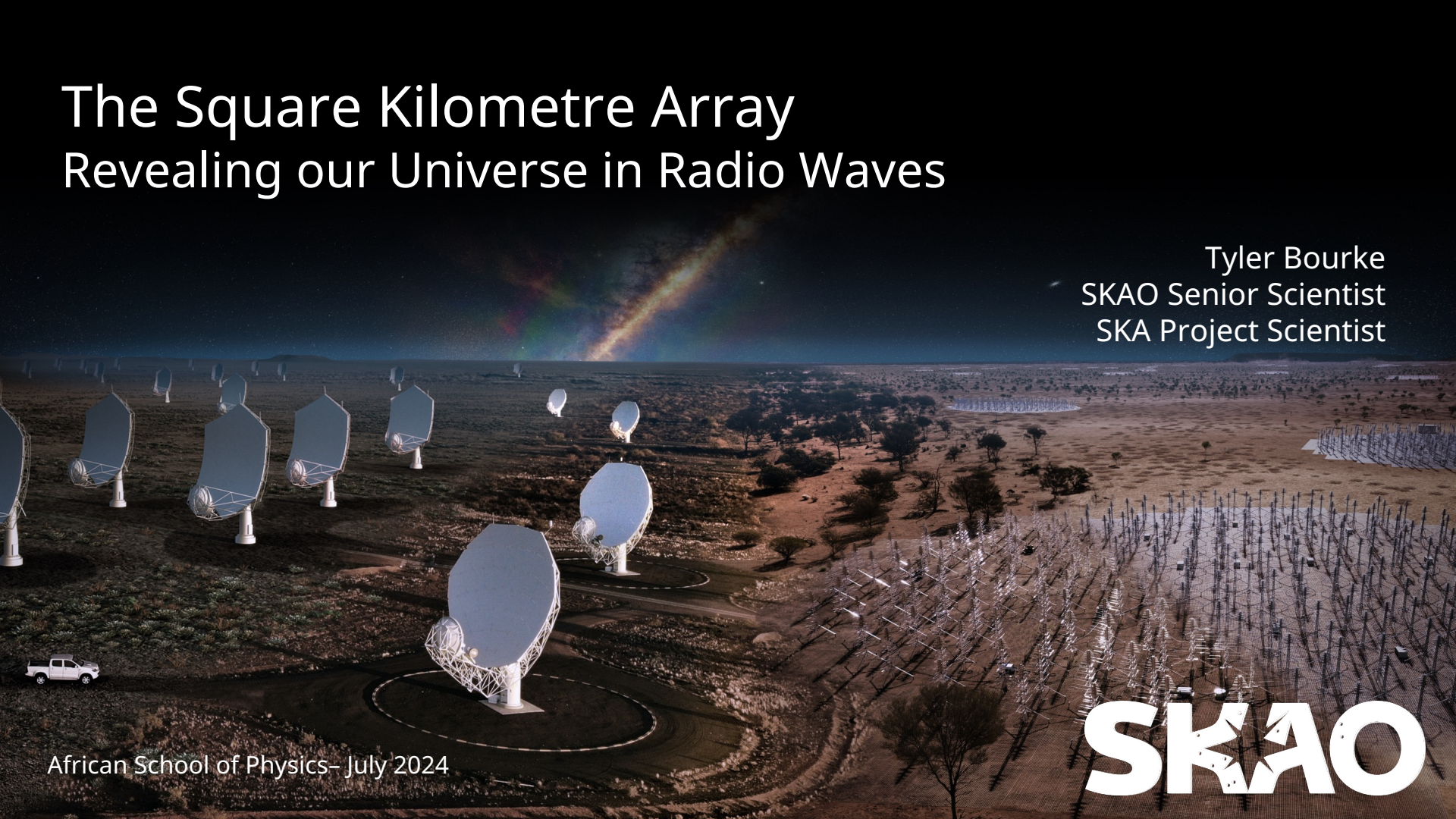
The Square Kilometre Array
Revealing our Universe in Radio Waves

Tyler Bourke
SKAO Senior Scientist
SKA Project Scientist



African School of Physics– July 2024

We recognise and acknowledge the Traditional Owners of the lands on which our facilities are located, and pay our respects to their Elders past and present.

We acknowledge the Wajarri Yamaji as the Traditional Owners and native title holders of Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory, where we are building the SKA-Low telescope in Australia.*

We acknowledge the Whadjuk Noongar as the traditional owners of the land where our SKA-Low Science Operations Centre is situated in Perth, and the Southern Yamatji as the traditional owners of the land where our SKA-Low Engineering Operations Centre is situated in Geraldton.

I also pay my respects to all First Nations people in attendance.

A collaborative painting from Aboriginal Yamaji artists from WA for the SKAO *Shared Sky* exhibition. Credit: Yamaji Arts Centre.

*sharing sky and stars

Bethesda Arts Centre/Bethesda Foundation

Creation of the Sun

In the early times, the sun was asleep in his house, shining for himself alone. The earth was cold and dark. The mothers couldn't dry the ant-larvae to eat so they were hungry, and the people were cold.

Then the old woman gathered the children together: "My children, creep up to that old man the sun while he is sleeping. Creep up to that old Sun Armpit, and fling him into the sky, so that the earth can be warm for us, so that all the world will be bright."

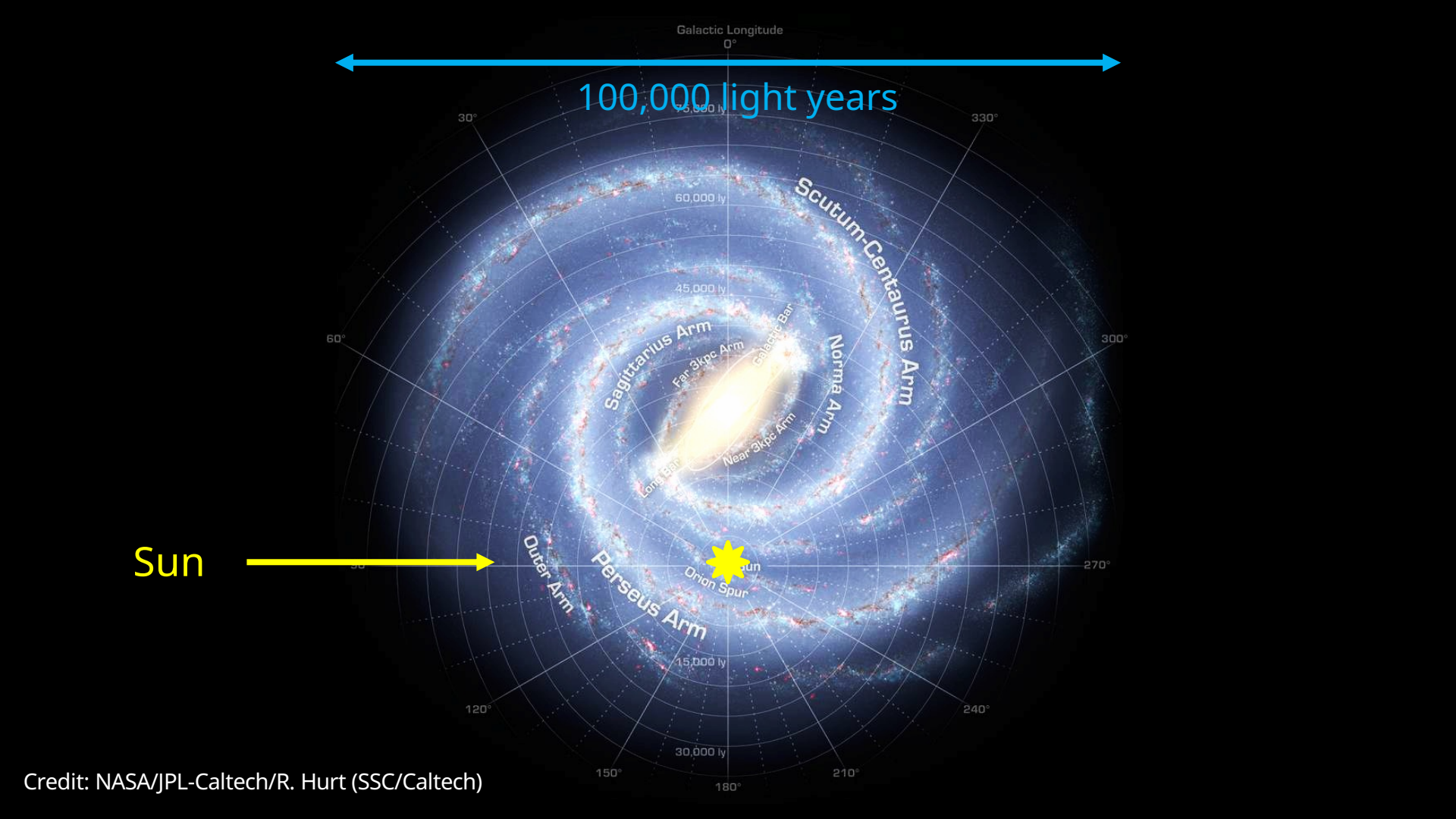
Jeni Couzyn

Introduction

Credit: Brendon Wainwright

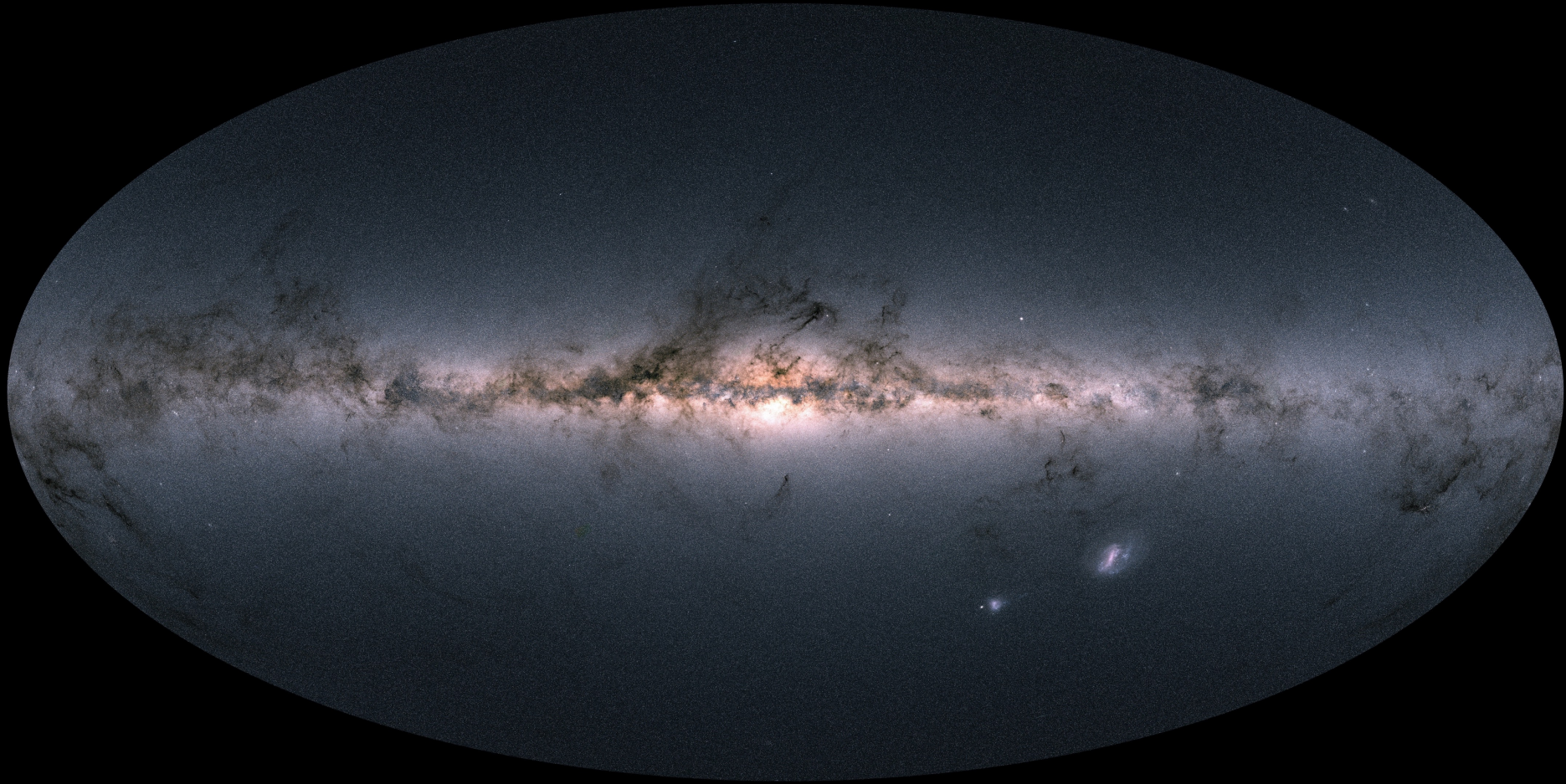
Credit: Rafael Defavari

Credit: Jacob Bers

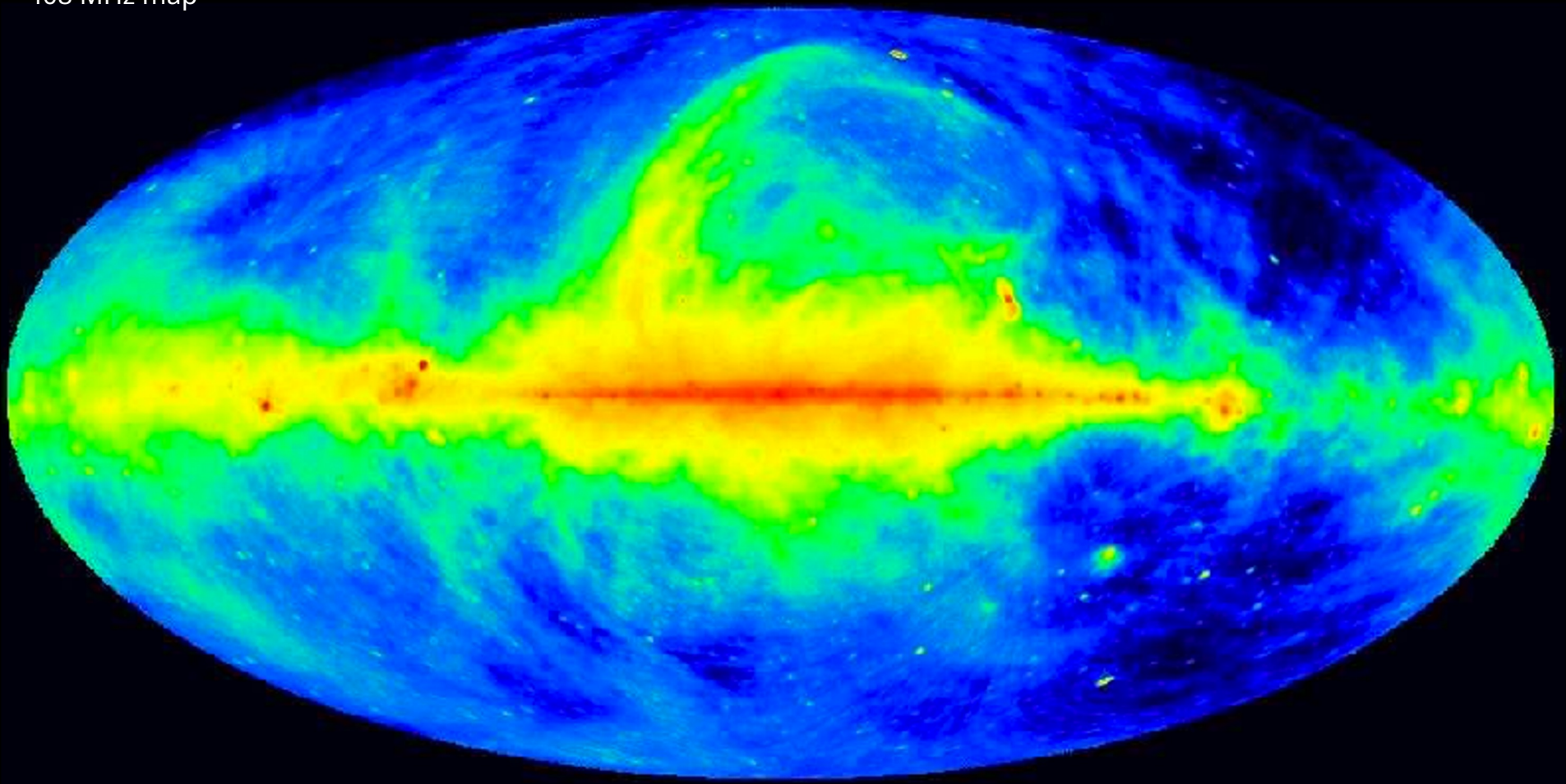


Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Gaia Satellite – over one billion stars

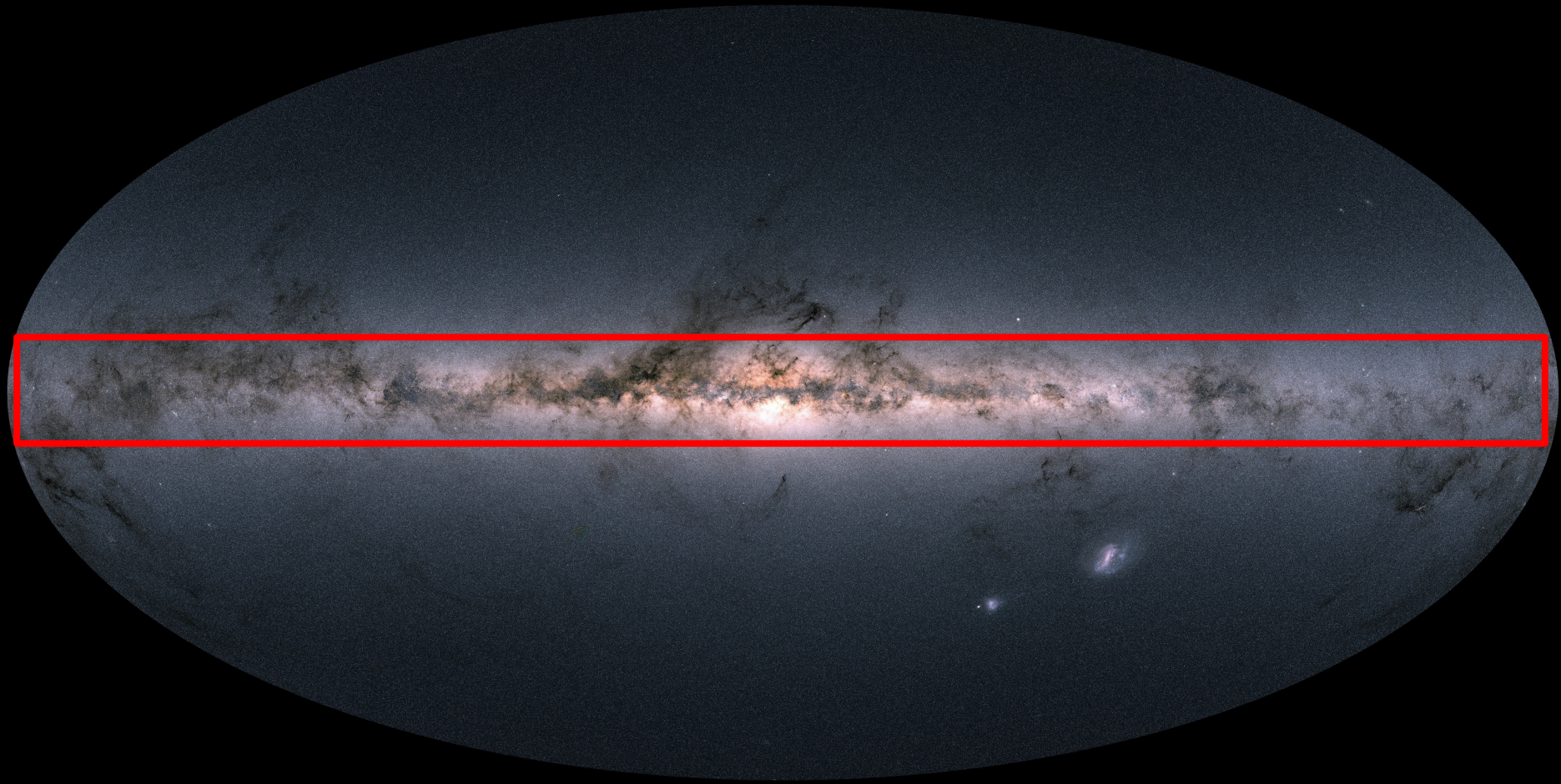


408 MHz map



Credit: Haslem et al. 1982, using Effelsberg 100-m, Lovell 76-m, Parkes 64-m)

Gaia Satellite – over one billion stars



radio 408 MHz

H 1.4 GHz

radio 2.5 GHz

H_2

infrared (heat)

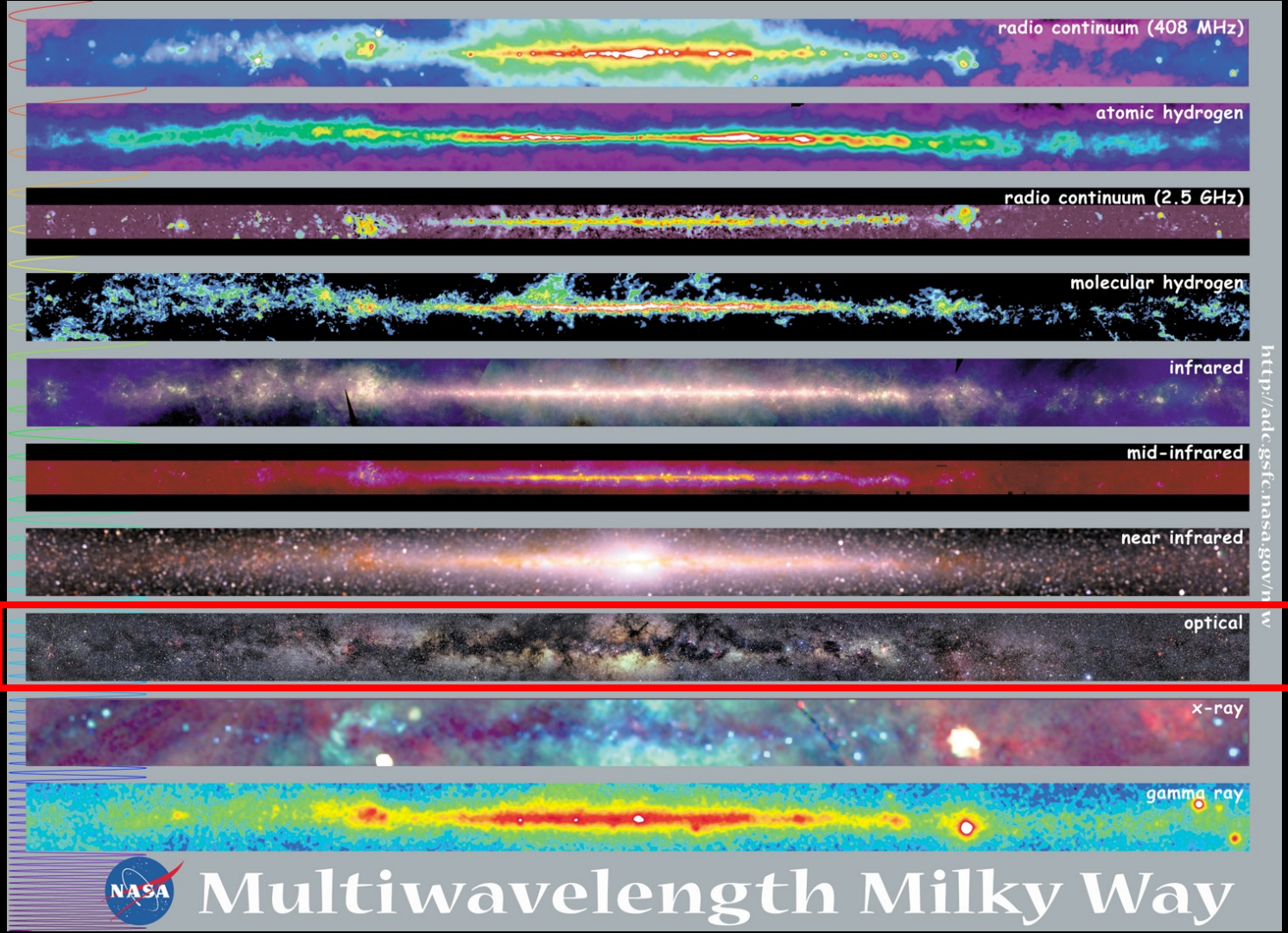
infrared (heat)

infrared (heat)

