ASTRO
IIT KANPUR

Singularity Mosaic

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Welcome to Singularity Mosaic, a project dedicated to exploring the enigmatic universe. We'll analyze astronomical data, focusing on black holes. Our journey will cover the history of astronomy and modern coordinate systems. We'll also dive into fascinating deep-sky objects.

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Cosmic Timeline

Ancient Wisdom to New Models

From Ptolemy's geocentric views (where the Earth was taken as the centre of the universe) to Copernicus's heliocentric model (where the Sun was taken as the centre of the universe).

Mapping the cosmos

There are three major celestial coordinate systems which map universe. Which are equitorial , alt-az and galactic

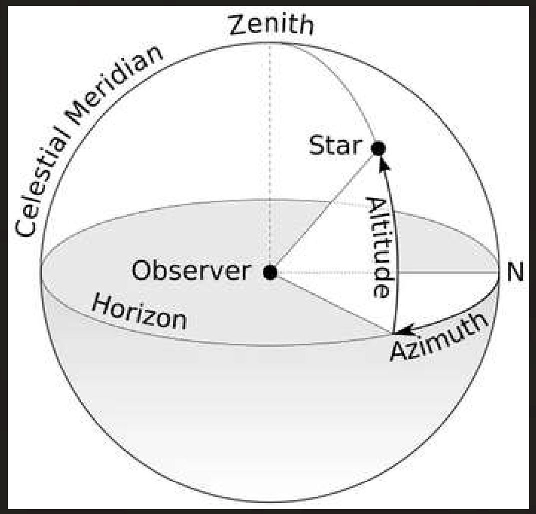
Modern Astronomical eyes

Modern telescopes include the EHT, Hubble Telescope, VLA, ALMA, JWST, Chandra, and others. Are our eyes in trhe vast universe

Cosmic phenomenon

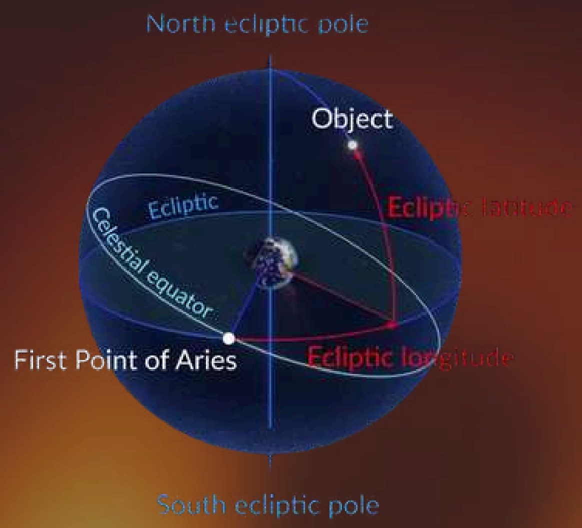
Phenomena like quasar, pulsar, blackhole, magnetar, etc. This phenomenas are still making us wonder about our universe

Three Key Coordinate Systems



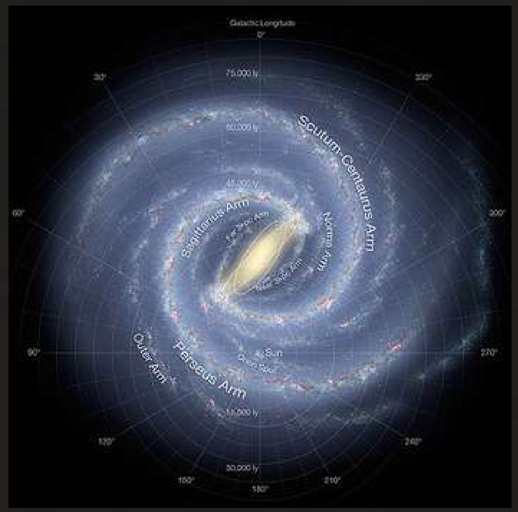
Alt-Az

The horizontal system uses altitude (above horizon) and azimuth (from north). Both change with location and time, making it useful for navigation and telescope pointing.



Equatorial

Right Ascension (like longitude), Declination (like latitude). Earth-centered, fixed stars. Used for star catalogs, object identification. This system uses the Earth's equator projected onto the celestial sphere. The Ecliptic system's reference plane is Earth's orbit around the Sun.



Galactic

Galactic longitude and galactic latitude use a Sun-centred system aligned with the Milky Way plane. These coordinates help astronomers map galaxy structure and study the distribution of stars, gas, and dust across our galaxy efficiently. And Sagittarius A is taken as the centre

Conversions and Applications

Complex Conversions

Converting between systems requires complex mathematical formulas.

Streamlined Tools

Tools like Python and online calculators simplify these transformations.

