Multimessenger astronomy

Seeing the universe with wider eyes

Between the eyes and ears there lie
The sounds of colour and the light of a sigh
And to hear the sun, what a thing to believe
But it's all around if we could but perceive
To know ultra-violet, infra-red, and x-rays
Beauty to find in so many ways

Lyric credit: Graham Edge, 'The Word'

Prepared & presented by John C Neal

Multimessenger astronomy

Context -

- ***Visible light gives us only a partial understanding*** of astronomical objects and processes
- The ***widening collection of observatories and instrumentation*** - the ‘messengers’ – is changing that
- ***Transient phenomena***, if missed, are a missed opportunity. Rapid communication of events is essential.
- ***Richer, more timely and accessible data sets***
- ***Multimessenger astronomy promotes collaboration*** and a wider understanding of the universe

Multimessenger astronomy

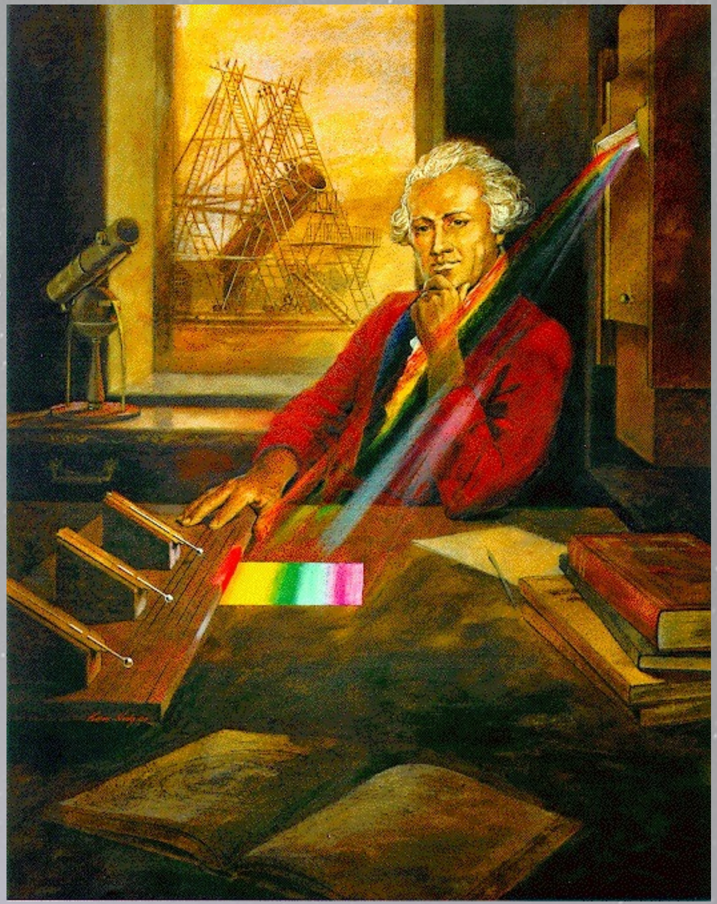
Content -

- Historical background
- ***Electromagnetic messages*** - light of various kinds
- ***Particulate messages*** – things with at least a little mass
- ***Gravimetric messages*** – things that go bump in the night
- Making use of wider eyes – a new age of astronomical collaboration

Historical background . . .

- Our understanding of light and colour begins with Isaac Newton in 1672 when he split a beam of light with a prism to reveal a spectrum

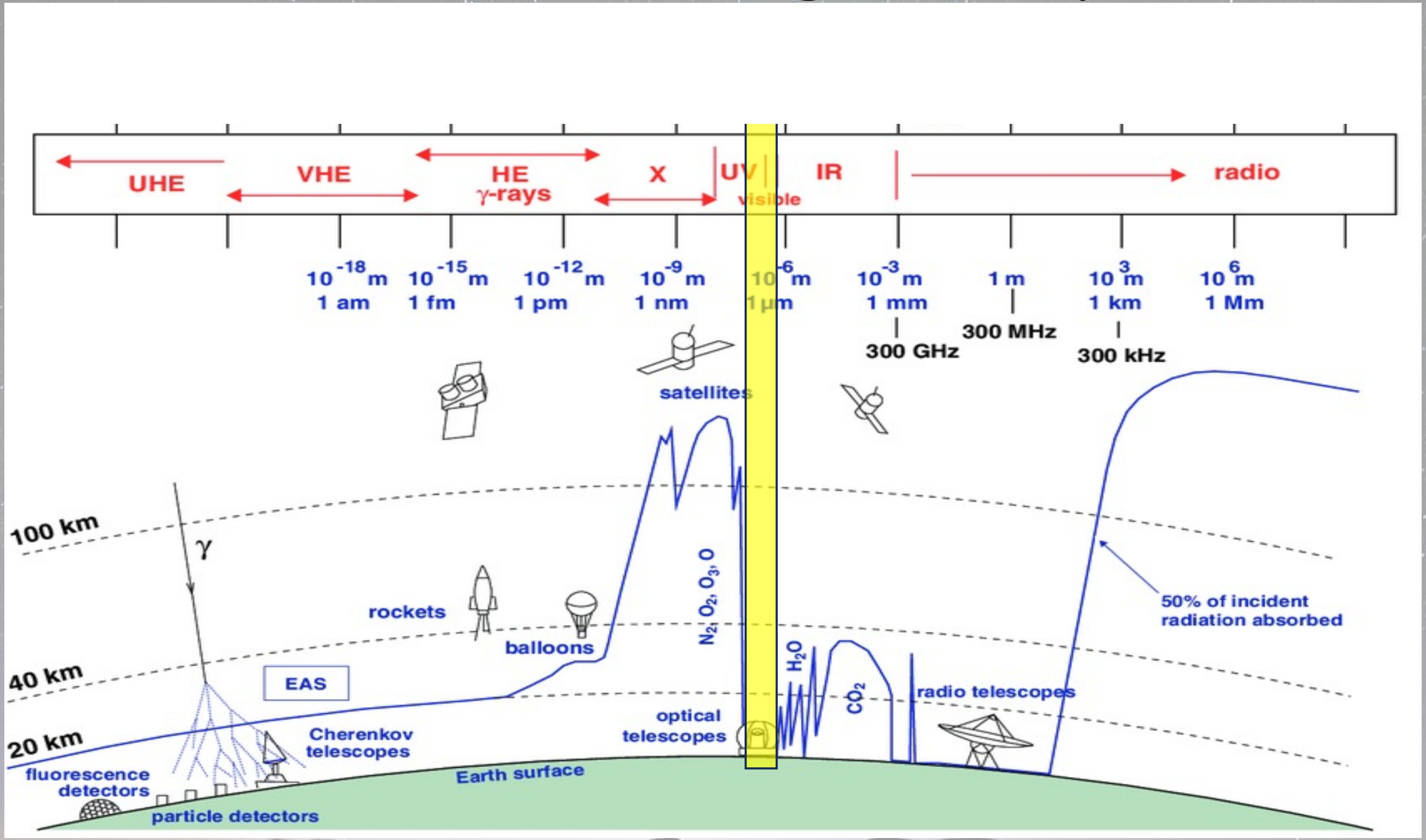
- William Herschel in 1800 noticed the temperature of a blank area beyond the red portion of the spectrum had a higher temperature - the infrared



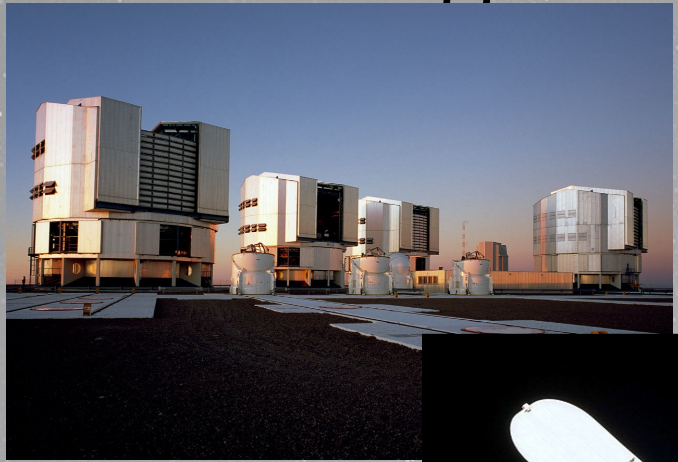
. . . historical background

- James Clerk Maxwell united electricity and magnetism with his electromagnetic field equations
- These predicted light and other forms of electromagnetic radiation (eg radio waves) were part of a continuous spectrum.
- Developments in radio, radar and particle physics led astronomers to make use of the broader electromagnetic spectrum.

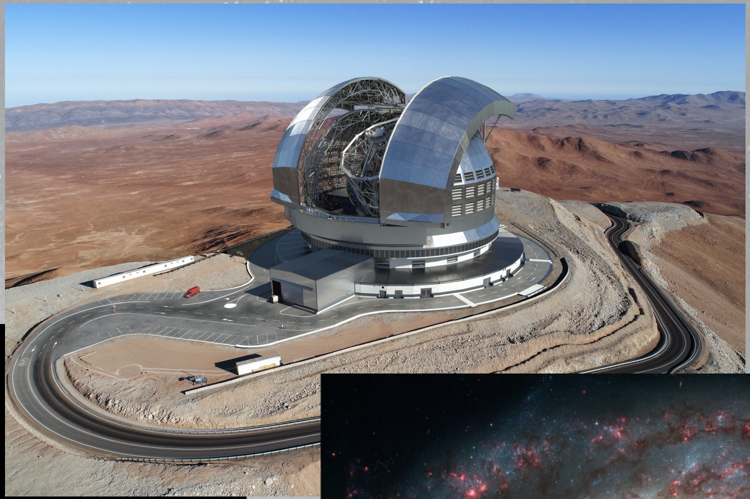
Regions of the electromagnetic spectrum



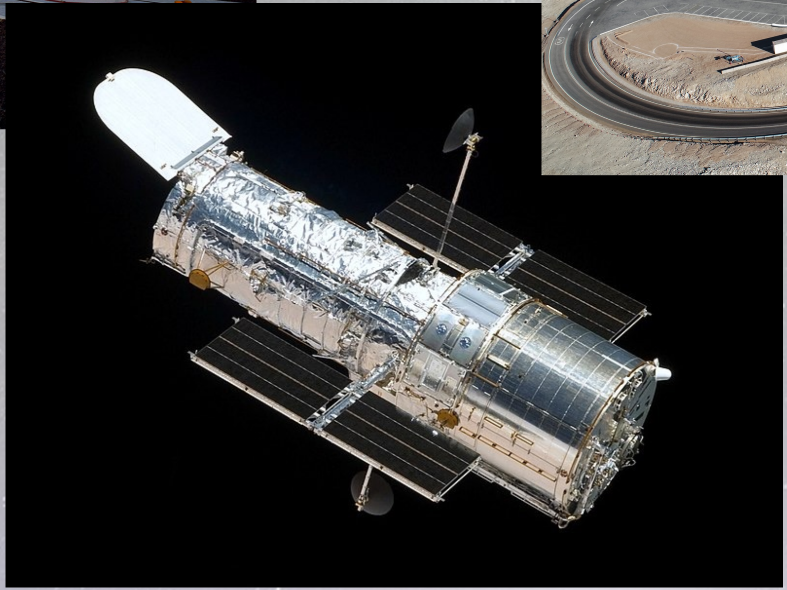
‘Visible’ light observatories



ESO Very Large
Telescope, Chile



ESO European
Extremely Large
Telescope

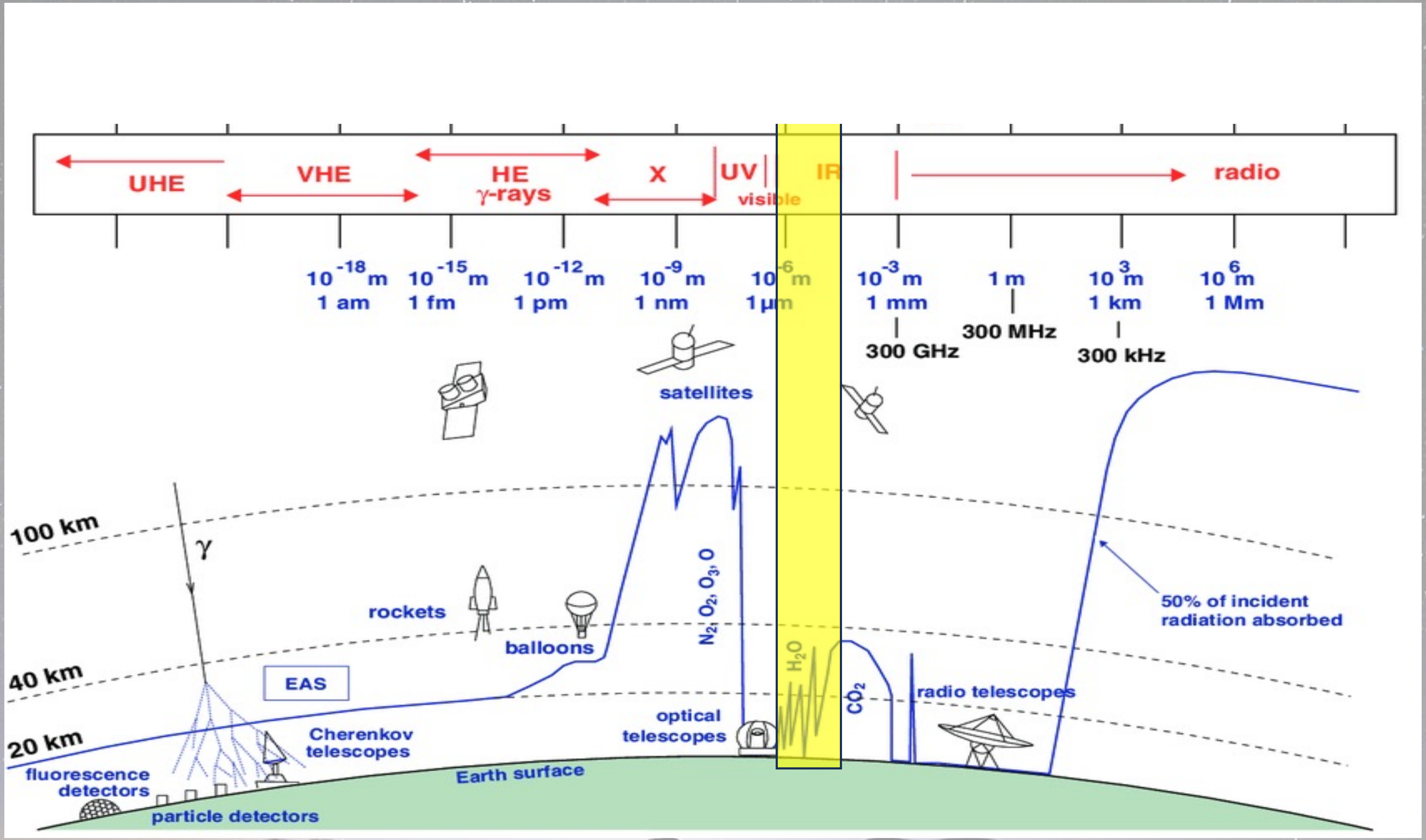


NASA Hubble
Space Telescope

M51
Whirlpool galaxy

Image credits: ESO; NASA/STScI

Infrared



UHE
VHE
HE
γ-rays
X
UV
IR
visible
radio
10^-18 m
1 am
10^-15 m
1 fm
10^-12 m
1 pm
10^-9 m
1 nm
10^-6 m
1 μm
10^-3 m
1 mm
1 m
10^3 m
1 km
10^6 m
1 Mm
300 GHz
300 MHz
300 kHz
satellites
100 km
γ
rockets
balloons
N2, O2, O3, O
H2O
CO2
50% of incident
radiation absorbed
40 km
EAS
radio telescopes
optical
telescopes
20 km
Cherenkov
telescopes
fluorescence
detectors
Earth surface
particle detectors

