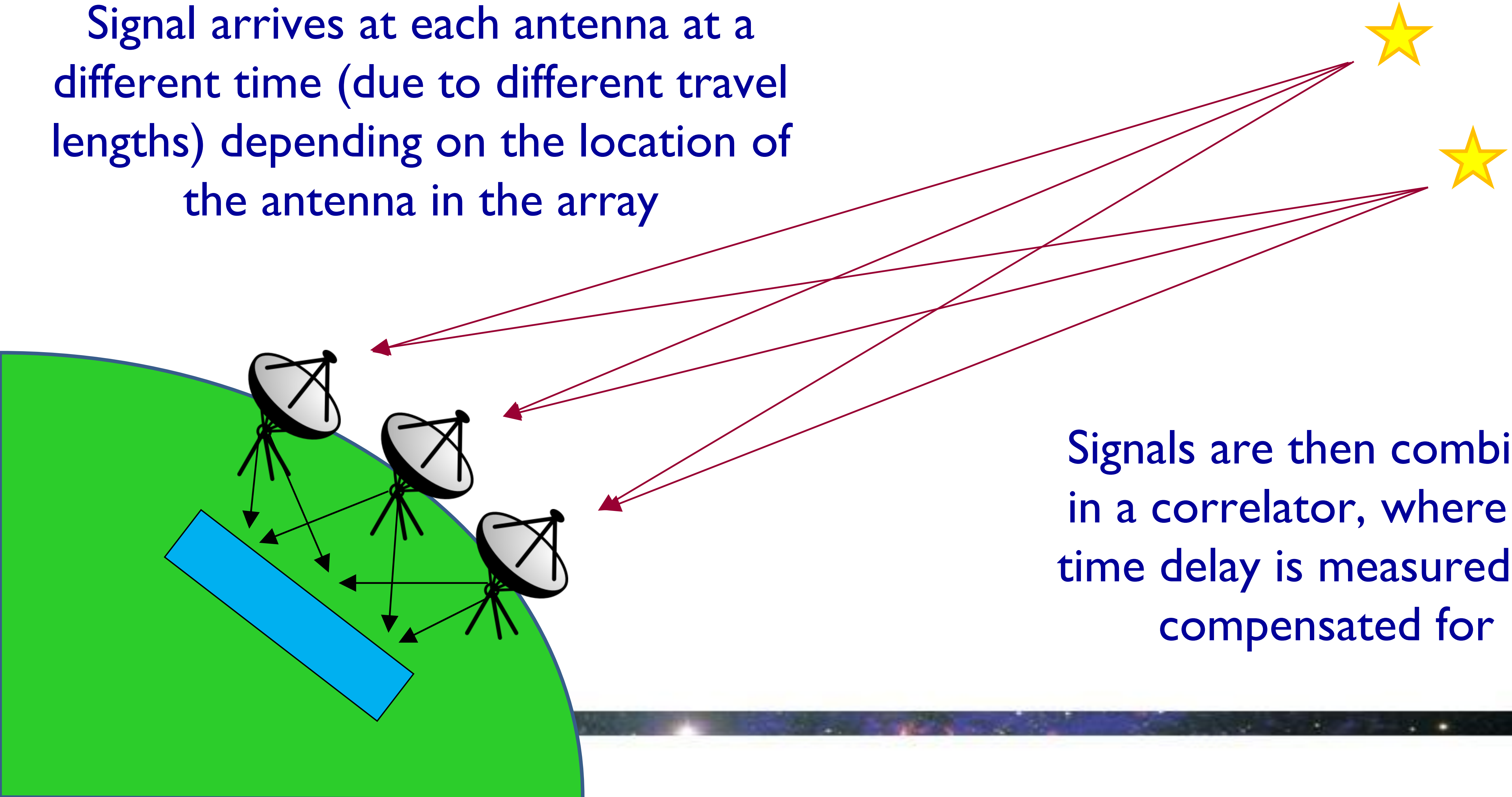
An *interferometer* measures the interference pattern produced by multiple apertures, much like a 2-slit experiment