Telescope Control

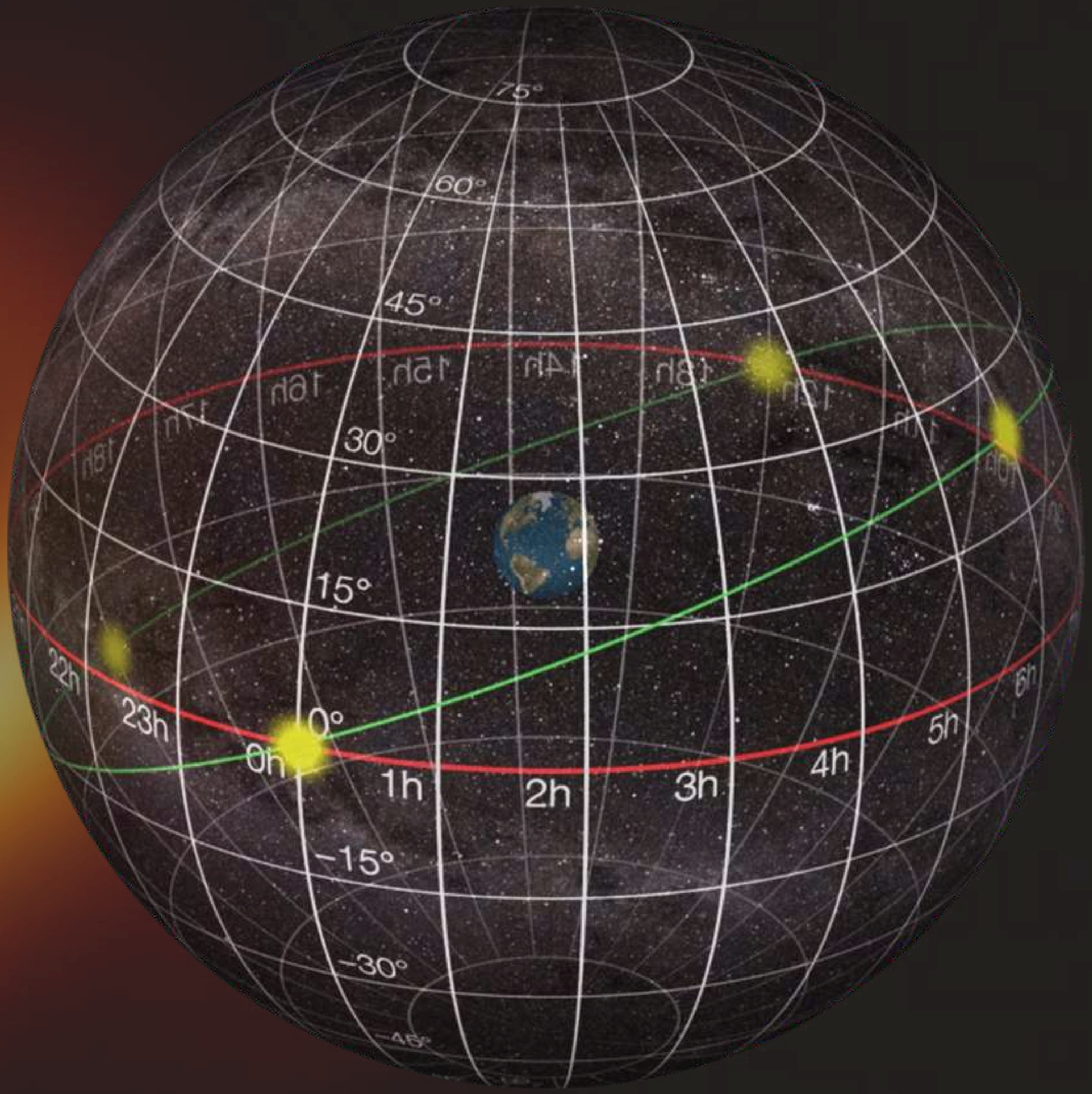
Equatorial coordinates are corrected for date and time for accurate tracking using the Horizontal system.

Mapping the Milky Way

Galactic coordinates reveal the large-scale structures within our galaxy.

Solar System Understanding

Ecliptic coordinates are essential for tracking and understanding planet movement.



Telescope Handling

We learned here how to use a telescope and point using it

1 Aligning with Polaris

We first align the polarscope on telescope with Polaris

2 Balancing the telescope

Balance the telescope by changing the counterweights and also shifting the tube. Such that both the RA and DEC axis are fully free

3 Pointing to the object

Change the RA and Dec value of the telescope to that of the object and fine-tune it using the slow motion controls

4 Focusing the object

To see the object clearly focus the eyepiece using focuser

Deep-Sky Objects: Cosmic Zoo

Neutron Stars

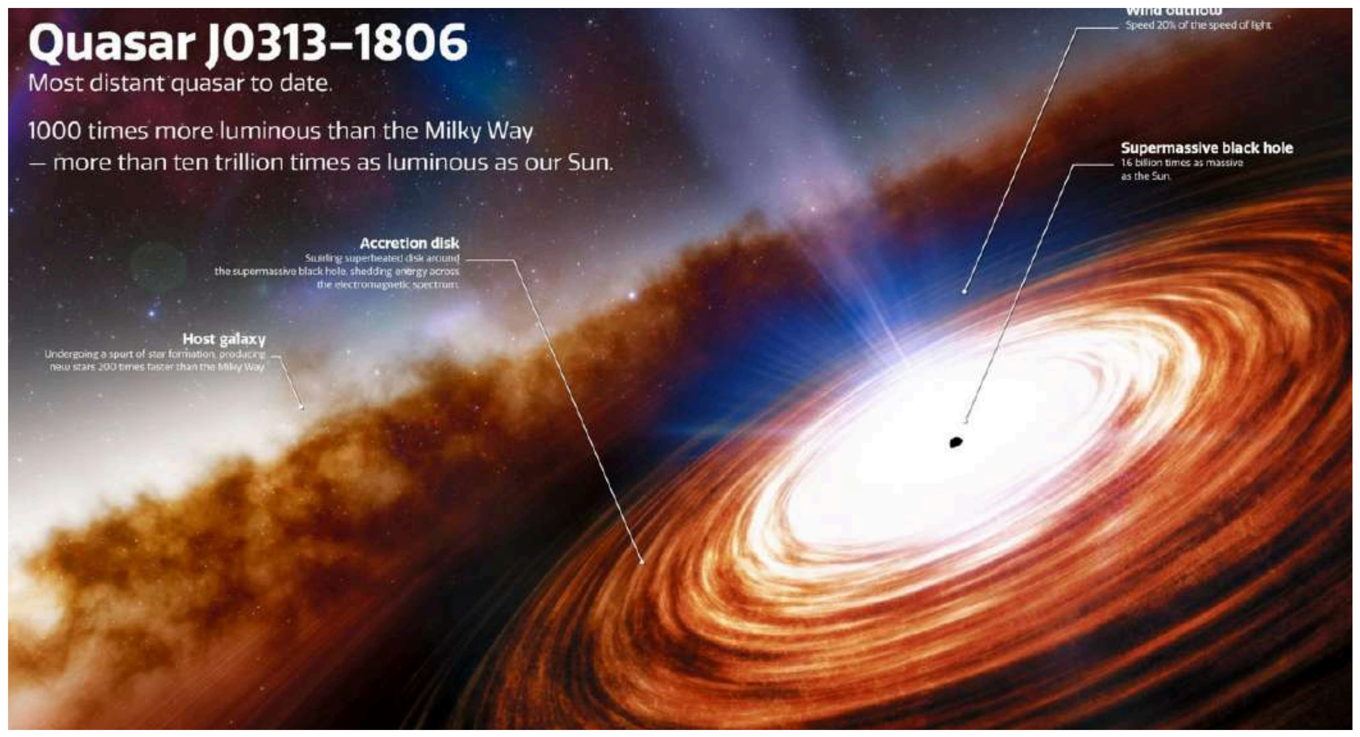
Incredibly dense remnants left after supernova explosions. These incredibly dense remnants form after massive star supernova. They consist mainly of neutrons. PSR J1614-2230 is twice the Sun's mass.