optical

X-rays

Gamma rays

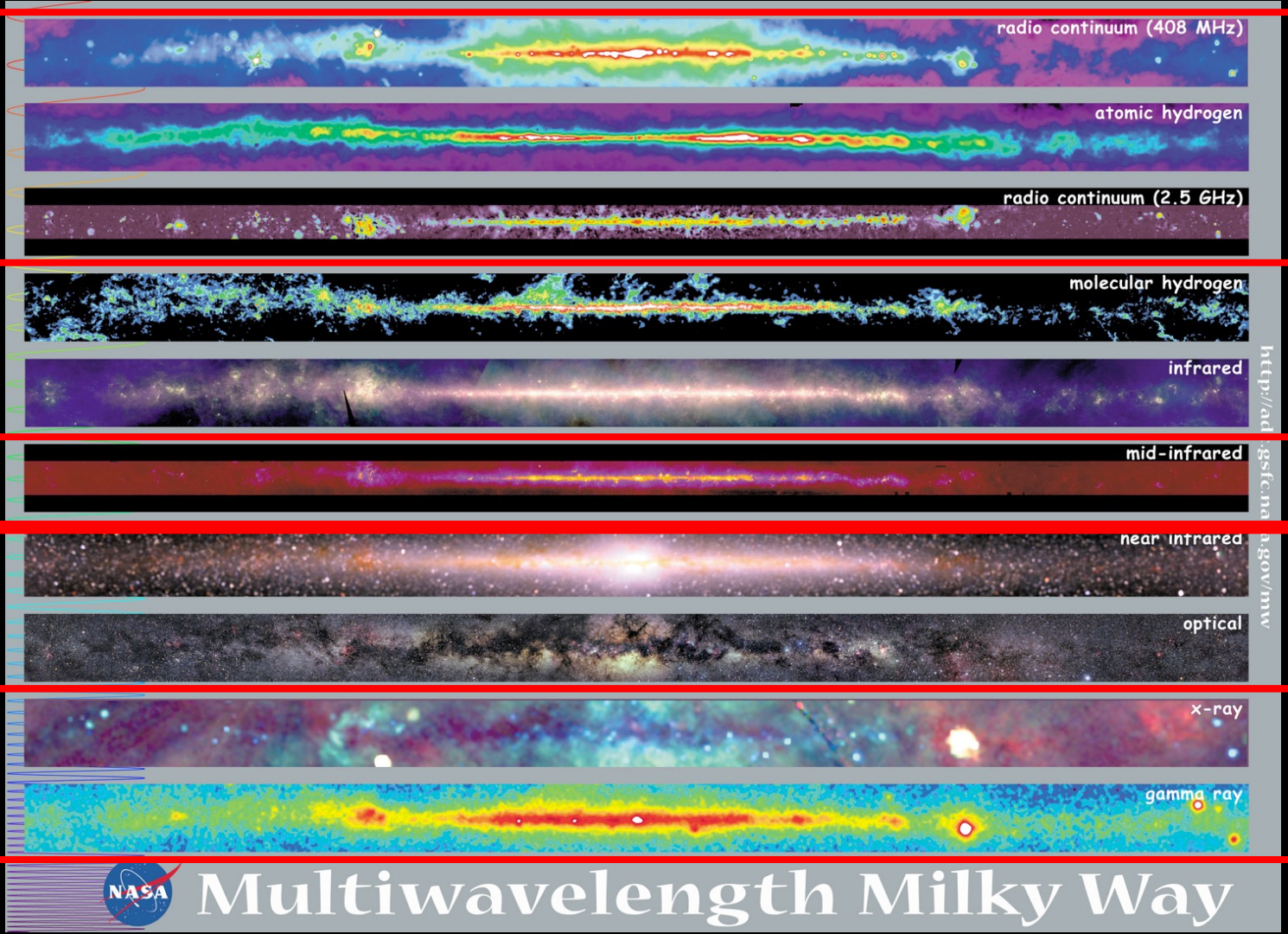


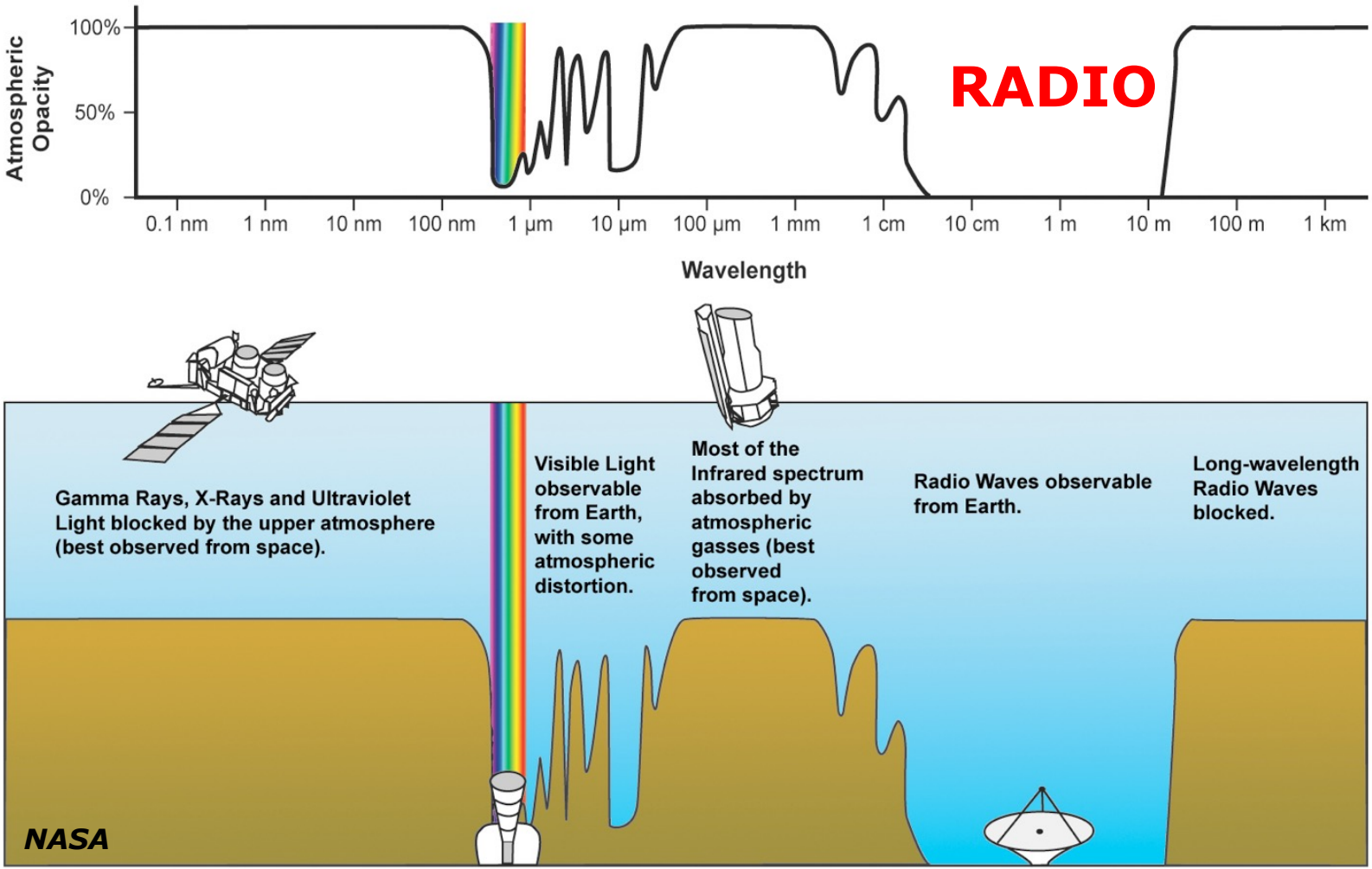
SKA

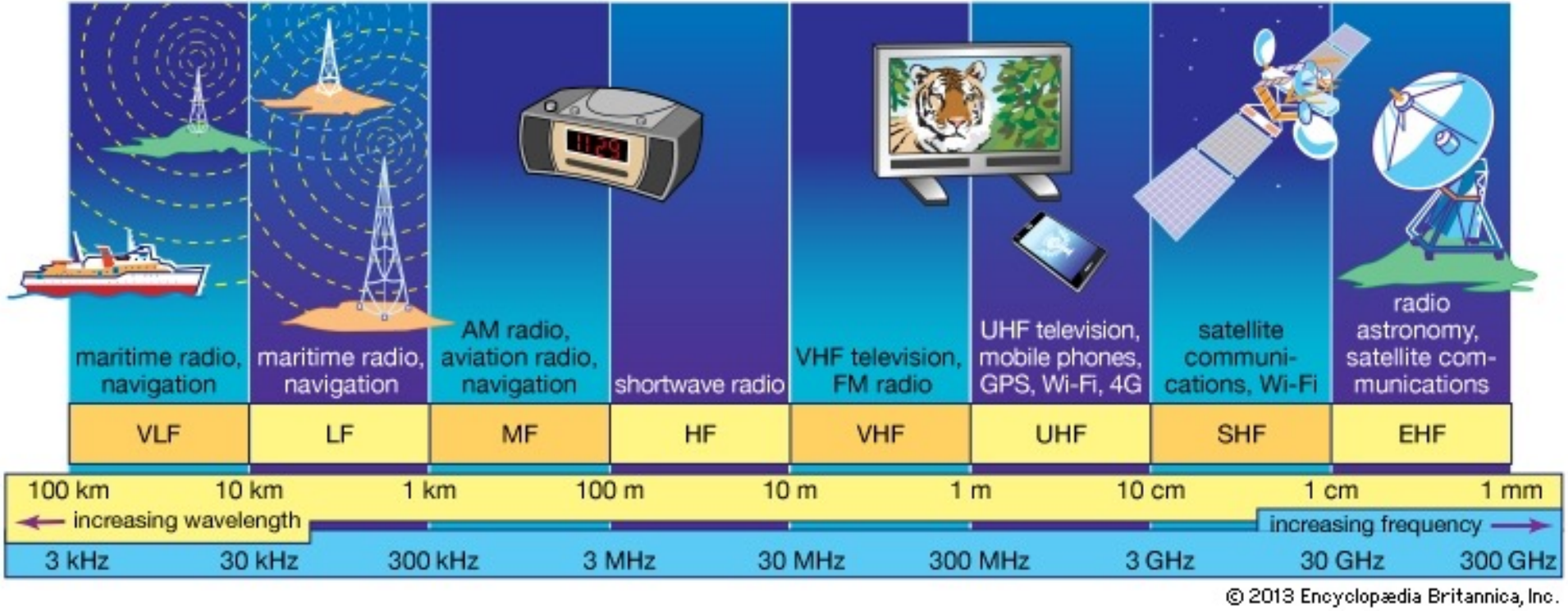
Webb

Hubble/
ELTs

Satellites
in space

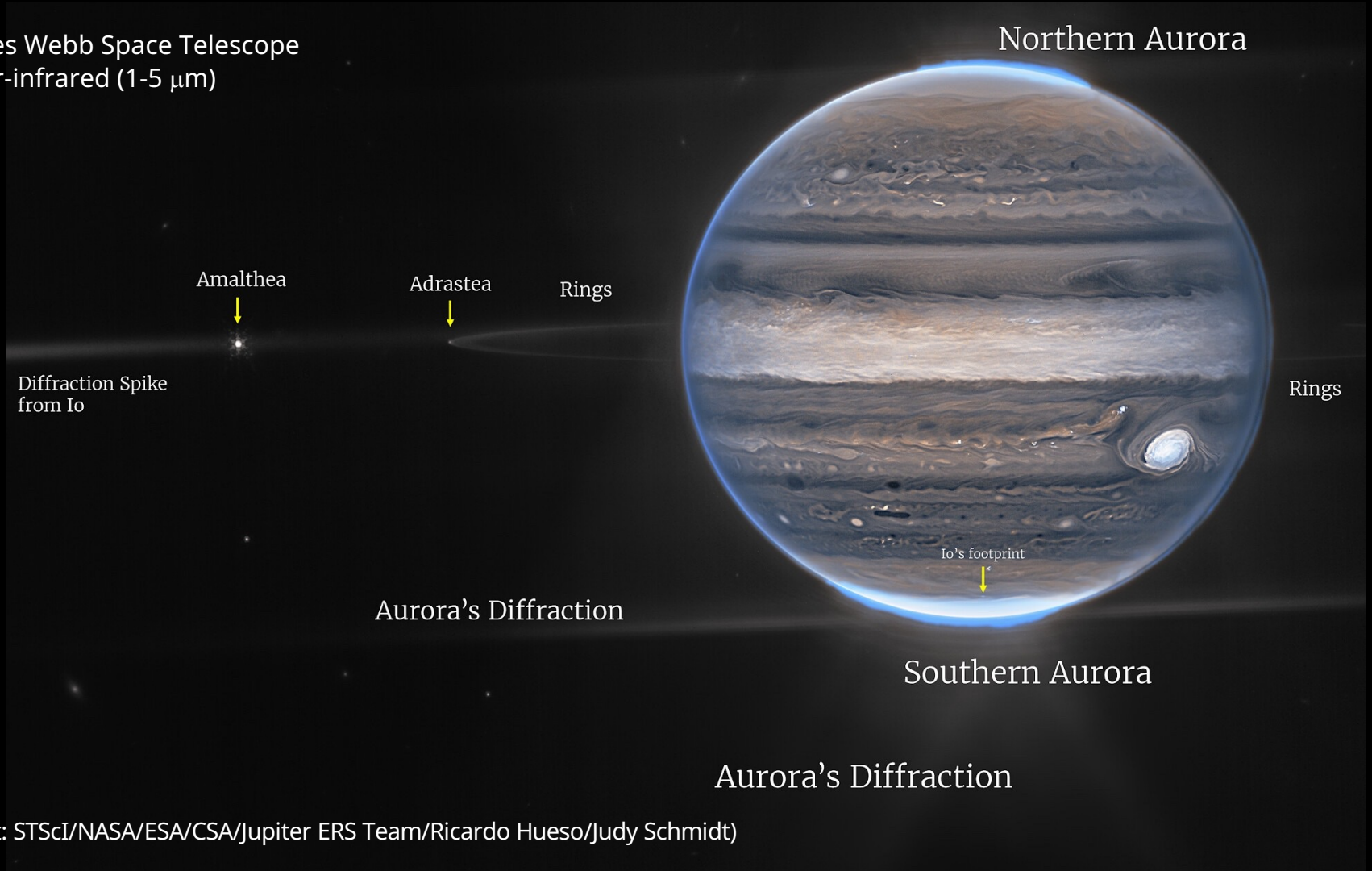



Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
RADIO
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.
NASA



Ionosphere

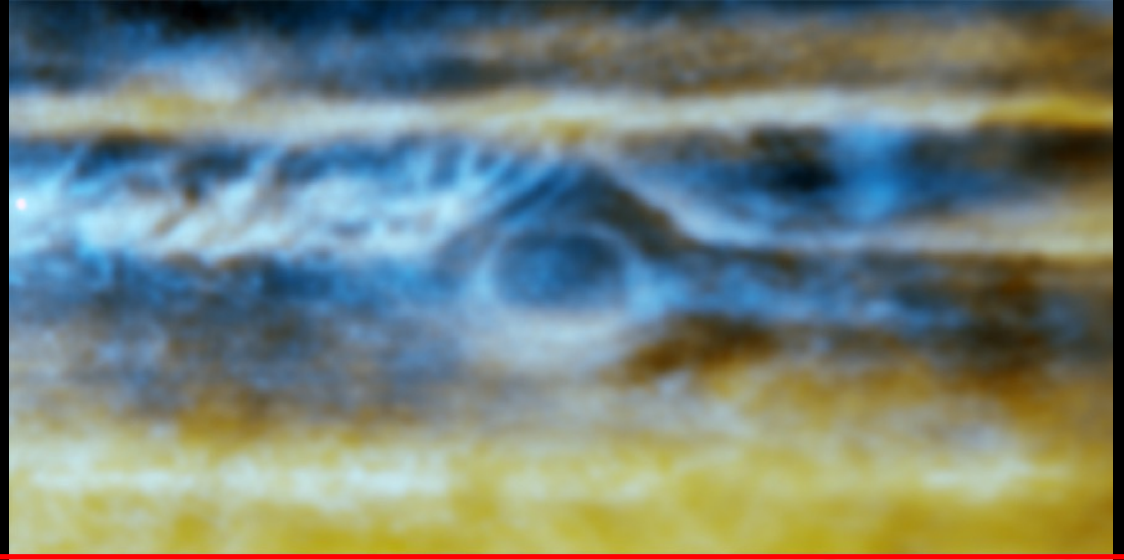
SKA



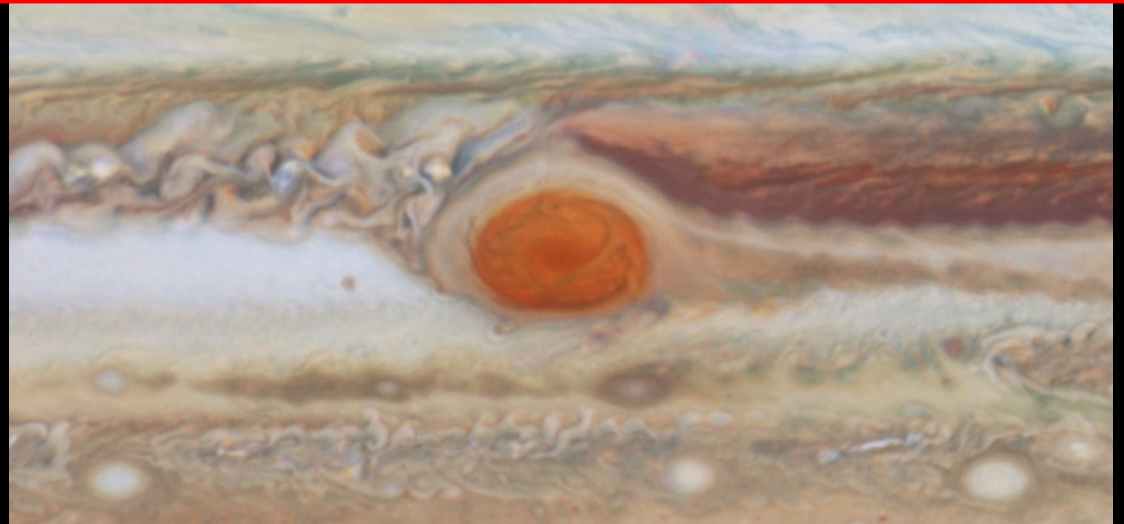
Credit: STScI/NASA/ESA/CSA/Jupiter ERS Team/Ricardo Hueso/Judy Schmidt)

Very Large Array (radio)
12-18 GHz (2 cm)
8-12 GHz (3 cm)
(SKA-Mid Band 5)

Observing 100 km below the clouds

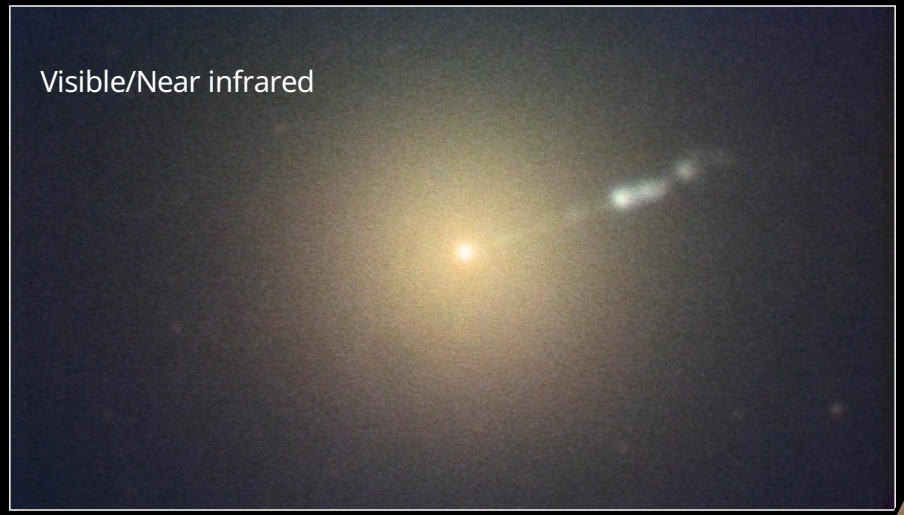


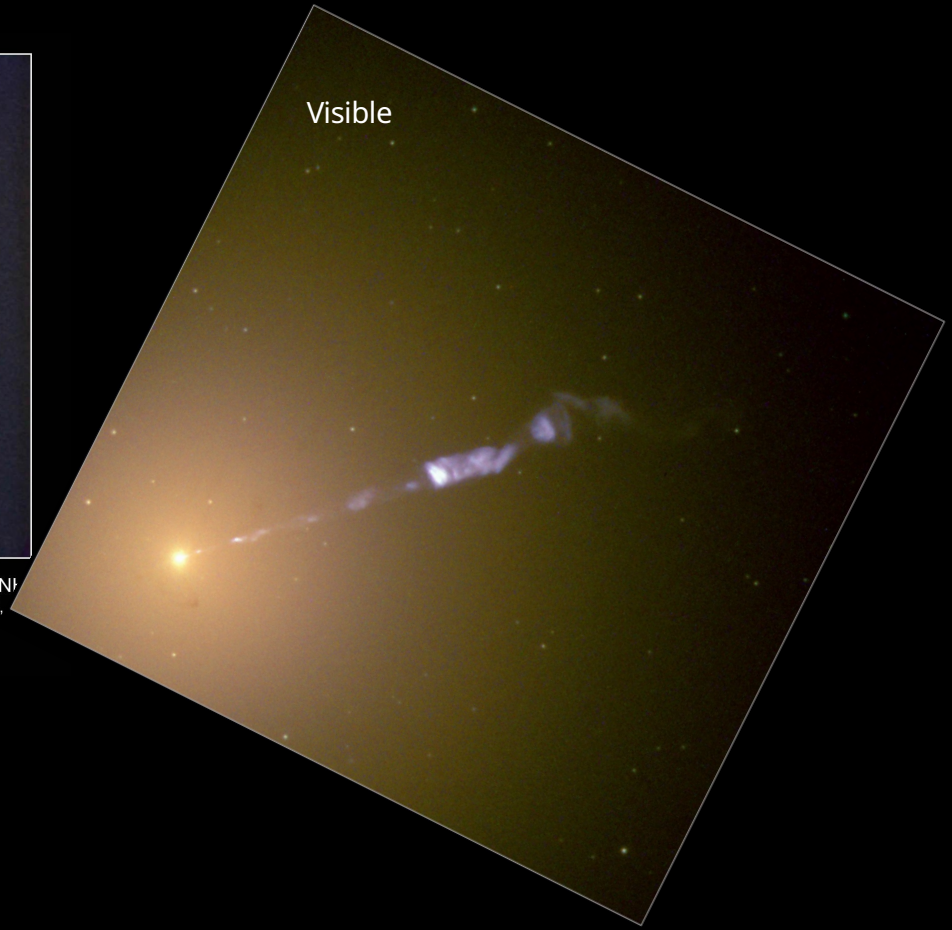
Hubble (optical)



