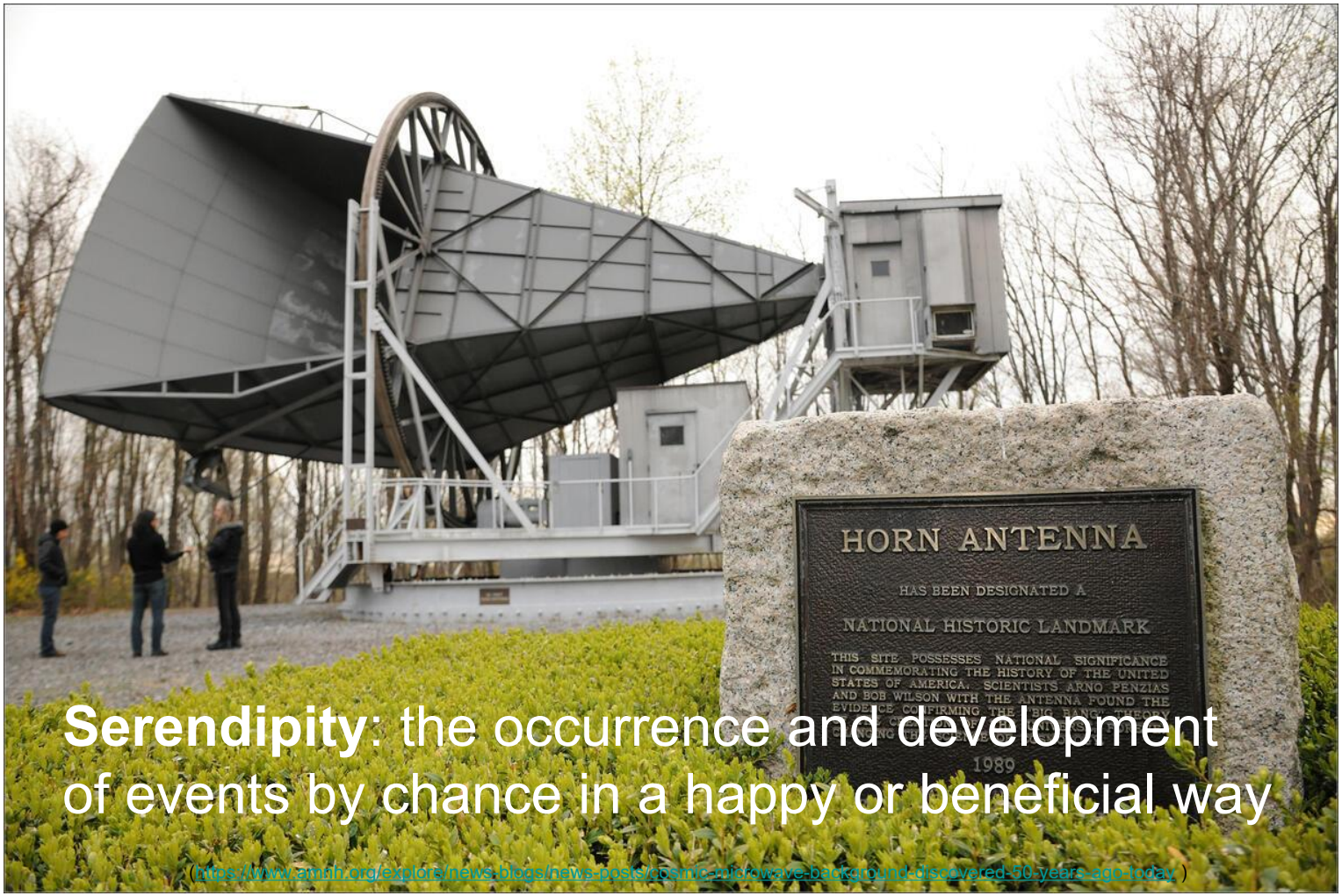
1960s: Decade of Serendipity (in Astronomy)



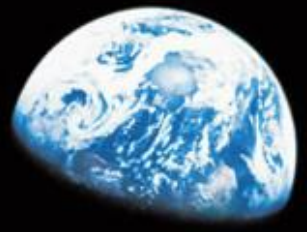
Serendipity: the occurrence and development of events by chance in a happy or beneficial way

(https://www.amnh.org/explore/news-blogs/news-posts/cosmic-cmb/cosmic-microwave-background-discovered-50-years-ago-today)

John Matthews
Professor of Physics, U. of New Mexico

1960s: when was that?

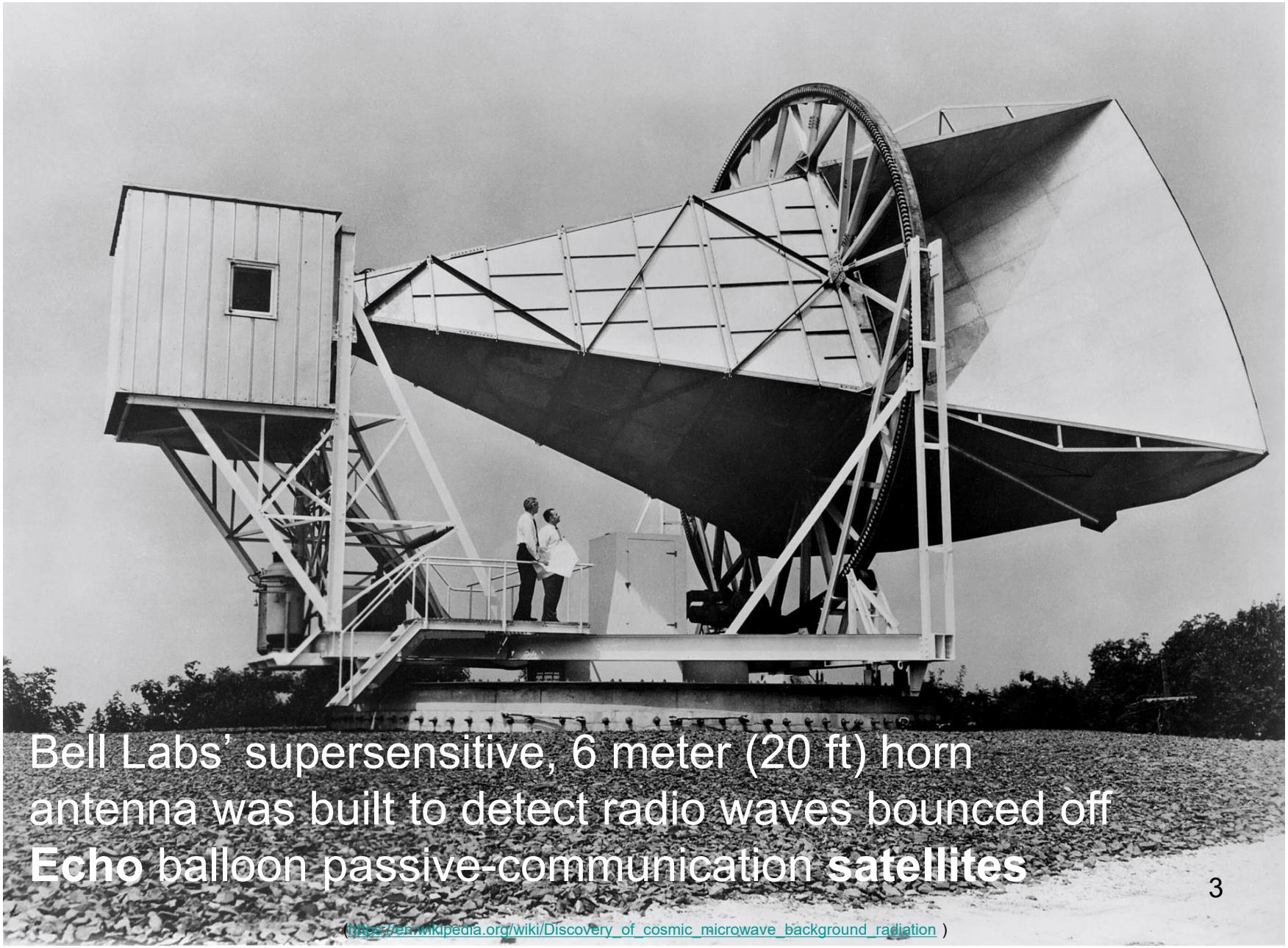
"Oh, my God! Look at that picture over there! Here's the Earth coming up. Wow, is that pretty!" Anders exclaimed, while orbiting the Moon.



Earthrise: William Anders,
from **Apollo 8** in **Lunar orbit,**
70 miles above the surface, December 24, 1968

(http://100photos.time.com/photos/nasa-earthrise-apollo-8)

Echo Project pioneered communications using satellites



Bell Labs' supersensitive, 6 meter (20 ft) horn antenna was built to detect radio waves bounced off **Echo** balloon passive-communication **satellites**

(https://en.wikipedia.org/wiki/Discovery_of_cosmic_microwave_background_radiation)

Echo tried huge, reflective balloons for communications

By the mid-1960s, "**active**" communication satellites were determined to be a more effective solution than a "**passive**" system like Echo.

People and car for scale

(https://tempo.gsfc.nasa.gov/news/_first_communications_satellite_echo)

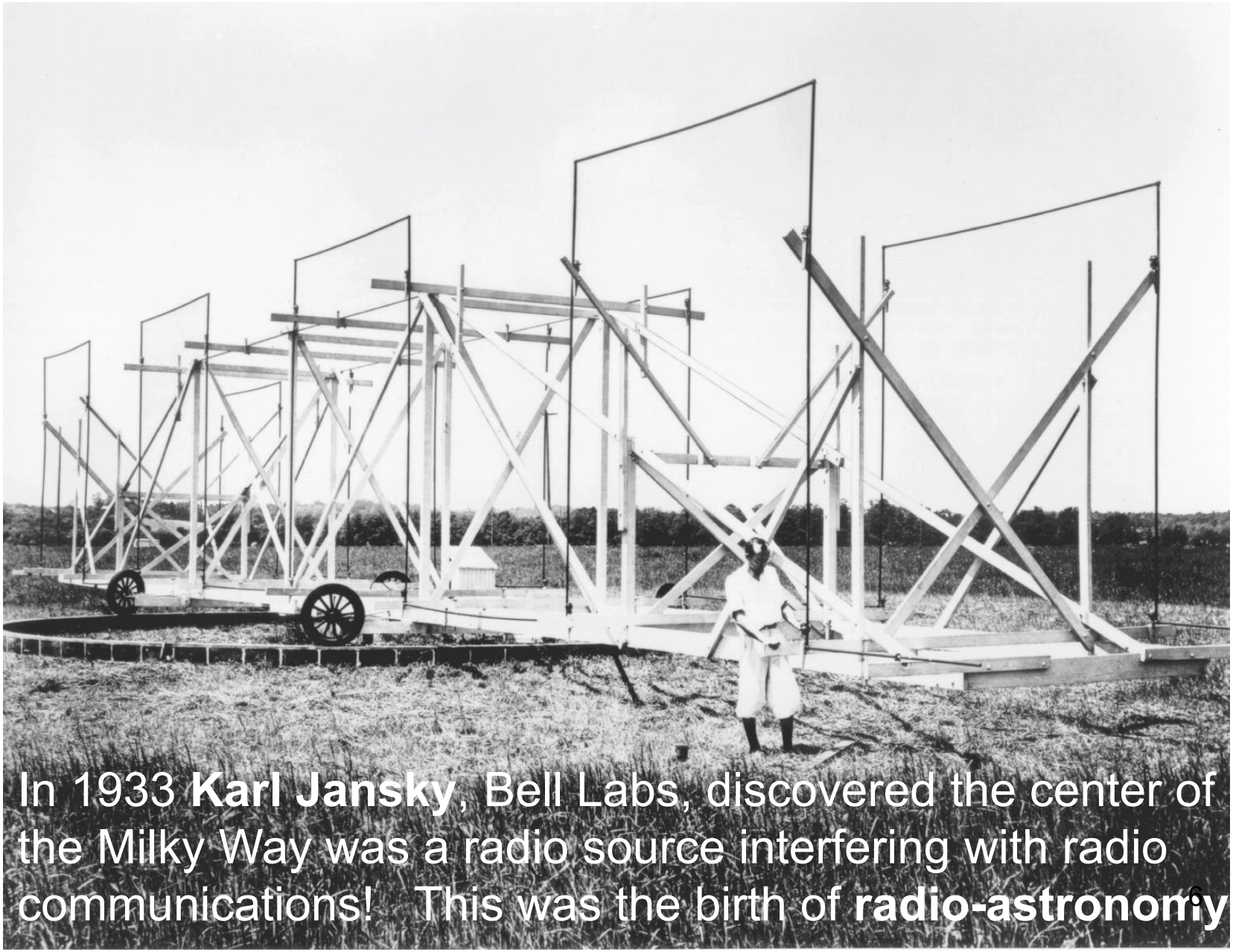
Static Inflation Test of 135 Ft Satellite In Weeksville, NC
NASA Langley Research Center 6/28/1961 Image # EL–1996–00052

Not needed, “maybe we can do some radio-astronomy with it?”

Curiously **radio-astronomy** began with radio communications. **Karl Jansky** (next slide) discovered that the radio signals “interfering” with radio communications were from the center of the Milky Way!

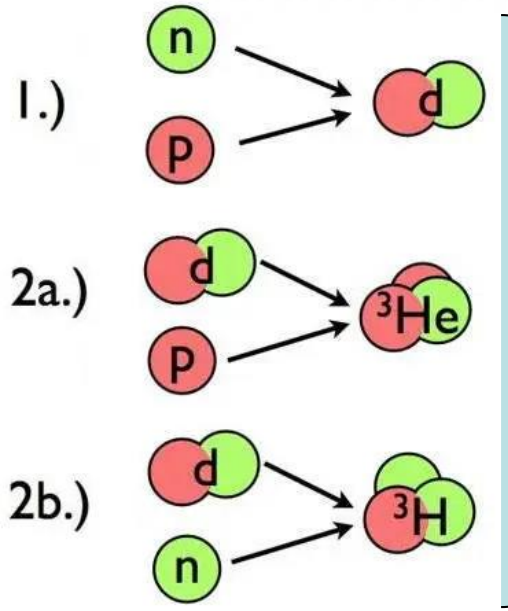
(https://en.wikipedia.org/wiki/Discovery_of_cosmic_microwave_background_radiation)

Milky Way center was the first astronomical radio source

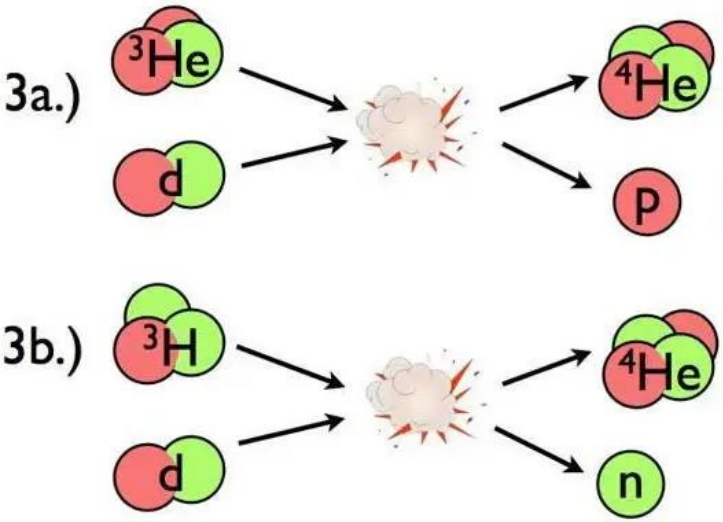


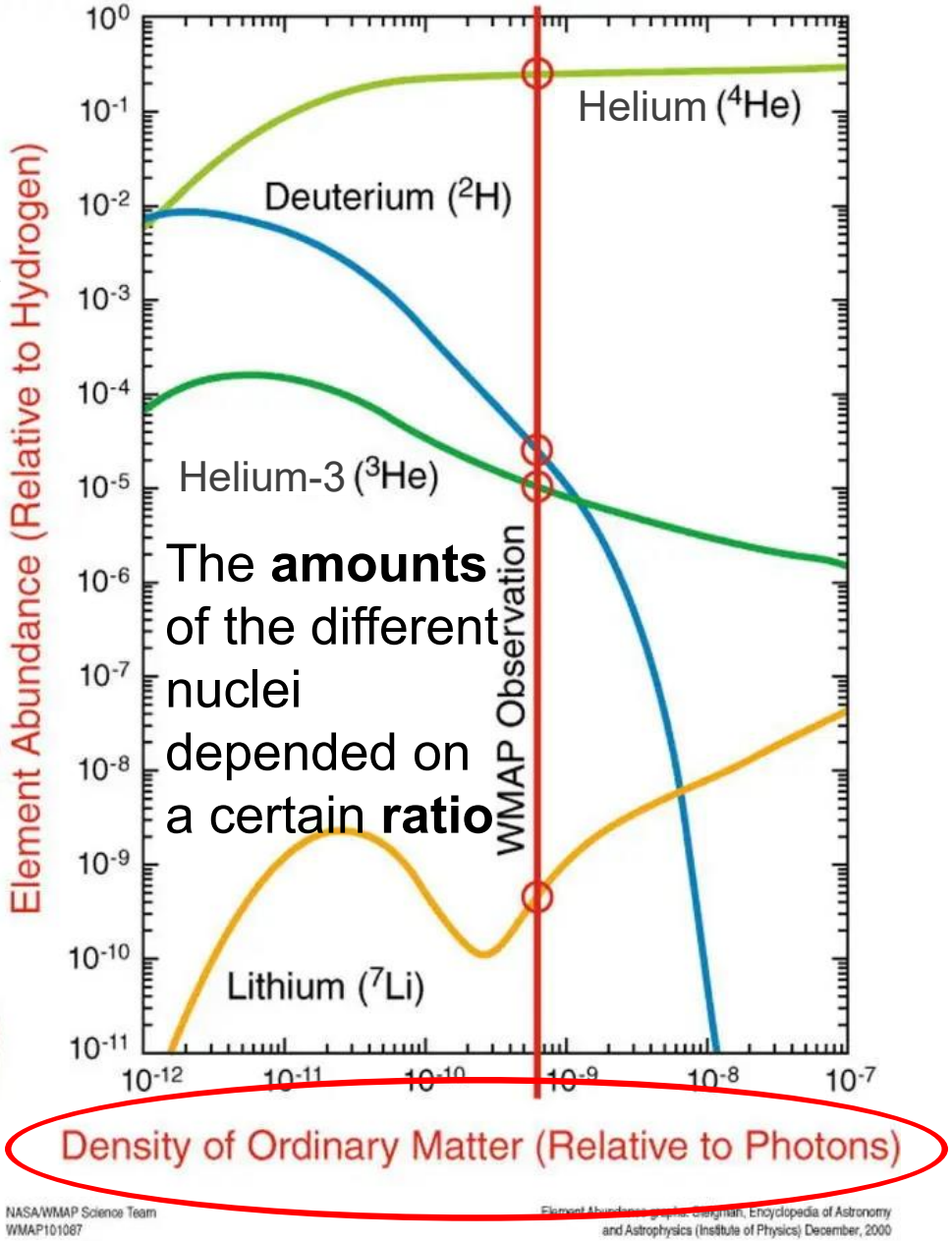
In 1933 **Karl Jansky**, Bell Labs, discovered the center of the Milky Way was a radio source interfering with radio communications! This was the birth of **radio-astronomy**

About 13.7 billion years before the 1960s, the 1st nuclei formed



Simplest **nuclear fusion**

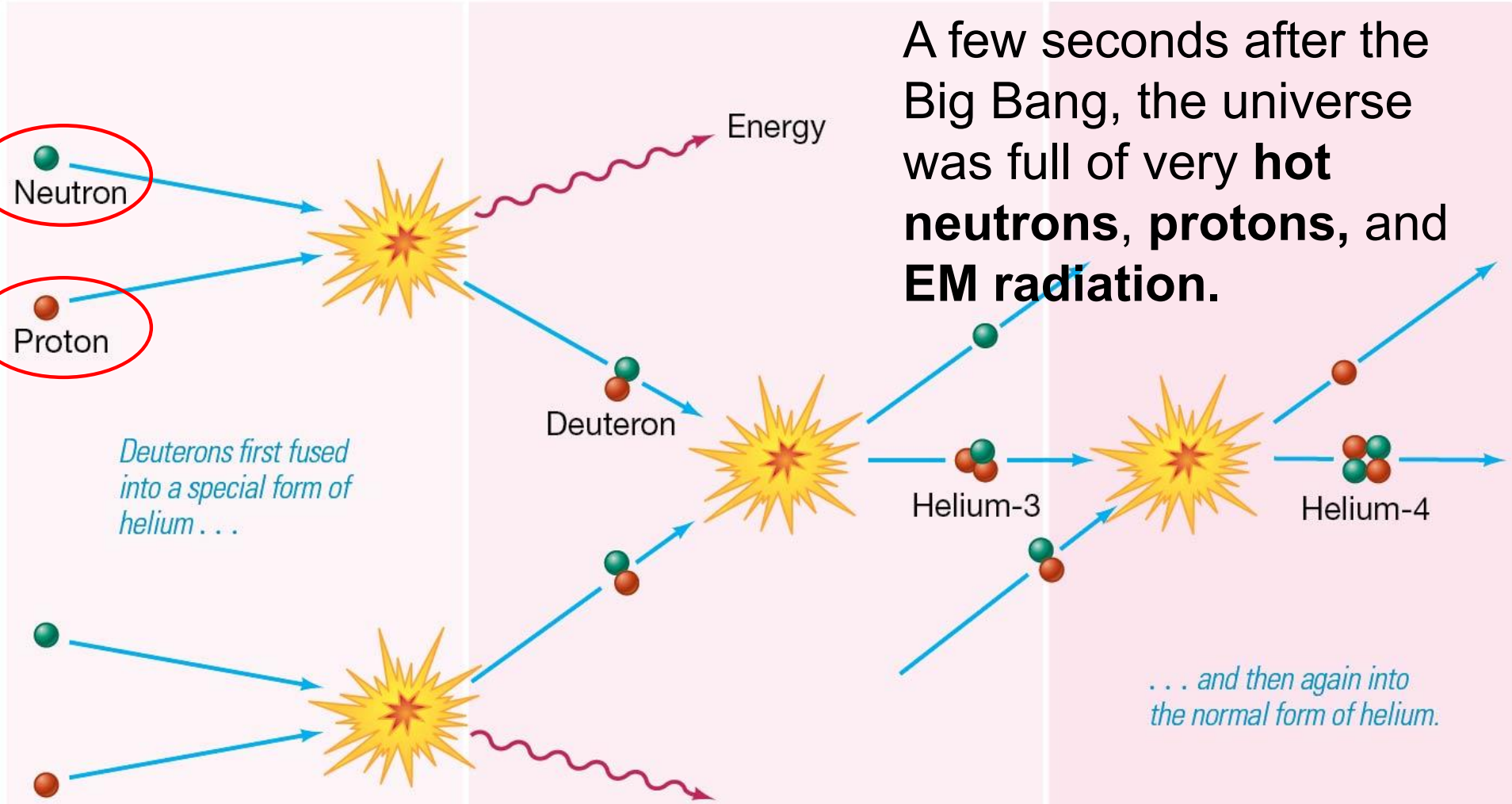




The **amounts** of the different nuclei depended on a certain **ratio**

(https://bigthink.com/starts-with-a-bang/how-heaviest-elements-made/)

For nuclear fusion the early universe had to be very hot

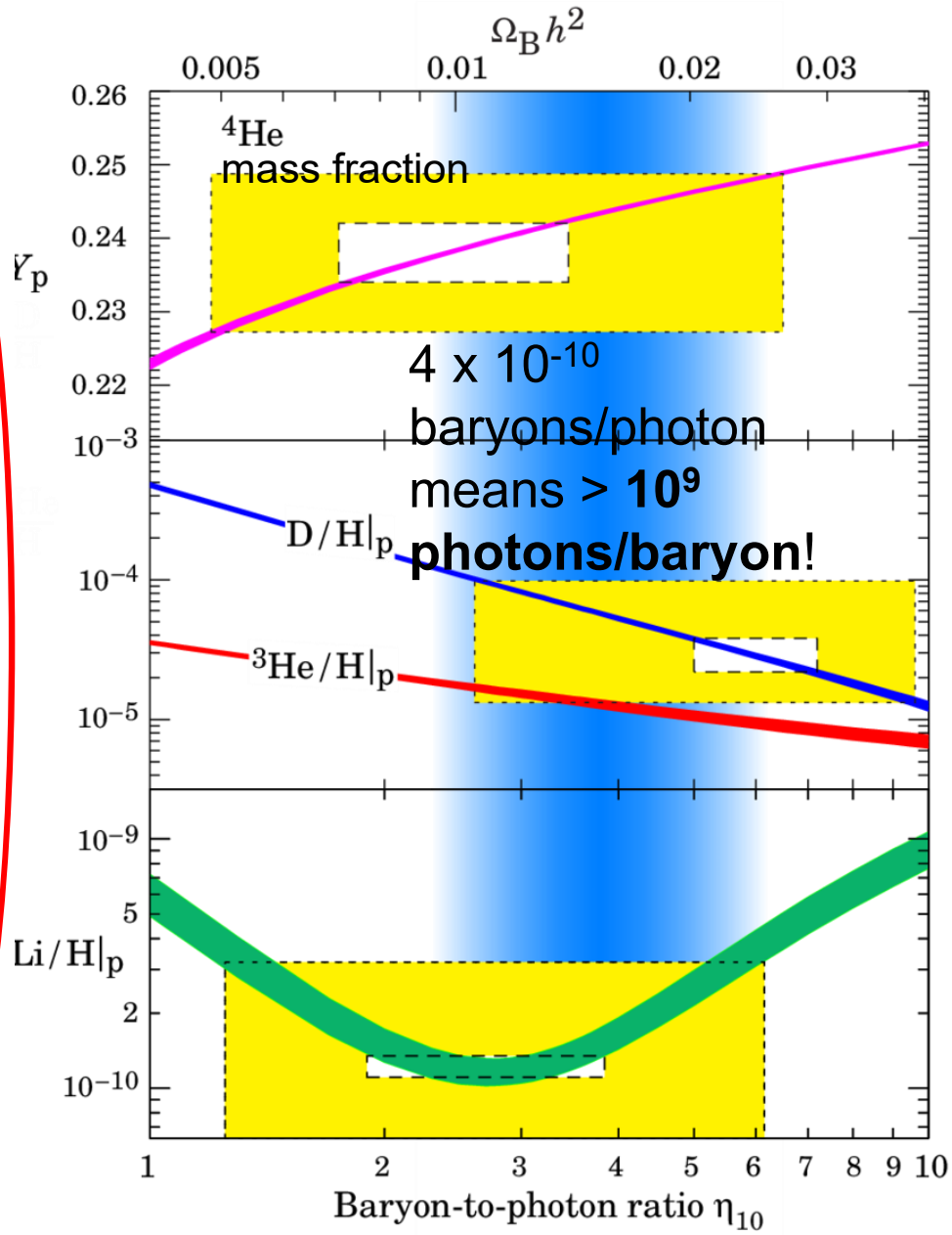


A few seconds after the Big Bang, the universe was full of very **hot neutrons**, **protons,** and **EM radiation.**

Primordial nuclear-synthesis reached the final ratio of H:He about 1000s after the Big Bang

For some reason primordial fusion mostly stopped at helium!

Nuclear isotope abundance/hydrogen

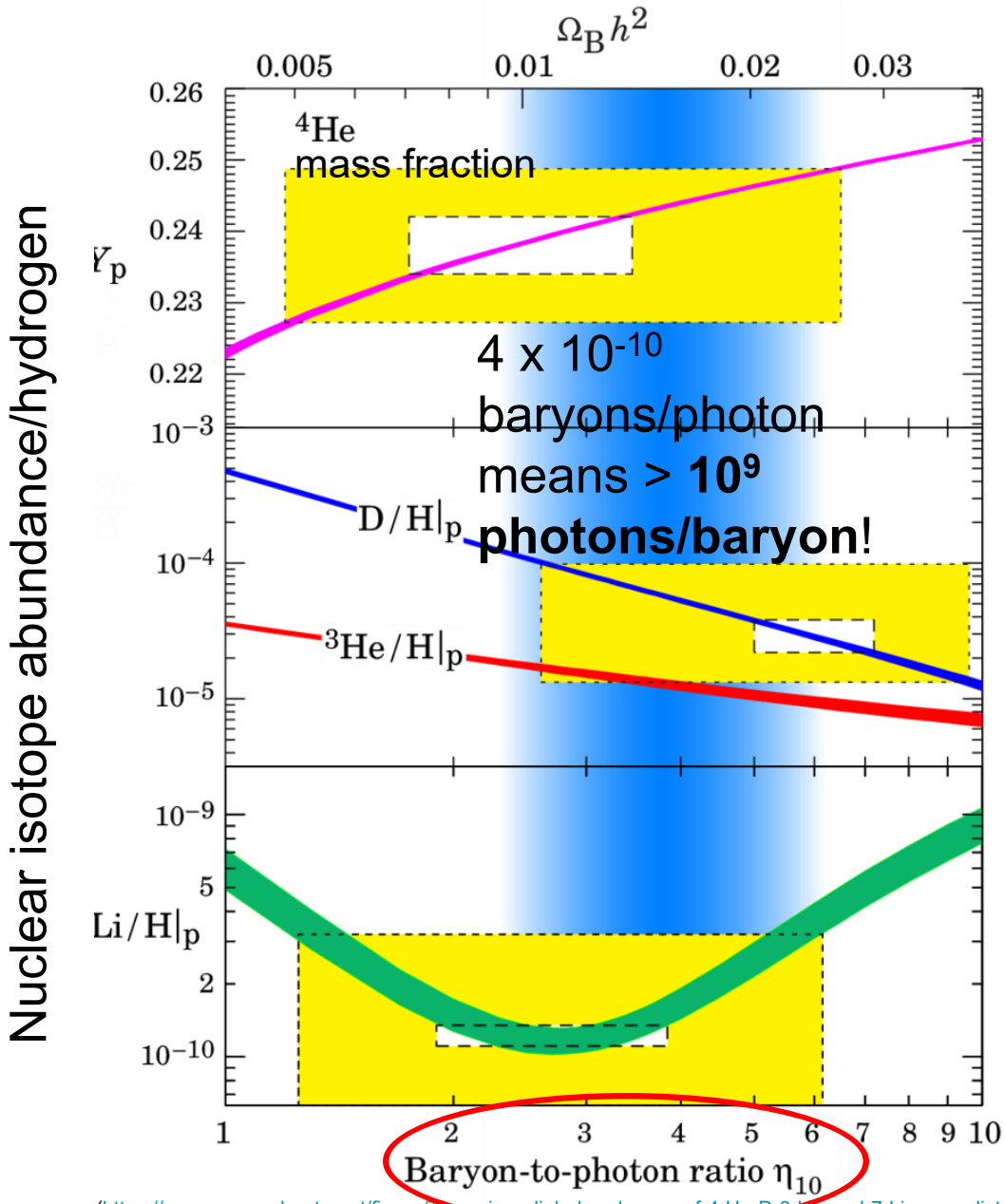


Curiously the 1st nuclei, and the universe today, are mostly hydrogen and helium (**H** and **He**).

Why is that?

(https://www.researchgate.net/figure/The-primordial-abundances-of-4-He-D-3-He-and-7-Li-as-predicted-by-the-standard-BBN_fig2_2007022)

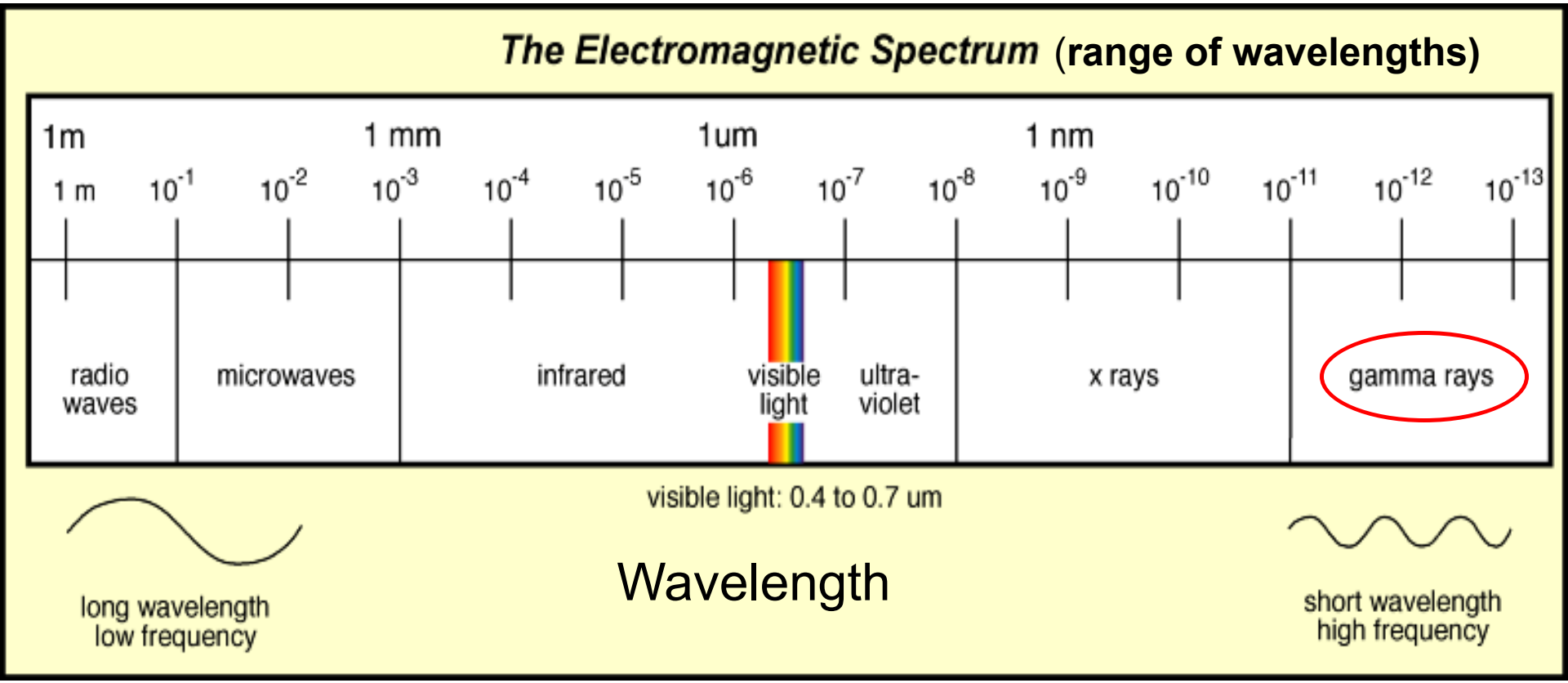
Theoretical isotope predictions needed a lot of EM radiation



So called **Big Bang Nucleosynthesis**, agreement with measured nuclear abundances needed a **"huge flux"** of **electromagnetic radiation** (gamma ray photons).

(https://www.researchgate.net/figure/The-primordial-abundances-of-4-He-D-3-He-and-7-Li-as-predicted-by-the-standard-BBN_fig2_2007022)

EM radiation is a type of wave

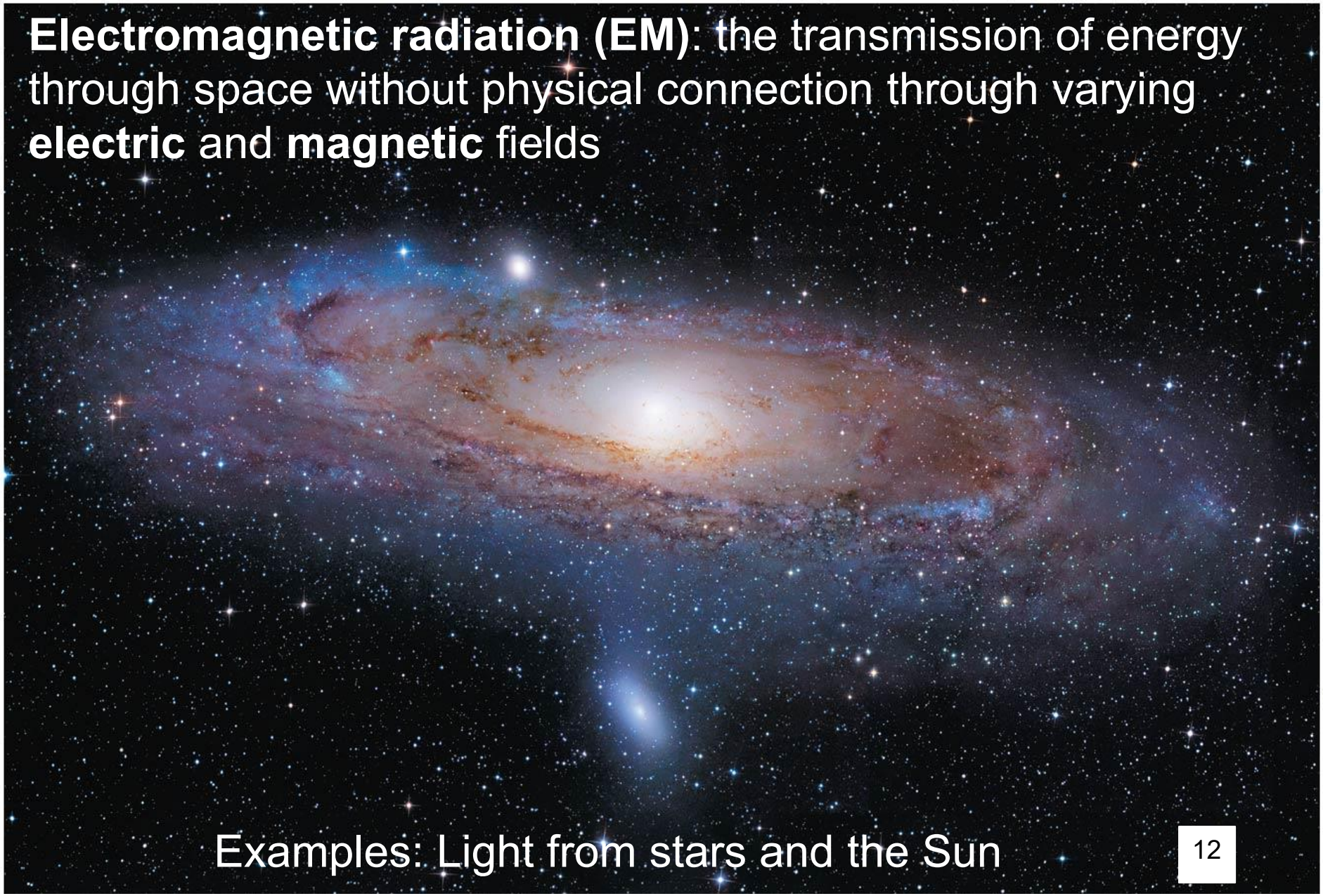


Gamma-rays are the EM waves with the **shortest** wavelengths

(http://www.columbia.edu/~vjd1/electromag_spectrum.htm)

Our eyes see visible light, just a tiny part of the EM spectrum

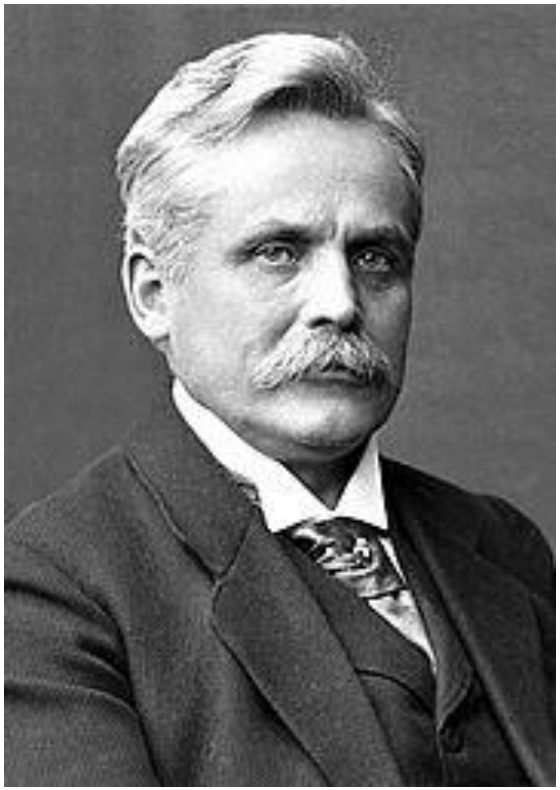
Electromagnetic radiation (EM): the transmission of energy through space without physical connection through varying **electric** and **magnetic** fields

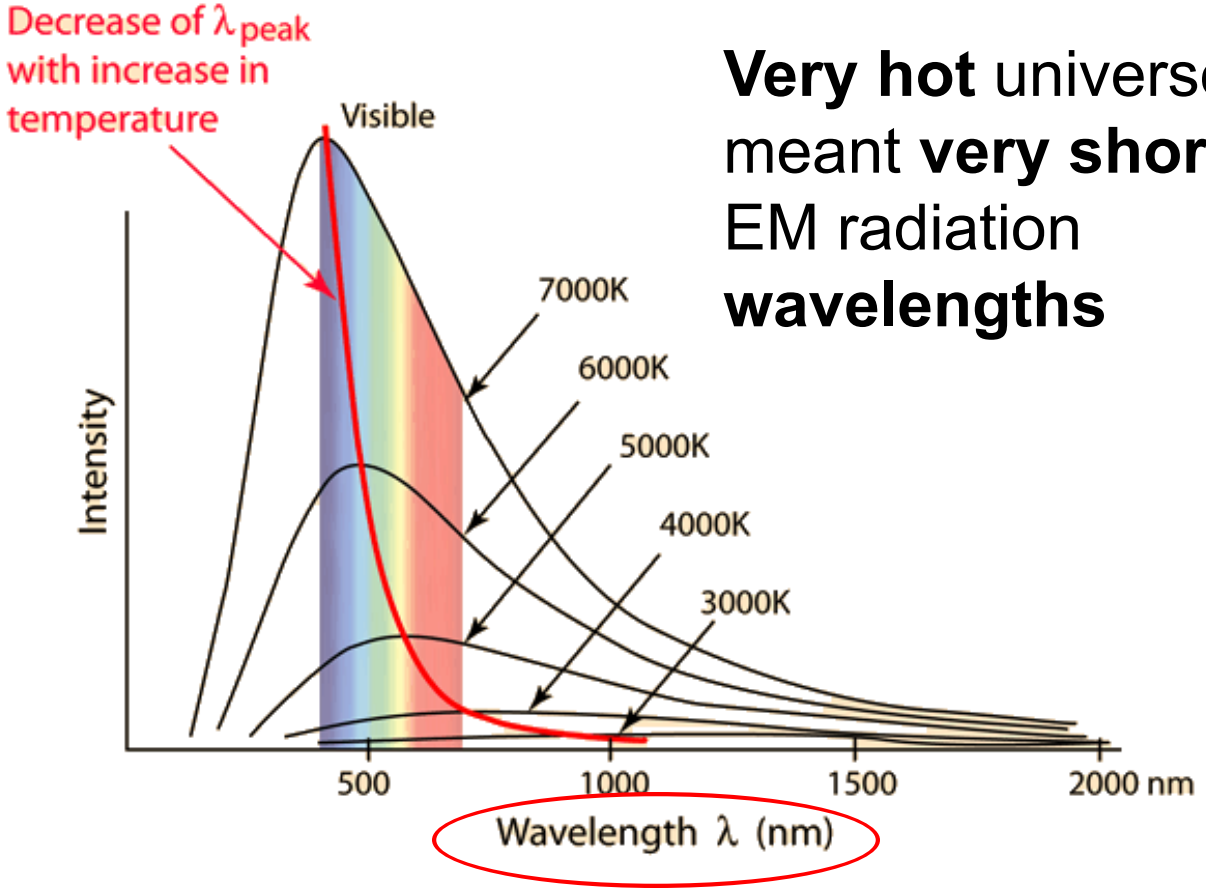


Examples: Light from stars and the Sun

Hot objects emit a spectrum of wavelengths

In 1893 Wien showed that the **wavelength** of **peak-emission**, λ_{peak}, was related to the **temperature** of the source, T(K): the **hotter** the source the **shorter** the wavelength.