White Dwarfs

The evolutionary end-stage for most low-mass stars. Small to medium stars become white dwarfs. They exhaust their nuclear fuel. Sirius B is a prime example, Earth-sized but solar mass.

Pulsars and Quasars: Cosmic Beacons

Explore the universe's most captivating phenomena. Pulsars are rapidly rotating neutron stars, emitting precise beams of radiation. Quasars are incredibly luminous galactic nuclei powered by supermassive black holes. These cosmic beacons offer a glimpse into extreme astrophysics.



Black Holes: Gravity's Ultimate Victory

1

Gravity's Dominance

Nothing, not even light, escapes a black hole's grip. They form from collapsing massive stars.

2

Event Horizon

This boundary marks the point of no return. Beyond it, escape is impossible.

3

Supermassive Black Holes

Located at galactic centers, they can be billions of solar masses. Sagittarius A* is our Milky Way's giant.

4

Stellar Black Holes

These form from individual stars, ranging from 3 to 100 solar masses. Cygnus X-1 was one of the first discovered.

Event Horizon Telescope: Seeing the Unseeable

Historic Black Hole Image
M87* was imaged in 2019.

Global Telescope Network
The EHT uses Very Long Baseline Interferometry (VLBI).

Unprecedented Resolution
Imaging an orange on the moon is now possible.

Future Cosmic Targets
Next, imaging Sagittarius A* at the Milky Way's center.

How EHT works:

Global Synchronization
The EHT9s telescopes are time-synced using hydrogen maser atomic clocks.

Central Data Correlation
Data is flown (literally!) to supercomputing centers (MIT, Max Planck) for processing.

Petabytes of Data
Each site records raw radio signals onto physical hard drives 4 up to 4 PB total.

Image Reconstruction
Powerful algorithms turn noisy, sparse data into a visible black hole

Interferometry: Virtual Telescopes

Interferometry combines signals from multiple telescopes to create a single, larger virtual telescope. This technique significantly improves resolution and sensitivity. Very Long Baseline Interferometry (VLBI) is a powerful application, combining distant observatories.

Signal Combination

Individual telescope signals are merged.

Resolution Boost

Achieving finer details in celestial objects.

Enhanced Sensitivity

Detecting fainter cosmic sources.

VLBI in Practice

Data from ALMA and the South Pole Telescope are combined.

UV Coverage and Fourier Transforms

The UV Plane

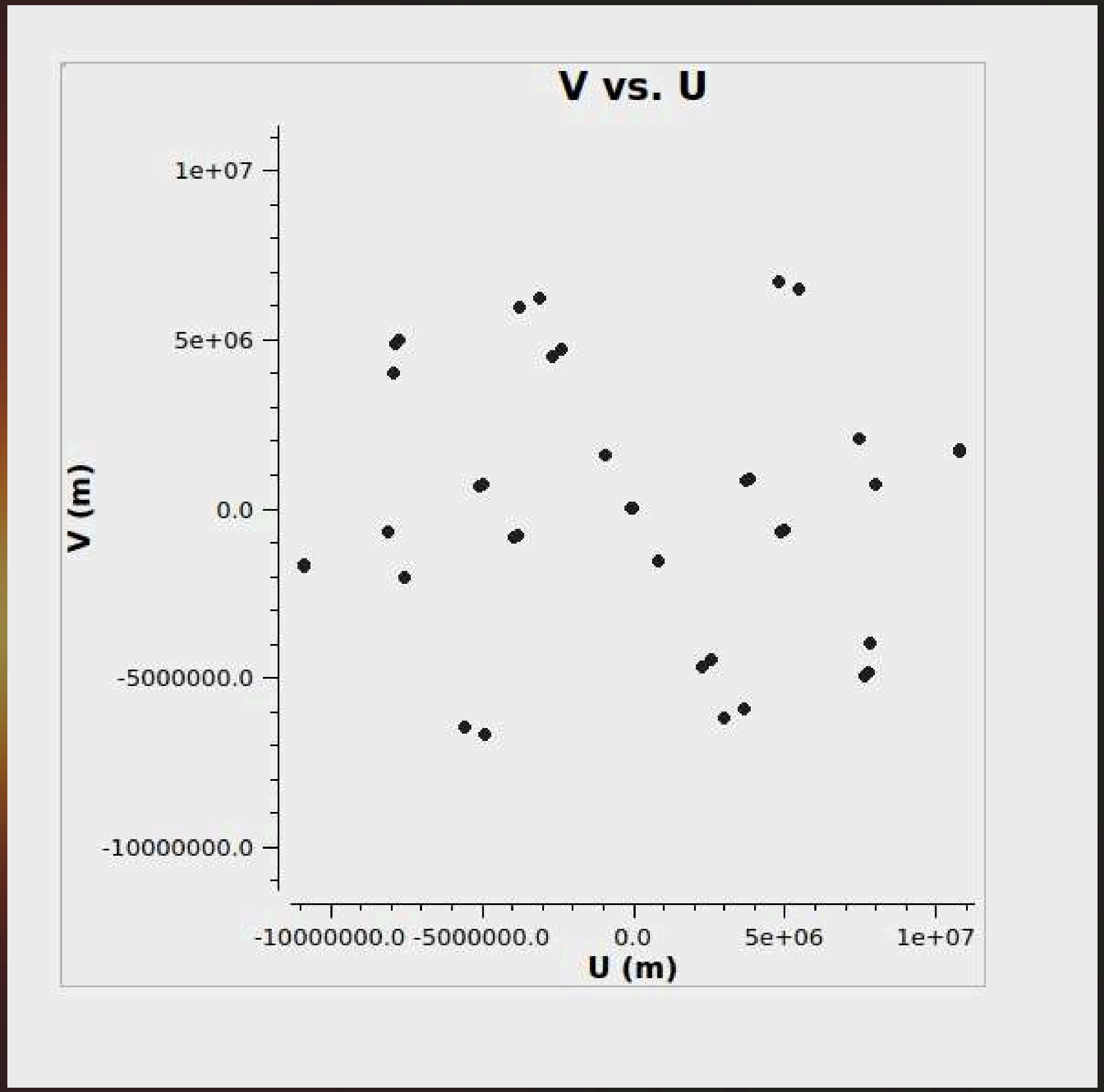
This plane represents the spatial frequencies sampled by an interferometer. Each baseline provides a point.

