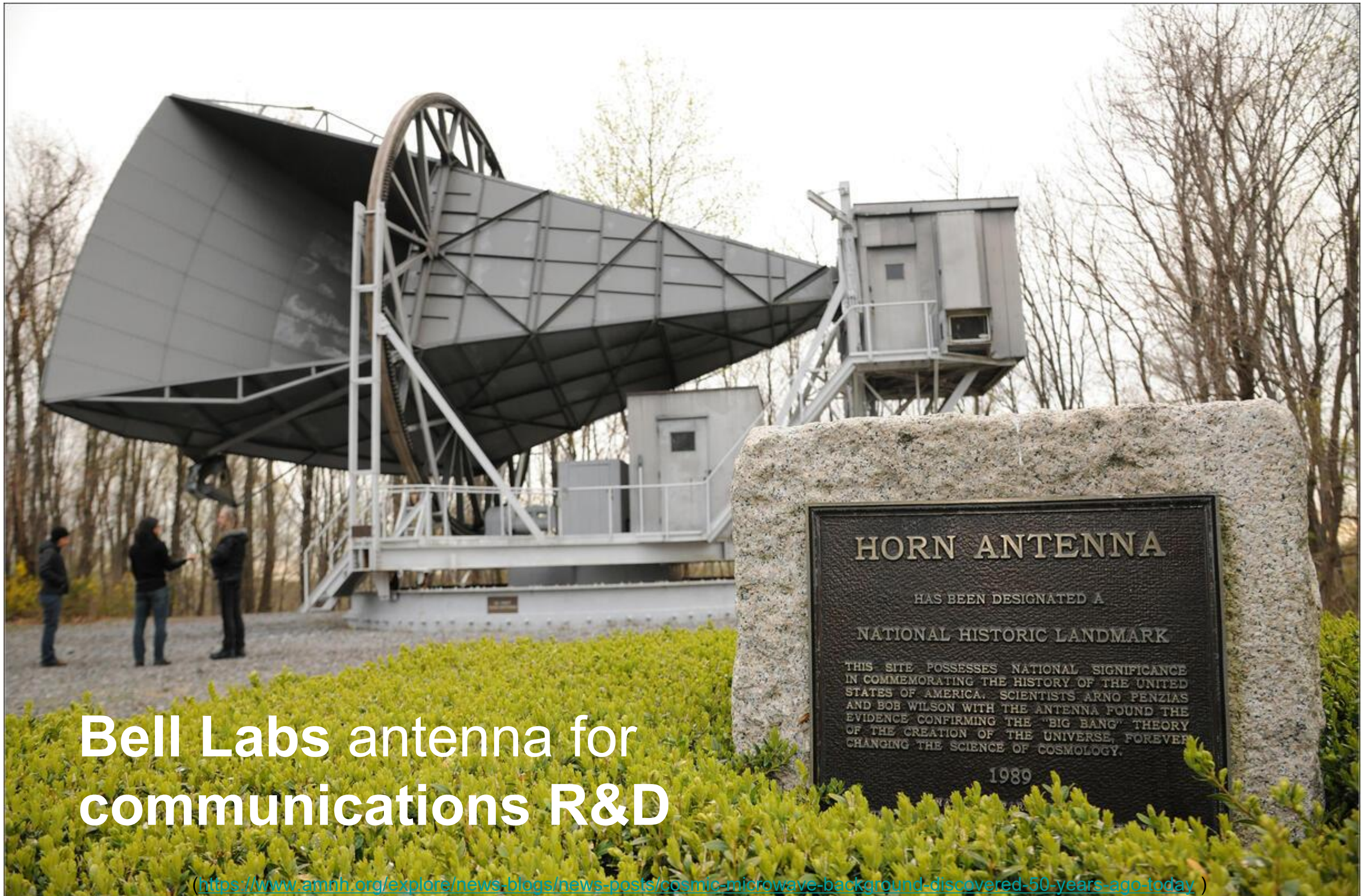
1960s: Decade of Serendipity



Bell Labs antenna for **communications R&D**

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

John Matthews

Professor of Physics, U. of New Mexico

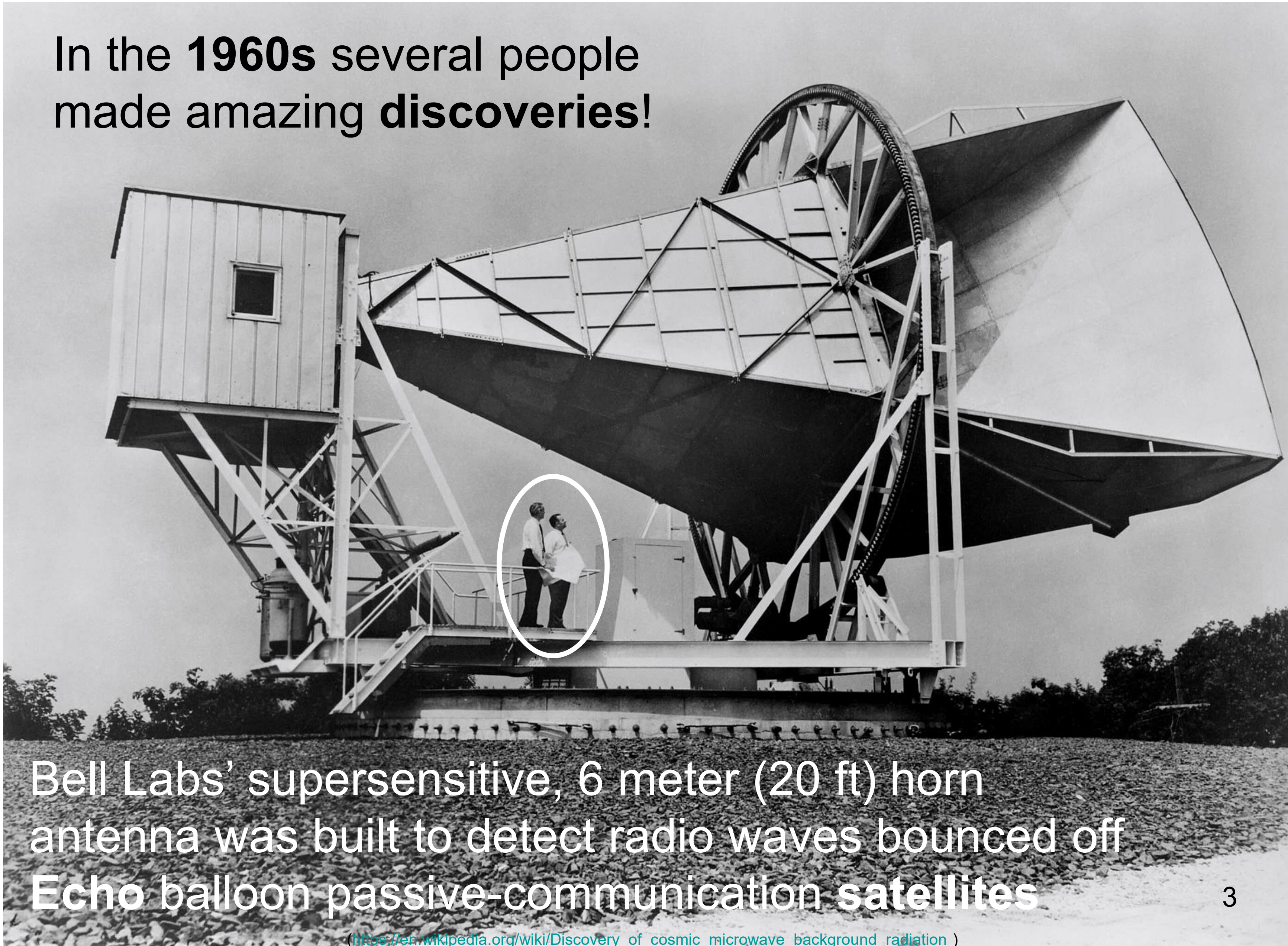
1960s, when was that?

"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)

“Maybe we can do some radio-astronomy with it?”

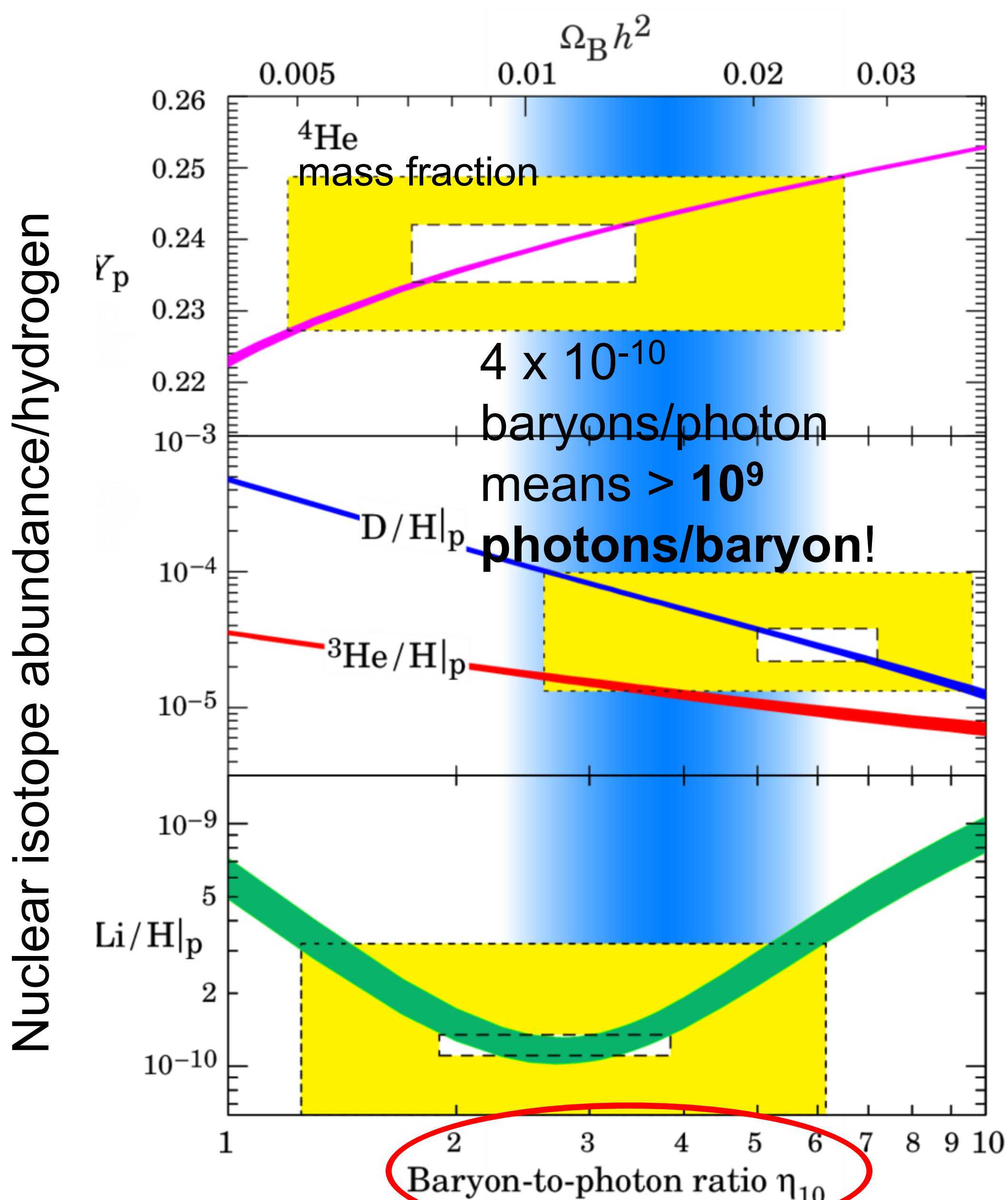


In the **1960s** several people made amazing **discoveries**!