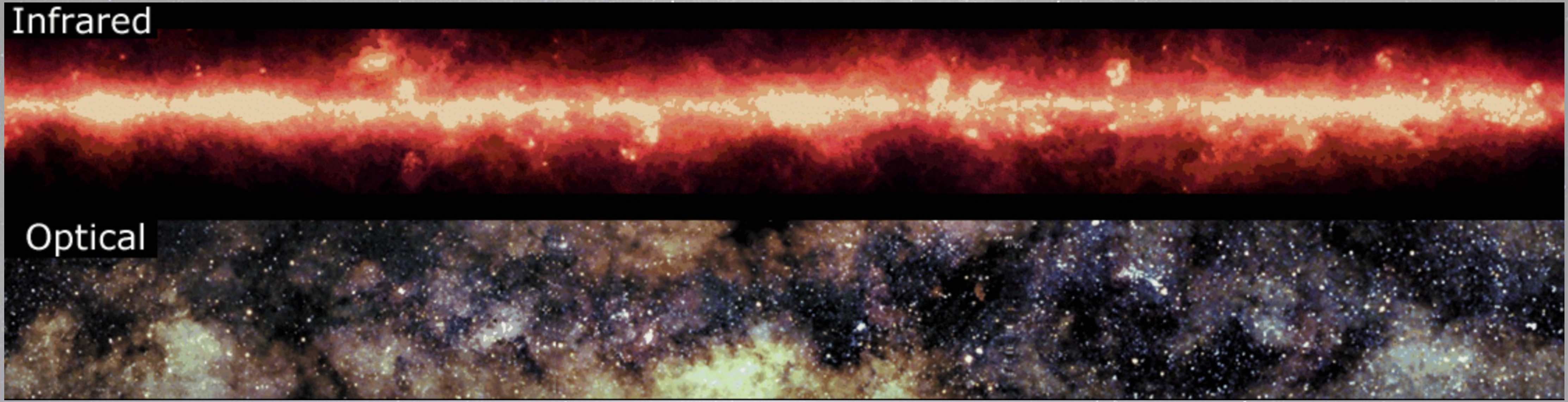
Infrared (IR) . . .

Why use IR light and what are its limitations ?

- ***IR light penetrates interstellar dust*** better than visible light which is scattered by dust – ***useful for studies of galactic and protoplanetary disks***
- Light from very distant (early universe) galaxies is red shifted into the infrared and mm/sub-mm wavebands revealing otherwise invisible objects (*cf last years talk from Matt Bothwell*)
- Can be done from ground based observatories BUT pick the wavelength carefully

Infrared (IR) . . .

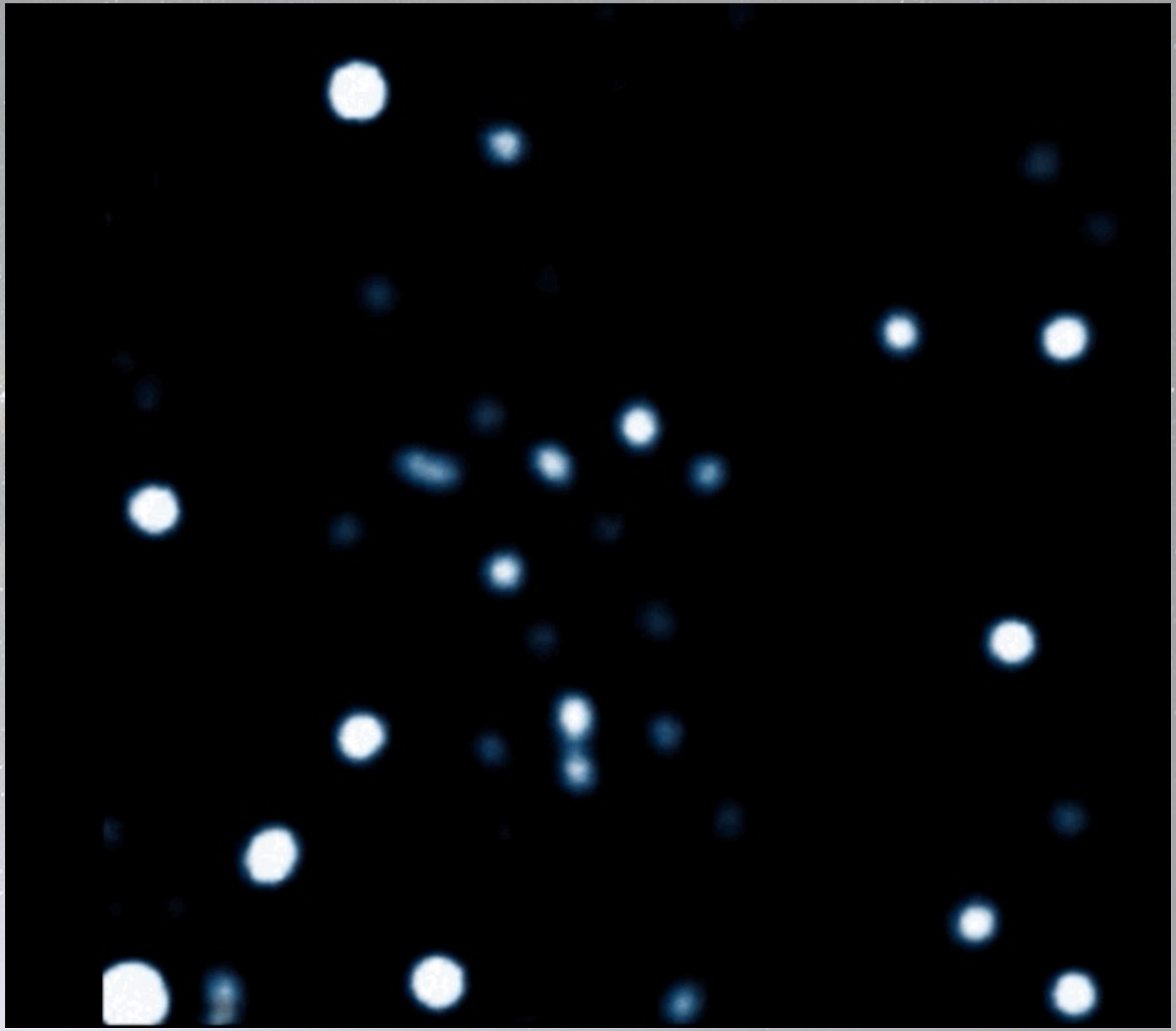
Dust and gas obscure our visible light view of the centre of the Milky Way – we get more info from the Infrared



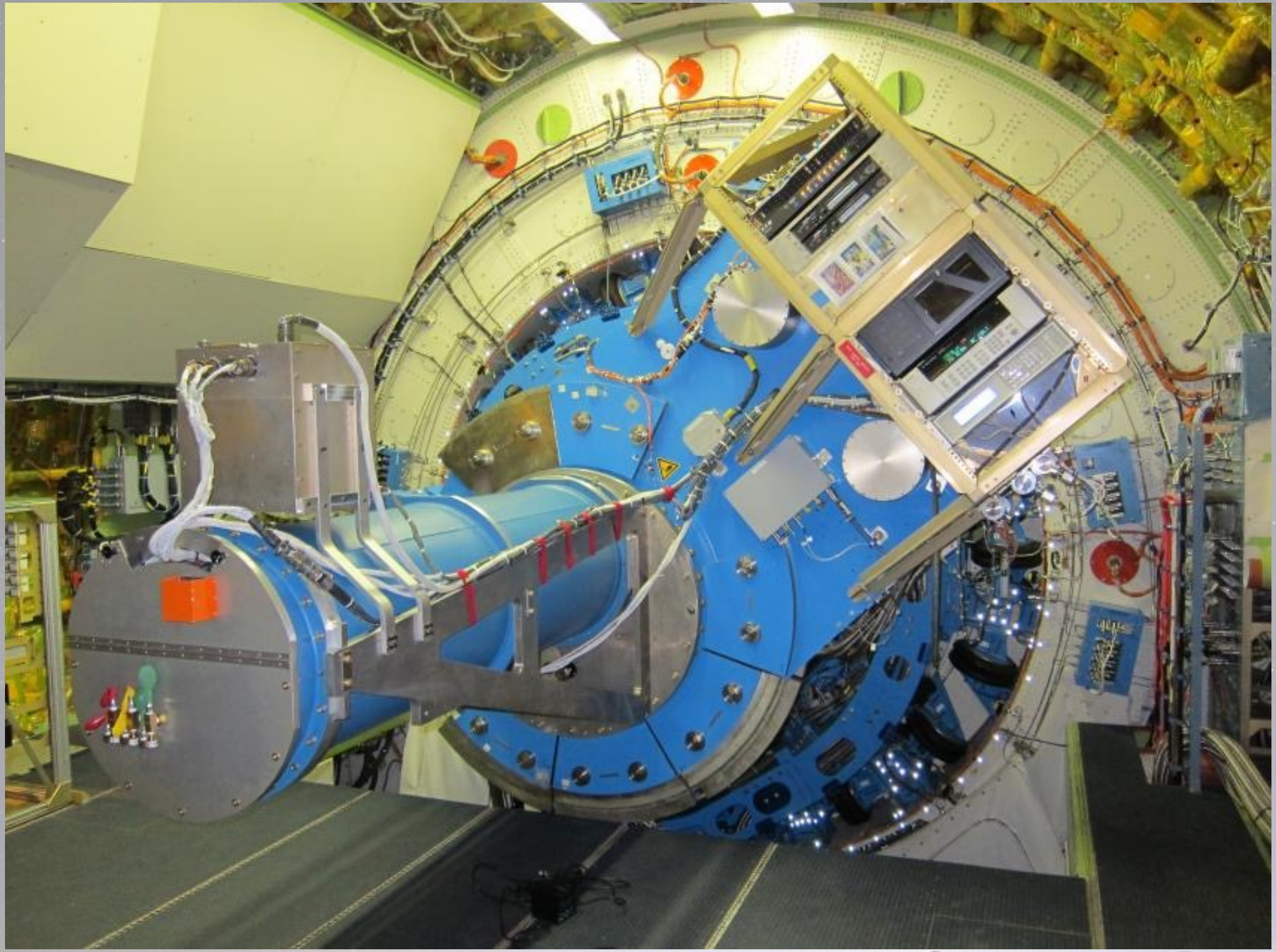
Infrared . . .

Andrea Ghez and Reinhard Genzel used IR to track the ‘S’ stars at the centre of the Milky Way over a 16 year period.

The data showed the stars were orbiting a very compact but invisible object - a black hole!



Infrared . . .



Infrared imager and spectrometer and its mounted in an unusual place . . .

Image credit:
NASA/SOFIA/EXES/Mathew Richter

Infrared . . .

This is the NASA **S**tratospheric **O**bservatory for **I**nfrared **A**stronomy –

SOFIA

Image credit:
NASA/SOFIA/EXES/Mathew Richter

Infrared . . .

A SOFIA programme observed the polarised IR light between M51’s spiral arms to reveal magnetic fields in the cold, dusty, molecular regions of M51.

This work revealed new information about magnetic fields at galactic scales and the influence they have on the distribution of cold/dark gas and dust in the outskirts of the galactic arms.

Infrared . . .

