Introduction to the basic concepts and terminology of radio interferometry

EUROPEAN ARC
ALMA Regional Centre || Germany

universitätbonn

Universität zu Köln

ALMA community days

German ARC node – April 2017

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Outline

Part 1: by L. Moser

- Introduction to aperture synthesis
- Interferometers: spatial filters

Part 2: by S. Mühle

- Interferometers: spectral setup
- An overview of receivers and correlator

Part 3: by B. Magnelli

- The sensitivity of an interferometer

Thanks to A. Sanchez-Monge and A. Karim for slides and comments!

Part 1:
aperture synthesis, spatial filters

German ARC: ALMA community days (March 2017)

Atacama Large Millimeter/submillimeter Array

Image credit: Mélisse Bonfand

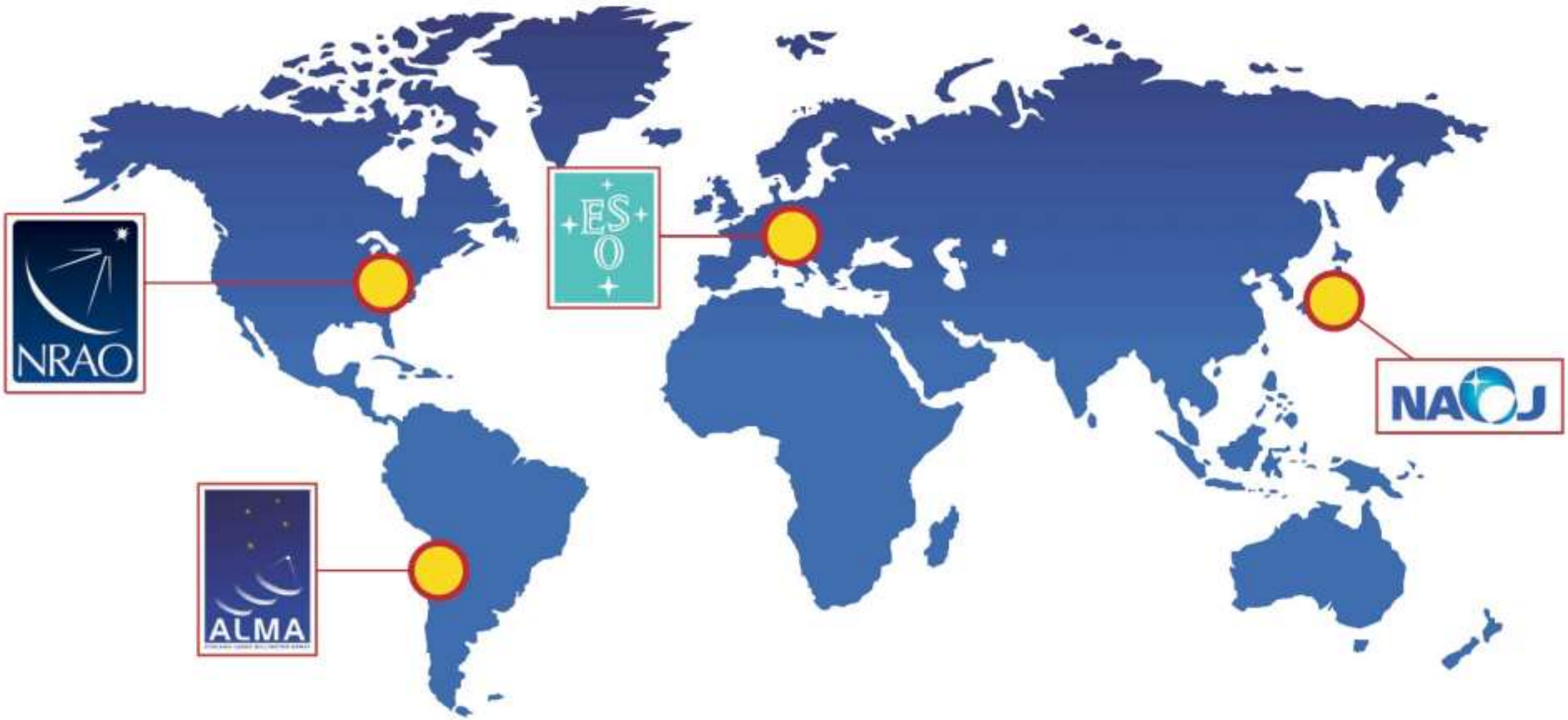
Where is ALMA?

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 in Cycle 5 is …

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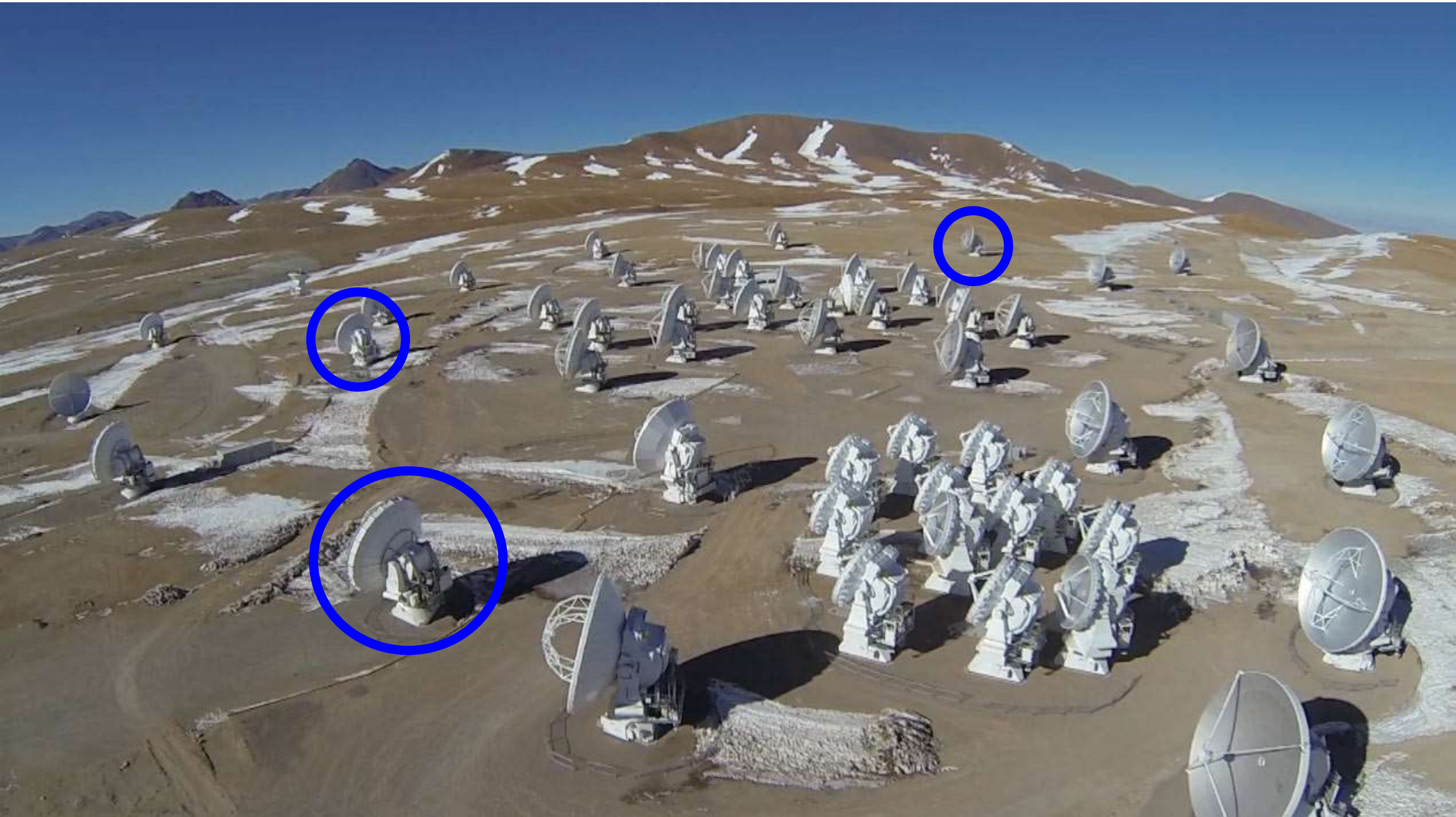
ALMA in Cycle 5 is …

43x	**12m antennas**
10x	7m antennas (ACA)
3x	12m antennas (TP)



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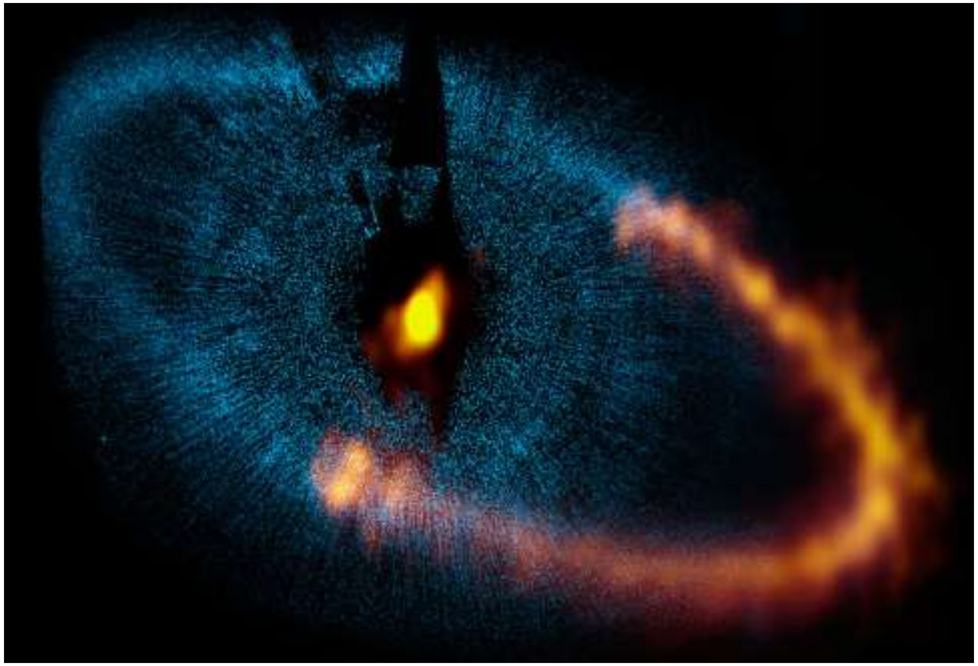
What can ALMA do?

HL Tau

protoplanetary disks

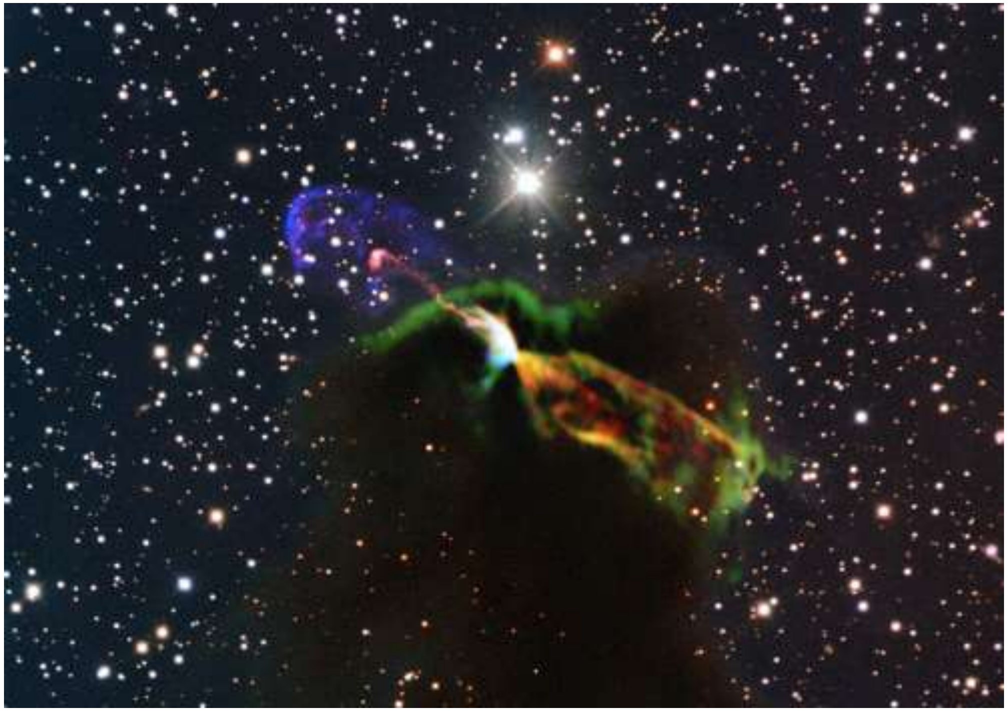
Formalhaut



debris disks

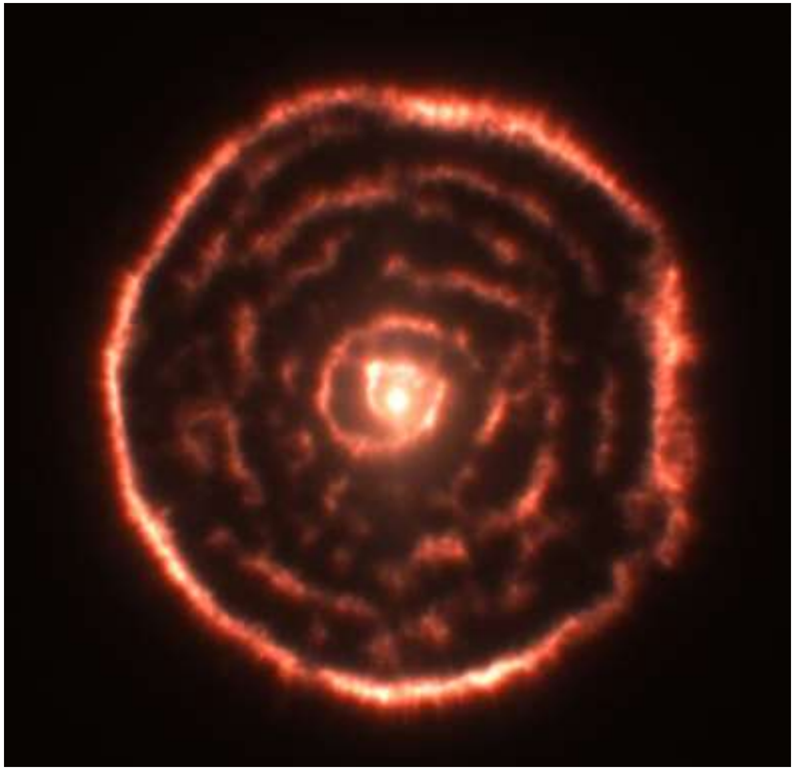
What can ALMA do?

Herbig-Haro 46/47



molecular outflows and jets

R Sculptoris



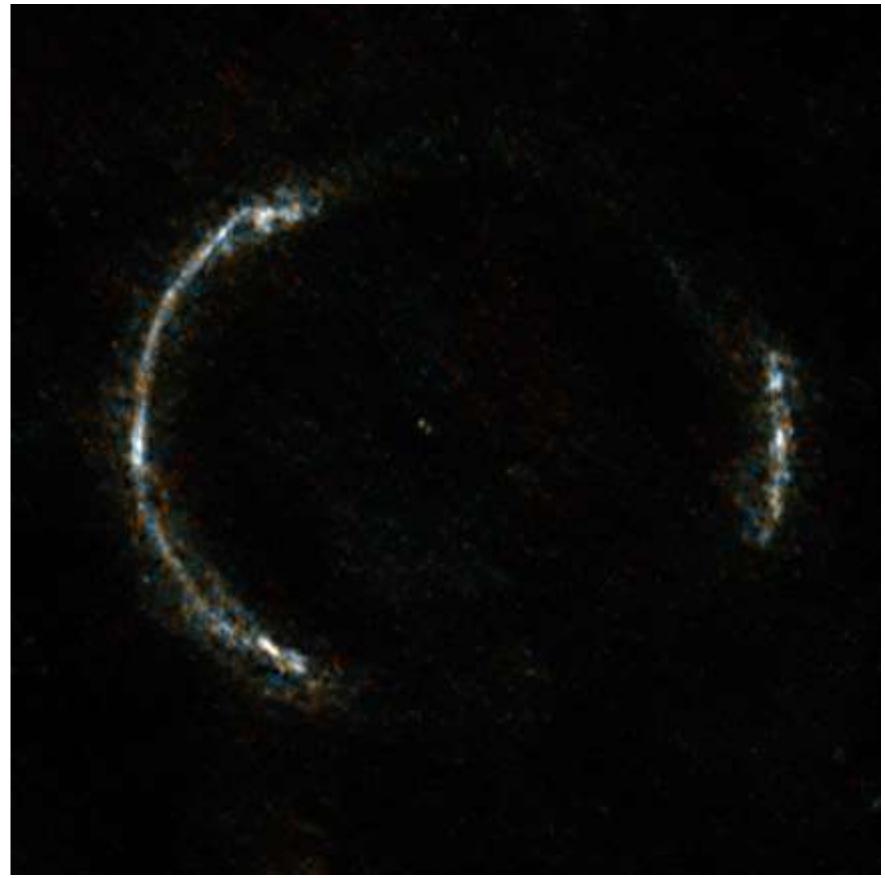
red giants and old stars

What can ALMA do?

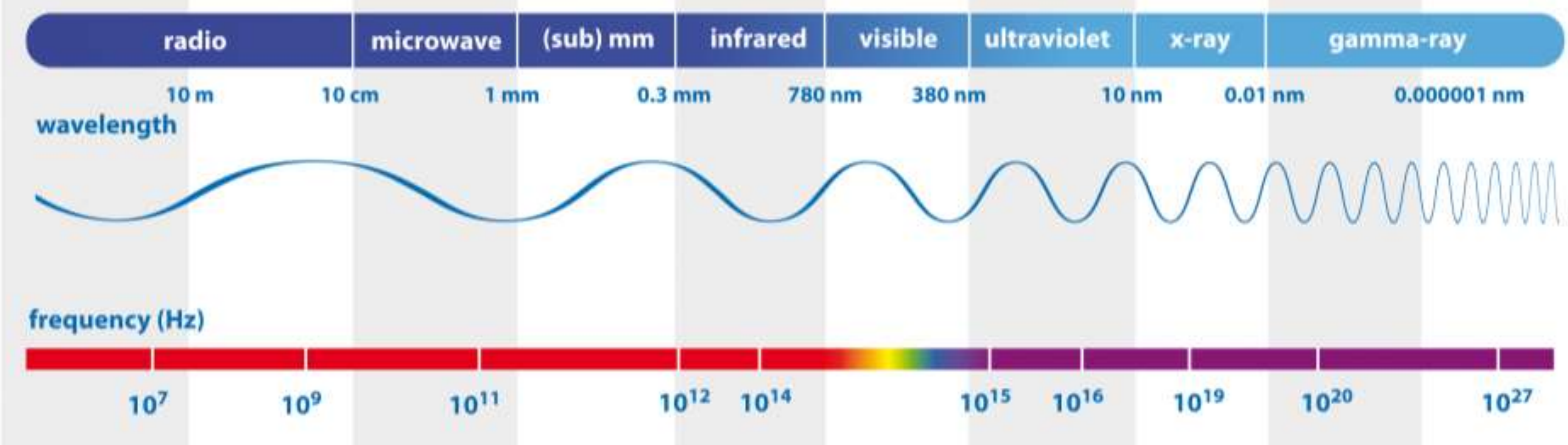
Antennae galaxies

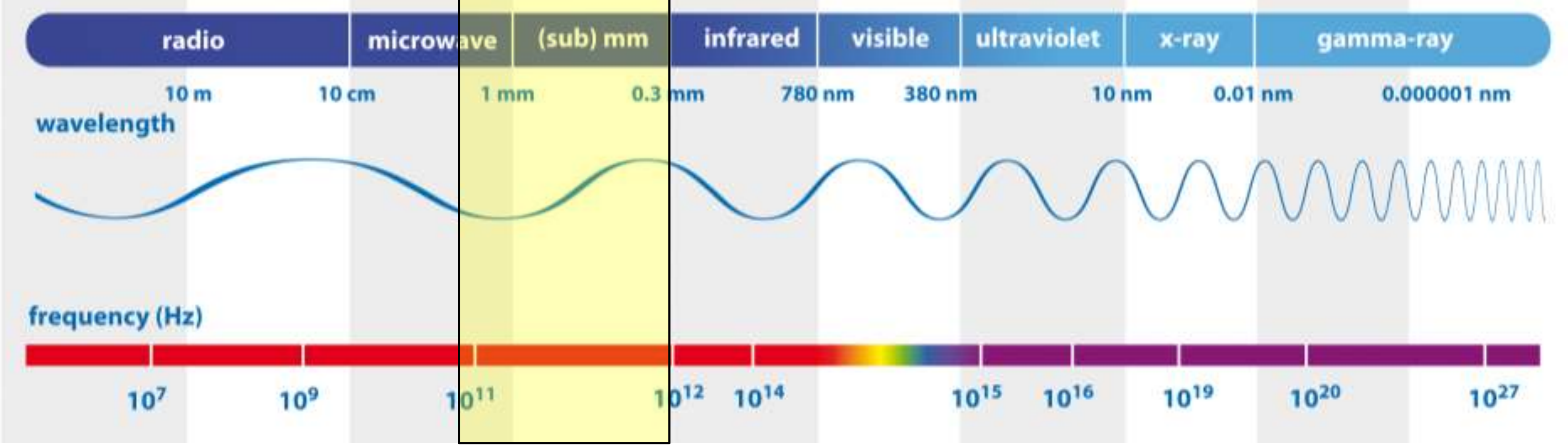
galaxy mergers

SPT.81



lensed galaxies


radio
microwave
(sub) mm
infrared
visible
ultraviolet
x-ray
gamma-ray
10 m
10 cm
1 mm
0.3 mm
780 nm
380 nm
10 nm
0.01 nm
0.000001 nm
wavelength
frequency (Hz)
10^7
10^9
10^11
10^12
10^14
10^15
10^16
10^19
10^20
10^27



ALMA observable range

“**Cold Universe**”

Why is ALMA on the Chajnantor plateau?

… at this altitude (5000 m) the water vapor in atmosphere is low

1 feet = 0.3 meters

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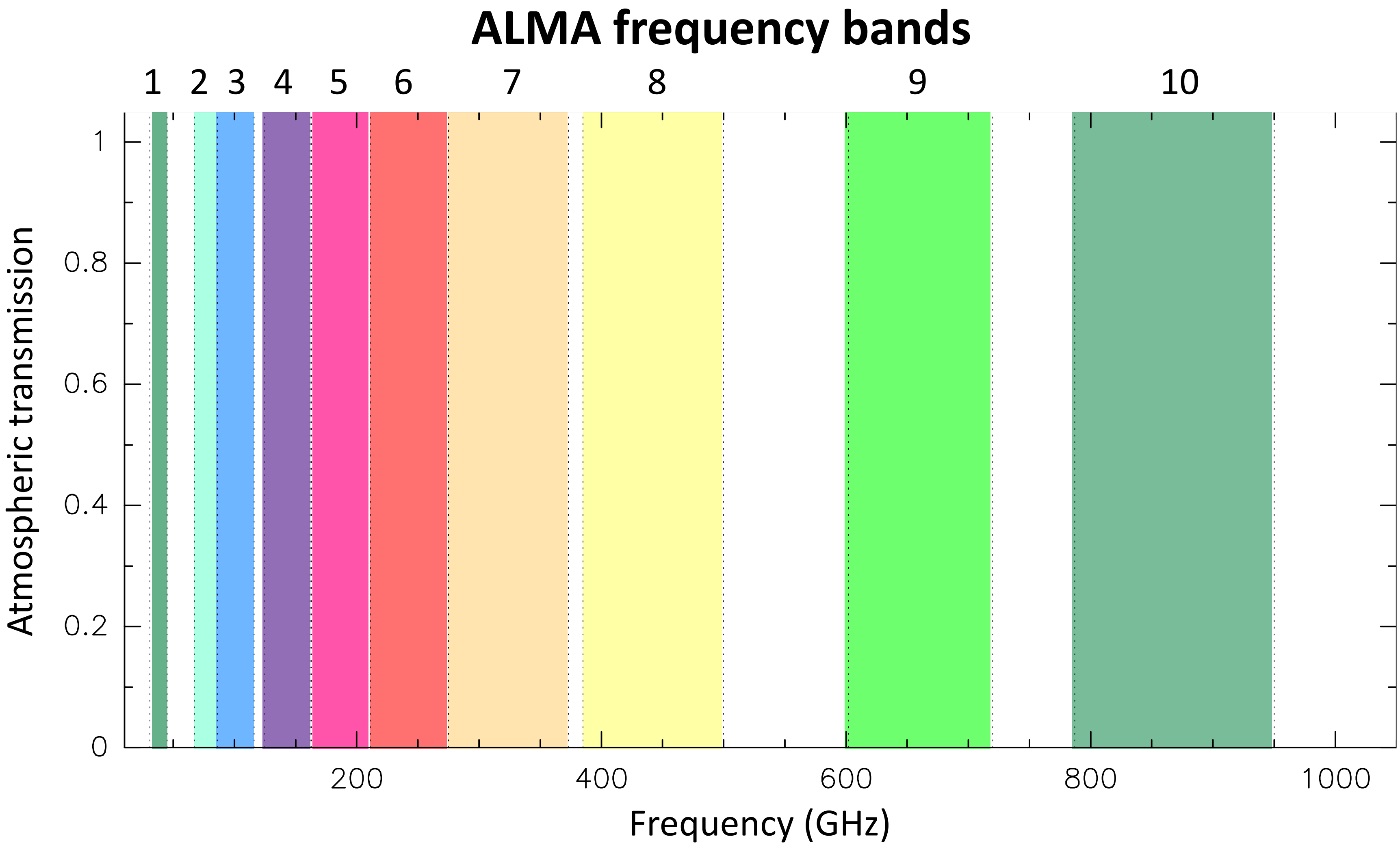

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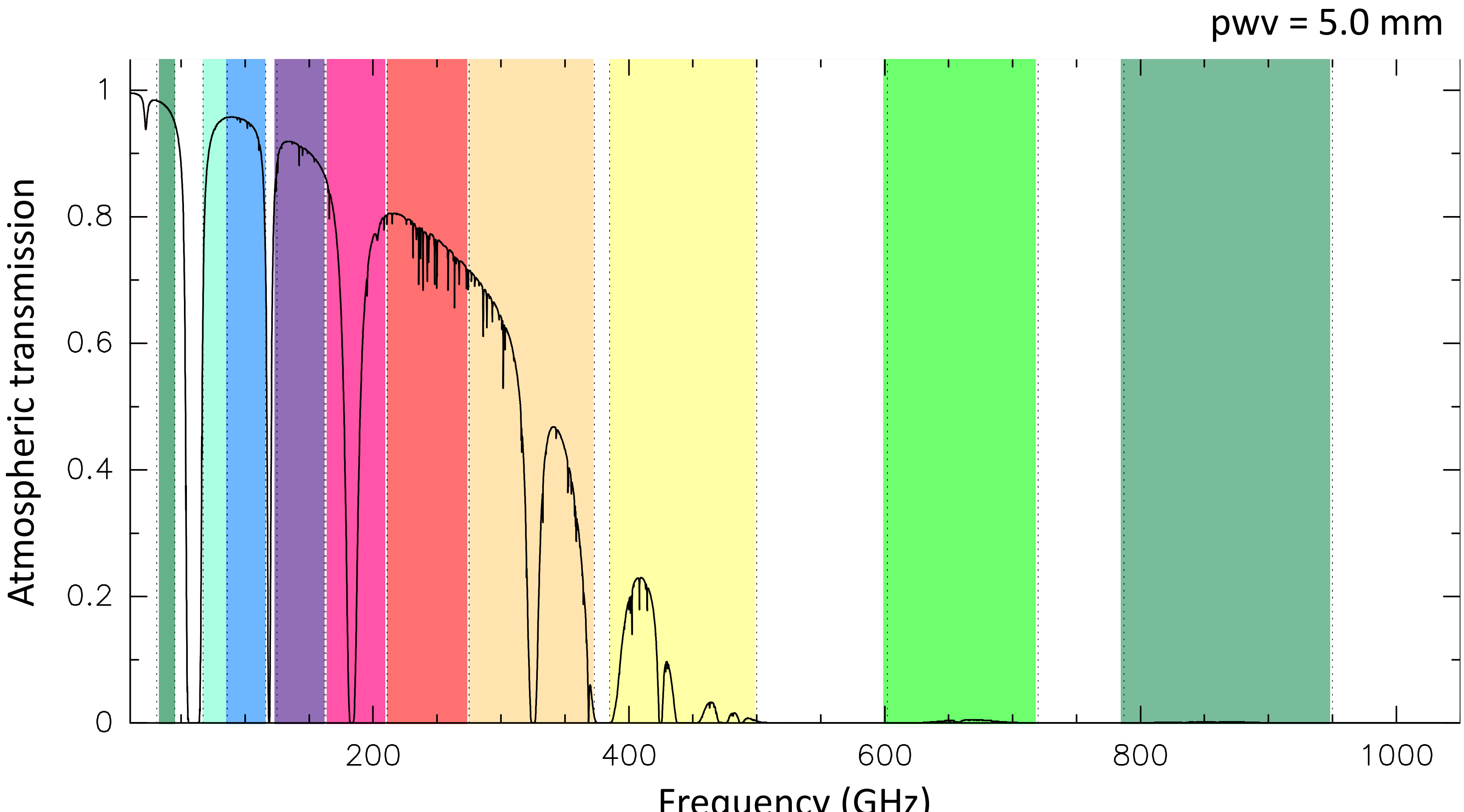
ALMA frequency bands



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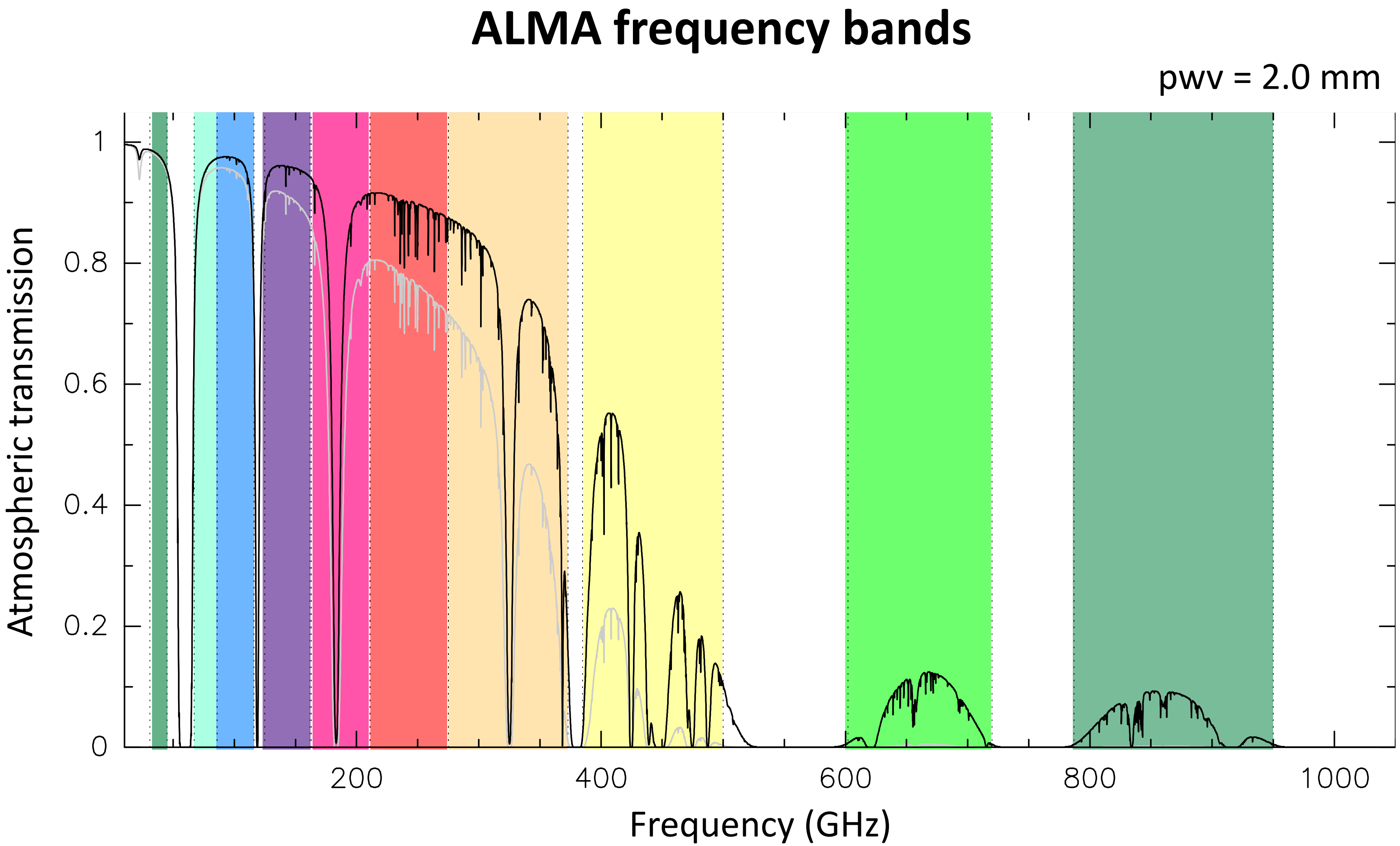

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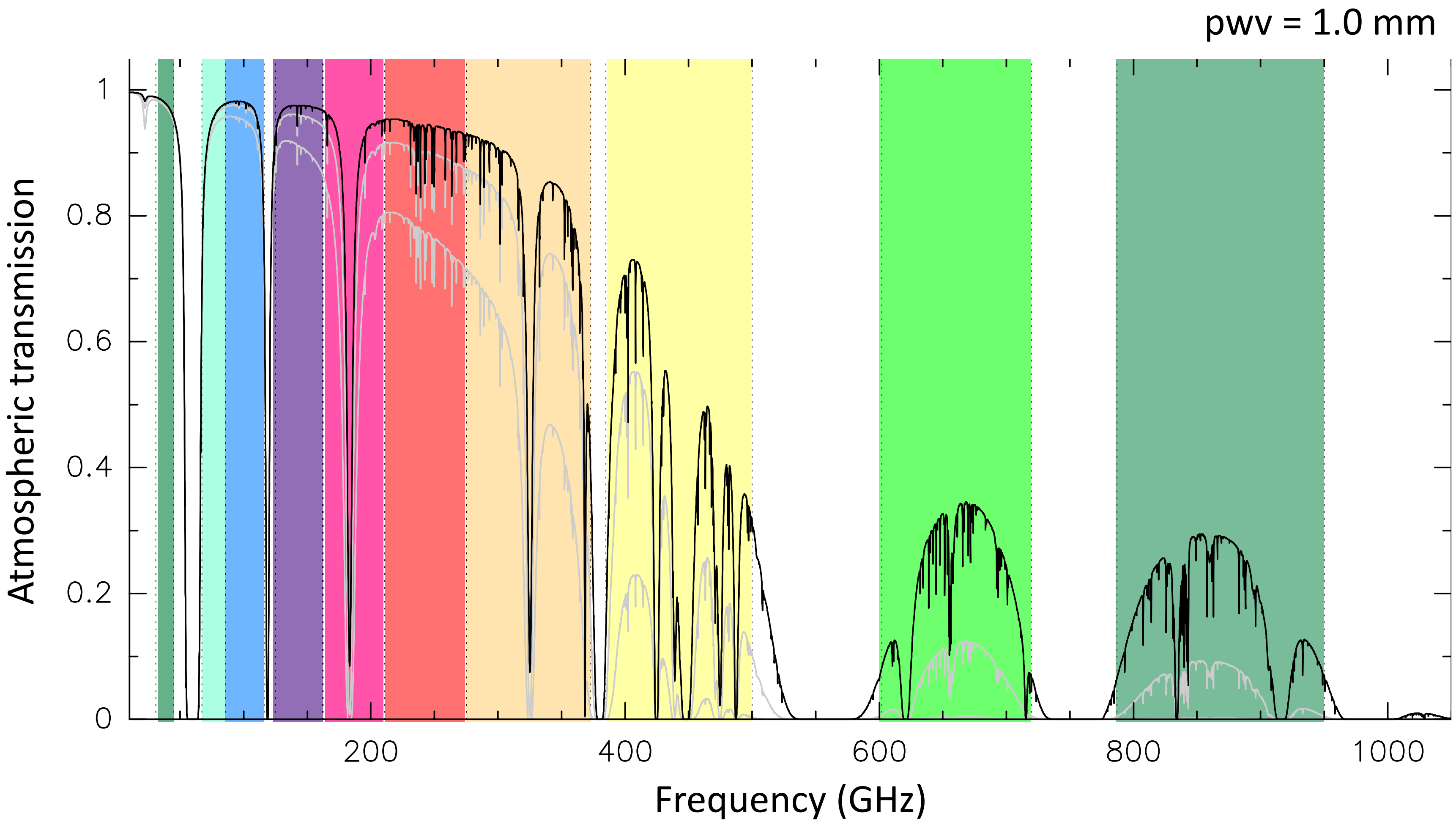

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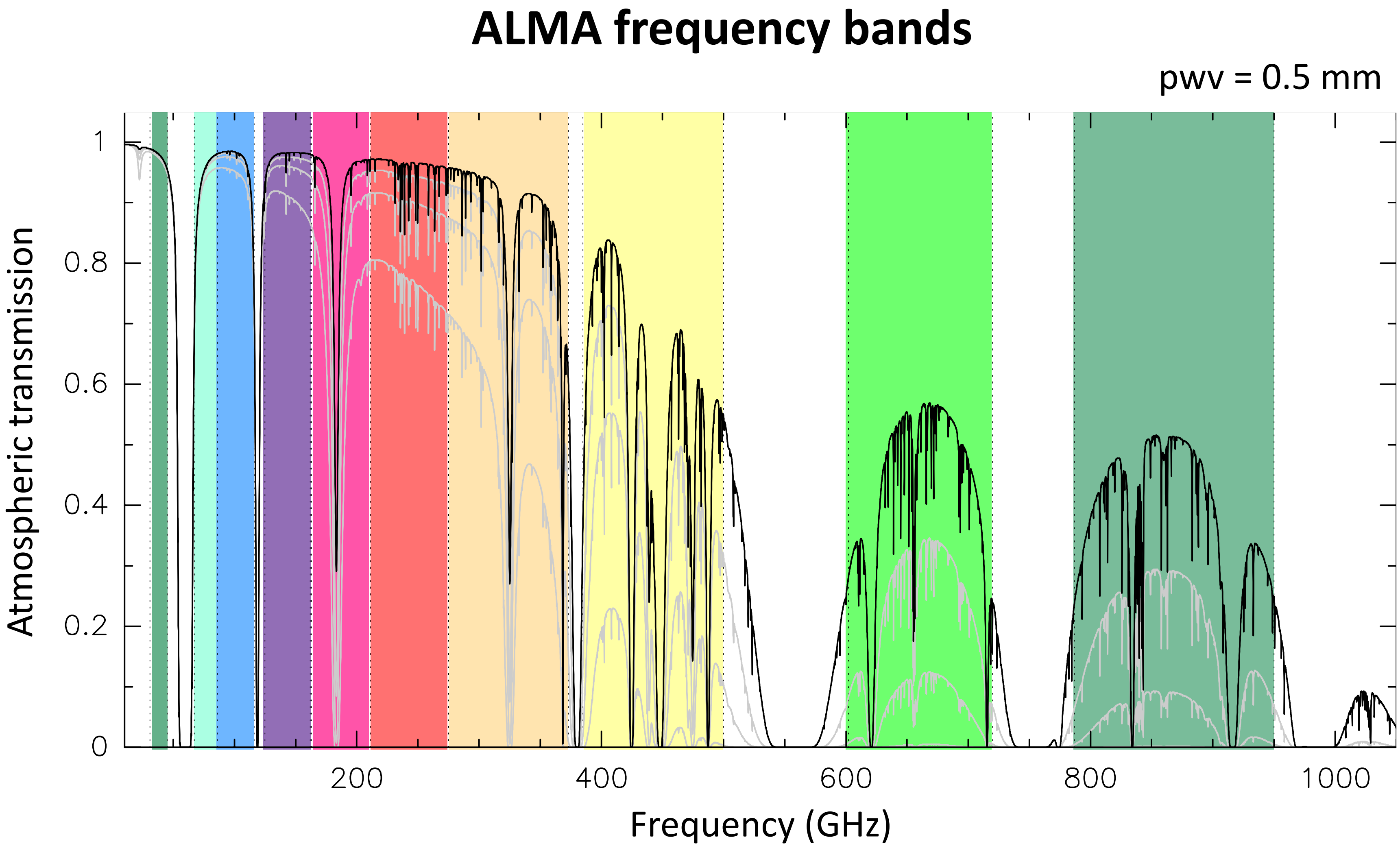