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)

BBN isotope predictions needed a huge flux of gamma-rays



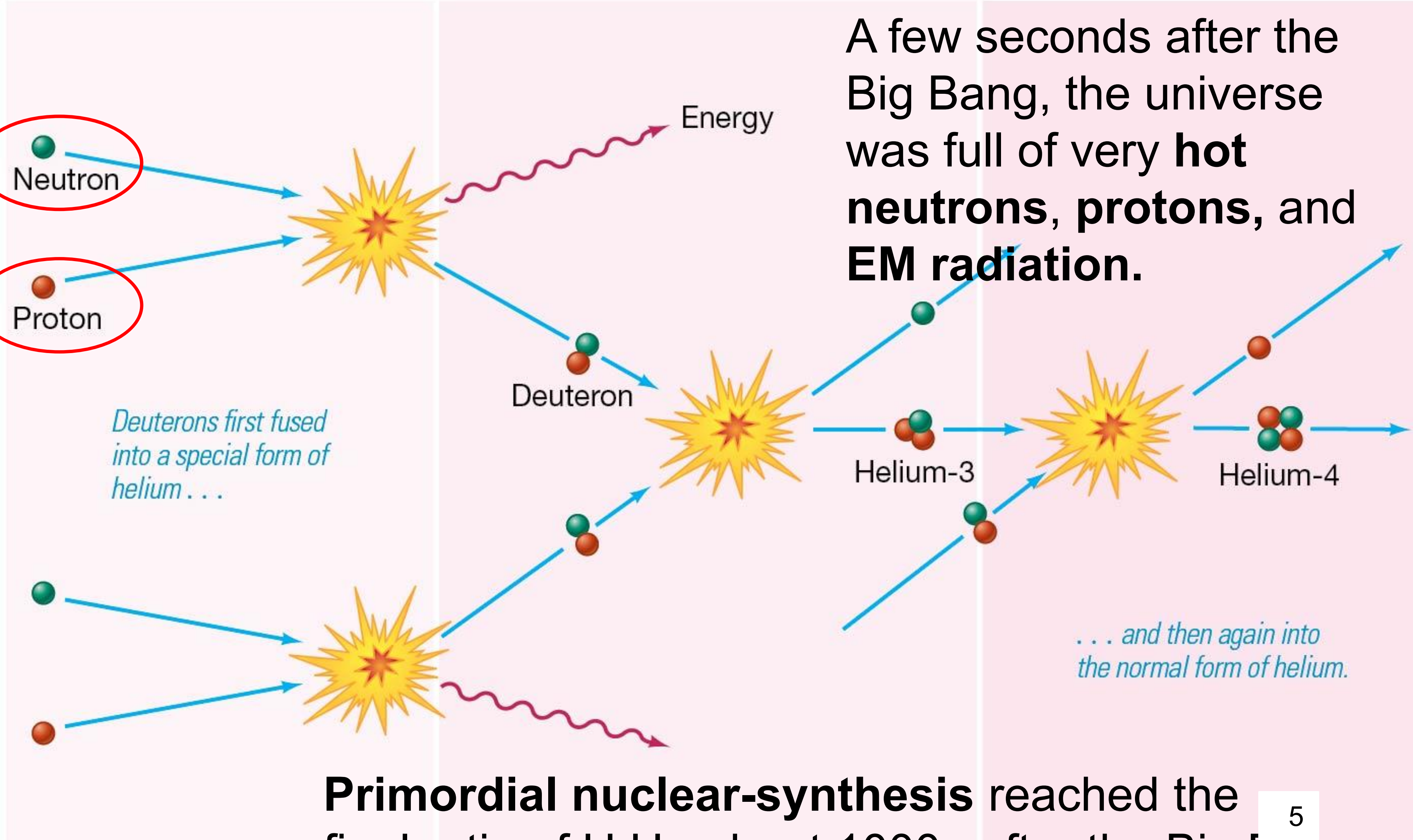
(https://www.researchgate.net/figure/The-primordial-abundances-of-4-He-D-3-He-and-7-Li-as-predicted-by-the-standard-BBN_fig2_2007022)

The universe is mostly **H** and **He**: why is that?

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

For nuclear fusion to happen the universe had to be very hot

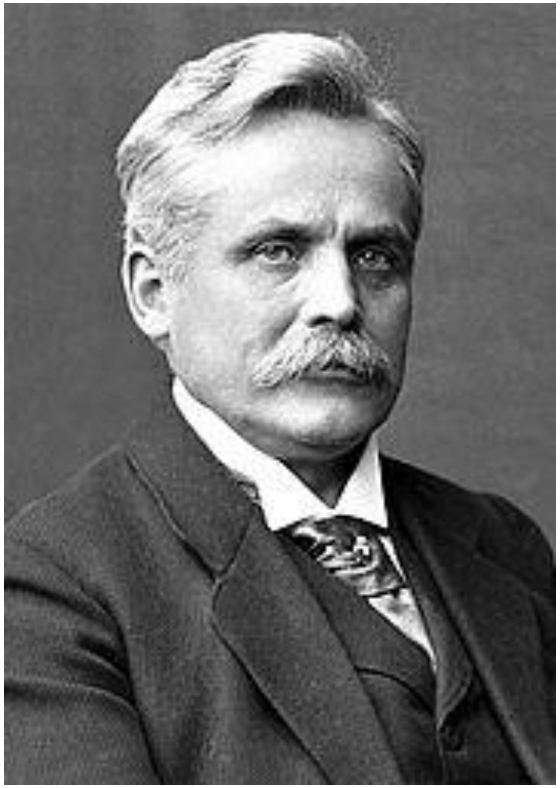
A few seconds after the Big Bang, the universe was full of very **hot neutrons**, **protons,** and **EM radiation.**

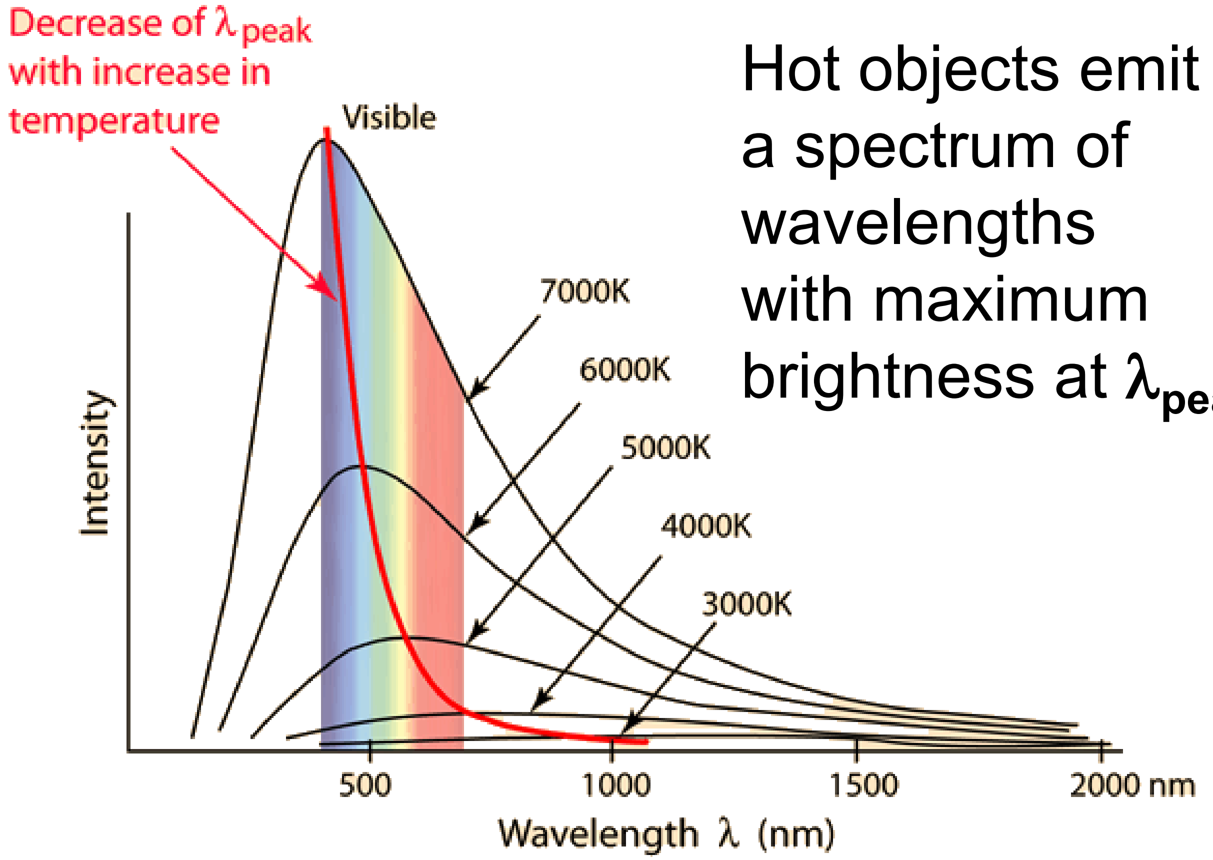


Primordial nuclear-synthesis reached the final ratio of H:He about 1000s after the Big Bang

Very hot typically means very short EM radiation wavelengths

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



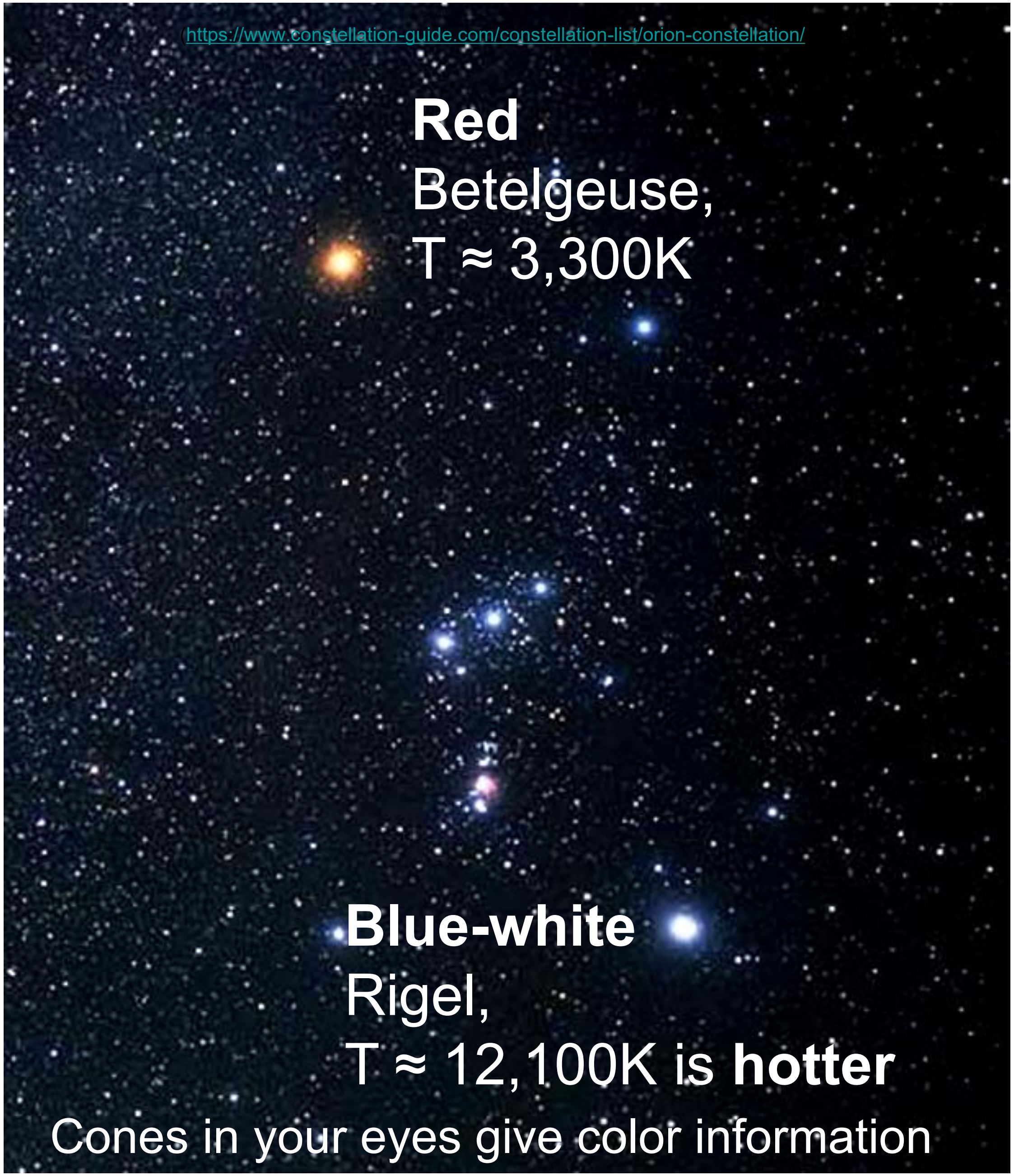


Hot objects emit a spectrum of wavelengths with maximum brightness at $\lambda_{\mathbf{peak}}$

