# ALMA Capturing

## How dœs the Atacama Large Millimeter Array telescope capture photons?

Martin Tournebœuf

Dreamlab Technologies

1st March 2024

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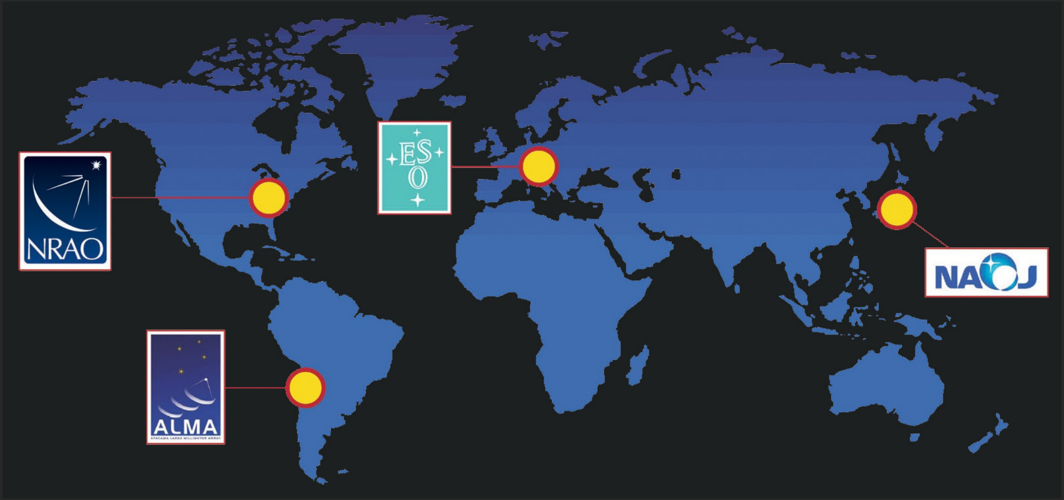
# Collaboration




Credit: ARCS

# Geolocation

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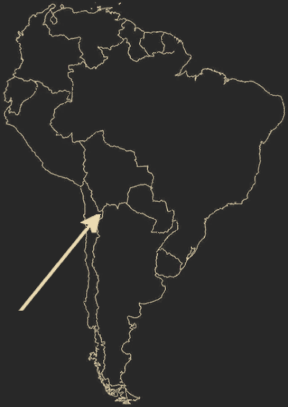

# Geolocation

1. Safety
2. Altitude
3. Humidity
4. Latitude
5. Turbulences
6. Accessibility

| | |
|---|---|
| Altitude | 5000m |
| Antenna | 66 |
| Wavelength | 1mm |
| Frequency | 300GHz |
| Water (WVP) | 1mm |
| Temperature | -269°C |

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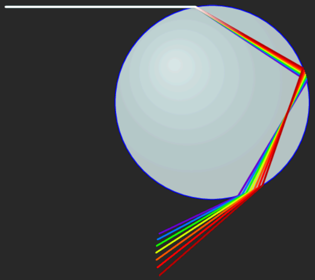

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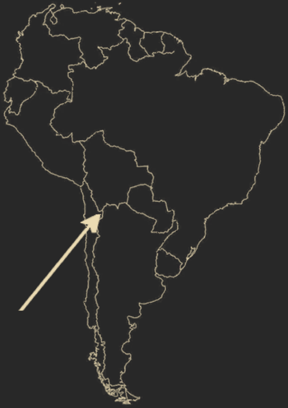

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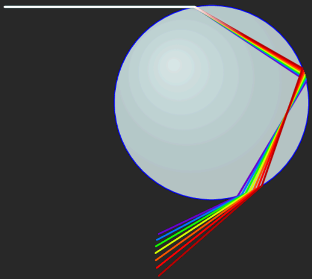

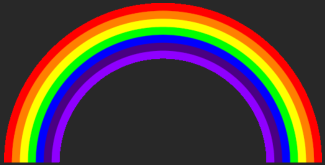

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**Takeaway**

Water + Light = Rainbow

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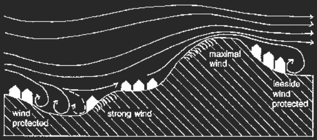


Credit: Walkato university

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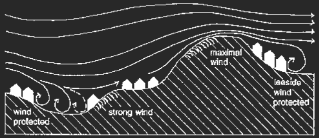


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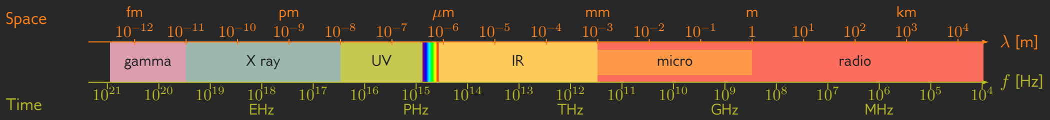

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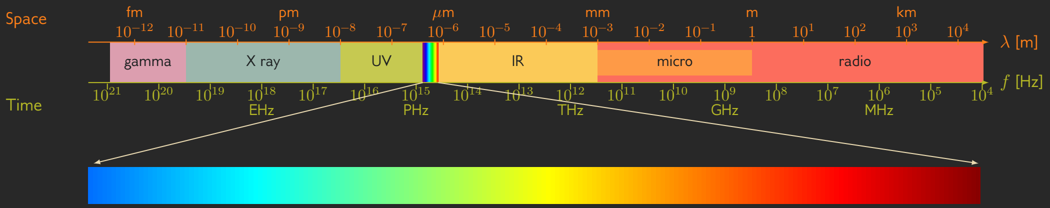

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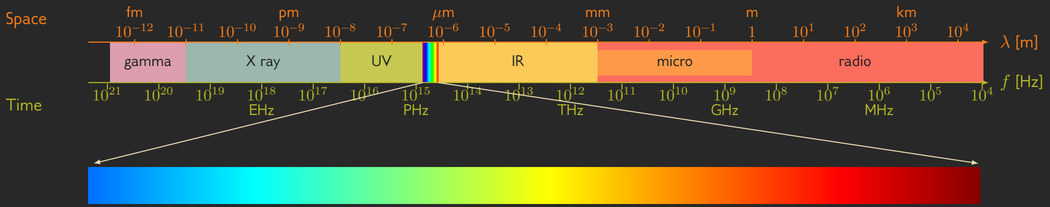
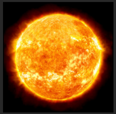
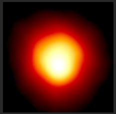



Sirius

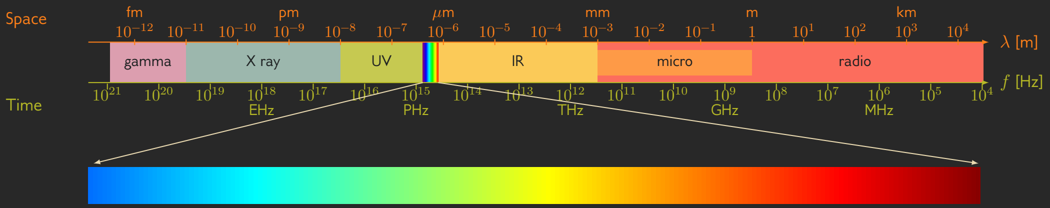


Sun



Betelgueuse

# Electrolocation

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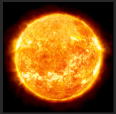

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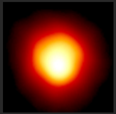
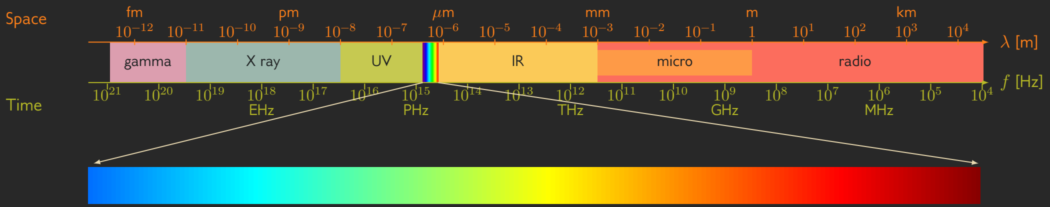


Betelgueuse

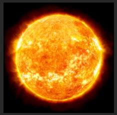
Look at the stars
Look how they shine for you
And everything you do
Yeah, they were all yellow

Anticredit: Coldplay (2000)

# Electrolocation




Sirius



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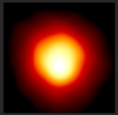
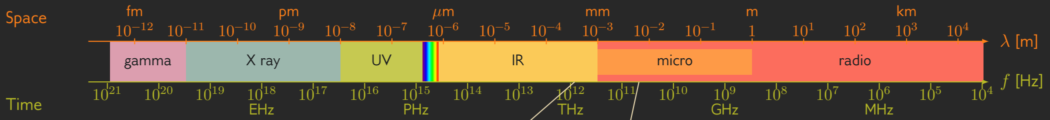


Betelgueuse

Look at the stars
Look how they shine for you
And everything you do
Yeah, they were all yellow

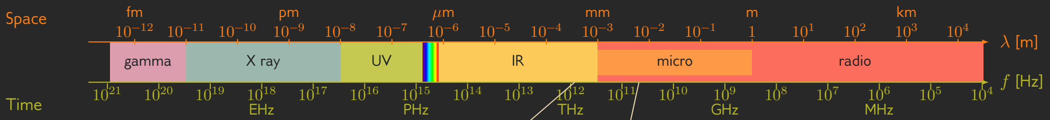
Your eye evolved to see the sun
Stars have different colors

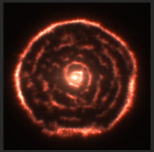
# Electrolocation




ALMA (telescope)

# Electrolocation

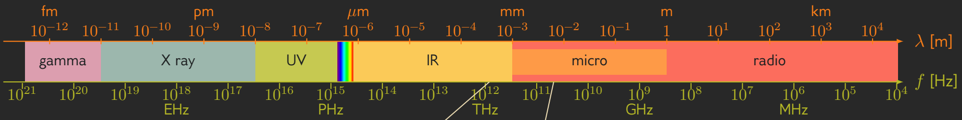


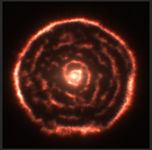



R Sculptoris (star)

ALMA (telescope)

# Electrolocation

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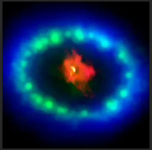
Sn1987a (star)

