Introduction to the basic concepts and terminology of radio interferometry

ALMA

EUROPEAN ARC
ALMA Regional Centre || Germany

universitätbonn

Universität zu Köln

Álvaro Sánchez-Monge

German ARC node – April 2018

Outline

Part 1

- Introduction to aperture synthesis
- Interferometers: spatial filters

Part 2

- An overview to the correlator and spectral receivers
- Interferometers: spectral setup

Part 1:

aperture synthesis, spatial filters

German ARC node

Key concepts to learn

Part 1

- Interferometer
- Baseline
- Primary beam
- Synthesized beam
- Largest angular scale

Telescopes … vs Radiotelescopes

Il “cannocchiale” di Galileo

Galileo Galilei

Telescopes … vs Radiotelesc

Where should I put the eye?

Il ***NUOVO*** “cannoccihale” di Galileo

Galileo Galilei

Atacama Large Millimeter/submillimeter Array

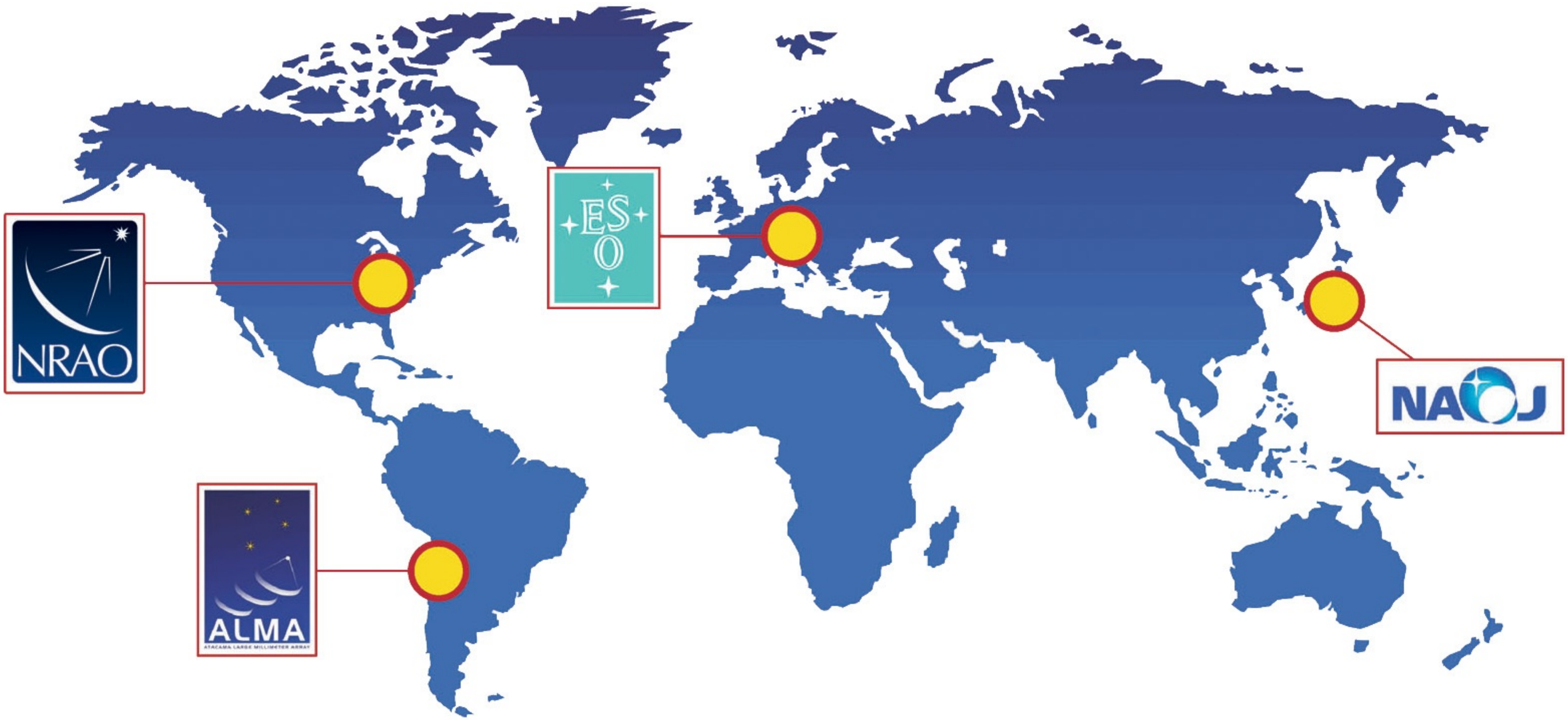
Where is ALMA?

Atacama desert (Chile)

... on the Chajnantor Plateau
at 5000 m height

... control center
at 2900 m height

What is ALMA?



International collaboration:

3 ARC (ALMA Regional Centers) + JAO (Joint ALMA Observatory)

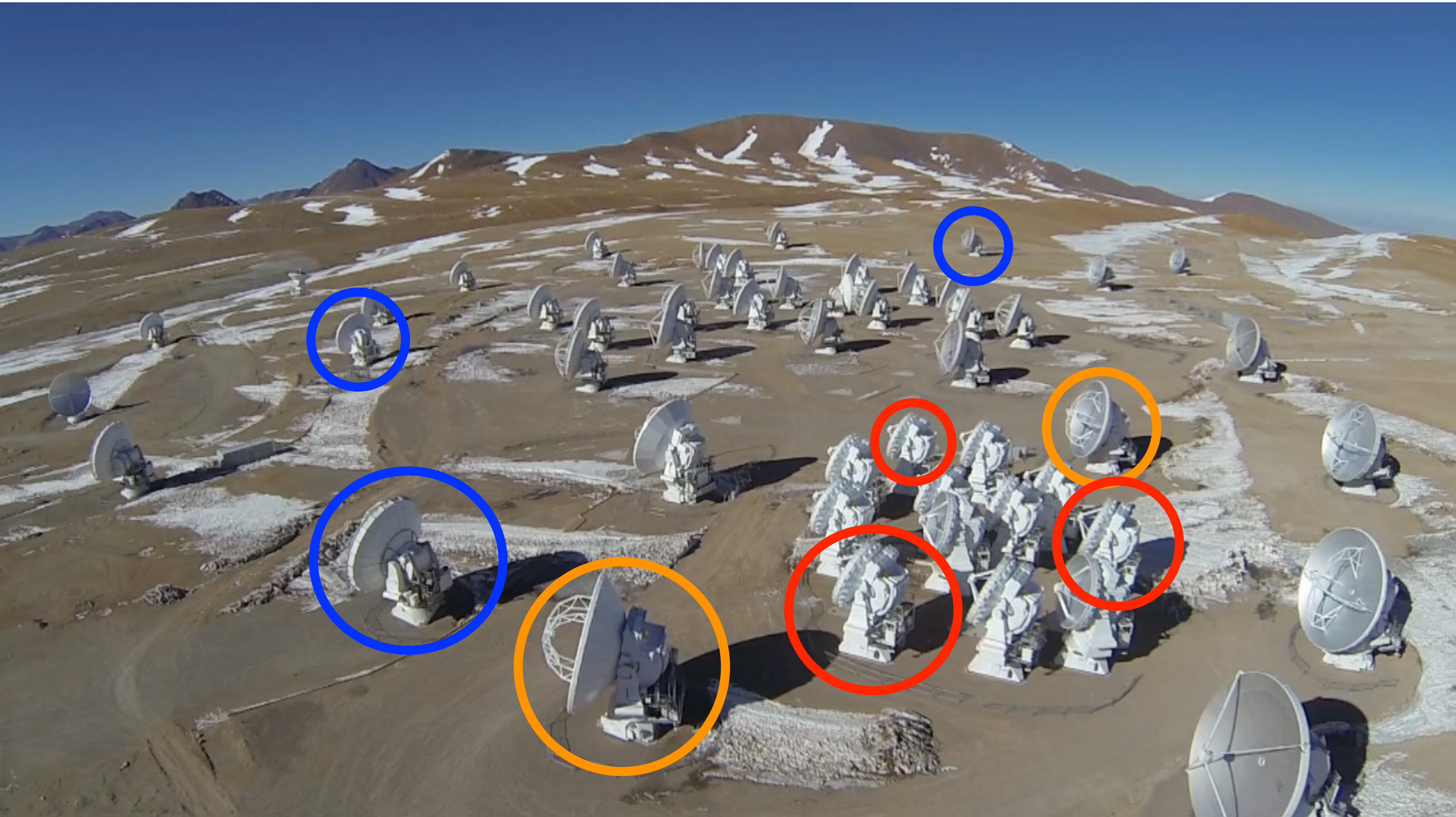
What is ALMA?

ALMA is …

What is ALMA?

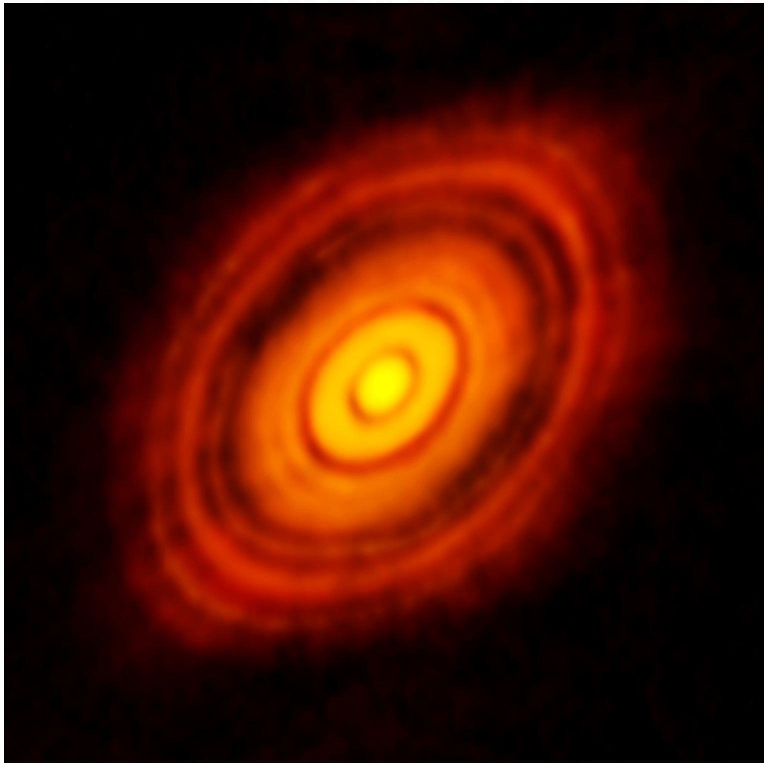
ALMA is ...

50x 12m antennas (main)
12x 7m antennas (ACA)
4x 12m antennas (TP)

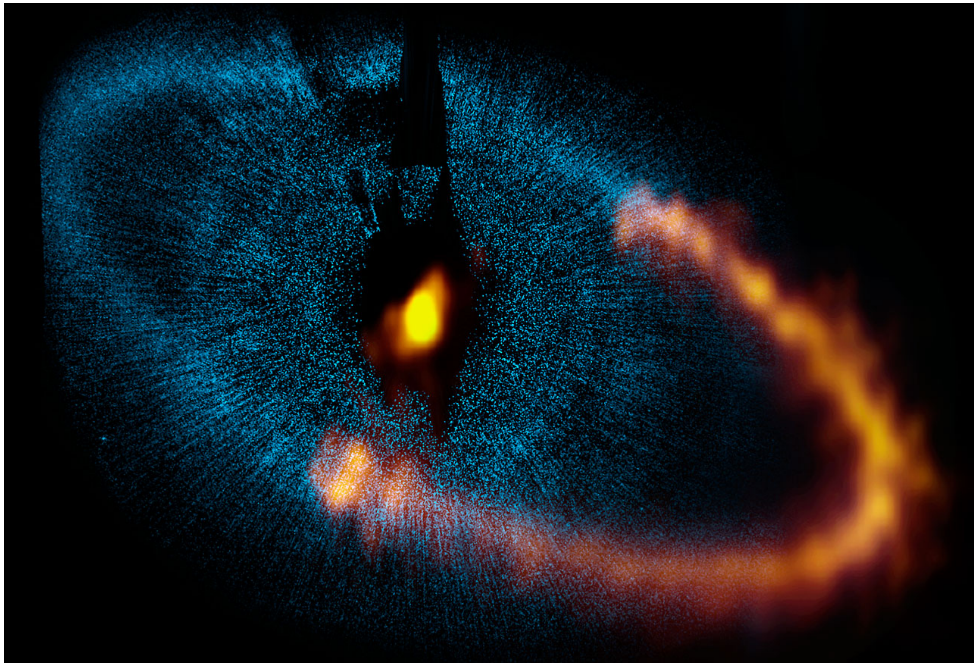


What can ALMA do?

HL Tau



Formalhaut

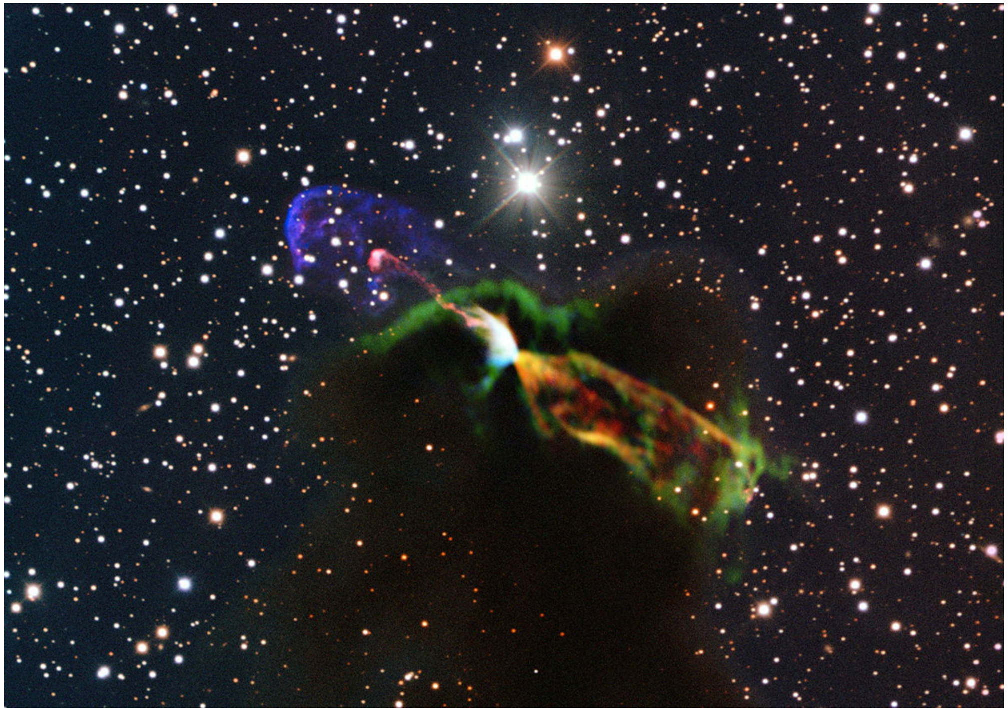


protoplanetary disks

debris disks

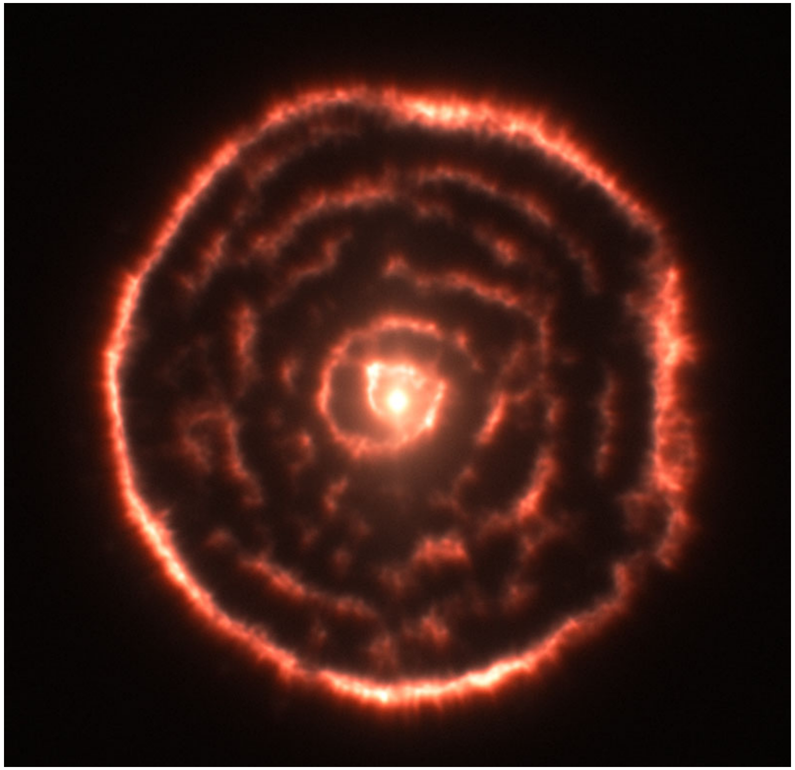
What can ALMA do?

Herbig-Haro 46/47



molecular outflows and jets

R Sculptoris



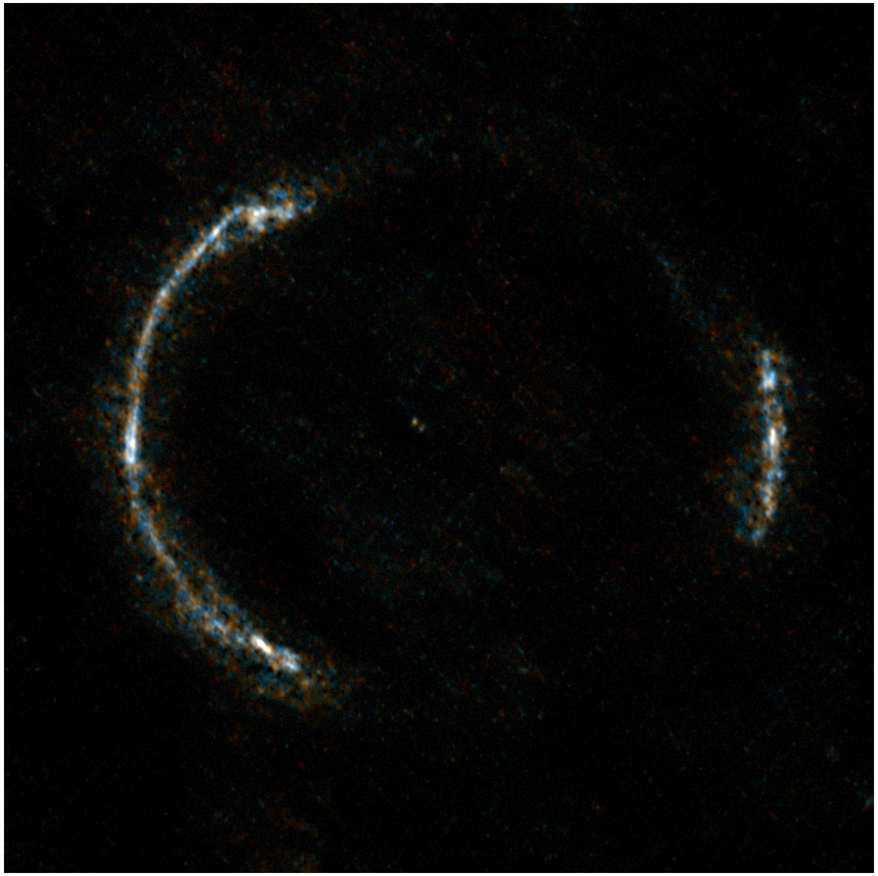
red giants and old stars

What can ALMA do?

Antennae galaxies

galaxy mergers

SPD.81

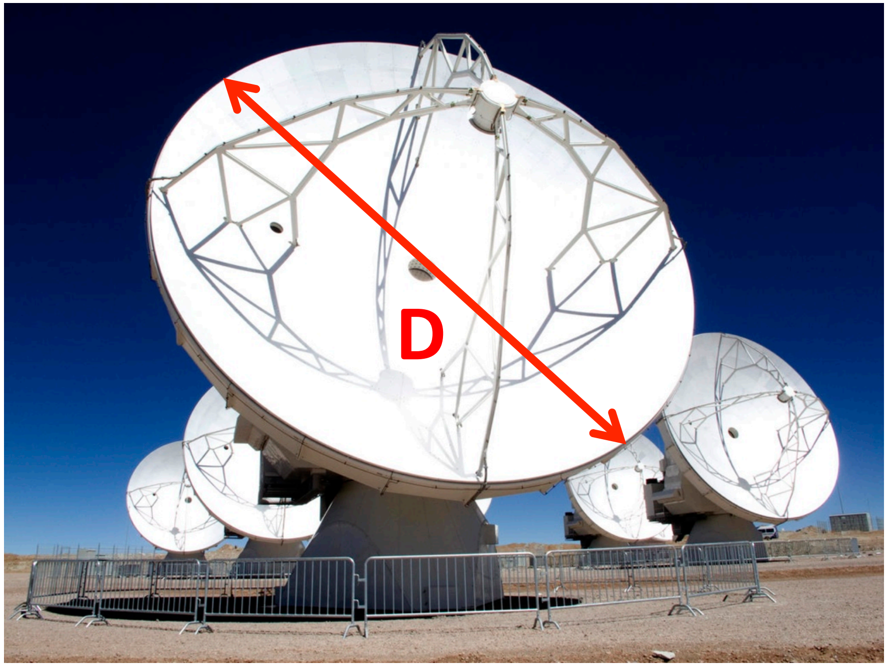


lensed galaxies

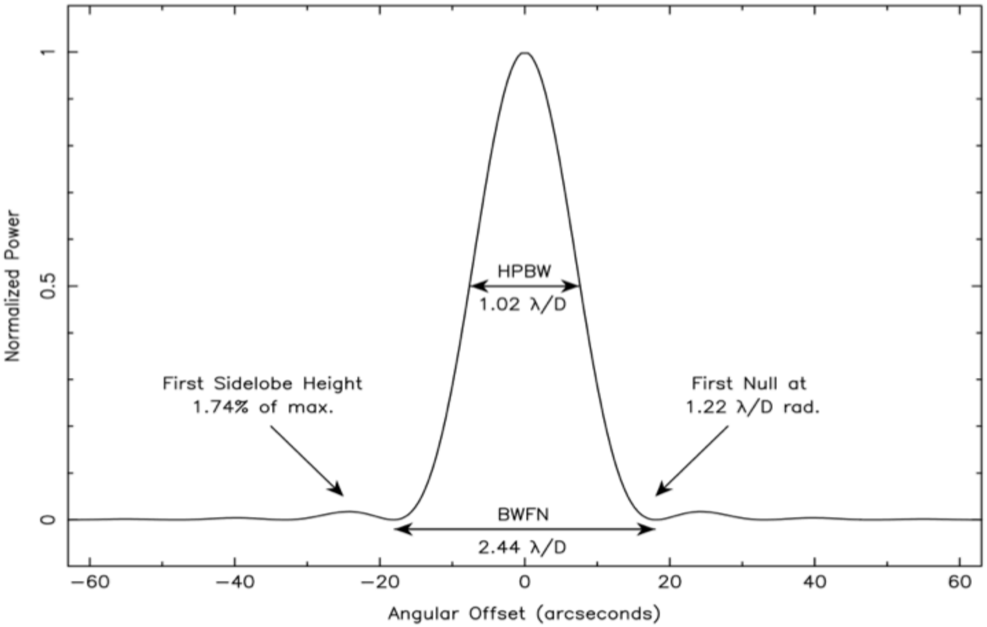
Why does ALMA need so many antennas?

… consider one single antenna (or single-dish)

Single-dish with diameter D



(1D) antenna power response



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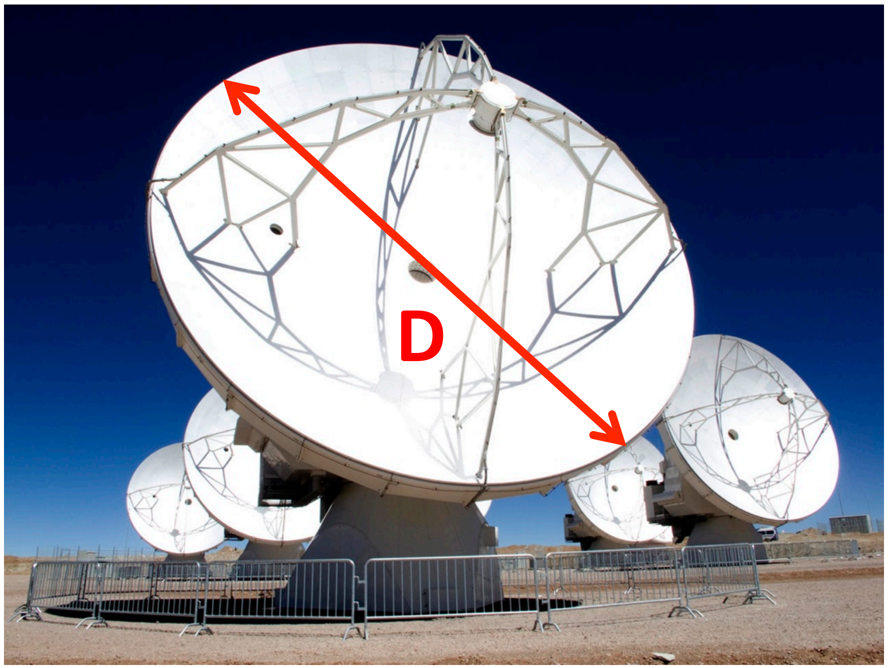
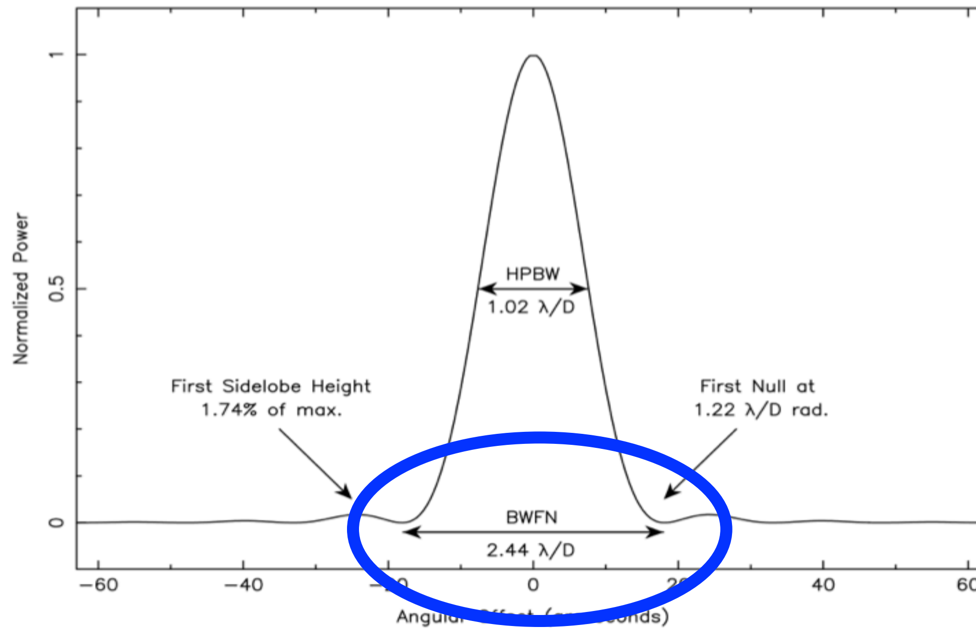
Single-dish with diameter D



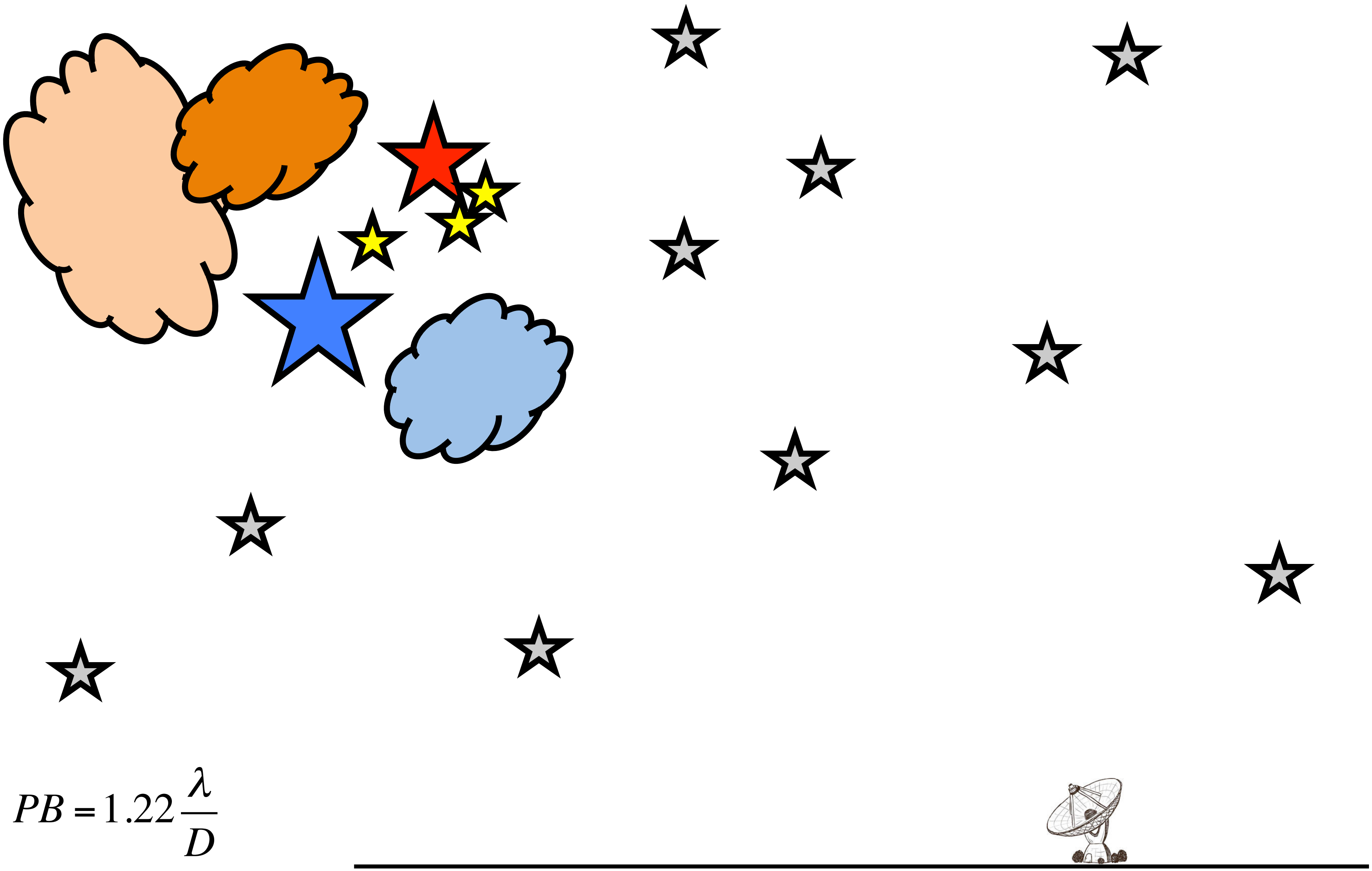
(1D) antenna power response



$$PB = 1.22\frac{\lambda}{D}$$

PRIMARY BEAM

Single-dish telescope



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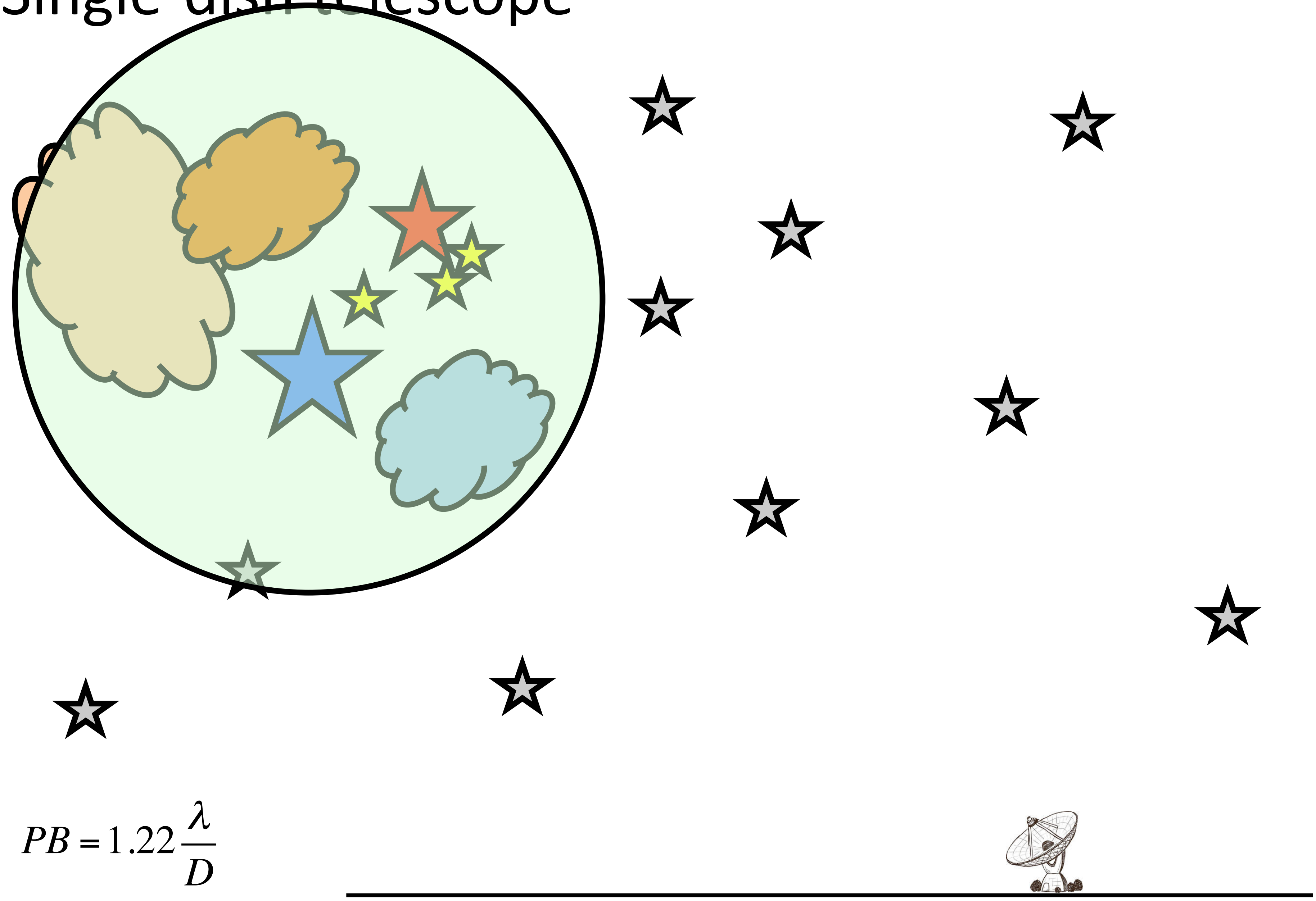
Single-dish telescope



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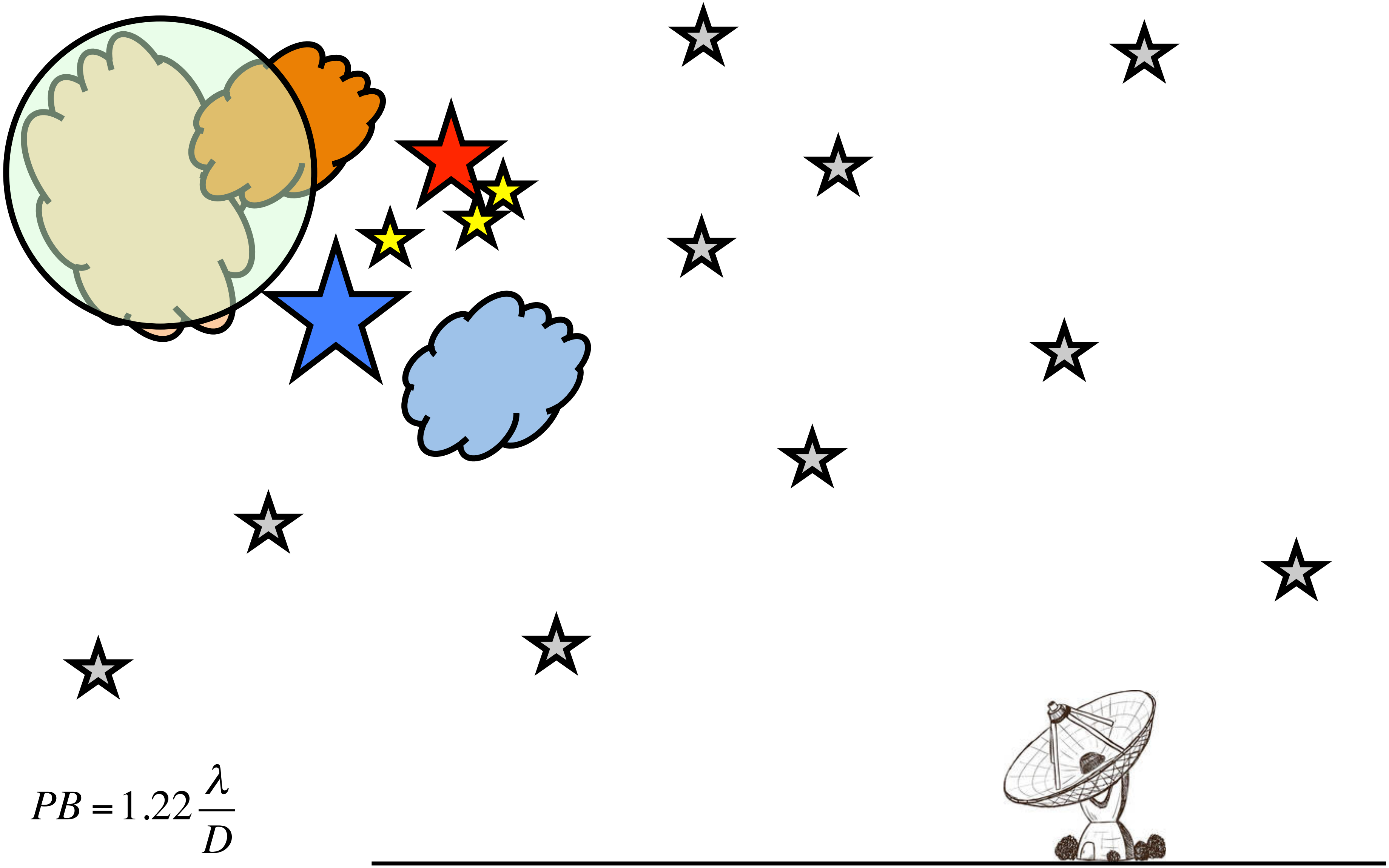
Single-dish telescope



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Single-dish telescope

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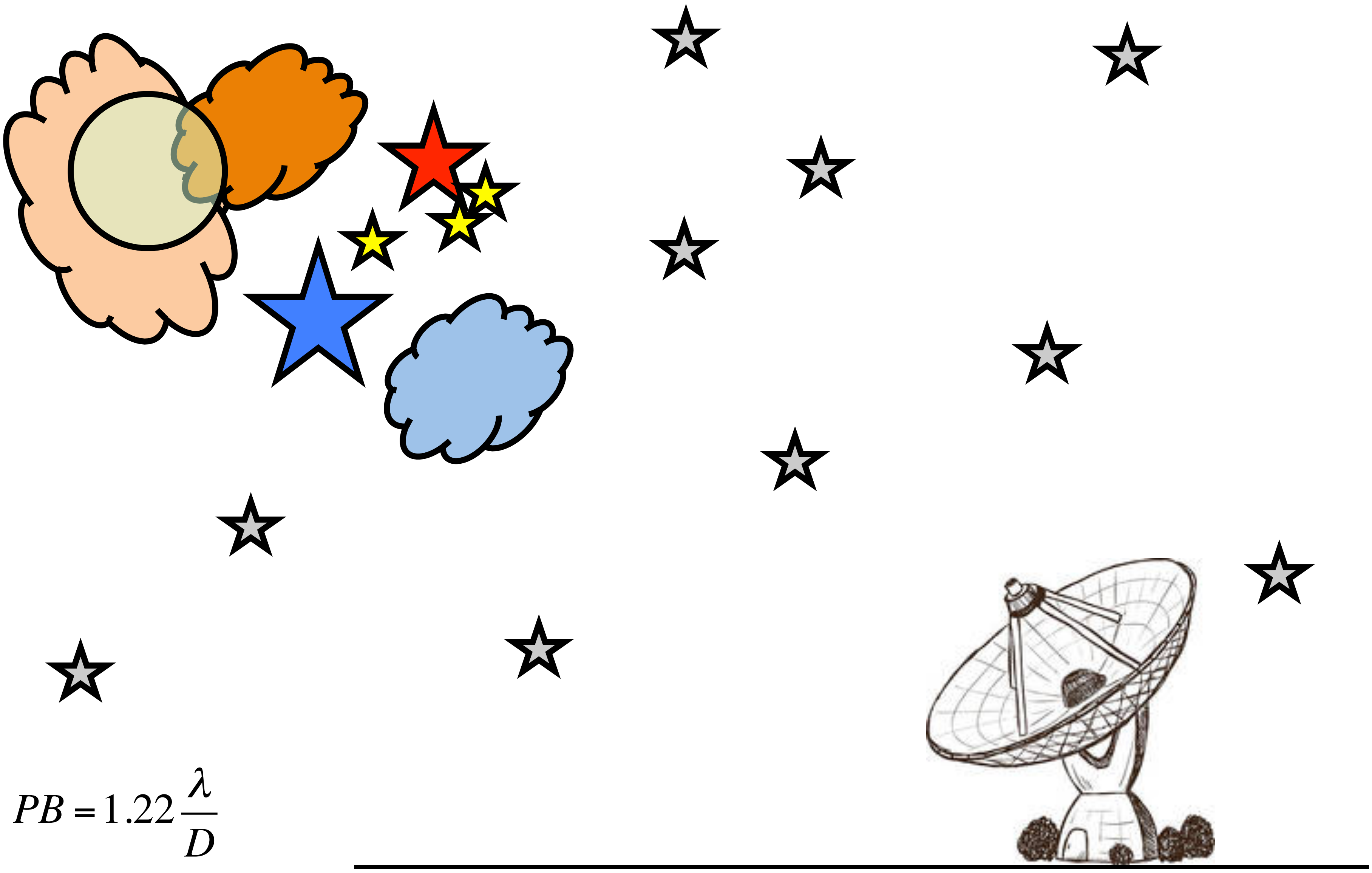