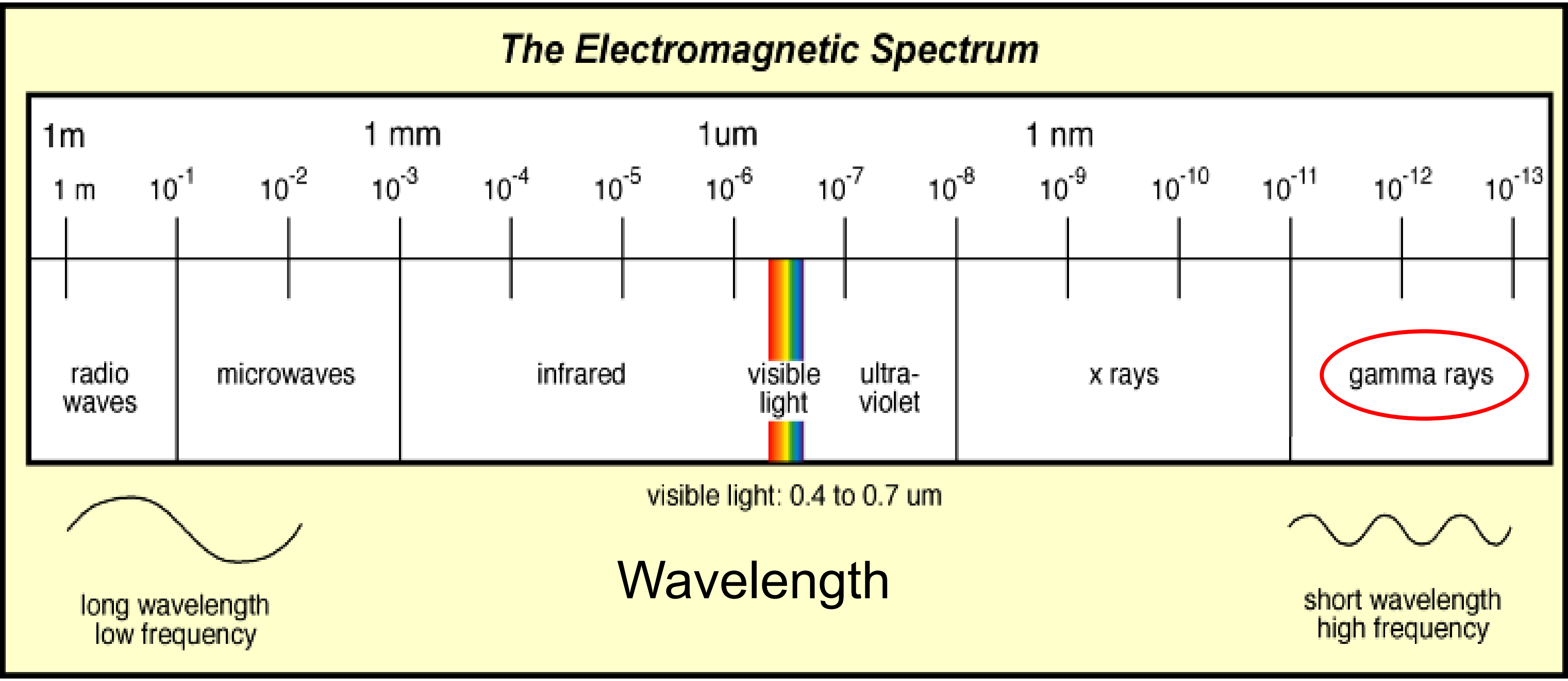
Wilhelm Wien, 1911 Nobel Prize in Physics

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

You experience this as the colors of bright stars



We call very short wavelength EM radiation gamma-rays

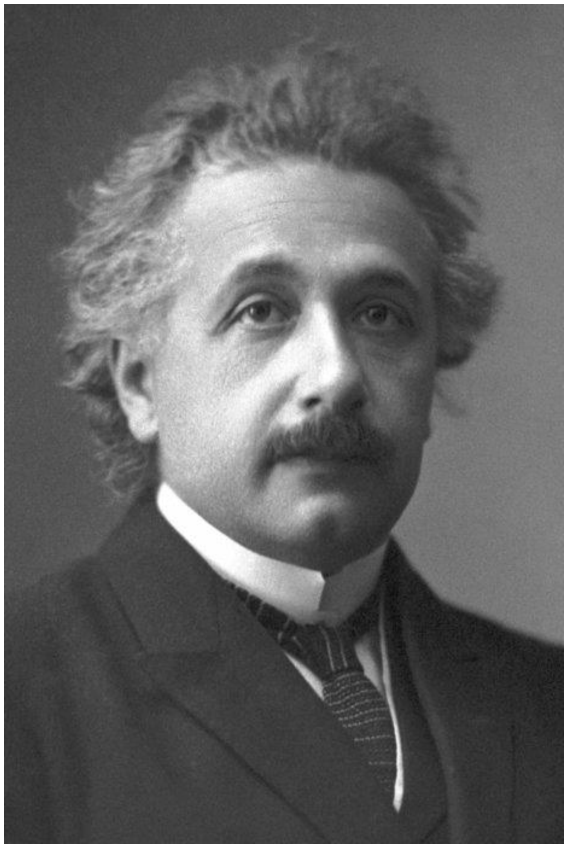


The **shortest wavelength** EM radiation is called **gamma-rays**

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

EM radiation comes in packets called photons: crazy but true

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



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

The energy of a photon is $\mathbf{E_\gamma = h\ f = h\ c\ /\ \lambda}$.

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

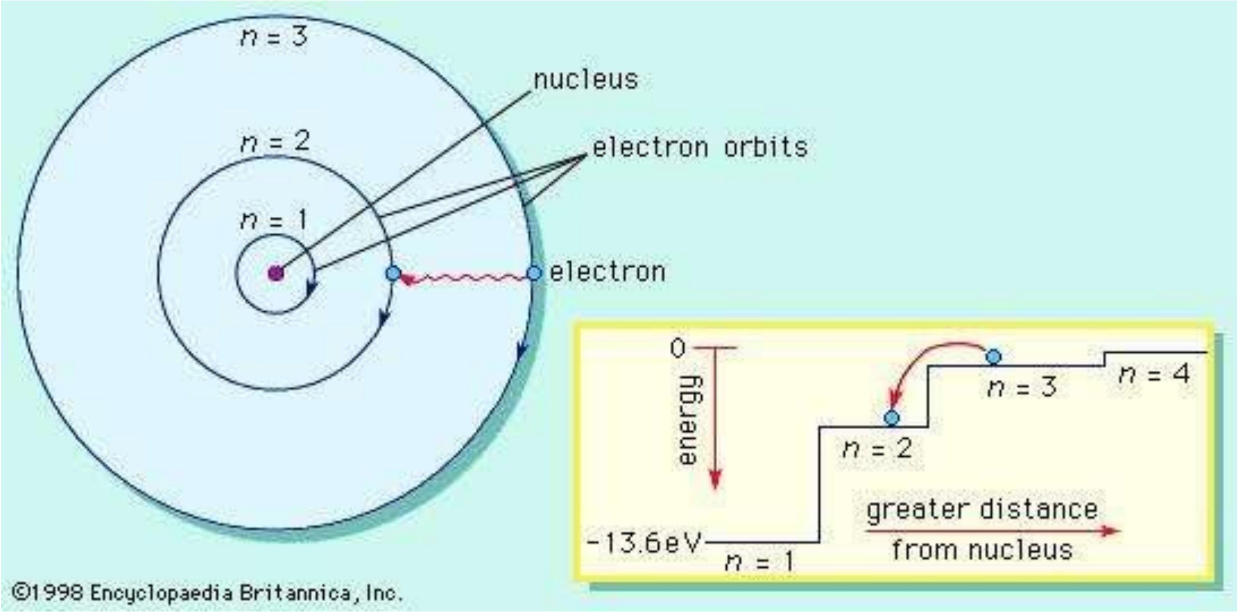
Albert Einstein, 1921 Nobel Prize in Physics

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

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.

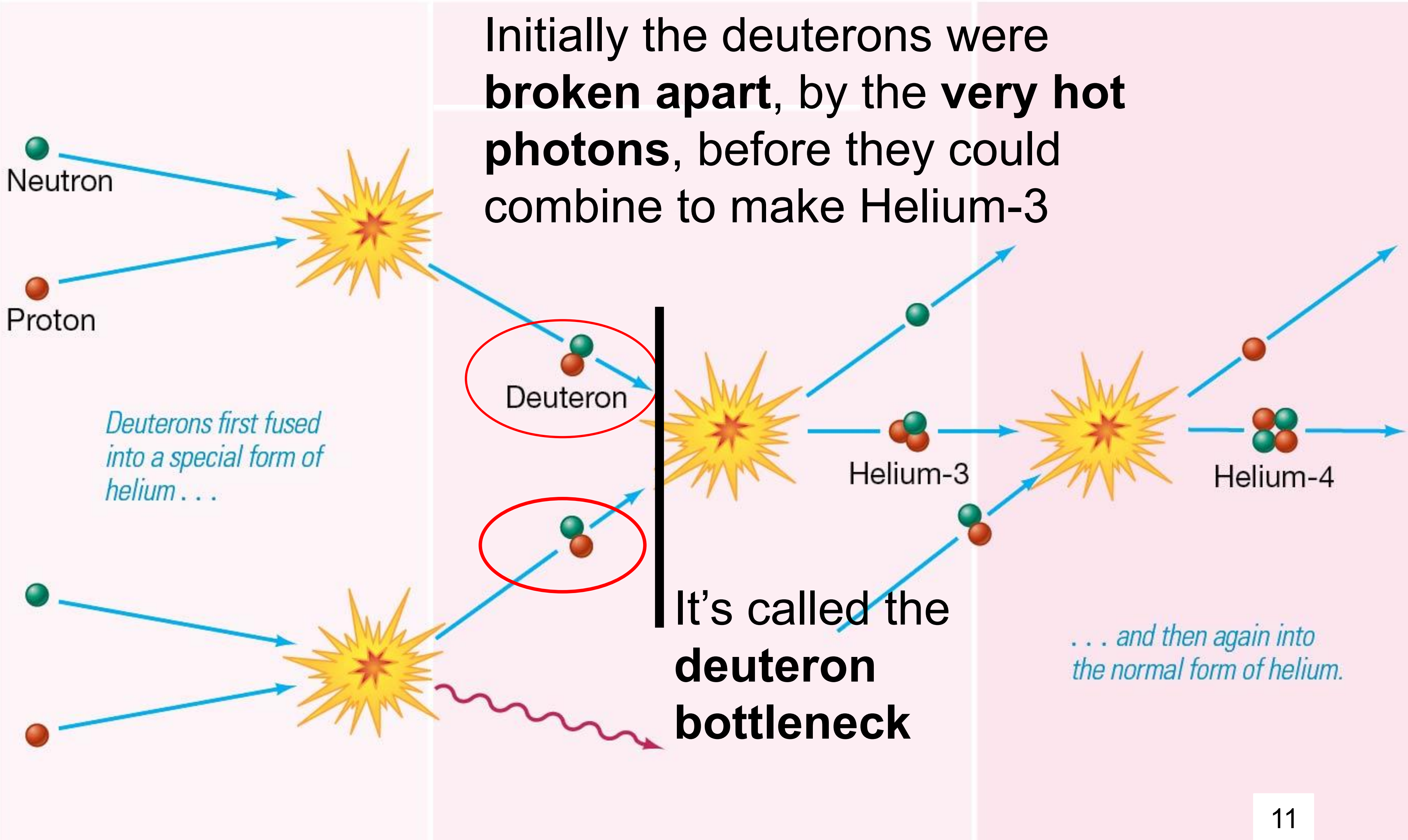


(https://www.nobelprize.org/prizes/physics/1922/bohr/facts/ and https://www.britannica.com/science/atom/Orbits-and-energy-levels)