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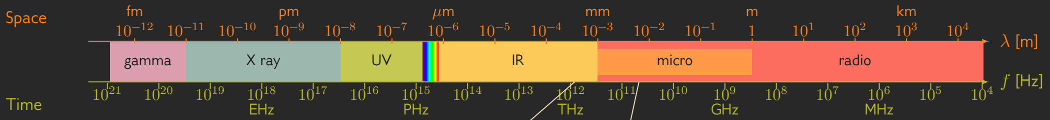


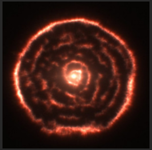
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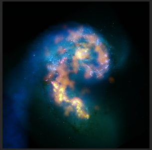
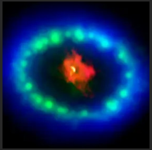

Ngc 4038/4039 (galaxy)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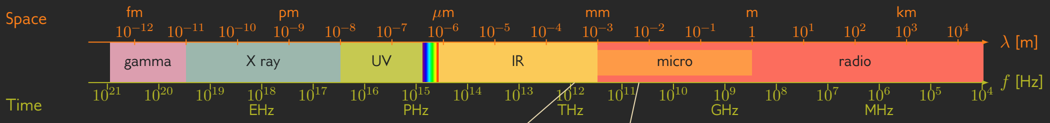


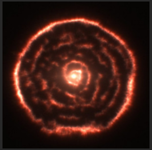
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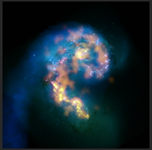
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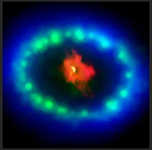
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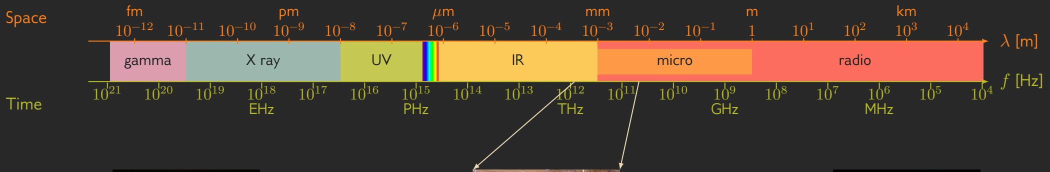


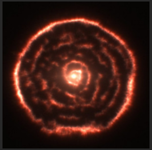

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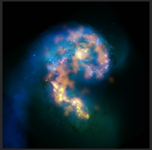

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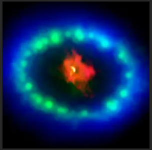

Sn1987a (star)

M87* (black hole)

Hercules a (galaxy)

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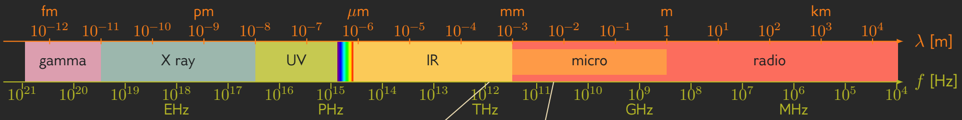
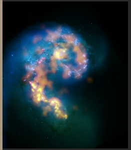



## Takeaway

ALMA is capturing **millimeter** wavelength
(or **300 GHz** = 300,000,000[m/s] / 0.001[m])

R Sculptoris (star)

ALMA (telescope)



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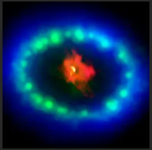

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Hercules a (galaxy)

# Pipeline


## The radio waves is ...

- Emited by the source

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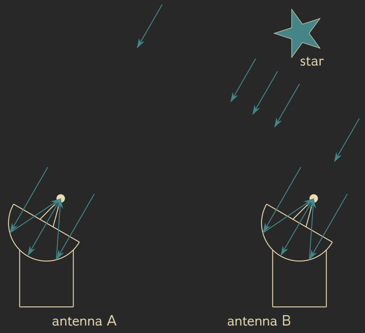
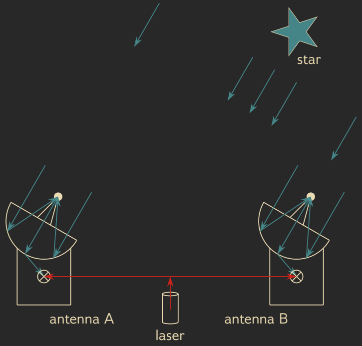



## The radio waves is ...

- Emited by the source
- Concentrated by the antenna
  convex reflector

# Pipeline




## The radio waves is ...

- Emited by the source
- Concentrated by the antenna convex reflector
- Downconverted and digitalised by mixing with the central laser frequency

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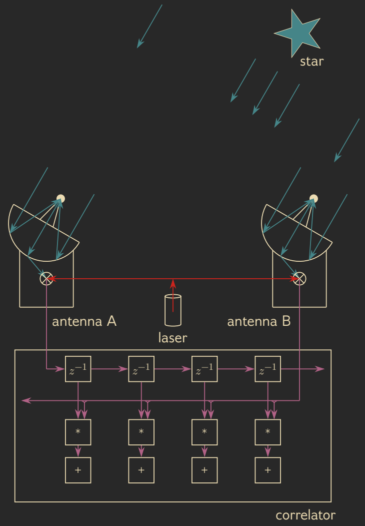


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- Concentrated by the antenna convex reflector
- Downconverted and digitalised by mixing with the central laser frequency
- Correlated to other antenna measurement

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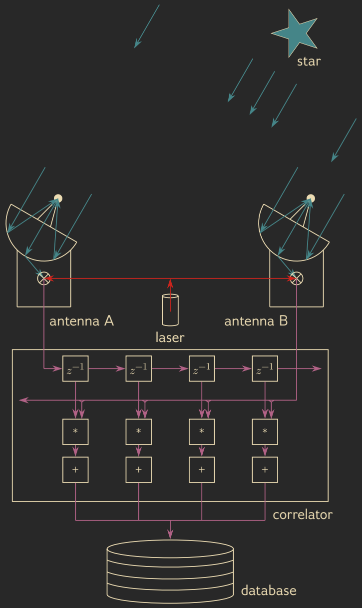
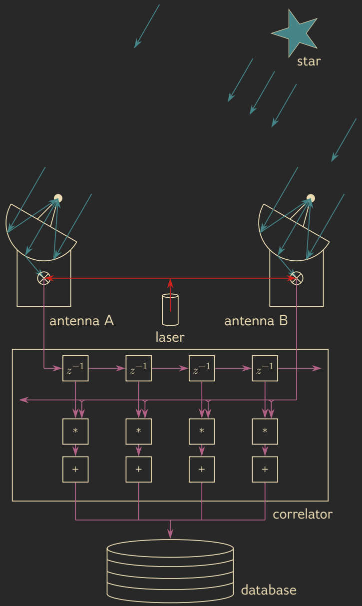
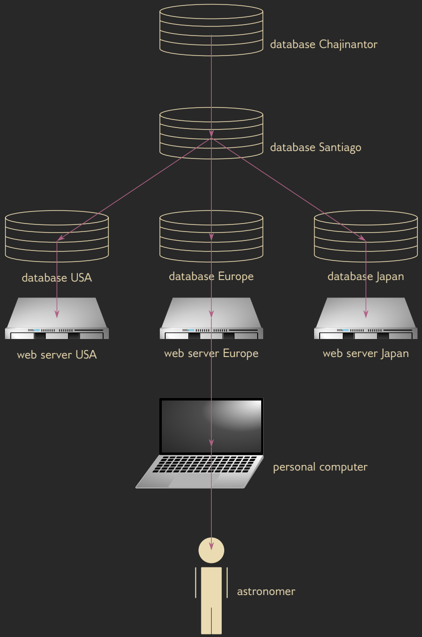



## The radio waves is ...

- Emited by the source
- Concentrated by the antenna convex reflector
- Downconverted and digitalised by mixing with the central laser frequency
- Correlated to other antenna measurement
- Stored in a digital database

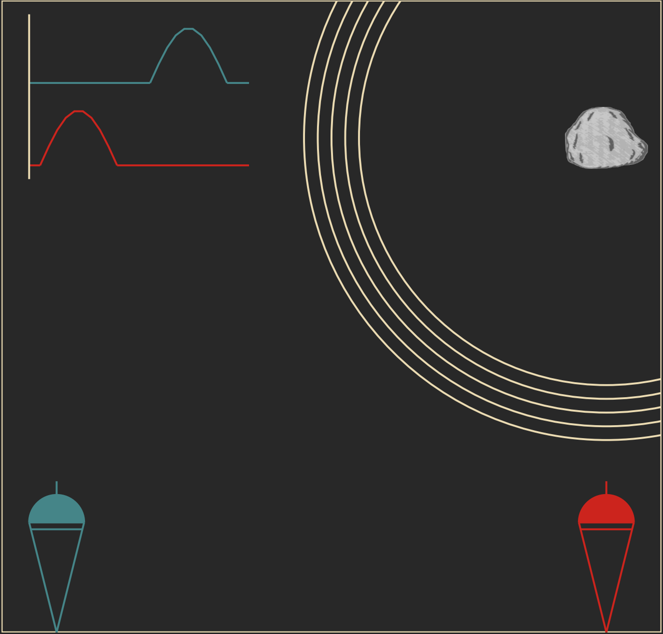
# Pipeline


star
antenna A
antenna B
laser
$z^{-1}$
$z^{-1}$
$z^{-1}$
$z^{-1}$
*
+
correlator
database


database Chajinantor
database Santiago
database USA
database Europe
database Japan
web server USA
web server Europe
web server Japan
personal computer
astronomer

# 2/ Example





# Emission

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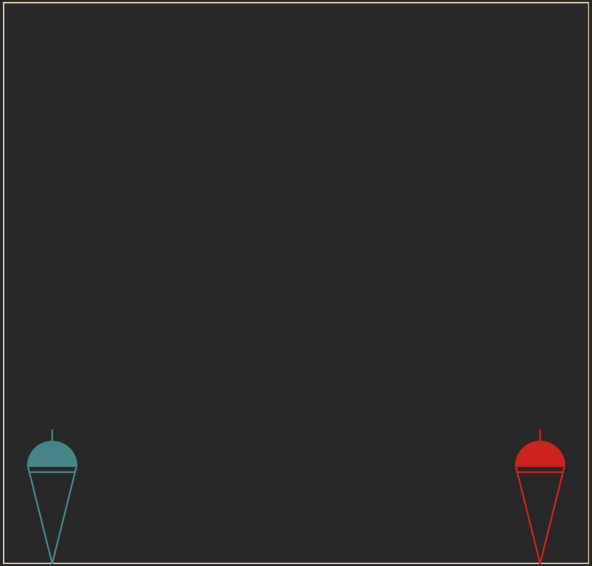

