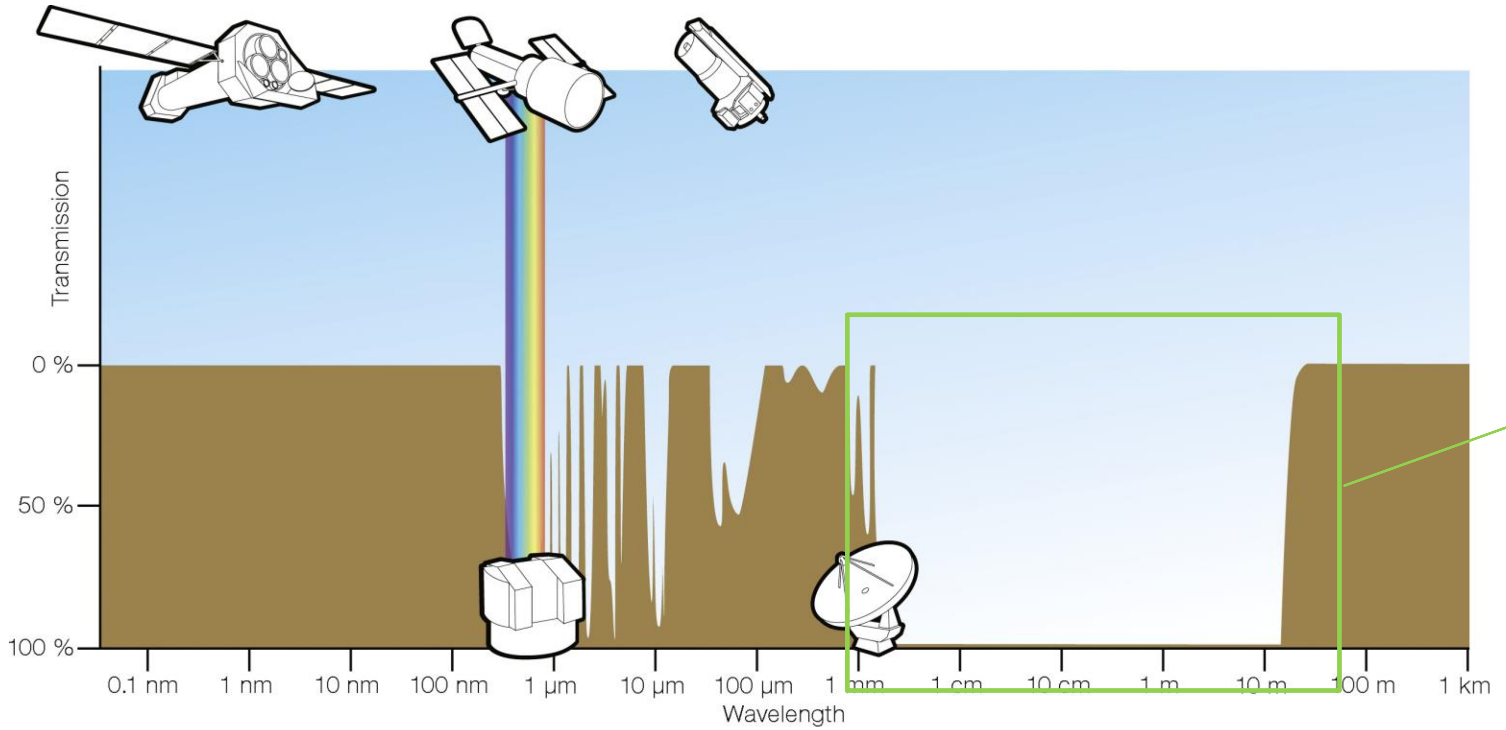
A BEGINNER'S GUIDE TO RADIO TELESCOPES AND INTERFEROMETERS

FELIX THIEL

2024 EIEIOO SUMMER SCHOOL

WHY RADIO ASTRONOMY ?



Credit: ESA/Hubble (F. Granato)

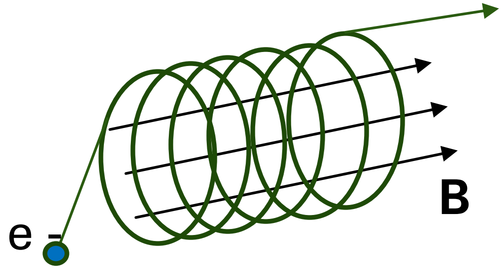
The radio part of the EM spectrum falls on a big window in our atmosphere that is transparent spanning almost five orders of magnitude in wavelength

A big window in frequency means a large variety of physics that we can trace

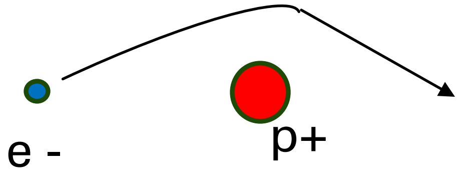
WHAT CAN WE OBSERVE ?

Continuum Emission

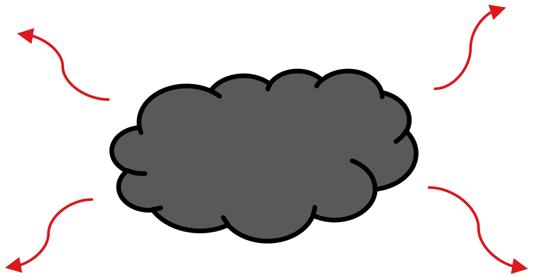
Synchroton



Free-Free

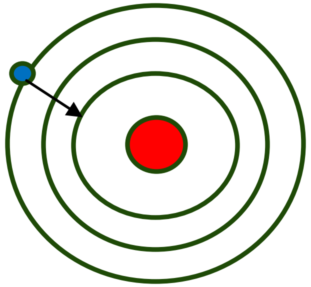


Blackbody (thermal)



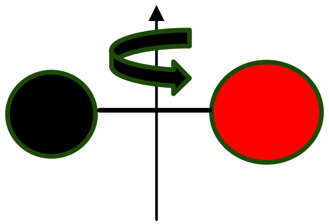
Spectral Line Emission

Recombination



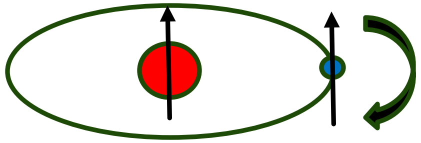
e.g. H92α

Rotation/Vibration



e.g. CO

Spin-flip



e.g. Hydrogen

HOW DO WE OBSERVE ?

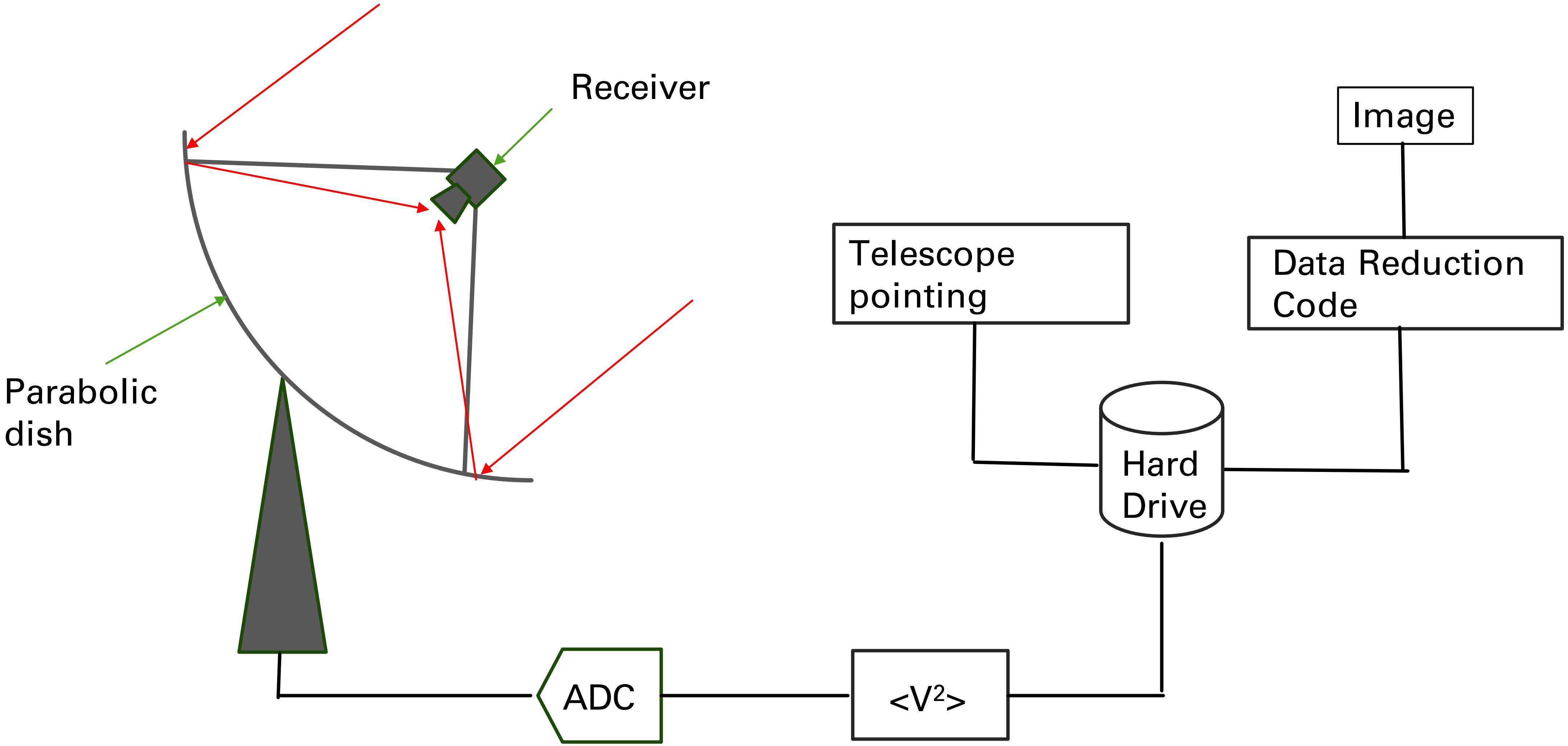
Secondary reflector

Receiver

Dish (primary reflector)

Radio astronomers :)

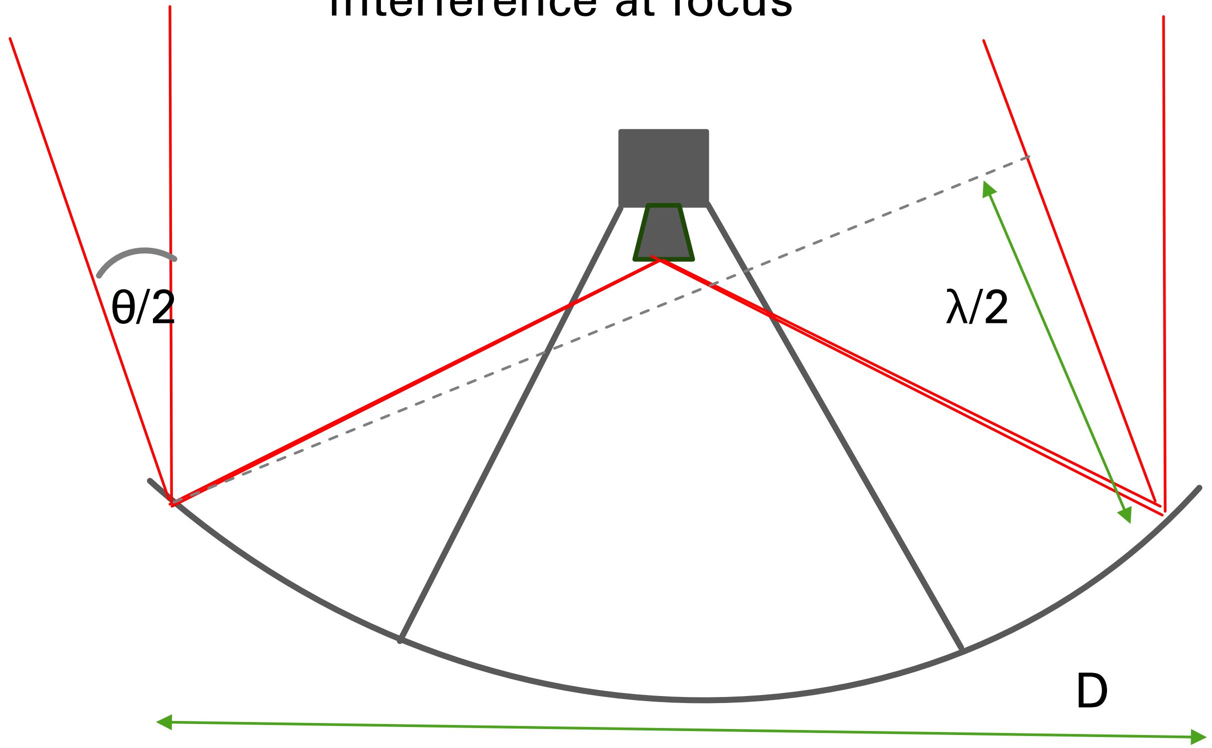
HOW DOES A RADIO TELESCOPE WORK ?