Niels Bohr, 1922 Nobel Prize in Physics

Thanks to Bohr and Einstein, the deuterons were broken apart

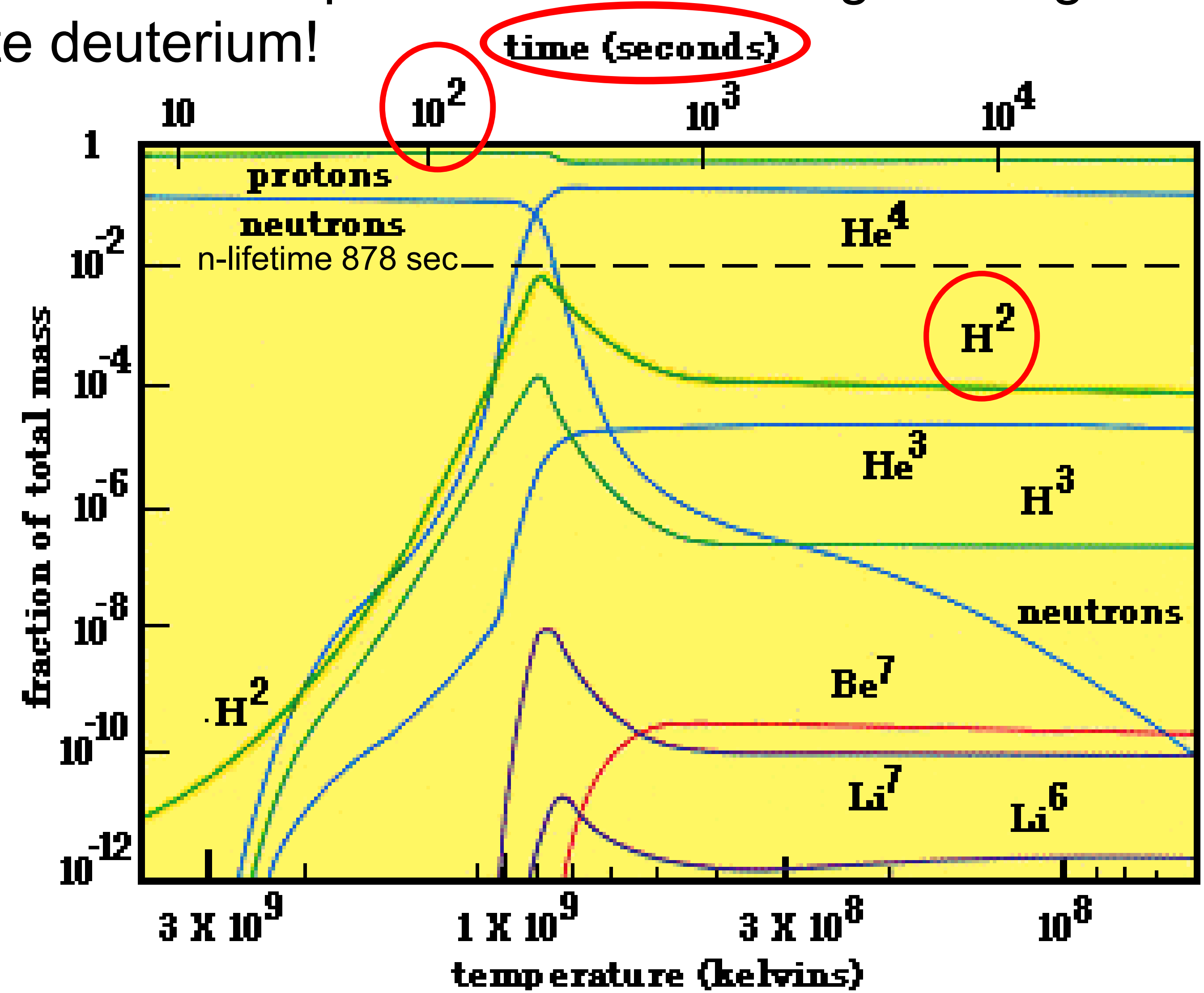
Initially the deuterons were **broken apart**, by the **very hot photons**, before they could combine to make Helium-3



It's called the **deuteron bottleneck**

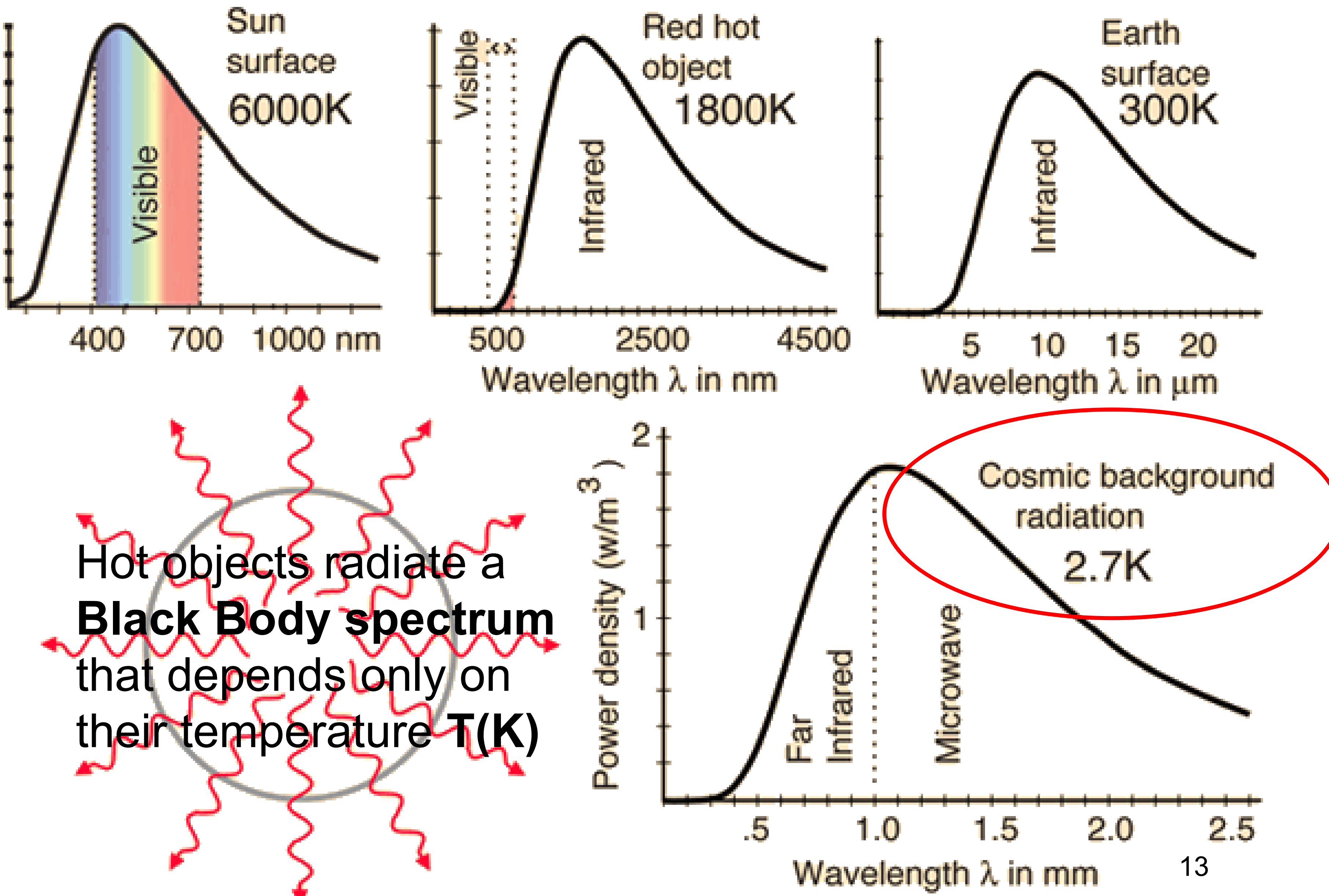
Universe expansion cooled the universe "just in time"

Between 10^2, and $4x10^2$ seconds the universe had cooled enough that the EM radiation photons were no longer energetic enough to dissociate deuterium!



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

Photon wavelengths get stretched to radio wavelengths today



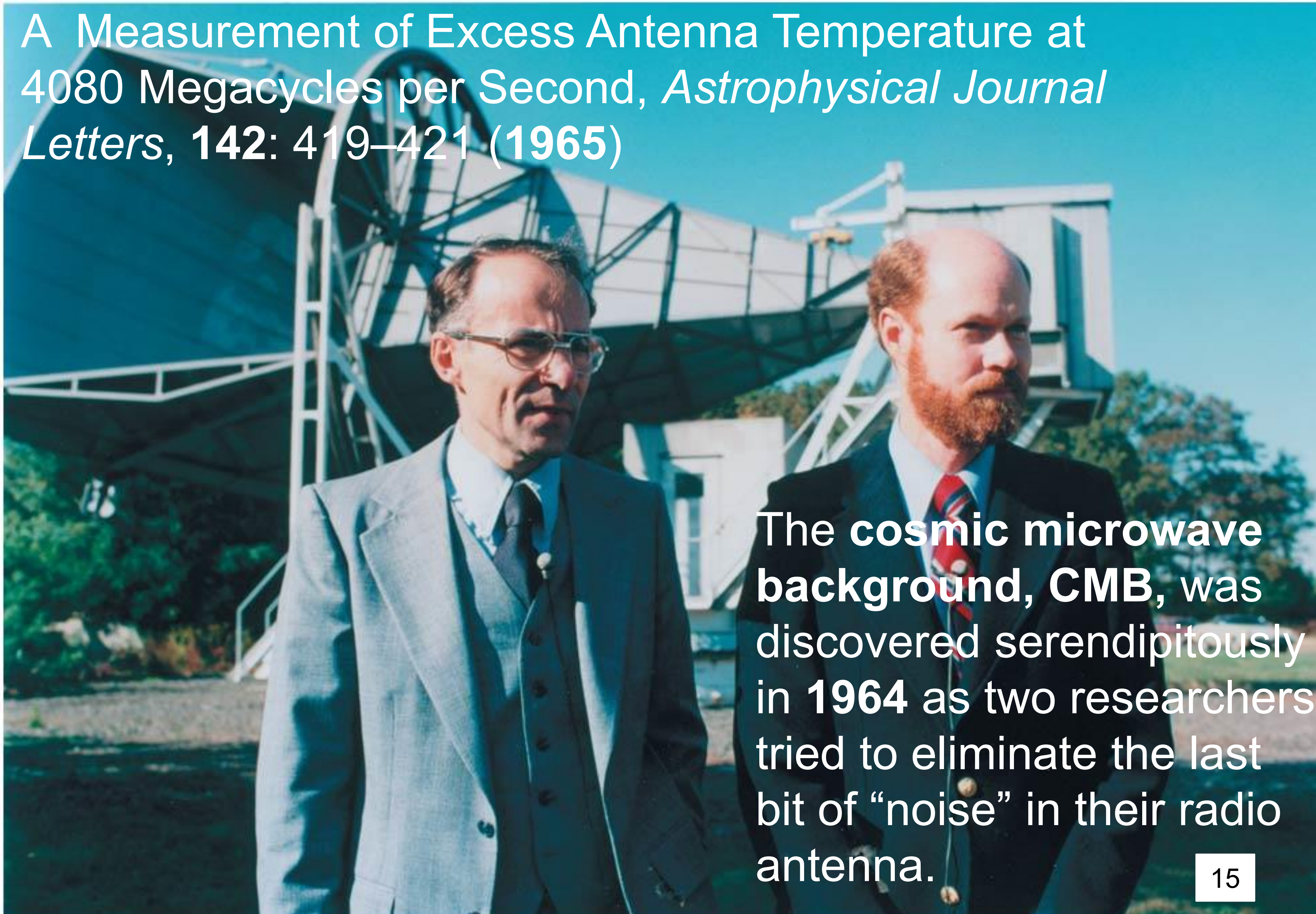
Hot objects radiate a **Black Body spectrum** that depends only on their temperature **T(K)**

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

The sensitive antenna had an irreducible background "hum"

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



A Measurement of Excess Antenna Temperature at 4080 Megacycles per Second, *Astrophysical Journal Letters*, **142**: 419–421 (**1965**)

The **cosmic microwave background, CMB,** was discovered serendipitously in **1964** as two researchers tried to eliminate the last bit of “noise” in their radio antenna.