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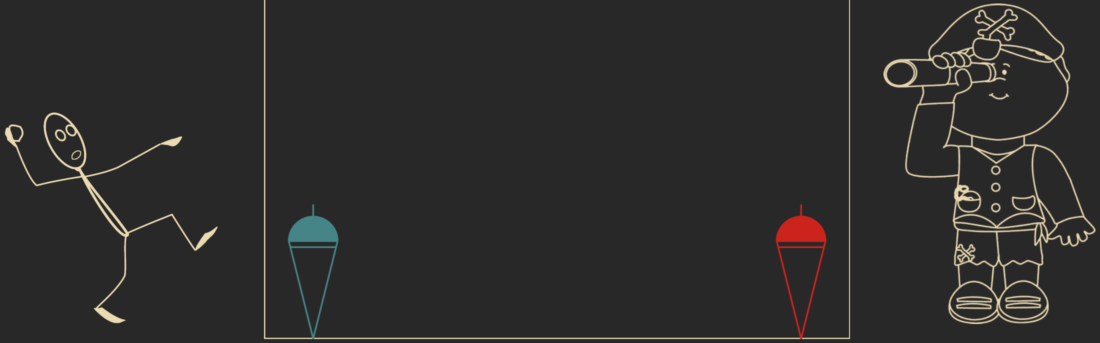

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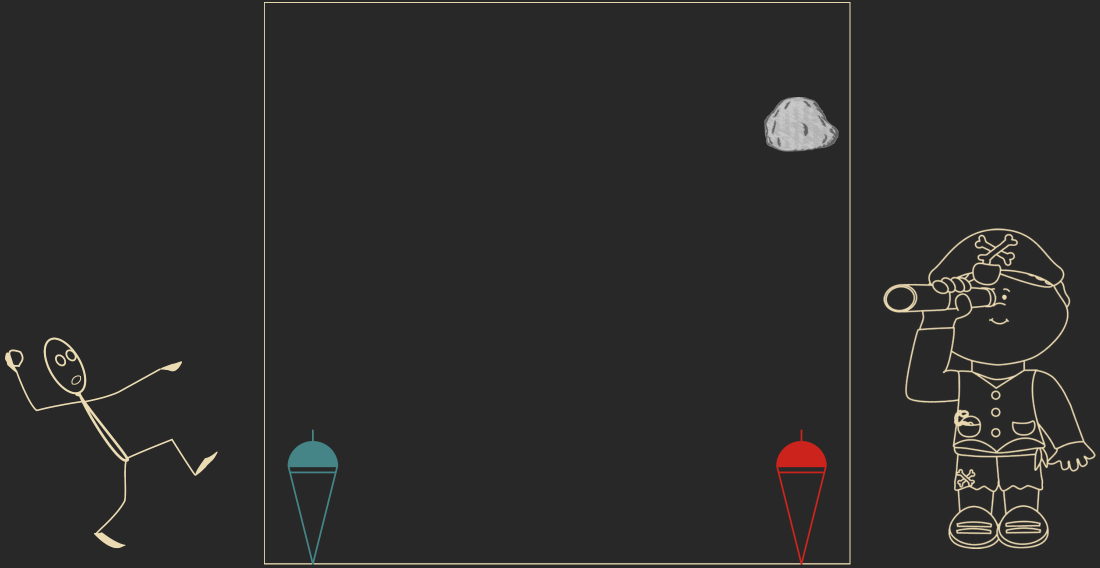

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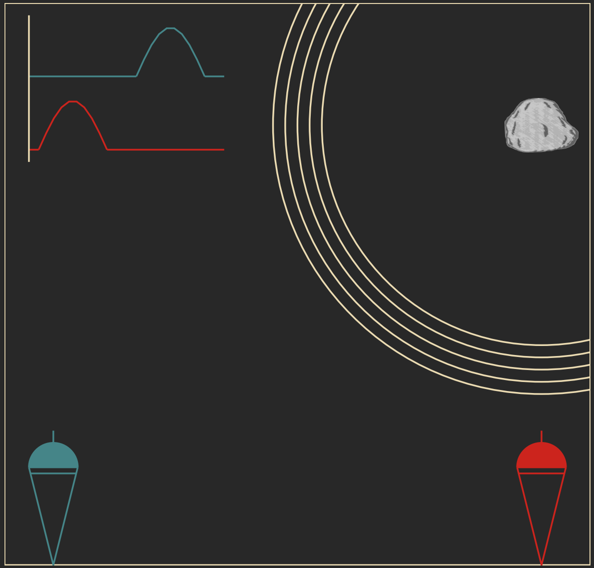
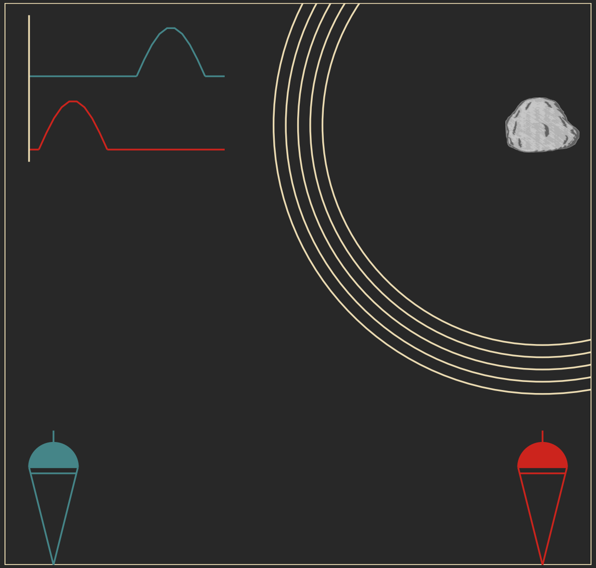
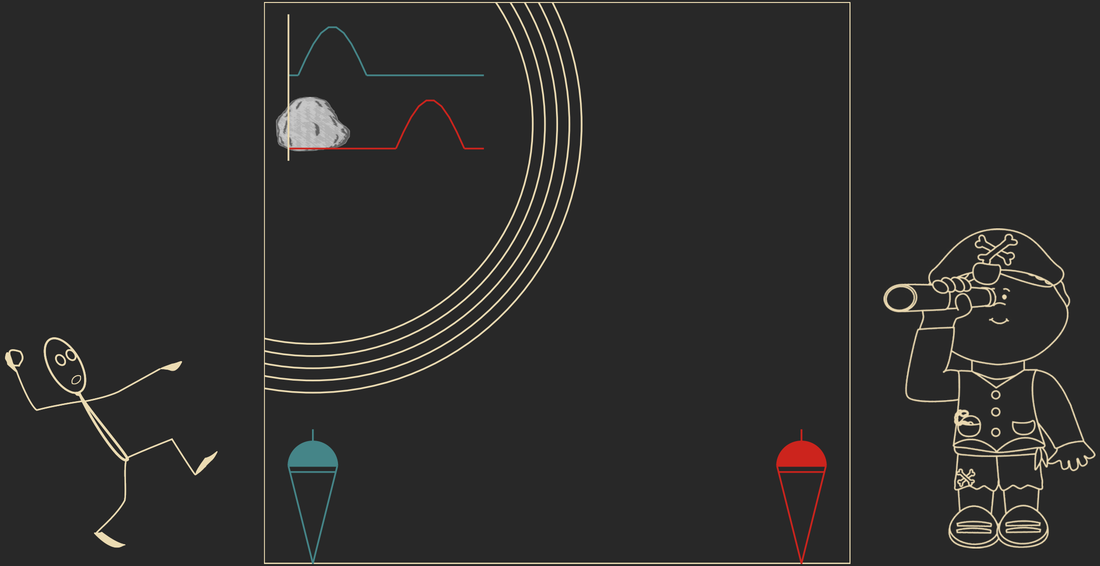


# Propragation



# Reception



Credit: Joseph Fourier 1822

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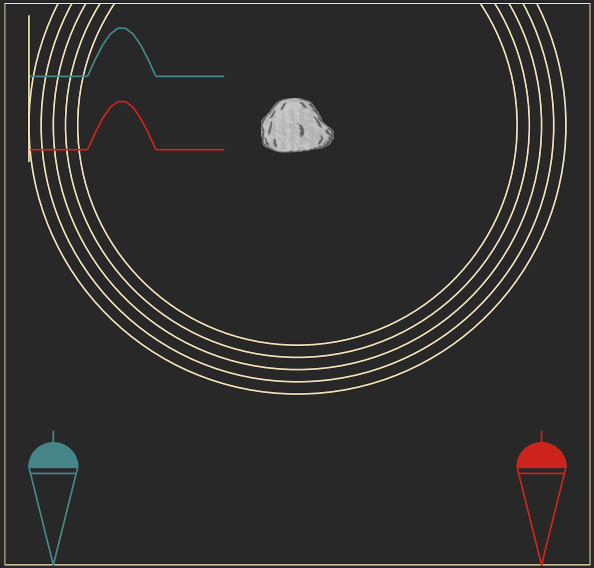

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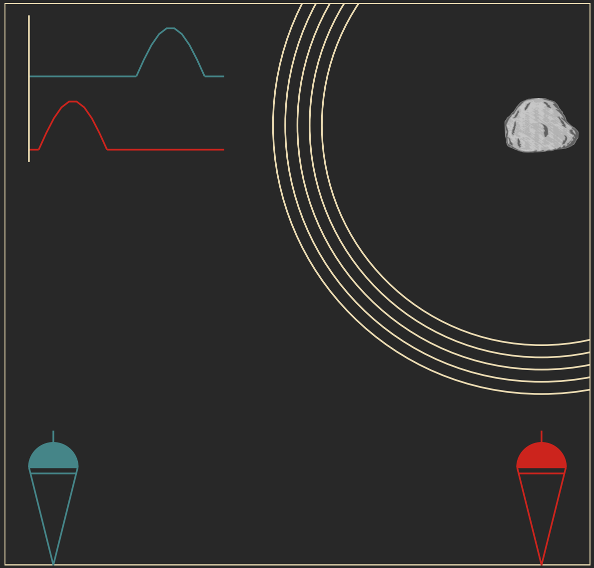