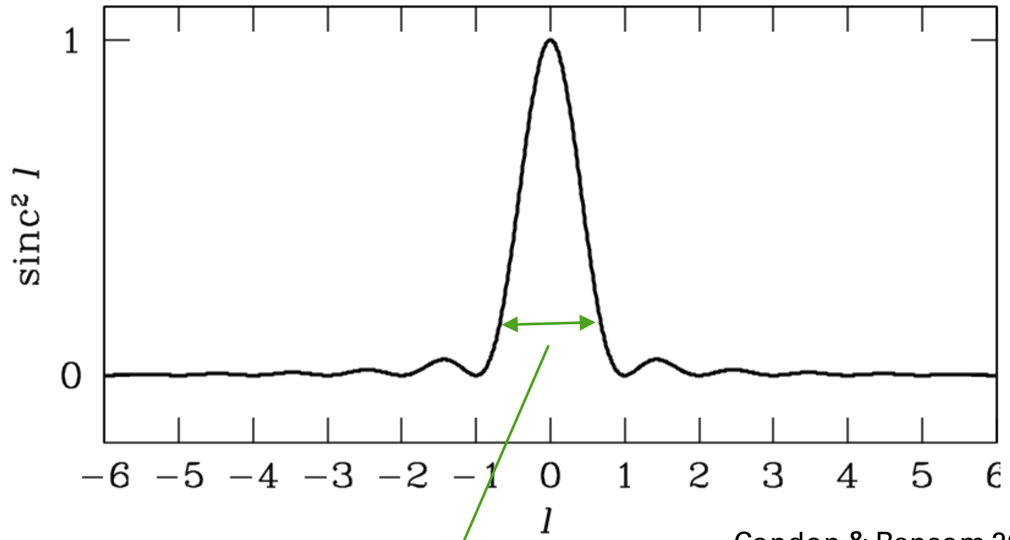
THE DIFFRACTION LIMIT

Equal pathlength = Constructive interference at focus

Unequal pathlength = Destructive interference at focus



Telescope response



Condon & Ransom 2016

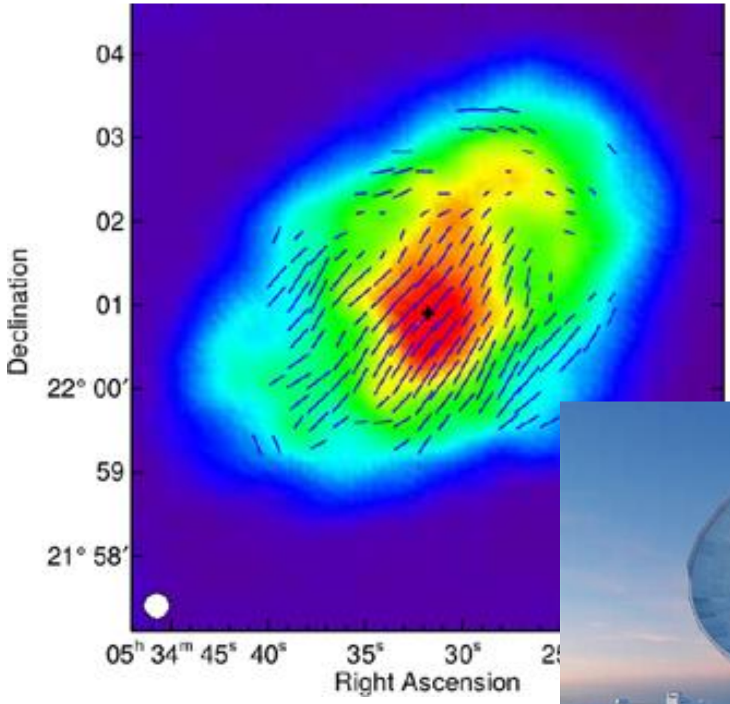
$$\theta \sim \lambda/D$$

"Diffraction limited angular resolution"

A bigger telescope and higher observing frequency gives higher resolution.

THE DIFFRACTION LIMIT

150 GHz IRAM-NIKA2, 30 m

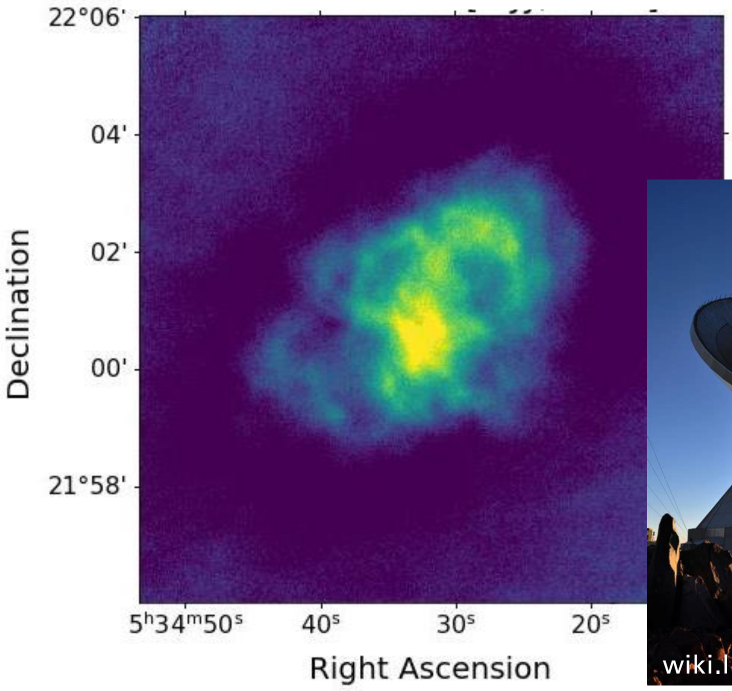


The Crab Nebula (M1)

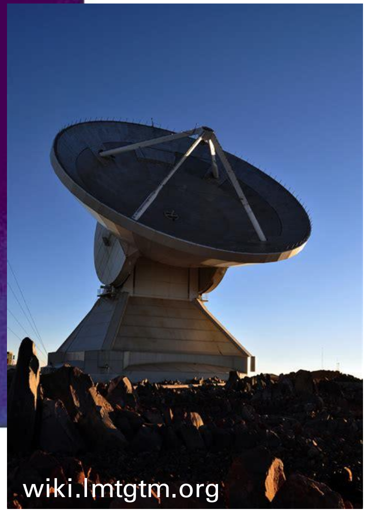
Ritacco+ 2018

IRAM 30 m, Spain

272 GHz LMT-ToITEC, 50 m



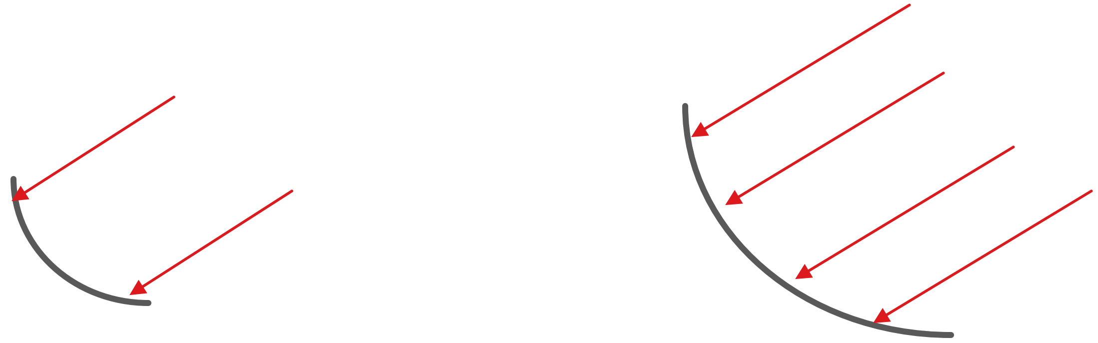
Thiel 2023 (MSc Thesis)
Data reduced by Joey Golec



Large Millimetre Telescope (LMT), Mexico

THE BOTTOM LINE

1. Radio waves are big, so to achieve a good resolution we need a big telescope
2. Telescopes are light buckets a bigger telescope will collect more light



3. Point sources will appear to have the size of the beam given by:

$$\theta \sim \lambda/D$$

SOME OF THE WORLD'S BIGGEST

Green Bank Telescope, West Virginia,US:

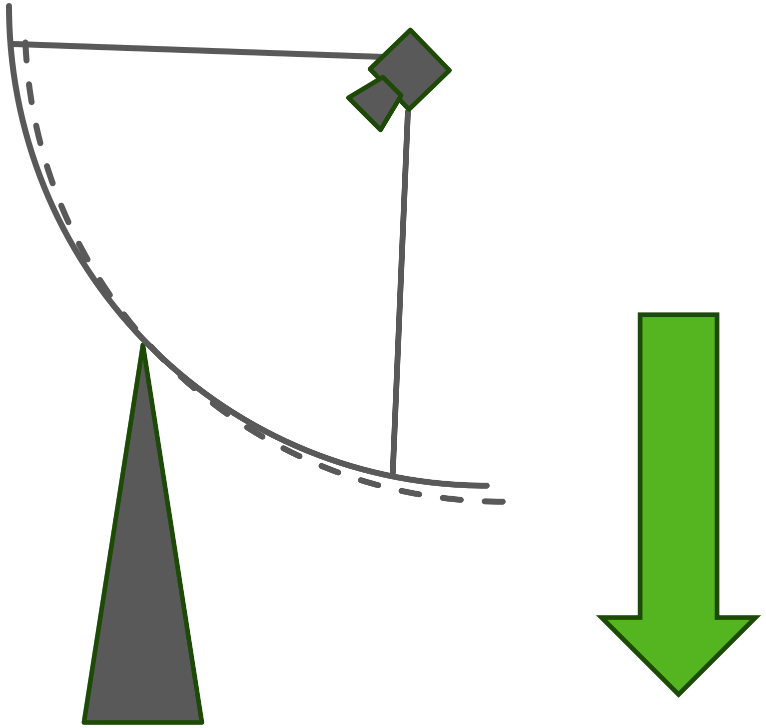
- 100m Dish
- Offset Gregorian optical system
- 100 MHz to 116 GHz