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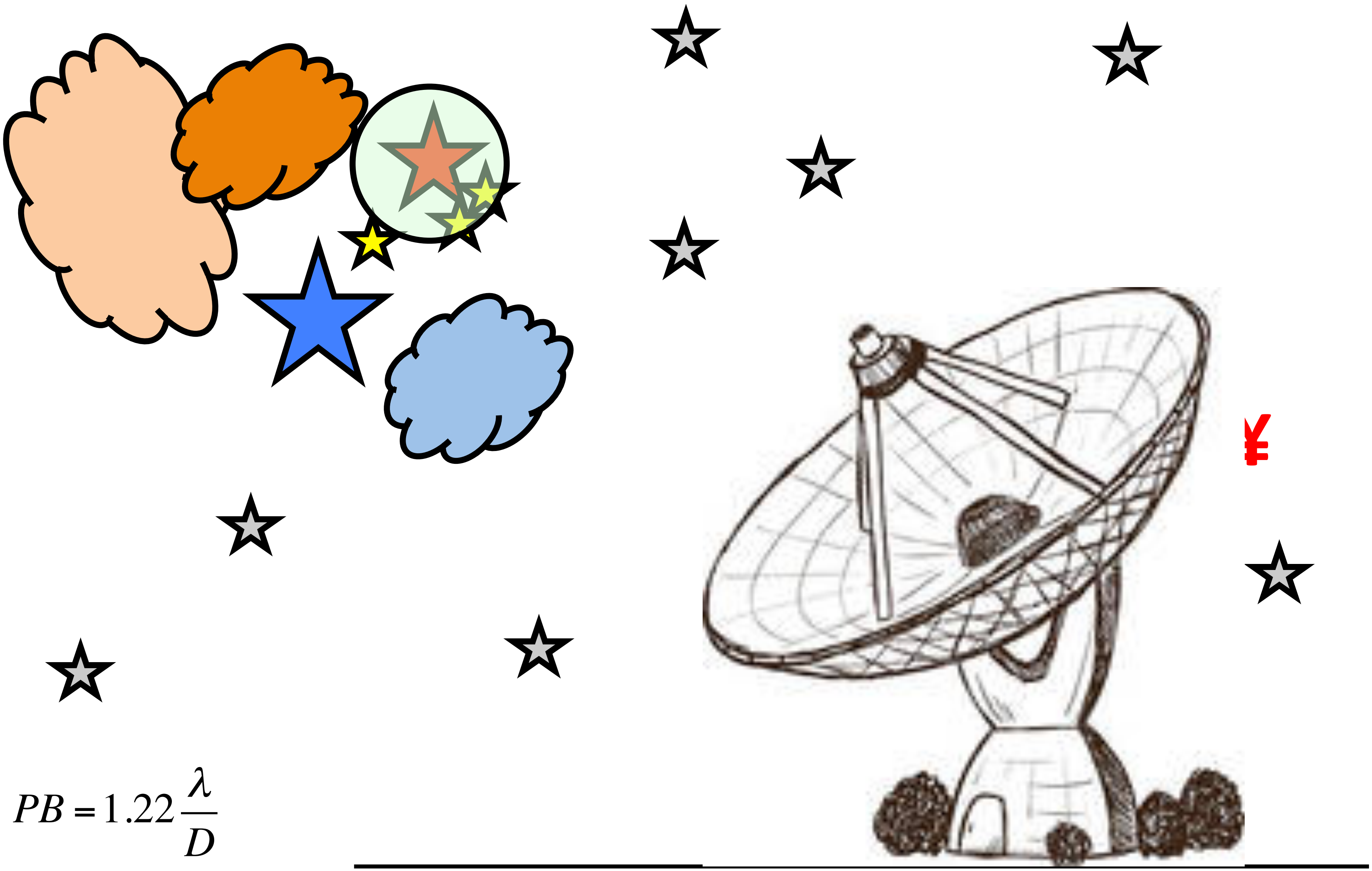
Single-dish telescope



$$PB = 1.22\frac{\lambda}{D}$$

Interferometer – multiple dishes

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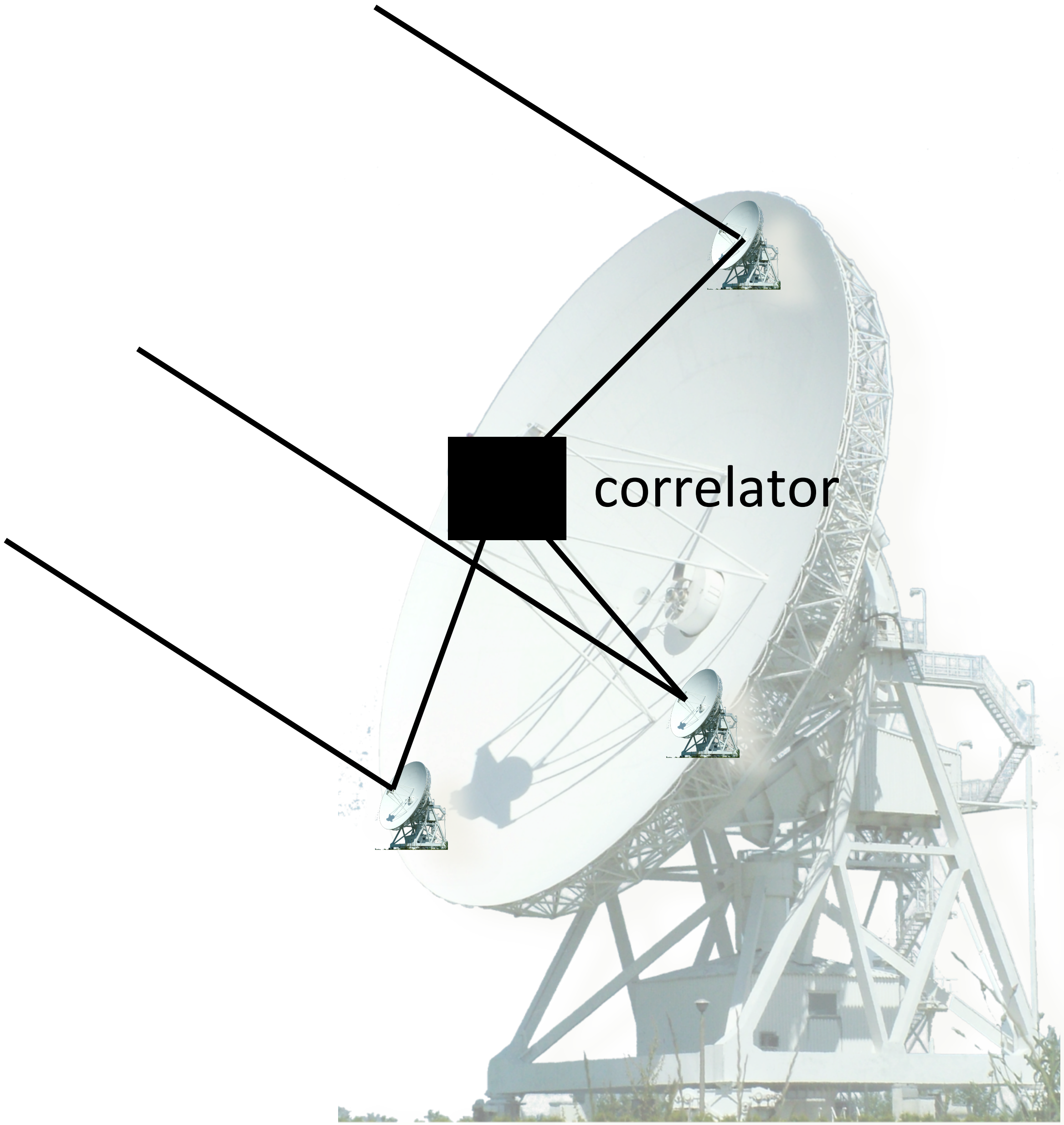
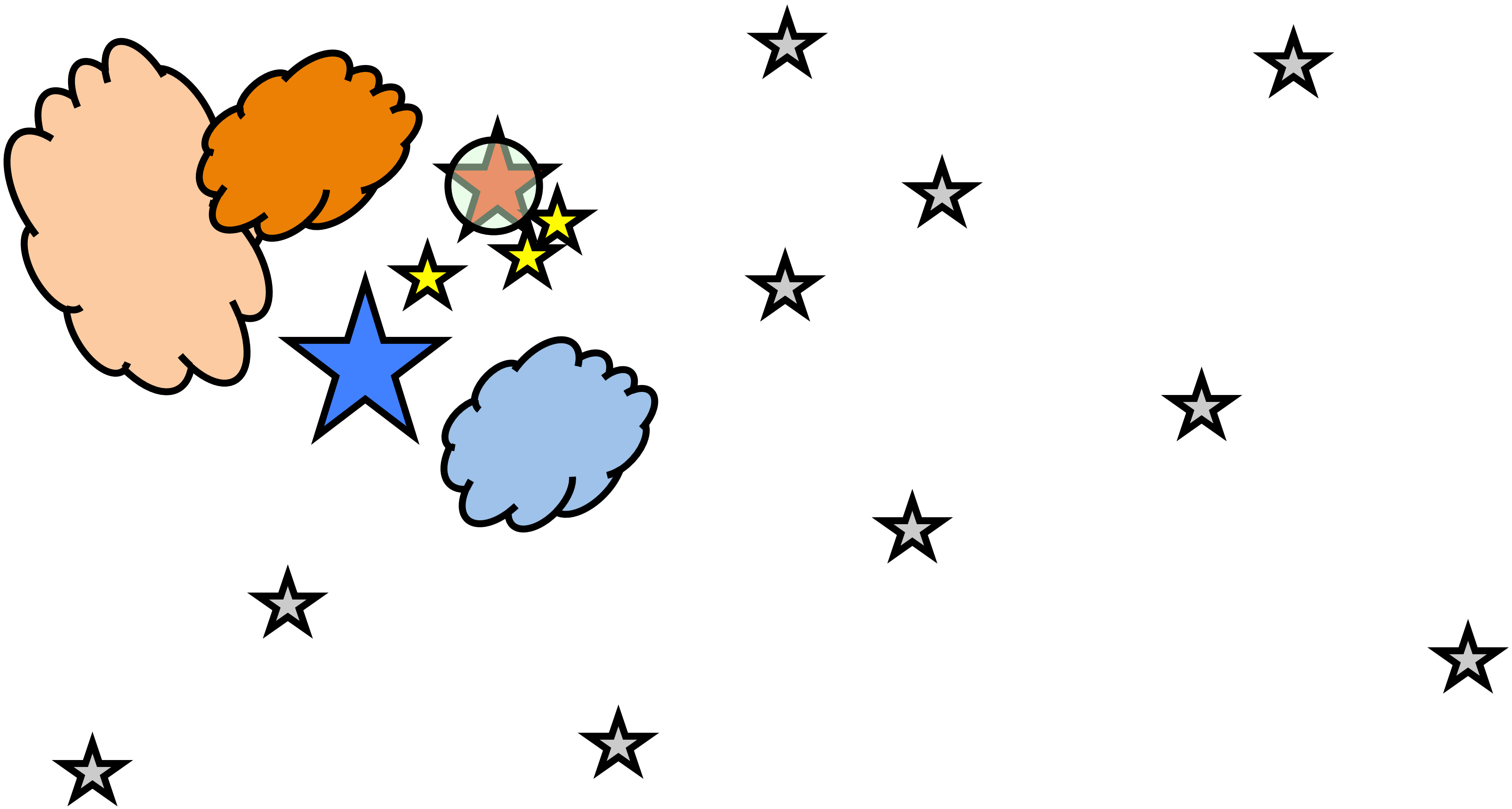


Interferometer – multiple dishes

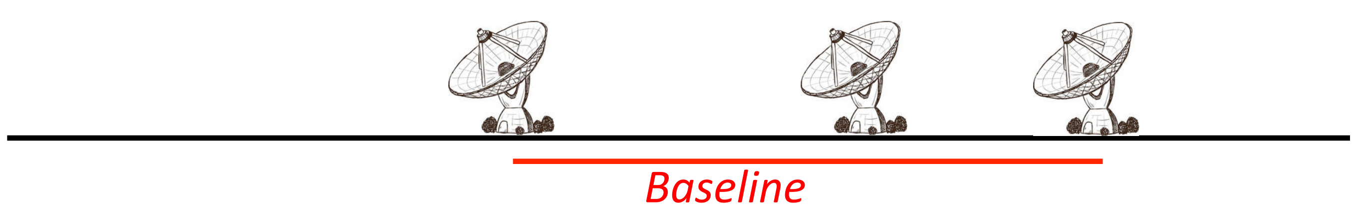
$$Beam = 1.22\frac{\lambda}{B}$$

$$PB = 1.22\frac{\lambda}{D}$$

Interferometer – multiple dishes



$$Beam = 1.22 \frac{\lambda}{B}$$



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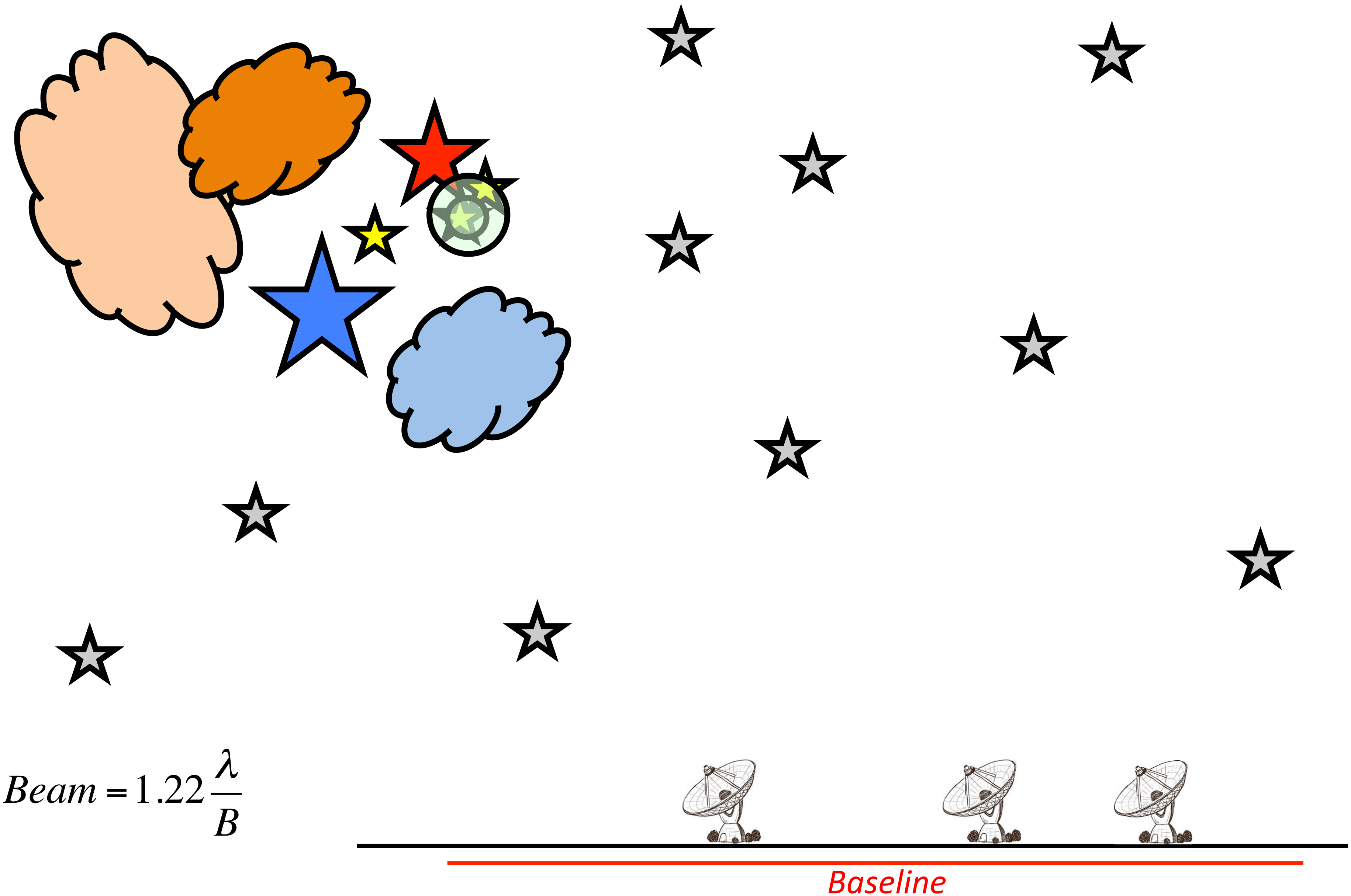
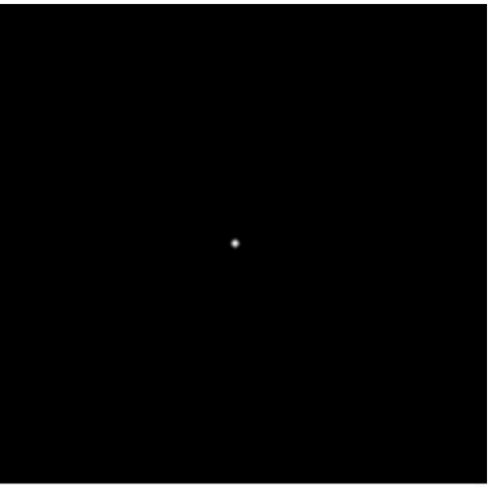
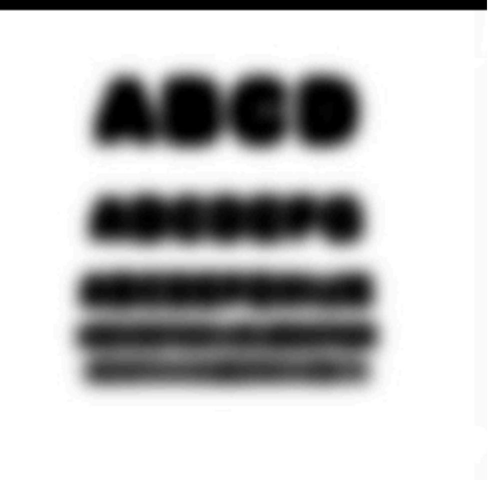


$$Beam = 1.22\frac{\lambda}{B}$$

Interferometer – multiple dishes

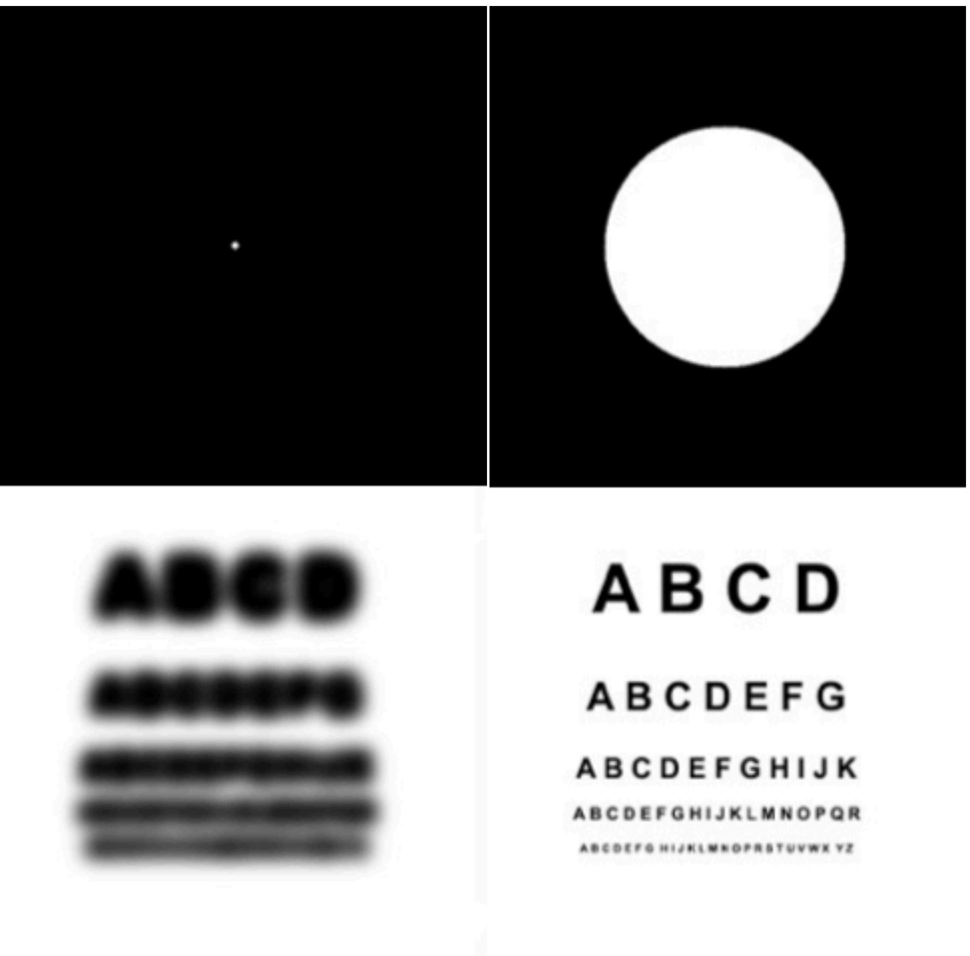
Small Single-Dish





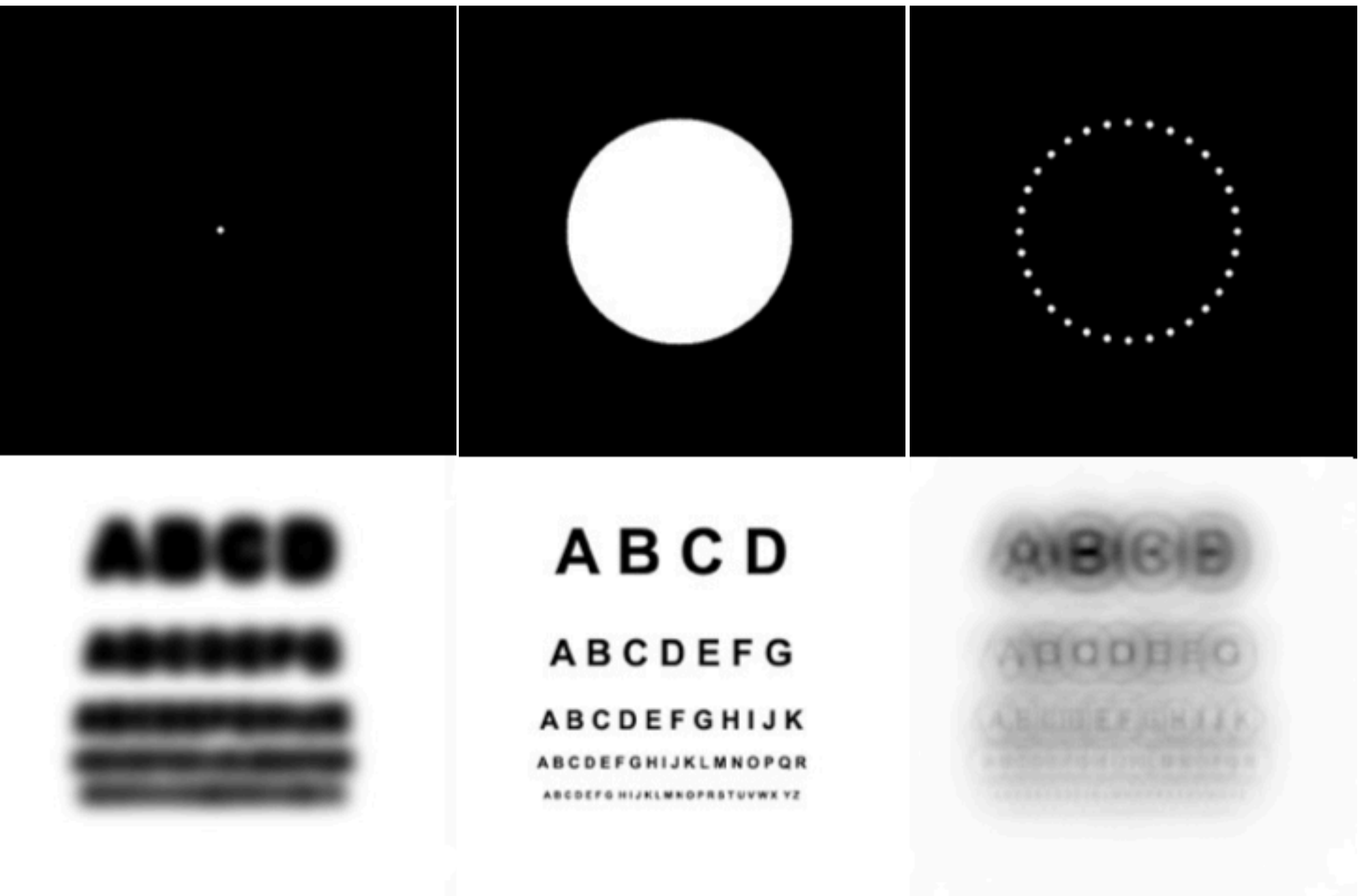
Interferometer – multiple dishes

Large Single-Dish



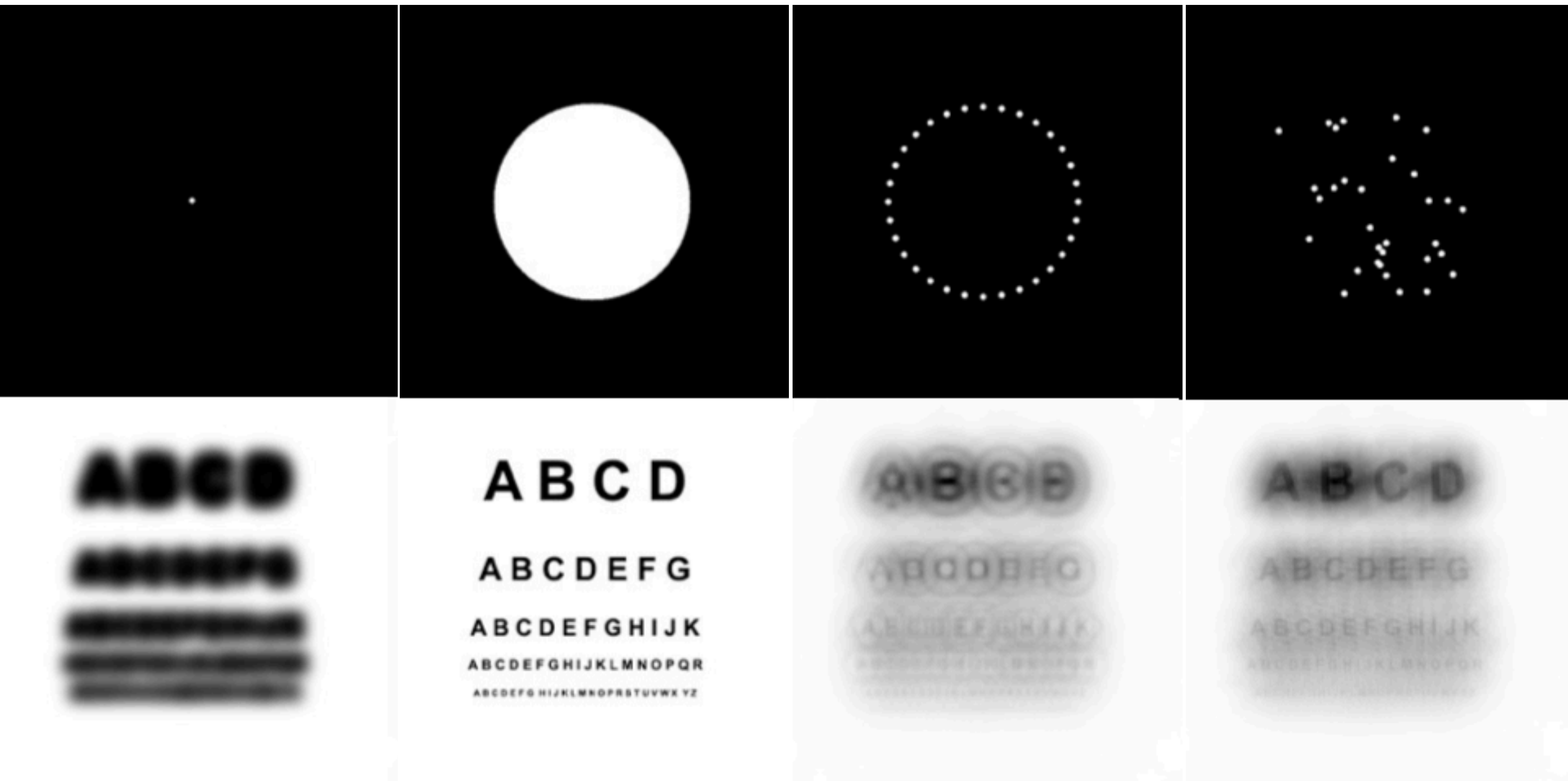
Interferometer – multiple dishes

“Circular” dishes



Interferometer – multiple dishes

"Random" dishes



Interferometers as spatial filters

… a bit of equations (Fourier Transform)

$$V(u,v) = \int\int I(l,m)\, e^{2\pi i(ul+vm)}\, dl\, dm$$

Interferometers as spatial filters

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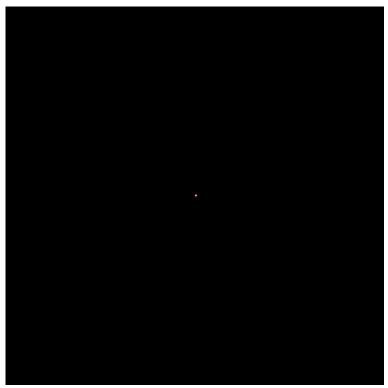
I (l,m)

V (u,v)

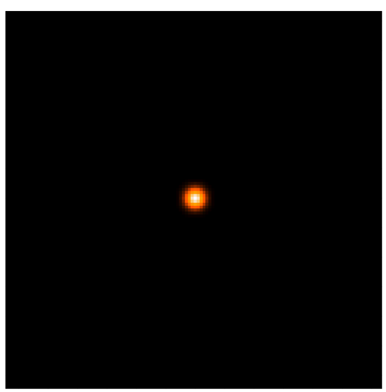
δ Function



⇌

Constant

Gaussian



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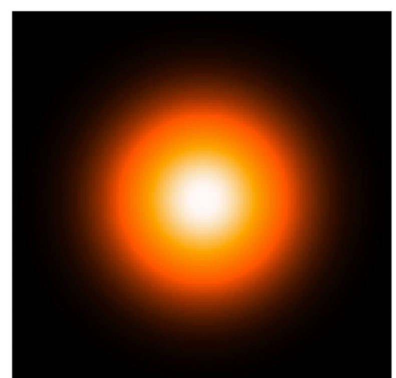


Gaussian

Interferometers as spatial filters

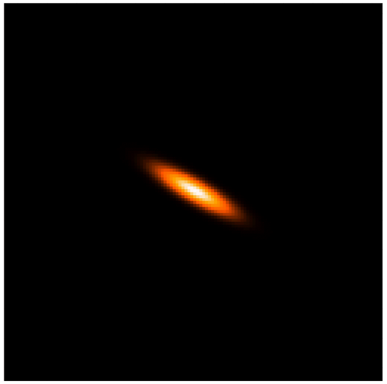
… a bit of equations (Fourier Transform)

$$V(u,v) = \int\int I(l,m) e^{2\pi i(ul+vm)} \, dl \, dm$$

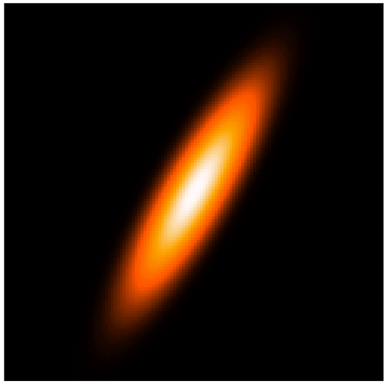
I (l,m)

V (u,v)

elliptical Gaussian



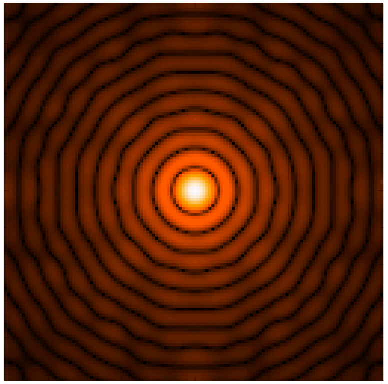
$\rightleftharpoons$



elliptical Gaussian

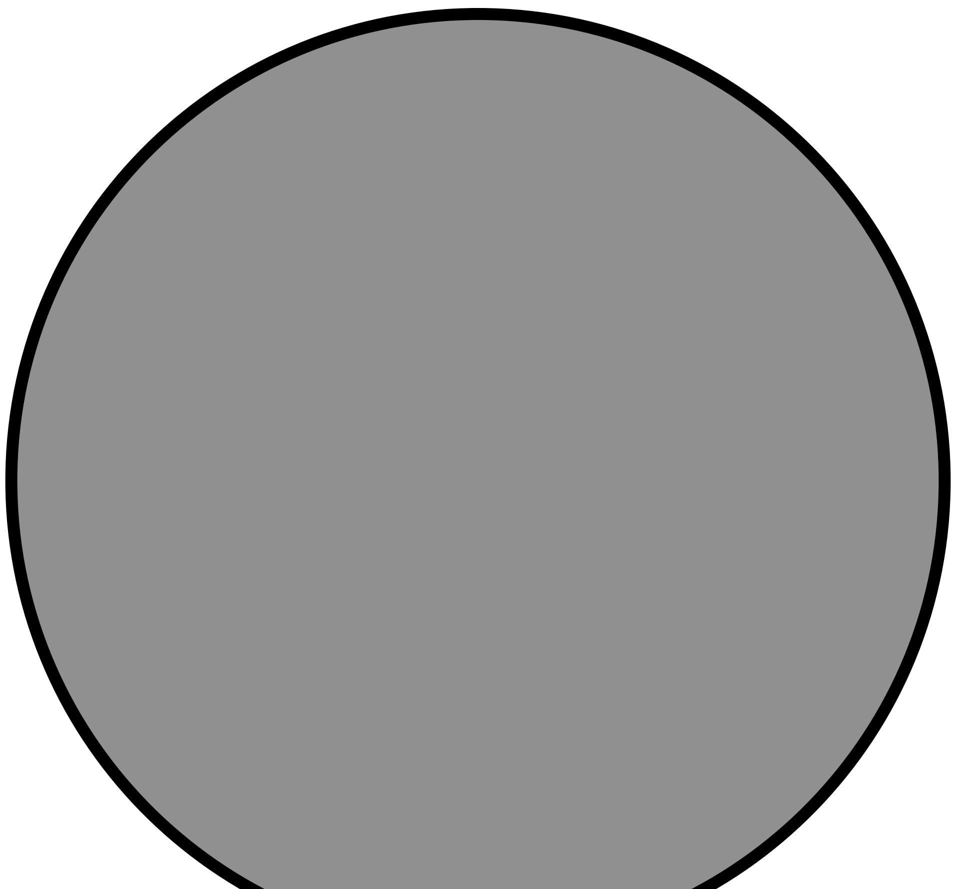
Disk

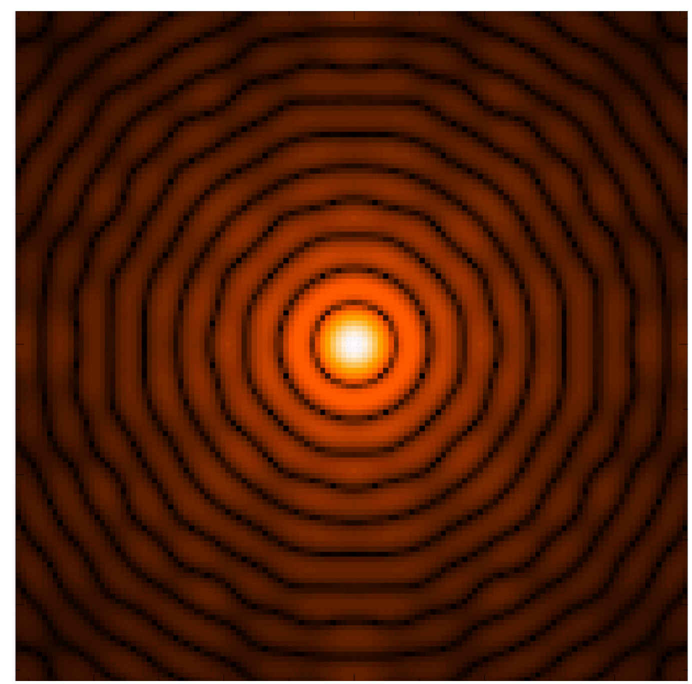
$\rightleftharpoons$



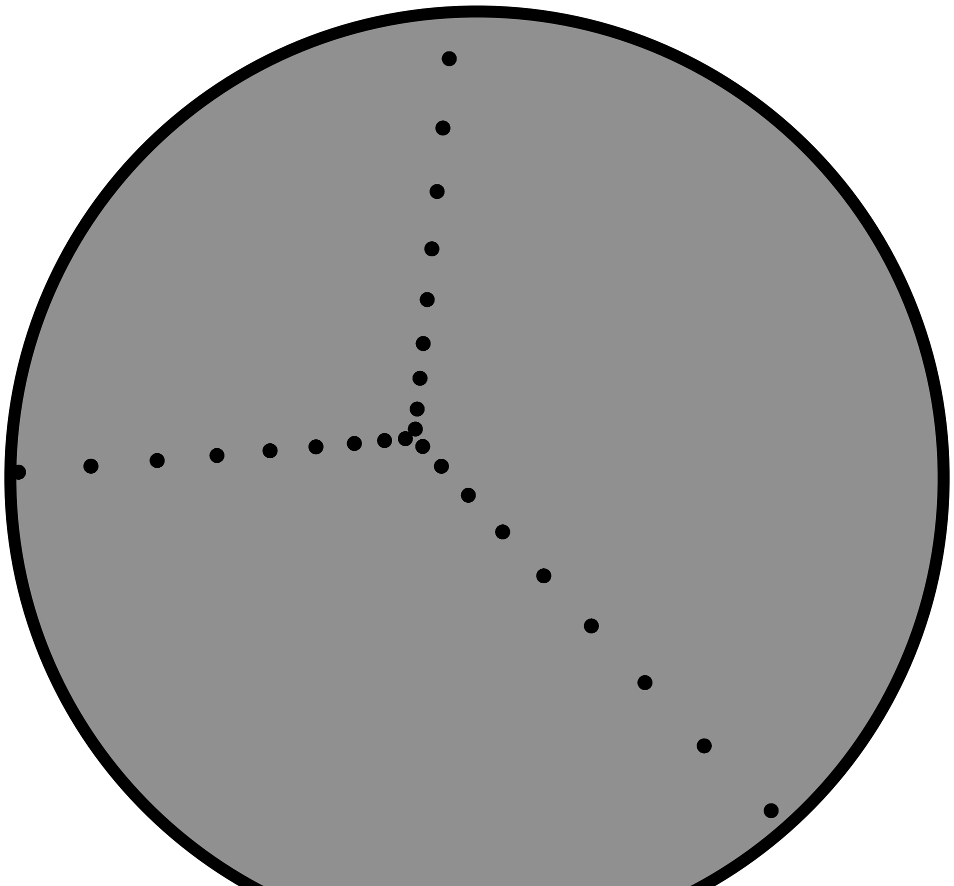
Bessel

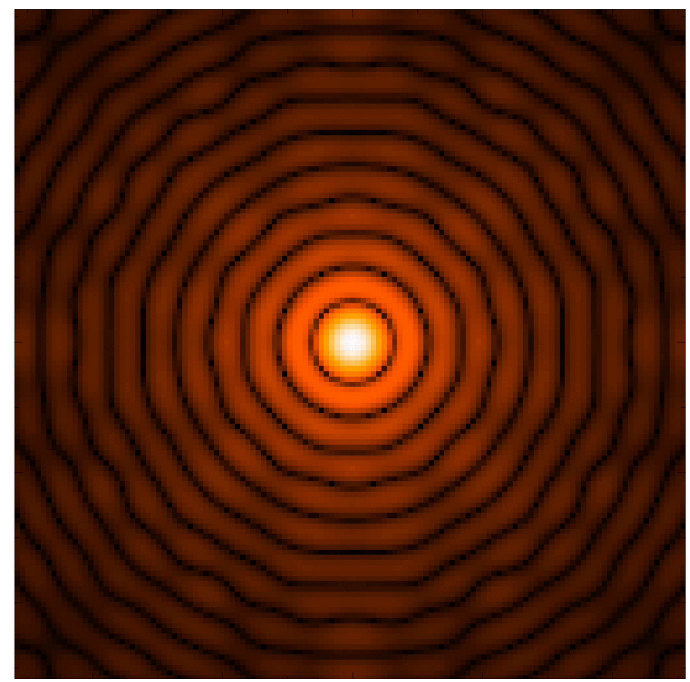
Interferometers as spatial filters



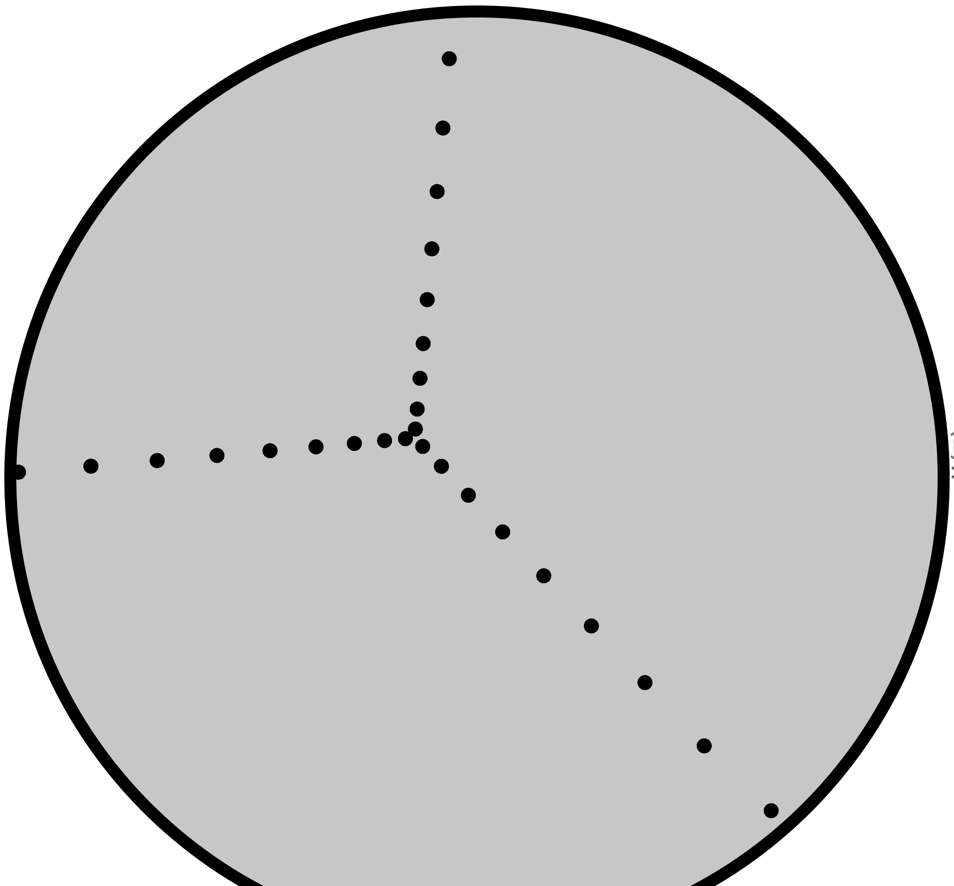


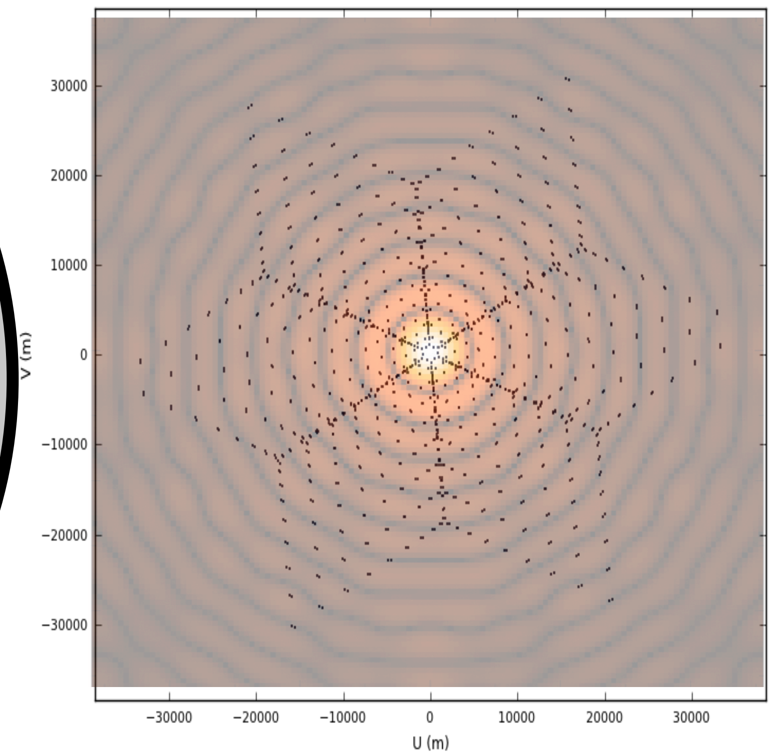
Interferometers as spatial filters





Interferometers as spatial filters

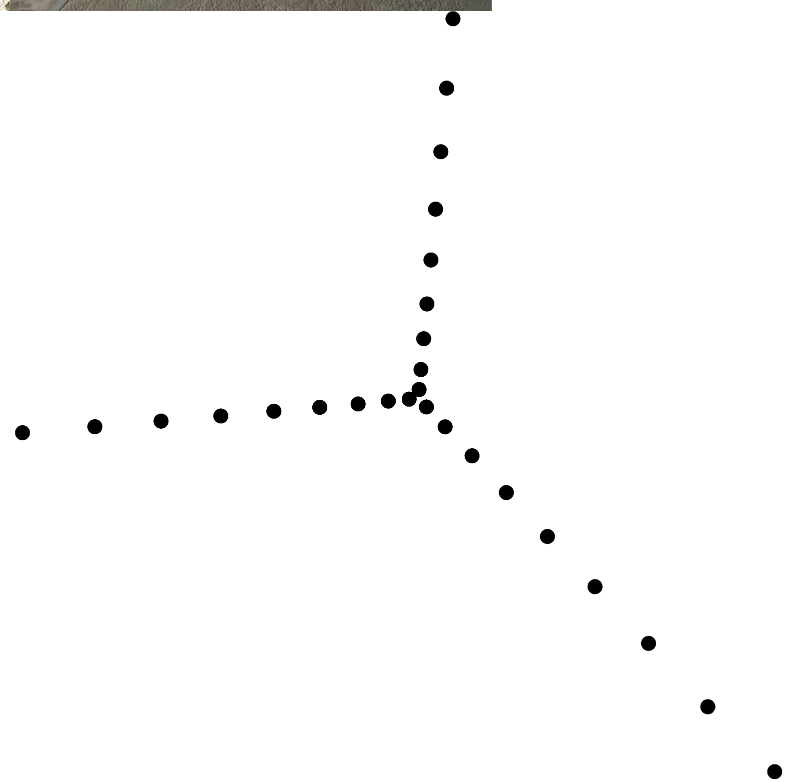


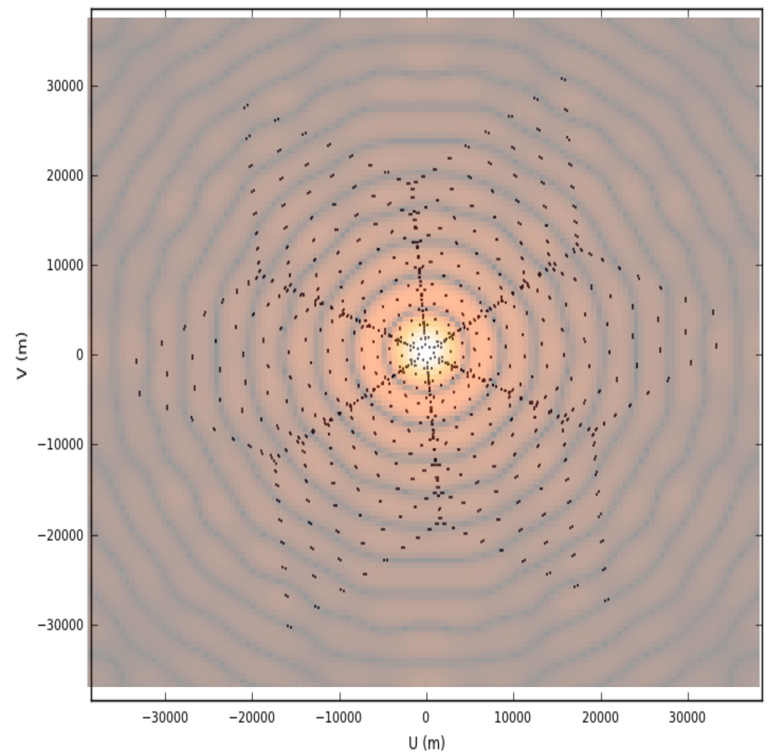


Example: VLA

Very Large Array (VLA)

- 27 antennas of 25 meters (diameter)
- observing from cm to mm wavelengths
- in New Mexico (USA)

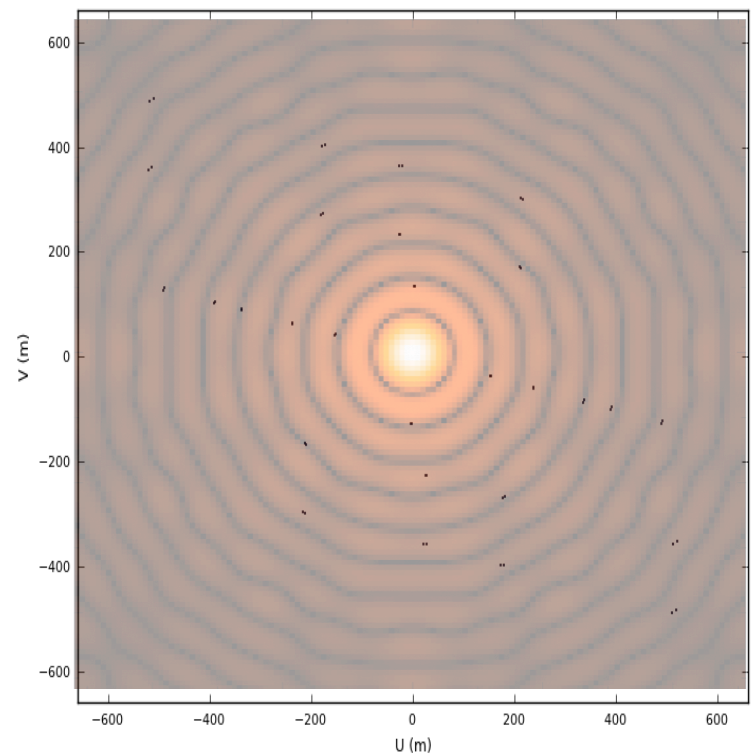




Example: PdBI

Plateau de Bure Interferometer (PdBI)

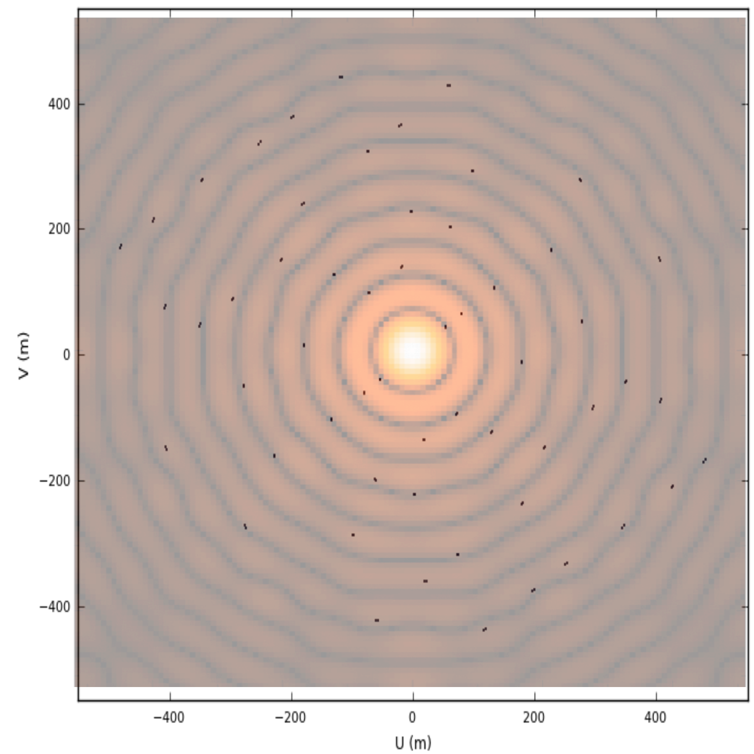
- 6 antennas of 15 meters (diameter)
- observing from mm to submm
- in Grenoble (France)