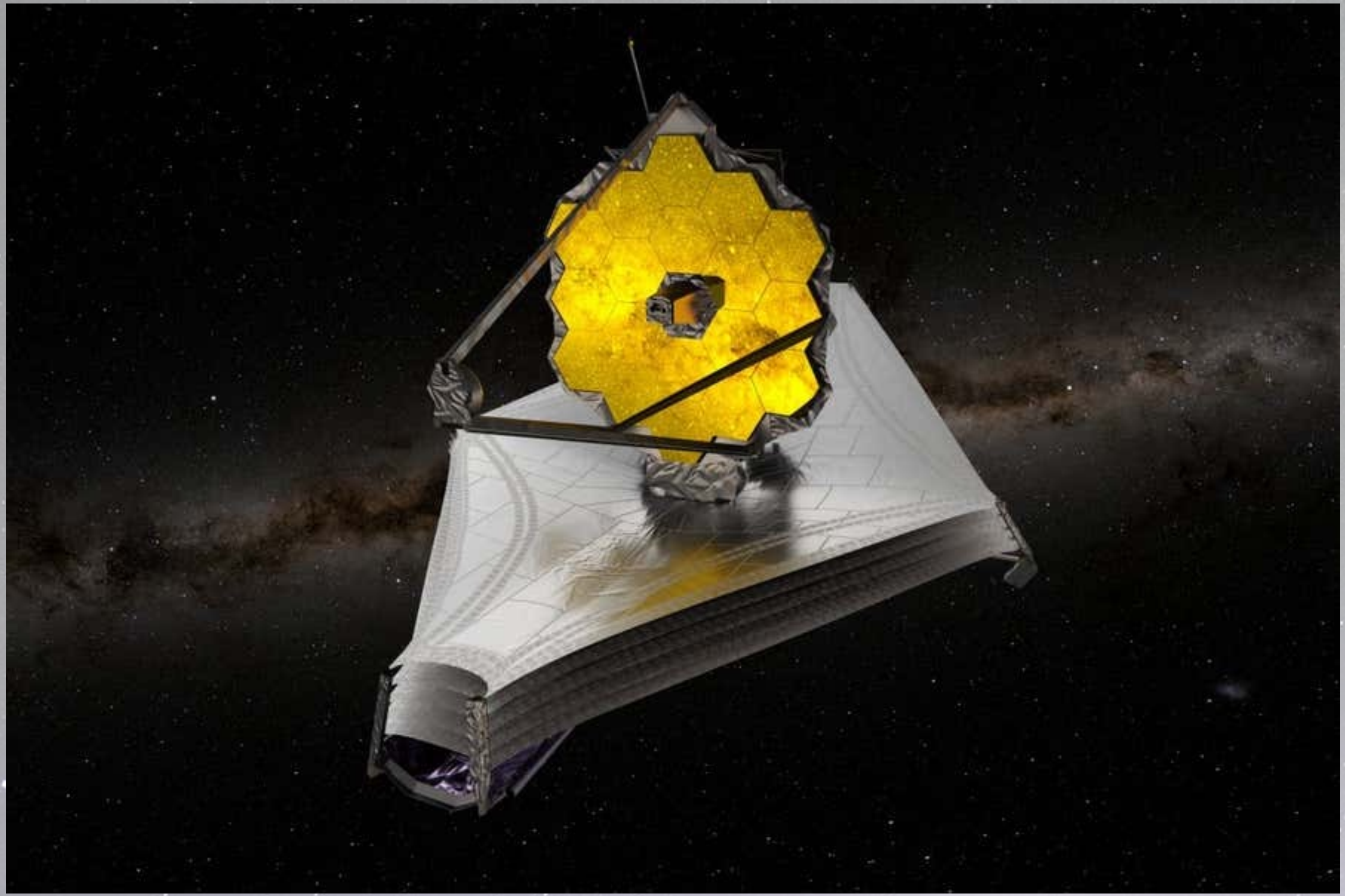


Image credit: NASA/ESA

James Webb Space Telescope

JWST imaged the R136 region of the Tarantula nebula in the Large Magellanic Cloud

Infrared . . .

Image: NASA/ESA

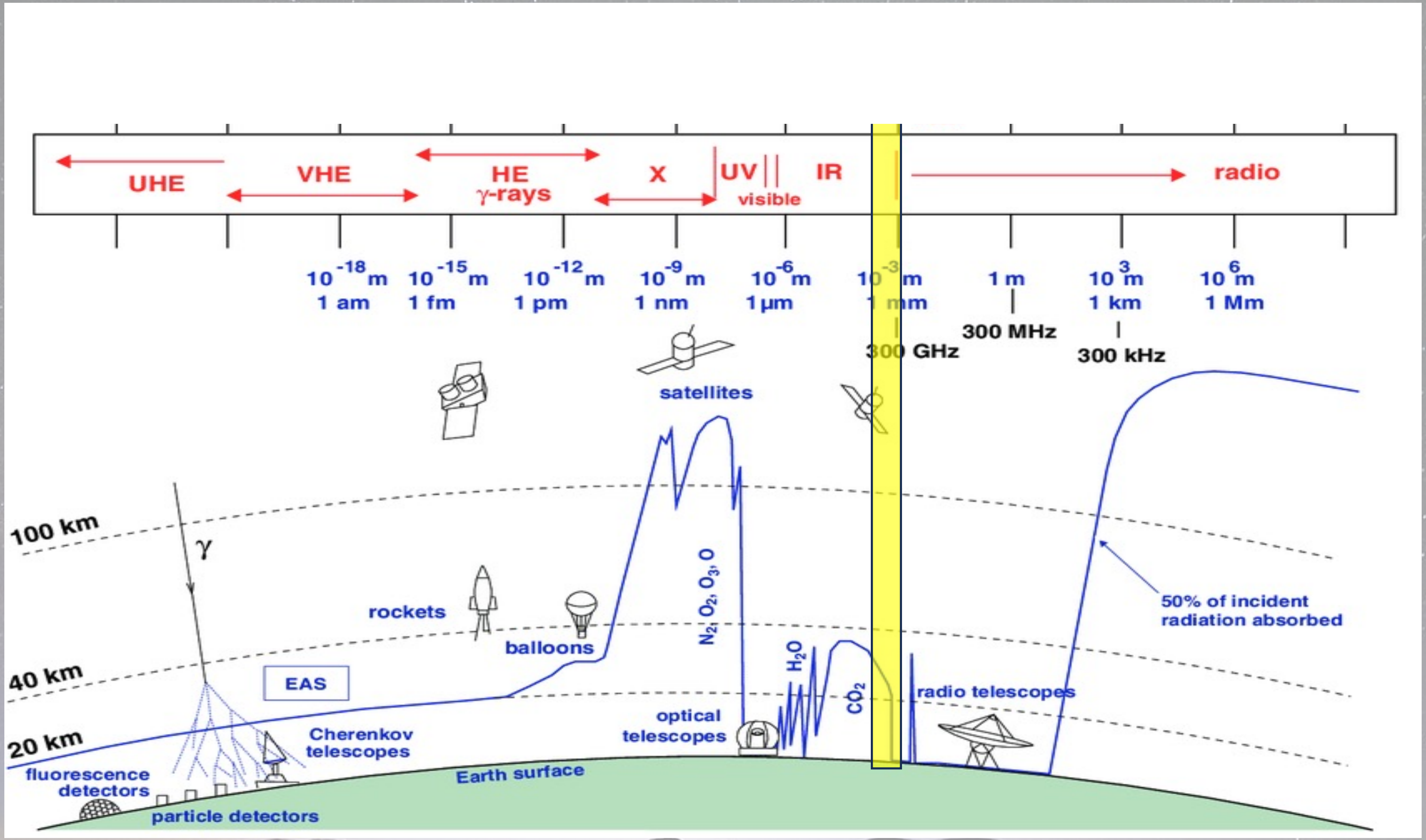
'Visual' light

Image: NASA/ESA

JWST Near infrared

up next . . . mm/Submm

Millimeter / Submillimeter



Millimeter / Submillimeter . . .

Why use it and what are its limitations ?

- ***Great for probing the chemistry of molecular clouds,*** supporting research into star/galaxy formation and their evolution

BUT there is an important limitation that creeps in here . . .

- Angular resolution is the level of detail a telescope can see
- It's a function of the wavelength of light and the diameter of the telescope aperture

Angular resolution gets worse as you move to longer wavelengths

. . . for example

Angular resolution (AR)

To illustrate the problem (note, **small AR is GOOD**)-

Telescope	**λ**	**Aperture (m)**	**AR (arcsec)**
Celestron EdgeHD 8	560 nm (Visible)	0.2m	0.694188
Sub-mm telescope	0.34 mm (sub-mm)	12m	7.055799

So how do we get useable resolution at longer wavelengths ??

Arrays and aperture synthesis

The Atacama Large Millimeter (and sub-Millimeter) Array - ALMA

64 dishes deployed at an elevation of 5000m in the Atacama desert in Chile.

Image credit: ESO

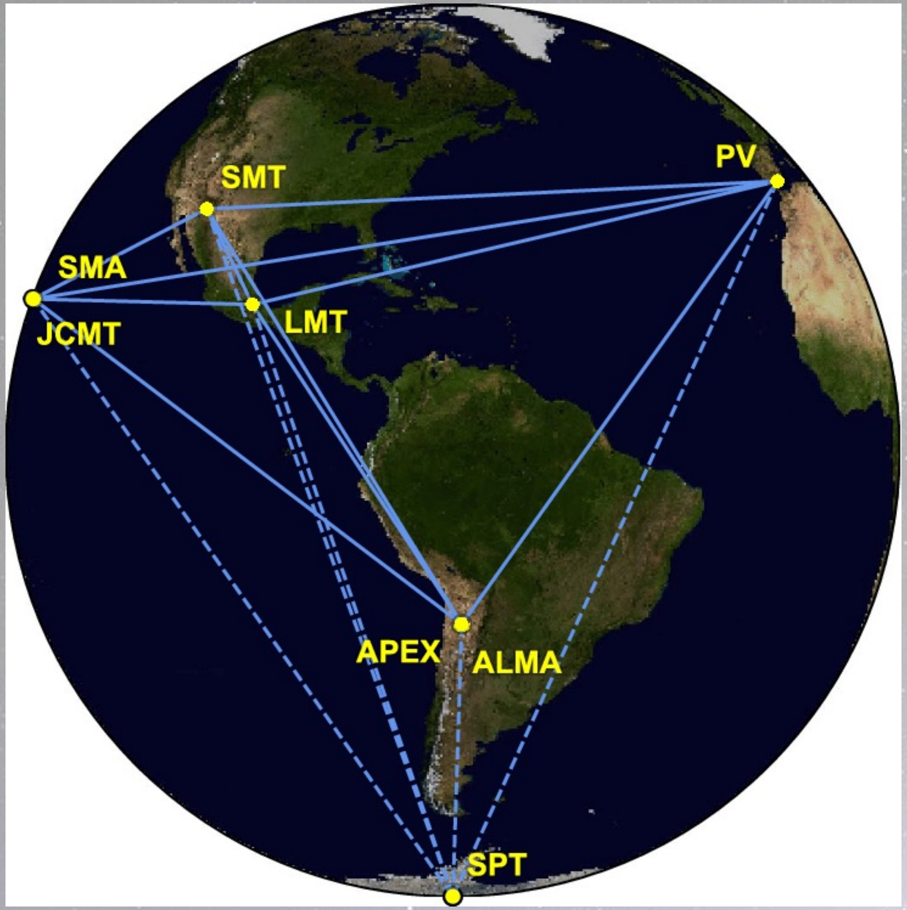
The signals from each dish are mathematically combined with each other using techniques known as **interferometry** and **aperture synthesis** to create the equivalent of a large aperture telescope.

It allows ALMA to achieve **milliarcsecond resolution.**

Interferometry and aperture synthesis

- The more dishes you have the better!!
- How they are spaced out determines sensitivity and resolution.
- Dishes can be anything from a few metres to thousands of kilometers apart

VERY LONG baselines . . .



The observatories of the Event Horizon Telescope in 2017/18

SMT – SubMillimeter Telescope - Arizona
SMA – SubMillimeter Array - Hawaii
JCMT – James Clerk Maxwell Telescope -
LMT – Large Millimeter Telescope - Mexico
APEX – Atacama Pathfinder Experiment - Chile
ALMA – Atacama Large Millimeter Array - Chile
SPT – South Pole Telescope – South Pole
PV – IRAM 30m Telescope – Spain

Although just 8 observatories, they benefit from being a very long way apart !

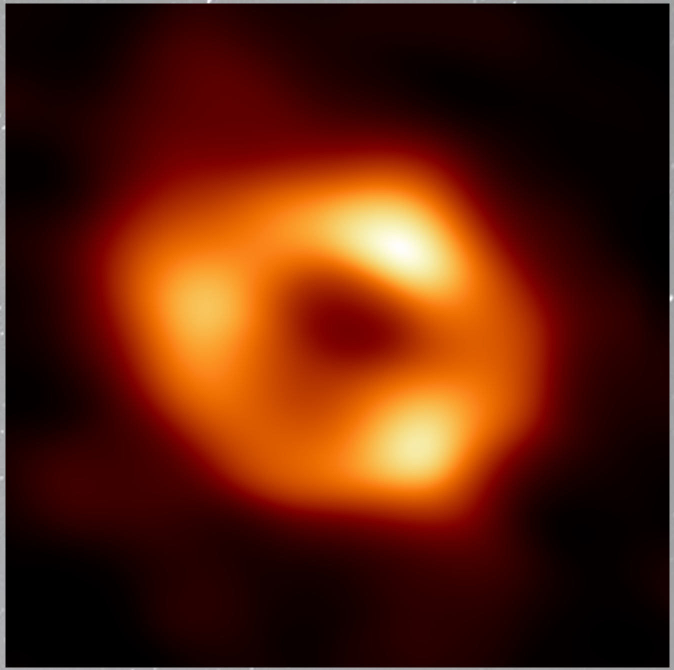


Image credits: EHT Collaboration

Millimeter wavelength observations

A typical visual light image of NGC4038 – the Antennae Galaxy in Corvus

Galaxies in collision

The central region was studied in Sub-mm by ALMA . . .

Image credit: NASA/STScI

Millimeter wavelength observations . . .