Credit: de Pater et al., NRAO/AUI/NSF, NASA

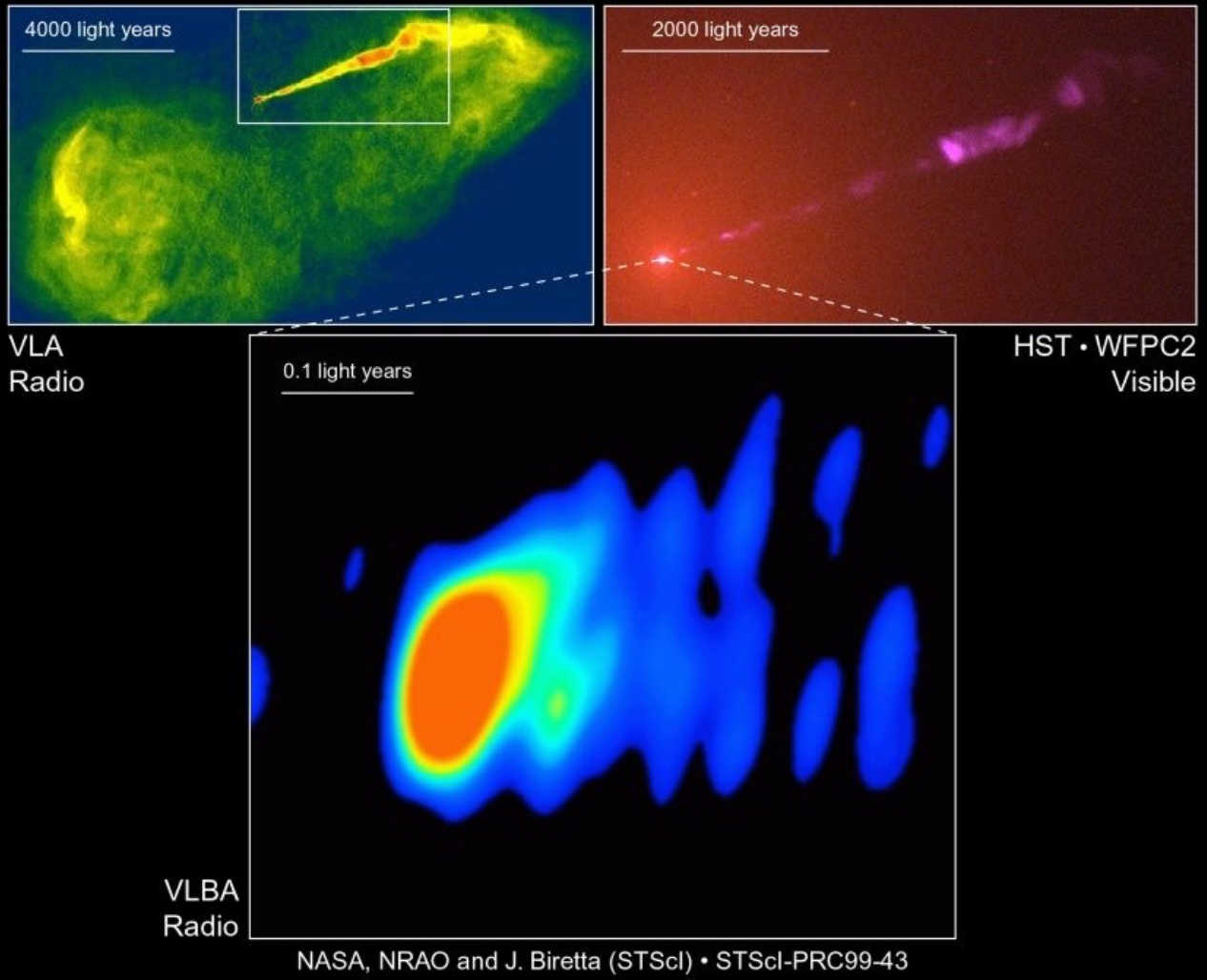
Giant Elliptical Galaxy M87

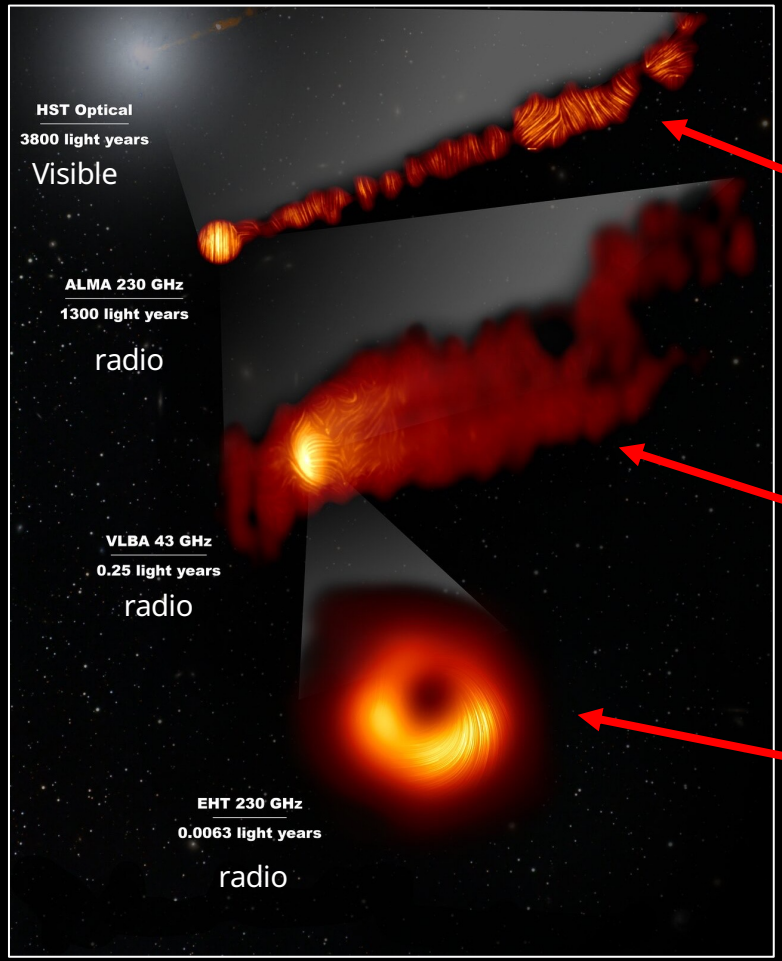




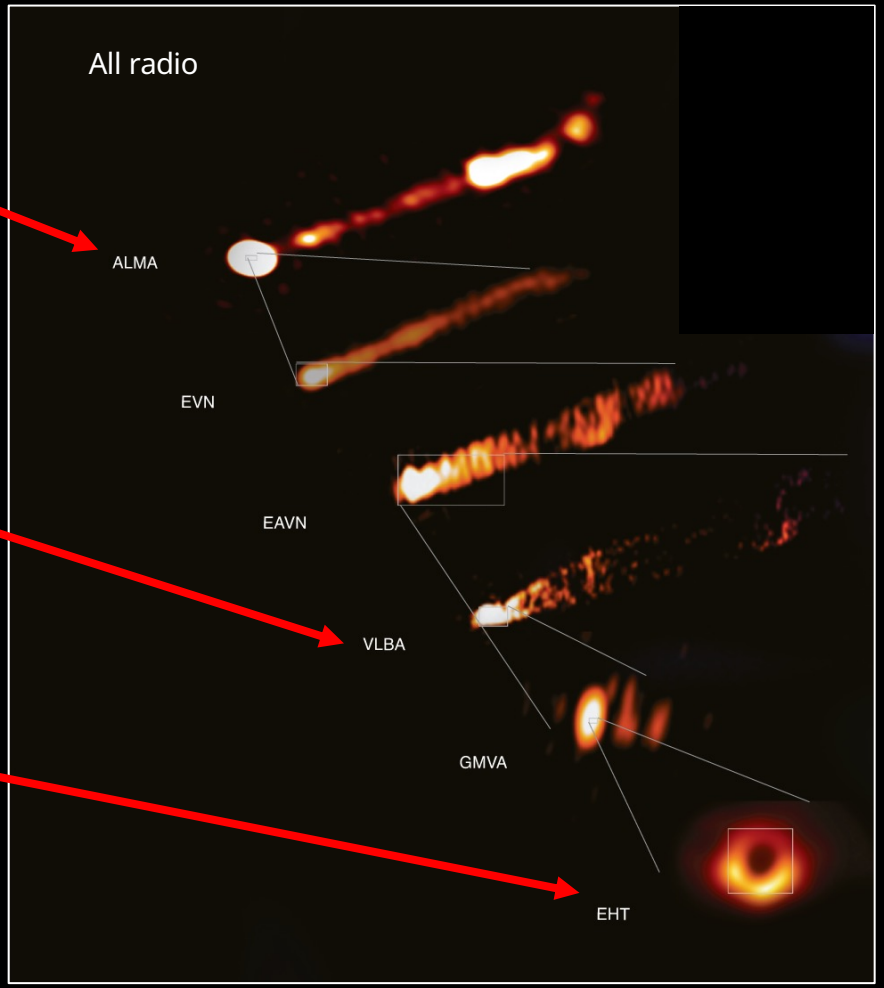
Credit: STScI/NASA/Hubble Heritage Team

Giant Elliptical Galaxy M87

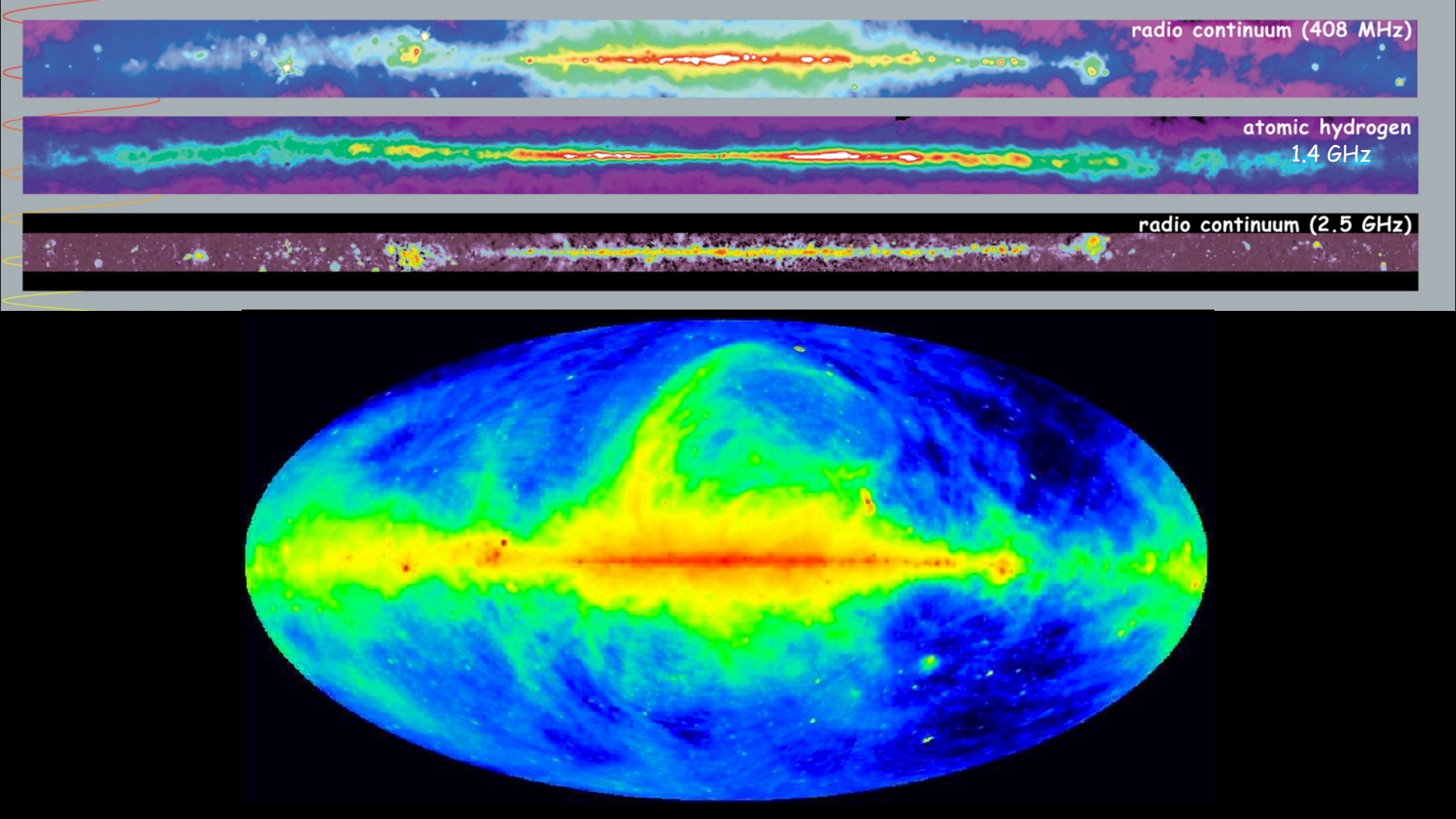


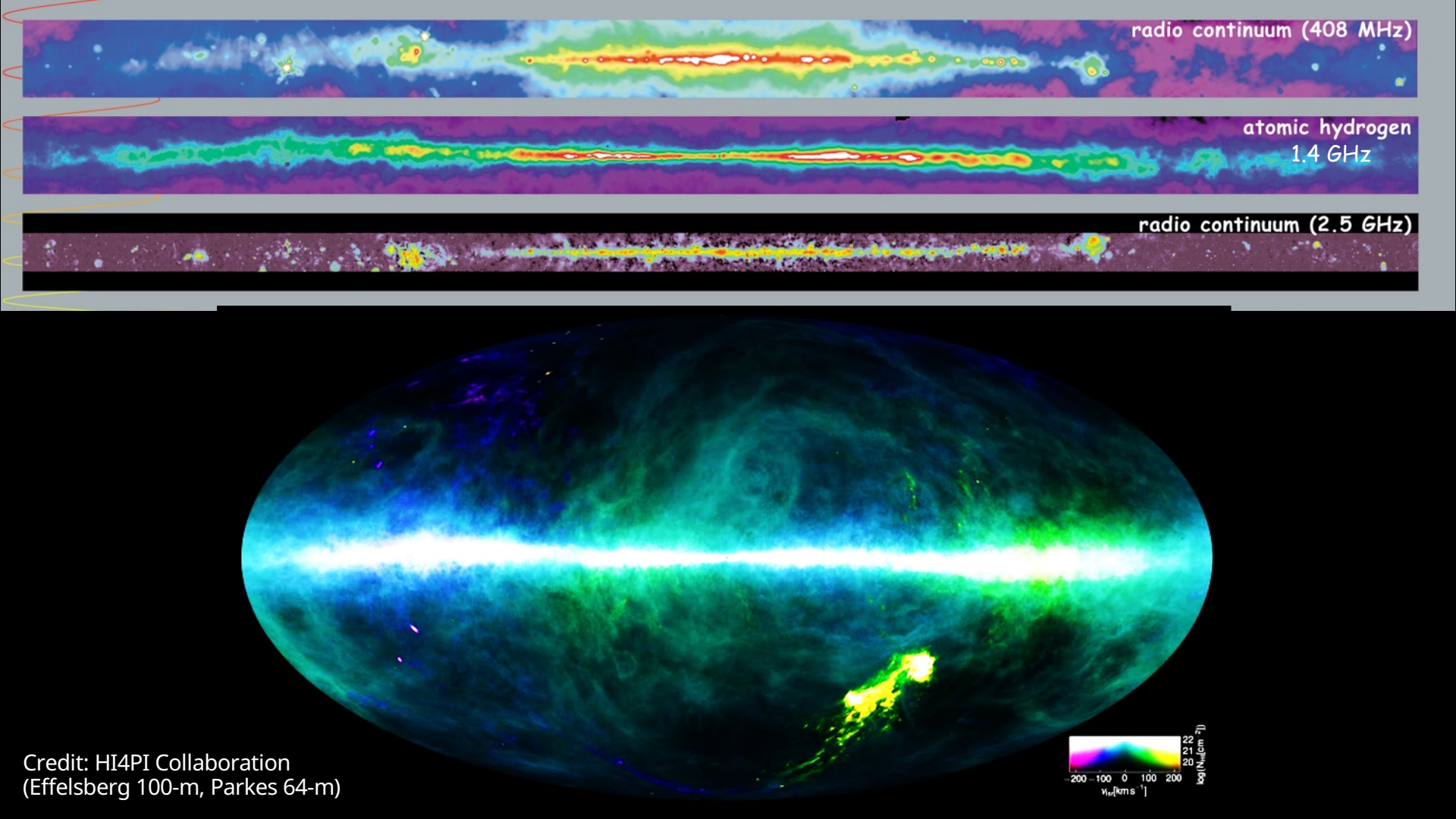


EHT Collaboration; ALMA (ESO/NAOJ/NRAO), Goddi et al.; NASA, ESA and the Hubble Heritage Team (STScI/AURA); VLBA (NRAO), Kravchenko et al.; J. C. Algaba, I. Martí-Vidal

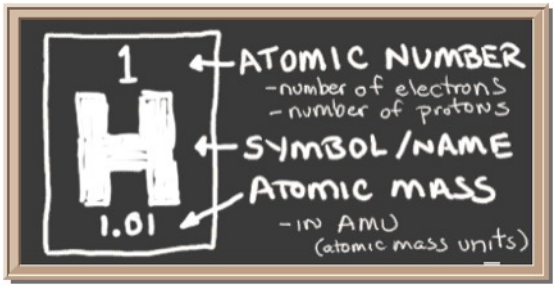


EHT; ALMA; EVN; EAVN; VLBA; GMVA; HST; Swift; Chandra; NSTA; Fermi-LAT; H.E.S.S.; MAGIC; VERITAS; NASA; ESA, by J.C. Algaba


radio continuum (408 MHz)
atomic hydrogen
1.4 GHz
radio continuum (2.5 GHz)

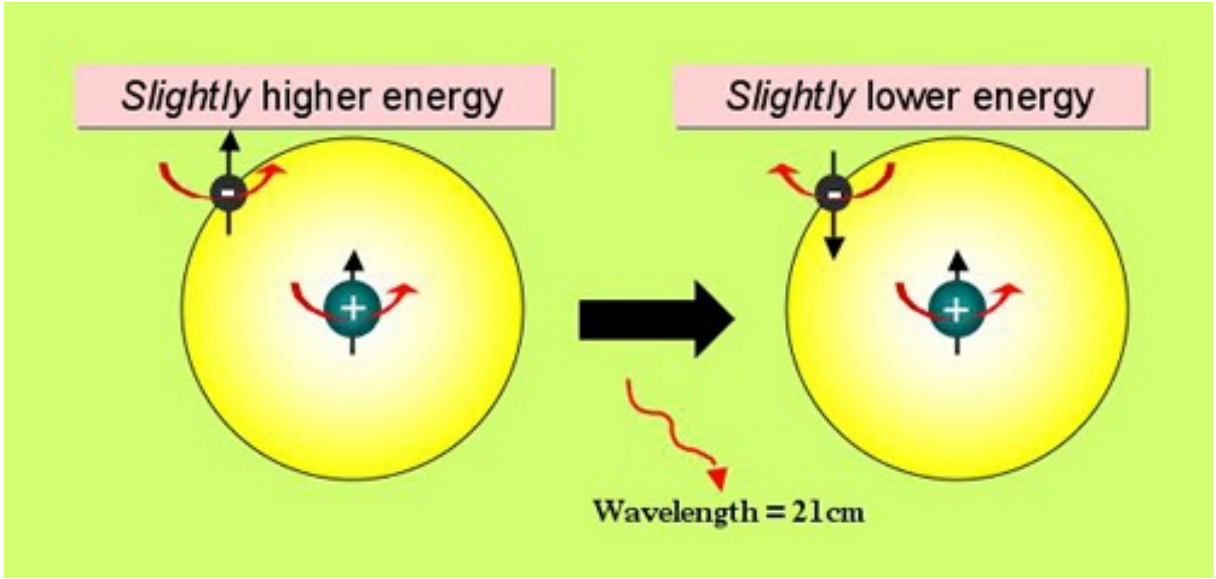

radio continuum (408 MHz)
atomic hydrogen
1.4 GHz
radio continuum (2.5 GHz)
Credit: HI4PI Collaboration
(Effelsberg 100-m, Parkes 64-m)

The Hydrogen Atom

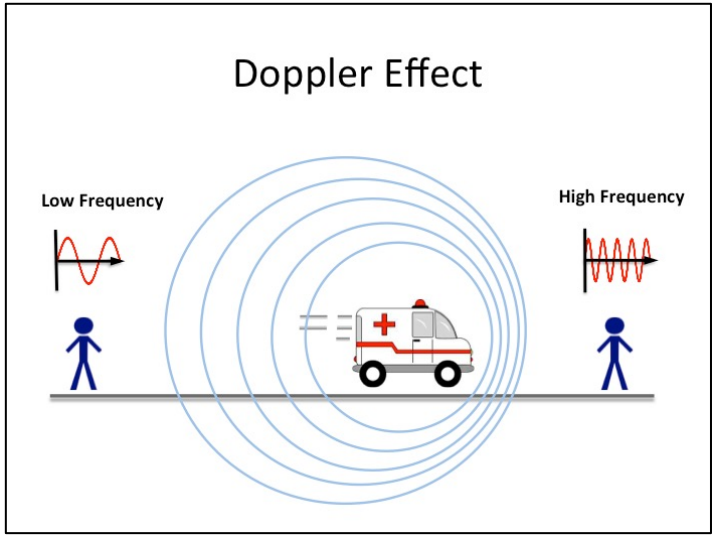


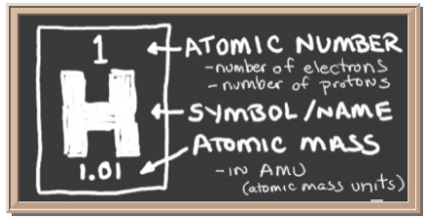
- Most abundance element in the Universe, by far!
- Primary transition is in the radio (1420 MHz = 21 cm)
- Map out structure in our Galaxy, and external galaxies

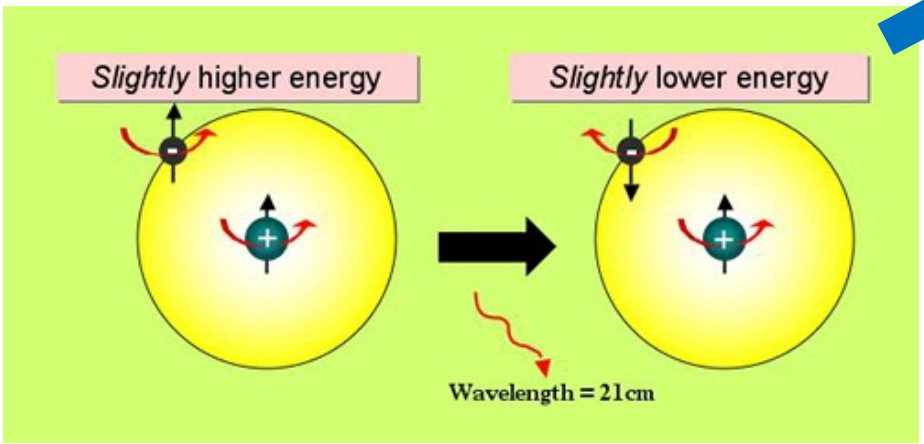
"Doc" Ewen, PhD student, 1951

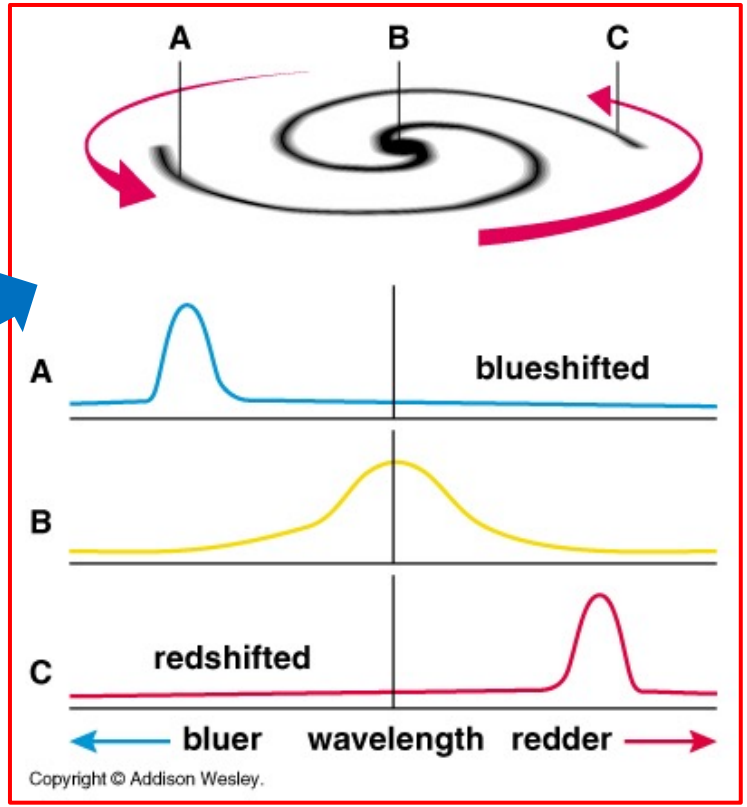


Every 100 million years!


Doppler Effect
Low Frequency
High Frequency


1
H
1.01
ATOMIC NUMBER
-number of electrons
-number of protons
SYMBOL/NAME
ATOMIC MASS
-in AMU
(atomic mass units)


Slightly higher energy
Slightly lower energy
Wavelength = 21cm


A
B
C
A
blueshifted
B
C
redshifted
bluer
wavelength
redder
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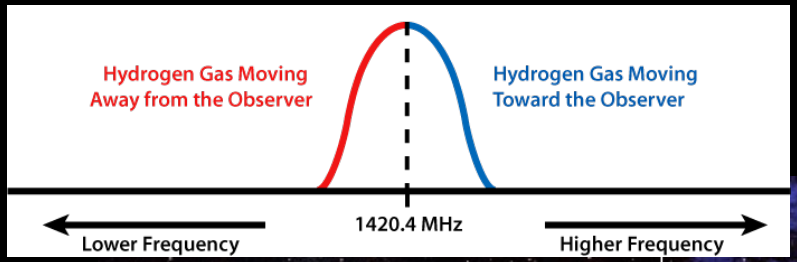
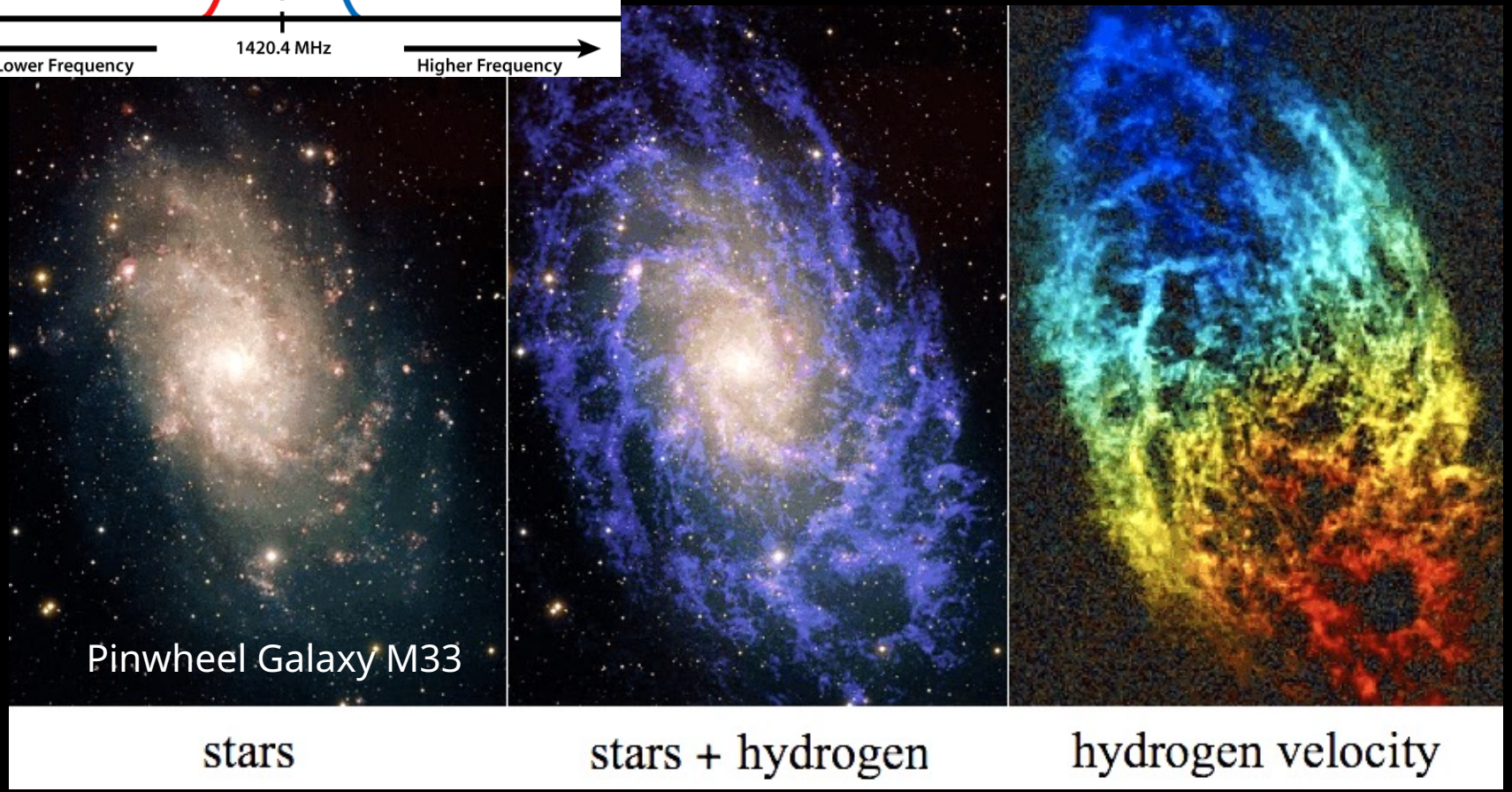
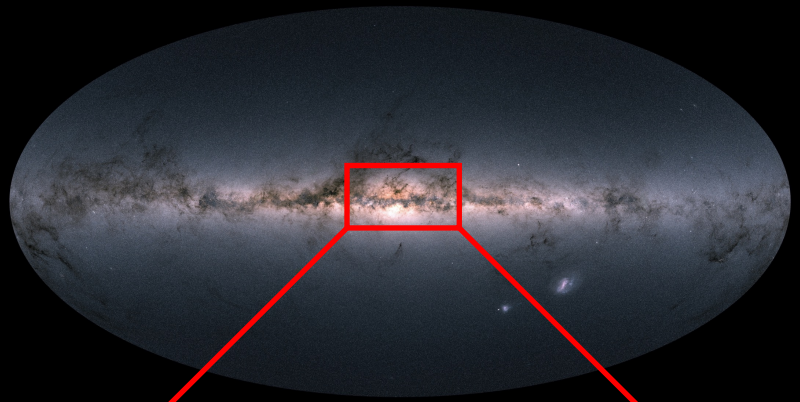
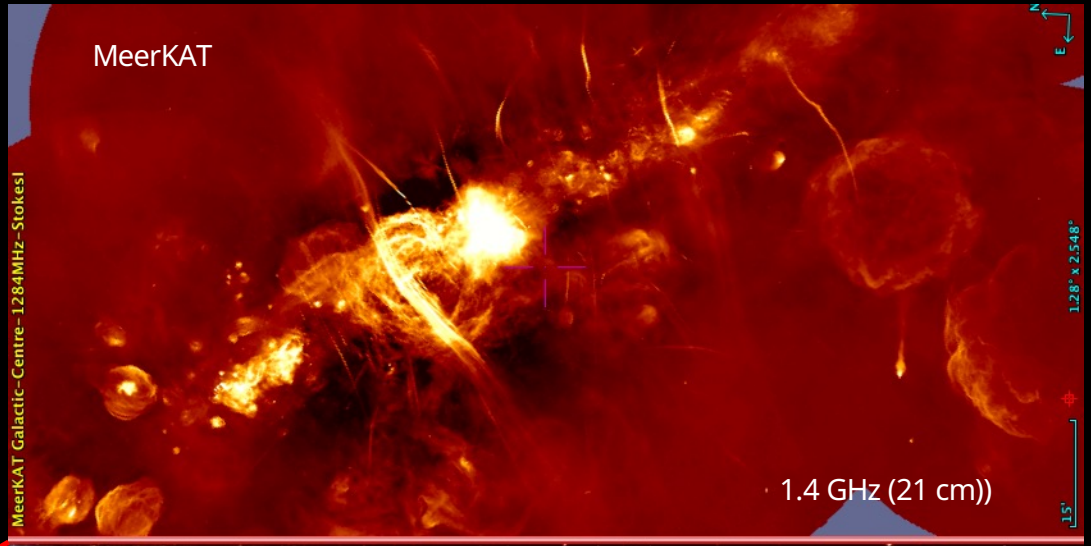
Princeton