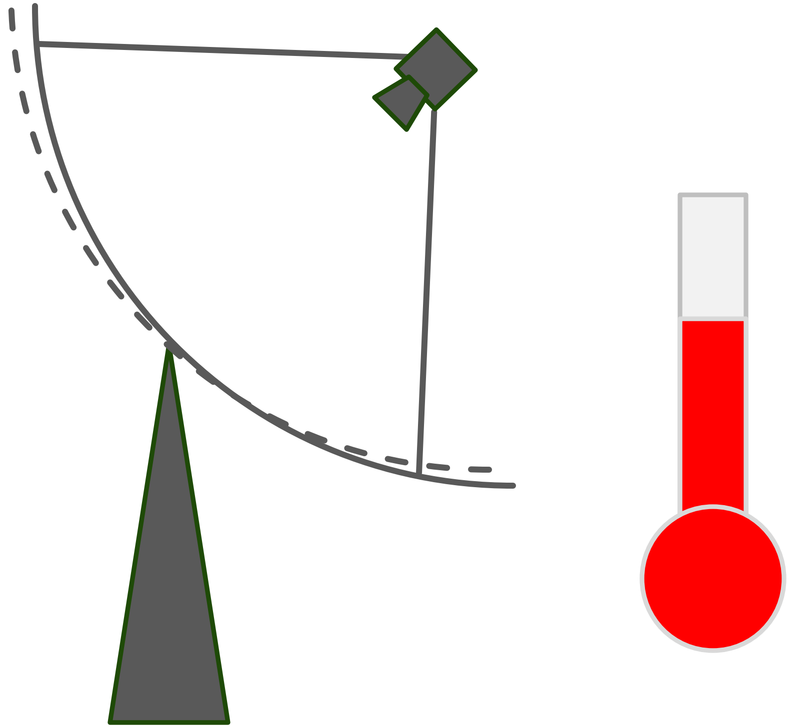
Effelsberg 100 m, Effelsberg, Germany:

- 100m Dish
- Gregorian optical system
- 408 MHz to 86 GHz

BIG DISH TELESCOPES ARE TRICKY

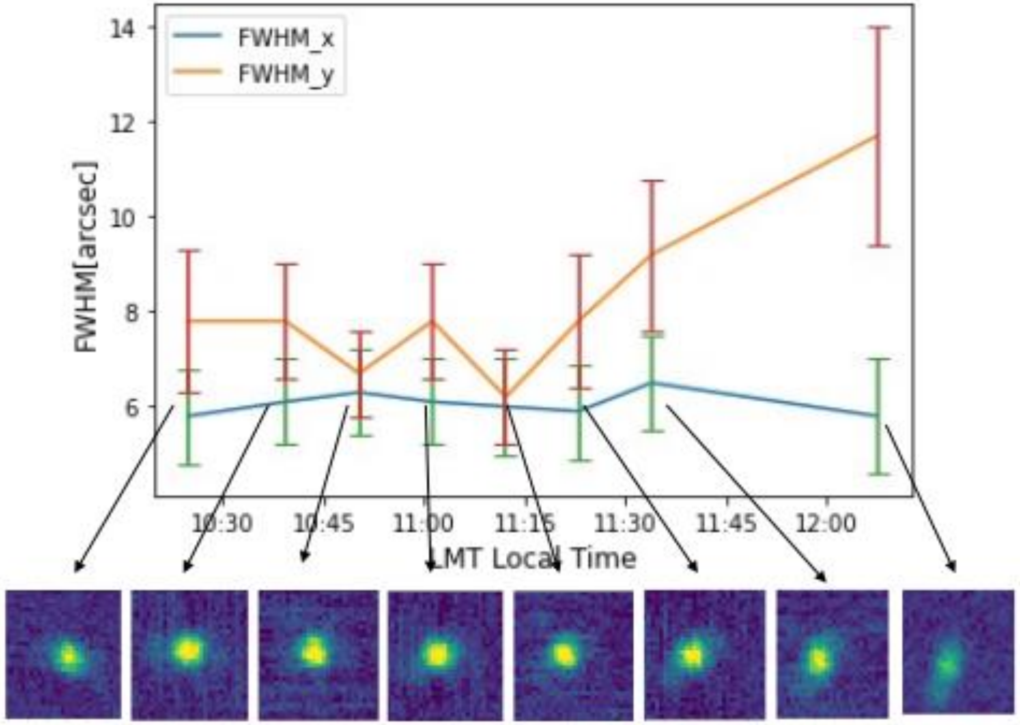
Both gravity and temperature can deform the surface of the dish degrading resolution





BIG DISH TELESCOPES ARE TRICKY

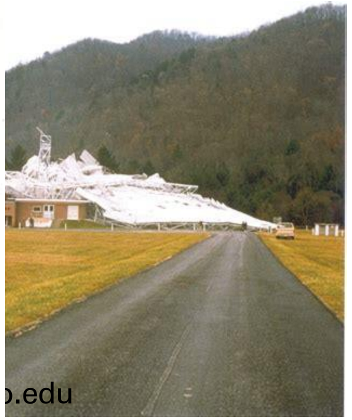
3C 147 observations with LMT dish thermalizing and deforming



Thiel 2023 (MSc Thesis)

Big telescopes are also prone to structural failures when they get old (ex. Green Bank 300 ft)

Radarpages



.edu

ber 16th 1988

HOW CAN WE DO BETTER ?

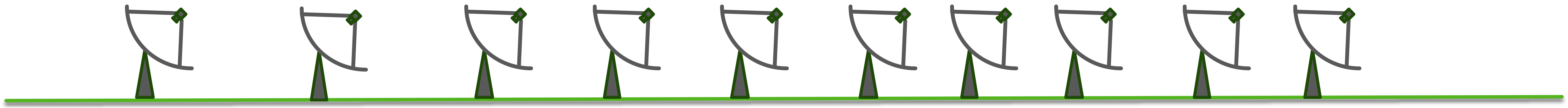
Step 1: Start with a big dish

HOW CAN WE DO BETTER ?

Step 2: Split it up into little segments

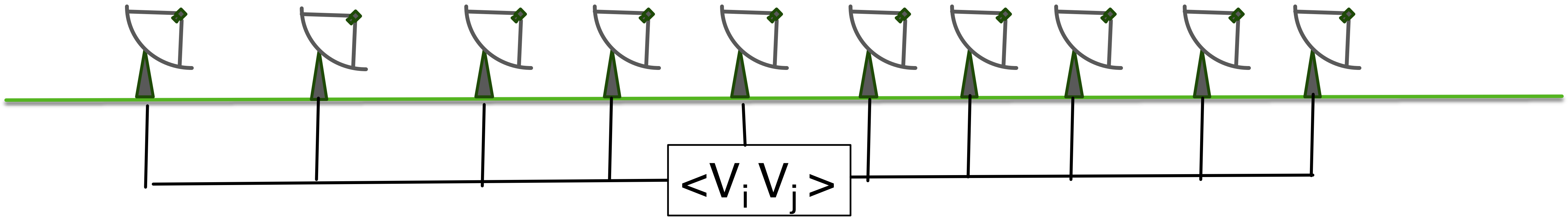
HOW CAN WE DO BETTER ?

Step 3: Put each segment on the ground with its own receiver



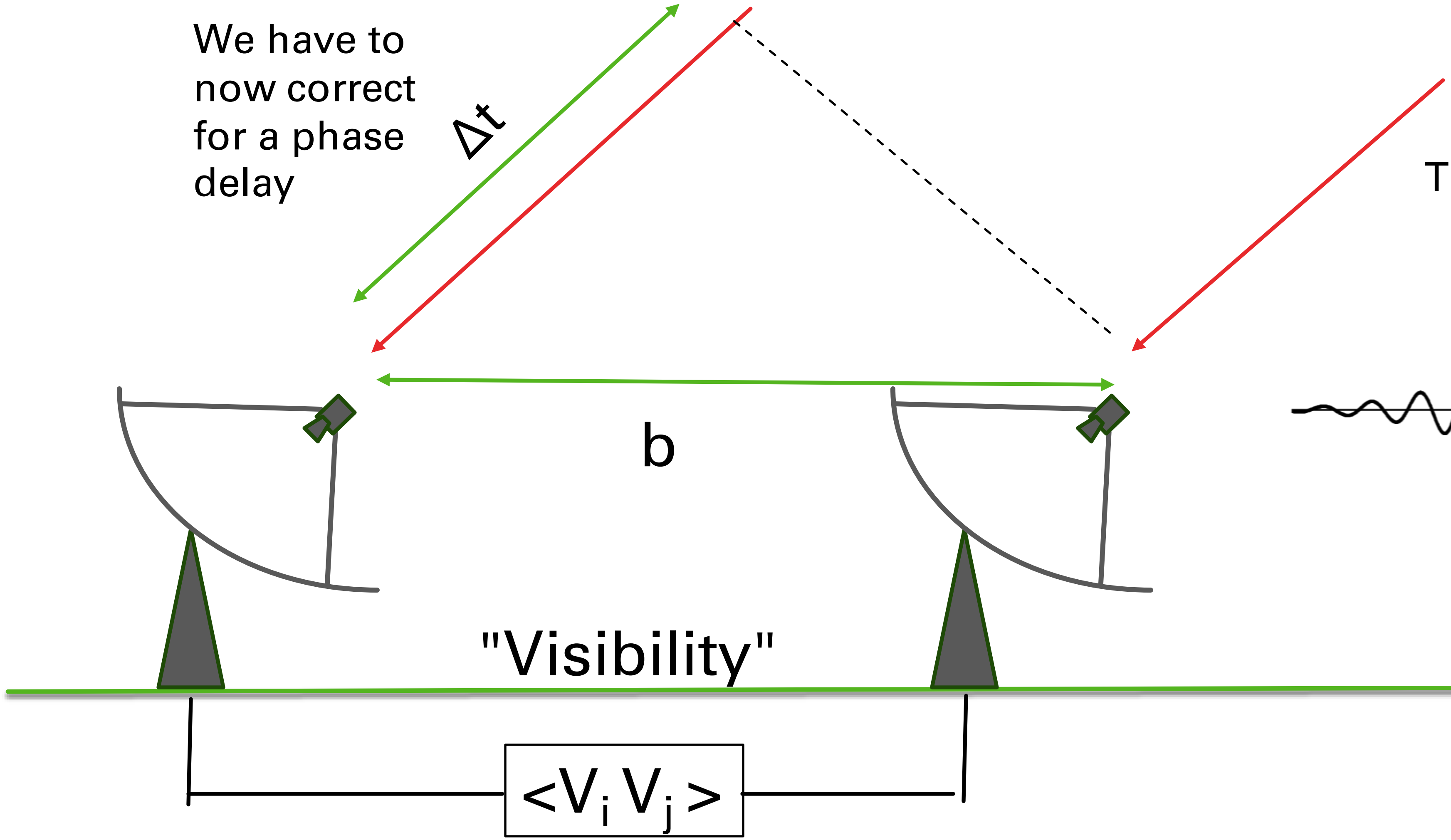
HOW CAN WE DO BETTER ?