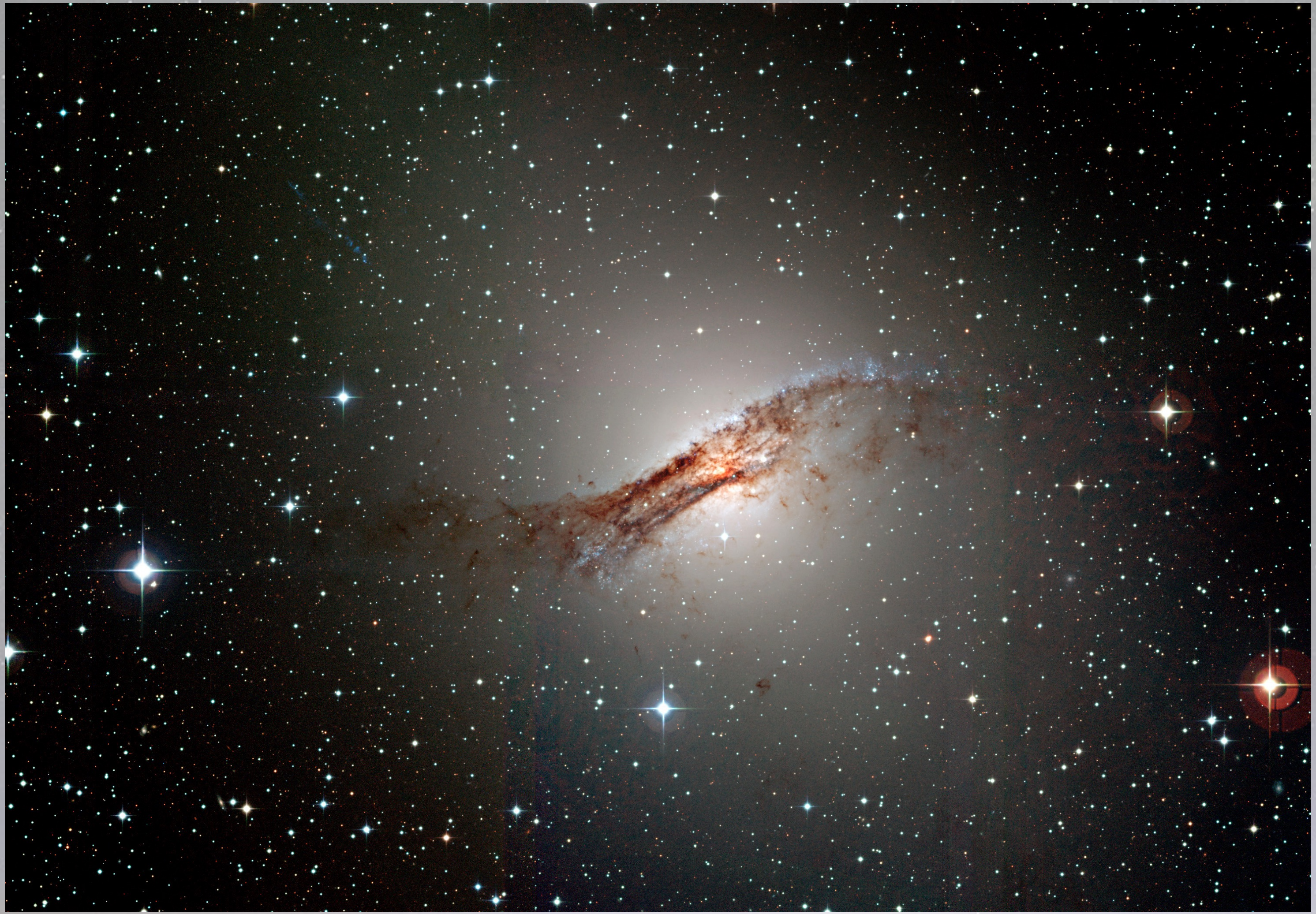
Visible light

Image credit: NASA/ESA

ALMA – sub Millimeter

Image credit: ALMA (ESO/NAOJ/NRAO)

Centaurus A – visible light

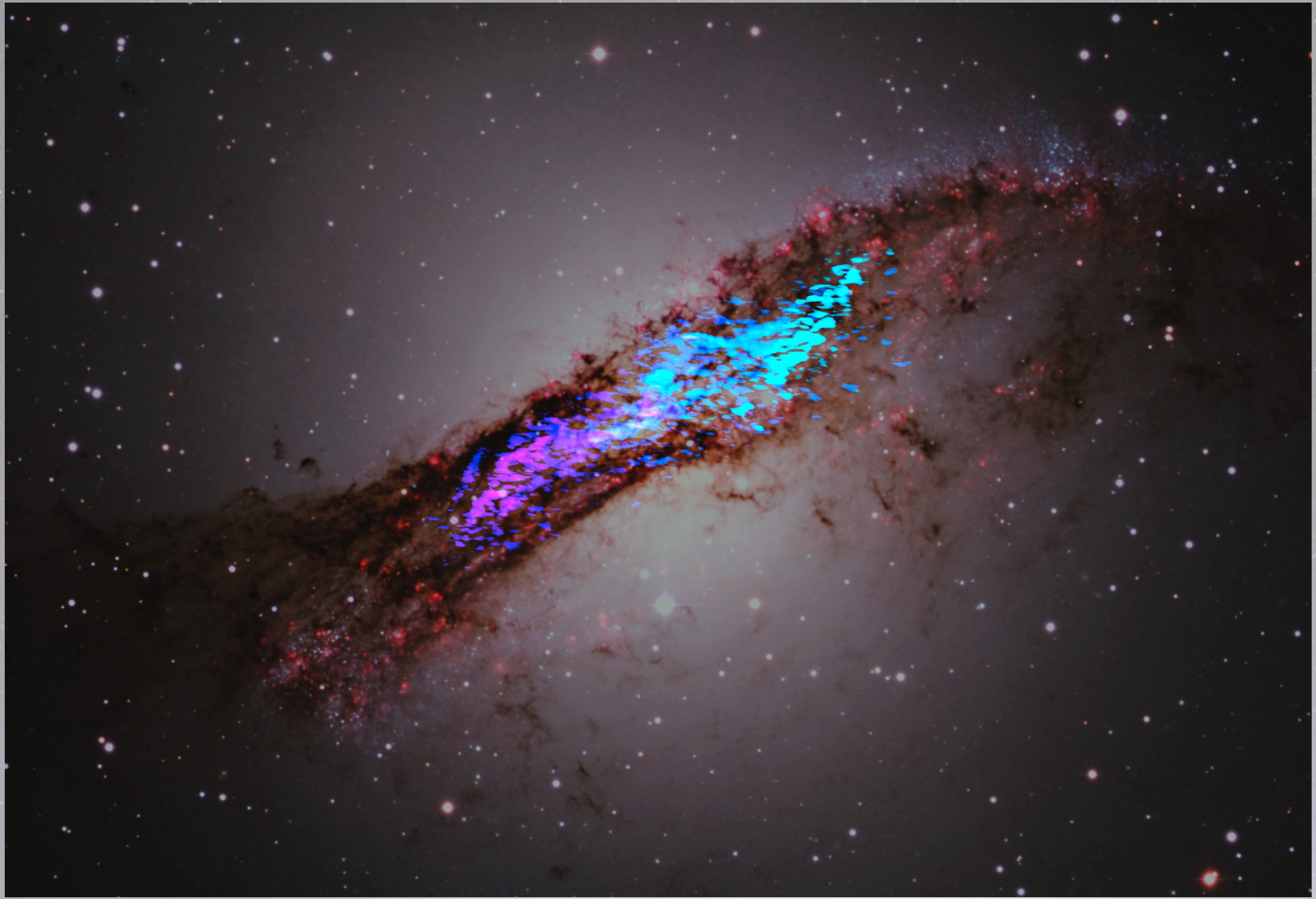


A visible light image of Centaurus A (NGC5128).

This galaxy has also been studied using ALMA . . .

Image credit: ESO

Millimeter wavelength observations . . .

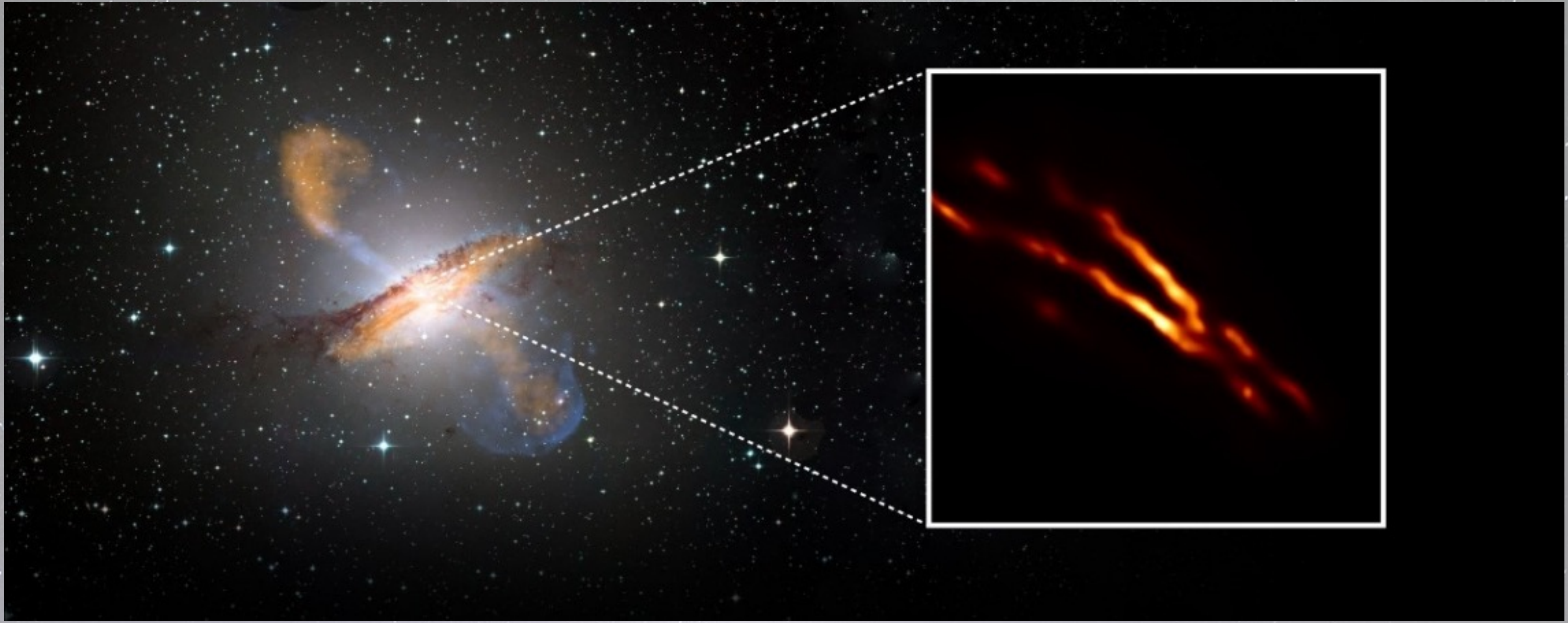


ALMA, observed the carbon monoxide gas in Centaurus A using light centered around a wavelength of 1.3mm

The data showed red and blue shift – dark blue/ violet colour indicates gas moving towards us and light blue indicates gas moving away.

This allows determination of the galaxy's rotation rate.

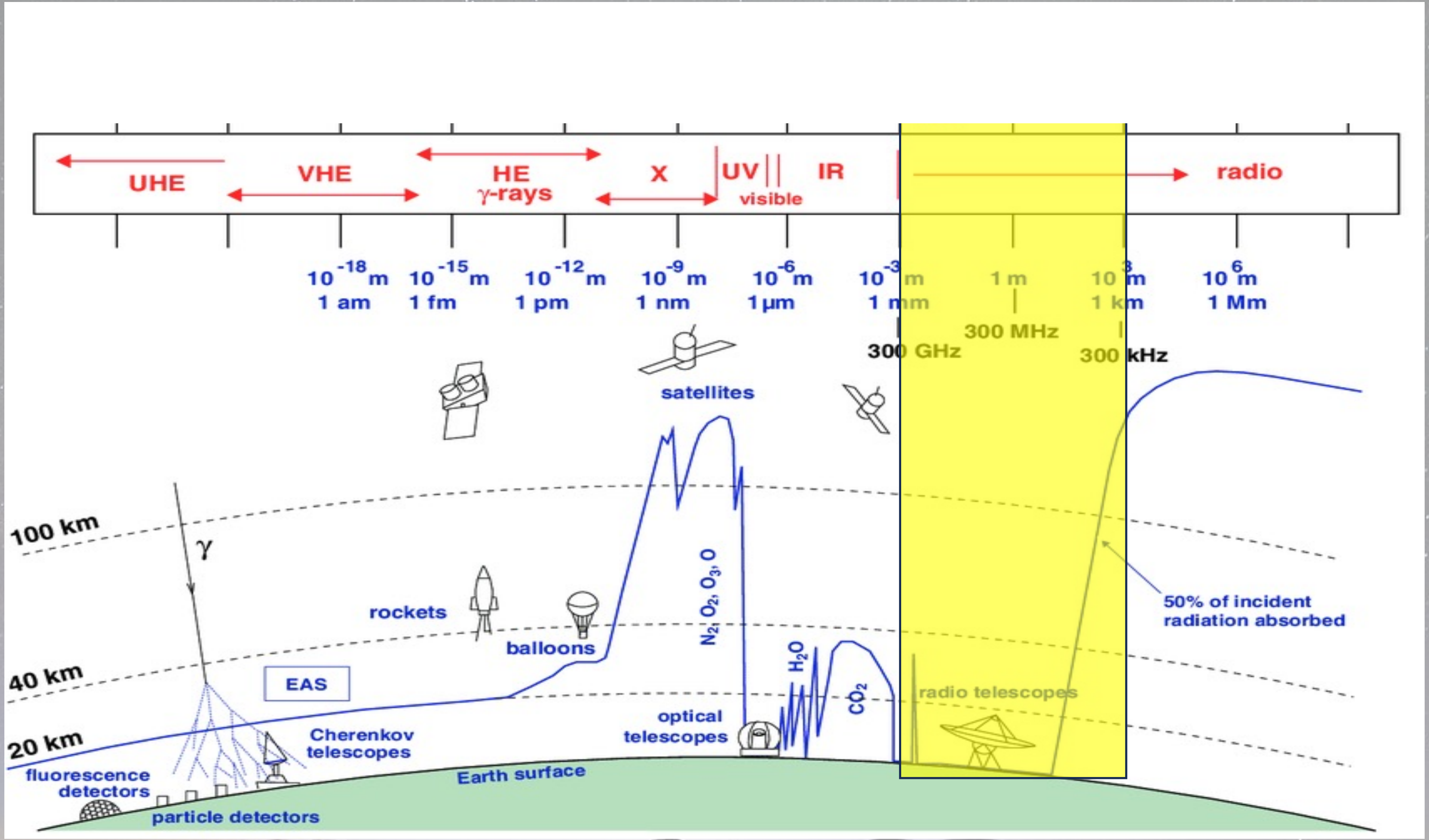
EHT mm scale observations of Centaurus A



Credit: Janssen, M., Falcke, H., Kadler, M. *et al.* EHT observations of the jet launching and collimation in Centaurus A. *Nat Astron* **5**, 1017–1028 (2021). https://doi.org/10.1038/s41550-021-01417-w

up next . . . Radio

Radio wavelengths



Radio . . .