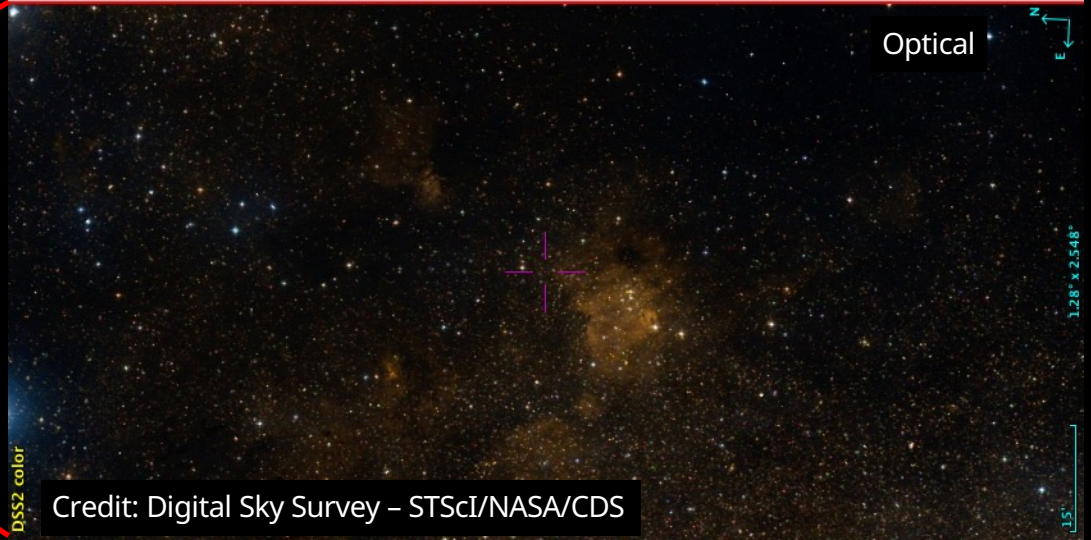


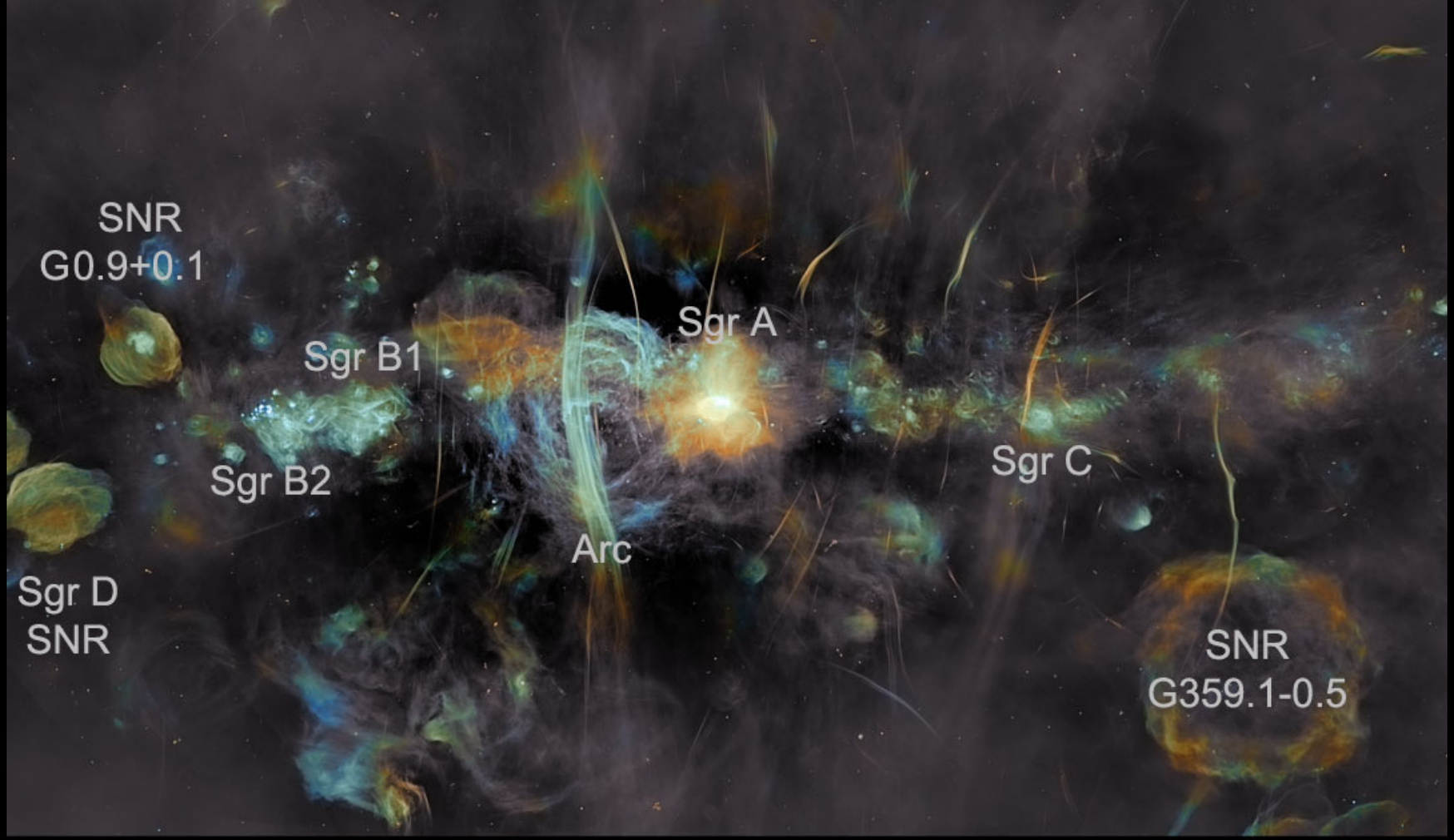


NOAO/NRAO/Westerbork



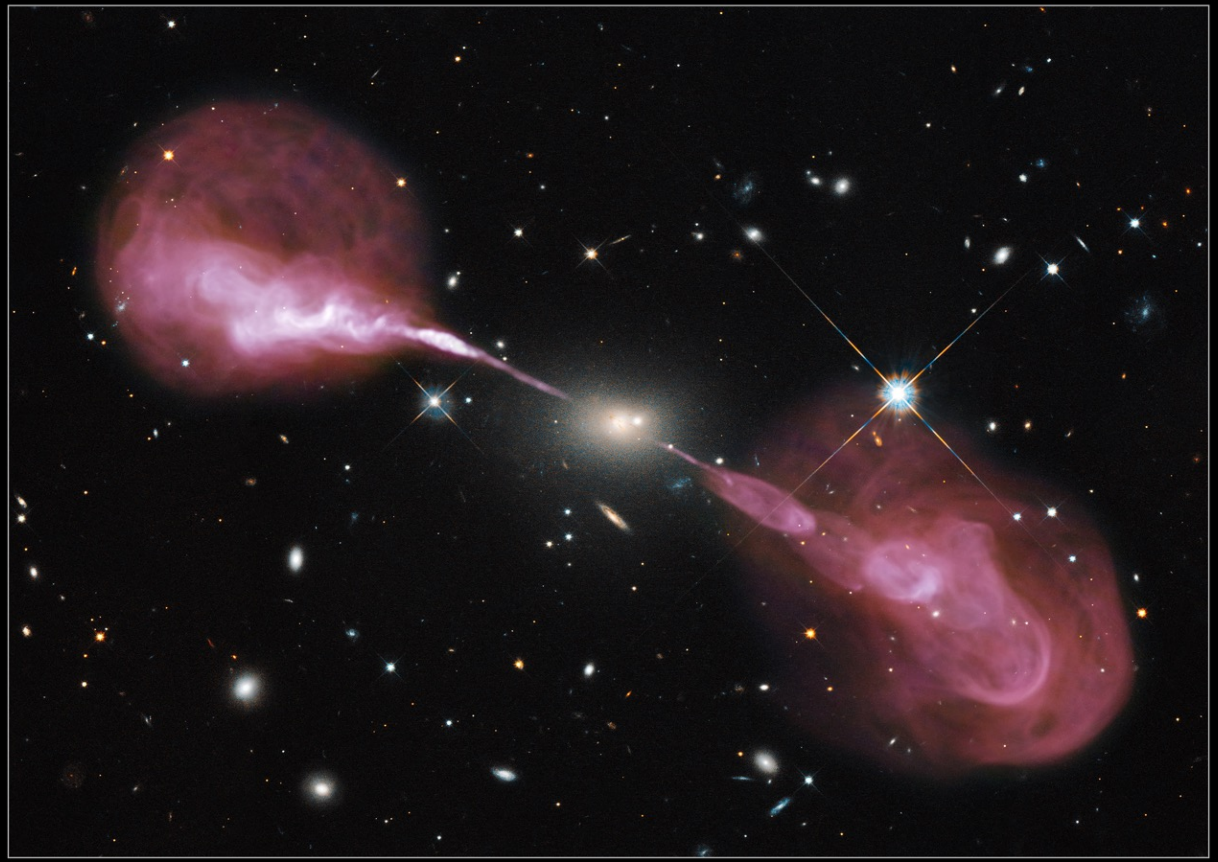

MeerKAT
MeerKAT Galactic-Centre-1284MHz-StokesI
1.4 GHz (21 cm))


Optical
DSS2 color
Credit: Digital Sky Survey – STScI/NASA/CDS


SNR
G0.9+0.1
Sgr B1
Sgr A
Sgr B2
Sgr C
Arc
Sgr D
SNR
SNR
G359.1-0.5
SARAO, Heywood et al. (2022) / J. C. Muñoz-Mateos
Spectral index
-1.8
-1.0
0
1.0

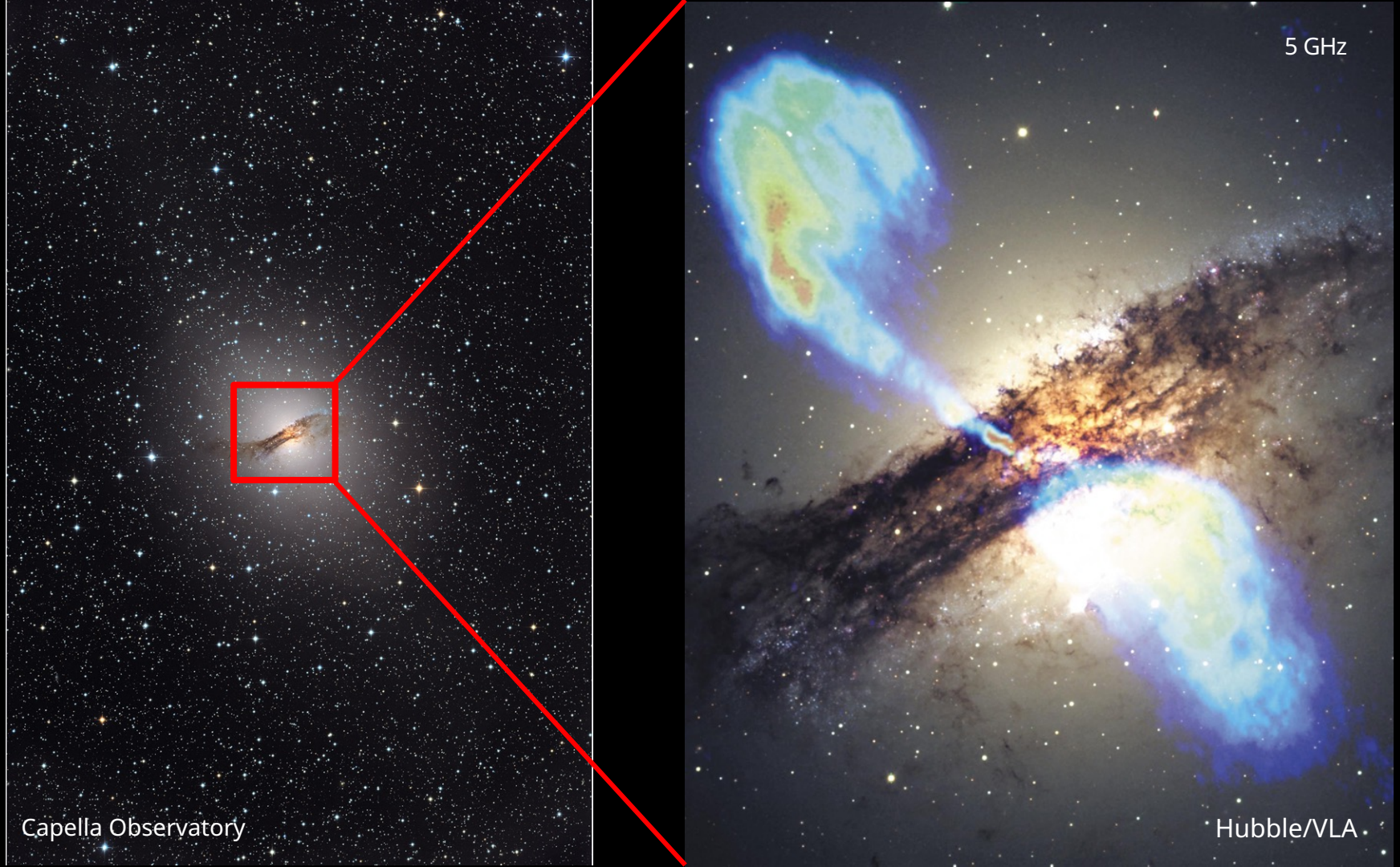
Radio Galaxy Hercules A

VLA + Hubble



Hubble Heritage

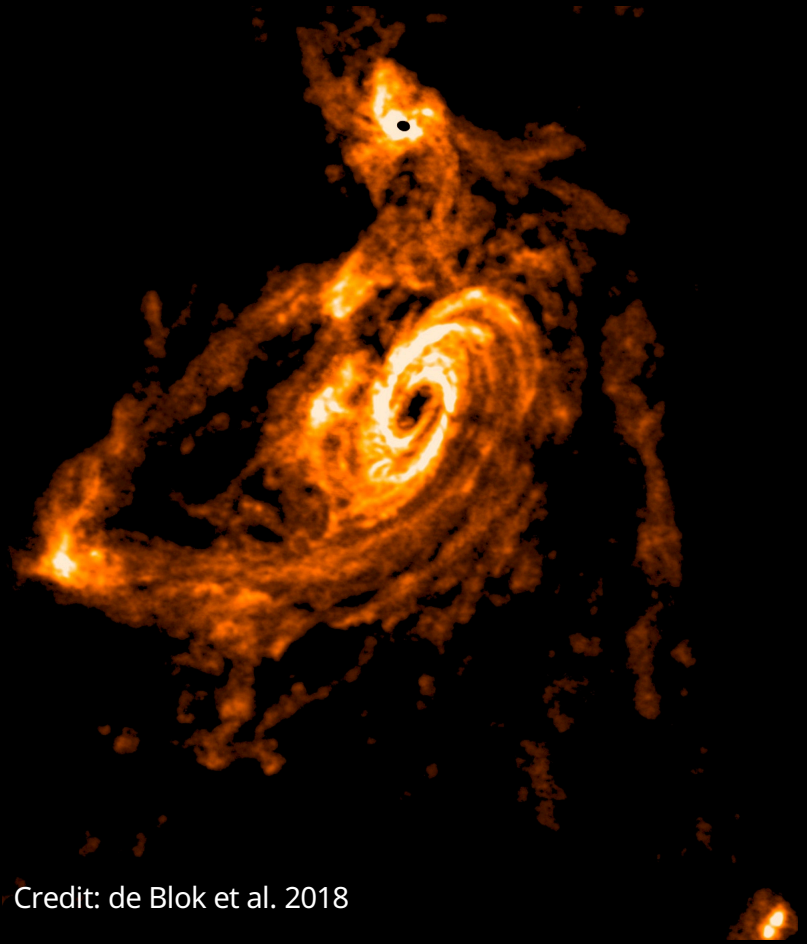
NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI–PRC12–47


5 GHz
Capella Observatory
Hubble/VLA

M81 group of galaxies

Credit: Nicolas Villegas

1.4 GHz Neutral Hydrogen (HI) distribution
Imaged with the VLA



Credit: de Blok et al. 2018

The SKA

The SKAO mission: to build and operate cutting-edge radio telescopes to transform our understanding of the Universe, and deliver benefits to society through global collaboration and innovation

Prime Science Motivation: Study the history of the Universe in Hydrogen

Will enable transformational science in many other areas

South Africa – Karoo region

Western Australian Outback


SKA– Key Science Drivers
The history of the Universe
Testing General Relativity
(Extreme Gravity, Gravitational Waves)
Cosmic Dawn & Reionisation
(First Stars and Galaxies)
Cradle of Life
(Planets, Molecules, SETI)
Galaxy Evolution
(Normal Galaxies z~2-3)
Cosmic Magnetism
(Origin, Evolution)
Cosmology
(Dark Matter, Large Scale Structure)
Our Galaxy
(Star Birth & Death, Matter Evolution, Structure)
Exploration of the Unknown
Huge range of transformational science enabled by the SKA

SKA Observatory (SKAO)

One Observatory

Two Telescopes

Three Continents

SKAO HQ
United Kingdom

SKA Phase 1

SKA-Mid

~200 steerable dishes across 150 km
Karoo, **South Africa**

SKA-Low

~131,000 log-periodic antennas across 74 km
Murchison, **Western Australia**

SKA Observatory (SKAO)

One Observatory

Two Telescopes

Three Continents

SKAO HQ
United Kingdom

SKA Phase 2

SKA-Mid

~2000 steerable dishes across Africa

SKA-Low

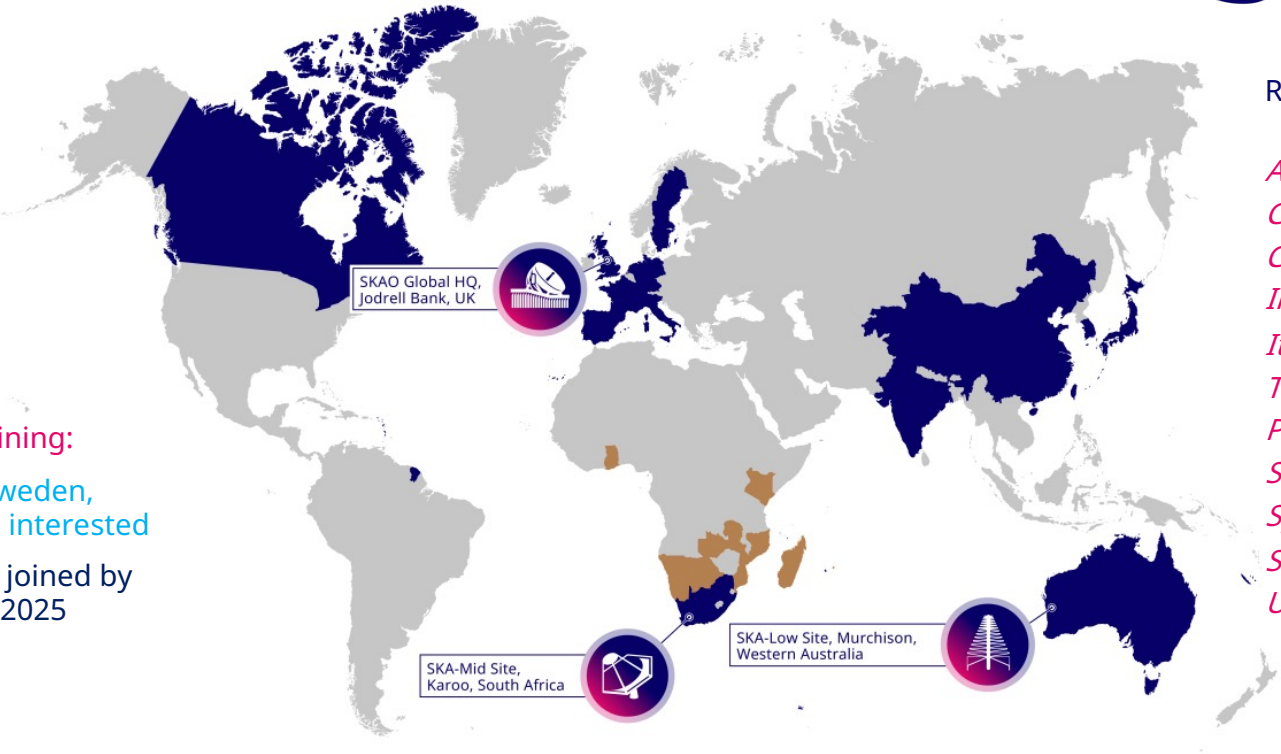
~> 500,000 antennas across Australia

SKAO – global partnership (IGO since 2021)

One Observatory

Two Telescopes

Three Continents



Ratified Members:

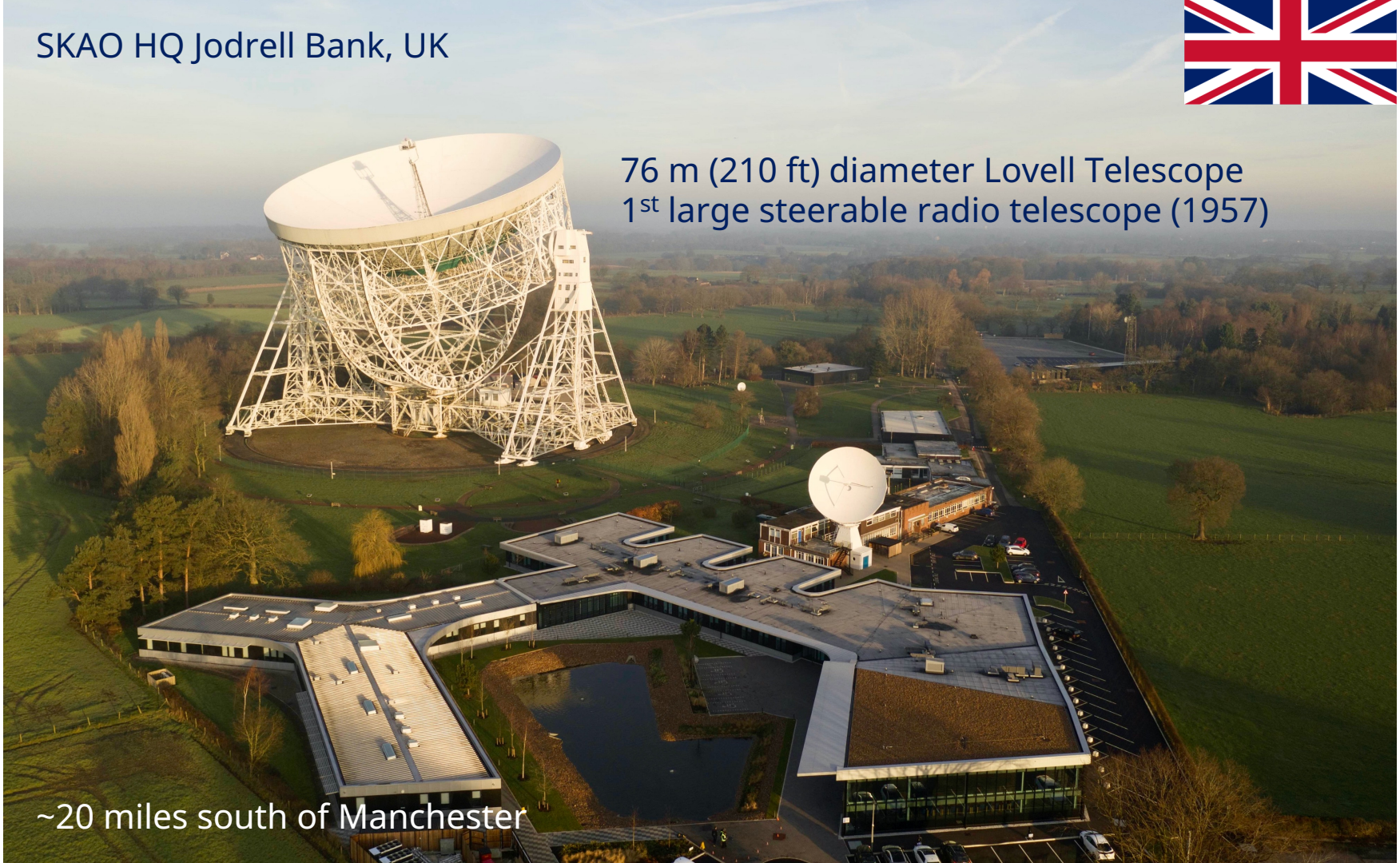
Australia
Canada
China
India
Italy
The Netherlands
Portugal
South Africa
Spain
Switzerland
United Kingdom

Various stages of joining:

France, Germany, Sweden, South Korea, others interested

Some will have fully joined by end 2024, others in 2025

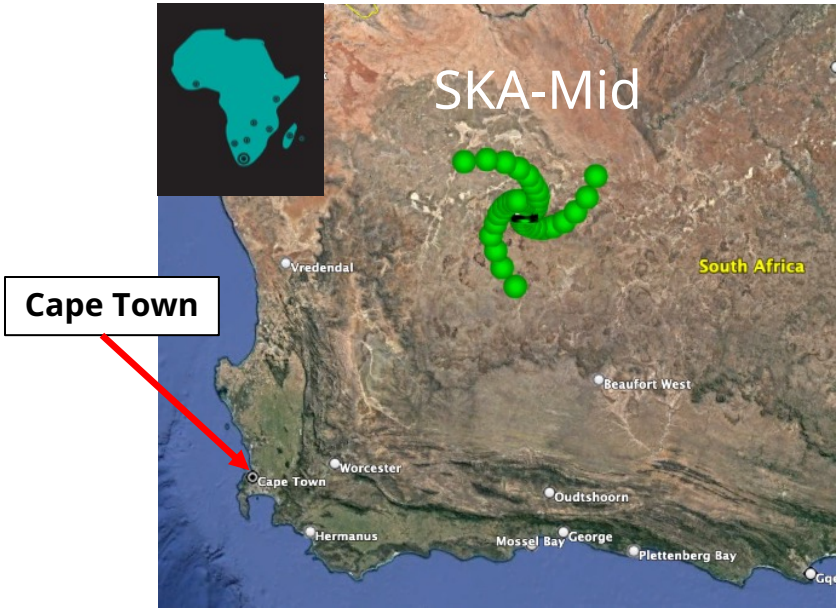
SKAO HQ Jodrell Bank, UK



76 m (210 ft) diameter Lovell Telescope
1st large steerable radio telescope (1957)

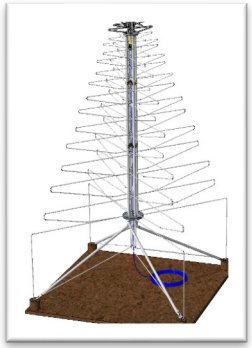
~20 miles south of Manchester

SKA-Mid in South Africa

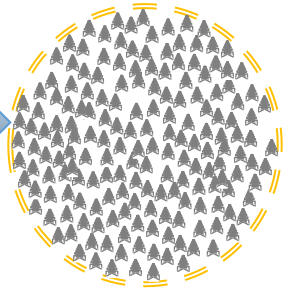


197 steerable dishes (15m and 13.5m diameter)
Maximum distance between dishes 150 km

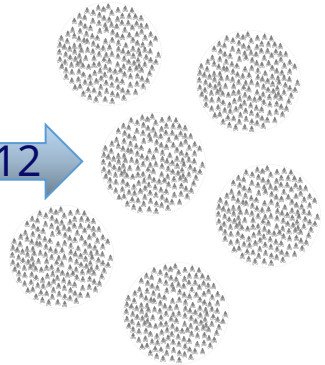
SKA-Low in Australia: an Array of Arrays



256



512



SKA-Low Antenna

"receiver"

SKA-Low Station

"telescope"

SKA-Low Array

"array of telescopes"

131,072 antennas, grouped into 512 stations
(256 antennas per station)
Maximum distance between stations 74 km

Why an array of telescopes?

$$\text{Resolving Power} = \frac{\text{wavelength}}{\text{diameter}}$$

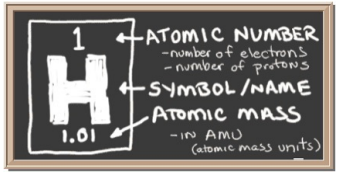
Hubble

2.4 metre mirror
1 micron (1 millionth of a metre)

"Resolving Power" **2,400,000**
(Actually the inverse)

Green Bank Telescope (WV)