Step 4: Hook them up to a correlator

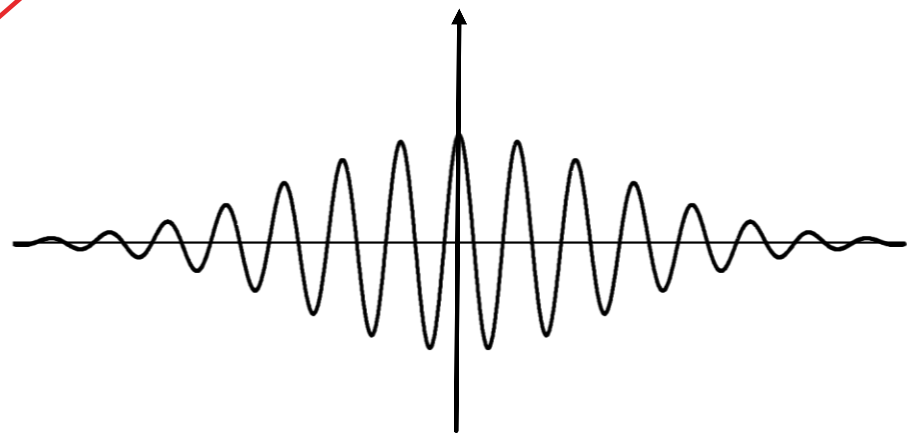


THE RADIO INTERFEROMETER

We have to now correct for a phase delay

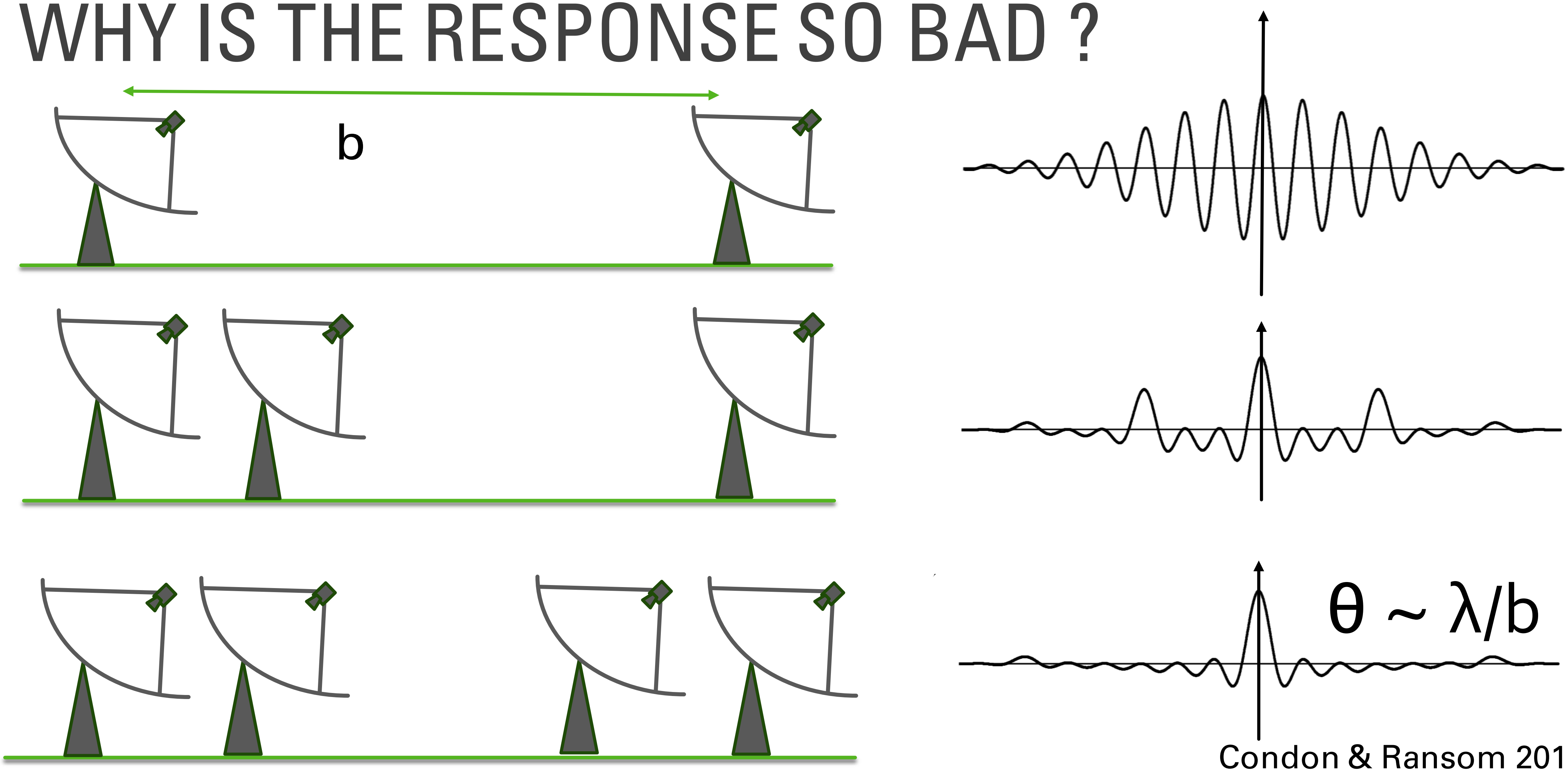


Telescope response



Condon & Ransom 2016

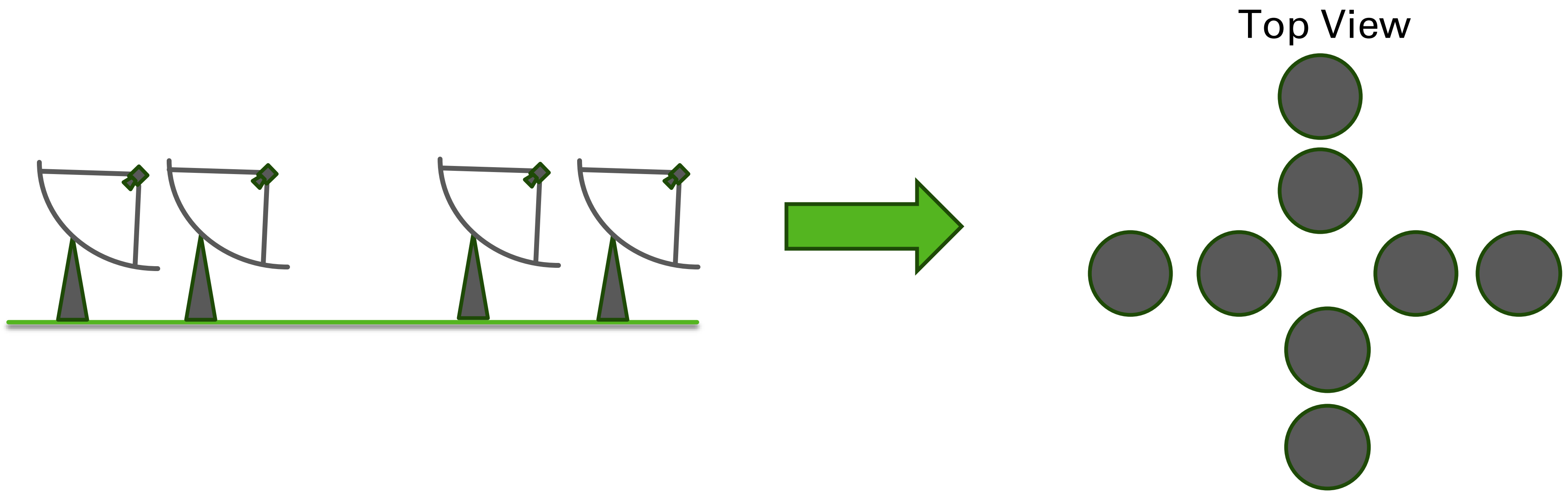
WHY IS THE RESPONSE SO BAD ?



Condon & Ransom 2016

THE VISIBILITY

- Since the visibility is defined for a pair of telescopes it is a function of baseline and it turns out to be the Fourier transform of the on-sky brightness distribution
- Which means that our simple 1D interferometer will only recover structures in 1 direction on the sky so we really need telescopes in all kinds of directions

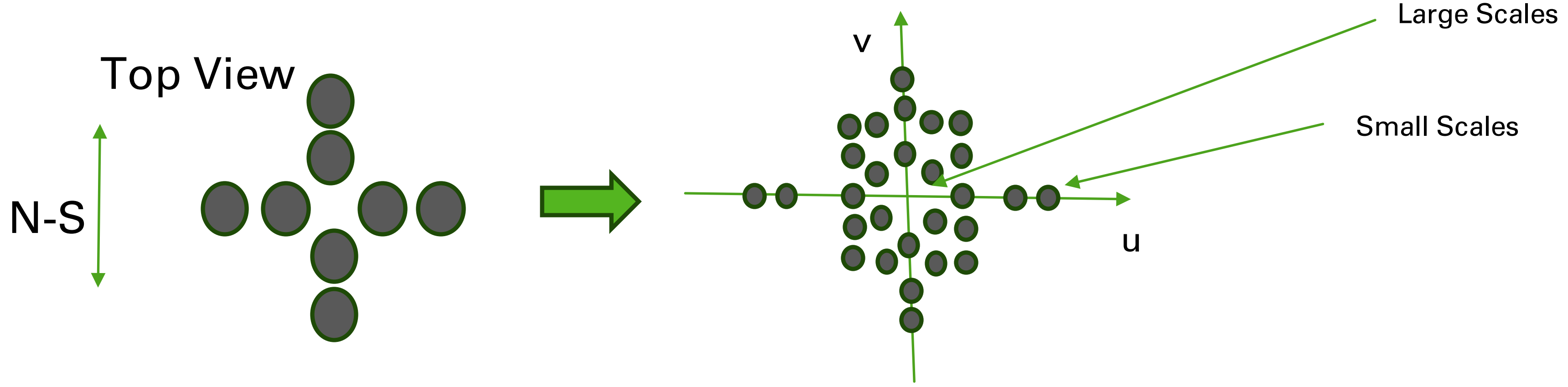


THE VISIBILITY

- So the visibility really is a function of both the North-South (v) and the East-West (u) extent of each baseline in the frame of the sky

$$\mathcal{V}(u,v,w) = \int\int \frac{I_\nu(l,m)}{(1-l^2-m^2)^{1/2}} \exp[-i2\pi(ul+vm+wn)]dl\,dm.$$

- We usually keep track of this in something called a u-v-coverage plot which is also the Fourier plane



THE VISIBILITY

1. Ideally we want to sample the entire uv-space to maximize the amount of structures that we can resolve. Not do we only have a smallest angular scale given by

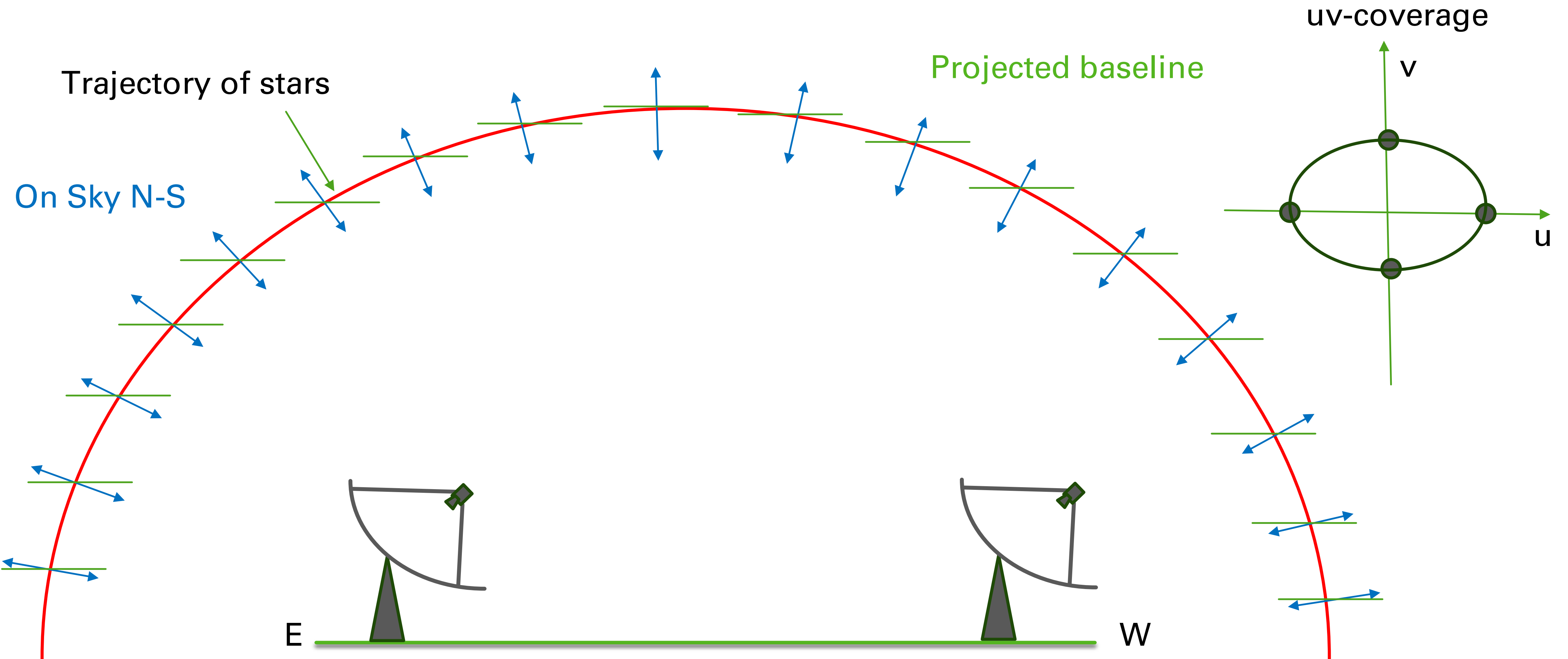
$$\theta \sim \lambda/b_{max}$$

2. We also have a largest angular scale given by

$$\theta \sim \lambda/b_{min}$$

So we want as many telescopes as possible in our array. However, we will never be able to fill the smallest scales because we can't telescopes on top of each other. While we can never fully sample our uv-plane we can improve coverage by using......