Example: SMA

SubMillimeter Array (SMA)

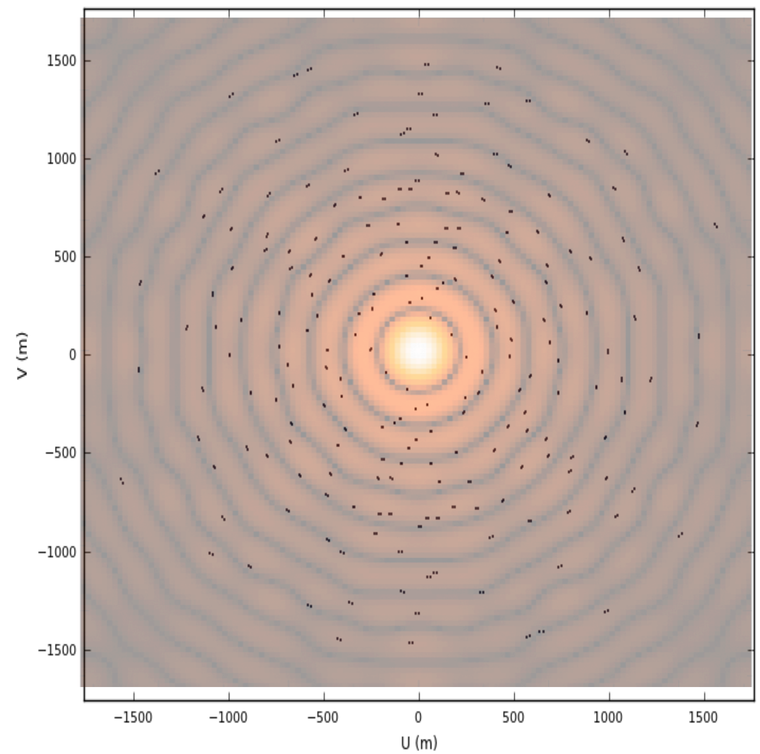
- 8 antennas of 6 meters (diameter)
- observing from mm to submm
- in Hawaii (USA)



Example: CARMA

Combined Array for Research in mm Astro (CARMA)

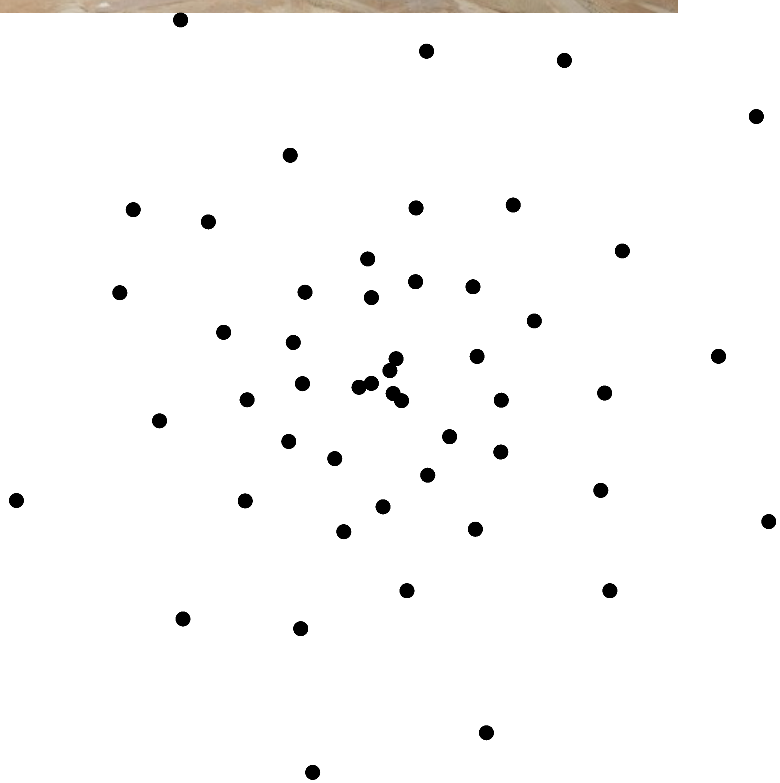
- 23 antennas of 10.4/6.1/3.5 meters
- observing from cm to mm wavelengths
- in California (USA)

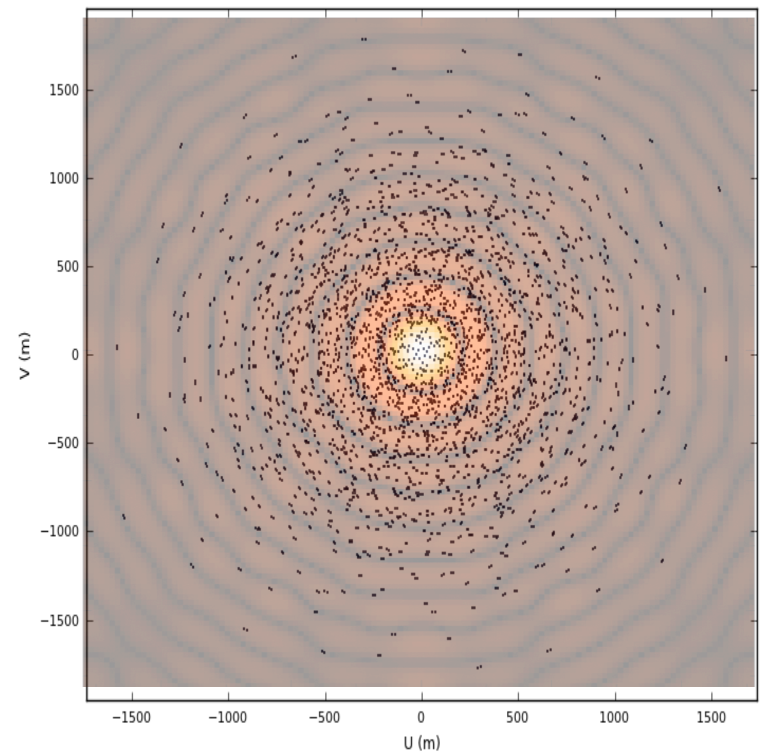


Example: ALMA

Atacama Large mm/submm Array (ALMA)

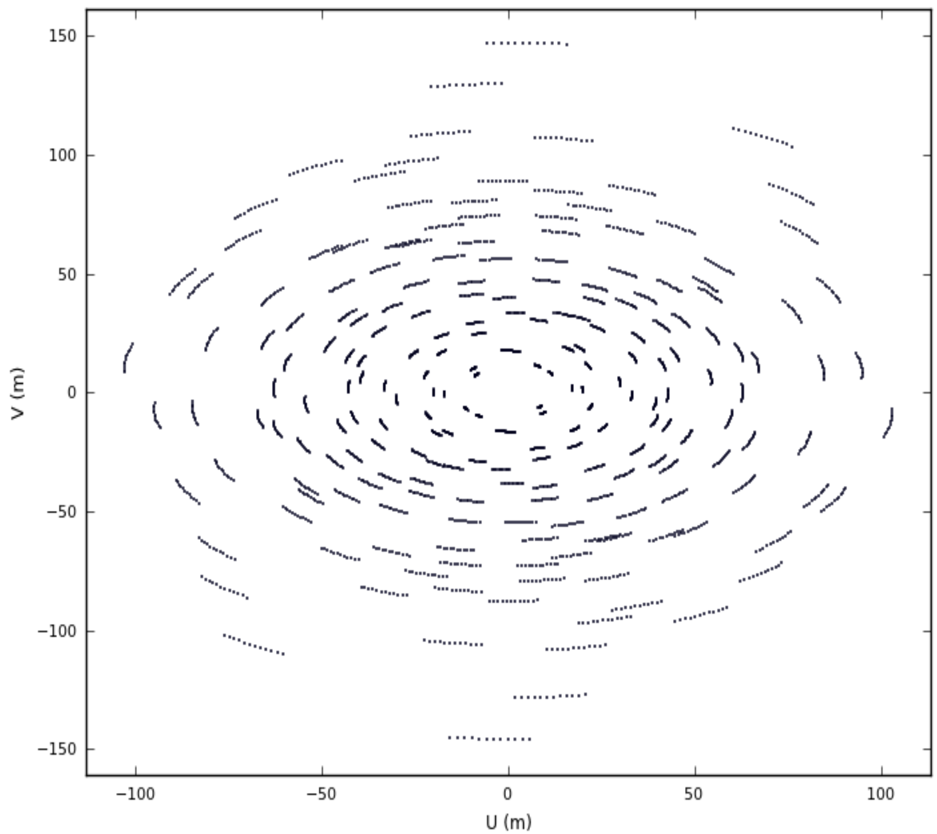
- 50 antennas of 12/7 meters
- observing from mm to submm
- in Llano Chajnantor (Chile)





Interferometers as spatial filters

- samples of V(u,v) are limited by the number of telescopes, and the Earth-sky geometry



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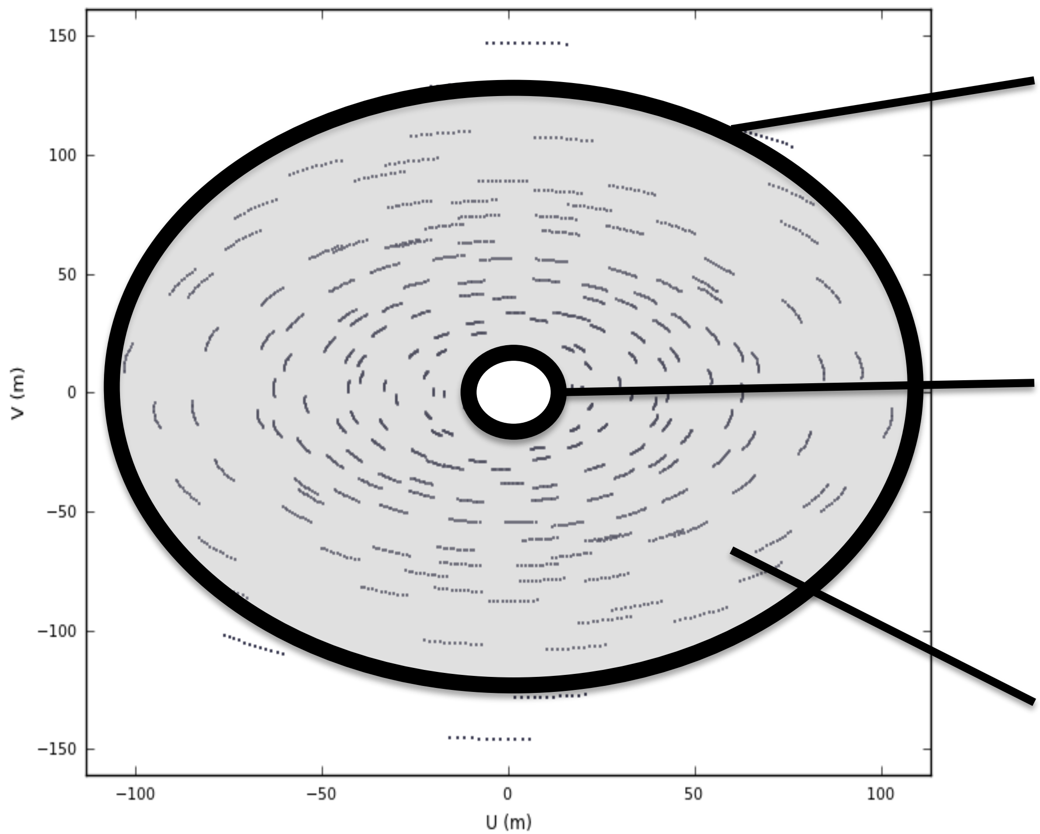
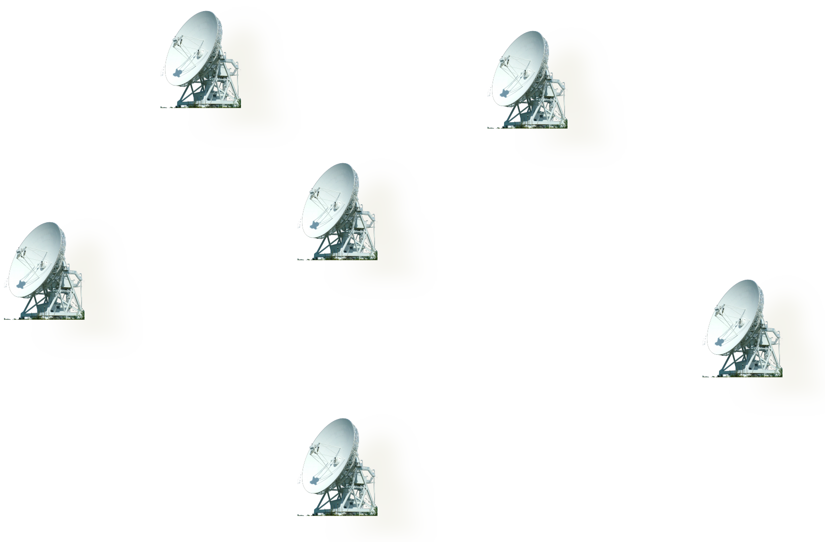


outer boundary:
- no small scales
- resolution limit

inner hole:
- no large scales
- extended structures

irregular coverage:
- information missing

Primary beam, synthesized beam, and LAS

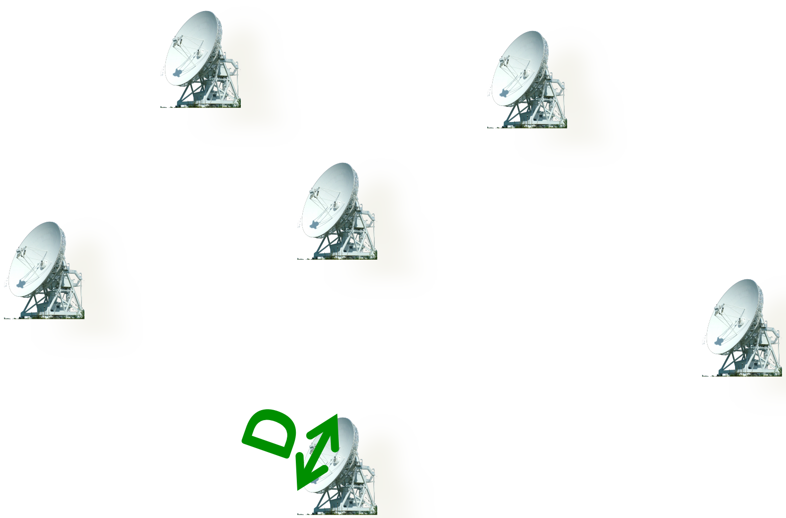


PRIMARY BEAM

SYNTHESIZED BEAM

LARGEST ANGULAR SCALE

Primary beam, synthesized beam, and LAS



PRIMARY BEAM

$$PB = 1.22\frac{\lambda}{D}$$

SYNTHESIZED BEAM

LARGEST ANGULAR SCALE

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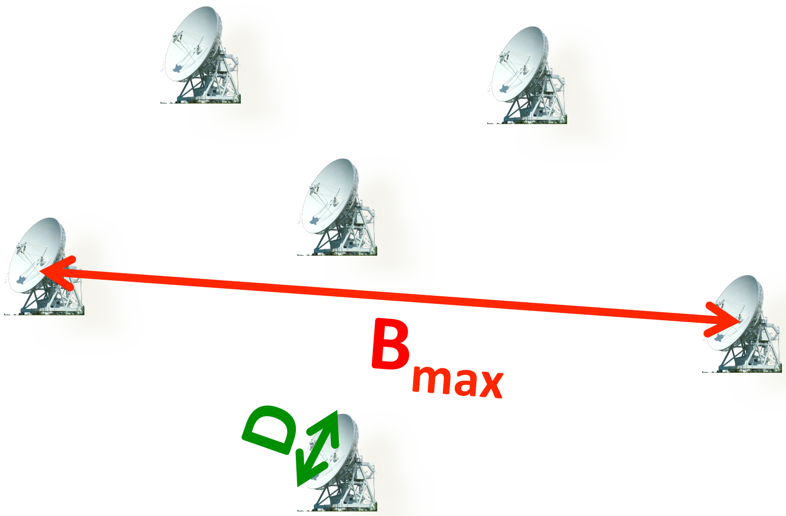


PRIMARY BEAM

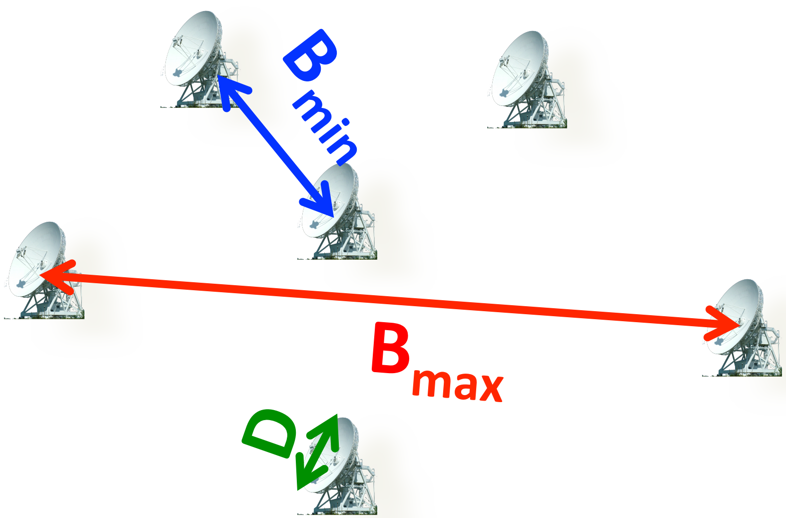
$$PB = 1.22\frac{\lambda}{D}$$

SYNTHESIZED BEAM

$$\theta_{beam} = 1.22\frac{\lambda}{B_{\max}}$$

LARGEST ANGULAR SCALE

Primary beam, synthesized beam, and LAS



PRIMARY BEAM

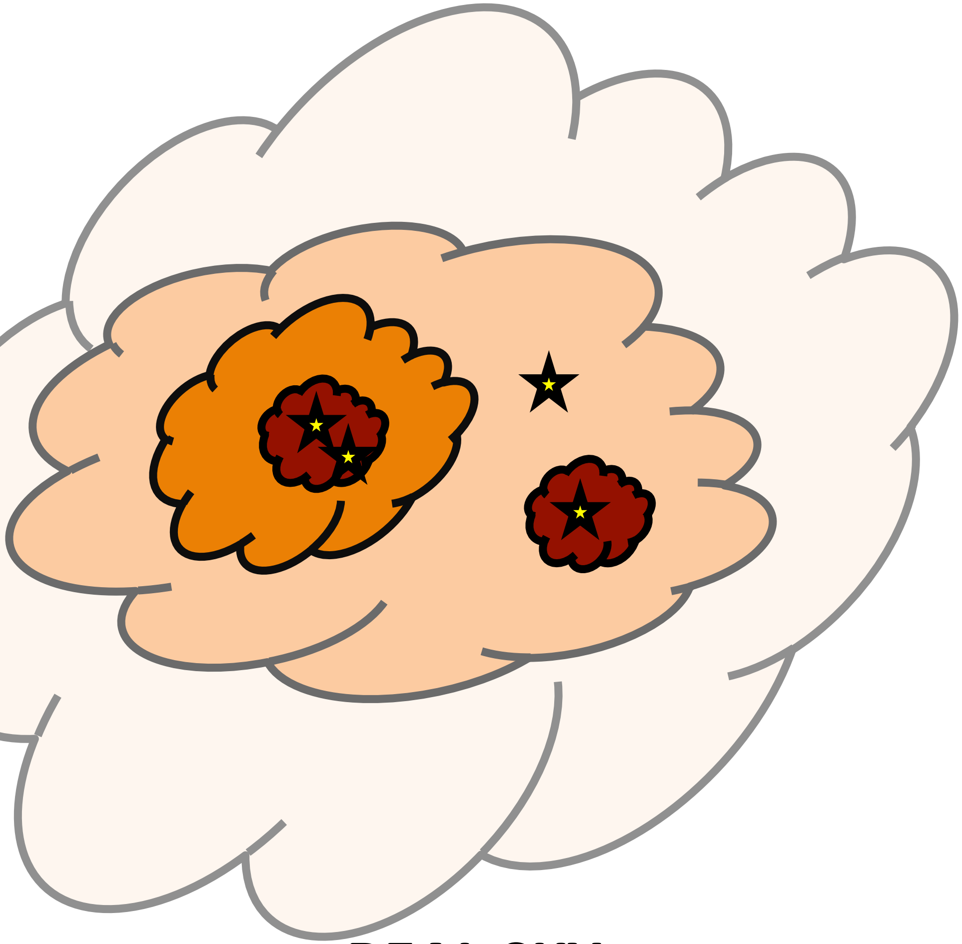
$$PB = 1.22\frac{\lambda}{D}$$

SYNTHESIZED BEAM

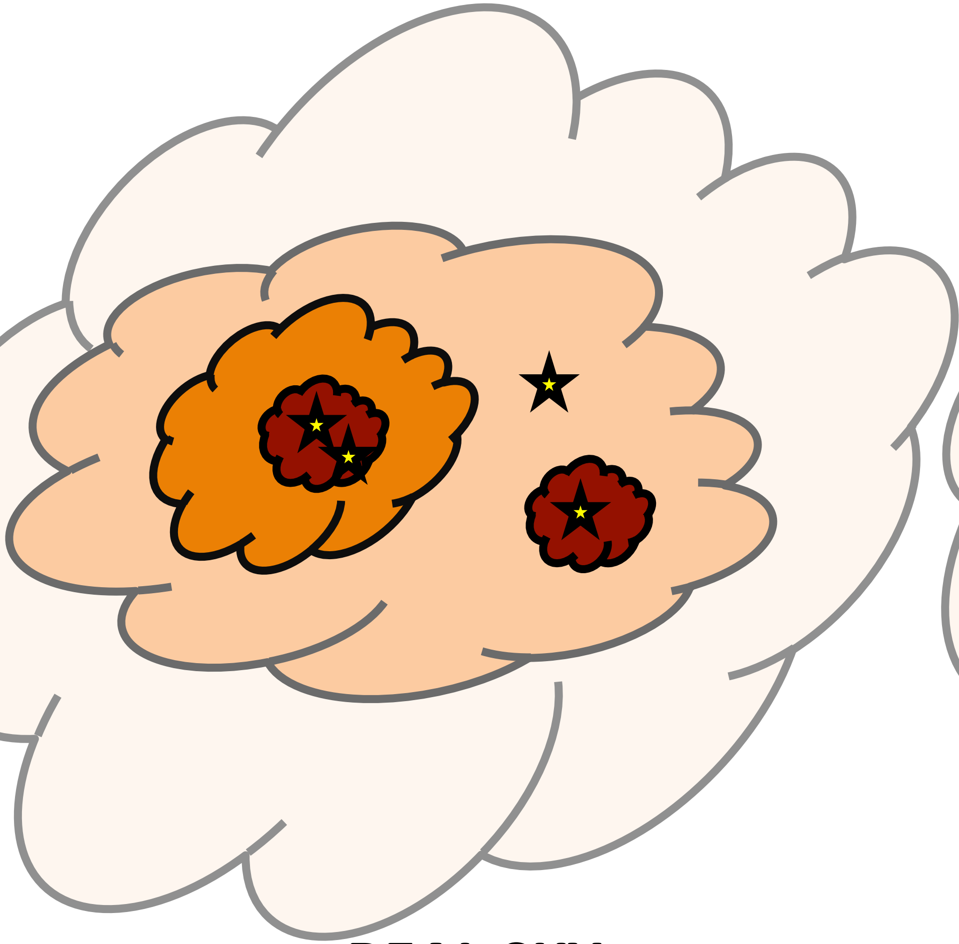
$$\theta_{beam} = 1.22\frac{\lambda}{B_{\max}}$$

LARGEST ANGULAR SCALE

$$LAS = 1.22\frac{\lambda}{B_{\min}}$$



REAL SKY



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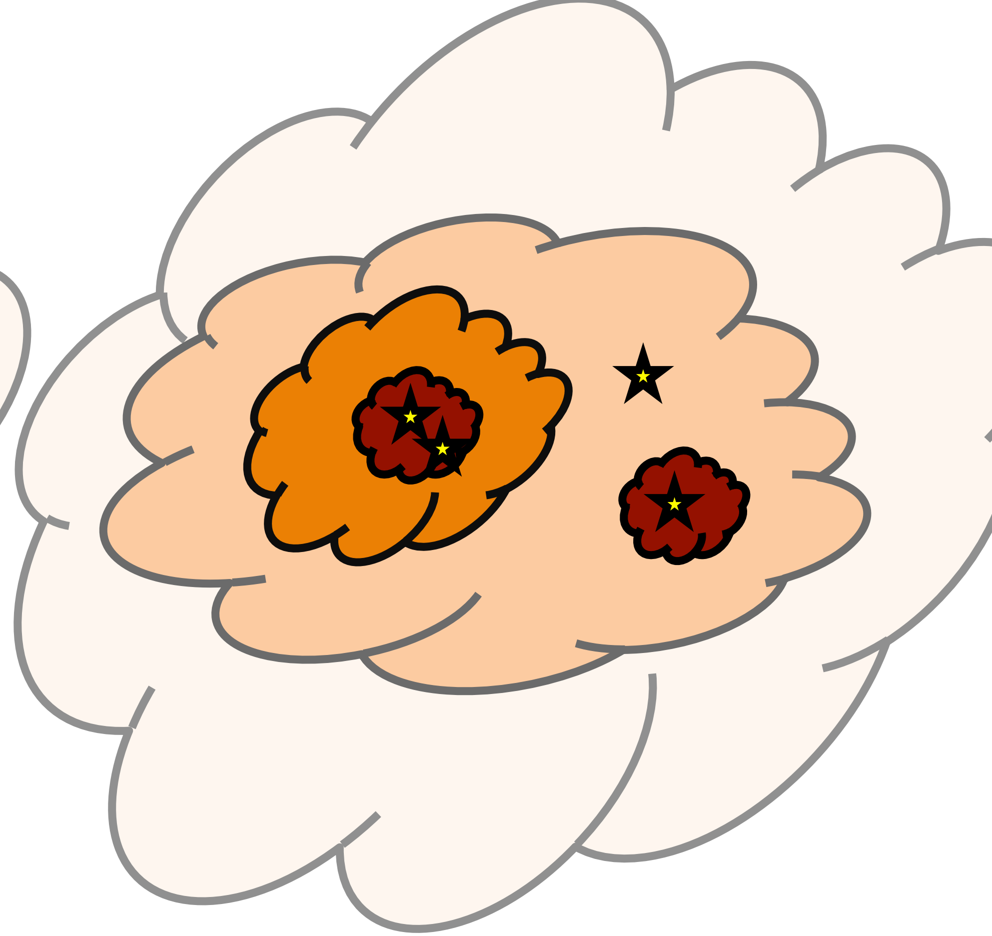
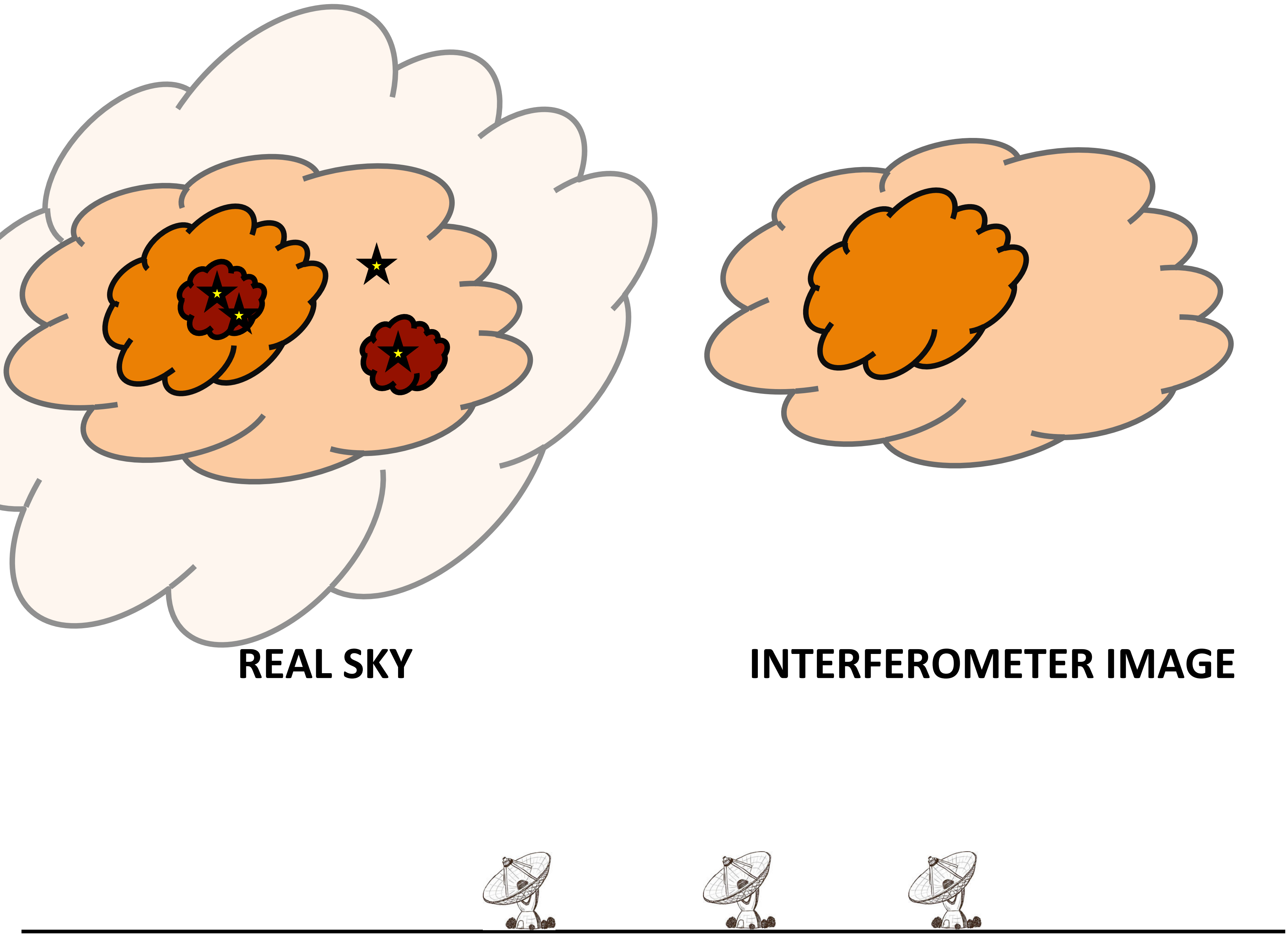
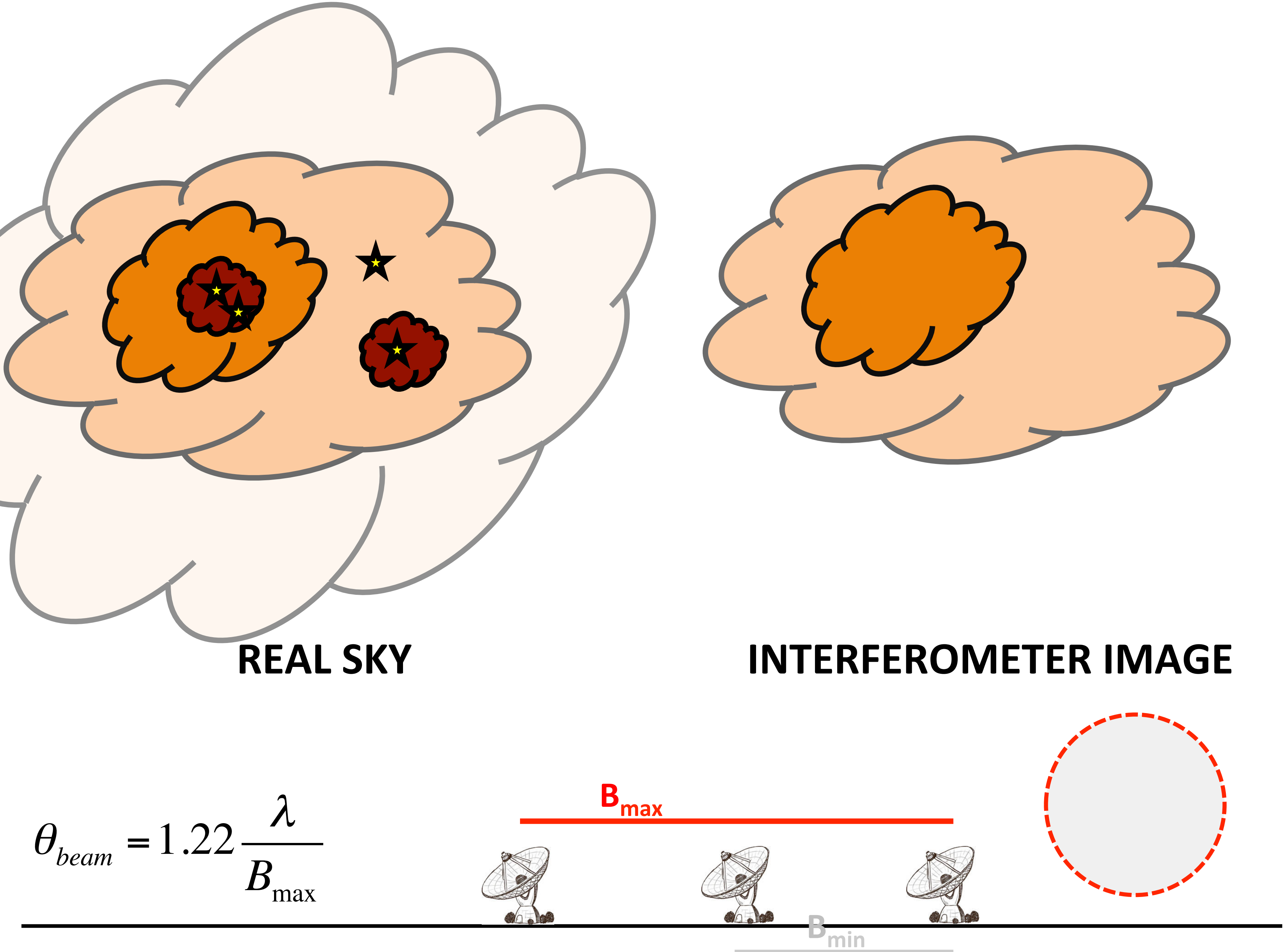
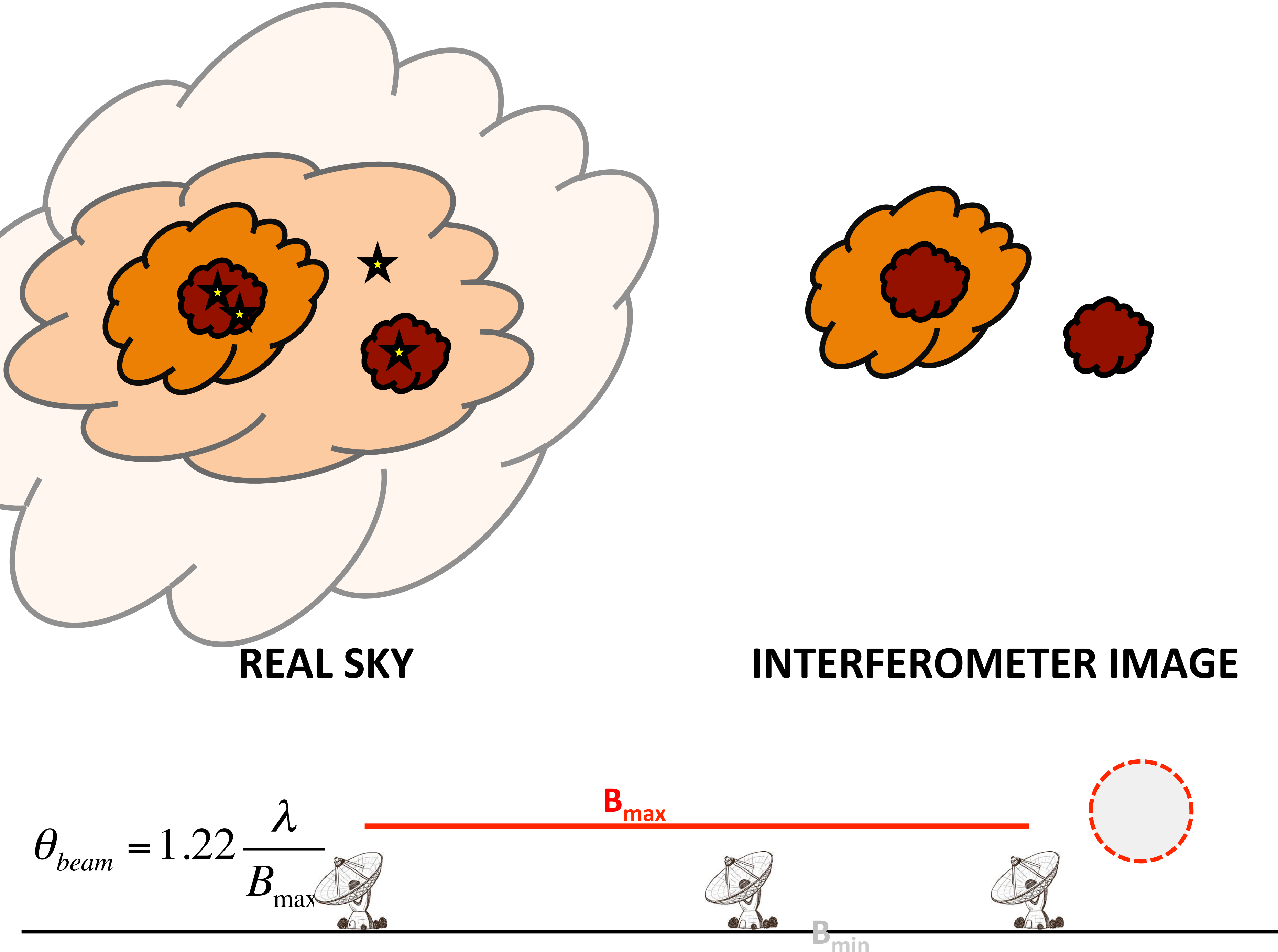


WHAT WE WANT TO OBTAIN


REAL SKY
INTERFEROMETER IMAGE



$$\theta_{beam} = 1.22 \frac{\lambda}{B_{\max}}$$



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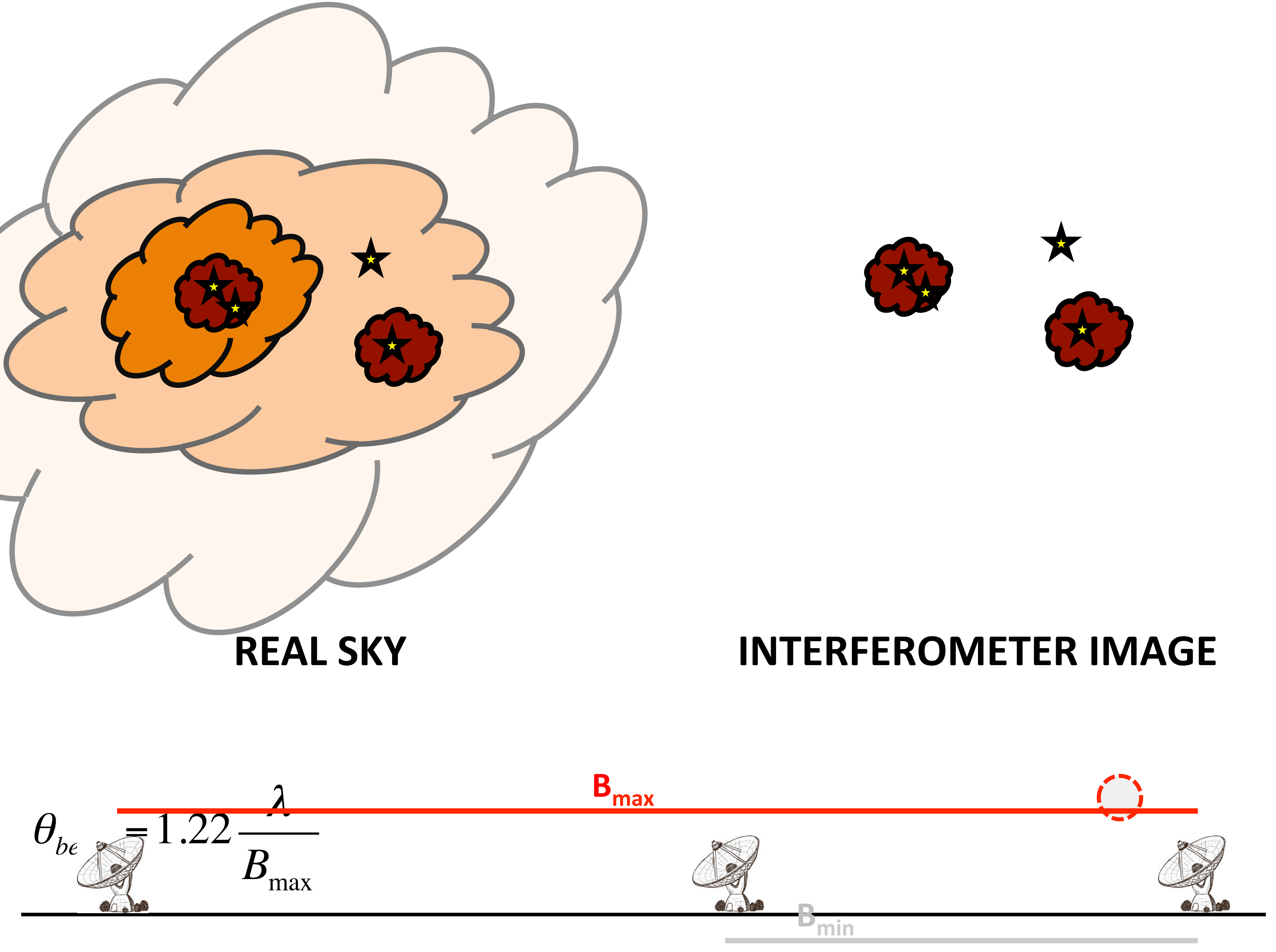
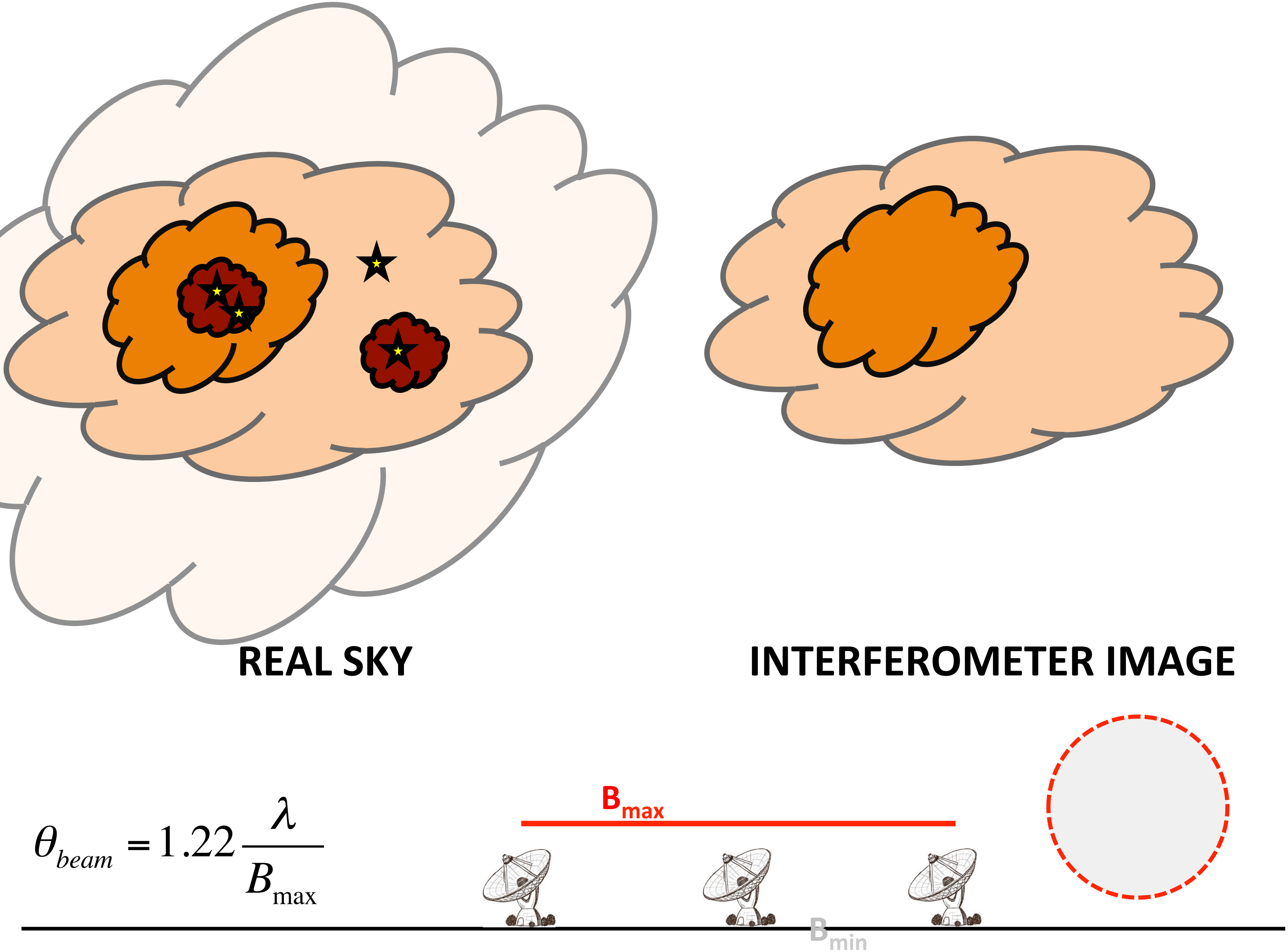
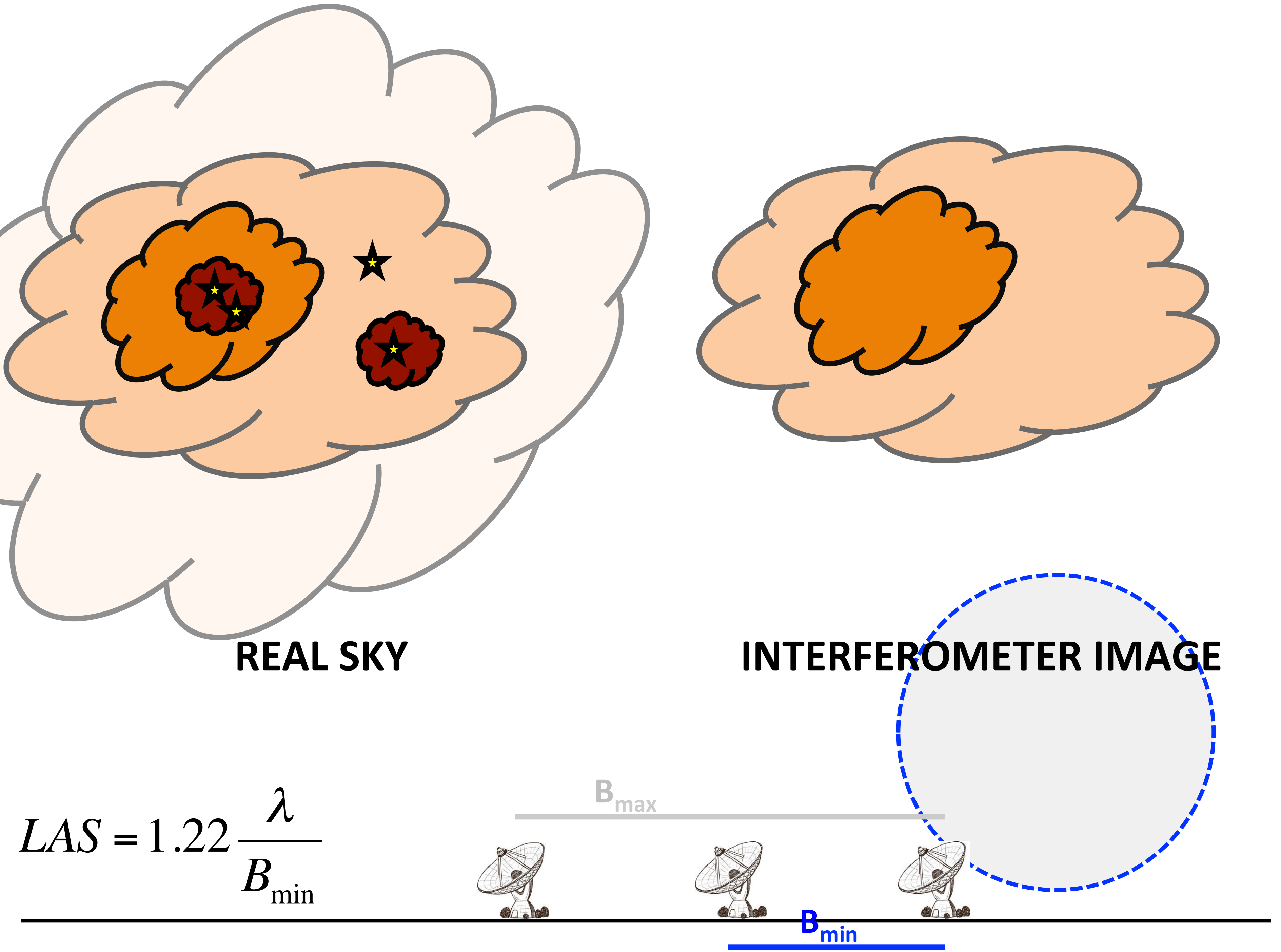
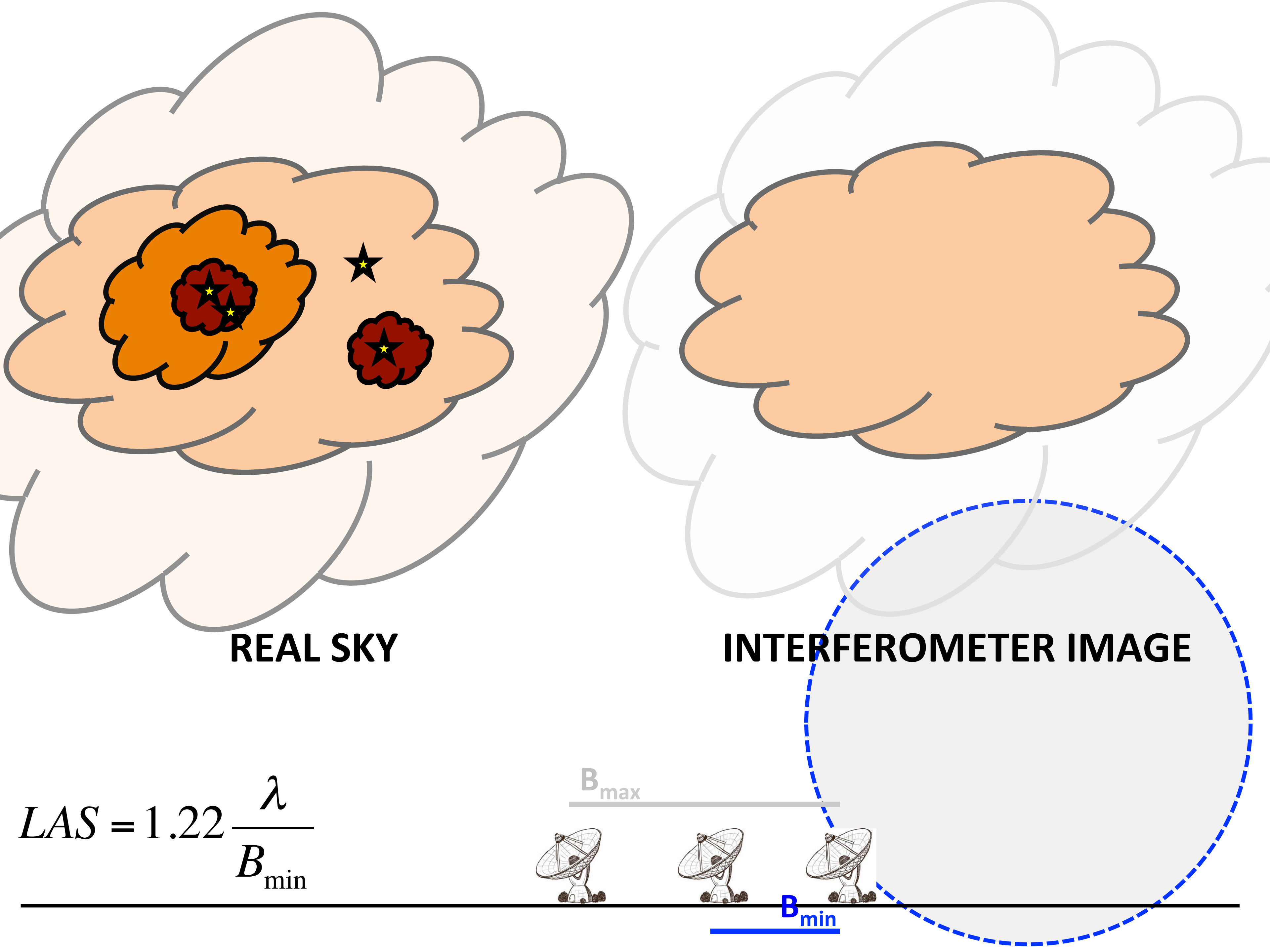