100 metre dish
20 centimetres



"Resolving Power" **500**

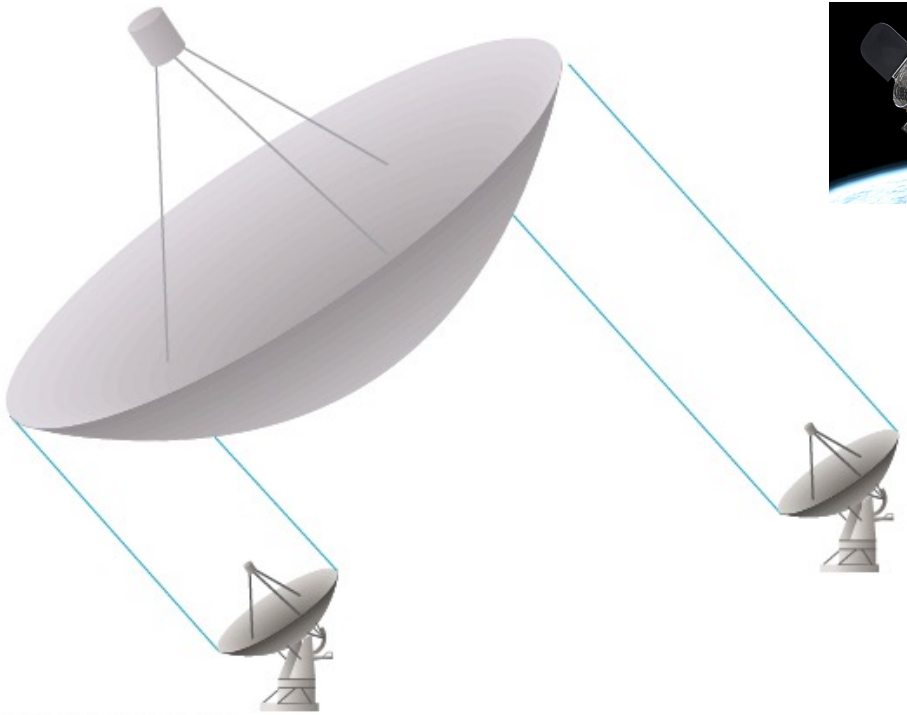
NASA/NRAO

Why an array of telescopes?

$$\text{Resolving Power} = \frac{\text{wavelength}}{\text{diameter}}$$

2.4 metre mirror
1 micron (1 millionth of a metre)

"Resolving Power" **2,400,000**



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SKA-Mid array
150 km "dish"

20 centimetres (~1.5 GHz)
"Resolving Power" **750,000**

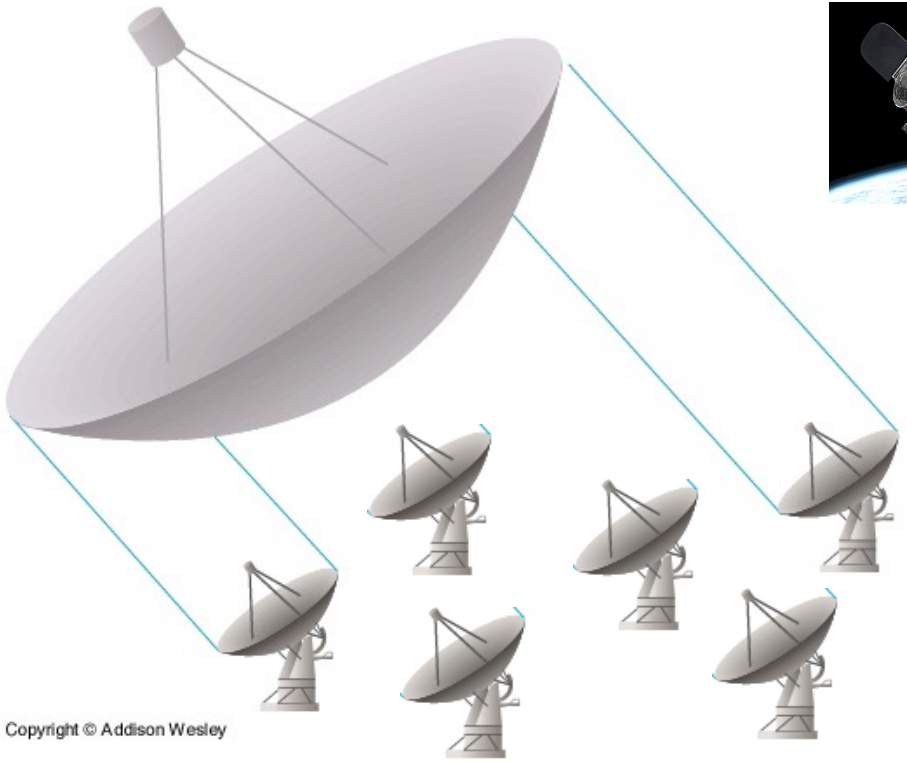
2 centimetres (~15 GHz)
"Resolving Power" **7,500,000**

Why an array of telescopes?

$$\text{Resolving Power} = \frac{\text{wavelength}}{\text{diameter}}$$

2.4 metre mirror
1 micron (1 millionth of a metre)

"Resolving Power" **2,400,000**

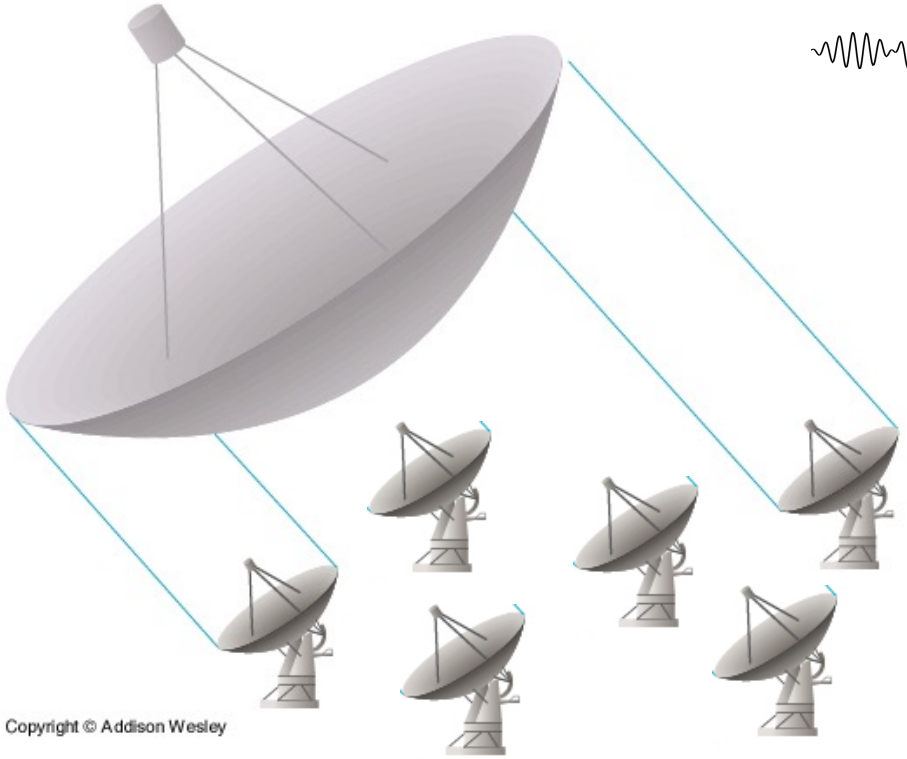


SKA-Mid array
150 km "dish"

20 centimetres (~1.5 GHz)
"Resolving Power" **750,000**

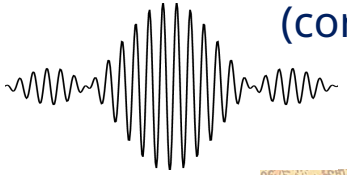
2 centimetres (~15 GHz)
"Resolving Power" **7,500,000**

Why an array of telescopes?



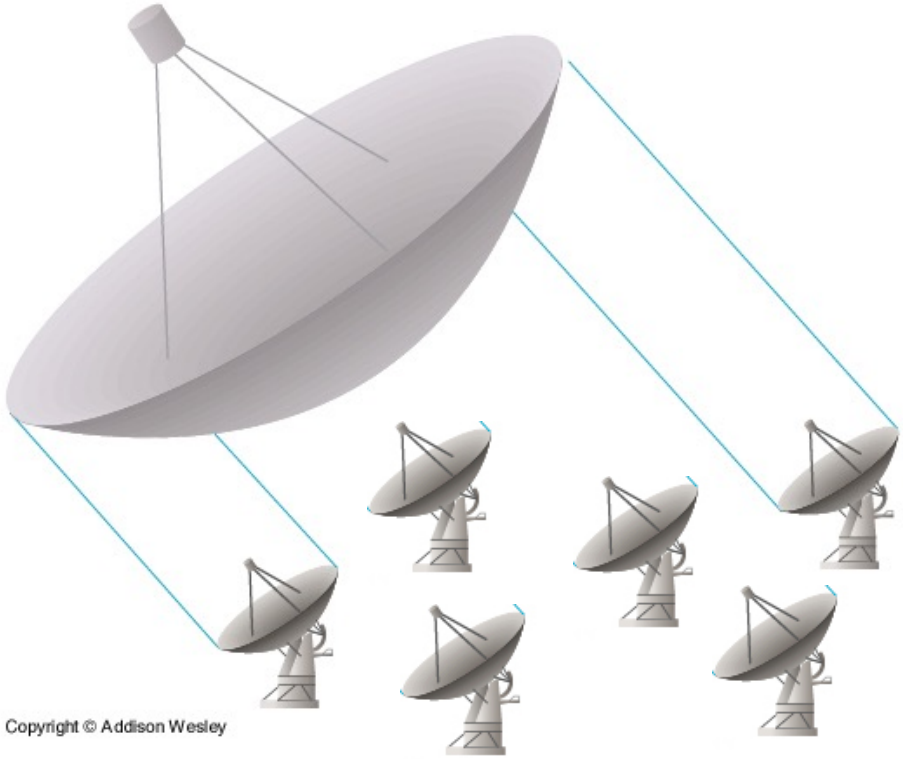
"Interferometry"

Combining signals (pairs of dishes)
(correct for "path length")



CHARA Array
loverelyvs.pics

Why a Square Kilometre Array?



Radio Interferometry: Theory, Techniques and Applications,
IAU Coll. 131, ASP Conference Series, Vol. 19, 1991,
T.J. Cornwell and R.A. Perley (eds.)

THE HYDROGEN ARRAY

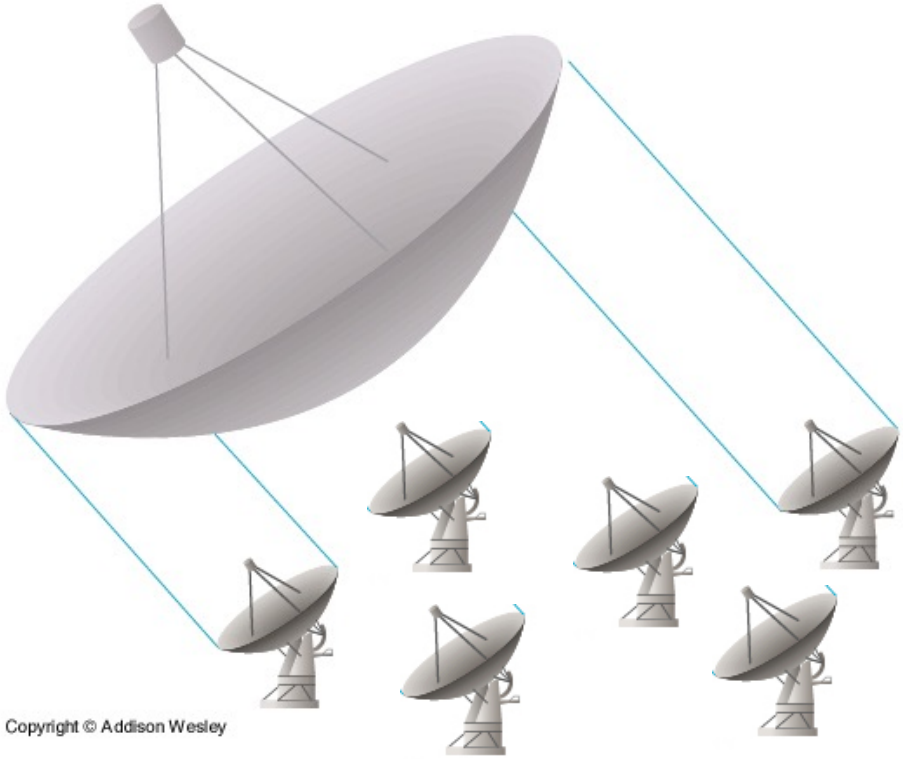
P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

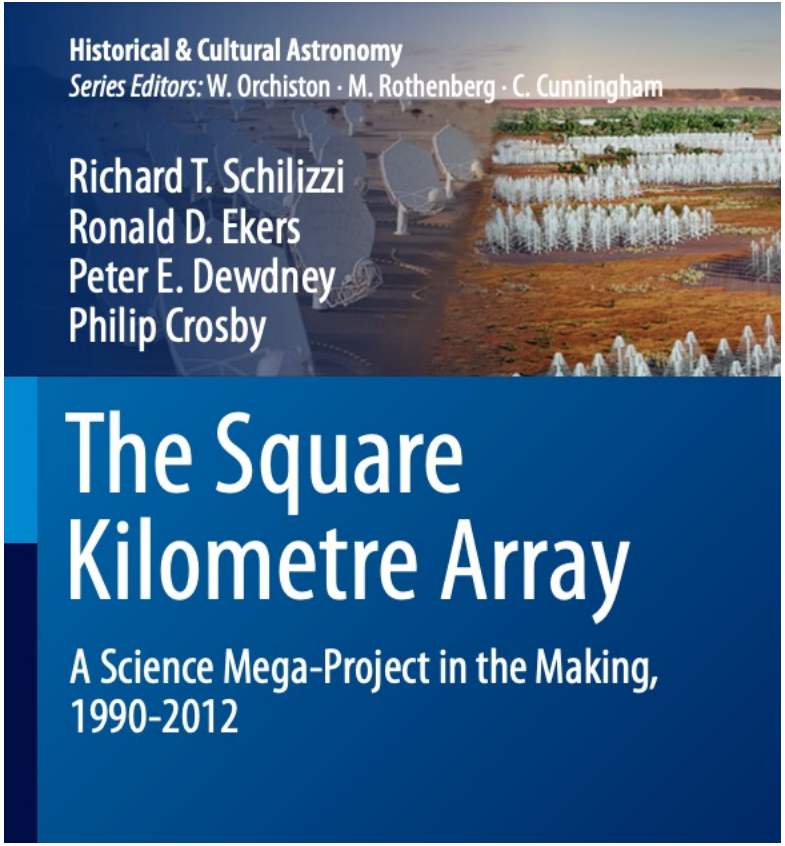
ABSTRACT The time is ripe for planning an array with a collecting area of 1 km² (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

Square Kilometre refers to the total collecting area, not the size on the ground.

SKA-Mid will have dishes spread over 150 km, but in phase 1 will ”only” have a collecting area of 33,000 m^2

Why a Square Kilometre Array?





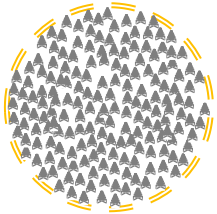
https://link.springer.com/book/10.1007/978-3-031-51374-9

How does SKA1 compare to other radio telescopes?

SKA as a Big Data machine

SKA-Low

2 Pb/s



9 Tb/s

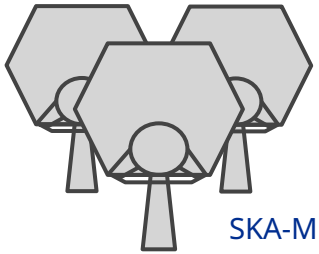
Perth

CSP

8 Tb/s

SDP

100 Gb/s



SKA-Mid

20 Tb/s

Cape Town

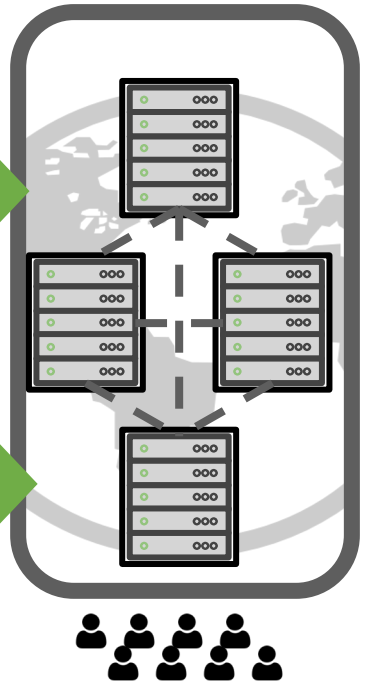
CSP

9 Tb/s

SDP

100 Gb/s

SKA Regional Centres



CSP = Correlator/beamformer (Central Signal Processing)

SDP = Science Data Processor

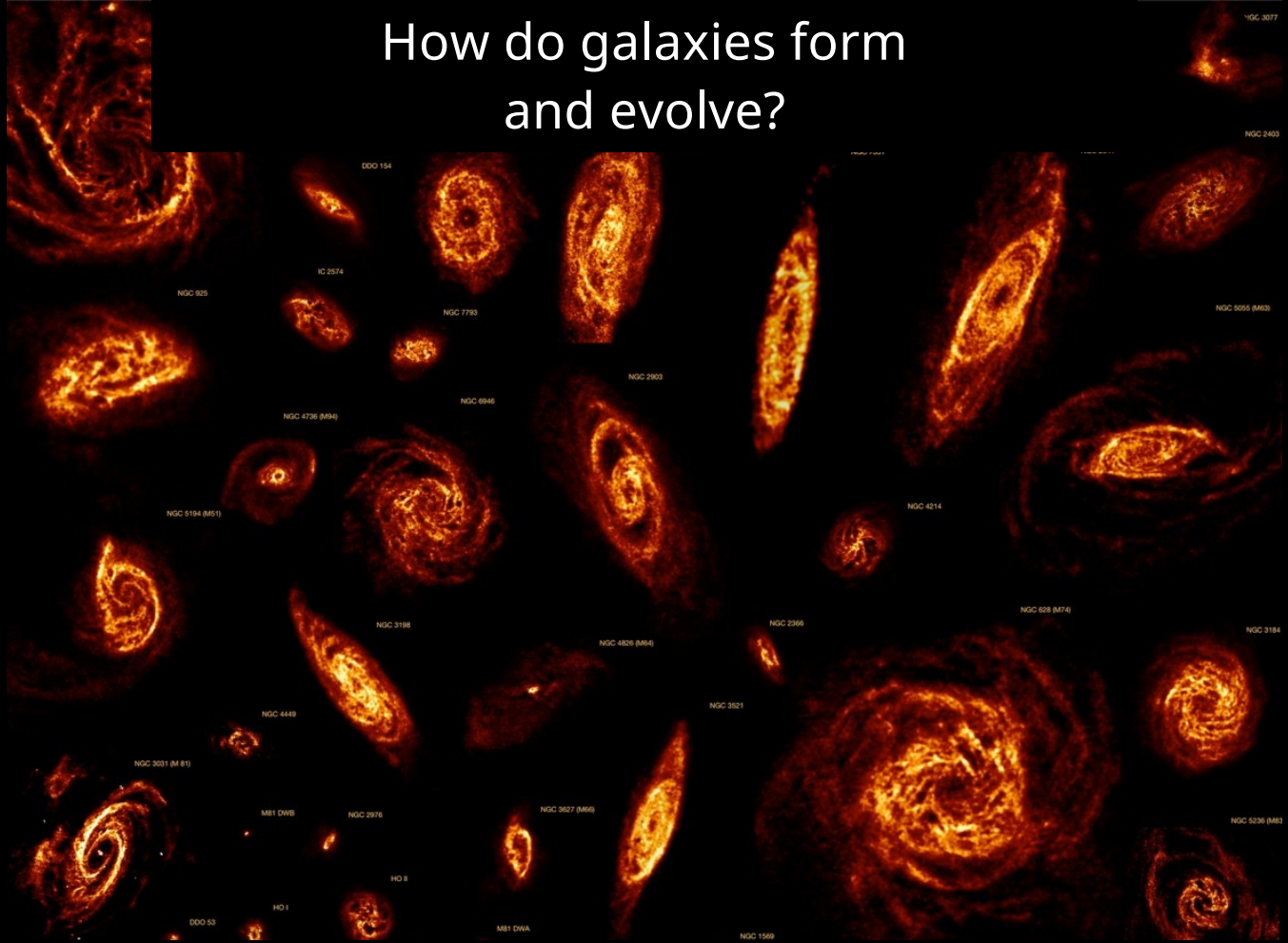
Data Archive ~600 PB/yr

Facebook ~1400 PB/yr

Science with the SKA

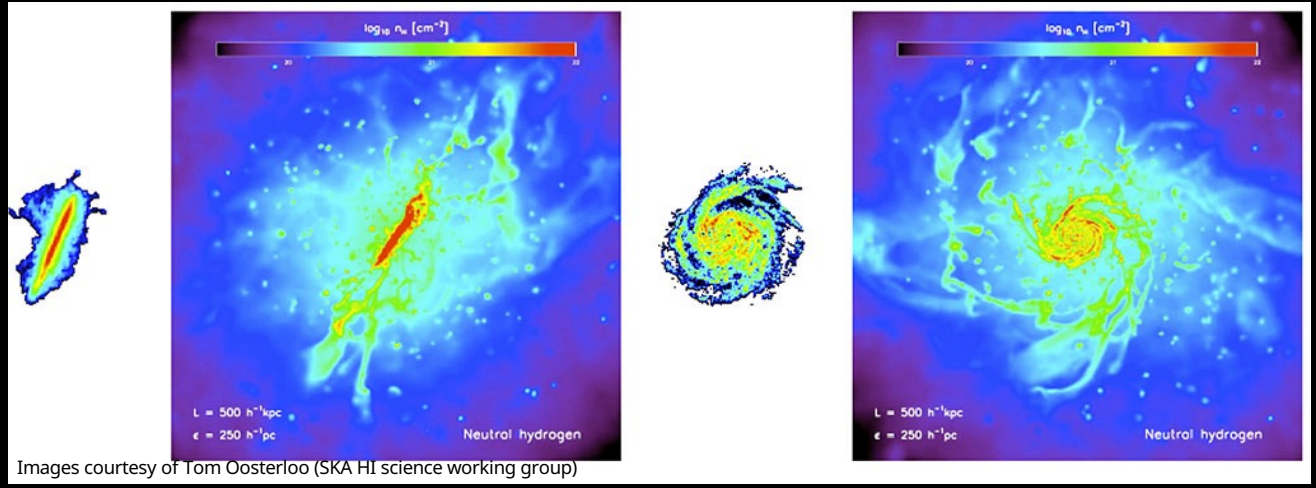

SKA– Key Science Drivers
The history of the Universe
Testing General Relativity
(Extreme Gravity, Gravitational Waves)
Cosmic Dawn & Reionisation
(First Stars and Galaxies)
Cradle of Life
(Planets, Molecules, SETI)
Galaxy Evolution
(Normal Galaxies z~2-3)
Cosmic Magnetism
(Origin, Evolution)
Cosmology
(Dark Matter, Large Scale Structure)
Our Galaxy
(Star Birth & Death, Matter Evolution, Structure)
Exploration of the Unknown
Huge range of transformational science enabled by SKAO

How do galaxies form and evolve?

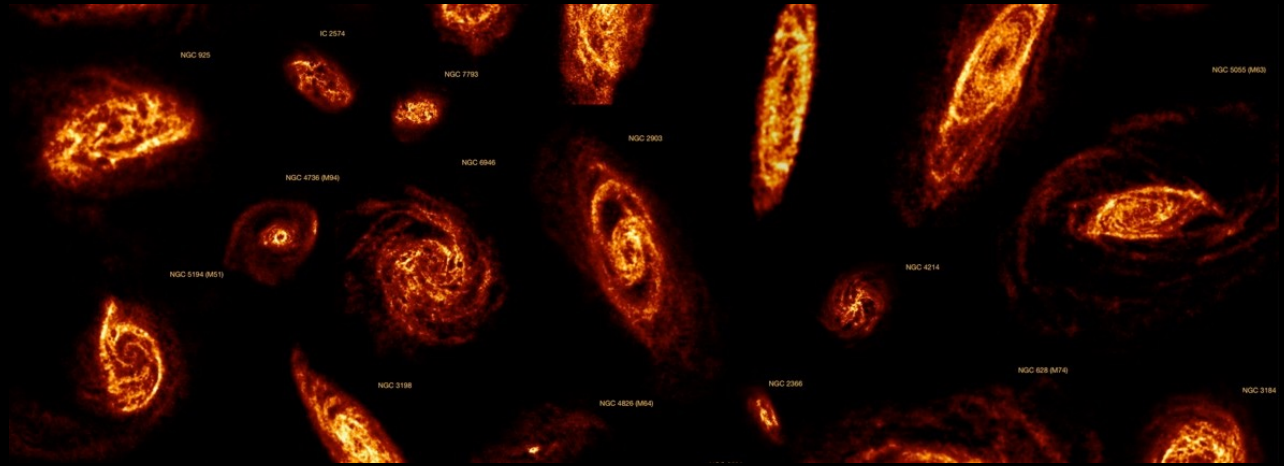


HI Nearby Galaxy Survey (THINGS)

observed HI simulated HI observed HI simulated HI

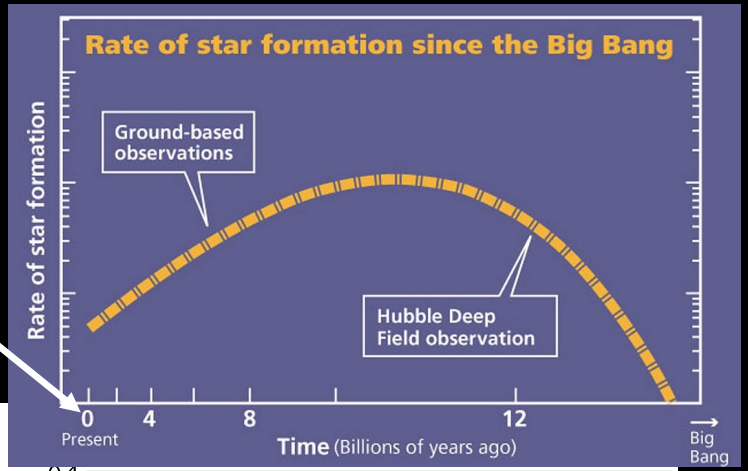


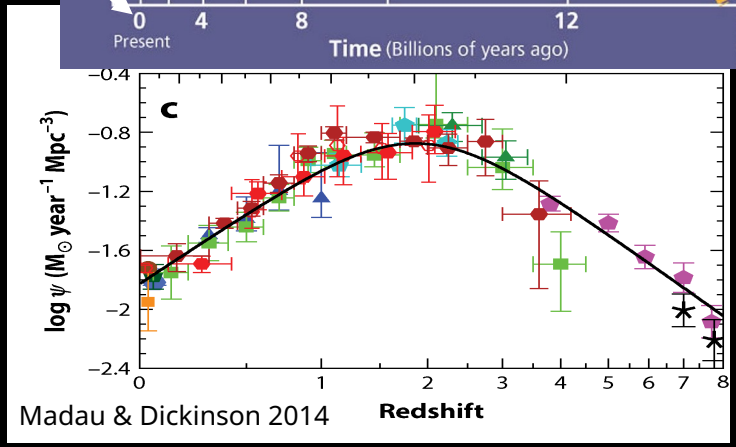
Images courtesy of Tom Oosterloo (SKA HI science working group)