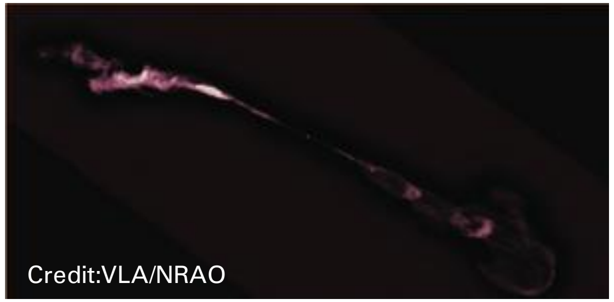
EARTH-ROTATION APERTURE SYNTHESIS (ERAS)



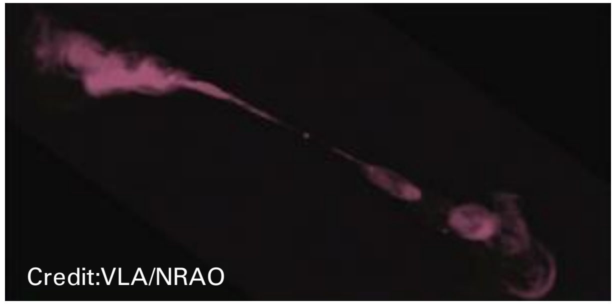
AN EXAMPLE: THE VERY LARGE ARRAY (VLA)

- 27, 25m dishes near Socorro, New Mexico
- Can be arranged in four different configurations
- 1 GHz to 50 GHz

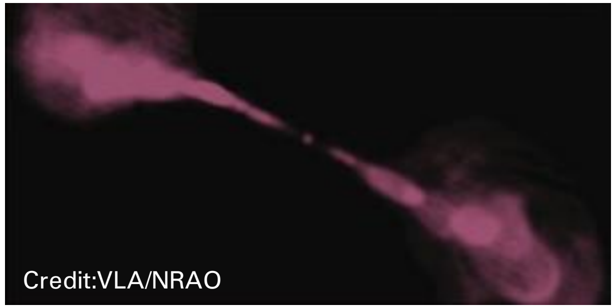
Radio Galaxy Hercules A as seen by the VLA



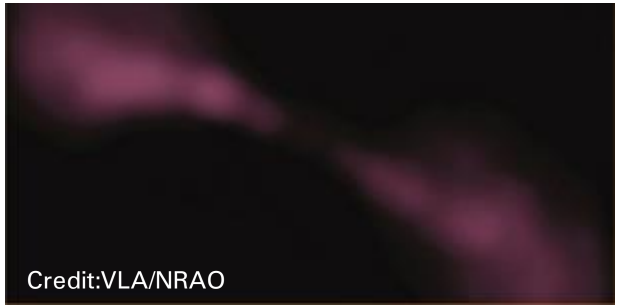
A-Configuration ~35 km array diameter



B-Configuration ~11 km array diameter



C-Configuration ~3 km array diameter



D-Configuration ~1 km array diameter

CAN WE DO BETTER IN RESOLUTION?

Shorter Wavelength/higher frequency

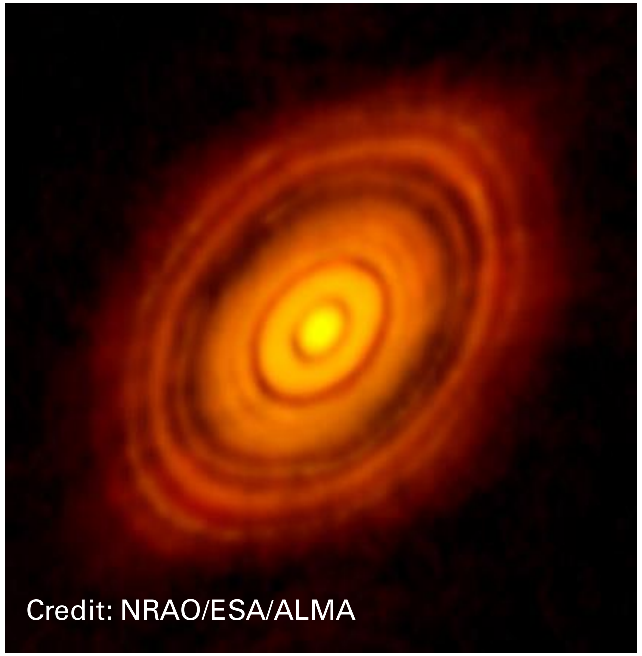
$$\theta \sim \lambda / b_{max}$$

THE ATACAMA LARGE MILLIMETRE ARRAY

High-frequency radio interferometer in the Atacama Desert in Chile

- 50, 12 m and 12, 7m dishes
- 35 GHz to 950 GHz

Protoplanetary disk HL Tau as seen by ALMA with 35 mas resolution



This is the equivalent of resolving a penny at a distance of 120 km

CAN WE DO BETTER IN RESOLUTION?

Longer baseline

$$\theta \sim \lambda / b_{max}$$

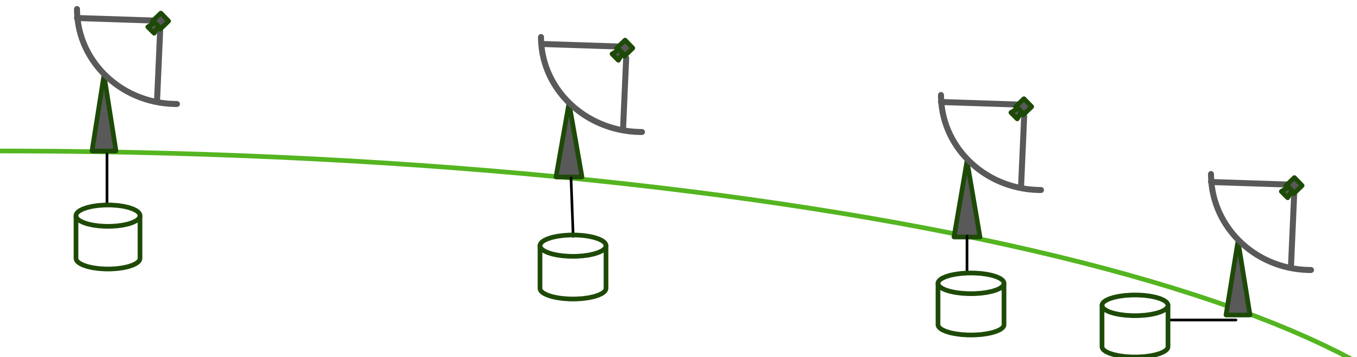
VERY LONG BASELINE INTERFEROMETRY (VLBI)

- Baselines of several hundreds to thousands of kilometres

- First Challenge: we have to correlate the data after the fact and have to record raw wave-forms --> Lots of data !!!!

- Second Challenge: Low uv-coverage

- Third Challenge: Synchronization/Timing



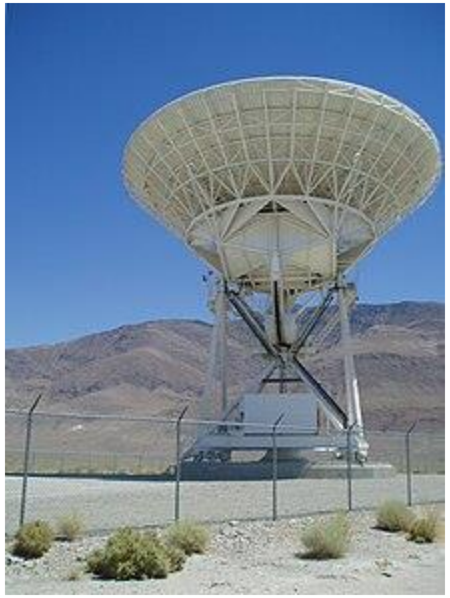
FIRST VLBI IN CANADA, 1967

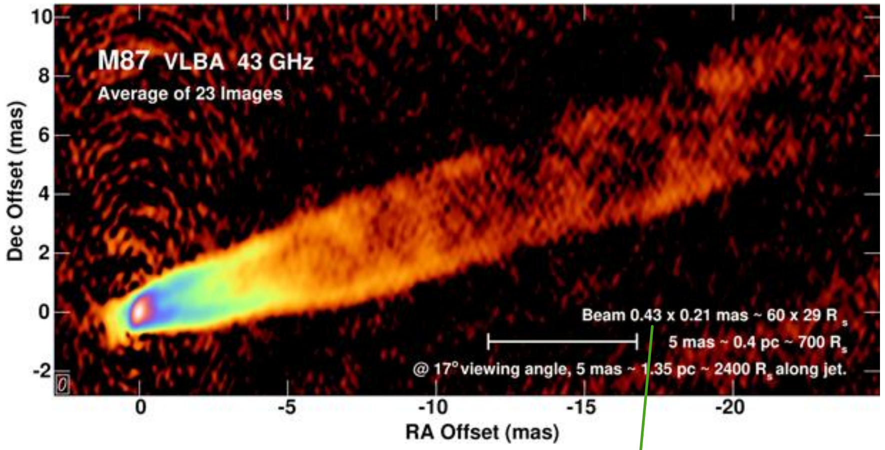
Galt 26 m Telescope, Penticton, BC

Algonquin 43 m Telescope, Algonquin Provincial Park, ON

First Successful attempt at VLBI in 1967 with a 3074 km baseline at 448 MHz

AN EXAMPLE: THE VERY LONG BASELINE ARRAY





Walker+ 2018

- 10, 25 m telescopes spread across the United States with baselines up to 8,611 km
- 300 MHz- 90 GHz

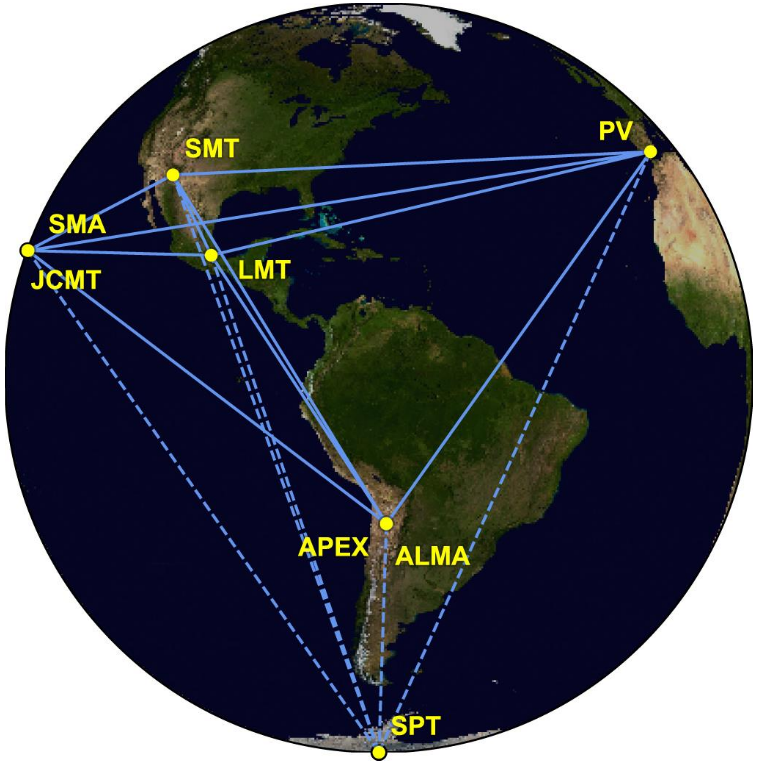
This is about 100 times the resolution of the HL Tau ALMA image with a frequency about three times as low

CAN WE DO BETTER IN RESOLUTION?