Fourier Transform

This mathematical tool converts raw UV data into a celestial image. It's the core of image reconstruction.

Incomplete Coverage Challenges

When UV coverage is sparse, advanced image reconstruction techniques are necessary.



From Frequency to Images

Spatial Frequencies

The Fourier Transform decomposes an image into its constituent spatial frequencies.

Applications

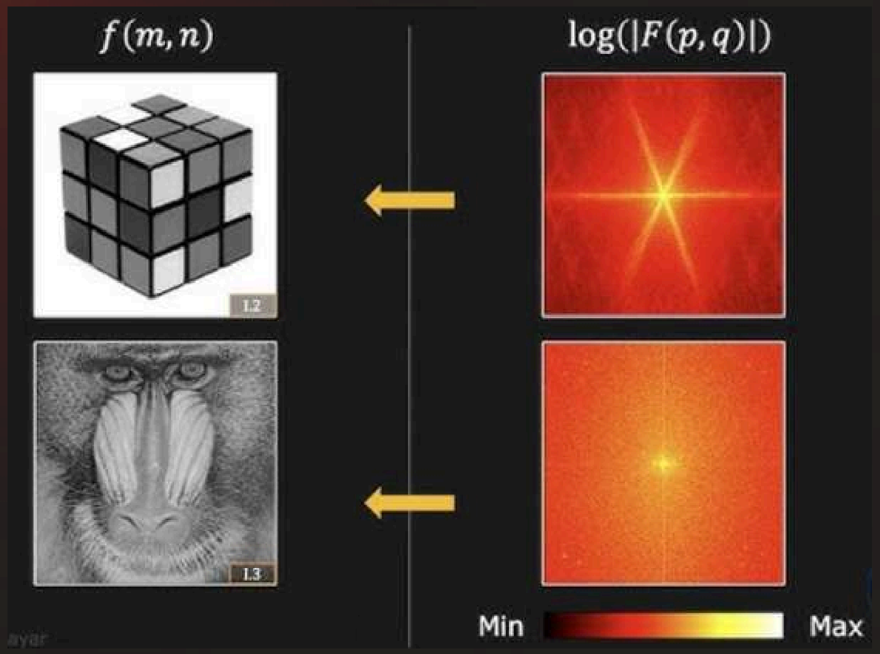
Used in image filtering, compression, and reconstruction. MRI image formation is a prime example.

Convolution Theorem

This theorem simplifies complex calculations in the frequency domain.The observed image is therefore a convolution of the true sky brightness with the point spread function (PSF) or synthesized beam.