CMB detection confirmed a Hot Big Bang prediction!

The Nobel Prize in Physics 1978

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

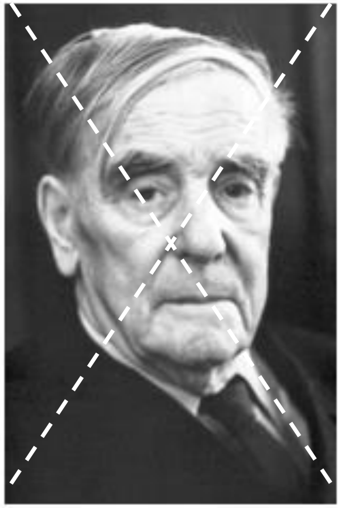


Photo from the Nobel Foundation archive.

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"

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 - 13 **gamma-ray bursts** had been 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.

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

Radio astronomy benefitted from WW II radar instrumentation

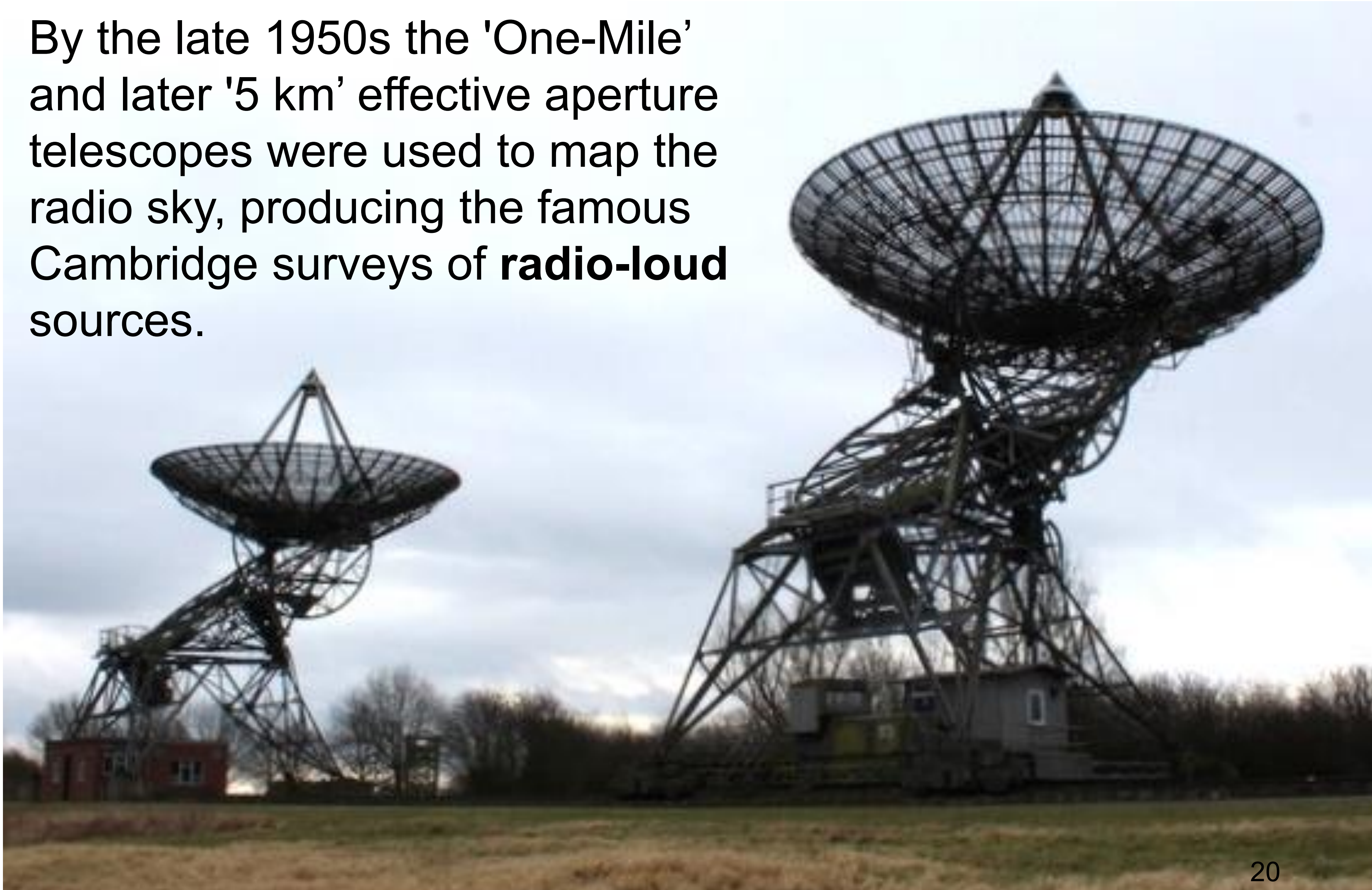
Mullard EL34 Power Pentode

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

- 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.

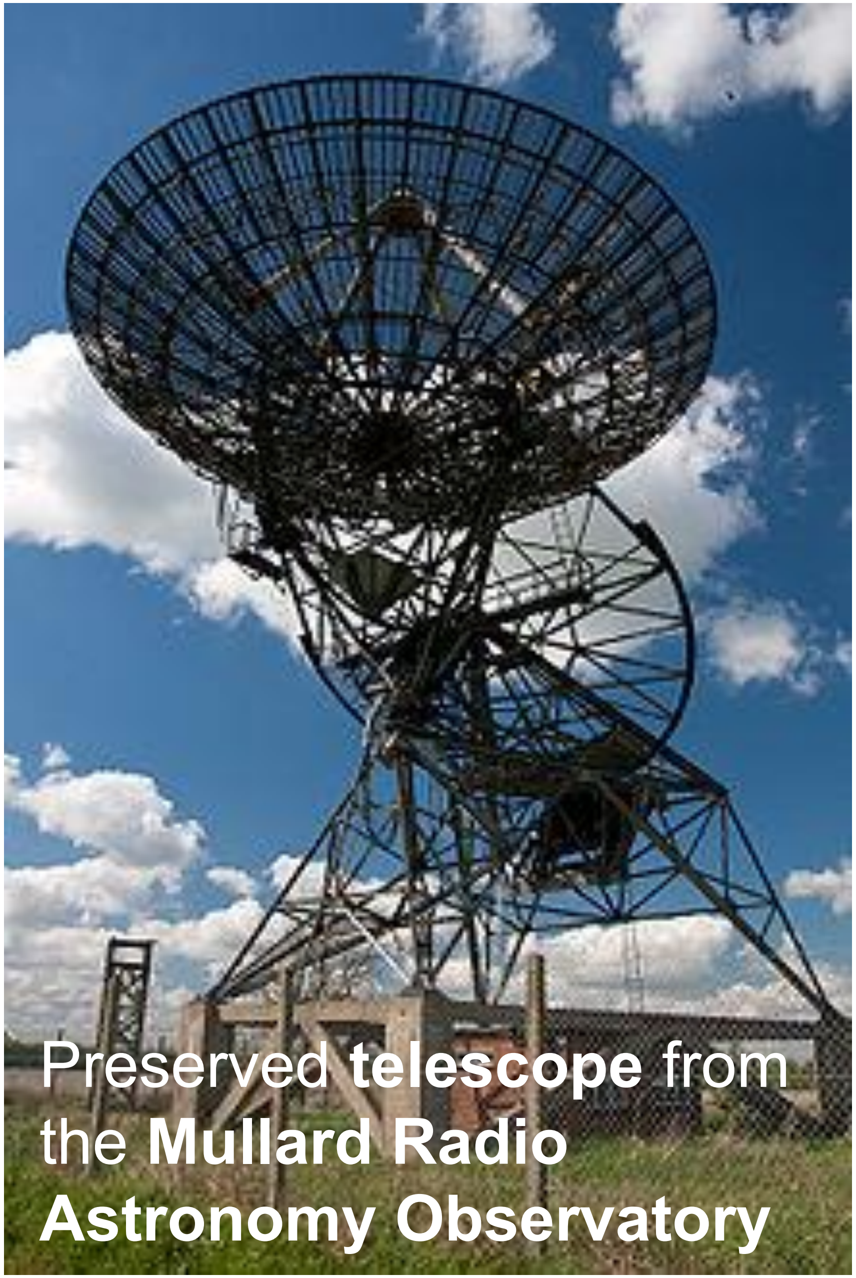
Cambridge 2C and 3C radio surveys

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?



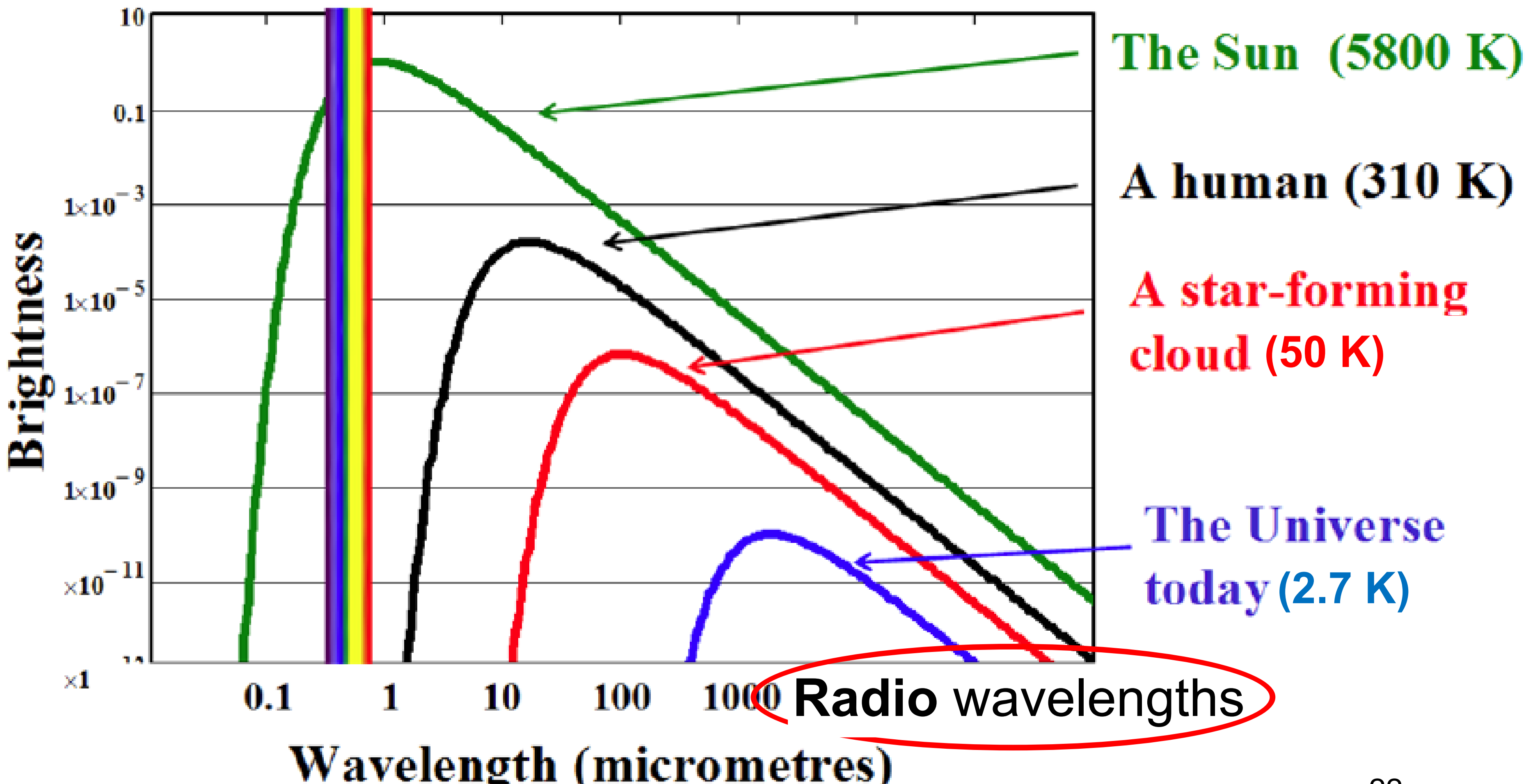
Radio-loud sources – are those with high luminosity at **radio wavelengths**.