***However, the interference patterns measured by radio telescopes are produced by *multiplying* - not adding - the wave signals measured at the different telescopes (i.e. apertures)**

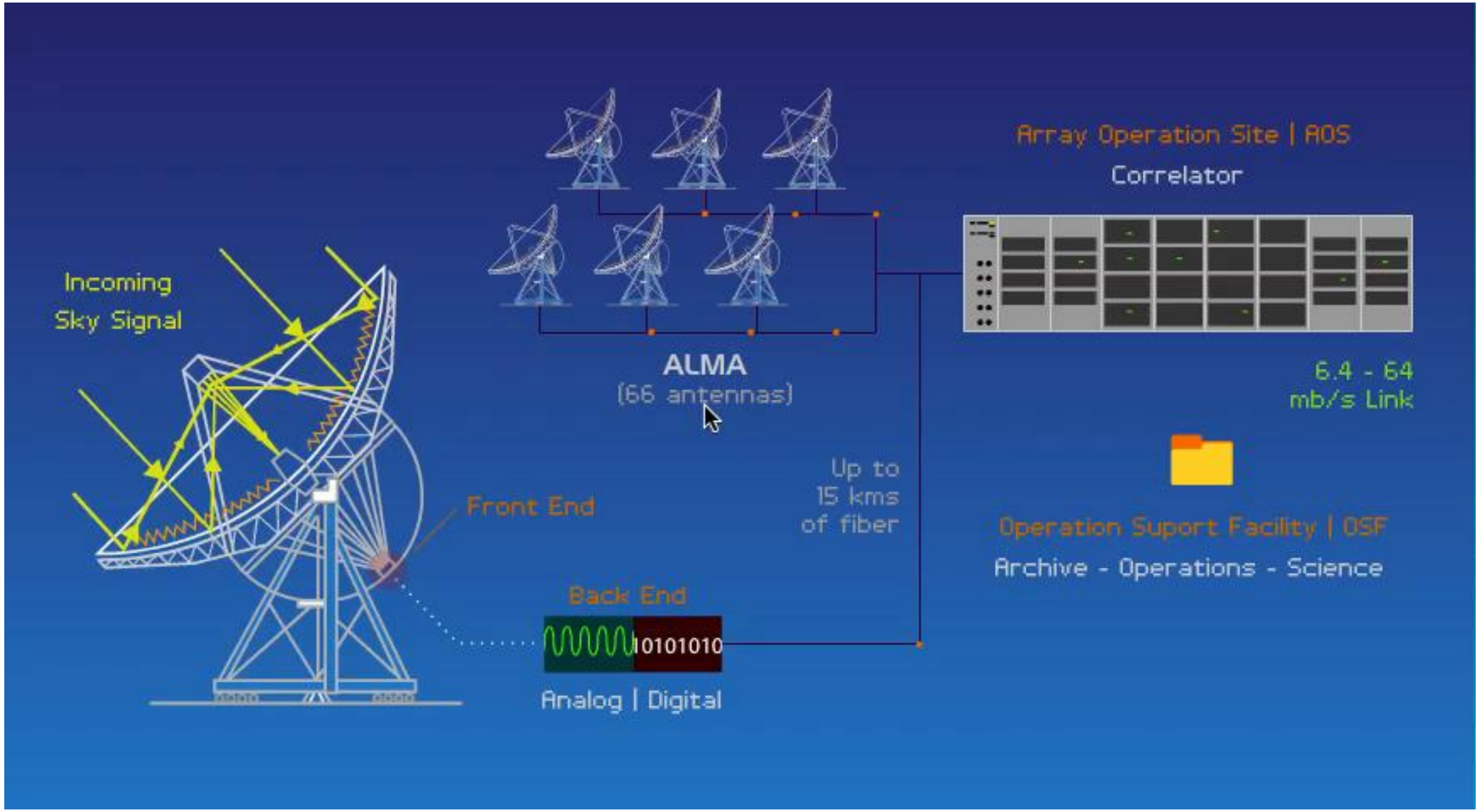
How Do We Use Interferometry?