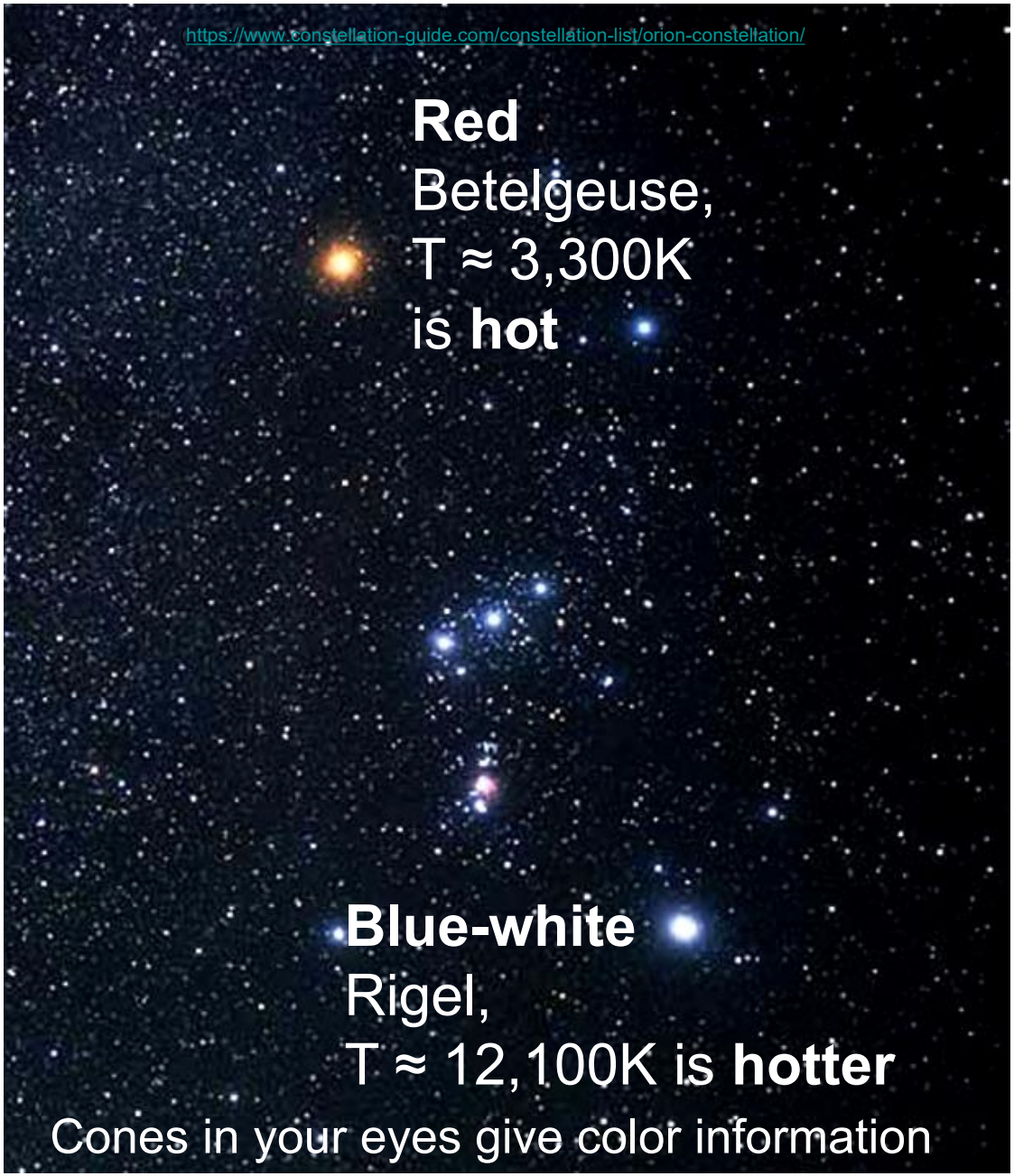


Very hot universe meant **very short** EM radiation **wavelengths**

Wilhelm Wien, 1911 Nobel Prize in Physics

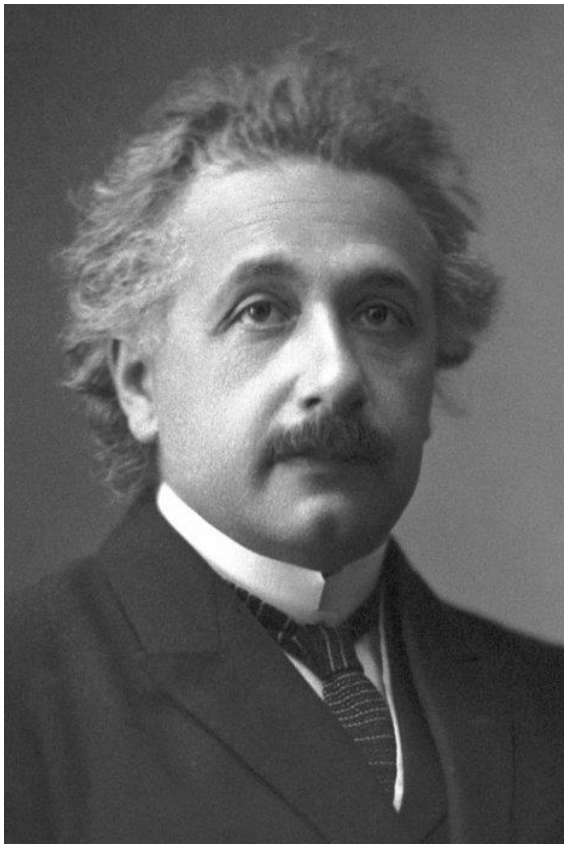
(https://www.nobelprize.org/prizes/physics/1911/summary/ and *http://hyperphysics.phy-astr.gsu.edu/hbase/wien.html*)

You can experience this as the colors of bright stars



EM radiation comes in packets called photons: crazy but true

Einstein realized that EM radiation has both wave characteristics (wavelength and frequency) and particle characteristics (well defined energy).



EM radiation are waves with *e.g.* well defined frequency, **f**, or equivalently wavelength, λ, and they come as **localized wave packets** called **photons**.

The energy of a photon depends on its wave property, frequency (or wavelength),
$\mathbf{E_\gamma = h\,f = h\,c\,/\,\lambda}$.

Thus the **shortest wavelength photons**, the gamma-rays, have the **highest energy.**

Albert Einstein, 1921 Nobel Prize in Physics

(https://www.nobelprize.org/prizes/physics/1921/summary/ and *https://www.slideshare.net/aus_autarch/vu4-lightmatter2009*)

Technology/medicine takes advantage of the EM spectrum

- **Gamma rays** with the shortest wavelengths have the **highest energies**.

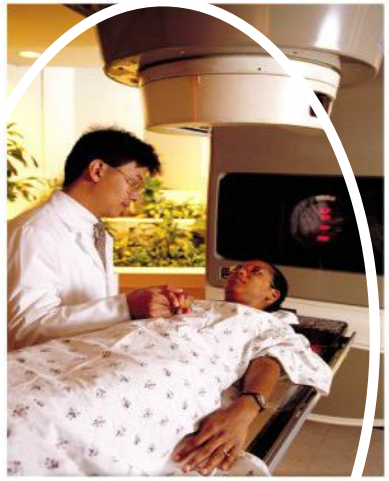
(a) Mobile phone: radio waves

(b) Microwave oven: microwaves

(c) TV remote: infrared light

(d) Tanning booth: ultraviolet light

(e) Medical imaging: X rays.

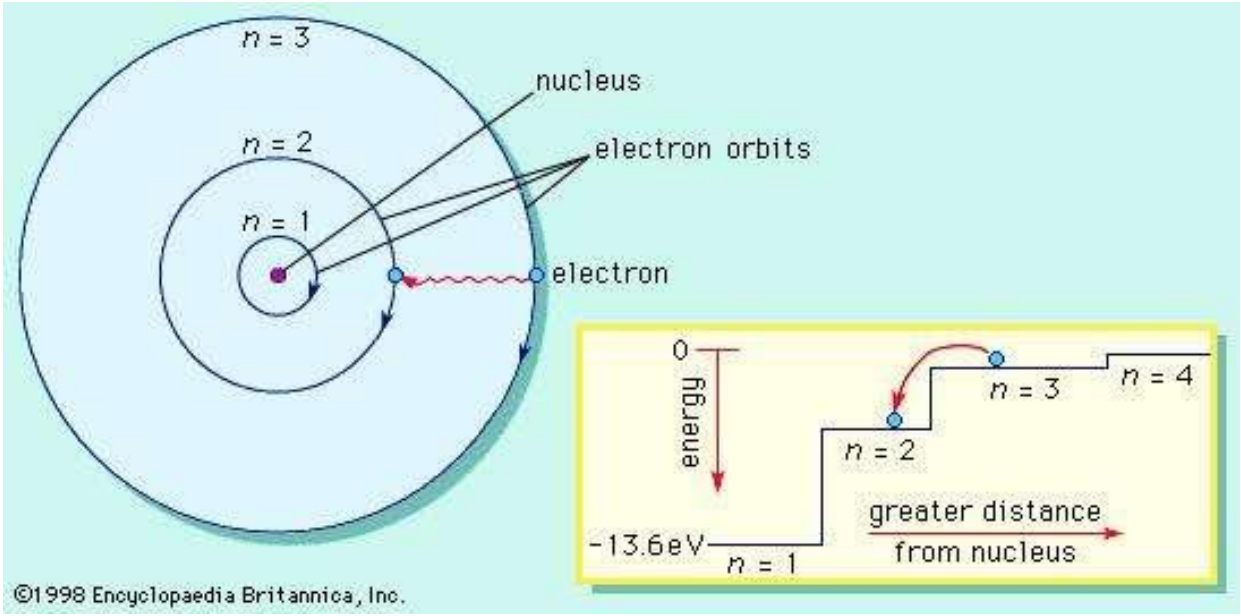


(f) Cancer radiotherapy: gamma rays

Photons of just the right energy interact with atoms/nuclei

The **Bohr model** included two critical features: **quantized energy levels** and **emission/absorption** of **EM** radiation only during energy level transitions.

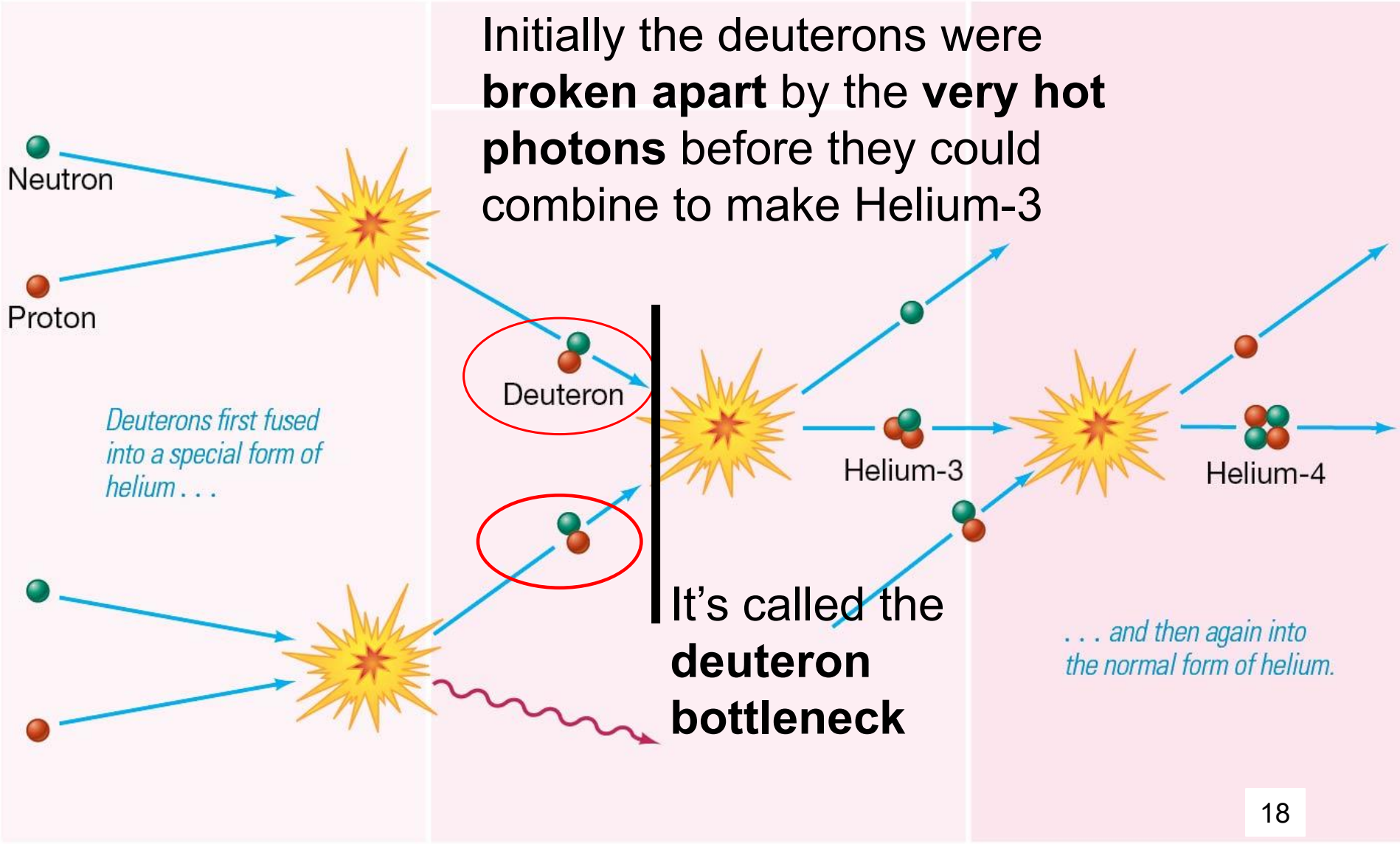
Schematic of hydrogen atom making a transition from a higher to lower energy level.



(https://www.nobelprize.org/prizes/physics/1922/bohr/facts/ and https://www.britannica.com/science/atom/Orbits-and-energy-levels)

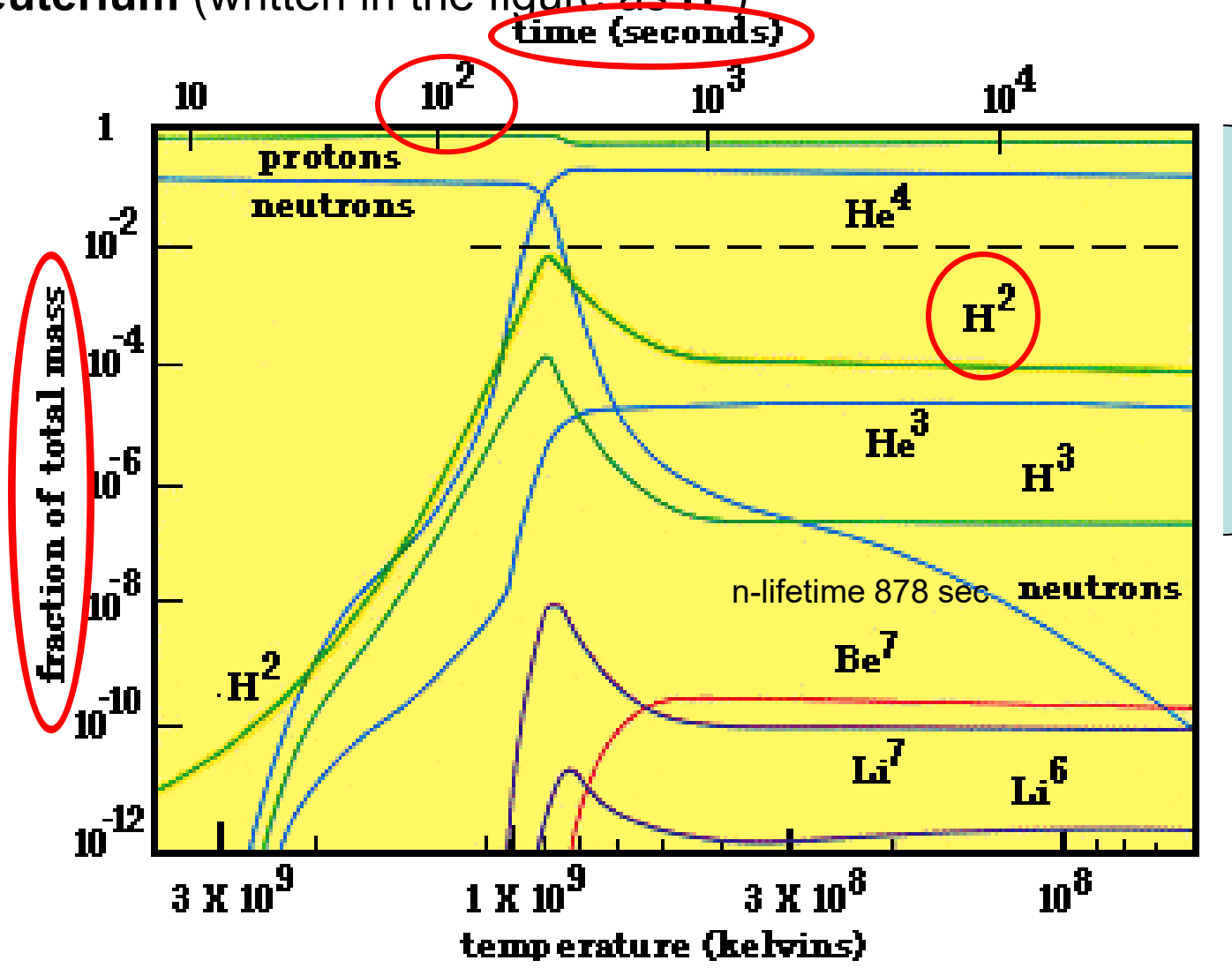
Niels Bohr, 1922 Nobel Prize in Physics

Thanks to Bohr and Einstein, the deuterons were broken apart



Universe expansion cooled the universe “just in time”

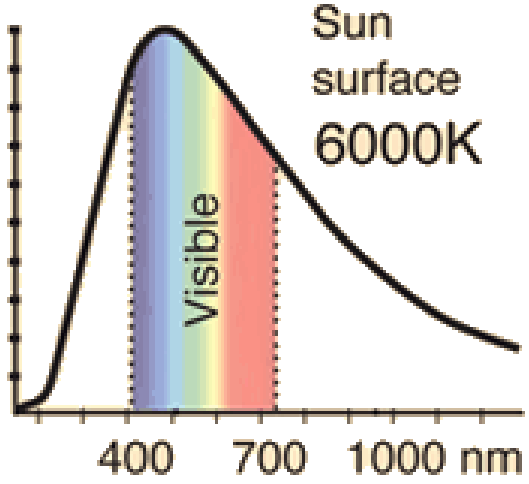
Between 10^2 and $4x10^2$ seconds, the universe had cooled enough that the EM radiation photons were no longer energetic enough to dissociate the isotope **deuterium** (written in the figure as H^2)

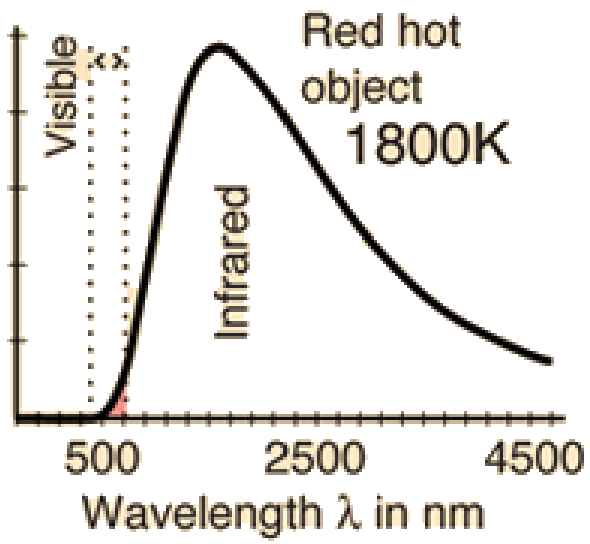


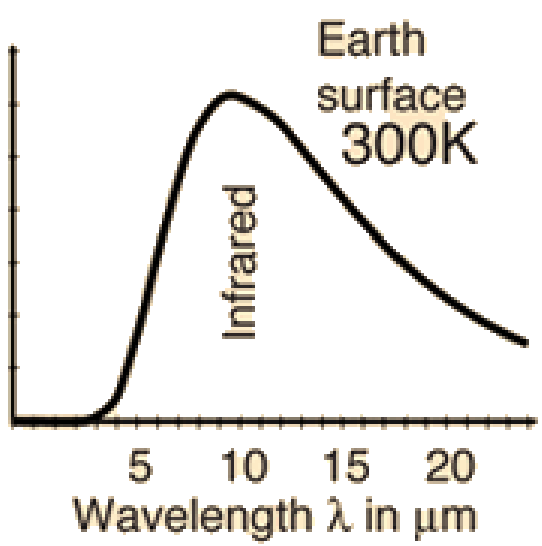
The lightest nuclei formed but little else.

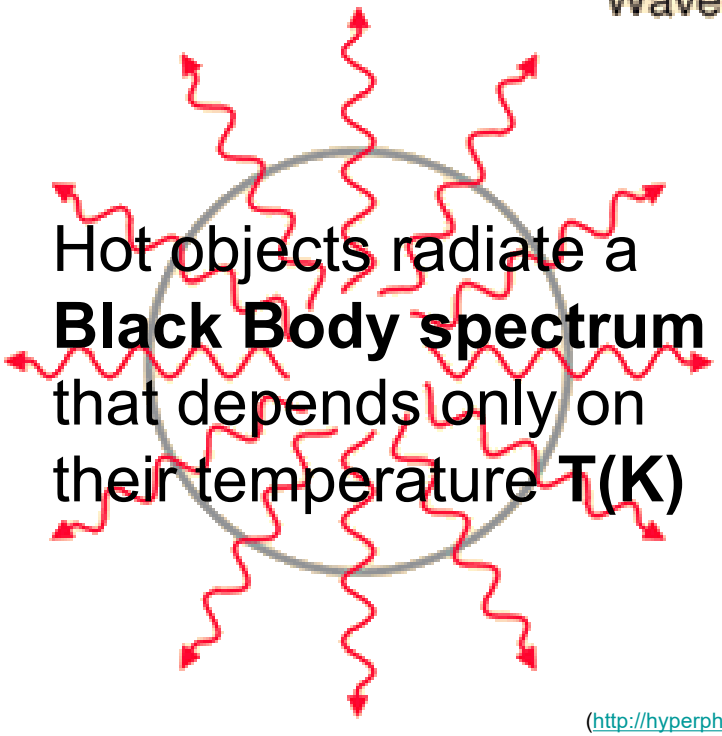
(http://www.astro.ucla.edu/~wright/BBNS.html)

Gamma rays were then stretched by the universe expansion

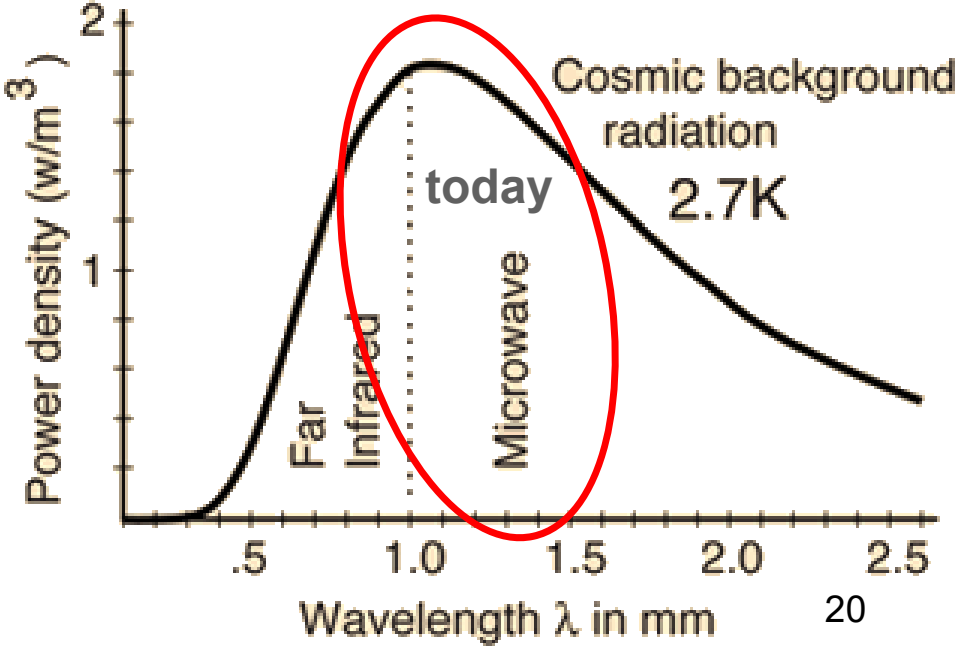






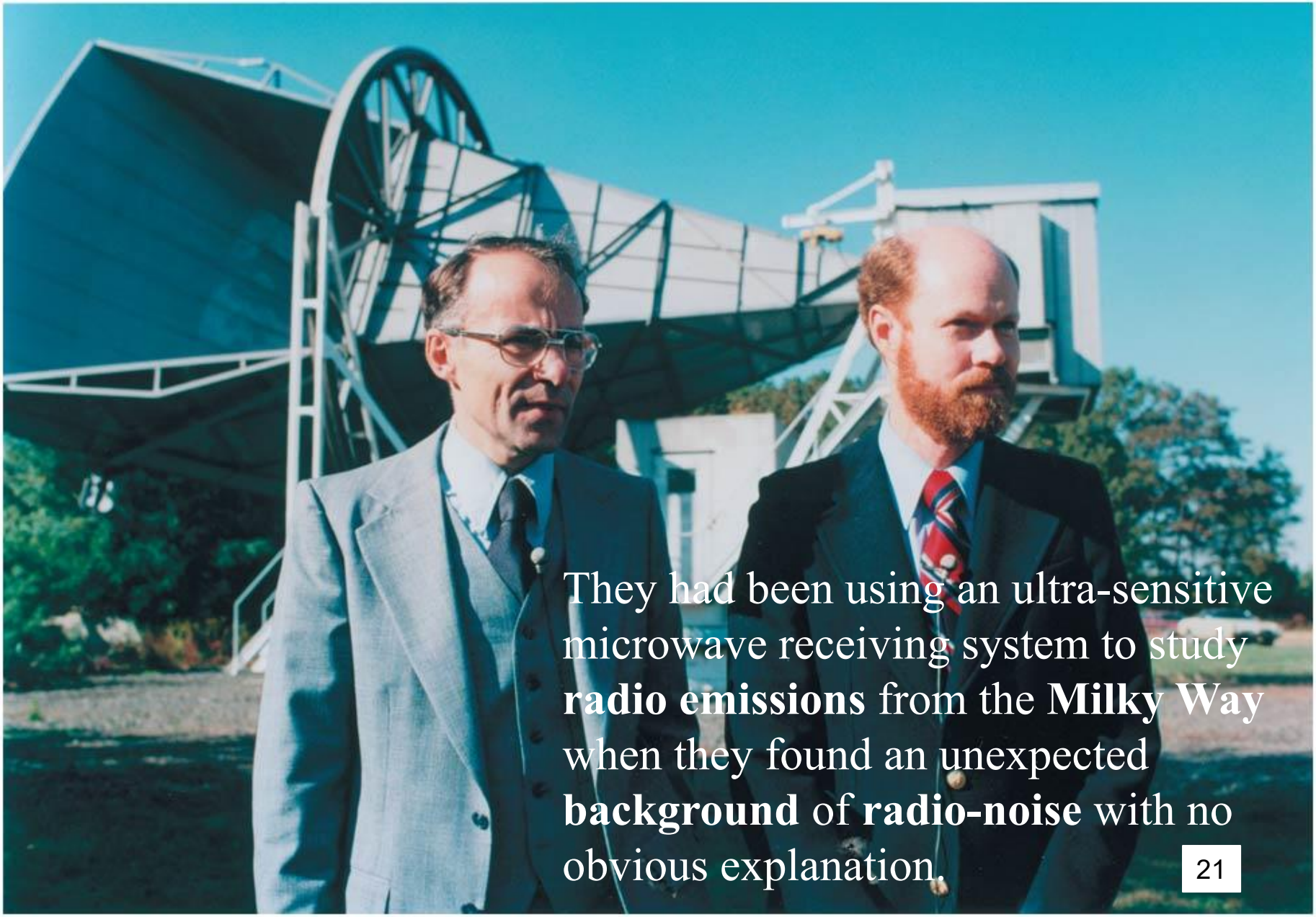


Hot objects radiate a **Black Body spectrum** that depends only on their temperature **T(K)**



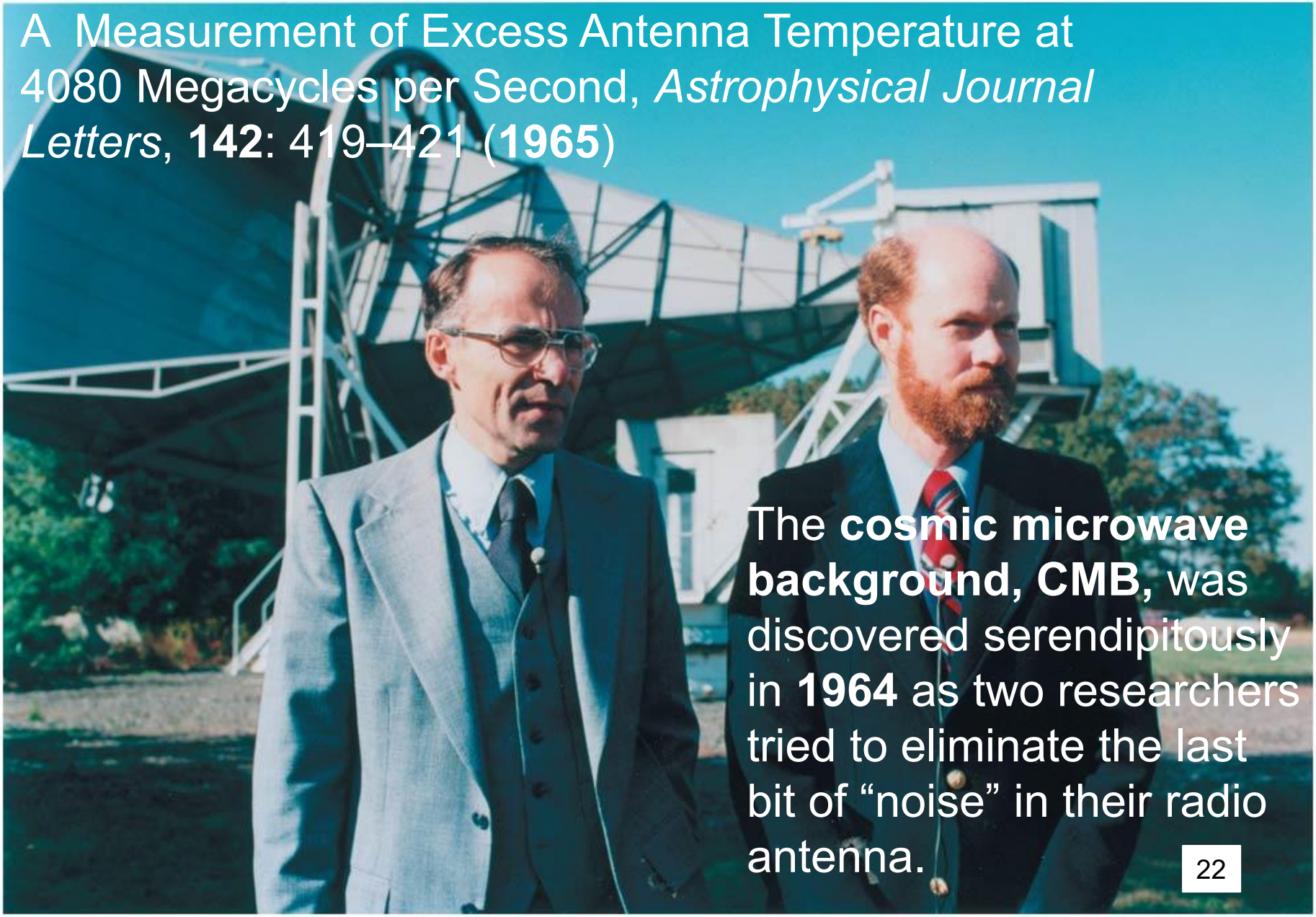
(http://hyperphysics.phy-astr.gsu.edu/hbase/bkg3k.html#c3)

The “cast off” radio antenna struggled with unexpected radio-noise



They had been using an ultra-sensitive microwave receiving system to study **radio emissions** from the **Milky Way** when they found an unexpected **background** of **radio-noise** with no obvious explanation.

Antenna's radio-noise was the "huge flux" from the Big Bang



CMB detection confirmed a Hot Big Bang prediction!

The Nobel Prize in Physics 1978

(https://www.nobelprize.org/prizes/physics/1978/summary/)

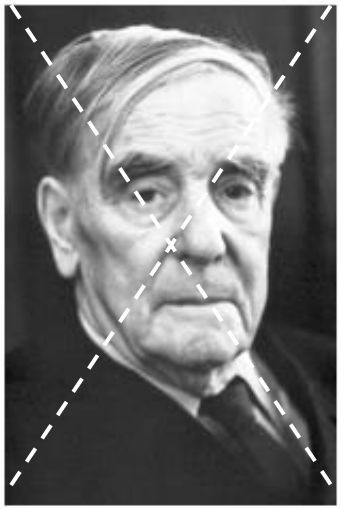


Photo from the Nobel Foundation archive.

Pyotr Leonidovich Kapitsa

Prize share: 1/2

Photo from the Nobel Foundation archive.

Arno Allan Penzias

Prize share: 1/4

Photo from the Nobel Foundation archive.

Robert Woodrow Wilson

Prize share: 1/4

The Nobel Prize in Physics 1978 was divided, one half awarded to Pyotr Leonidovich Kapitsa "for his basic inventions and discoveries in the area of low-temperature physics", the other half jointly to Arno Allan Penzias and Robert Woodrow Wilson "for their discovery of cosmic microwave background radiation"

Curiously the 1960s had several serendipitous discoveries

1963 - Researchers realized that **Quasars** were at immense distances and must have an extreme energy source.

On May 20, 1964, American radio-astronomers Robert Wilson and Arno Penzias discovered the **cosmic microwave background** radiation (CMB)

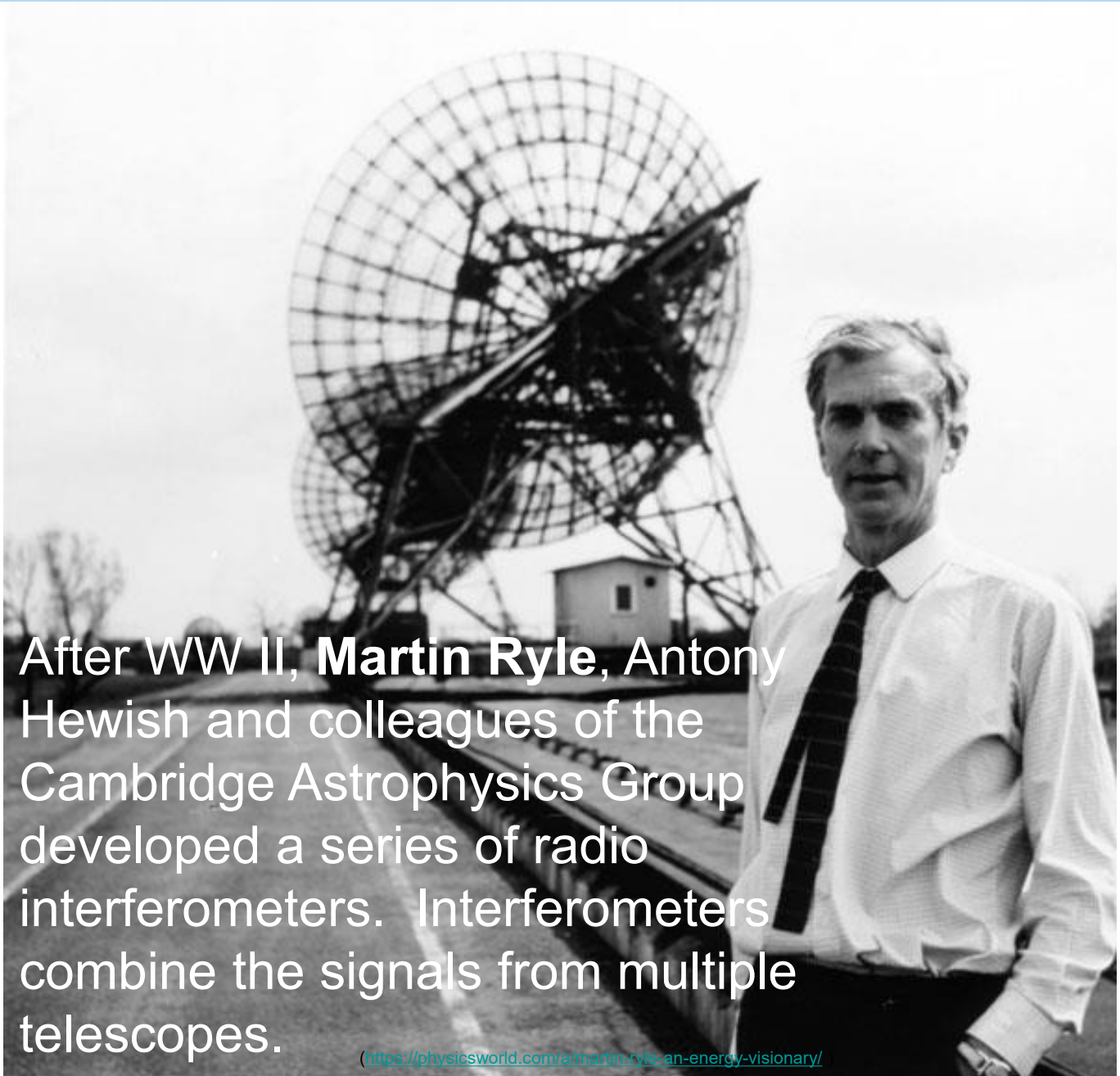
1966 - Halton Arp published a "**catalog of peculiar galaxies**" (now known to be dominated by colliding galaxies).