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

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

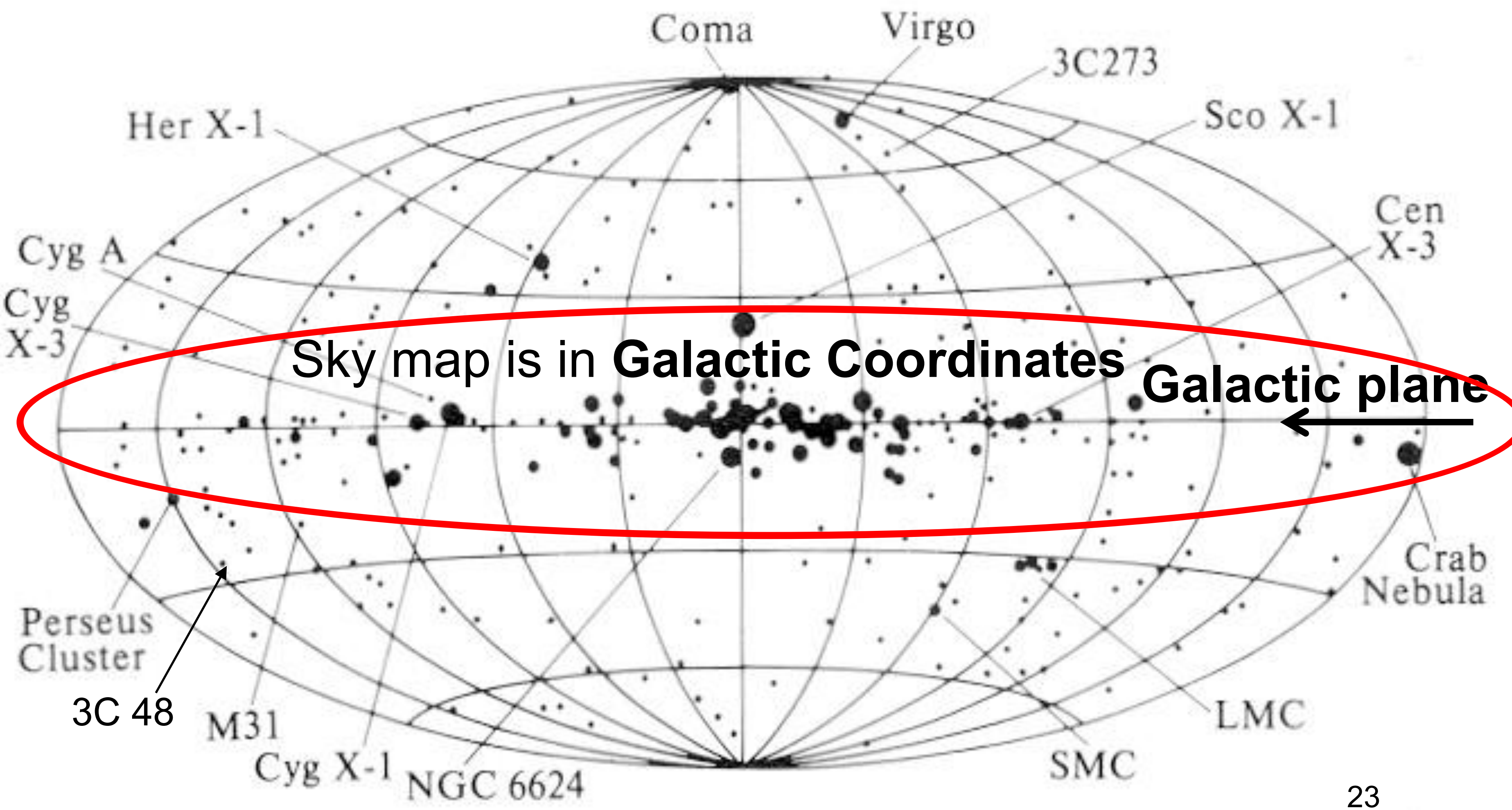
Conventional sources are not radio-loud

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



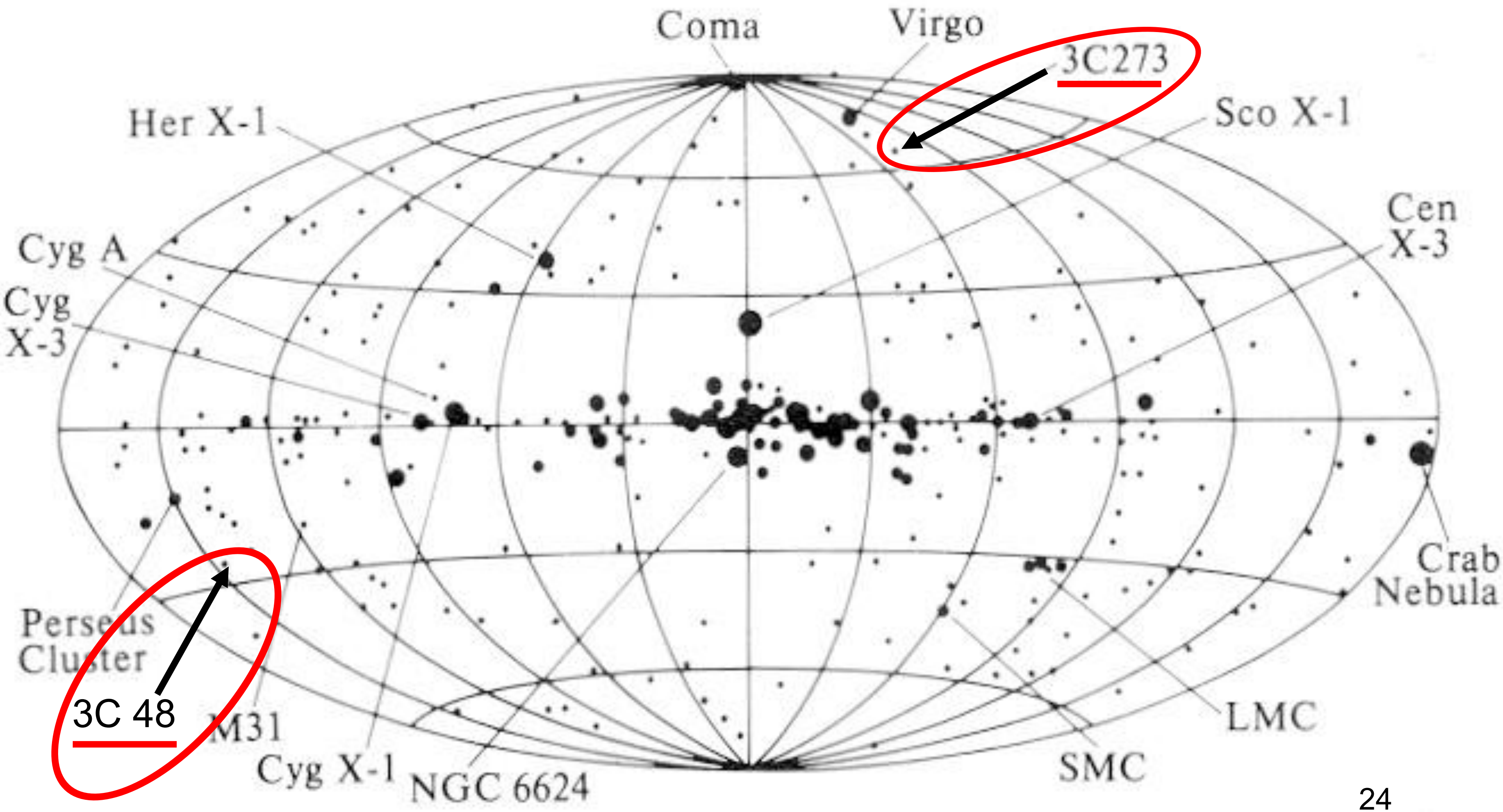
Many of the radio sources were likely in the Milky Way

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

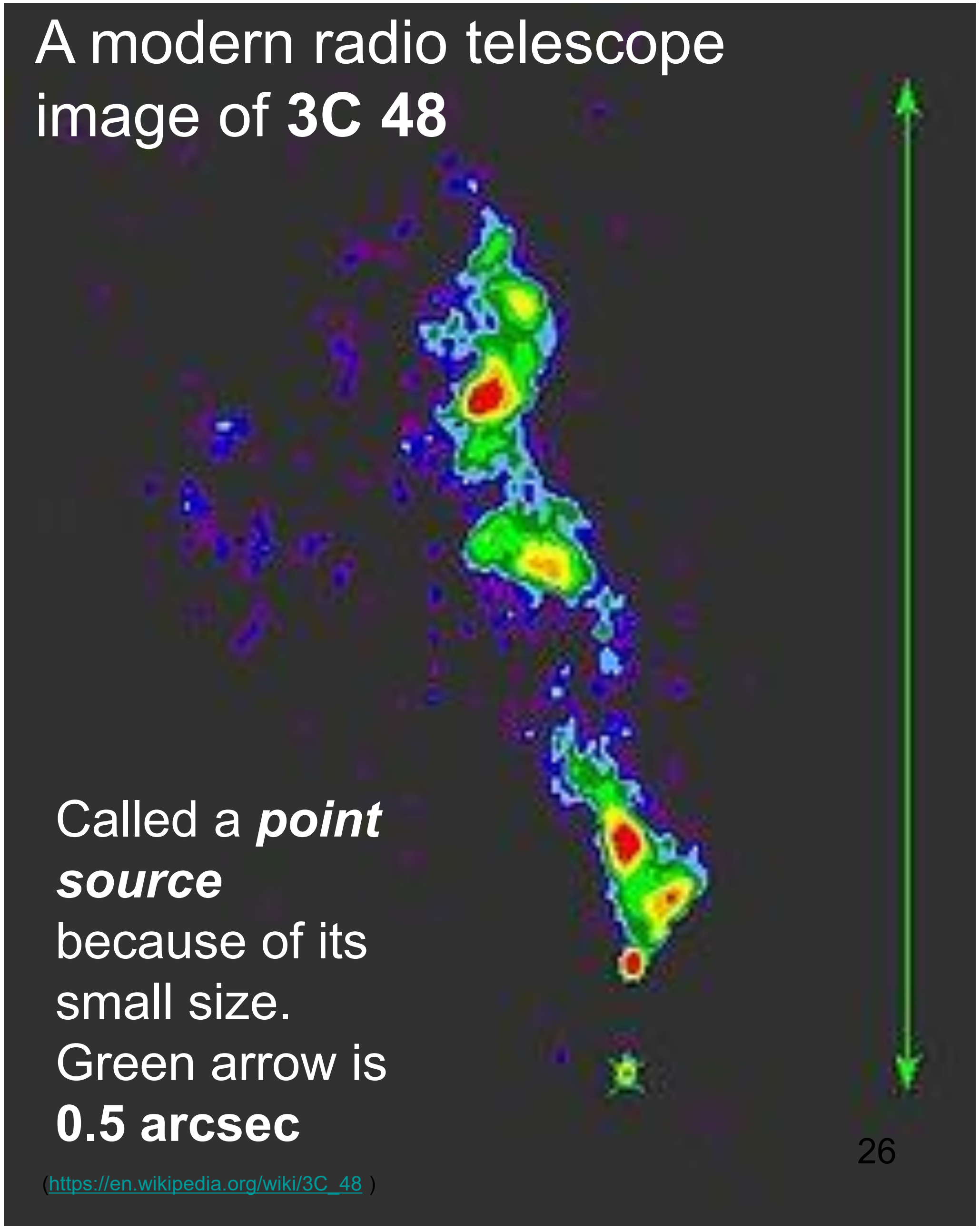
Optical counterparts of the Cambridge **3C catalog sources** should help unravel the *physics* of these radio-loud objects.