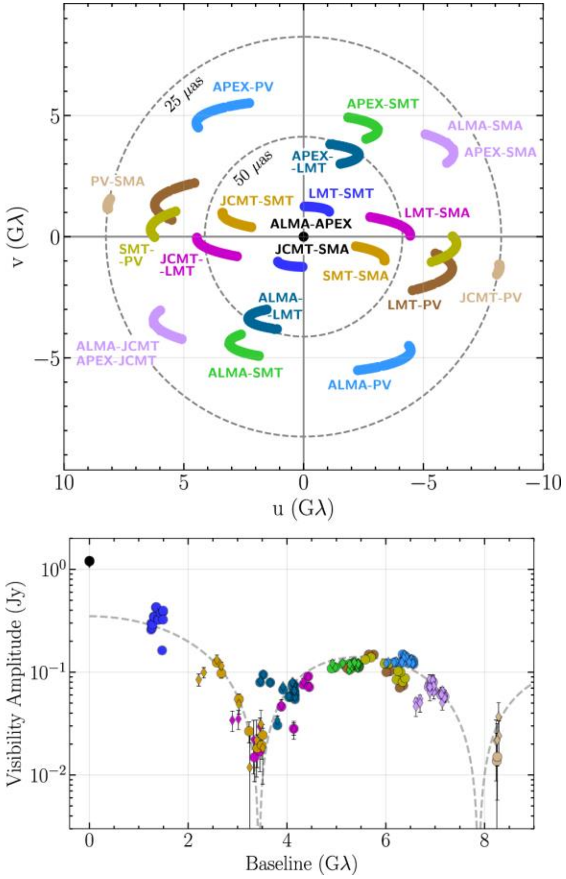
Shorter Wavelength/higher frequency

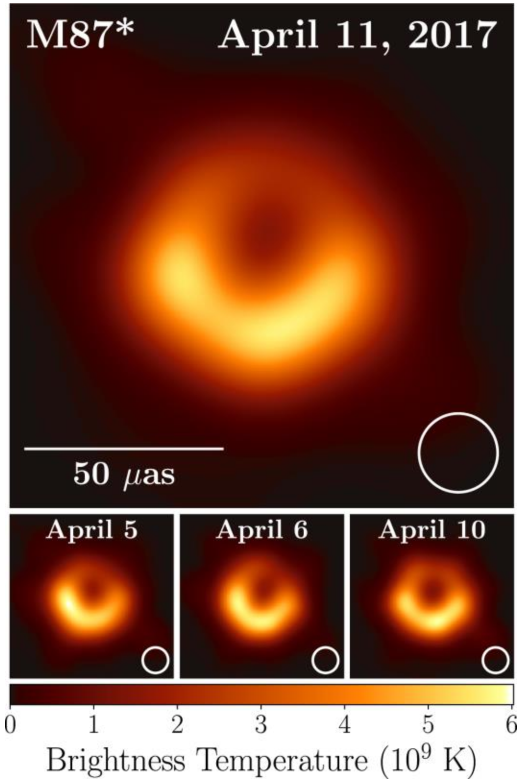
$$\theta \sim \lambda/b_{max}$$

THE EVENT HORIZON TELESCOPE



8 Telescopes observing the black hole at the center of M87 at 230 GHz with 25 microarcsecond resolution





This resolution is about 10 times higher than the VLBA image of M87 by Walker et al.

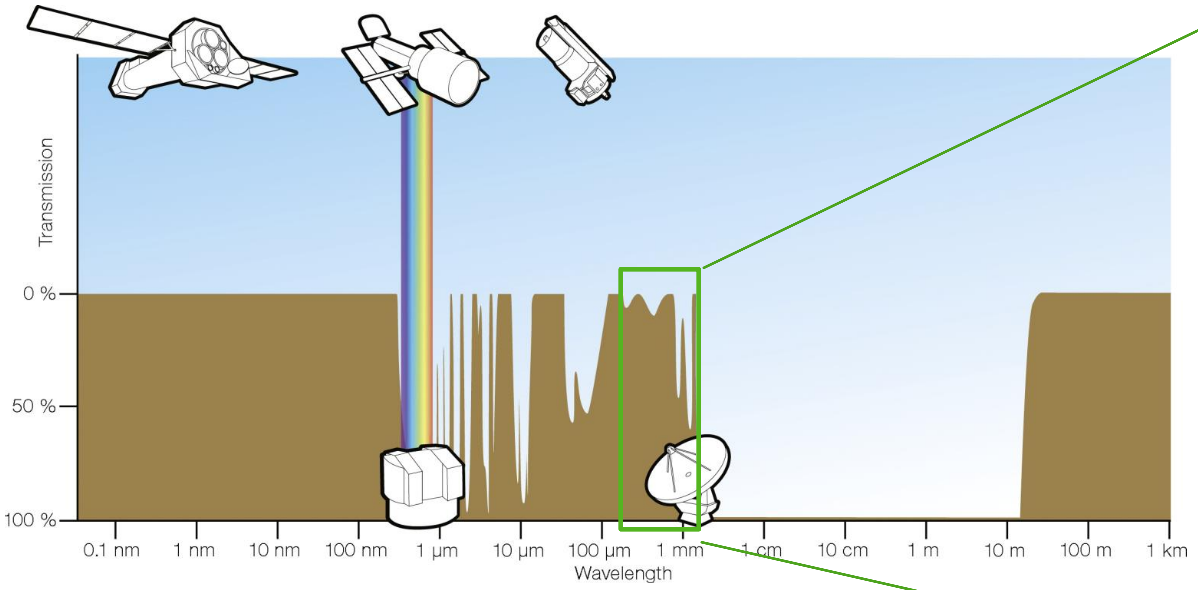
CAN WE DO BETTER IN RESOLUTION?

$$\theta \sim \lambda/b_{max}$$

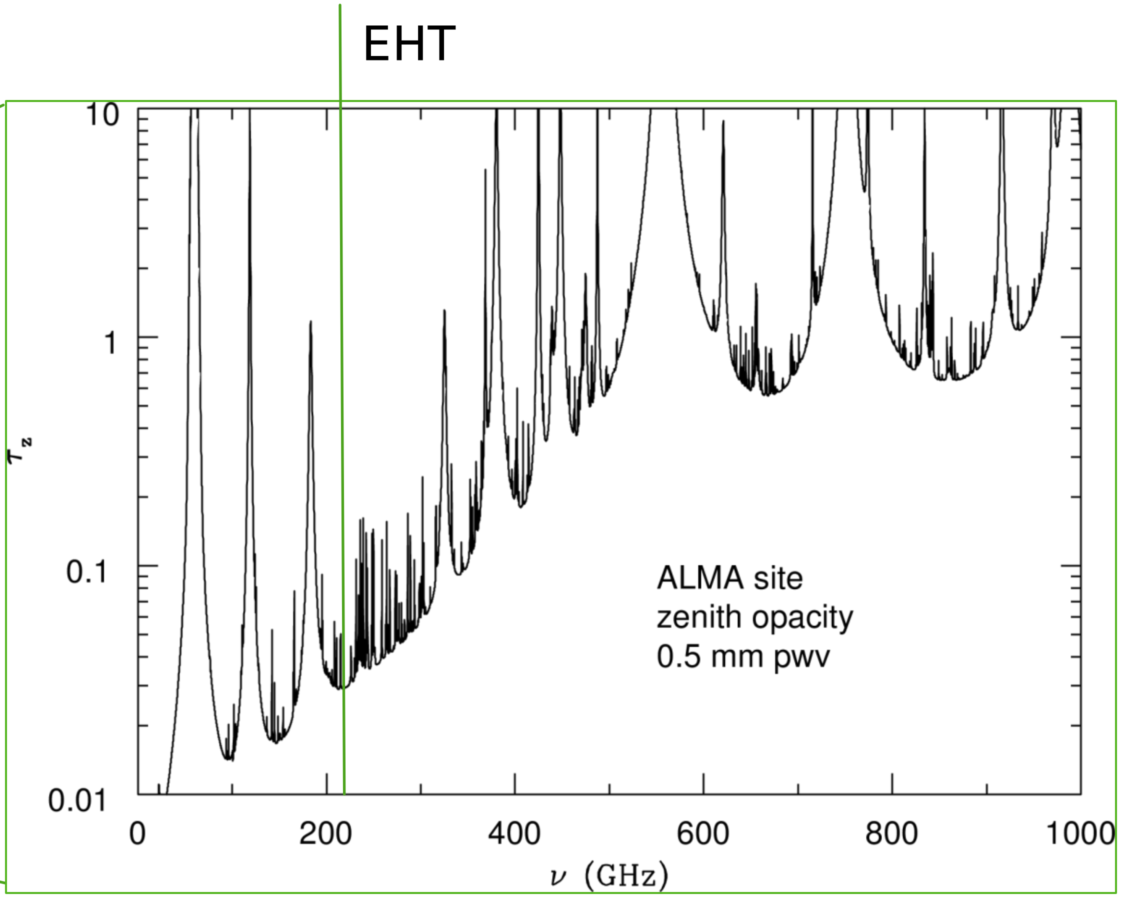
We can't really make the baseline any bigger without going into space (Really expensive)

But we could try to push to higher frequencies....