Image credit: NRAO

The Karl Jansky Very Large Array in New Mexico consists of 27 movable dishes, each of 25m diameter arranged on a Y shaped track.

The Lovell Telescope (aka Jodrell Bank)

Now the international HQ for what will be the largest radio telescopes in the world - the Square Kilometer Array

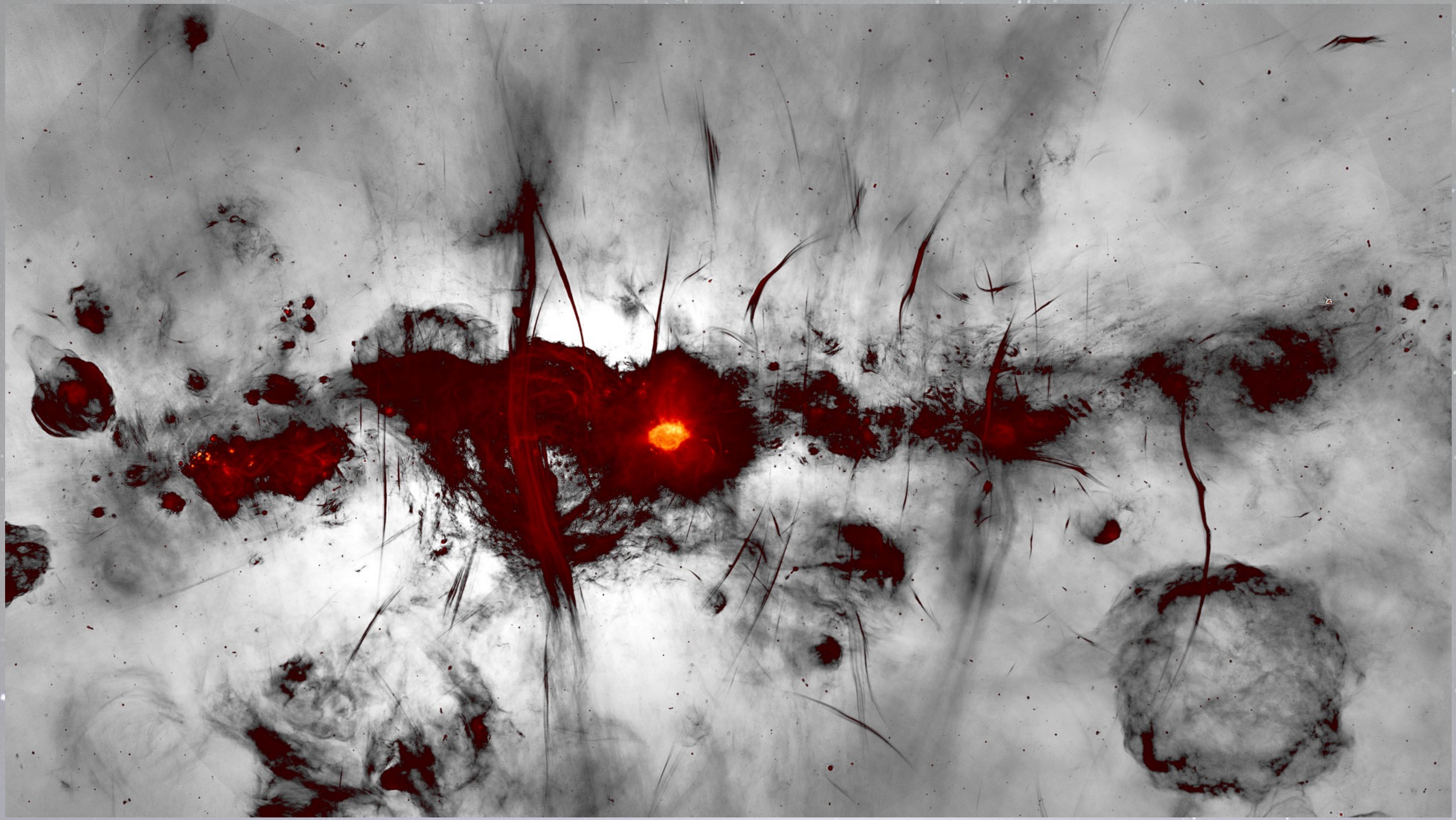
Square Kilometer Array (SKA-Mid)

Image credit: SARAO

Located in South Africa this will have 197 dishes when complete.

MeerKAT – its proof of concept test array of 64 dishes – has already contributed important observations

MeerKAT



MeerKAT's 2° x 1° view of the centre of the Milky Way. Approx 1000 x 500 light years.

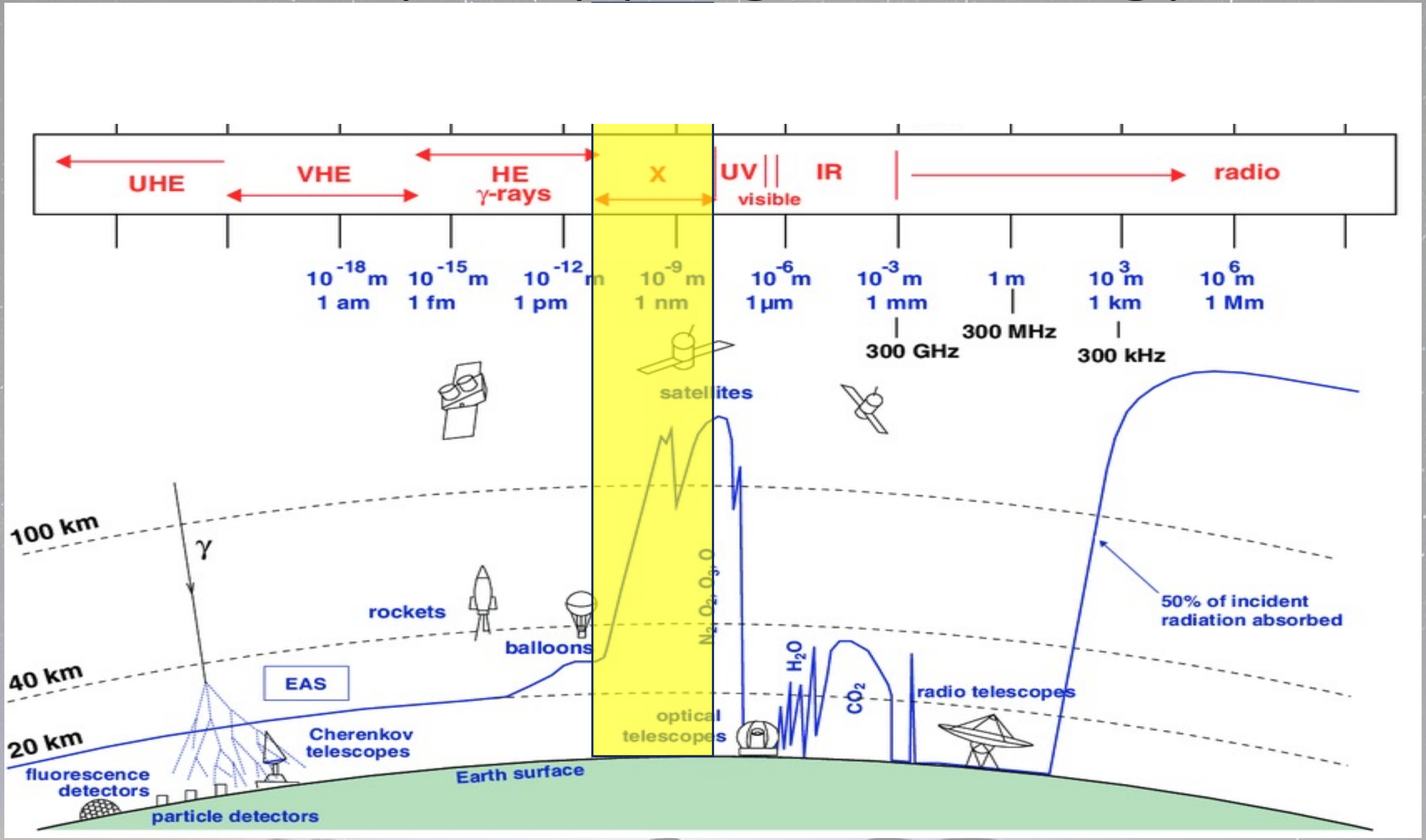
The image shows radio signatures of many known supernova remnants but also many previously unseen filamentous features. Some of these are believed to be remnants of historic outflows from Sgr A*

Square Kilometer Array (SKA-Low)

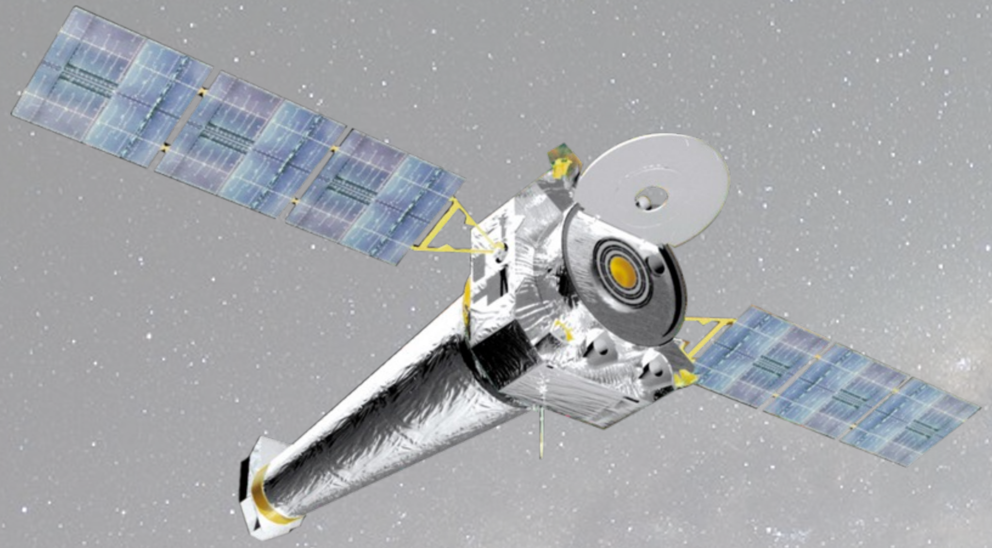
Image credits: SKAO

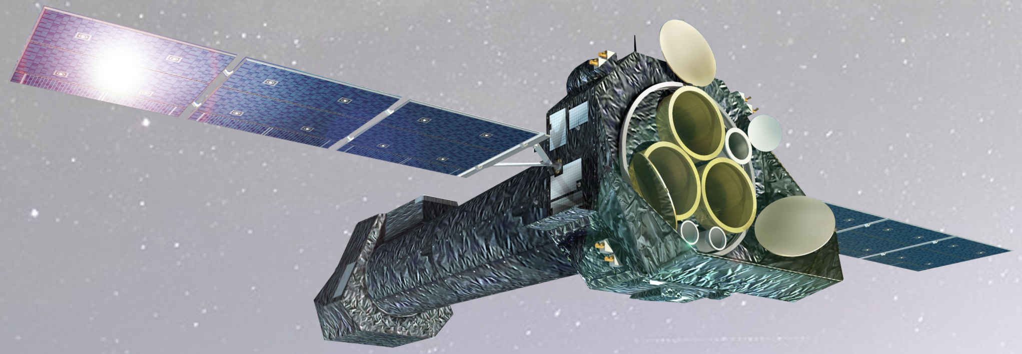
SKA-Low in Western Australia will have 512 stations, each containing 256 antennas

Xray astronomy – upping the energy!



