Lecture 1

Key Science Projects with the SKA:

New frontiers in radio astronomy

Lecturer: **Dr Vijay Mahatma** (vm462)

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Syllabus Overview

- Introduction to Big Data Radio Astronomy and Key Science Projects
  - Lecture 1: SKA Key Science Projects
  - Lecture 2: Brief history of radio astronomy and the SKA telescope
  - Lecture 3: The modern "large-N" radio interferometers
- Instrument simulations and design tools
  - Lecture 4: Intro into numerical methods for electromagnetic modelling
  - Lectures 5 and 6: Mutual coupling in antenna arrays
- Science Data Processing
  - Lecture 7: Calibration of radio observations
  - Lecture 8: Imaging techniques
  - Lecture 9: Advanced imaging techniques
  - Lecture 10: Time-domain radio astronomy
- Computing infrastructure
  - Lecture 11: Federation and scaling approaches for exascale data
  - Lecture 12: Data centre challenges and opportunities
- Advanced ML and Bayesian methods for data analysis and science extraction
  - Lecture 13: Nested sampling and MCMC
  - Lecture 14: Applications of Bayesian analysis
  - Lecture 15: Signal emulation for astrophysics and cosmology
  - Lecture 16: Simulation-based inference in astrophysics and cosmology

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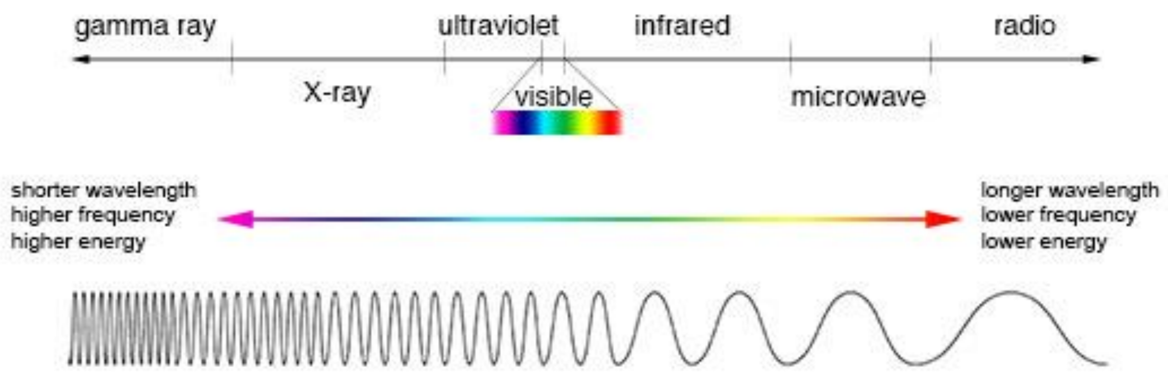
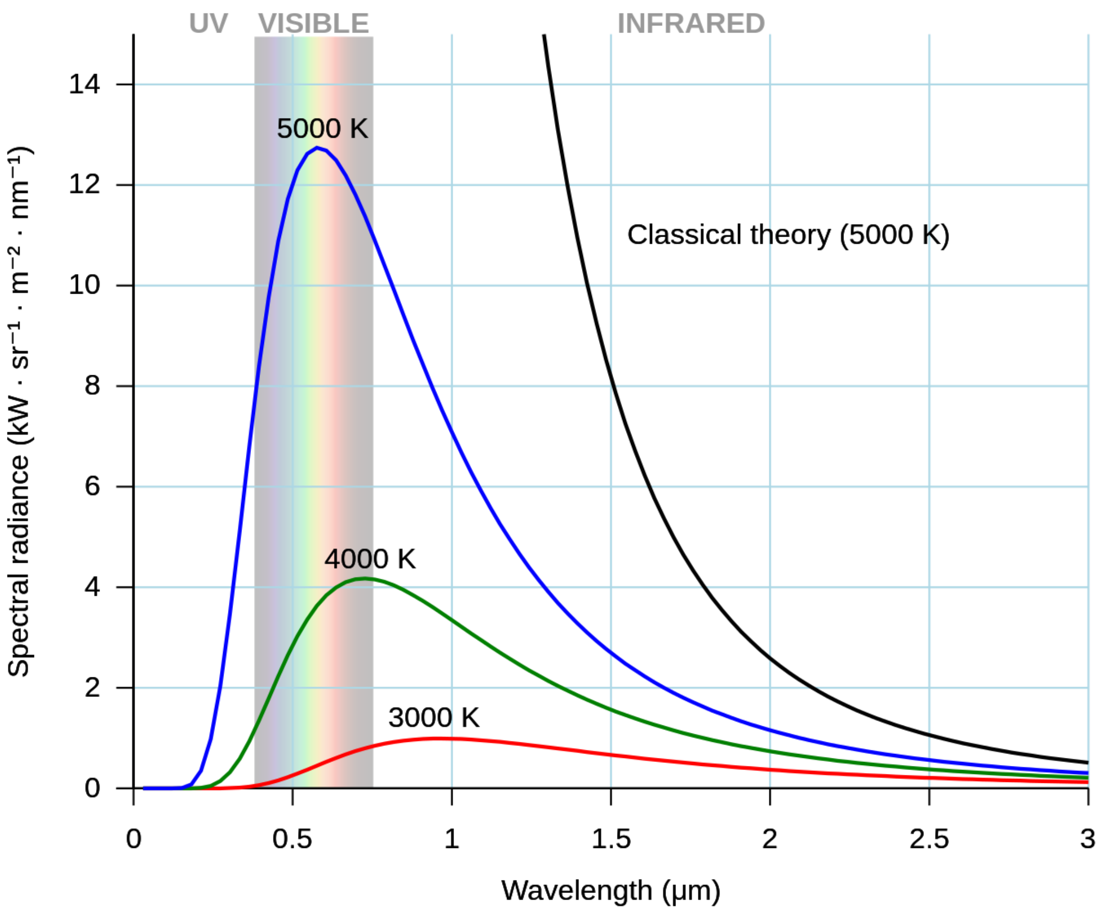
Viewing the Universe:
Electromagnetic radiation

- We see things (either through a telescope or the human eye) because of radiation
- Radiation is simply energy released by an energy source – it can be understood either as particles or waves
- Different types of radiation come from different physical processes in the universe – we mostly see electromagnetic radiation
- The energy released in the form of a wave has a wavelength – distance between successive crests.

Viewing the Universe:
Electromagnetic radiation

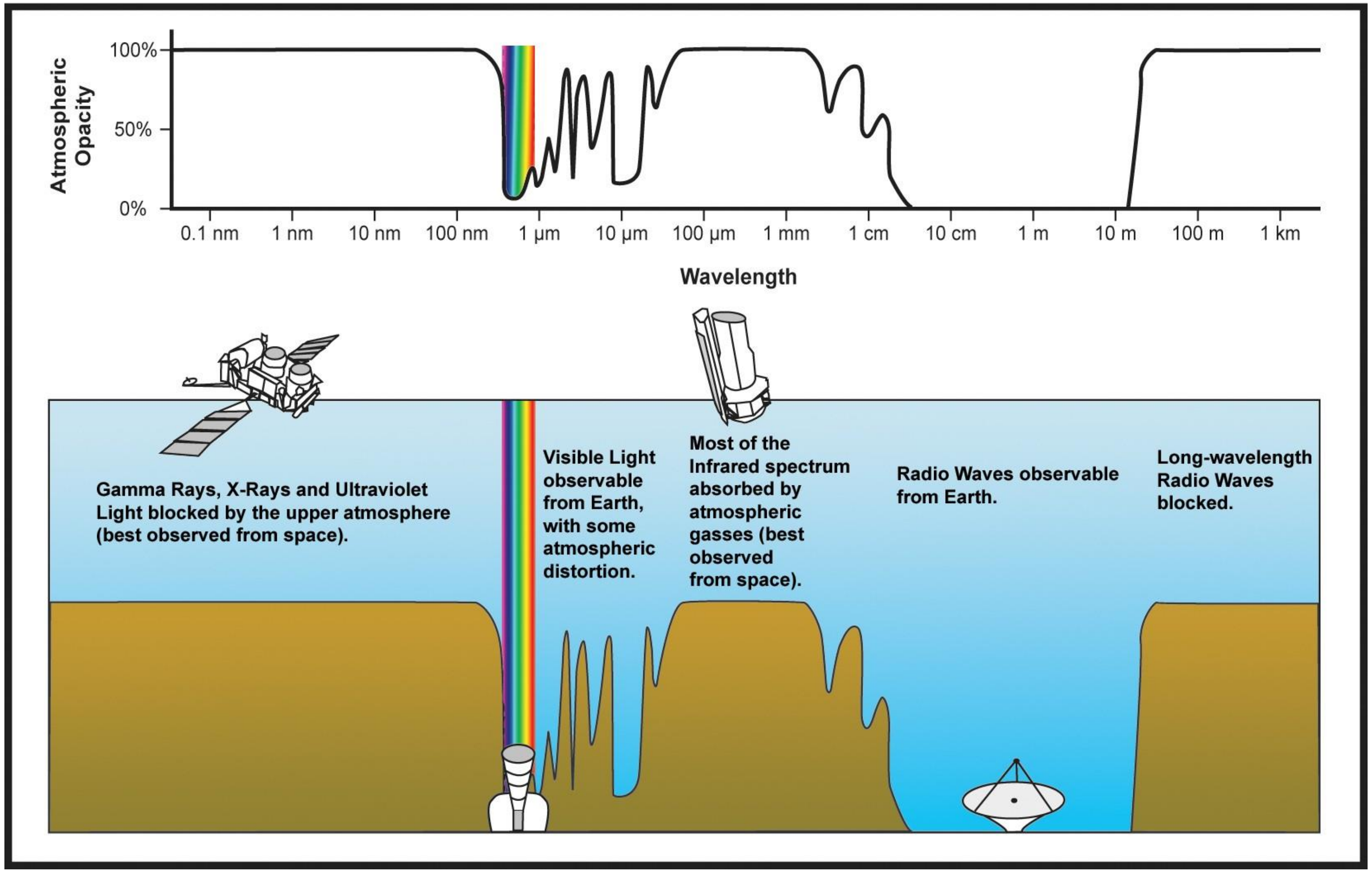
- Blackbody radiation -- a type of thermal electromagnetic radiation
- For a blackbody (e.g. the Sun), a single temperature of the object creates radiation at many different wavelengths.
- It has a 'continuous spectrum' of wavelengths, described by an approximate functional form.





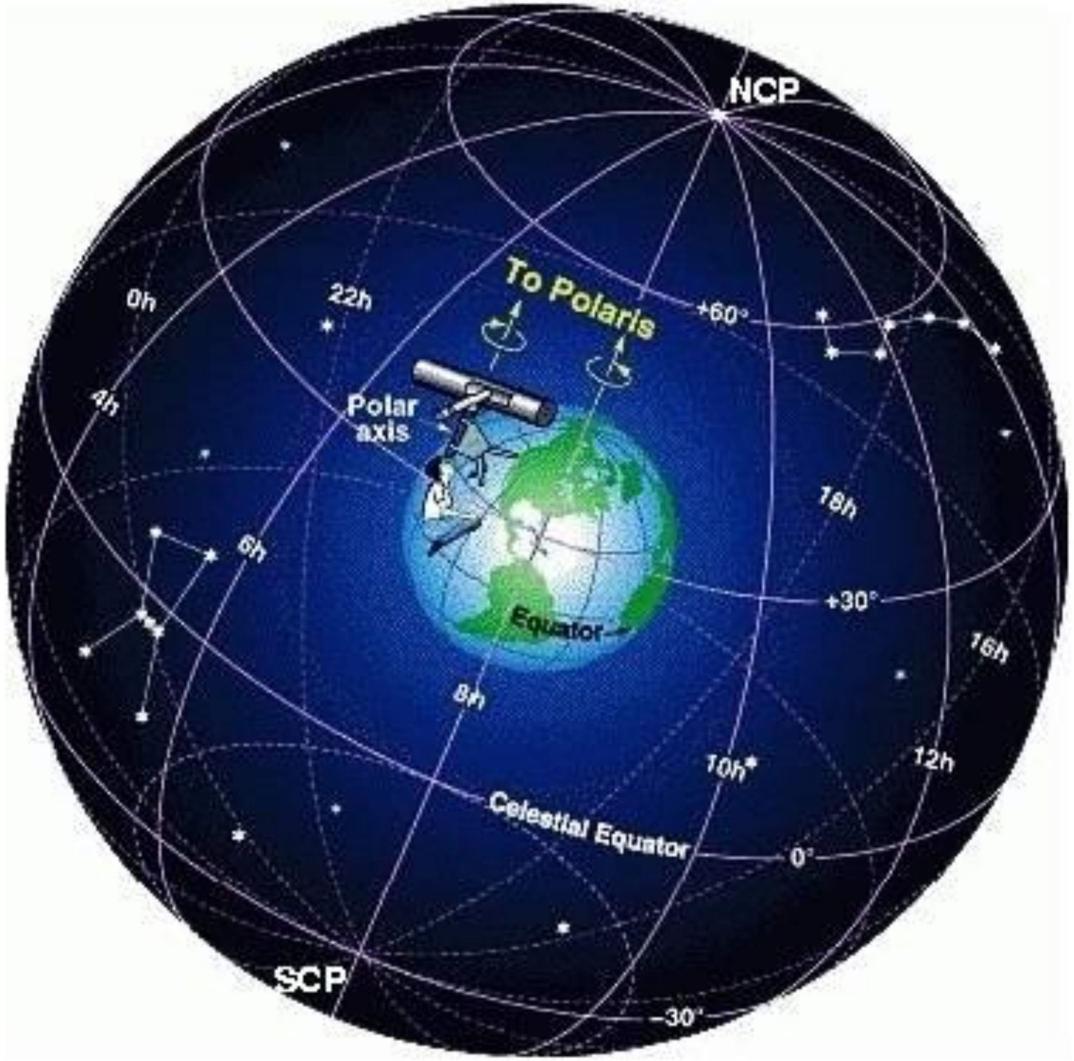
Rayleigh-Jeans law for blackbody radiation