Star Formation Rate PEAKED

You are here

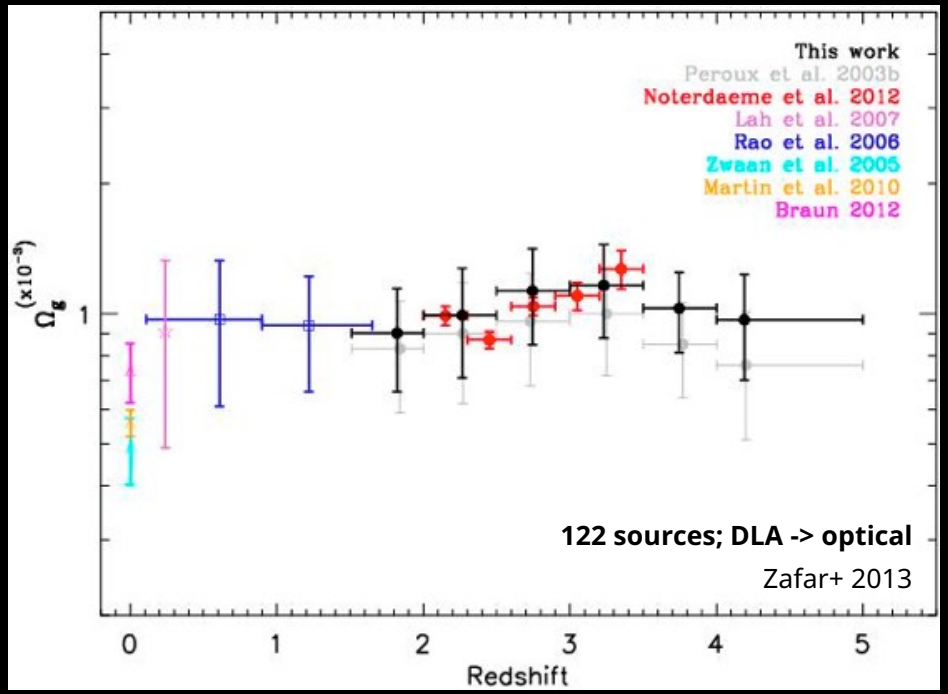




Madau & Dickinson 2014

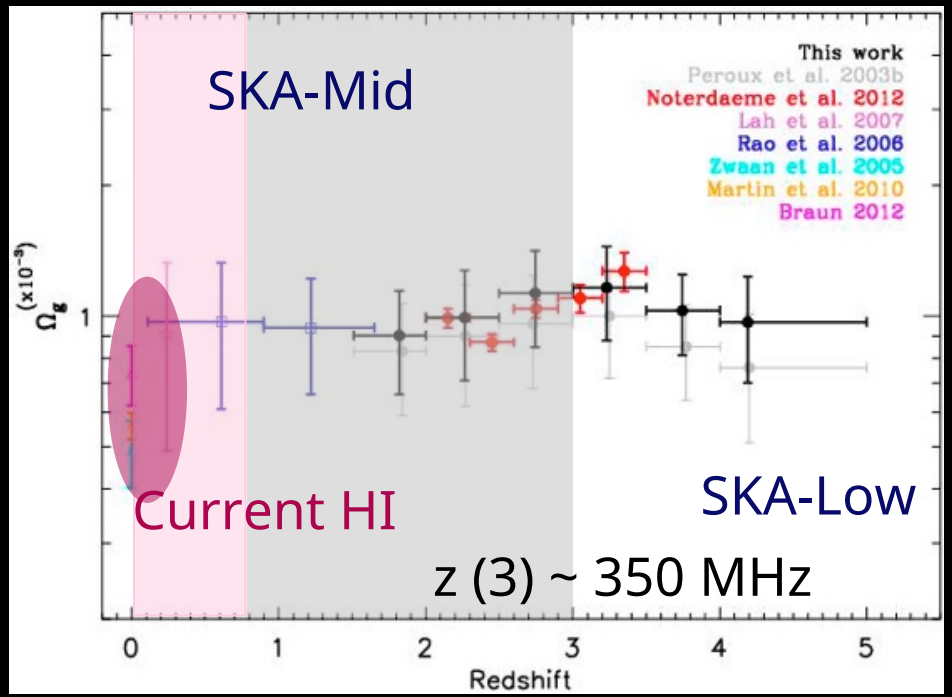
Hydrogen Mass Evolution FLAT

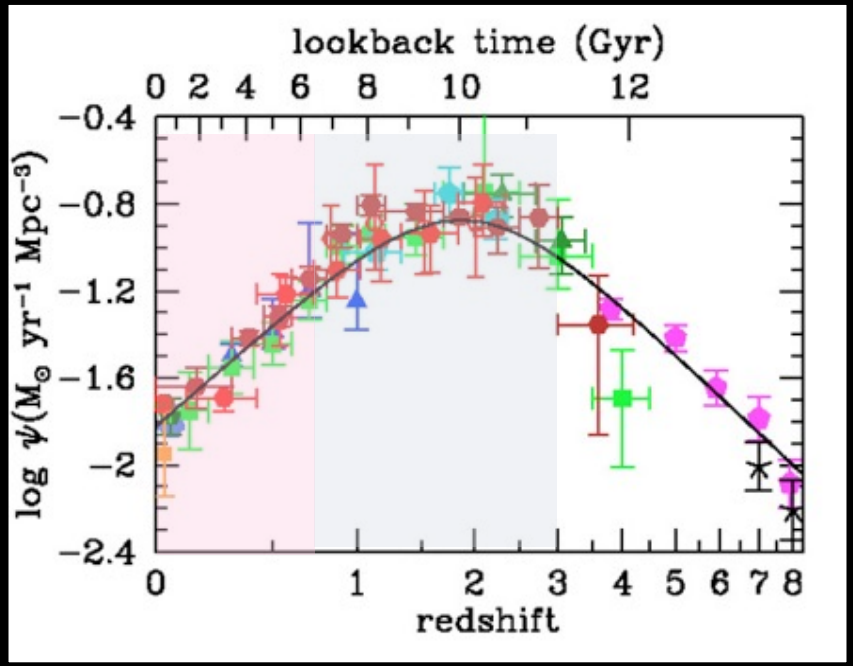
(or is it?, e.g. Bird+ 2017)



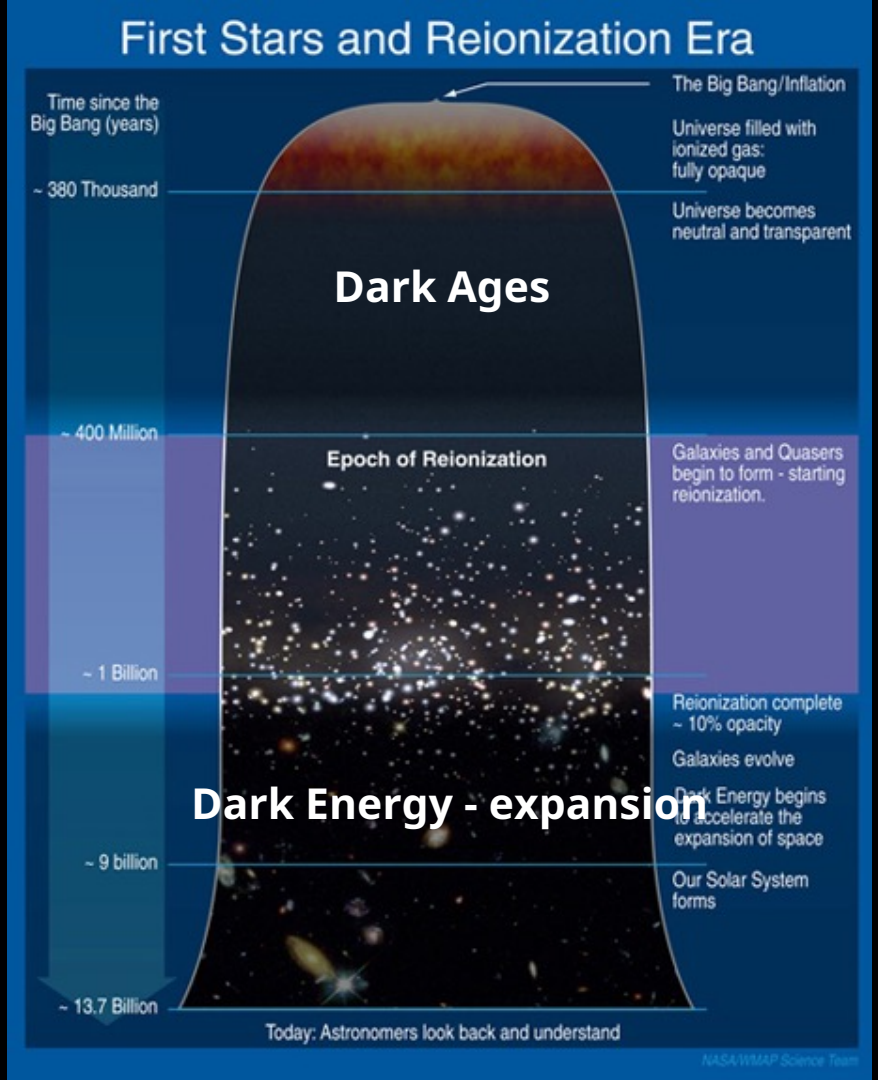
PROBLEM:
Stars form from Hydrogen

SKA-Mid – detect many galaxies in HI to z ~ 3 – very challenging
SKA-Low – formation of structure in the Universe (next slide)

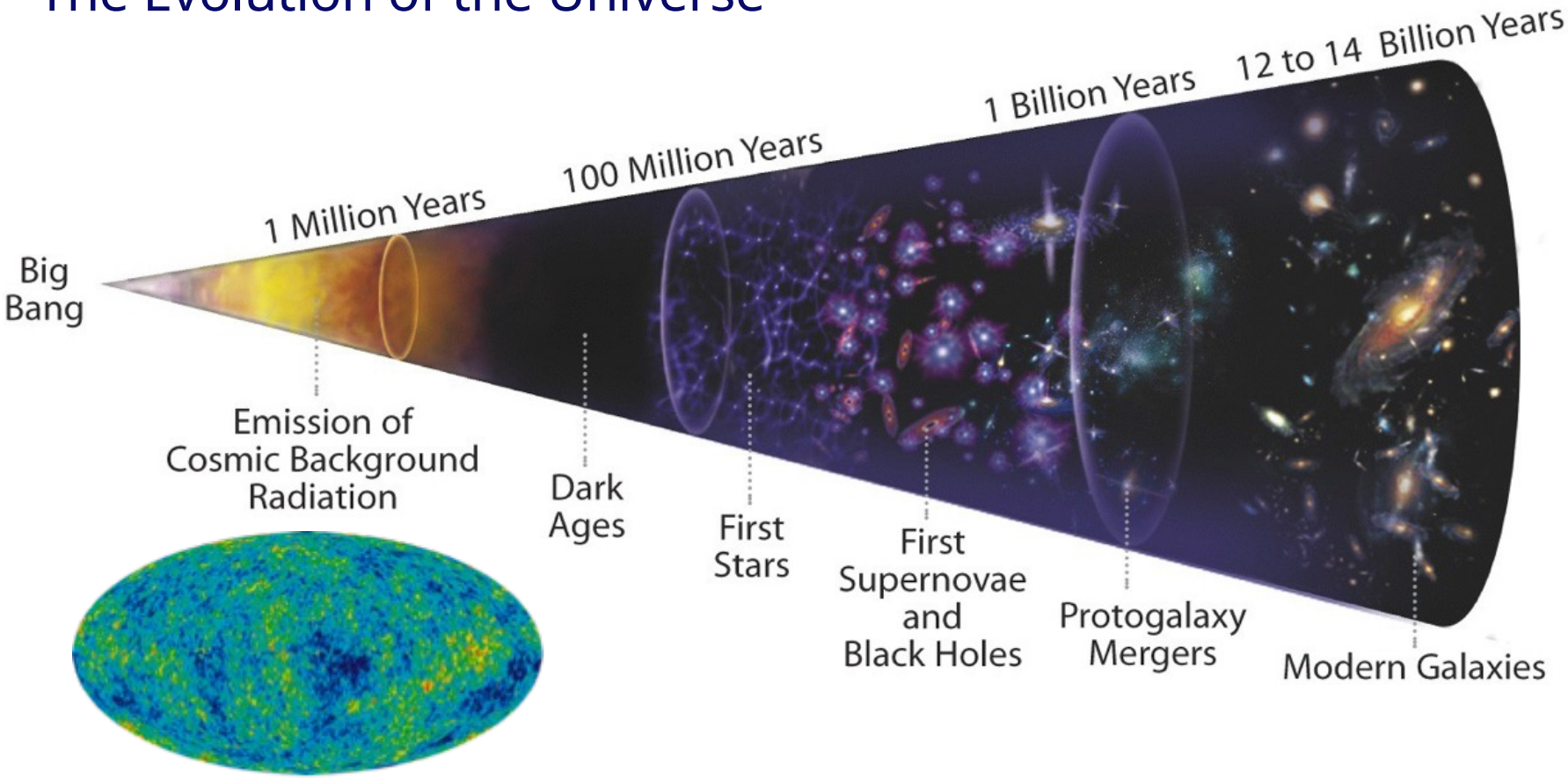




Time since Big Bang	Event
380,000 yrs	CMB
400 million yrs	Stars form
1 Billion yrs	Galaxies evolve
9 Billion yrs	Solar System forms
13.7 Billion yrs	Humans



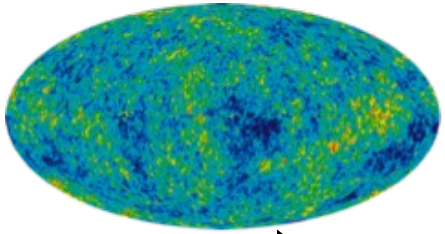
The Evolution of the Universe

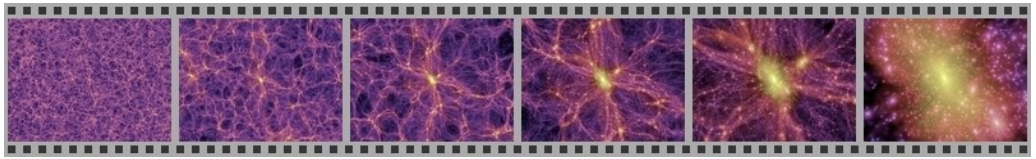


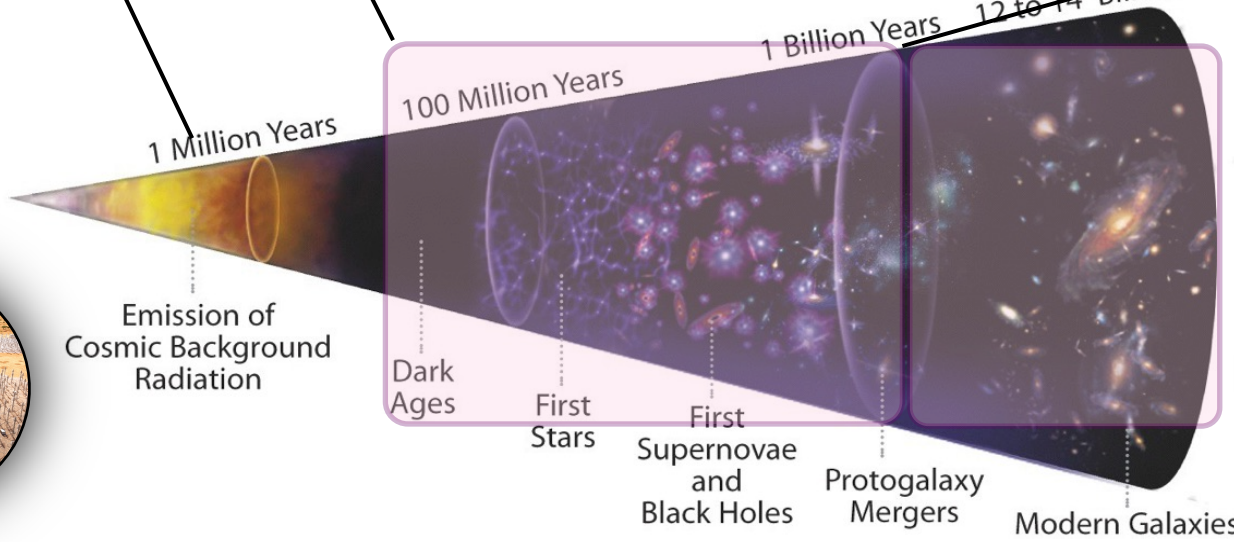
The Evolution of the Universe – A Movie

CMB snapshot at ~400,000 yrs

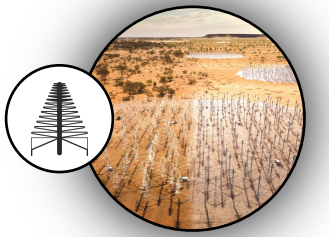
SKA-Low will observe the evolution of HI emission to make a movie of the Universe until the formation of the first modern galaxies







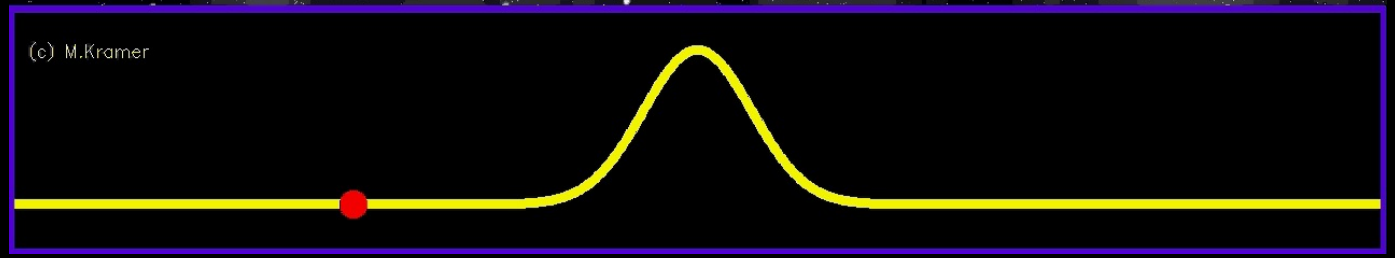
SKA-Low

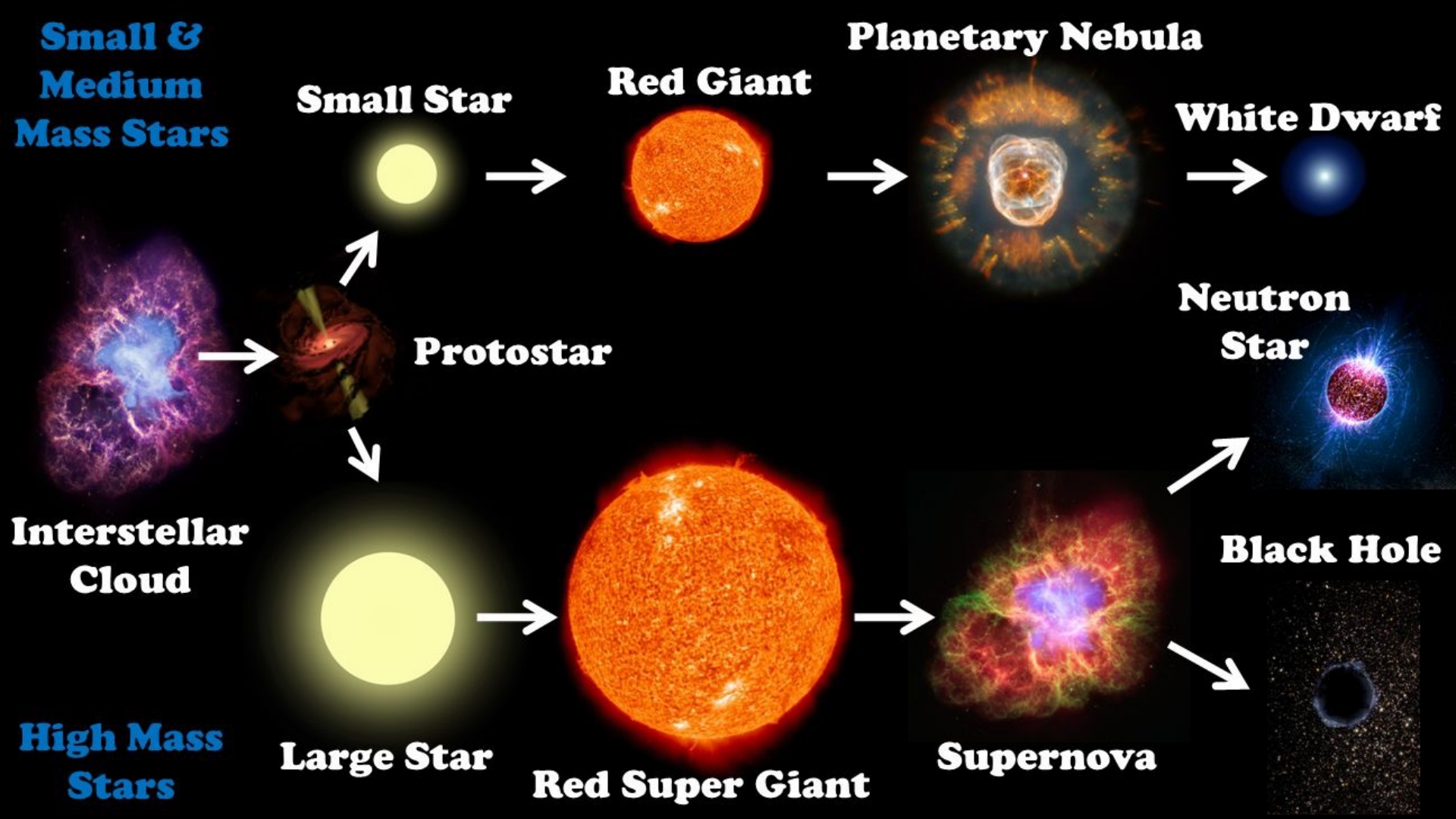


SKA-Mid

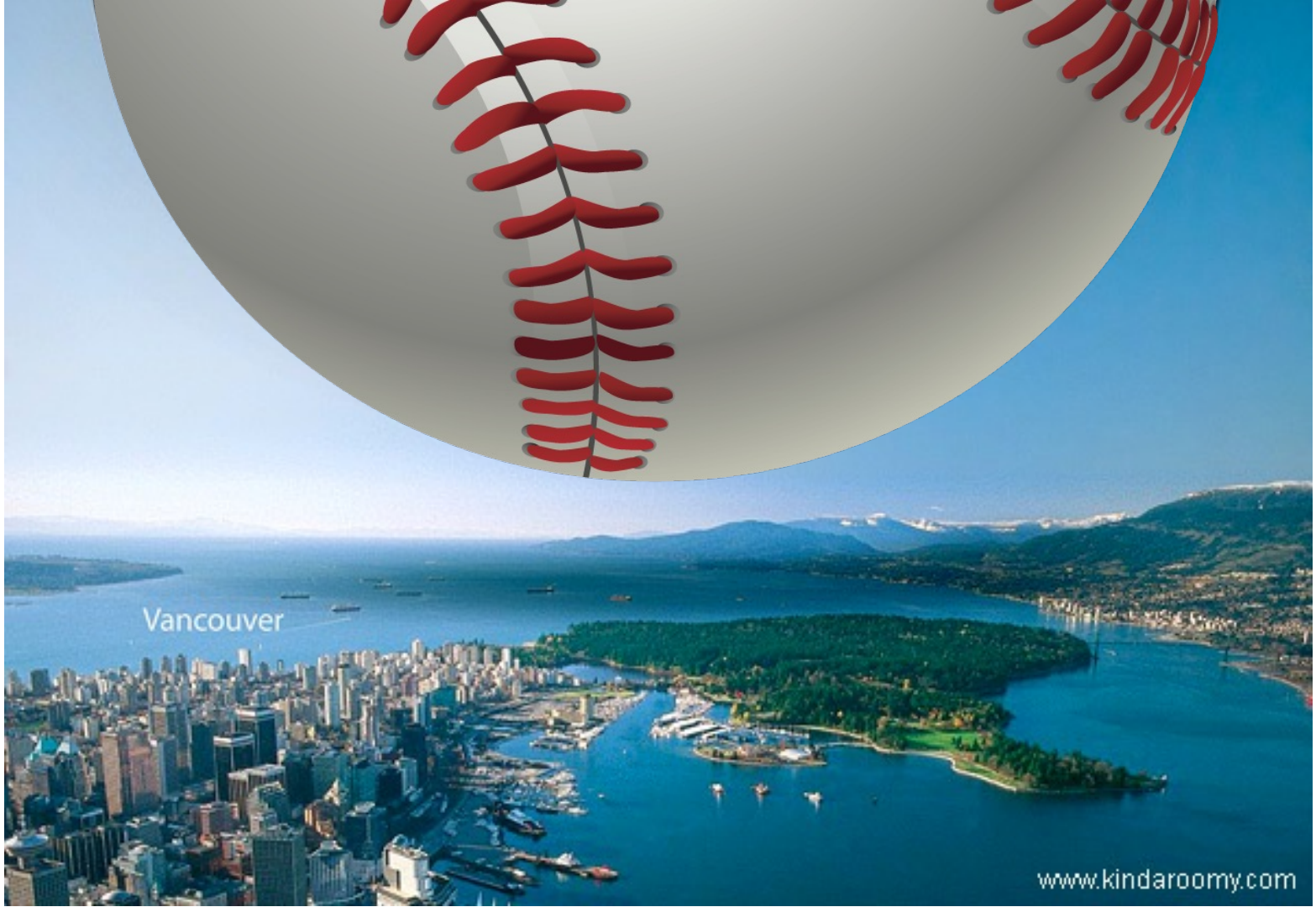
Without radio astronomy, we would not know of Pulsars

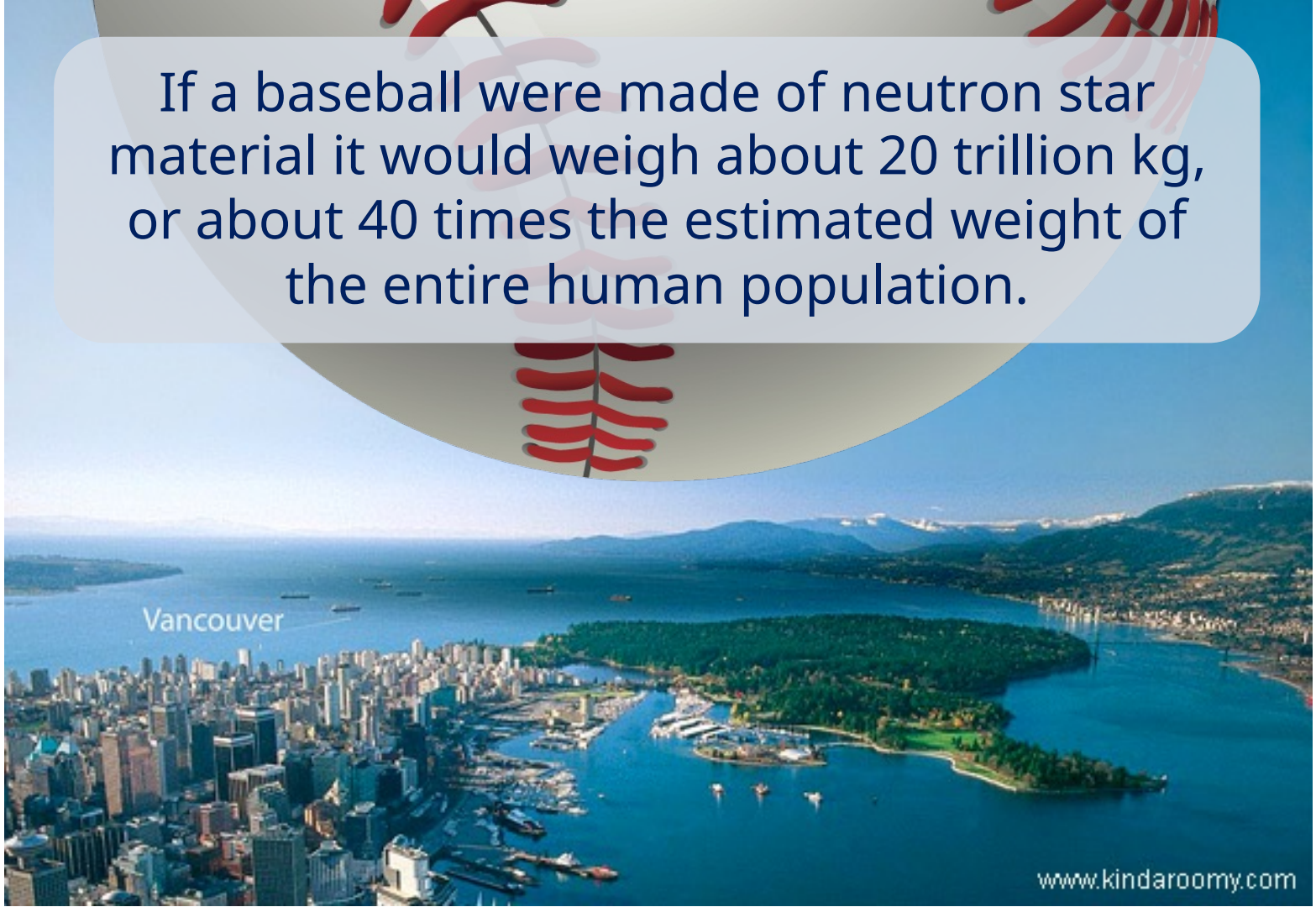
5.757451924362137(2) ms (Verbiest et al. 2008) = 2 atto (10^{-18}) seconds uncertainty!