Xray observatories



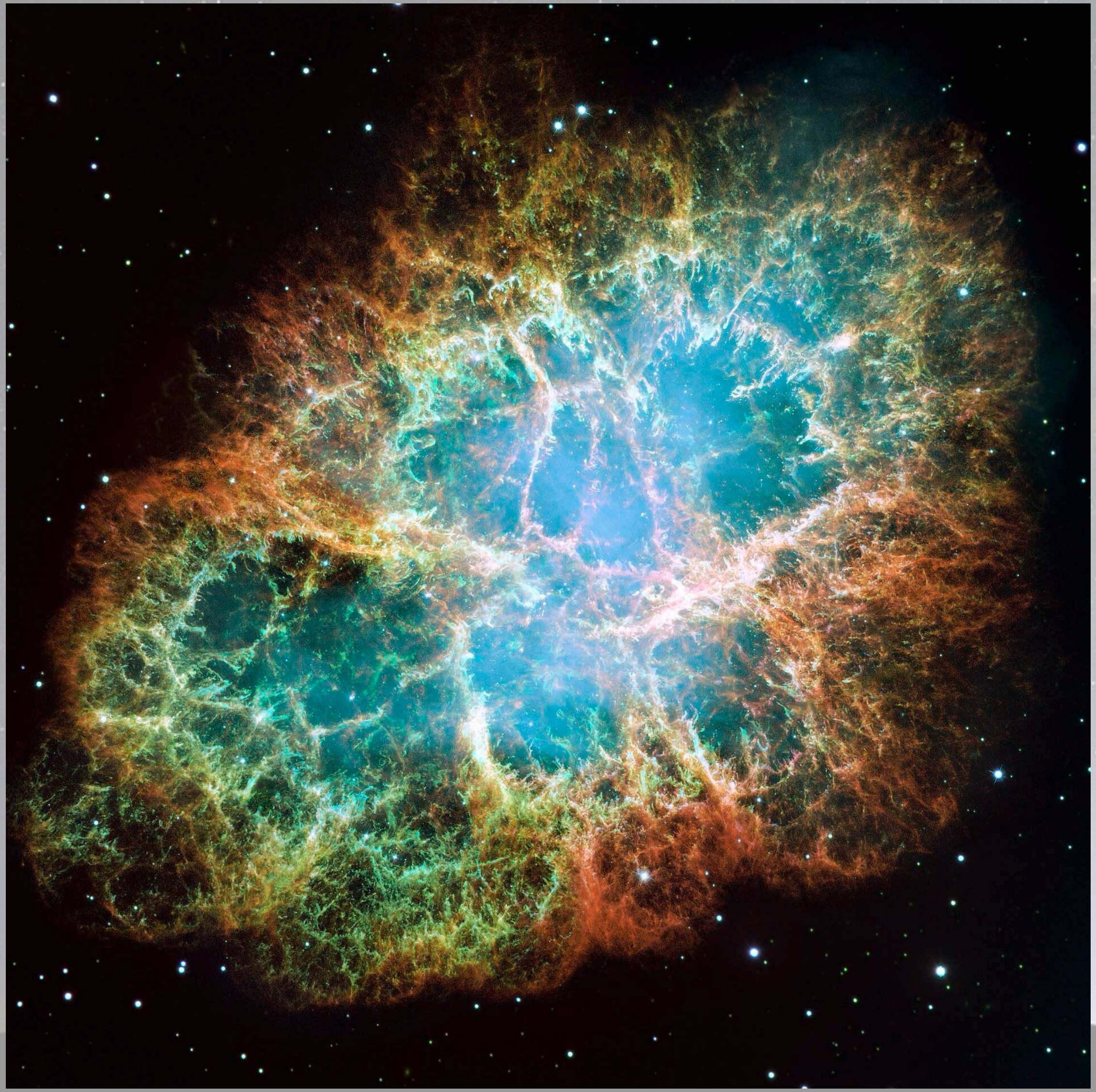


Earth’s atmosphere blocks pretty well all Xray photons.

NASA’s **Chandra Xray Observatory** has been the pre-eminent space based Xray instrument. It continues to operate today.

ESA’s **XMM-Newton** instrument was launched in 1999 and is equipped with advanced Xray imaging capabilities.

M1 – The Crab Nebula

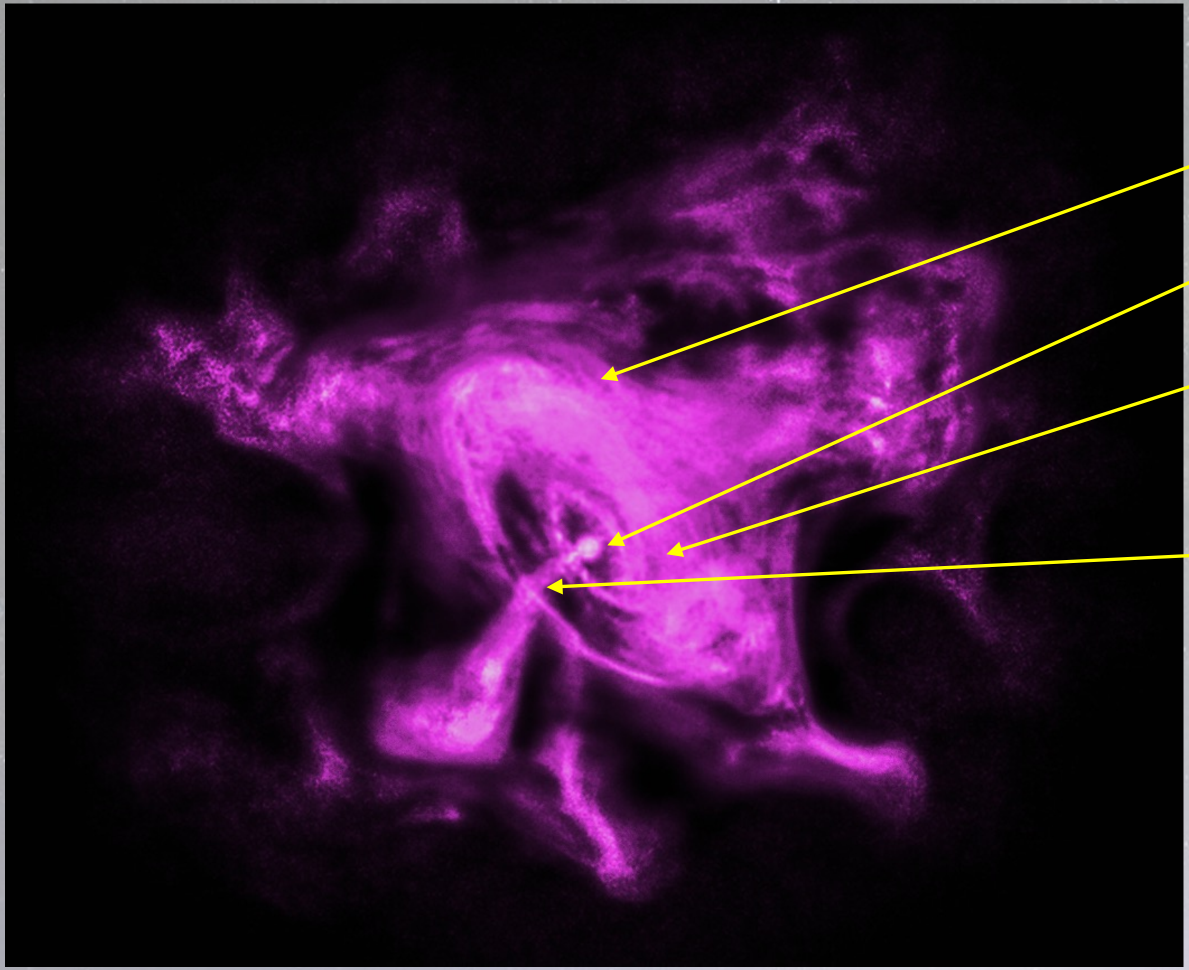


A visual light image of the well known supernova remnant of 1054, the Crab Nebula.

Supernovae result when a dying massive star sheds its outer layers and collapses in on itself to leave a compact object such as a neutron star or a black hole.

So lurking, unseen at another wavelength . . .

M1 – The Crab Nebula in XRay



The Crab pulsar -

A ***pulsar wind nebula*** envelops the highly magnetized, rapidly rotating ***neutron star***

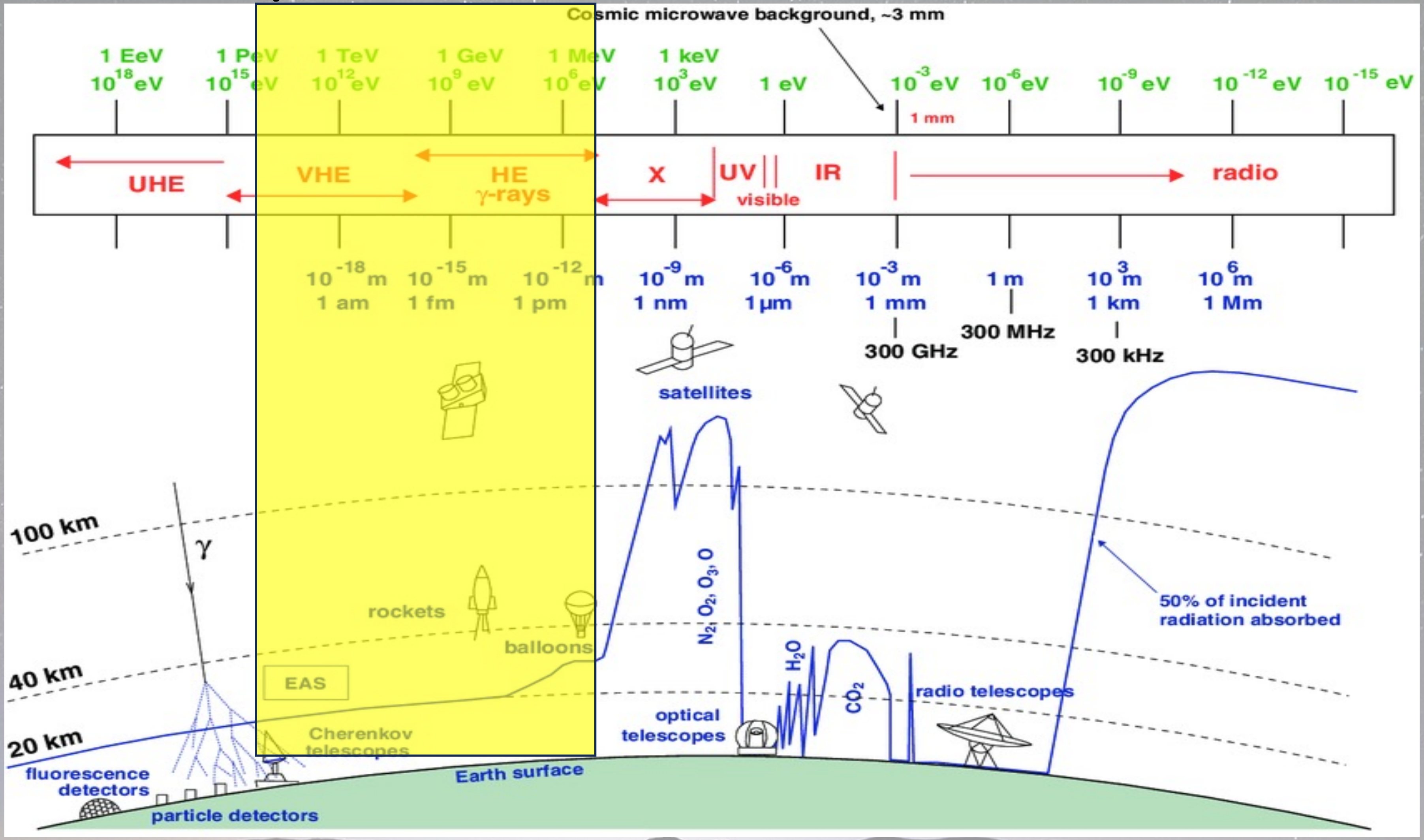
The ***strong gravitational field pulls in and accretes gas and dust*** left by the supernova explosion, accelerating it to very high energies.

It also has a variable ***polar jet***

Most of the xray light is synchrotron radiation – a consequence of the strong magnetic field in the vicinity of the neutron star.

Image credit: X-ray (NASA, IXPE)

Gamma ray observations



Why do Gamma Ray astronomy?

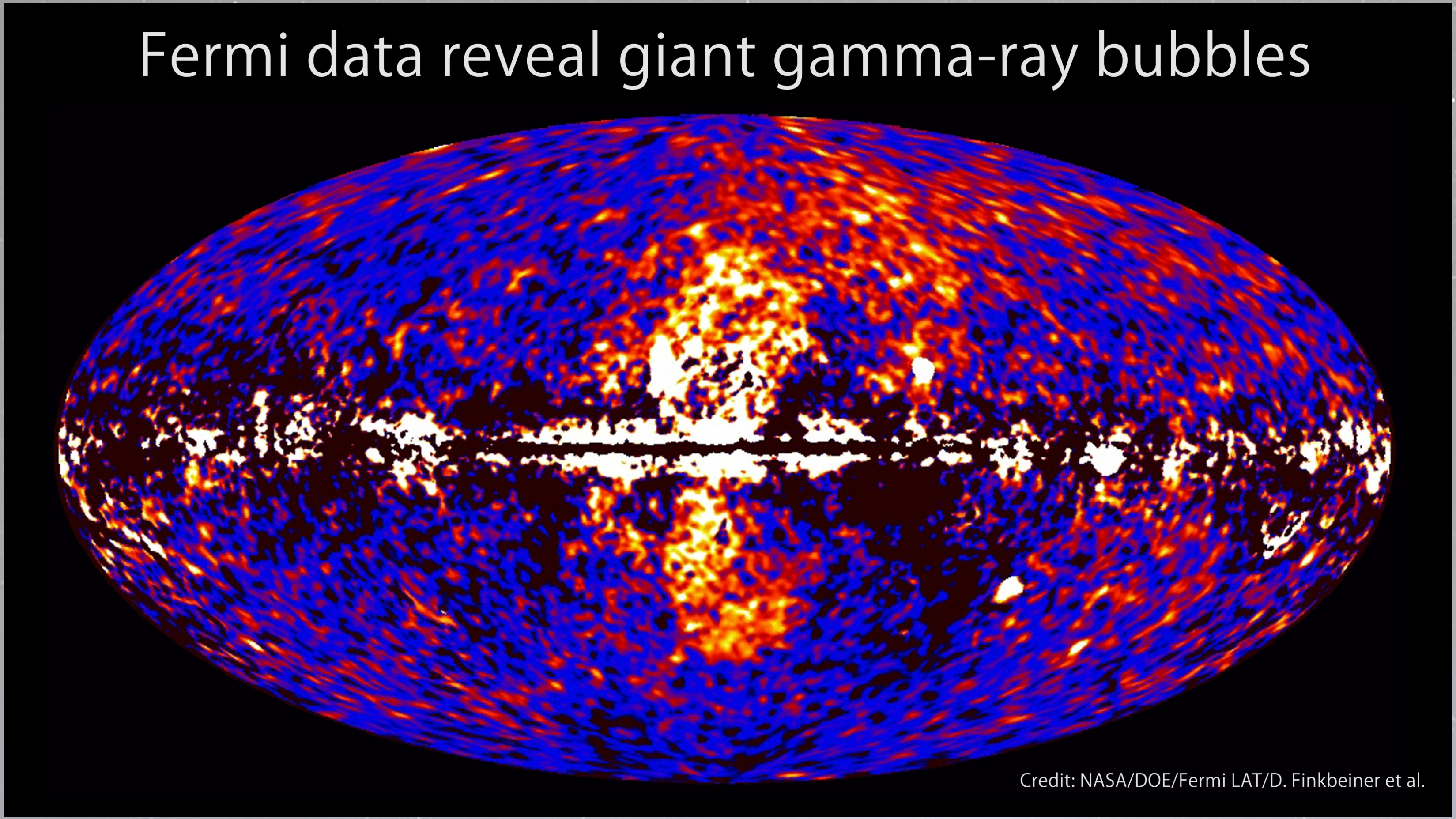
- Associated with the most energetic astronomical objects and processes - supermassive black holes, neutron stars / pulsars, core collapse supernovas
- Gama ray astronomy raises many questions: ***Eg. WHY are nearly a third of the gamma ray objects observed in the Milky Way lacking in the radio and X-ray spectrum?***
- Further study with advanced observatories should improve our understanding of these significant areas

Gamma ray observatories

Gamma rays largely absorbed by interaction with the Earths atmosphere

Space based observatories such the NASA **Fermi Large Area Telescope** (Fermi LAT) and ESA's **Integral X-Ray / Gamma Observatory** have provided important observations

The FERMI 'Bubbles'



FERMI discovered bubbles of gamma ray activity extending above and below the plane of the Milky Way. Subsequently also detected in the radio spectrum.