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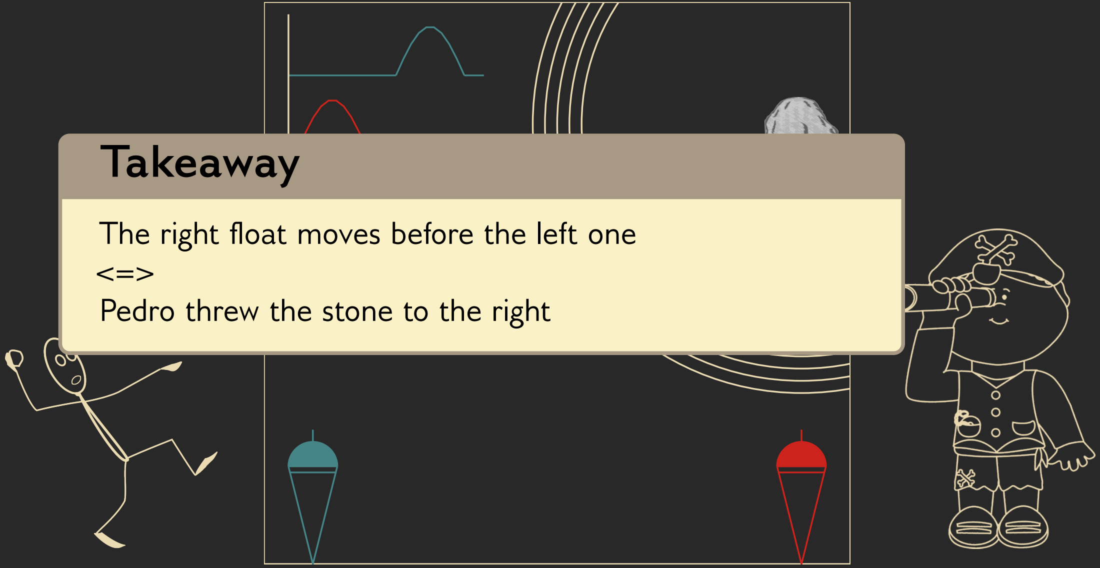


## Takeaway

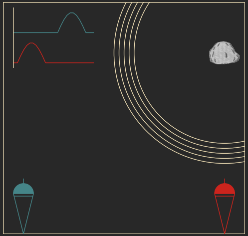
The right float moves before the left one

<=>

Pedro threw the stone to the right

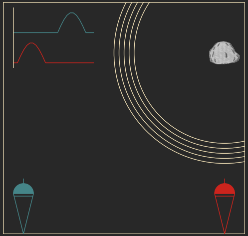
Credit: Joseph Fourier 1822

# Degeneration



The complex reality:

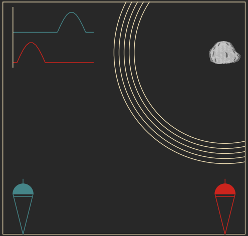
# Degeneration



The complex reality:

| Problem | Solution |
|---|---|
| | |
| | |
| | |
| | |

# Degeneration



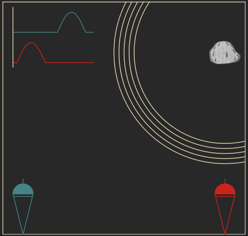
The complex reality:

| Problem | Solution |
|---|---|
| Waves are **continuous** | |
| | |
| | |
| | |

Glossary: baseline = pair of detector

For n detectors, there are $\frac{n(n-1)}{2}$ baselines

# Degeneration



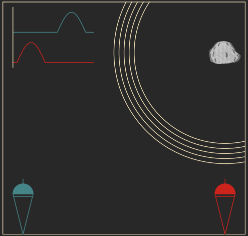
The complex reality:

| Problem | Solution |
|---|---|
| Waves are **continuous** | Have more **baselines** |
| | |
| | |
| | |

Glossary: baseline = pair of detector

For n detectors, there are $\frac{n(n-1)}{2}$ baselines

# Degeneration



The complex reality:

| Problem | Solution |
|---|---|
| Waves are **continuous** | Have more **baselines** |
| Space angle have 2 **dimensions** ($\theta$ and $\phi$) | |
| | |
| | |

Glossary: baseline = pair of detector

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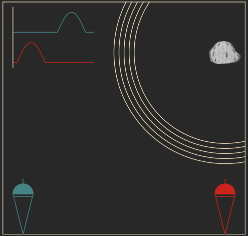

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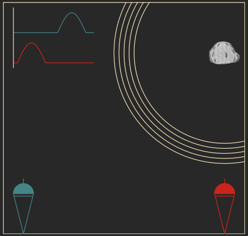

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| Problem | Solution |
| --- | --- |
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| Space angle have 2 **dimensions** ($\theta$ and $\phi$) | Have more **baselines** |
| There may be more than **one punctual** rock | |
| | |

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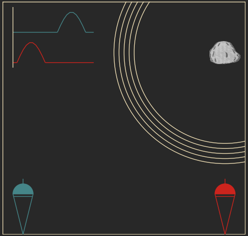
# Degeneration



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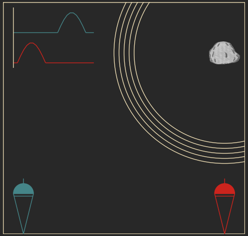


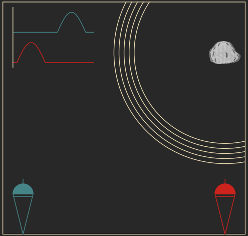
The complex reality:

| Problem | Solution |
|---|---|
| Waves are **continuous** | Have more **baselines** |
| Space angle have 2 **dimensions** ($\theta$ and $\phi$) | Have more **baselines** |
| There may be more than **one punctual** rock | Have more **baselines** |
| Electric **noise**, atmospheric **cloud**, spurious **signal** | |

Glossary: baseline = pair of detector

For n detectors, there are $\frac{n(n-1)}{2}$ baselines

# Degeneration



The complex reality:

| Problem | Solution |
|---|---|
| Waves are **continuous** | Have more **baselines** |
| Space angle have 2 **dimensions** ($\theta$ and $\phi$) | Have more **baselines** |
| There may be more than **one punctual** rock | Have more **baselines** |
| Electric **noise**, atmospheric **cloud**, spurious **signal** | Calibrate, drop |

Glossary: baseline = pair of detector

For n detectors, there are $\frac{n(n-1)}{2}$ baselines

# 3/ Detail

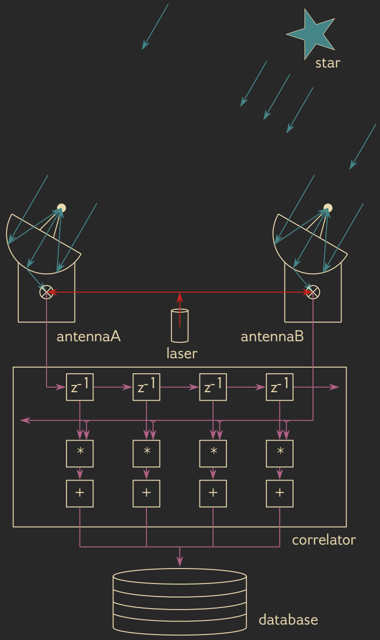
1/ Introduction

2/ Example

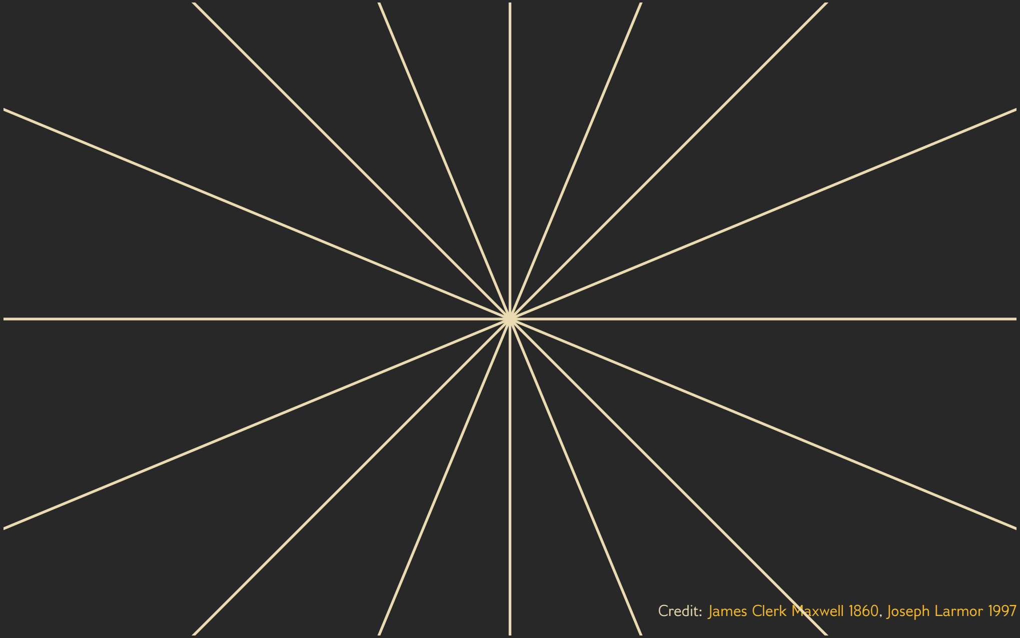
3/ Detail

- Antenna
- Electronic
- Correlator
- Quantity

4/ Conclusion



# Draw me a Photon!



Credit: James Clerk Maxwell 1860, Joseph Larmor 1997

# Electromagnetic Equation

| | | | | | |
|---|---|---|---|---|---|
| 1. | $\nabla\cdot$ | $E$ | $= \rho/\epsilon_0$ | Gauss | Flux |
| 2. | $\nabla\cdot$ | $B$ | $= 0$ | Colomb | Magnetism |
| 3. | $\nabla\times$ | $E$ | $= -\partial_t B$ | Faraday | Induction |
| 4. | $\nabla\times$ | $B$ | $= \mu_0(J + \epsilon_0 \partial_t E)$ | Ampere | Circuital |

$$\boxed{\partial_t^2 E = c_0^2 \nabla^2 E}$$

$$\frac{\partial^2 E}{\partial t^2} = c_0^2 \left( \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} \right)$$

Source: Electromagnetic Wave Equation (Wikipedia)

# Hydrodynamic Equation

| | | | Name | |
|---|---|---|---|---|
| 1. | $\nabla \cdot V$ | $= q$ | Fluid | Incompressibility |
| 2. | $\nabla \cdot W$ | $= 0$ | Vortex | Divergence |
| 3. | $\nabla \times V$ | $= -\partial_t W$ | Vortex | Velocity |
| 4. | $\nabla \times W$ | $= (J + \partial_t V)/a_0^2$ | Mass | Conservation |

$$\boxed{\partial_t^2 V = a_0^2 \nabla^2 V}$$

$$\frac{\partial^2 V}{\partial t^2} = c_0^2 \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right)$$

Source: On Fluid Maxwell Equations (T. Kambe 2012) and Wave Equation (Wikipedia)