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

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

1st breakthrough from improved radio source location

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

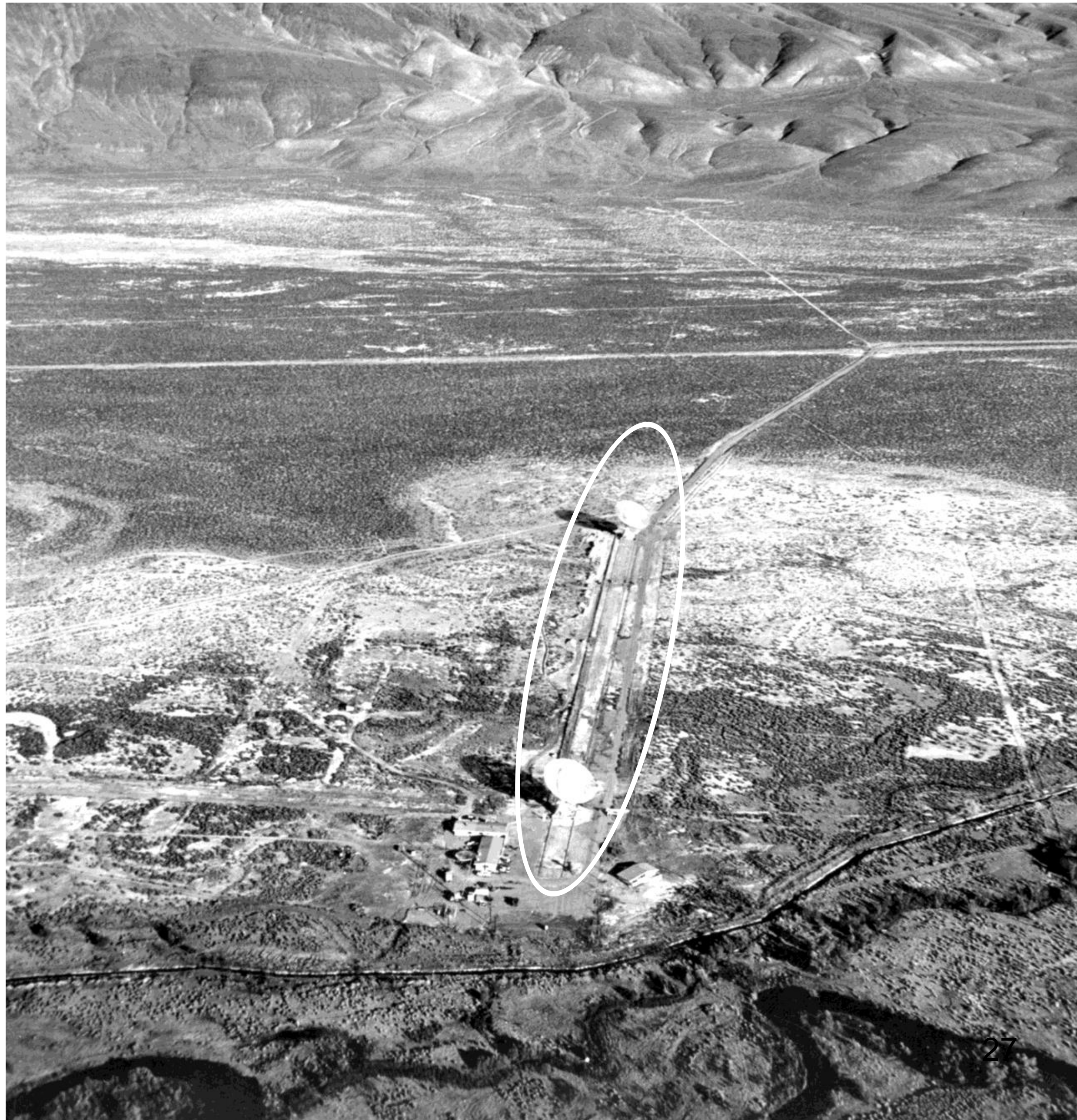


Position uncertainty of 3C 48 needed to be reduced

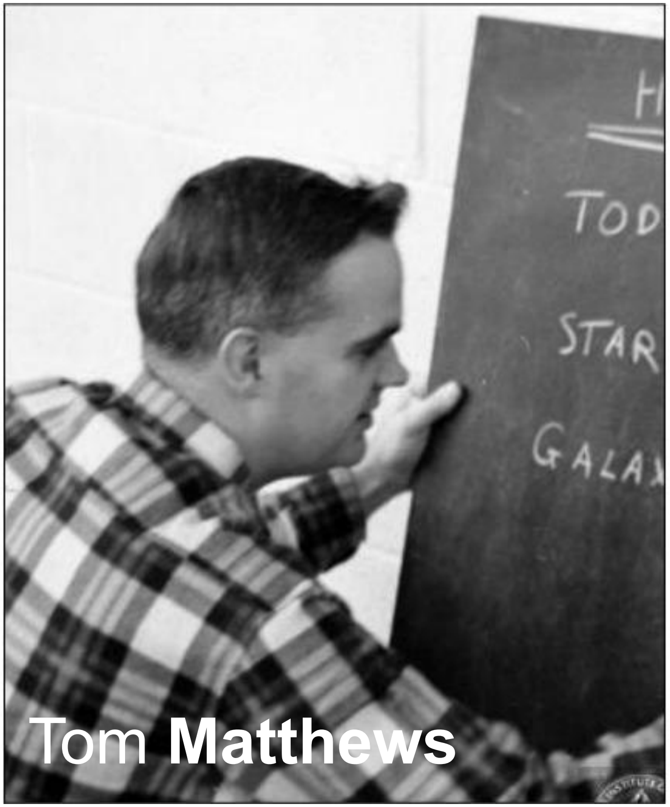
To link the **3C 48** radio source with an optical object required improved radio-position information.

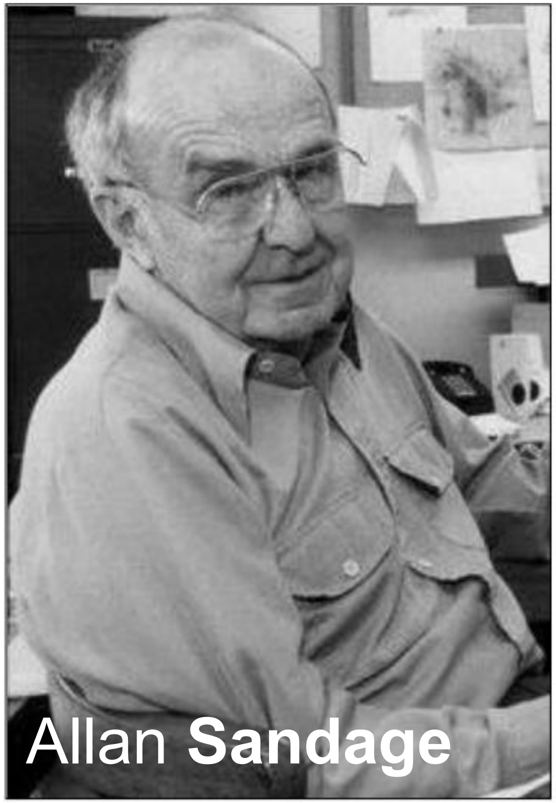
This was **Matthews'** roll using the Owen's Valley Radio Observatory interferometer.

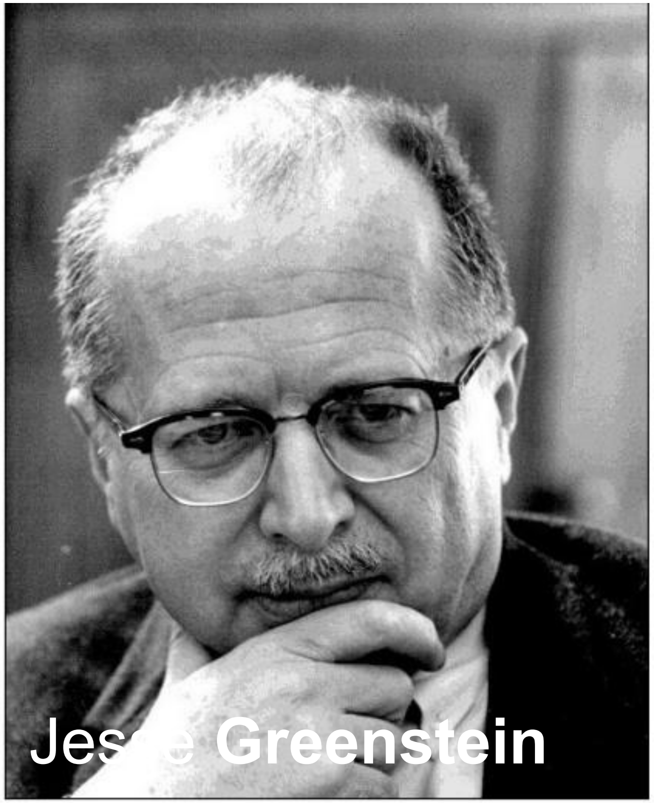
(http://kiss.caltech.edu/Tolman-Bacher/big_science.html)



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



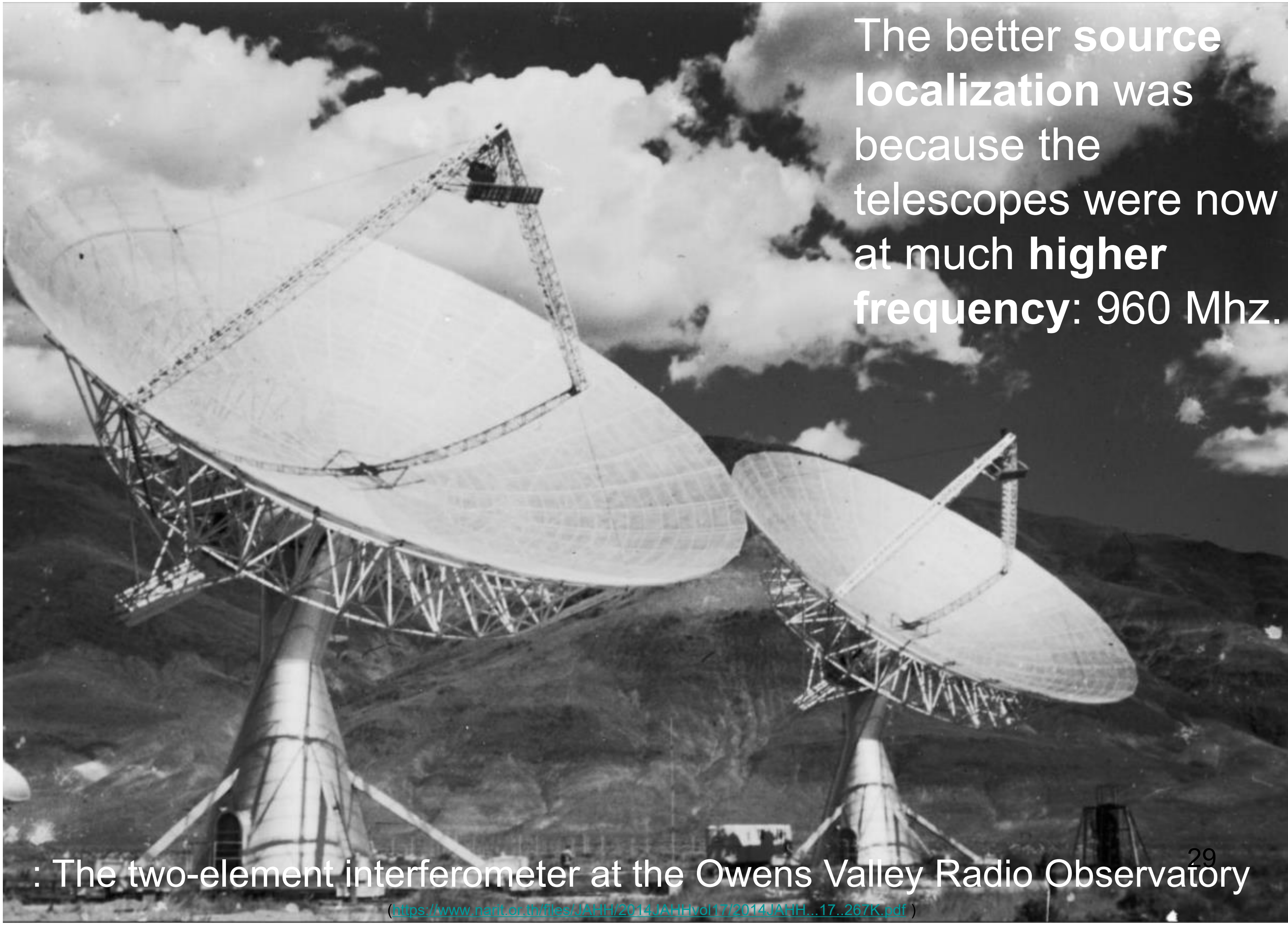




Fortunately a few years earlier, Jesse Greenstein had revolutionized the measurement of radio source positions with the **Owen’s Valley Radio Observatory**.