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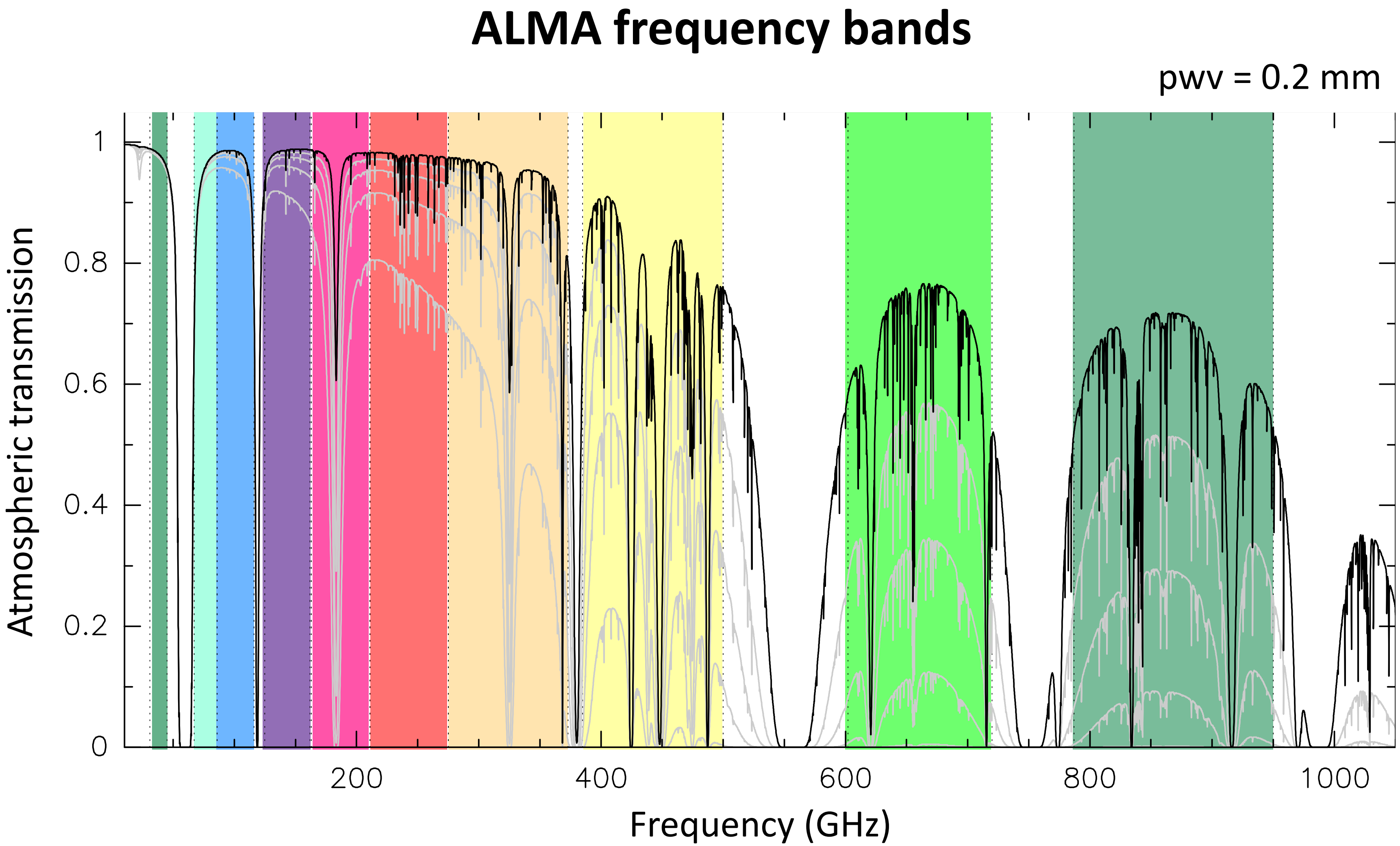
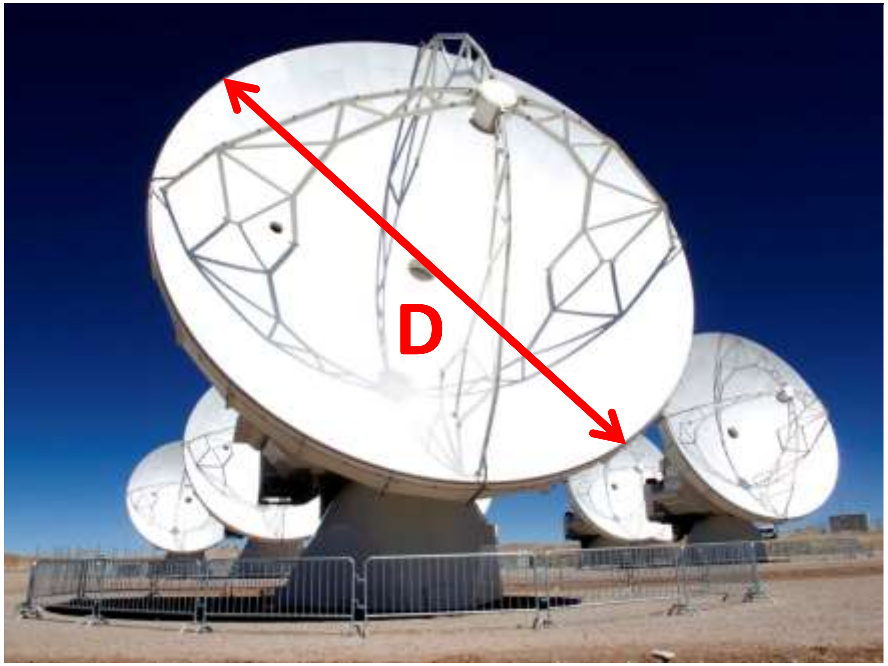


Why so many antennas? … instead of one

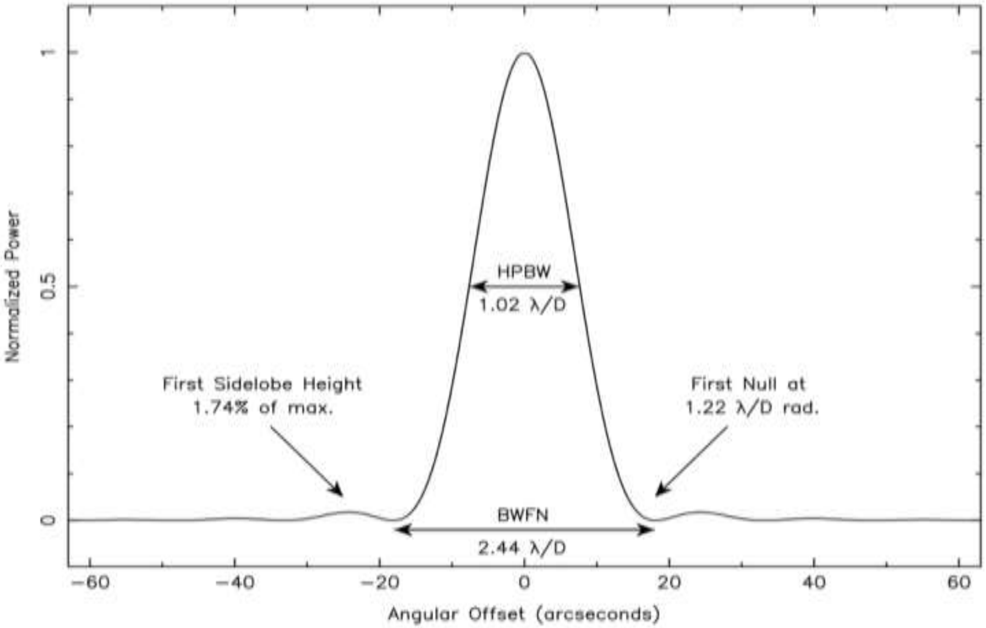
Image credit: Mélisse Bonfand

Single-dish response

Single-dish with diameter D



(1D) antenna power response



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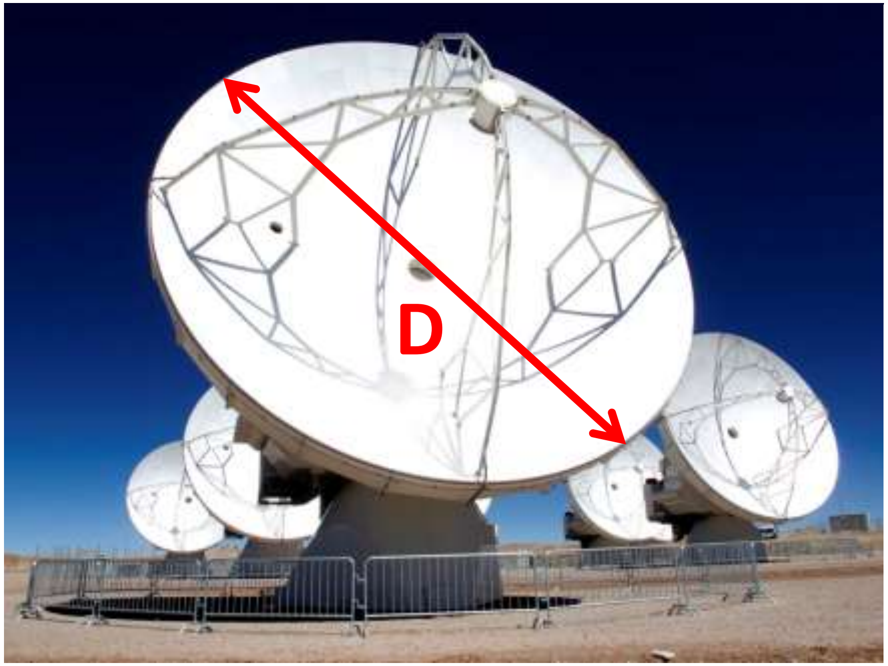

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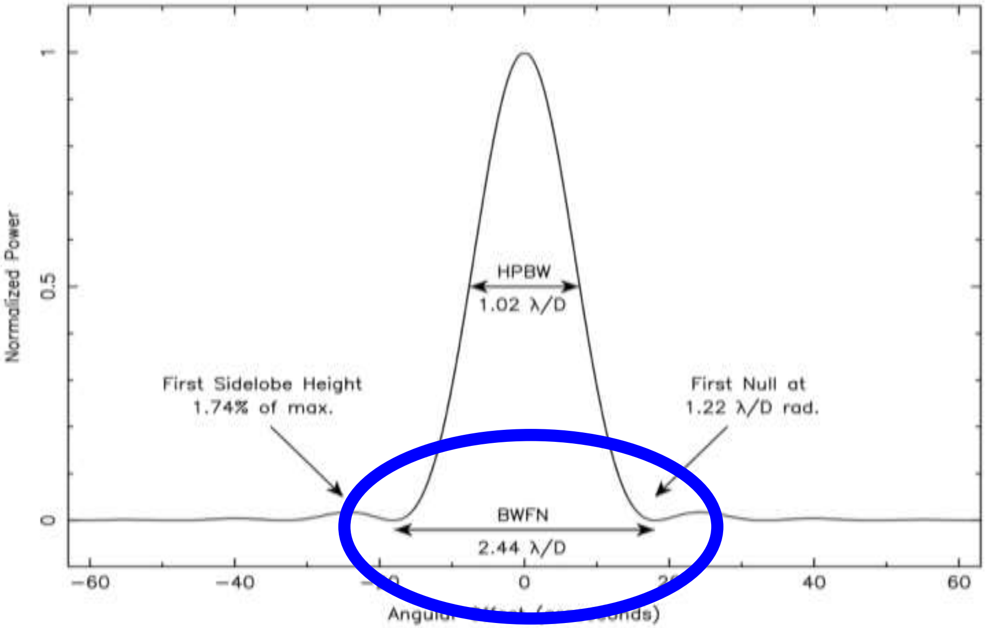
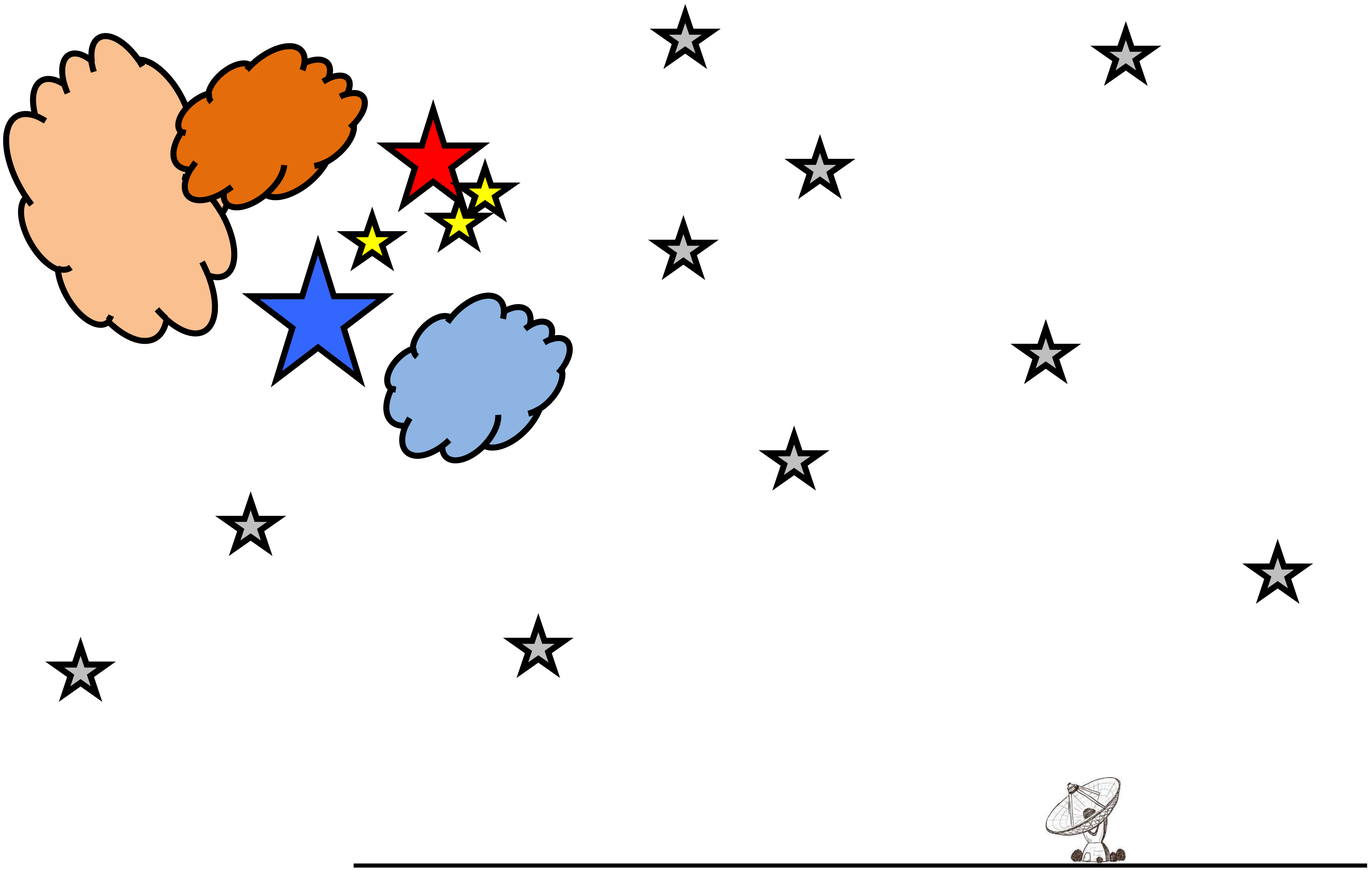


$$PB = 1.22\frac{l}{D}$$

PRIMARY BEAM

Single-dish response



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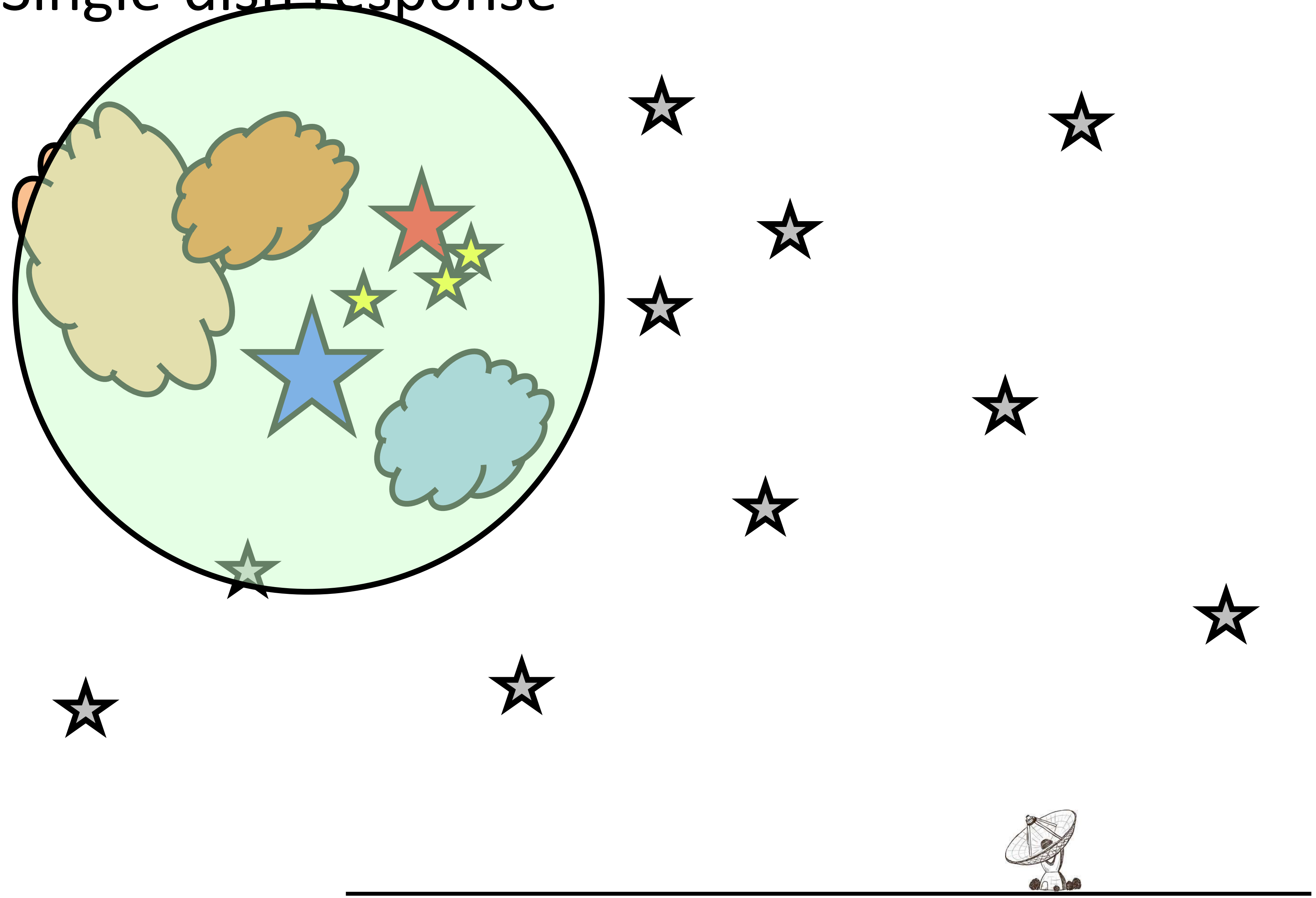

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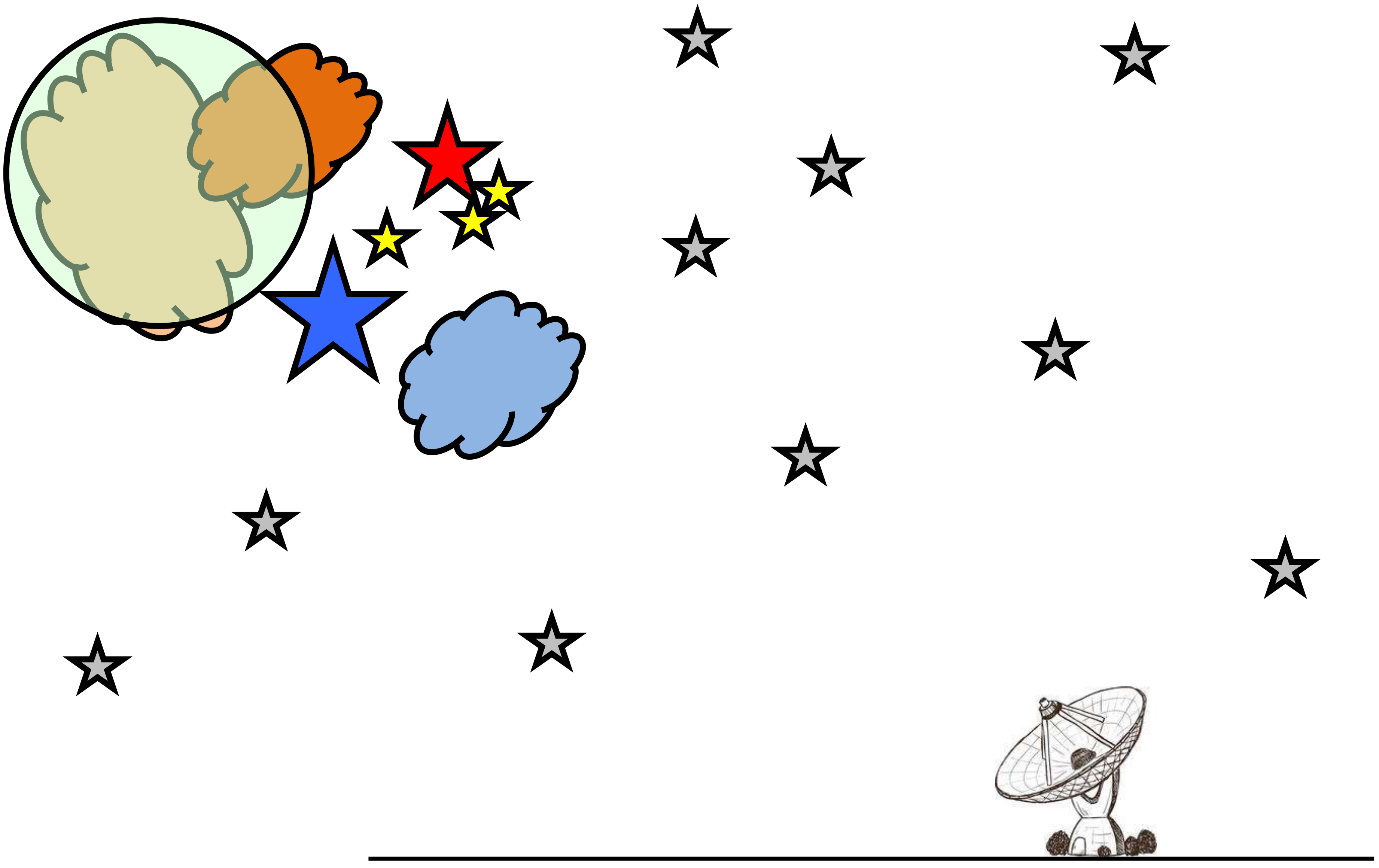

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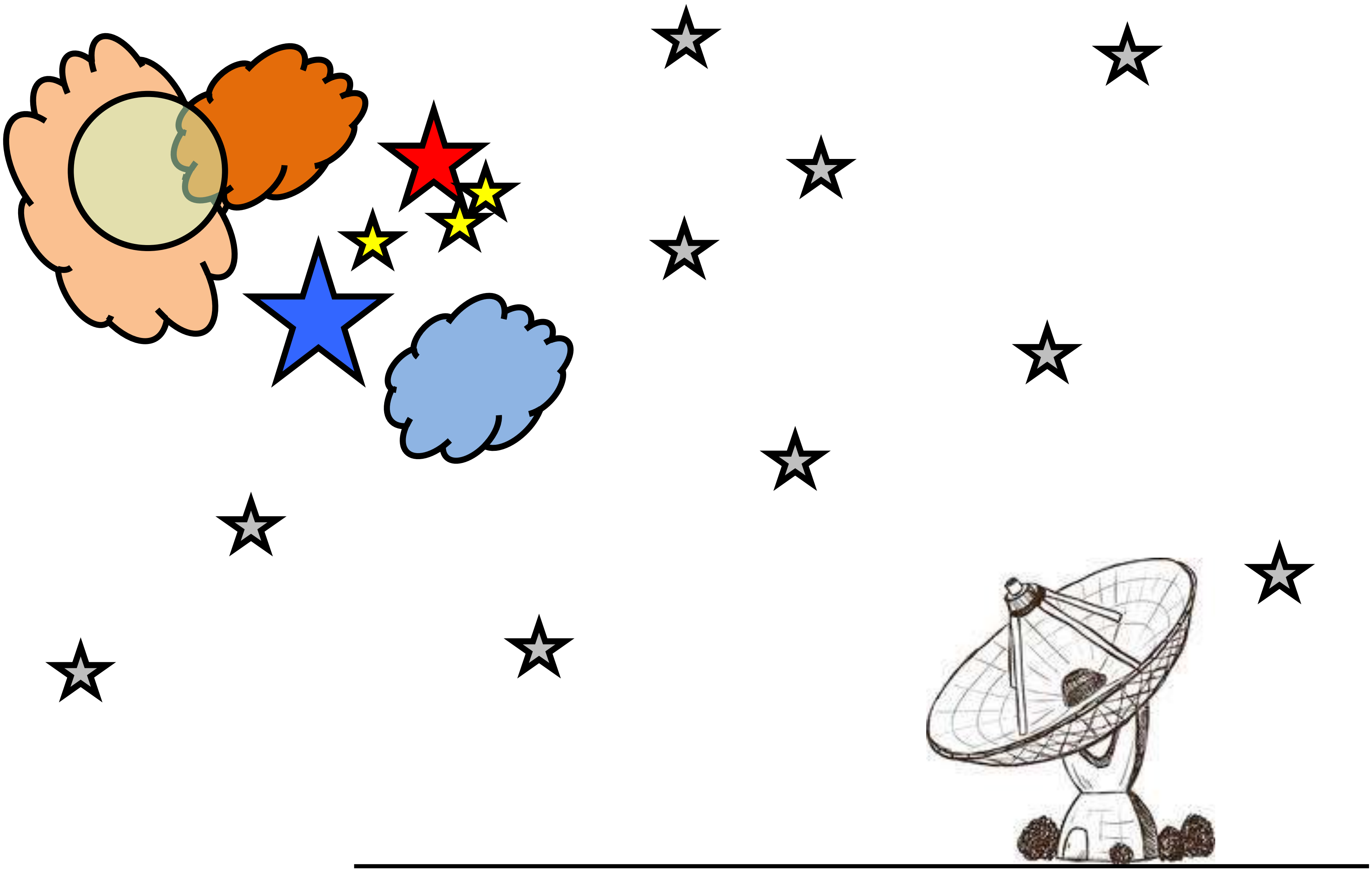

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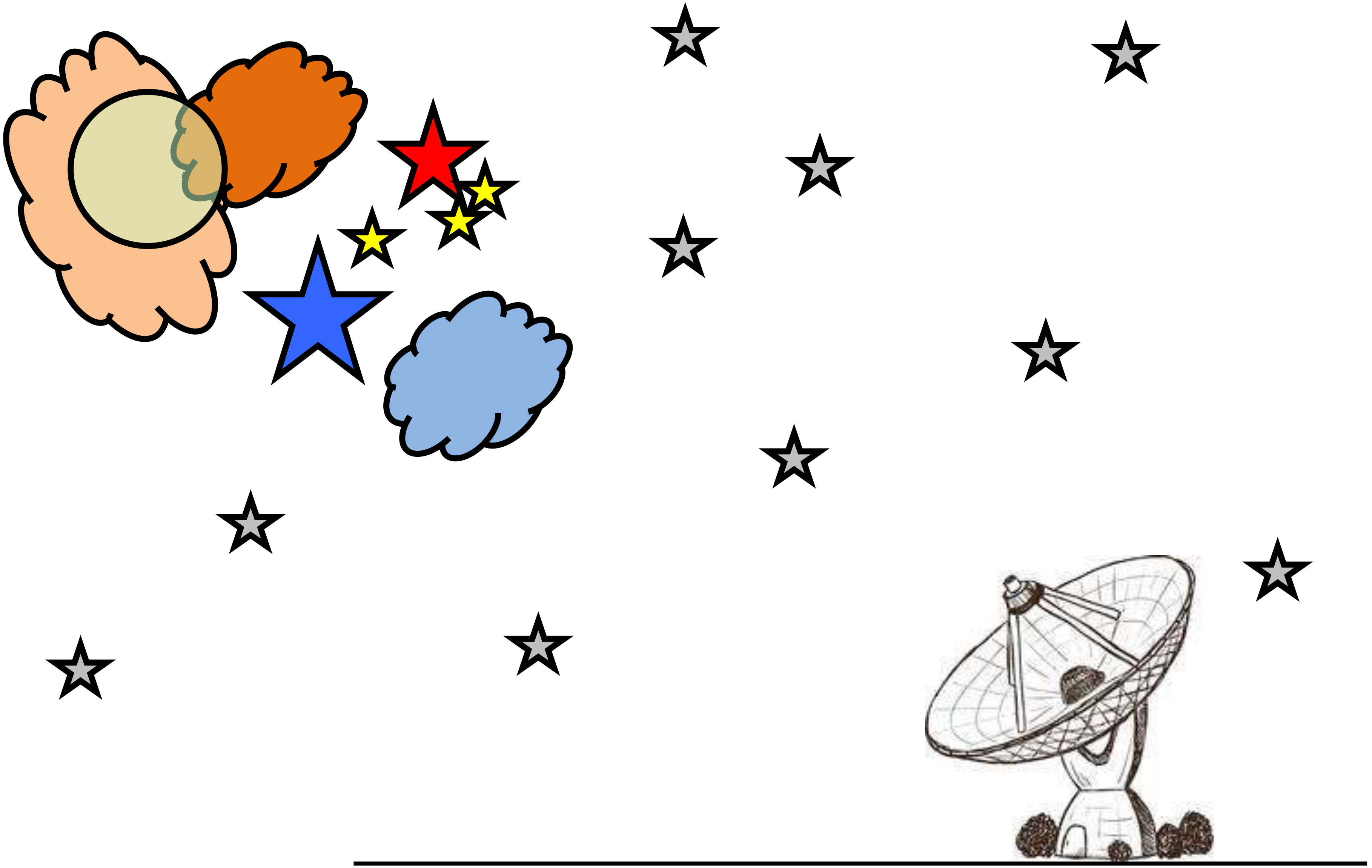

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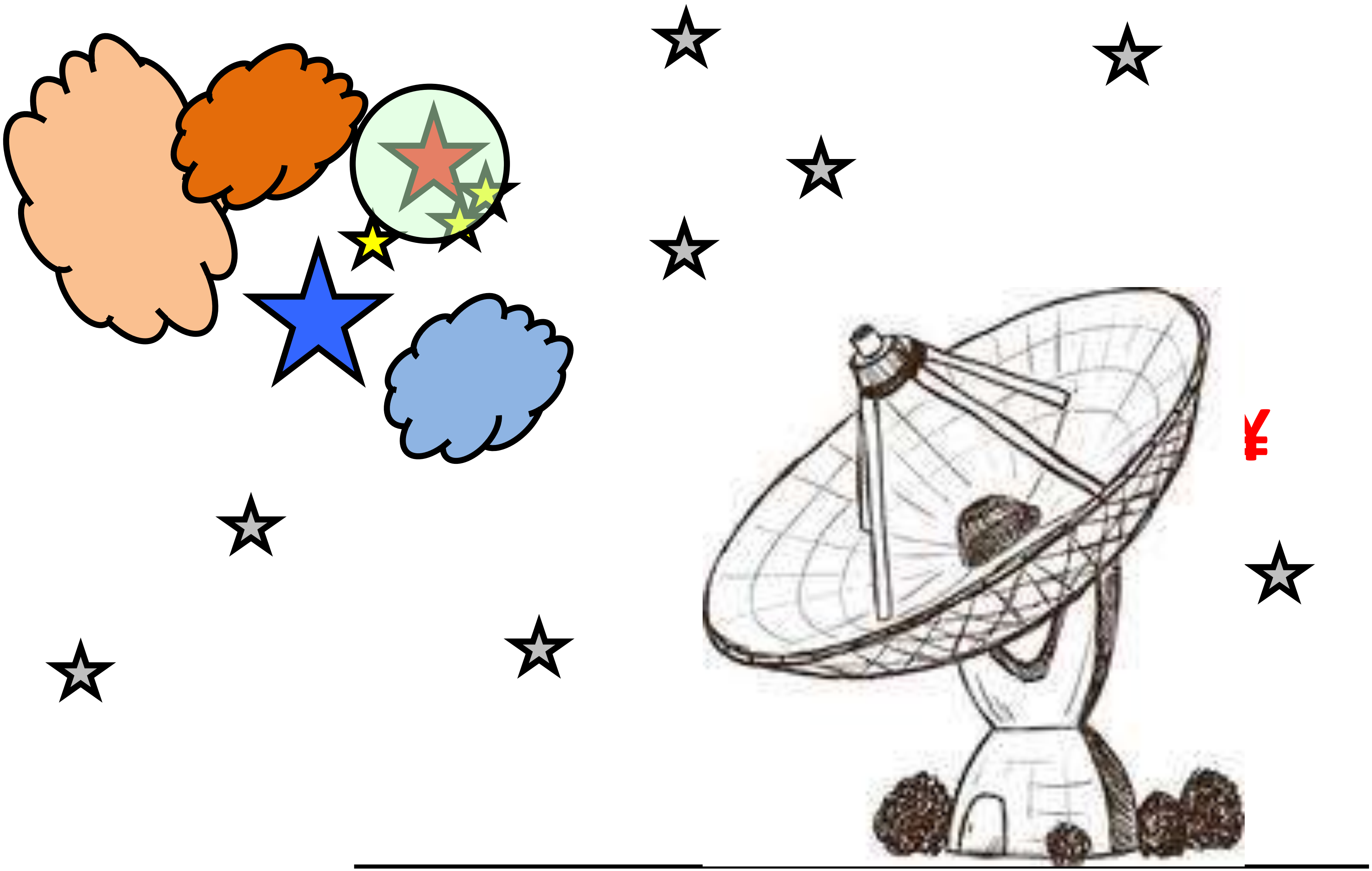

Interferometer – multiple dishes

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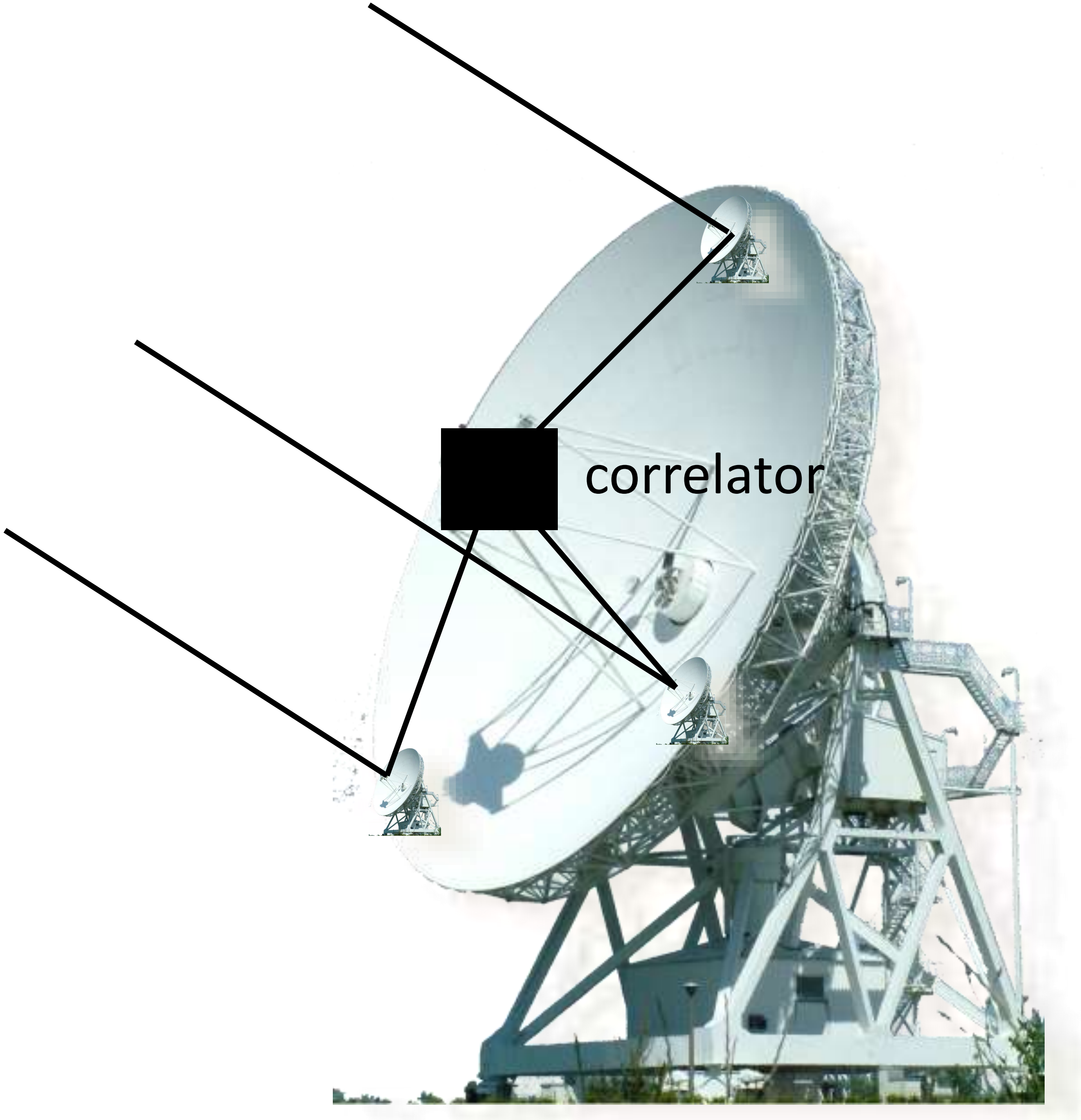

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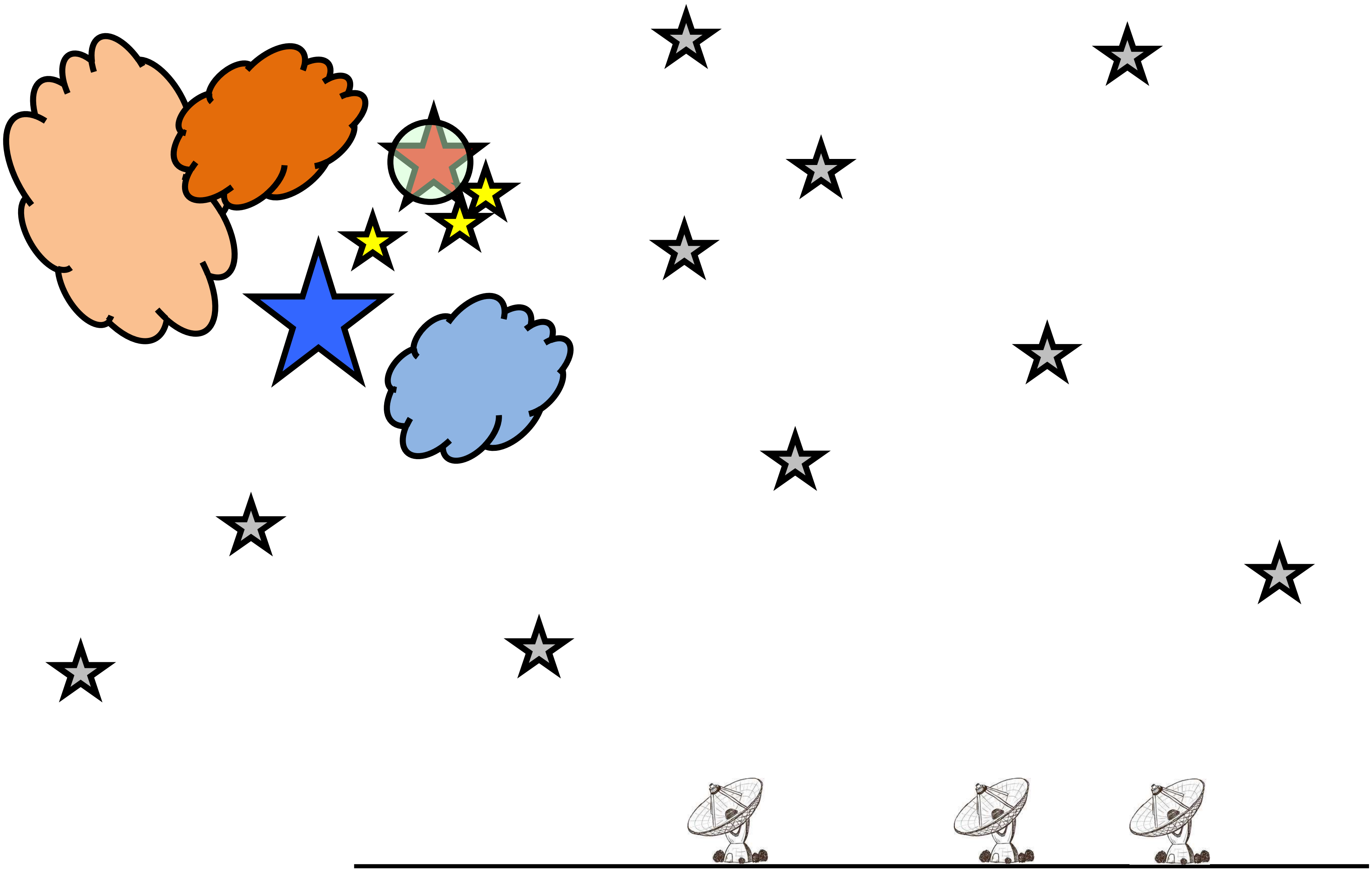

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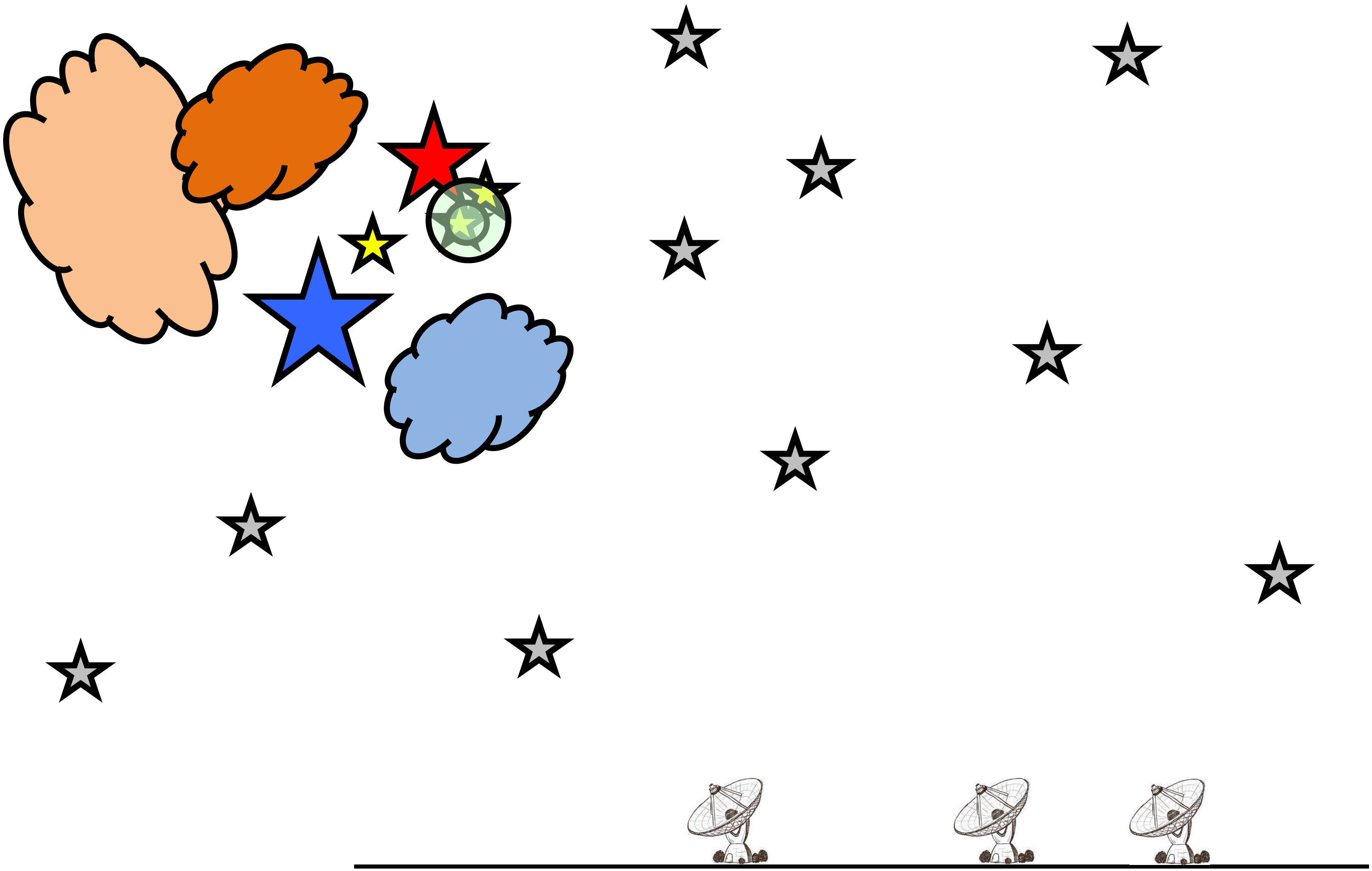
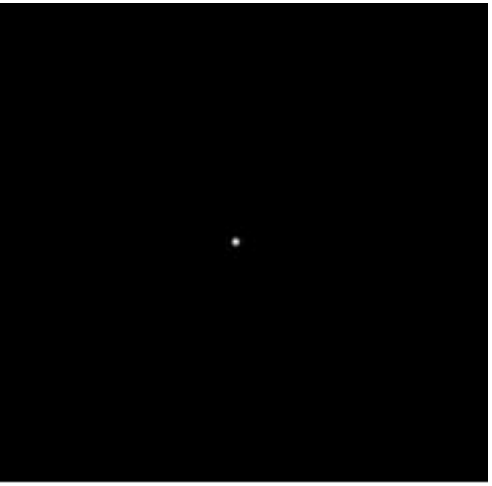