Viewing the Universe – the radio window



Radio astronomy

- Universe is full of radio signals
- We've been collecting these radio signals and transforming them into 2D maps of the radio sky since the 1930s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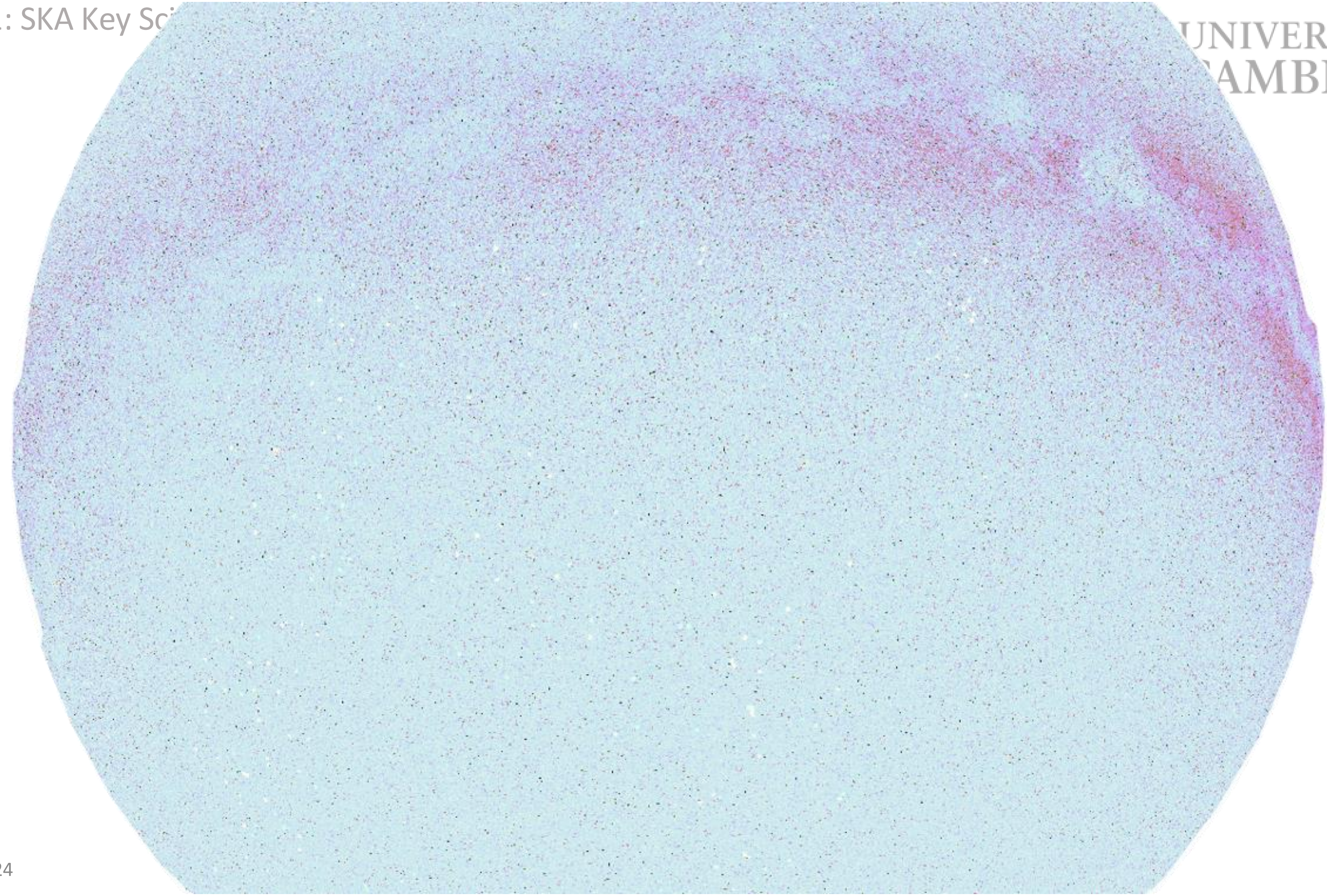
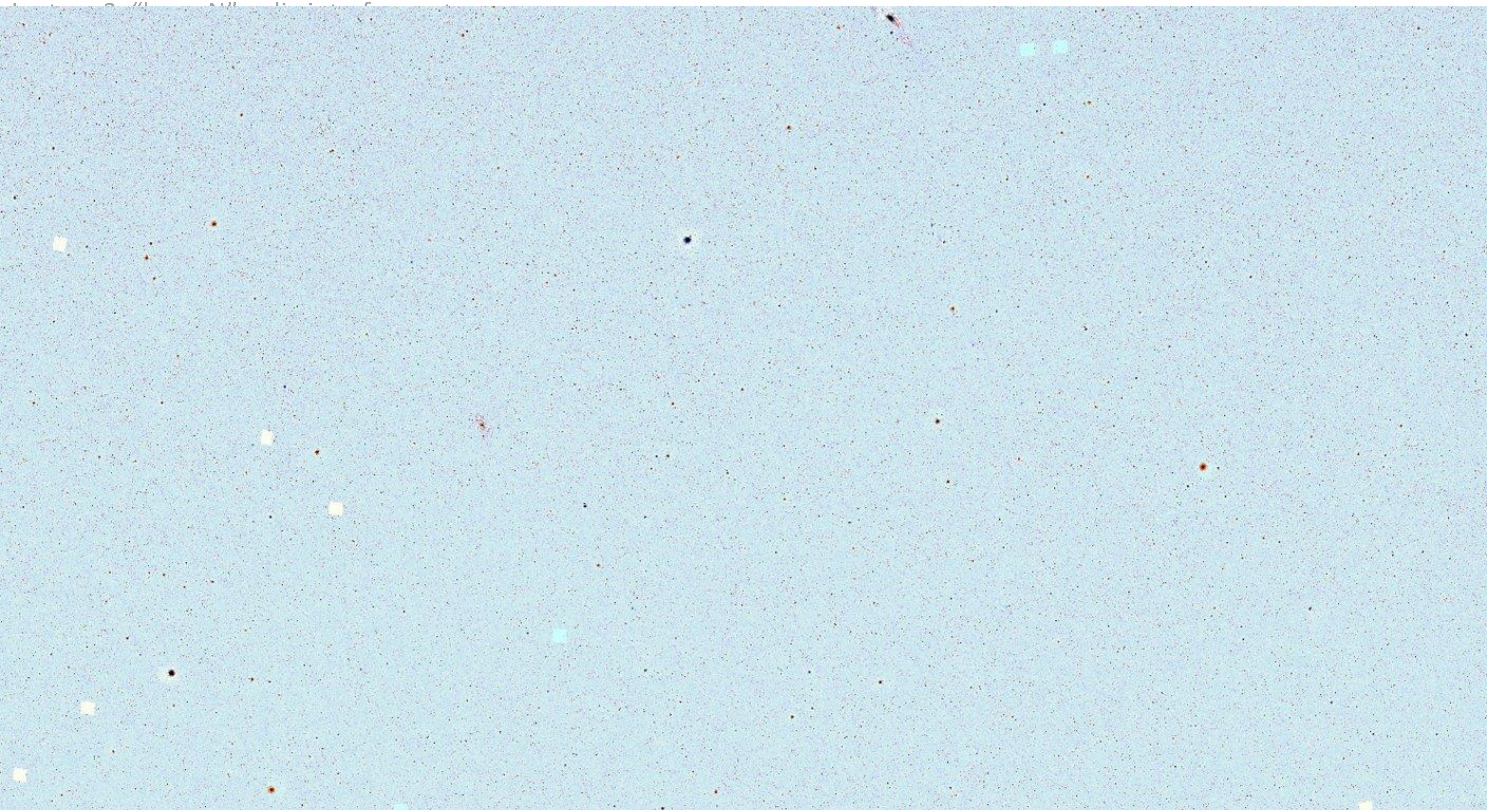
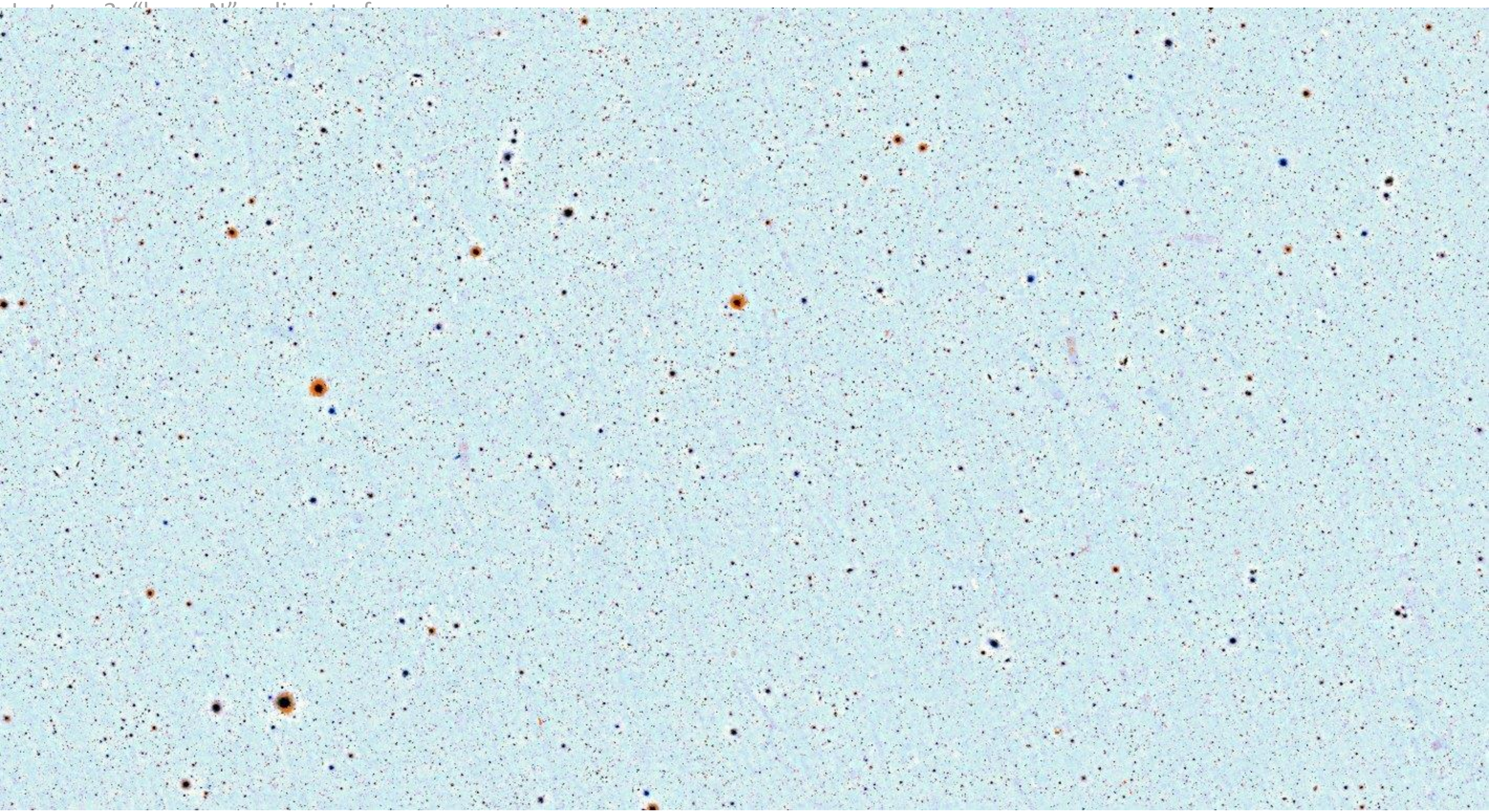
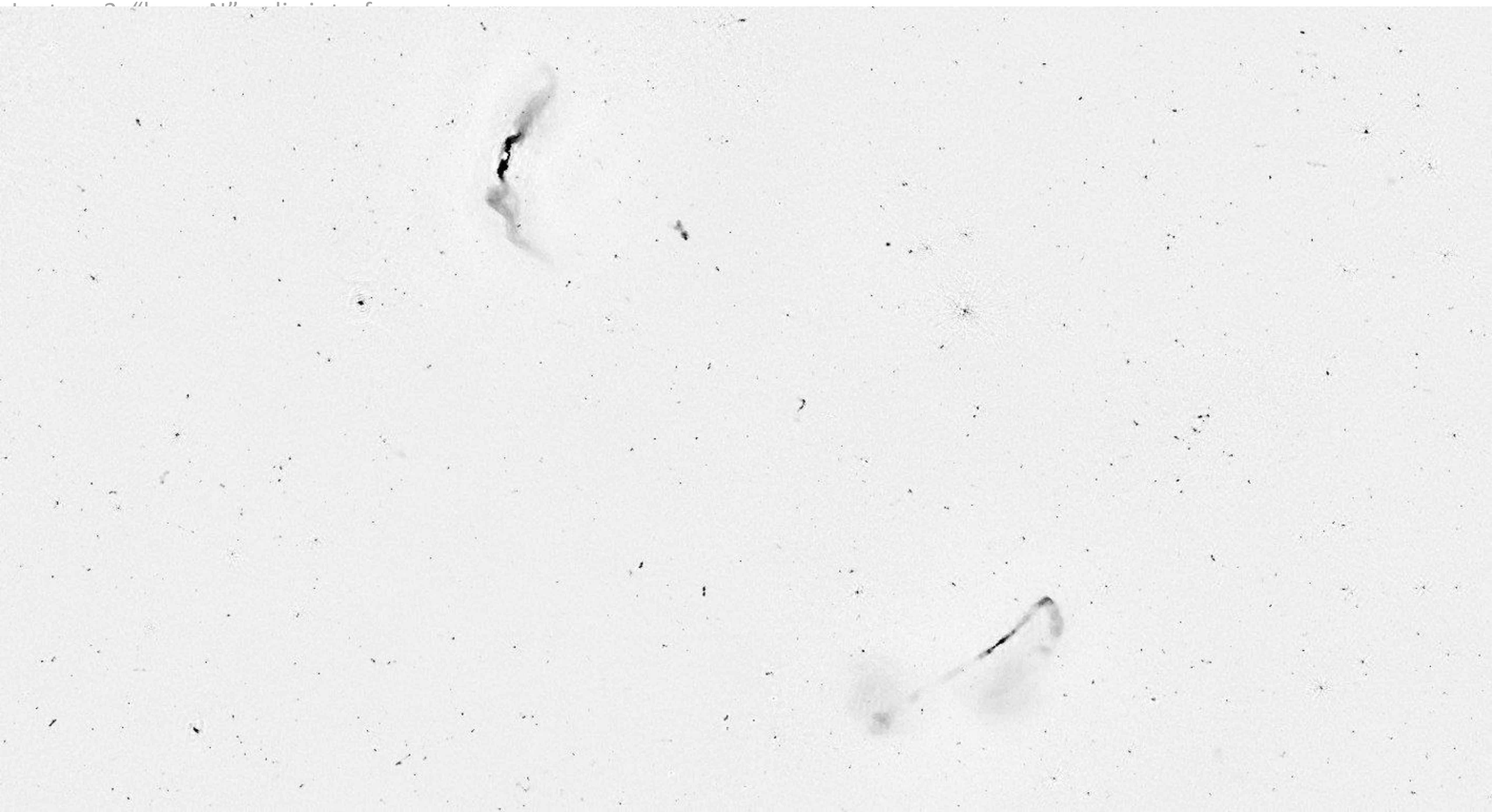
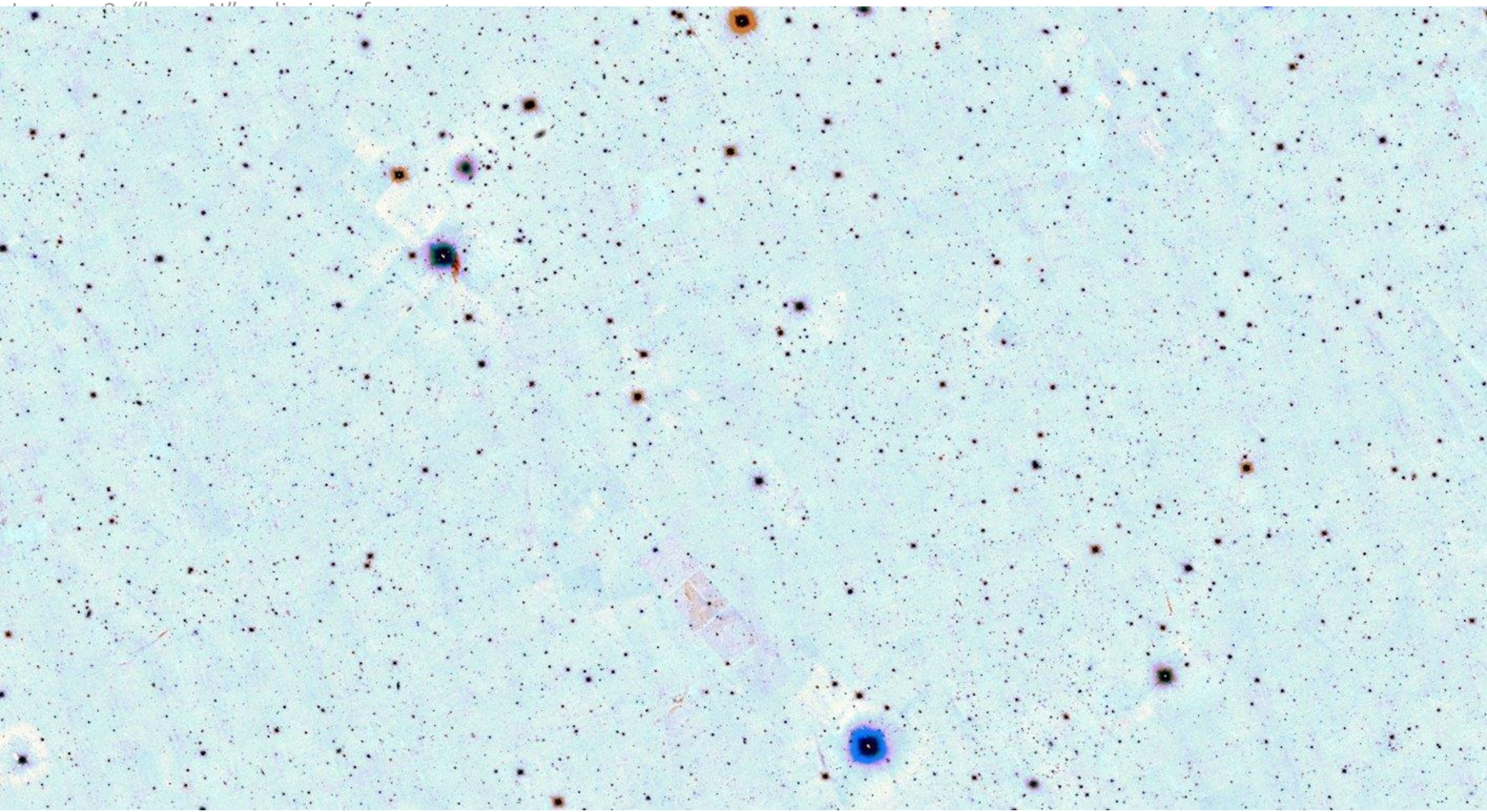
Polar axis
0h
22h
4h
6h
8h
10h
12h
16h
18h
+60°
+30°
0°
-30°
Equator
Celestial Equator
SCP