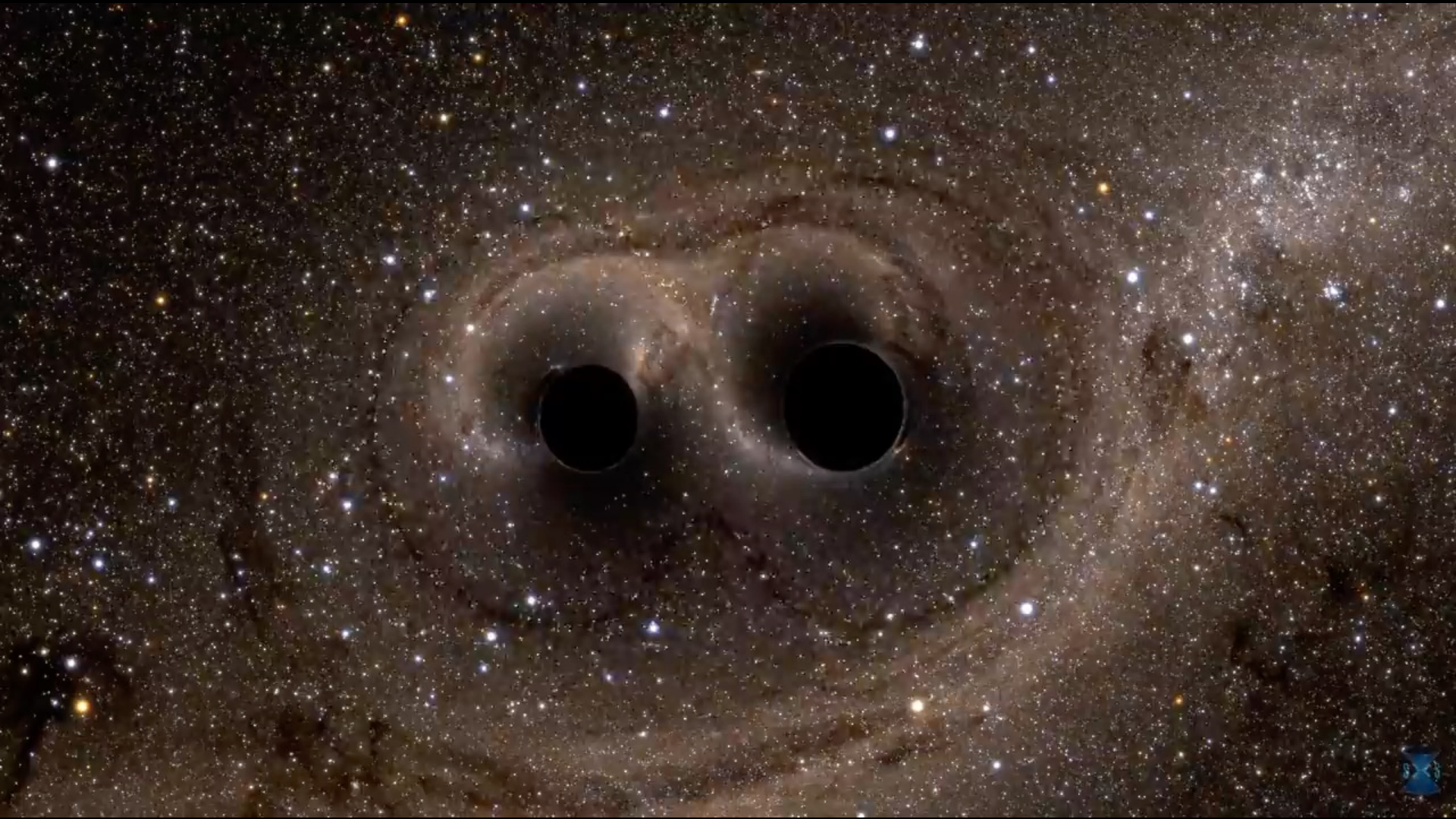


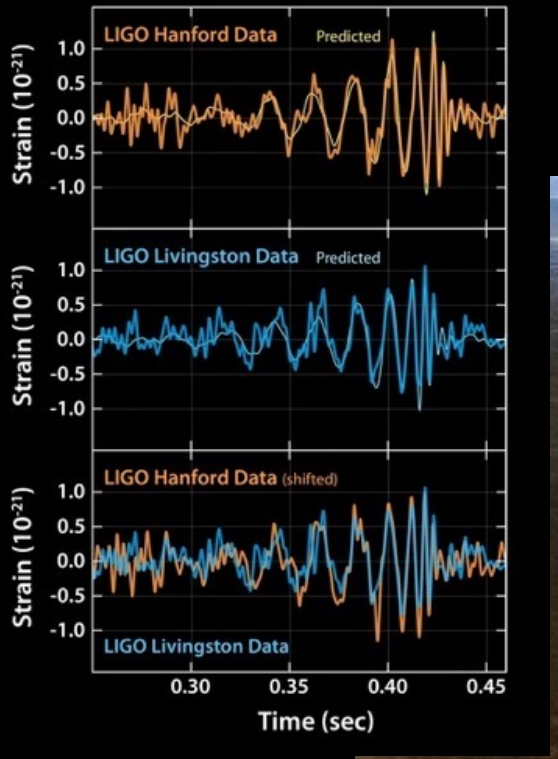

Small & Medium Mass Stars
Small Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Neutron Star
Interstellar Cloud
Black Hole
High Mass Stars
Large Star
Red Super Giant
Supernova

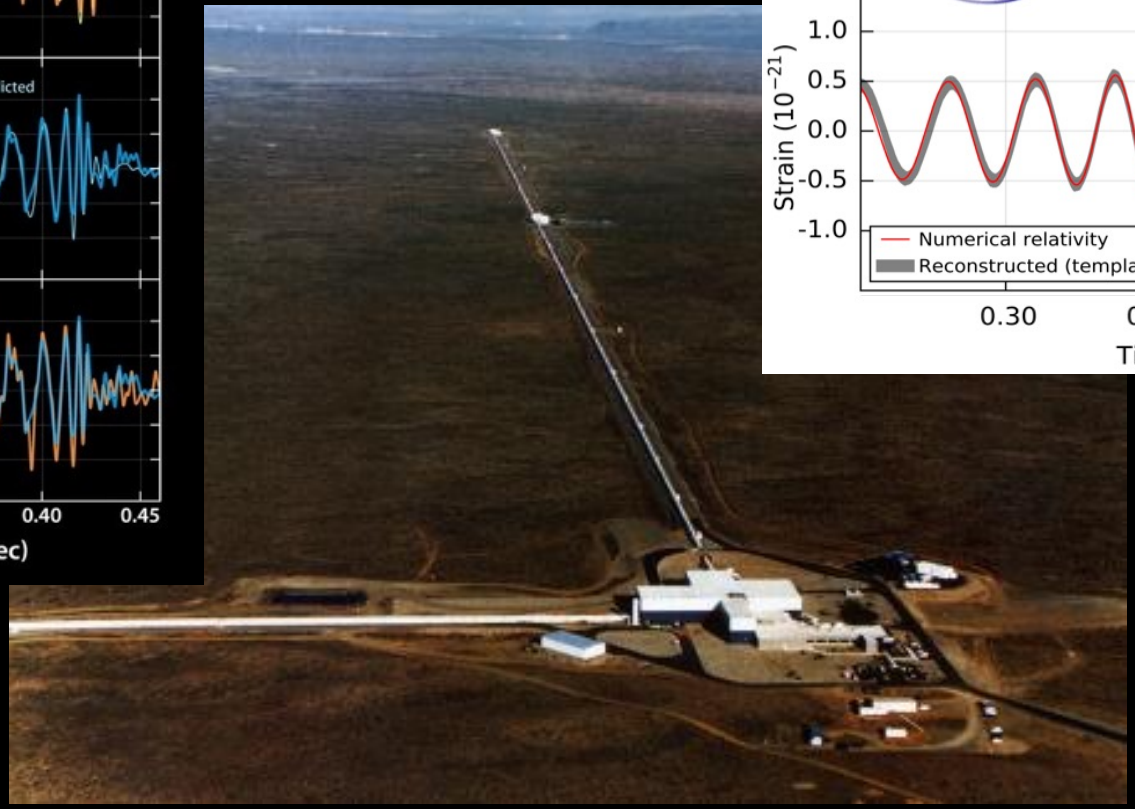

Neutron Star
Vancouver
www.kindaroomy.com

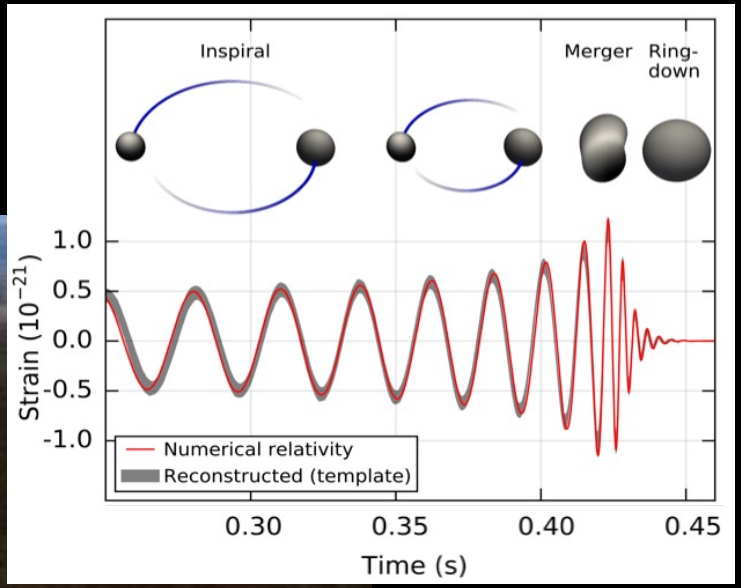

Vancouver
www.kindaroomy.com


If a baseball were made of neutron star material it would weigh about 20 trillion kg, or about 40 times the estimated weight of the entire human population.
Vancouver
www.kindaroomy.com



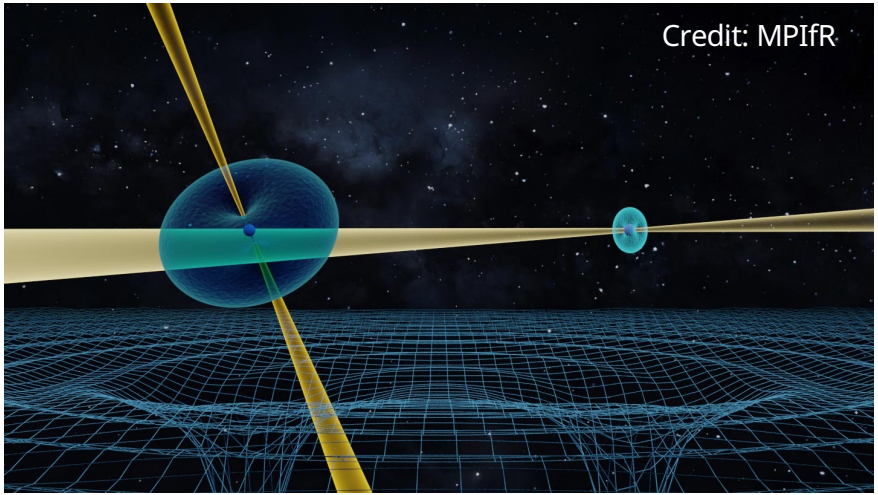

LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)



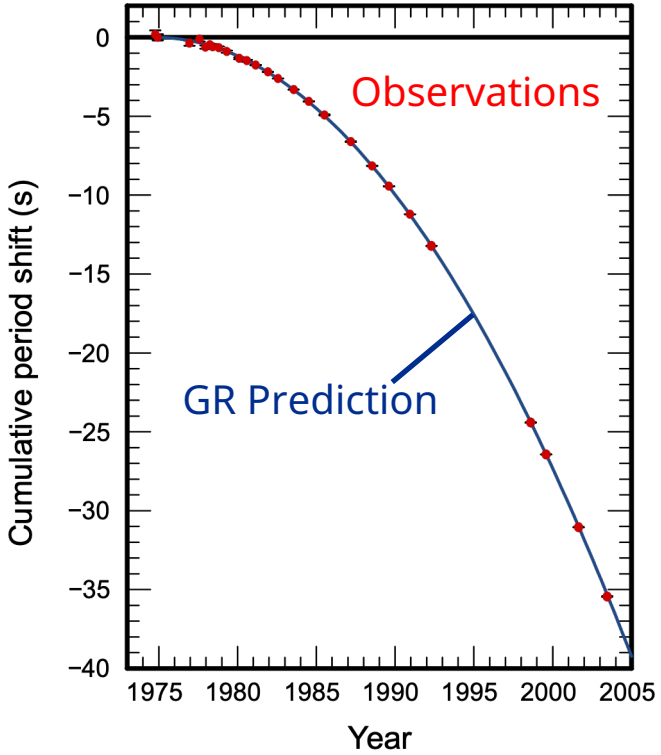

Inspiral
Merger
Ring-down
Strain (10−21)
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
0.30
0.35
0.40
0.45
Time (s)

Test General Relativity in strong field regime

Tests of GR in strong field regime via:
Pulsar – White Dwarf binaries
Pulsar – Neutron Star binaries
Pulsar – Pulsar binaries
Pulsars around Galactic Centre
Pulsar – Black Hole binaries

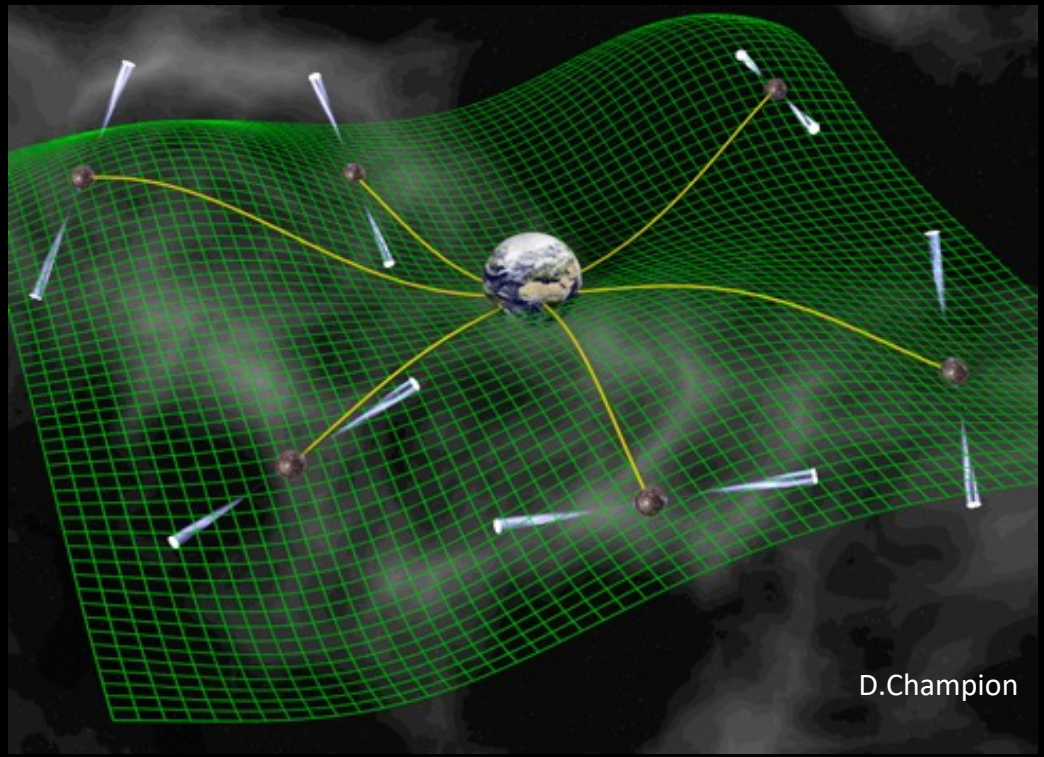


Pulsar (Neutron Star) Binary Orbital Decay – Obs. v Theory

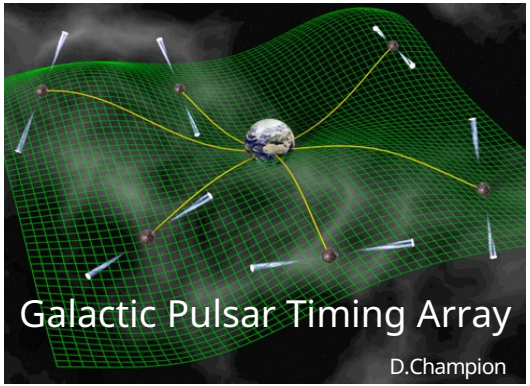


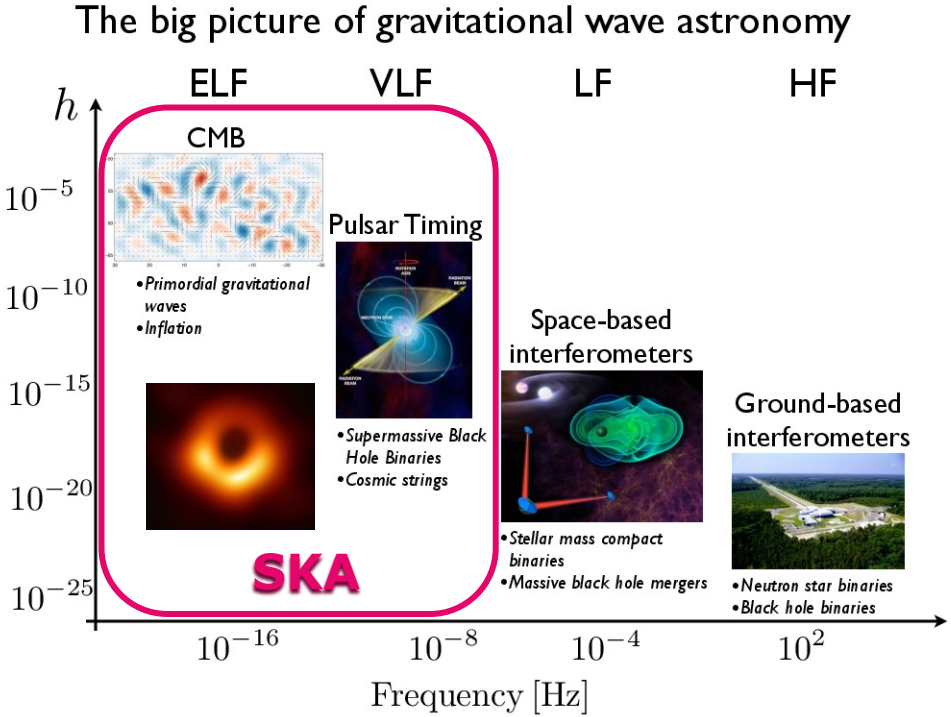
99.99% agreement with GR

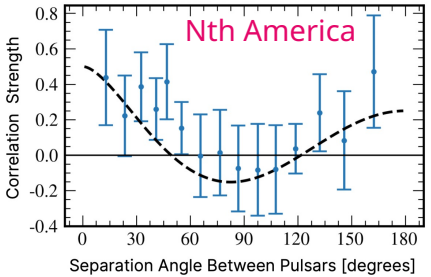
(e.g., Kramer+ 2021 Phy. Rev. X)

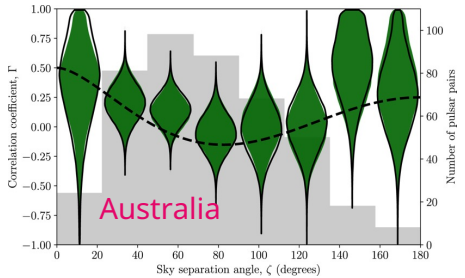

D.Champion

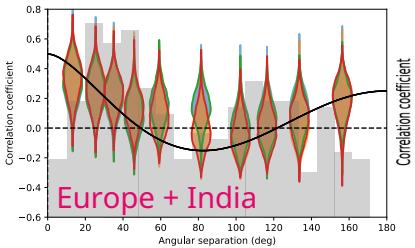
Gravitational Waves with Pulsars (Multi-messenger Physics)

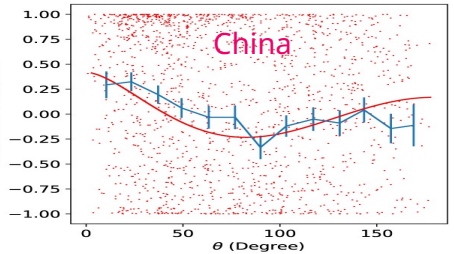












Fast Radio Bursts
extreme astrophysics in the radio

Discovered by chance in 2007

Typically last ~ms – 100x shorter than the blink of an eye

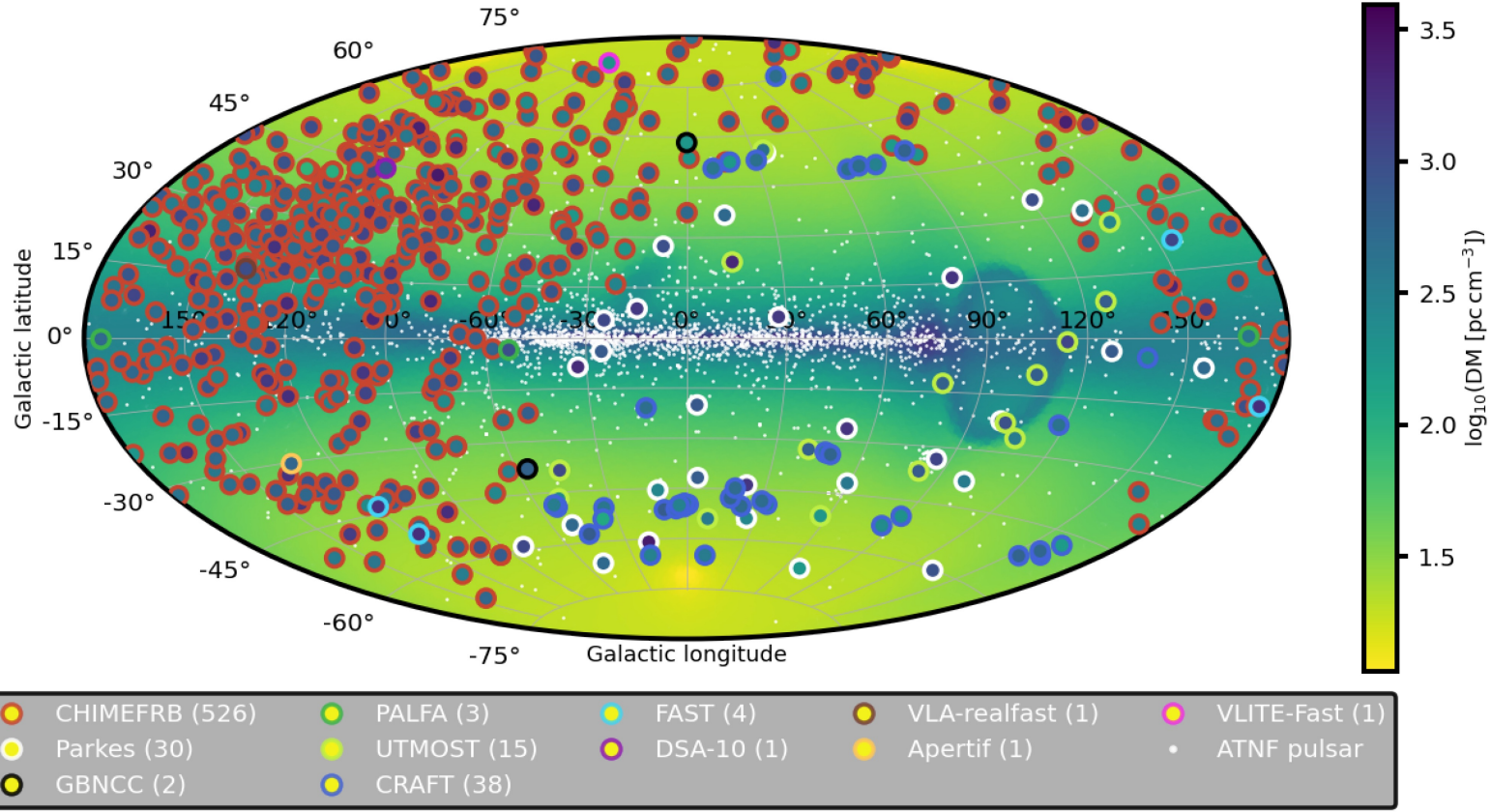
Emitted a long time ago in galaxies far far away

Energy emitting in ~ms same a Sun emits in one day

(thanks to Jason Hessels)