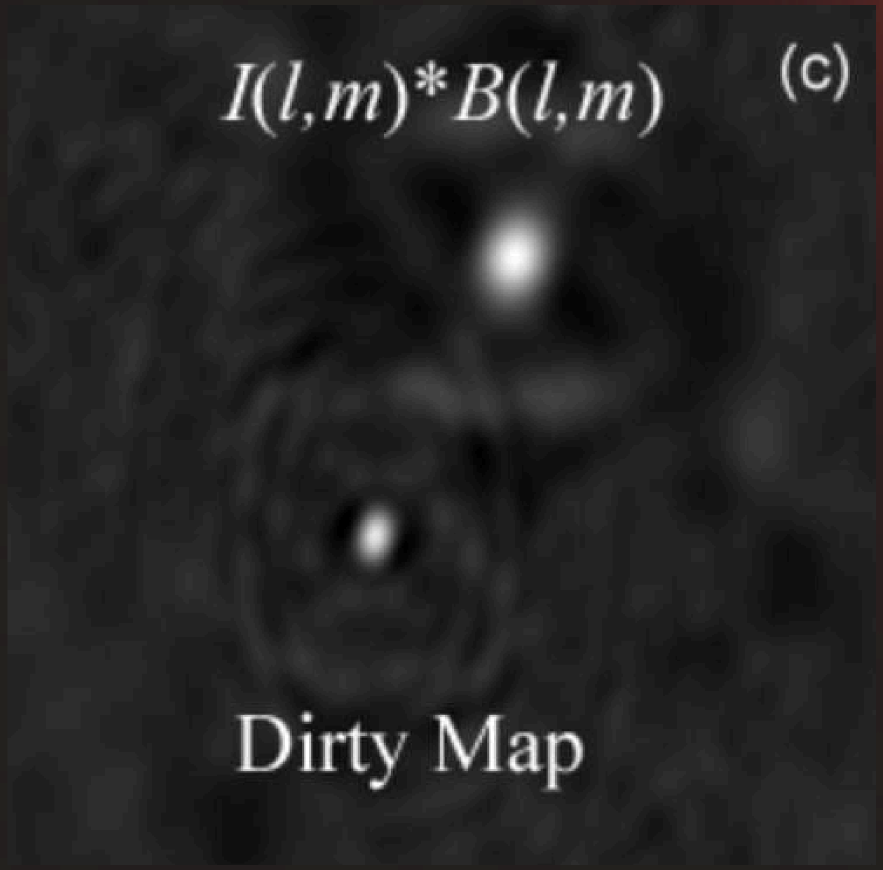
Amplitude & Phase

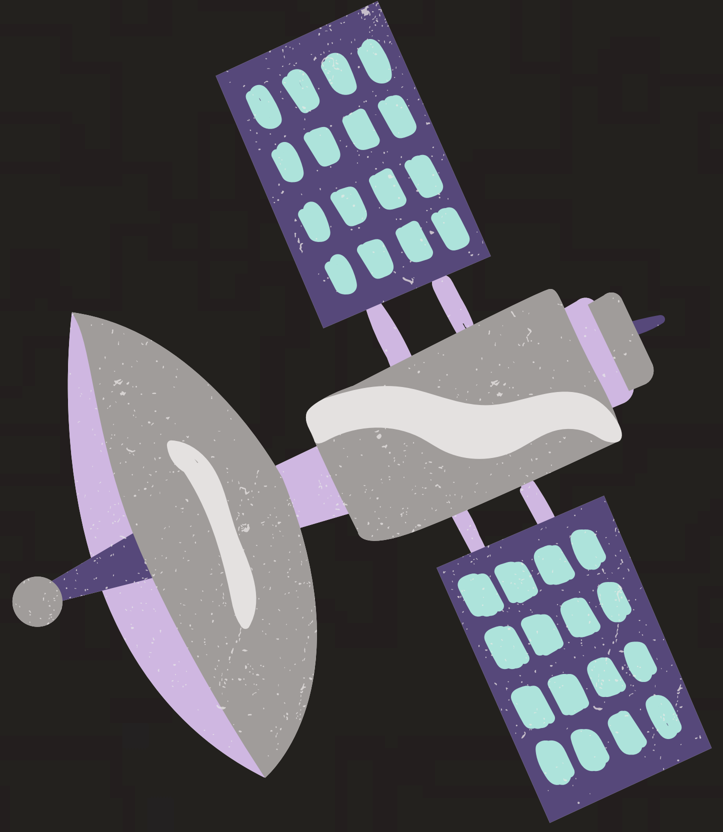
Both amplitude and phase components encode vital image information.



What is Dirty Image?

- The first image produced by a radio interferometer (array of radio telescopes).
- Created by taking the inverse Fourier transform of measured data ("visibilities").
- Not a true sky image4contains distortions and artifacts.

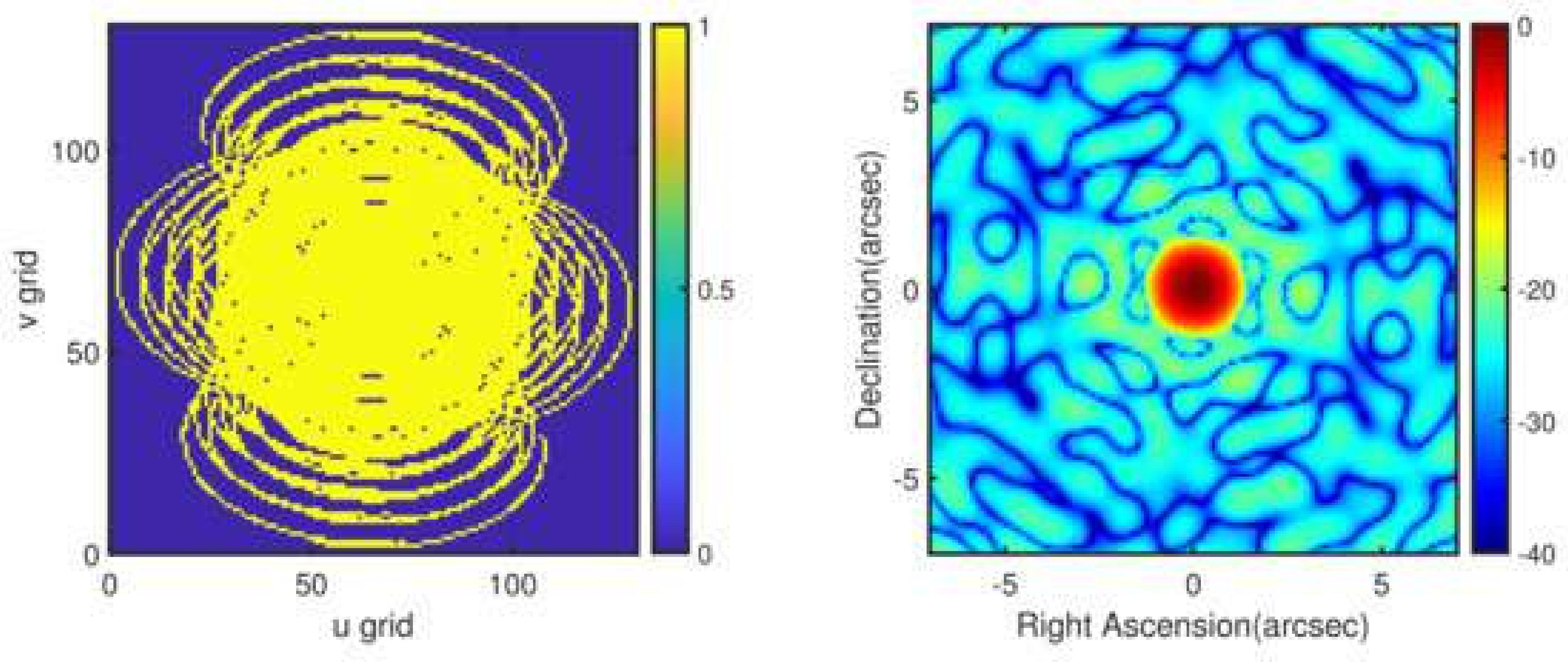




Why it is Dirty?

- The image is a mix of the real sky and unwanted patterns (sidelobes, noise).
- These patterns come from the **Dirty Beam**.

What is Dirty Beam?



(a) The u-v mask of an 8 h tracking (b) Dirty beam

- *The "point spread function"* (PSF) of the interferometer array.
- Shows how a single point in the sky would appear in the dirty image.
- Has a sharp central peak but many sidelobes (ripples and negative regions).
- Caused by incomplete and uneven sampling of the sky by the telescope array.

CLEAN Algorithm: Refining the Image

CLEAN is a foundational algorithm in radio astronomy imaging, designed to remove artifacts caused by incomplete data from radio interferometers. By iteratively identifying and subtracting the effects of the instrument's response (the "dirty beam"), CLEAN enables astronomers to reconstruct much clearer and more accurate images of the radio sky.