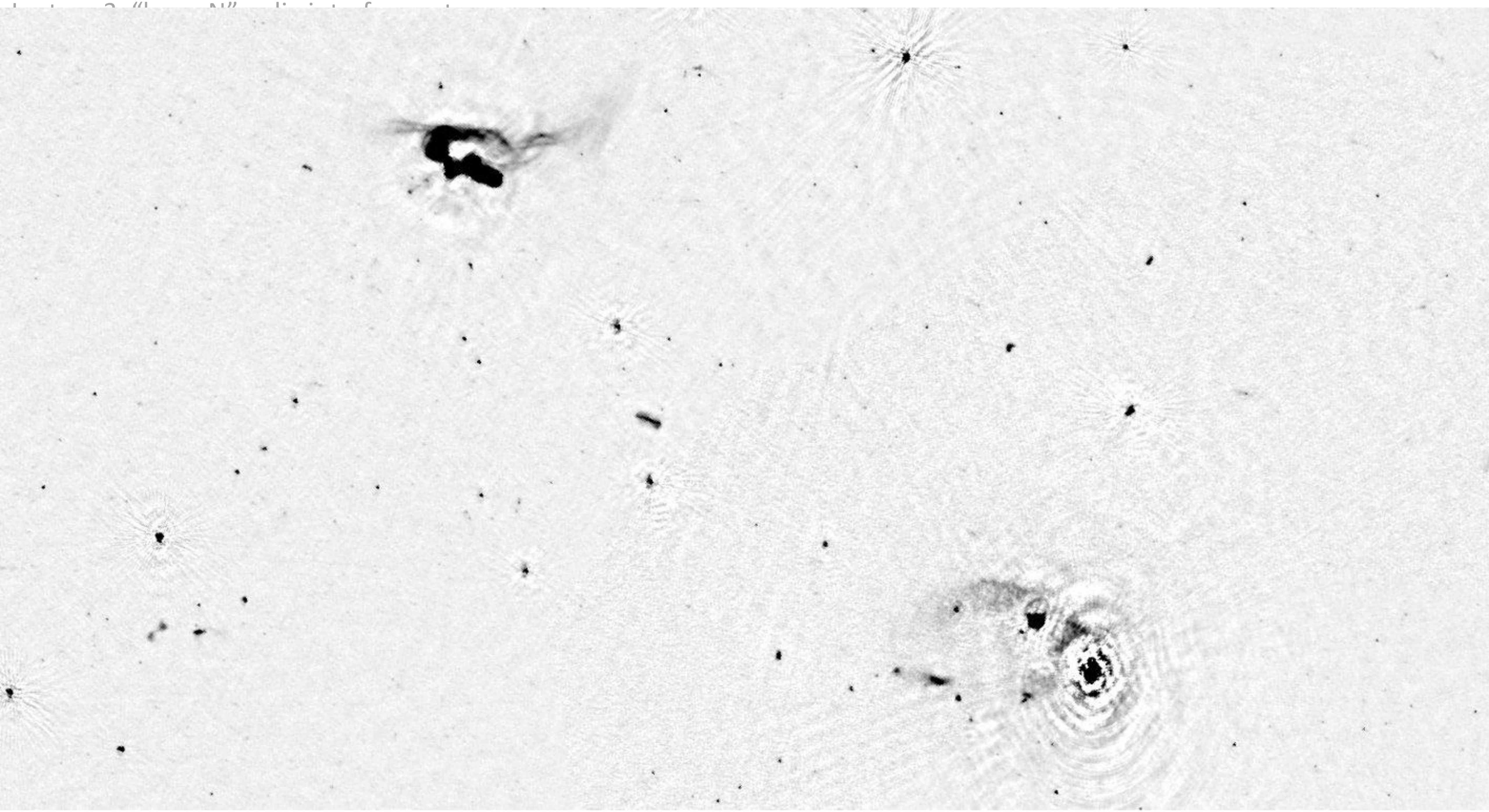


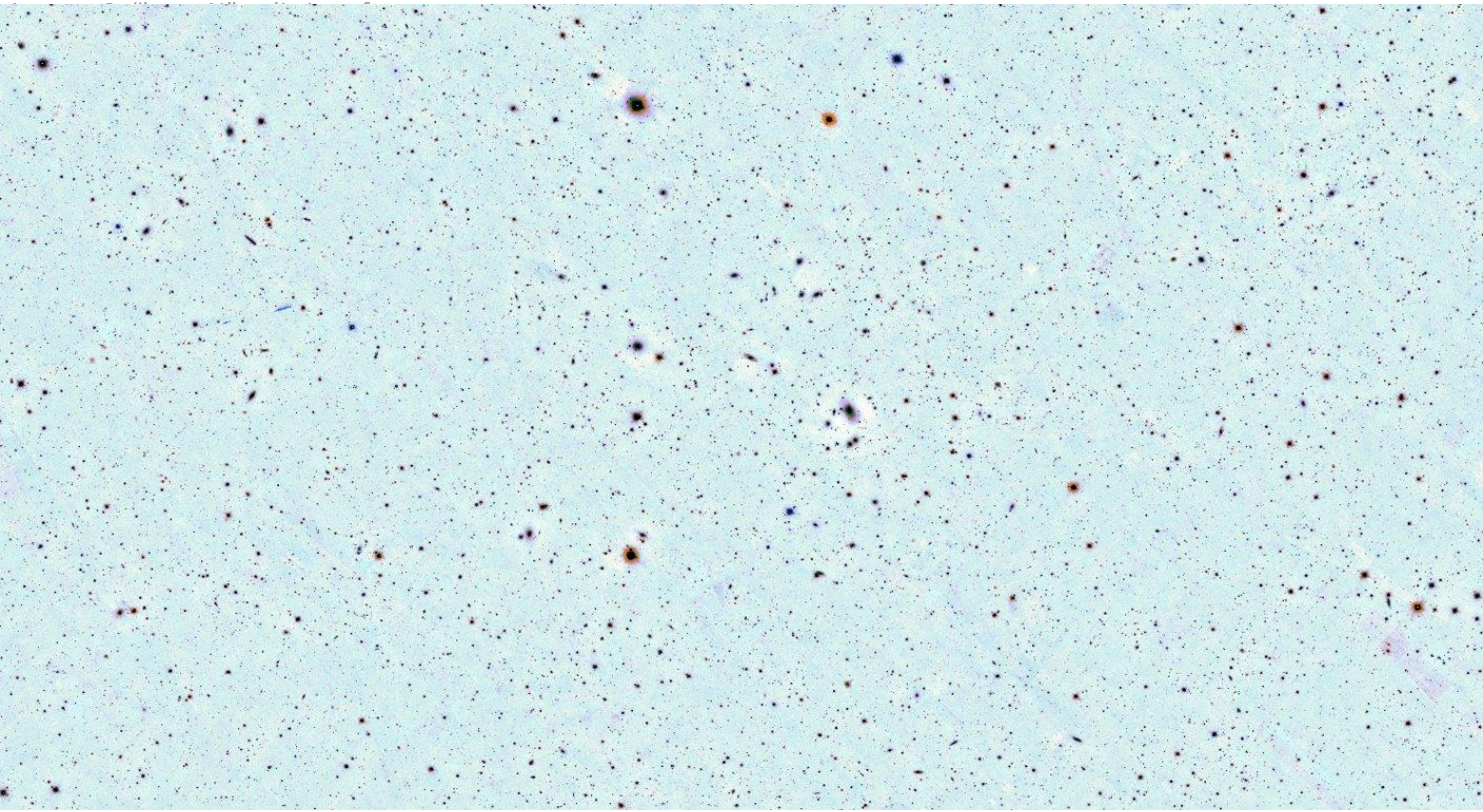


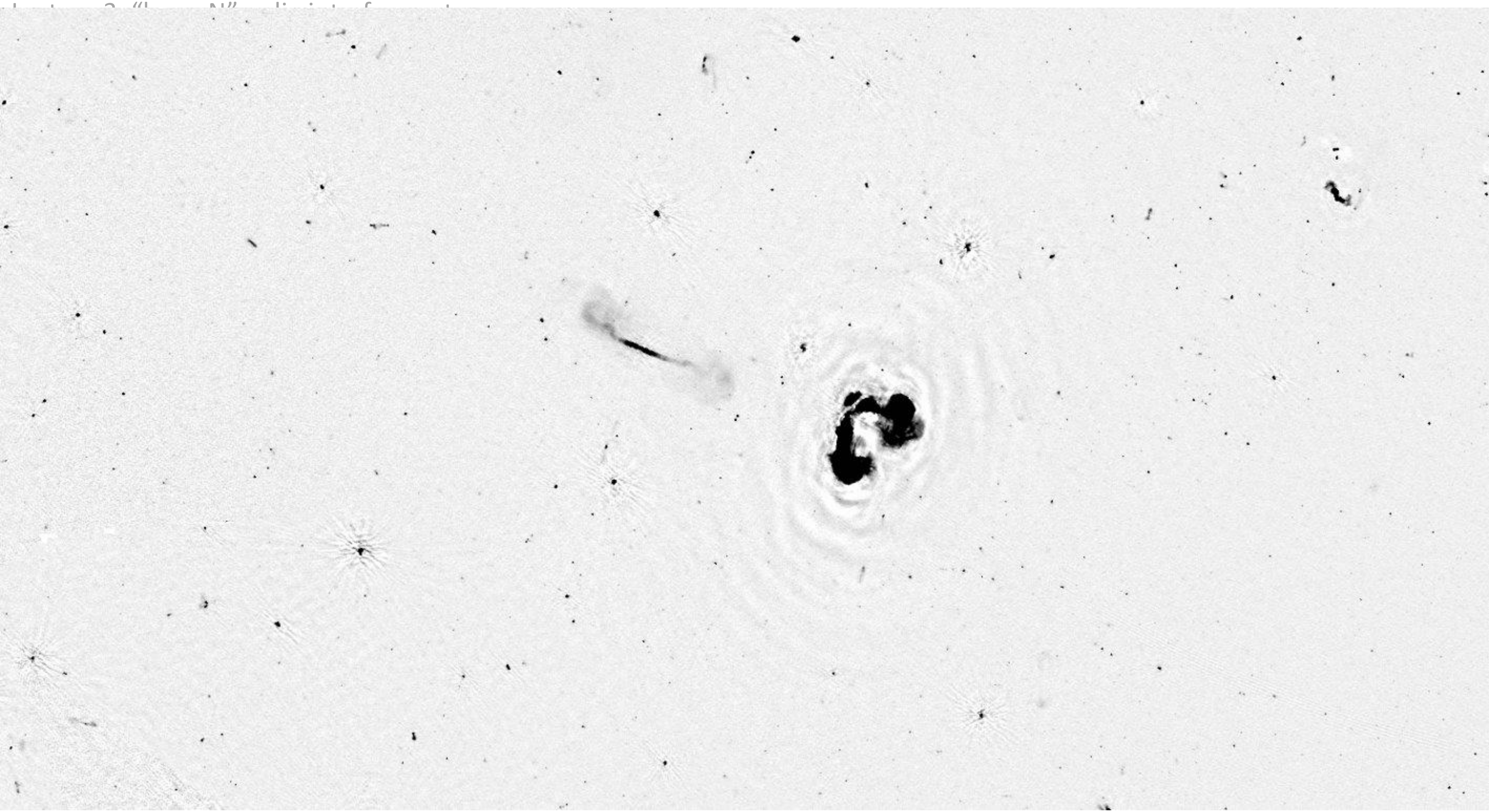




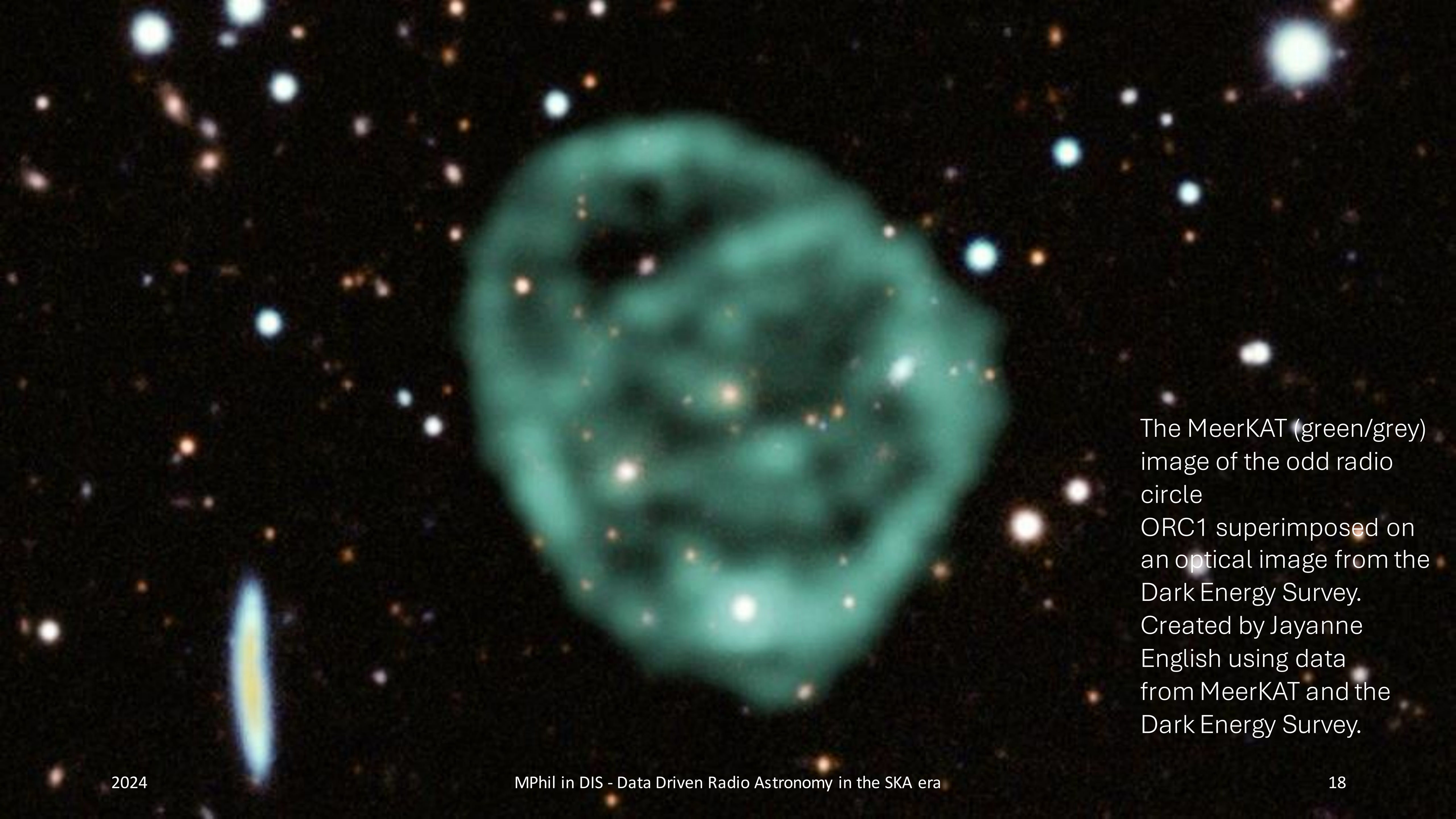




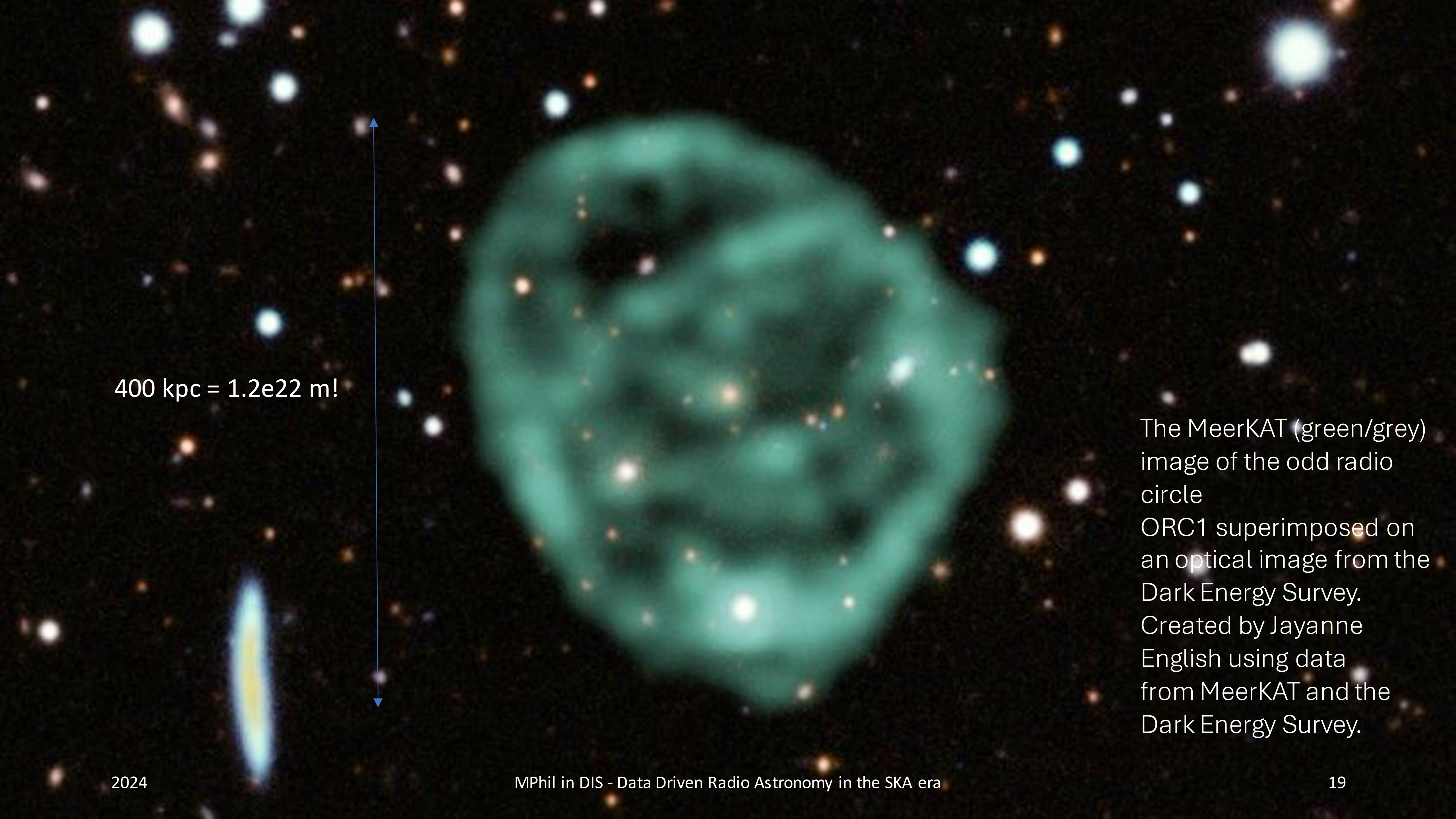




A galaxy-sized wind is revealed billowing out from a giant star factory, in a dust-enshrouded nucleus, that was triggered as two galaxies merge.Credit:N. Ramírez-Olivencia et el. [radio]; NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), edited by R. Cumming [optical]



The MeerKAT (green/grey) image of the odd radio circle
ORC1 superimposed on an optical image from the Dark Energy Survey.
Created by Jayanne English using data from MeerKAT and the Dark Energy Survey.



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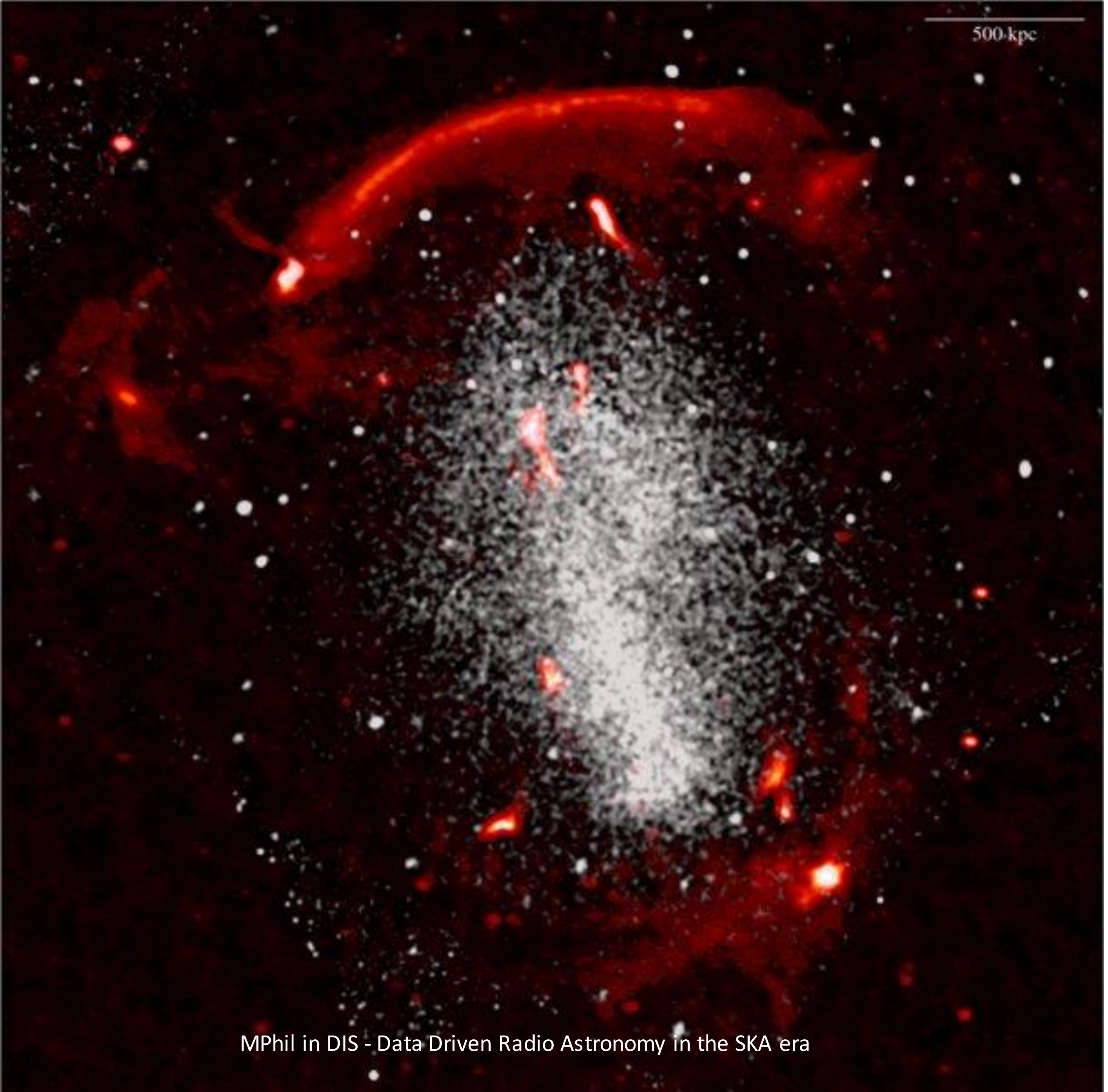

The merging galaxy cluster CIZA J2242.8+5301. The cluster is well-known for its giant radio source, dubbed the 'Sausage', in the North. Multiple radio sources including extended radio emission and tailed radio galaxies are detected with LOFAR observations (in red; Hoang et al. 2017). The cluster also hosts extremely hot gas in the cluster centre, seen with Chandra X-ray observations (in white; Ogrean et al. 2014). Image credits: Duy Hoang/LOFAR Surveys Team

The scientific research process in radio astronomy

Scientific hypothesis

- What mystery do we want to uncover
- What work has already been done – literature review

Formulate project

- Plan work (hypothesis, data preparation, analysis, conclusions)
- Form a team

Request telescope observations

- Decide what radio telescope you need
- Form document requesting telescope time
- Hope you get the time

Process telescope data and create required data products

- Data reduction/calibration using HPC

Perform scientific analysis and draw scientific conclusions

- Use HPC systems to analyse images/spectra

Write and publish research article in peer-reviewed journal

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Principle Investigator (PI) project

Key Science Projects (KSPs)

- “Key Science Projects” (KSPs) are observing projects that require large observing time allocations over a period longer than one *Time allocation cycle*.”
- Much larger than a PI project:
    - PI projects are when a few astronomers propose telescope time for a single science objective: "*We want to study the M31 galaxy to understand its thermal gas properties*. *We will understand how this galaxy works*. *We wish for 10 hours of telescope time*."