REAL SKY
INTERFEROMETER IMAGE
B max
θ be = 1.22 λ / B max
B min


REAL SKY
INTERFEROMETER IMAGE
$\theta_{beam} = 1.22 \frac{\lambda}{B_{\max}}$
B_{max}
B_{min}


REAL SKY
INTERFEROMETER IMAGE
$LAS = 1.22 \frac{\lambda}{B_{min}}$
B_{max}
B_{min}


REAL SKY
INTERFEROMETER IMAGE
$LAS = 1.22 \frac{\lambda}{B_{min}}$
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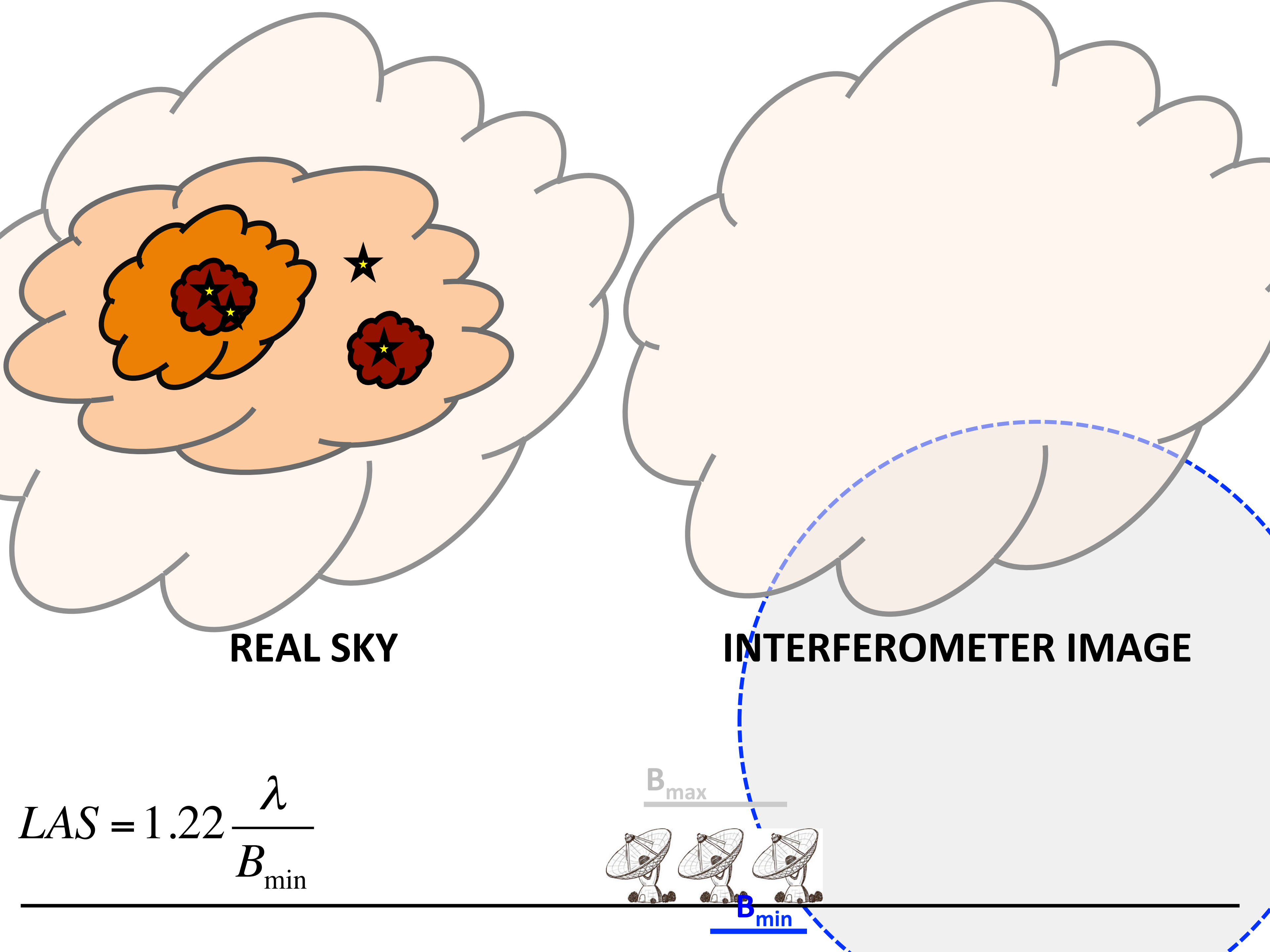

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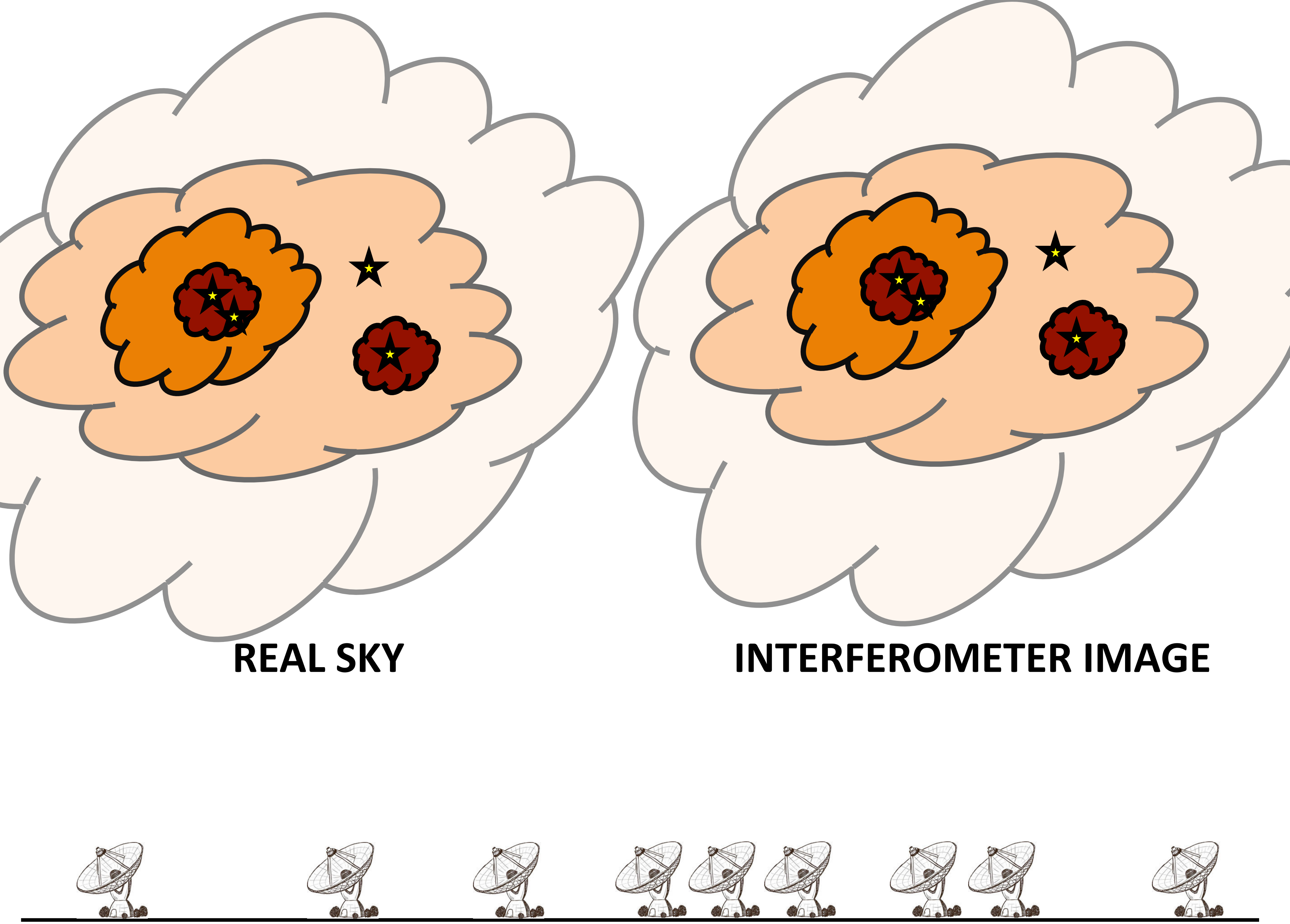
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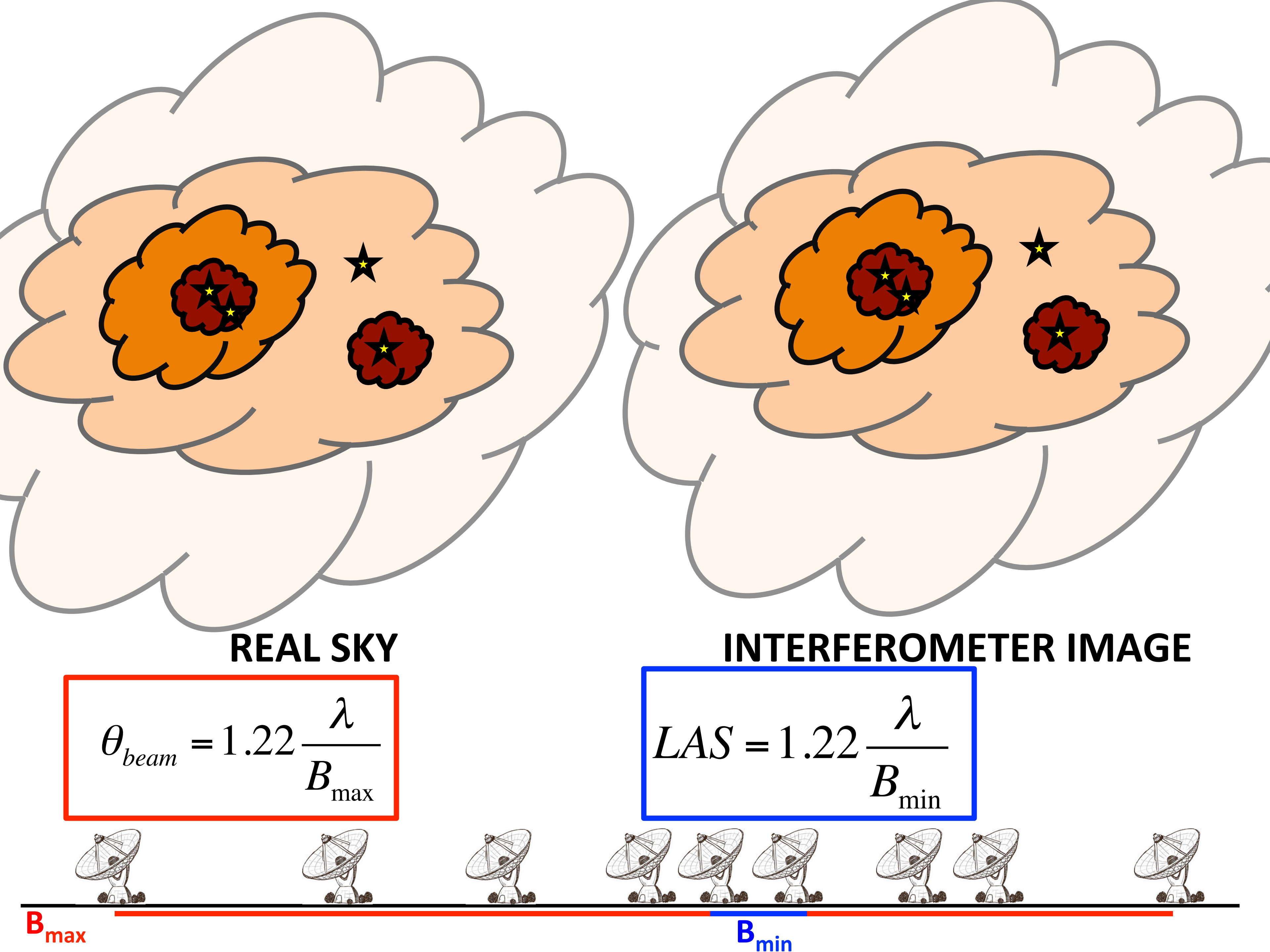
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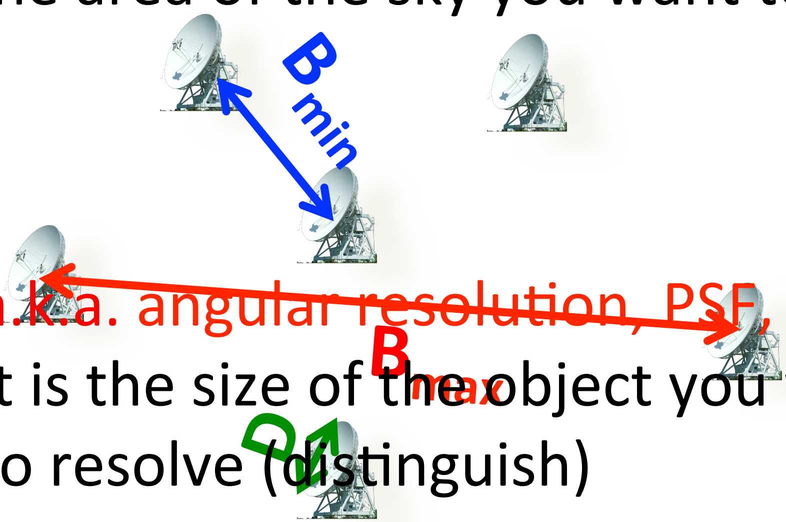
Primary beam, synthesized beam, and LAS

PRIMARY BEAM

a.k.a. field of view (FOV), ...
the area of the sky you want to observe

$$PB = 1.22\frac{\lambda}{D}$$



SYNTHESIZED BEAM

a.k.a. angular resolution, PSF, ...
it is the size of the object you want to resolve (distinguish)

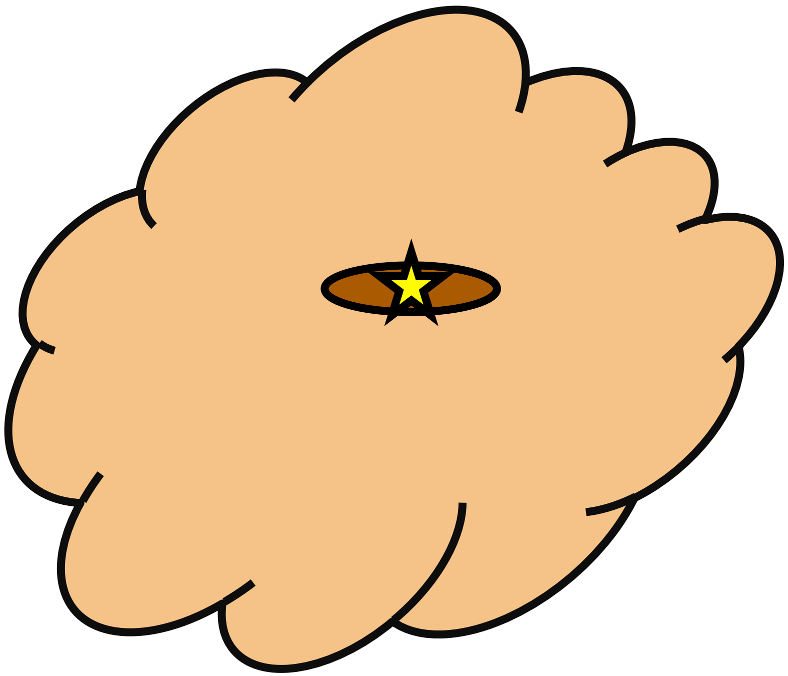
$$\theta_{beam} = 1.22\frac{\lambda}{B_{\max}}$$

LARGEST ANGULAR SCALE

a.k.a. maximum angular size, ...
the largest size of your object
how big it is?

$$LAS = 1.22\frac{\lambda}{B_{\min}}$$

Example I: compact protoplanetary disk



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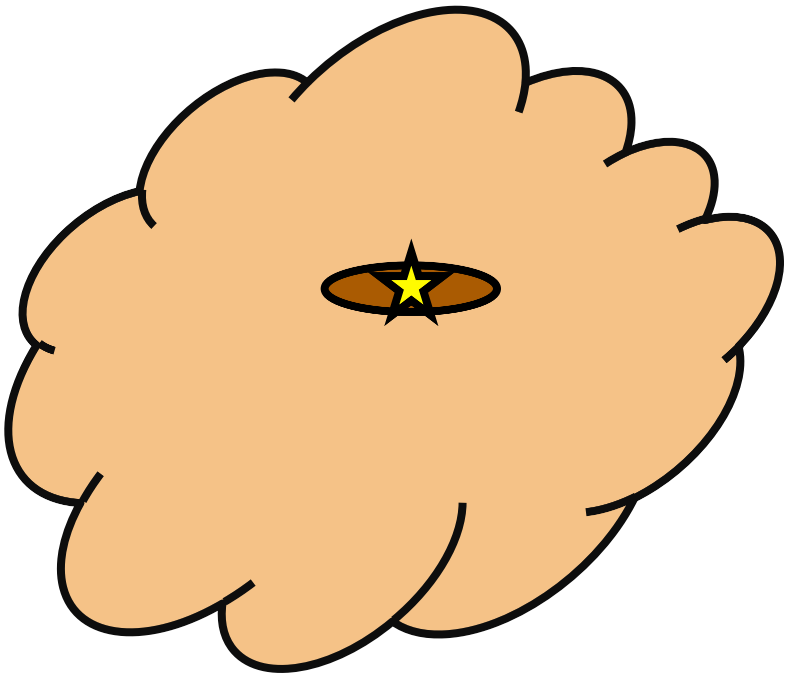

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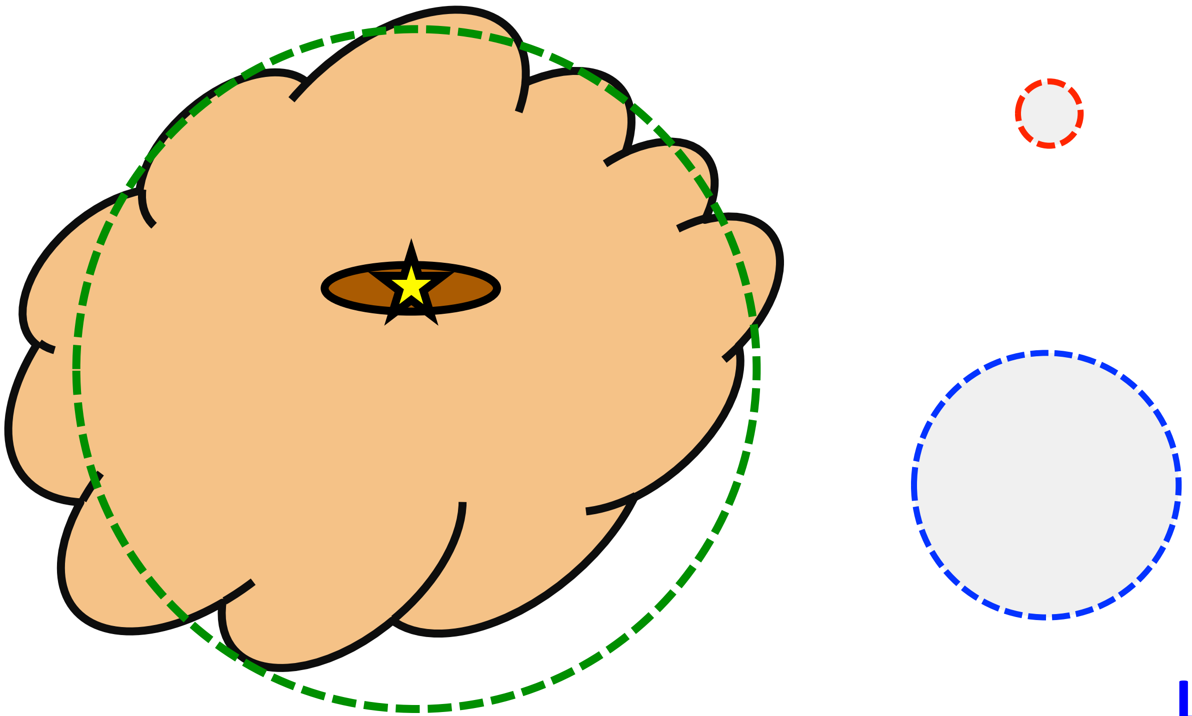

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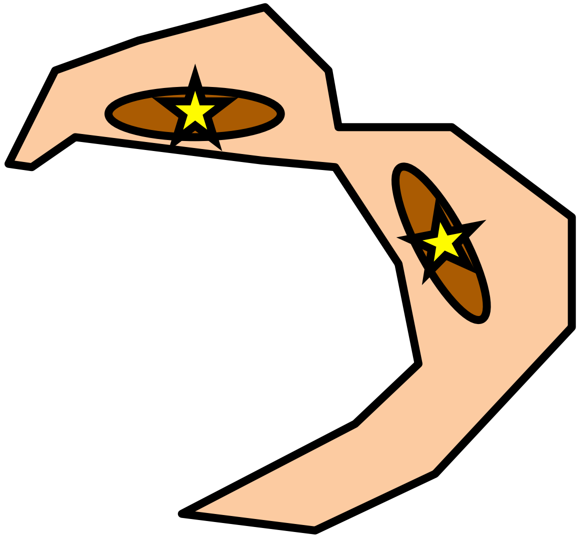

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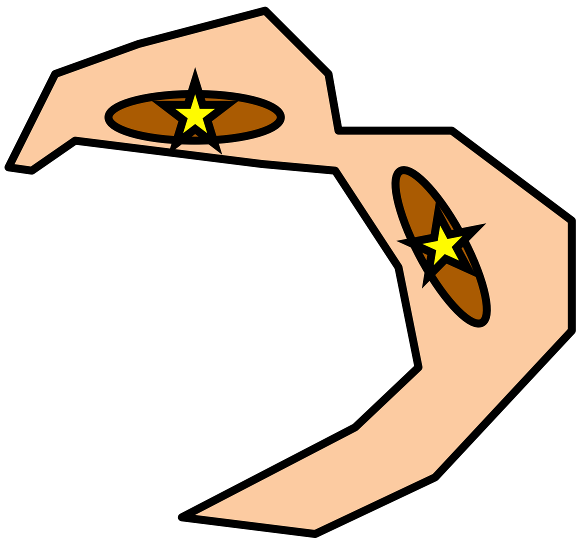

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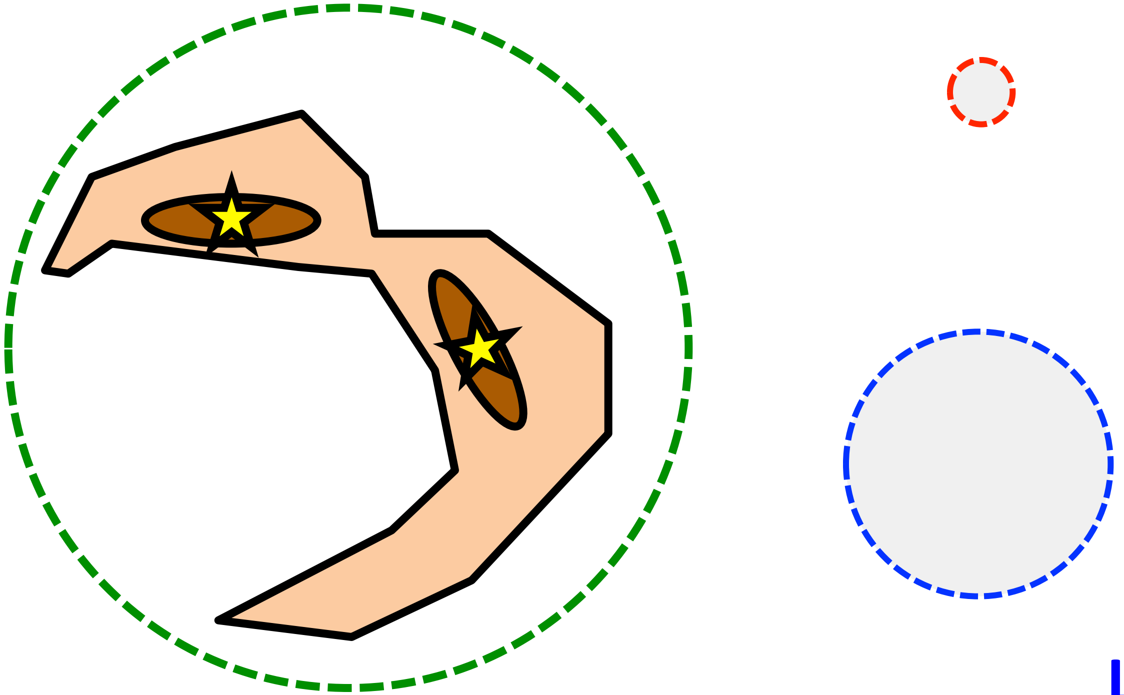

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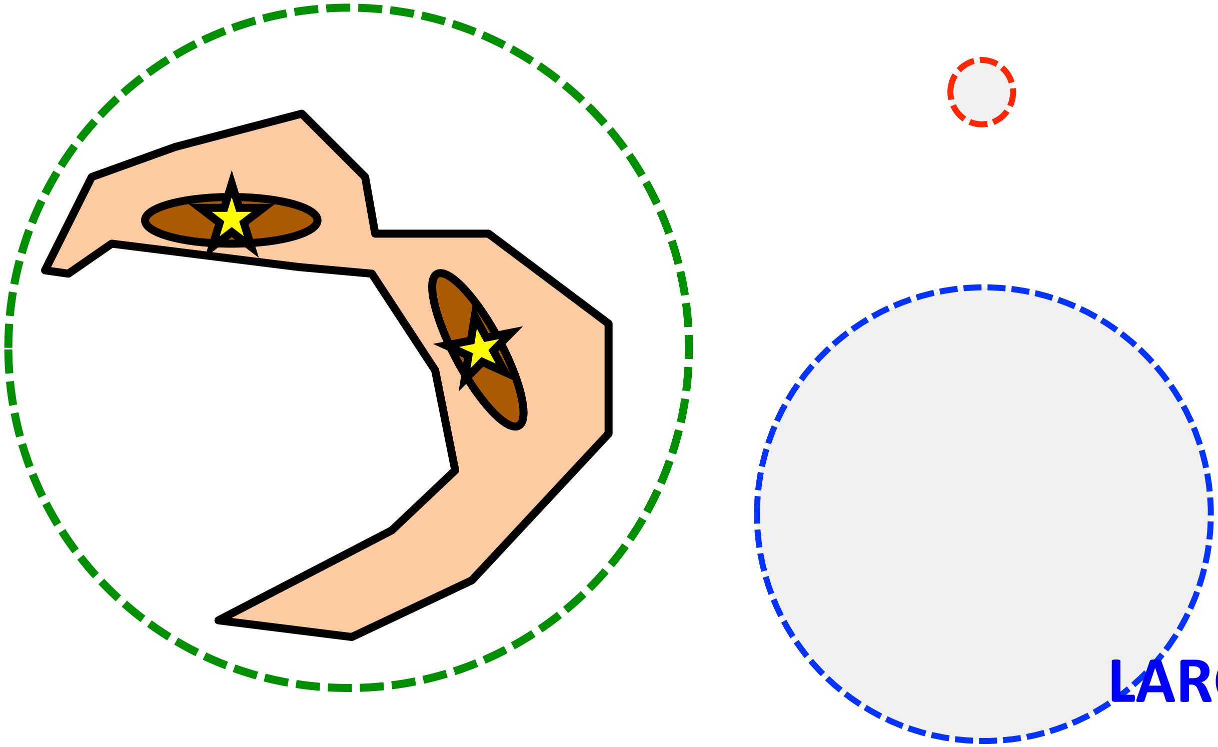

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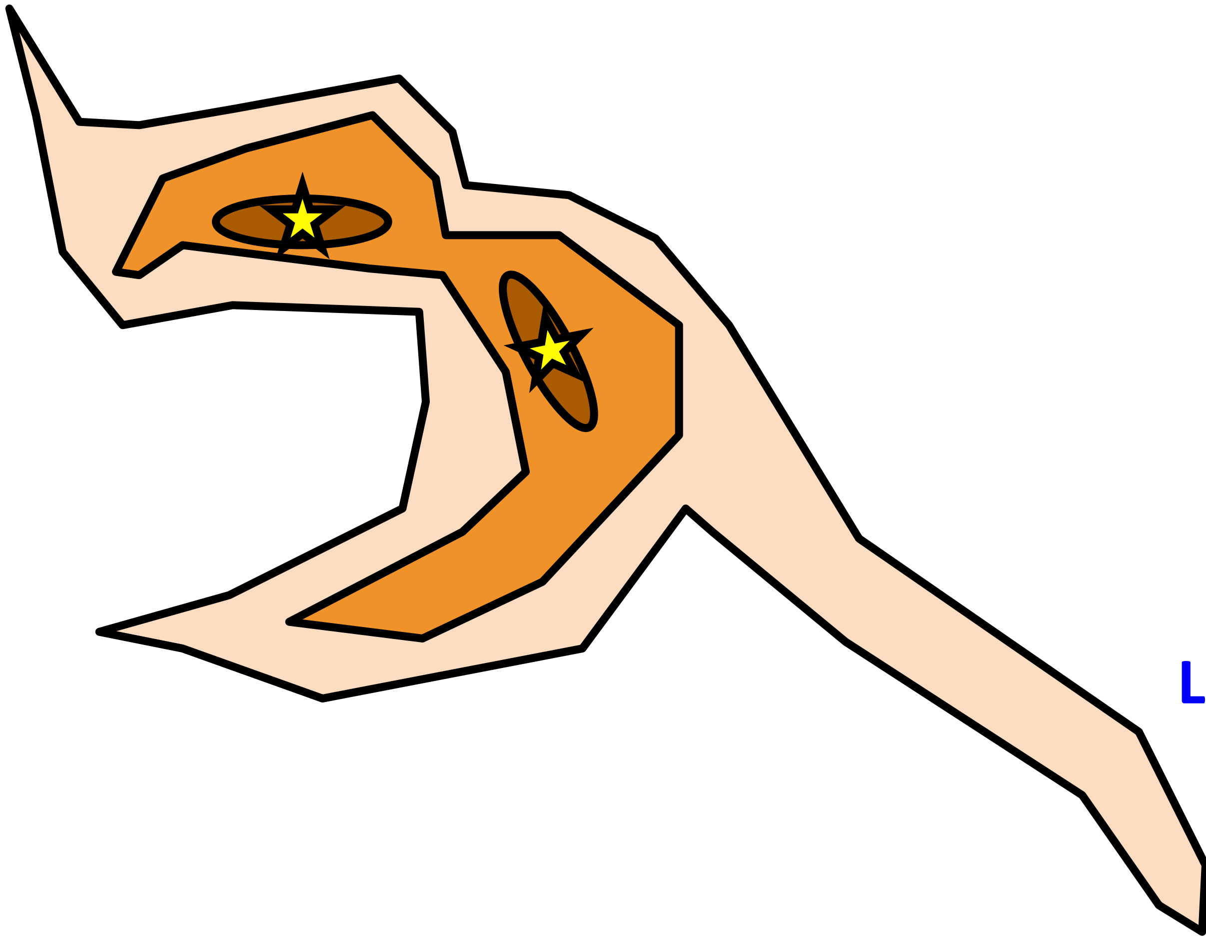

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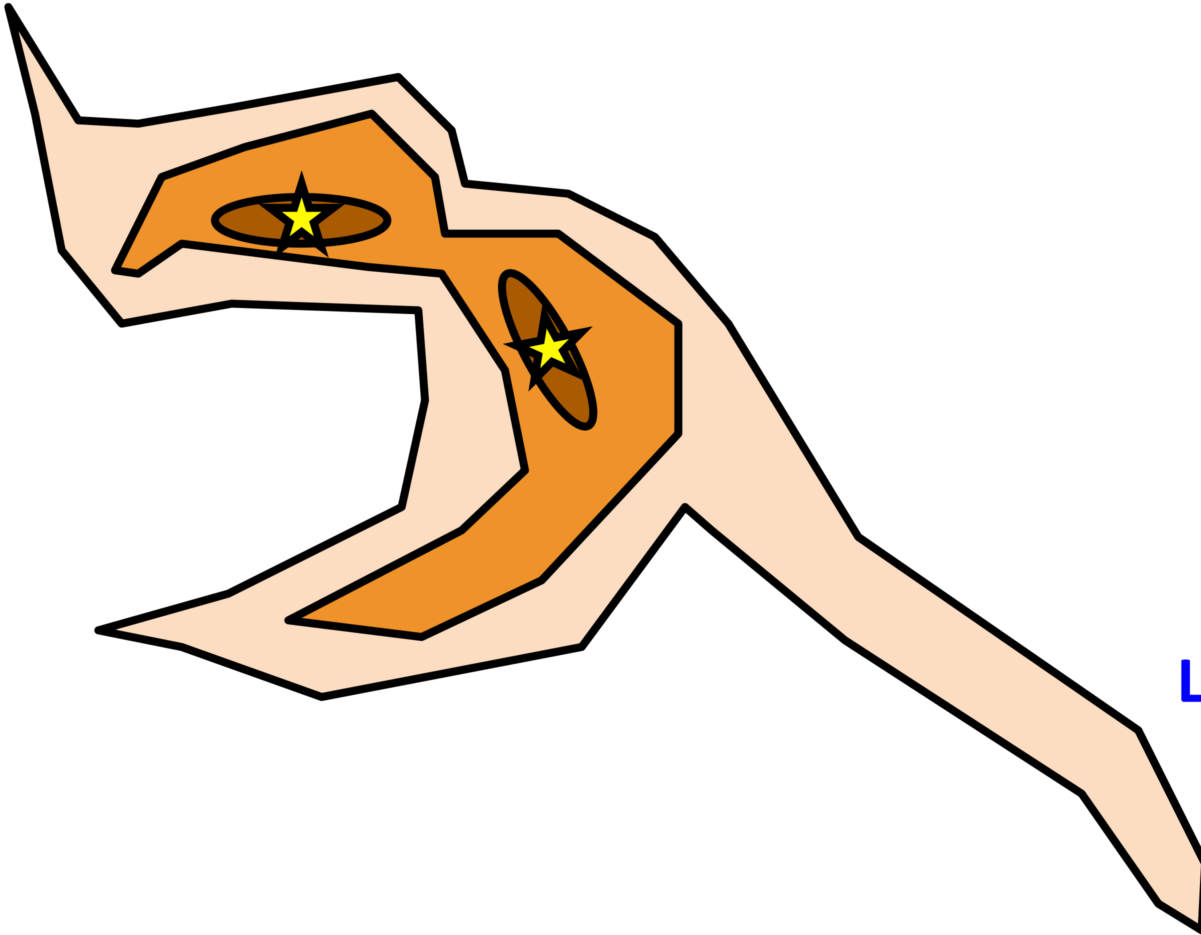

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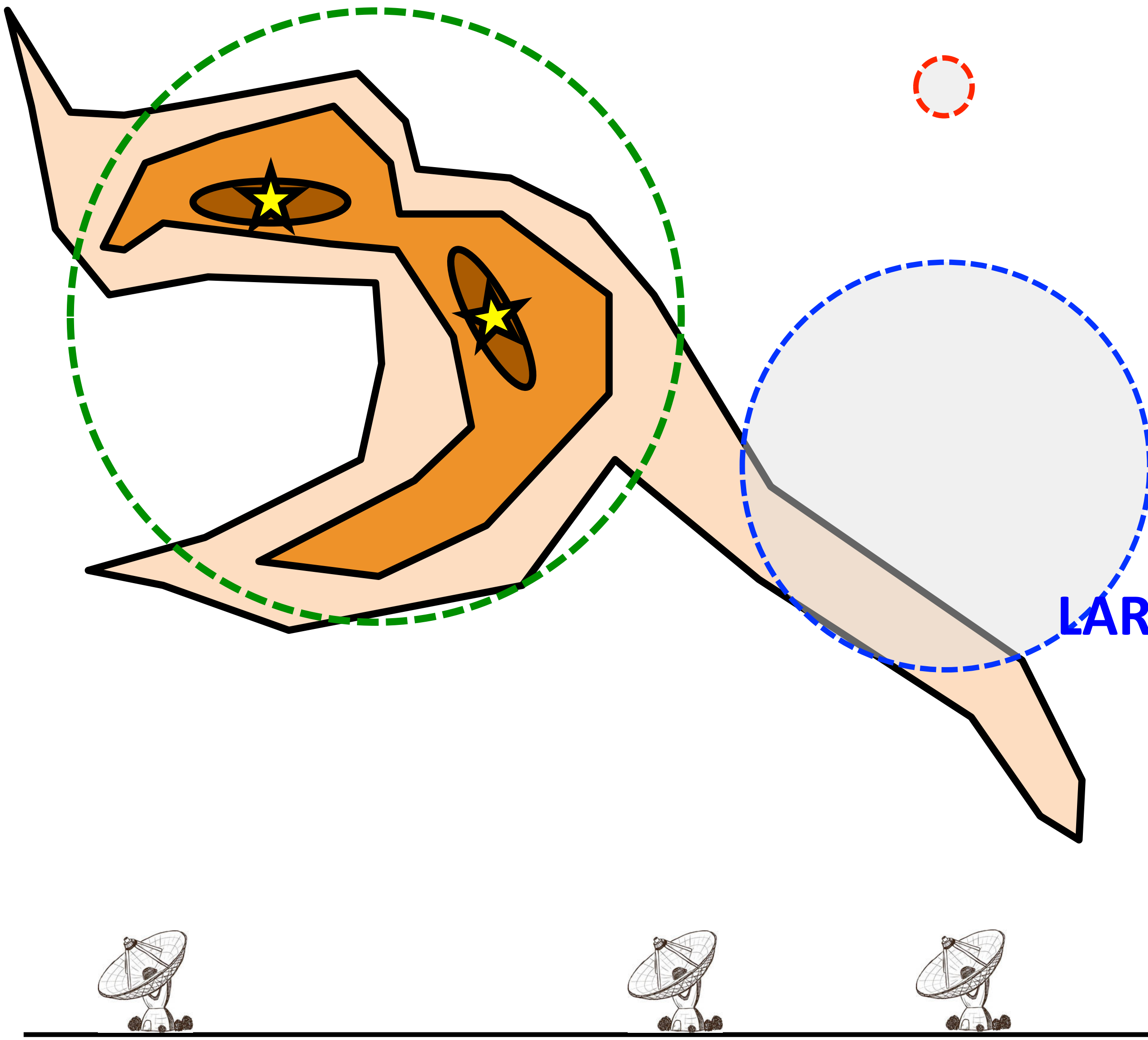

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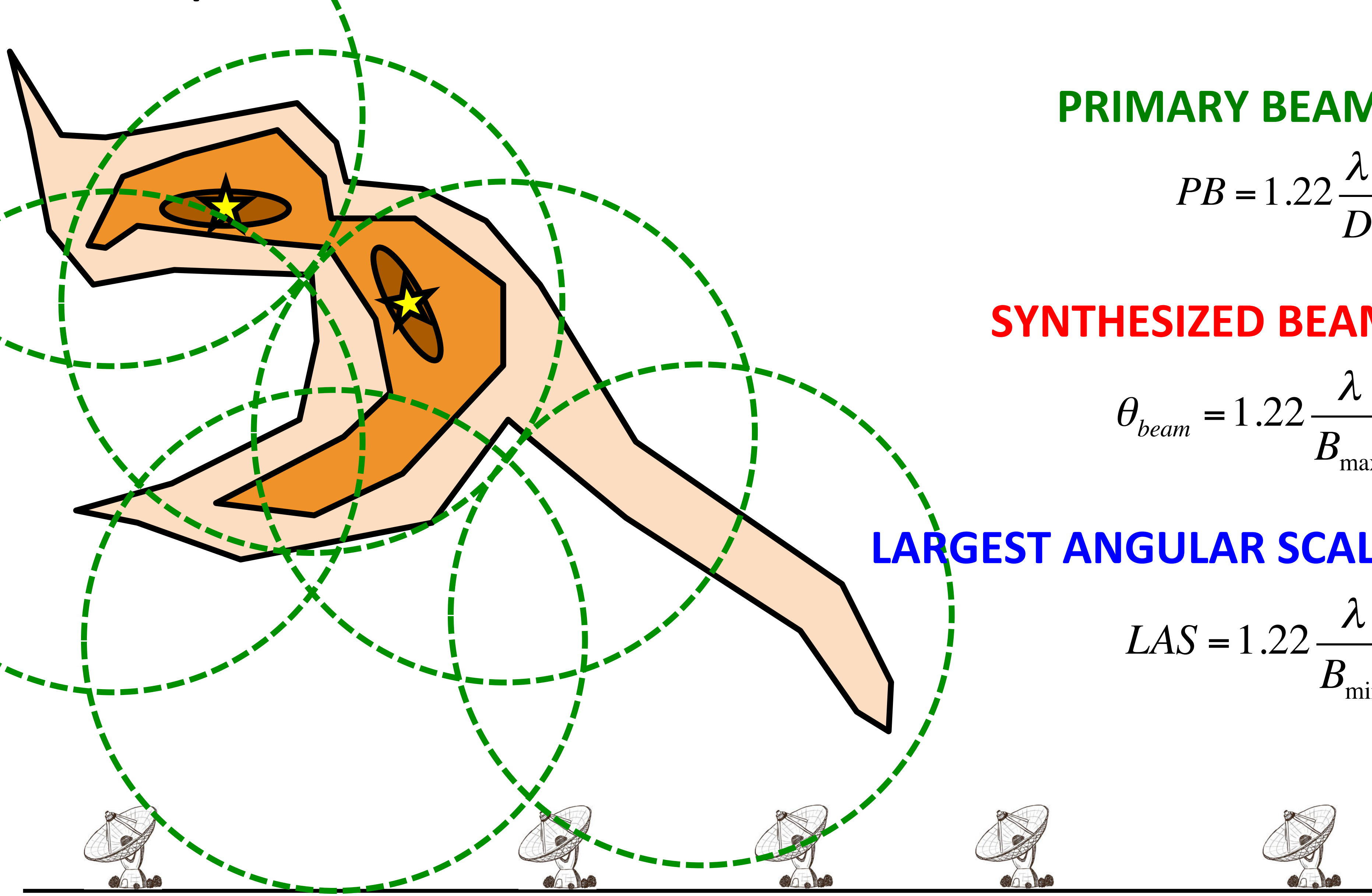

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Outline

Part 1

- Introduction to aperture synthesis
- Interferometers: spatial filters

Part 2

- An overview to the correlator and spectral receivers
- Interferometers: spectral setup

Part 2:
spectral setup, receivers and correlator

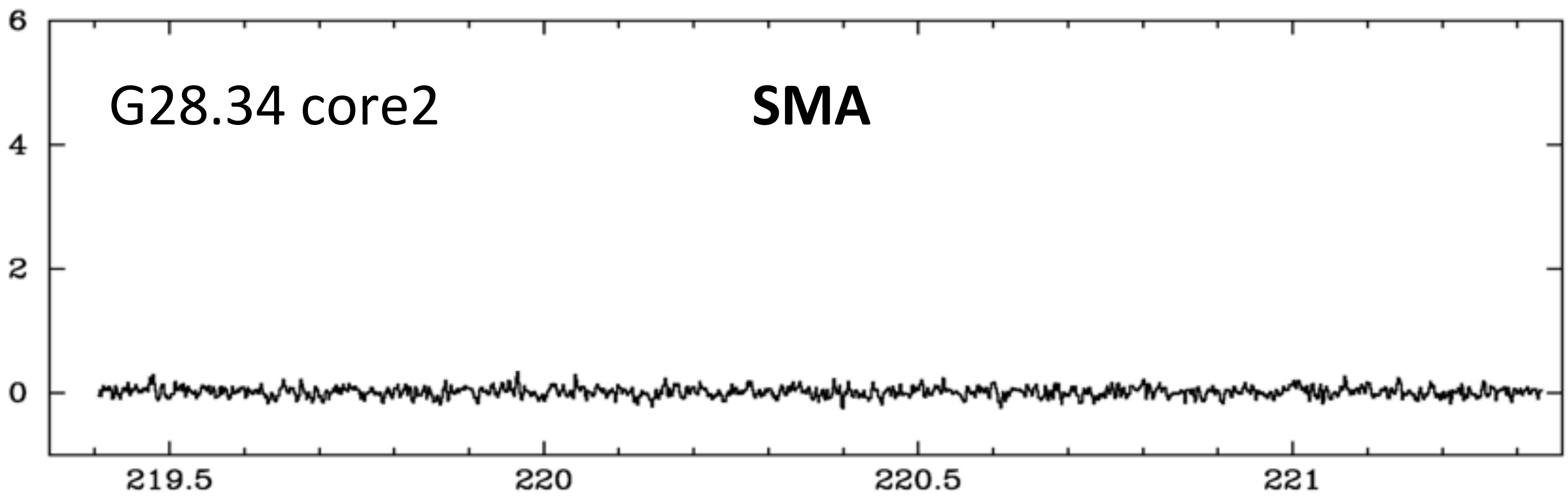
German ARC node

Key concepts to learn

Part 2

- Spectral lines
- Rest frequency
- Source velocity and redshift
- Line width
- Spectral resolution

Can we detect spectral lines?