They suggest highly energetic outflows from the supermassive black hole at the centre of our galaxy colliding with gas/dust, possibly during earlier epochs.

Up next CTAO . . .

Ground based gamma ray observing

In Dec 2023, LST-1 (prototype above) detected gamma rays from a quasar 8 billion light years away

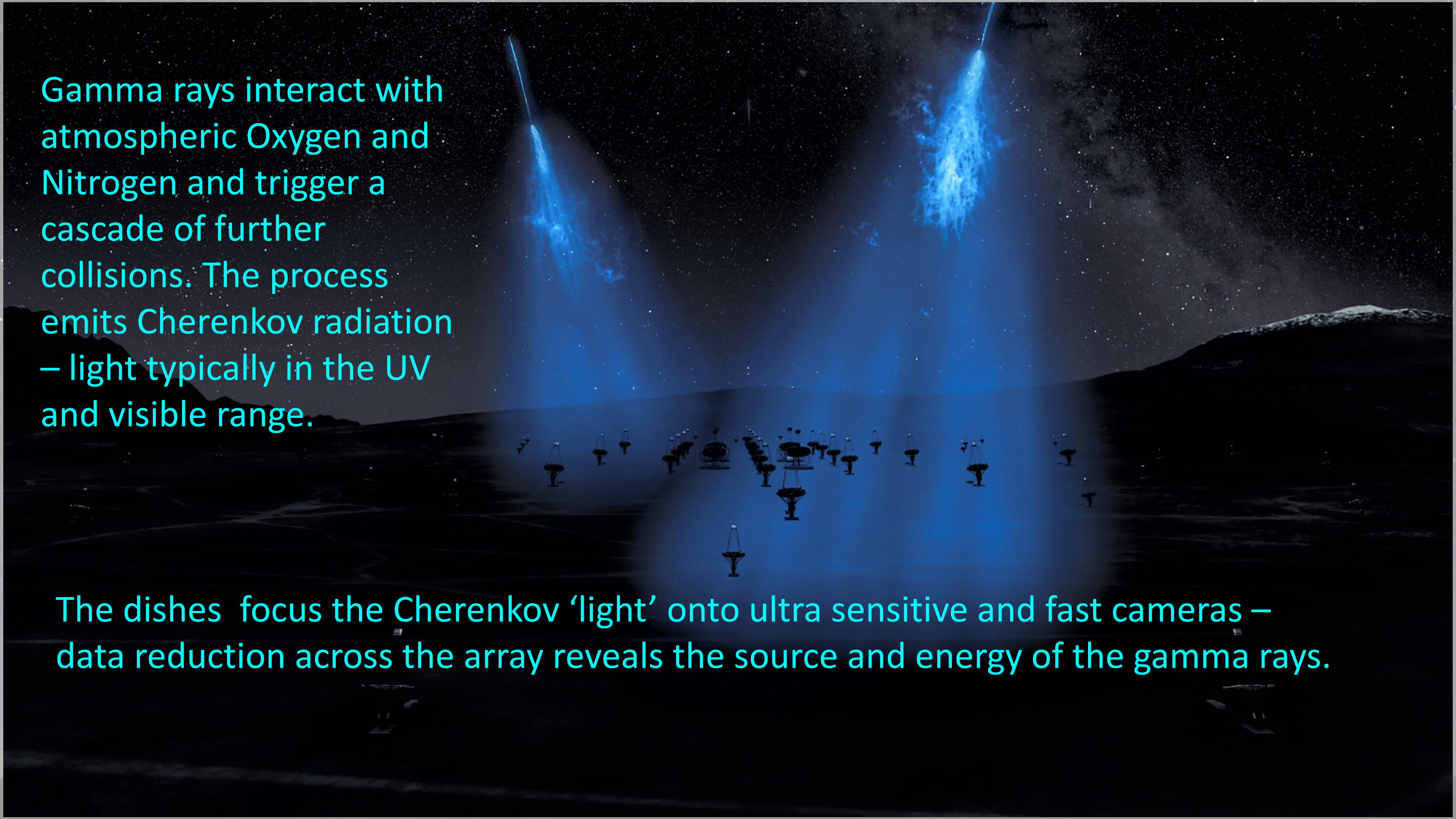
The Cherenkov Telescope Array Observatory (CTAO)

The ***La Parma array will consist of 13 telescopes*** and will focus on the CTAO's low- and mid-energy ranges

The ***Atacama array will have 51 telescopes*** and will concentrate on mid to high energy gamma-rays

. . . So how does that work

Cherenkov gamma ray 'air showers'



Gamma rays interact with atmospheric Oxygen and Nitrogen and trigger a cascade of further collisions. The process emits Cherenkov radiation – light typically in the UV and visible range.

The dishes focus the Cherenkov 'light' onto ultra sensitive and fast cameras – data reduction across the array reveals the source and energy of the gamma rays.

What about 'Cosmic rays'?

Cosmic 'ray' is a bit of a misnomer !

- cosmic rays are NOT electromagnetic radiation, they are particles - mainly protons, electrons and some atomic nuclei
- they are associated with the most energetic processes and objects – supernovae, neutron stars, black holes etc
- travel at relativistic speeds and can accelerate 'light' photons to higher energies via Inverse Compton Scattering
- can be detected by Cherenkov telescopes and space based instruments

Beyond the electromagnetic spectrum . . .

So what have we covered so far ?

- the electromagnetic spectrum
- a range of observatories
- looked at examples of what we can learn using these tools

Where do we go from here ?

- what other ‘messengers’ are available?
- how do we make good use of all these ‘wider eyes’?

Neutrinos and why we are interested in them

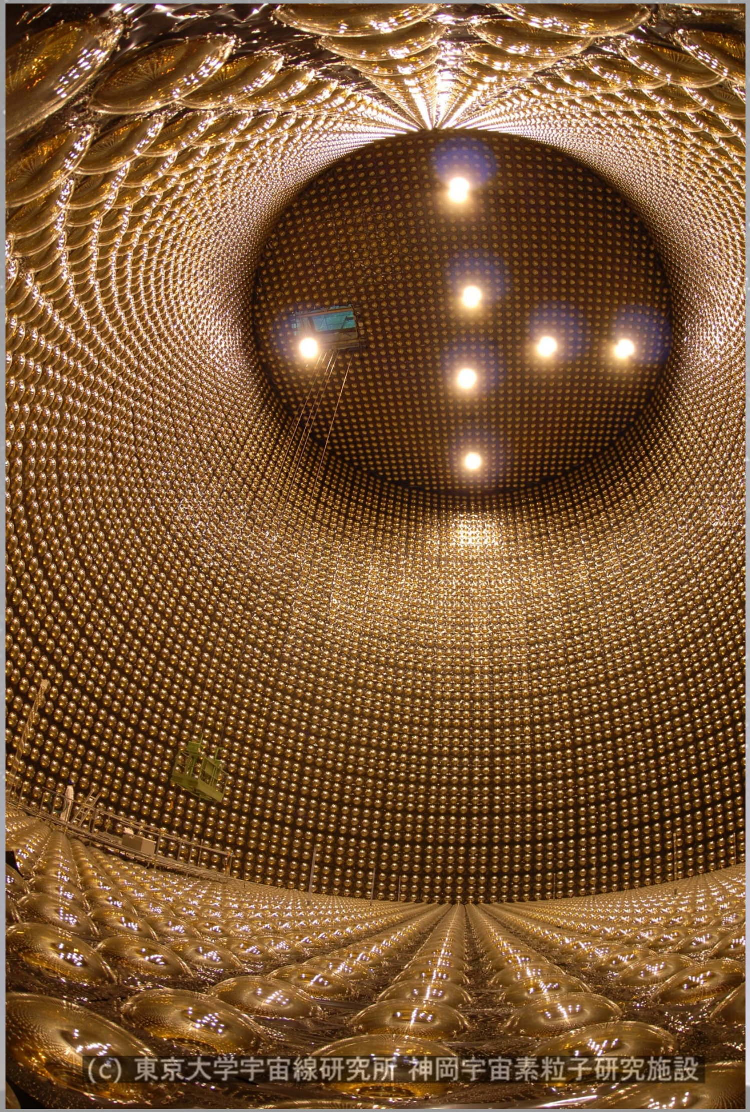
Neutrinos are subatomic particles which -

- have ***negligible mass*** and ***no electric charge***
- ***aren't blocked or deflected by interstellar material***
- ***interact only weakly with the Earths atmosphere*** or the Earth itself!!

Neutrinos are generated by the highest energy objects and processes;

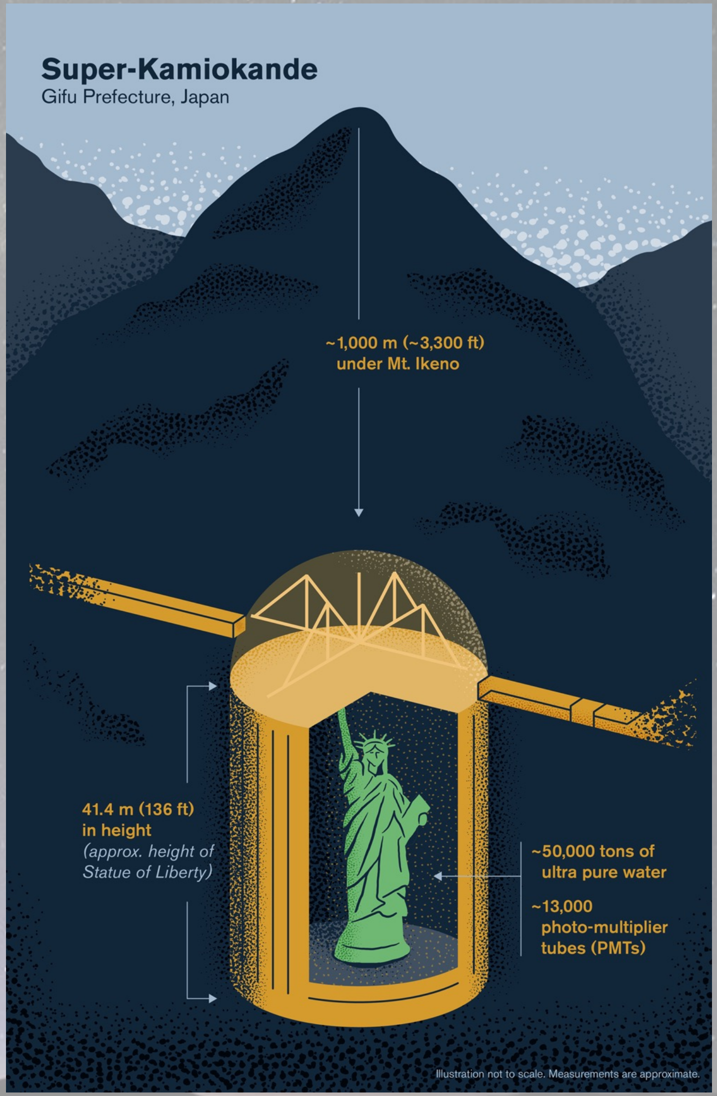
- core collapse supernovae
- supermassive black holes in Active Galactic Nuclei
- gamma ray bursts from explosive events; eg neutron star mergers
- accretion disk interactions with compact objects - neutron stars or black holes

Neutrino 'observatories' - Super-Kamiokande



A 40m tall 'tank' 1000m beneath a mountain in Japan. Lined with photomultiplier tubes and filled with purified water. ***The instrument very rapidly detects, tracks and records Cherenkov light showers caused by the passage of neutrinos.***

The system differentiates neutrino signals from gamma rays and also provides source location information.