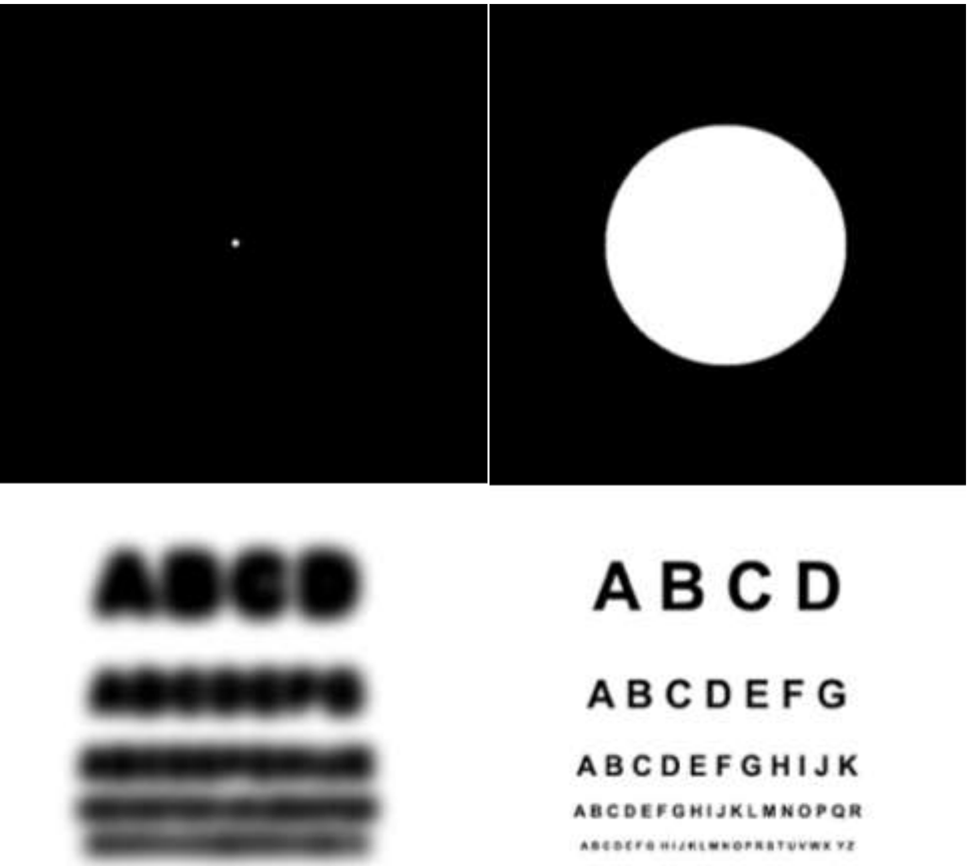
Interferometer – multiple dishes

Small Single-Dish



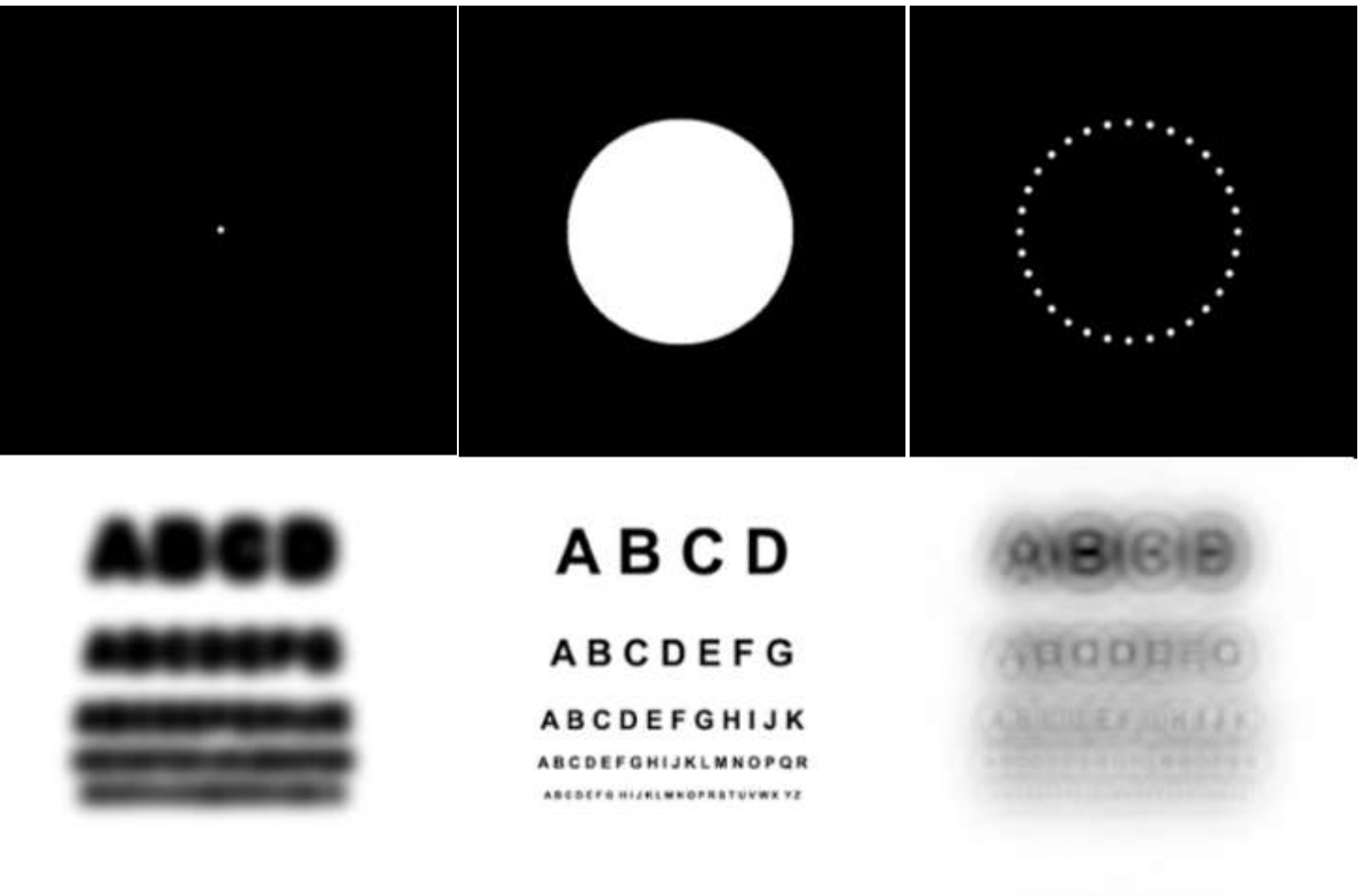
Interferometer – multiple dishes

Large Single-Dish



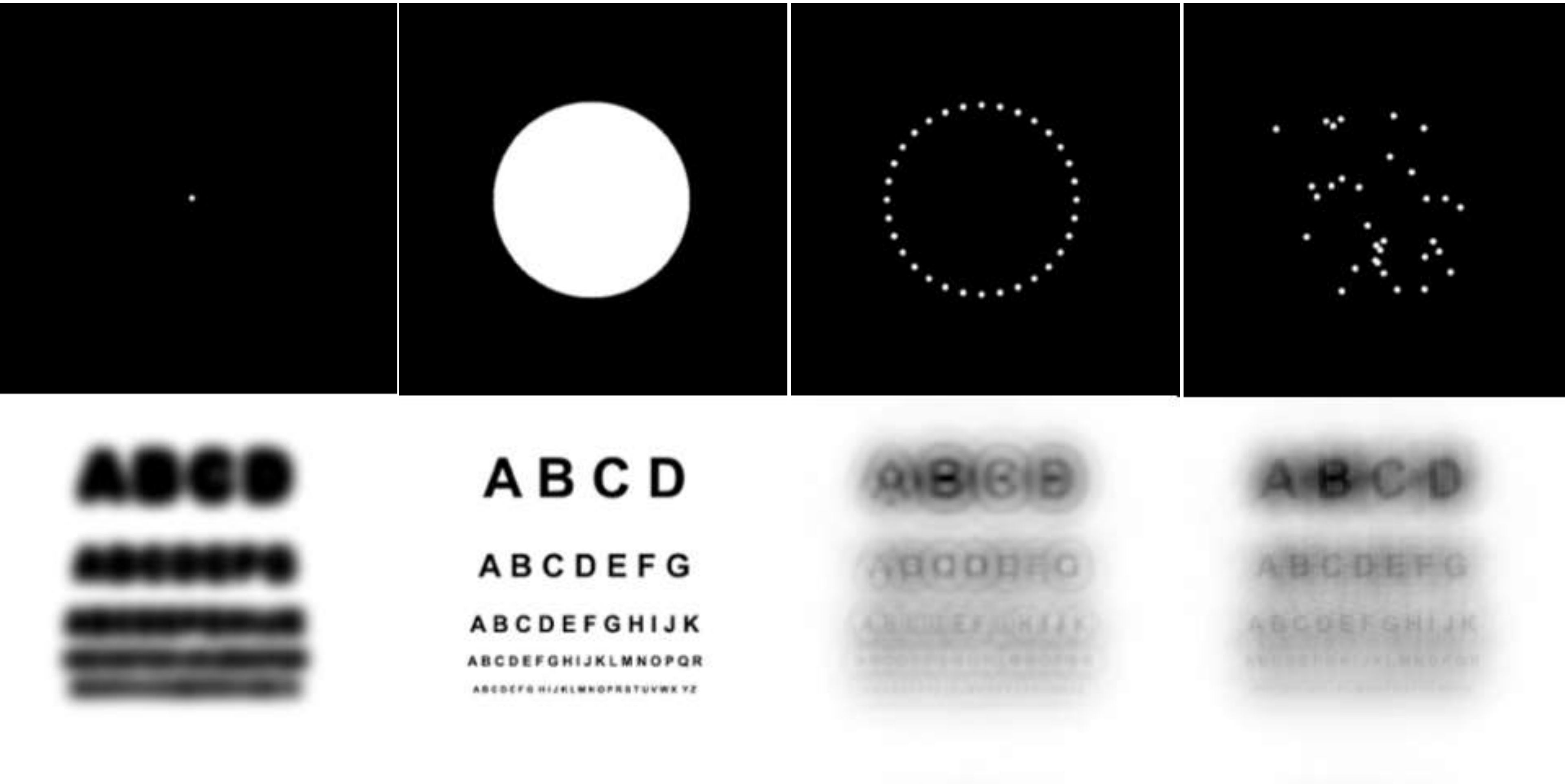
Interferometer – multiple dishes

“Circular” dishes



Interferometer – multiple dishes

"Random" dishes



Interferometry – visibilities

… a bit of equations (Fourier Transform)

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

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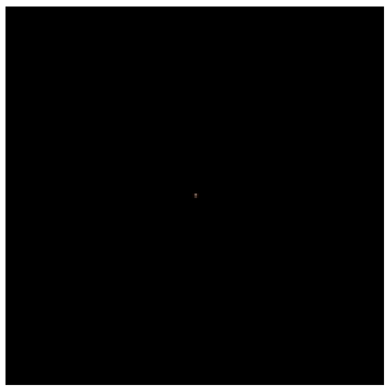
I (l,m) | | | V (u,v)

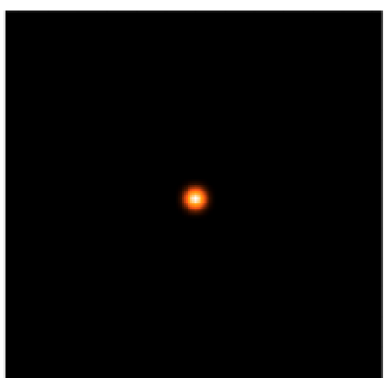
δ Function



⇌

Constant

Gaussian



⇌

Gaussian

Interferometry – visibilities

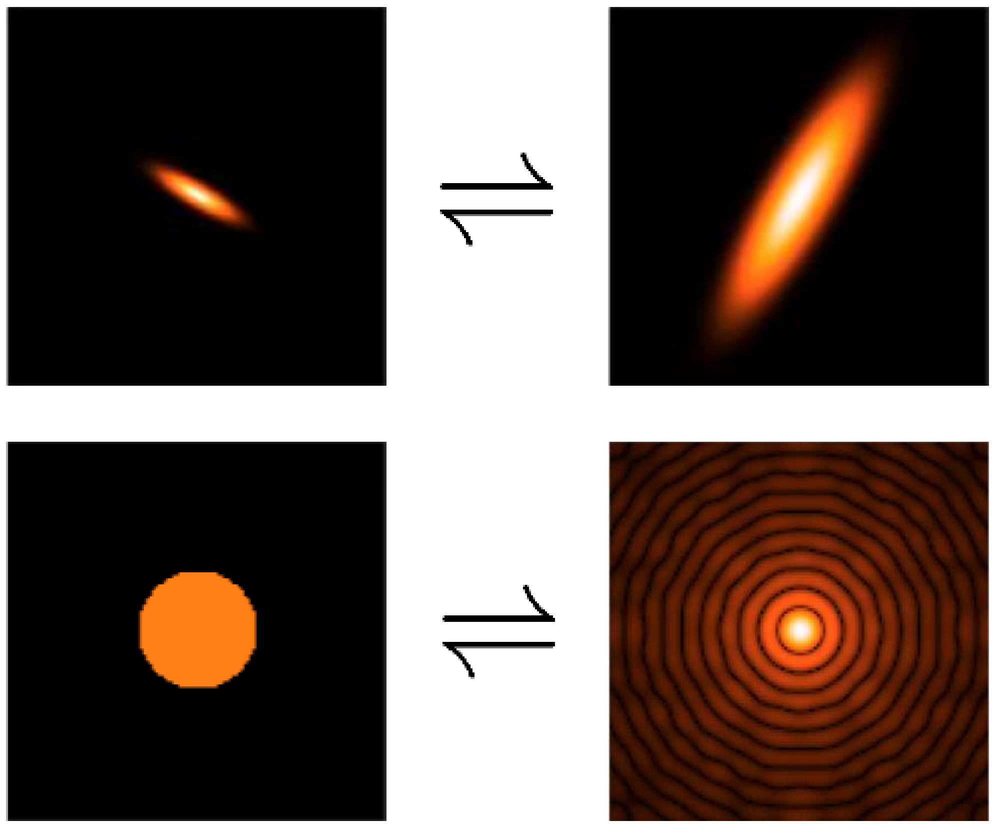
… a bit of equations (Fourier Transform)

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

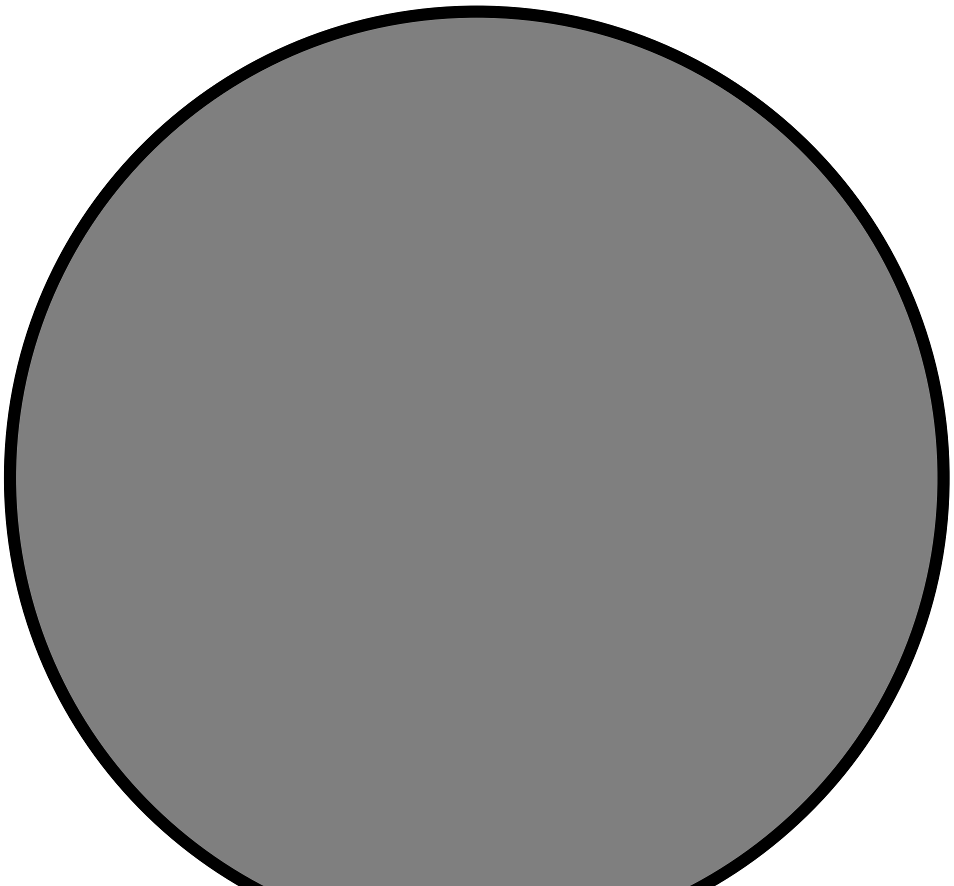
I (l,m) | V (u,v)

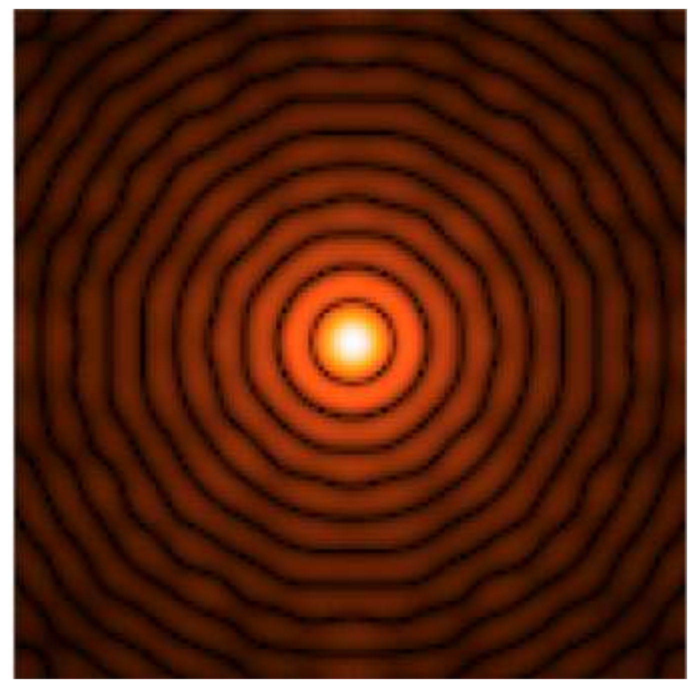
elliptical Gaussian | elliptical Gaussian

Disk | Bessel



Interferometry – spatial filters





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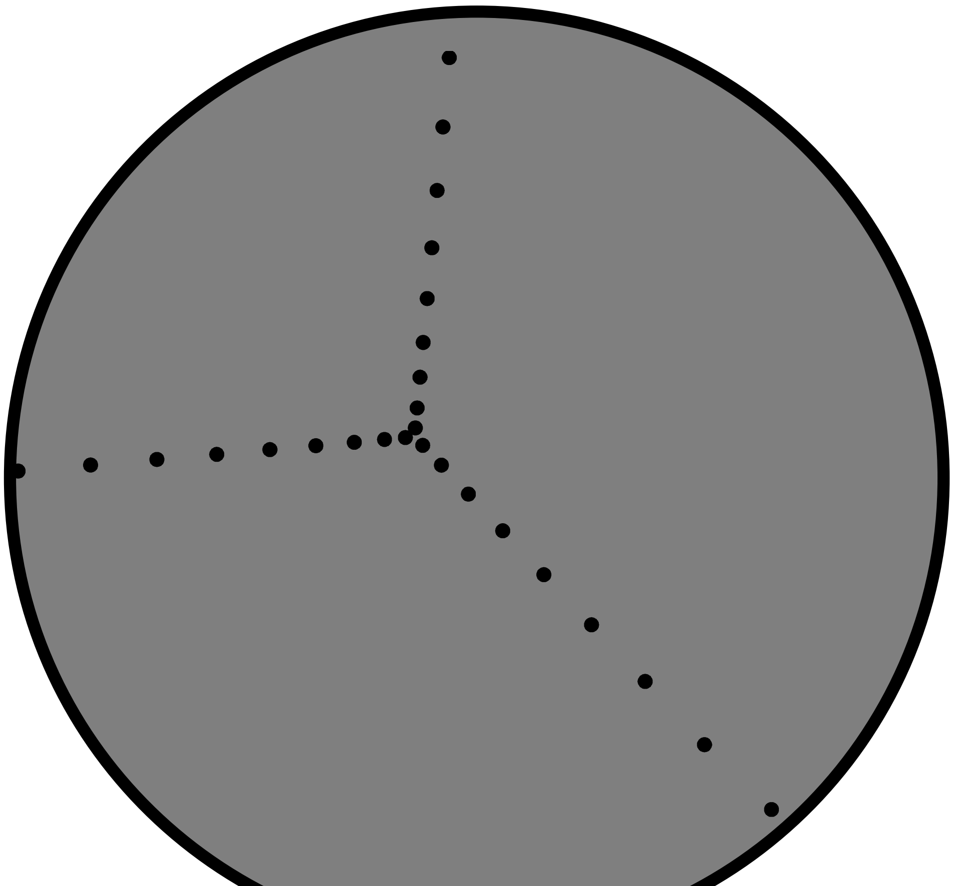

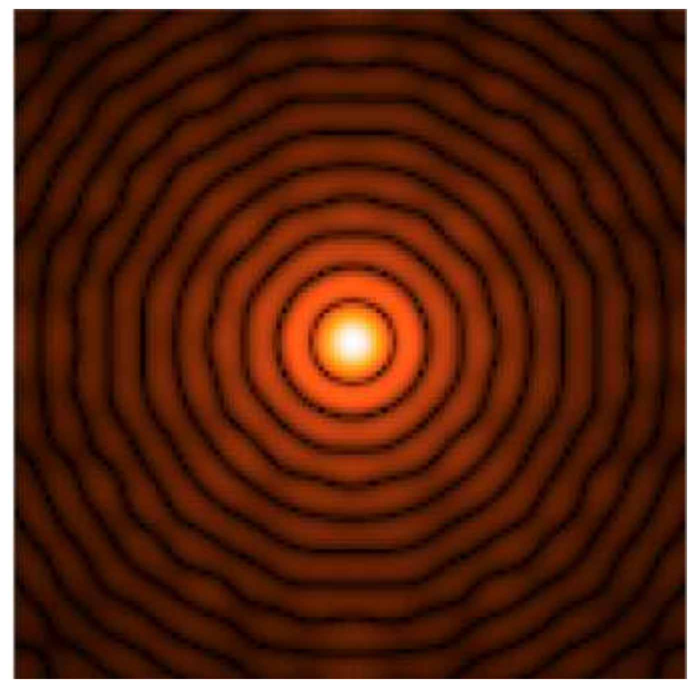

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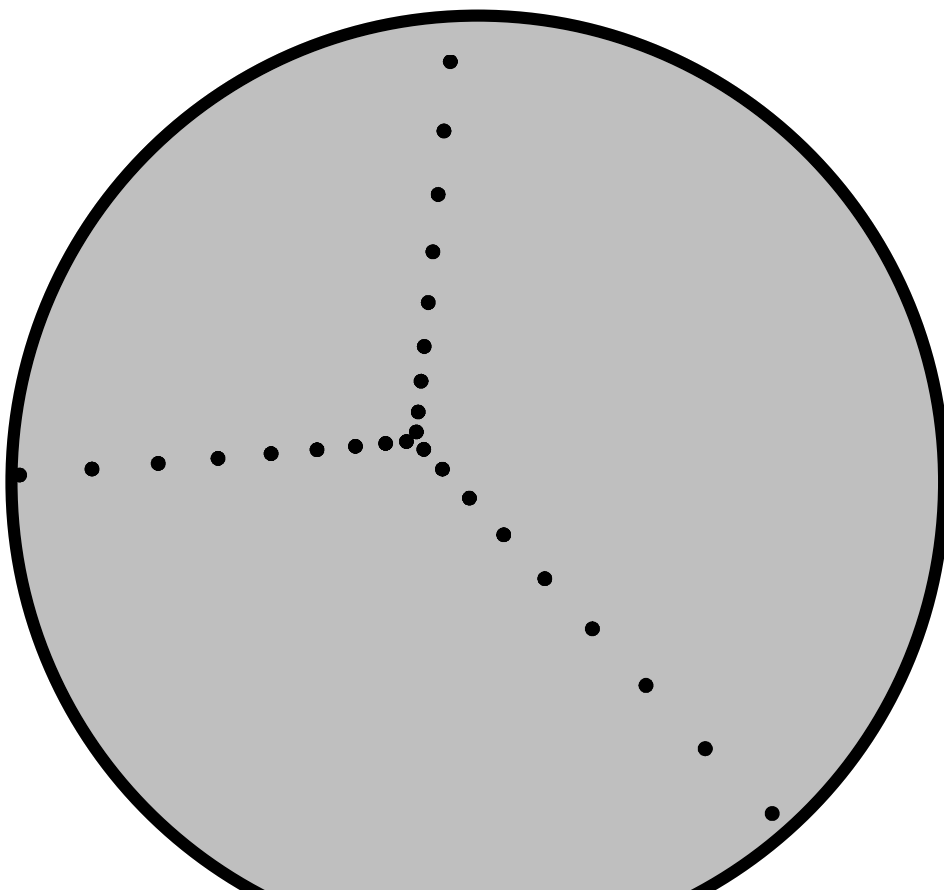
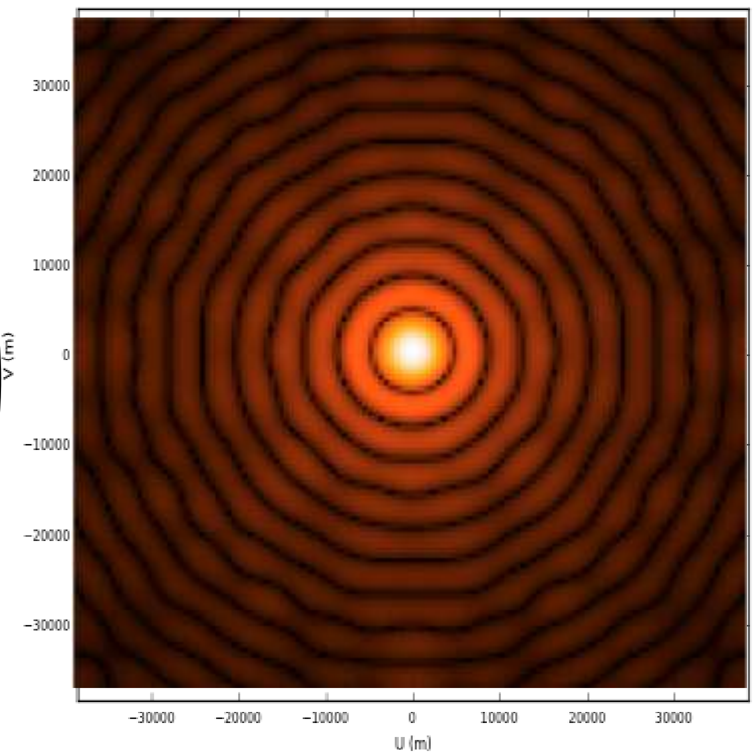
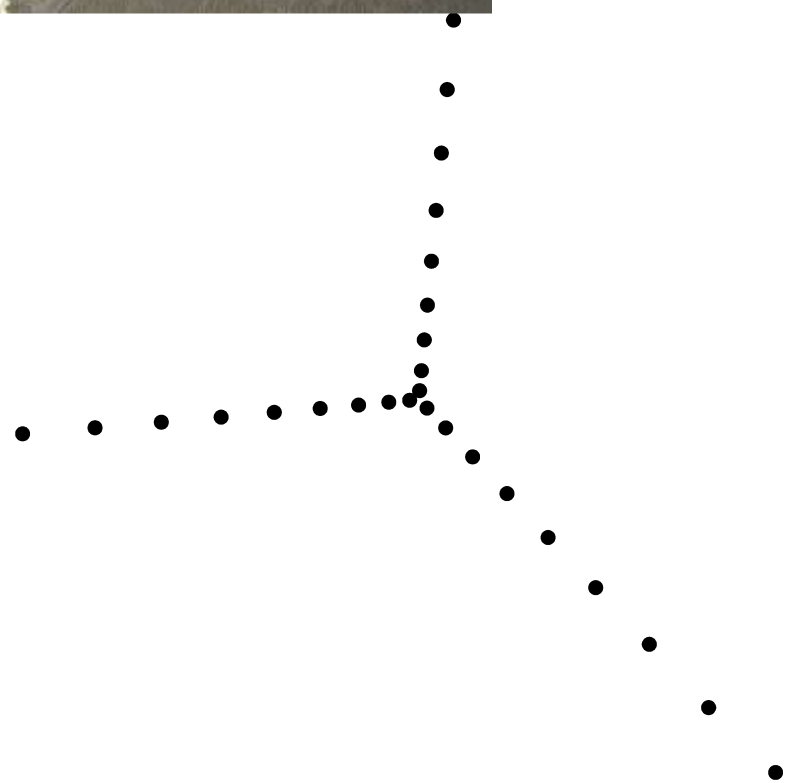


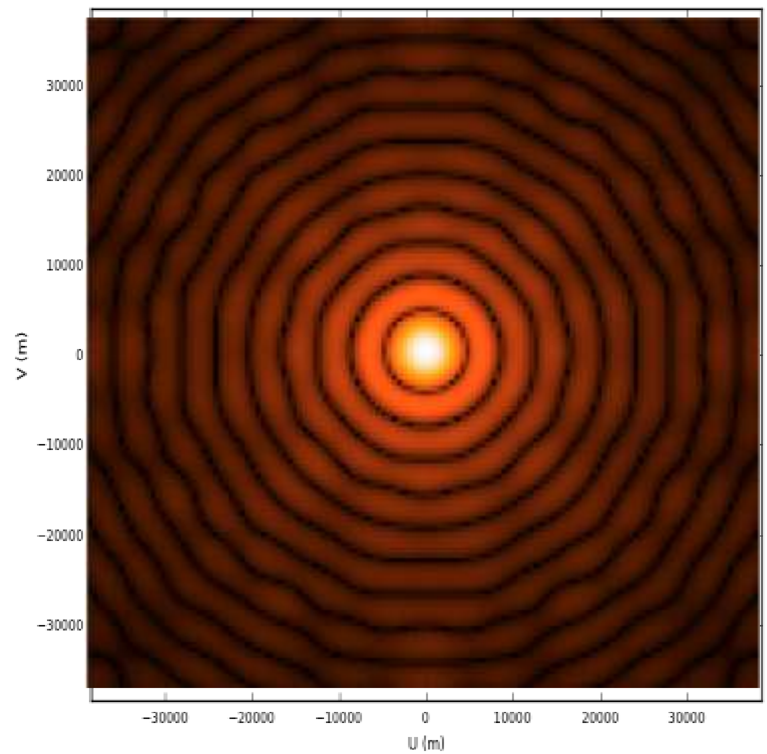


Example: VLA

Very Large Array (VLA)

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

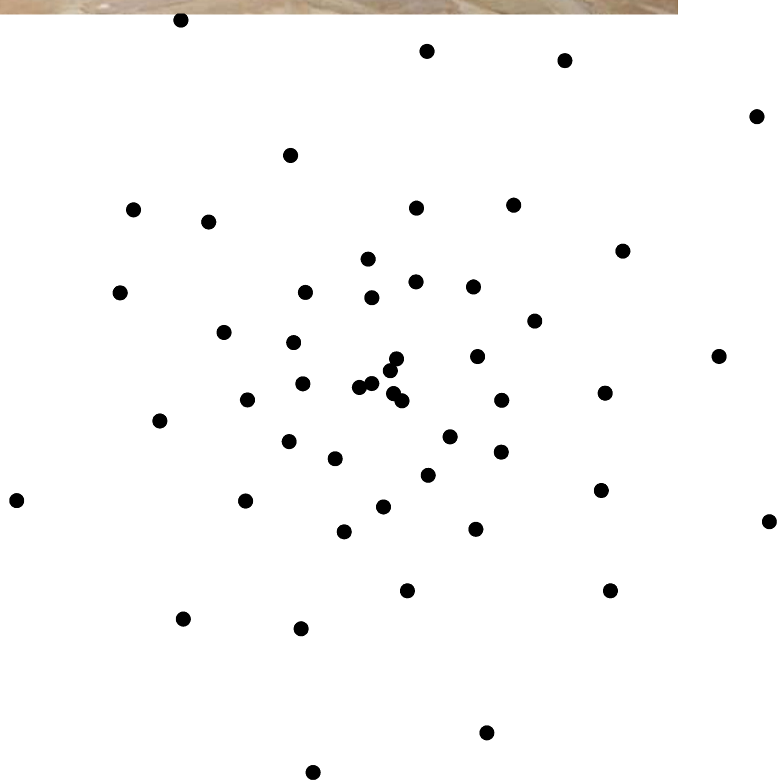


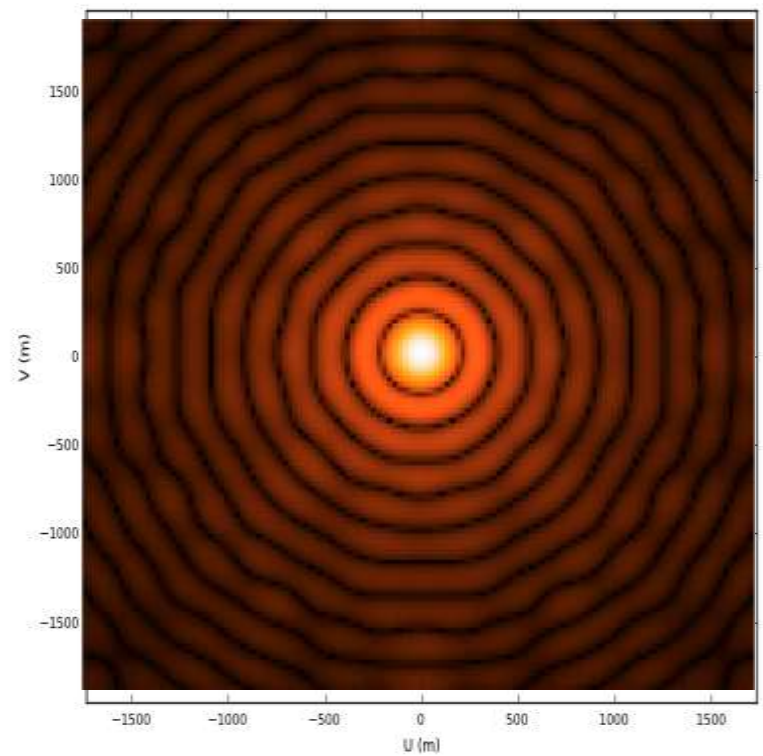


Example: ALMA

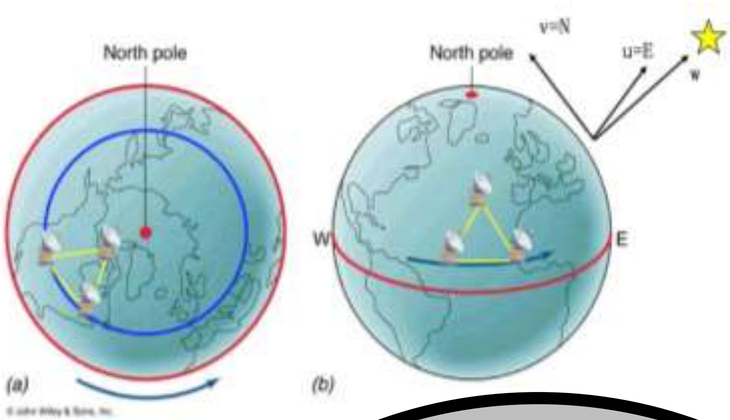
Atacama Large mm/submm Array (ALMA)

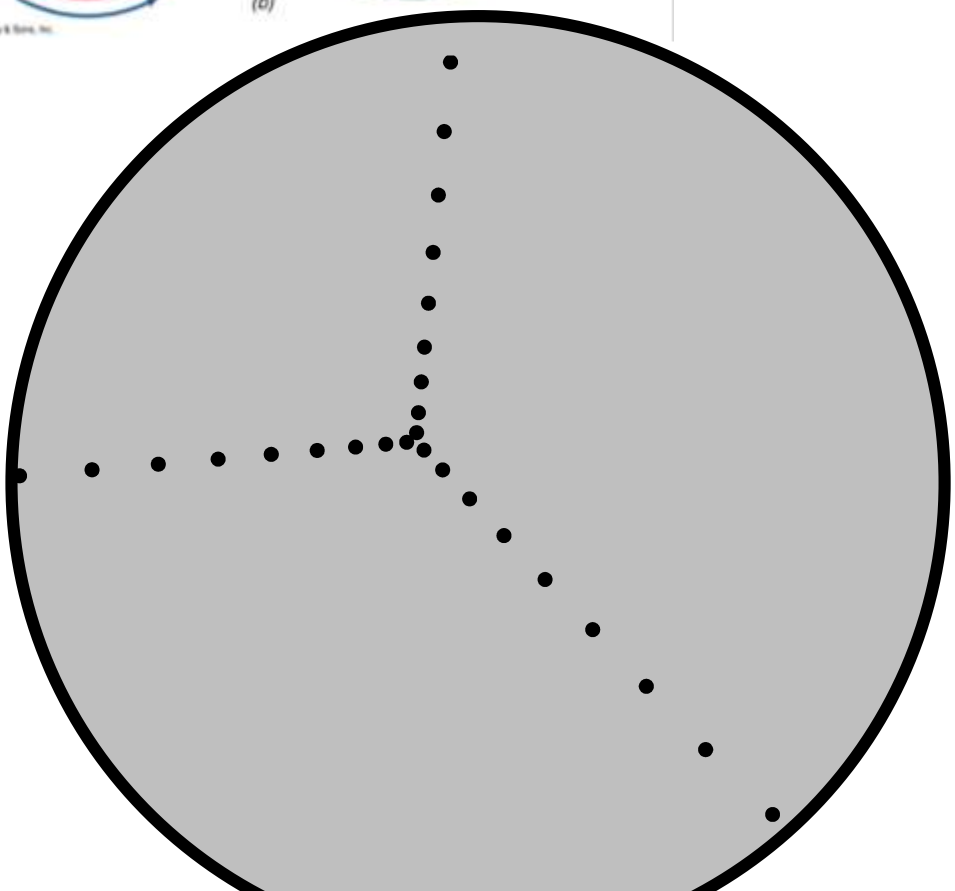
- 50 antennas of 12/7 meters
- observing from mm to submm
- in Llano Chajnantor (Chile)