# Electromagnetic Wave

**Photons** are the carriers of the **electric** force.

1. Created by decelerated **charges**
2. Displaced by electromagnetic field **currents**
3. Destroyed by accelerating **charges**

Without **electric** force there would be no **light** (and reciprocally)

# Electromagnetic Wave

**Photons** are the carriers of the **electric** force.

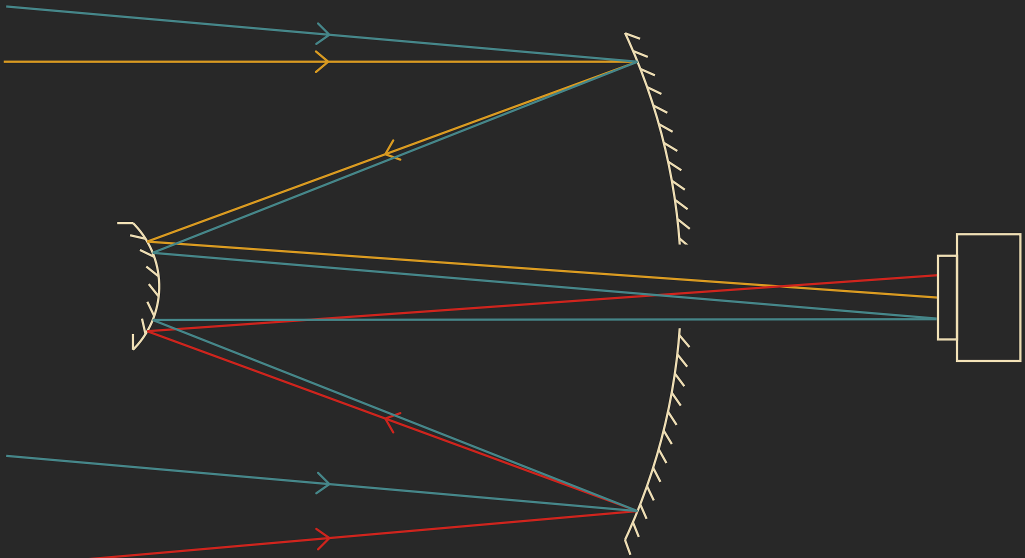
**Takeaway**

Distortion of the electromagnetic field

3. Destroyed by accelerating **charges**

Without **electric** force there would be no **light** (and reciprocally)

# Photon Concentration Fields

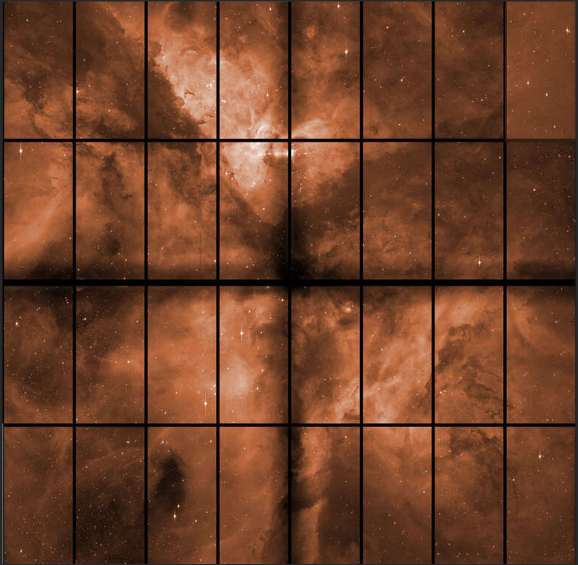


Credit: Laurent Cassegrain 1672, Abul Hasan Ibn Ishaq 890

# Capturing Visible Photon with Carge-Coupled Device (CCD)

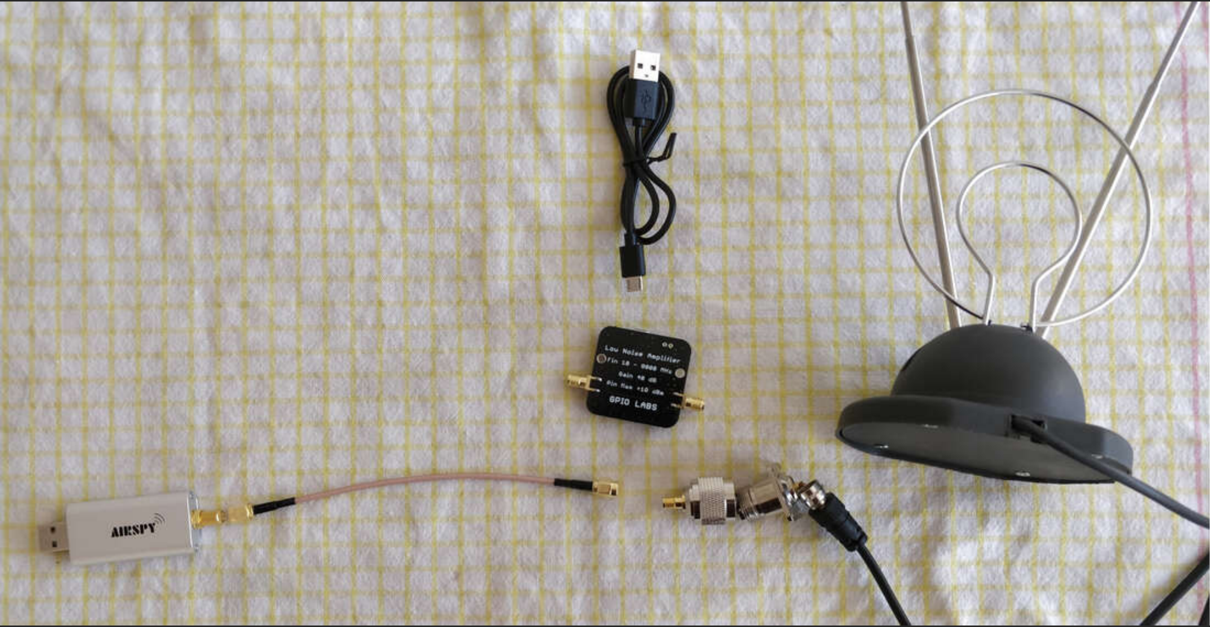
Credit: Willard S. Boyle 1969, ESO, OmegaCam, 2011

# Capturing Visible Photon with Carge-Coupled Device (CCD)



Credit: Willard S. Boyle 1969, ESO, OmegaCam, 2011

# Capturing Radio Photon: Open Wire



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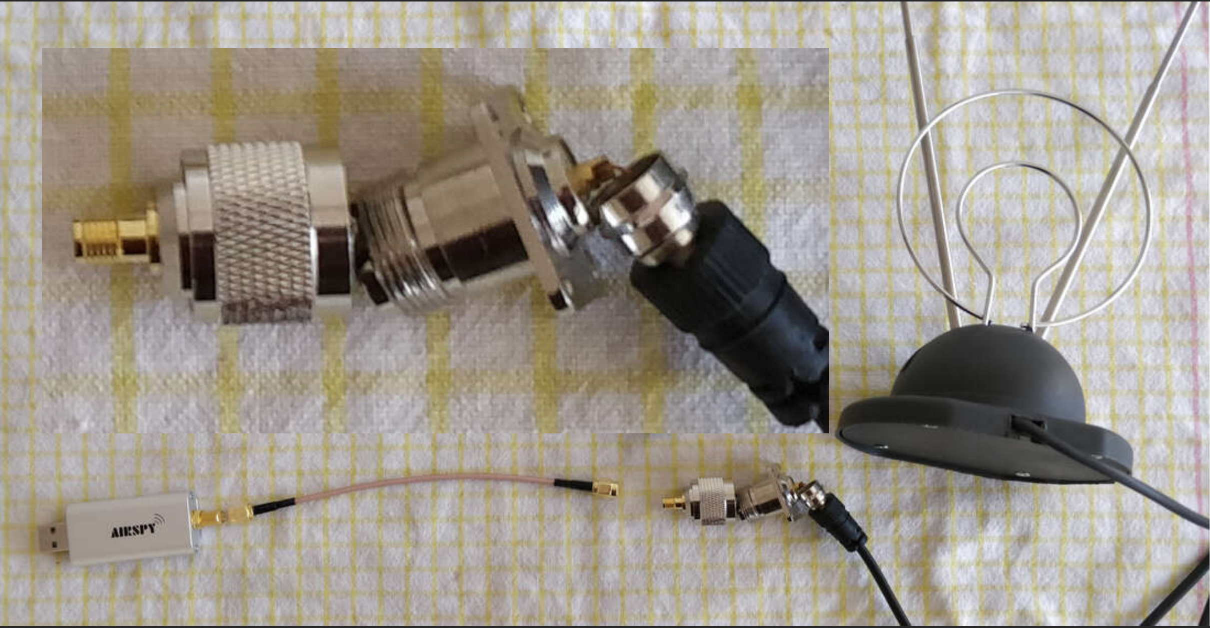
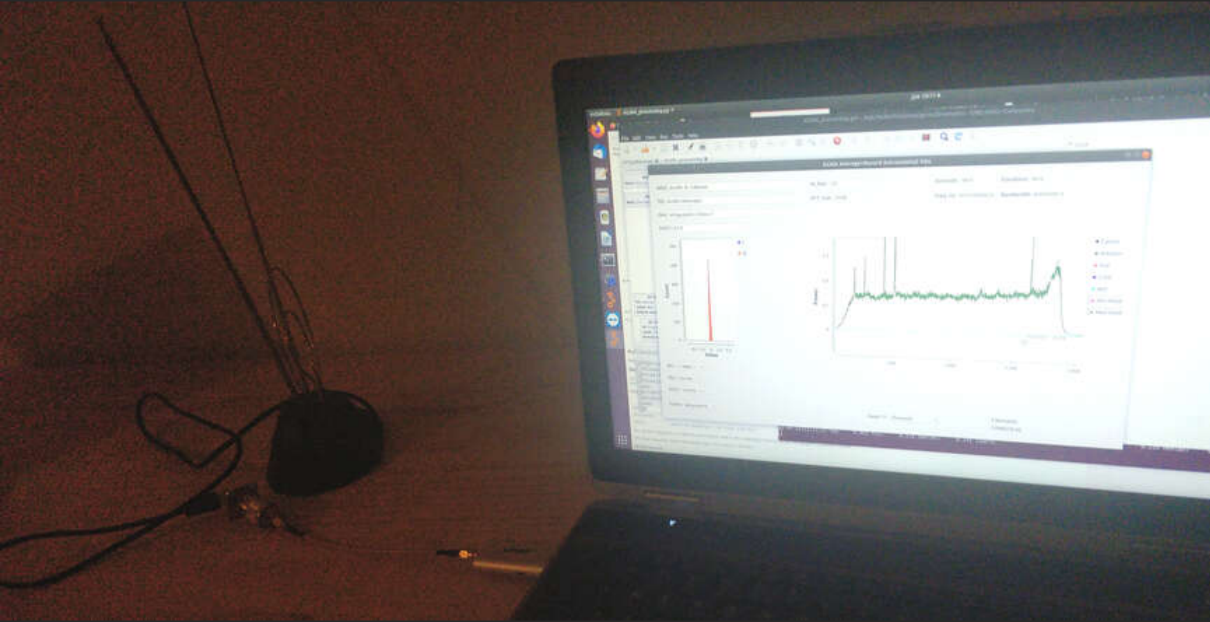
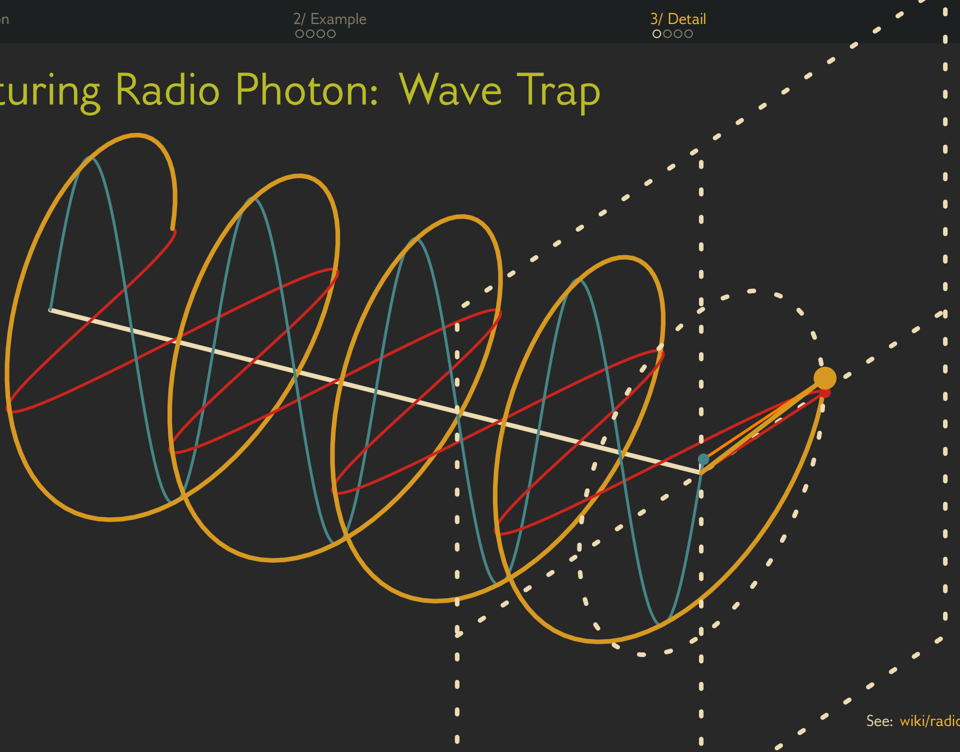