Two Cycles for CLEAN Algorithm

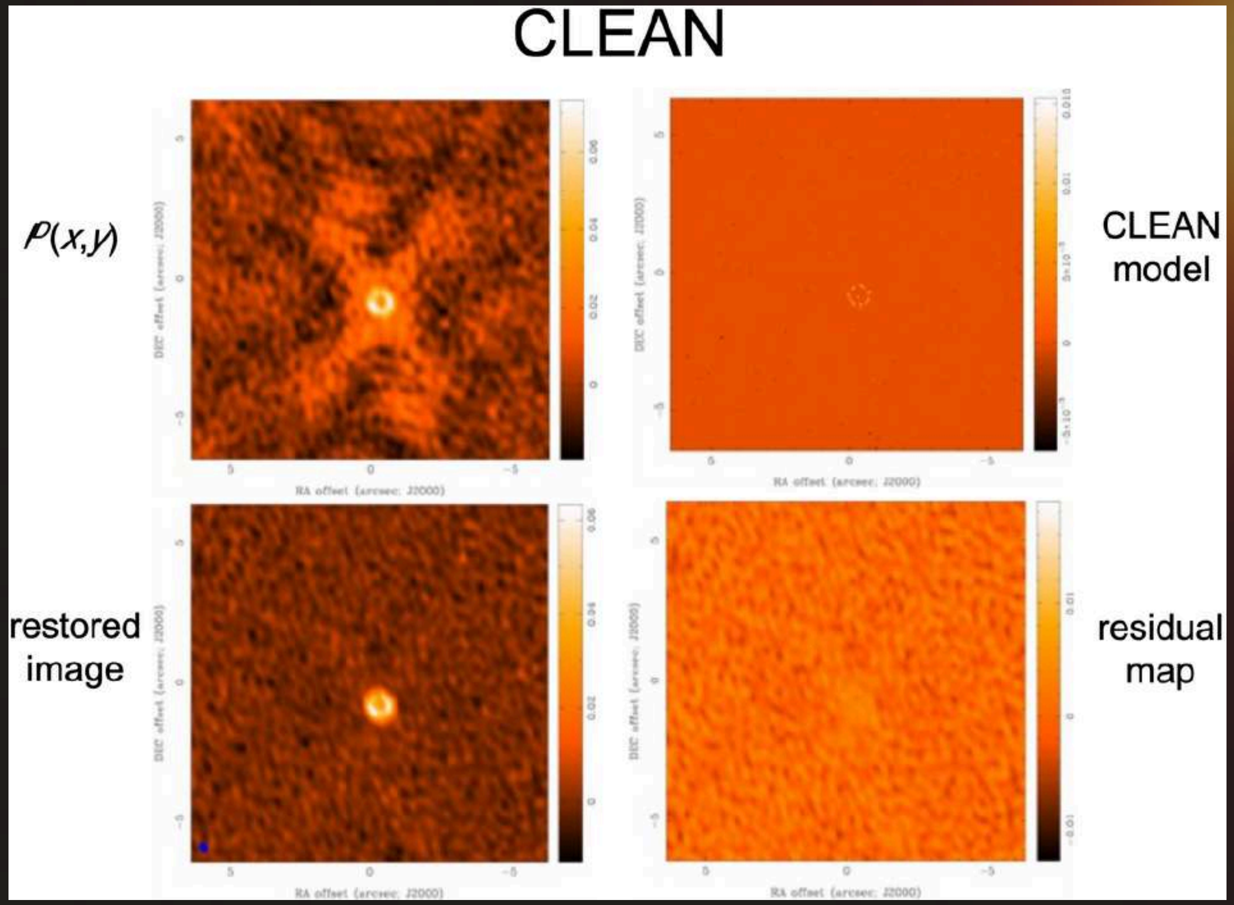
Major Cycle

Minor Cycle

How CLEAN Algorithm works

Find the Peak: Locate the brightest pixel in the current residual image

Record Component: Add a fraction (gain factor) of this peak to a clean component list



Subtract Beam: Remove a scaled version of the dirty beam pattern centered on the peak location

Iterate: Repeat until stopping criteria are met (threshold or maximum iterations)

Restore: Convolve clean components with an idealized "clean beam" and add residuals

Image Cleaning Process

Minor Cycle

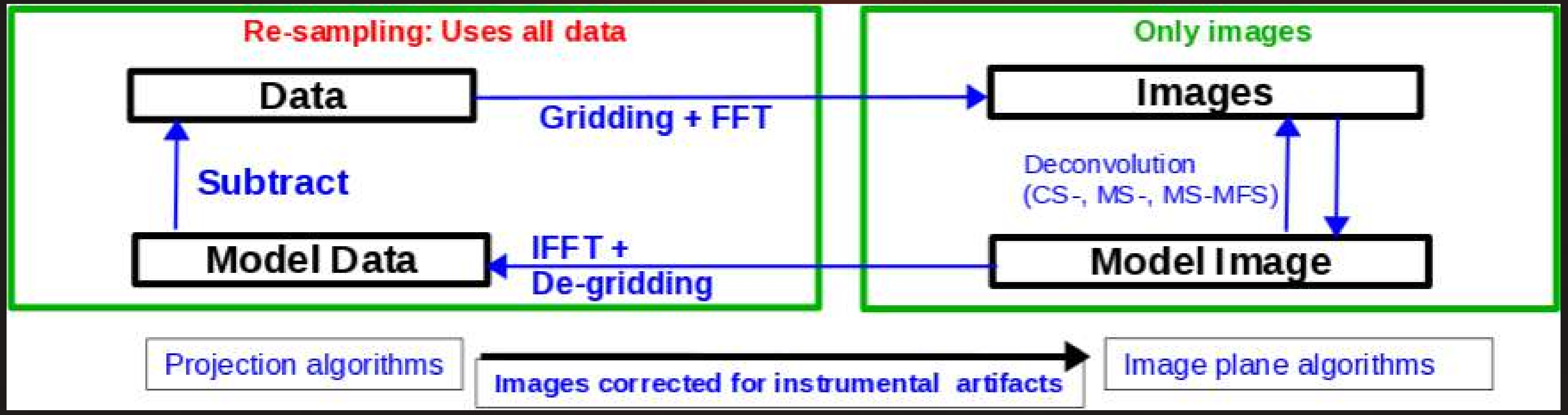
Image Domain Processing:

- CLEAN components are searched for and subtracted from the image
- Only the central portion of the dirty beam is used for subtraction
- Operates on a list of the largest residuals (not the full image)
- Much faster than using the full PSF for each subtraction
- The loss in accuracy is the trade-off price we pay to cut down the computational cost.