    - KSPs typically involve international collaboration of > 50 astronomers, are self-managing communities and strive to achieve large scientific goals: "*As a team of experts, we want to study and understand how galaxies evolved from the beginning of the universe. We wish for 1000 hours of telescope time. This will foster collaboration and innovation to produce the required data products needed for our science objectives*. *We will use <x> HPC with <x> TB/PBs of storage*."

Key Science Projects (KSPs) in the modern era

- Allow a coordinated approach to ensure that key science objectives are addressed efficiently and effectively
- Facilitate the delivery of derived data products (catalogues etc) as resources back to the wider scientific community
- Facilitate the sharing of knowledge and expertise among KSP members through extensive scientific and technical collaboration
- Provide a mechanism for ongoing oversight of observing programs that consume large observatory resources (principally observing time).
- Are large enough for grants to be written to purchase hardware

A paradigm shift in radio astronomy

- We are preparing for a paradigm shift from the next-generation instrument – the Square Kilometer Array
- The previous images were taken from SKA 'pathfinder' and 'precursor' telescopes – technologies, techniques, methods will be used to develop the SKA (hardware and software).
- This is conceived to enable groundbreaking science in the next few decades – SKA KSPs

The SKA

- One of the largest scientific projects in human history
- A radio telescope that will chase the boundaries of 21st century astronomy
- Two radio telescopes, research infrastructure and an advanced computing machine
  - Job creation
  - Technological innovation
  - Economic impact
- SKA Observatory (SKAO) is inter-governmental organization, funded and governed by an international treaty

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The SKA – two radio telescopes

Credit: SKAO

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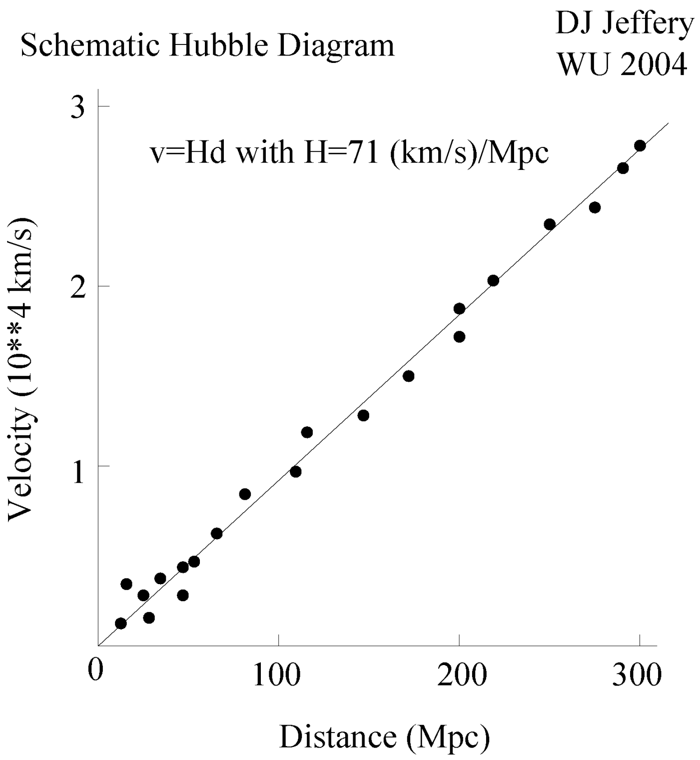
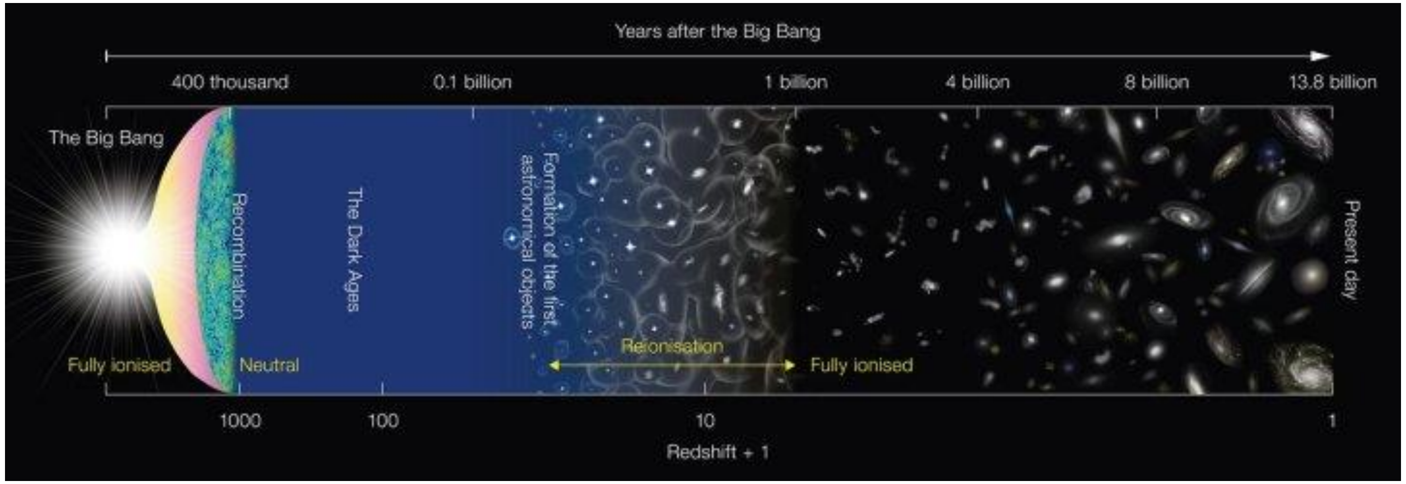
Key Science Objectives for the SKA

- Probing the cosmic dawn
- Challenging Einstein
- Cosmology and Dark Energy
- Exploring galaxy evolution
- Our home galaxy
- Seeking the origins of life
- Studying our nearest star
- Understanding cosmic magnetism
- The bursting sky