# Capturing Radio Photon: Open Wire

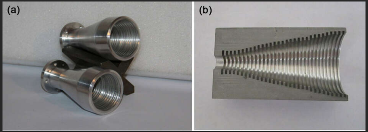


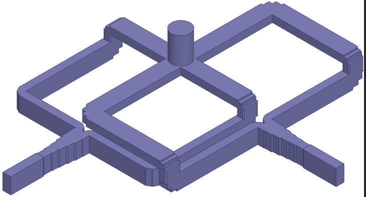
# Capturing Radio Photon: Wave Trap

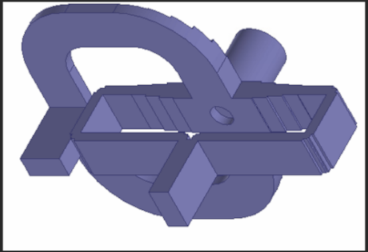


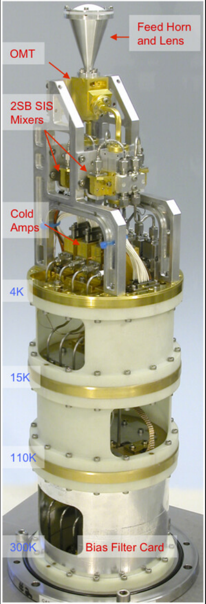
See: wiki/radio_wave

# Capturing Radio Photon: Feed Horn and OMT



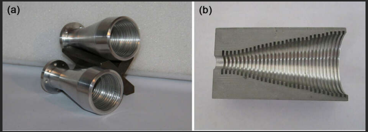



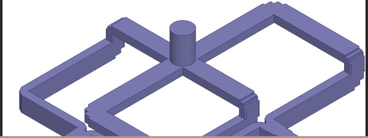


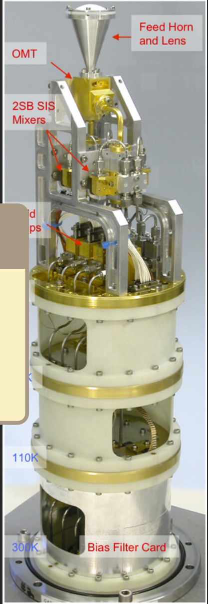



Credit: Chile, UC, Ignacio Barrueto, 2016 and Chile, UC, Nicolas Reyes, 2014 and Canada, HIA, Charles Cunningham, 2011 and Taiwan, ASIAA, Yau De(Ted) Huang, 2016.
See Feed Horn (Wikipedia)

# Capturing Radio Photon: Feed Horn and OMT

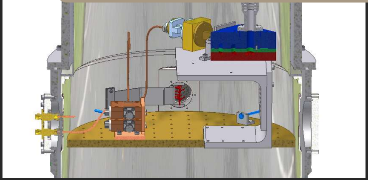


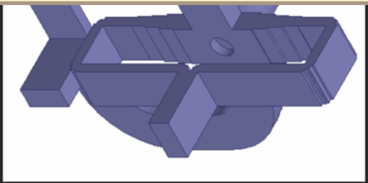






## Takeaway

1. Radio antennas measure both the **amplitude AND phase** of the incident light ("coherent detectors")
2. ALMA antenna receivers have only **one pixel**





Credit: Chile, UC, Ignacio Barrueto, 2016 and Chile, UC, Nicolas Reyes, 2014 and Canada, HIA, Charles Cunningham, 2011 and Taiwan, ASIAA, Yau De(Ted) Huang, 2016.
See Feed Horn (Wikipedia)

# Electronic Pipeline

From 300GHz analog to 150MHz digital

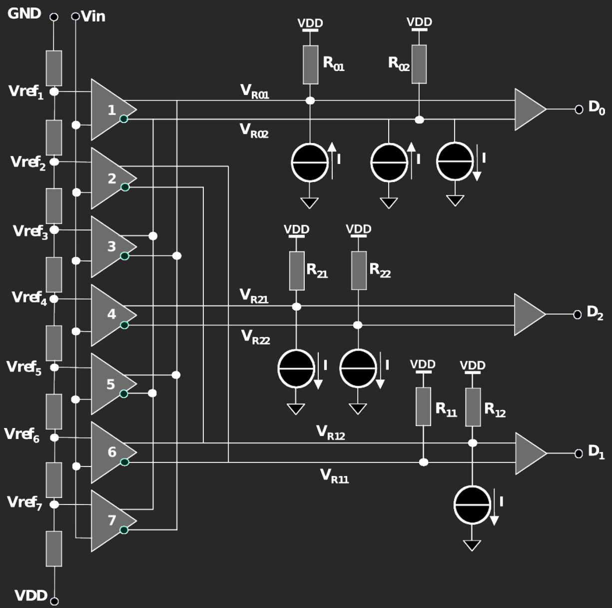

Credit: ALMA, Sergio Otarola

# Electronic Pipeline

From 300GHz analog to 150MHz digital

| N | Fct | Acc | Name |
|---|---|---|---|
| 1 | Polarisation | OMT | OrthoMode Transducer |
| 2 | Amplification | CLNA | Cryogenic Low-Noise Amplifiers |
| 3 | Filtering | BPF | BandPass Filter |
| 4 | Equalisation | GE | Dual Gain Equalizer |
| 5 | Down-convertion | SIS | Superconductor–Insulator–Superconductor Mixer |
| 6 | Digitalization | ADC | Analog to Digital Converter |
| 7 | Multiplexing | MUX | Multiplexer |
| 8 | Transport | FO | Fiber Optic |

# Digitalisation



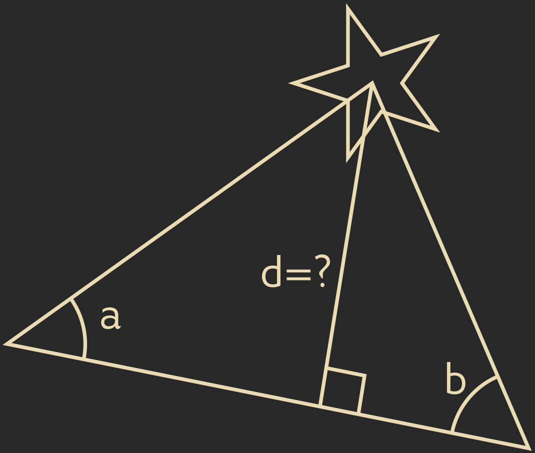
# Correlator Misunderstanding

What correlation is not:

# Correlator Misunderstanding

What correlation is not:

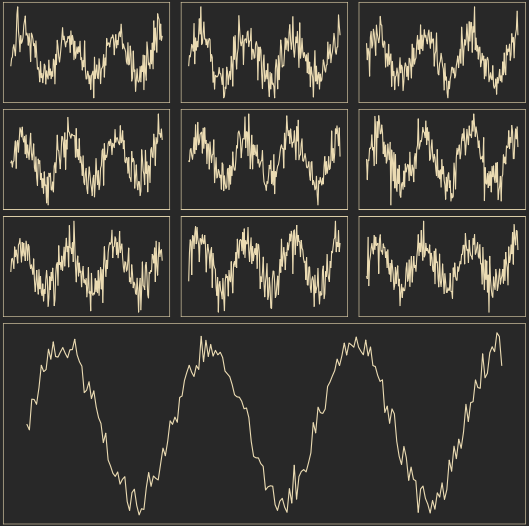
- Triangulation



# Correlator Misunderstanding

What correlation is not:

- Triangulation
- Combination

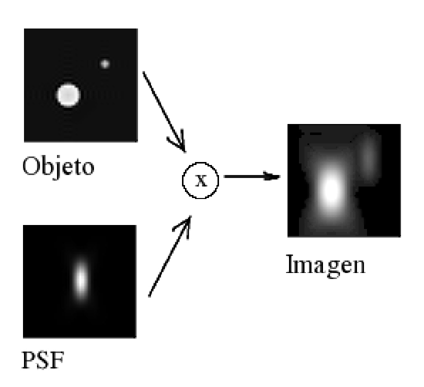


# Correlator Misunderstanding

$$(f * g)(x) := \int f(\tau)g(x - \tau)\, d\tau$$

What correlation is not:

- Triangulation
- Combination
- Convolution




Source: Covolution (Wikipedia Spanish)

# Correlator Misunderstanding

$$(f * g)(x) := \int f(\tau)g(x - \tau)\, d\tau$$

What correlation is not:

- Triangulation
- Combination
- Convolution

What correlation is:

More: Cross-Correlation (Wikipedia)

# Correlator Misunderstanding

$$(f * g)(x) := \int f(\tau) g(x - \tau) \, d\tau$$

$$(f \star g)(x) := \int f^*(\tau) g(x + \tau) \, d\tau$$

What correlation is not:

- Triangulation
- Combination
- Convolution

What correlation is:

- Sliding product

More: Cross-Correlation (Wikipedia)

# Correlator Misunderstanding

$$(f * g)(x) := \int f(\tau)g(x-\tau)\,d\tau$$

What correlation is not:

**Takeaway**

The Cross-Co-Re-Lation

$$)g(x+\tau)\,d\tau$$

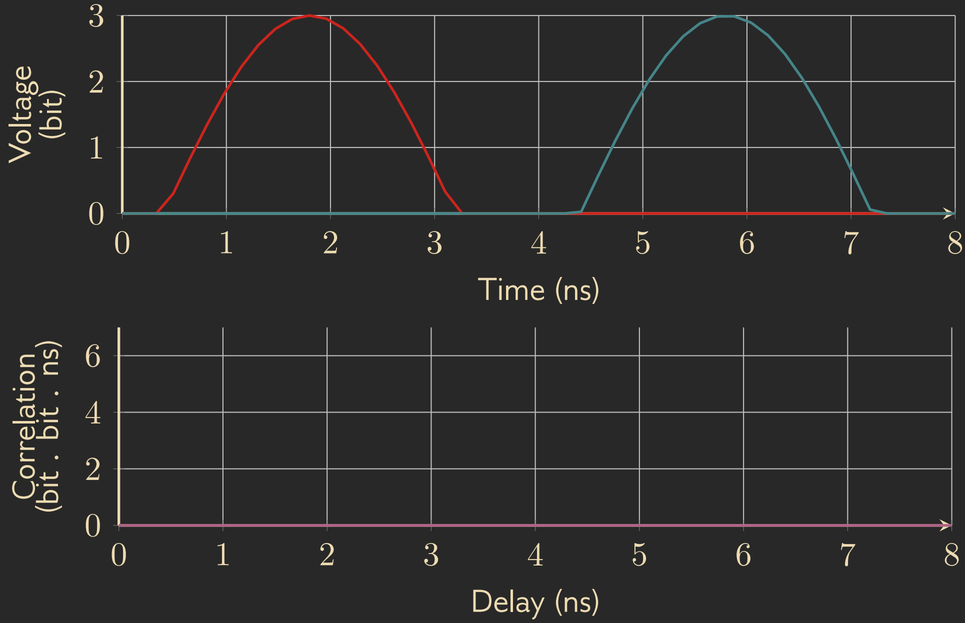
- Convolution

What correlation is:

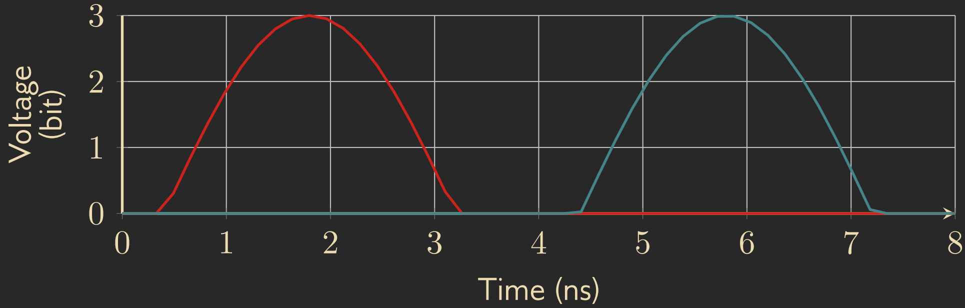
- Sliding product

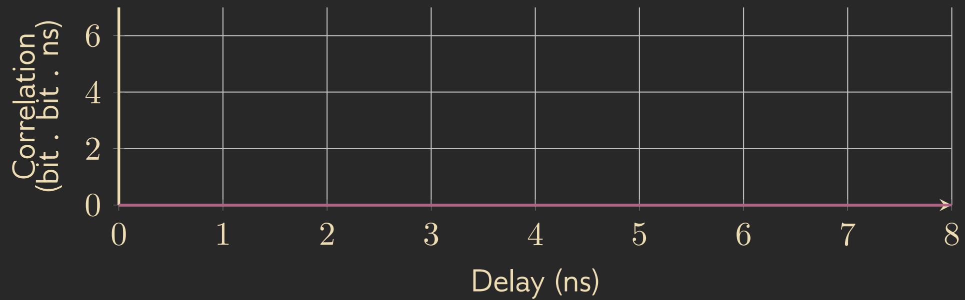
More: Cross-Correlation (Wikipedia)

# Correlator Sliding Product

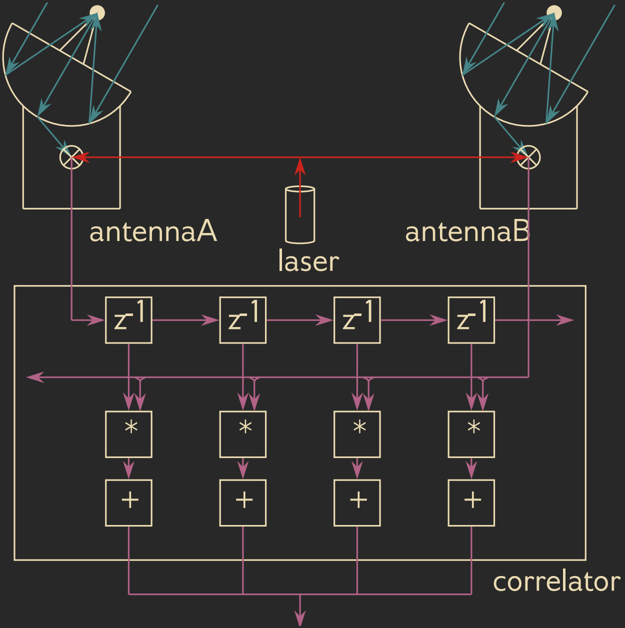


# Correlator Sliding Product



# Correlator Electronics



# Quantity: Requirements

$$\boxed{1.7 \times 10^{16} Hz}$$

| Number | Quantity | Explanation |
|---|---|---|
| $64^2$ | Antenna Pairs | Ordered for leads vs lags |
| $2^2$ | Cross Polarisations | XX, XY, YX, YY |
| 8 | Base Bands | Tunable from 31.25 MHz to 2 GHz |
| 8192 | Spectral Channels | Covering each baseband |
| 62.5 MHz | Input Frequency | Digital signal speed |
| 2 | Nyquist Sampling | 2 measures per wavelength |

Note: Each operation is a 2 bits complex multiply-and-add.

Source: 64 Antenna Correlator Specifications and Requirements

# Quantity: Processing Power

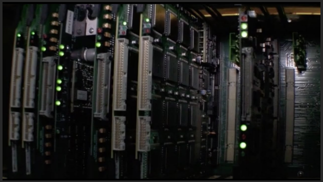
$$\boxed{1.7 \times 10^{16} Hz}$$

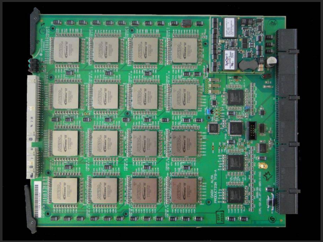
| Number | Quantity | Explanation |
|---|---|---|
| 4 | Quadrants | Cupboards each processing 2 basebands |
| 32 | Planes | Shelves Filled with motherboards |
| 4 | Circuit Cards | Actually implemented with 16 cards of 16 ASICS |
| 64 | ASIC | FPGA |
| 4096 | Multiply-add | Also include including 20 bits of integration |
| 125 MHz | Clock Rate | Real Time Electronics |

Note: Each operation is a 2 bits complex multiply-and-add.

Ref: The ALMA Correlator (Escoffier 2007)

# Quantity: The Correlator Room





Source: The ALMA correlator (Escoffier 2007) and Lights glowing on the ALMA correlator (S. Argandoña 2012) and The ALMA Correlator (NRAO 2021) and Upgrading the ALMA Digital System (Quertier 2020)

# 4/ Conclusion

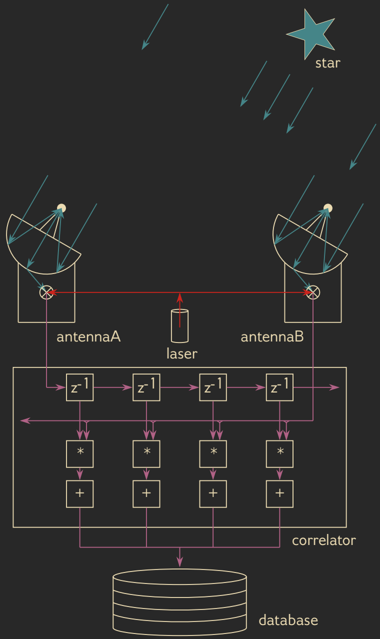
1/ Introduction

2/ Example

3/ Detail

4/ Conclusion

- Summary
- Takeaway
- Further
- Questions?