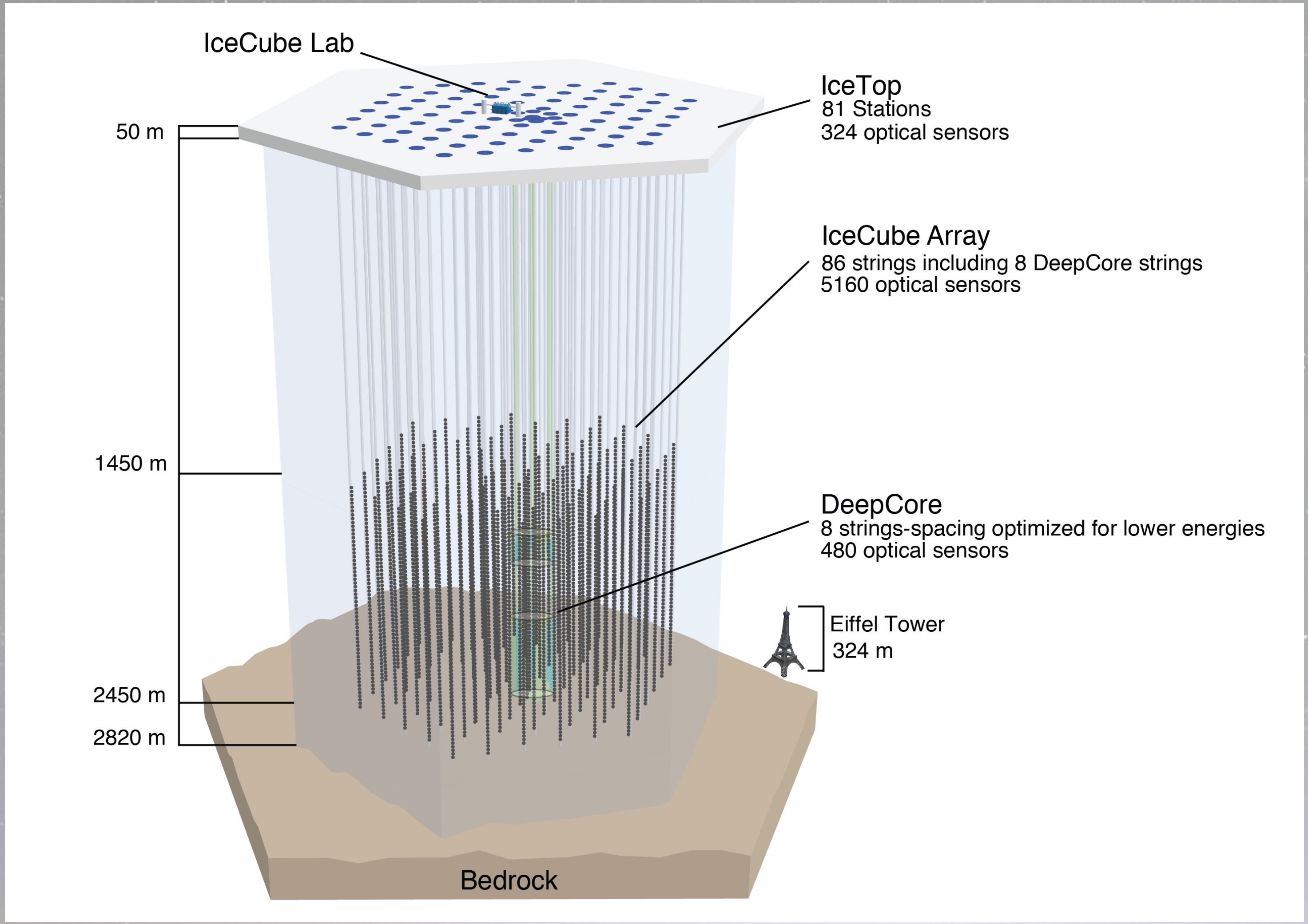
Neutrino ‘observatories’

ICECUBE
NEUTRINO OBSERVATORY

IceCube is a neutrino observatory located at Amundsen-Scott South Pole Station, Antarctica.

Image credit: Martin Wolf, IceCube/NSF

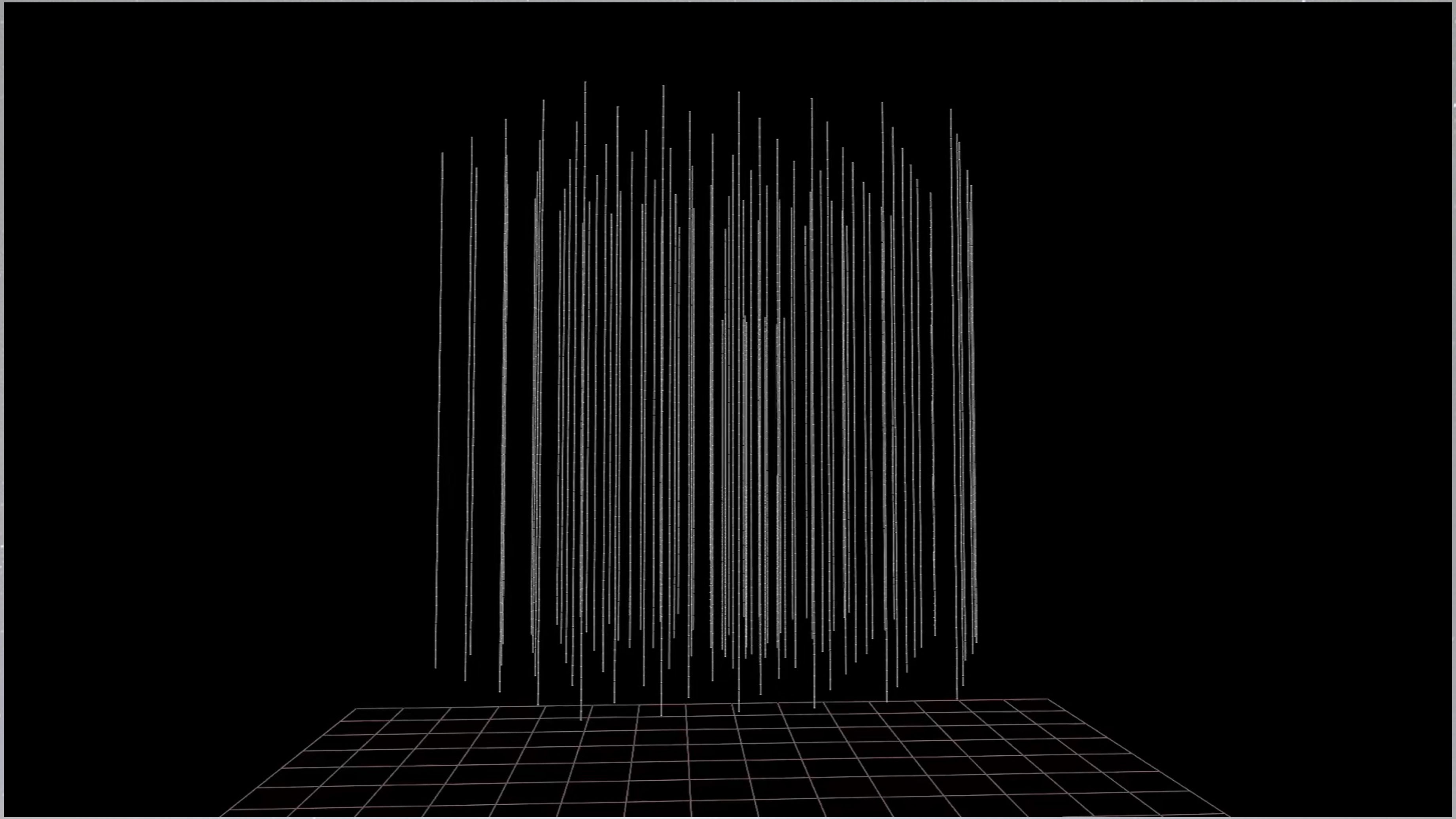
IceCube Lab



Consists of ***86 strings of 60 optical sensors lowered into 2.5km deep boreholes in the ice.***

The ***sensors detect the Cherenkov light from neutrino interactions*** with the water in the ice.

IceCube neutrino detection



Prepared & presented by John C Neal

Gravity wave astronomy - LIGO

Livingstone, Louisiana

Image credit: Caltech/MIT/LIGO Lab

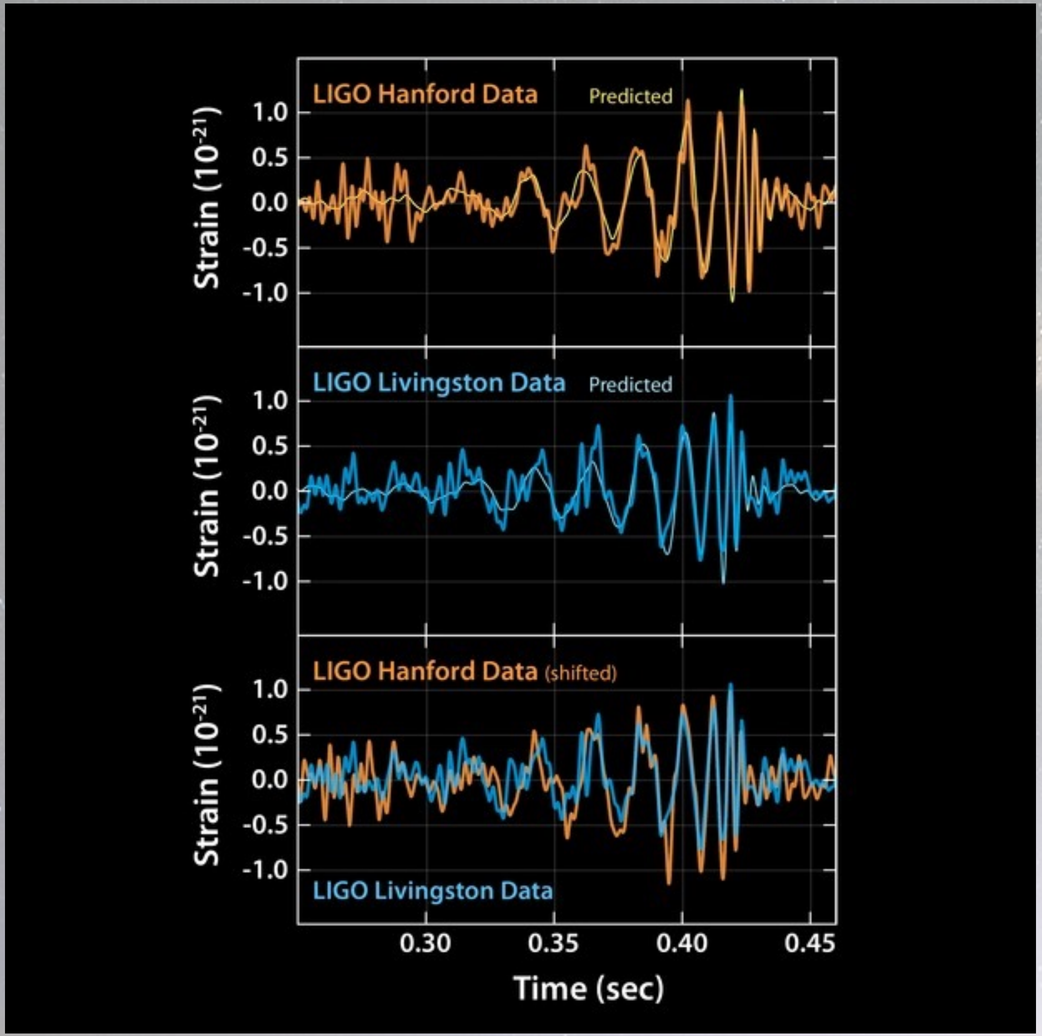
Hanford, Washington

Image credit: Caltech/MIT/LIGO Lab

The two observatories of the Laser Interferometer Gravitational-Wave Observatory – LIGO

‘Virgo’ is another (smaller) gravity wave observatory in Italy.

Gravity wave astronomy . . .



Gravity ***waves were a prediction of general relativity***. They were expected to be ***associated with the most energetic astronomical events***. Eg black hole and neutron star mergers.

Since 2015 LIGO has recorded gravity waves which match predictions for the merger of binary black hole systems. Similarly merger of neutron stars has subsequently been detected.

Making use of these ‘wider eyes’

Prepared & presented by John C Neal

Multimessenger astronomy in action 1

Supernova SN1987a

23 Feb 1987 10:37:55 UTC	**SN Discovered on a visual image captured from Las Campanas Observatory in Chile**
23 Feb 1987 07:35:35 UTC	Kamiokande team confirmed a burst of 12 neutrinos was recorded on the same date. These observations were also supported by simultaneous neutrino events recorded in the US and Russia.
This confirmed the neutrinos arrived 3 hours before the first electromagnetic evidence of the supernova was recorded. This phenomenon gives advanced warning of an event allowing other 'messengers' to prepare for observations	

Multimessenger astronomy in action 2

Neutrino detection of source TXS0506 + 056 (an AGN)

Timeline	
22 Sep 2017	IceCube detected a high energy neutrino track
+ 1 min	IceCube alerted the wider astronomical community which rapidly initiated observations across multiple wavelengths.
By 28 Sep 2017	FERMI reported a gamma ray signal from within 0.1 degree of a previously catalogued quasar showing variable emissions. The MAGIC Gamma Ray Telescope (a Cherenkov instrument) detected high energy gamma rays from the object. Subsequent observations at both Radio and XRay wavelengths also confirmed the outburst and origin.
This was the first time that a known astronomical object had been observed to generate neutrinos since SN1987a .	

Multimessenger astronomy in action 3

Kilonova in NGC4993 resulting from binary Neutron star merger

Timeline	
17/08/2017 12:41:04.43 UTC	Gravity wave GW170817 detected by LIGO; characterised as neutron star / neutron star merger located in 13 square degree box on the sky.
+ 1.7s	Fermi and INTEGRAL gamma ray satellites detected a 2s GRB designated GRB 170817A with location box overlapping with LIGO. Fermi automatically triggered alerts to the astronomical community.
+ 10h 52m	Las Campanas Observatory in Chile identified an optical source within the elliptical galaxy NGC4993 in the constellation of Hydra 40Mpc distant
+ 15h 18m	Detected by the Swift X-ray satellite
+ 9 days	Detected by the Chandra X-ray Observatory
+ 16 days	Detected in the radio spectrum by the VLA
You couldn’t wish for a better example of multimessenger astronomy in action !!	

Vera Rubin Observatory

Credit: Rubin Observatory/NOIRLab/NSF/AURA/Y. AlSayyad

Data processing challenges -

- ***20 terabytes data per night***
- ***~10 million alerts per night***

Telescope / Camera -

- 8.4-meter Survey Telescope in Chile
- ***3.2 gigapixel widefield camera giving FOV = 9.6 square degrees***

Operational features -

- ***Automated survey of the visible sky every 3-4 nights*** between Declination -72° to +12°
- Surveys of objects / events at Solar system; Milky Way; Extragalactic scales
- ***Near real time comparison of prior image with automated alerting on difference***