1967 - **Pulsars** were discovered by Jocelyn Bell.

1968 - Thomas Gold proposed pulsars were spinning **neutron stars** which emit radiation similar to a rotating beacon.

1969~72 - **Sixteen gamma-ray bursts** of non-local origin were detected by the Vela military satellites. In1997, i.e. 28 years post-discovery, gamma-ray bursts were found to be at huge distances requiring some extreme energy source.

Precision radio-astronomy requires interferometers



After WW II, **Martin Ryle**, Antony Hewish and colleagues of the Cambridge Astrophysics Group developed a series of radio interferometers. Interferometers combine the signals from multiple telescopes.

(https://physicsworld.com/a/martin-ryle-an-energy-visionary/

Radio-astronomy benefitted from WW II radar instrumentation

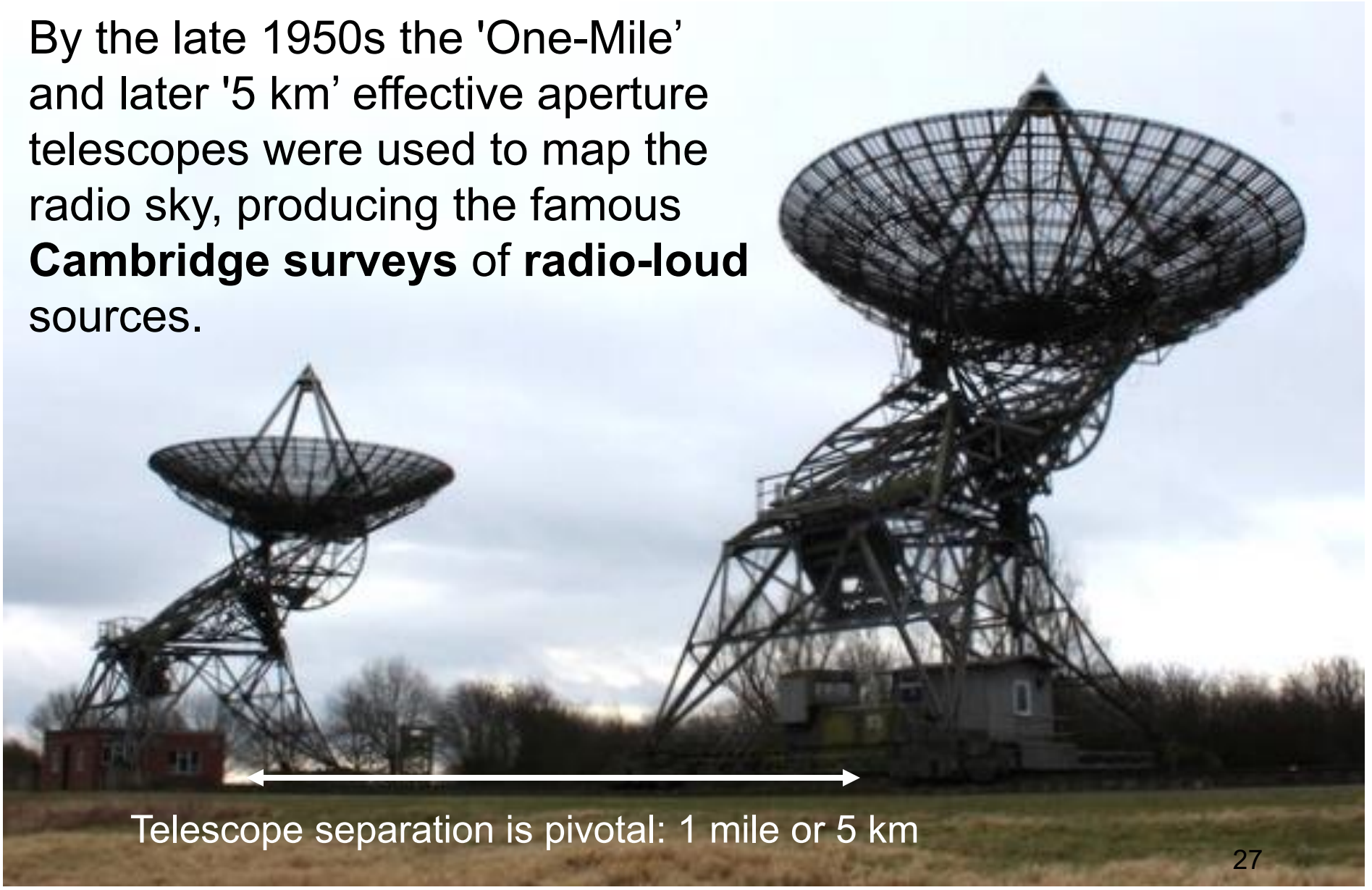
Mullard EL34 Power Pentode

- Mullard produced 40% of vacuum tubes used by Britain during WW II.
- 1955 - Mullard Company donated £100,000 for an additional radio telescope and associated facilities.
- **Mullard Observatory** opened on July 27, 1957.

(https://en.wikipedia.org/wiki/Mullard_Radio_Astronomy_Observatory)

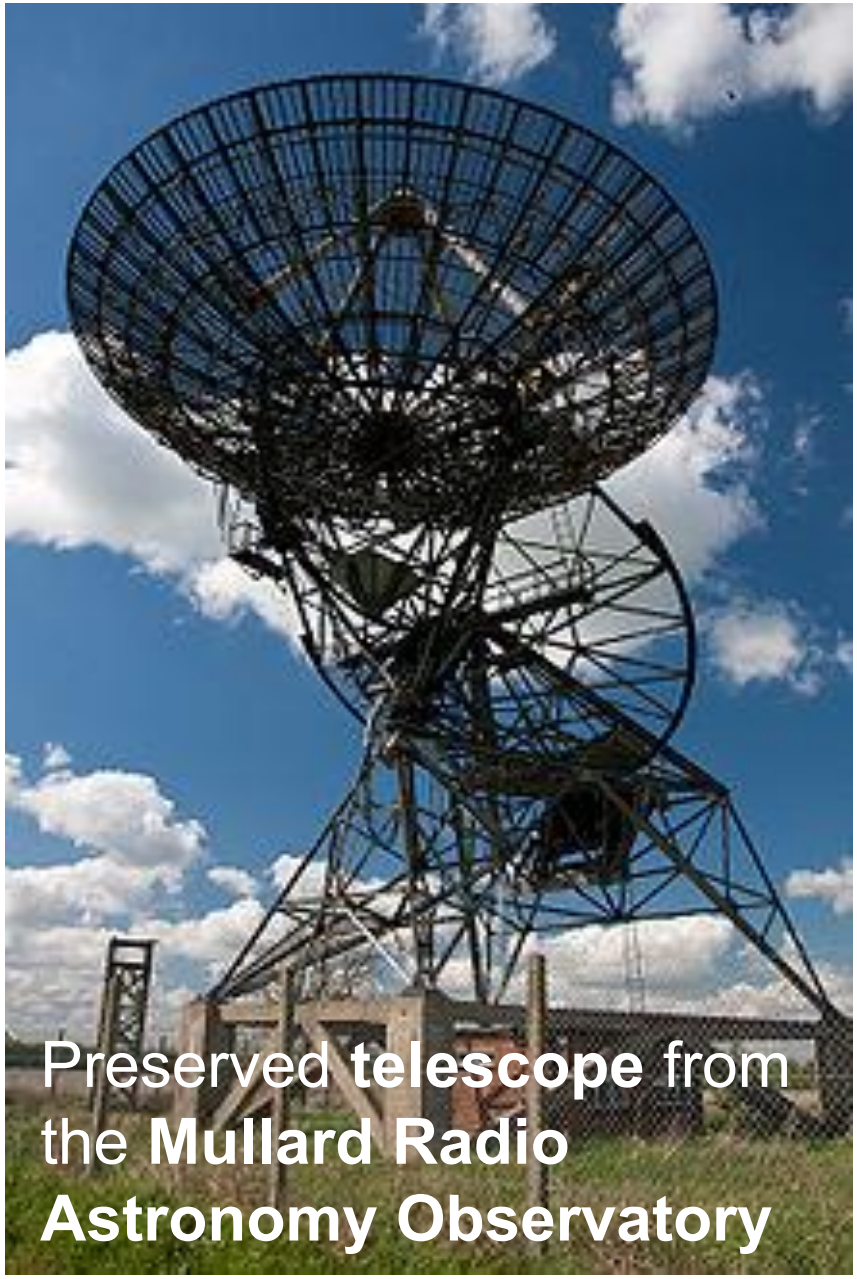
Cambridge 2C and 3C radio surveys

By the late 1950s the 'One-Mile' and later '5 km' effective aperture telescopes were used to map the radio sky, producing the famous **Cambridge surveys** of **radio-loud** sources.



(https://physicsworld.com/a/martin-ryle-an-energy-visionary/)

What were those “radio-loud” sources?



Preserved **telescope** from the **Mullard Radio Astronomy Observatory**

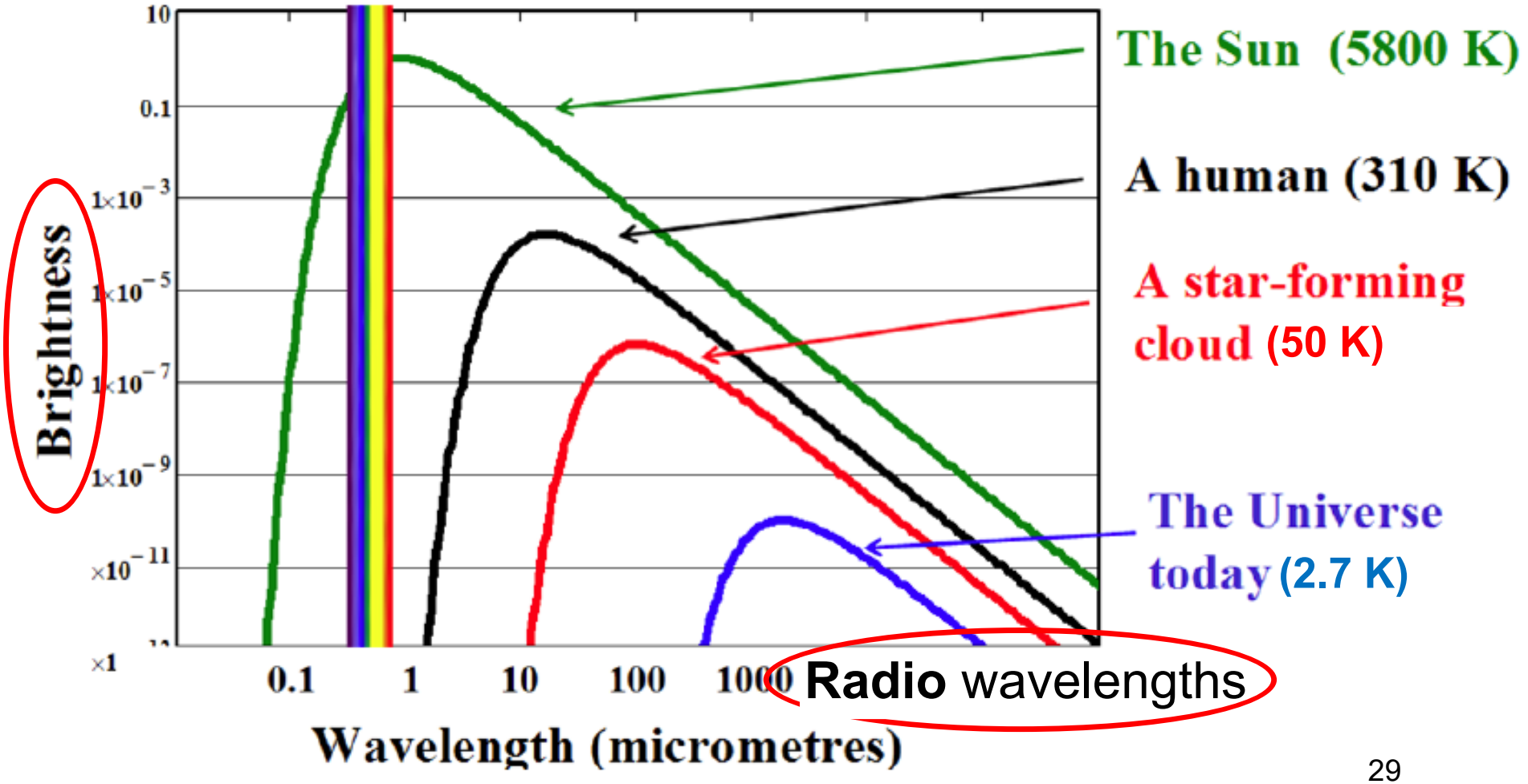
Radio-loud sources – are those with high luminosity at **radio wavelengths**.

Stars – which are bright at much shorter wavelengths, are **radio-quiet**.

(https://en.wikipedia.org/wiki/Mullard_Radio_Astronomy_Observatory)

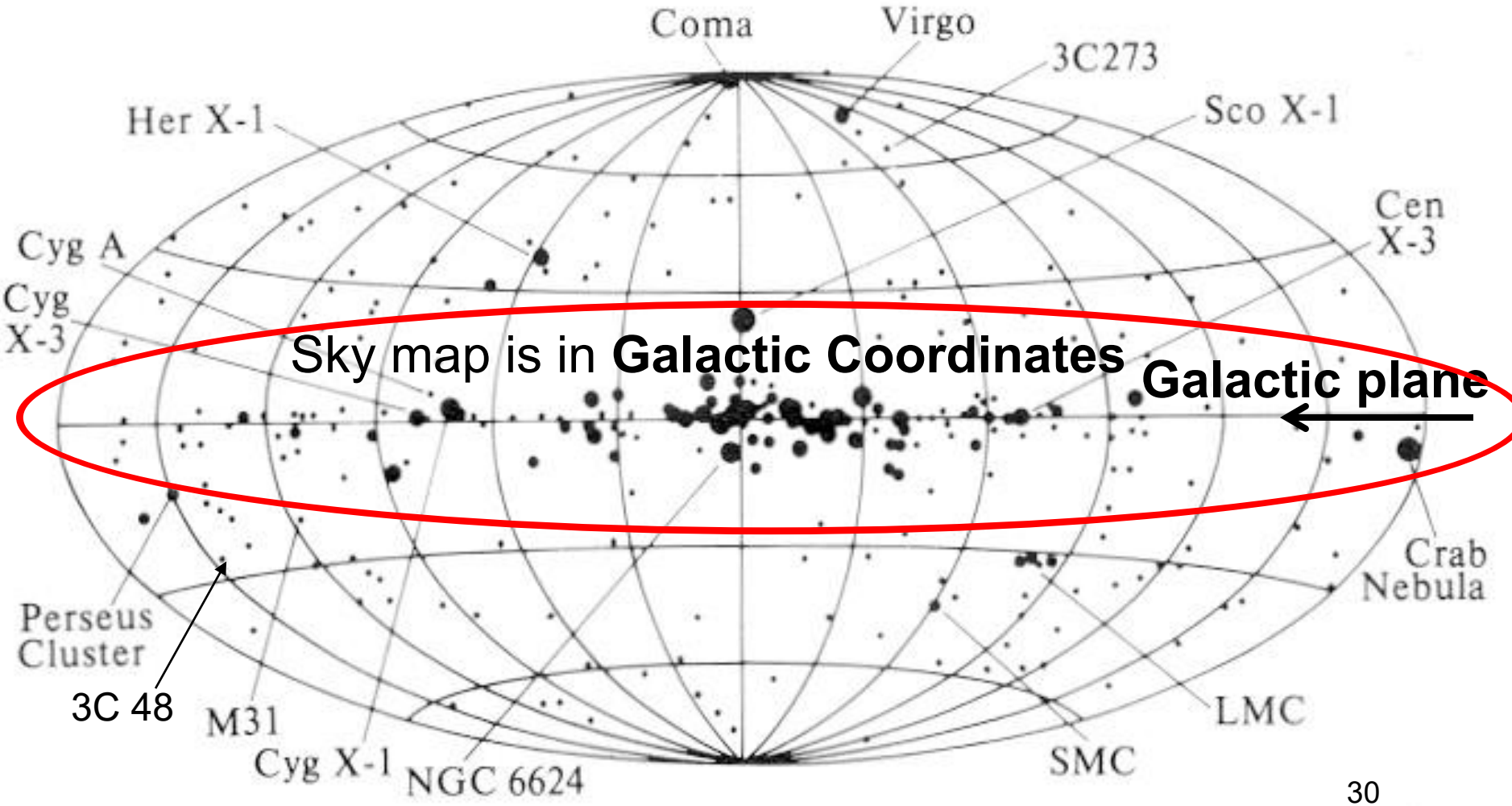
Conventional sources are not radio-loud

Normal sources of electro-magnetic radiation have almost no emission (brightness) at **radio wavelengths**! So **radio-loud** is totally **unexpected**.



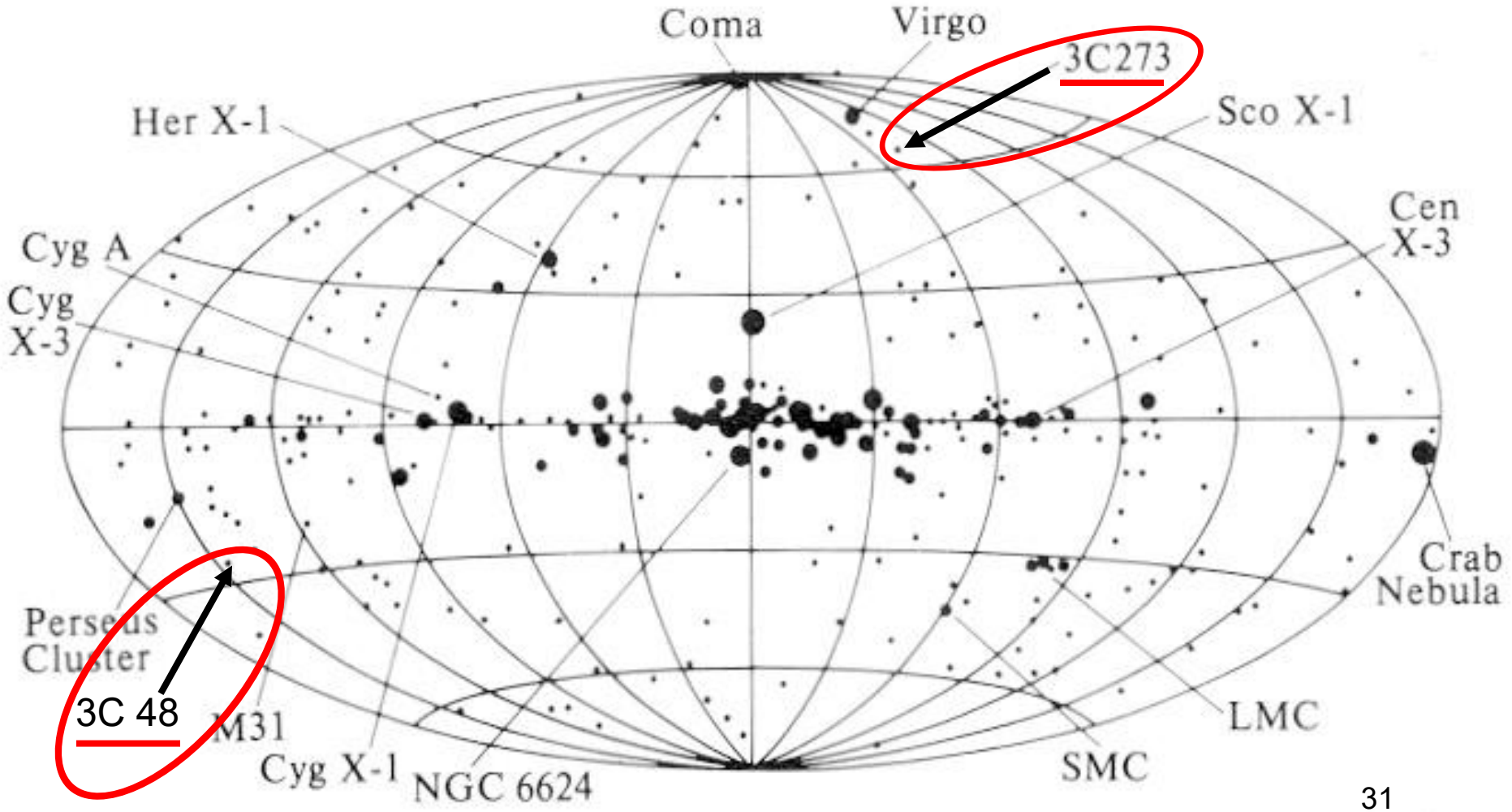
Many of the radio sources were likely within the Milky Way

The Cambridge **2C** and **3C** surveys of **radio-loud sources** resulted in a map, the **black dots**, on the sky like this:



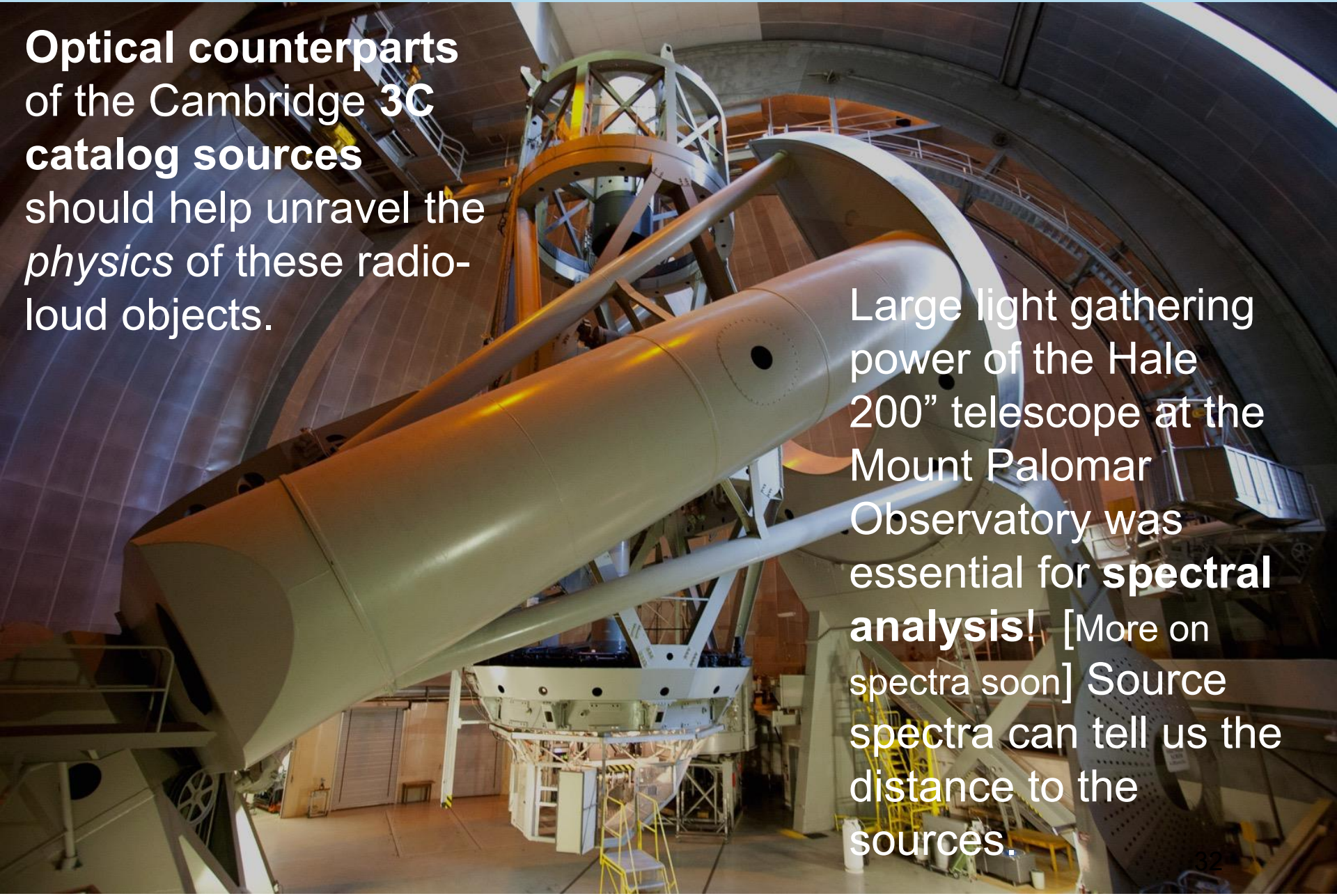
(http://inspirehep.net/record/1244094/plots)

Particularly unexpected were the likely extra-galactic sources



(http://inspirehep.net/record/1244094/plots)

The hunt was on for optical counterparts



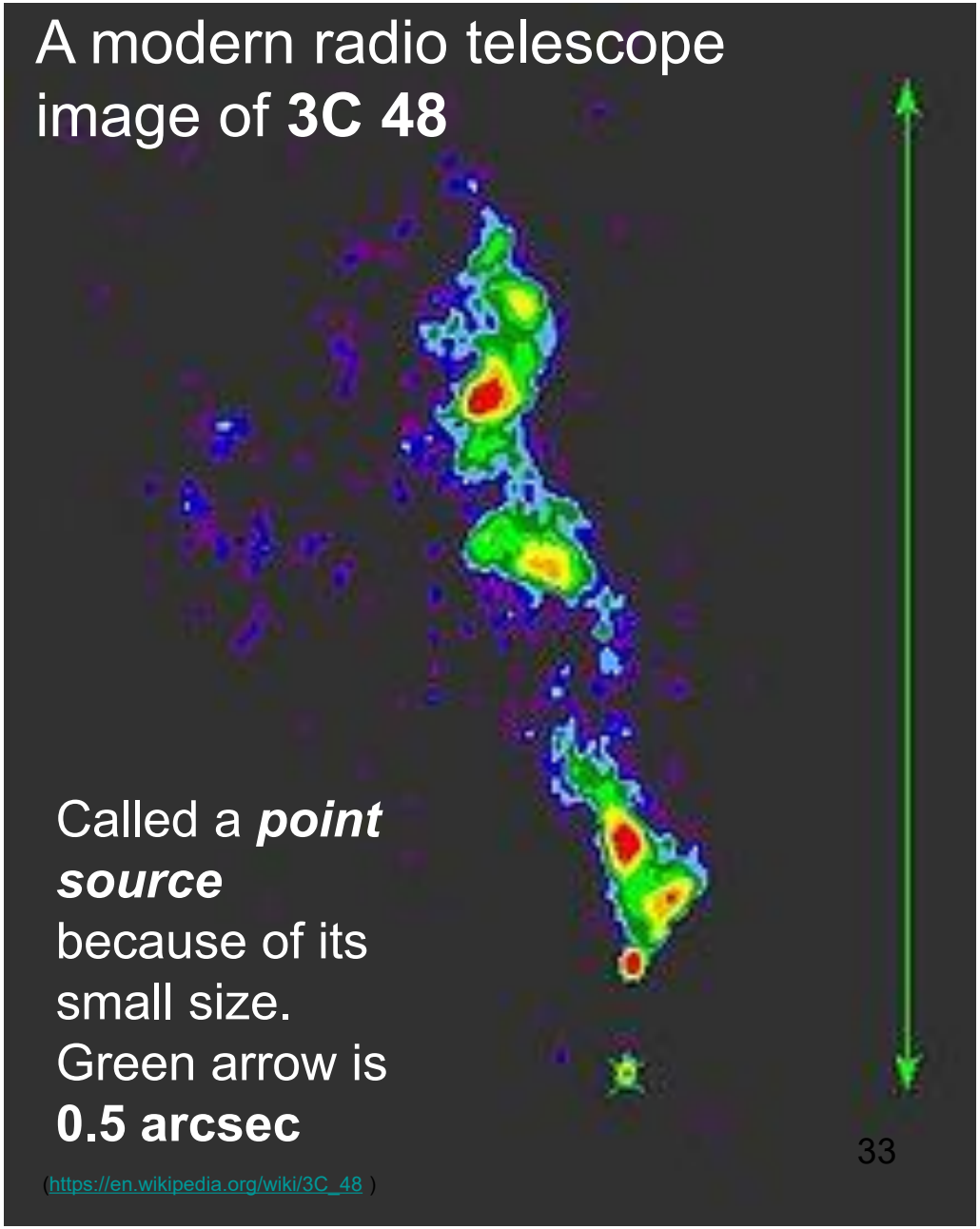
Optical counterparts of the Cambridge **3C catalog sources** should help unravel the *physics* of these radio-loud objects.

Large light gathering power of the Hale 200” telescope at the Mount Palomar Observatory was essential for **spectral analysis!** [More on spectra soon] Source spectra can tell us the distance to the sources.

(http://www.astro.caltech.edu/palomar/about/telescopes/hale.html)

1st breakthrough was from improved radio source location

1960 - a star-like object was associated with the radio source 3C 48 by Thomas **Matthews** and analyzed by Allan **Sandage**.

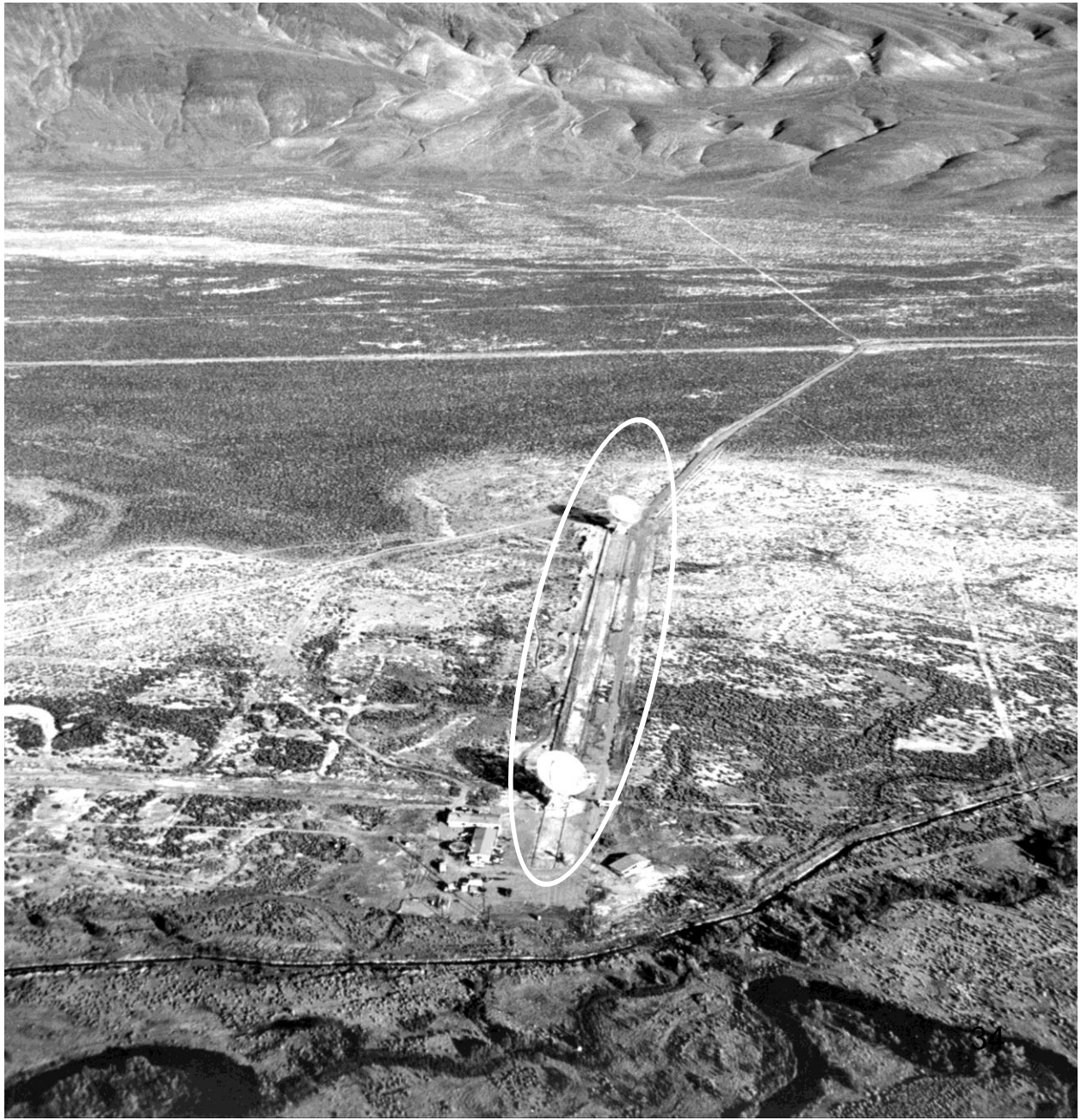


The position uncertainty of 3C 48 needed to be reduced

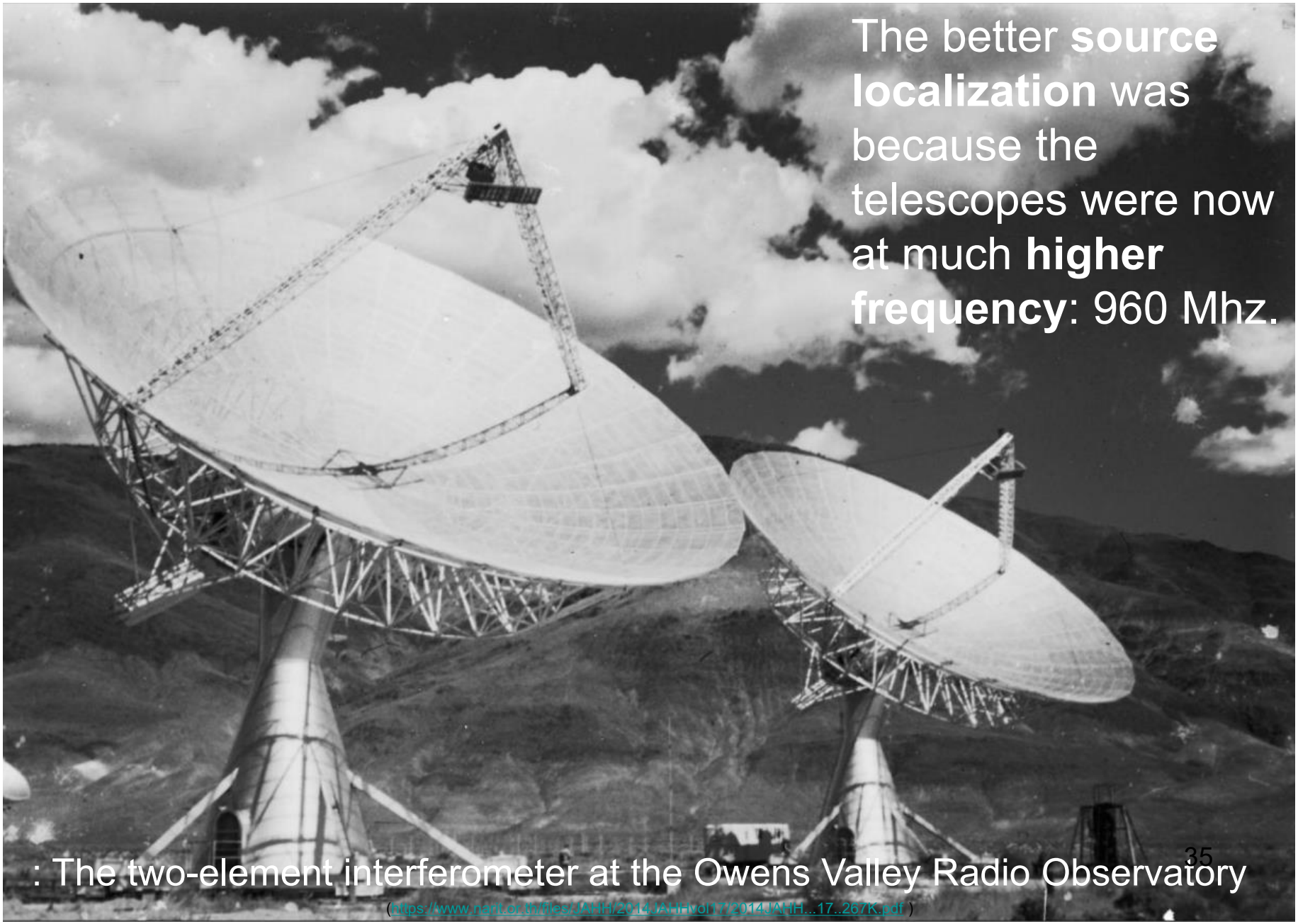
To link the **3C 48** radio source with an optical object required improved **radio-position** information.

This was **Matthews'** roll using the Owen's Valley Radio Observatory interferometer.

(http://kiss.caltech.edu/Tolman-Bacher/big_science.html)



Improved source localization was the game changer



The better **source localization** was because the telescopes were now at much **higher frequency**: 960 Mhz.