# Summary

# Takeaway

## 1 /Introduction

1. Water + light = rainbow
2. Wind + obstacle = turbulences
3. Alma captures **millimeter** wavelength

## 2/ Example

1. Rock at right <=> right float moves first
2. Baseline number > antenna size
3. Constrain possible scenarios with independent measures

## 3/ Detail

1. Light = wave of electromagnetic field disruption
2. Coherent detectors, measure phase **and** amplitude
3. Alma's antennas have only one pixel

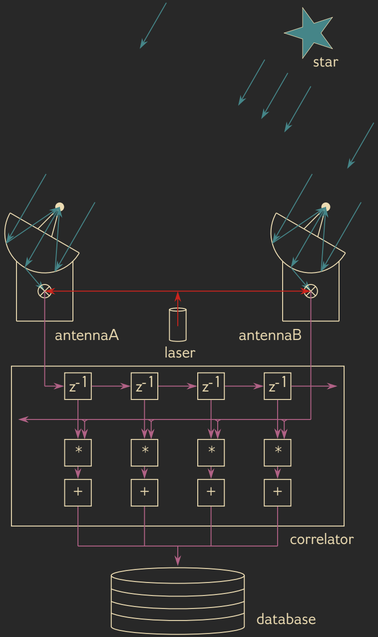
## 4/ Conclusion

1. Physics: Electro-magnetic waves
2. Electronics: Transistors
3. Computing: Cross-correlation

# Further

| ALMA | Electronics | Physics |
|---|---|---|
| technical handbook | digital x-correlation (gary) | aperture synthesis (me) |
| system diagram | transitor amplifier (utube) | spectral lines (sransom) |
| 2030 physics (memo 621) | mixers (liam) | molecules (ddallaca) |
| 2030 system | adc (memo 532) | radiative processes |
| brochure | 2030 corr (memo 617) | interferometry and synthesis |
| manual en escuela | demux | fundamentals |
| story of project | transistor animated (utube) | NGC4697 bh mass |
| casa guides | sis mixer | phangs galaxy survey |
| vlbi | phase-lock loop (wiki) | large programs |
| science pipeline | lo1 optical fiber (memo 443) | vlbi m87 bh |

# Questions?

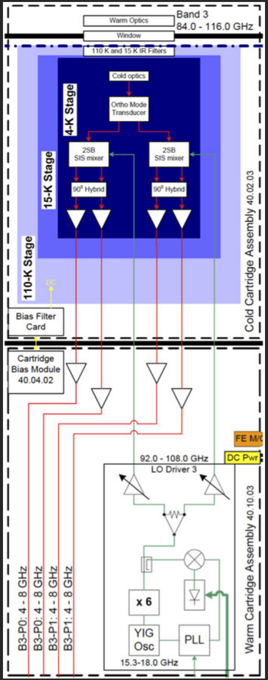

star
antennaA
laser
antennaB
z-1
z-1
z-1
z-1
*
*
*
*
+
+
+
+
correlator
database

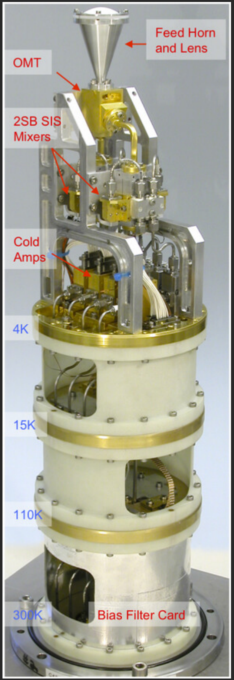
# Appendix

# Band List

| N | Freq (GHz) | Wavelength (mm) | Country | Shape | Yig freq (GHz) | Warm mult | Cold mult |
|---|---|---|---|---|---|---|---|
| 1 | 31.3 - 45 | 6.7 - 9.5 | Taiwan/Chile | SSB | 31.0 – 40.0 | 1 | 1 |
| 2 | 67 - 90 | 3.3 - 4.5 | Europe/Chile | SSB | 13.2 - 15.7 | 6 | 1 |
| 3 | 84 - 116 | 2.6 - 3.6 | Canada | 2SB | 15.3 - 18.0 | 6 | 1 |
| 4 | 125 - 163 | 1.8 - 2.4 | Japan | 2SB | 22.2 - 25.8 | 3 | 2 |
| 5 | 163 - 211 | 1.4 - 1.8 | Sweden | 2SB | 13.8 - 16.9 | 6 | 2 |
| 6 | 211 - 275 | 1.1 - 1.4 | USA | 2SB | 12.3 - 14.7 | 6 | 3 |
| 7 | 275 - 373 | 0.8 - 1.1 | France | 2SB | 15.62 - 20.37 | 6 | 3 |
| 8 | 385 - 500 | 0.60 - 0.78 | Japan | 2SB | 21.72 - 27.44 | 3 | 6 |
| 9 | 602 - 720 | 0.42 - 0.50 | Netherlands | DSB | 22.51 - 26.45 | 3 | 9 |
| 10 | 787 - 950 | 0.32 - 0.38 | Japan | DSB | 14.8 - 17.4 | 6 | 9 |

# Band 3 Diagram



# Interstellar Molecules

| 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| H2 | H2O | NH3 | CH4 | CH3OH | CH2CH(OH) | CH3COOH | (CH3)2O |
| CO | H2S | H2CO(?) | SiH4 | CH3SH | c-C2H4O | HC(O)OCH3 | CH3CH2CN |
| CSi | HCN | H2CS | CH2NH | C2H4 | HC(O)CH3 | HOCH2C(O)H | CH3CH2OH |
| CP | HNC | C2H2 | NH2CN | H(CC)2H | H3C-CC-H | H3C-CC-CN | CH3C4H |
| CS | CO2 | HNCO | CH2CO | CH3CN | CH3NH2 | H2C6 | HCC-CC-CC-CN |
| NO | SO2 | HNCS | HCOOH(?) | CH3NC | CH2CH(CN) | H(CC)3H | C8H |
| NS | MgCN | H3O+ | HCC-CN | HC(O)NH2 | HCC-CC-CN | H2C=CH-C(O)H | CH3C(O)NH2 |
| SO | MgNC | SiC3 | HCC-NC | HCC-C(O)H | C6H | CH2CCHCN | C8H- |
| HCl | NaCN | C3S | c-C3H2 | HC3NH+ | C6H- | C7H | CH3CHCH2 |
| NaCl | N2O | H2CN | l-C3H2 | HC4N | H2NCH2CN | | |
| KCl | NH2 | c-C3H | CH2CN | C5N | | | |
| AlCl | OCS | l-C3H | H2COH+ | C5H | | | |
| AlF | CH2 | HCCN | C4Si | H2CCCC | | | |
| PN | HCO | CH3 | C5 | H2CCNH | | | |
| SiN | C3 | C2CN | HNCCC | C5N- | | | |
| SiO | C2H | C3O | C4H | c-H2C3O | | | |
| SiS | C2O | HCNH+ | C4H- | | | | |
| NH | C2S | HOCO+ | HC(O)CN | | | | |
| OH | AlNC | CO2 | | | | | |
| C2 | HNO | C3N- | | | | | |
| CN | SiCN | HCNO | | | | | |
| HF | N2H+ | HSCN | | | | | |
| FeO | SiNC | H2O2 | | | | | |
| LiH | c-SiC2 | | | | | | |
| CH | HOC+ | | | | | | |
| CH+ | HOC+ | | | | | | |
| CO+ | HCS+ | | | | | | |
| SO+ | H3+ | | | | | | |
| SH | OCN- | | | | | | |
| O2 | HCP | | | | | | |
| N2 | CCP | | | | | | |

| 10 | 11 | 12 | 13 |
|---|---|---|---|
| (CH3)2CO | HCC-CC-CC-CC-CN | C6H6 | HCC-CC-CC-CC-CC-CN |
| HOCH2CH2OH | CH3C6H | CH3CH2CH2CN | |
| CH3OCH2OH | HC(O)OCH2CH3 | | |
| H3C-CH2-C(O)H | | | |
| CH3(CC)2CN | | | |

Credit: USA, NASA, 2023

# CO Emission Lines

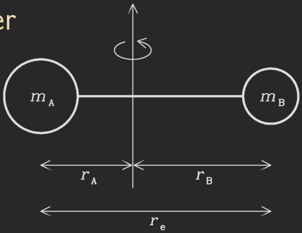
$$\nu(J \rightarrow J-1) = \frac{hJ}{4\pi^2 m {r_e}^2}$$

Frequency

Orbital number

mass

diameter



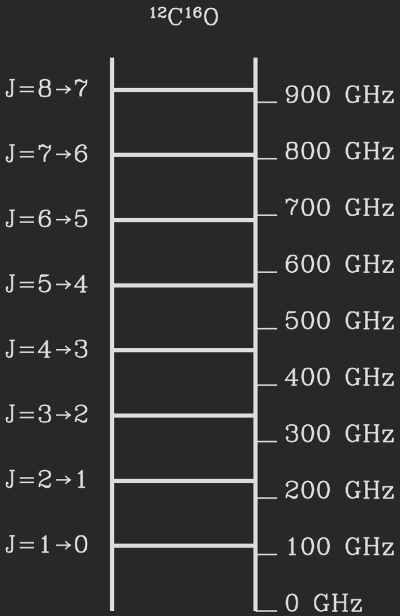

Because the rotational energy is:
$E_{rot} = \frac{h}{2\pi I} J(J+1)$

Where I is the inertial moment is:
$I = m_A r_A^2 + m_B r_B^2$

So the difference between 2 levels is:
$\Delta E_{rot}(J \rightarrow J-1) = [J(J+1) - (J-1)J]\frac{\hbar^2}{2I} = \frac{\hbar^2 J}{I}$

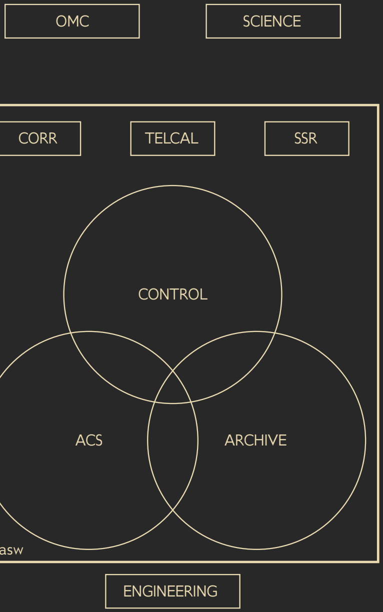
Converting to frequency with another Planck constant gives:

$\nu = \frac{\Delta E_{rot}}{h} = \frac{\hbar J}{2\pi I}$




Credit: USA, NRAO, sransom, 2018

# Software Trinity




Continuous integration
Casa
BulkData
OMC
AlmaSw
Control
Scheduling
SSR
Archive
Corr
TelCal
Subsystems
AcsRemoteTMCDB
AcsStartup
AcsPassive
Component Channel
ACS
AcsData
Patches
External products
AcsSw
Build
Consistency
Database
Services
Network
Harddisk
Underworld
SelfChecking
InputParsing
NTLAS
LogDetector
Meta