Zhang et al (2008)

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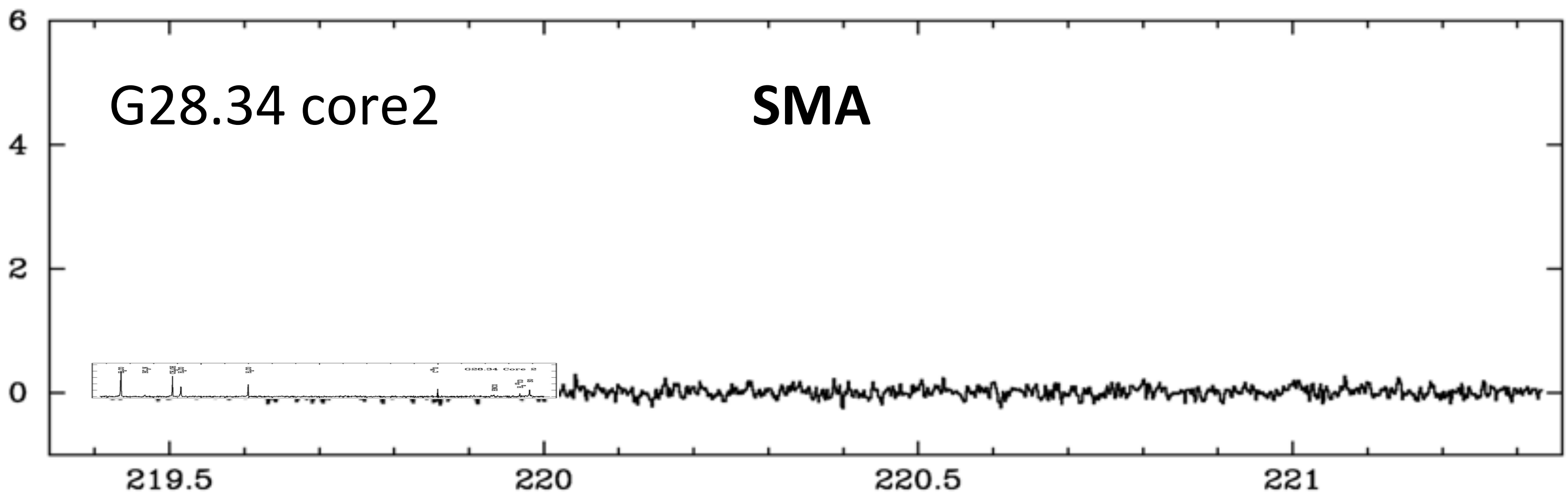

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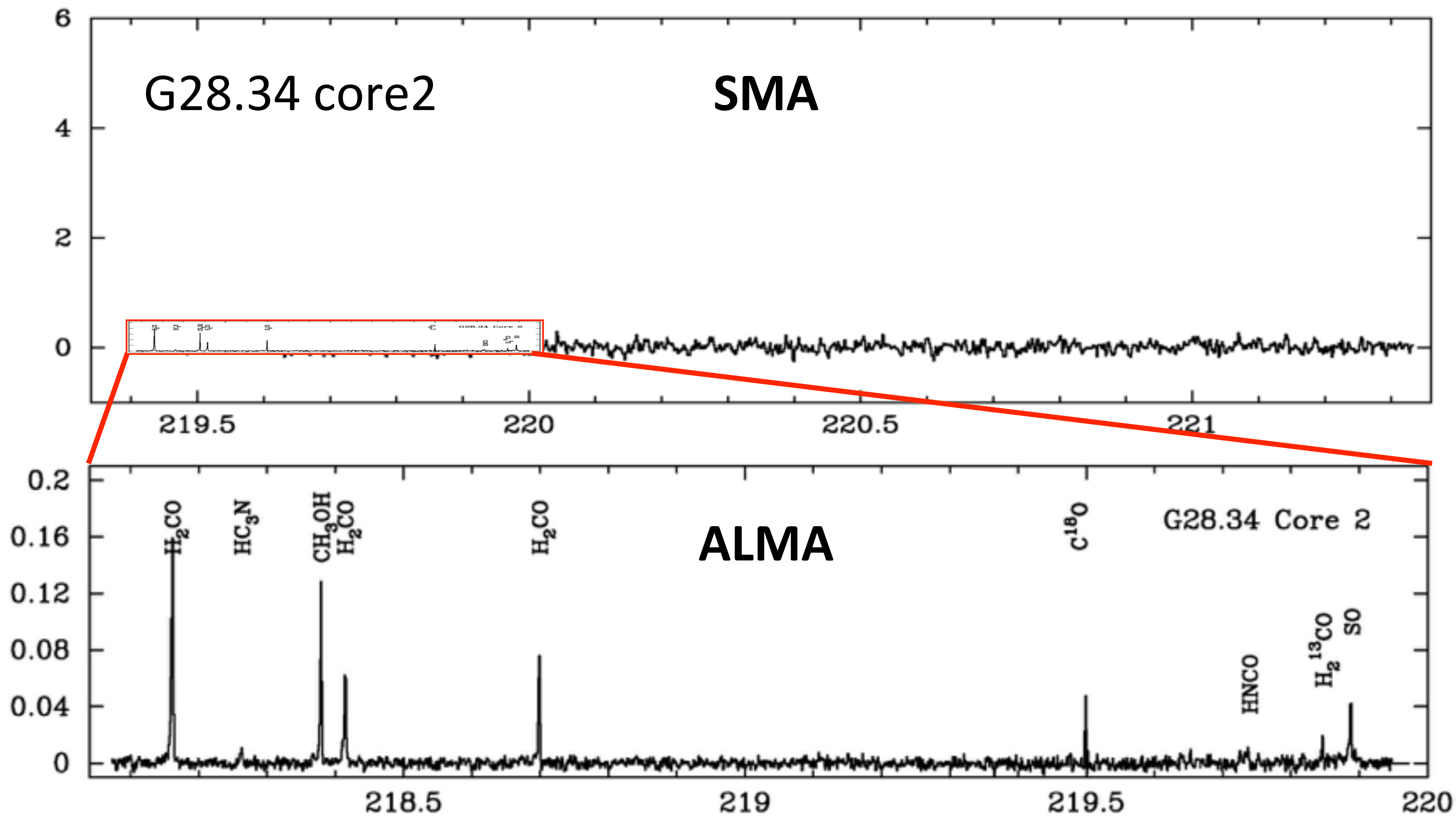

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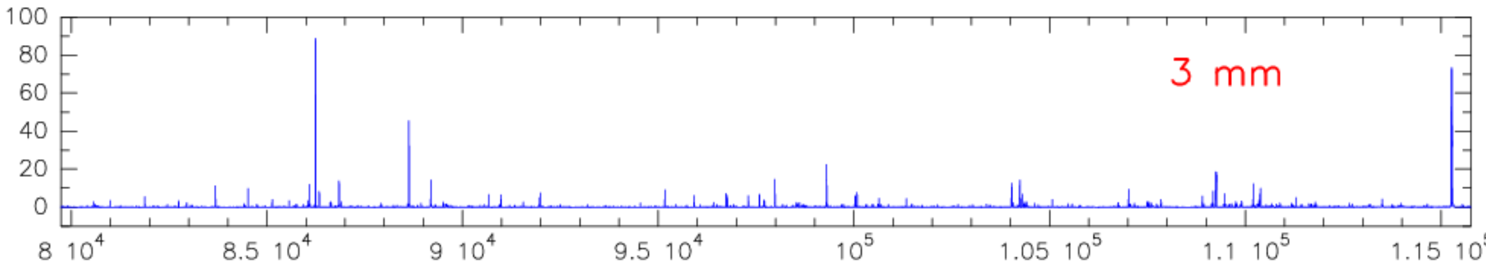
Zhang et al (2014)

Can we detect spectral lines?

When sensitivity can be a problem
… entering the ALMA era



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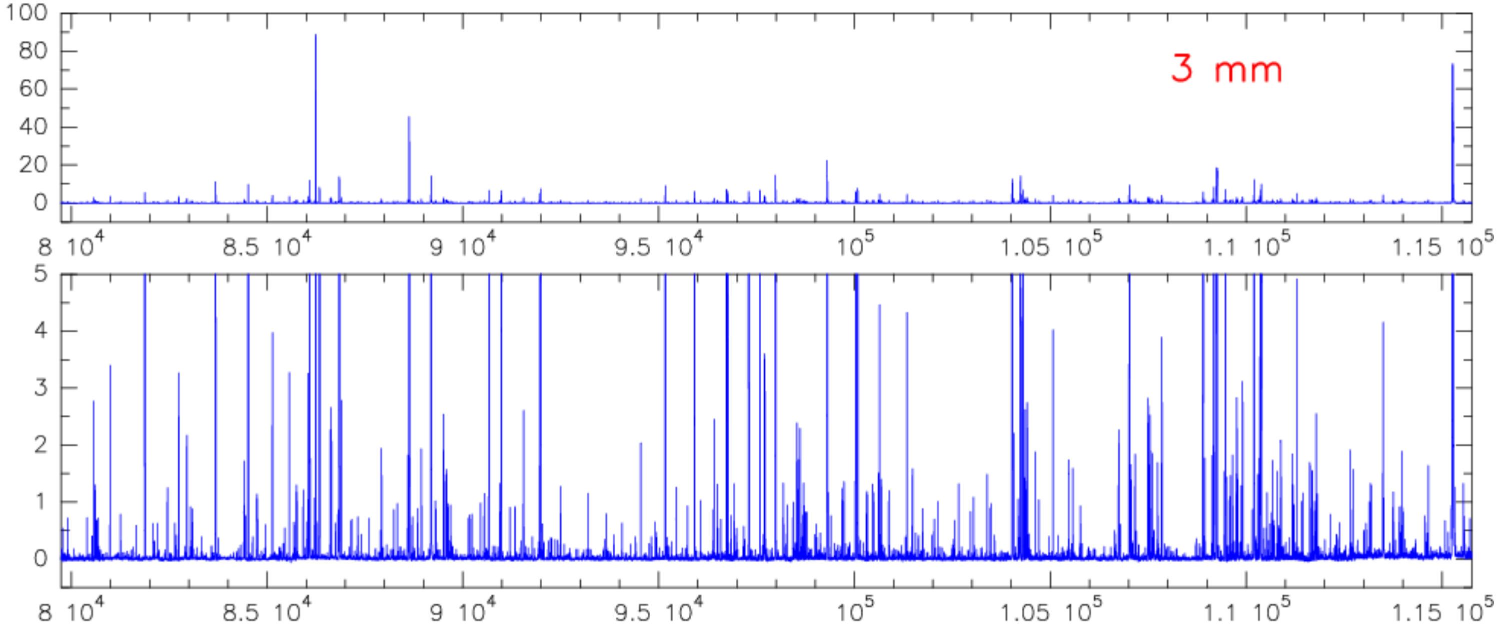

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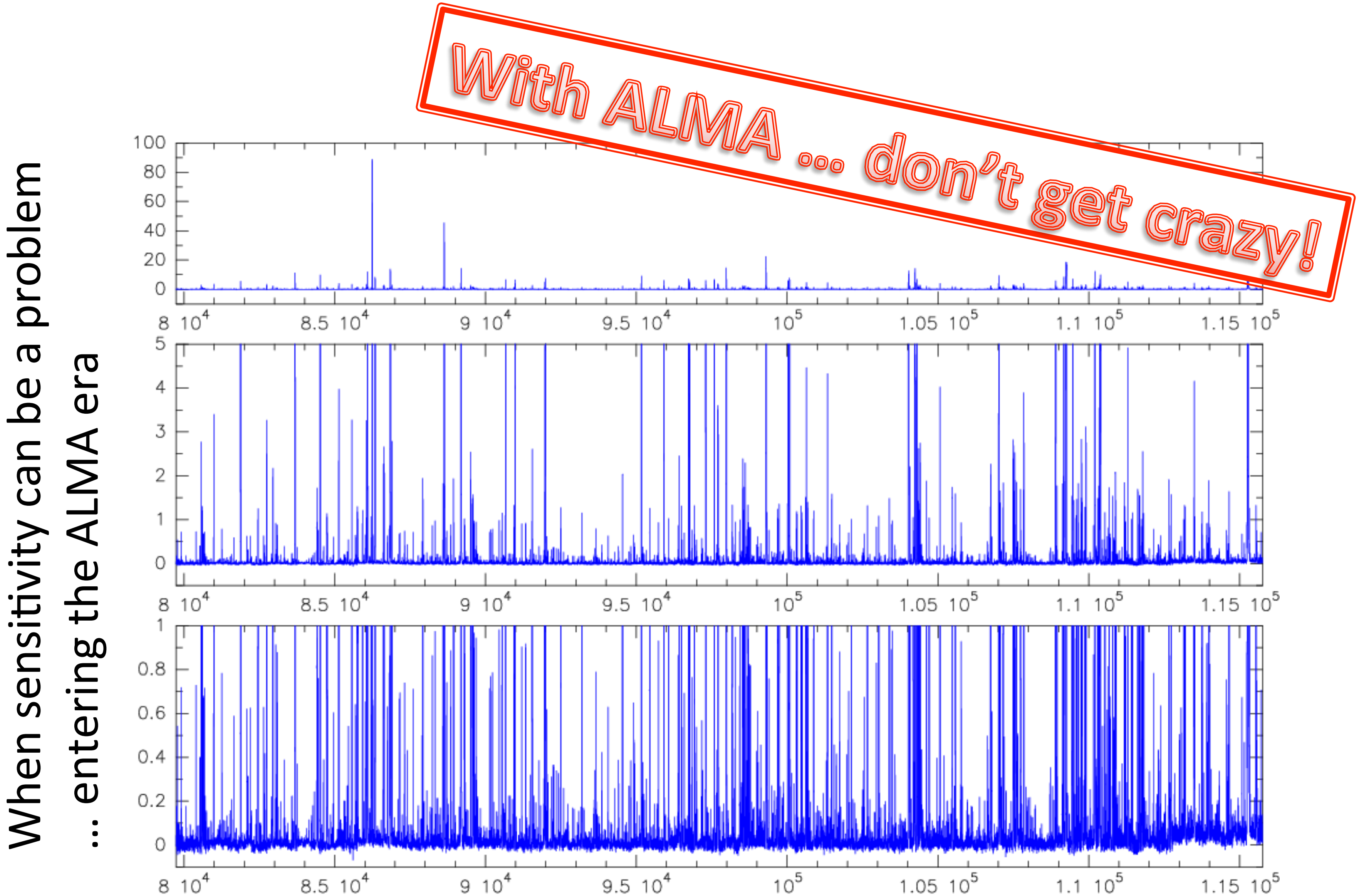

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- velocity / redshift of the source
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Basic concepts of spectral line observations

<u>Rest frequency</u>

Basic concepts of spectral line observations

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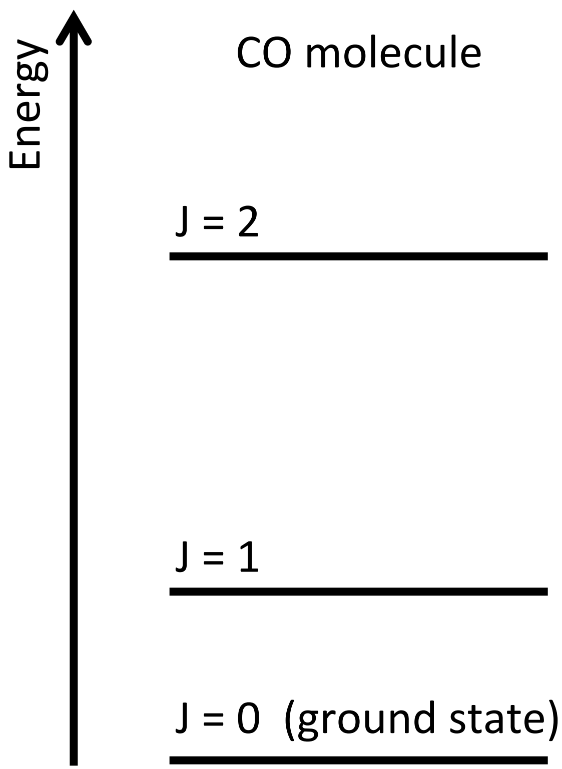
spectral line: transition between two different energy levels of a molecule, atom or ion



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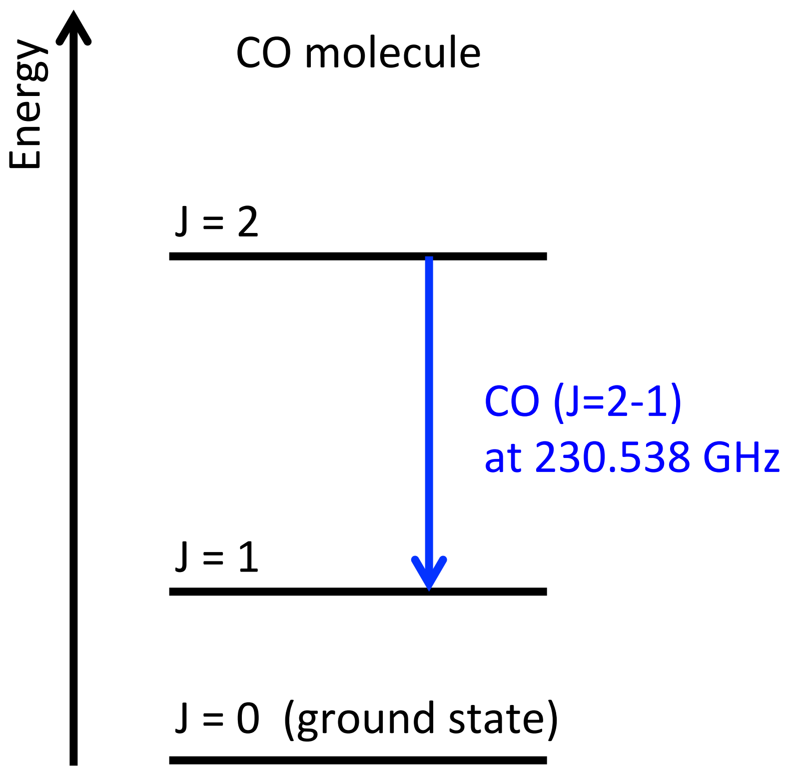

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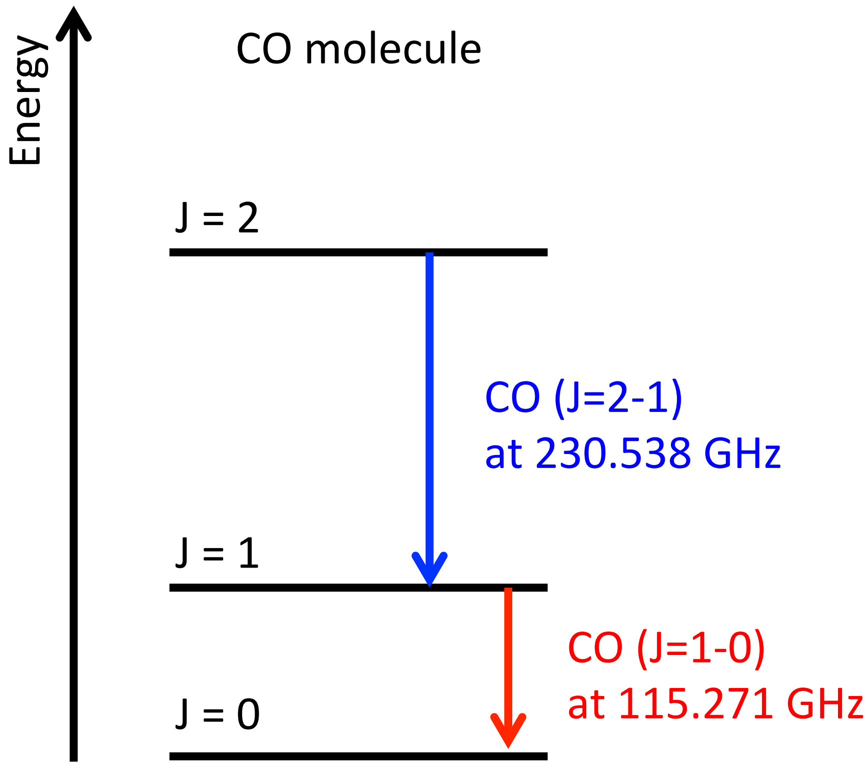

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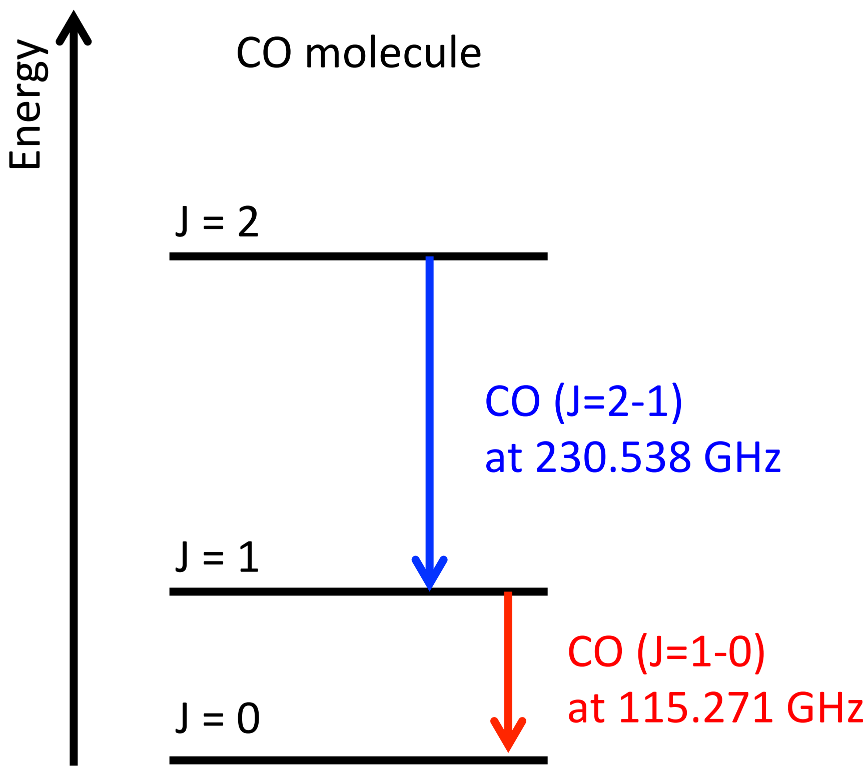

Rest frequencies can be found in molecular databases:

CDMS
www.astro.uni-koeln.de/cdms

JPL
spec.jpl.nasa.gov

Splatalogue
www.splatalogue.net

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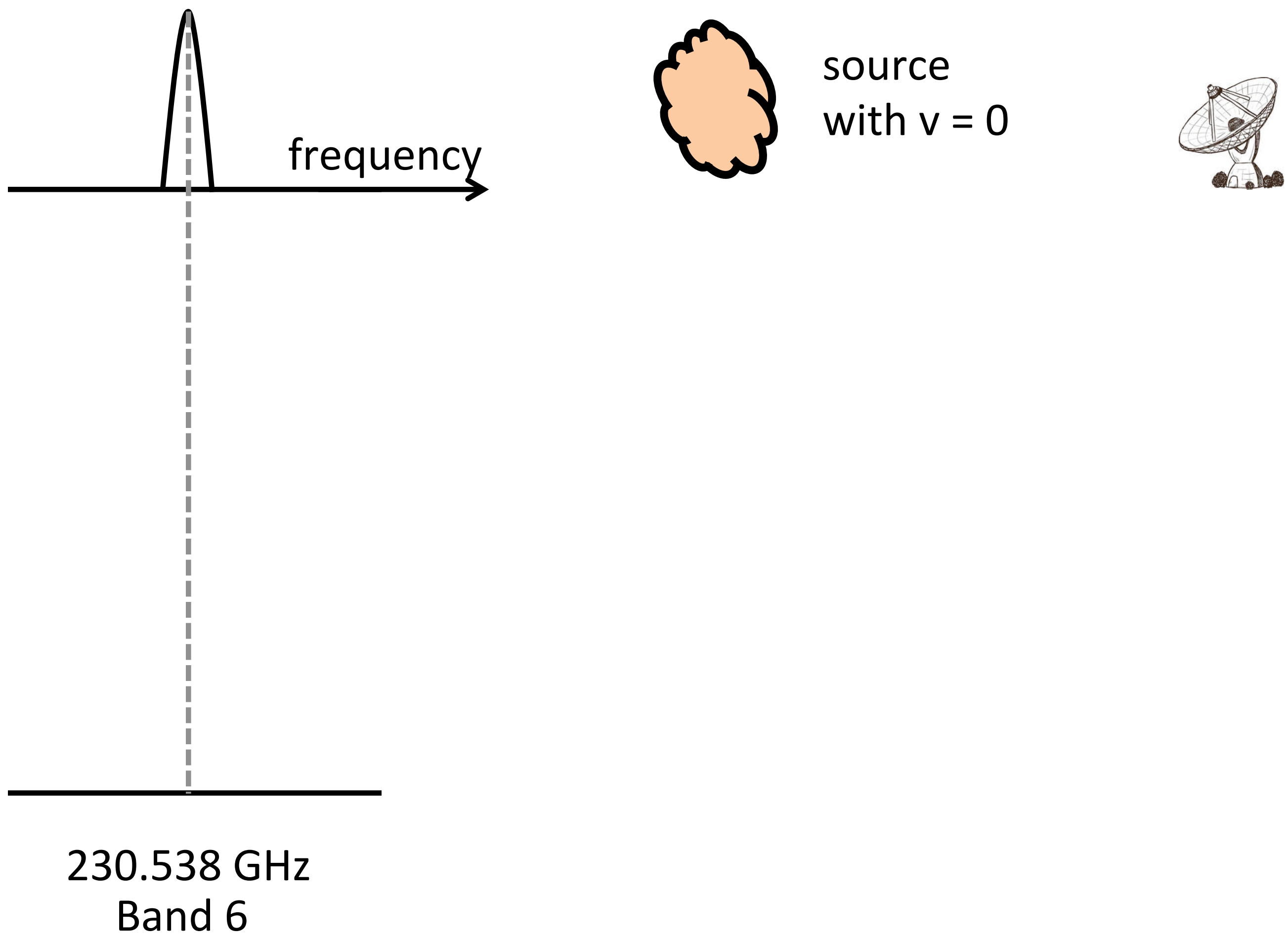

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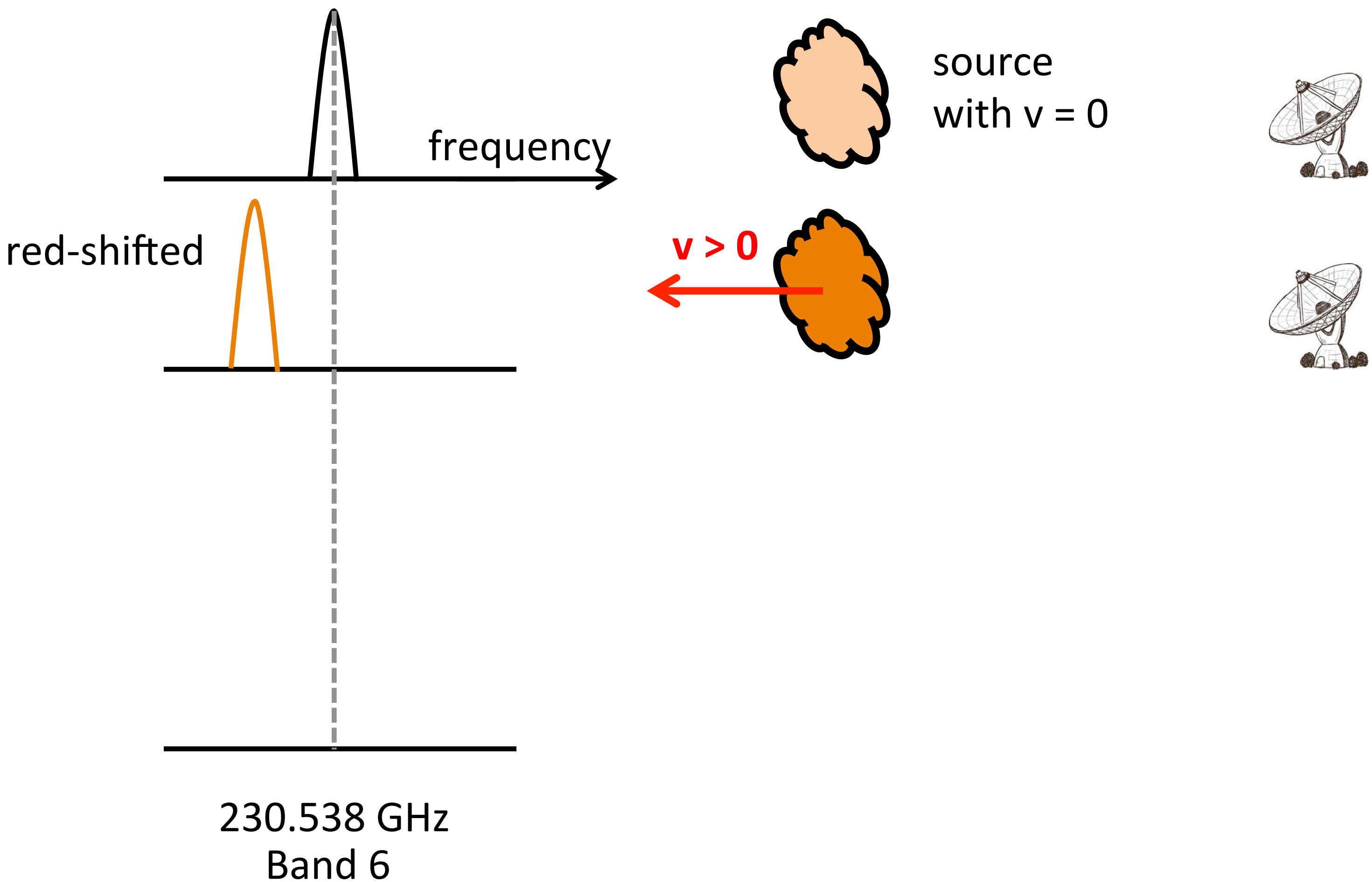

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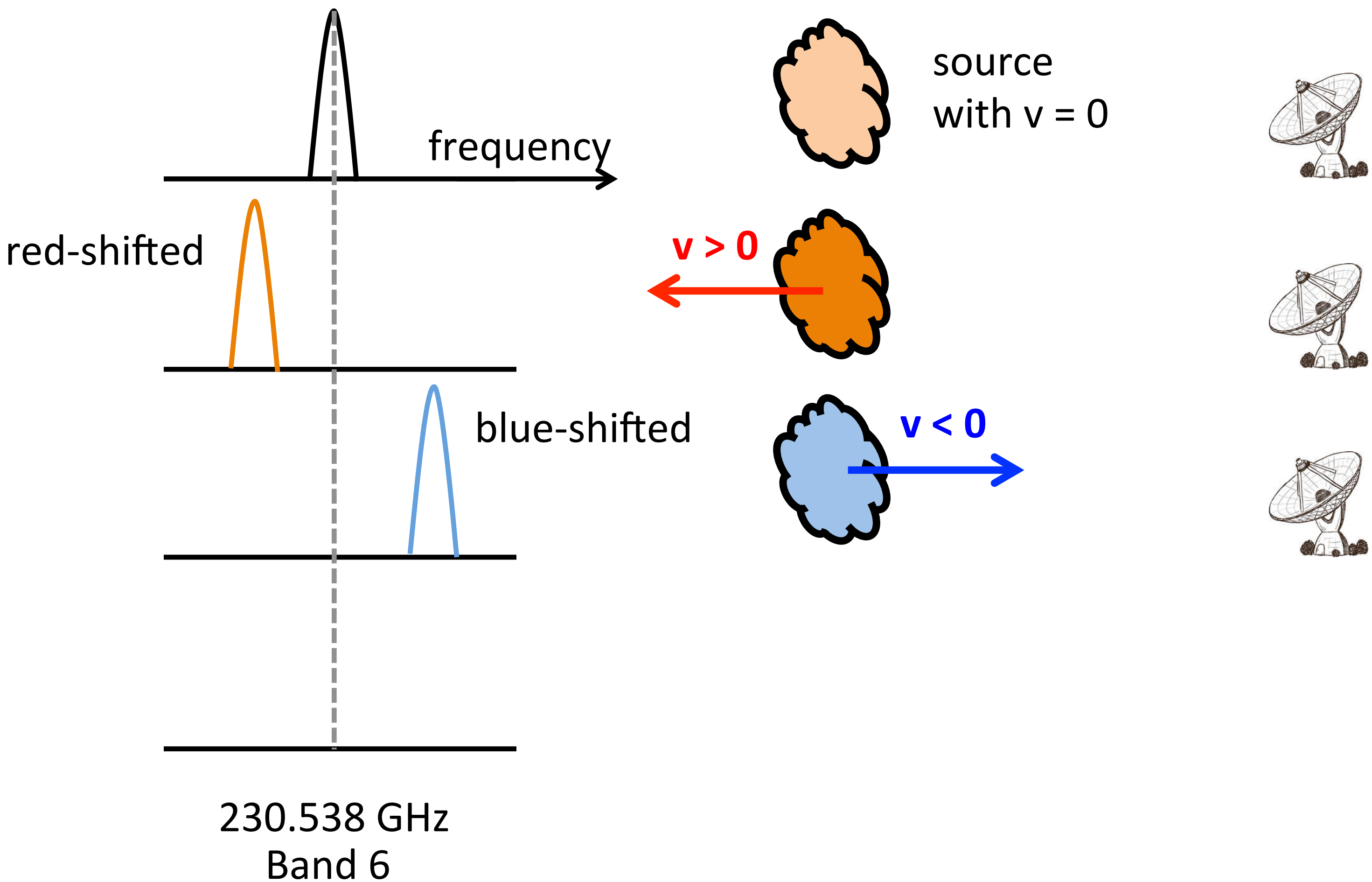

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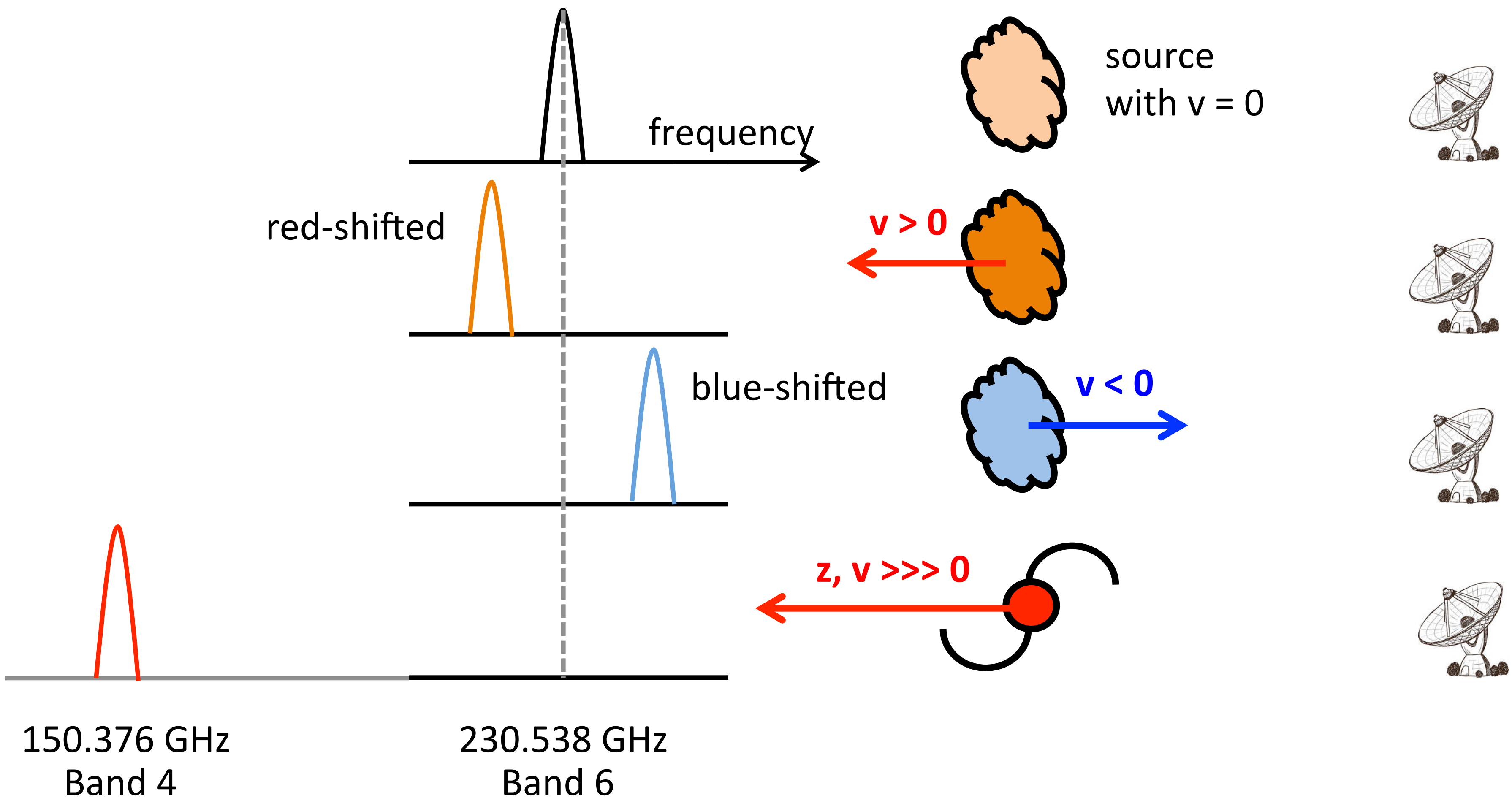

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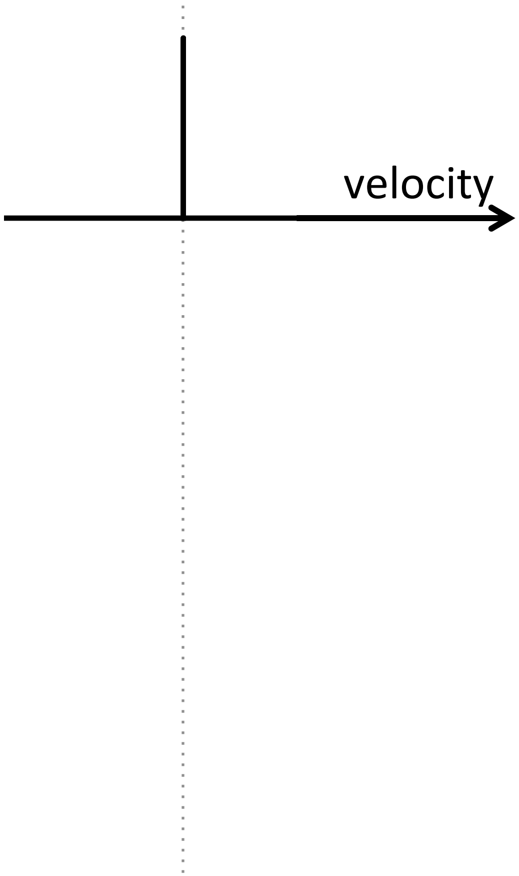

each spectral line has an exact frequency

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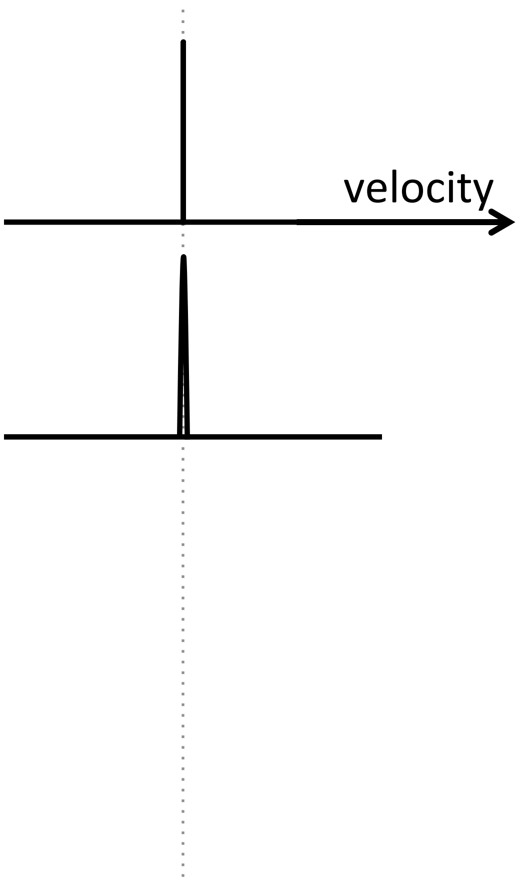

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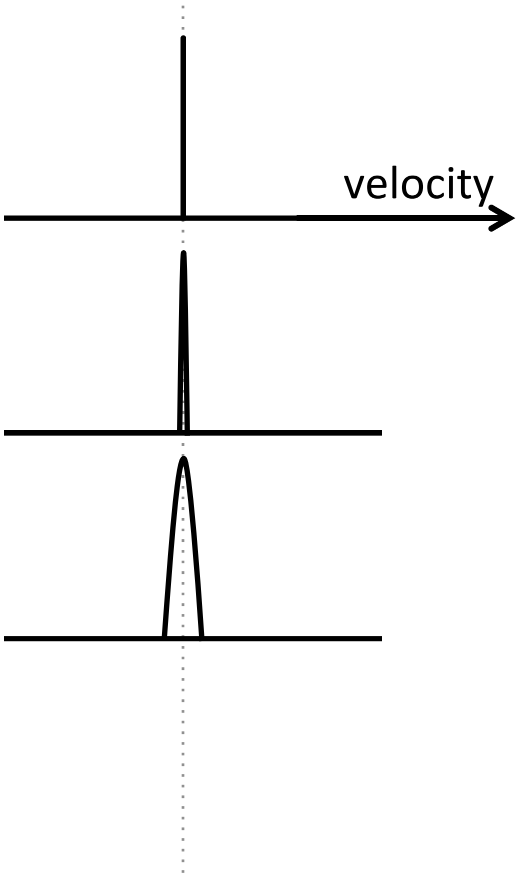

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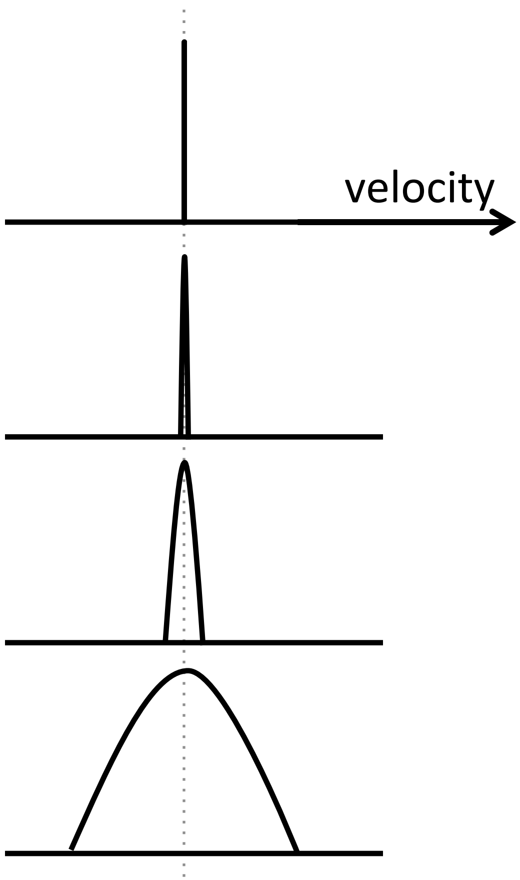

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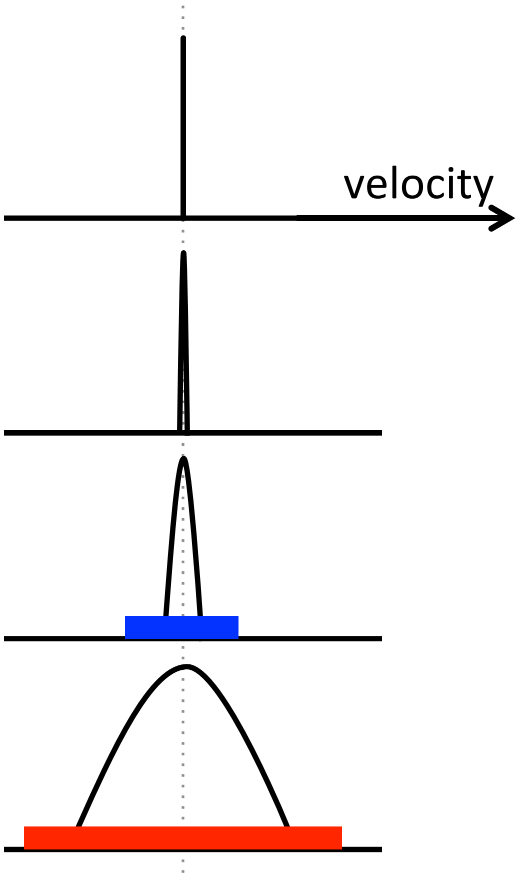

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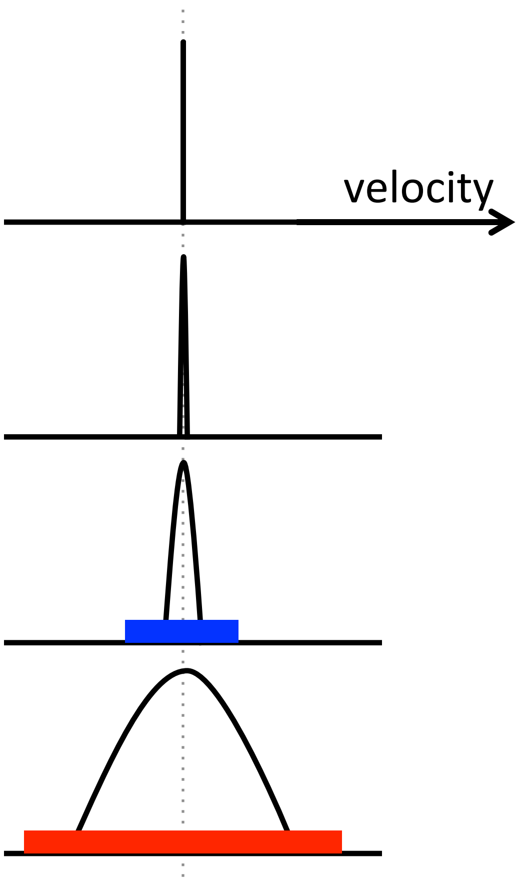

velocity linewidth (km/s)

frequency linewidth (Hz)

$$\Delta V = -\Delta \nu \frac{c}{\nu_0}$$

Depending on the linewidth of the line, you will cover a narrower/broader **frequency** (***velocity***) range

What do we need to know?