Probing the cosmic dawn





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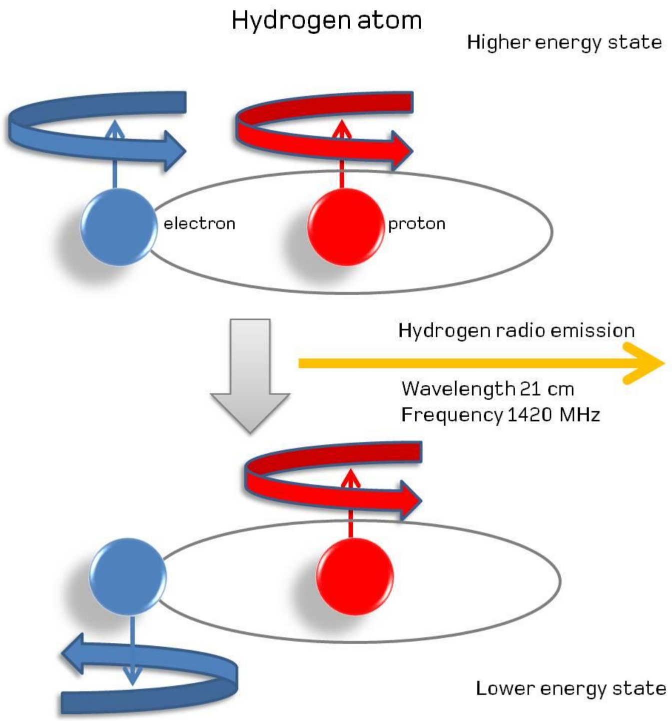
Probing the cosmic dawn

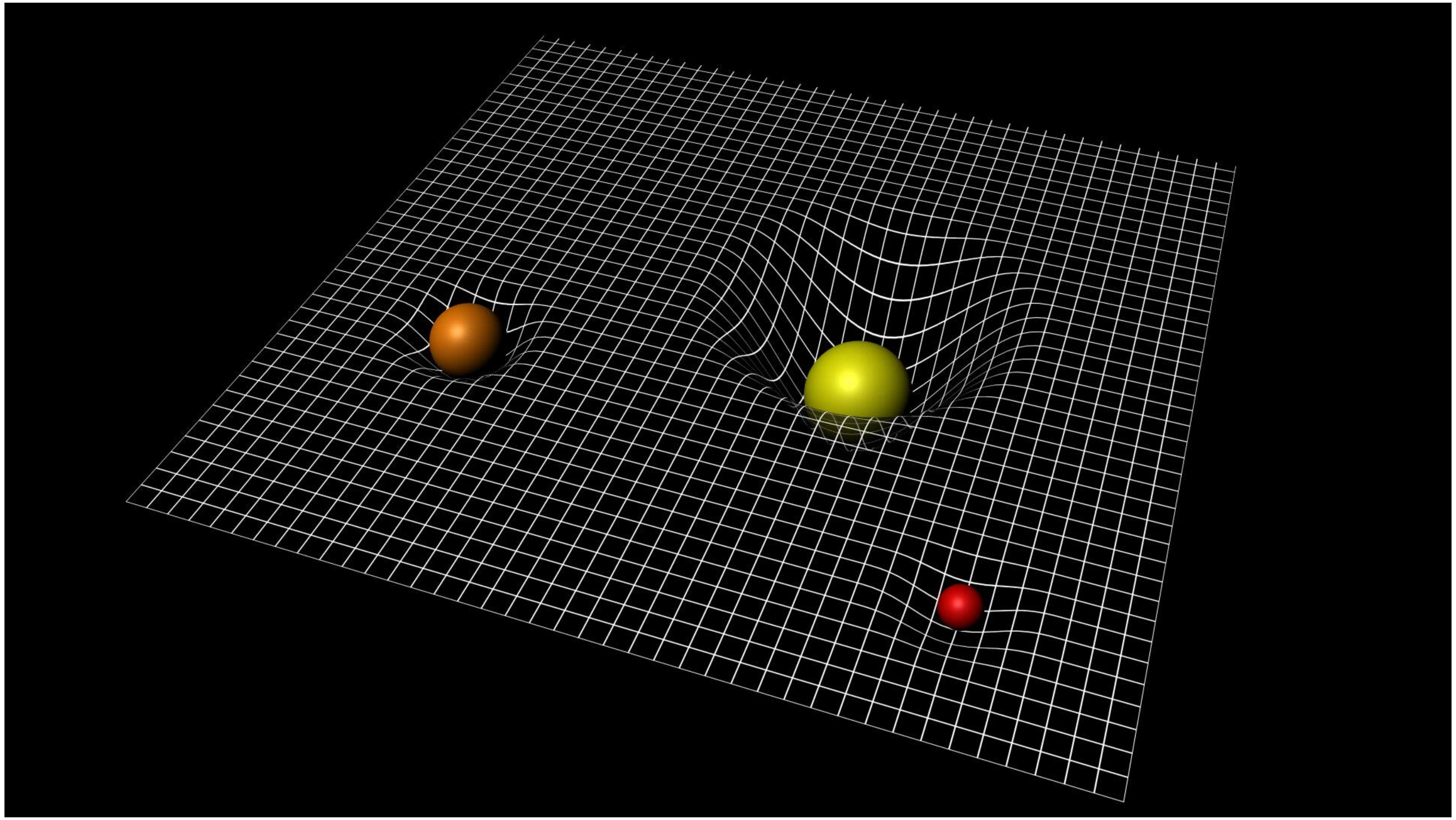
The race to catch the 21cm Hydrogen Spectral Line 14bn years ago



Credit: SKAO

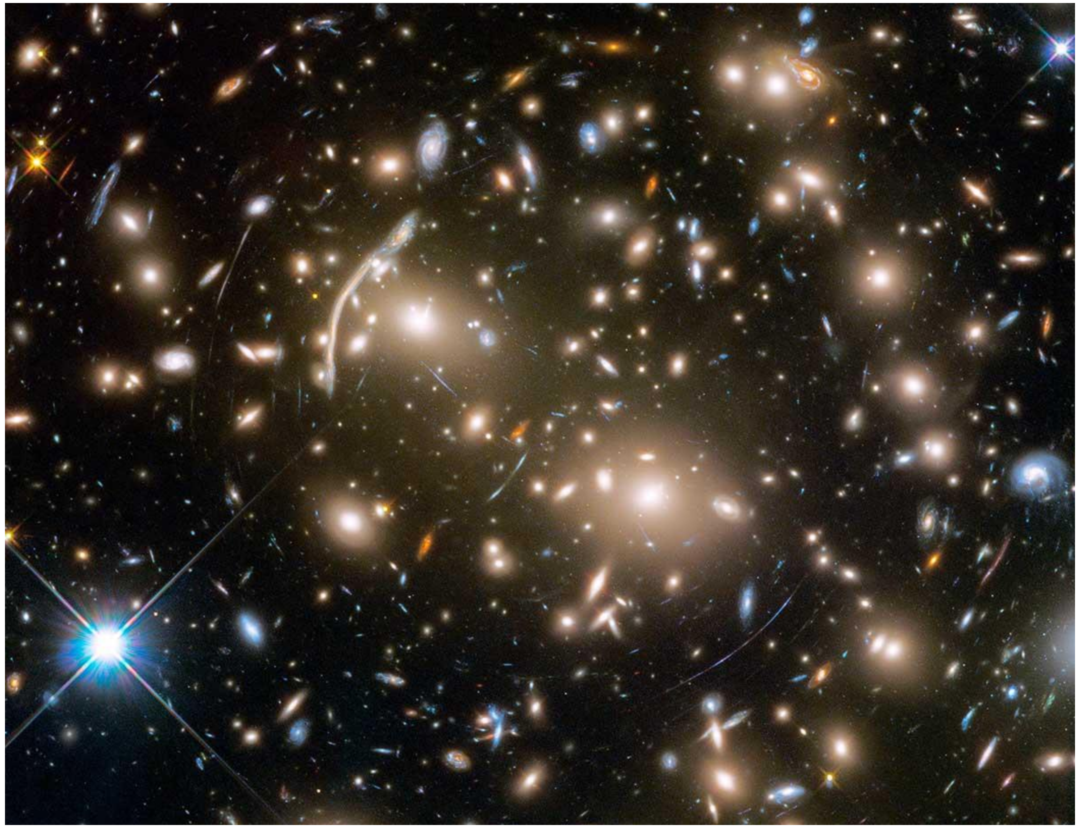
- The Universe was a fog of neutral (uncharged) hydrogen atoms during the Recombination era
- These atoms don't emit radiation, except once every 11 million years.
- A quantum-mechanical transition occurs, where the 'spin' of the electron flips
- This change in atomic state releases a packet of energy, that radiates at precisely 21cm, or 1.4 GHz – radio frequencies
- But since the first hydrogen atoms to now, that radiation has 'red-shifted', meaning it radiates at wavelength of 2m, or 150 MHz, by the time it reaches Earth
- Radio telescopes with 150 MHz receivers are trying to detect this Hydrogen line from the Recombination era.
- One of the primary drivers for the new SKA telescope

Challenging Einstein



Credit: ESA

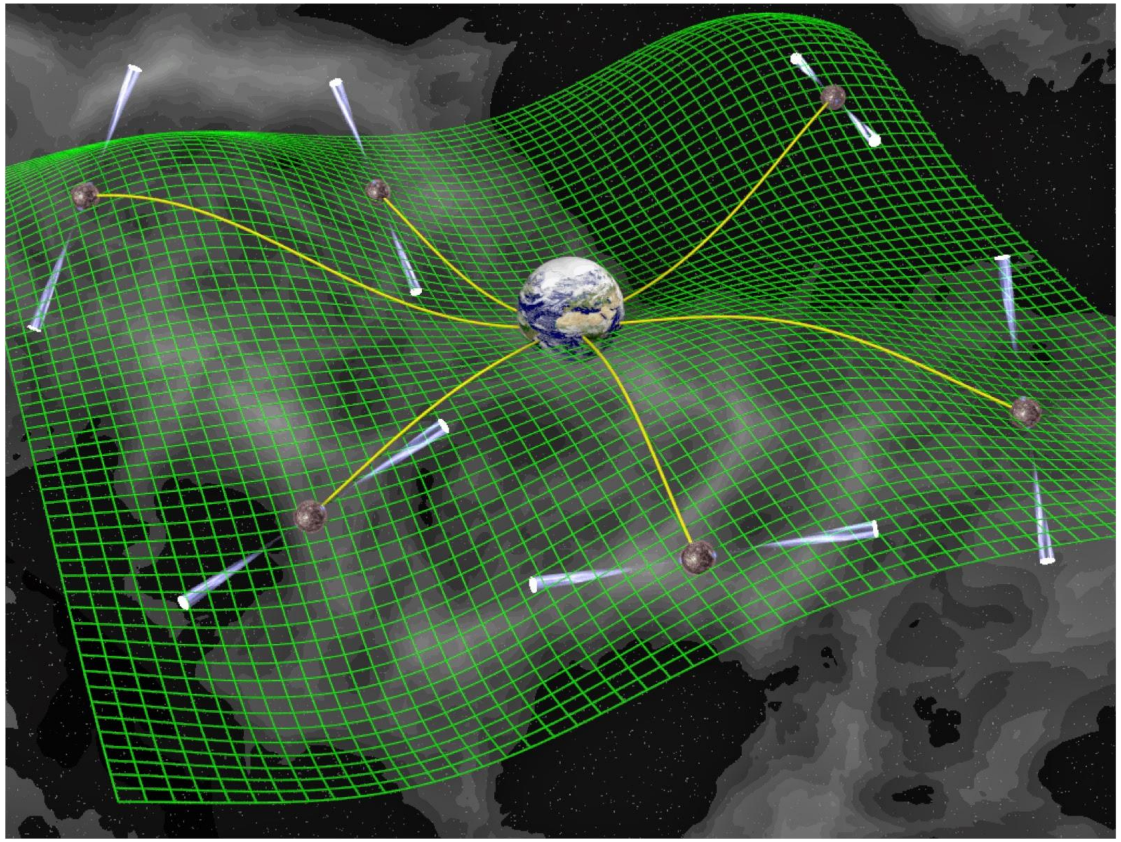
Challenging Einstein



Galaxy cluster Abell 370, located about 4 billion light-years away, contains an astounding assortment of several hundred galaxies tied together by the mutual pull of gravity. Entangled among the galaxies are mysterious-looking arcs of blue light. These are actually distorted images of remote galaxies behind the cluster. Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI)

- The existence of Gravitational Lenses (arcs) is direct evidence for the theory of General Relativity.
- This is also seen in deep radio images of the sky

Challenging Einstein

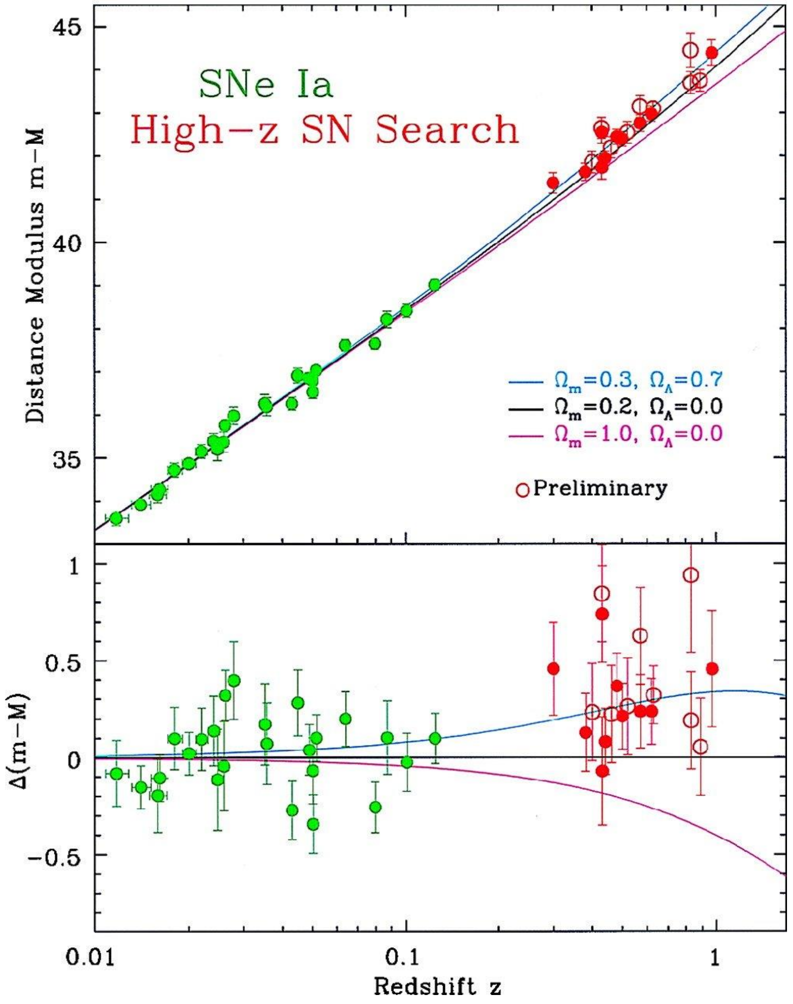


Credit: David Champion/NASA

- We can challenge the predictions made by Einstein by understanding Gravitational Waves.
- The LIGO instrument successfully detected GW in 2015 – exactly a century published his theory
- We can probe this in more detail with radio waves, by detecting pulsars
- Pulsars are rapidly rotating neutron stars that emit bipolar beams of radio waves
- Since they are spinning beams, their detection should be regular in time. But if gravitational waves are present around them, the detection spikes will become irregular.