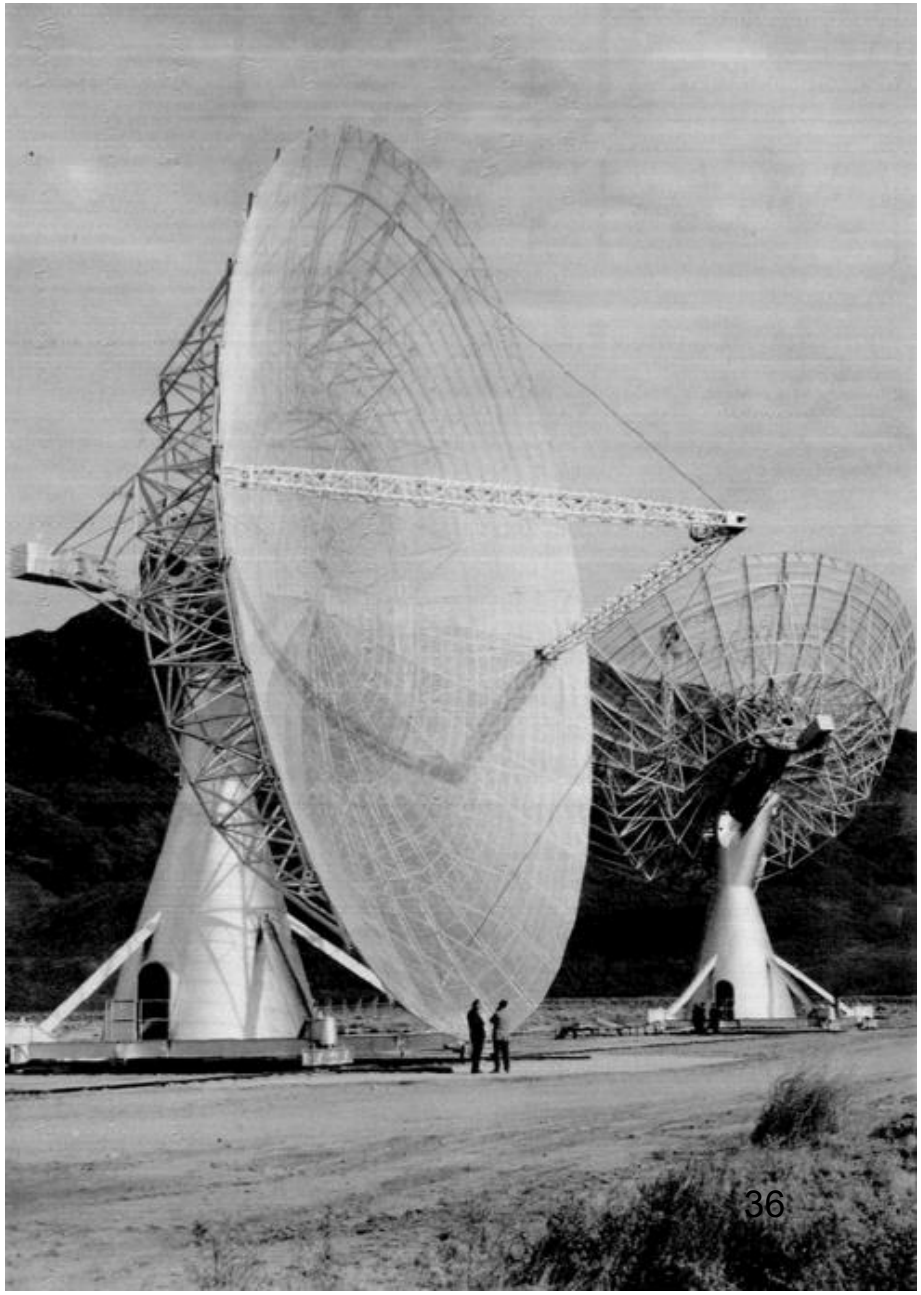
: The two-element interferometer at the Owens Valley Radio Observatory

(https://www.nrao.edu/archives/files/JAHH/2014/JAHHvol17/2014JAHH...17..267K.pdf)

High frequency means shorter wavelengths critical for pointing

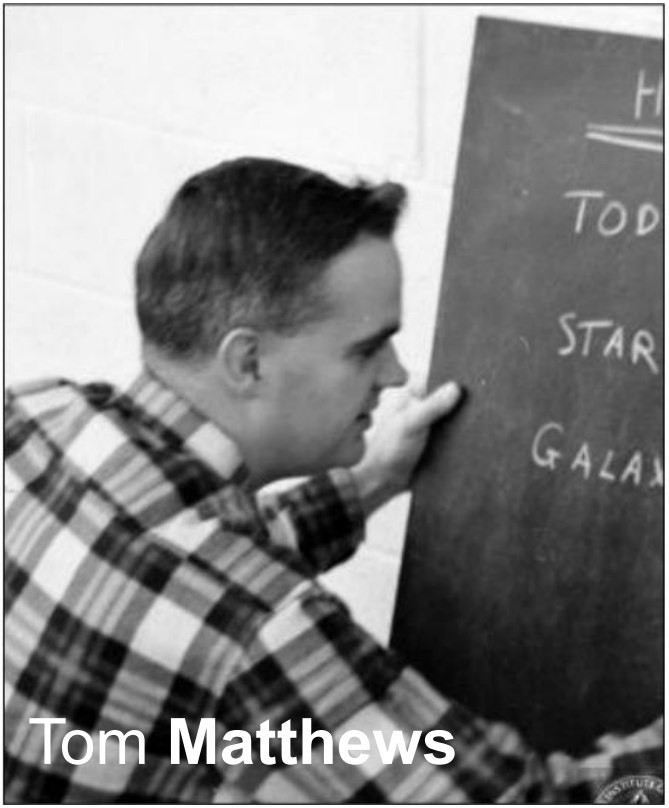
Owen's Valley Radio Observatory radio source positions were accurate up to 10-seconds of arc (**Jesse Greenstein** 1961)

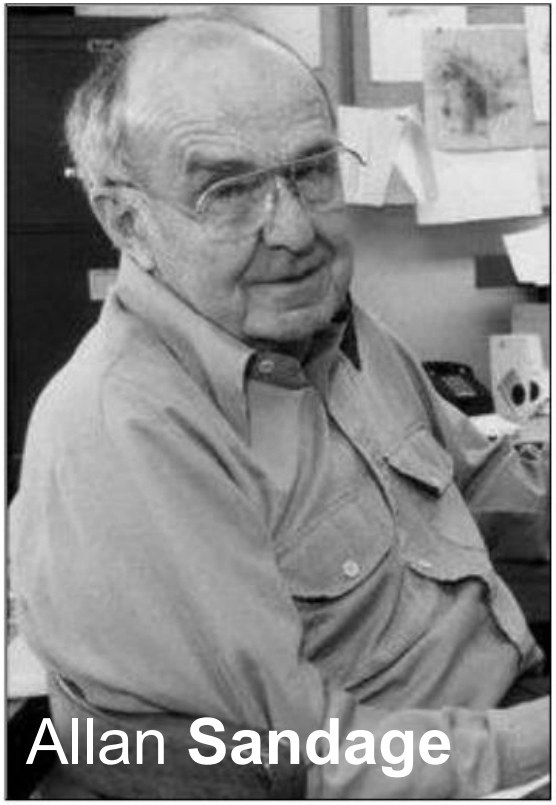
Jesse Greenstein, here in 1957 with a more famous Porter drawing, was one of the prime movers behind the establishment of radio astronomy at Caltech.

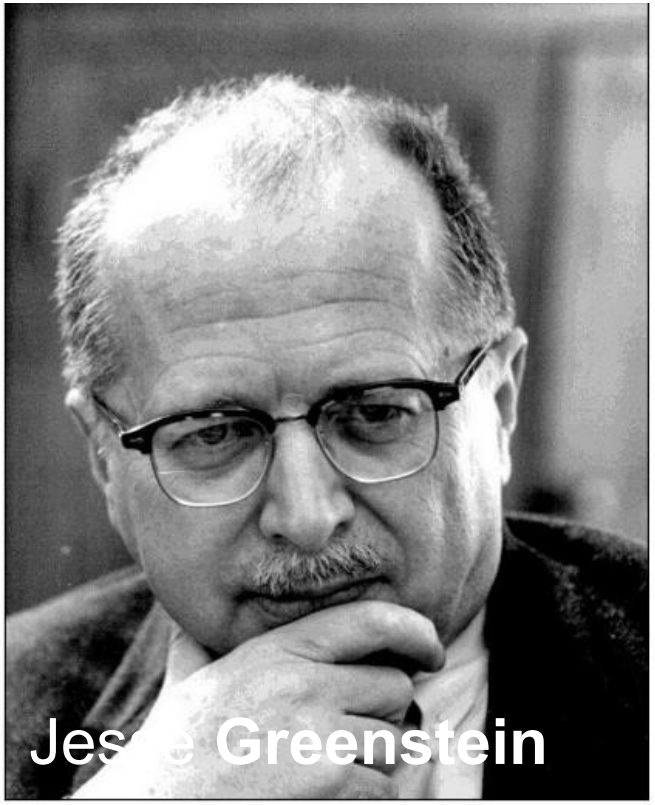


(http://calteches.library.caltech.edu/626/2/Cohen.pdf)

Matthews identified 3C 48 with what appeared to be a 16th magnitude star.







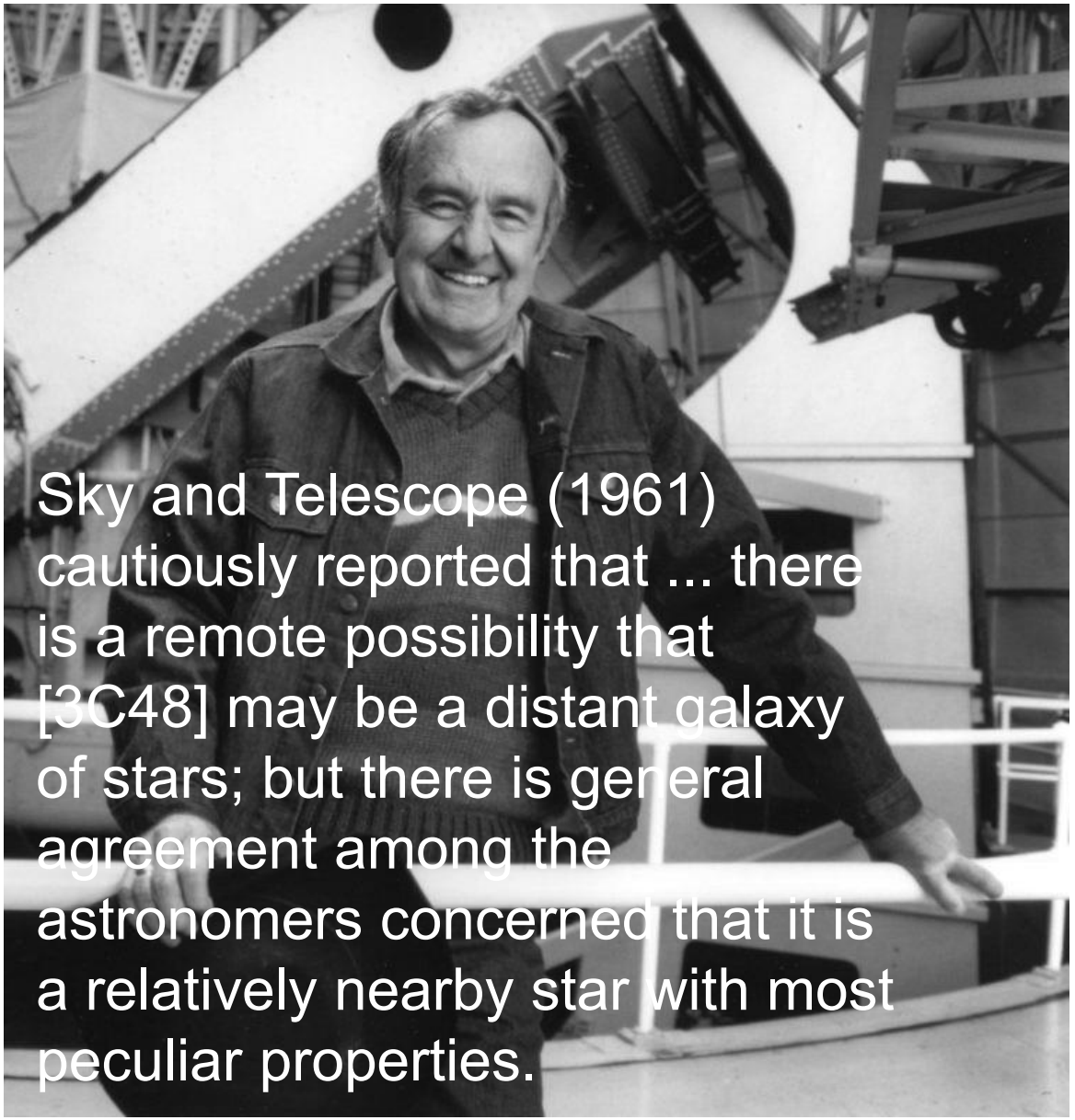
Fortunately a few years earlier, Jesse **Greenstein** had revolutionized the measurement of radio source positions with the **Owen's Valley Radio Observatory**.

(https://www.narit.or.th/files/JAHH/2014JAHHvol17/2014JAHH...17..267K.pdf)

Frustratingly having a spectrum of the source didn't help

Sandage's roll was to obtain a spectrum with the state-of-the-art 200" Hale telescope.

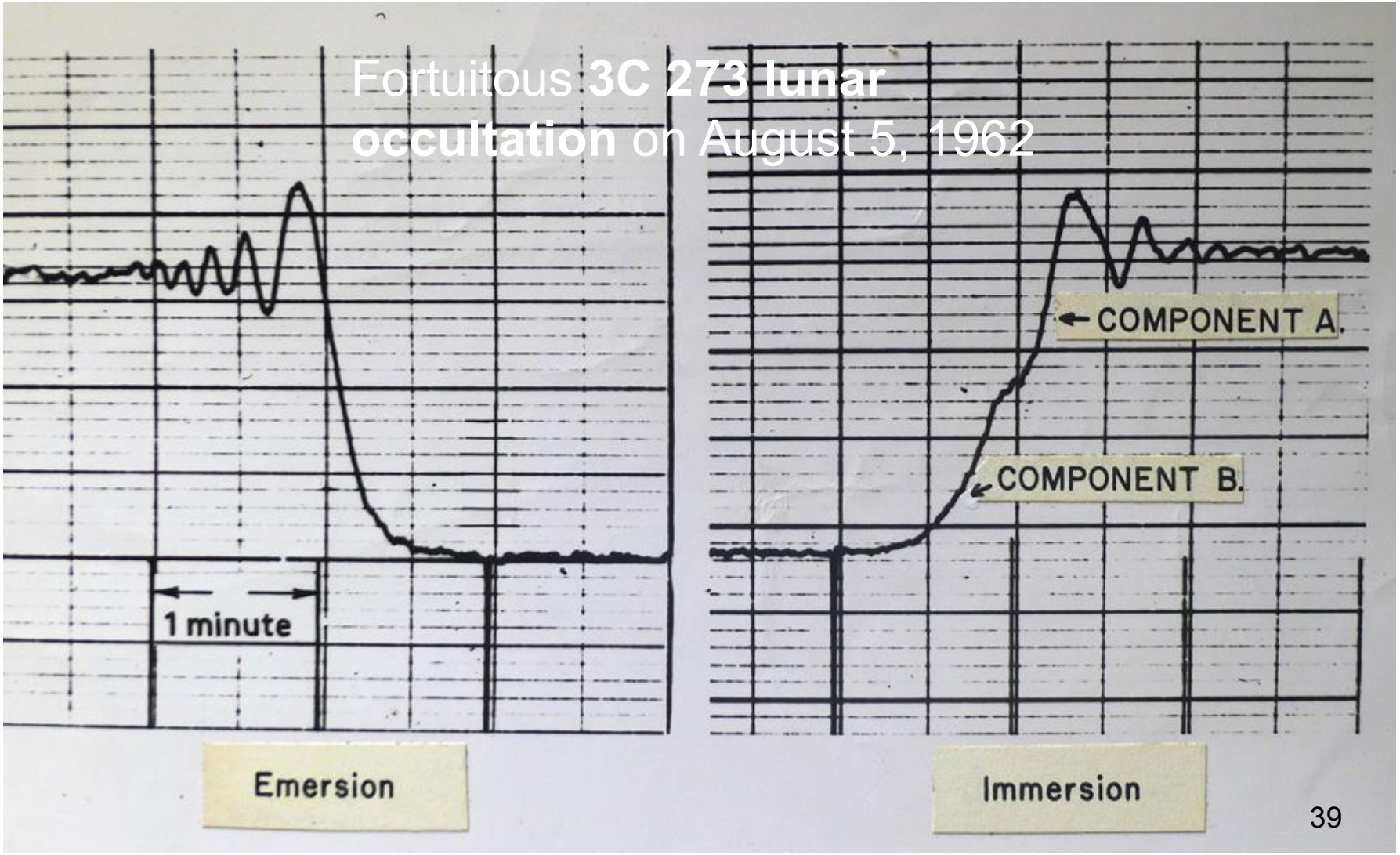
However the **spectrum** of the faint blue star contained many **unknown broad emission lines.**



(http://www.phys-astro.sonoma.edu/brucemedalists/sandage/)

2nd breakthrough was from a serendipitous source occultation

In 1962/3 the location of another radio source, **3C 273**, was pinpointed using the Parkes Radio Telescope.



(https://www.parkes.atnf.csiro.au/people/sar049/3C273/images/3C273_5August1962_Plots_med.png)

The Moon's motion determined the position of 3C 273

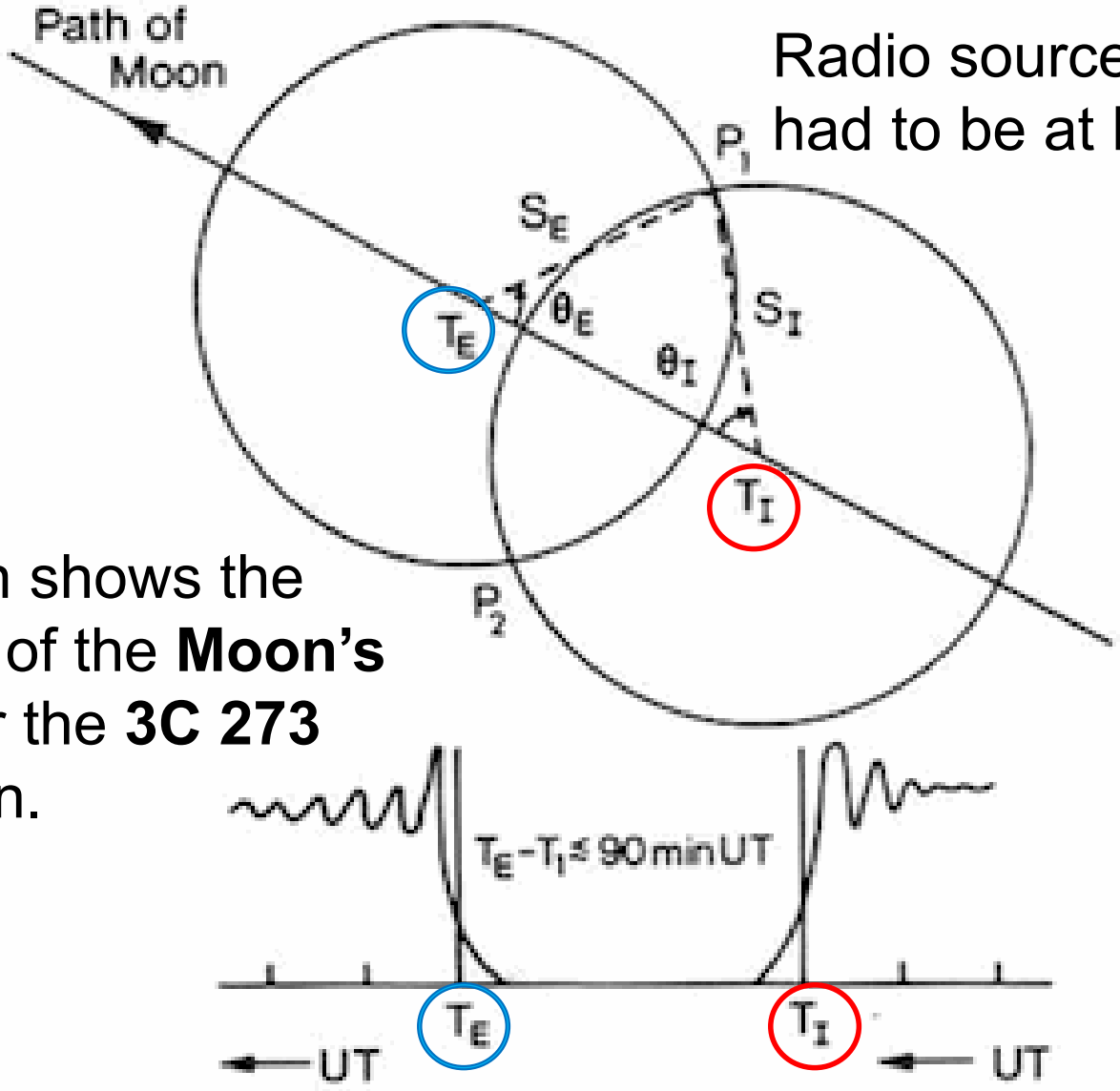


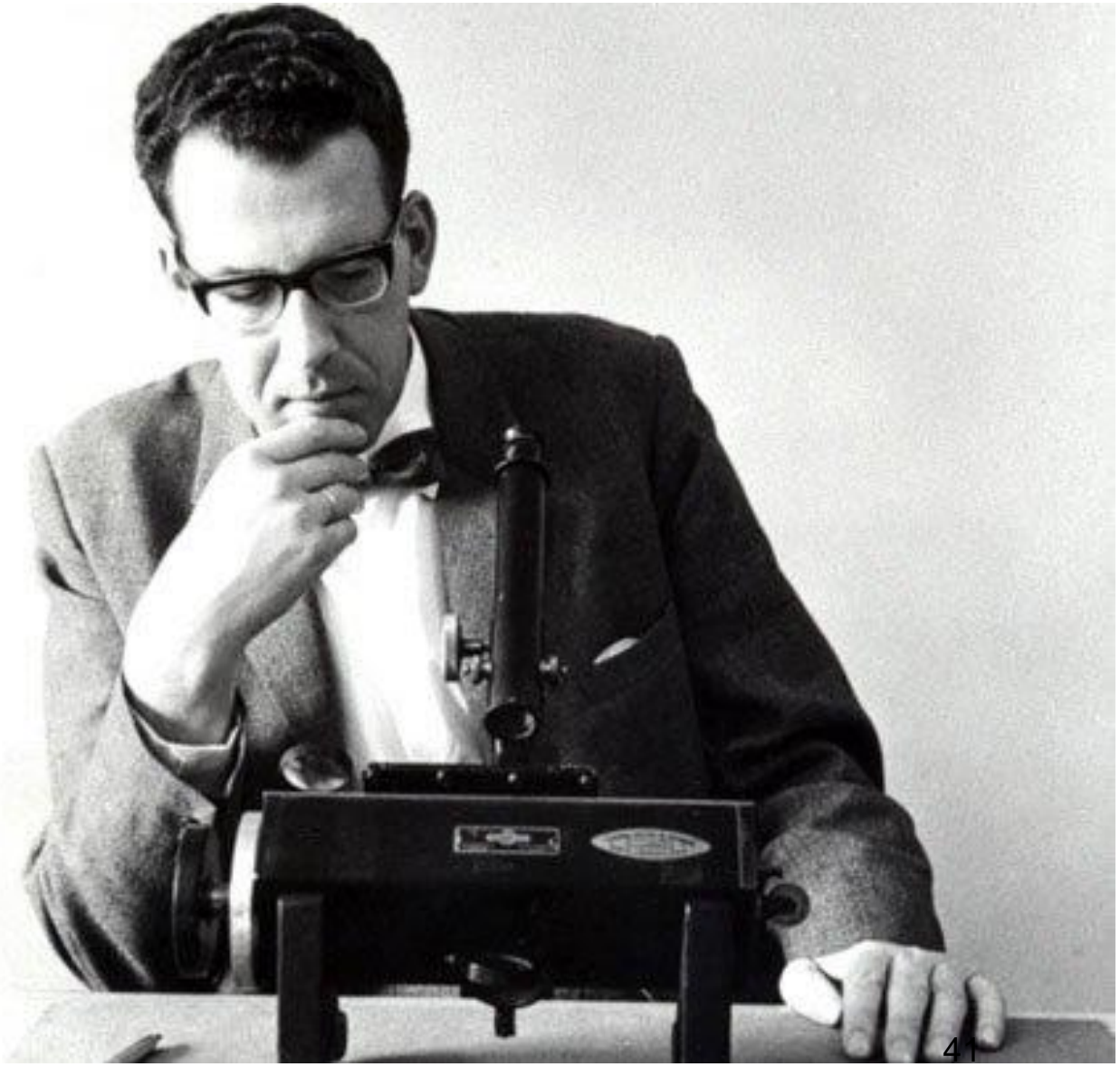
Illustration shows the geometry of the **Moon's** motion for the **3C 273** occultation.

(https://www.parkes.atnf.csiro.au/people/sar049/3C273/images/3C273_5August1962_Plots_med.png)

Sometimes being second is an advantage

3C 273 was then associated with its optical counterpart, and **Maarten Schmidt** obtained an optical spectrum also using the 200” Hale Telescope.

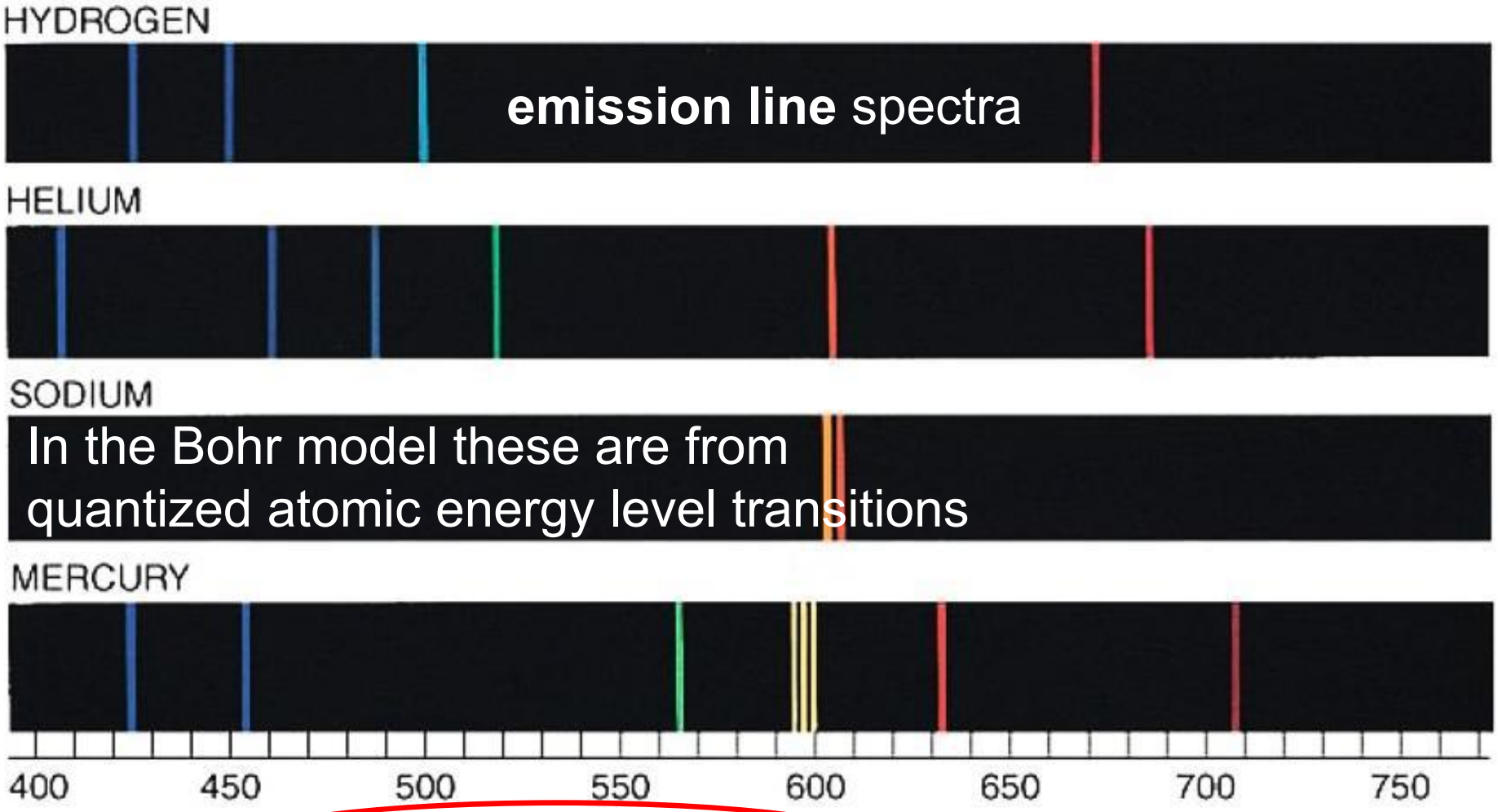
This spectrum revealed the same ***strange emission lines*** as **3C 48**.



(https://www.caltech.edu/about/news/fifty-years-quasars-38937)

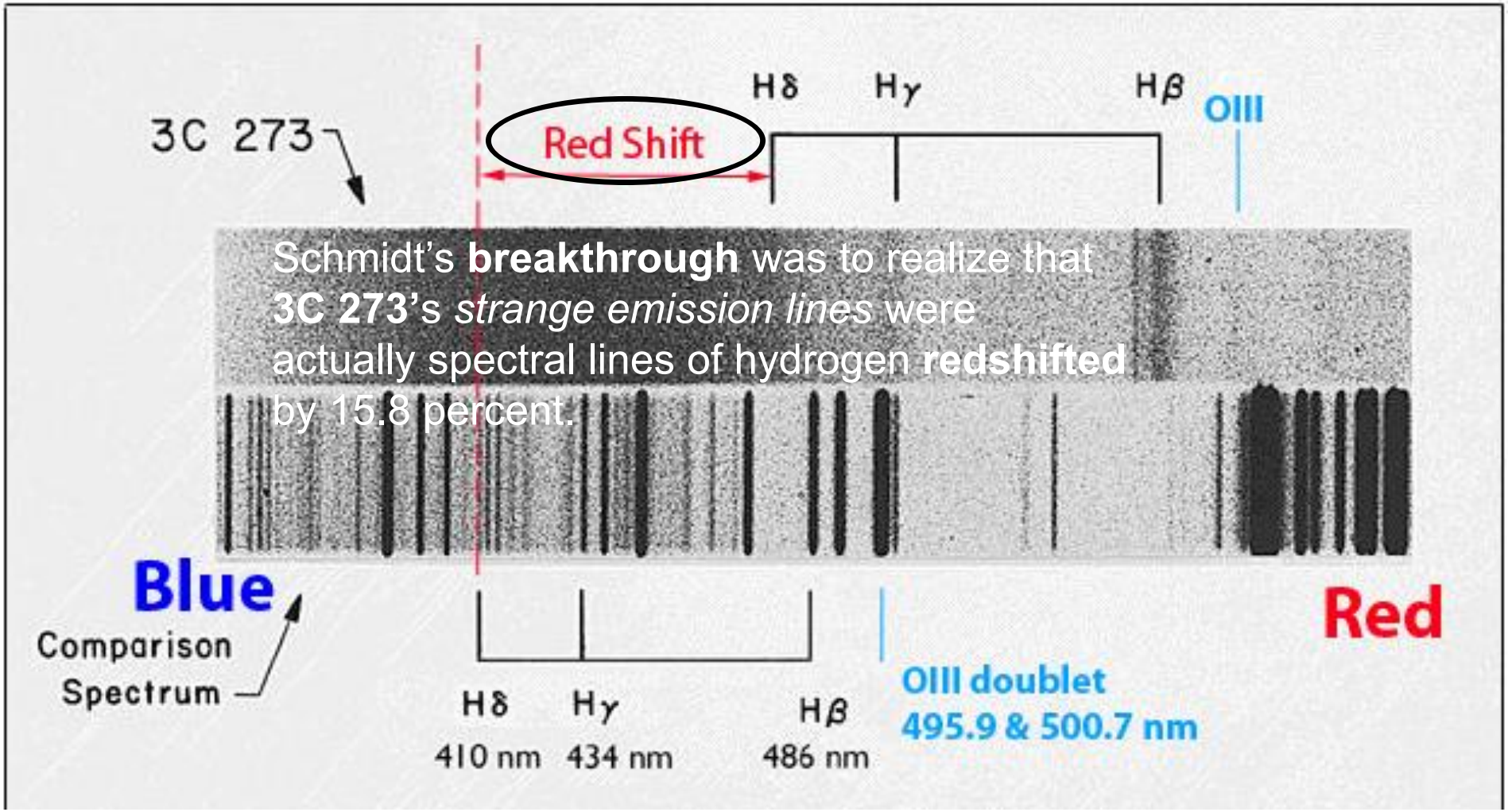
Spectra are like *fingerprints* uniquely identifying each atom

Atoms (molecules) emit/absorb light only at certain **wavelengths** which are **distinctive** to each **atom**.



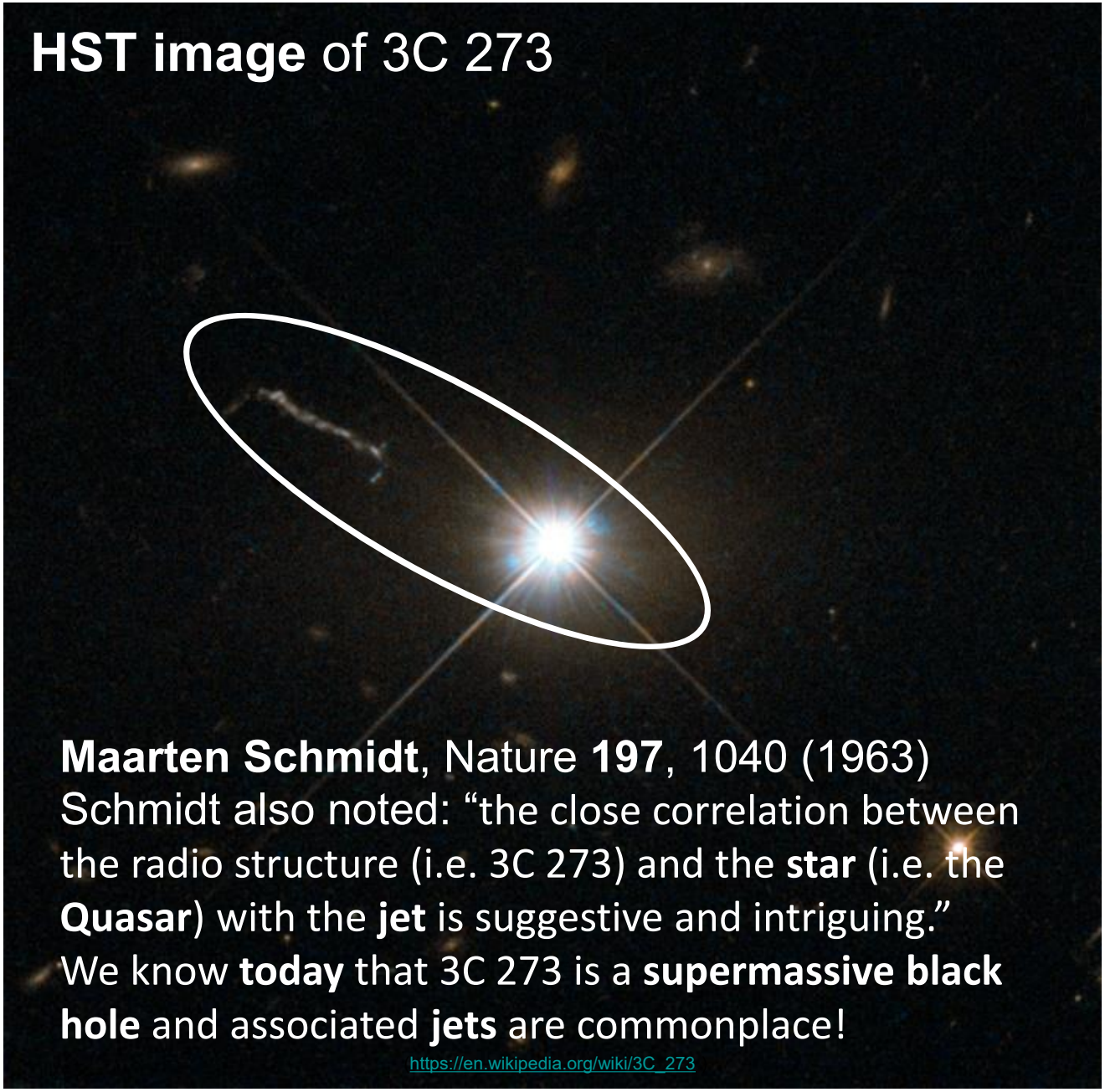
((http://faculty.virginia.edu/skrutskie/ASTR1210/notes/lines/lines.html)

3C 273 *strange spectrum* was just an unexpected redshift

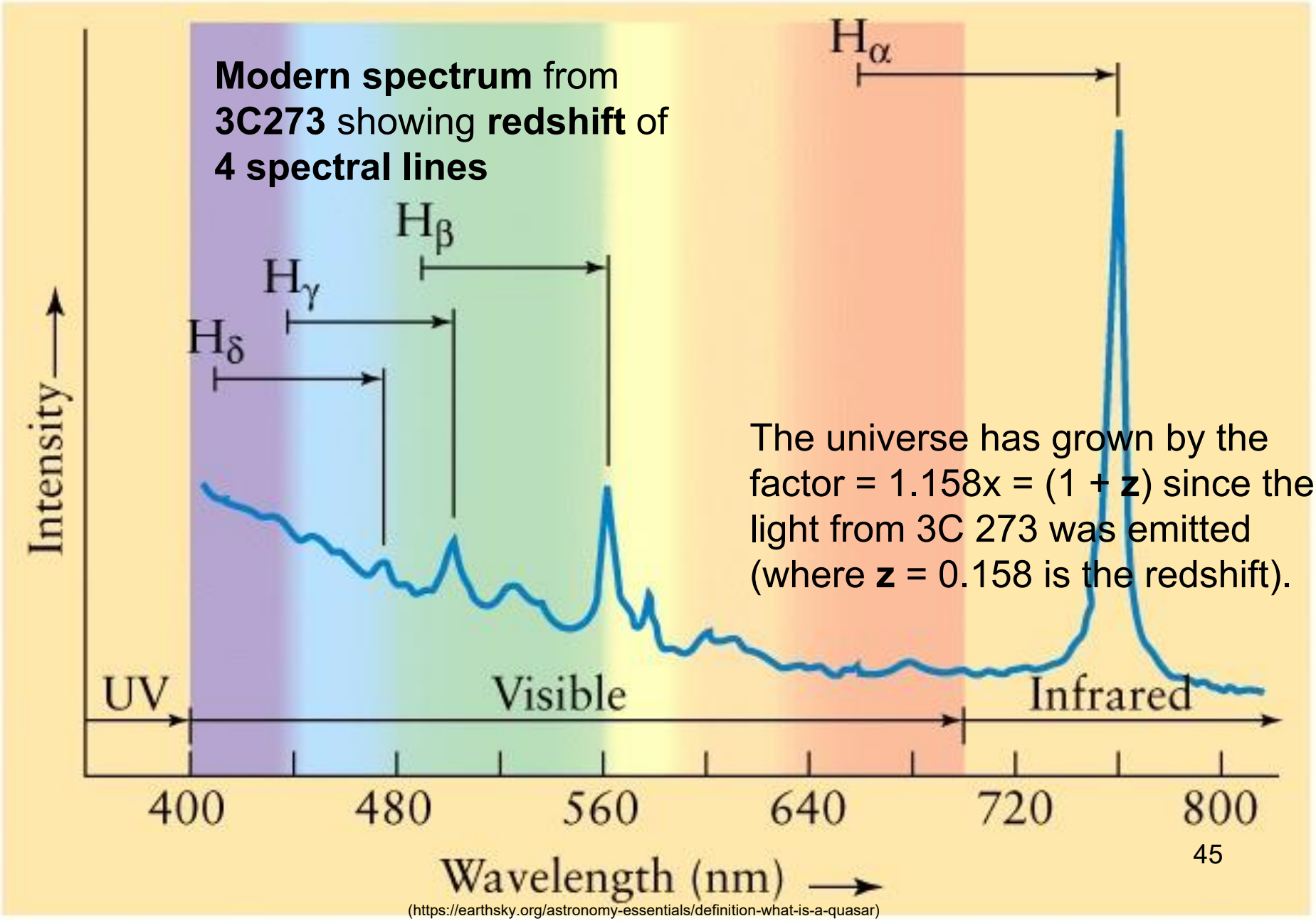


(https://www.parkes.atnf.csiro.au/people/sar049/3C273/)

Nature article titled "3*C* 273: A Star-Like Object with Large Red-Shift"



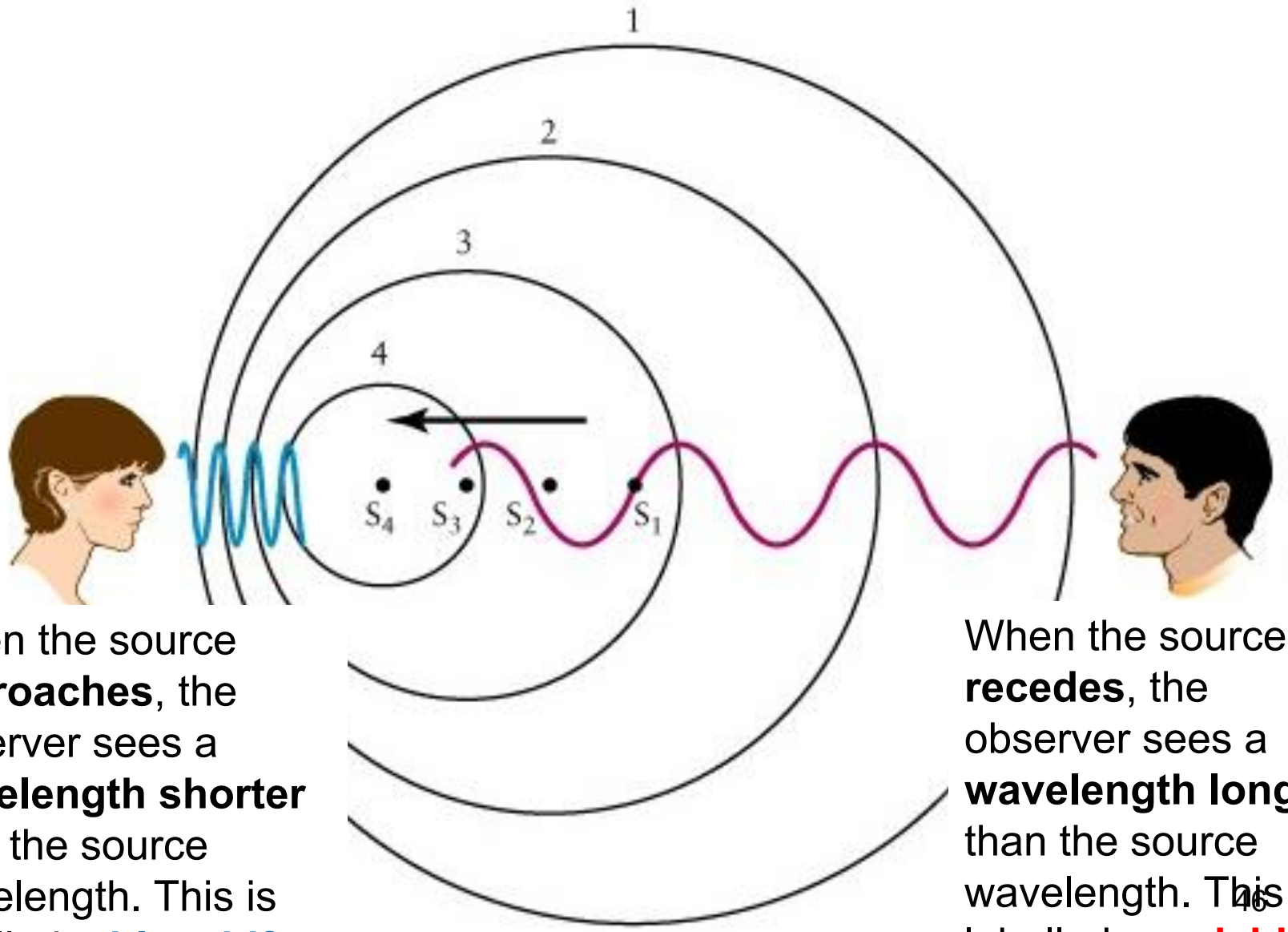
Unexpected redshift was from the expansion of the universe!