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Spectral observations in a radio-interferometer

- frequency bands
- receivers
- correlator

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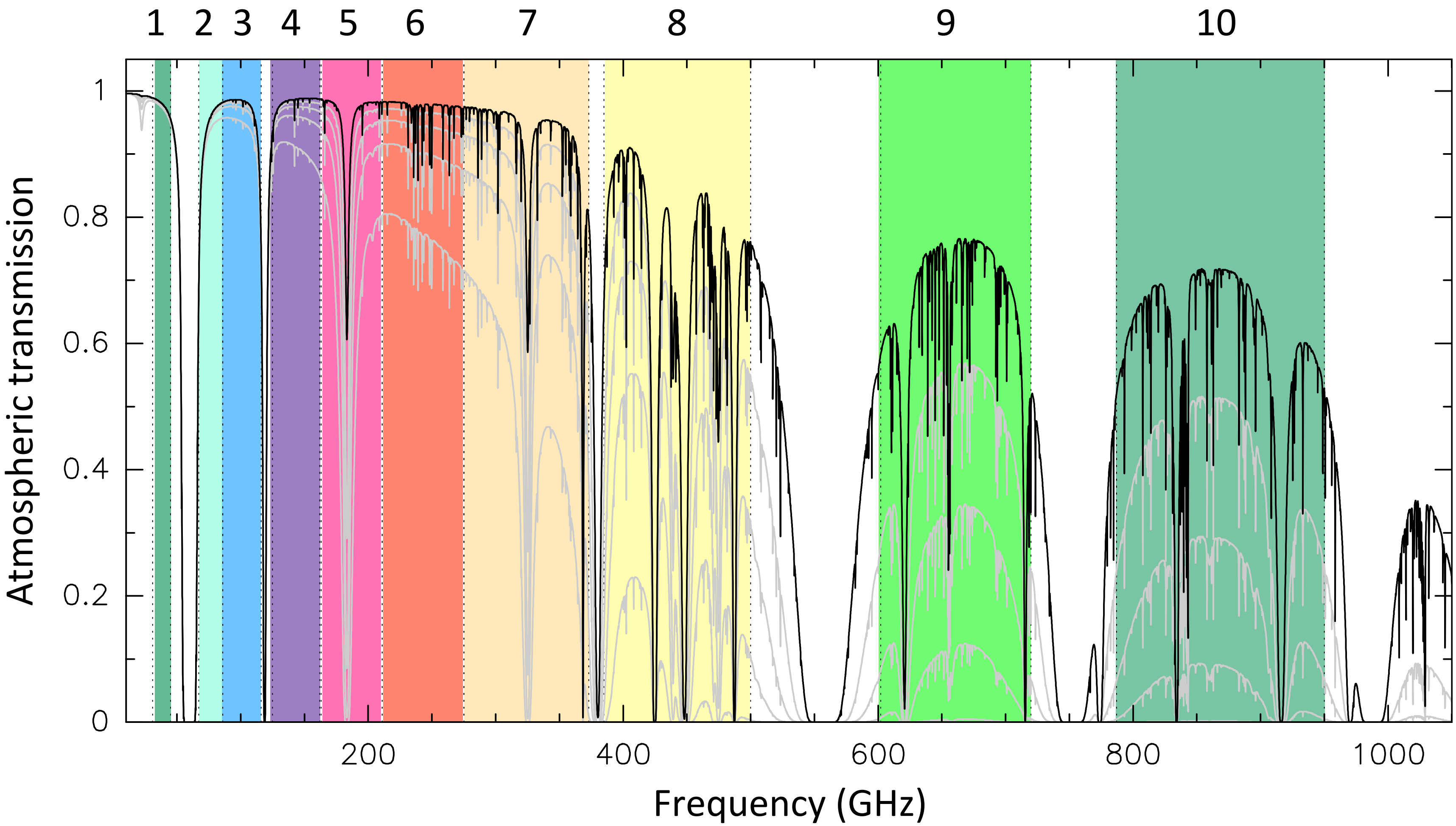
ALMA frequency bands



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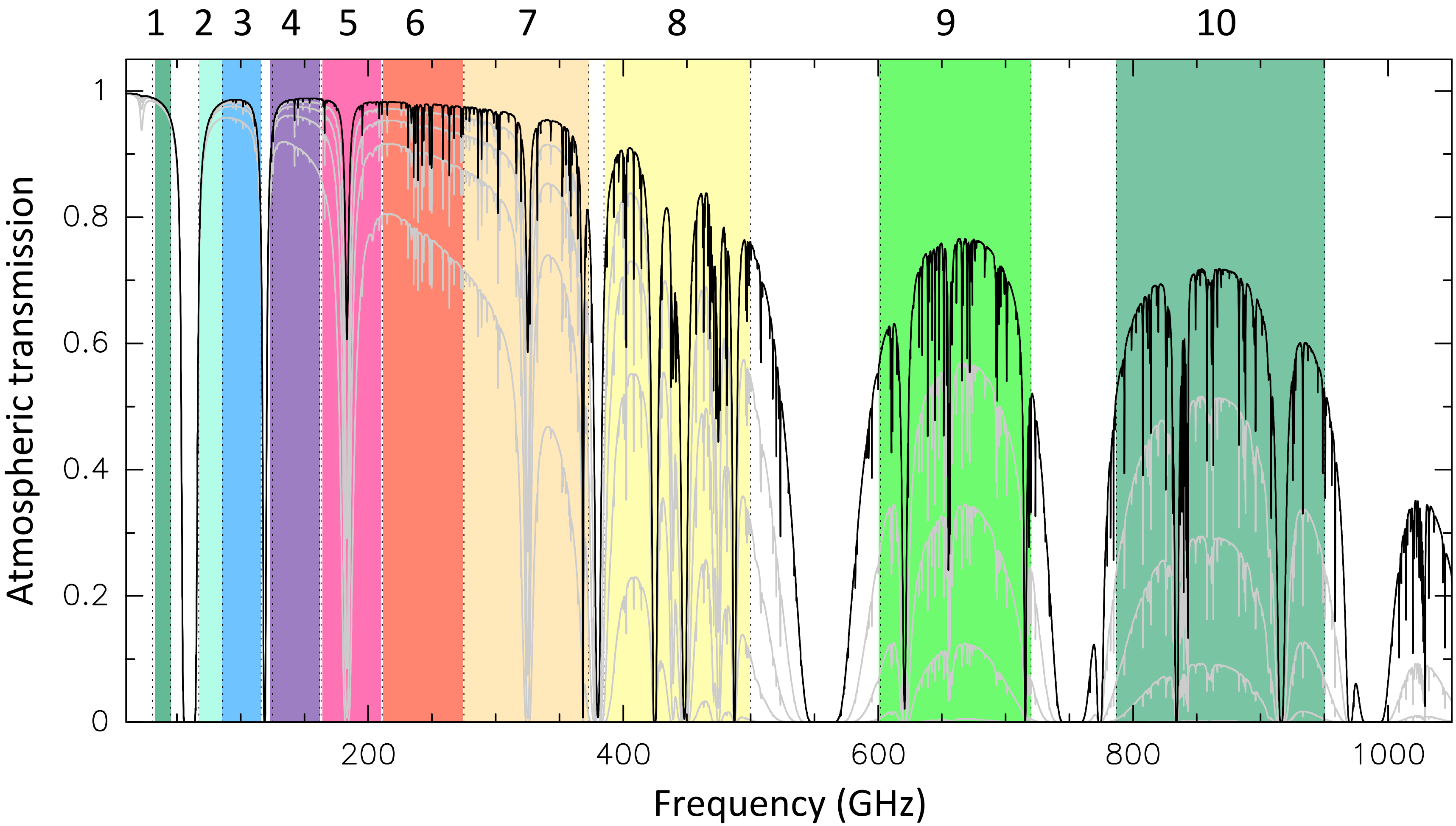

Band 3: 84 – 116 GHz

Band 4: 125 – 163 GHz

Band 5: 159 – 211 GHz

Band 6: 211 – 275 GHz

Band 7/8: 275 – 373 GHz / 385 – 500 GHz

Band 9/10: 602 – 720 GHz / 787 – 950 GHz

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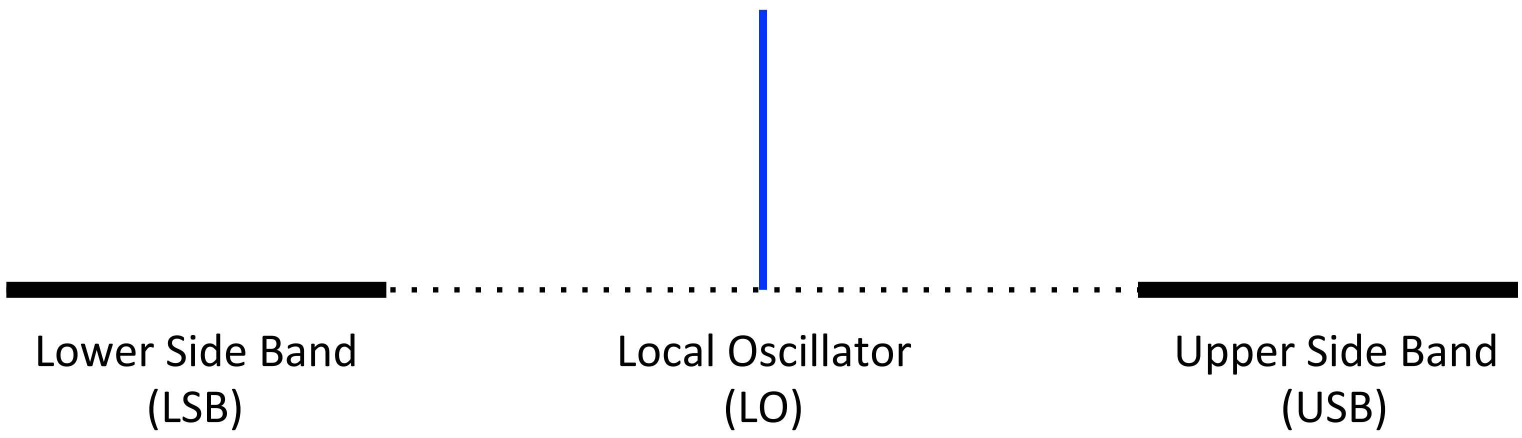
ALMA receivers

Heterodyne receivers
are sensitive to Lower Side Band (LSB) and Upper Side Band (USB)



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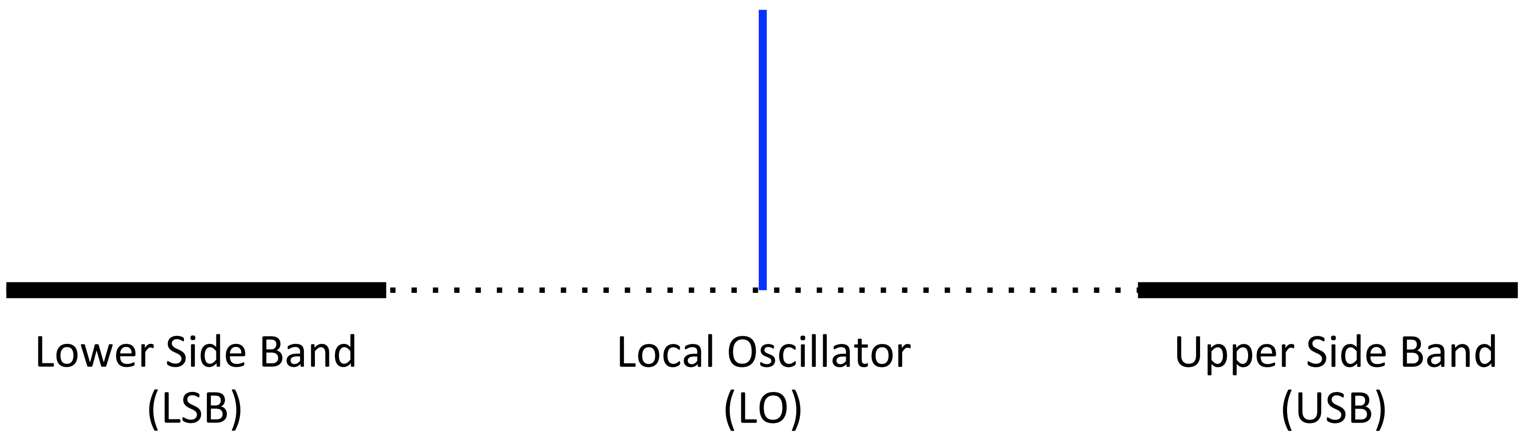
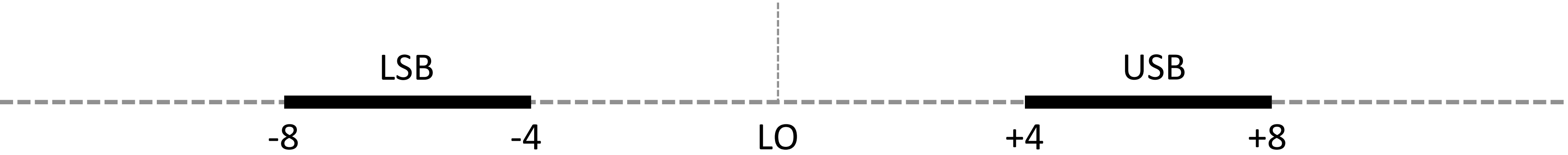


Heterodyne receivers can be:

- **SSB** (single) outputs LSB **or** USB
- **DSB** (double) outputs the sum LSB+USB (separated in correlator)
- **2SB** (two) outputs LSB **and** USB (separately)

ALMA receivers

ALMA B3 / B4 / B5 / B7 / B8 2SB receivers 4-8 GHz



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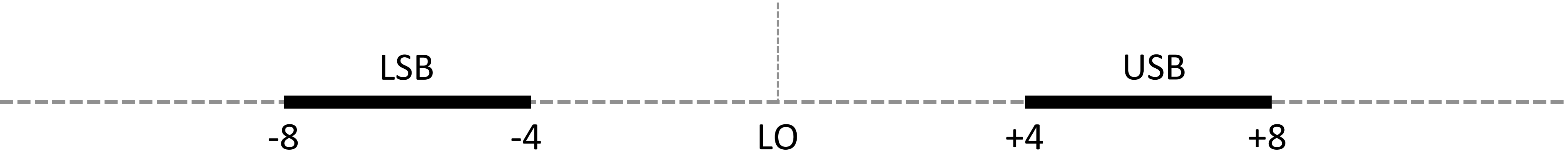
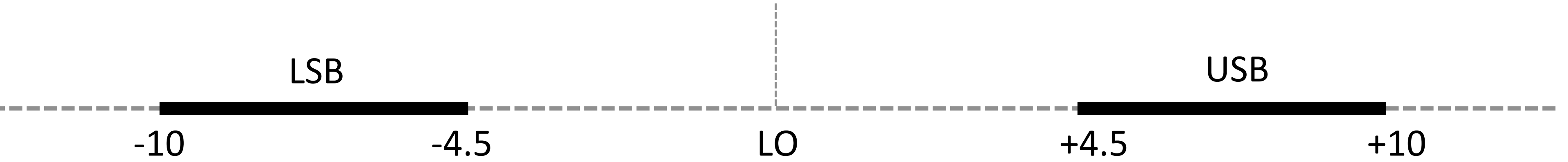


ALMA B6 2SB receivers 4.5-10 GHz



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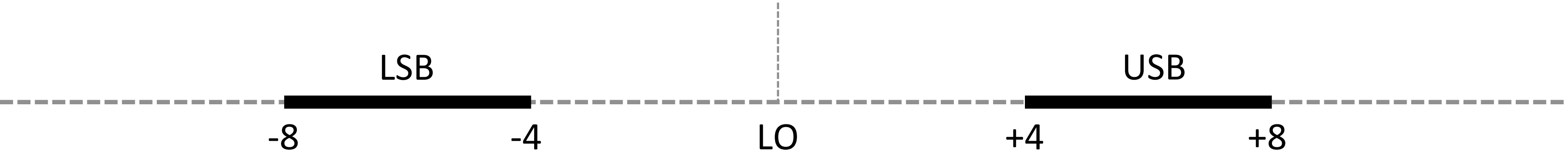
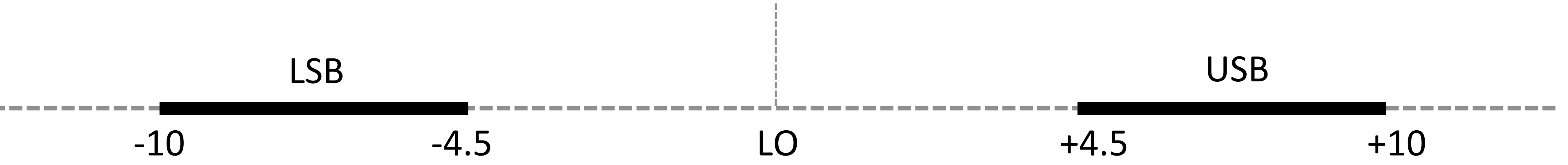
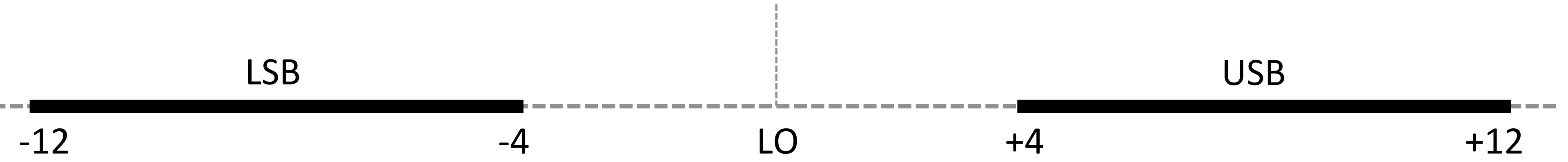


ALMA B6   2SB receivers 4.5-10 GHz



ALMA B9 / B10   DSB receivers 4-12 GHz



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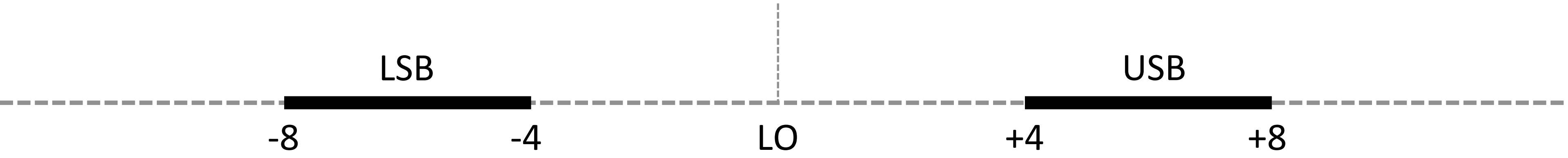

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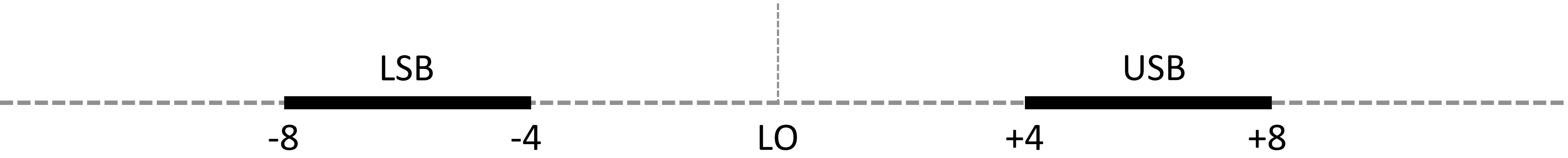
Band 4:	125 – 163 GHz	Band 8:	385 – 500 GHz
Band 6:	211 – 275 GHz	Band 9/10:	602 – 720 GHz / 787 – 950 GHz

ALMA B3 / B4 / B5 / B7 / B8 2SB receivers 4-8 GHz



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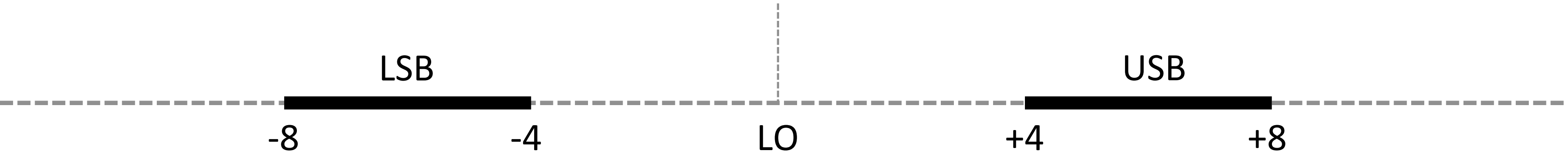

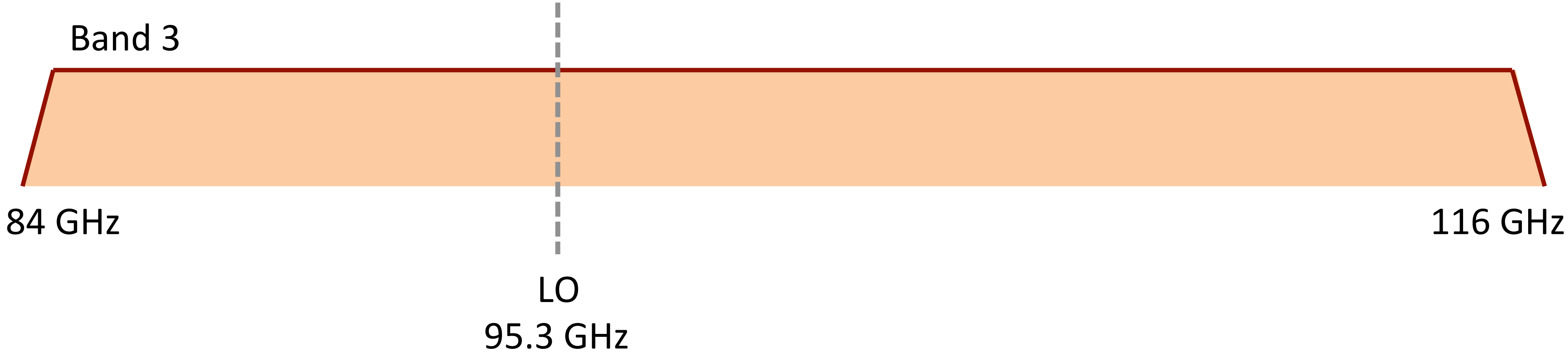

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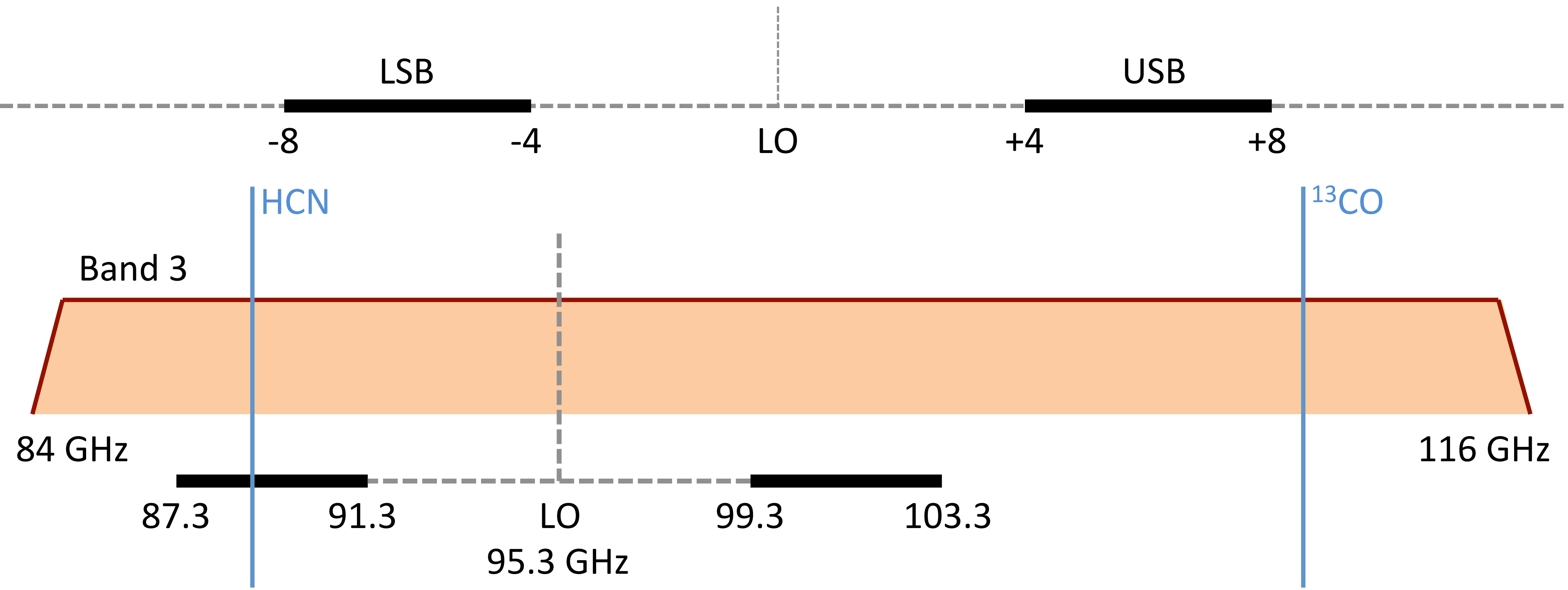

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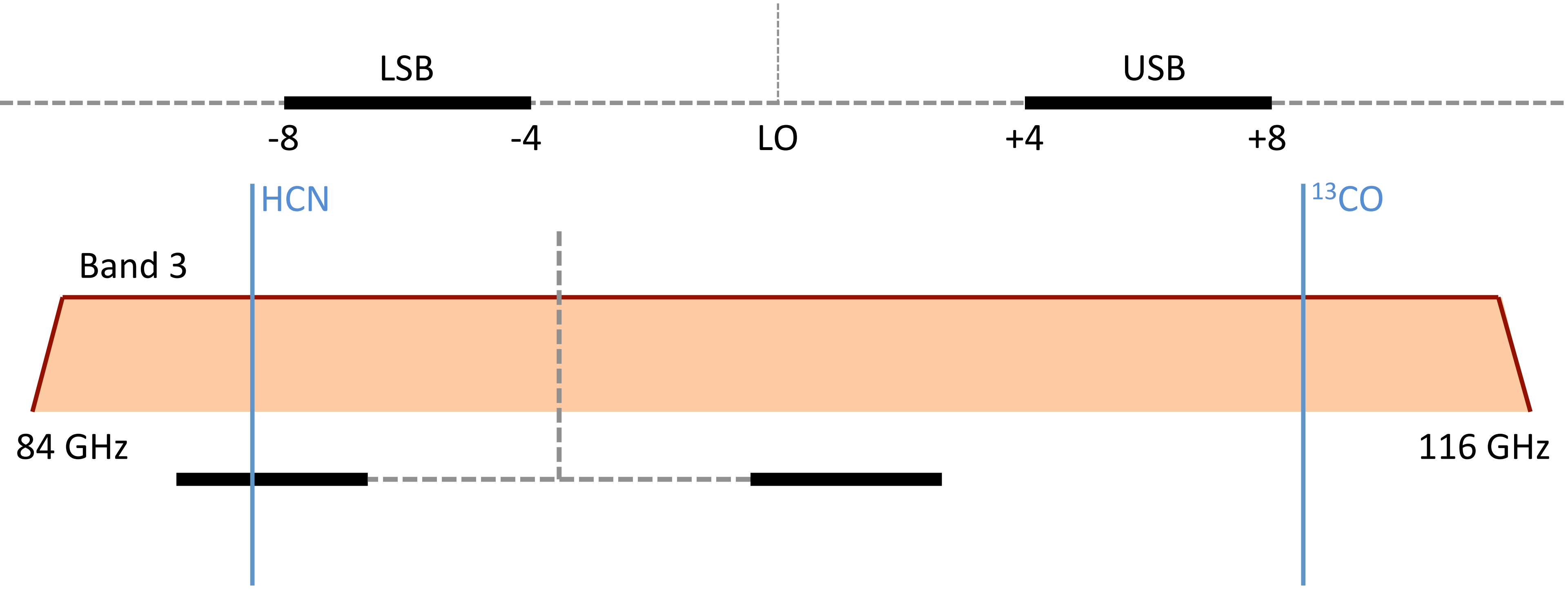

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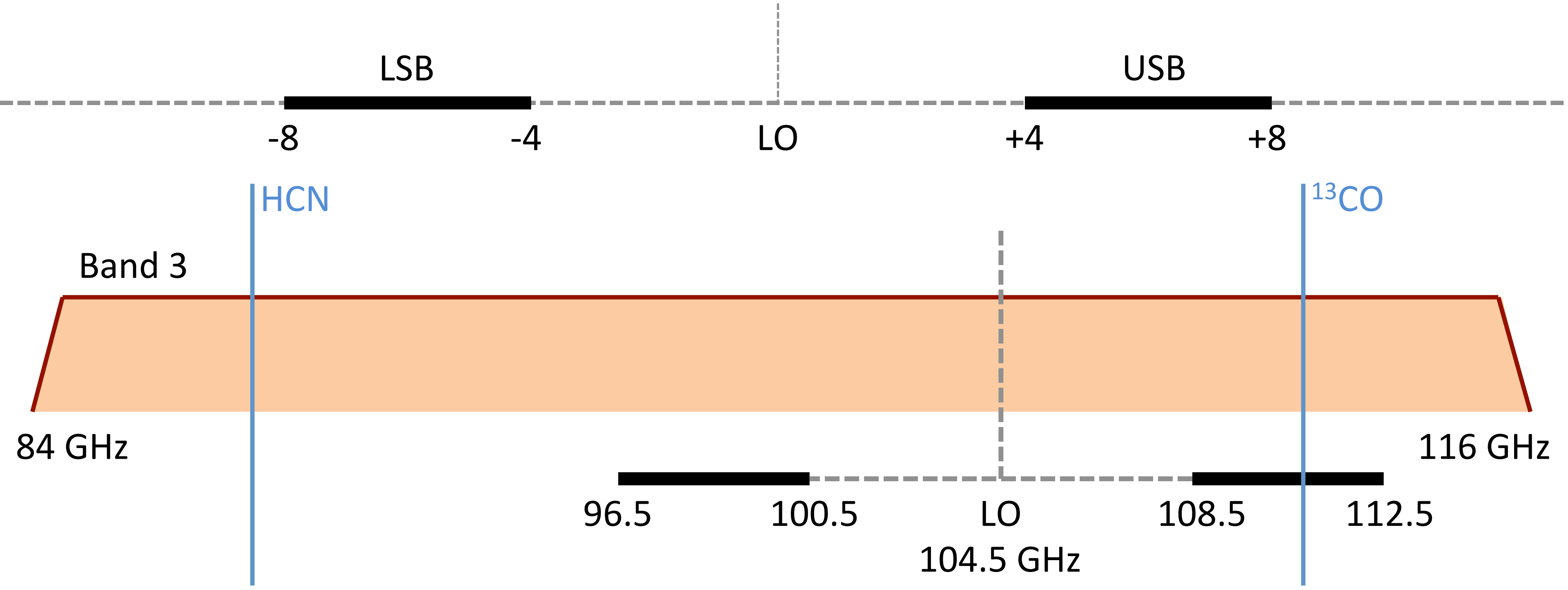

What do we need to know?

- frequency of the lines to observe
- velocity /redshift of the source
- line shape / velocity coverage and resolution
- …

Spectral observations in a radio-interferometer

- frequency bands
- receivers
- **spectral resolution (correlator)**

ALMA correlator / 4 basebands

basebands

information from 64 antennas
2 GHz input
up to 8192 channels
2 polarizations Horizontal / Vertical
up to 4 polarization products (HH, VV, HV, VH)

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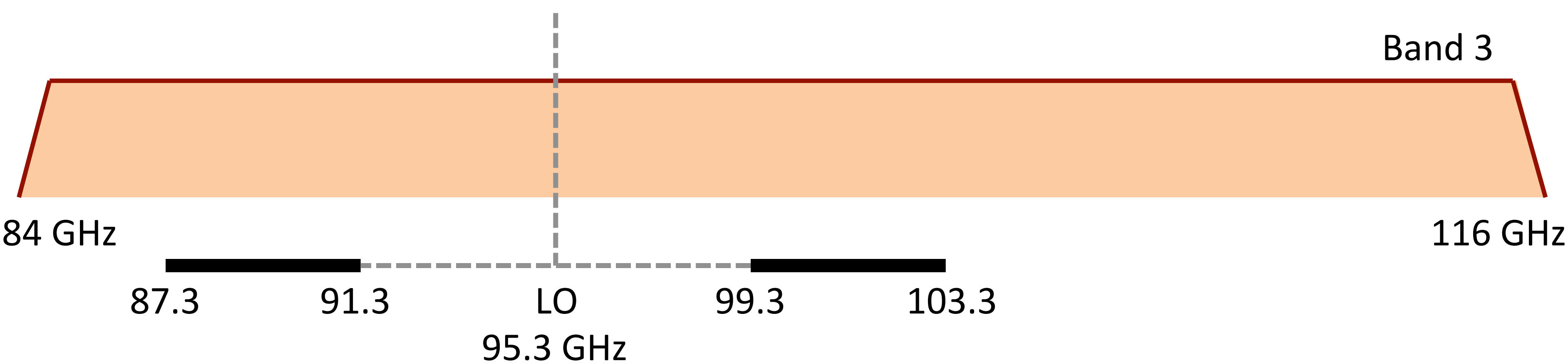

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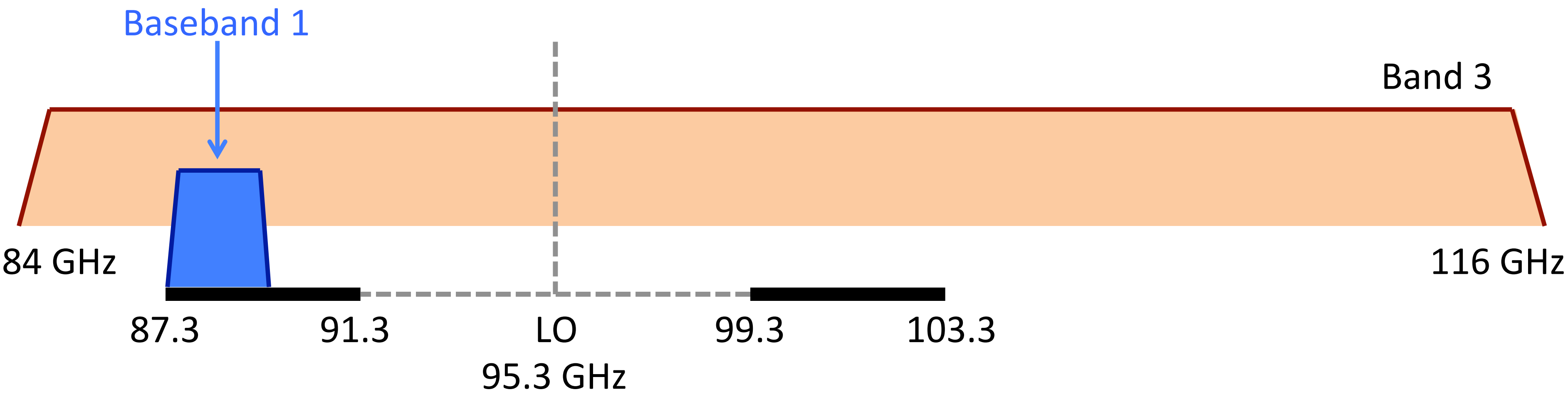

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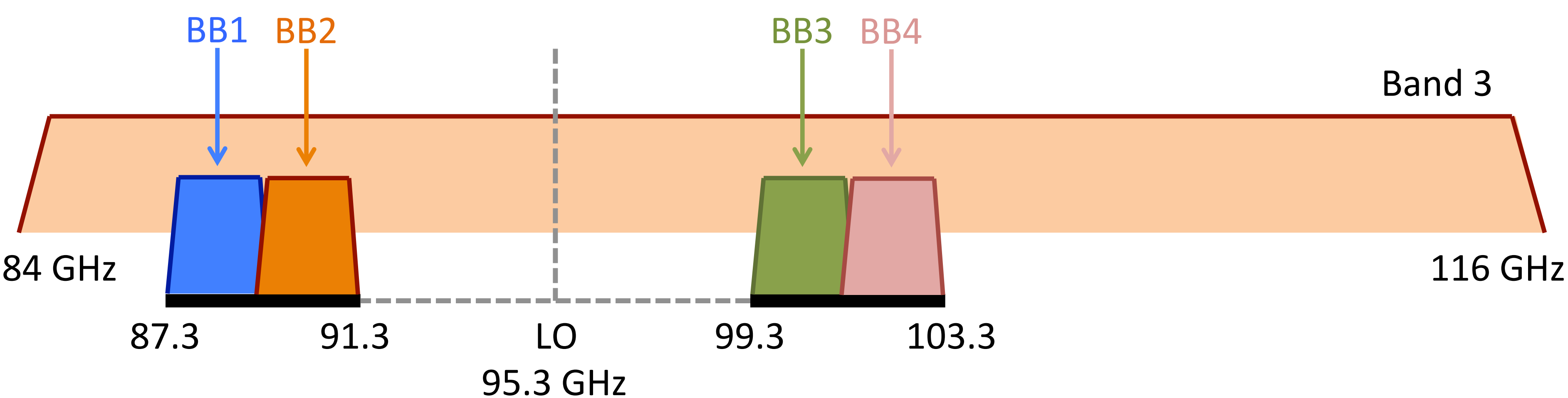

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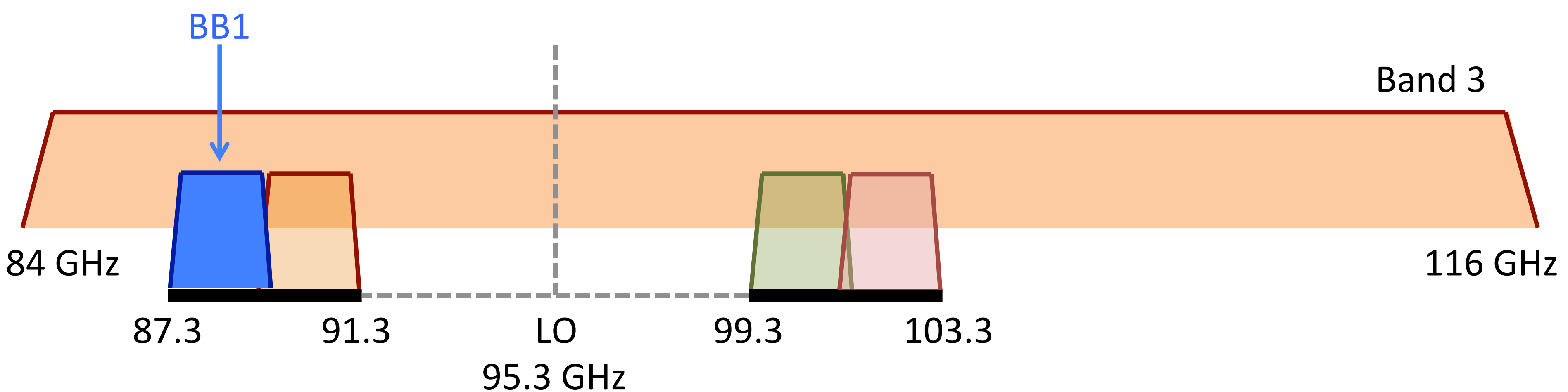

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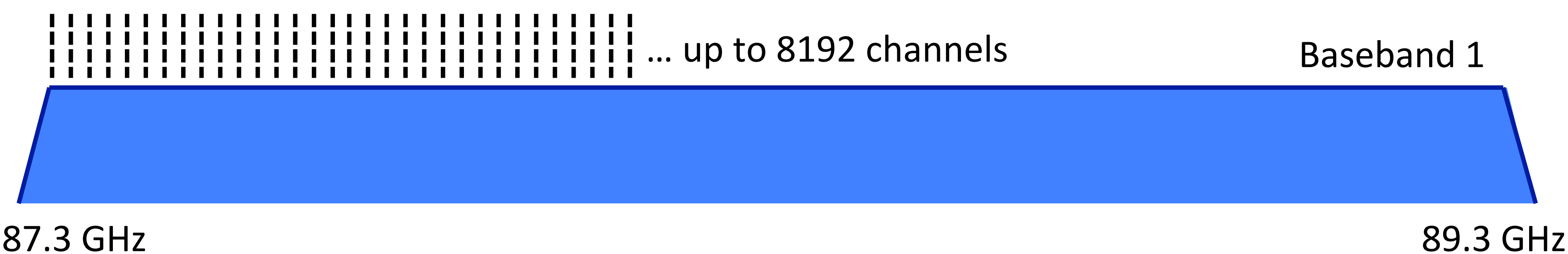

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2 GHz input

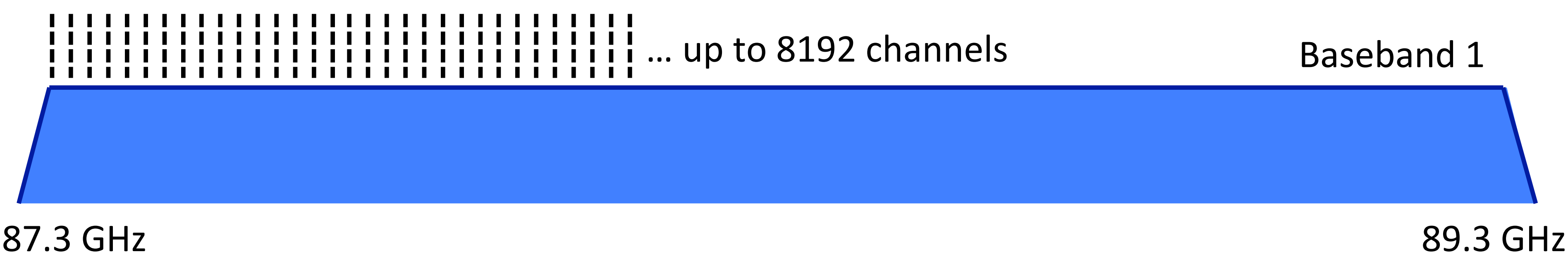
up to **8192 channels**

2 polarizations Horizontal / Vertical

up to 4 polarization products (HH, VV, HV, VH)

channel width (**spectral resolution**):

2 GHz / 8192 = 244 kHz (0.8 km/s)



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basebands

information from 64 antennas

2 GHz input

up to **8192 channels**

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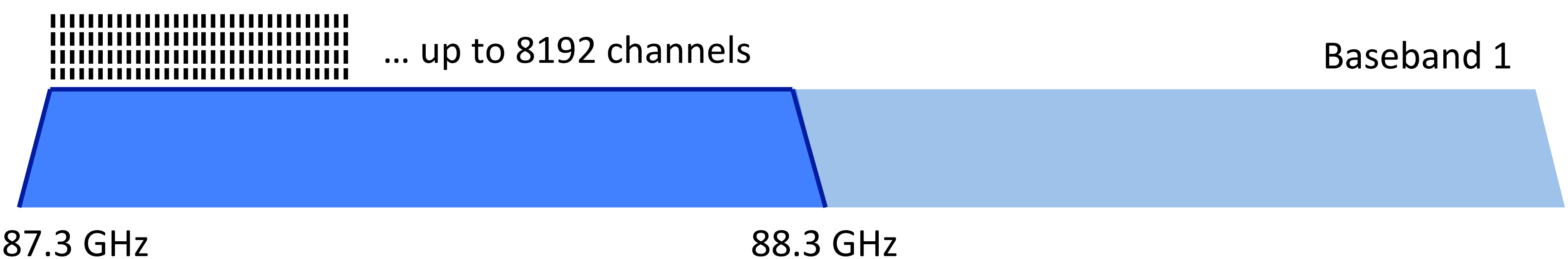
channel width (**spectral resolution**):

1 GHz / 8192 = 122 kHz (0.4 km/s)



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channel width (**spectral resolution**):

64 MHz / 8192 = 7.5 kHz (0.025 km/s)

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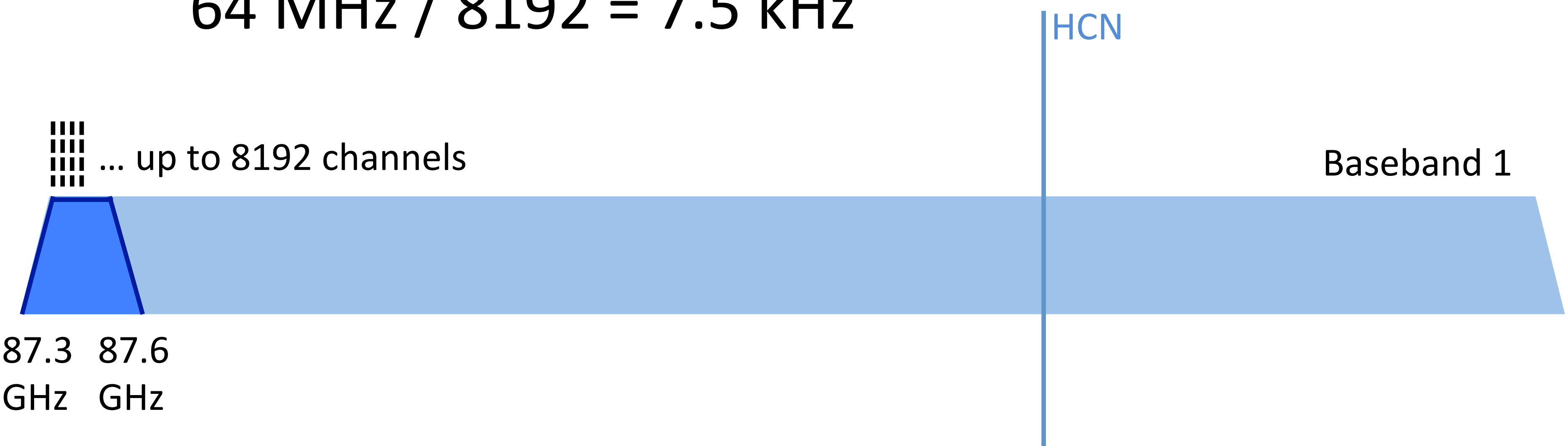