Signal arrives at each antenna at a different time (due to different travel lengths) depending on the location of the antenna in the array



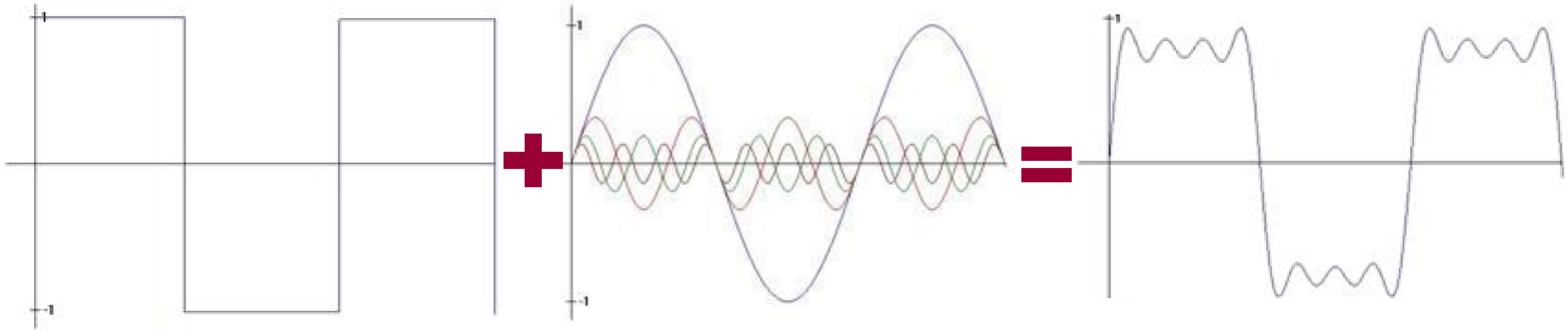
Signals are then combined in a correlator, where the time delay is measured and compensated for

An Interferometer In Action



Introducing the Fourier Transform

Fourier theory states that any well behaved signal (including images) can be expressed as the sum of sinusoids



Reference signal

4 sinusoids

Sum of sinusoids & signal

The Fourier transform is the mathematical tool that decomposes a signal into its sinusoidal components

The Fourier transform contains *all* of the information of the original signal

Visibility and Sky Brightness

The van Cittert-Zernike theorem

Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)