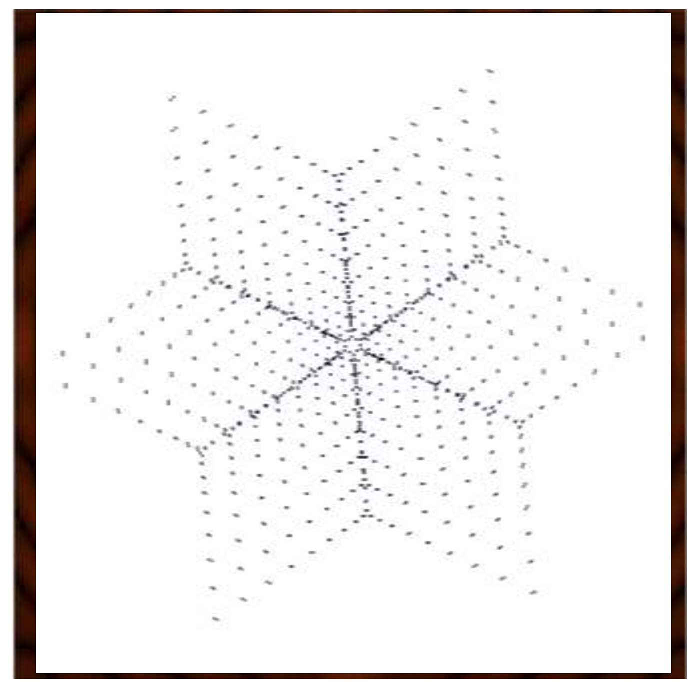




Interferometry – snapshots vs Earth rotation







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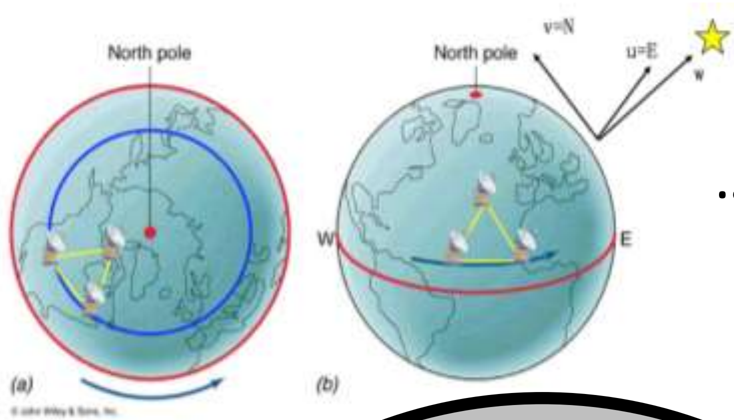
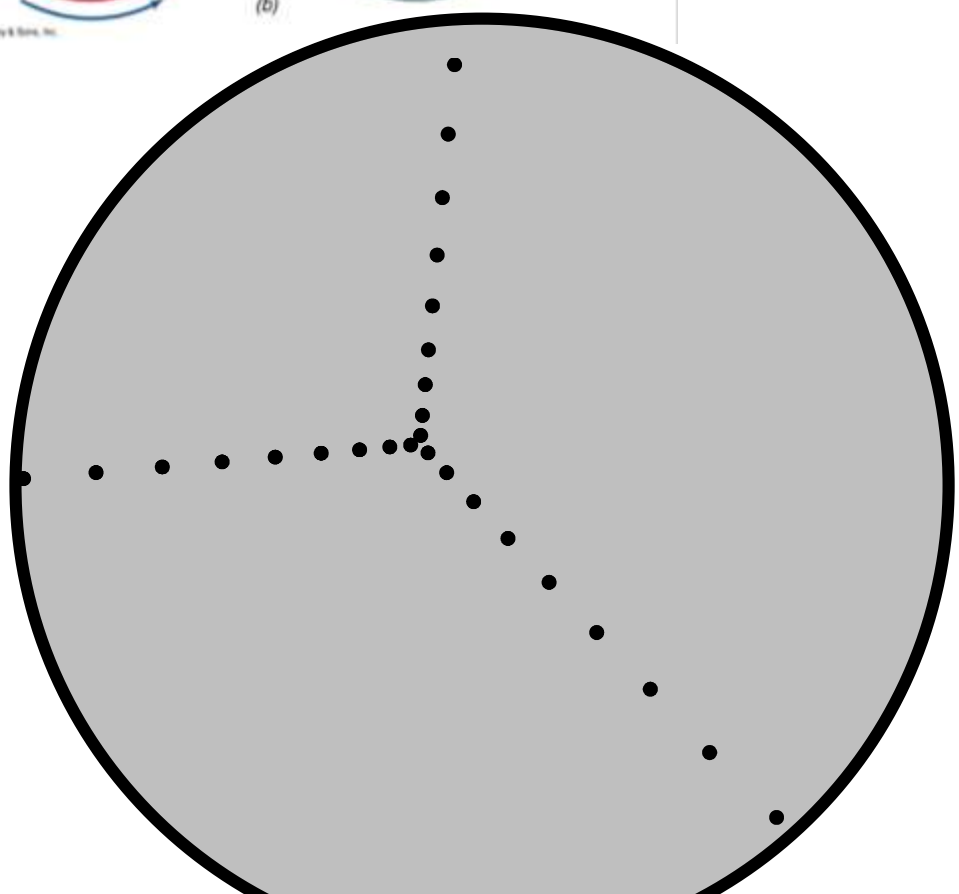
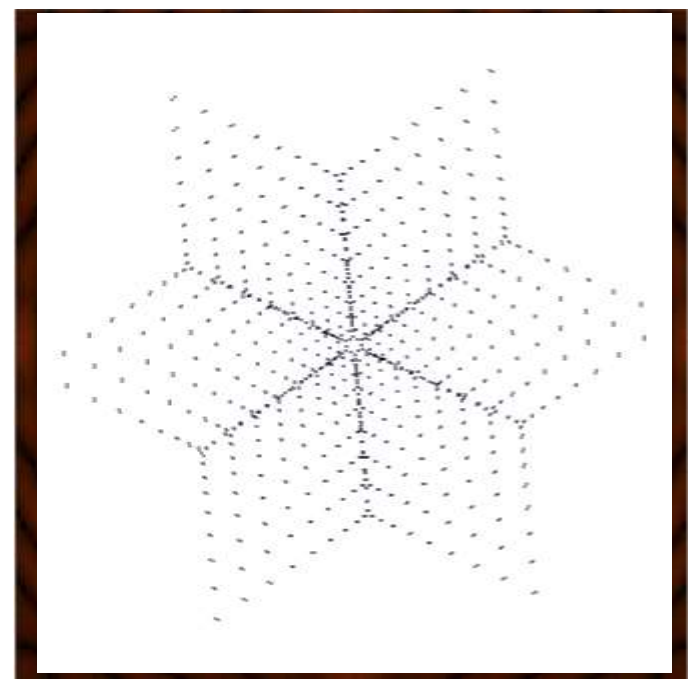


... we can just wait for the Earth to rotate





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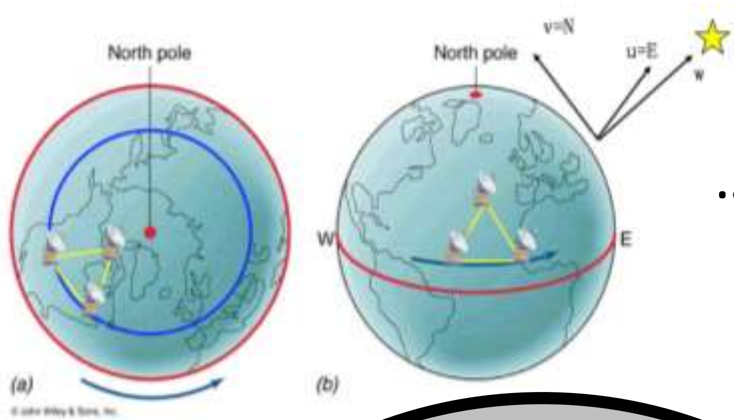

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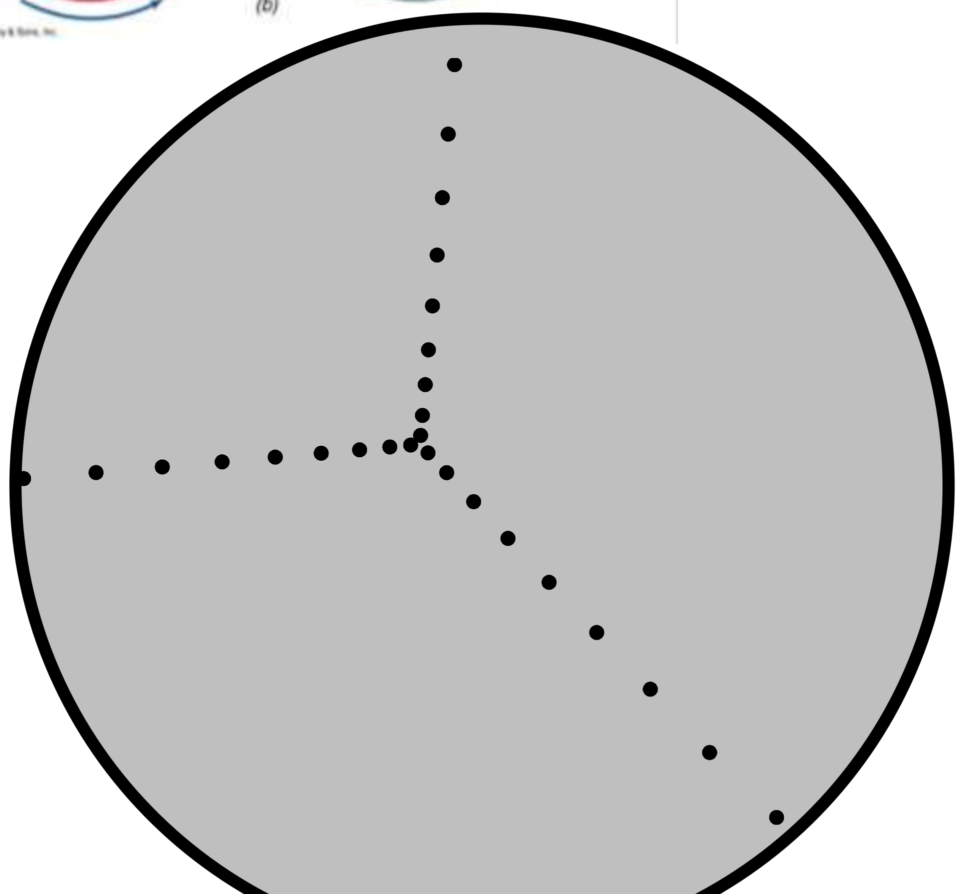

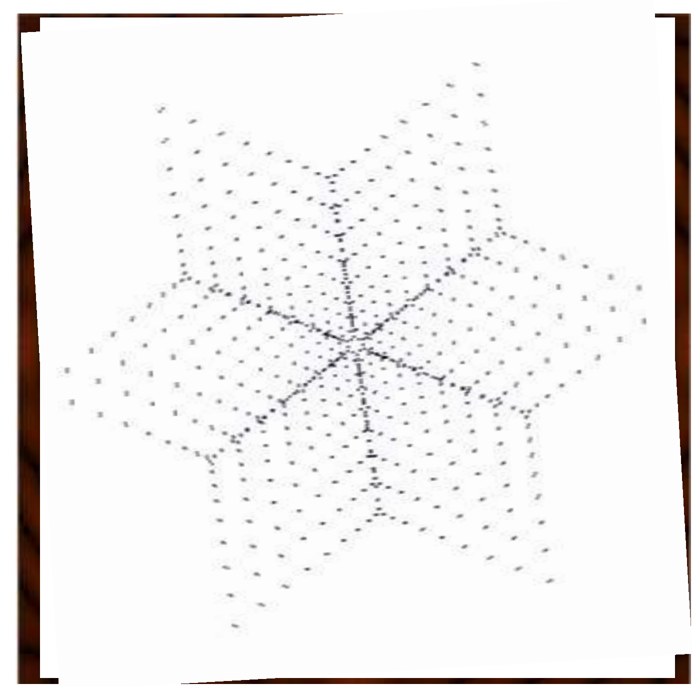

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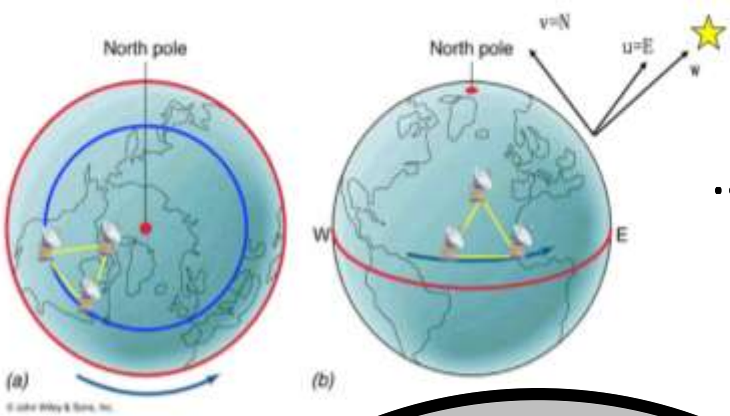

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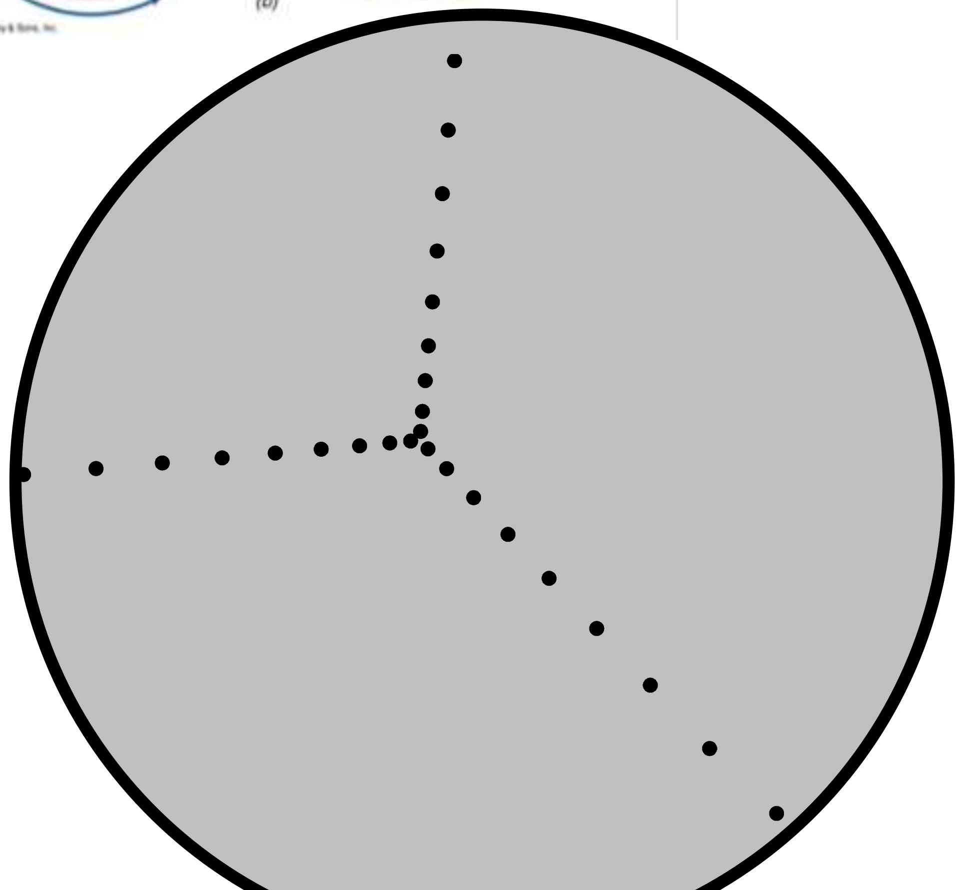

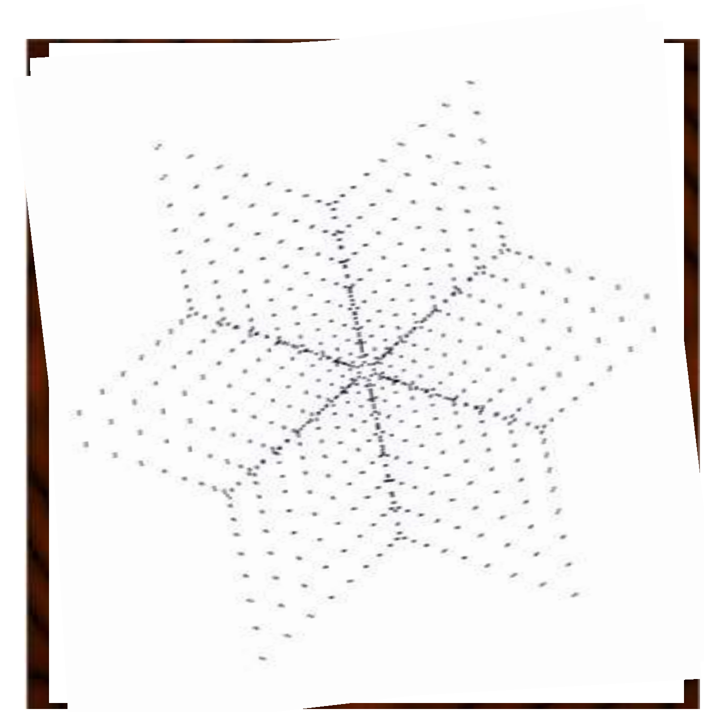

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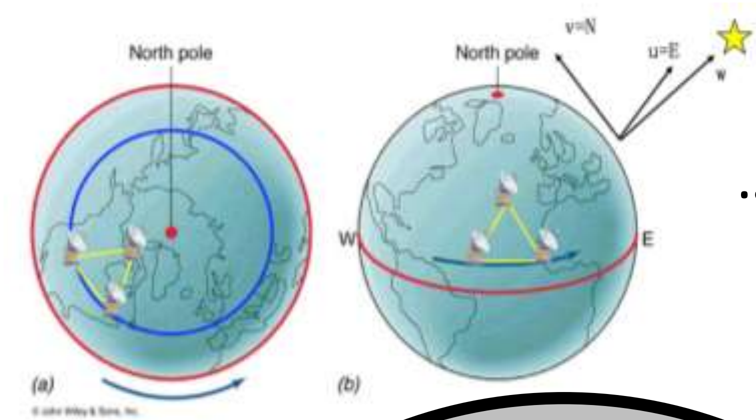

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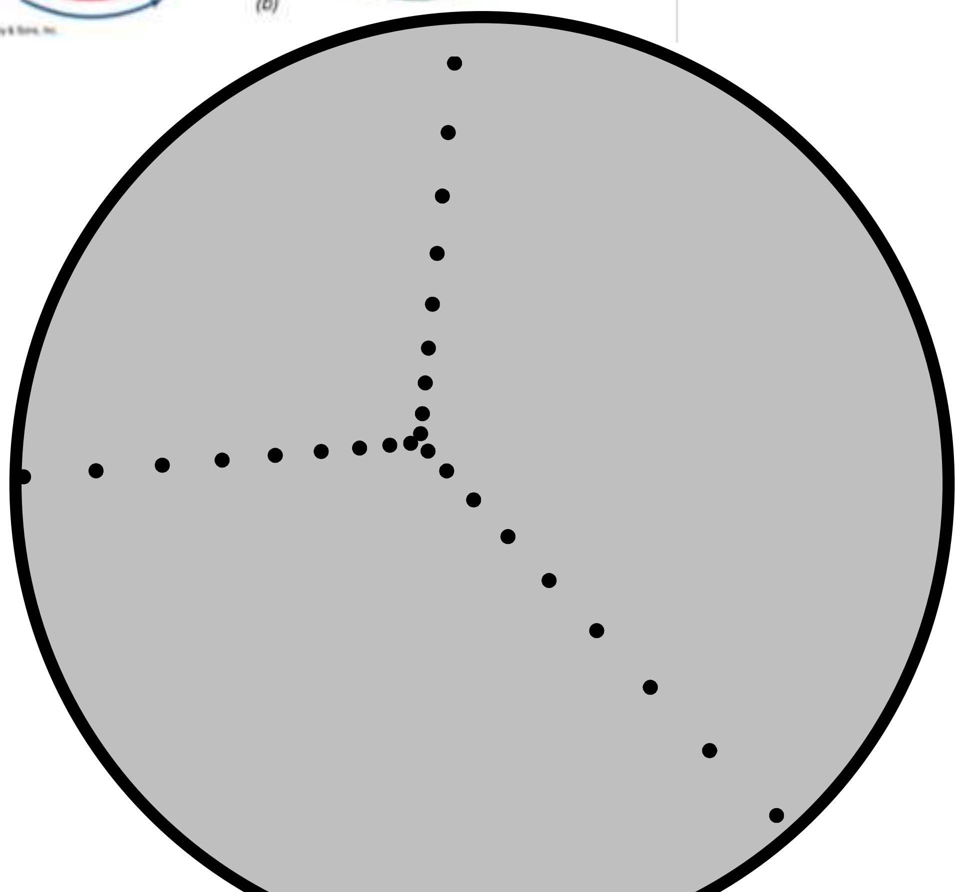

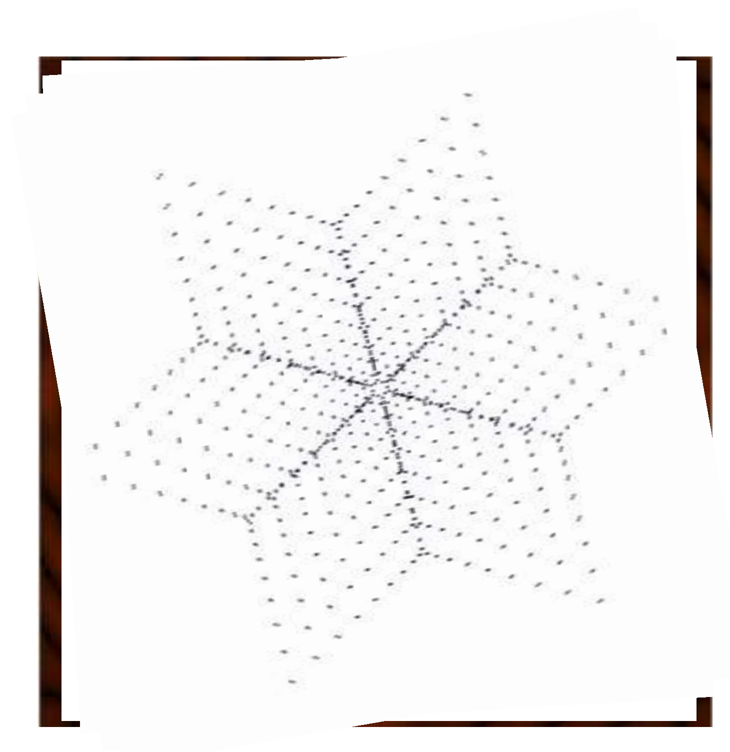

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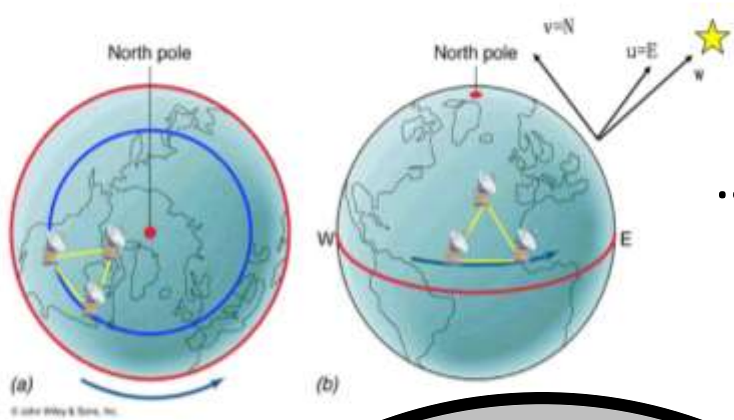

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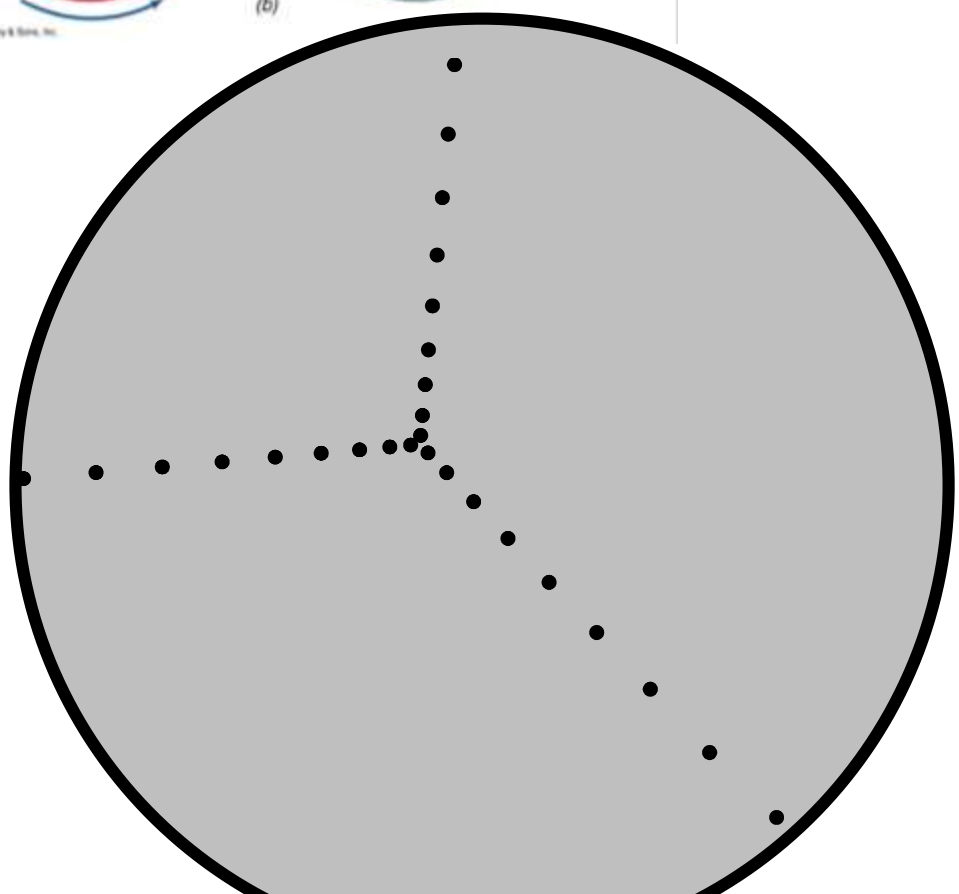
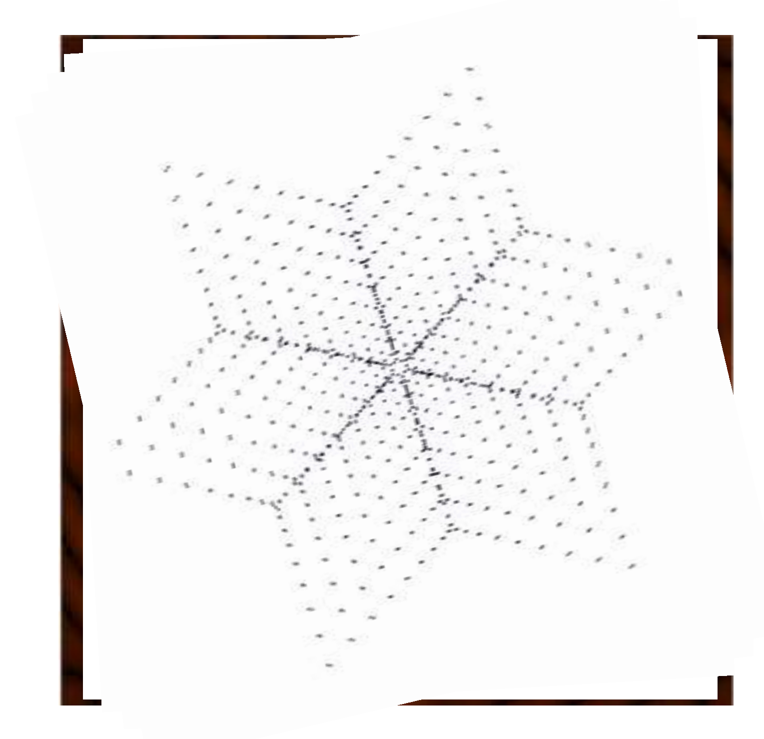
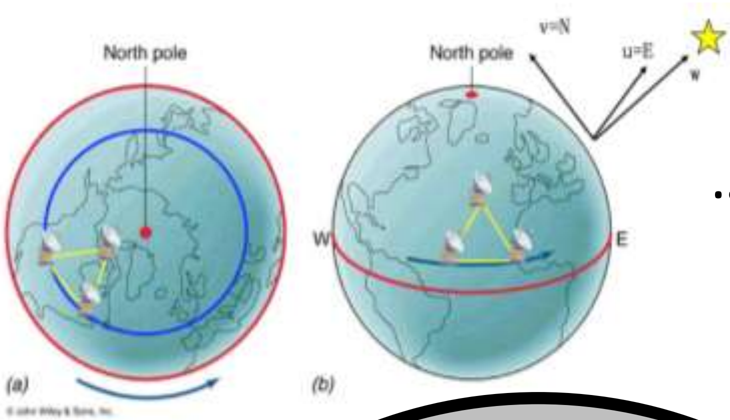
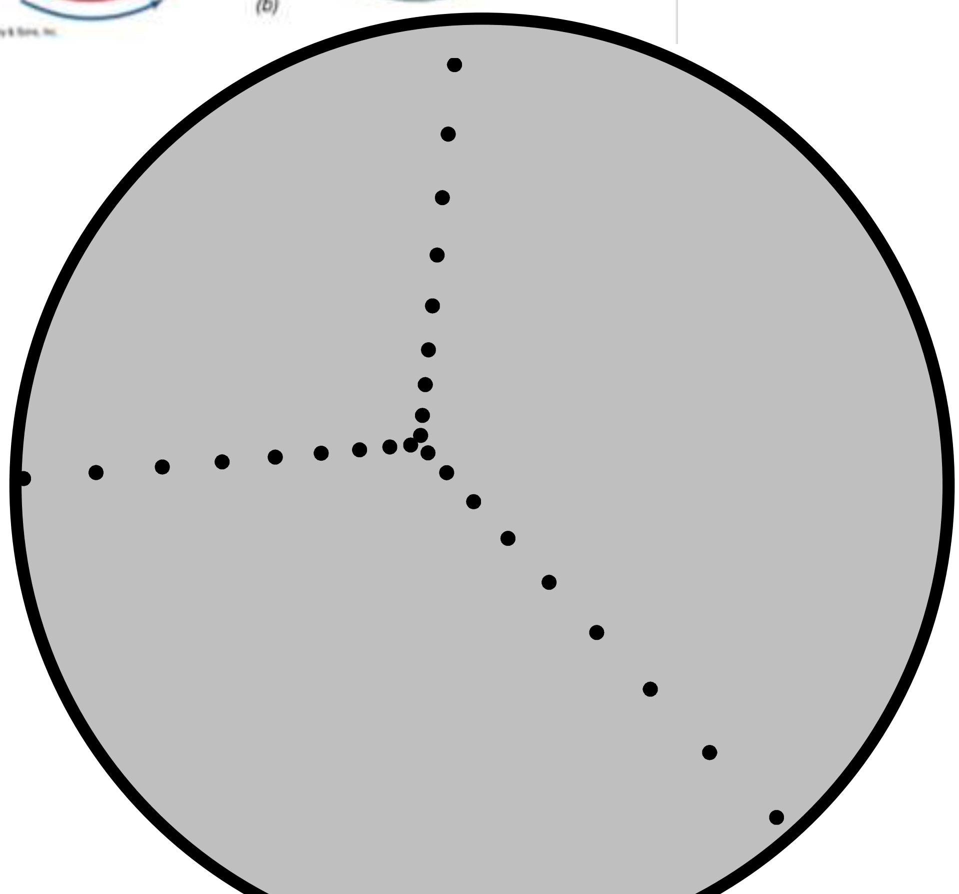


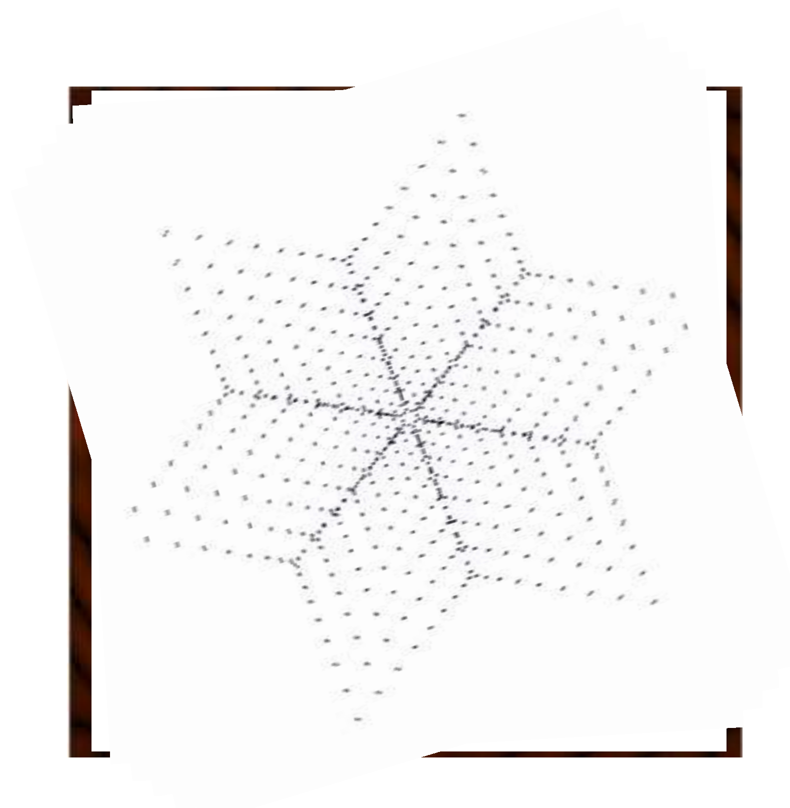


Interferometry – snapshots vs Earth rotation

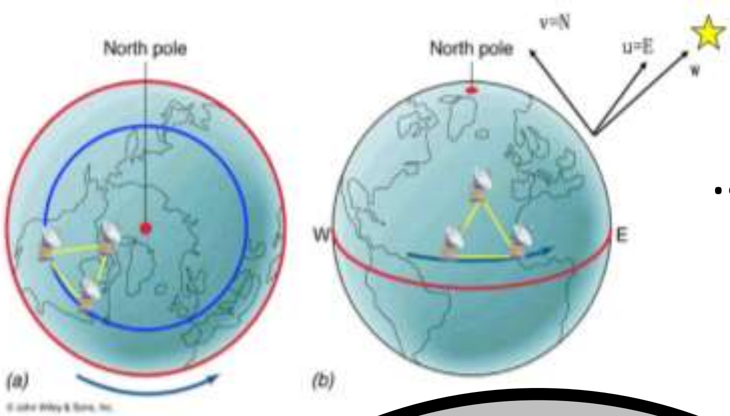


… we can just wait for the Earth to rotate

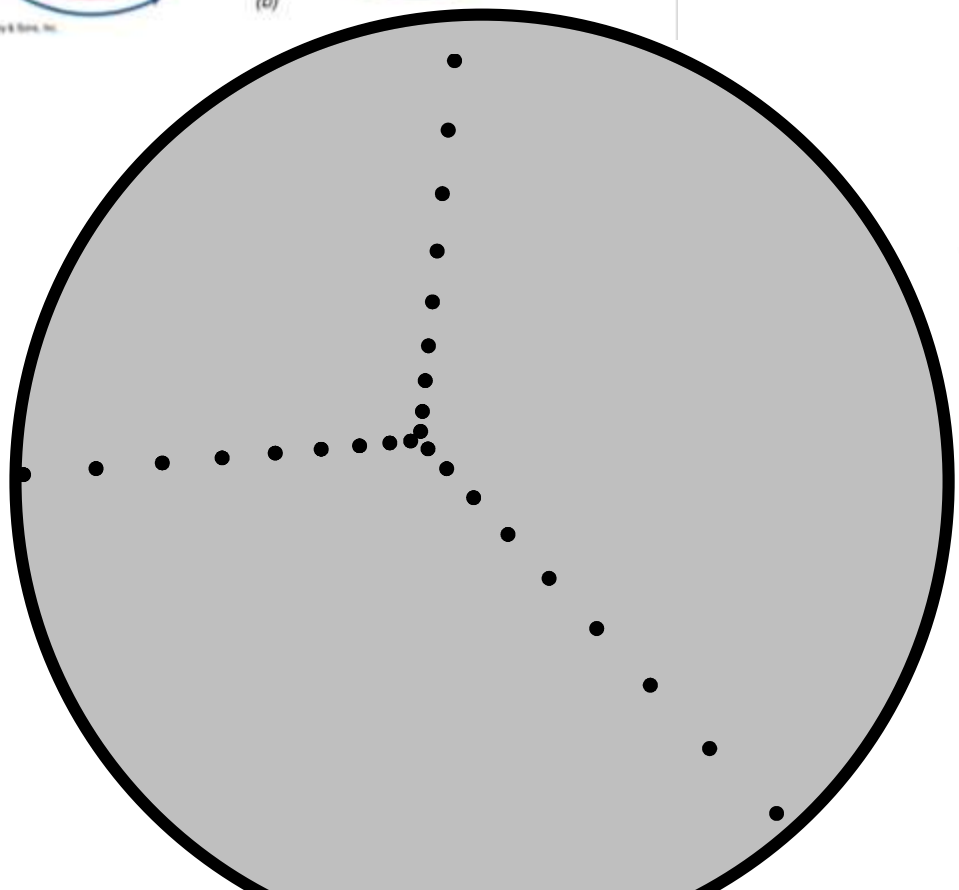


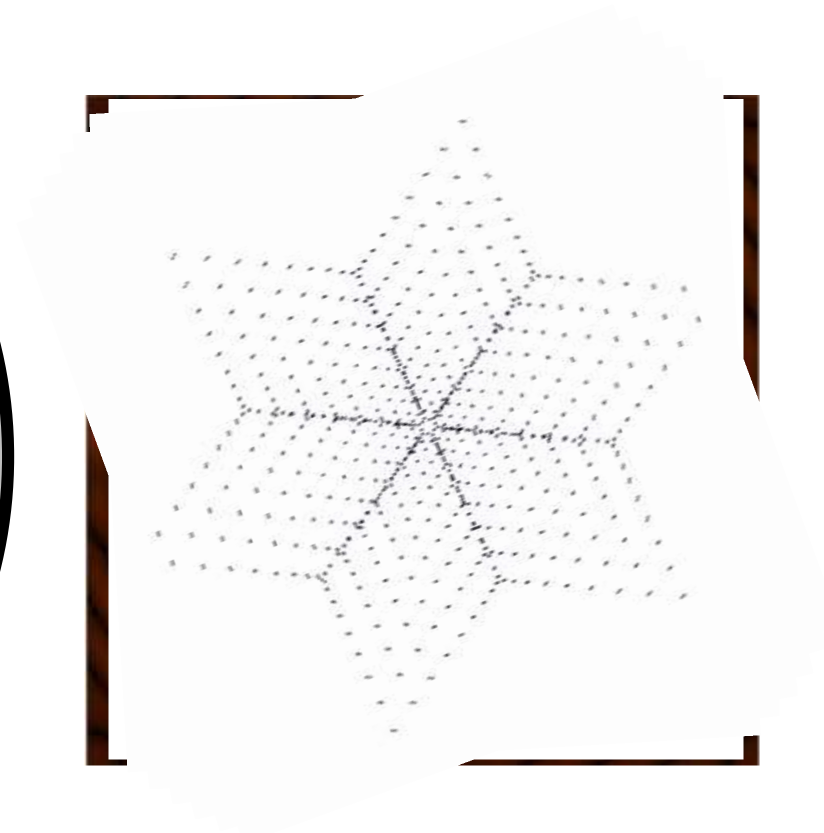


Interferometry – snapshots vs Earth rotation

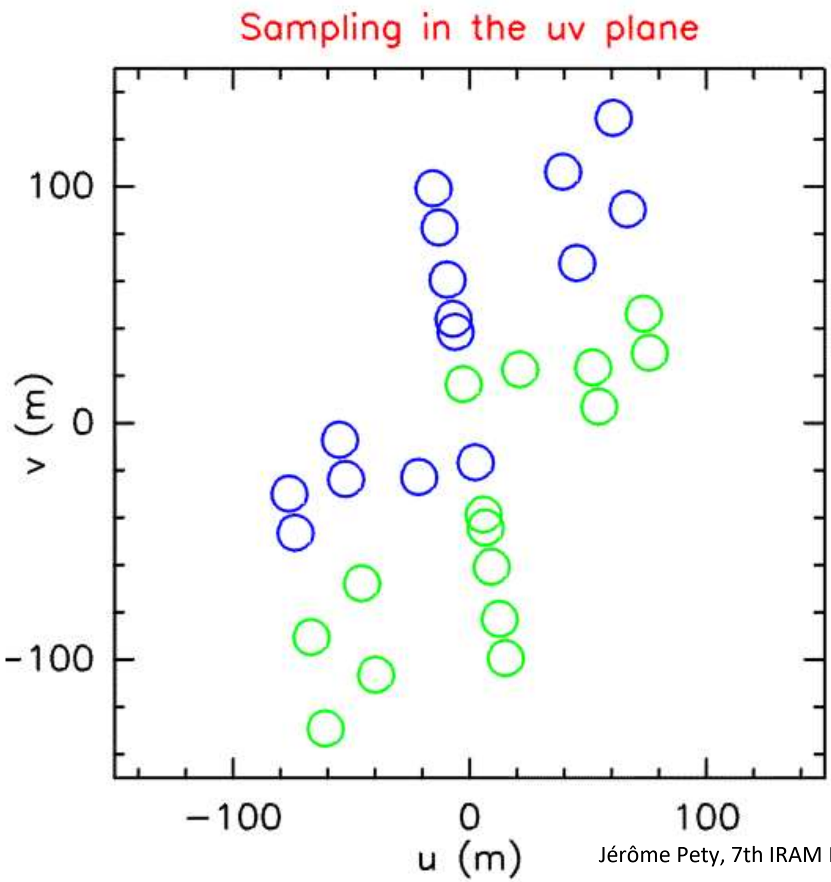


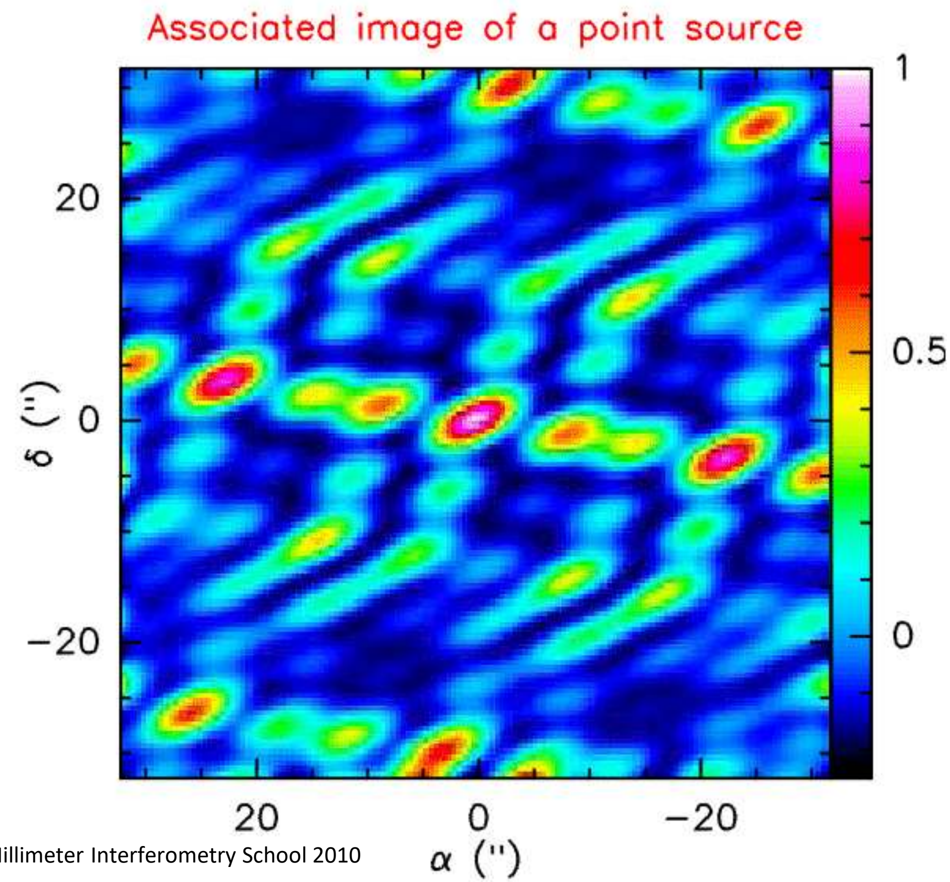
… we can just wait for the Earth to rotate