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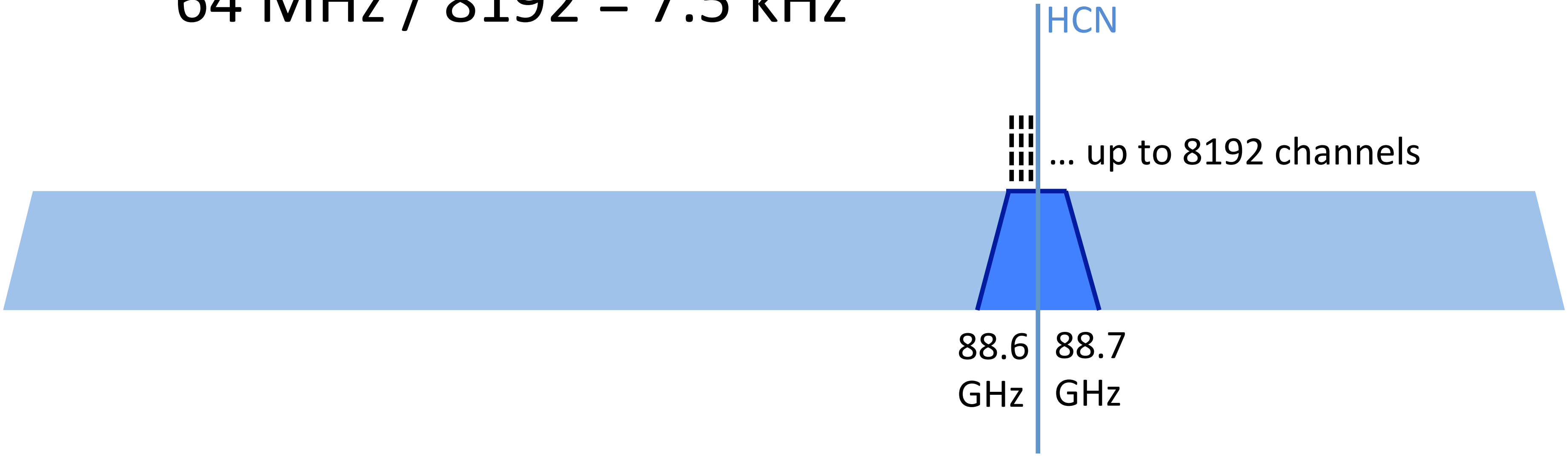
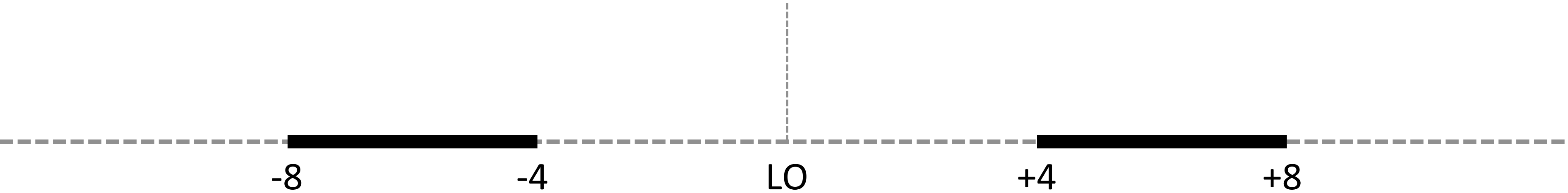
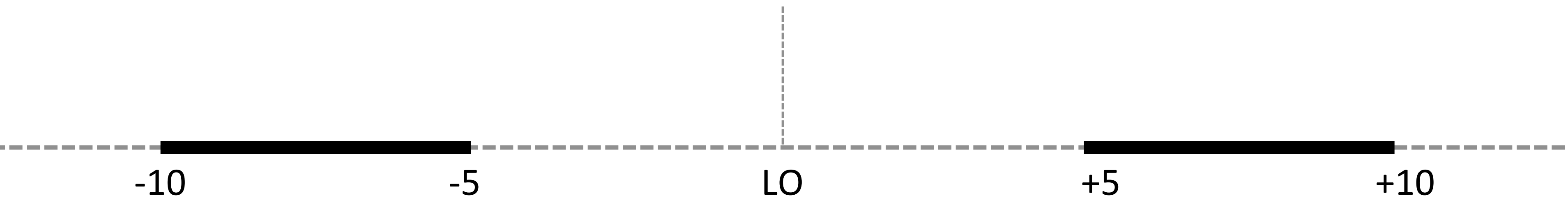


ALMA correlator (examples)

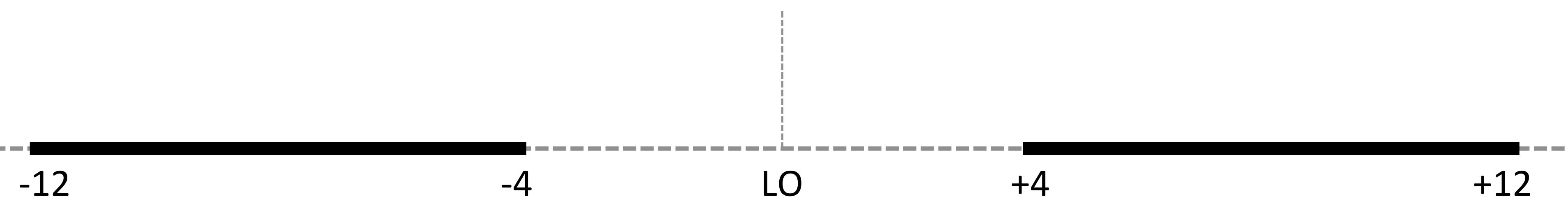
ALMA B3 / B4 / B5 / B7 / B8 — 2SB receivers 4-8 GHz



ALMA B6 — 2SB receivers 4.5-10 GHz



ALMA B9 / B10 — DSB receivers 4-12 GHz



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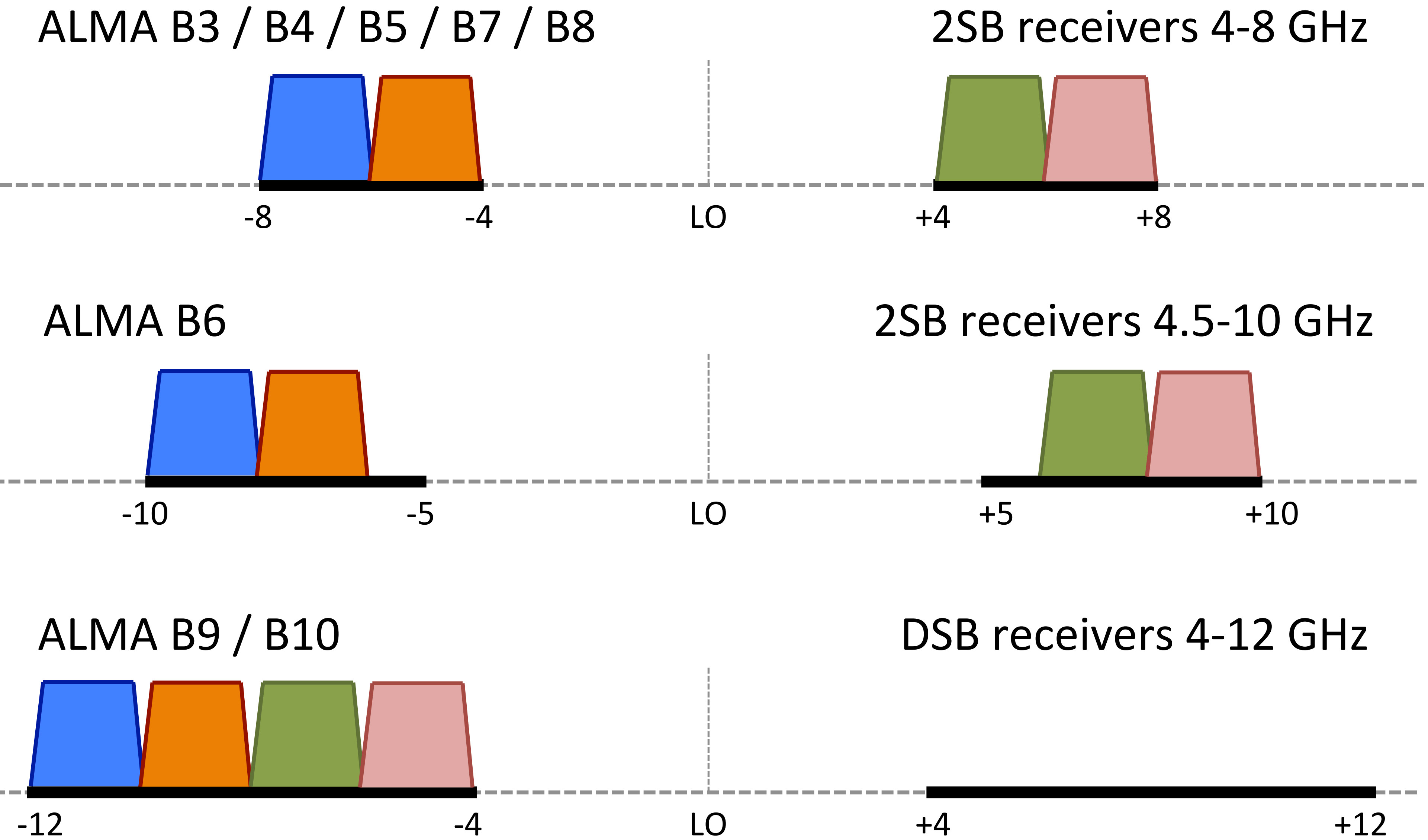

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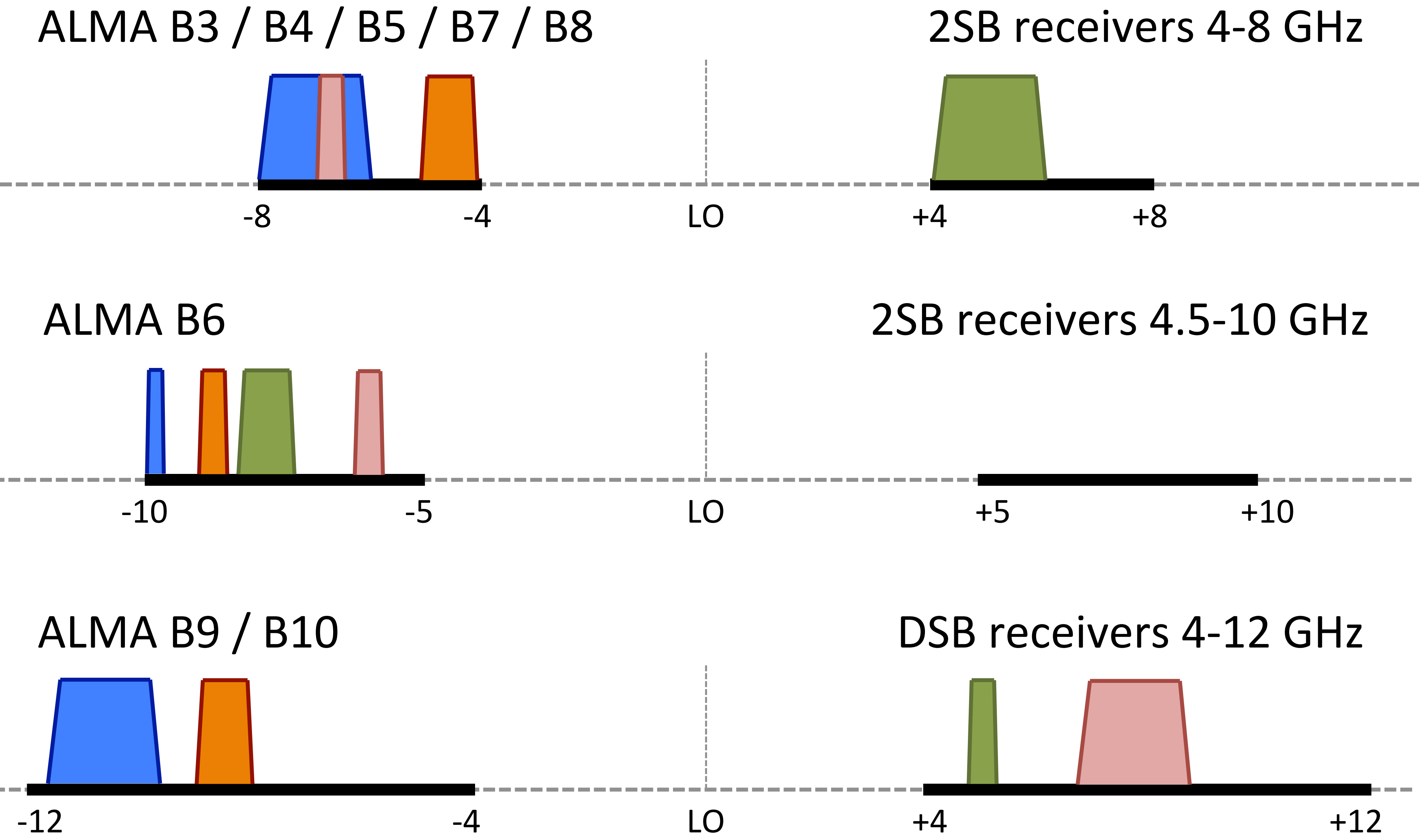

Spectral setup in the almaOT (EXAMPLE)

We want to observe three lines in our target:

HCN(1-0), HCO^+(1-0) and $H^{13}CO^+$(1-0)

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HCN(1-0)	→ Δv = 7 km/s
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For our ALMA observations we would need:

Bandwidth	> 20 km/s	to properly cover the extend of the lines
Resolution	< 0.7 km/s	for the HCN and HCO^+ lines
	< 0.3 km/s	for the $H^{13}CO^+$ line

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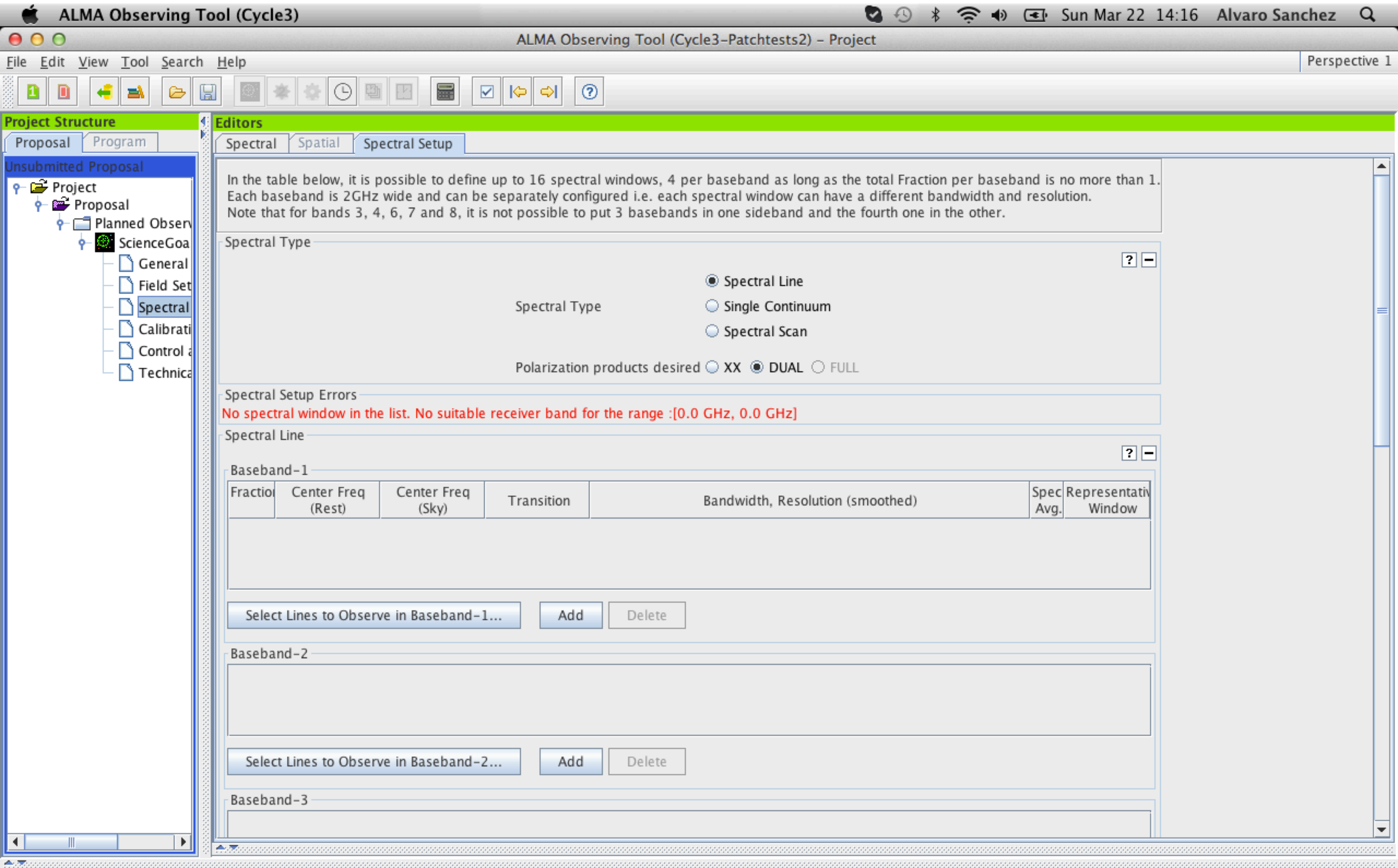

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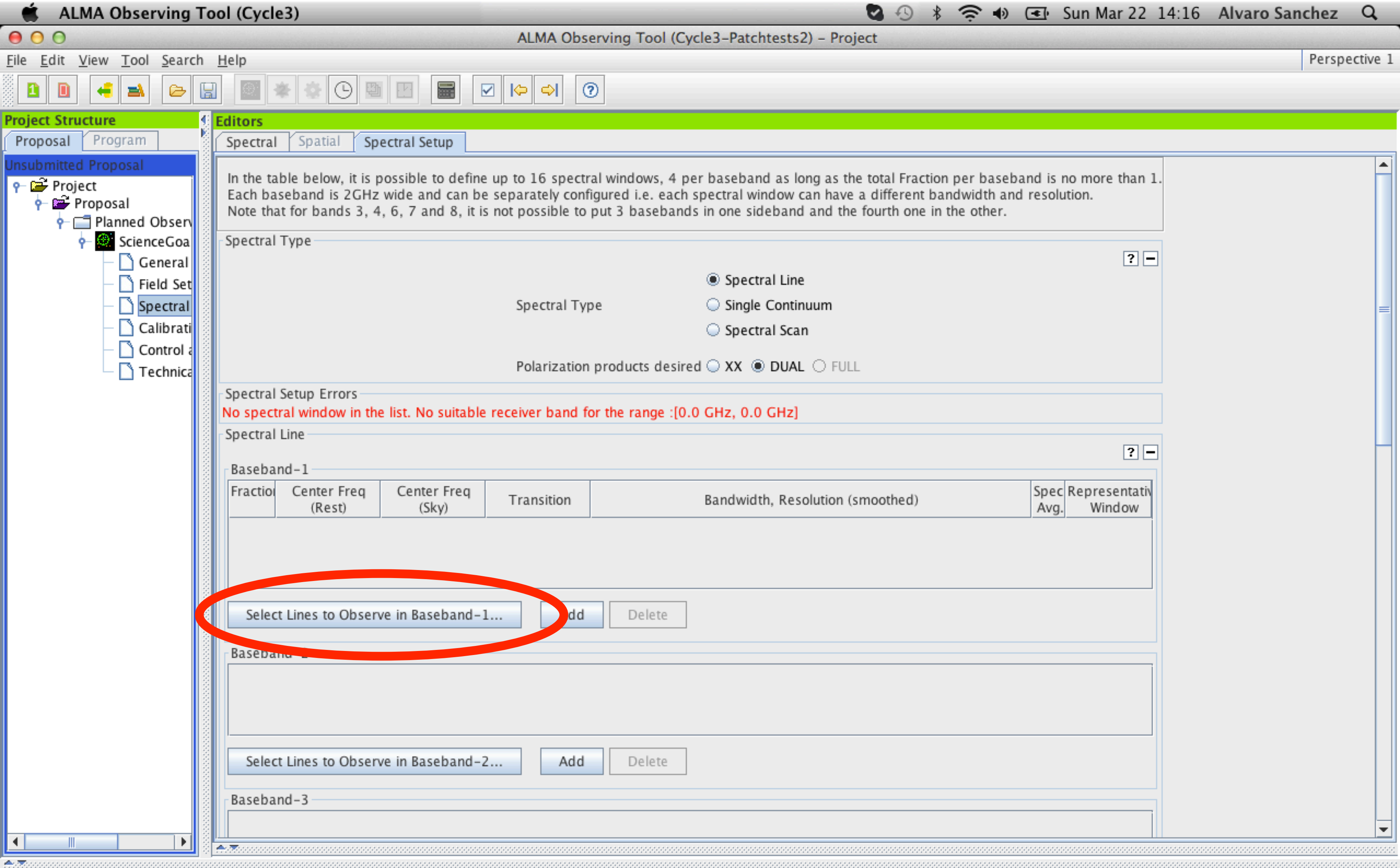

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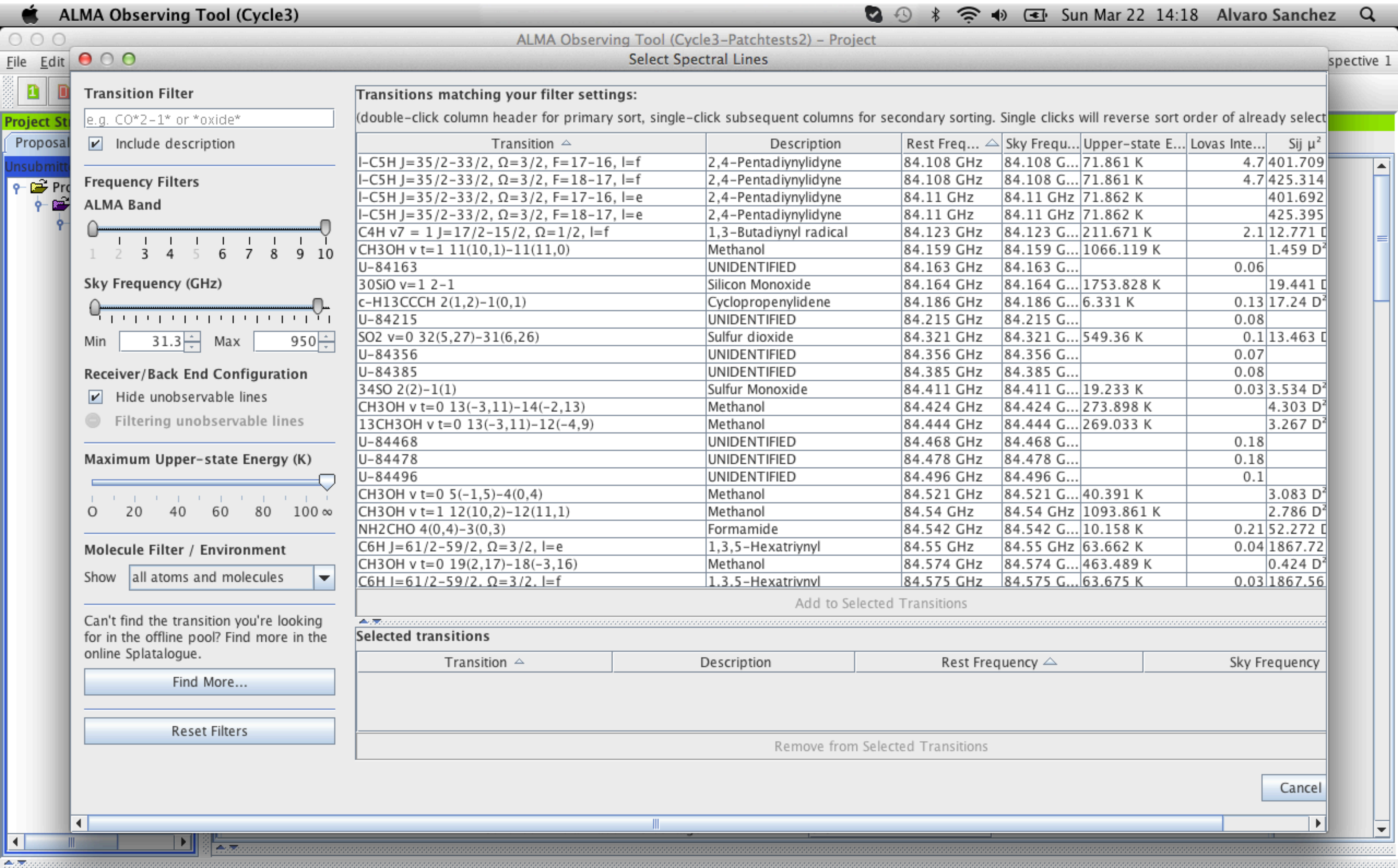

Transition	Description	Rest Freq...	Sky Frequ...	Upper-state E...	Lovas Inte...	Sij μ²
l-C5H J=35/2-33/2, Ω=3/2, F=17-16, l=f	2,4-Pentadiynylidyne	84.108 GHz	84.108 G...	71.861 K	4.7	401.709
l-C5H J=35/2-33/2, Ω=3/2, F=18-17, l=f	2,4-Pentadiynylidyne	84.108 GHz	84.108 G...	71.861 K	4.7	425.314
l-C5H J=35/2-33/2, Ω=3/2, F=17-16, l=e	2,4-Pentadiynylidyne	84.11 GHz	84.11 GHz	71.862 K		401.692
l-C5H J=35/2-33/2, Ω=3/2, F=18-17, l=e	2,4-Pentadiynylidyne	84.11 GHz	84.11 GHz	71.862 K		425.395
C4H v7 = 1 J=17/2-15/2, Ω=1/2, l=f	1,3-Butadiynyl radical	84.123 GHz	84.123 G...	211.671 K	2.1	12.771 D
CH3OH v t=1 11(10,1)-11(11,0)	Methanol	84.159 GHz	84.159 G...	1066.119 K		1.459 D²
U-84163	UNIDENTIFIED	84.163 GHz	84.163 G...		0.06	
30SiO v=1 2-1	Silicon Monoxide	84.164 GHz	84.164 G...	1753.828 K		19.441 D
c-H13CCCH 2(1,2)-1(0,1)	Cyclopropenylidene	84.186 GHz	84.186 G...	6.331 K	0.13	17.24 D²
U-84215	UNIDENTIFIED	84.215 GHz	84.215 G...		0.08	
SO2 v=0 32(5,27)-31(6,26)	Sulfur dioxide	84.321 GHz	84.321 G...	549.36 K	0.1	13.463 D
U-84356	UNIDENTIFIED	84.356 GHz	84.356 G...		0.07	
U-84385	UNIDENTIFIED	84.385 GHz	84.385 G...		0.08	
34SO 2(2)-1(1)	Sulfur Monoxide	84.411 GHz	84.411 G...	19.233 K	0.03	3.534 D²
CH3OH v t=0 13(-3,11)-14(-2,13)	Methanol	84.424 GHz	84.424 G...	273.898 K		4.303 D²
13CH3OH v t=0 13(-3,11)-12(-4,9)	Methanol	84.444 GHz	84.444 G...	269.033 K		3.267 D²
U-84468	UNIDENTIFIED	84.468 GHz	84.468 G...		0.18	
U-84478	UNIDENTIFIED	84.478 GHz	84.478 G...		0.18	
U-84496	UNIDENTIFIED	84.496 GHz	84.496 G...		0.1	
CH3OH v t=0 5(-1,5)-4(0,4)	Methanol	84.521 GHz	84.521 G...	40.391 K		3.083 D²
CH3OH v t=1 12(10,2)-12(11,1)	Methanol	84.54 GHz	84.54 GHz	1093.861 K		2.786 D²
NH2CHO 4(0,4)-3(0,3)	Formamide	84.542 GHz	84.542 G...	10.158 K	0.21	52.272 D
C6H J=61/2-59/2, Ω=3/2, l=e	1,3,5-Hexatriynyl	84.55 GHz	84.55 GHz	63.662 K	0.04	1867.72
CH3OH v t=0 19(2,17)-18(-3,16)	Methanol	84.574 GHz	84.574 G...	463.489 K		0.424 D²
C6H J=61/2-59/2, Ω=3/2, l=f	1,3,5-Hexatriynyl	84.575 GHz	84.575 G...	63.675 K	0.03	1867.56

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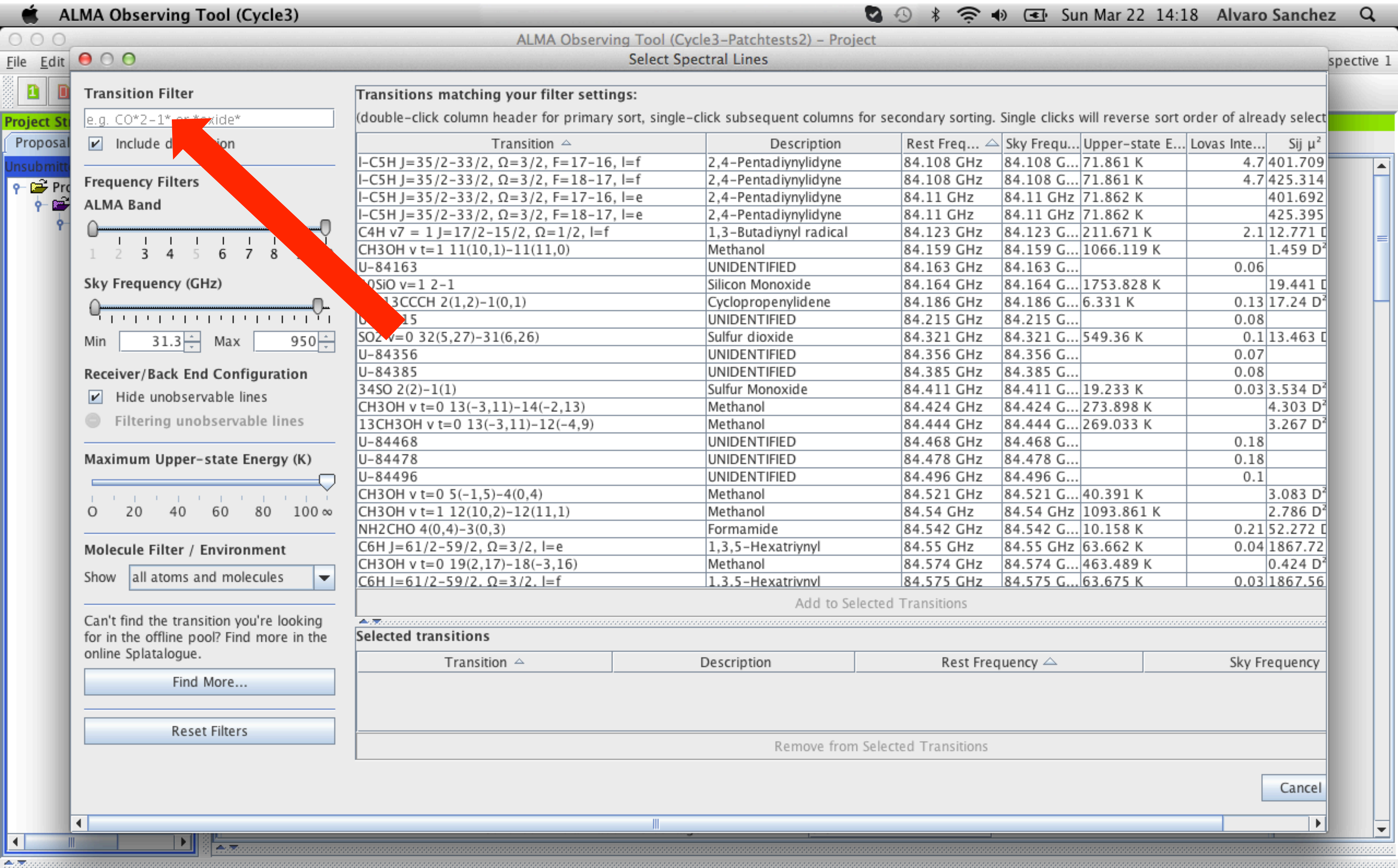

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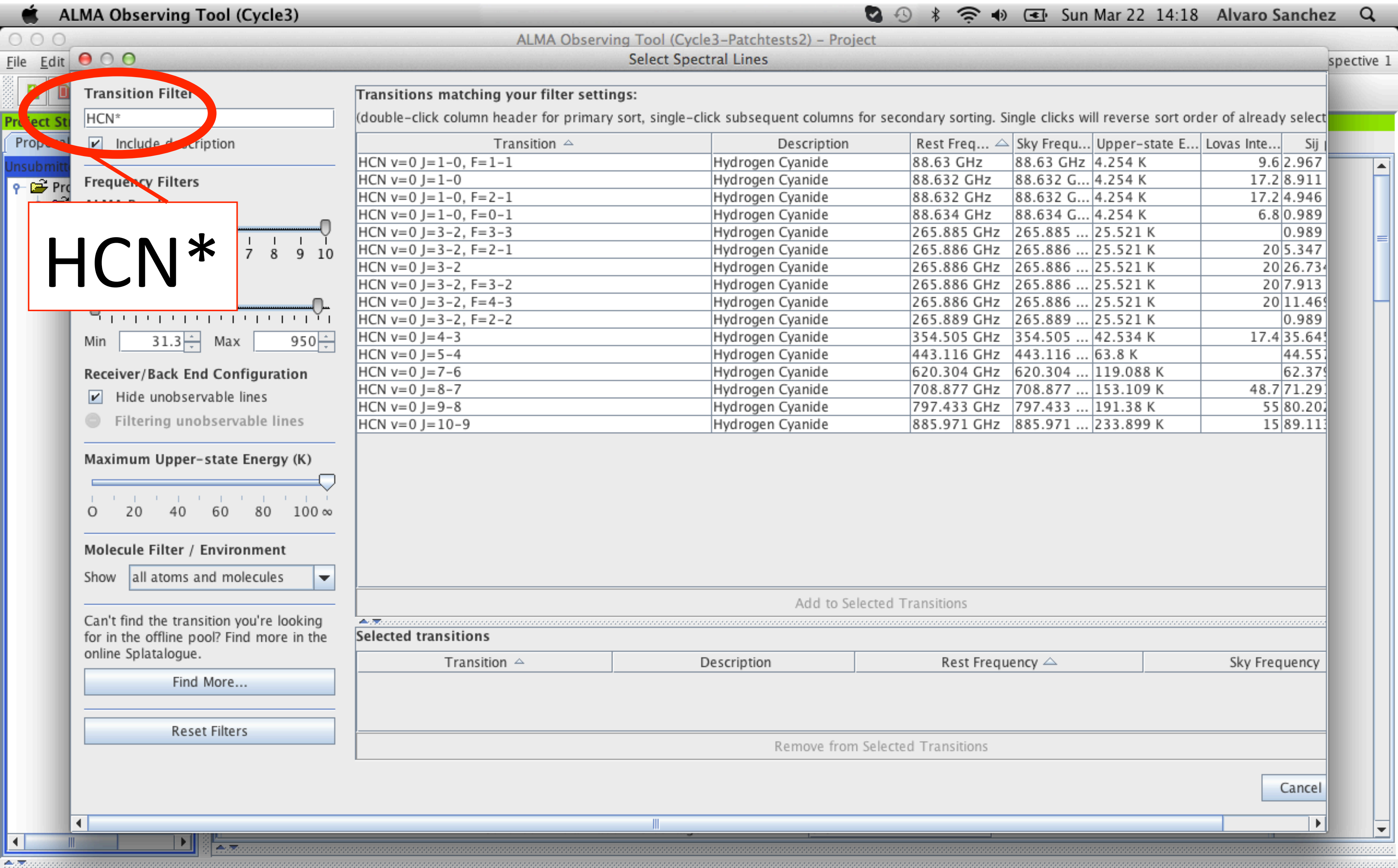

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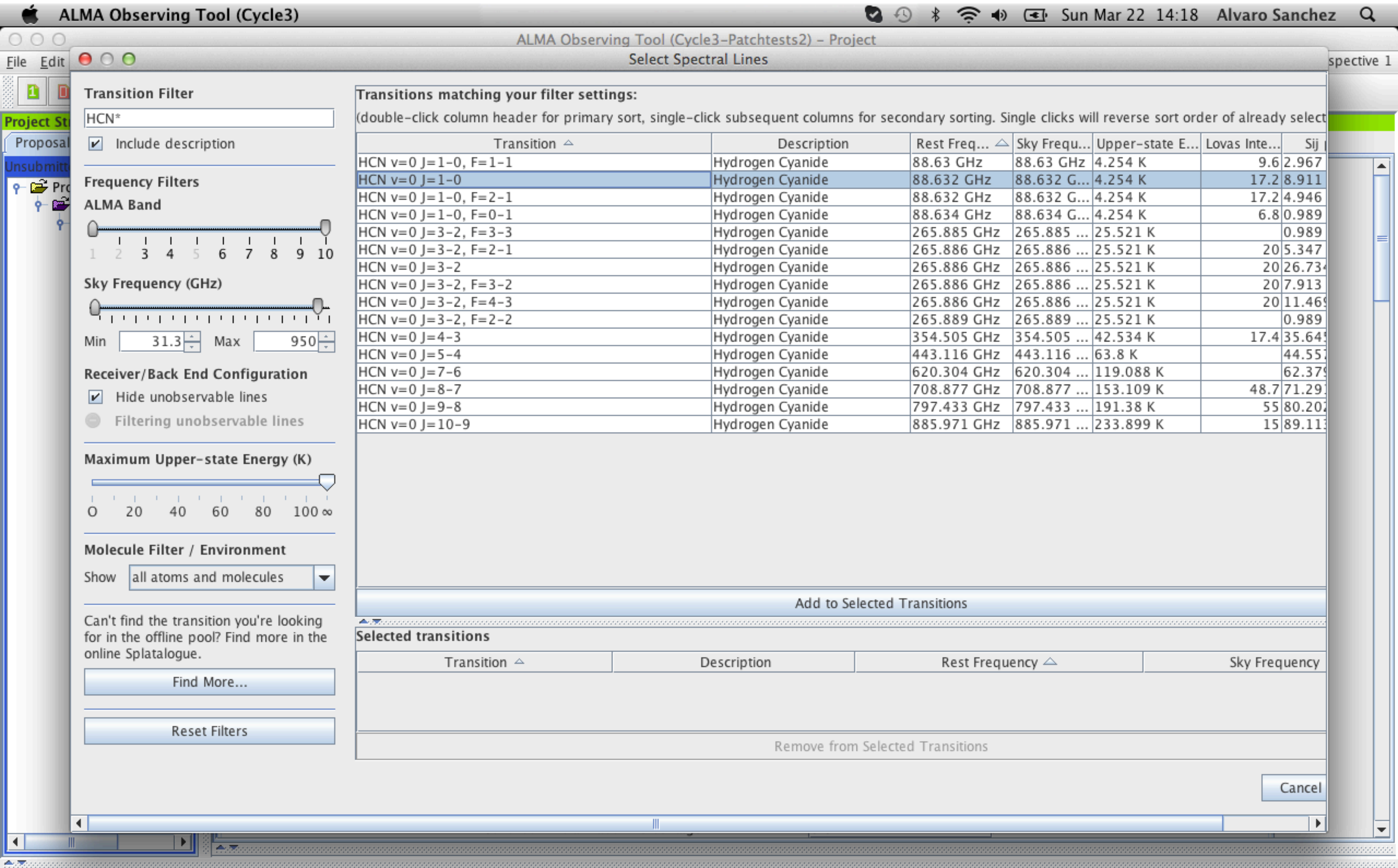

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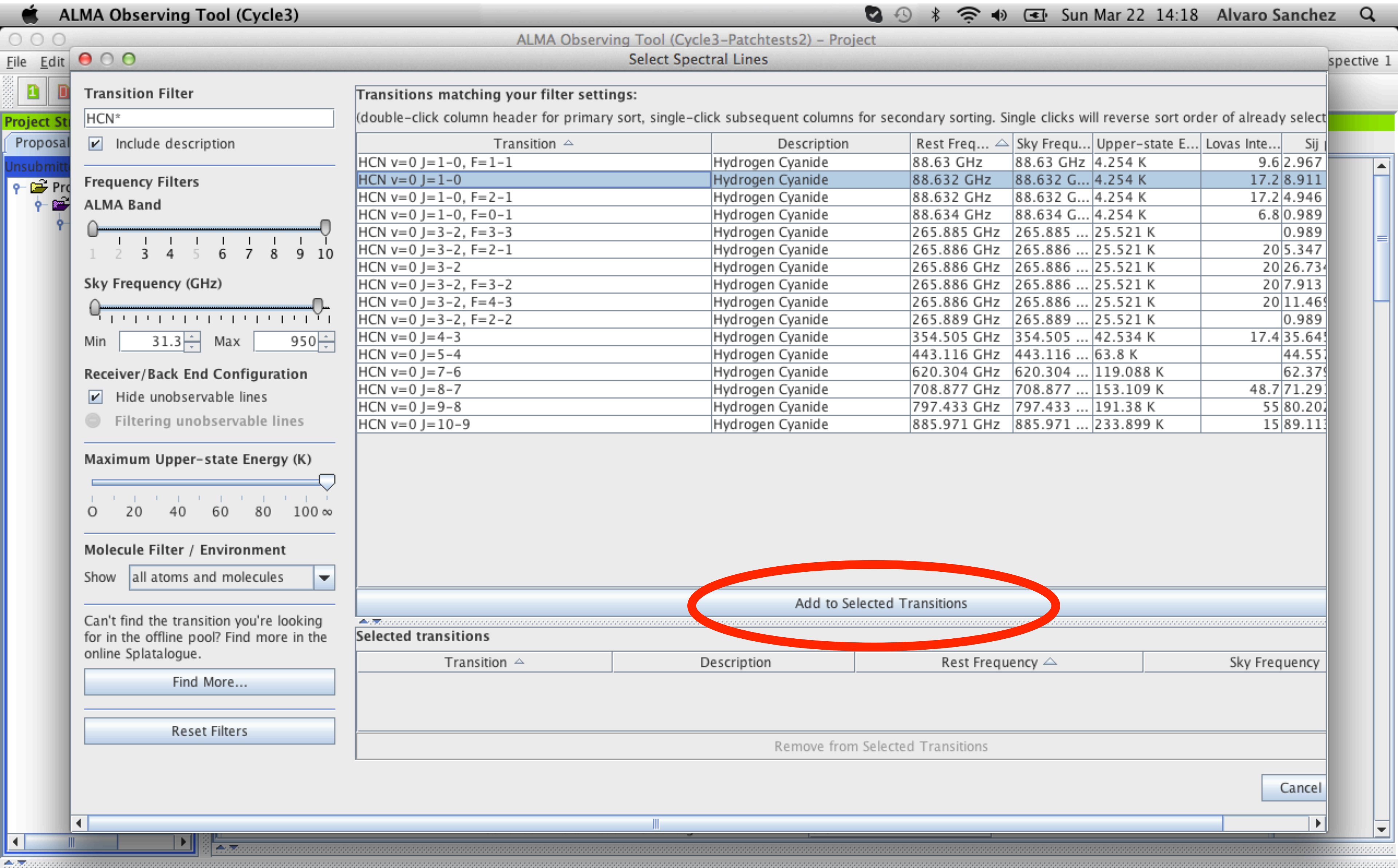

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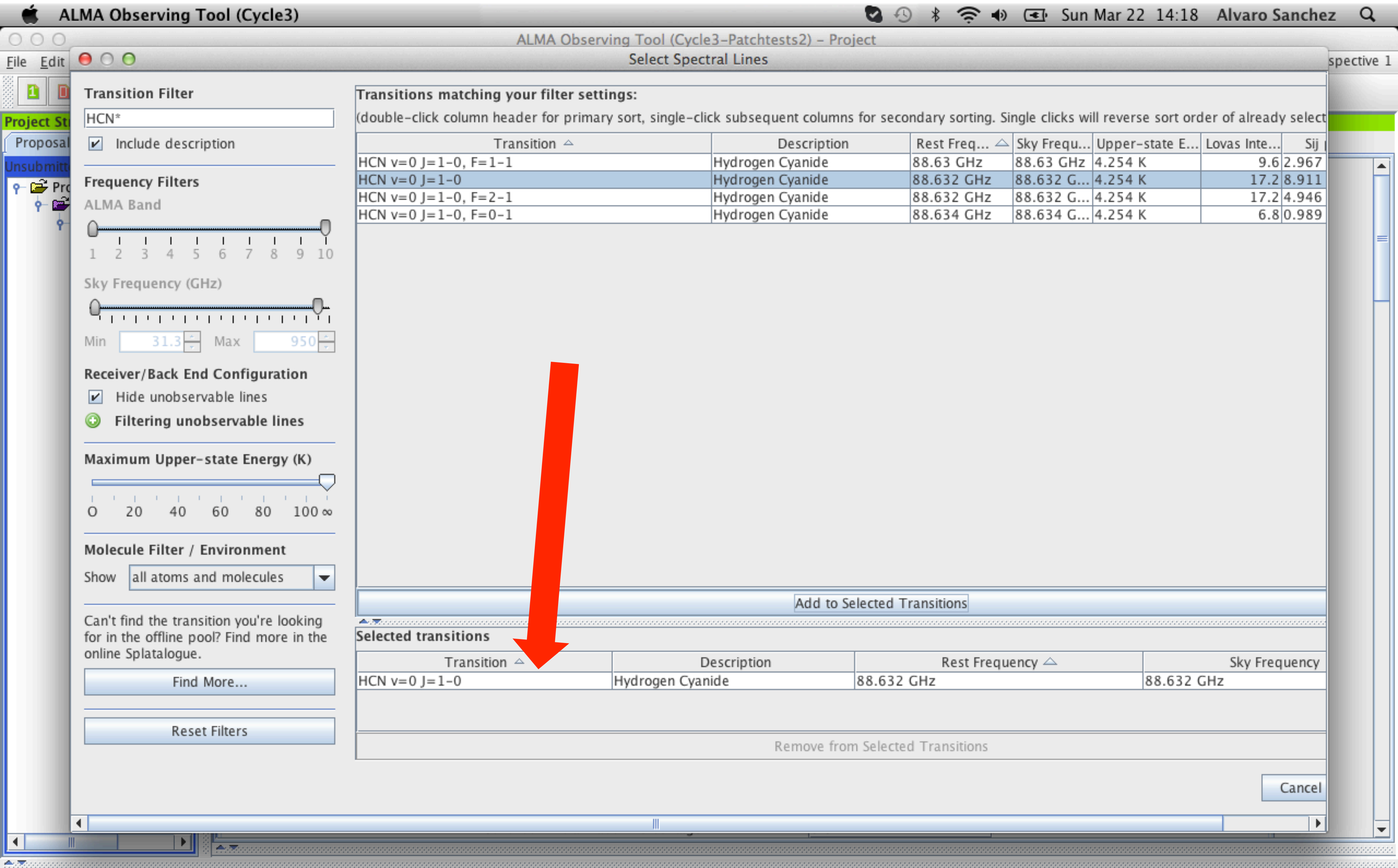