HIGHER FREQUENCIES ARE TRICKY



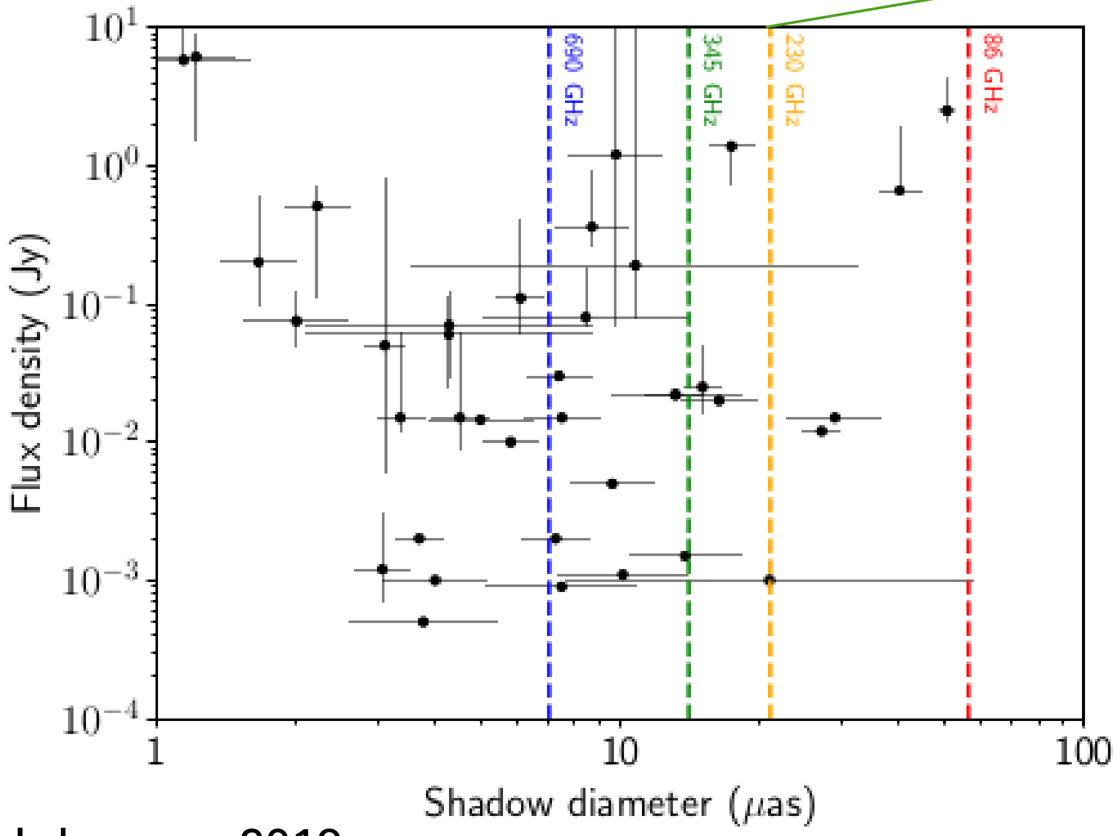
Credit: ESA/Hubble (F. Granato)



Credit: Condon and Ransom 2016/
https://almascience.eso.org/about-alma/weather/atmosphere-model

HOW MUCH BETTER COULD WE DO ?

EHT

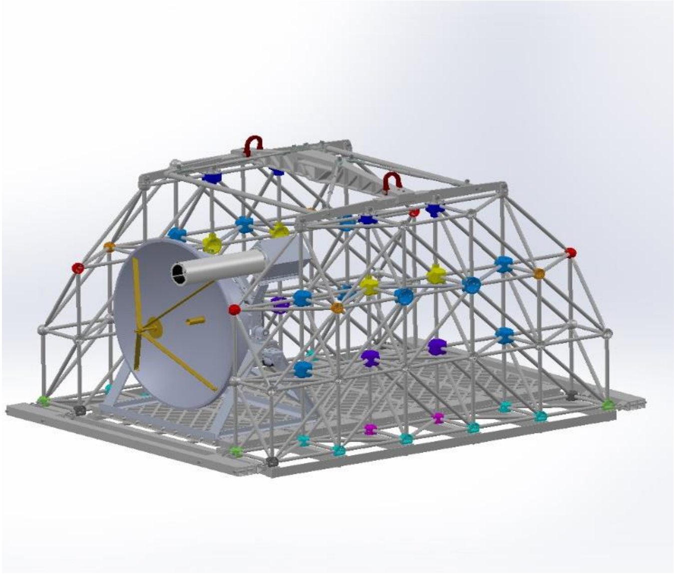


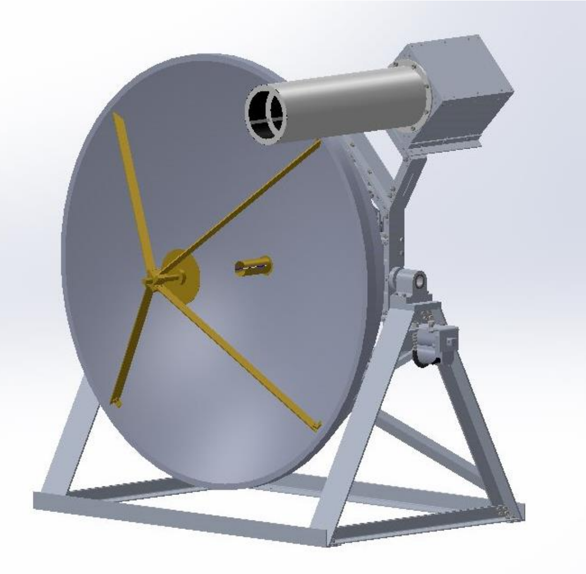
Johnson+ 2019

It looks like we can really do better however the atmosphere remains a problem, so there are two options:

1. Space-VLBI (Expensive!!!)
2. Balloon-borne-VLBI which operates above 99.5 % of the atmosphere (Tricky but might be doable)

THE BALLOON-BORNE VLBI EXPERIMENT (BVEX)





- Balloon-borne VLBI station prototype operating at K-band (22GHz) will launch from Timmins in the Summer of 2025
- BVEX will NOT:
  - Give us higher resolution
- BVEX will:
  - Give us more uv-coverage
  - Help us develop technologies required to do mm and sub-mm VLBI

COLLABORATORS

Collaborators:

Laura Fissel (PI, Queen's University)

Vincent Fish (MIT/Haystack)

Michael Johnson (SAO/CfA)

Lindy Blackburn (SAO/CfA)

Daryl Haggard (McGill University)

Adrian Sinclair (NRC-Herzberg)

Javier Romualdez (StarSpec Technologies)

Grad Students:

Mayukh Bagchi (Queen's University)

Felix Thiel (Queen's University)

Maggie Oxford (Queen's University)

Current and Past Undergrads:

Jess Lo (Queen's University)

Emily Butler (Queen's University)

Bonnie Slocombe (Queen's University)

Thomas Emo (Queen's University)

Jade Yeung (Queen's University)

Jake Devlin (Queen's University)

Willson Bonney (Queen's University)

Peter Simpson (Queen's University)

Amna Hasnain (Queen's University)