Earth rotation aperture synthesis and uv - coverage





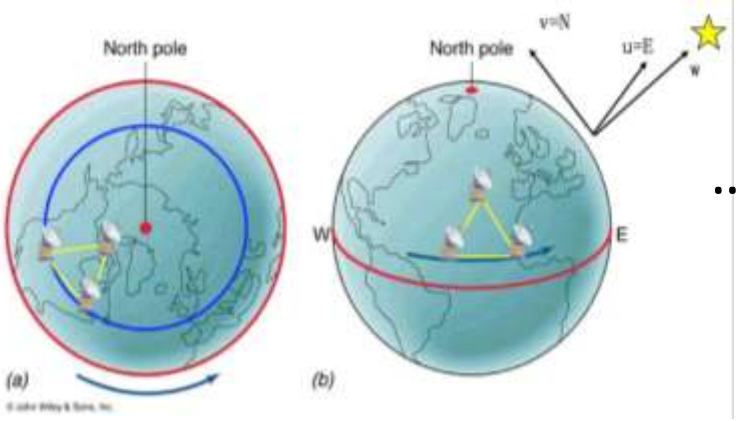
Jérôme Pety, 7th IRAM Millimeter Interferometry School 2010

Sampling function

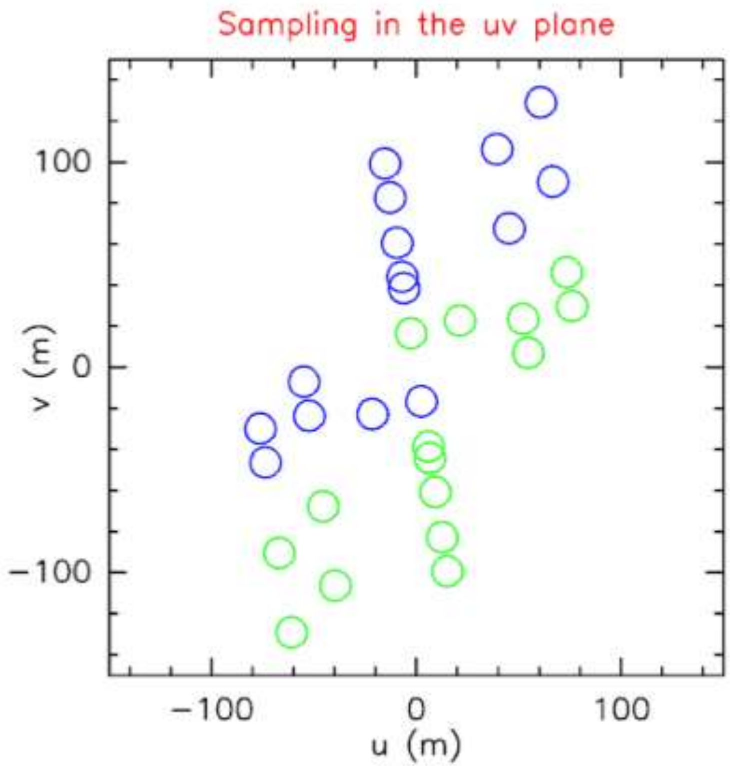
Dirty/synthesized beam / PSF

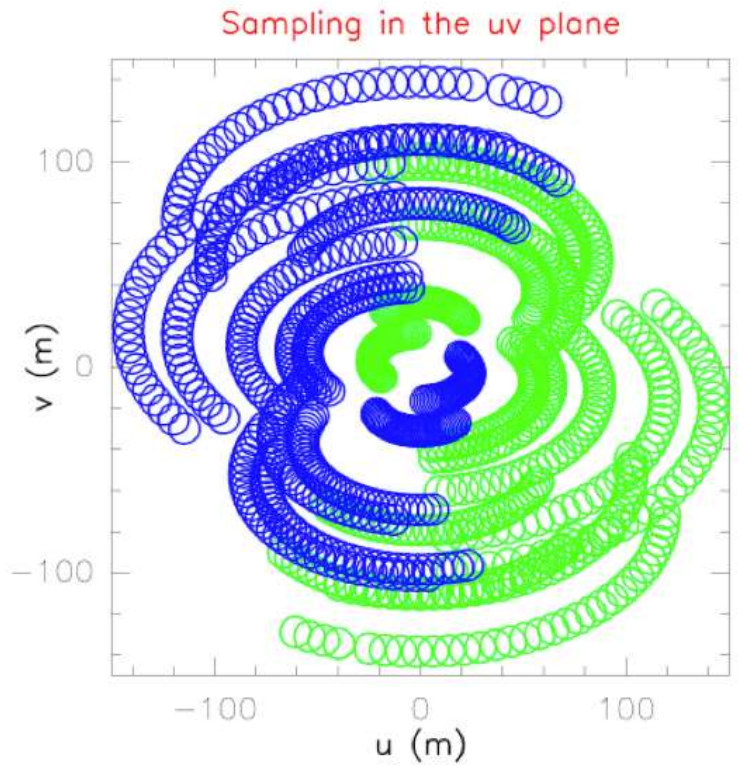
$S\ (u,v) = \sum \delta(u-u_0, v-v_0)$ ← FT → $B\ (l,m)$

Interferometry – snapshots vs Earth rotation

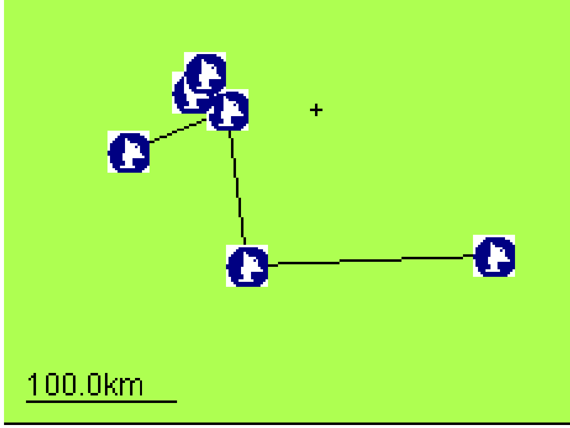


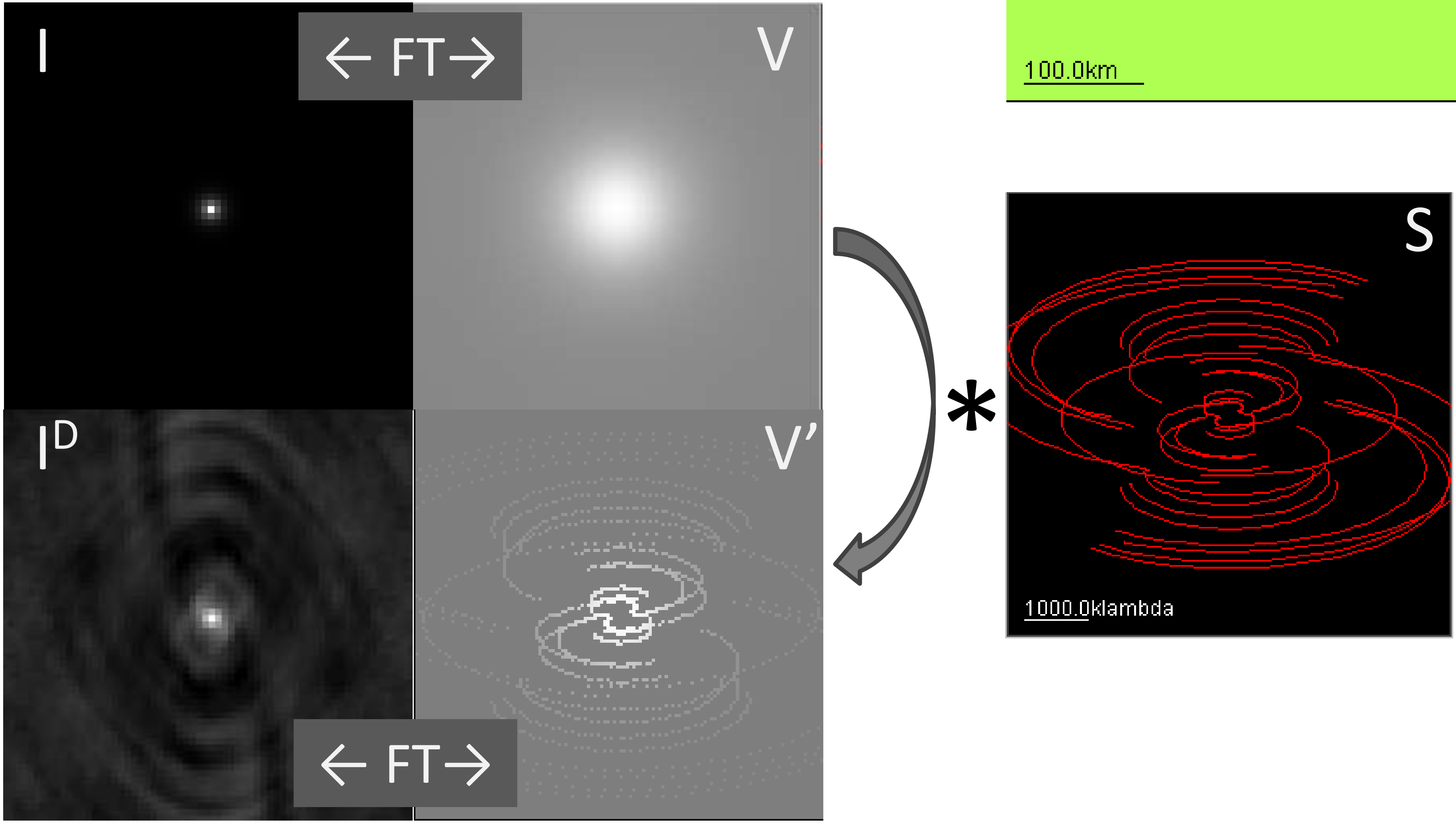
… we can just wait for the Earth to rotate



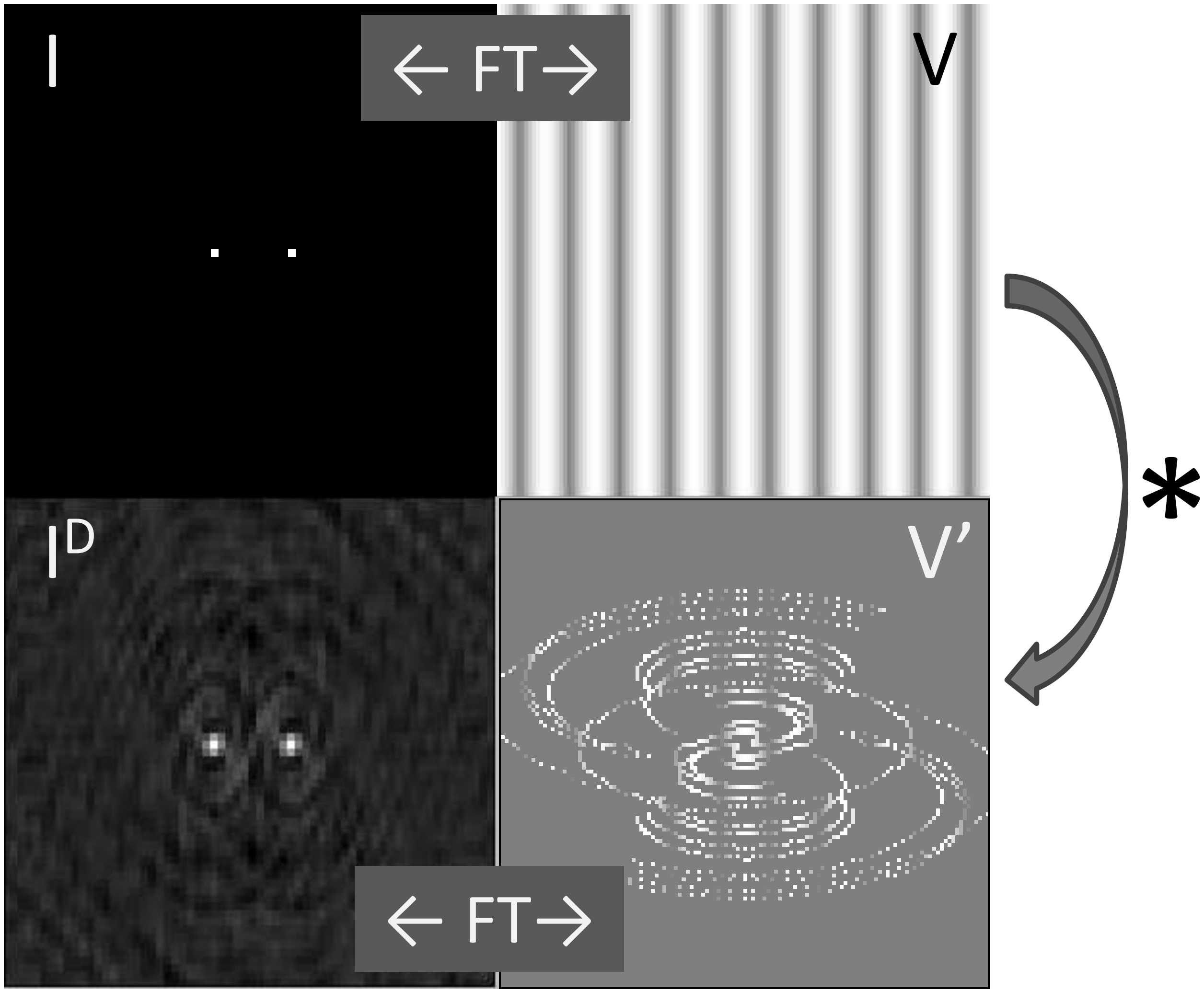


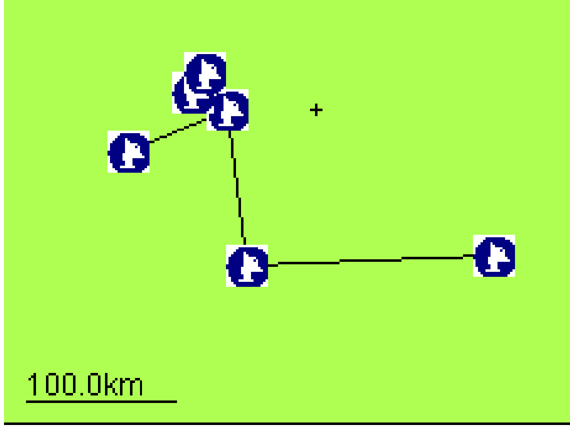
Narrow Gaussian with MERLIN

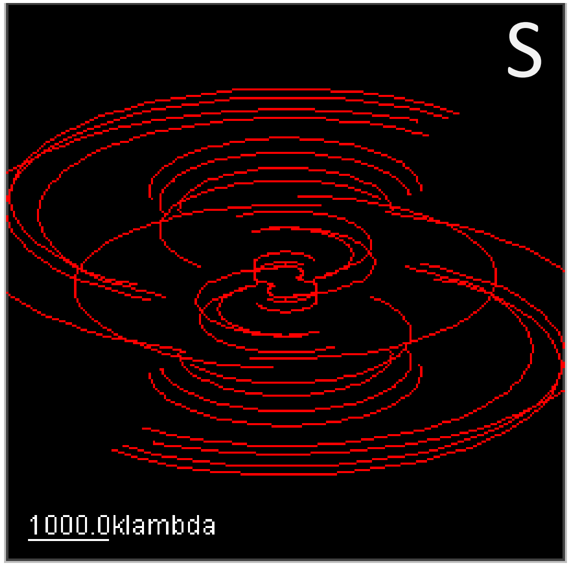




Wide double point source with MERLIN





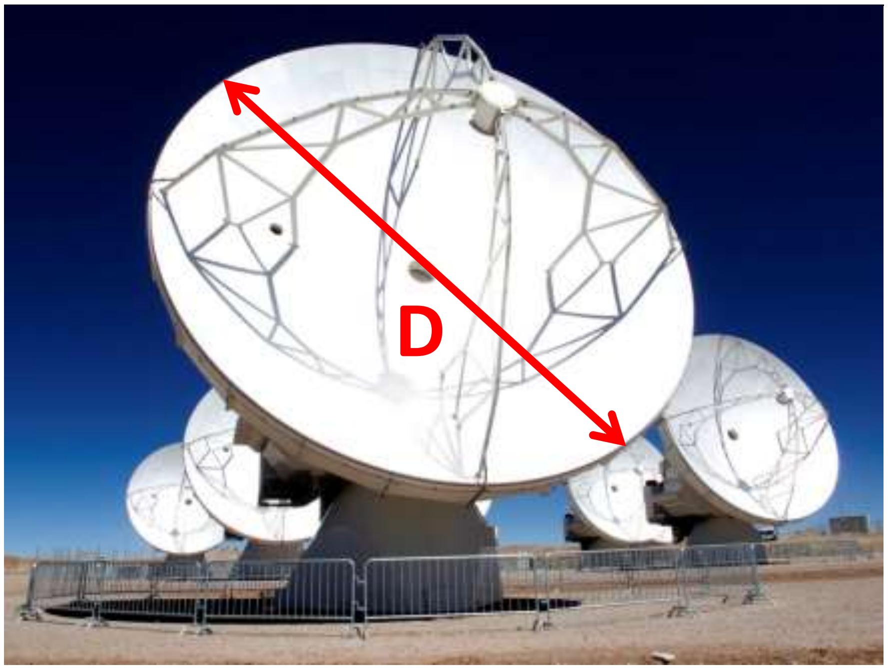


The basic principle in practice

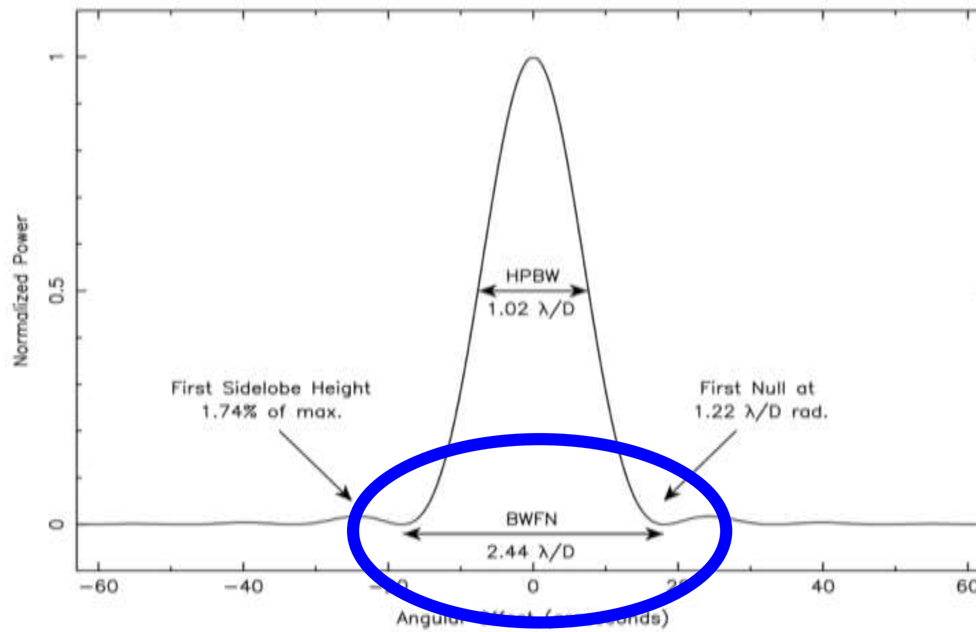
Sampled visibility		True visibility		Sampling function
$V'(u,v)$	$=$	$V(u,v)$	$\times$	$S(u,v)$
↑ FT ↓		↑ FT ↓		↑ FT ↓
$I^D(l,m)$	$=$	$I(l,m)$	$*$	$B(l,m)$
Dirty image		True image		Dirty beam

REMEMBER … Single-dish response

Single-dish with diameter D



(1D) antenna power response

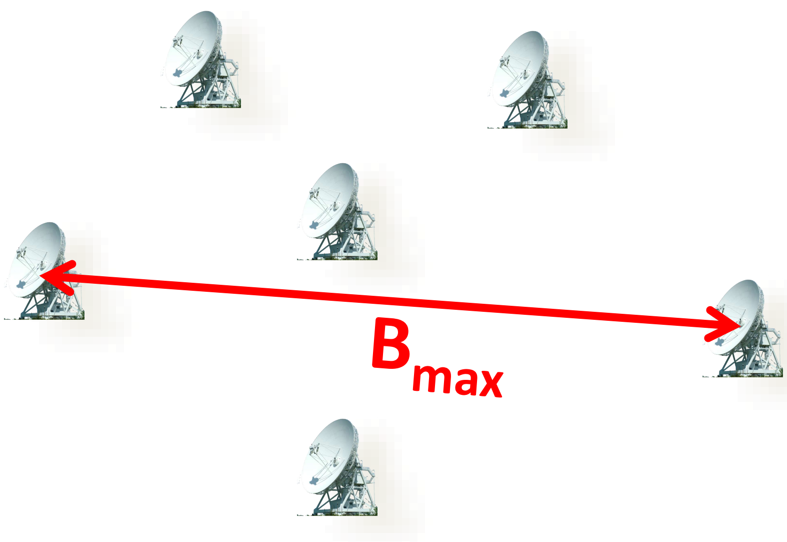


$$PB = 1.22 \frac{l}{D}$$

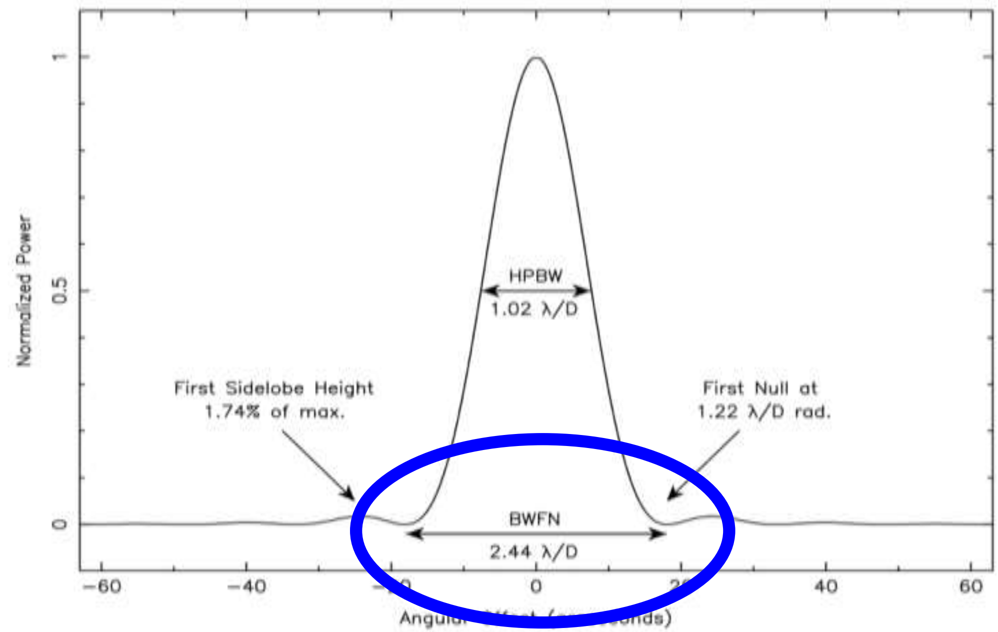
PRIMARY BEAM

Interferometer "response"

Interferometer with baseline B



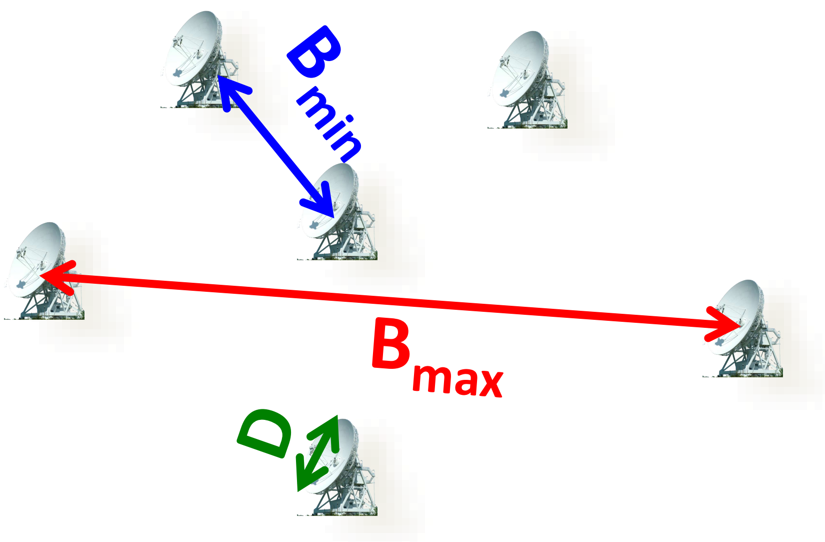
interferometer power response



$$q_{beam} = 1.22 \frac{l}{B_{\max}}$$

SYNTHESIZED BEAM

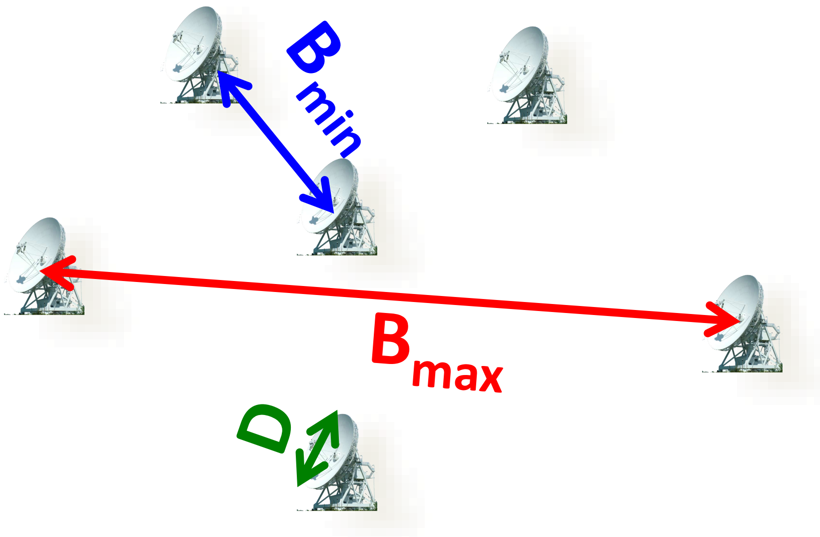
Synthesized beam, primary beam and LAS



SYNTHESIZED BEAM

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

Synthesized beam, primary beam and LAS



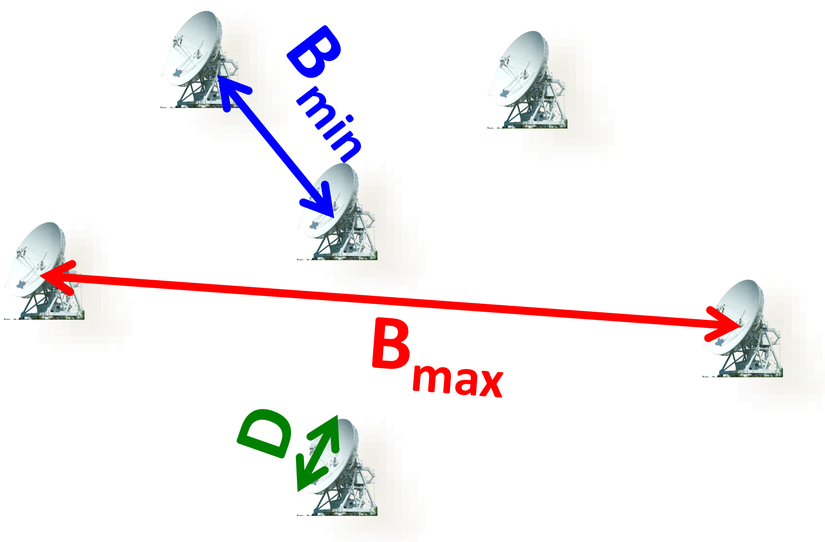
SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{\max}}$$

LARGEST ANGULAR SCALE

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

Synthesized beam, primary beam and LAS



SYNTHESIZED BEAM

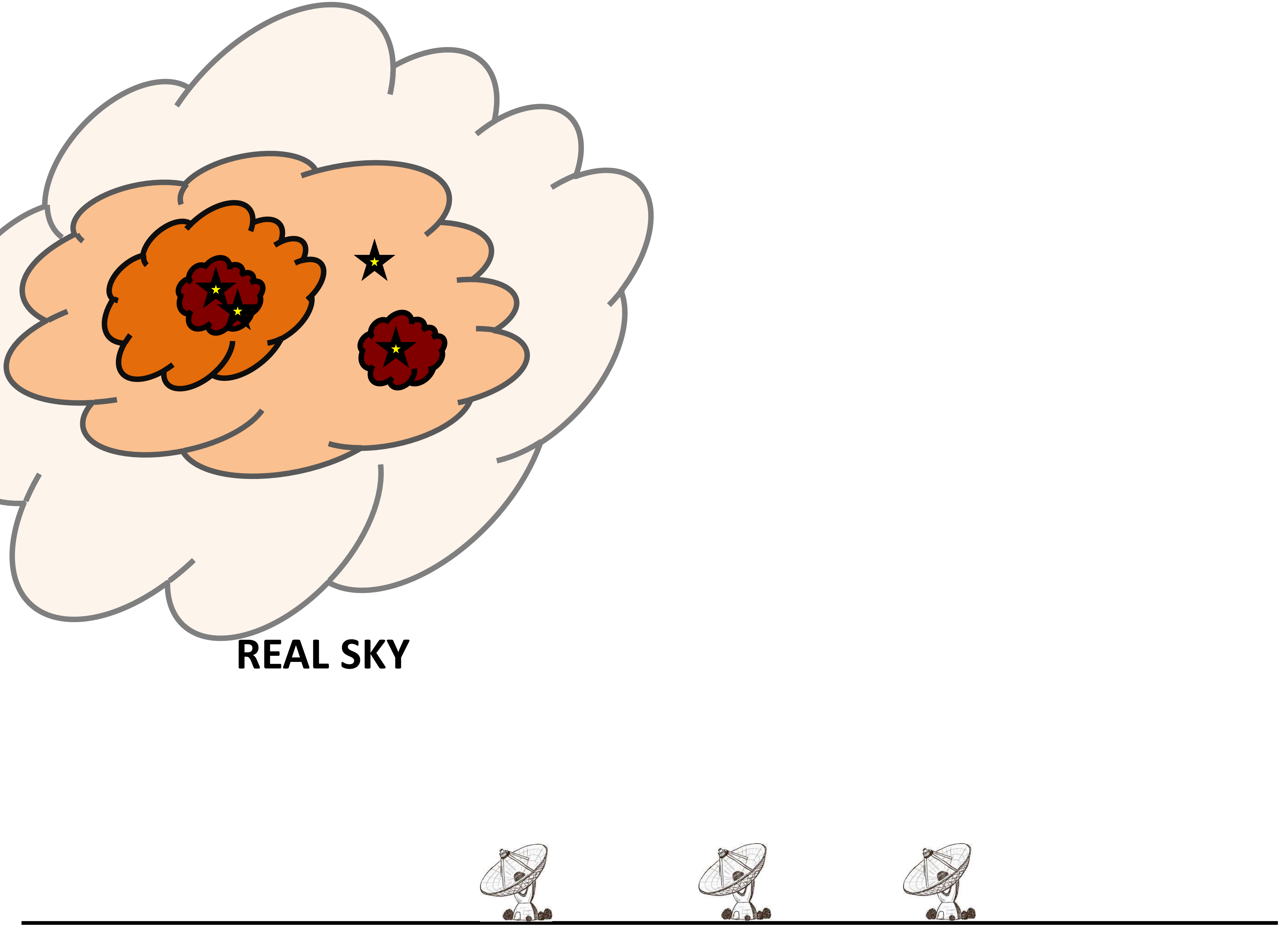
$$\theta_{beam} = 1.22\frac{\lambda}{B_{\max}}$$