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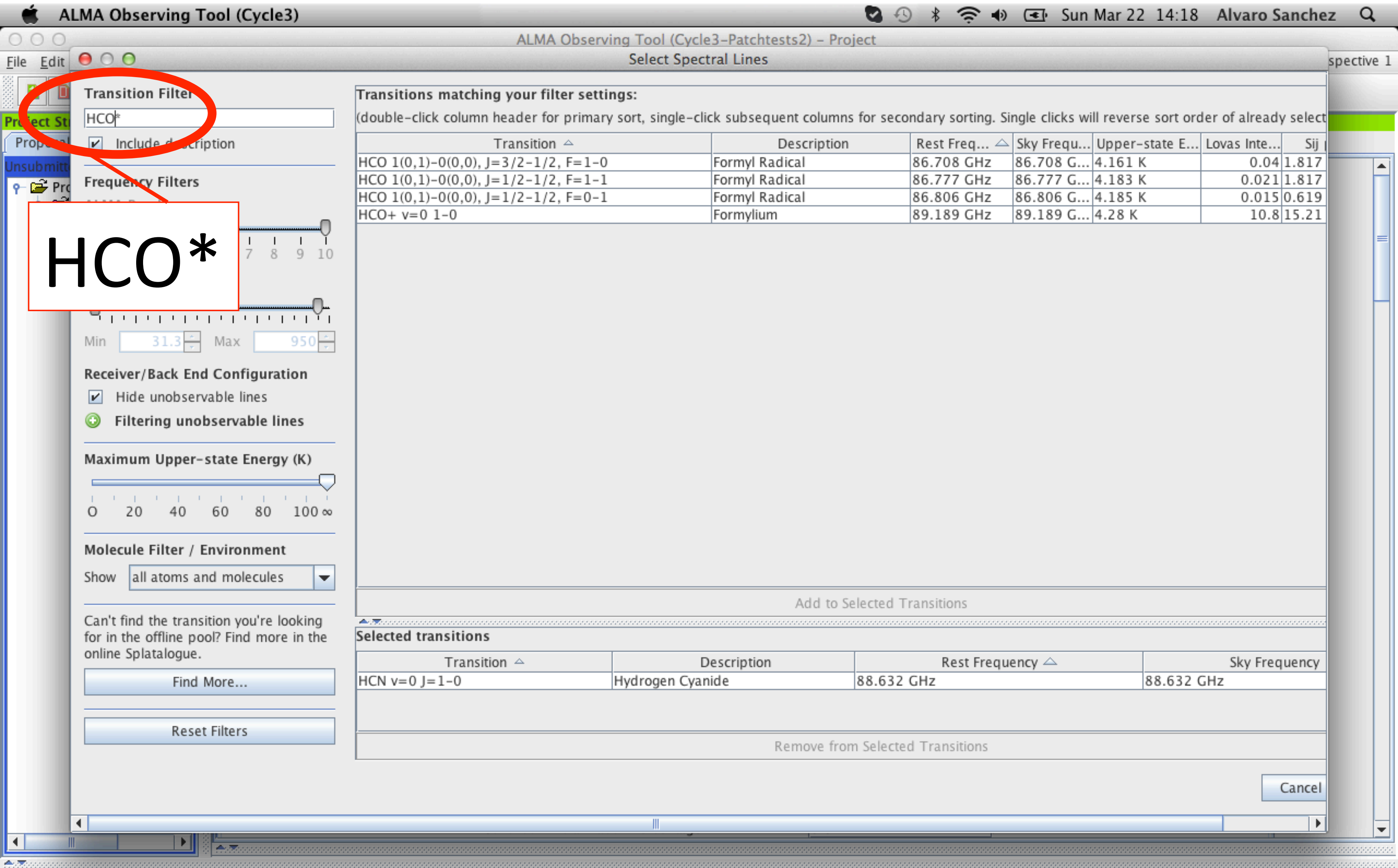

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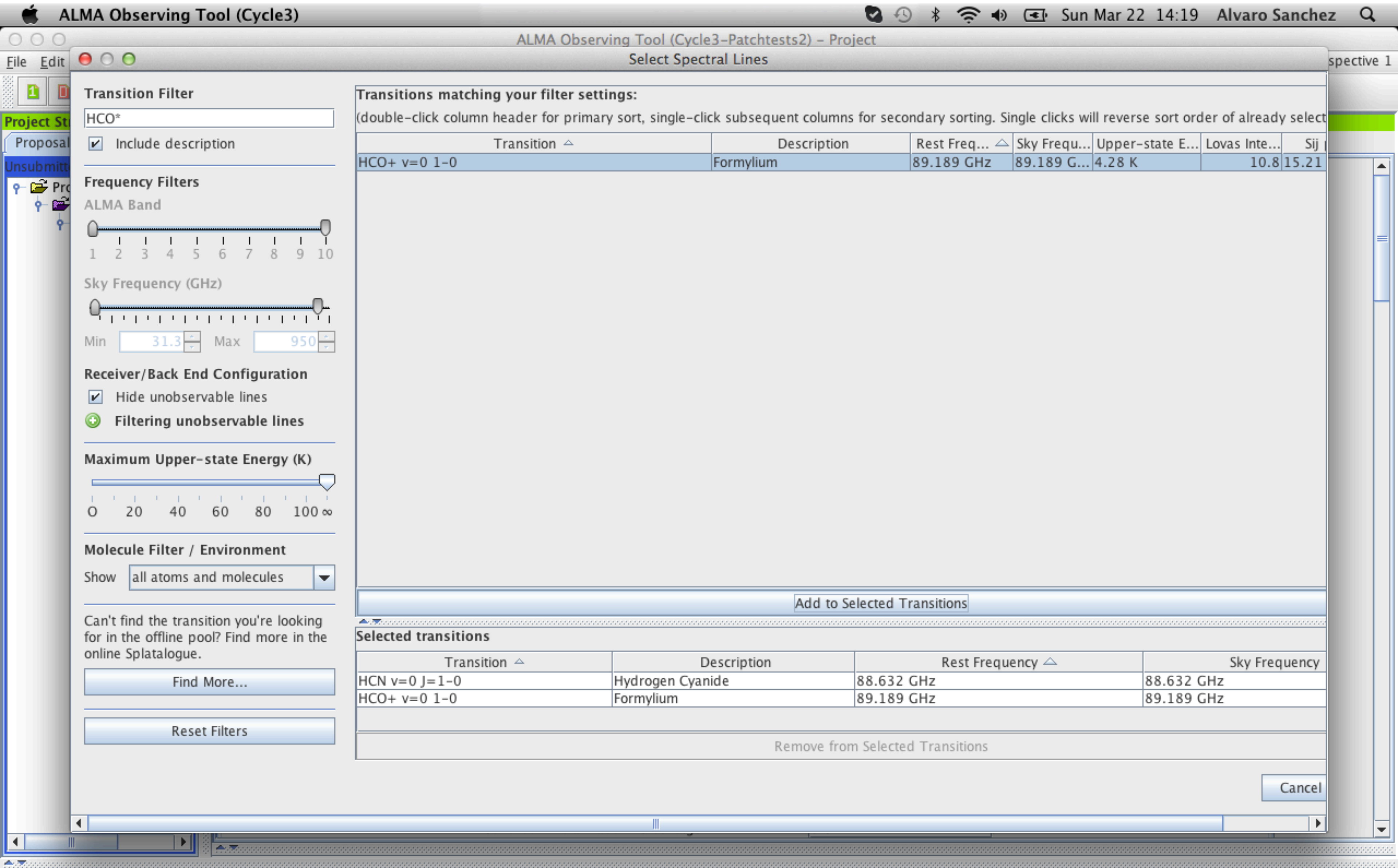

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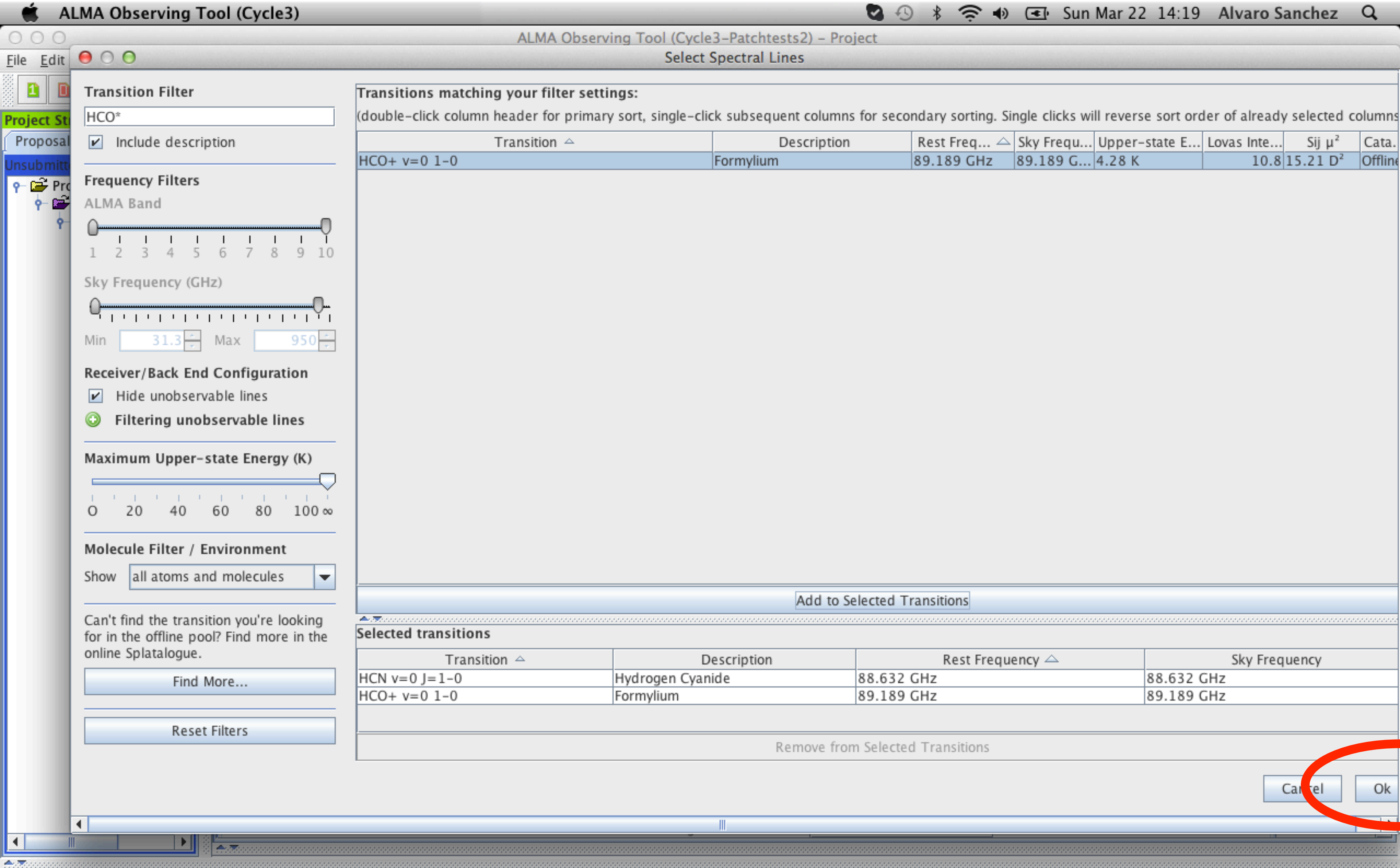

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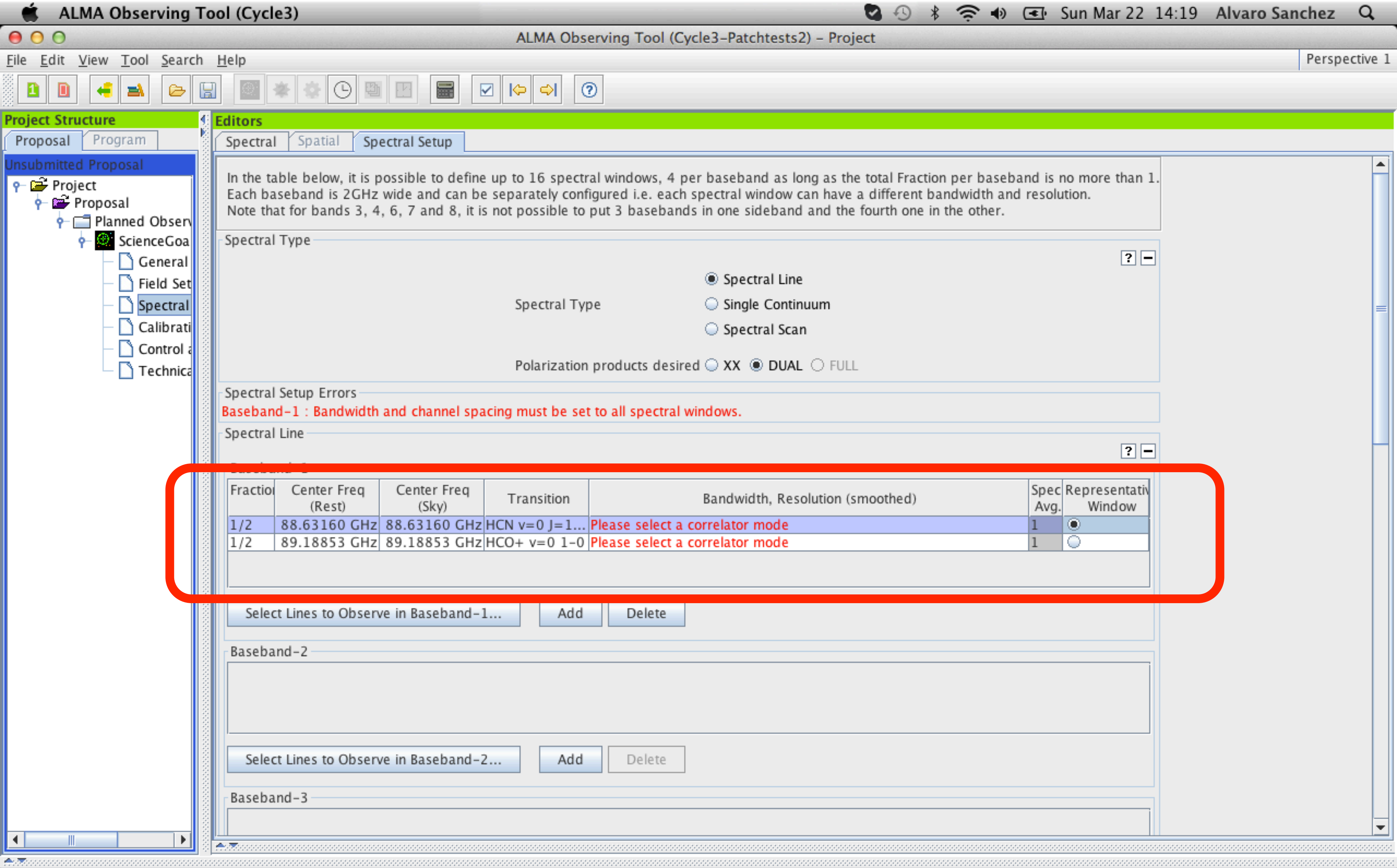

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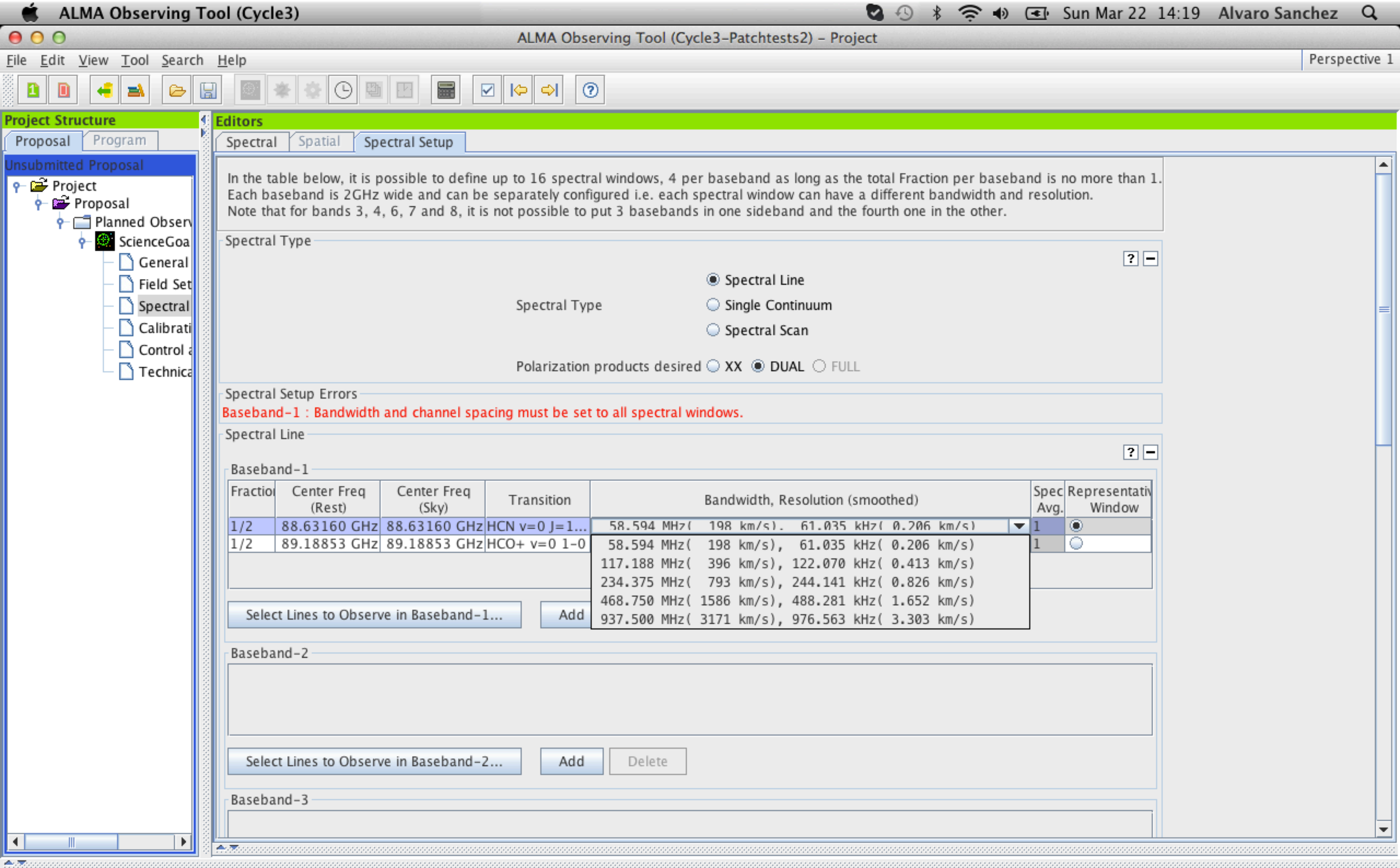

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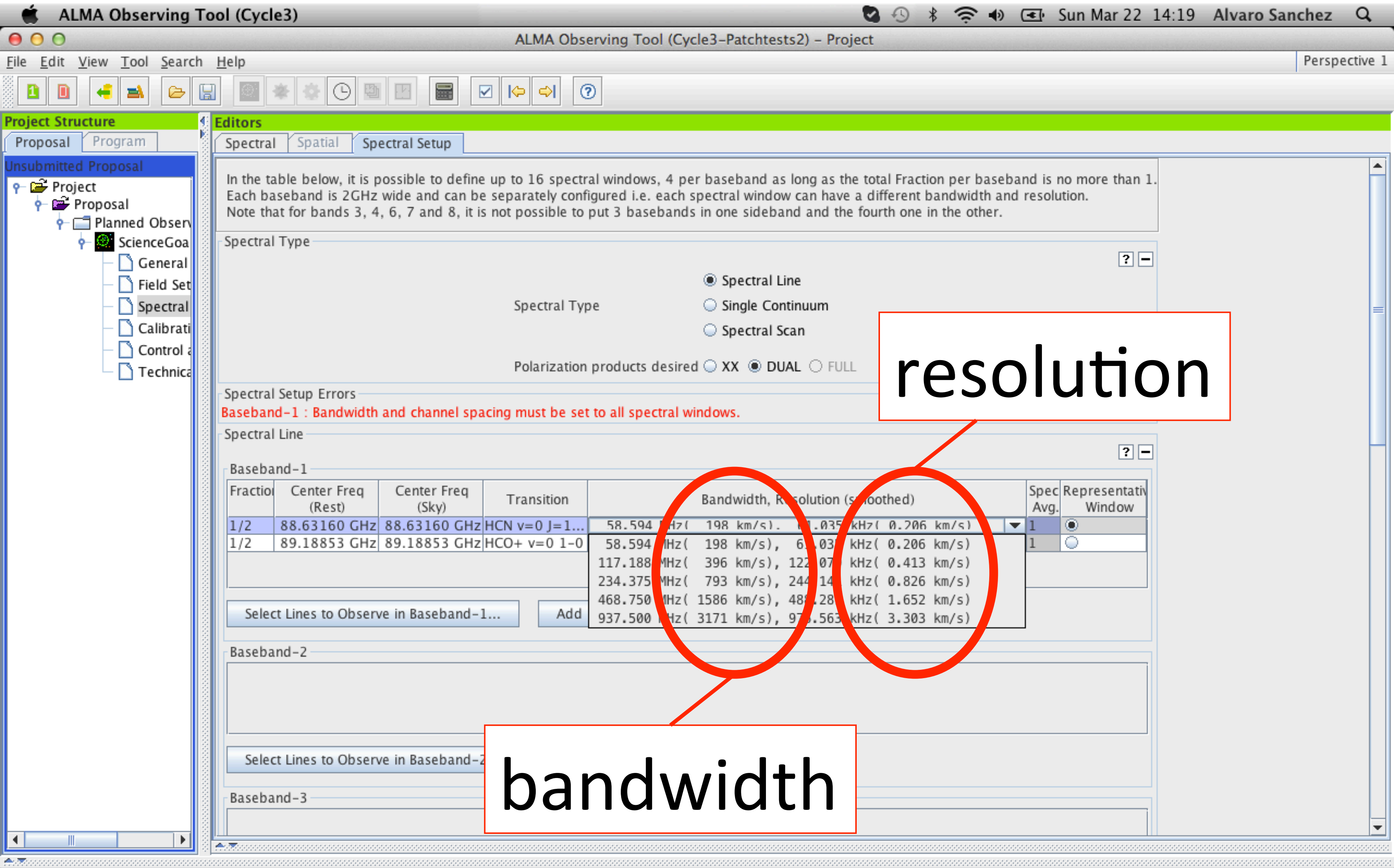

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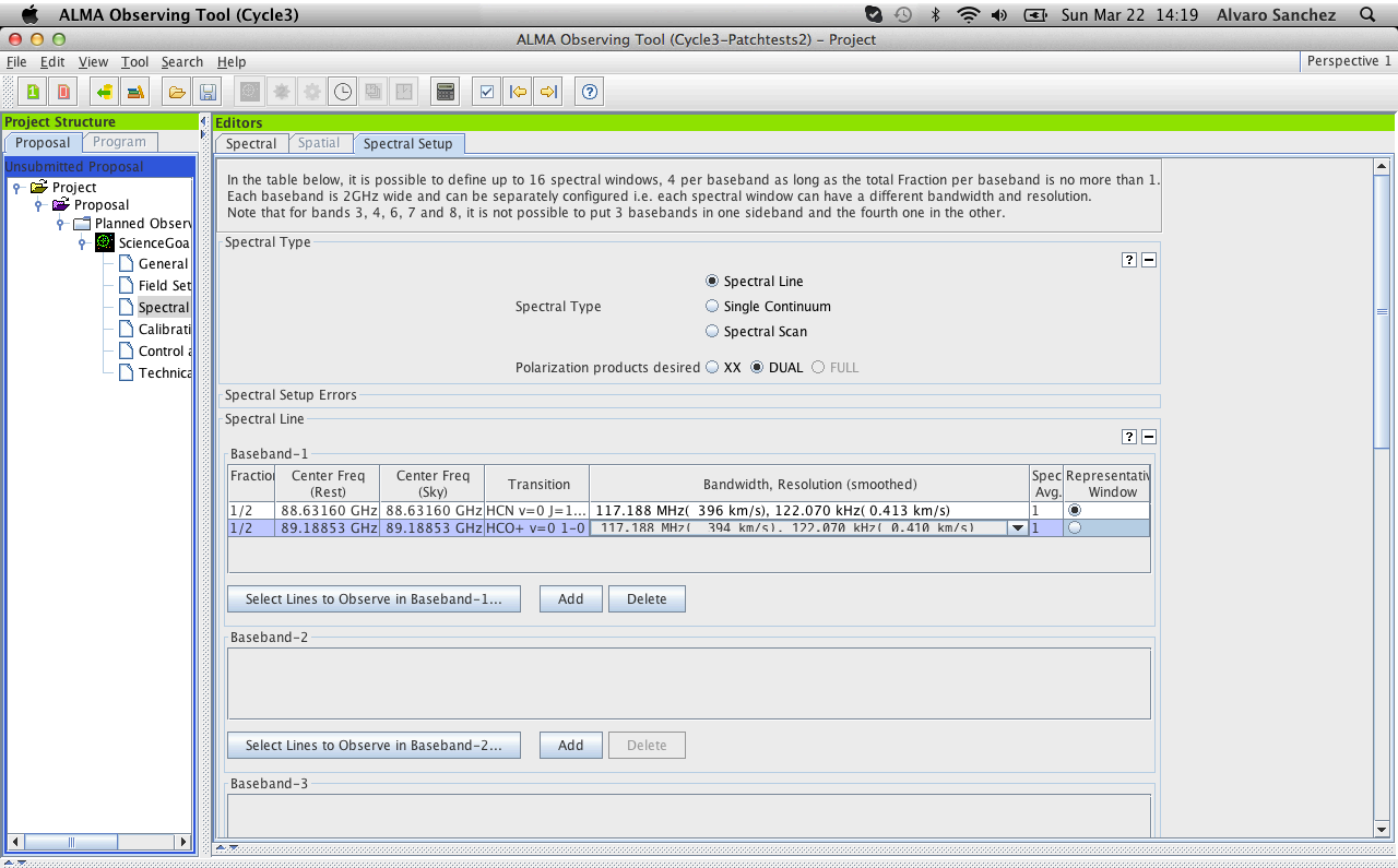

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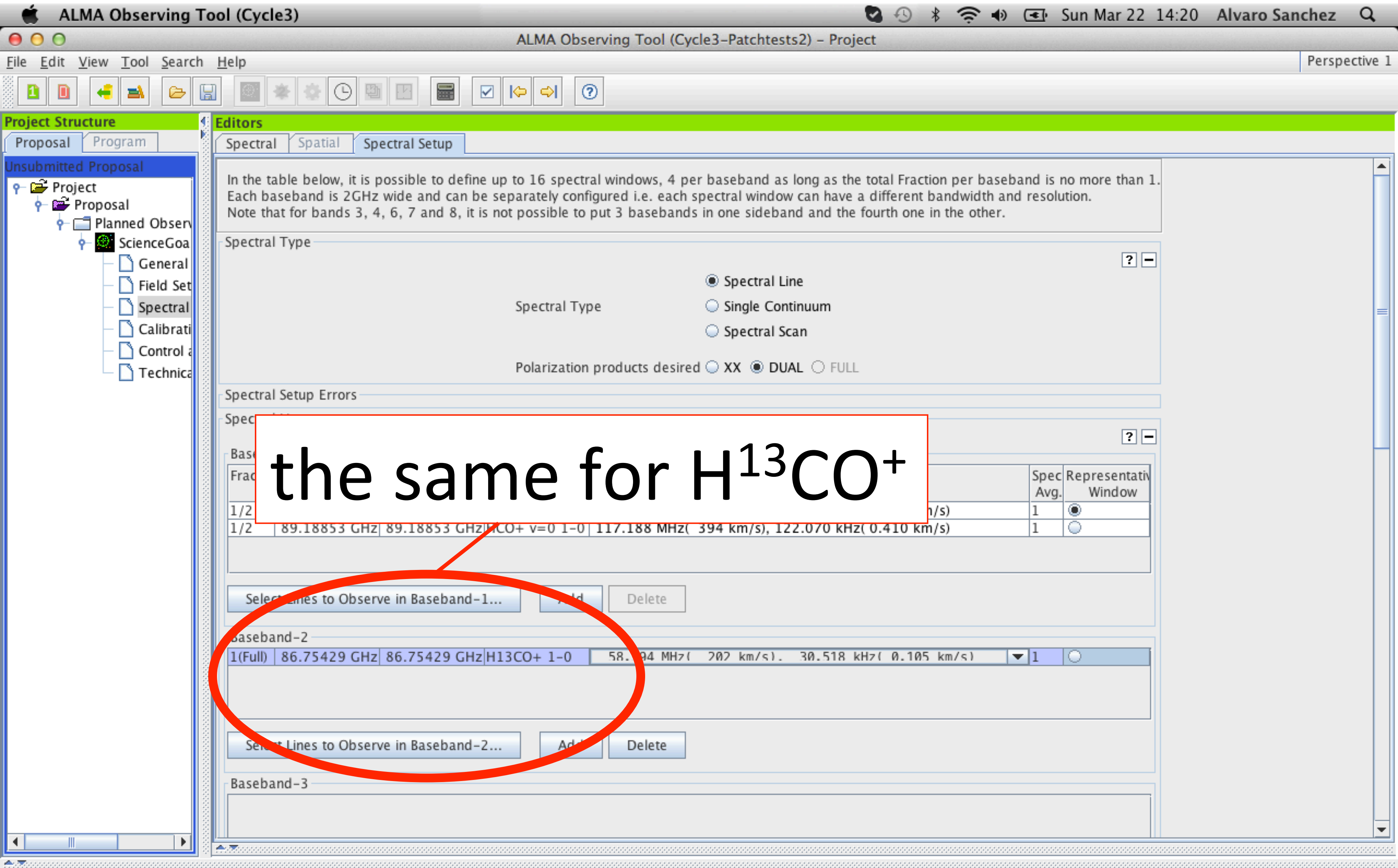

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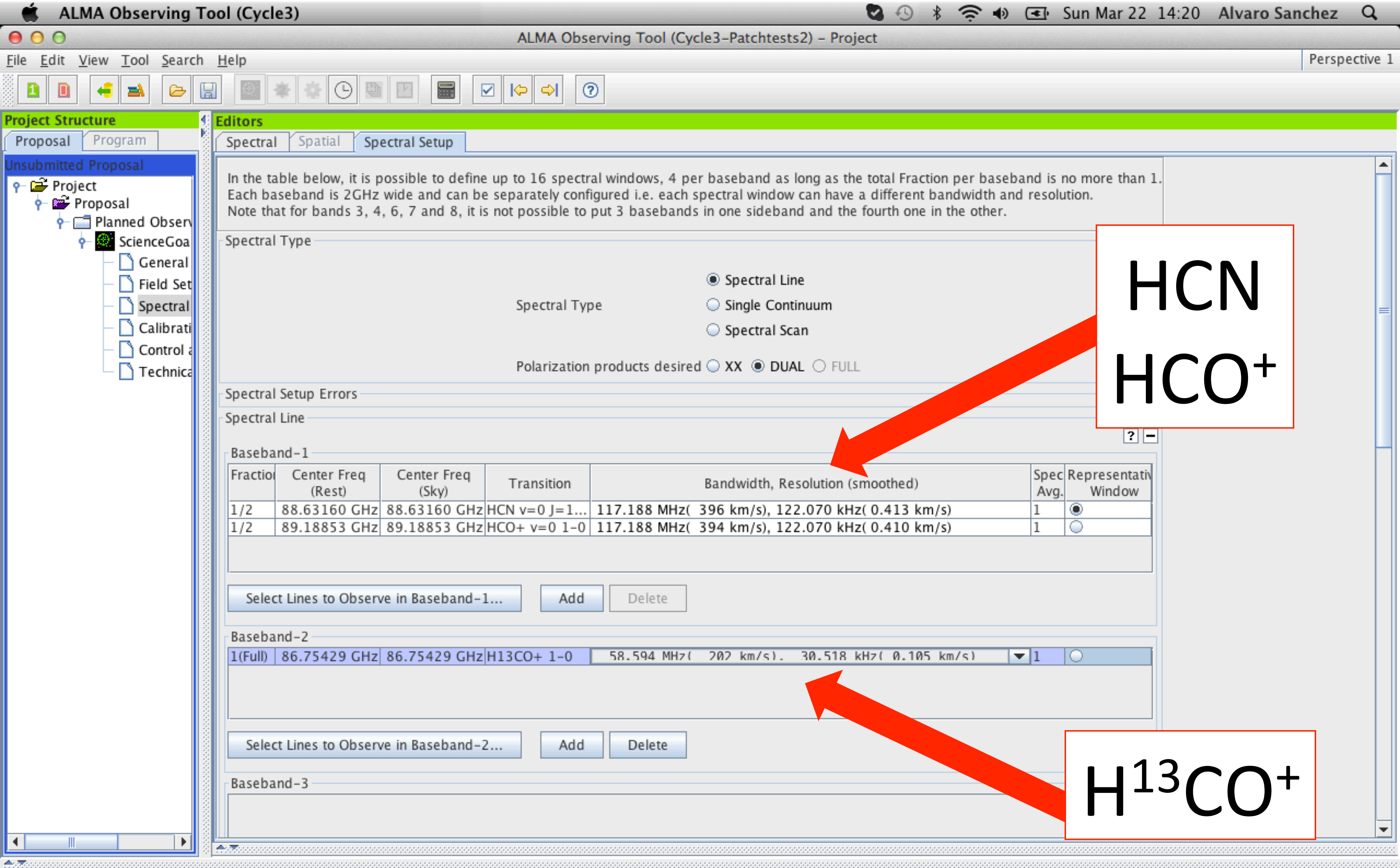

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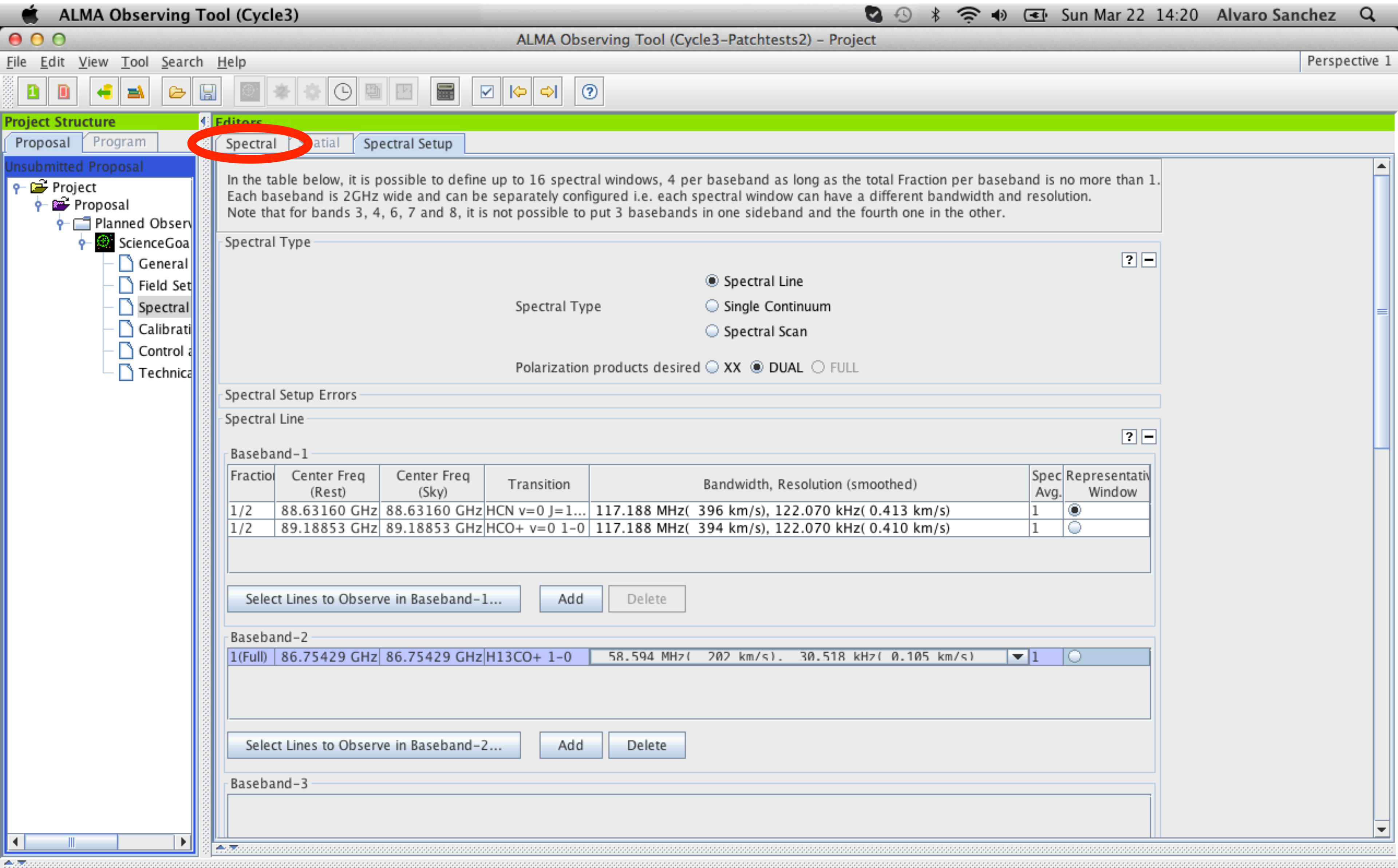

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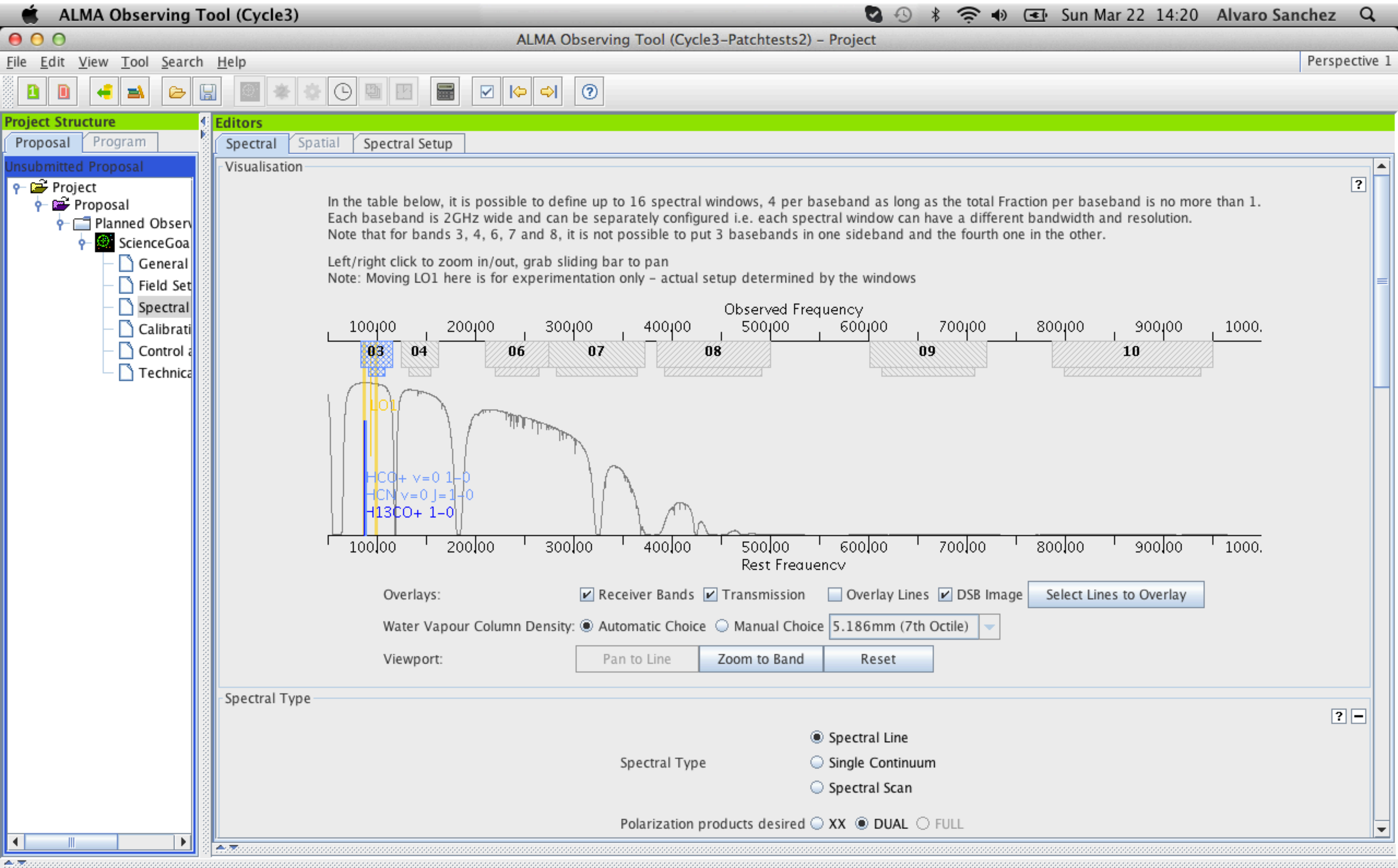

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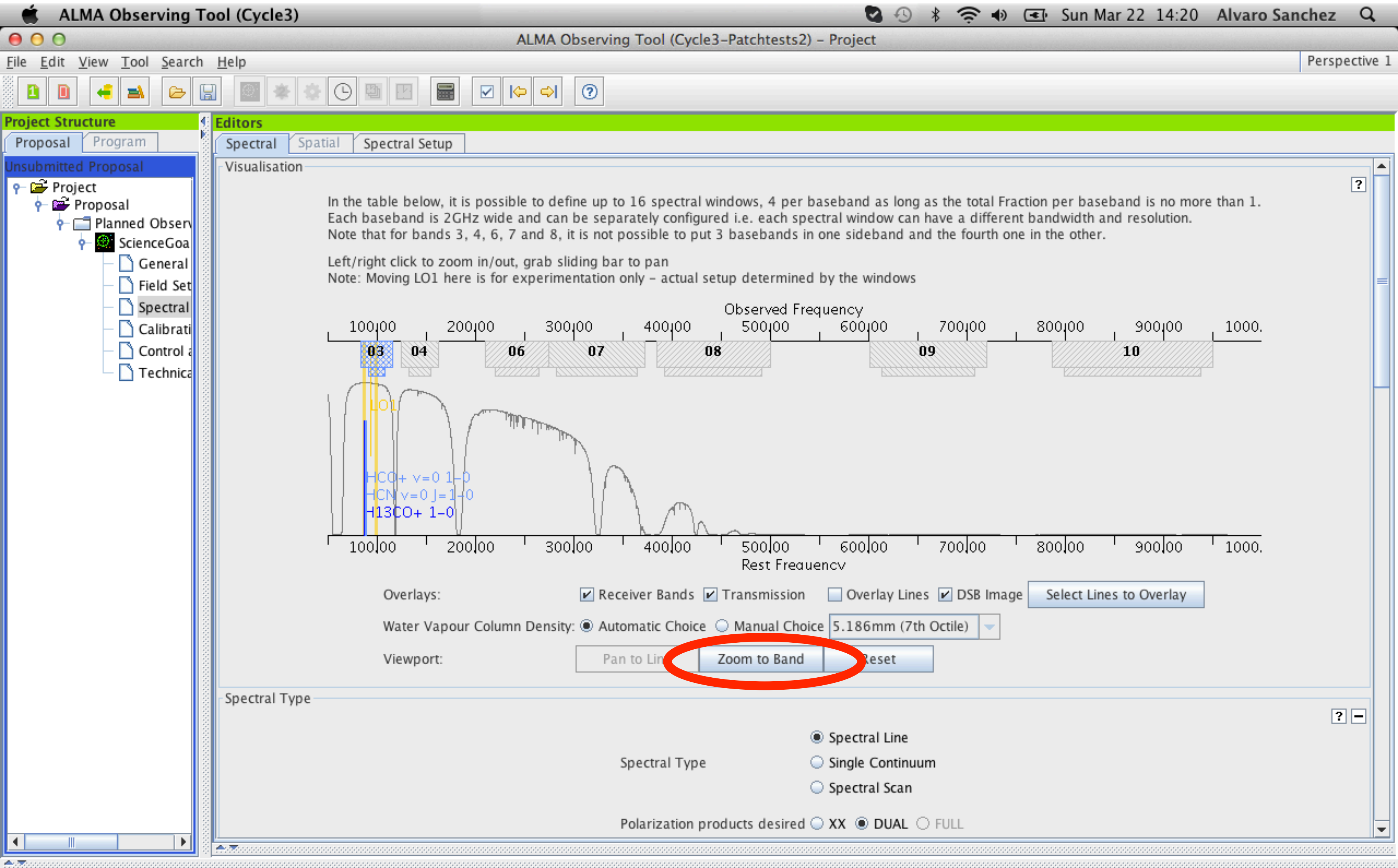

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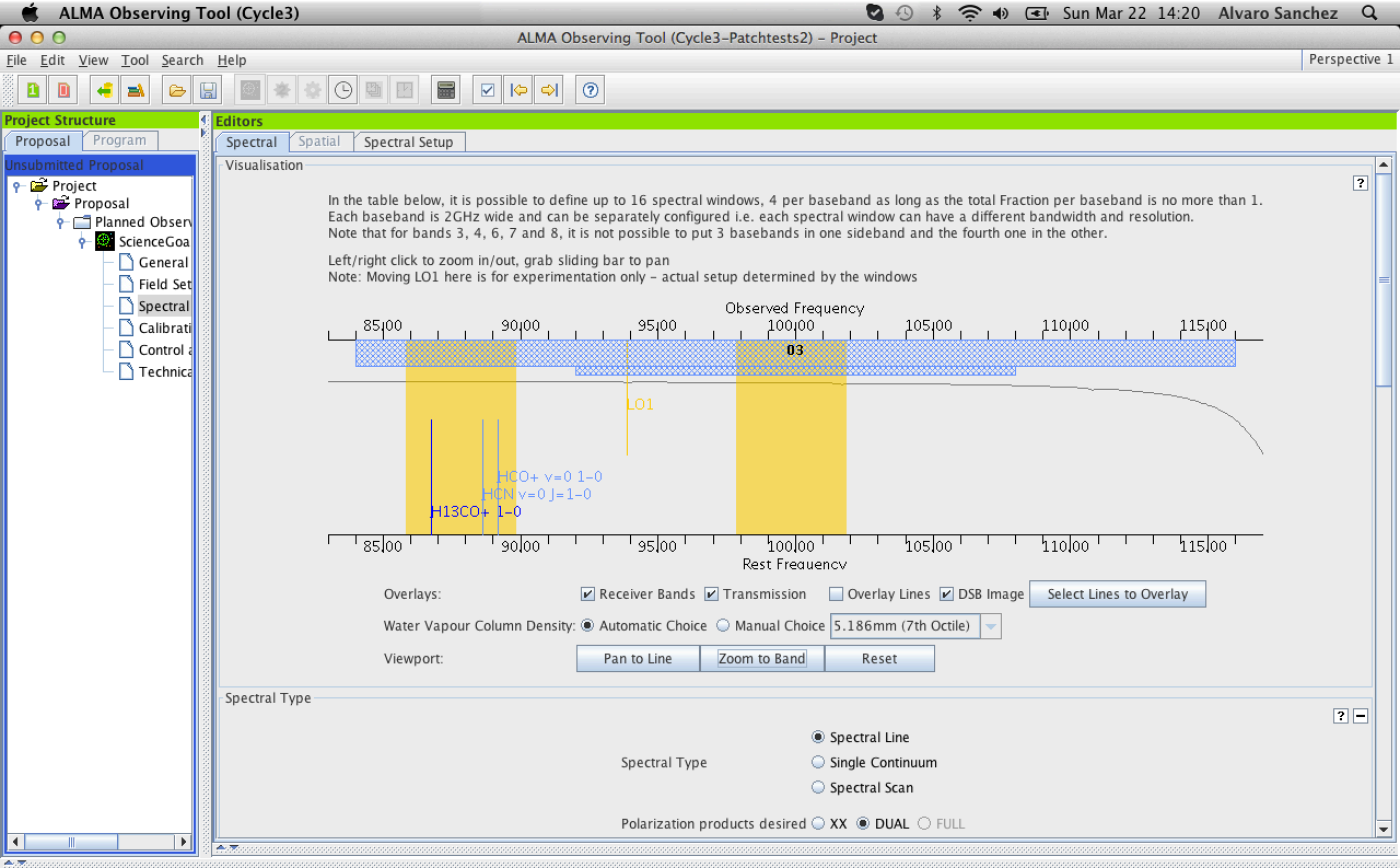

Concepts to take home

Part 1

- Interferometer
- Baseline
- Primary beam
- Synthesized beam
- Largest angular scale

Part 2

- Spectral lines
- Rest frequency
- Source velocity and redshift
- Line width
- Spectral resolution

Concepts to take home

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- Primary beam
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- Largest angular scale

Questions?

Part 2

- Spectral lines
- Rest frequency
- Source velocity and redshift
- Line width
- Spectral resolution