(https://earthsky.org/astronomy-essentials/definition-what-is-a-quasar)

For waves, source motion changes what you observe

You may know this as a **Doppler shift**



When the source **approaches**, the observer sees a **wavelength shorter** than the source wavelength. This is labelled a **blueshift.**

When the source **recedes**, the observer sees a **wavelength longer** than the source wavelength. This is labelled a **redshift**

(https://wisp.physics.wisc.edu/astro104/lecture6/lec6l.html)

Term “redshift” is based on observed VS source wavelength

The terms **blueshift**/**redshift** are used instead of saying shorter or longer wavelengths than at the source.

Interestingly redshifts dominate, and it is defined as:

redshift = **z** $\equiv (\lambda_{observed} - \lambda_{rest})/\lambda_{rest}$

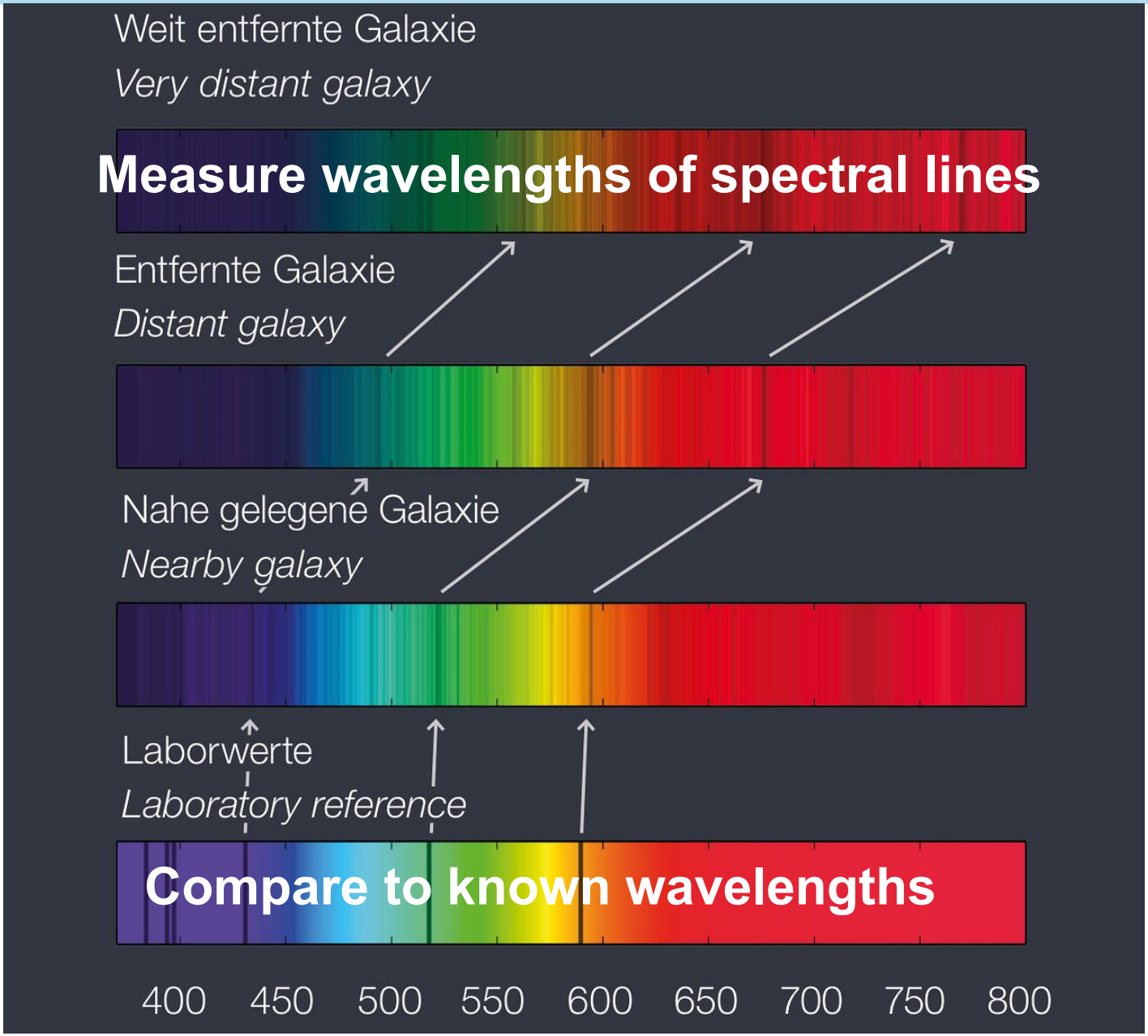
$\lambda_{observed}$ = observed **wavelength** (of light)

λ_{rest} = **wavelength** (of light) at the source

For sources that are **receding** from us with velocity, $v_{recession}$, much less than the speed of light, c:

$$\mathbf{z} = v_{recession}/c$$

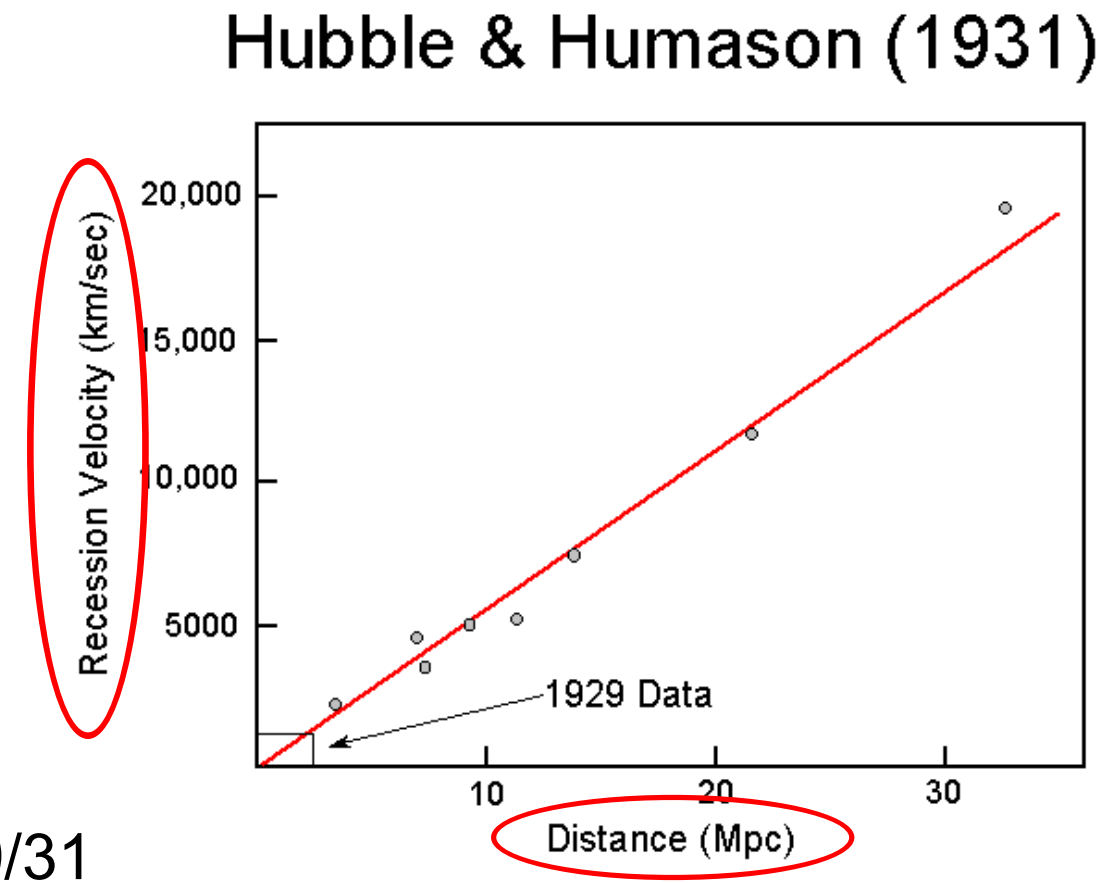
How do astronomers determine redshift?



(https://supernova.eso.org/exhibition/1111/)

Hubble observed that redshift ∝ to source distance

We now measure the distance to the most remote stars/galaxies with **Hubble's Law** (**graph**). Hubble saw that source **Recession Velocity** (speed) is highly correlated with source **Distance**.

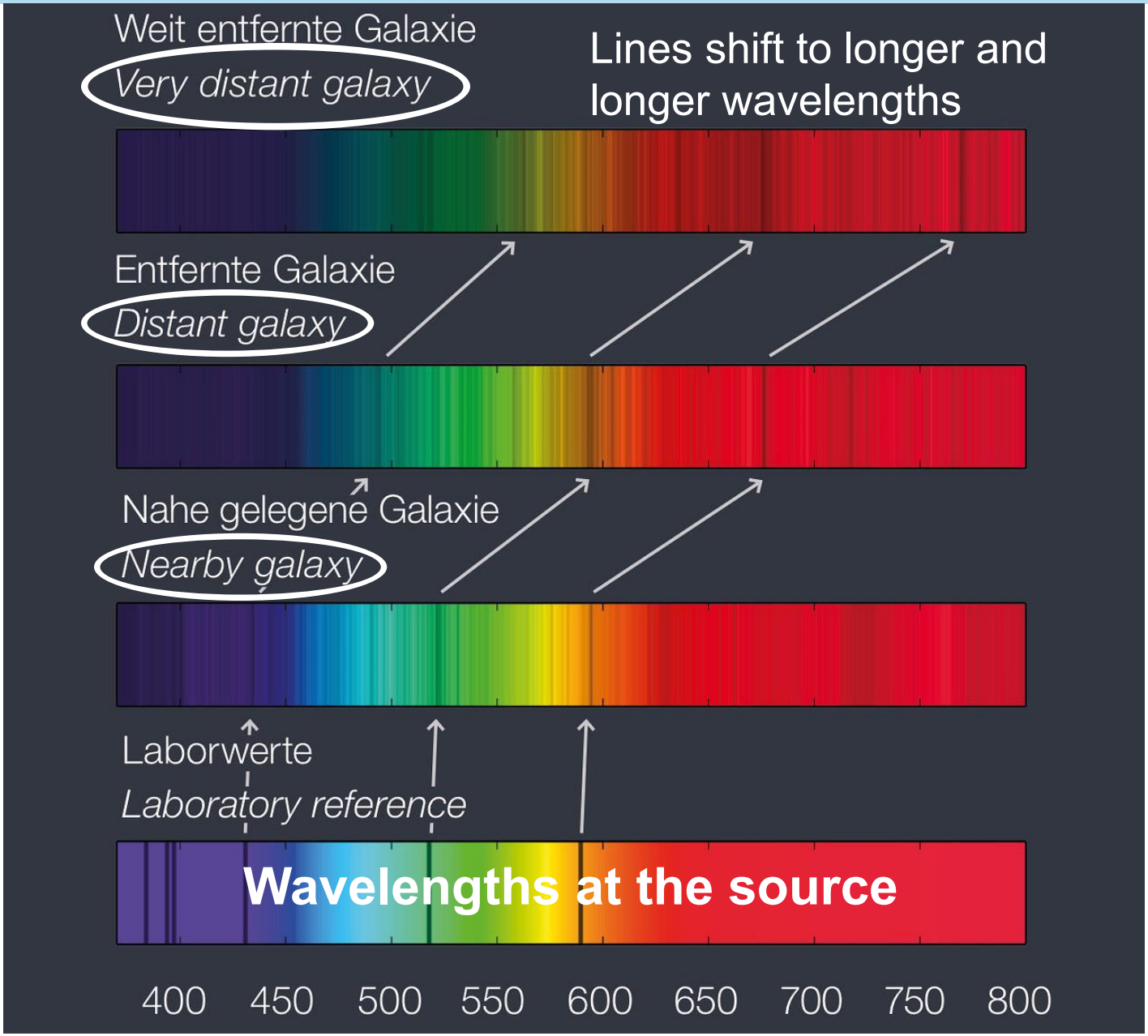


Edwin Hubble, 1929/31

All **distant galaxies** are **speeding away** from us!

(https://en.wikipedia.org/wiki/Edwin_Hubble and http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit5/expand.html)

All spectral lines move to longer and longer wavelengths



(https://supernova.eso.org/exhibition/1111/)

Hubble's Law: likely because the universe is expanding

- This linear relationship is called **Hubble's Law**. The slope of the line is characterized by **Hubble's constant** H_0:

$$\text{recessional velocity} = H_0 \times \text{distance}$$

- The value of Hubble's constant is approximately 70 (km/s)/Mpc. **Hubble's law** relates how **fast** galaxies are moving away from us at **different distances**. A larger value for H_0 implies a faster expansion rate.

- The **simplest explanation** for Hubble's observation was that the **entire universe is expanding.** If so, then at a time in the past it should have started from a single point - an idea known today as the **Big Bang**.

Expanding started from a “Big Bang”, coined by Fred Hoyle

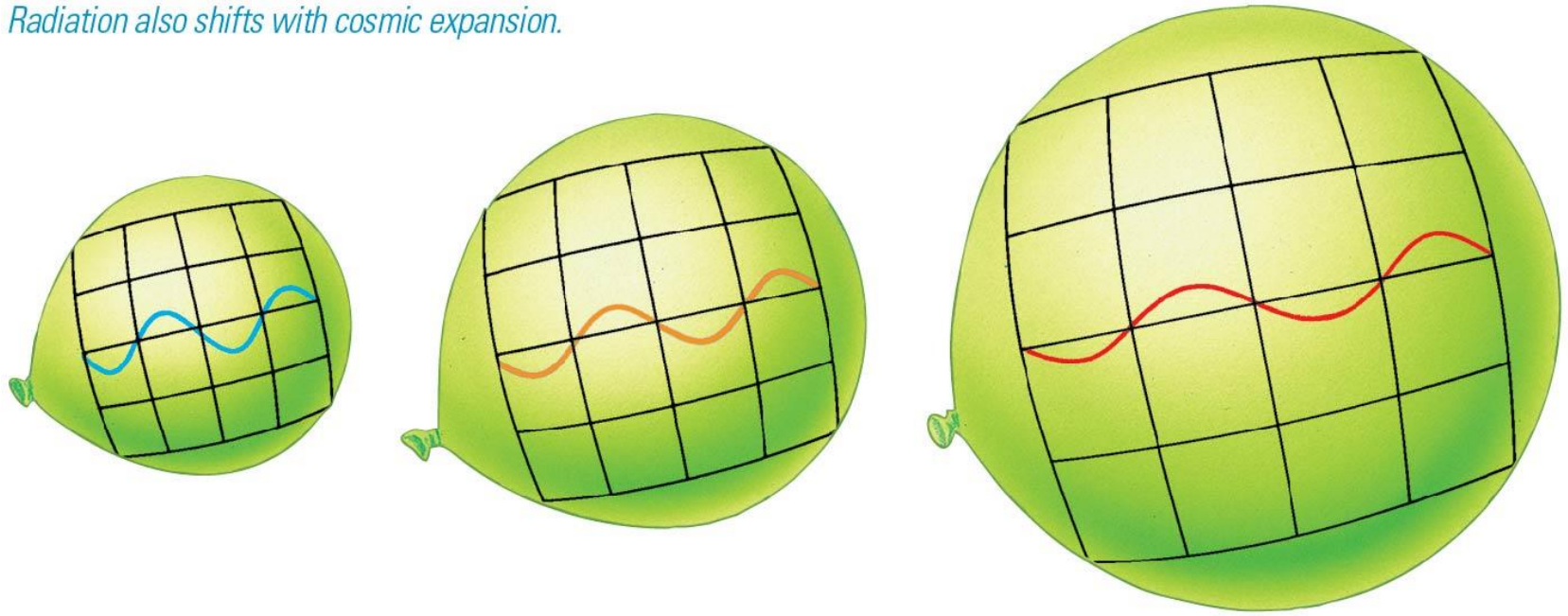
Hoyle used "**Big Bang**" for the first time in his “Nature of the Universe” talks, but **with derision**, to describe a theory on the origin of the universe that he didn't accept.

Fred Hoyle was a regular on BBC radio programs in the 1940s and 1950s, and one of the most influential figures in the field of stellar nucleosynthesis

(https://bigthink.com/starts-with-a-bang/big-bang-meaning/)

Universe expansion is recorded by the light that reaches Earth

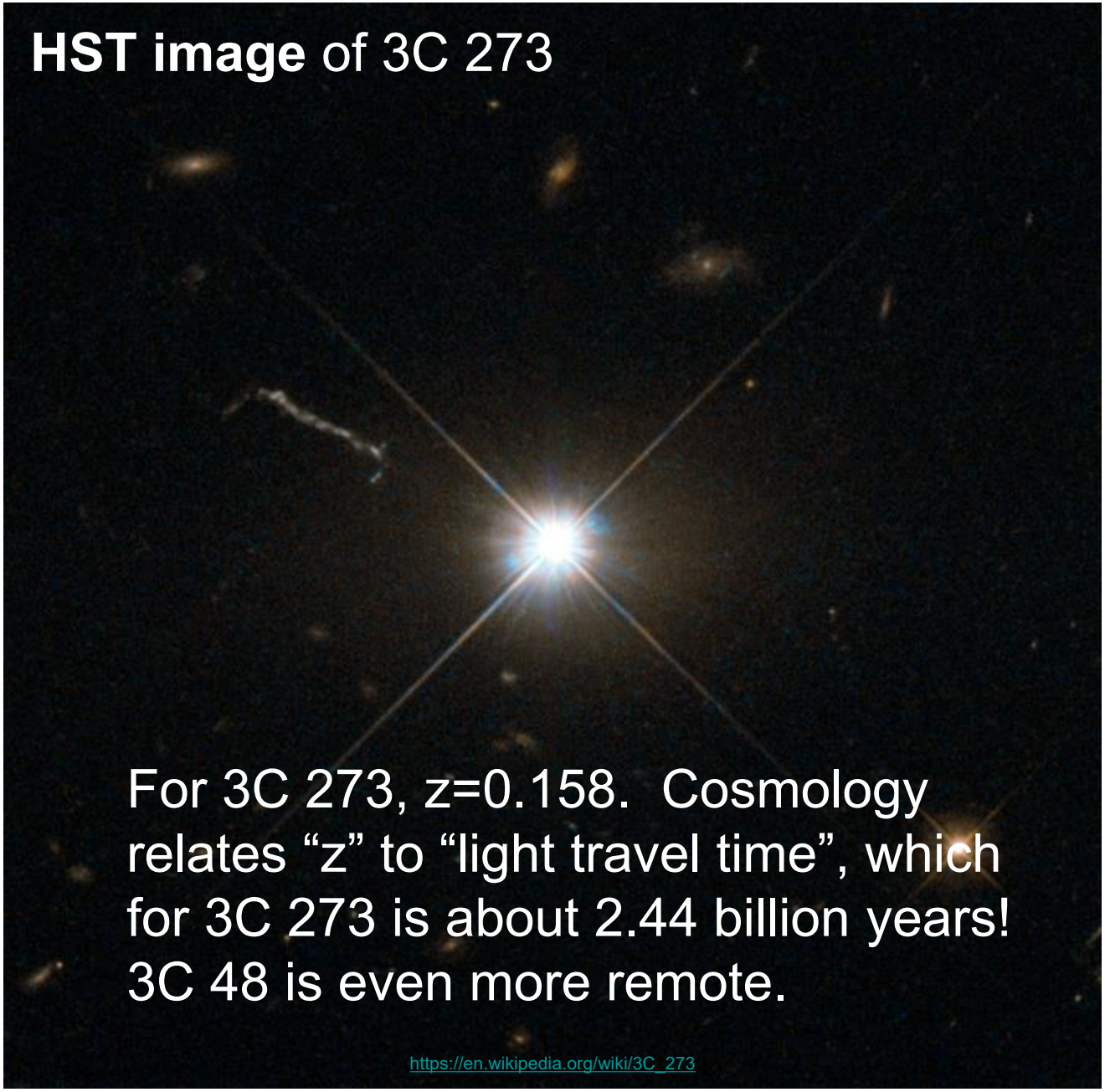
- As the universe expands so do the wavelengths of the light travelling through it!



Cosmologically the factor $\lambda_{observed} / \lambda_{rest} = 1 + z$ is not a Doppler effect but rather the fractional stretching of light wavelengths since leaving their source.

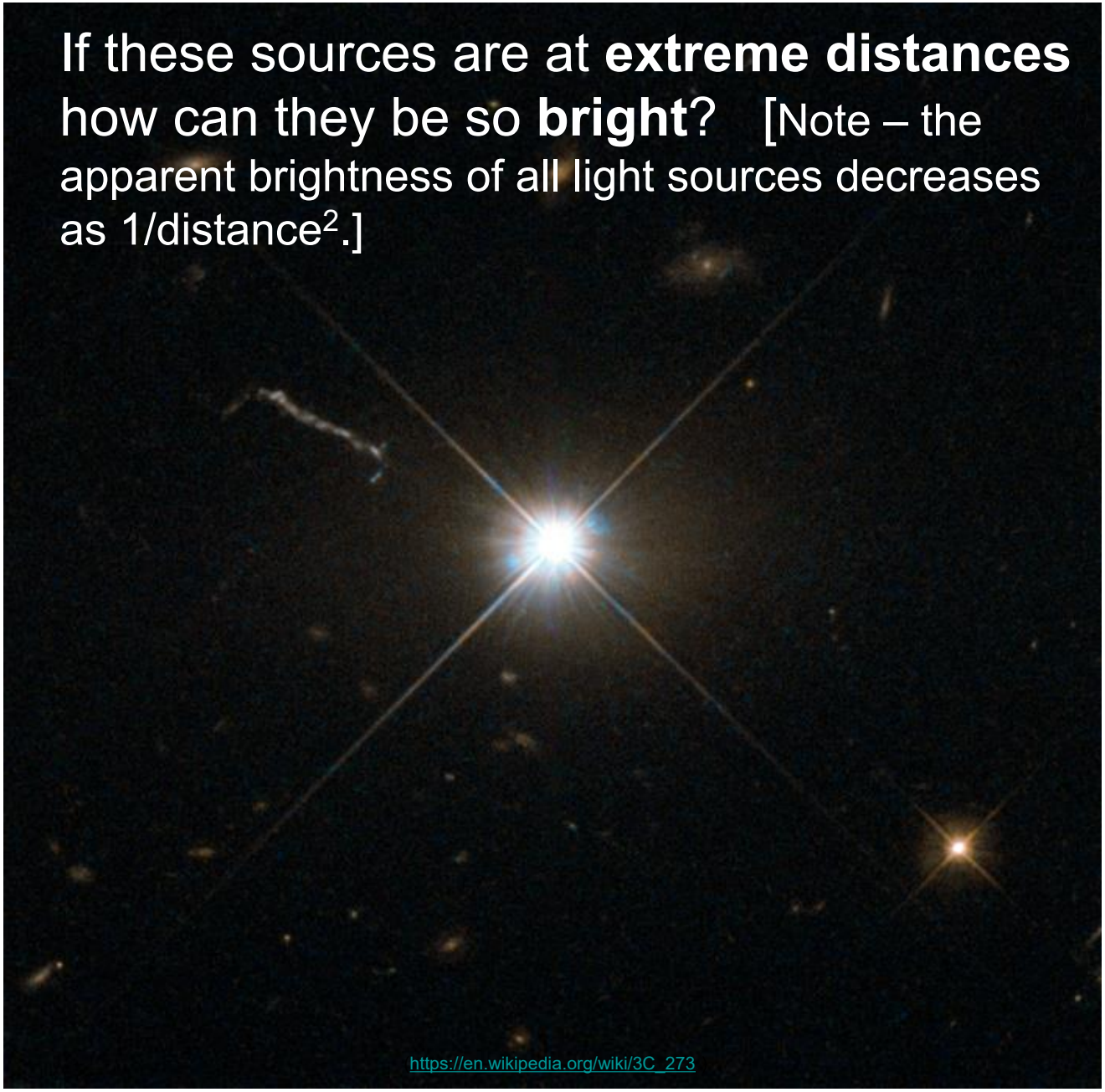
Because the **universe expansion scale factor** is also 1 + z, the universe (and the wavelengths of light) have grown by a factor of 1 + z since this light was emitted!

3C 48 and 3C 273 are at extreme distances



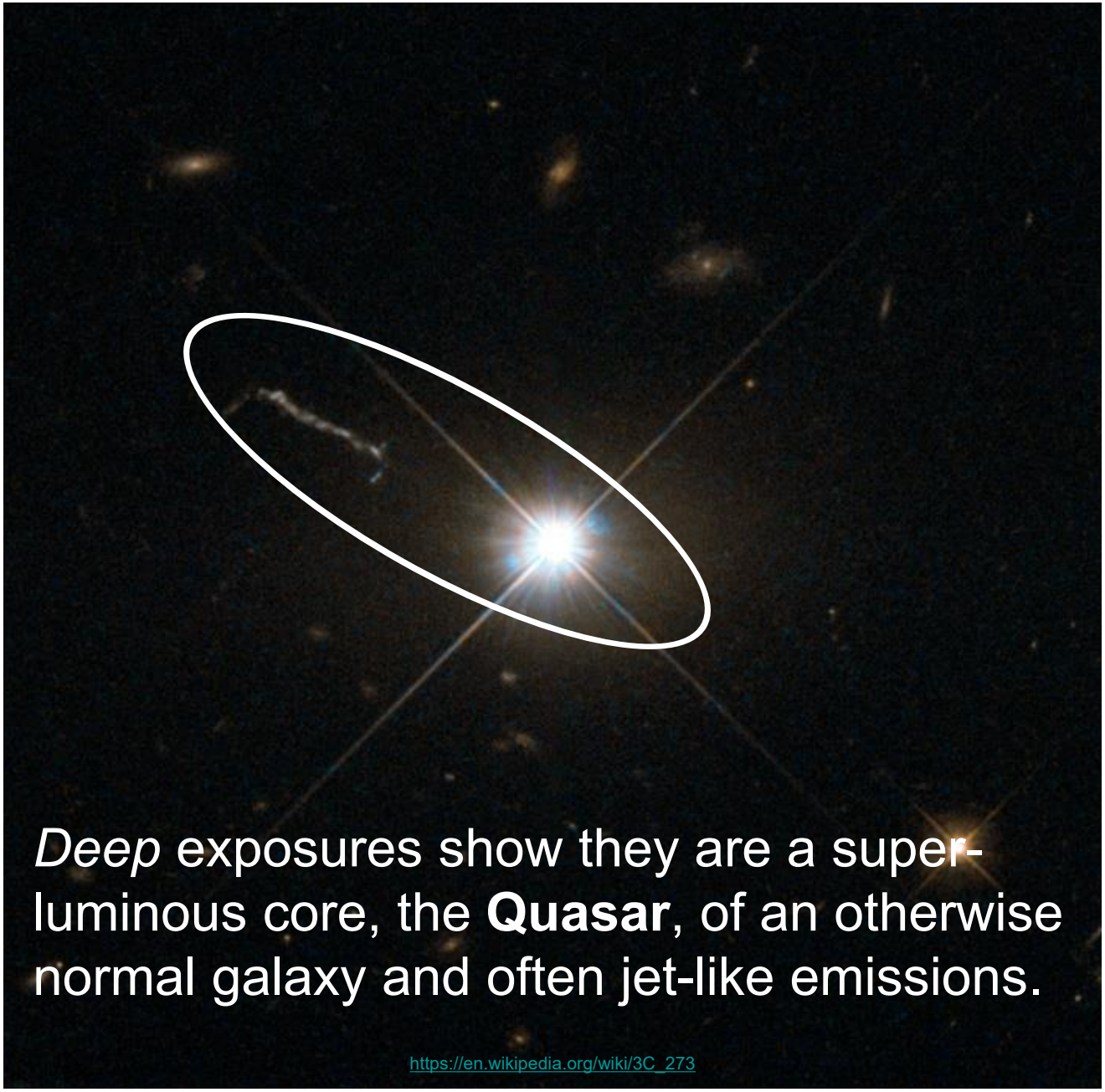
3C 48 and 3C 273 intrinsic luminosities were unimaginable

If these sources are at **extreme distances** how can they be so **bright**? [Note – the apparent brightness of all light sources decreases as $1/\text{distance}^2$.]



https://en.wikipedia.org/wiki/3C_273

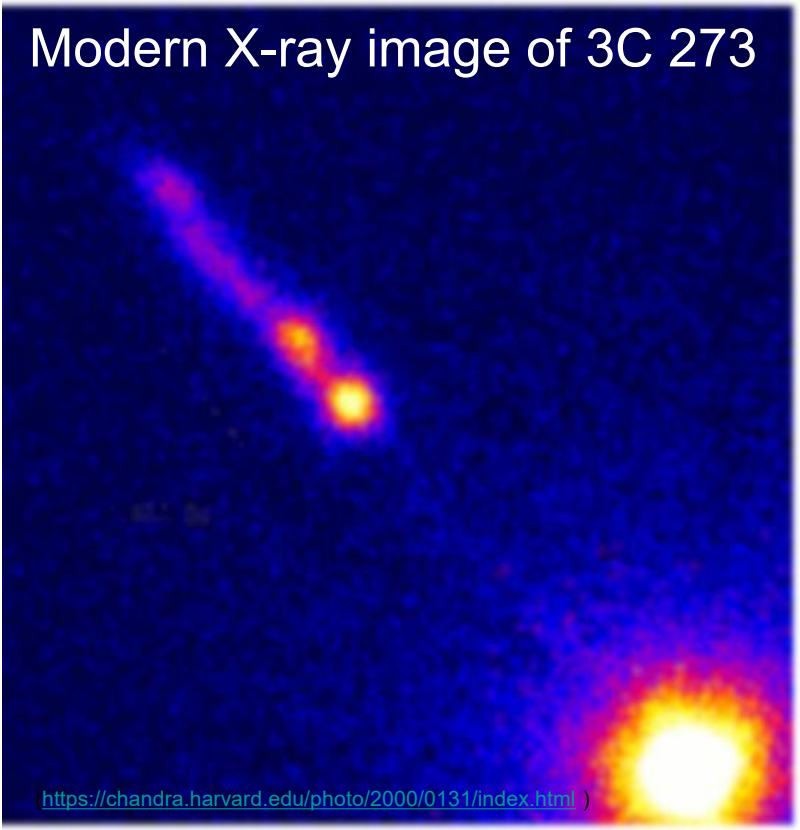
3C 48 and 3C 273 had other, non-star-like features



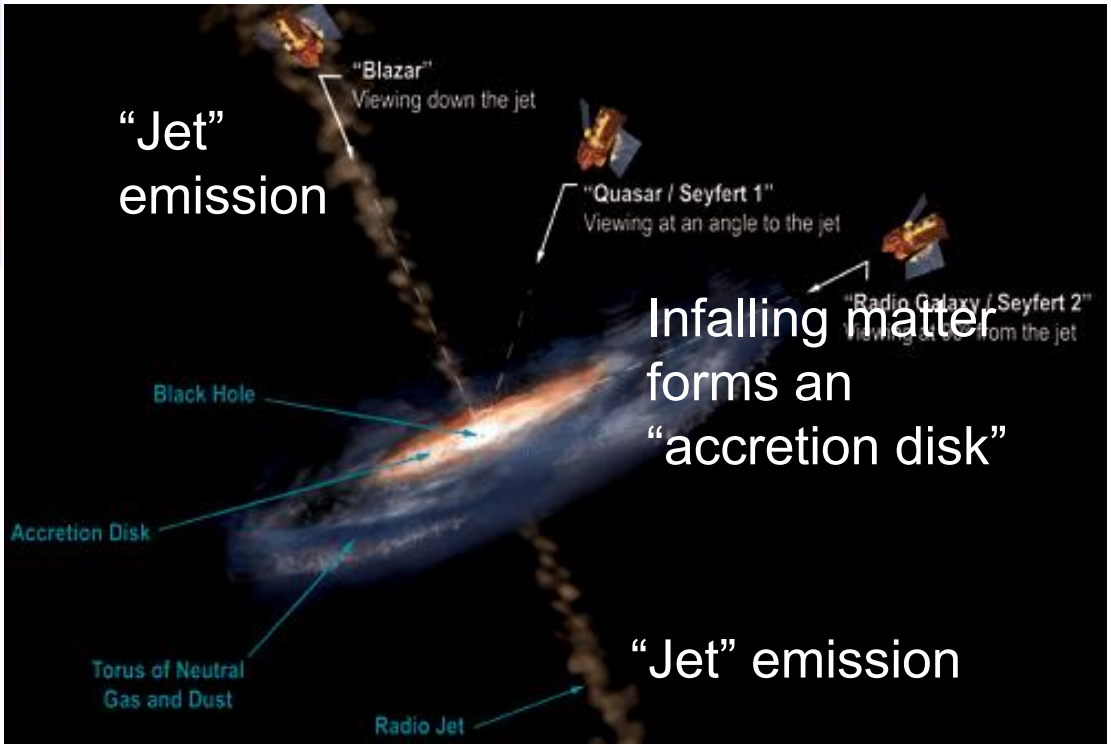
Deep exposures show they are a super-luminous core, the **Quasar**, of an otherwise normal galaxy and often jet-like emissions.

https://en.wikipedia.org/wiki/3C_273

Schmidt's "star-like object" is one of the closest Quasars



Quasars are thought to be super-massive Black Holes in a period of "peak" mass acquisition …
(Top left): X-ray image of 3C 273
(Bottom right): artist sketch of typical model of **super-massive Black Holes**

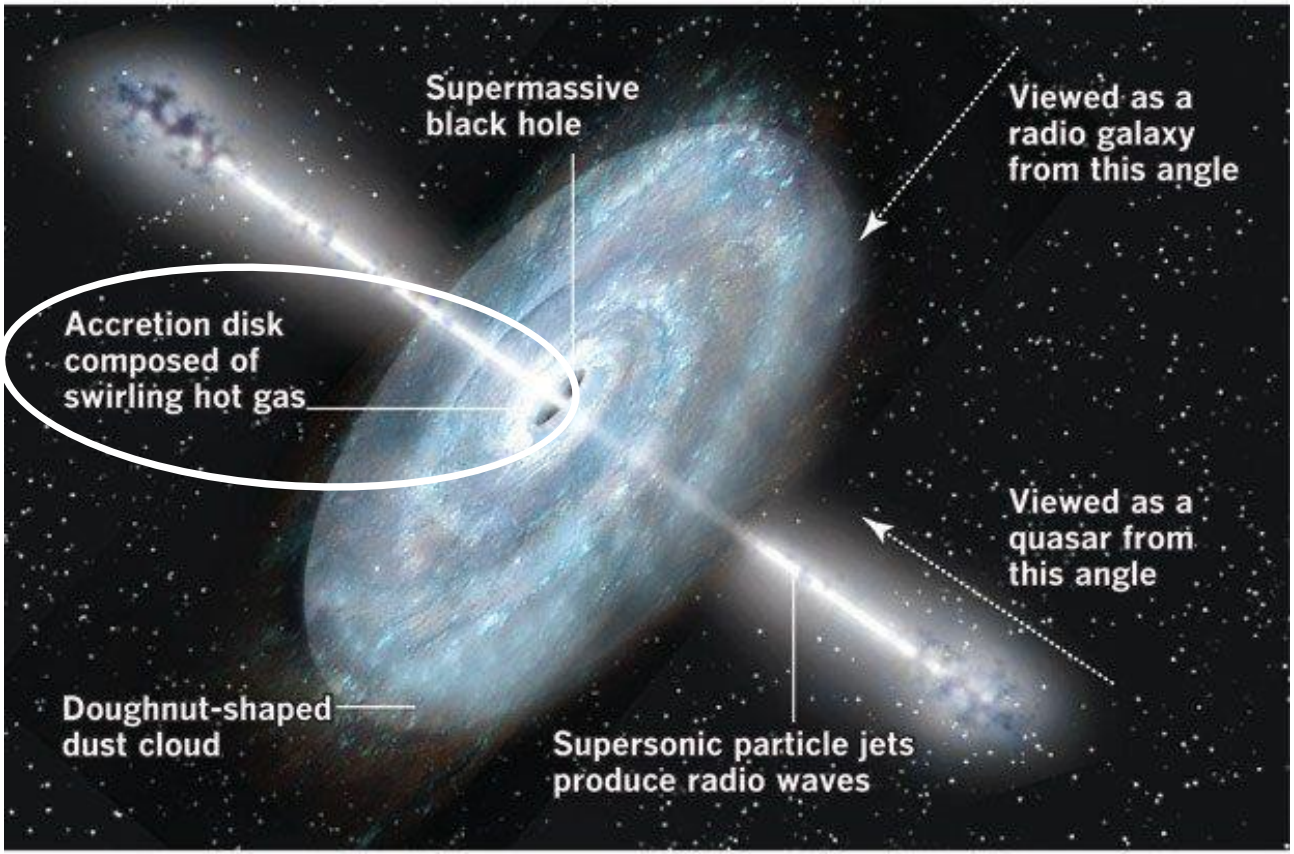


Quasars are mostly early-universe super-massive black holes

Quasars are likely the **most luminous** objects in the universe!

Quasars are **super-massive Black Holes** actively **accreting matter** found predominantly in the **early universe!**

The luminous glow of a quasar is powered by the accumulation of matter into a giant black hole at the center of a galaxy.

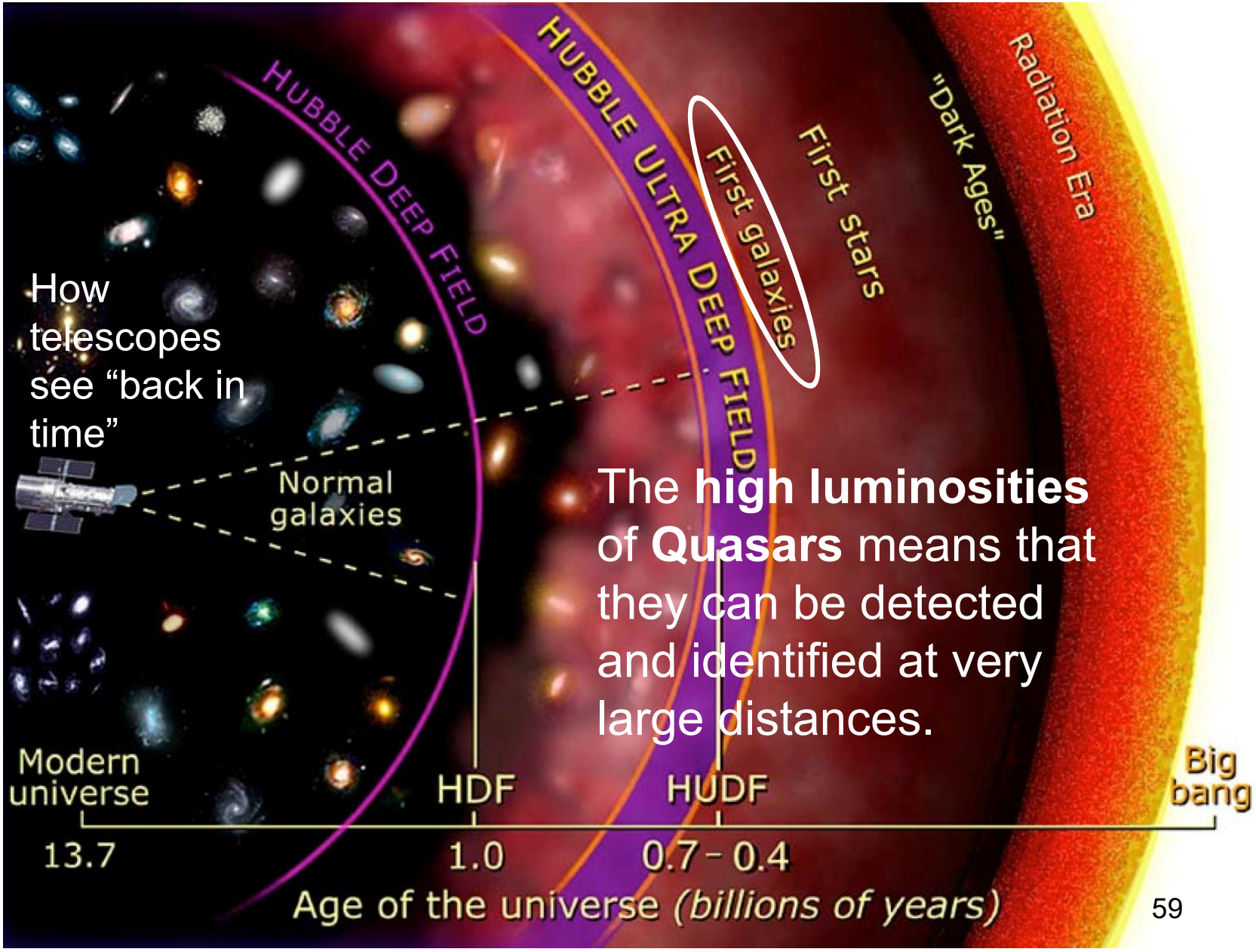


Source: Nature. Graphics reporting by BRADY MACDONALD

LORENA IÑIGUEZ ELEBEE Los Angeles Times

The **accretion disk** is very, very, very luminous!