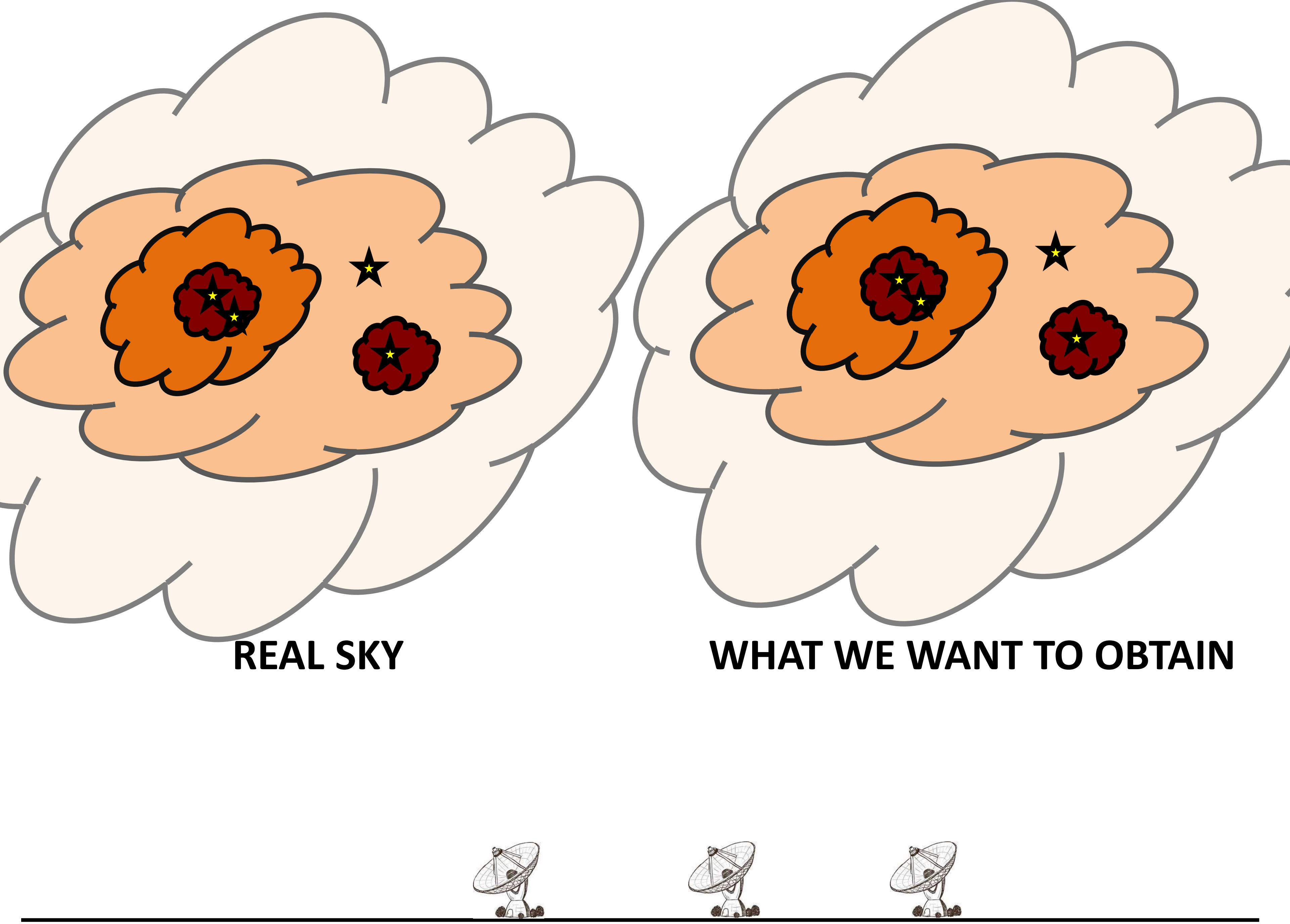
LARGEST ANGULAR SCALE

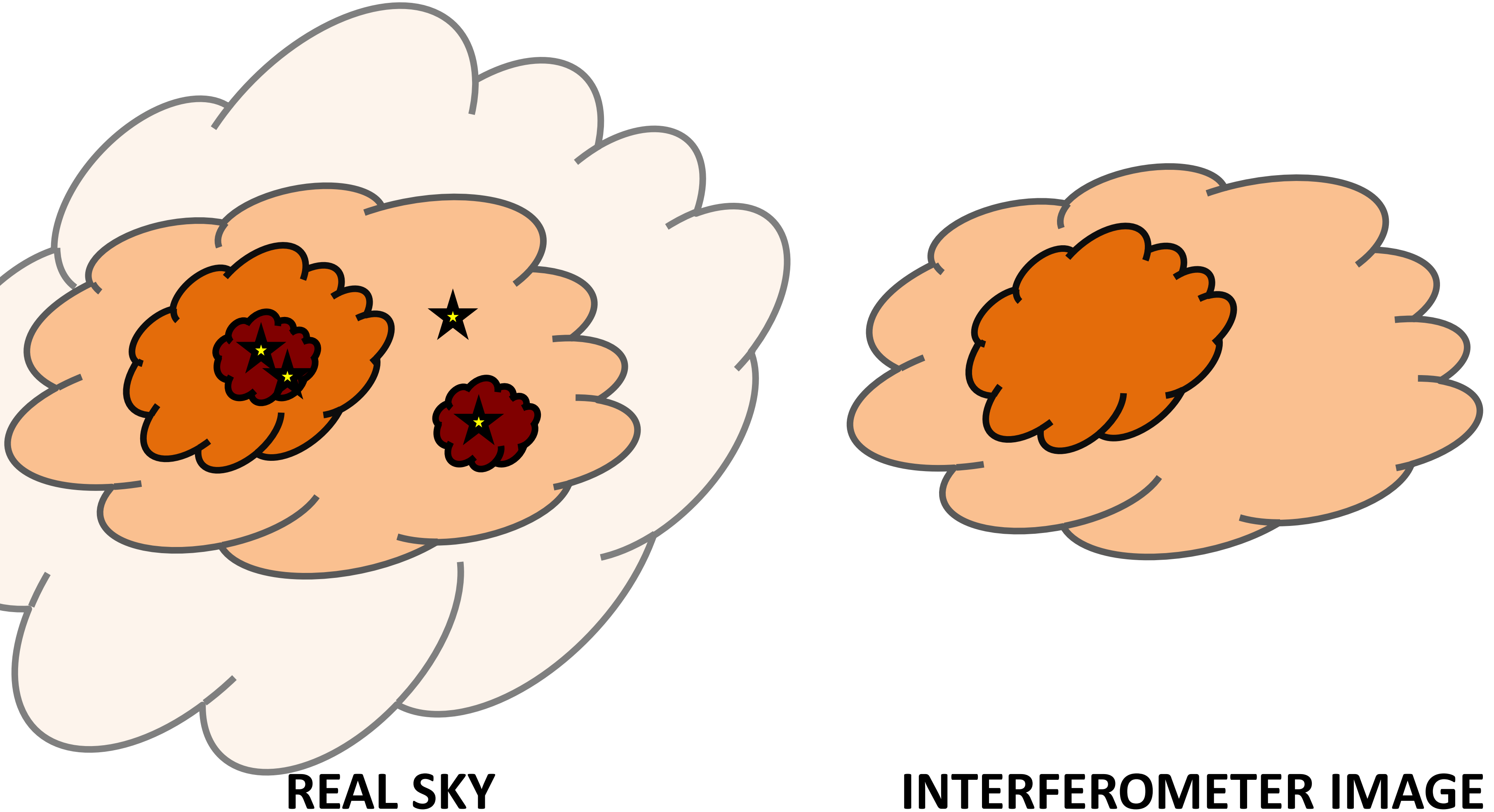
$$LAS = 1.22\frac{\lambda}{B_{\min}}$$

PRIMARY BEAM

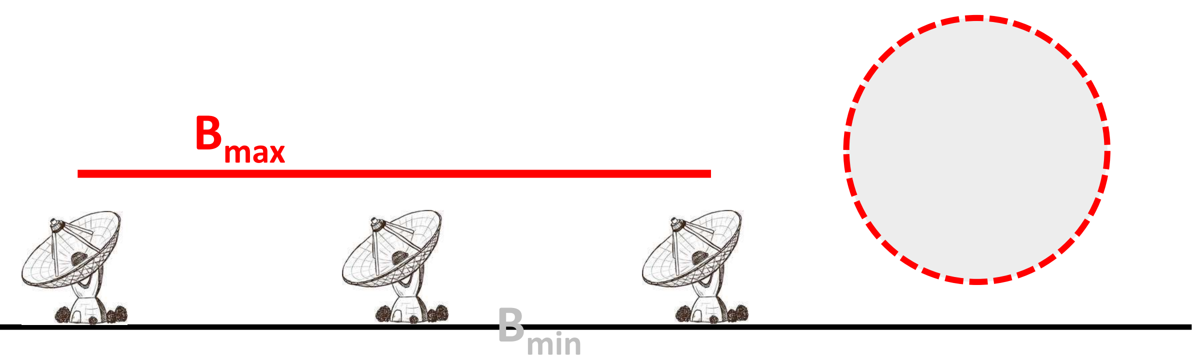
$$PB = 1.22\frac{\lambda}{D}$$

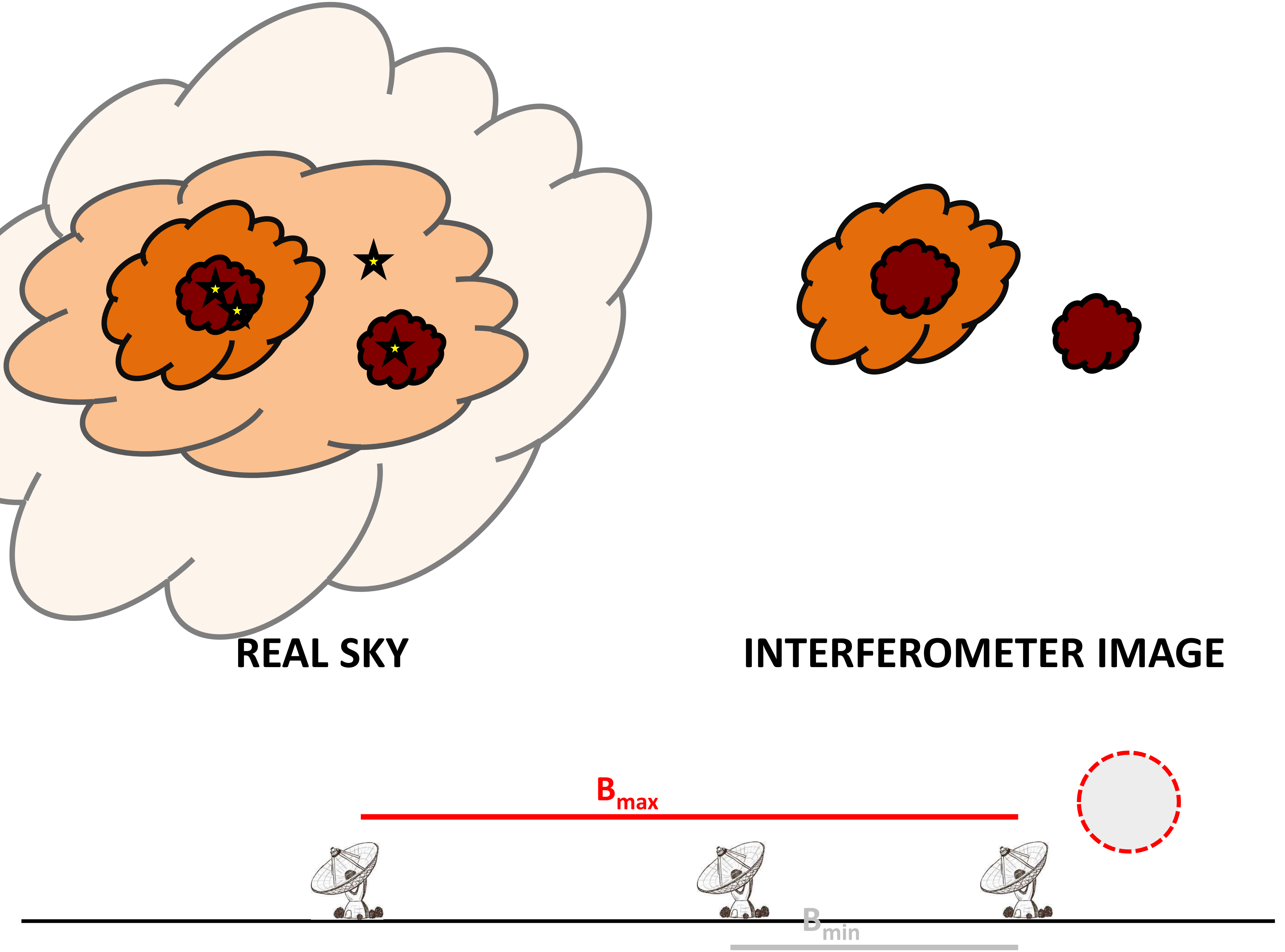

REAL SKY

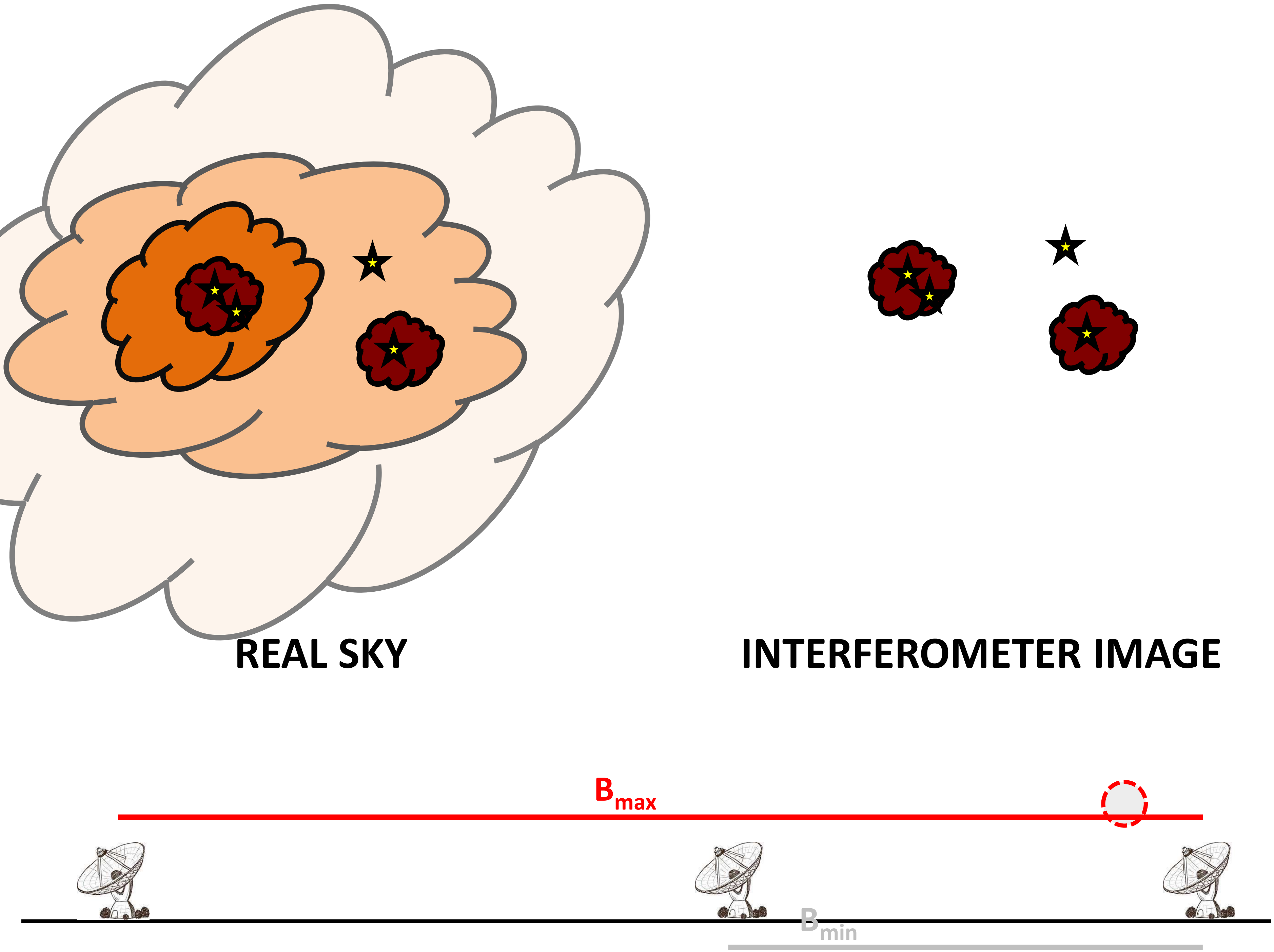

REAL SKY
WHAT WE WANT TO OBTAIN



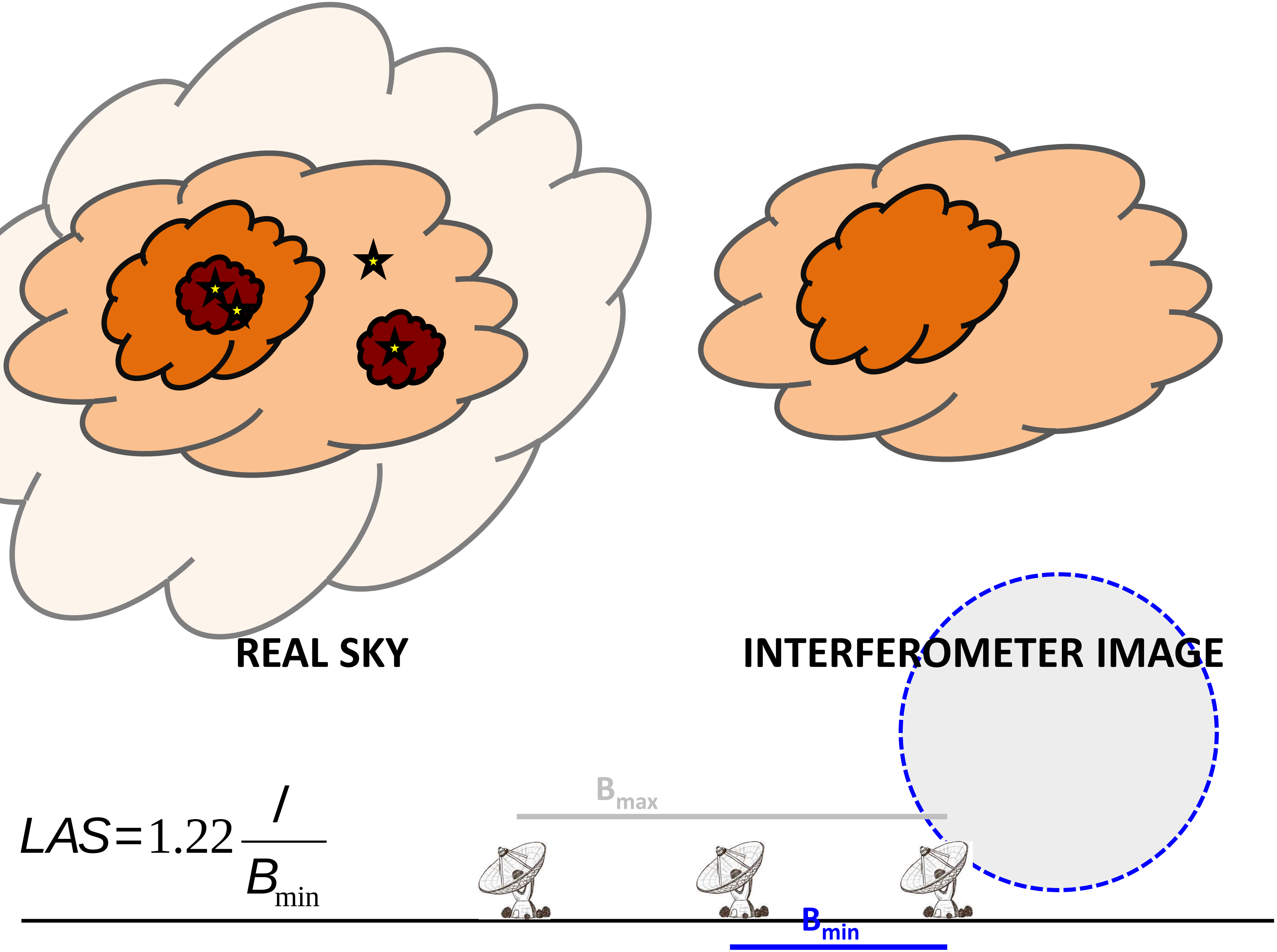
$$q_{beam} = 1.22 \frac{l}{B_{\max}}$$

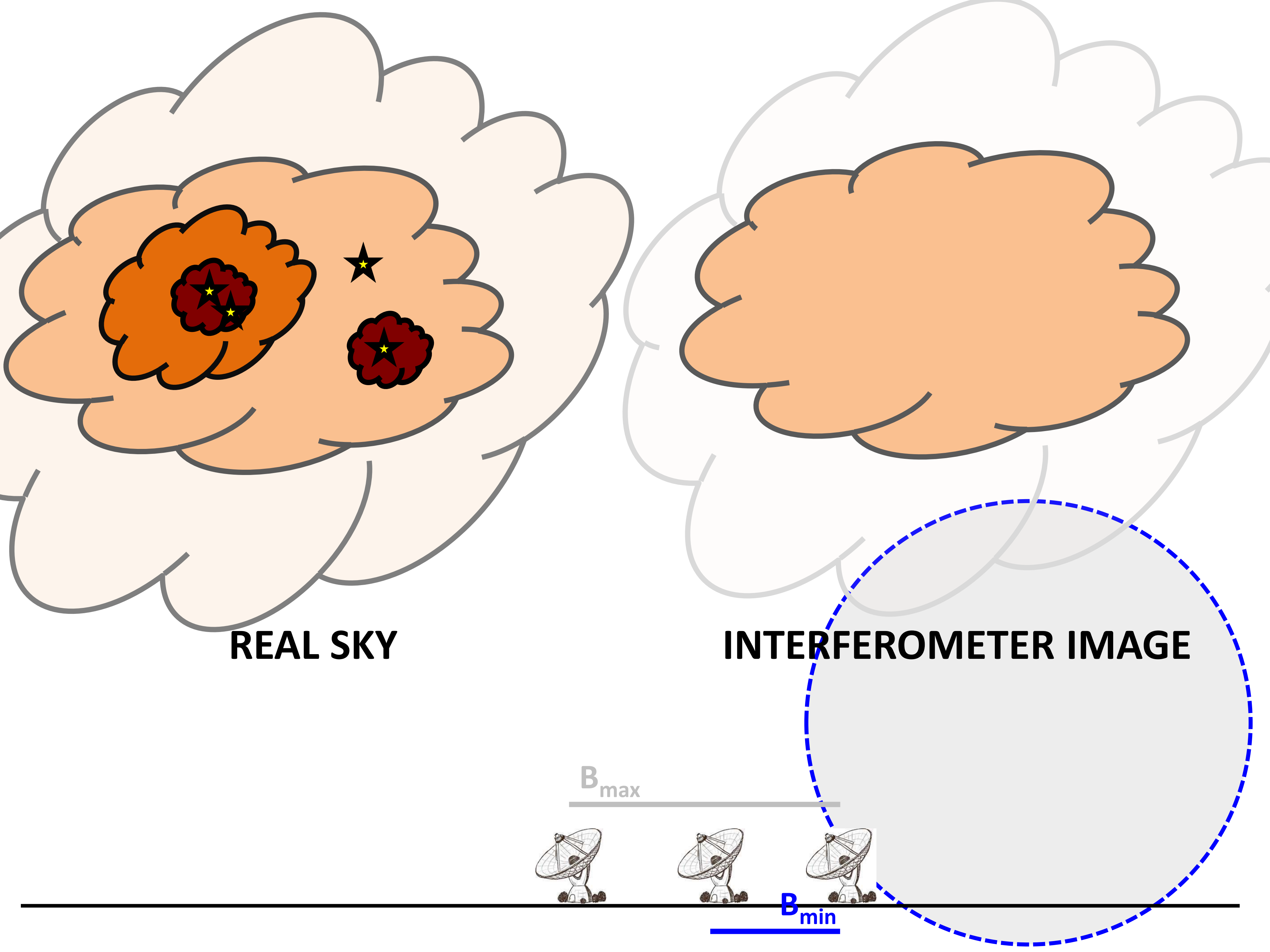


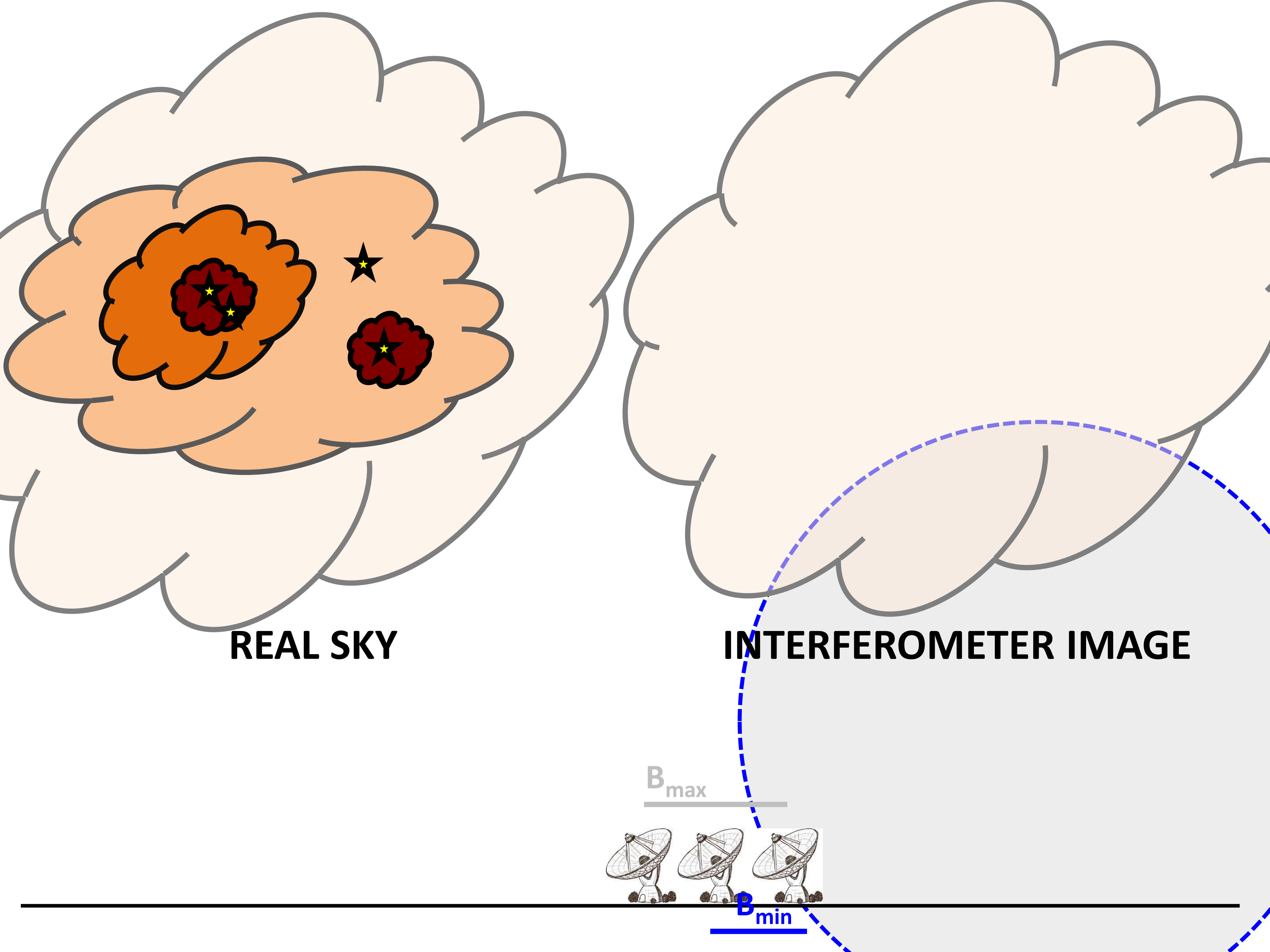

REAL SKY
INTERFEROMETER IMAGE
B_{max}
B_{min}

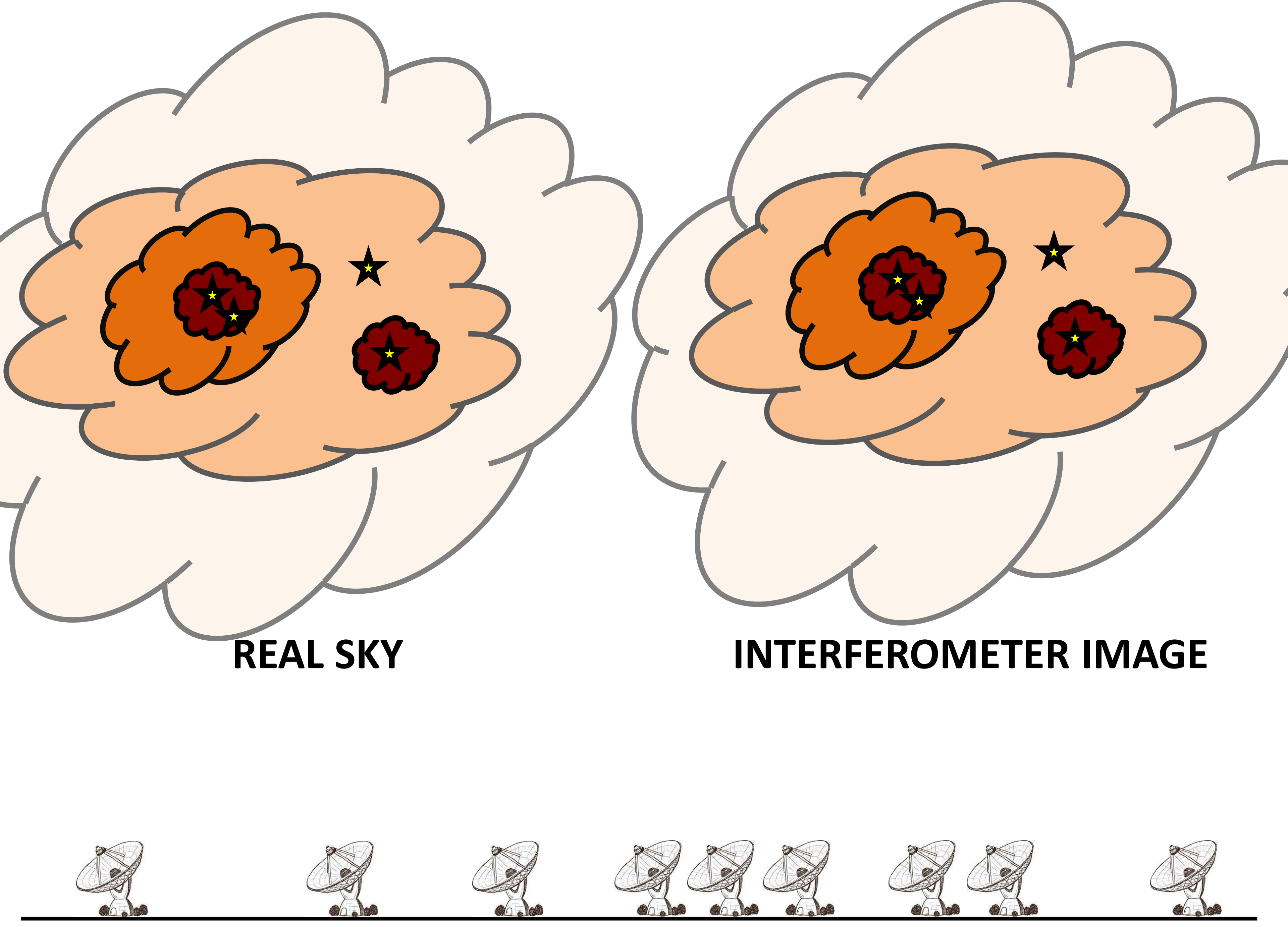


REAL SKY
INTERFEROMETER IMAGE
B_{max}
B_{min}


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


REAL SKY
INTERFEROMETER IMAGE
B_{max}
B_{min}


REAL SKY
INTERFEROMETER IMAGE
B_{max}
B_{min}

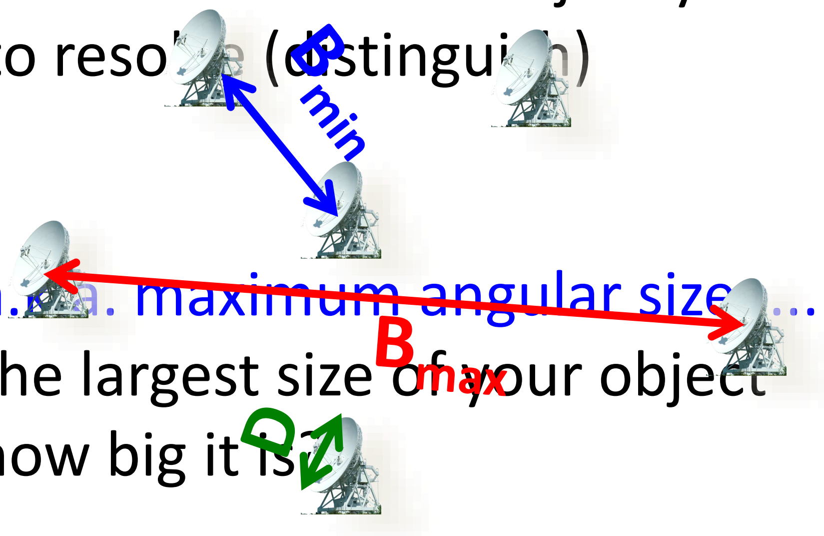

REAL SKY
INTERFEROMETER IMAGE

Synthesized beam, primary beam and LAS

SYNTHESIZED BEAM

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

$$q_{beam} = 1.22 \frac{/}{B_{\max}}$$



LARGEST ANGULAR SCALE

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

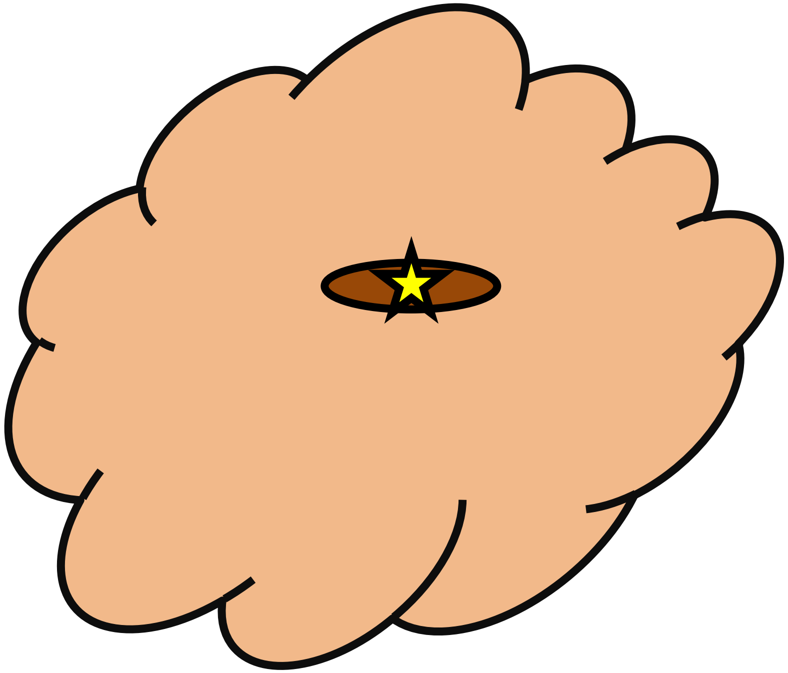
$$LAS = 1.22 \frac{/}{B_{\min}}$$

PRIMARY BEAM

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

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

Example I: compact protoplanetary disk



SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{max}}$$

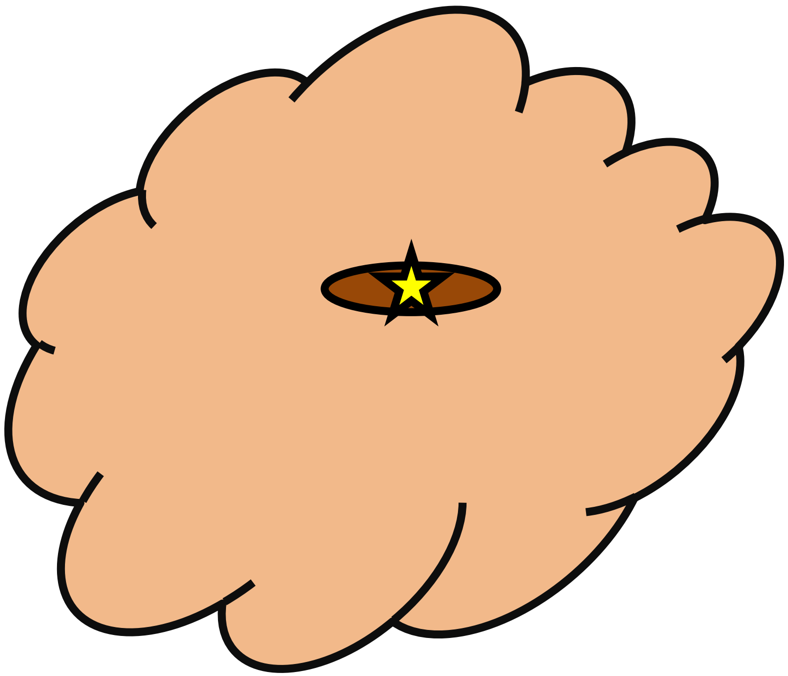
LARGEST ANGULAR SCALE

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

PRIMARY BEAM

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

Example I: compact protoplanetary disk



SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{\mathrm{max}}}$$

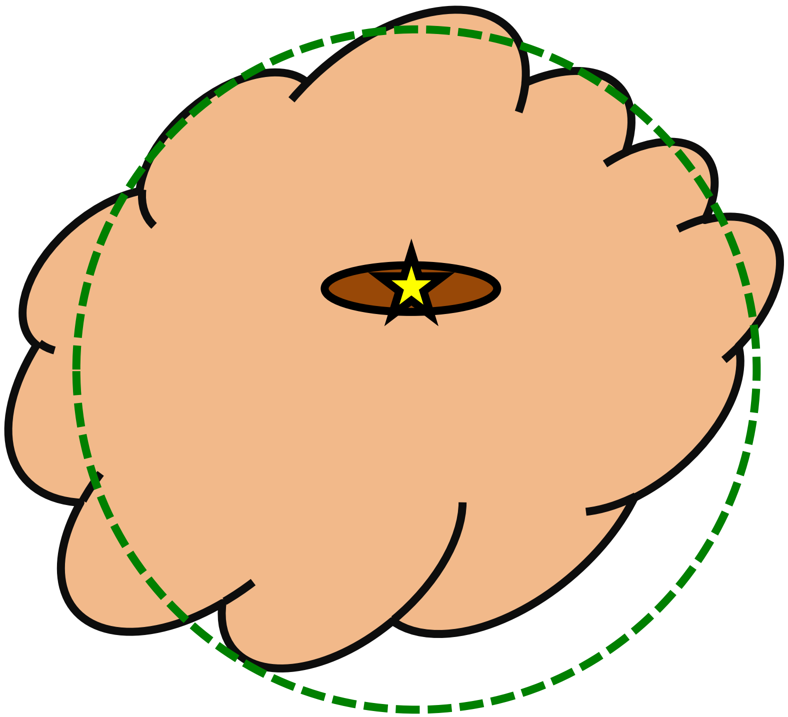
LARGEST ANGULAR SCALE

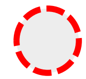
$$LAS = 1.22 \frac{l}{B_{\mathrm{min}}}$$

PRIMARY BEAM

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

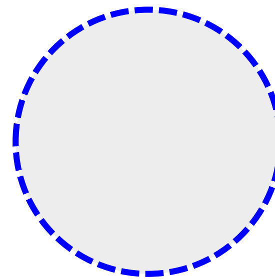
Example I: compact protoplanetary disk





SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{\mathrm{max}}}$$



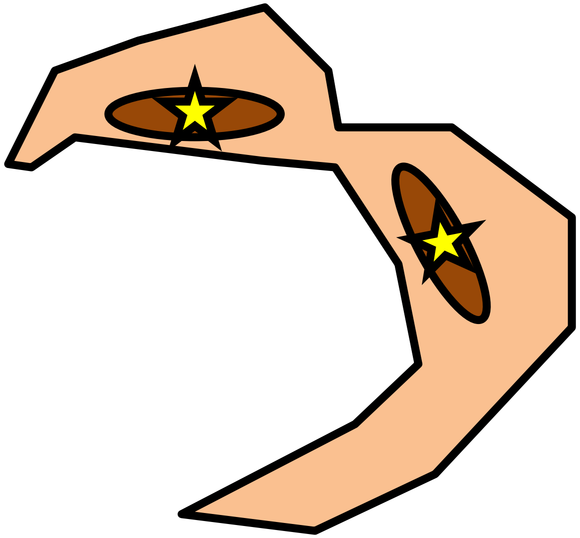
LARGEST ANGULAR SCALE

$$LAS = 1.22 \frac{l}{B_{\mathrm{min}}}$$

PRIMARY BEAM

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

Example II: disks and filament



SYNTHESIZED BEAM

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

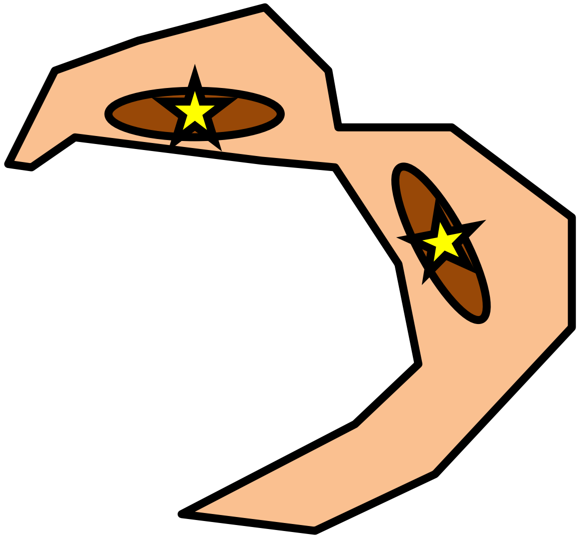
LARGEST ANGULAR SCALE

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

PRIMARY BEAM

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

Example II: disks and filament



SYNTHESIZED BEAM

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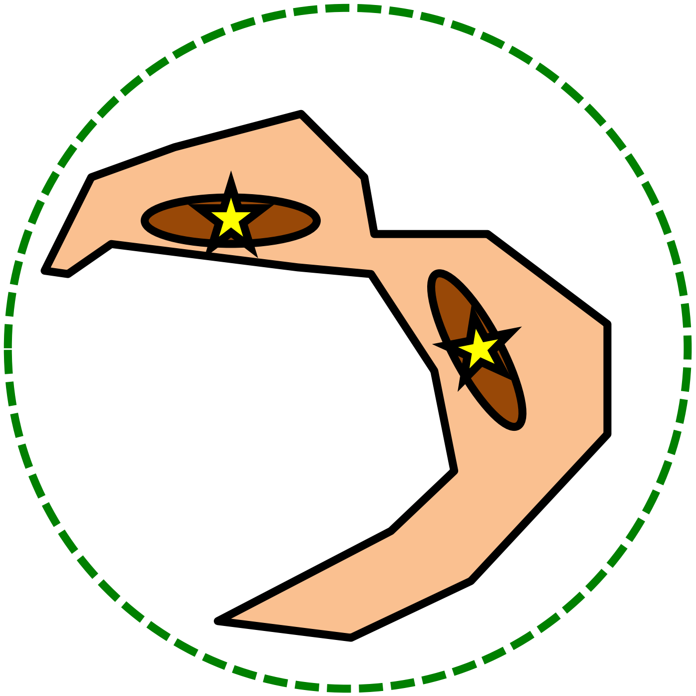
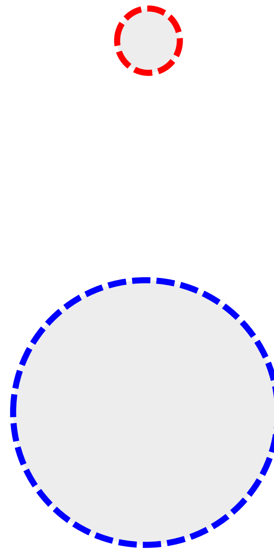
Example II: disks and filament





SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{\max}}$$

LARGEST ANGULAR SCALE

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PRIMARY BEAM

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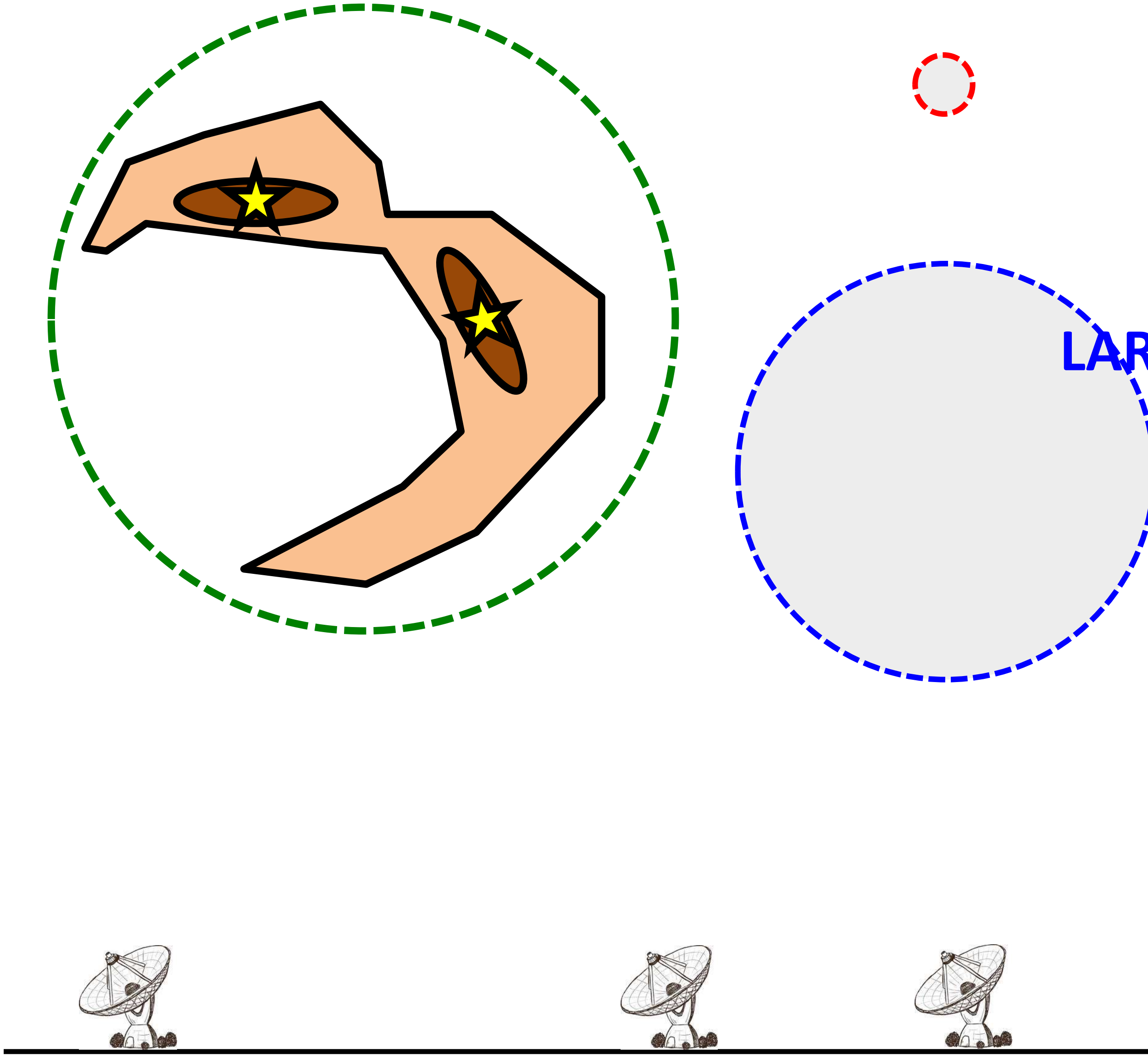
Example II: disks and filament