$$V(u,v) \xrightarrow{\textbf{FT}} T(x,y)$$

V(u,v) = the complex visibility function = $\iint T(x,y)e^{2\pi i(ux+vy)}dxdy$

T(x,y) = the sky brightness distribution = $\iint V(u,v)e^{-2\pi i(ux+vy)}dudv$

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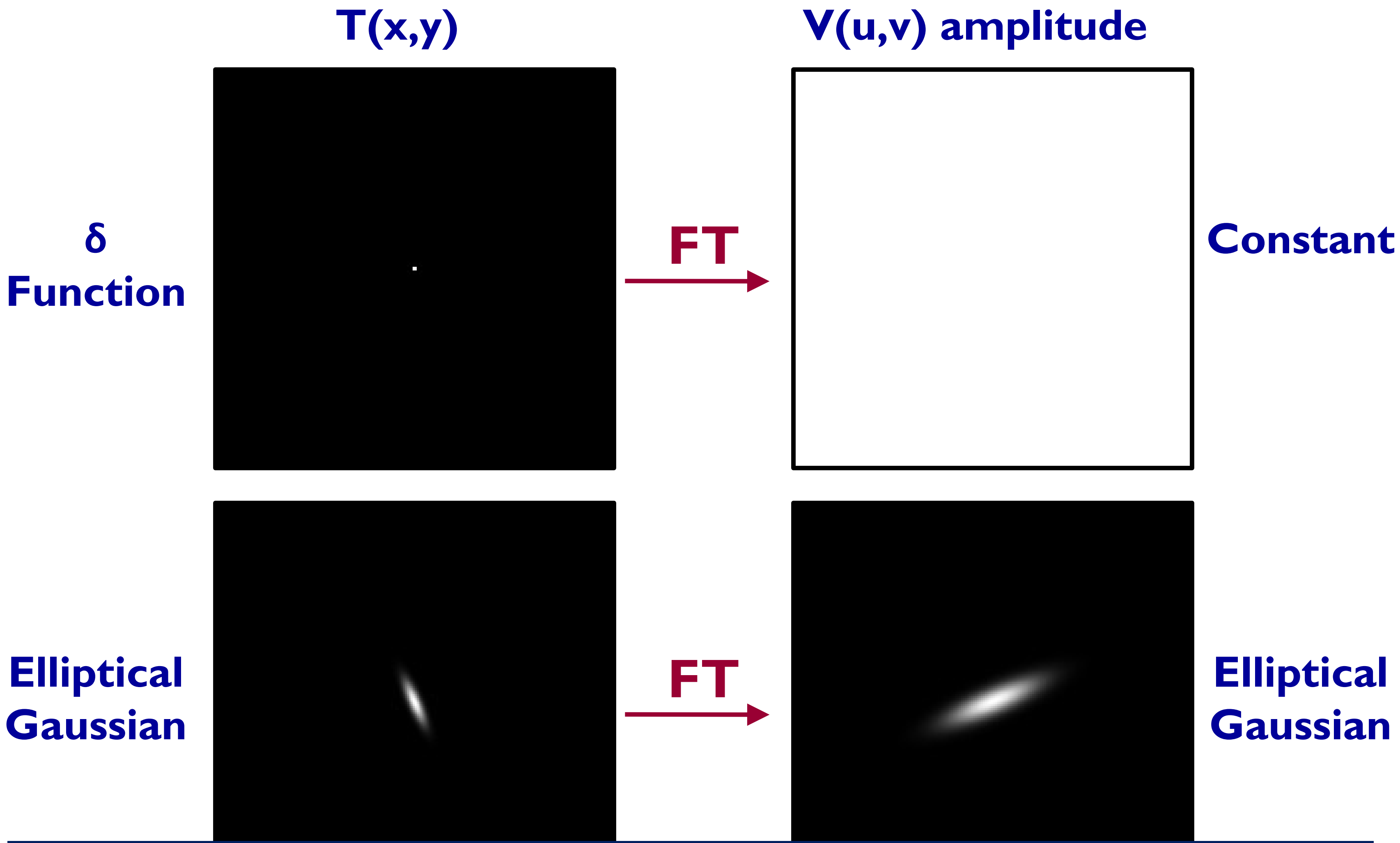
Examples of 2D Fourier Transforms



Rules of the Fourier Transform:

Narrow features transform to wide features (and vice versa)

Calibration Process

Calibration is *the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations.*

Steps in calibrating interferometric data:

1. Bandpass calibration (correct frequency-dependent telescope response)
2. Phase and amplitude gain calibration (remove effects of atmospheric water vapor and correct time-varying phases/amplitudes)
3. Set absolute flux scale

(Note: You don't have to worry about these in your observational set up!)

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A Brief Word on Calibration

Calibration requirements (Handled by ALMA):

Phase calibrator
Bright quasar near science target
Solves for atmospheric and instrumental variations with time

Bandpass calibrator
Bright quasar
Fixes instrumental effects and variations vs frequency

Absolute flux calibrator
Solar system object or quasar
Used to scale relative amplitudes to absolute value