Quasars should provide insights into the early universe

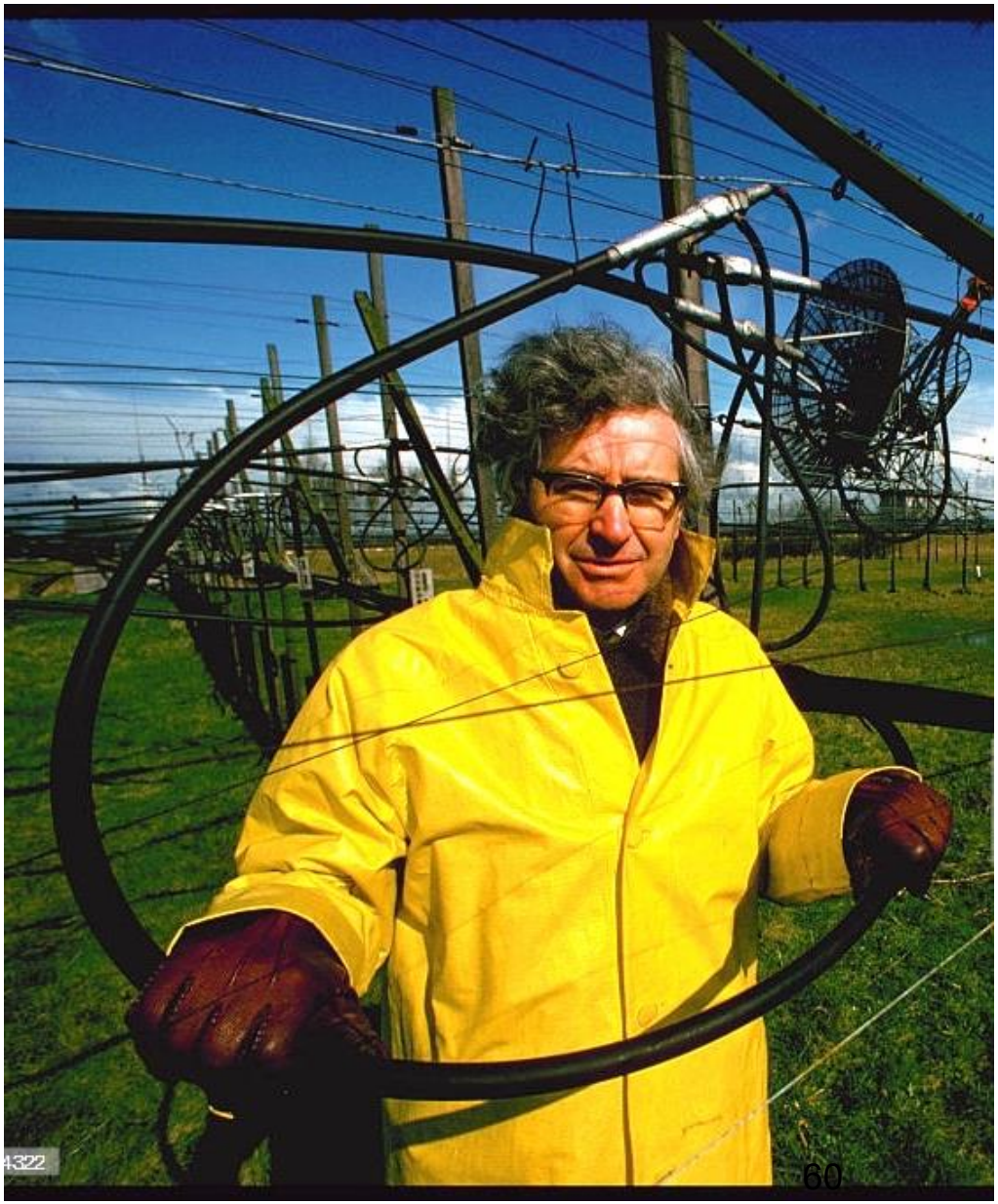


(https://en.wikipedia.org/wiki/Hubble_Ultra-Deep_Field)

Scientists are competitive: the hunt to find Quasars

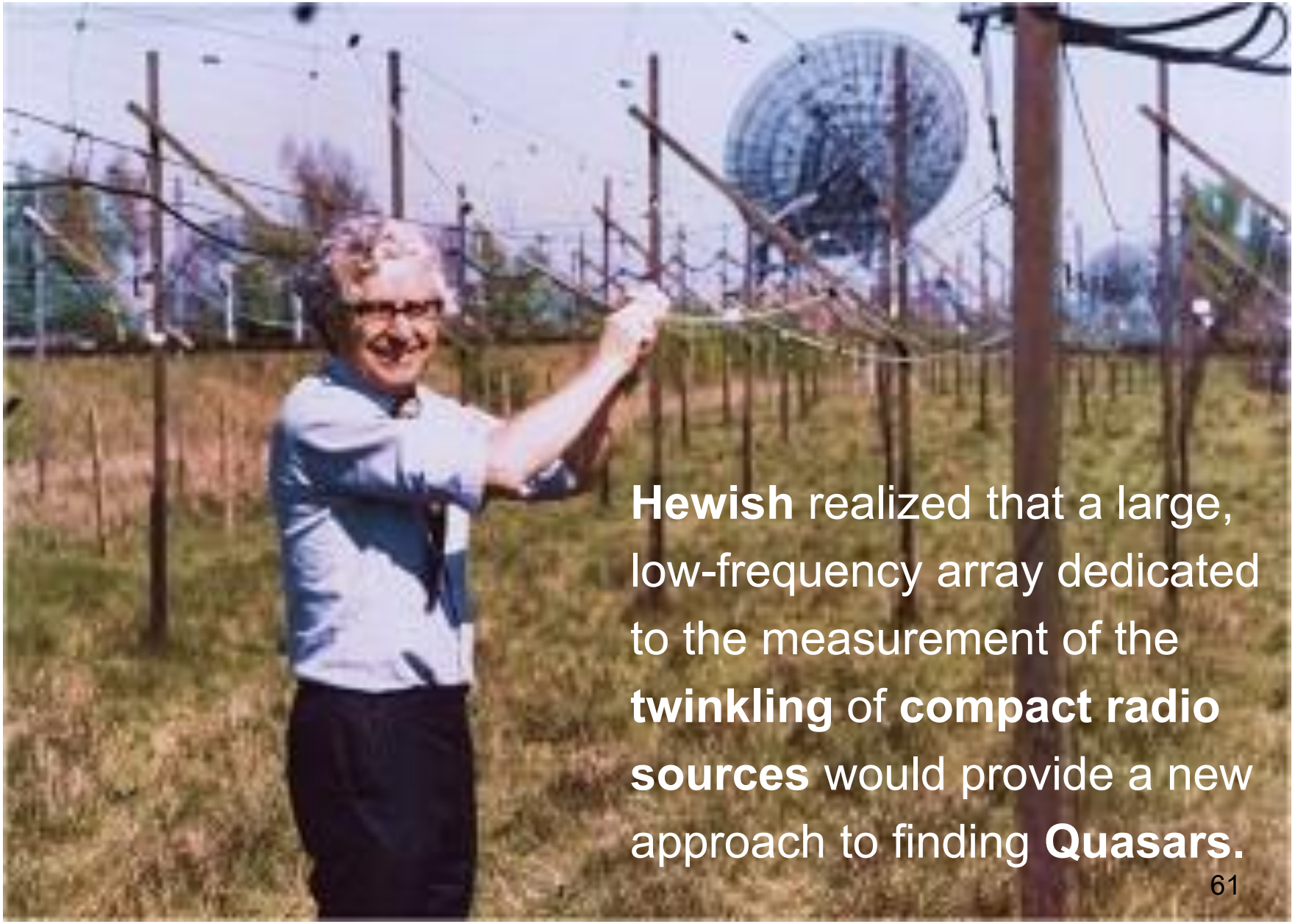
By 1964 a number of radio **Quasars** were known, some of these were **point-like**, *i.e.* had small angular sizes.

Antony Hewish showed that point-like radio sources would ***twinkle*** as the radio waves were slightly modified by small inhomogeneities in the solar wind flowing out from the Sun.



(https://www.gettyimages.com/detail/news-photo/professor-anthony-hewish-co-discoverer-of-the-pulsar-at-news-photo/524204322)

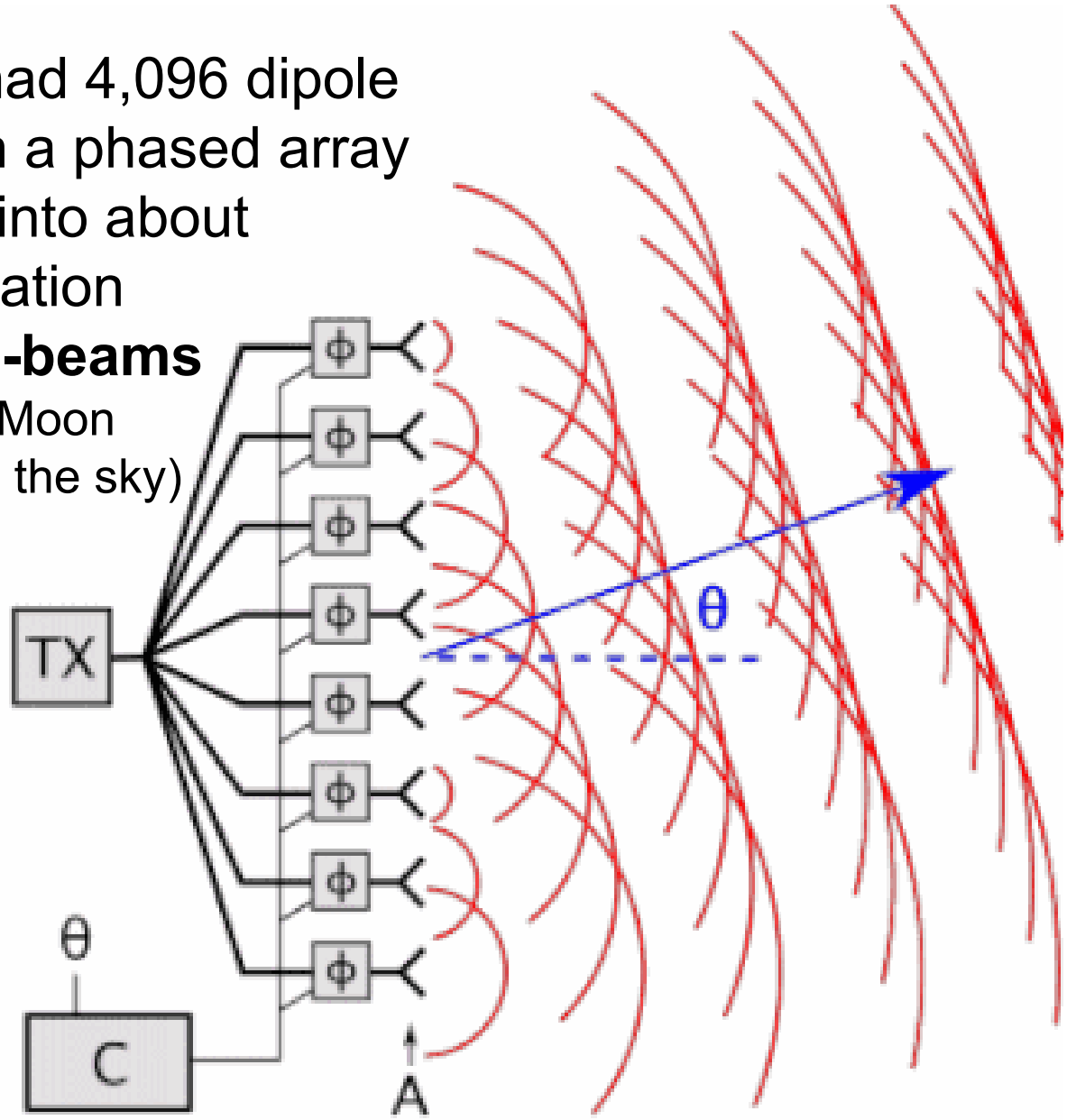
Hewish's "Interplanetary Scintillation Array"



https://www.phy.cam.ac.uk/research/research-groups/ap/heritage

In 1965 Hewish received a grant of £17,286 to construct it

The array had 4,096 dipole antennas in a phased array configured into about **5º**-in-declination **directional-beams**
(FYI: 5º = 10-Moon diameters on the sky)

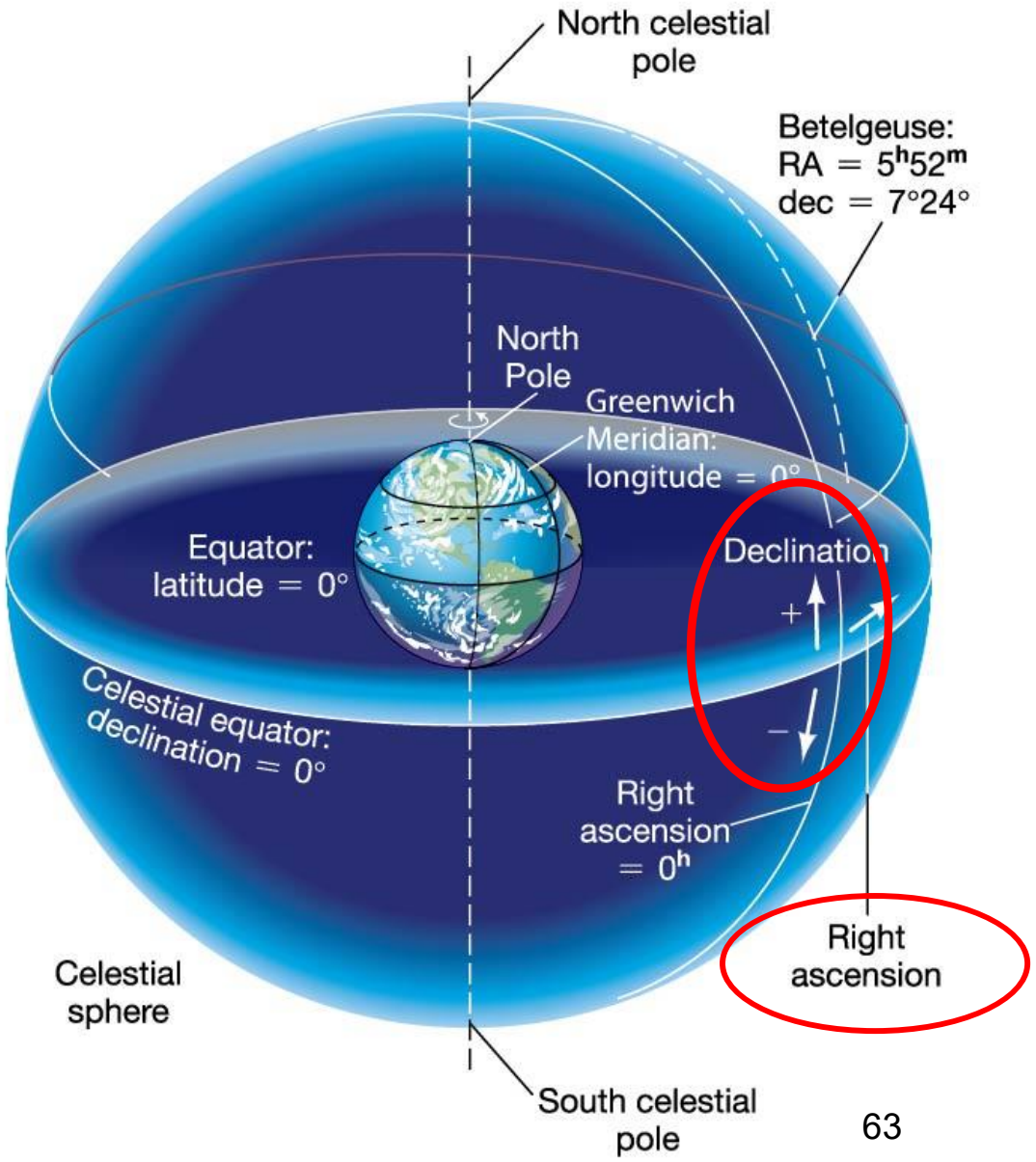


(https://en.wikipedia.org/wiki/Phased_array)

Earth: latitude/longitude. Stars: declination/right ascension.

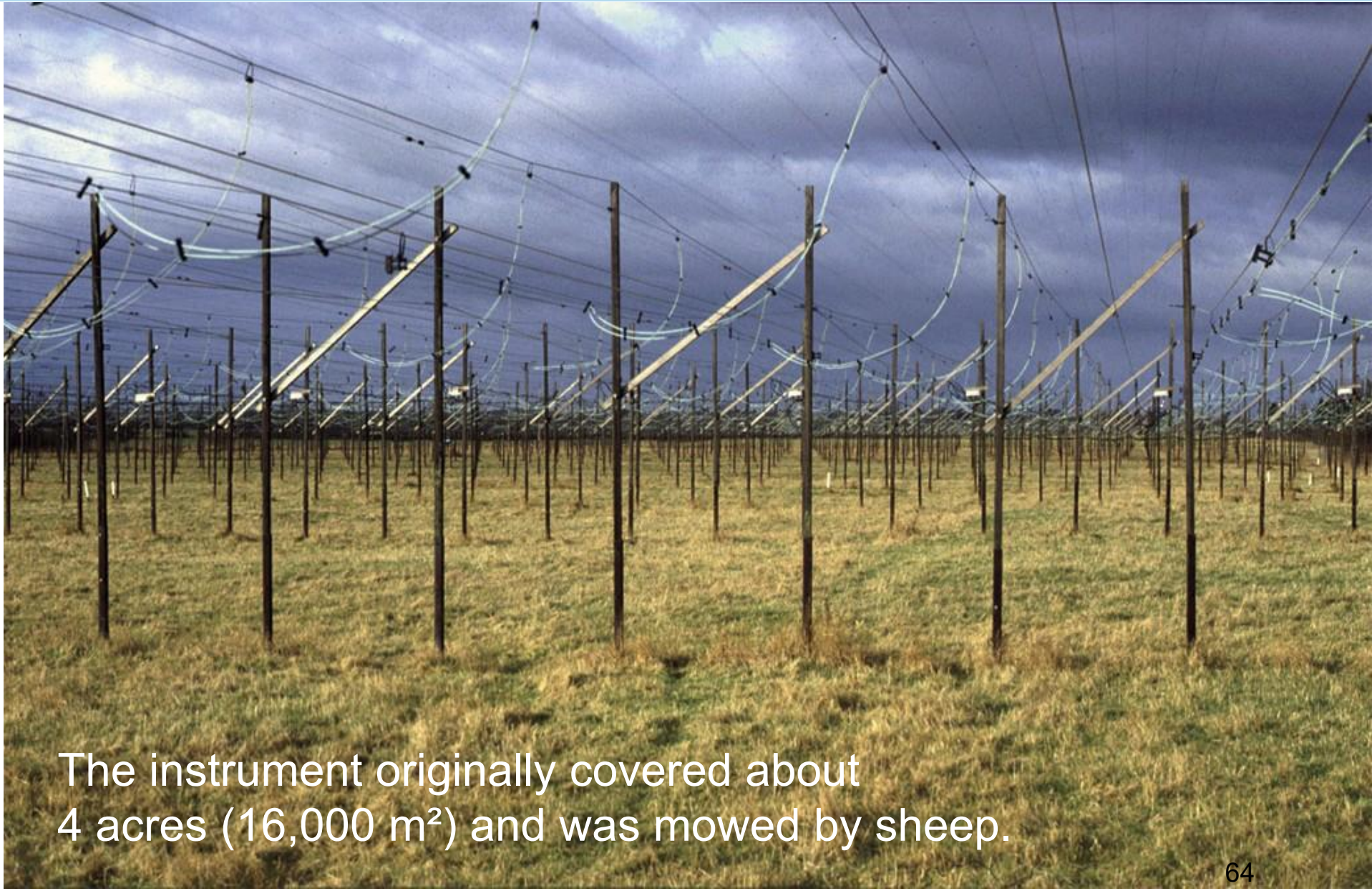
- **Declination** (like latitude): degrees north(**+**) or south(**-**) of the Celestial Equator.

- **Right Ascension** (like longitude): but measured in hours, minutes and seconds with 1 hour = 15°.



(b)

The “phased array” does not look like a radio telescope



(https://www.nature.com/articles/s41550-017-0323-x)

It took a couple of years to bring the array online

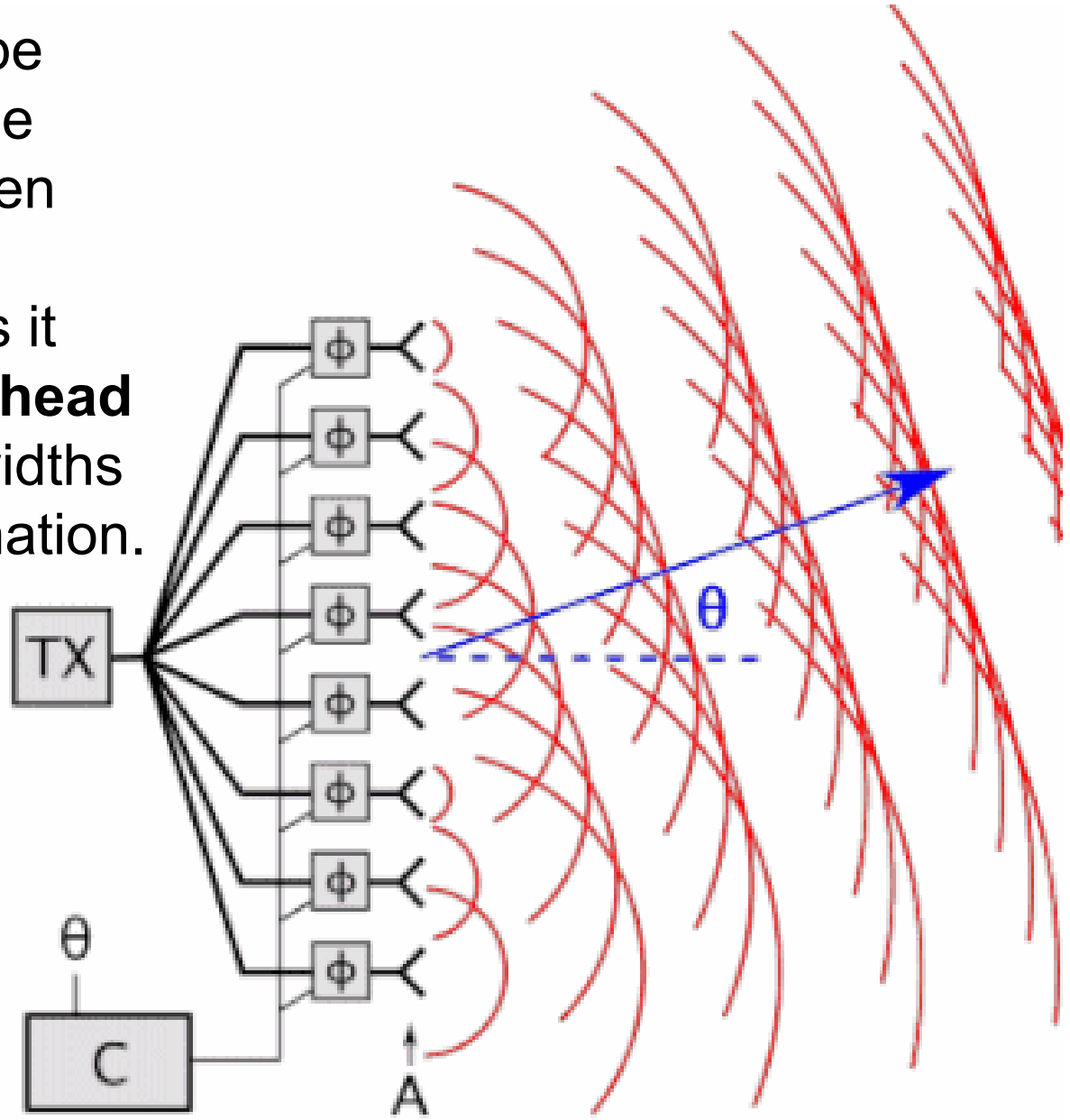
(https://sciencesprings.wordpress.com/2019/03/19/from-national-radio-astronomy-observatory-astronomers-find-cannonball-pulsar-speeding-through-space/dame-susan-jocelyn-bell-burnell-at-work-on-first-plusar-chart-1967-pictured-working-at-the-four-acre-array-in-1967-image-courtesy-of-mullard-radio-astronomy-observatory/)

The telescope was commissioned during July 1967

https://www.thetimes.co.uk/article/how-it-feels-to-be-passed-over-for-a-nobel-prize-by-jocelyn-bell-burnell-who-discovered-pulsars-cfjc0lmsx

4 of the declination-beams were recorded at any given time

The telescope **observed** the "sky", between declinations -8º to 44º, as it **drifted overhead** with beam widths ±3º in declination.



(https://en.wikipedia.org/wiki/Phased_array)

Fortunately data were not digital and computers inaccessible

Bell recalls: "The data stream was configured with four beams. The output appeared on **four** 3-track **pen recorders**, and produced 96 feet of chart paper every day (1foot/hour/beam). The charts were analyzed by-hand by me. We decided initially not to computerize the output. Until we were familiar with the behavior of our telescope and receivers, we thought it better to inspect the data visually. A **human** can recognize **signals** of **different character** whereas it is difficult to program a computer to do so.

After the first few hundred feet of chart analysis I could recognize the **twinkling sources**, and I could recognize radio interference (**noise**)."

(https://www.nature.com/articles/s41550-017-0323-x?platform=hootsuite)

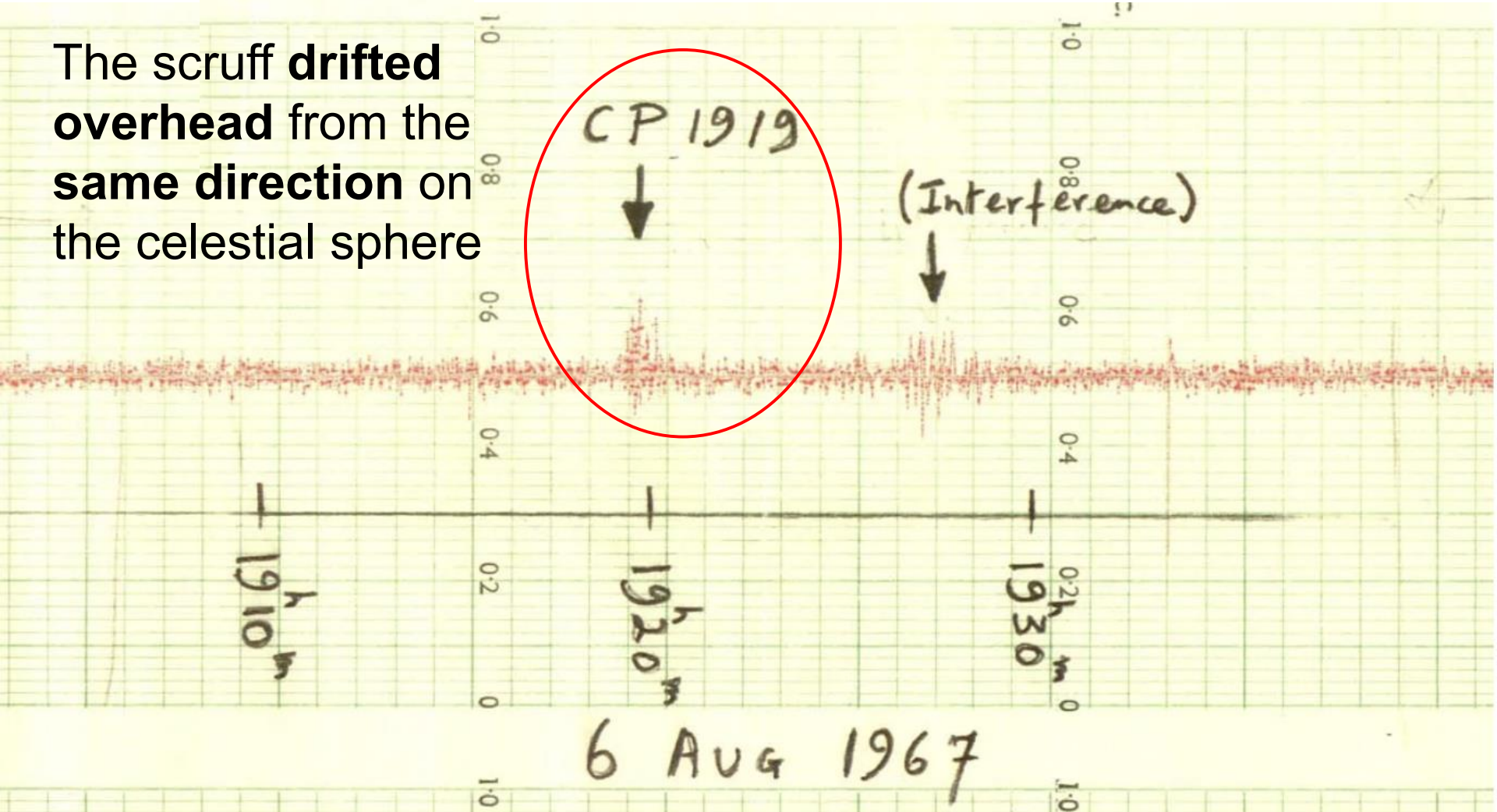
What is that *scruff* in the chart recording?

Bell recalls: “Six or eight weeks after starting the survey I became aware that on occasions there was a bit of **scruff** on the records, which did not look exactly like a twinkling source, and yet did not look exactly like man-made interference either.
Furthermore I realized that we had seen the **scruff** previously on the same part of the records *viz.* from the same patch of sky.” (**right ascension 1919**) [in constellation Velpecula]

(https://astro.univie.ac.at/en/latest/jocelyn-bell-burnell-yet-another-call-on-the-women/)

To Bell, scruff looked different from interference

The scruff **drifted overhead** from the **same direction** on the celestial sphere



Dark lines are spaced by 1 minute = ¼ - degree in RA

CP 1919 tells us pointing resolution likely about ¼ -degree!

(https://www.cam.ac.uk/stories/journeysofdiscovery-pulsars)

To interpret the scruff required faster chart recorders

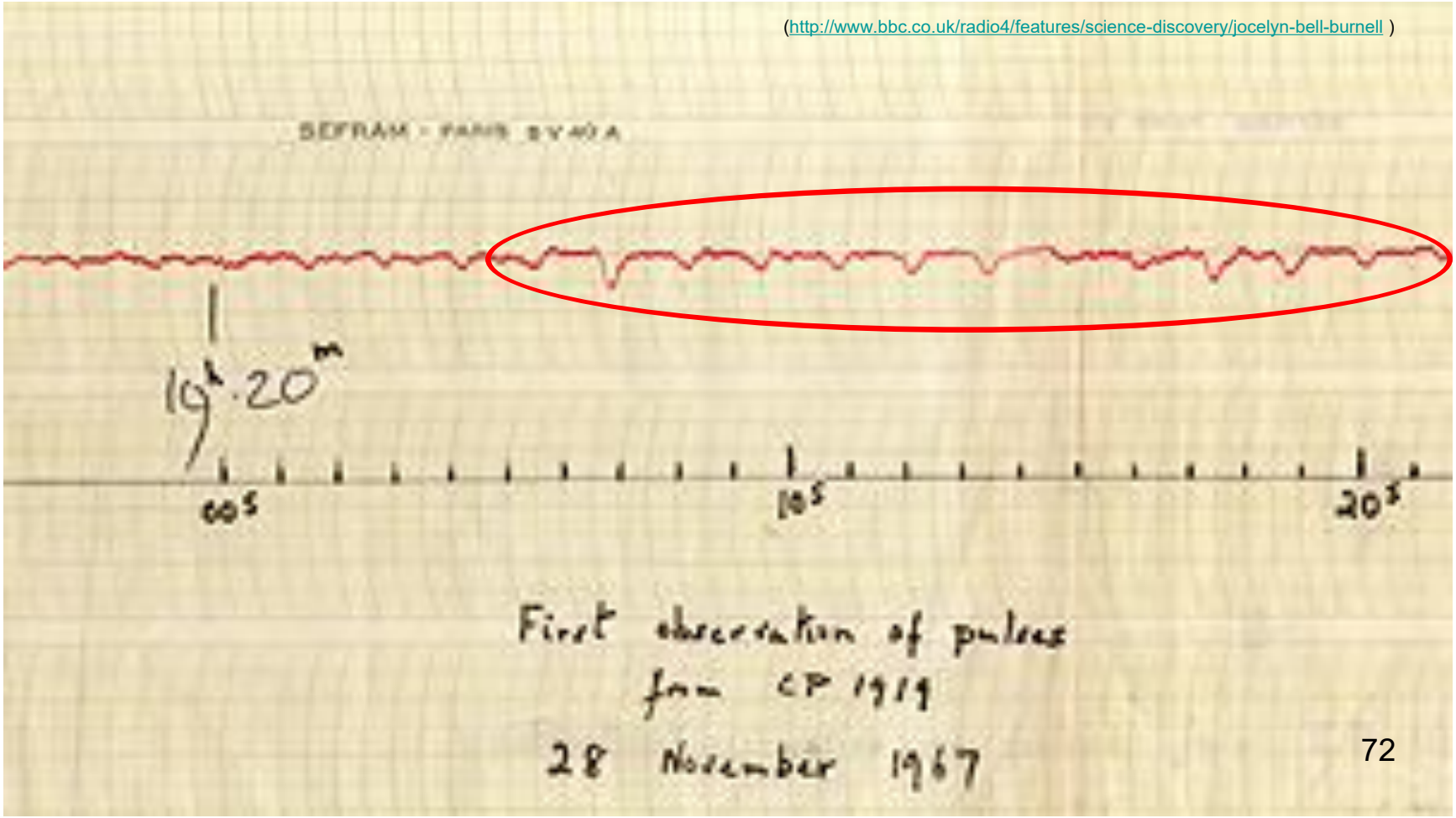
Bell recalls: "The source was transiting during the night — a time when solar-wind twinkling should be at a minimum, and **one idea** we had was that it was a **point source**. So we decided that it deserved closer inspection, and that this would involve making **faster chart recordings** as it transited.

Towards the end of October 1967, when we had finished doing some special tests on 3C 273 and when we had at last our full complement of receivers and recorders, I started going out to the observatory each day to make the fast recordings.

They were useless. For weeks I recorded nothing but receiver noise. Then one day I skipped the observations to go to a lecture, and on the next day on my normal recording I saw that the **scruff** had been there."

“At the end of November 1967 I got it on the fast recording”

Bell recalls: “As the chart flowed under the pen I could see that the signal was a series of pulses, and my suspicion that they were equally spaced was confirmed as soon as I got the chart off the recorder. They were 1 1/3 seconds apart.”



Bell soon identified 3 more pulsing sources!

Bell recalls: “Some days later I was analyzing a recording of a completely different part of the sky, I thought I saw some **scruff.** I rapidly checked through previous recordings of that part of the sky, and on occasions there was **scruff** there.”

Ultimately two 1968 publications in Nature by Hewish, Bell, et al. reported **4 rapidly pulsing radio sources**.

First paper in Nature on CP1919

Bell's pulsar discoveries were appendices in her thesis.

(Reprinted from Nature, Vol. 217, No. 5130, pp. 709–713, February 24, 1968)

Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

Reprint of second paper from Bell's thesis

(Reprinted from Nature, Vol. 218, No. 5137, pp. 126–129, April 13, 1968)

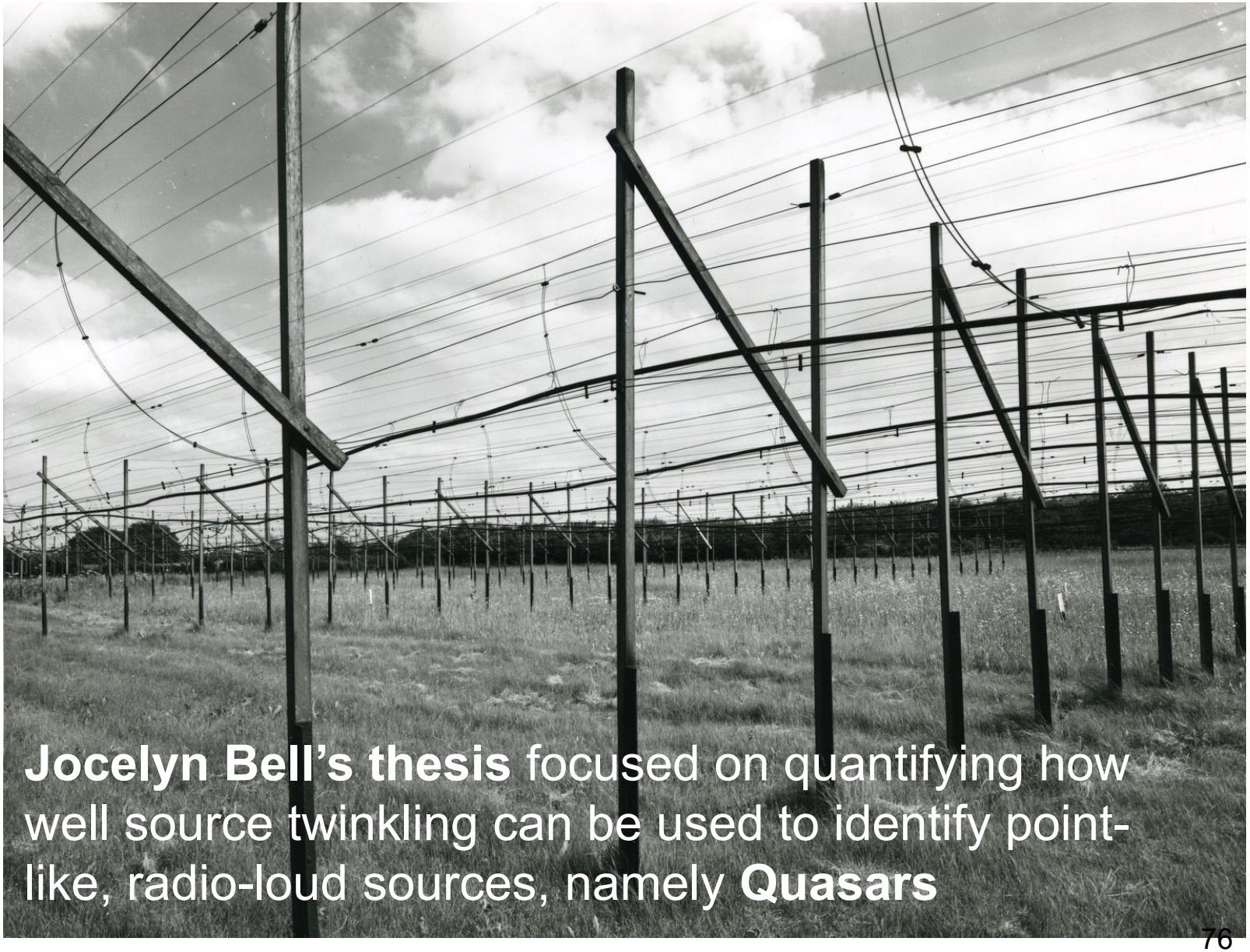
Observations of some further Pulsed Radio Sources

by
J. D. H. PILKINGTON
A. HEWISH
S. J. BELL
T. W. COLE

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Details are now given of three of the four pulsating radio sources discovered at Cambridge.

If not pulsars, what was Jocelyn Bell's thesis topic?