Cosmology & Dark Energy

- Early theories envisaged that the universe has been expanding since the Big Bang, but gravity will slowly slow this down, and cause the universe to eventually collapse in on itself (the Big Crunch)
- In 1998, a series of Supernova-search projects determined the luminosities and distances of supernovae. Plotted in the Hubble diagram, these objects did not follow the 'Hubble law'
- Lambda-CDM (Cold Dark Matter) model of the universe is widely accepted



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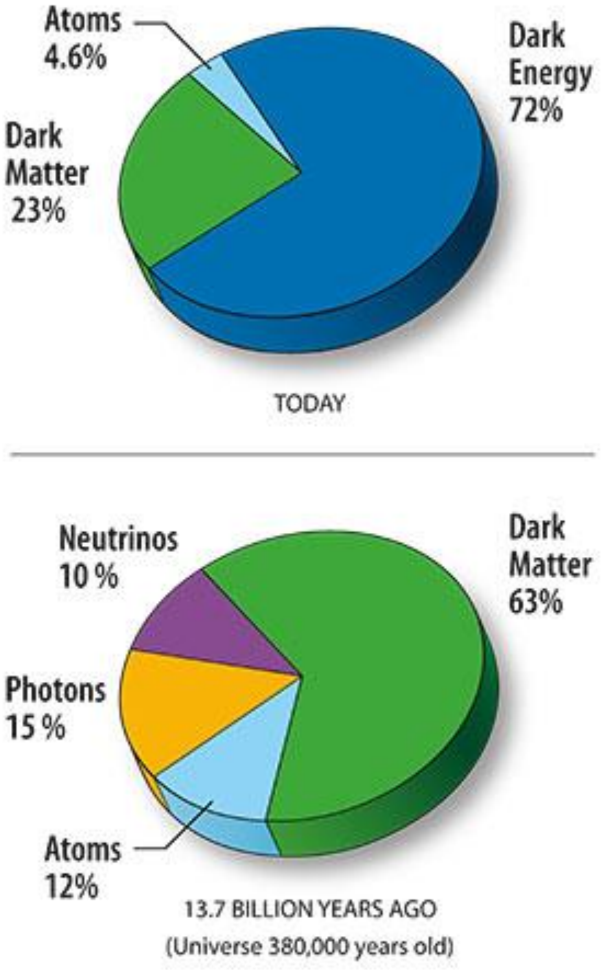
Cosmology & Dark Energy

Shedding light on Dark Energy

- The key to understanding dark energy and dark matter is to be able to map a large volume of the universe out to very large distances
- The SKA will conduct large surveys to map the youngest and newest galaxies, and study their evolution
- Can map the early HI distribution to trace dark matter



Credit: NASA/WMAP

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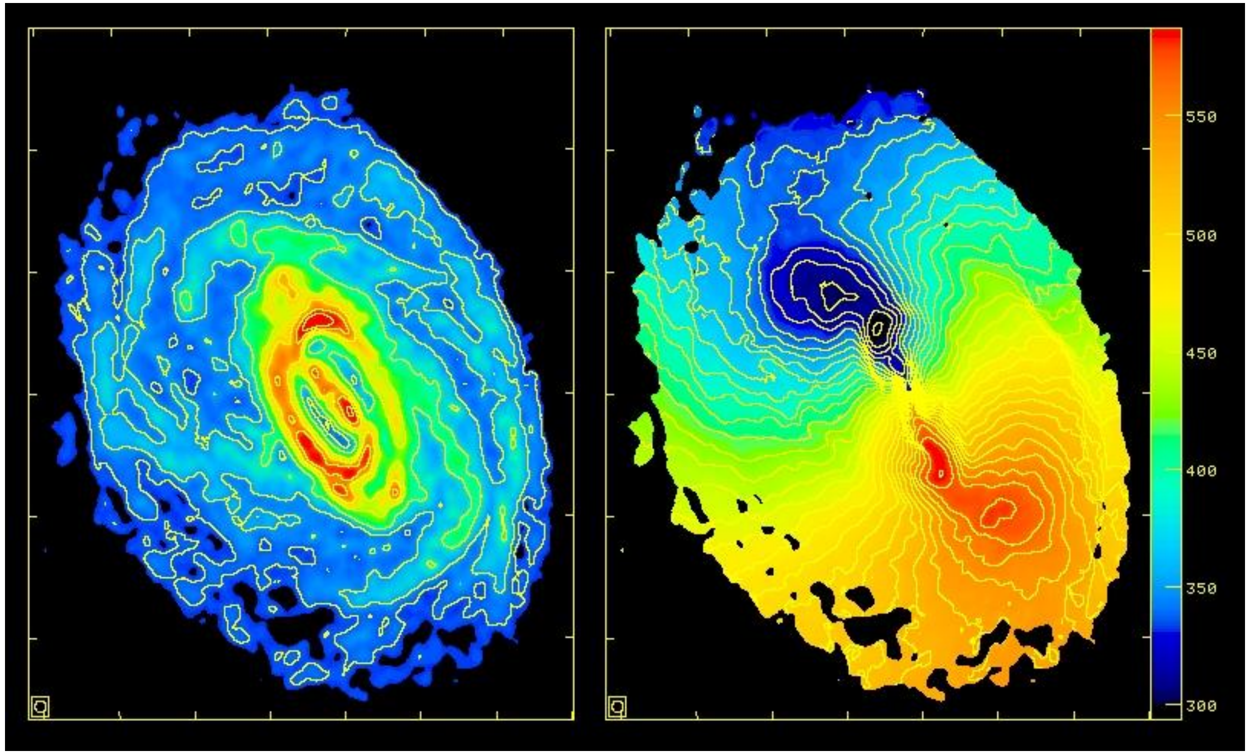
Exploring galaxy evolution

Shedding light on Dark Matter

- Lambda-Cold Dark Matter (Lambda-CDM) model: matter in the form of atoms and dark matter
- Hierachichal evolution of galaxies – atoms gravitate in regions of dark matter in the early universe. Can we detect this in the early galaxies?
- Map the hydrogen gas distributions of galaxies
- Is the gas rotating faster than would be expected from just the atoms that radiate? If yes, then we have a probe for Dark Matter existing.
- Radio telescopes allow us to see through dust clouds, which block optical light. They are also good at detecting neutral hydrogen and certain molecules abundant in galaxies
- SKA will have the sensitivity to map extremely faint galaxies

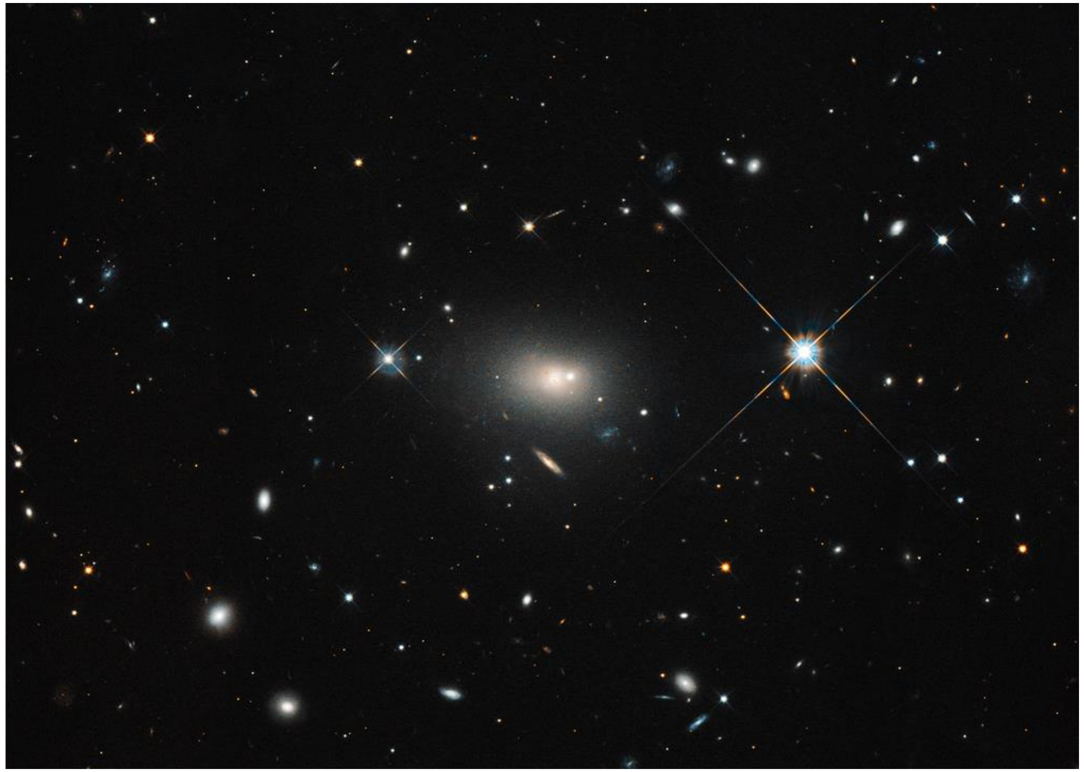


Credit: *ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO)*

Exploring galaxy evolution

Shedding light on Black Hole physics

- The most massive galaxies in the universe are elliptical in shape, and have masses > 10^13 times the mass of the Sun.
- They contain proportionately bigger black holes in their center
- These black holes are active, releasing bipolar jets of radio emission
- Although a fraction of galaxies host these radio jets, they have a profound effect on galaxy evolution
- They control how much a galaxy can grow
- The SKA will detect most of these objects in the observable Universe, and we can probe their physics with very large samples



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), and the Hubble Heritage Team (STScI/AURA)

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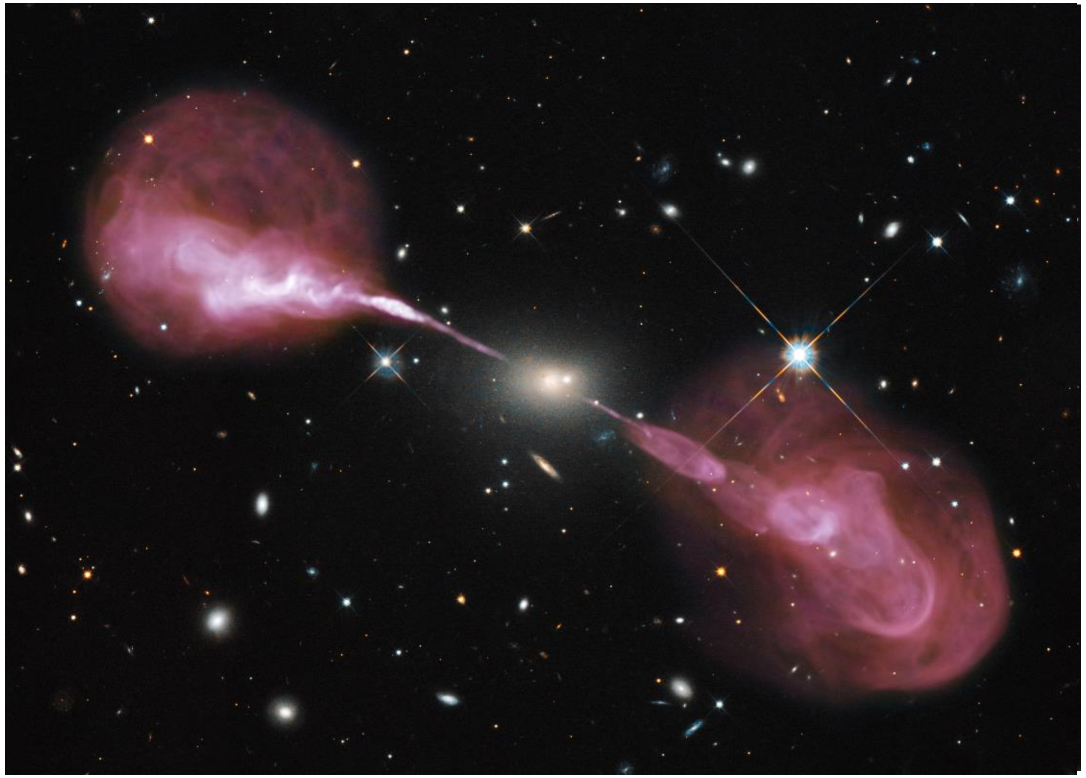

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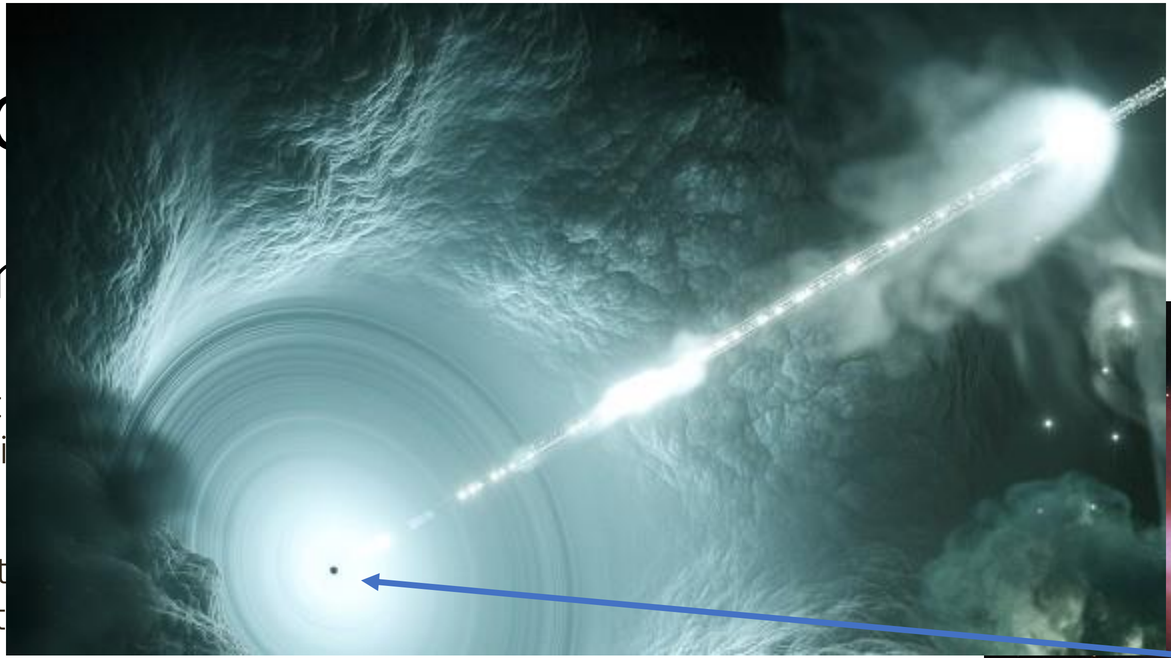