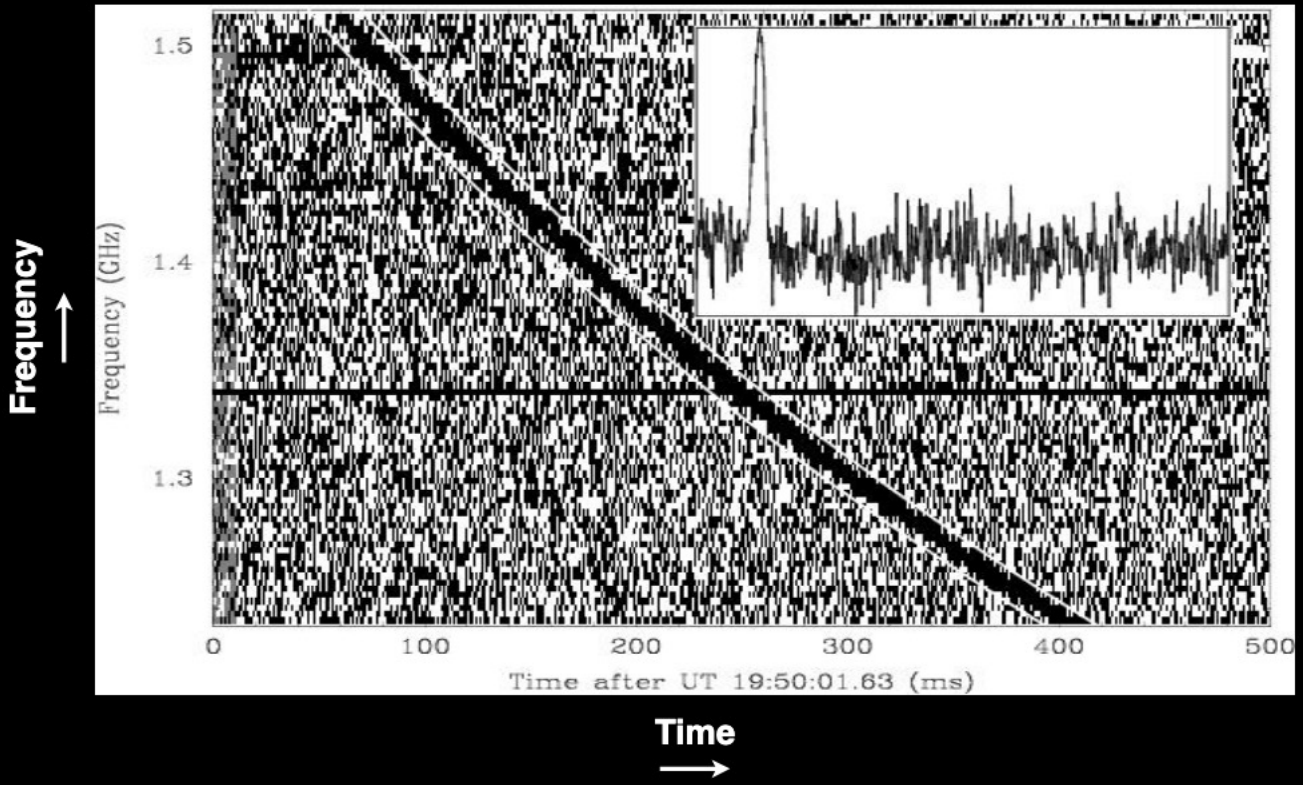
Hundreds of FRBs now detected

Estimated event rate: 10,000 sky^{-1} day^{-1}

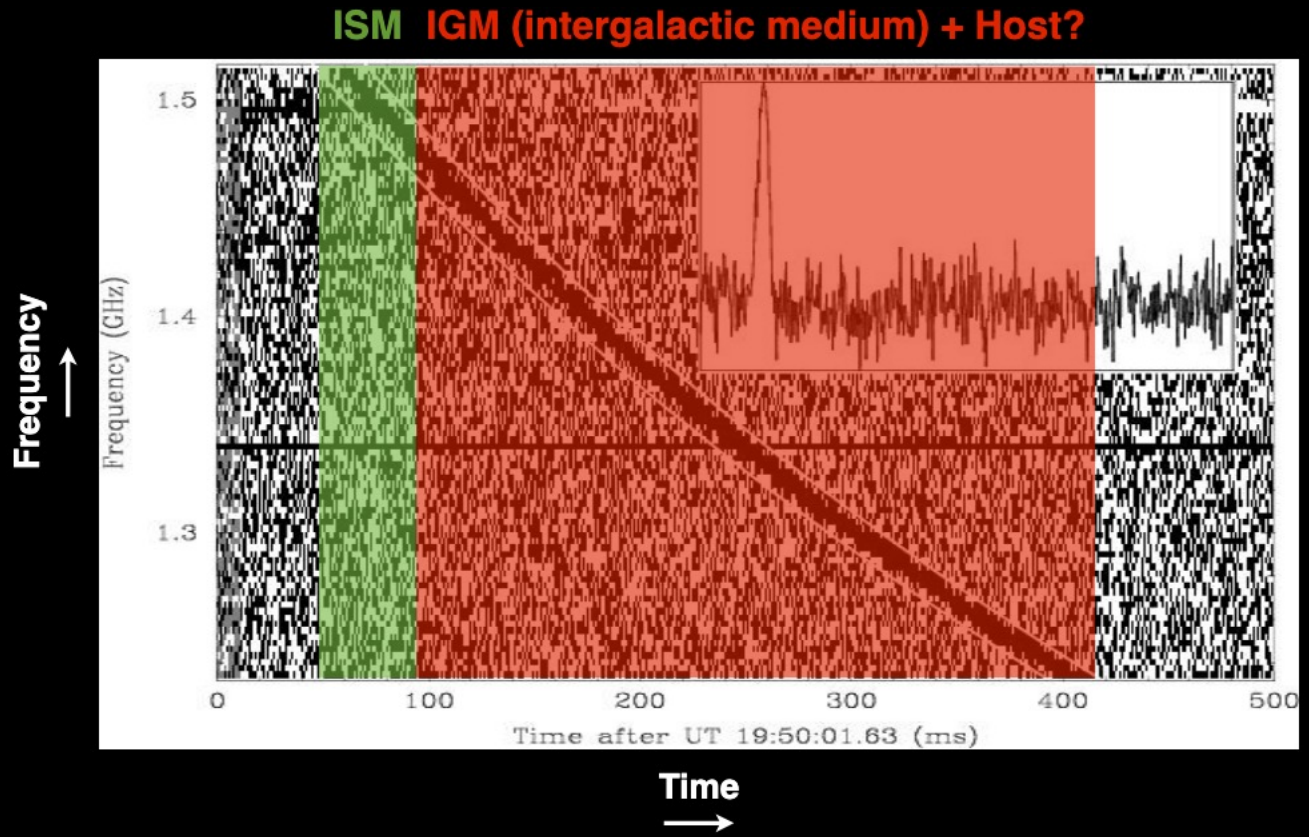


credit: Laura Driessen

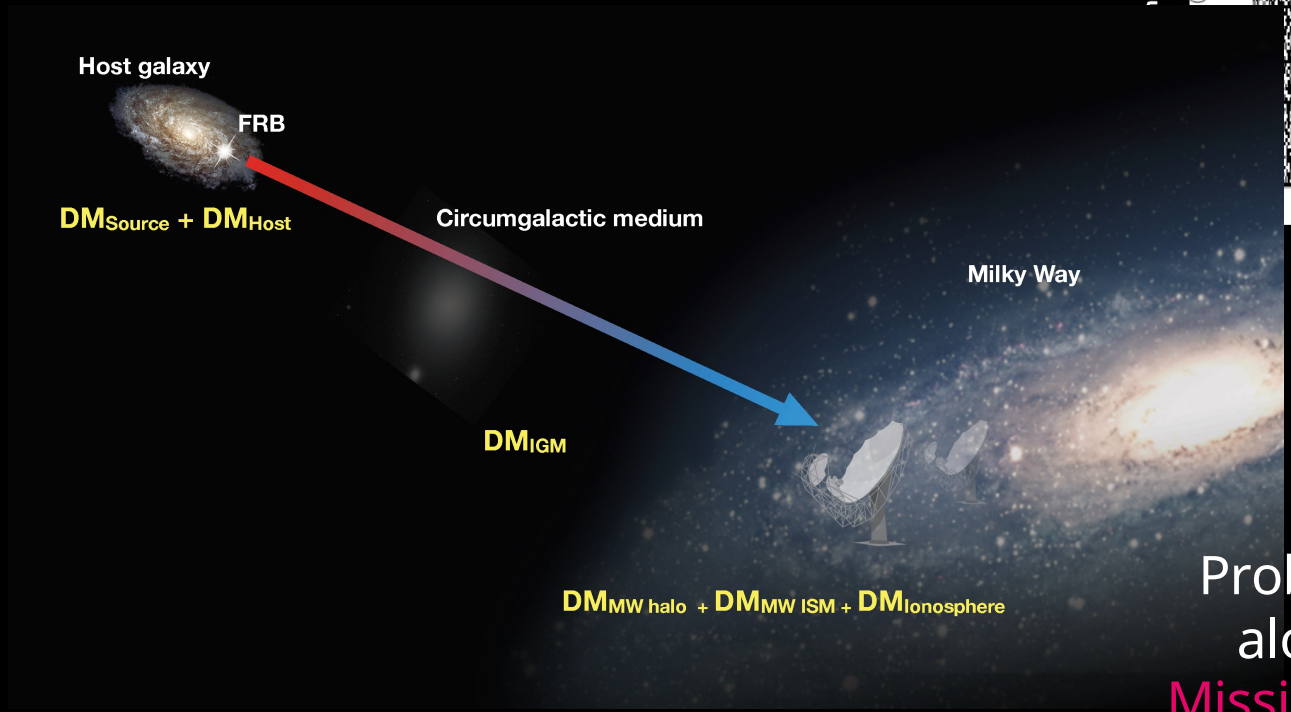
Lorimer Burst (2007)

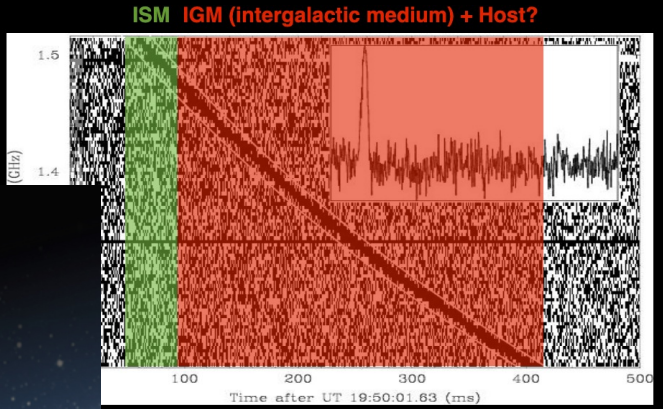


Lorimer Burst (2007)



How can we use them?





Time →

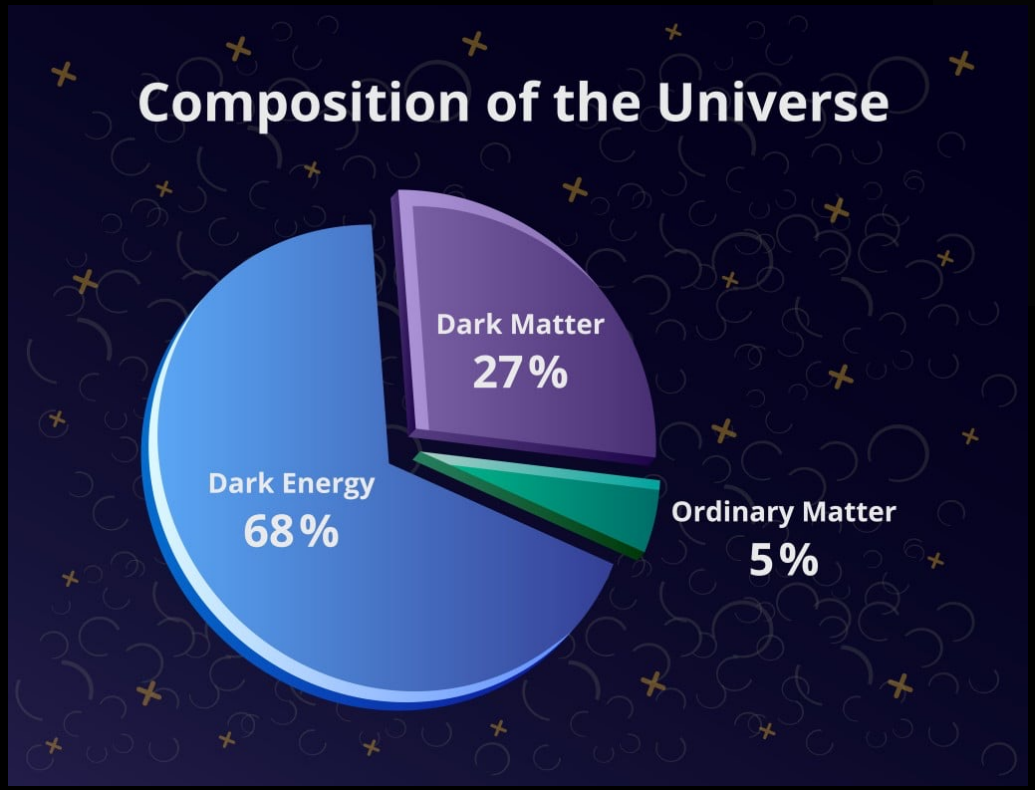
Dispersion Measure (DM)

Probe Baryon content along line-of-sight:
Missing Baryon Question

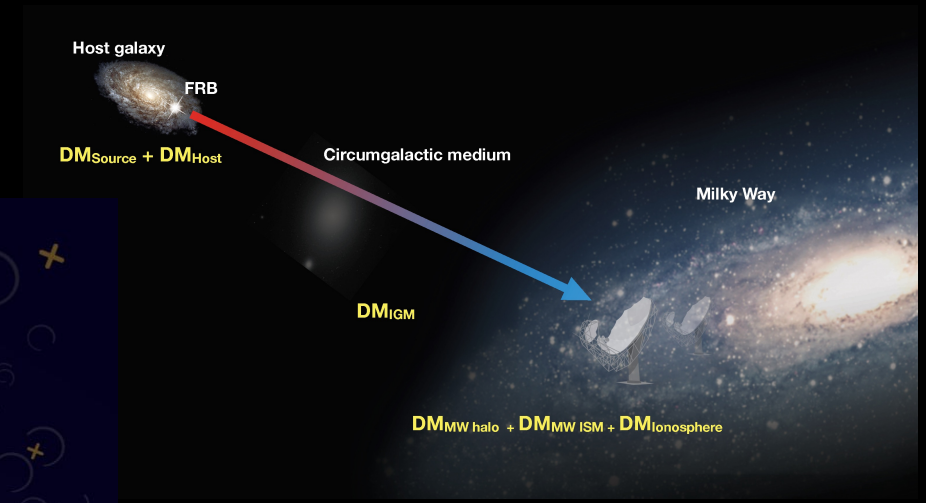
Caleb & Keane 2021

Baryon = normal matter

How can we use them?



ScienceABC



Probe Baryon content along line-of-sight:
Missing Baryon Question

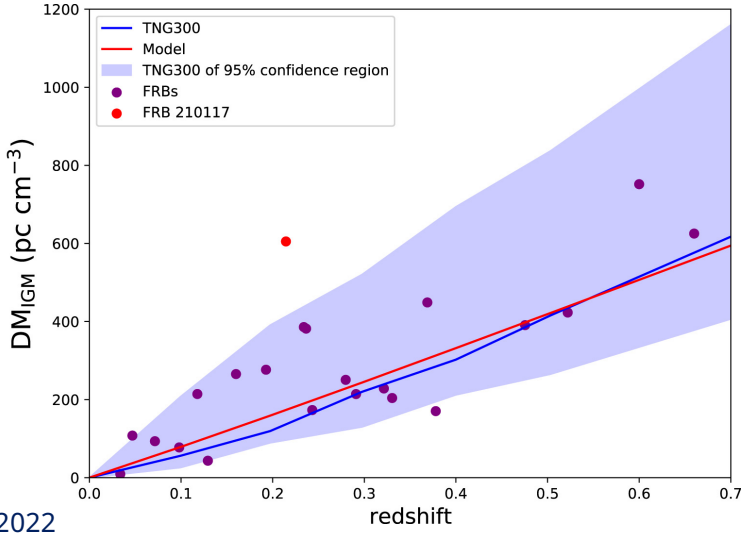
Baryon = normal matter

Missing Baryon Question with FRBs

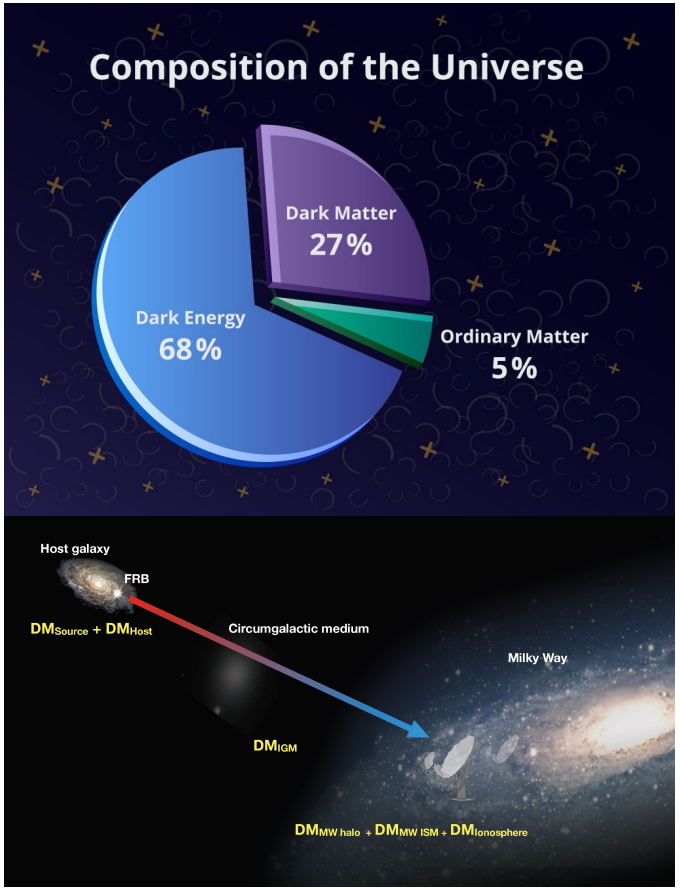
- ~1/4 of all baryons have not been detected
- FRBs sensitive to total electron column density, and hence the ionized matter content
- FRBs lie at cosmological distances
- Use FRB DM to infer baryon content

Early results are consistent with CMB and Big Bang Nucleosynthesis

The baryons are not "missing"



Yang+ 2022




Light Sails


Death Stars

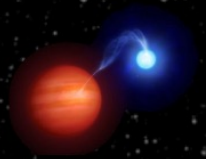

Merging Black Holes

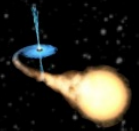

Supernovae


Magnetars


Accreting Massive Black Hole


The Unknown


Interacting Binary


Microquasar


Evaporating Black Holes


Black Hole Battery


Super-giant Pulses


Cosmic Comb


Gamma-ray Bursts


The Gruffalo

extra-Galactic

Galactic

Micro-quasars

Flare stars

SETI

Pernicious RFI

Atmospheric effects

Magnetars

Pulsars

We are here

According to the *arXiv*, there are >100 types of FRBs


"Blitzars"

Jason Hessels

Construction of the SKA

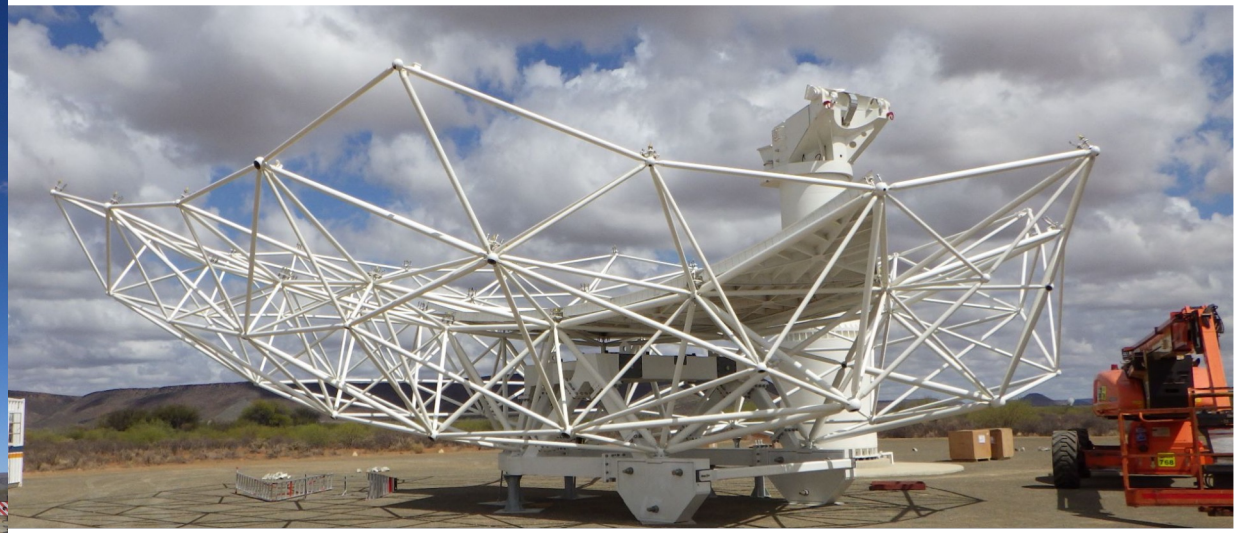
Construction is well underway – first test arrays late 2024/early 2025

SKA-Low

SKA-Low

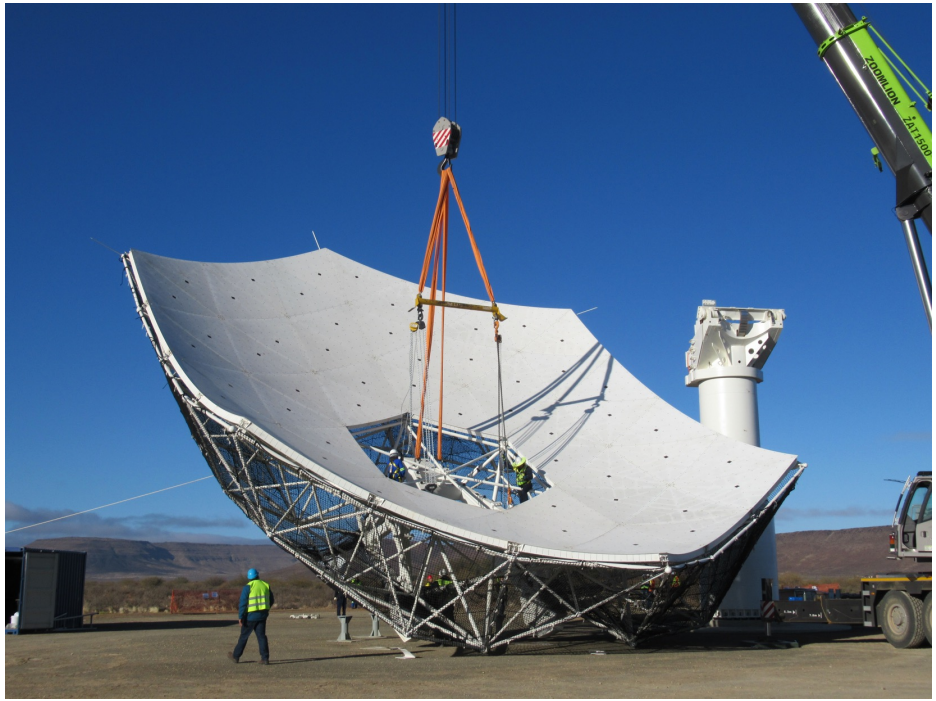
Construction is well underway – first test arrays late 2024/early 2025

SKA-Mid



Construction is well underway – first test arrays late 2024/early 2025

SKA-Mid



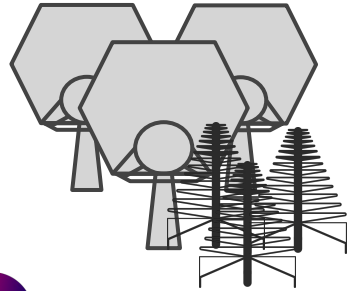
Video of the Big Lift – July 4, 2024

https://www.youtube.com/watch?v=jgXY7n7Jp3g

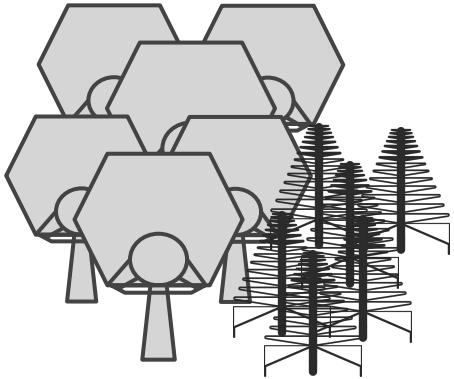
SKA-Mid

Major Milestones

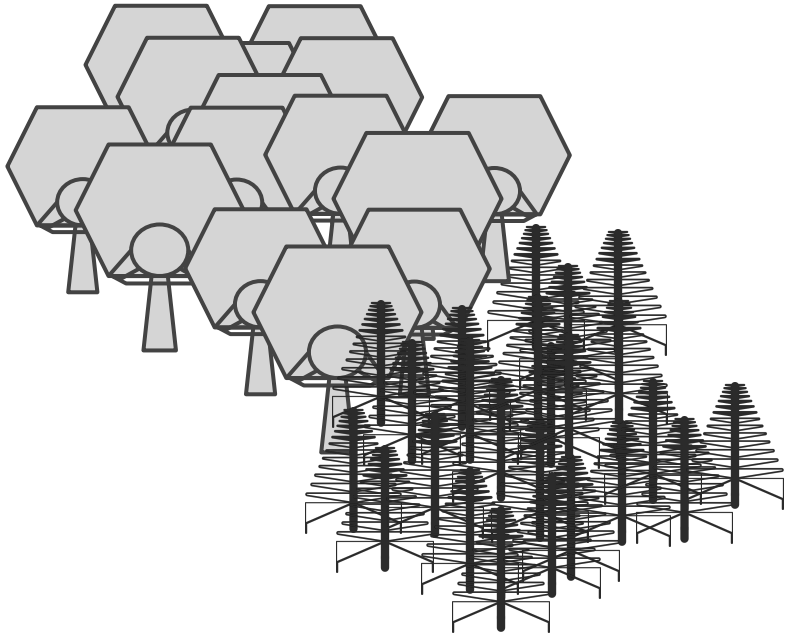
2024
Science Commissioning



2027
Science Verification



2029+
Observing programmes



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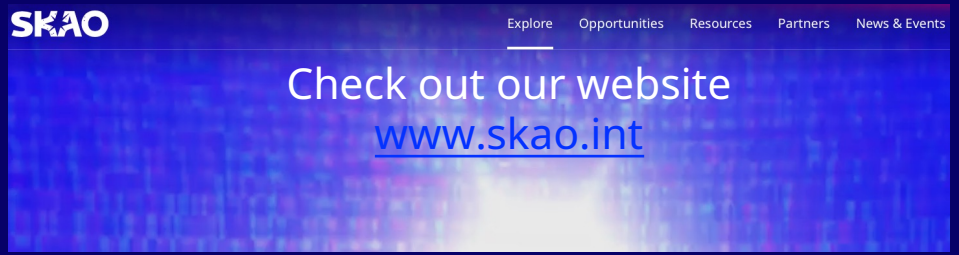

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SKAO

We recognise and acknowledge the Indigenous peoples and cultures that have traditionally lived on the lands on which our facilities are located.

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