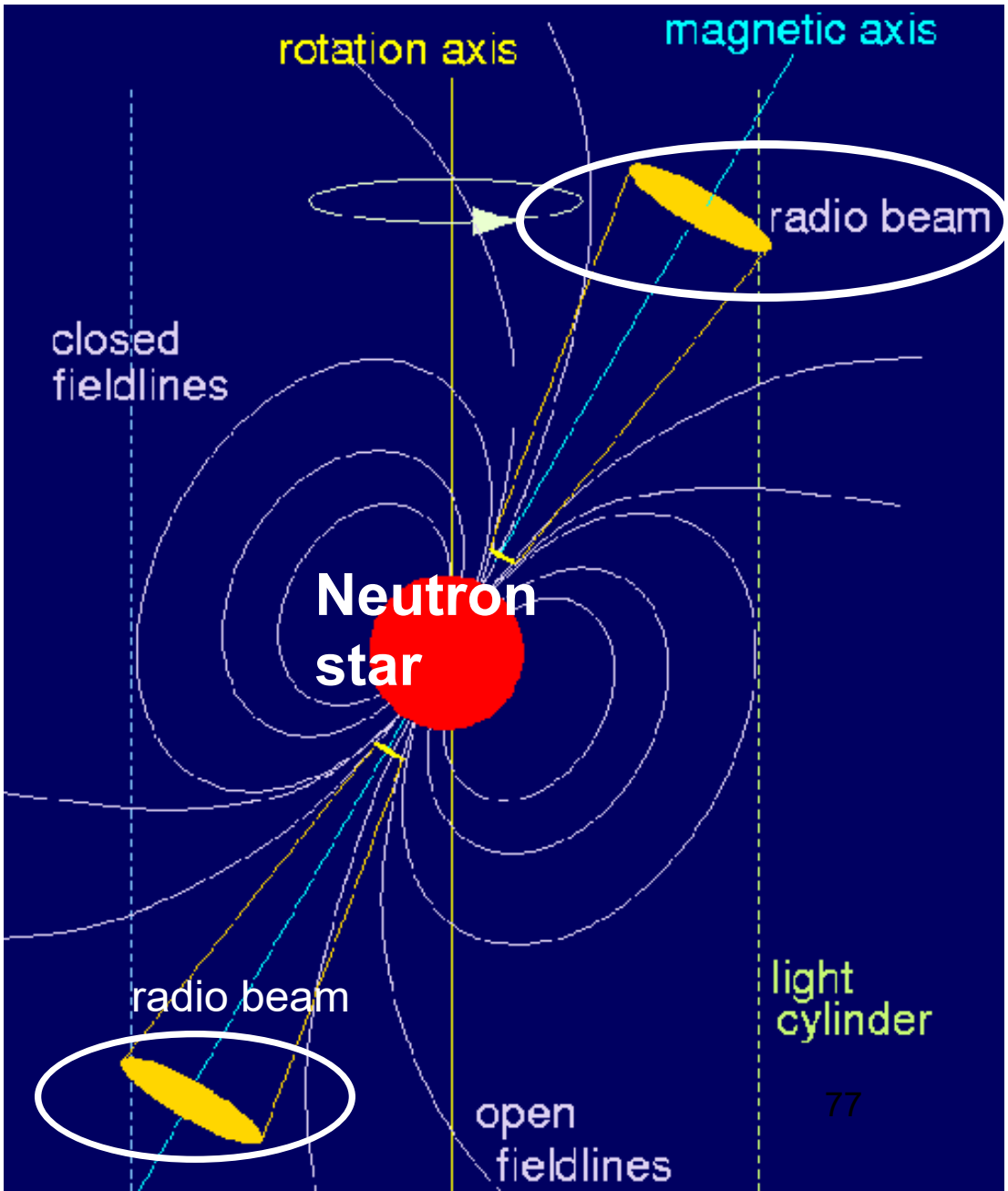
(https://www.nature.com/articles/s41550-017-0323-x?platform=hootsuite and https://collection.sciencemuseumgroup.org.uk/objects/co8105496/parts-from-the-cambridge-interplanetary-scintillation-array-radio-telescope-instrument-component)

Pulsar's were explained one year later

Thomas Gold's 1968 Nature paper proposed *Rotating* ***Neutron Stars*** *as the Origin of the Pulsing Radio Sources.*

Neutron stars' intense, rotating, magnetic fields result in beamed radio emission along the magnetic axis of the neutron star.

These **searchlight-like beams** cause a pulse when they sweep across the Earth.



(http://www.jb.man.ac.uk/distance/frontiers/pulsars/section2.html)

Rotating lighthouse beacon appears to flash on and off

- But why would a neutron star flash on, and off?

- This figure illustrates the analogy with a **lighthouse beacon.**

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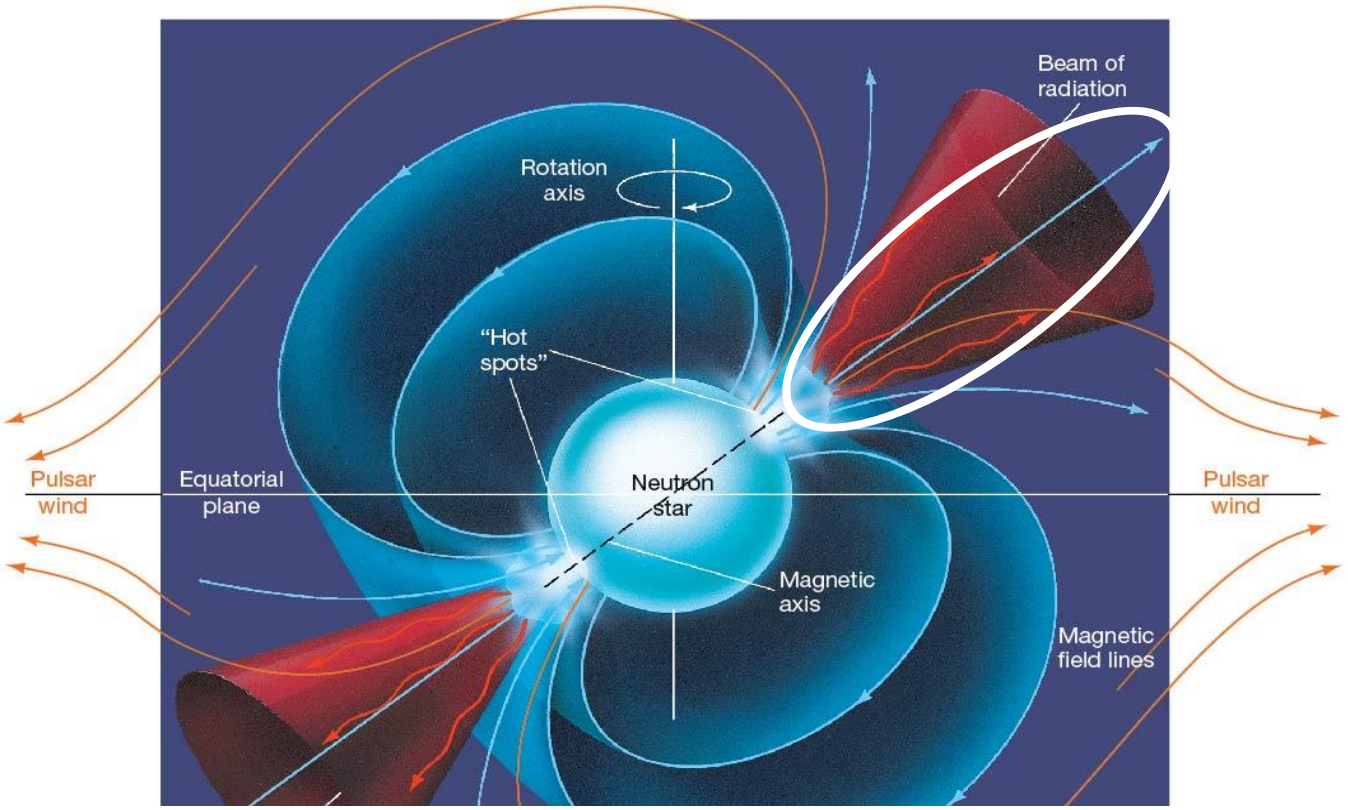
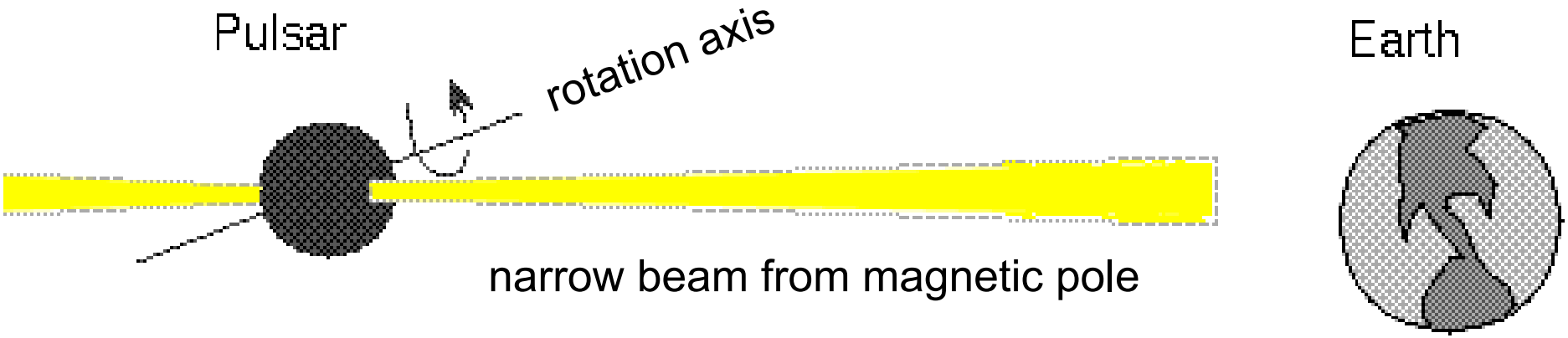


A lighthouse beacon is a good analogy for a rotating pulsar.

From scruff, to pulsar, to neutron star



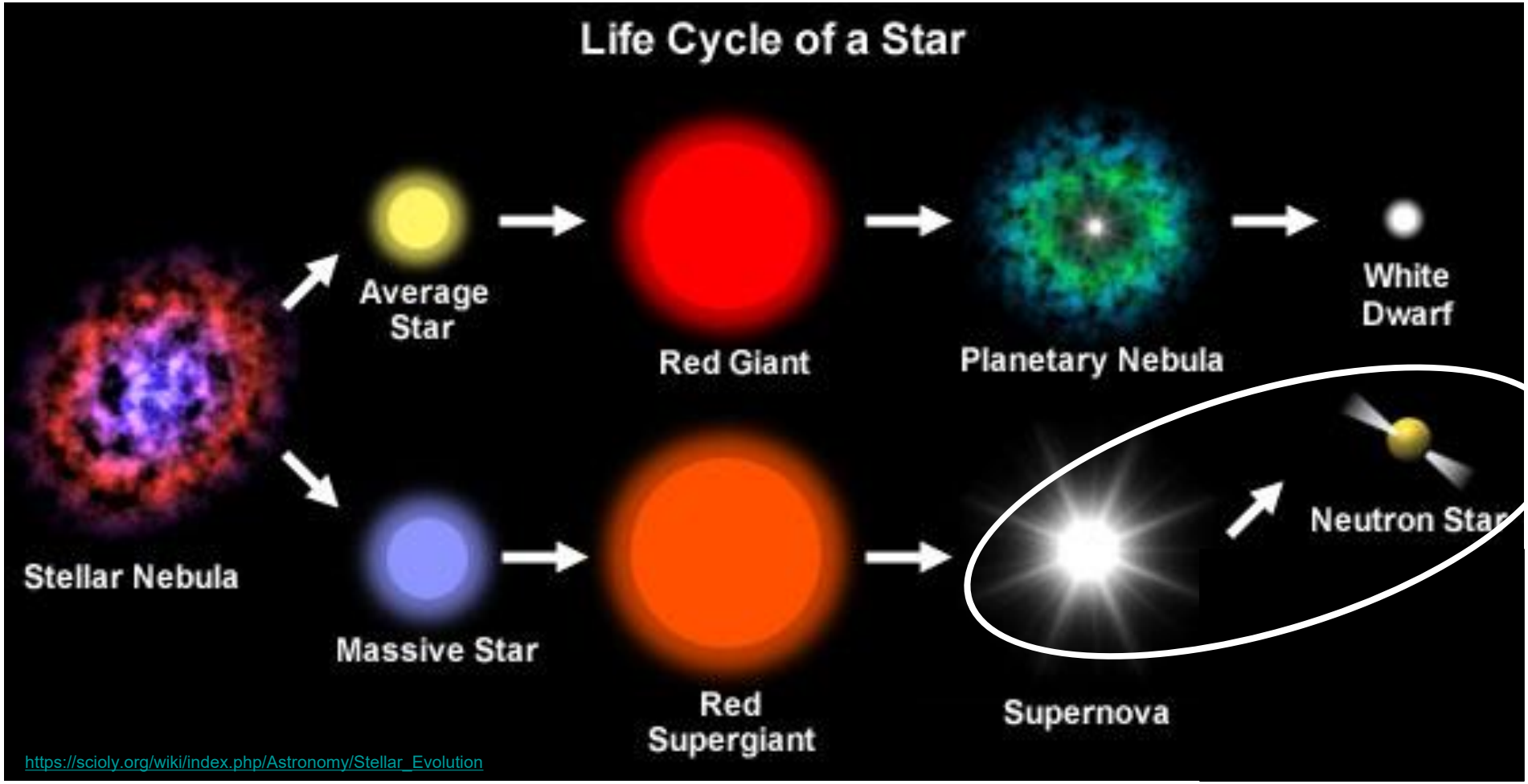
If the narrow synchrotron beam passes over the Earth, we see the neutron star flash on and off like a lighthouse beam does for ships at sea.

This lucky mechanism is almost the only way to observe the **neutron star** remnants of **Core Collapse supernovas**!

(http://www.astronomynotes.com/evolutn/s12.htm)

Conjectured supernova remnants were proposed in 1934

- **Neutron stars** form in the *death* of 10 ~ 20 solar-mass stars as **Core Collapse supernovas**. They have masses of 1 to 3 solar-masses but radii of about 10km!
- It took 34 years for **evidence** of their existence.



This was the 1st Nobel Prize in astronomy/astrophysics

The Nobel Prize in Physics 1974

(https://www.nobelprize.org/prizes/physics/1974/summary/)

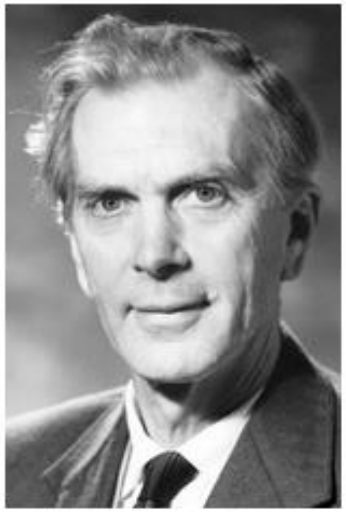


Photo from the Nobel Foundation archive.

Sir Martin Ryle

Prize share: 1/2

Photo from the Nobel Foundation archive.

Antony Hewish

Prize share: 1/2

The Nobel Prize in Physics 1974 was awarded jointly to Sir Martin Ryle and Antony Hewish "for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"

Nobel prize for Hewish and Ryle but not Bell

Jocelyn Bell received many significant awards over her career:

- **O**rder of the **B**ritish **E**mpire (1999)
- Dame Commander **OBE** (2007)
- **Special Breakthrough Prize in Fundamental Physics** (2018)

"*The $3 million award recognizes not only Bell Burnell's 1967 discovery of the weird, fast-spinning stellar corpses known as pulsars but also her scientific leadership in the 50 years since then.*"

(https://en.wikipedia.org/wiki/Jocelyn_Bell_Burnell)

President John F. Kennedy Signs the Nuclear Test Ban Treaty

Energetic gamma-rays are a *weapons* signature

Vela (velar: to *keep vigil over*) was the name of a group of satellites developed at Los Alamos and Sandia Labs to **monitor compliance** by the Soviet Union with the **1963 Partial Test Ban Treaty**.

Vela started in 1959 as a small-budget research program.

Vela satellites were launched in **pairs**

(https://phys.org/news/2015-09-vela-incident.html)

In 1967 our knowledge of the universe changed

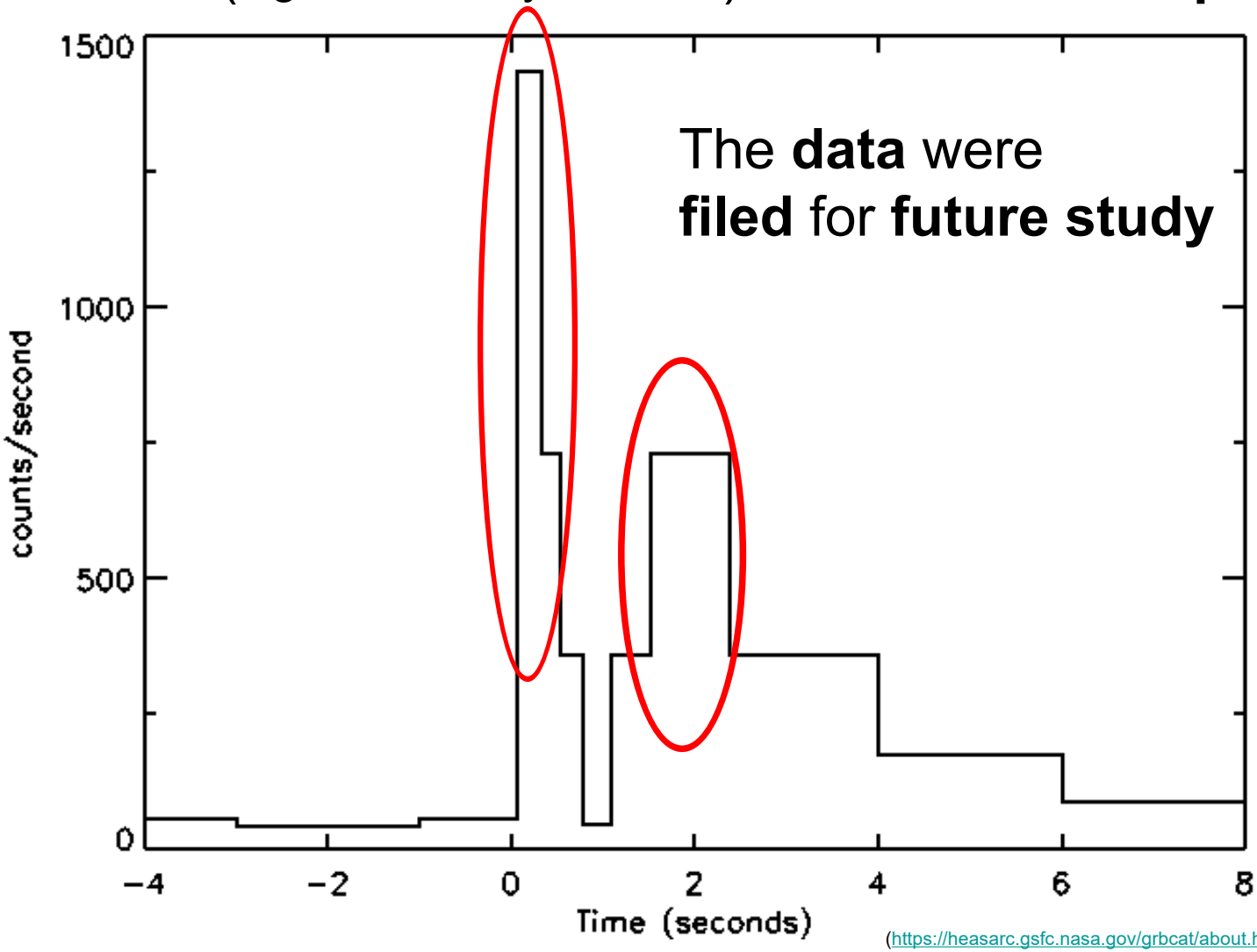
- On **July 2, 1967**, at 14:19 UTC, the Vela 4 and Vela 3 satellites detected a **burst** of **gamma radiation** that was **unlike** any **known nuclear weapons signatures**.

- Nuclear bombs produce a very brief, intense burst of gamma rays: less than one millionth of a second. The radiation then steadily fades as the unstable nuclei decay.

The observed burst of gamma-rays lasted several seconds

The signal detected by the Vela satellites had neither the intense initial flash nor the gradual fading.

The light curve (signal intensity VS time) had **two distinct peaks.**



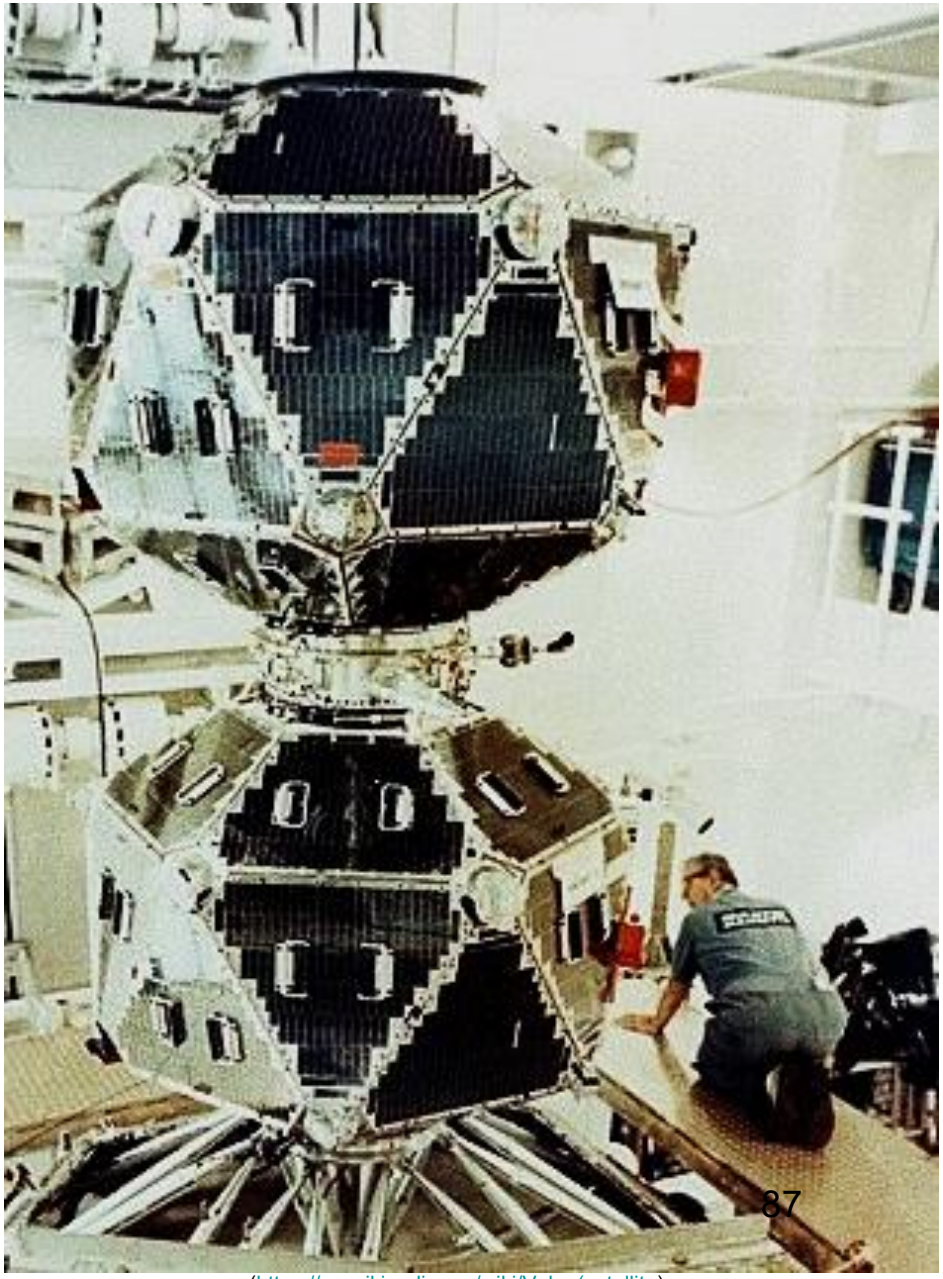
(https://heasarc.gsfc.nasa.gov/grbcat/about.html)

Vela 5 was launched on May 23, 1969

With **improved sensitivity** and **time resolution**, the Los Alamos team expected these new satellites to detect more gamma-ray bursts.

They found **twelve events** that did not coincide with any solar flares or terrestrial events.

Some of the new detections also showed the same double-peak pattern observed by Vela 4



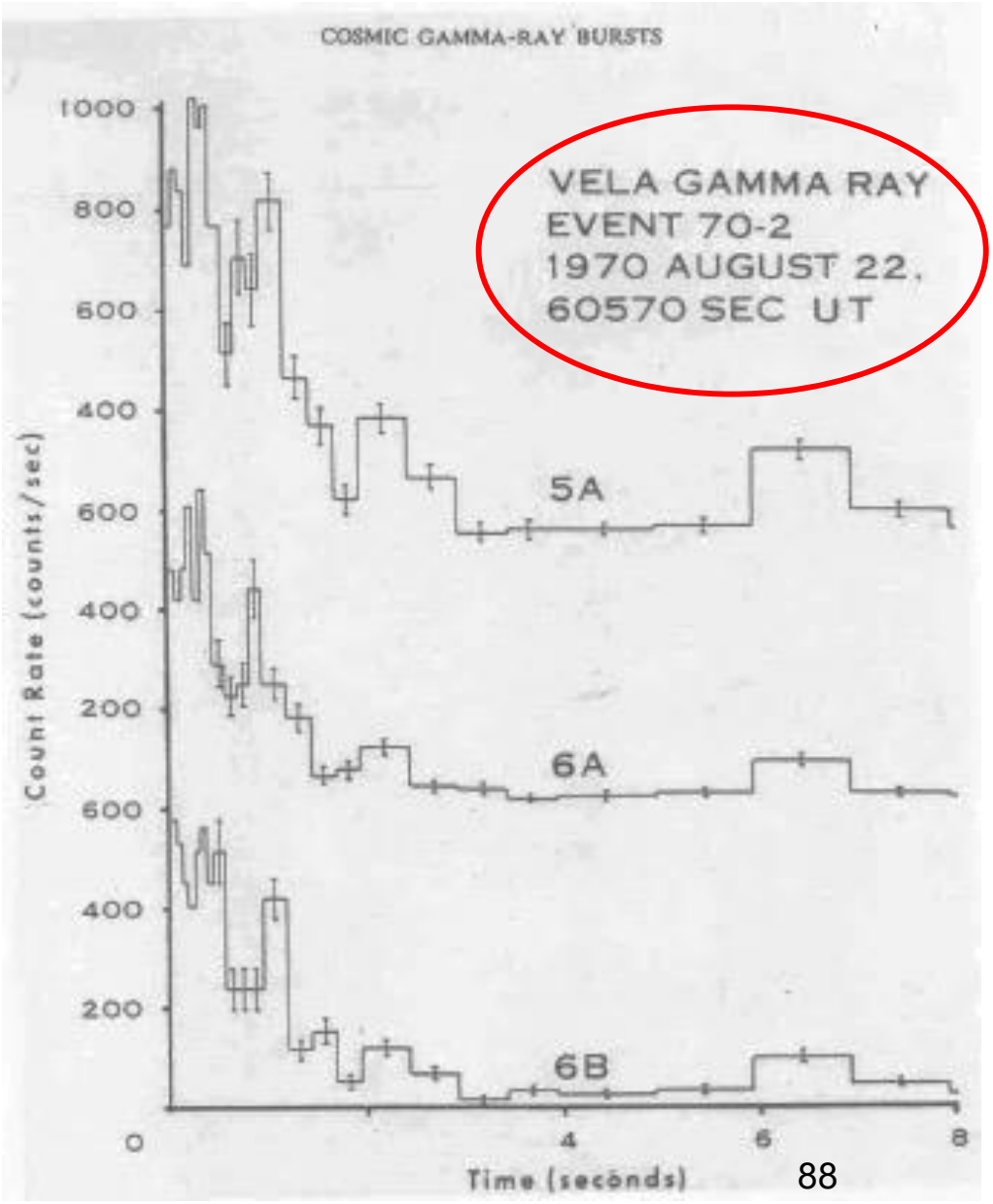
(https://en.wikipedia.org/wiki/Vela_(satellite))

Vela 6 satellites were launched on April 8, 1970

The Vela 6 satellite orbits were chosen to be as **far away** from **Vela 5** as possible.

This separation meant that, despite gamma rays traveling at the speed of light, a signal would be detected at slightly different times by the satellites.

By analyzing the **arrival times**, the Los Alamos team successfully traced the source direction of **sixteen gamma-ray bursts**.



(https://www.researchgate.net/figure/One-of-the-first-GRBs-observed-by-the-Vela-satellite-Reproduced-from-Strong-in-Gursky_fig5_1927258)

Directions of the gamma-ray bursts indicated non-local origin!

The bursts were **not** coming from the **Sun**, **Moon**, or other **planets** in **our solar system**.

In 1973, Ray Klebesadel, Roy Olson, and Ian Strong of the Los Alamos Scientific Laboratory published ***"Observations of Gamma-Ray Bursts of Cosmic Origin"***.

Abstract: Sixteen short bursts of photons in the energy range 0.2-1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from ~10^{-5} ergs/cm^2 to ~2 X 10^{-4} ergs/cm^2 in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Amazing science but not recognized. Likely too unexpected.

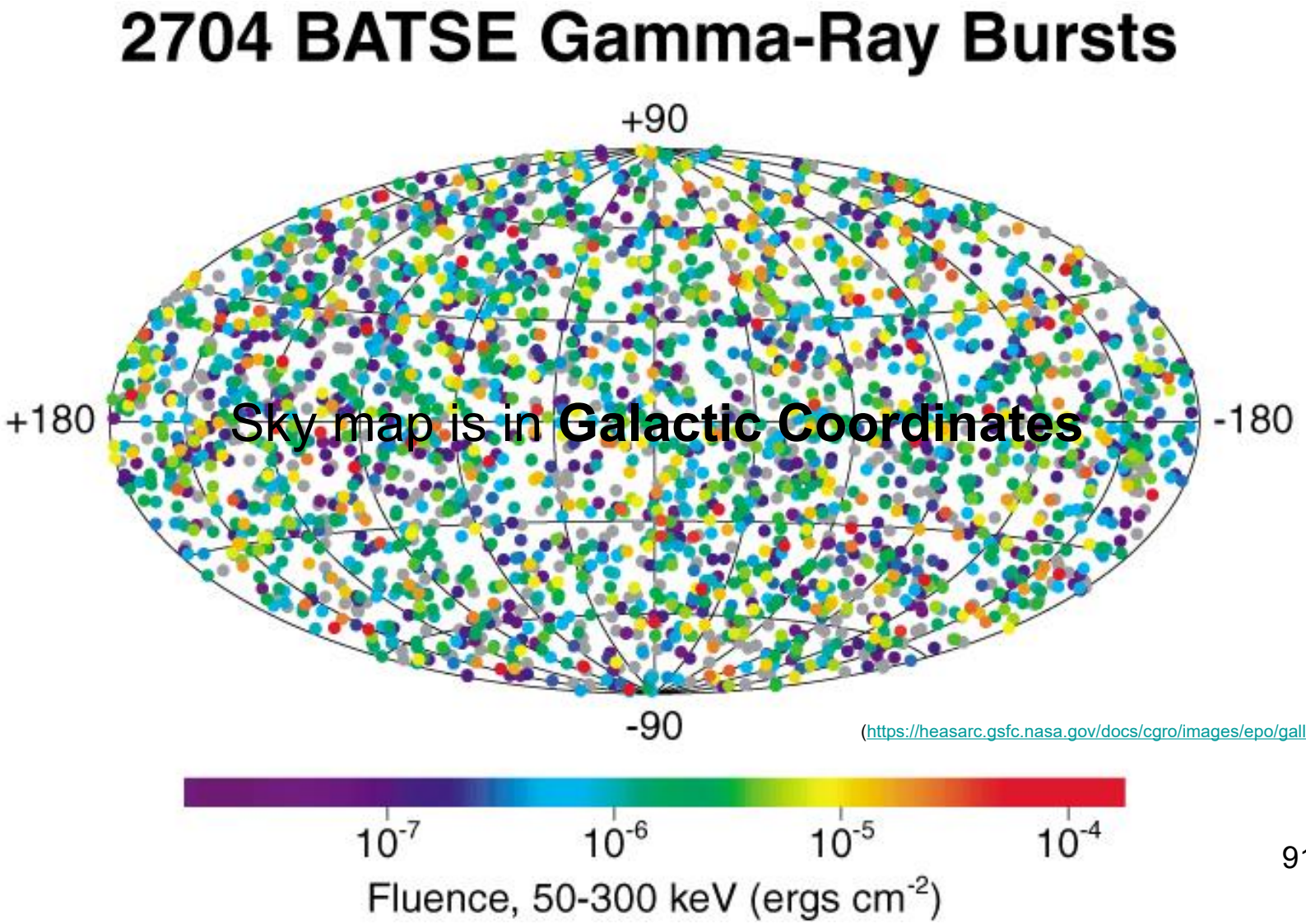
Gamma-ray bursts were just "**too unexpected**".

For some reason there was little press of **Ray Klebesadel's**, Roy Olson's, and Ian Strong's 1973 Gamma-ray Burst publication.

Ray Klebsadel (on the right) discovered the existence of gamma ray bursts in 1969 from observations made with the military satellite Vela. To his left are *Graziella Pizzichini* and *Chryssa Kouveliotou*.

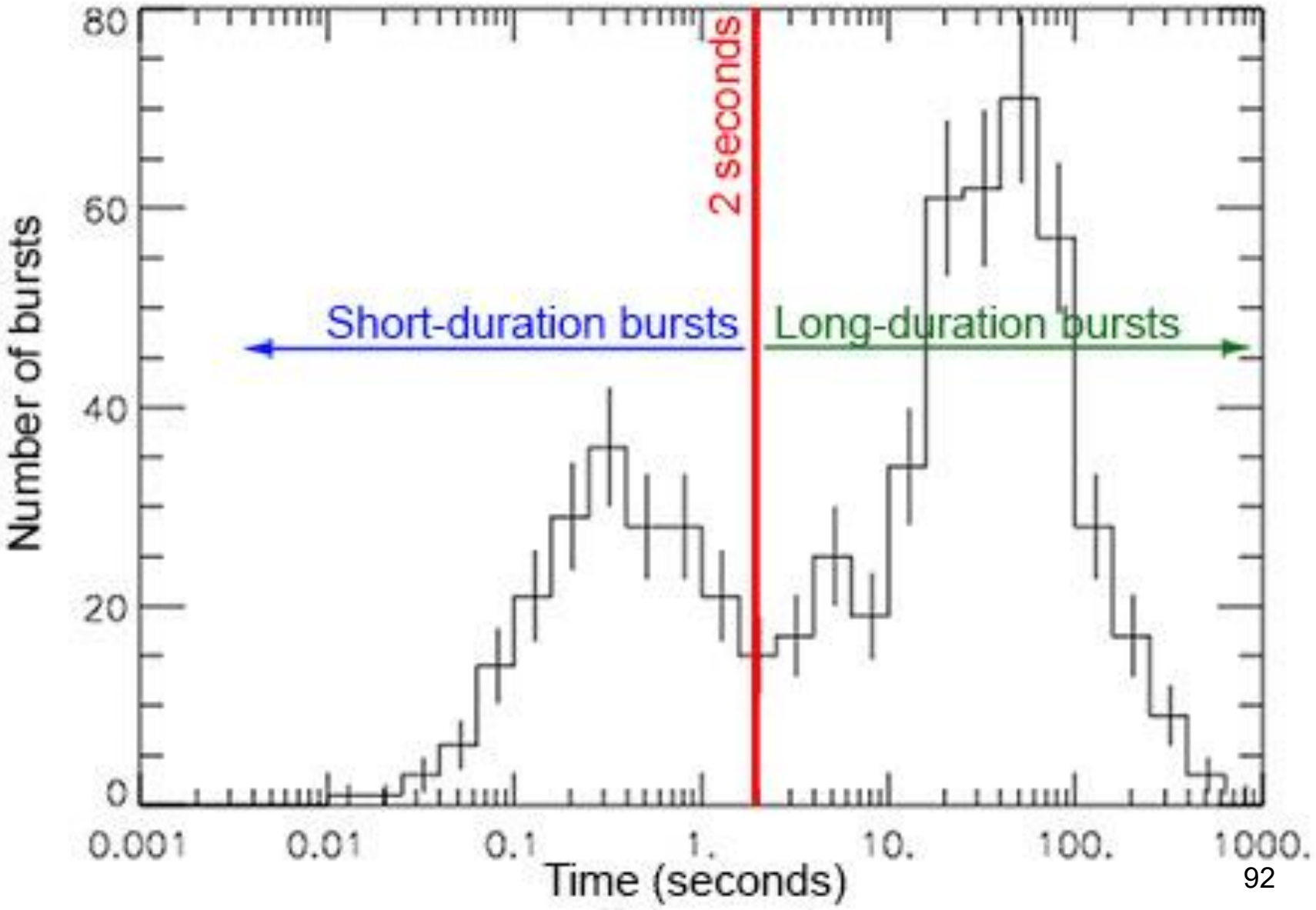
Gamma-ray burst detection is now an *industry*

Today the uniform distribution of Gamma Ray Bursts **exclude** our galaxy and support an **extra-galactic** origin.



(https://heasarc.gsfc.nasa.gov/docs/cgro/images/epo/gallery/grbs/)

Gamma-ray bursts' time-extent divide into two categories

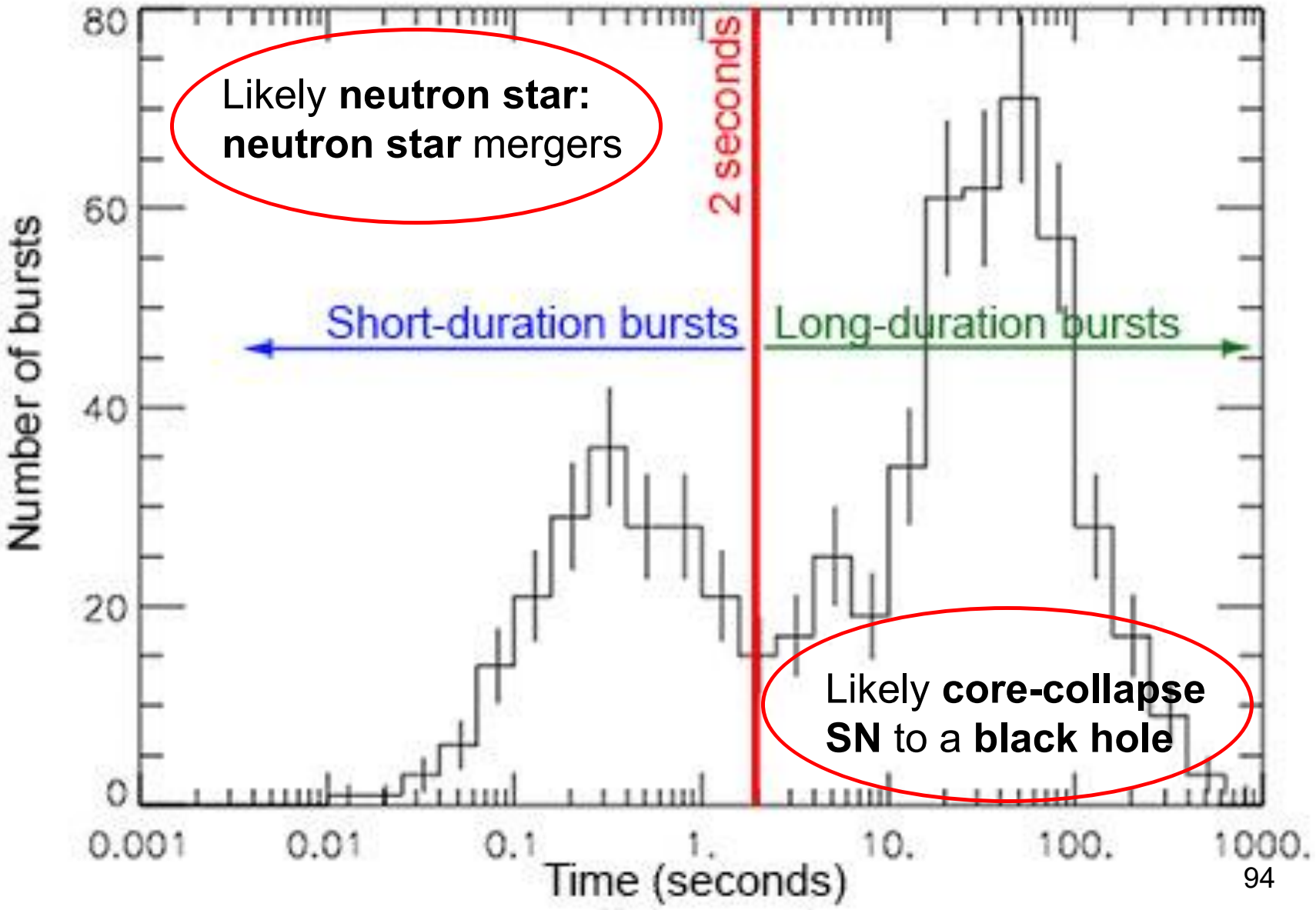


(https://gammaray.msfc.nasa.gov/batse/grb/duration/)

Gamma-ray burst optical counterparts: 24 years later

- 1997 - a gamma-ray burst (GRB 970508) was localized in direction and time for optical follow-up.
- By comparing photographs taken on May 8 and 9, 1997, one object was found to have increased in brightness.
- May 10 and 11, Charles Steidel recorded the spectrum of the variable object from the Keck Observatory.
- Mark Metzger analyzed the spectrum and determined a redshift **z** $\geq$ 0.835, placing the burst at a distance of at least 6.6 billion light years: definitely of **non-local origin**!
- Like Quasars, something seen from that **distance** must be **extremely unusual**!