SYNTHESIZED BEAM

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

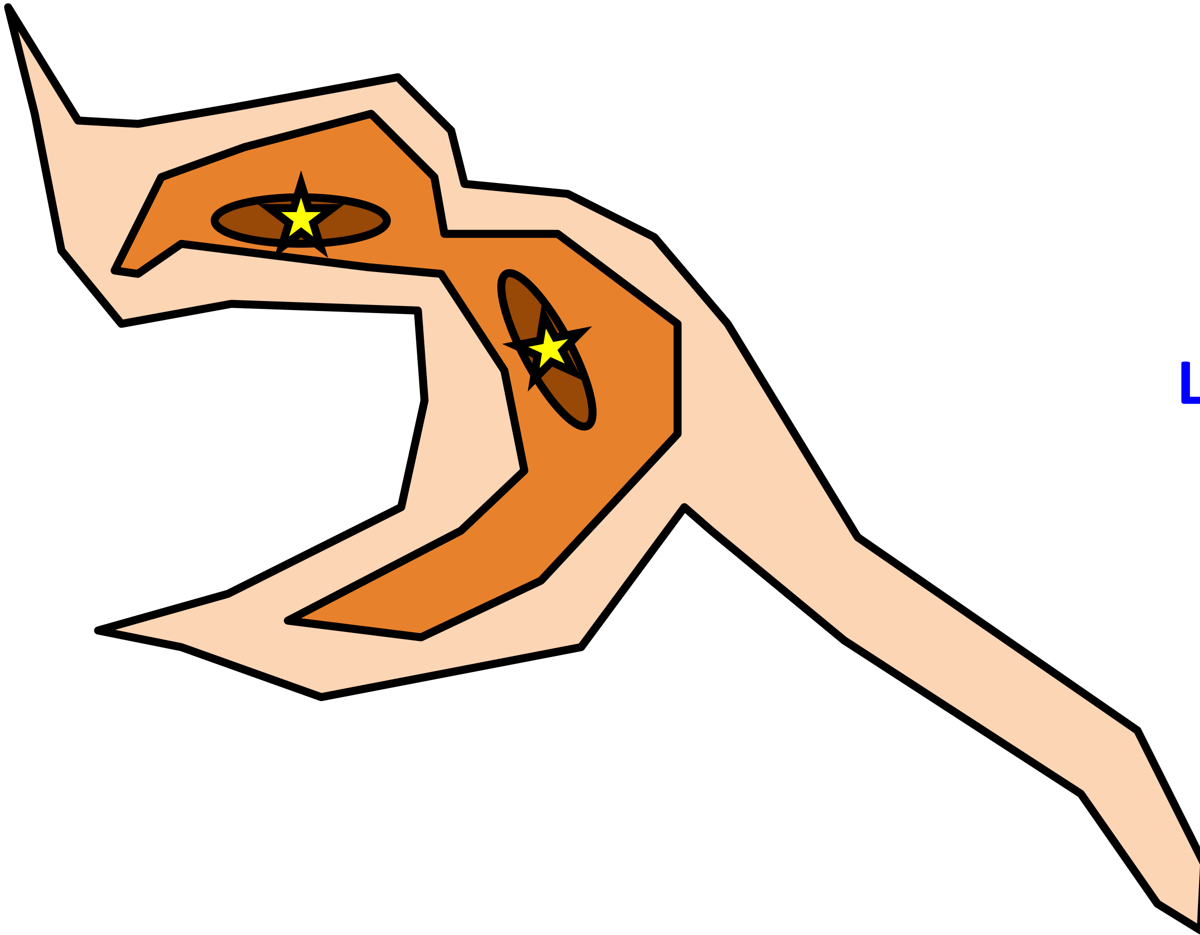
LARGEST ANGULAR SCALE

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

PRIMARY BEAM

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

Example III: disks and extended filament



SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{max}}$$

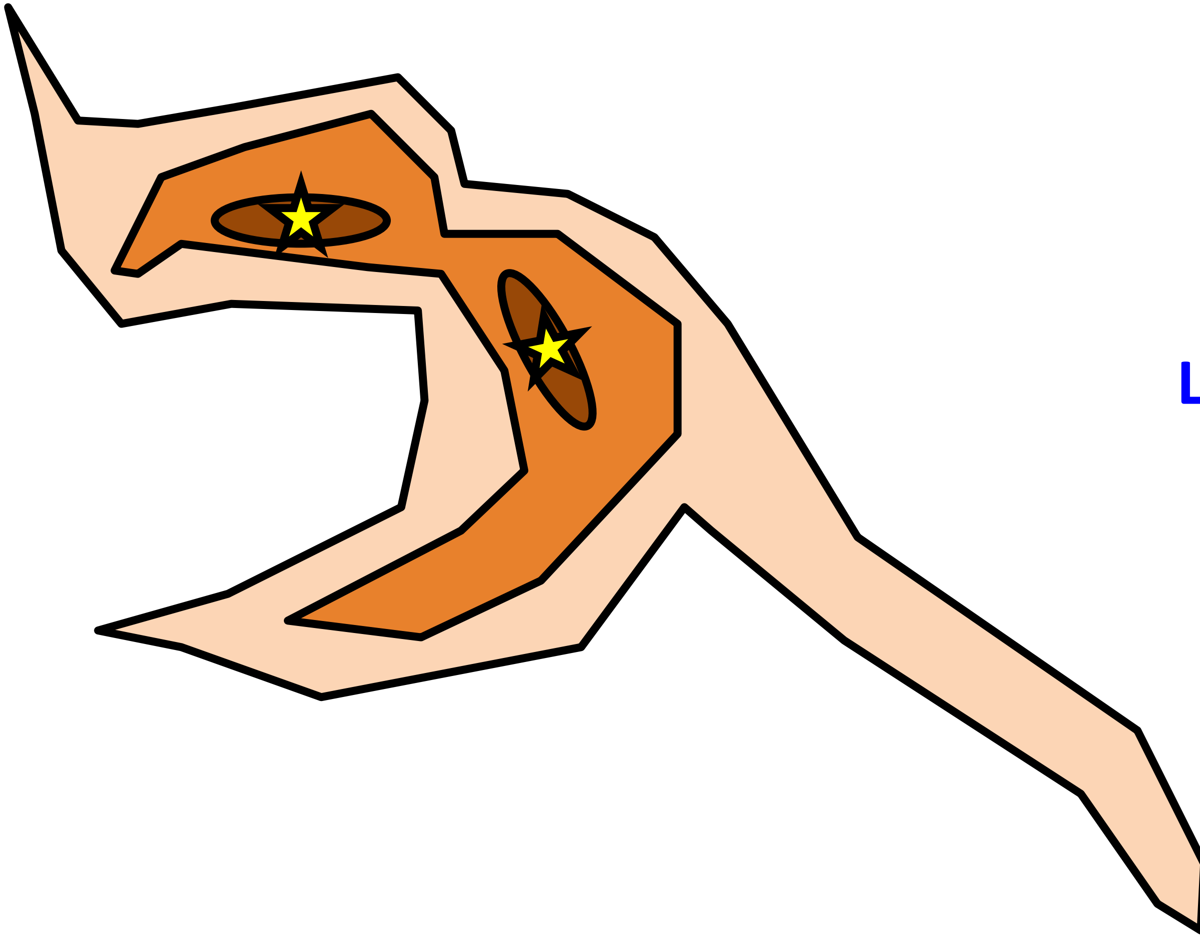
LARGEST ANGULAR SCALE

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

PRIMARY BEAM

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

Example III: disks and extended filament



SYNTHESIZED BEAM

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

LARGEST ANGULAR SCALE

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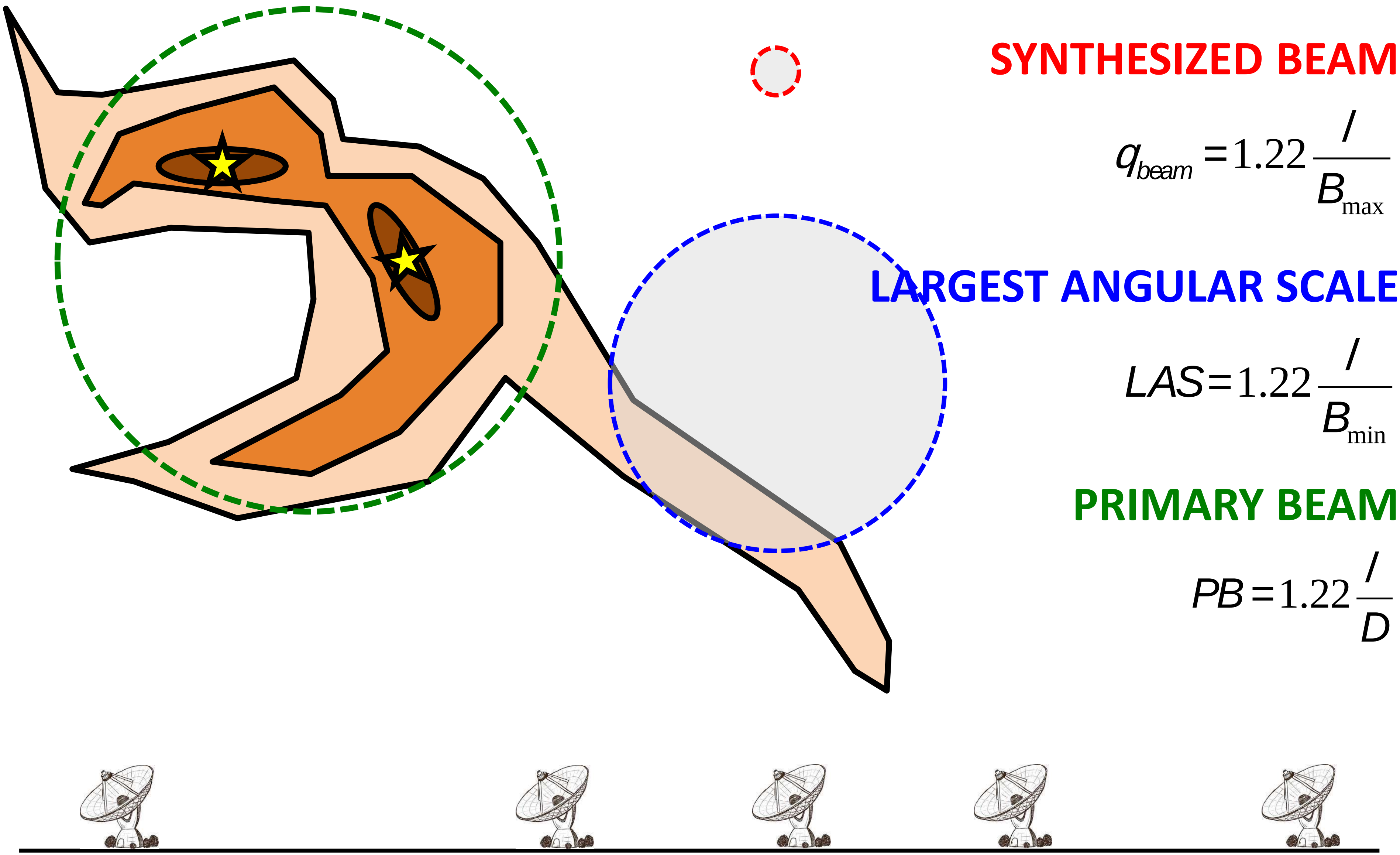
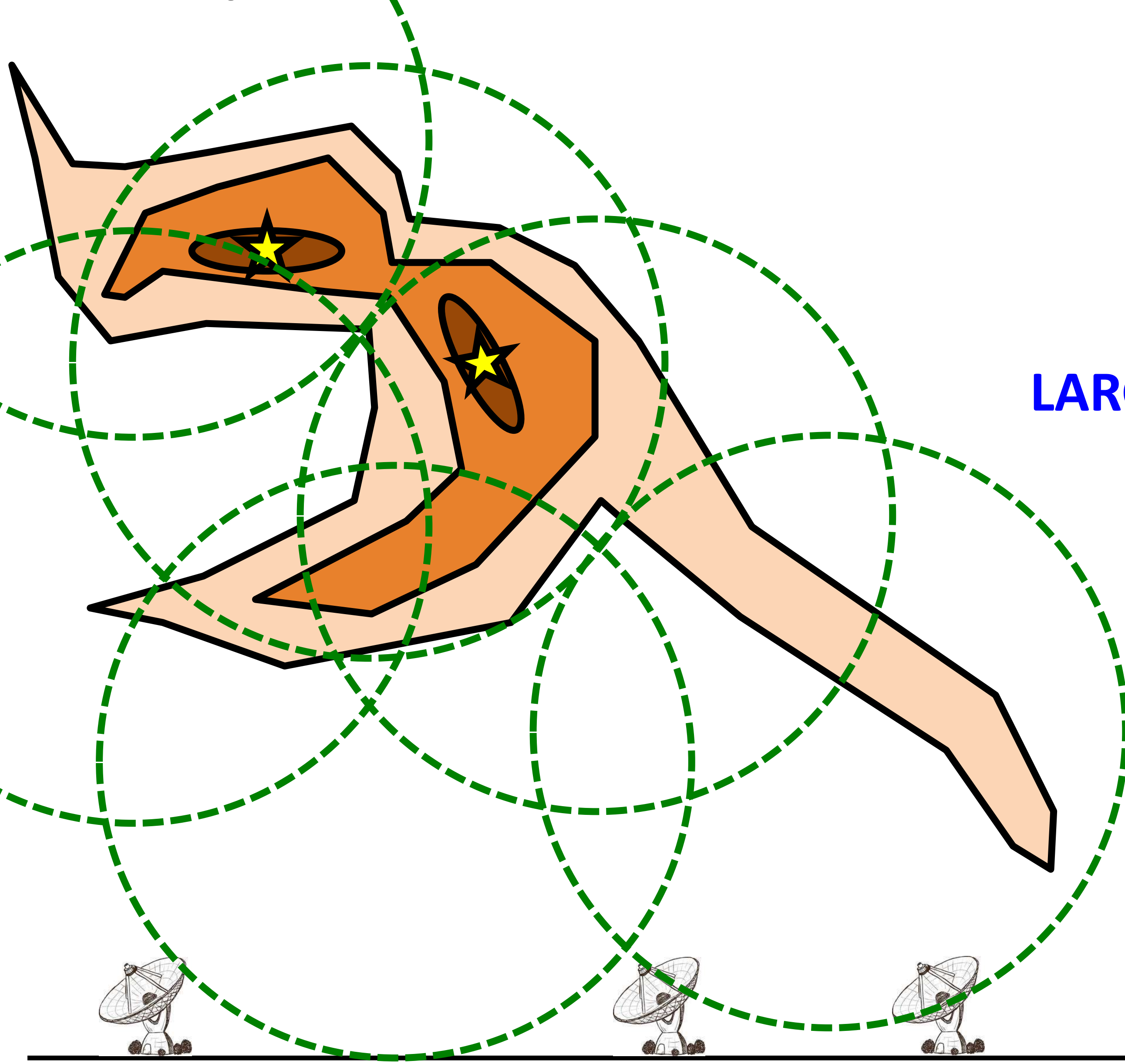
PRIMARY BEAM