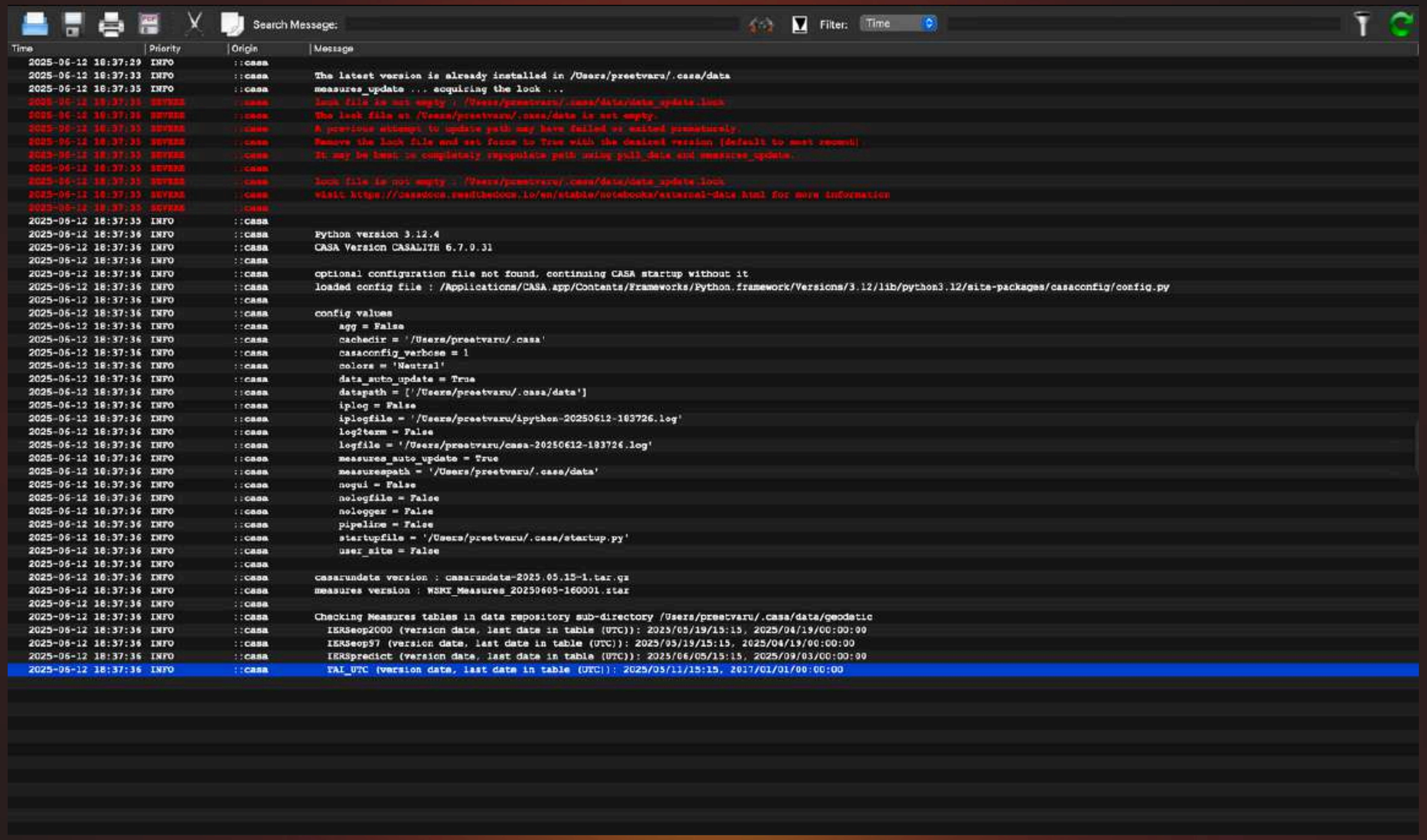
Major Cycle

Visibility Domain Correction:

- The list of CLEAN components from minor cycles are processed through Fast-Fourier-Transformation.
- Components are subtracted from the original visibility data.
- A new residual image is computed from updated visibilities.
- Corrects for errors that may have accumulated during minor cycle approximations.



CASA: Data Processing and Visualization



CASA Installation

Installing Common Astronomy Software Applications is the first step.

Loading EHT Data

EHT data is loaded and calibrated within CASA for analysis.

Visualizing Black Holes

The software enables detailed visualization of black hole images and models.

Visualising black holes

1. The ‘importuvfits’ command converts raw UVFITS files into CASA’s Measurement Set (MS) format :

```
importuvfits(fitsfile="SR1_M87_2017_095_lo_hops_netcal_StokesI.uvfits", vis
    ="M87_095_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_096_lo_hops_netcal_StokesI.uvfits", vis
    ="M87_096_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_100_lo_hops_netcal_StokesI.uvfits", vis
    ="M87_100_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_101_lo_hops_netcal_StokesI.uvfits", vis
    ="M87_101_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_095_hi_hops_netcal_StokesI.uvfits", vis
    ="M87_095_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_096_hi_hops_netcal_StokesI.uvfits", vis
    ="M87_096_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_100_hi_hops_netcal_StokesI.uvfits", vis
    ="M87_100_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_101_hi_hops_netcal_StokesI.uvfits", vis
    ="M87_101_hi.ms")
```

2. Use ‘listobs’ to examine the MS structure and metadata:

```
listobs(vis="M87_095_lo.ms")
```

3. The ‘plotms’ tool is used to visualise the UV-coverage, revealing the array geometry:

```
plotms(vis="M87_095_lo.ms", xaxis="u", yaxis="v", avgtime="1e8", avgscan=
    True, coloraxis="spw")
```

4. ‘mstransform’ is used to generate corrected MS files, resolving pointing table inconsis-tencies:

```
mstransform(vis="M87_2017_095_lo.ms", outputvis="M87_2017_095_lo_fixed.ms
    ", datacolumn="data")
mstransform(vis="M87_2017_096_lo.ms", outputvis="M87_2017_096_lo_fixed.ms
    ", datacolumn="data")
mstransform(vis="M87_2017_100_lo.ms", outputvis="M87_2017_100_lo_fixed.ms
    ", datacolumn="data")
mstransform(vis="M87_2017_101_lo.ms", outputvis="M87_2017_101_lo_fixed.ms
    ", datacolumn="data")
```