Gamma-ray bursts remain a “hot” topic

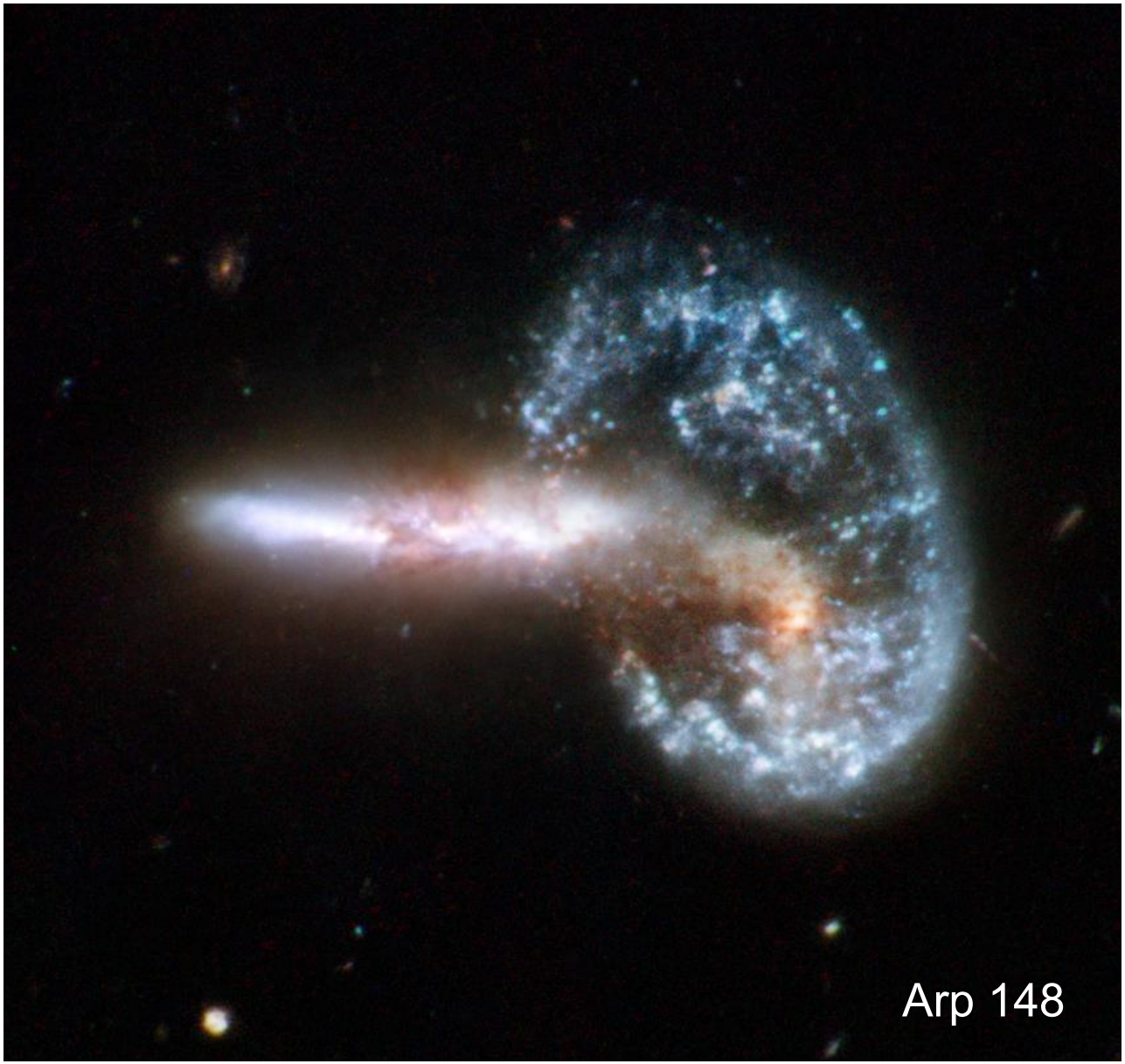


(https://gammaray.msfc.nasa.gov/batse/grb/duration/)

In 1968, Arp's *peculiar galaxies* were powerful visuals

In 1968, Halton Arp showed images from his 1966 catalog: "Atlas of **Peculiar Galaxies**" at an astronomy symposium at the U. of Toronto.

His presentations were the most **electrifying** at the meeting!

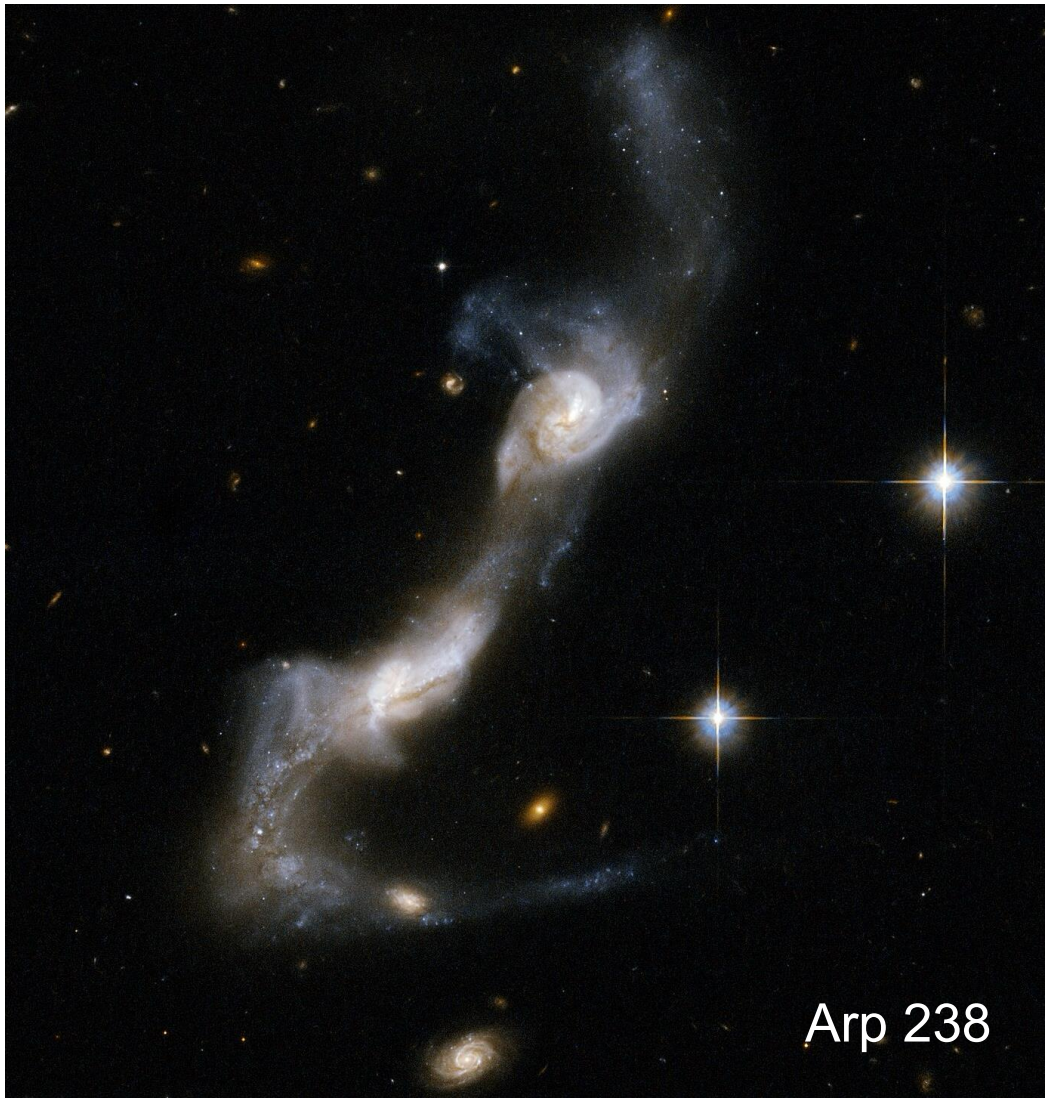


(https://en.wikipedia.org/wiki/Atlas_of_Peculiar_Galaxies)

Arp had ready access to the 200” Hale telescope

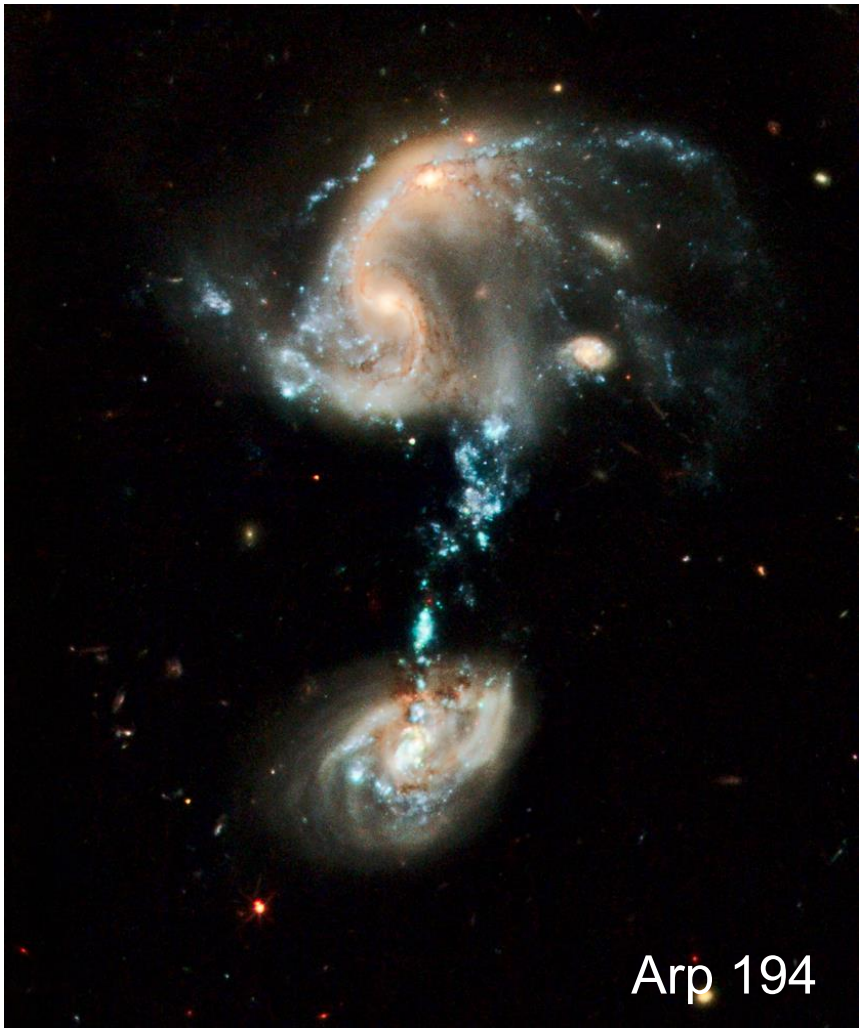
Arp focused on several topics including galaxies which showed unusual, or perturbed arms, or filamentary extensions.

(https://www.astroleague.org/al/obsclubs/arppec/arphalt.html)



What are these distorted galaxies?

Many of his images showed what appeared to be streams, or material-flow, linking the galaxies.

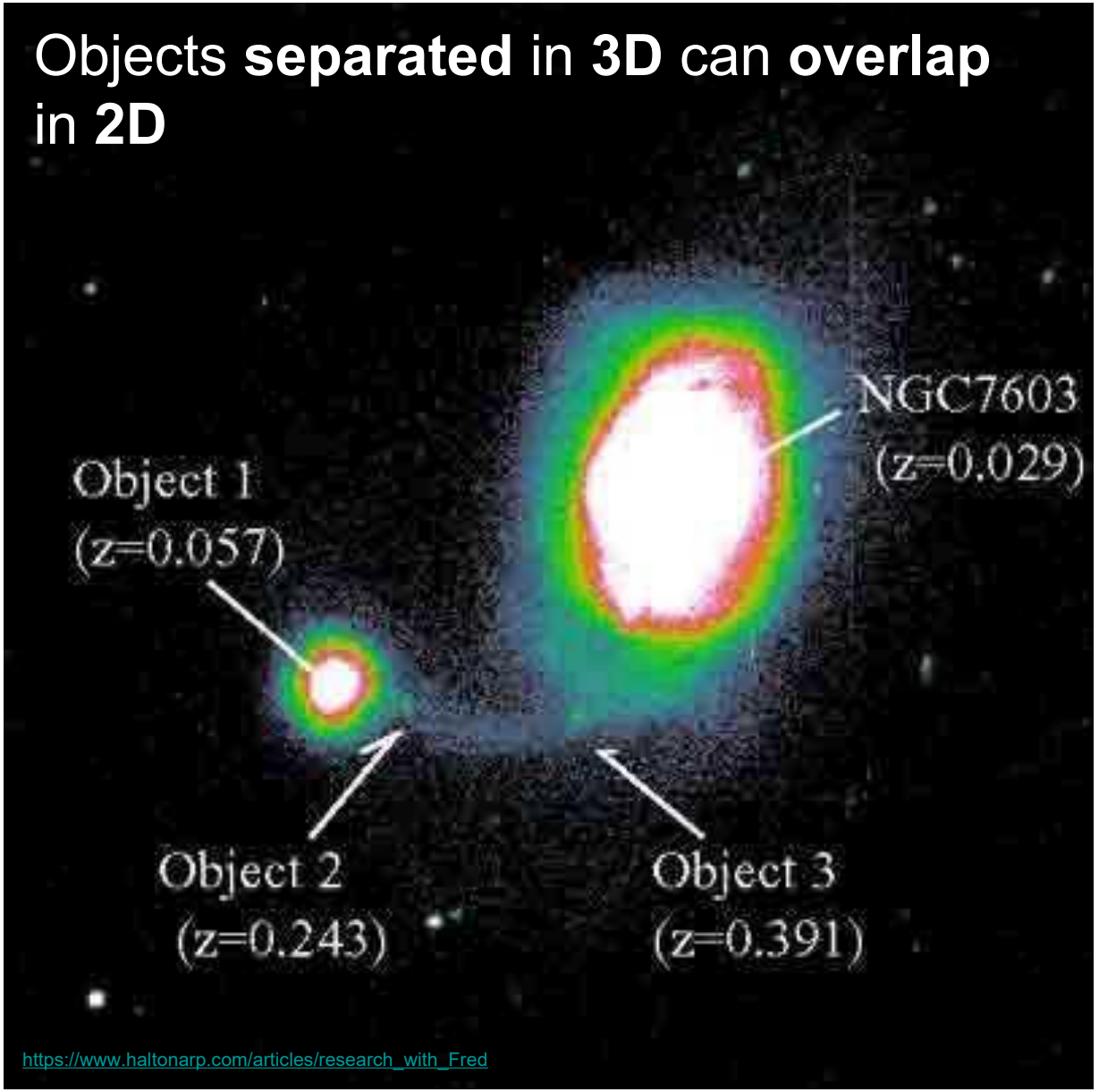


(https://en.wikipedia.org/wiki/Atlas_of_Peculiar_Galaxies)

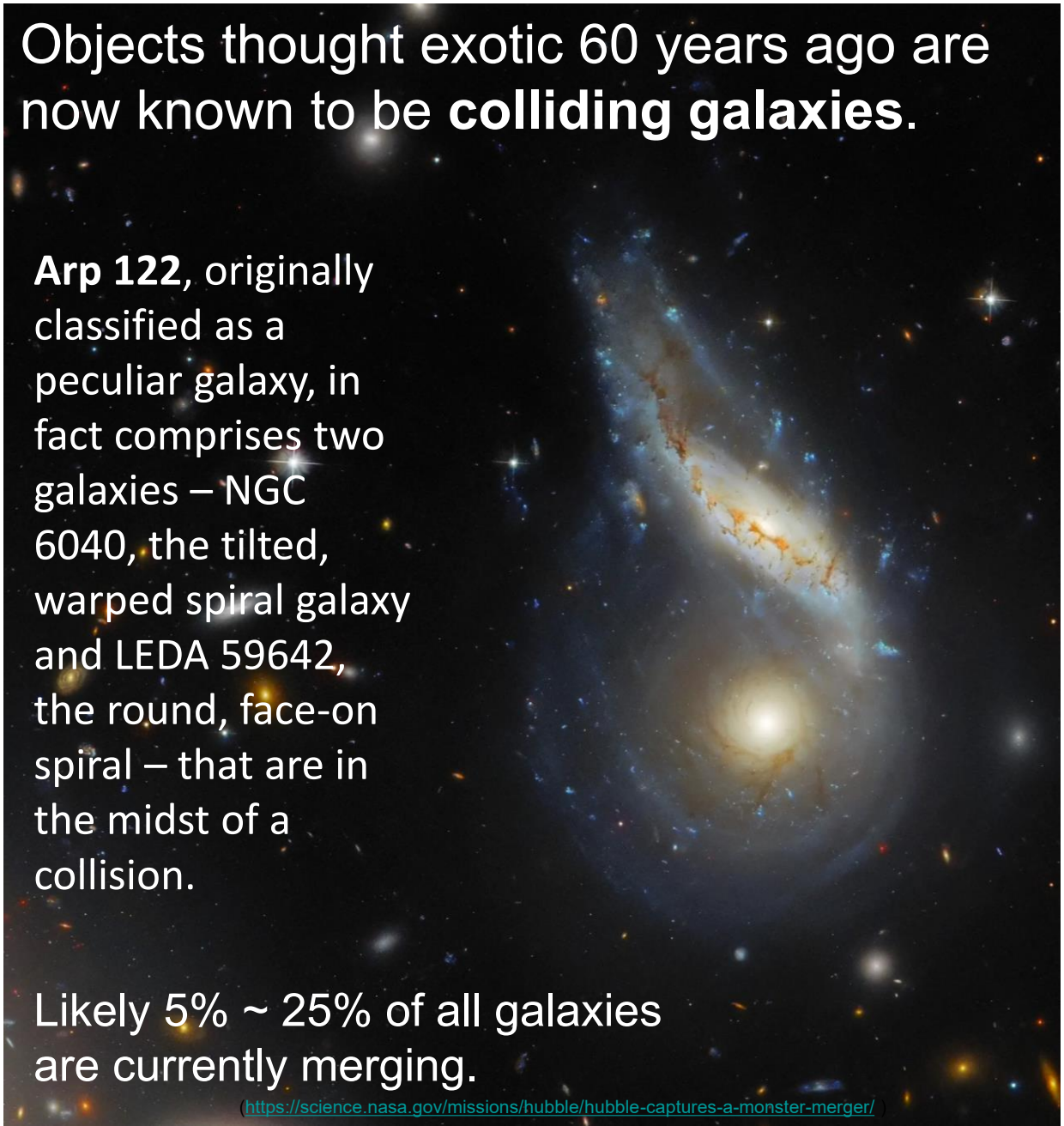
Is there truly a *Redshift Controversy*? Likely no.

A few of Arp's images show streams, or material-flow, **linking sources** at **very different red shifts**!

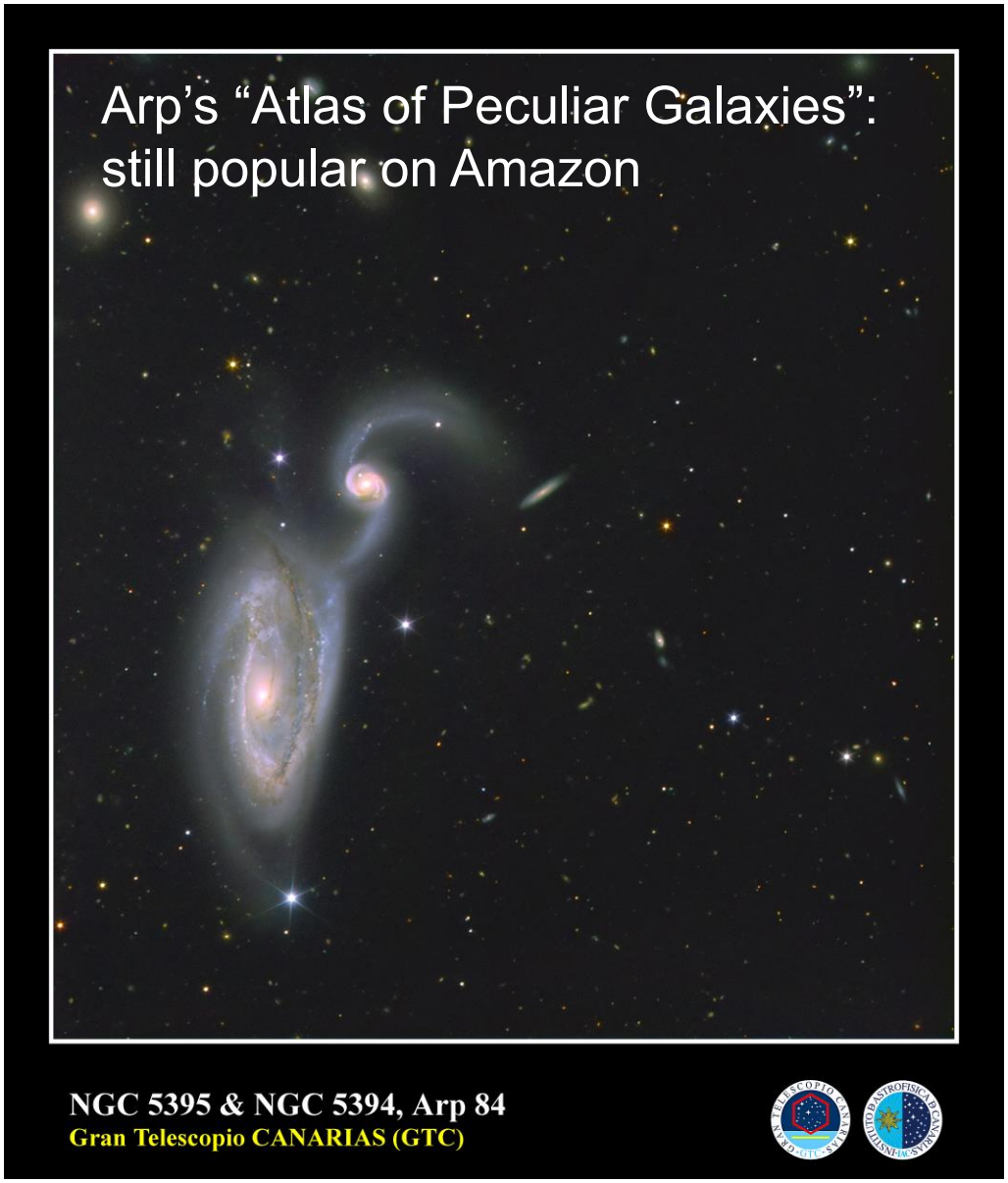
Based on these *pairings* Arp **challenged** the assignment of **redshifts** and the related **expansion** of the **universe** in his 1973 book: *The Redshift Controversy*.



Today galaxy collisions are known to be commonplace



What's left? For many, Arp's galaxies have a timeless beauty



(http://www.gtc.iac.es/multimedia/imageGallery.php)

(Arp 244: https://en.wikipedia.org/wiki/Atlas_of_Peculiar_Galaxies)

Summary - 1960s serendipitous discoveries in Astronomy

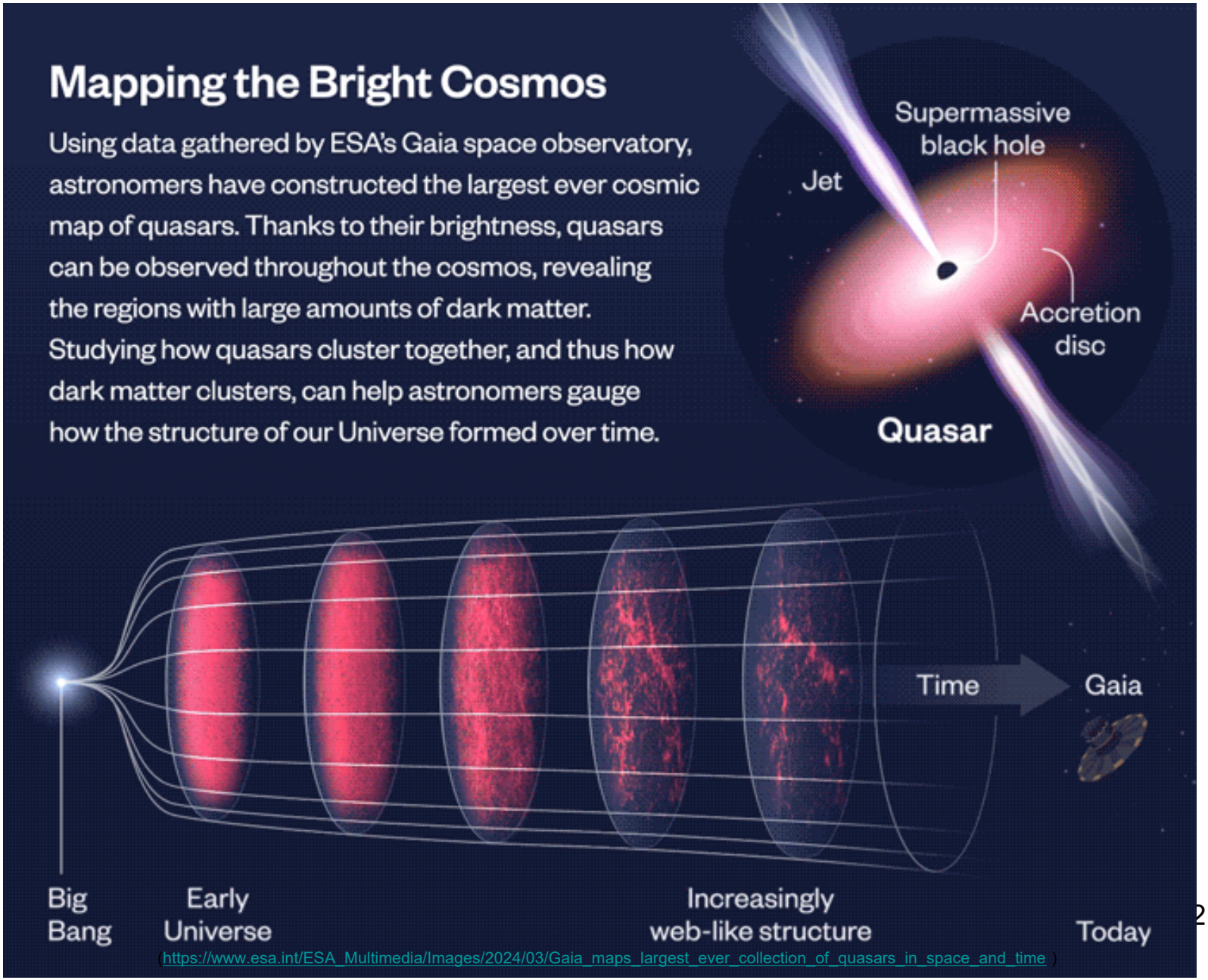
- **Quasars**: brightest sources in the universe explained by **supermassive black holes** in a ***peak feeding*** **period**

- **CMB:** remnant photons from the tiny (1 in 10^9) matter-anti-matter asymmetry and annihilation about 1 second after the Big Bang. The most concrete evidence for the Big Bang theory

- **Pulsars:** explained by *lighthouse* emissions from **young**, rapidly rotating **neutron stars**

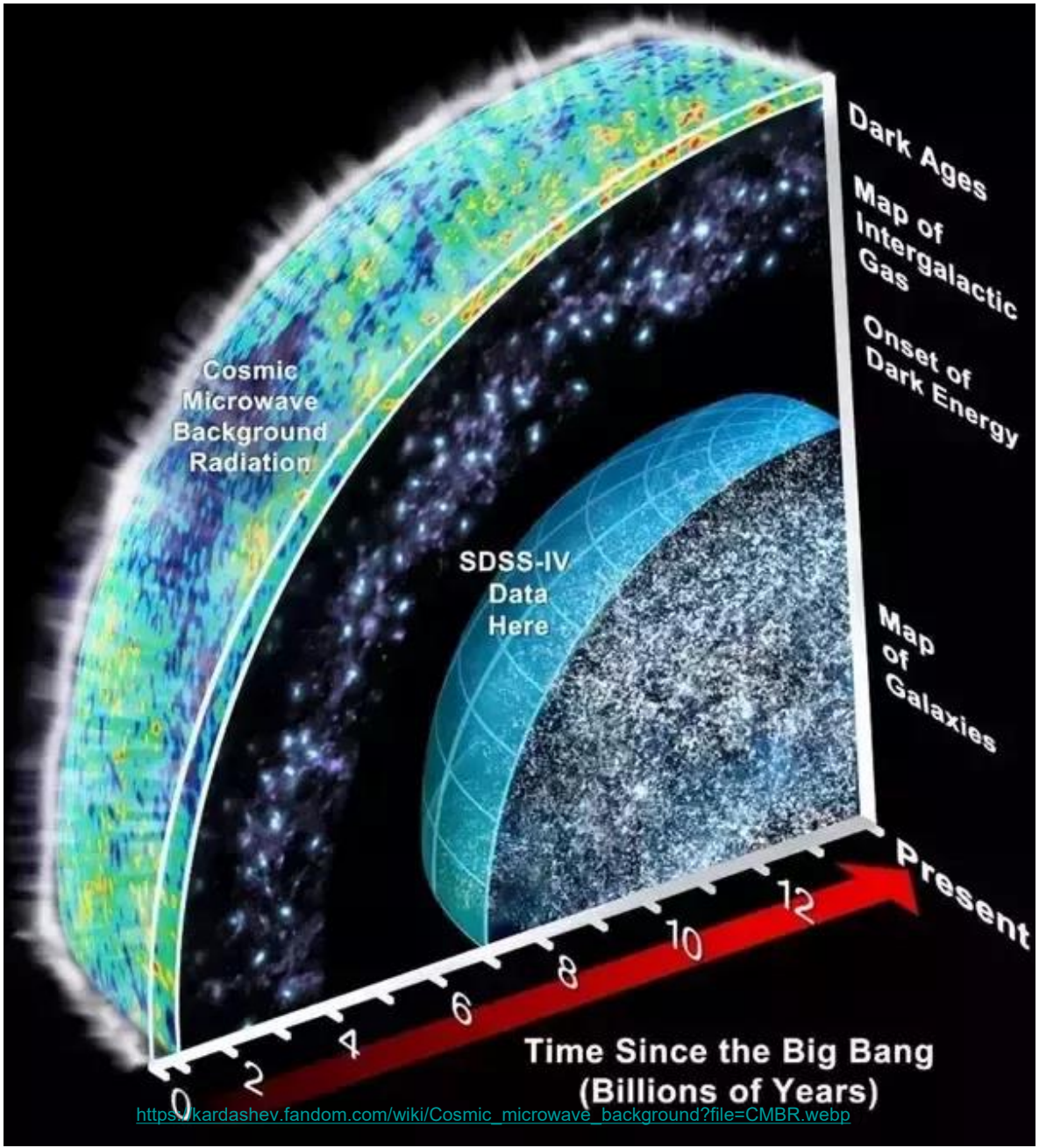
- **Gamma-ray bursts:** likely **neutron star:neutron star** mergers and/or **core collapse hypernovas** to **black holes.** Brightness is likely the result of significant *beamed* emissions.

Quasars today? Mapping the universe's web-like structure



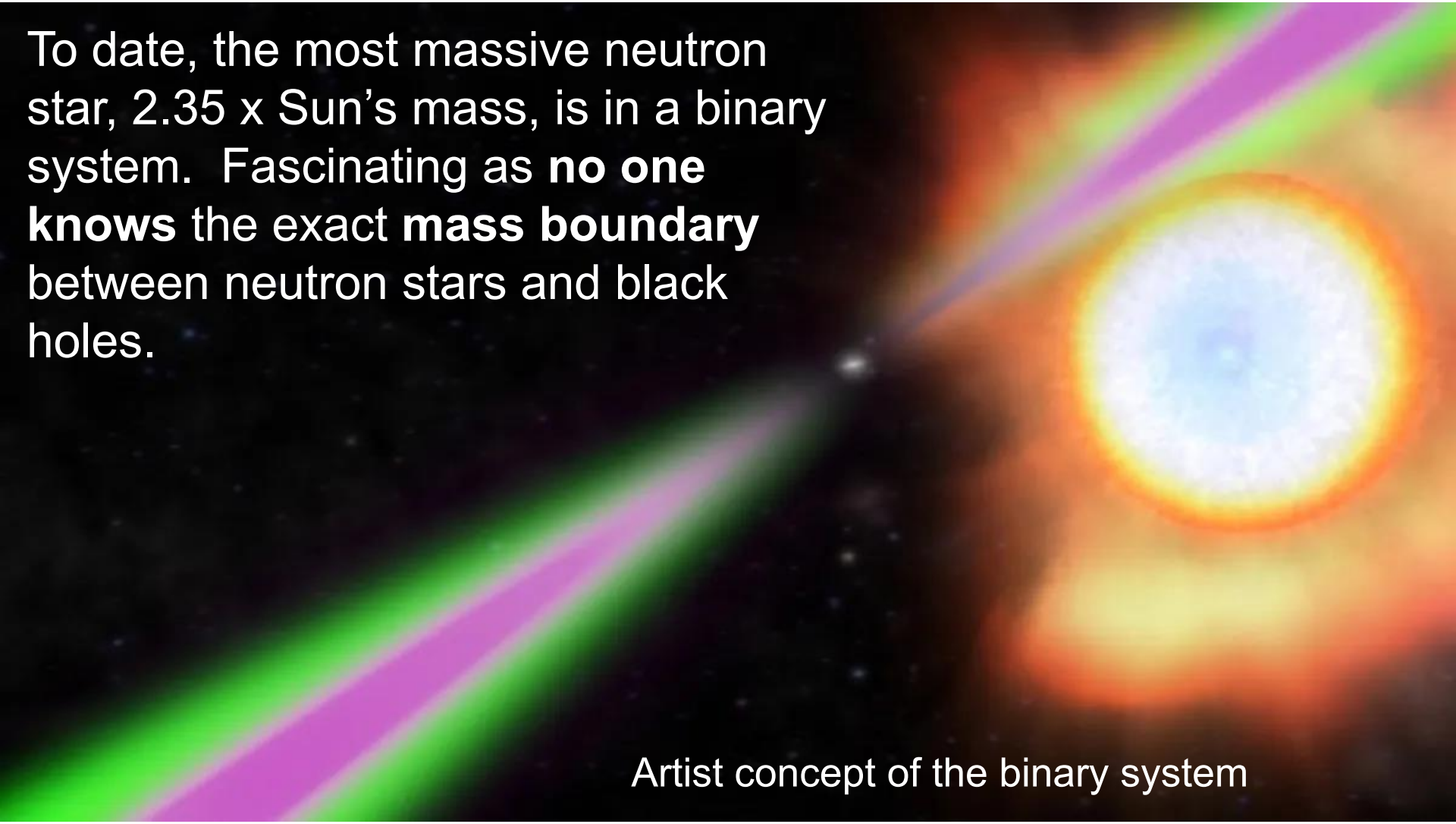
(https://www.esa.int/ESA_Multimedia/Images/2024/03/Gaia_maps_largest_ever_collection_of_quasars_in_space_and_time)

CMB today? Tiny CMB variations seed today's web of galaxies



https://kardashev.fandom.com/wiki/Cosmic_microwave_background?file=CMBR.webp

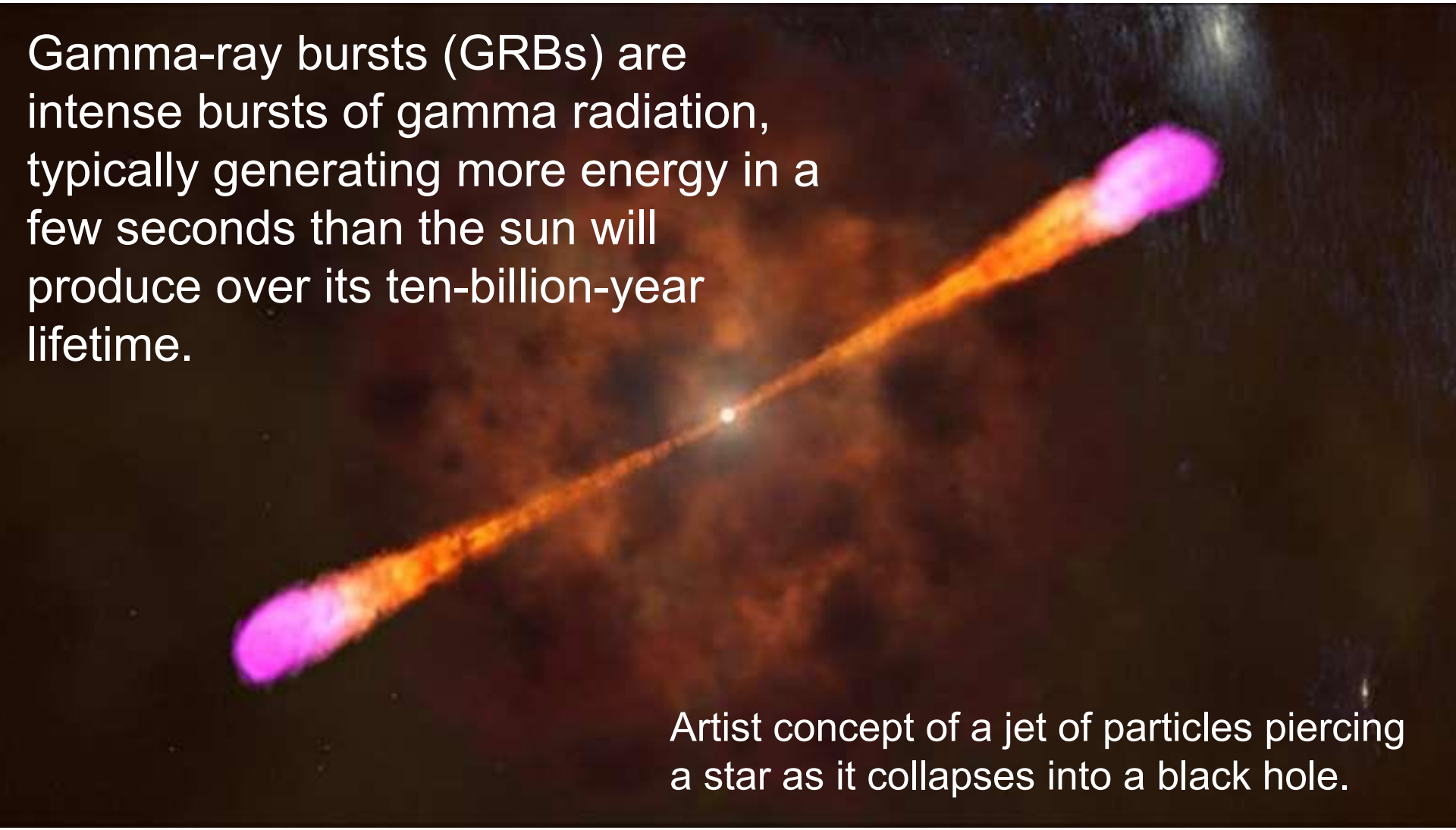
Pulsars today? What is the neutron star-black hole boundary?



(https://www.space.com/heaviest-neutron-star-shredding-companion)

GRBs today? The details are still a puzzle after 50+ years

Gamma-ray bursts (GRBs) are intense bursts of gamma radiation, typically generating more energy in a few seconds than the sun will produce over its ten-billion-year lifetime.



Artist concept of a jet of particles piercing a star as it collapses into a black hole.

(https://phys.org/news/2024-04-astrophysics-advances-gamma-ray.html#google_vignette)

Thank you

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1960s: Decade of Serendipity (in Astronomy)