Funding : CSA FAST program

THE EASY PART: BUILDING THE TELESCOPE

The Telescope

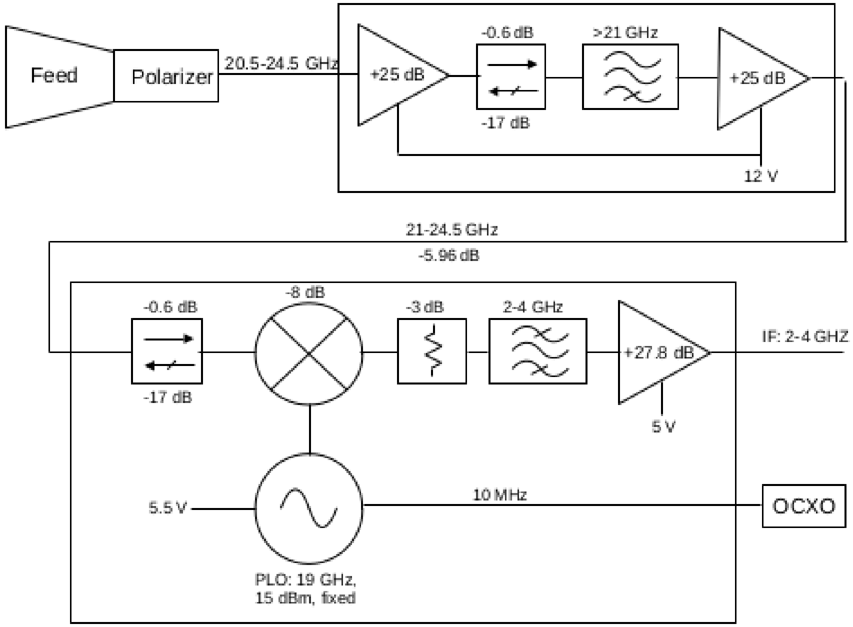
Felix Thiel

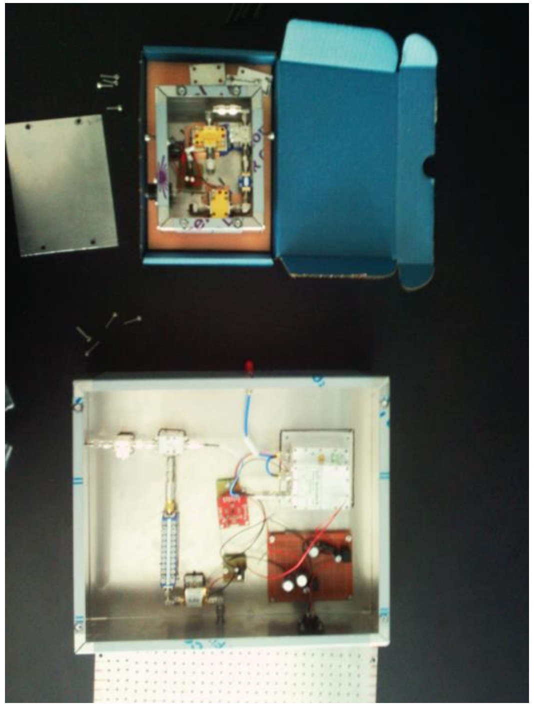
Mayukh Bagchi

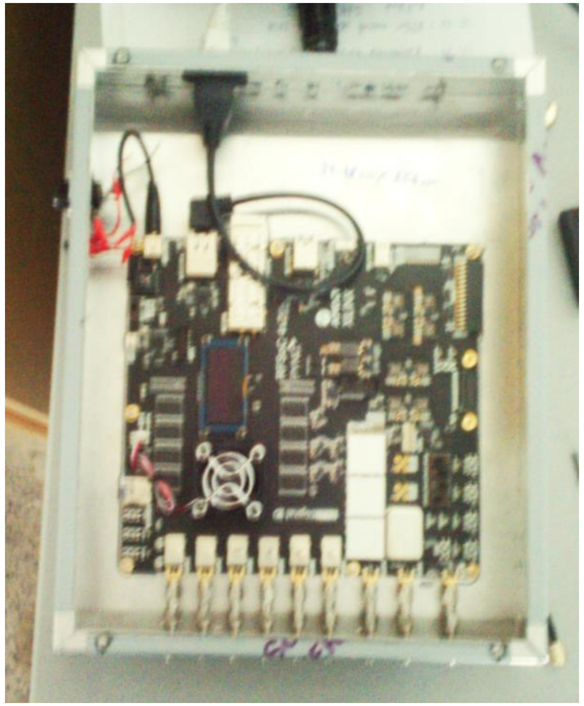
Bonnie Slocombe

THE EASY PART: BUILDING THE TELESCOPE

The Receiver and Backend



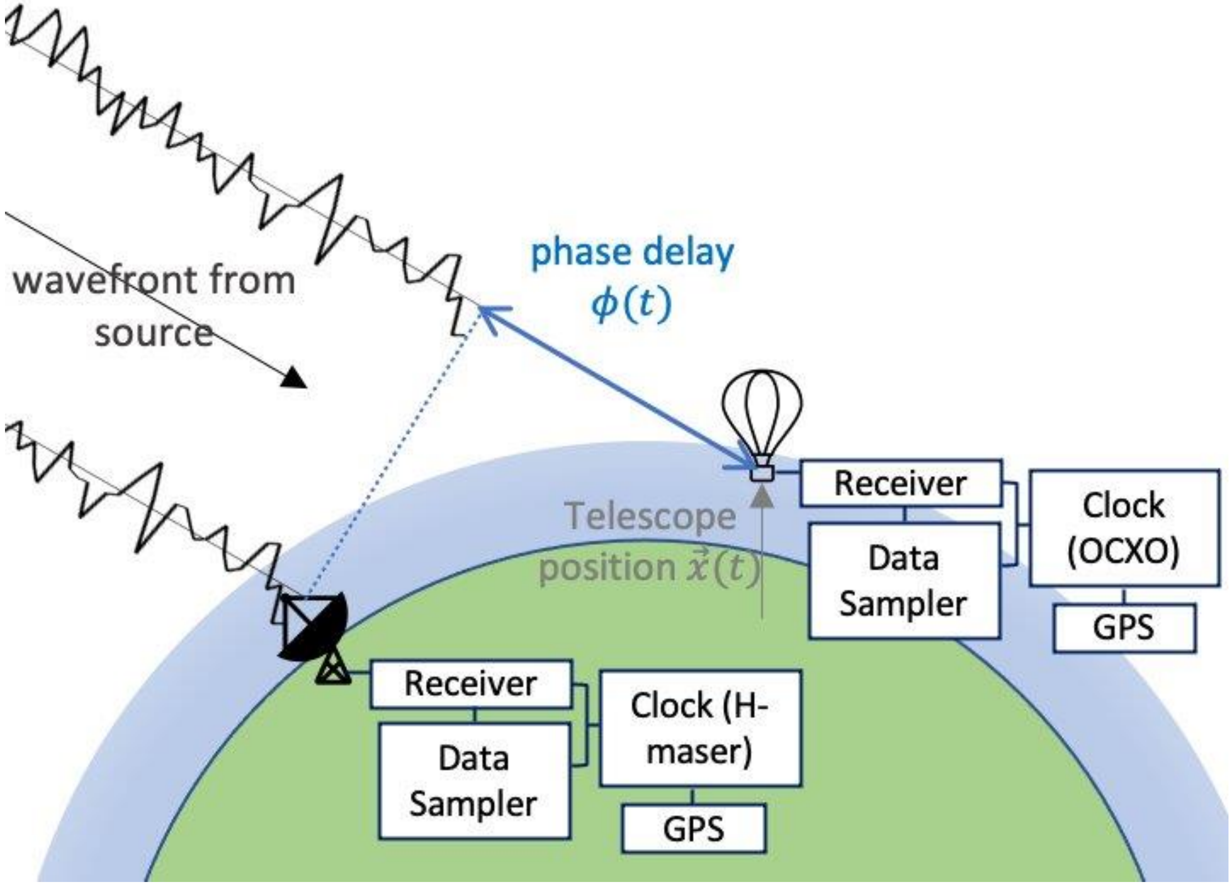




Felix Thiel

Mayukh Bagchi

TECHNICAL CHALLENGES



- To do interferometry we need to adjust for phase offsets
- We need to precisely know:
  - When a signal was recorded
  - Where a signal was recorded

POSITION TRACKING

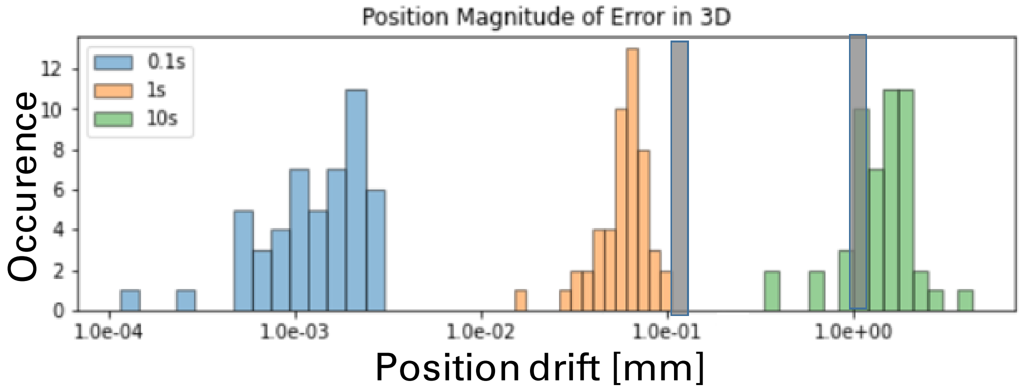
- Because the balloon won't be stationary we have to measure the position at every step of the way to a precision

$$\sim\lambda/10$$

- So at K-Band (22 GHz / 1.3 cm) we need ~1 mm, at 230 GHz/1.3mm we need 0.1 mm precision over the correlation time of ~1s
- The general idea: Use the GPS to get an absolute value, then use integrated accelerometer values to track the offsets
- Some lab tests done by undergrad Jess Lo:

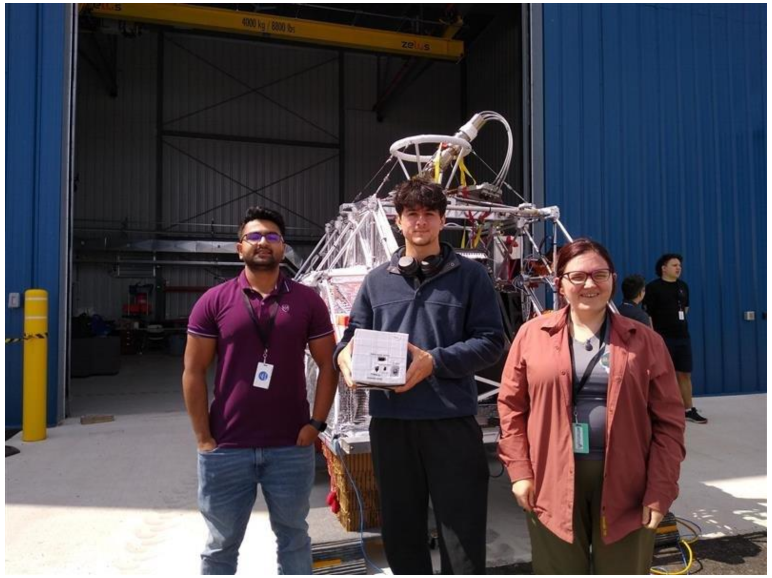
Jess Lo

Lab tests with a stationary 20-bit, +/-2 g ADXL355Z accelerometer sampling at 250 Hz

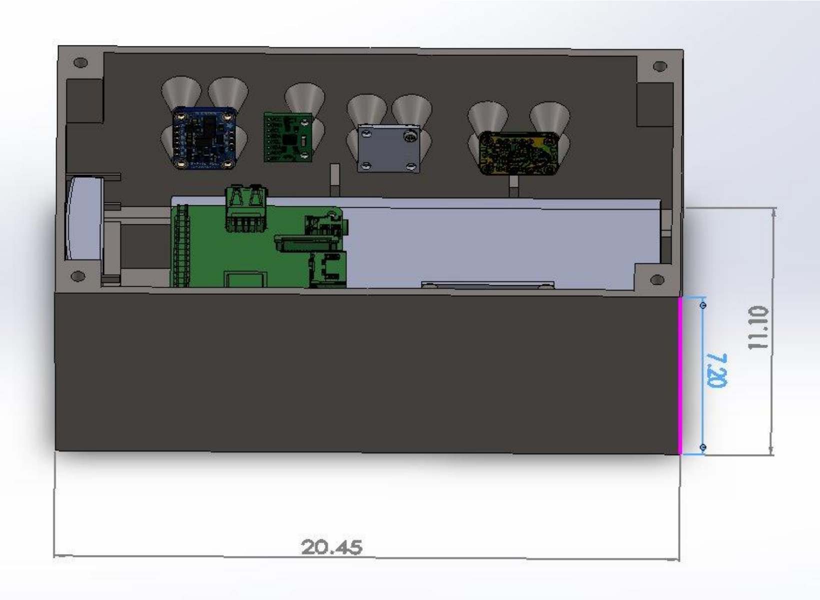


BVEXTRACKER

- While Jess's results were promising, we need demonstrate this on a balloon so we flew BVEXTracker an experiment only consisting of sensors during the summer of 2023
- The analysis is in progress so stay tuned!



BVEXTracker campaign team from Queen's University: Mayukh Bagchi, Thomas Emo (Mechanical Design), and Laura Fissel (PI)



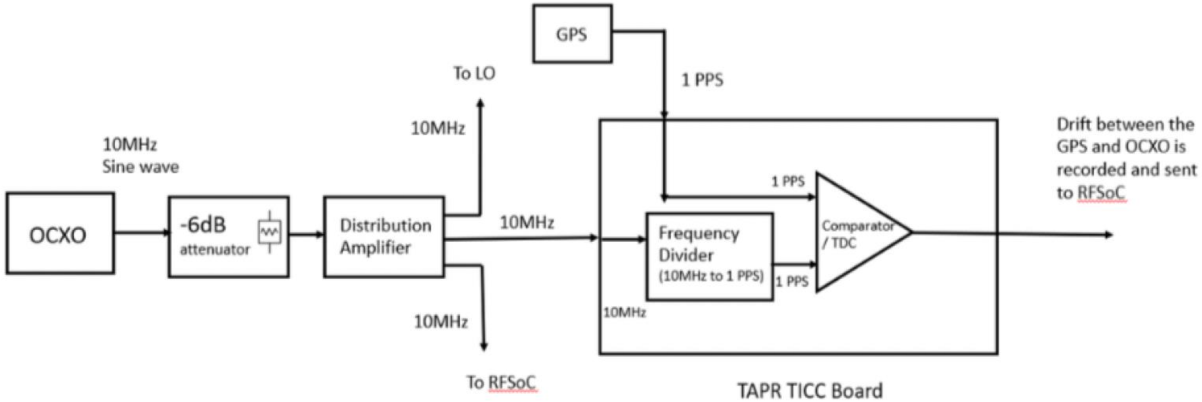
Sensor package including a gyroscope, accelerometer, magnetometer, IMU, GPS all read out by a Raspberry PI

TIMING STABILITY

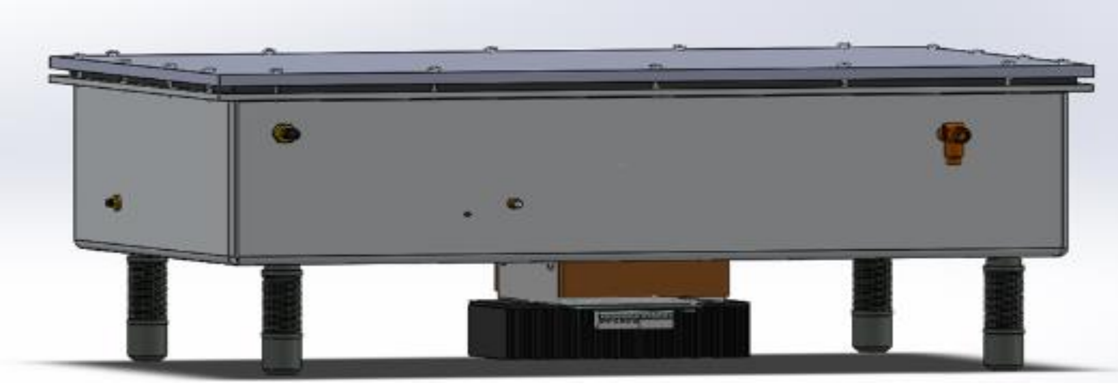
- Typically radio observatories use extremely precise hydrogen maser clocks, the problem is they are too big to fly on a balloon
- We will therefore fly an oven-controlled-crystal oscillator (OCXO)
- However the problem here is that the gondola vibrates, but also the pressure and temperature are not constant
- The Solution: Design a pressure vessel that will have the temperature controlled to ~0.1 K


Maggie Oxford


Mayukh Bagchi



The Timing Chain


Early iteration of the pressure vessel design

VALUABLE LESSONS FOR FUTURE BVEX MISSIONS

1. BVEX will (hopefully) demonstrate that we can do VLBI from the stratosphere making it a cost-effective alternative to space VLBI
2. While BVEX will not give us more resolution it will help us improve the uv-coverage of existing VLBI networks such as the VLBA
3. BVEX will also help us develop the technology and software requirement for future mm and sub-mm VLBI
4. Future high-frequency iterations of this experiment will help improve the resolution and sensitivity of black hole observations as well as

QUESTIONS ?