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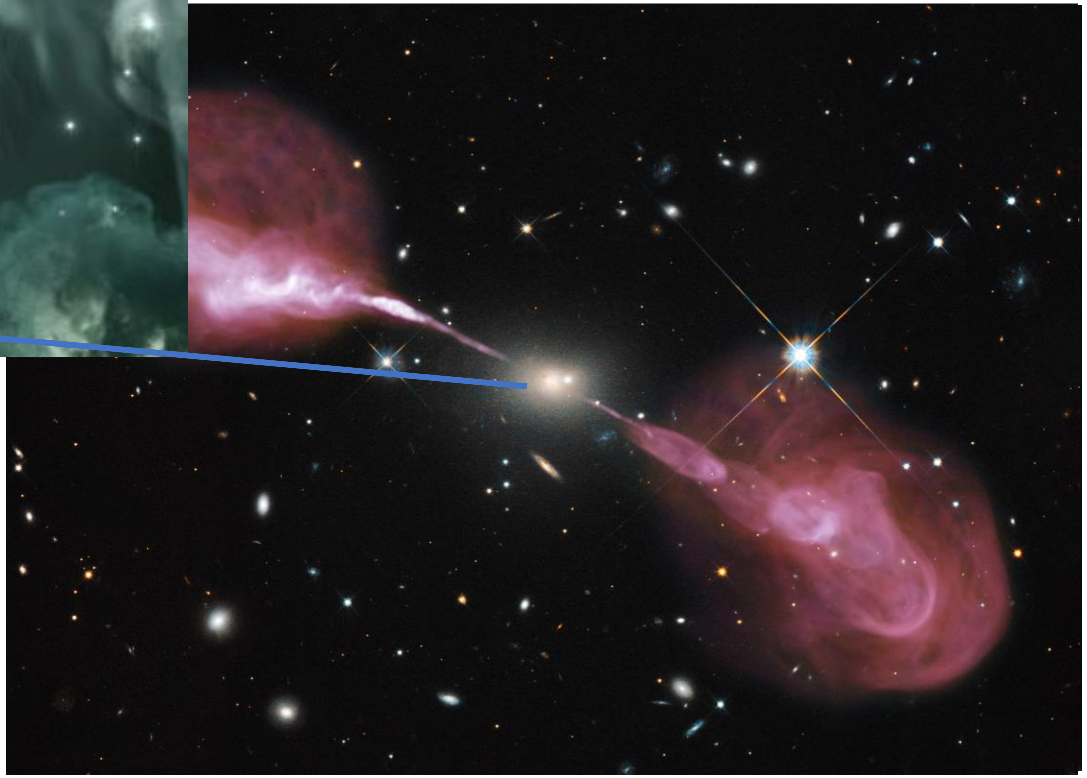
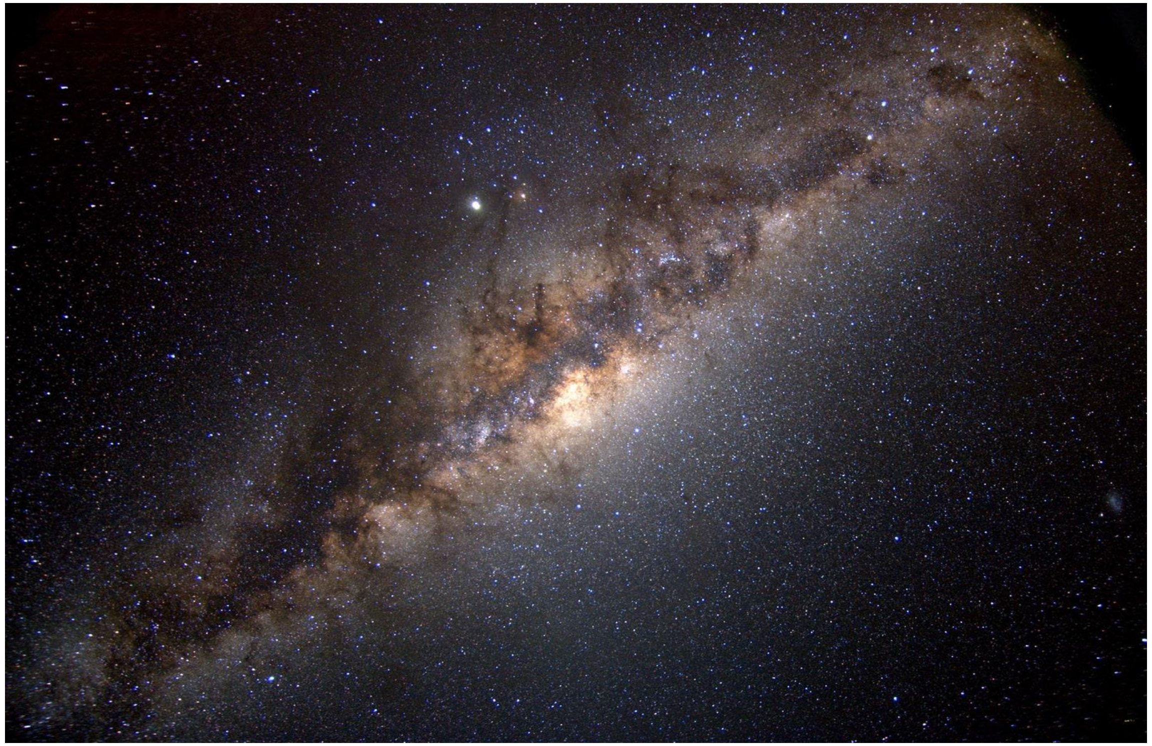


Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), and the Hubble Heritage Team (STScI/AURA)

Our home galaxy

- The internal structure of a galaxy contains gas, dust, stars, black holes, dark matter and many more objects. So far
- How do stars form and evolve? How do they explode?
- What is the interplay between gas and dust and objects that form over a lifetime of the Galaxy?
- What is the nature of supermassive black holes?
- What is the role of magnetic fields in the interstellar medium?
- Looking at our own galaxy gives unparalleled resolution and sensitivity to how a galaxy works internally.
- New radio telescopes have given more information on the energetics of our Galaxy,



Credit: NASA

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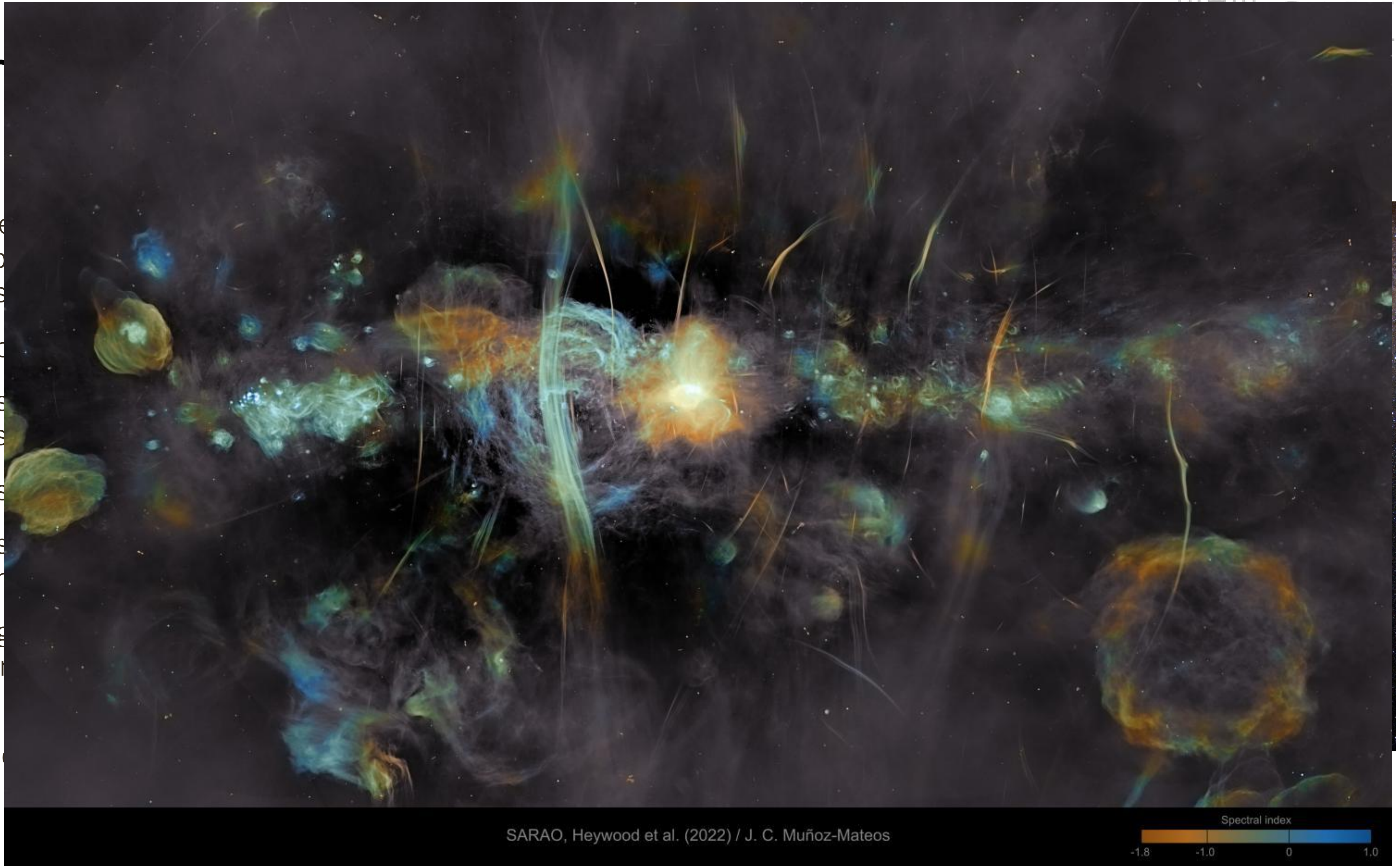
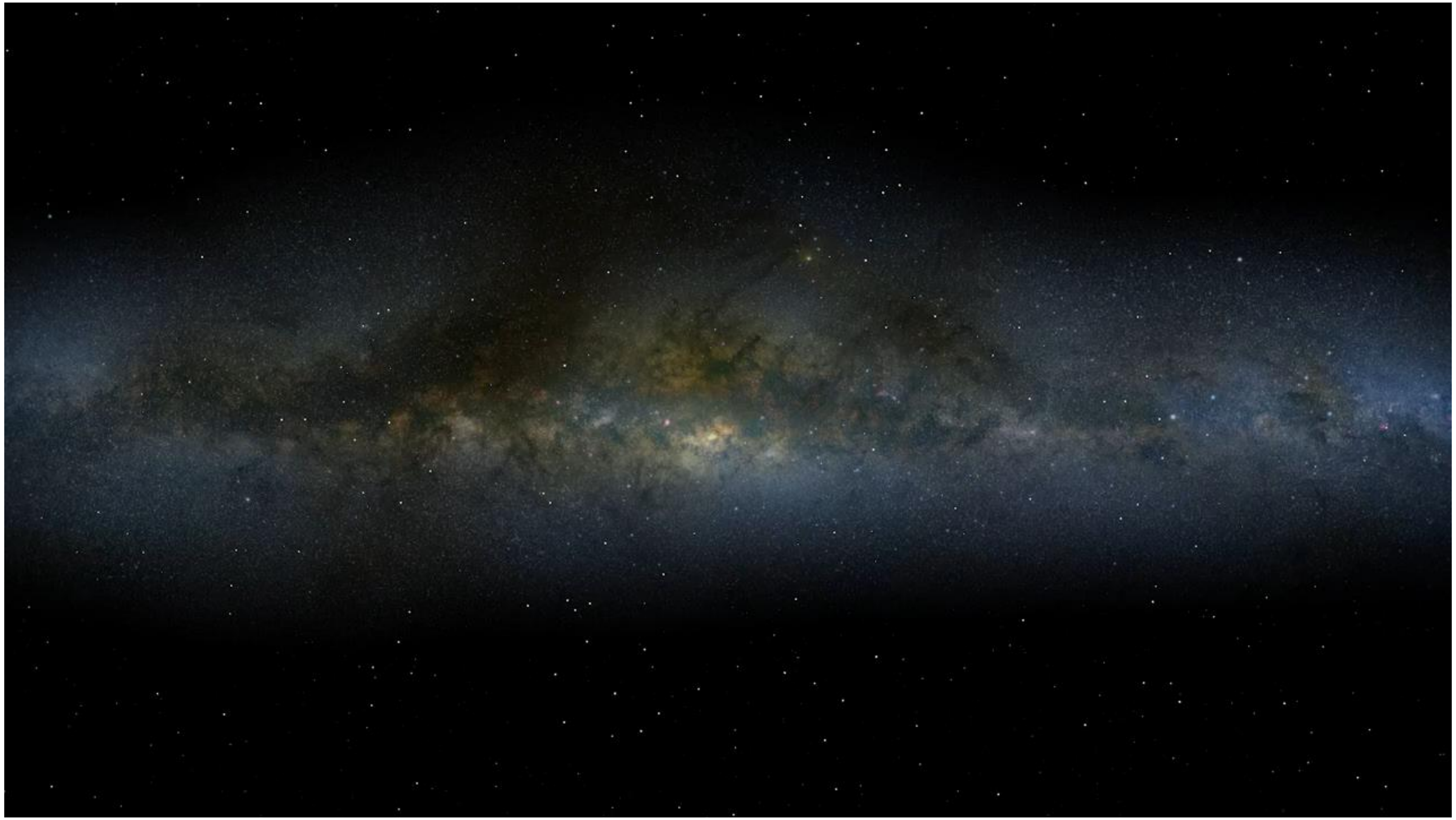


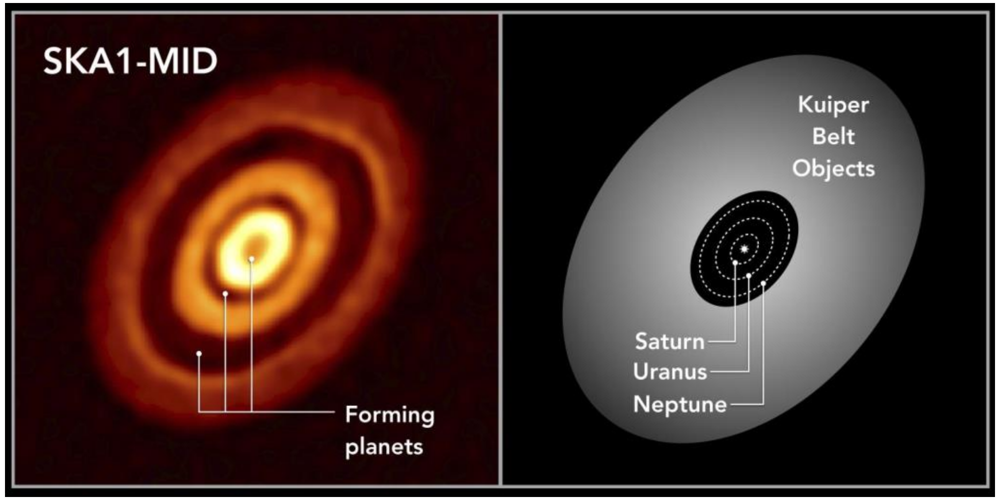
Seeking the origins of life



Credit: SKAO

Seeking the origins of life

- Newly forming stars have shrouds of dusty dics around them – we believe that fragmentation of these dics are the origins of planets
- This process is not well understood, but radio observations can observe these dust particles
- The solar system can bridge the gap between the early periods of star-planet formation and the late stages
- Organic molecules have been detected in a number of comets and other objects and emit radio waves
- Are we alone in the Universe? What composition of organic molecules and planetary atmospheres allows life to form?
- The Earth's magnetic field shields us from the Sun's harmful ejections – understanding the magnetic field structure of other planets help us understand habitability
- Sensitive radio telescopes will detect more planets in the Milky Way



Left: simulation of a radio observation of a protoplanetary disc. Right: Same-scale representation of the solar system (Ilee+20).