5. Unique field names are assigned before concatenation:

```
tb.open("M87_2017_095_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_095"])
tb.close()
tb.open("M87_2017_096_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_096"])
tb.close()
tb.open("M87_2017_100_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_100"])
tb.close()
tb.open("M87_2017_101_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_101"])
tb.close()
```

6. Multiple MS files are merged using concat, preserving field names and time order:

```
concat(vis=vis=["M87_2017_095_lo_fixed.ms", "M87_2017_096_lo_fixed.ms","
    M87_2017_100_lo_fixed.ms","M87_2017_101_lo_fixed.ms"],
   concatvis="M87_combined_distinct.ms",
   timesort=True, respectname=True, copypointing=False)
```

7. To plot the final image :

```
plotms(vis="M87_combined_distinct.ms", xaxis="u", yaxis="v",
   coloraxis="field", avgchannel="9999", avgtime="9999")
```

Python Assignment

[1]
```
from google.colab import drive
drive.mount('/content/drive')
```

```
Mounted at /content/drive
```

```
with open('/content/drive/MyDrive/Moons_and_Planets.csv','r') as f:
  lines = f.read().split('\n')
  data_moons = []
for line in lines:
    data_moons.append(line.split(','))
print(data_moons)
```

```
[['# Name of Moon', ' Name of Planet', ' Diameter (km)'], ['Moon', 'Earth', '1737.1'], ['Phobos', 'Mars', '11.1'], ['Deimos', 'Mars', '6.2'], ['Io', 'Ju
```

[3]
```
planets = ('Earth','Mars','Jupiter','Saturn','Uranus','Neptune','Pluto')
for planet in planets:
  count = 0
  for moon in data_moons[1:]:
    if len(moon) > 1 and moon[1].strip() == planet:
        count += 1
  print(f'{planet} has {count} moons')
```

```
Earth has 1 moons
Mars has 2 moons
Jupiter has 79 moons
Saturn has 82 moons
Uranus has 27 moons
Neptune has 14 moons
Pluto has 5 moons
```

```
dis = len(data_moons)
for i in range(1,dis):
  for j in range(1,dis-i-1):
    if float(data_moons[j][2]) < float(data_moons[j+1][2]):
      temp = data_moons[j]
      data_moons[j] = data_moons[j+1]
      data_moons[j+1] = temp
for moon in data_moons:
  print(moon)
```

```
['# Name of Moon', ' Name of Planet', ' Diameter (km)']
['Ganymede', 'Jupiter', '2634.1']
['Titan', 'Saturn', '2575.5']
['Callisto', 'Jupiter', '2408.4']
['Io', 'Jupiter', '1818.1']
['Moon', 'Earth', '1737.1']
['Europa', 'Jupiter', '1560.7']
```

Bulla Session

Team A : Intro to Warp Drive

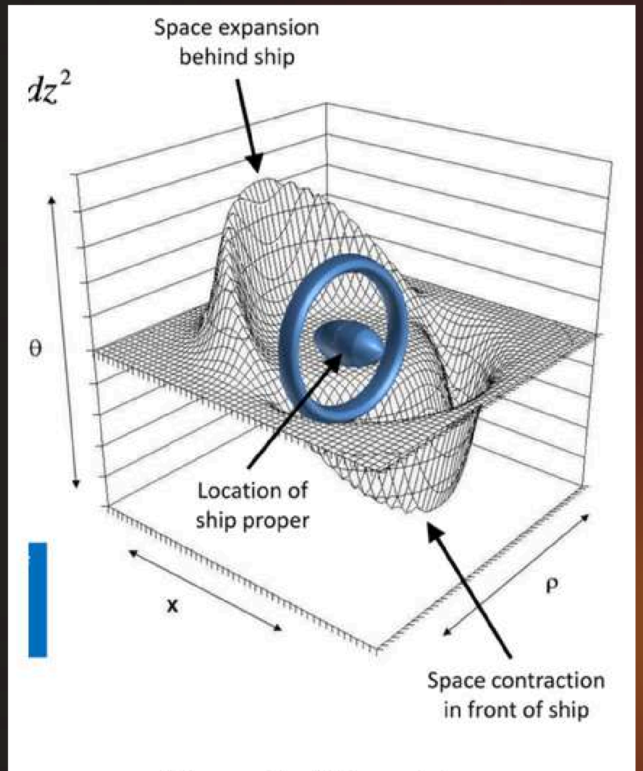
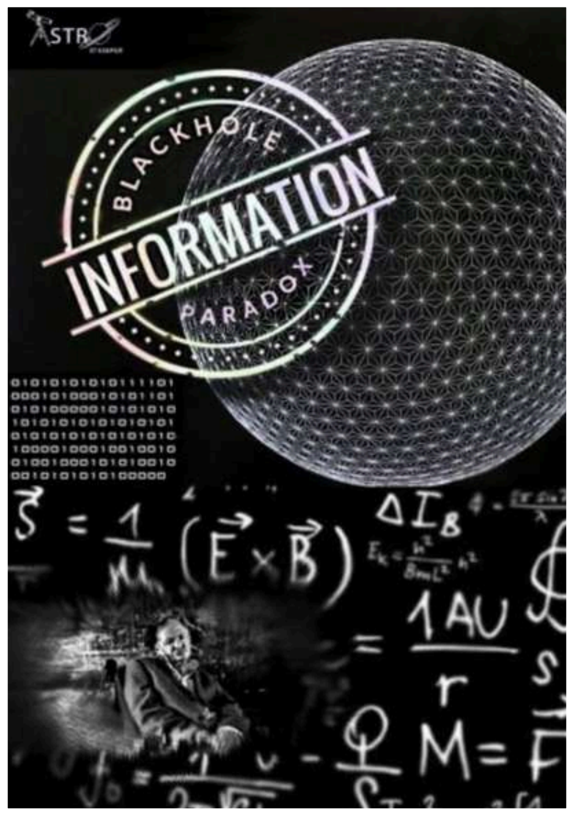


Figure 1: Warp drive

Team B : Information paradox



Team C: Brief info on Milky Way

THANK YOU