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

Example III: disks and extended filament



Example III: disks and extended filament



SYNTHESIZED BEAM

$$q_{beam} = 1.22 \frac{l}{B_{\max}}$$

LARGEST ANGULAR SCALE

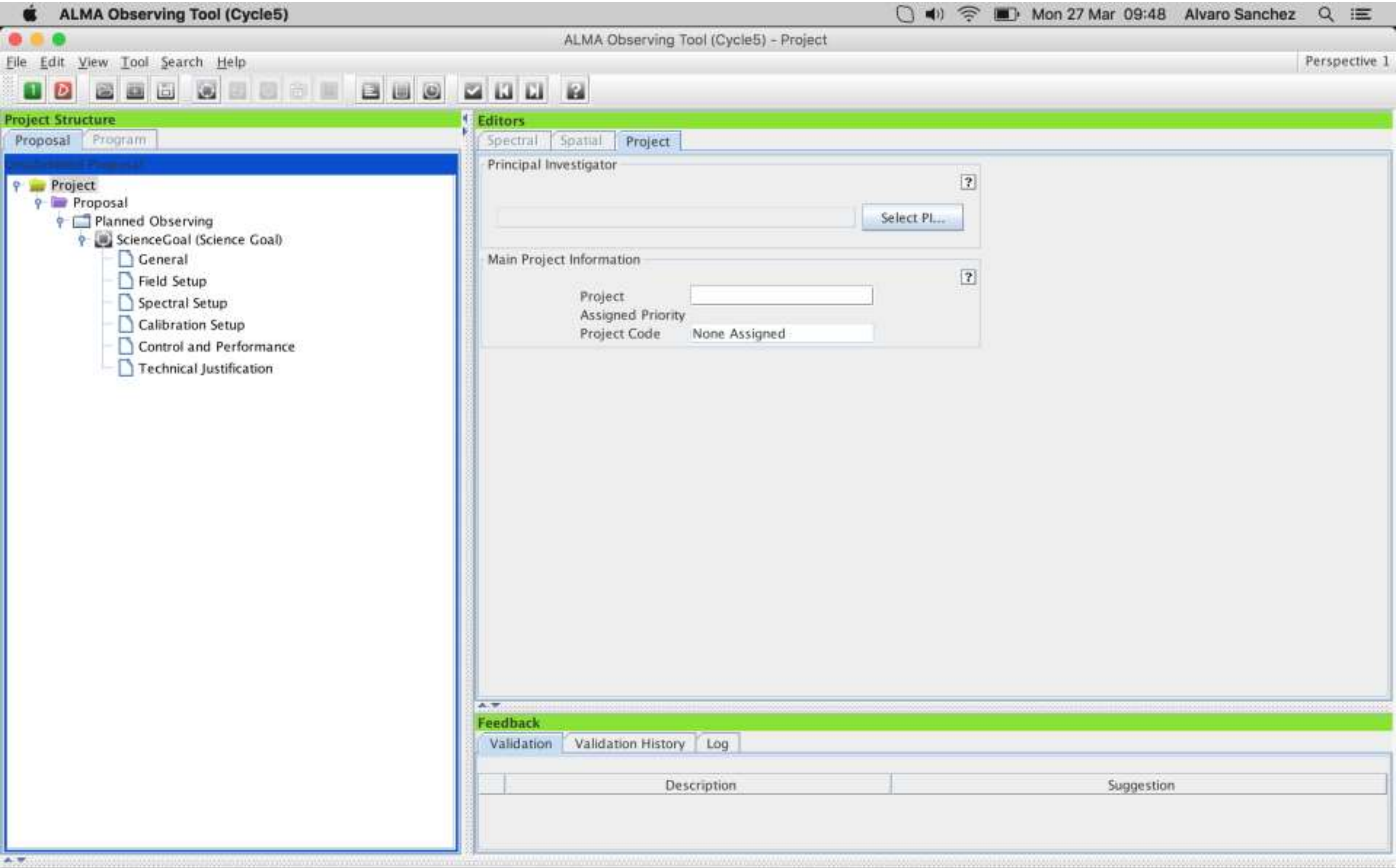
$$LAS = 1.22 \frac{l}{B_{\min}}$$

PRIMARY BEAM

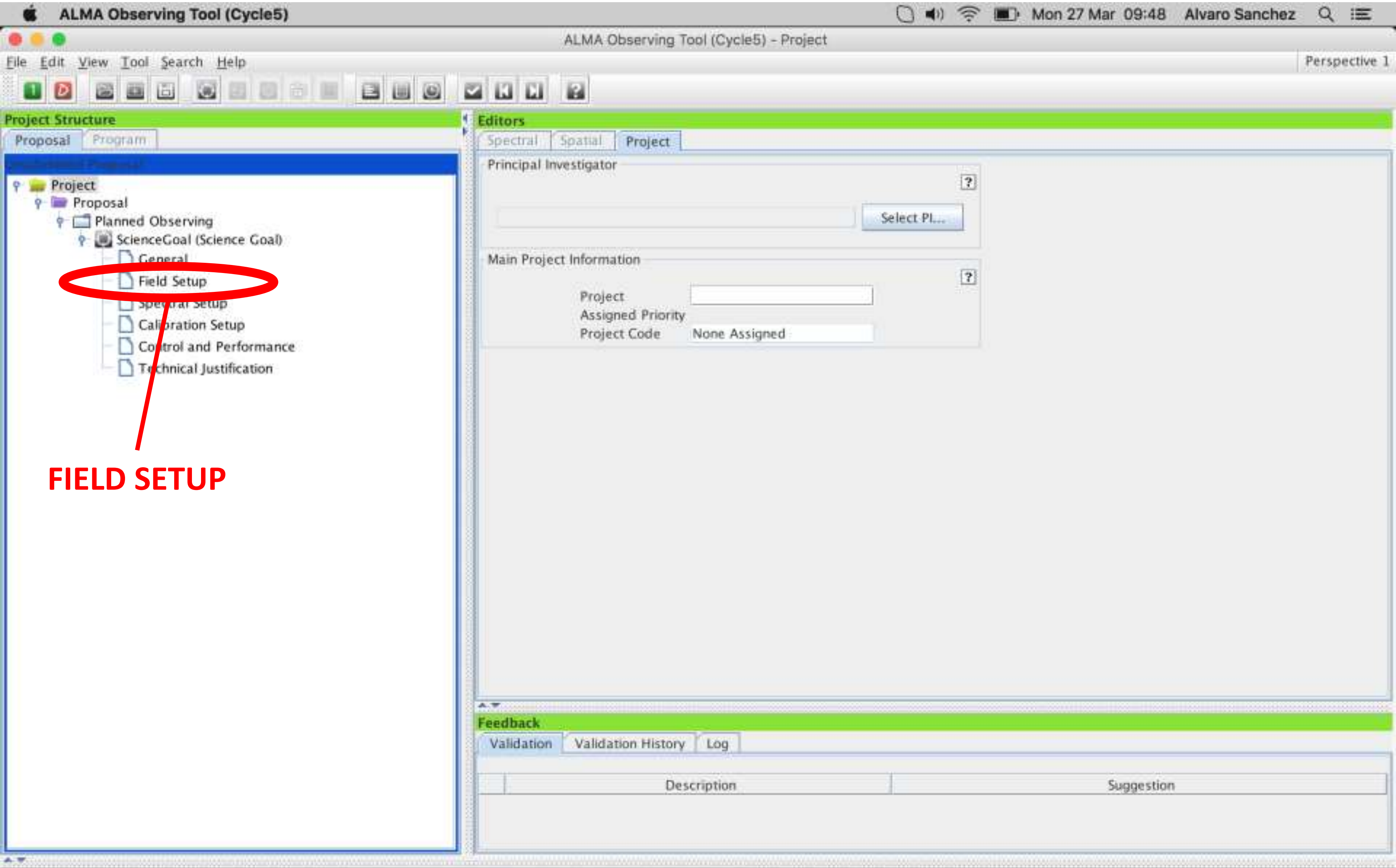
$$PB = 1.22 \frac{l}{D}$$

Practical work with the almaOT

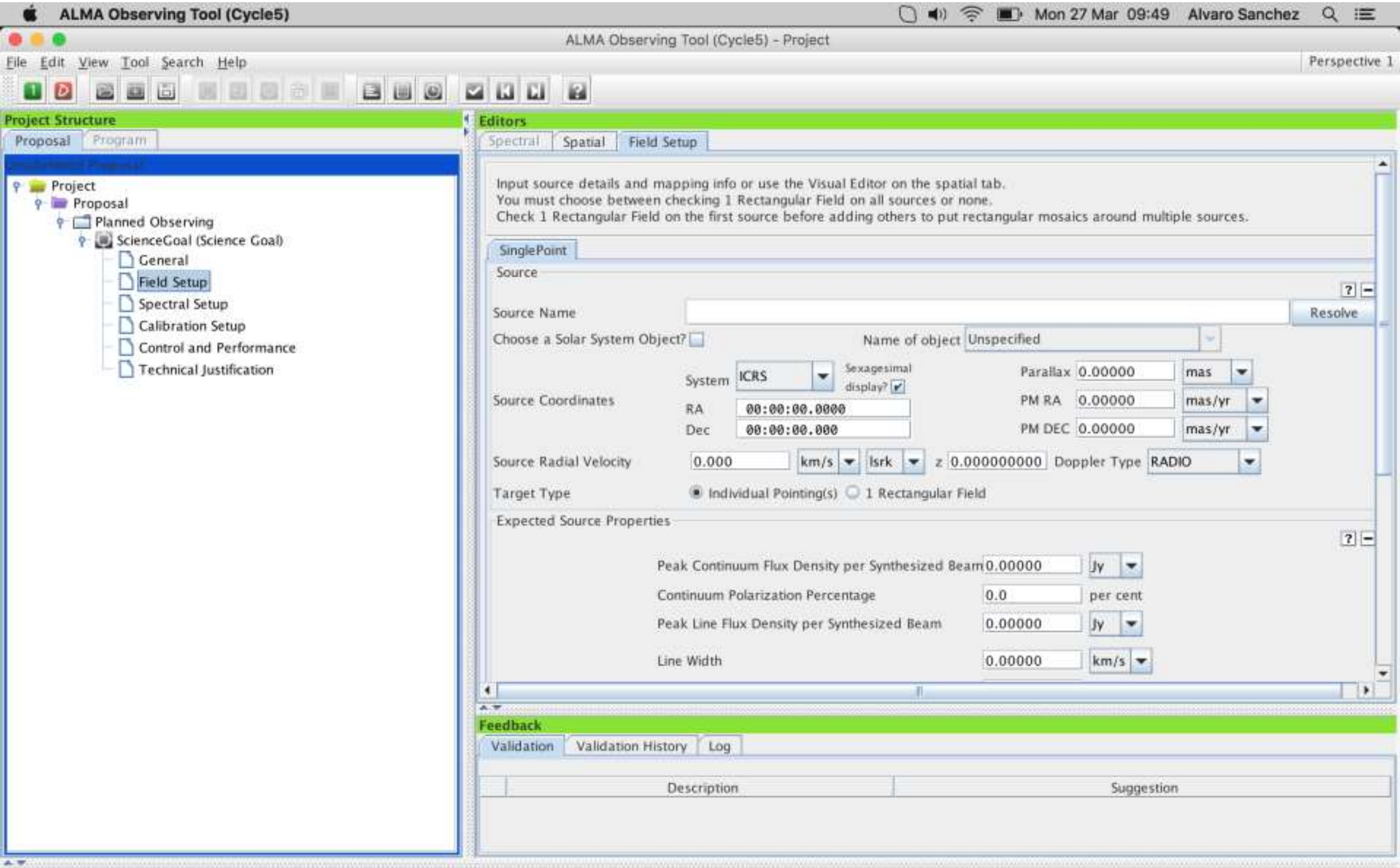
Starting the almaOT



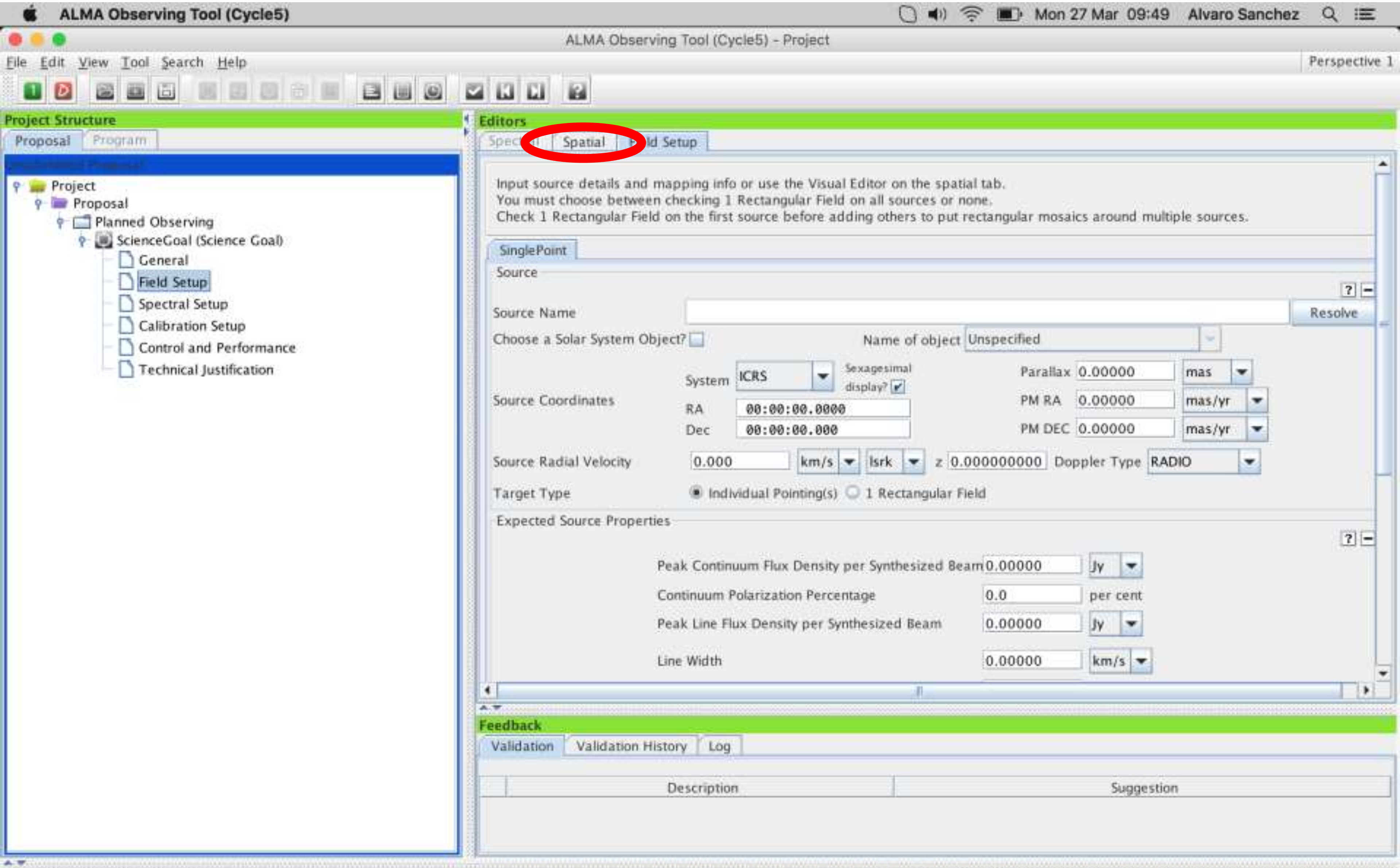
Field setup in the almaOT



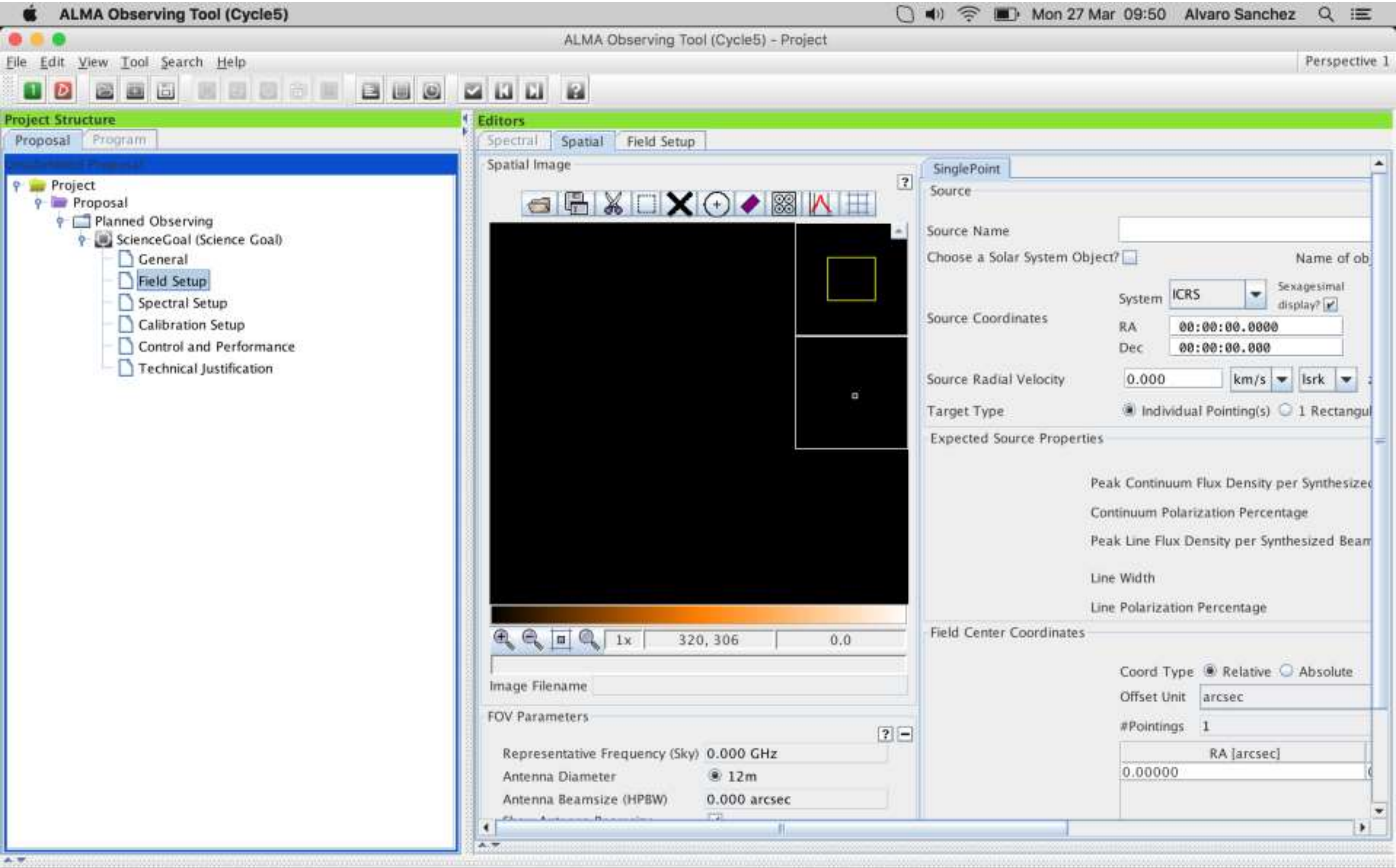
Field setup in the almaOT



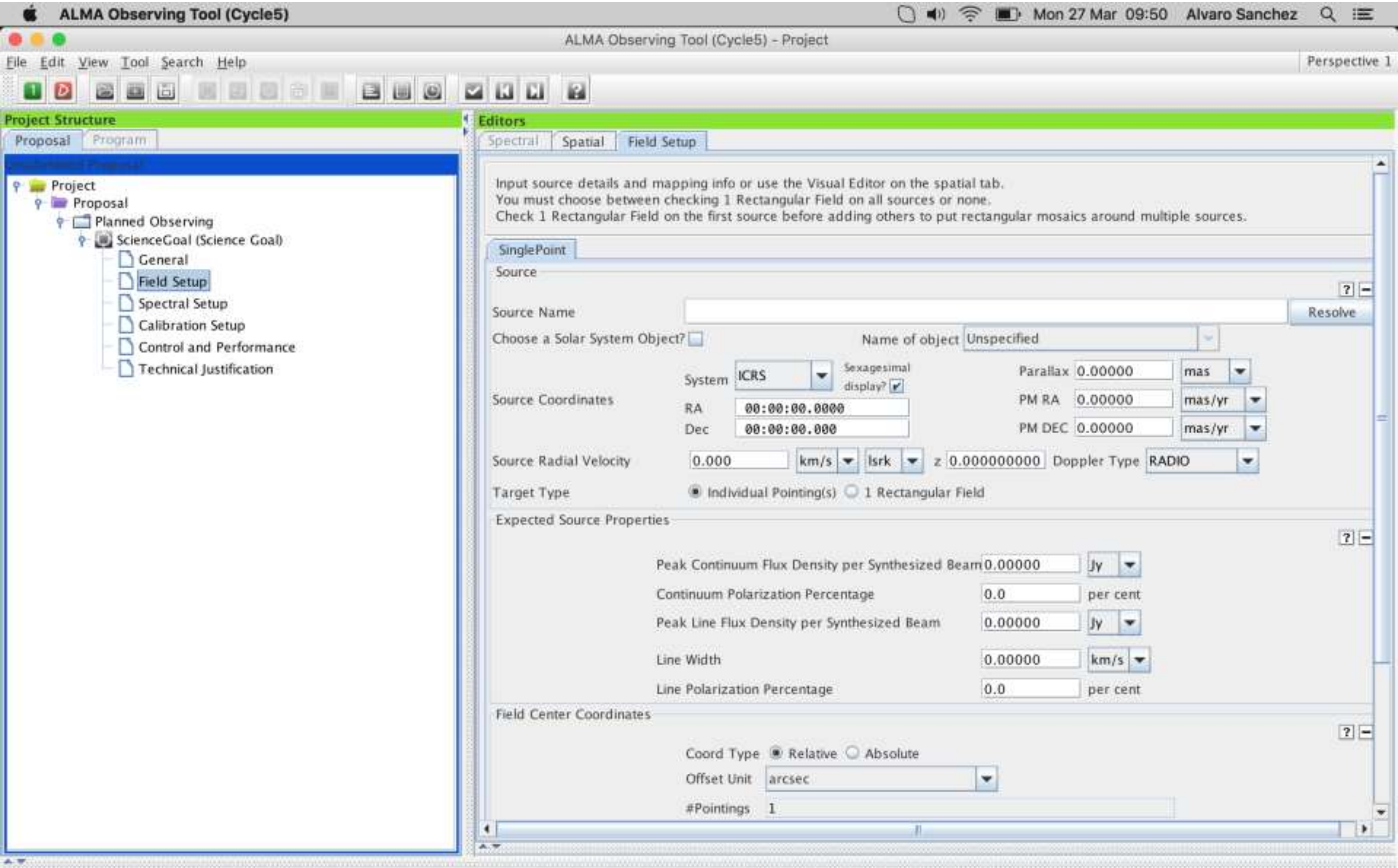
Field setup in the almaOT



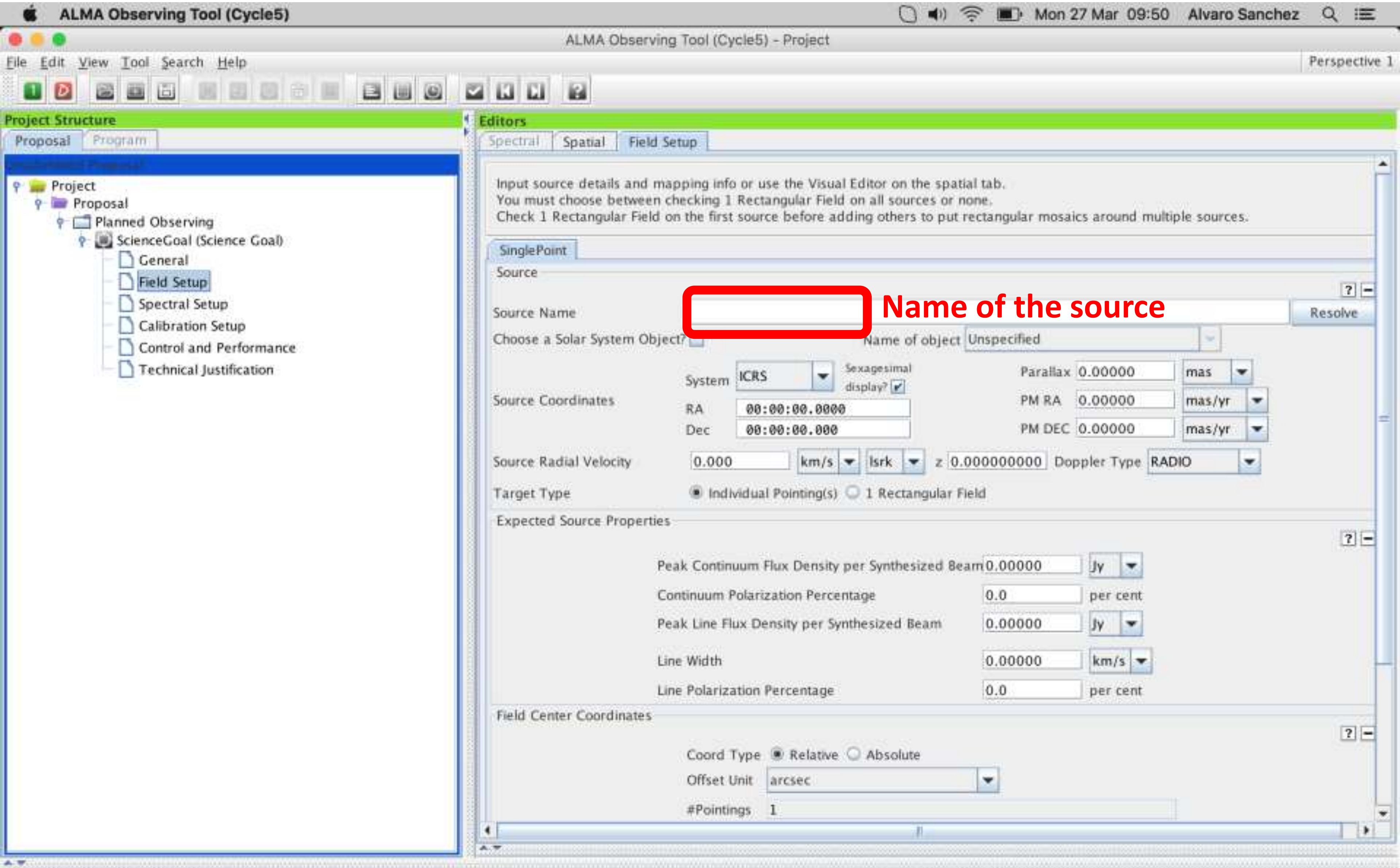
Field setup in the almaOT



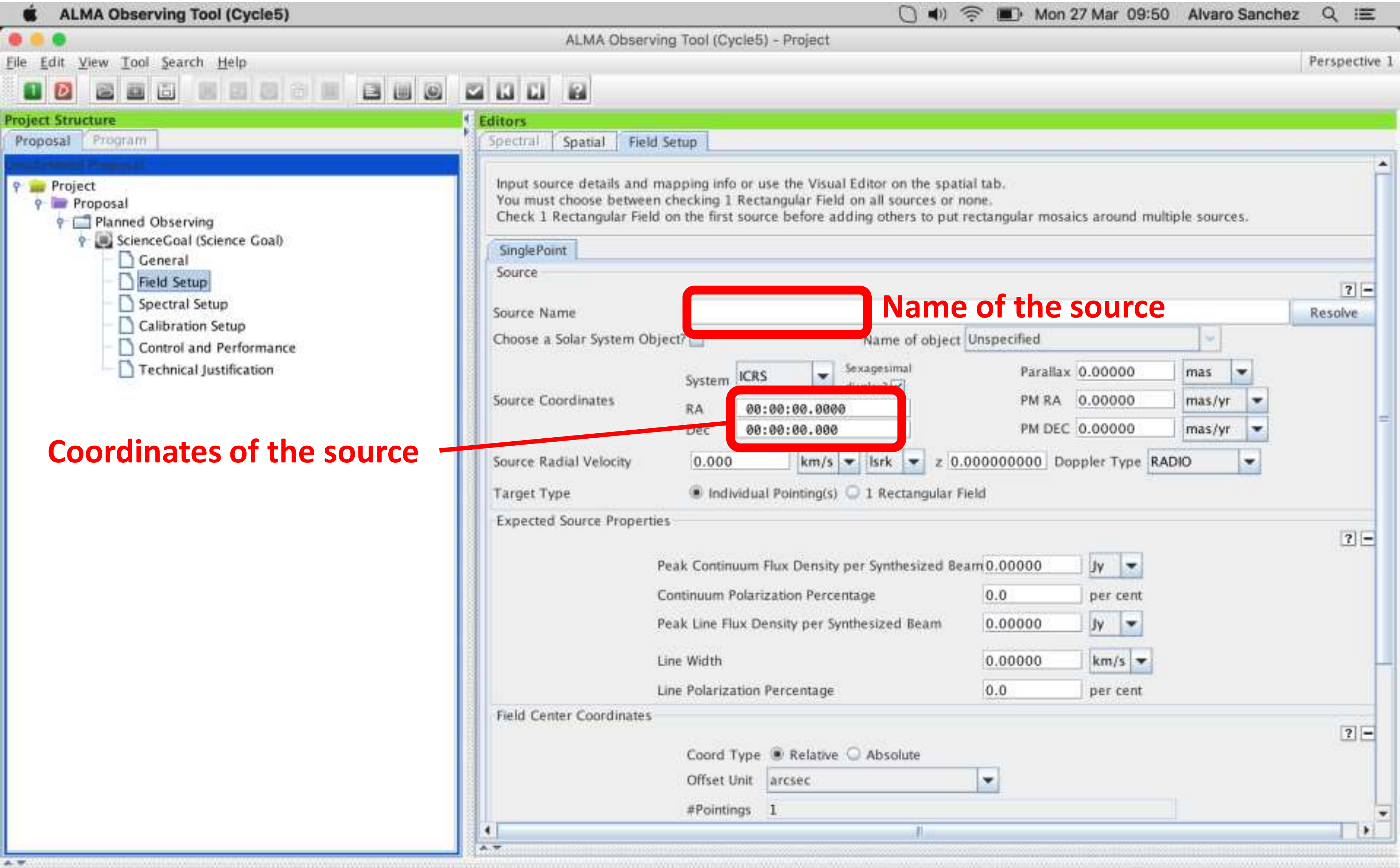
Field setup in the almaOT



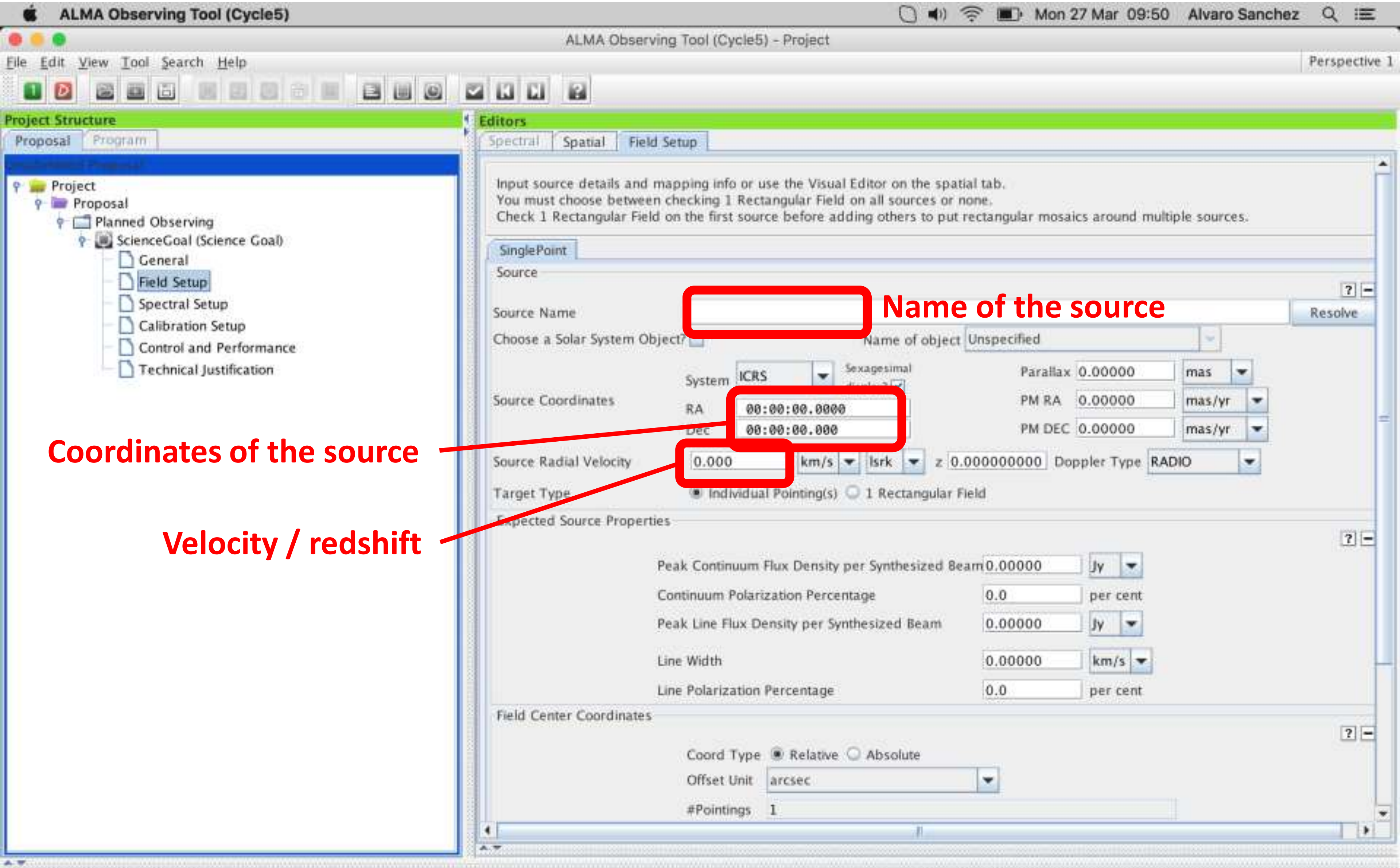
Field setup in the almaOT



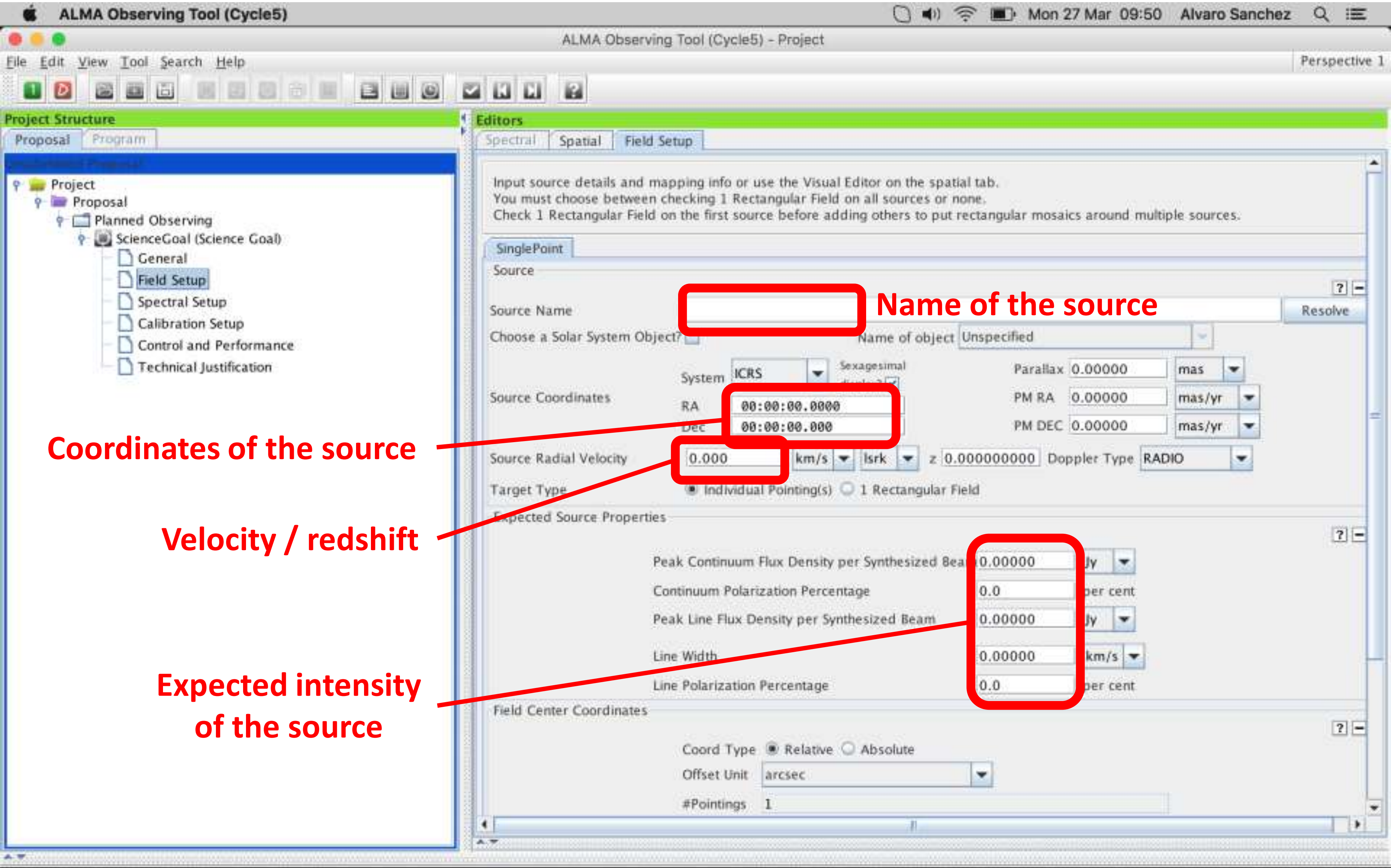
Field setup in the almaOT



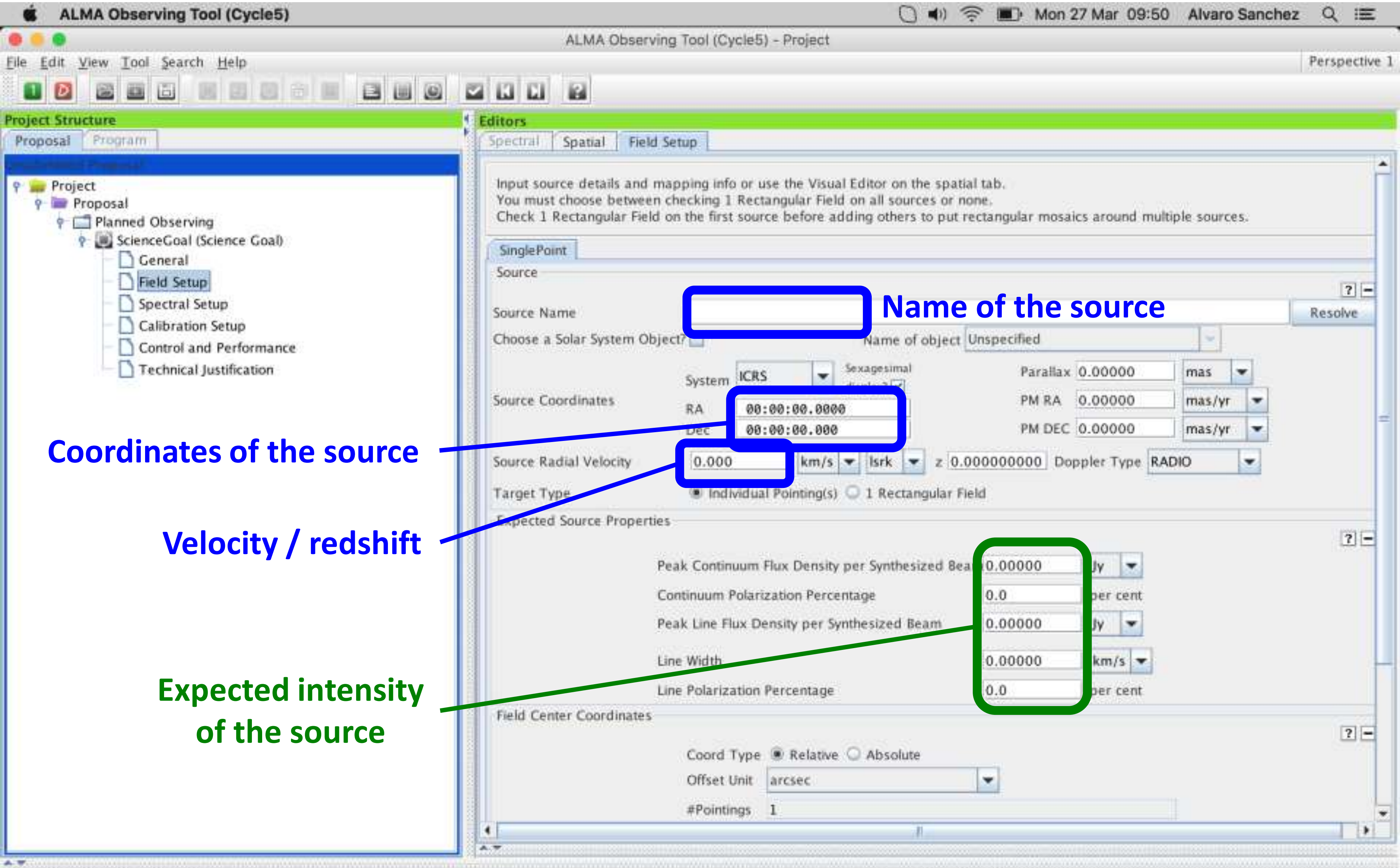
Field setup in the almaOT



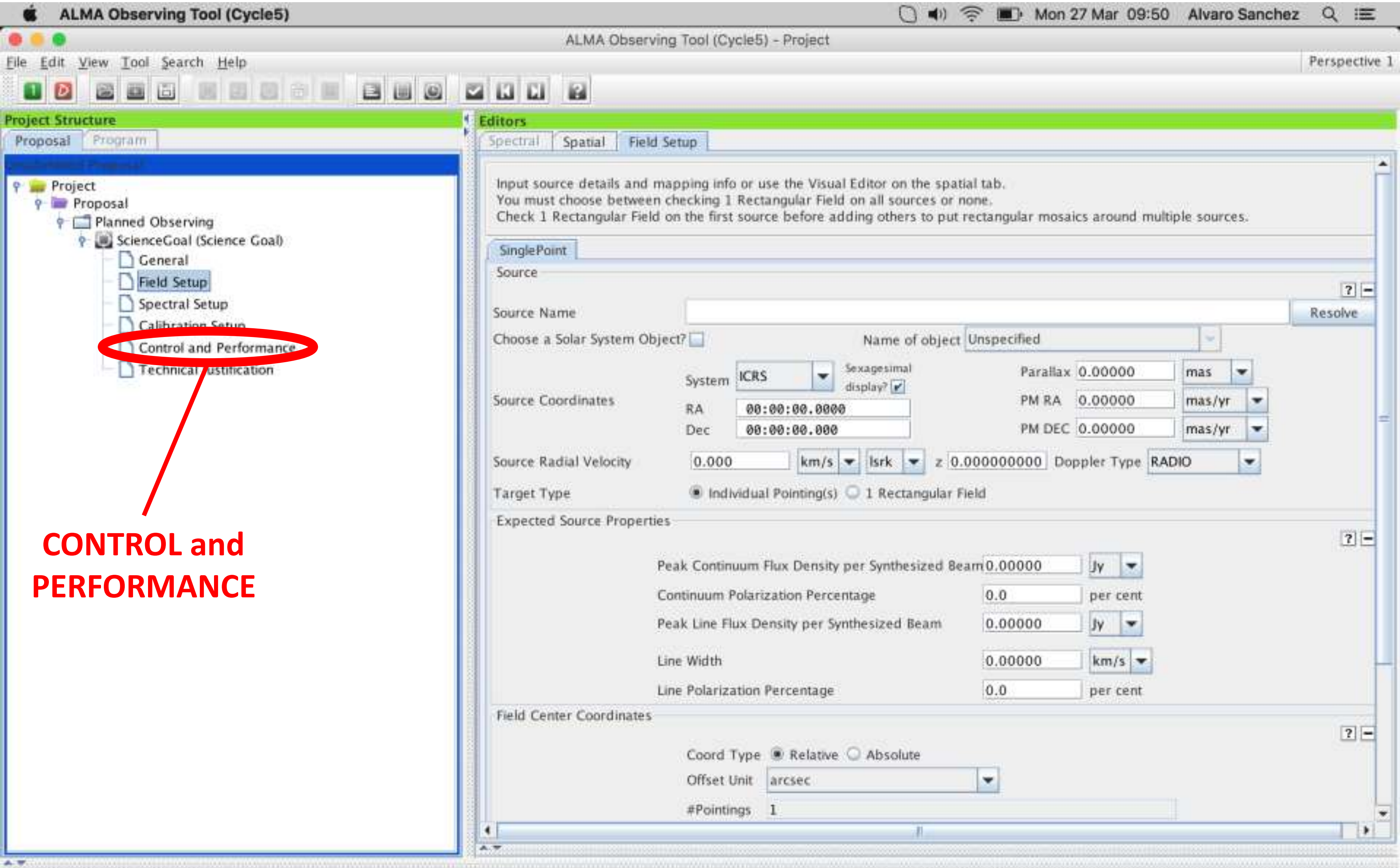
Field setup in the almaOT



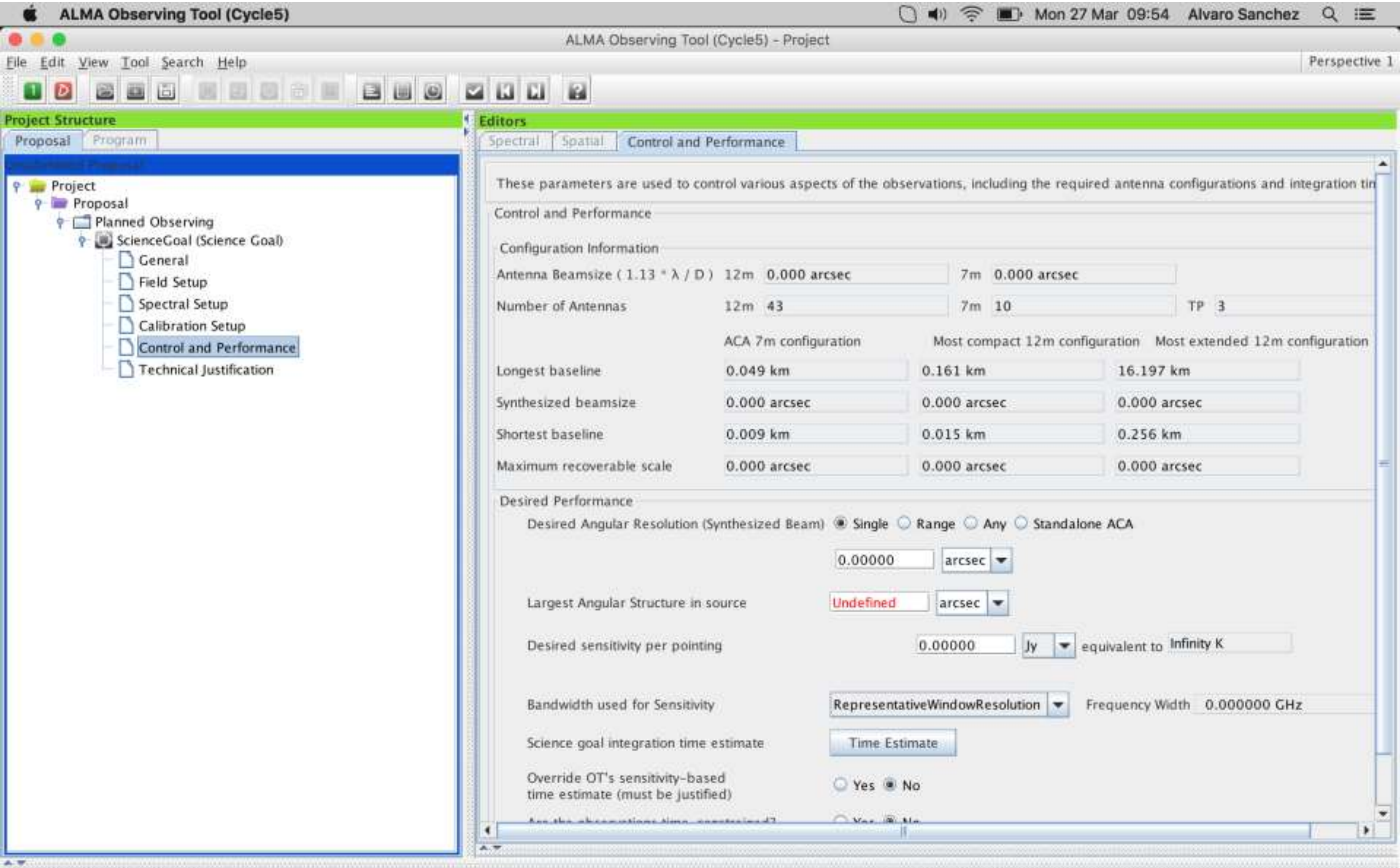
Field setup in the almaOT



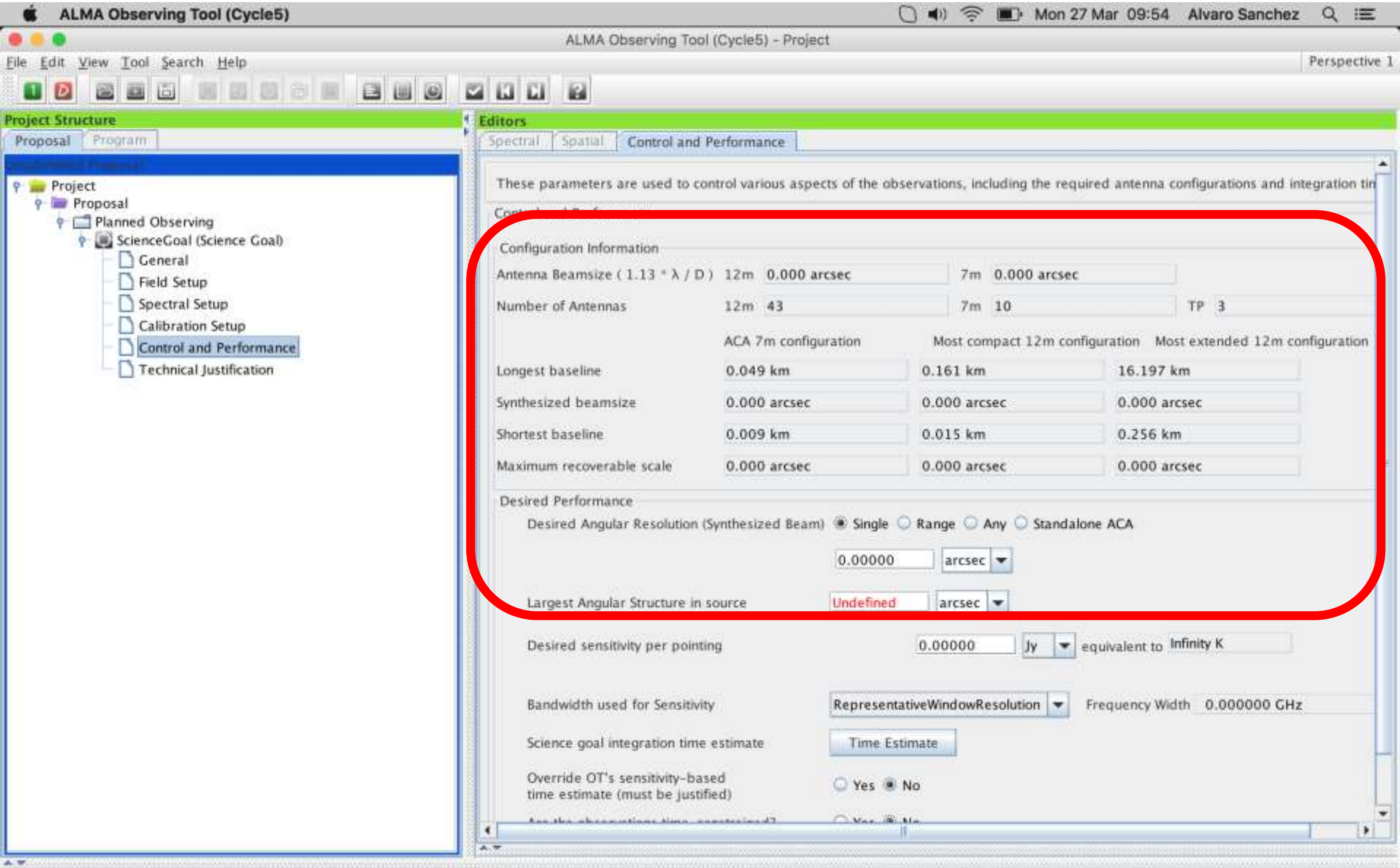
Field setup in the almaOT



Control and Performance in the almaOT



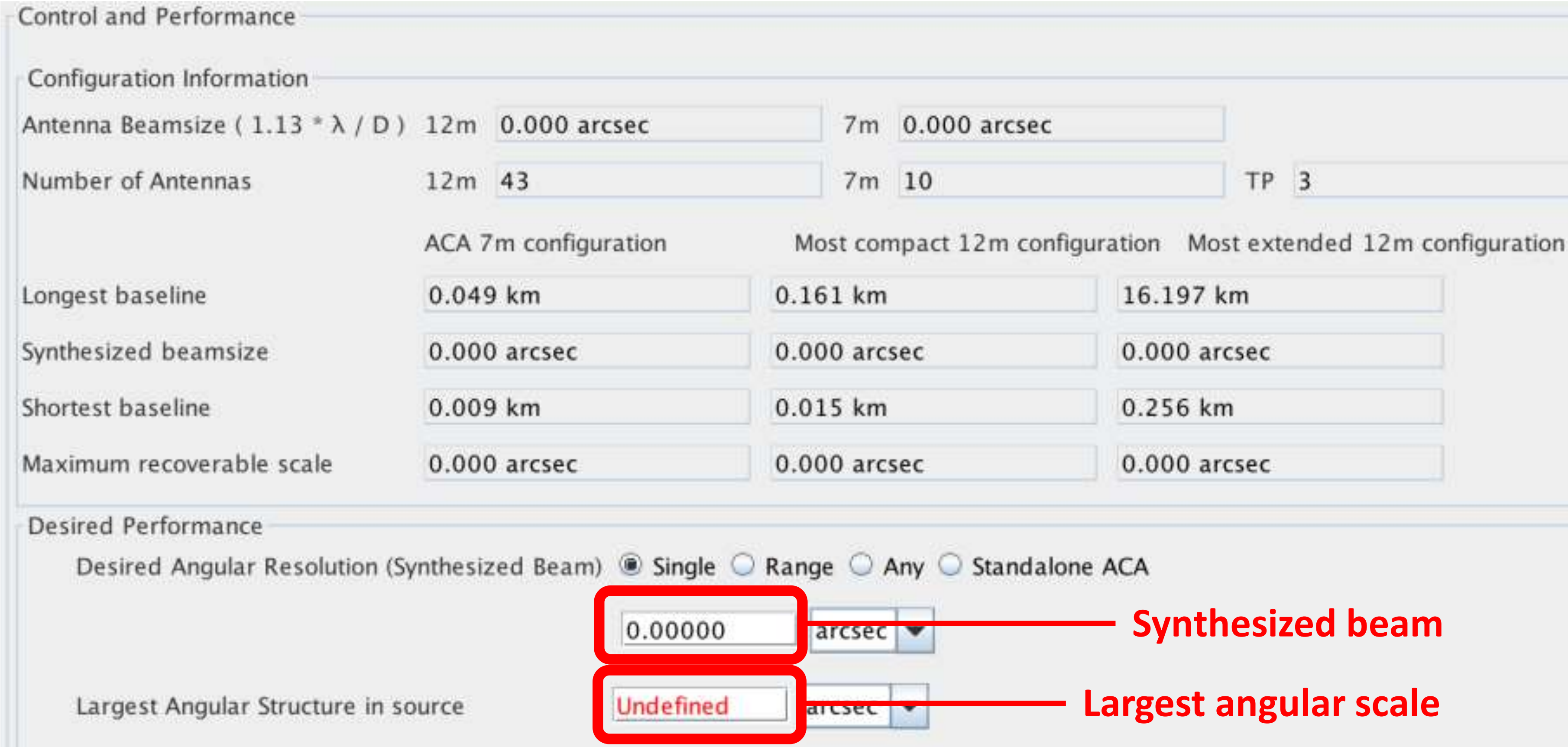
Control and Performance in the almaOT



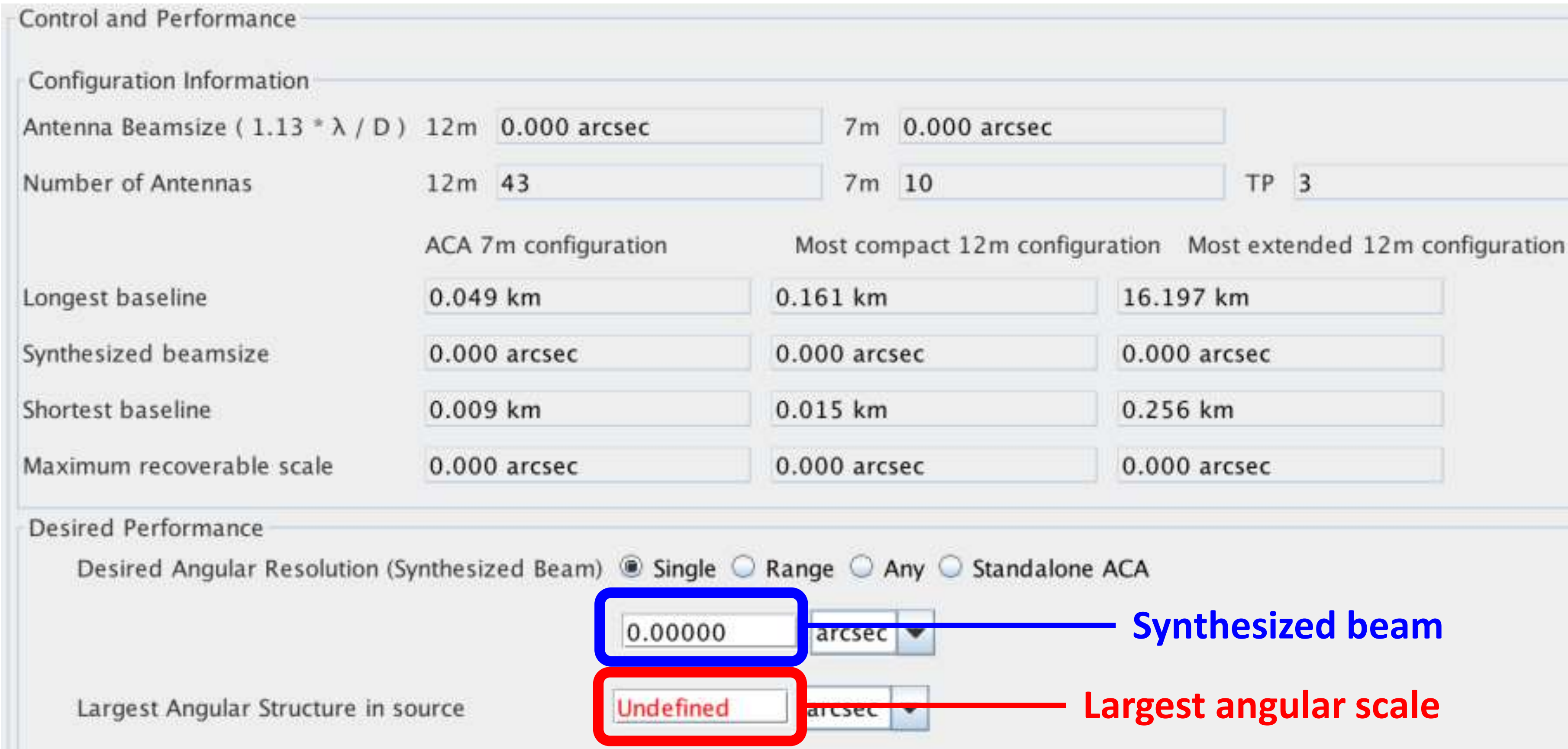
Control and Performance in the almaOT

Control and Performance in the almaOT

Control and Performance in the almaOT



Control and Performance in the almaOT



SYNTHESIZED BEAM

a.k.a. angular resolution, PSF, ...

it is the size of the object you want to resolve (distinguish)

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

Control and Performance in the almaOT

LARGEST ANGULAR SCALE

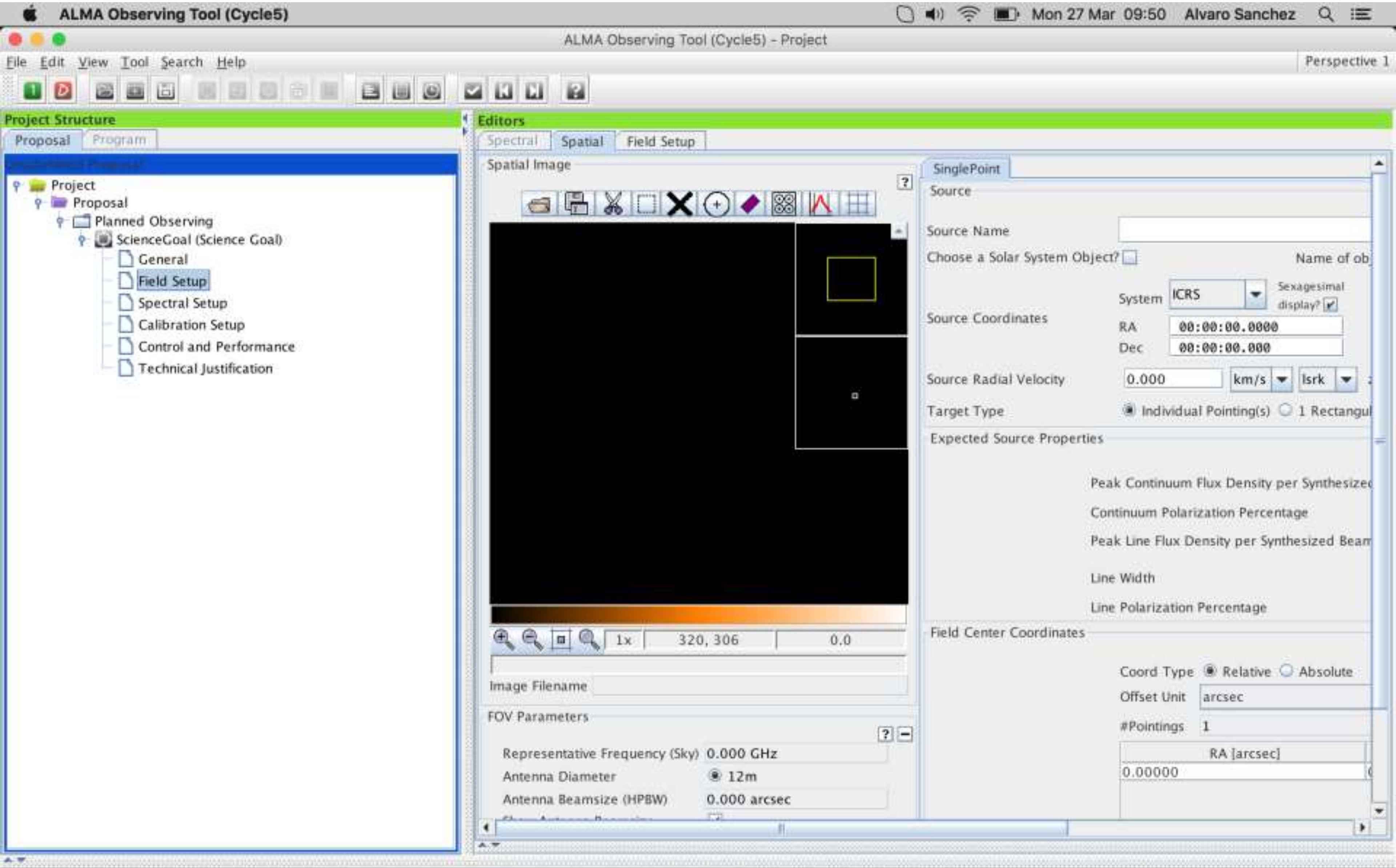
a.k.a. maximum angular size, ...

the largest size of your object

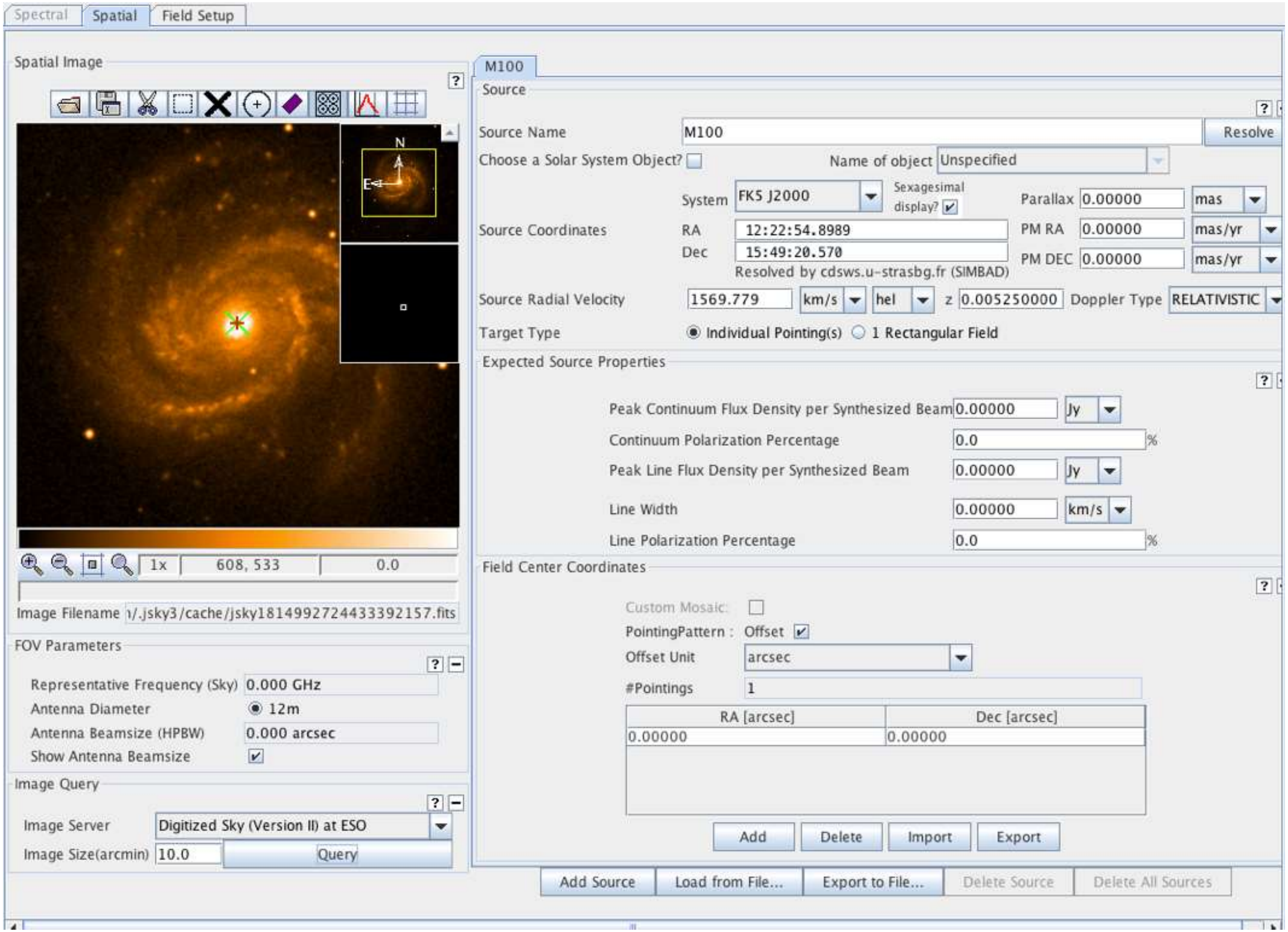
how big it is?

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

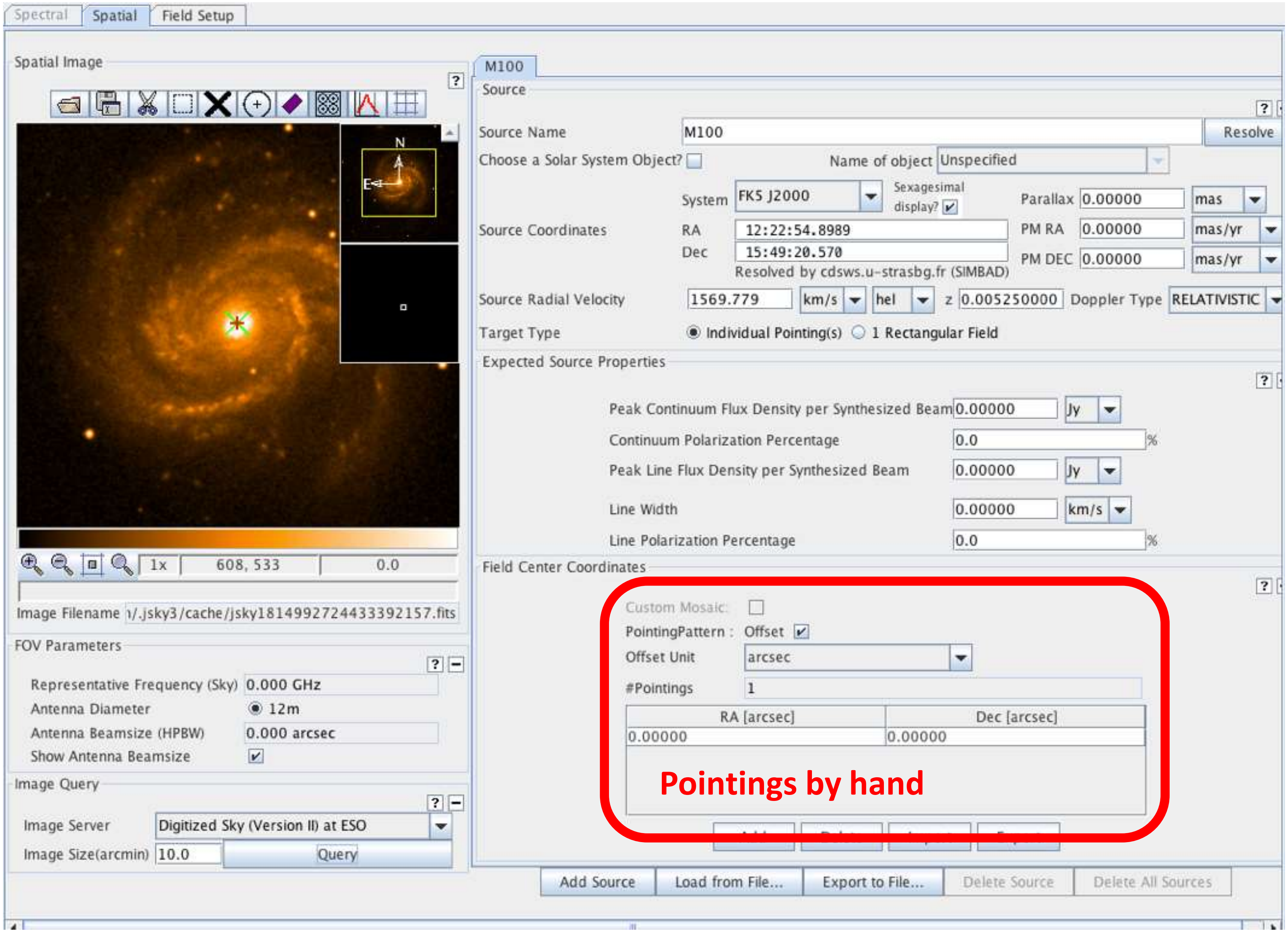
Mosaics in the almaOT



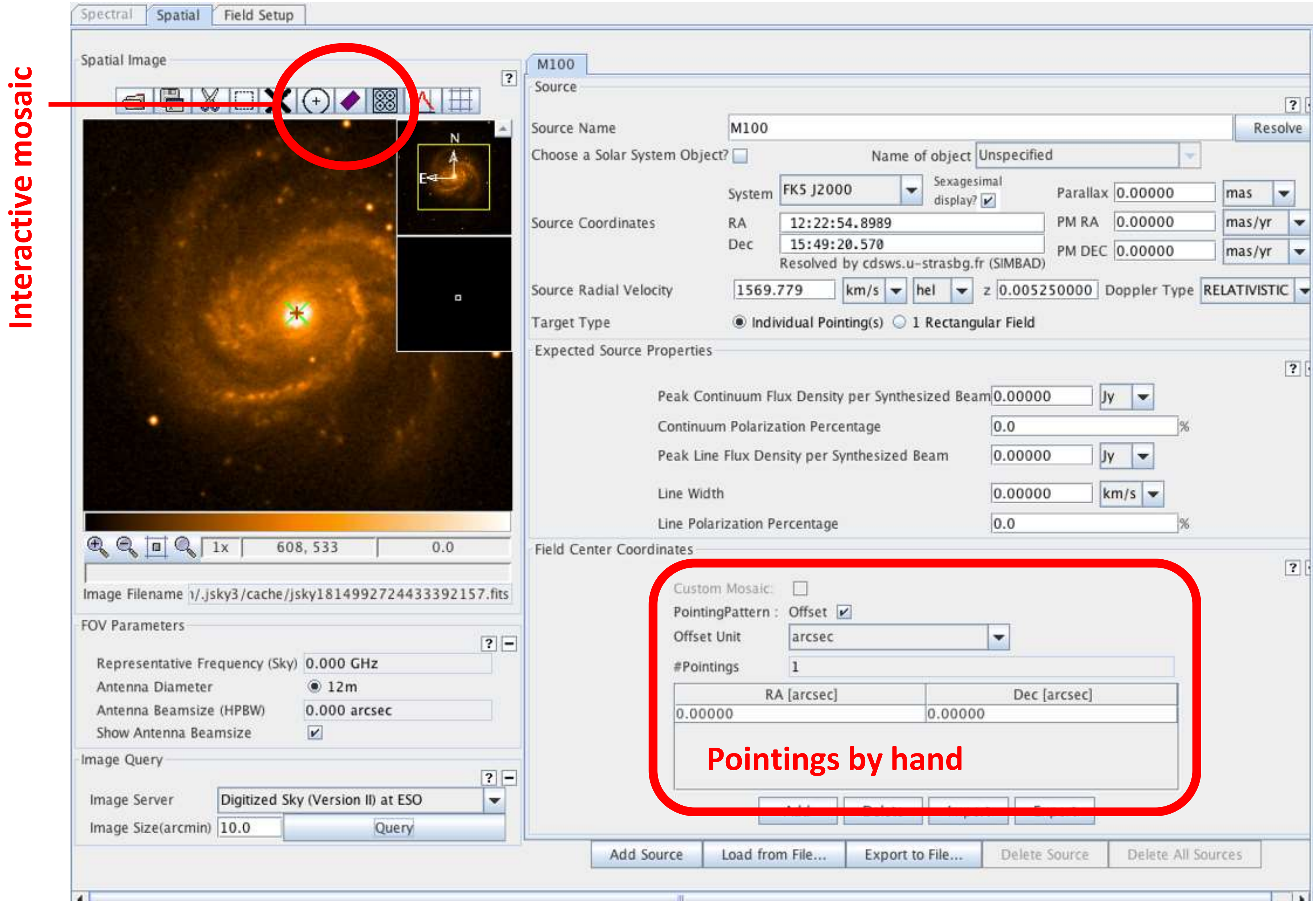
Mosaics in the almaOT



Mosaics in the almaOT



Mosaics in the almaOT



Break #1