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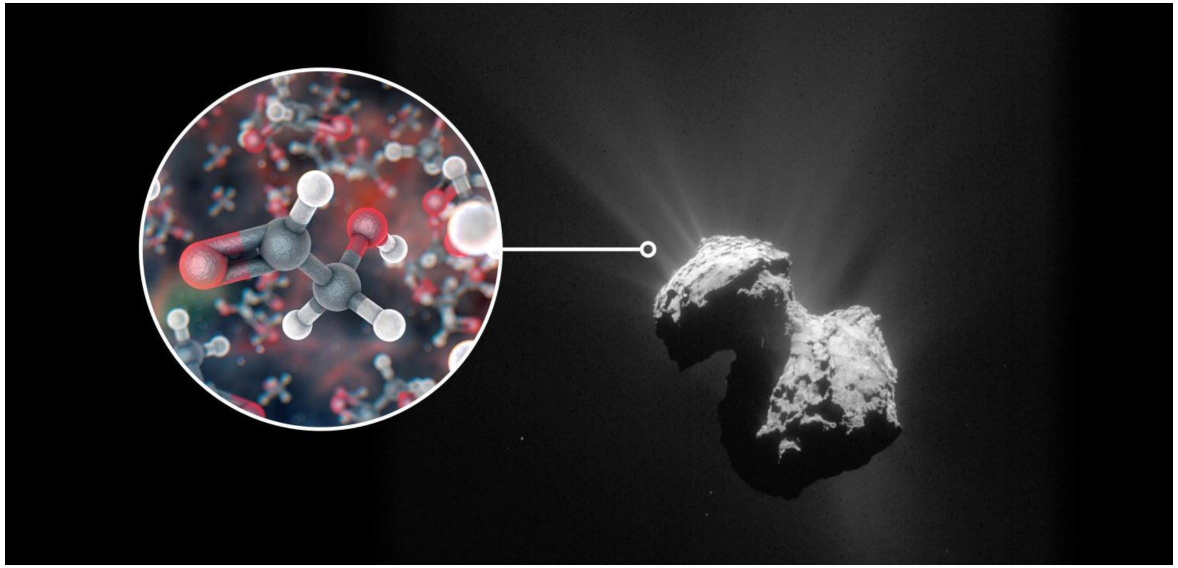
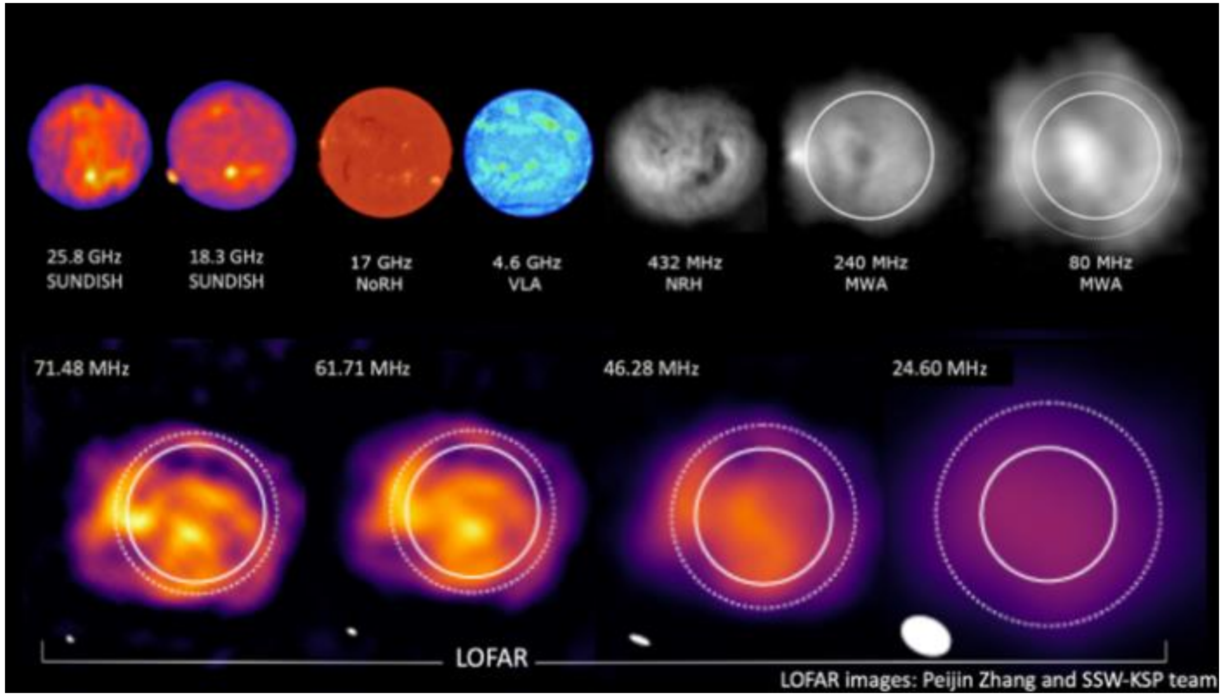


Credit: ESA/Rosetta/NAVCAM

Studying our nearest star

- Stars aren't just static objects, they are dynamic
- The Sun has solar flares, coronal mass ejections and strong magnetic fields
- The Suns coronoa (upper atmosphere) is hundreds of times hotter than the surface – direct violation of the laws of thermodynamics
- Magnetic fields drive high energy physics – emission from these processes radiate at radio wavelengths
- Unique probe of space weather in the heliosphere
- Understanding of these processes requires very highly sensitive radio observations



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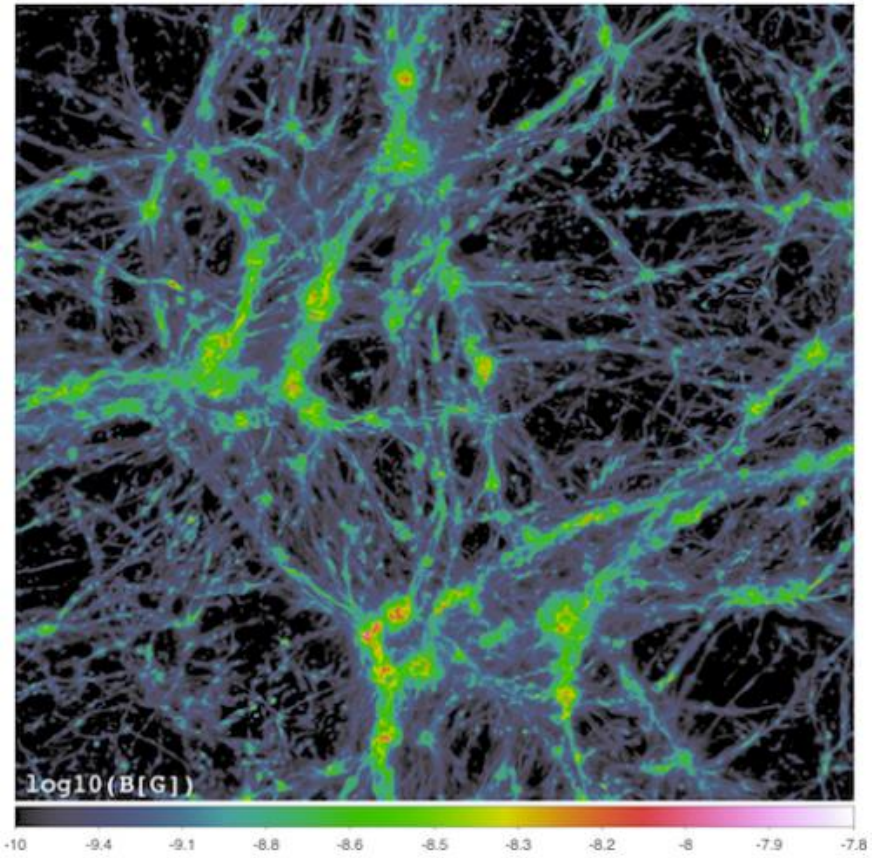
Understanding cosmic magnetism

- Magnetic fields pervade the universe on all scales
- From the smallest scales (magnetic fields between protons and electrons) to the largest scales (magnetic fields in galaxy clusters), they affect how the universe evolves
- How did strong magnetic fields originate at the beginning of the universe, how did they evolve to the present day?
- Mapping the magnetic field structure of the sky gives us clues
- Radio telescopes can indirectly map magnetic fields by detecting polarized synchrotron emission
- This leads to "Rotation Measure Grids", mapping the magnetic environments of different regions
- Newly sensitive radio telescopes can map the magnetized universe to high redshifts



Simulation of the magnetic field strengths in the cosmic web (Vazza+14)

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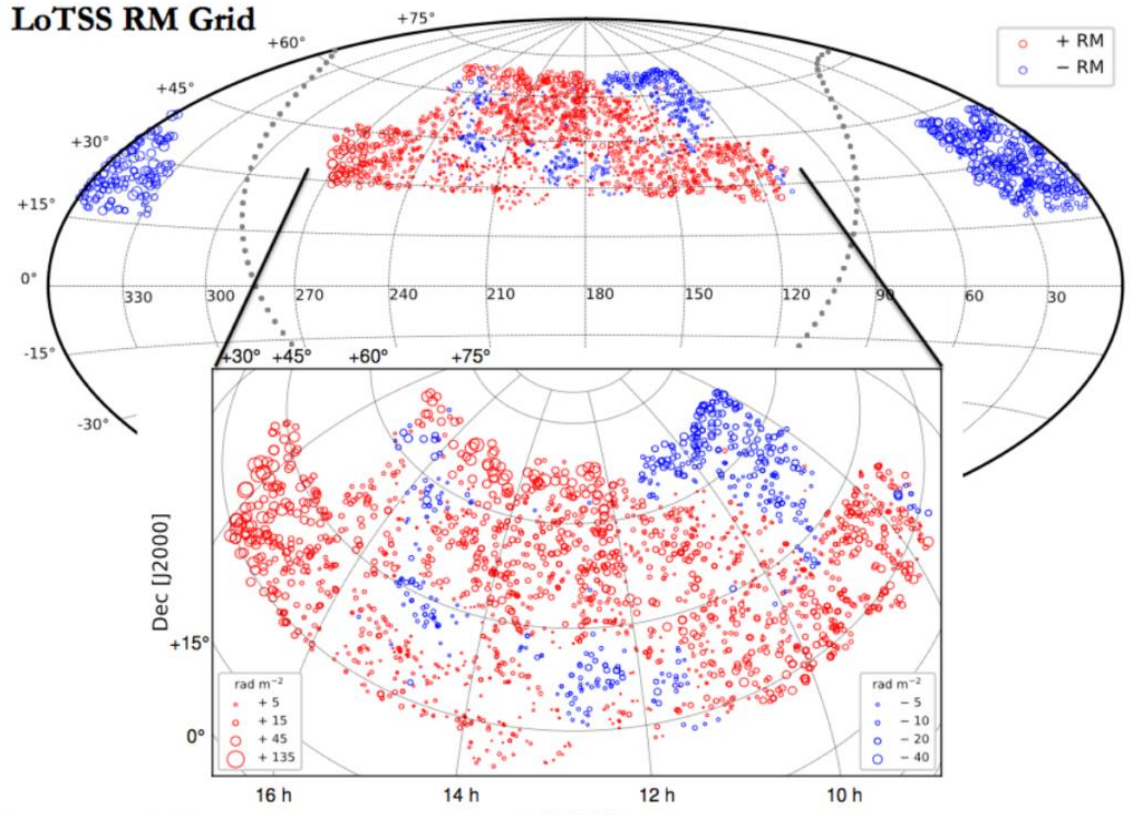
- From the smallest scales (magnetic fields between protons and electrons) to the largest scales (magnetic fields in galaxy clusters), they affect how the universe evolves
- How did strong magnetic fields originate at the beginning of the universe, how did they evolve to the present day?
- Mapping the magnetic field structure of the sky gives us clues
- Radio telescopes can indirectly map magnetic fields by detecting polarized synchrotron emission
- This leads to "Rotation Measure Grids", mapping the magnetic environments of different regions
- Newly sensitive radio telescopes can map the magnetized universe to high redshifts



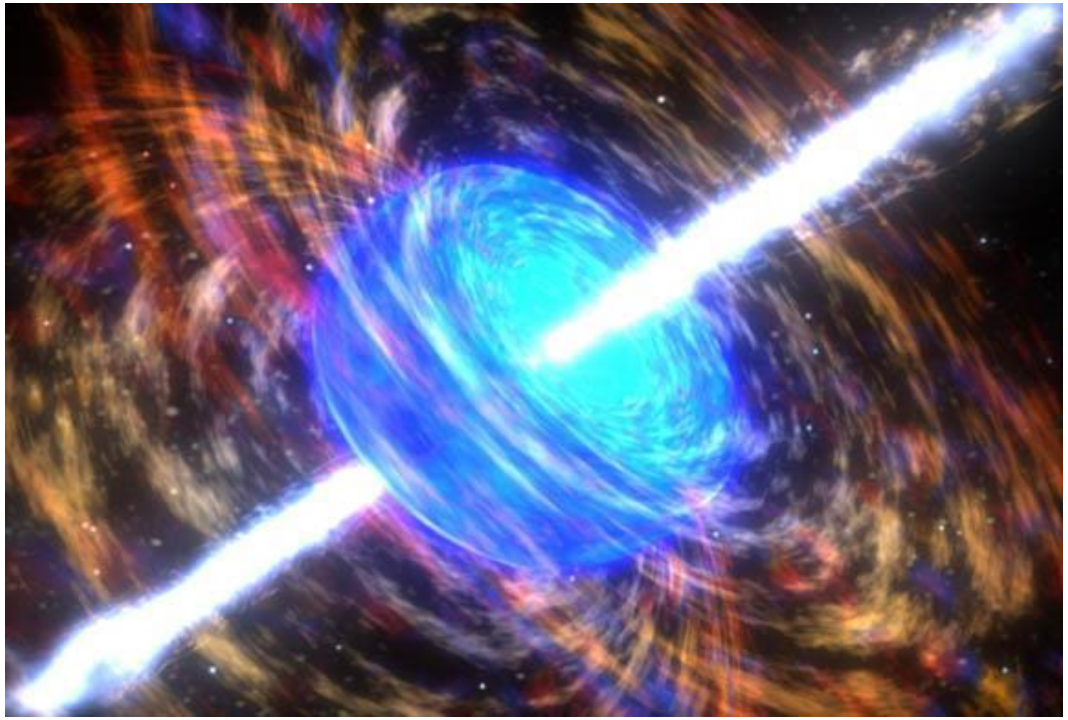
O'Sullivan et al. in prep.

The bursting sky

Credit: SKAO

The bursting sky

- Fast Radio Bursts (FRBs) -- millisecond bursts of radio waves that are only detected in the radio band
- First discovered in 2007, they can emit as much energy in a millisecond than the Sun does in a whole day
- Some have shone just once so far, others are repeating
- We do not know where they come from
- Require a large survey radio telescope – wide fields of view are needed to capture these transient events
- Extreme sensitivity will uncover more, fainter FRBs.
- New signal processing and data management tools have been developed to capture them in real time.
- Repeating FRBs allows for "Very Long Baseline Interferometry" and "Long Term Monitoring" to understand their physics.



Credit: SKAO

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The SKA – the road to understanding

- These Key Science Objectives will be tackled by the formation of Key Science Projects and *Science Working Groups*.
- Together, dedicated teams from across the world are, and will be, using high performance computing and the latest advances in data management to understand these mysteries.
- Long road between SKA observations and new discoveries:
  - Construction of the telescope
  - Development of the software and computing facilities to process the data in pseudo-real time
  - Availability of radio astronomers to perform the scientific analysis

Science Working Groups (SWGs)

- The Science Working Groups (SWGs) are a set of scientific advisory groups that provide input to the Square Kilometre Array Organisation (SKAO) on issues relating to the design, commissioning, and future operations of the SKA that are likely to affect the Observatory's scientific capability, productivity and user relations. The terms of reference will evolve as the Observatory begins scientific operations
- It is expected that the SWGs will provide advice and guidance, based on their experience with existing telescopes and from the perspective of potential users of the SKA, on the design and development of the SKA. Specific activities include:
  - Providing advice on the science impact of design changes to the SKA;
  - Providing advice on the expected commissioning and operation of the telescope;
  - Providing a conduit for information on nascent Key Science Projects;
  - Drawing attention to emerging research topics that may be addressed by the SKA;
  - Providing Scientific Organising Committee membership and topical speakers for SKA science meetings;
  - When possible, assisting the SKA Science Team in the dissemination and promotion of science enabled by the SKA to the broader community through presentations at major astronomy meetings, universities and research institutions

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Science Working Groups (SWGs)

- Extragalactic Spectral Line (non-HI)
- Our Galaxy
- Solar, Heliospheric & Ionospheric Physics
- Epoch of Reionization
- Cosmology
- Extragalactic Continuum (galaxies/AGN, galaxy clusters)
- Cradle of Life
- HI galaxy science
- Magnetism
- Pulsars
- Transients
- VLBI
- High Energy Cosmic Particles

Challenges of the SKA Key Science Projects and 21st Century radio astronomy

- Data volume
- Data processing (calibration -- lecture 7)
- Imaging (converting radio signals into 2D maps of the sky)
- Long term storage resources
- Efficient scientific analysis
- Computational costs in the future
- Data security
- People and funding

Summary

- New frontiers in radio astronomy driven by the new range of 'software' telescopes
- Science in the next few decades predicted to reach new discovery space
- Large computational challenges remain to enable the key science projects – covered in the rest of the course