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

Improved angular resolution was the game changer



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

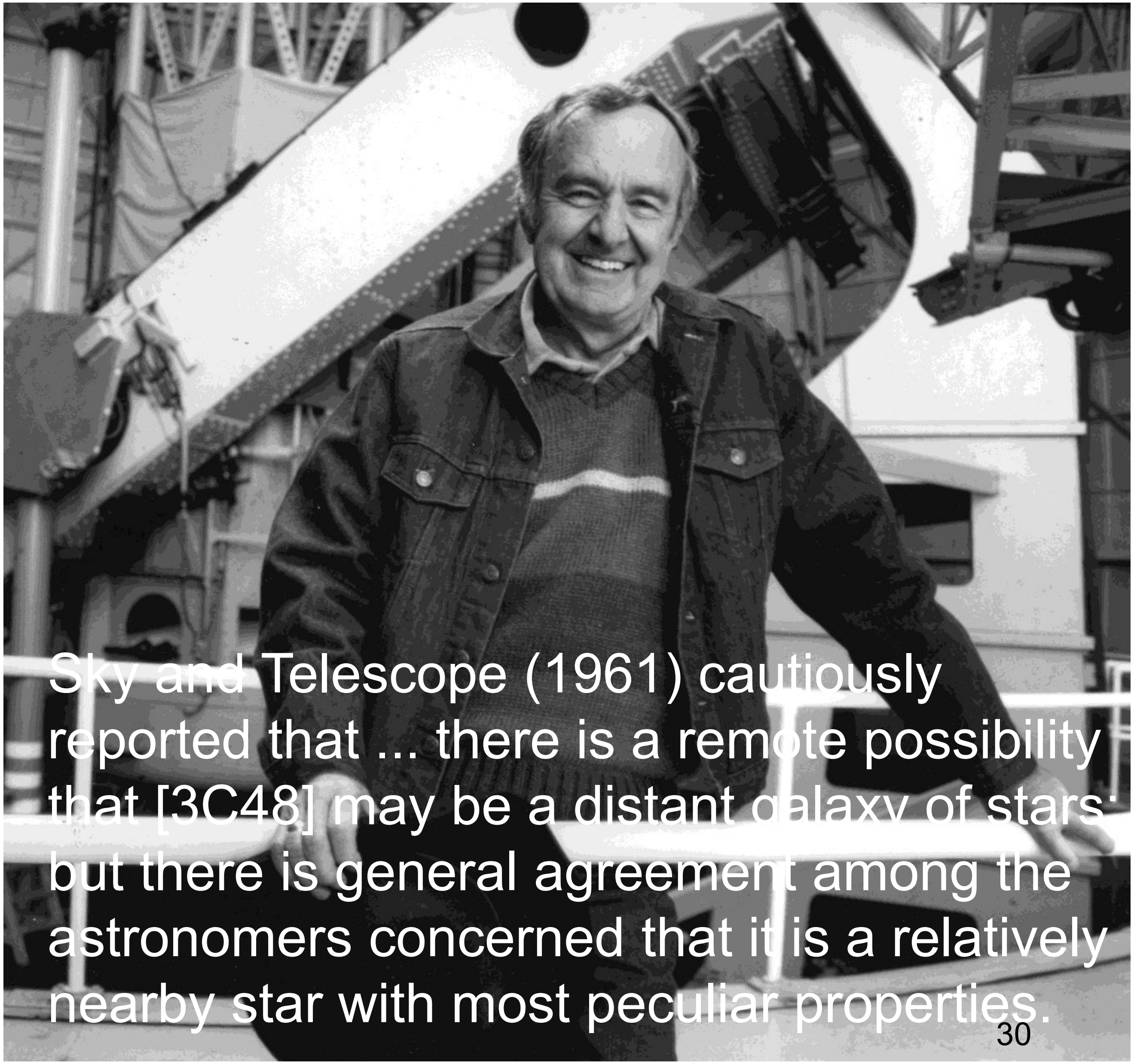
: The two-element interferometer at the Owens Valley Radio Observatory

(https://www.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.

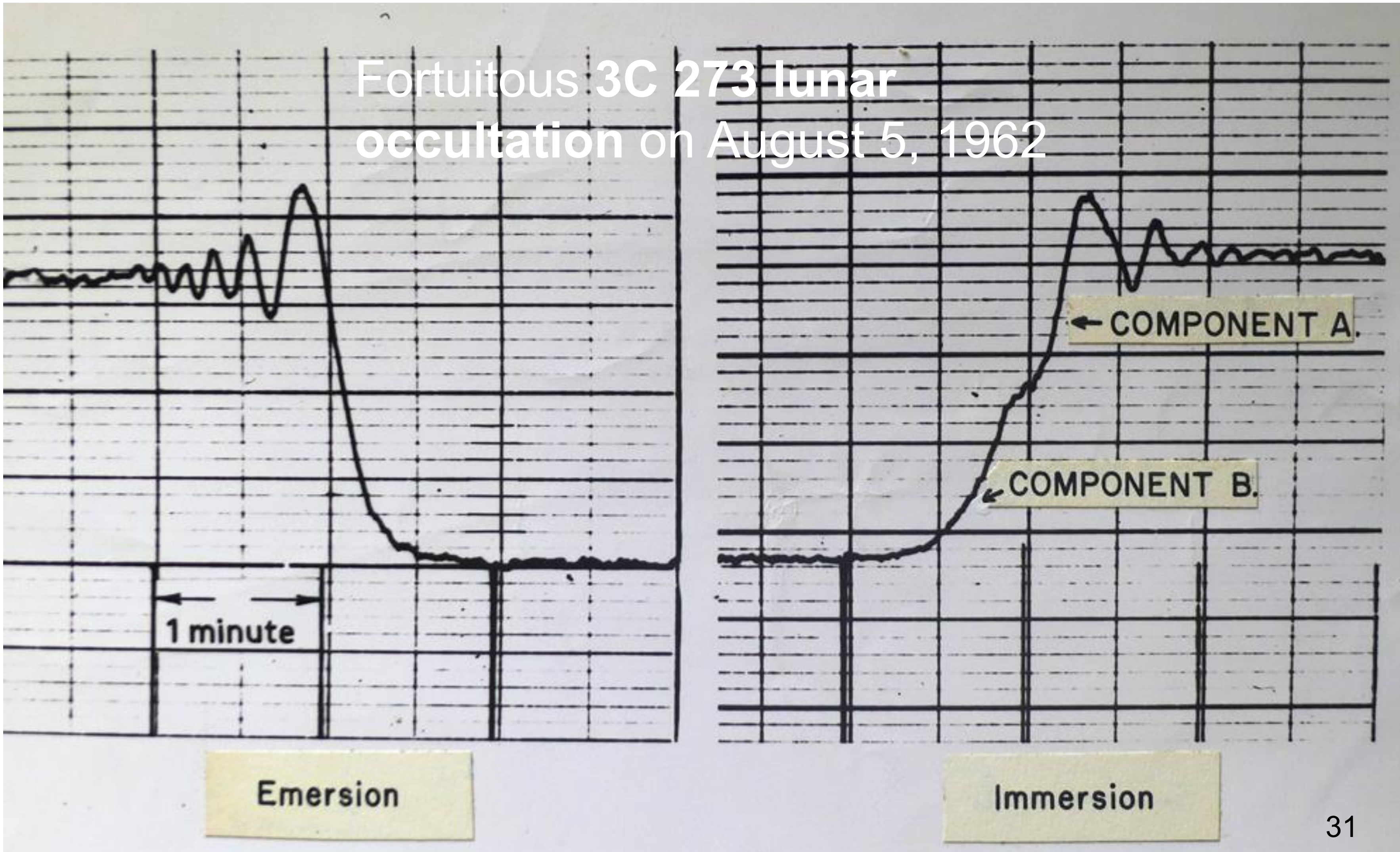
However the **spectrum** of the faint blue star contained many **unknown broad emission lines.**



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

2nd breakthrough 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)

Calculating the position of 3C 273

Radio source had to be at **P_1**

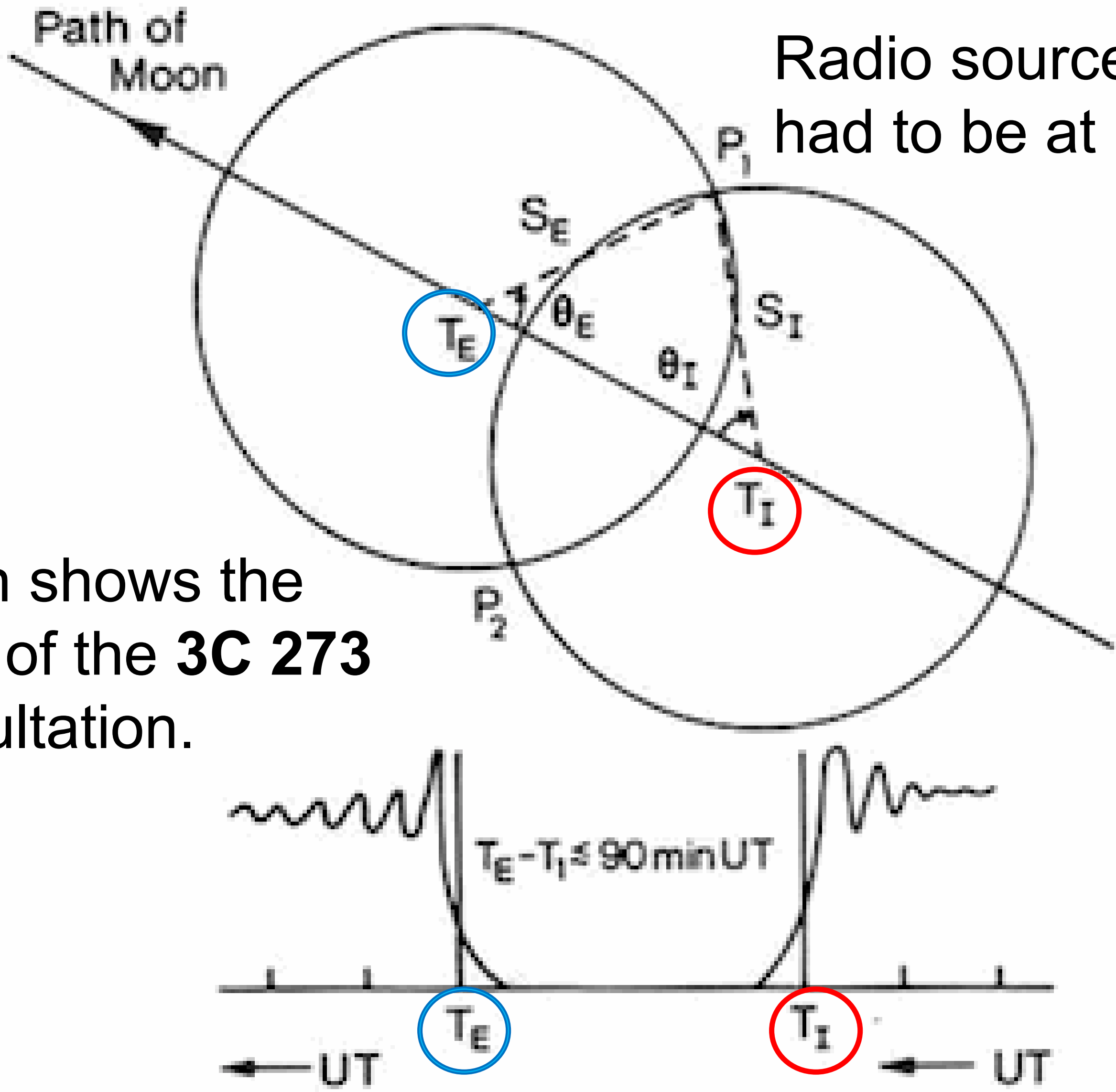


Illustration shows the geometry of the **3C 273** lunar occultation.

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

Sometimes being second is an advantage

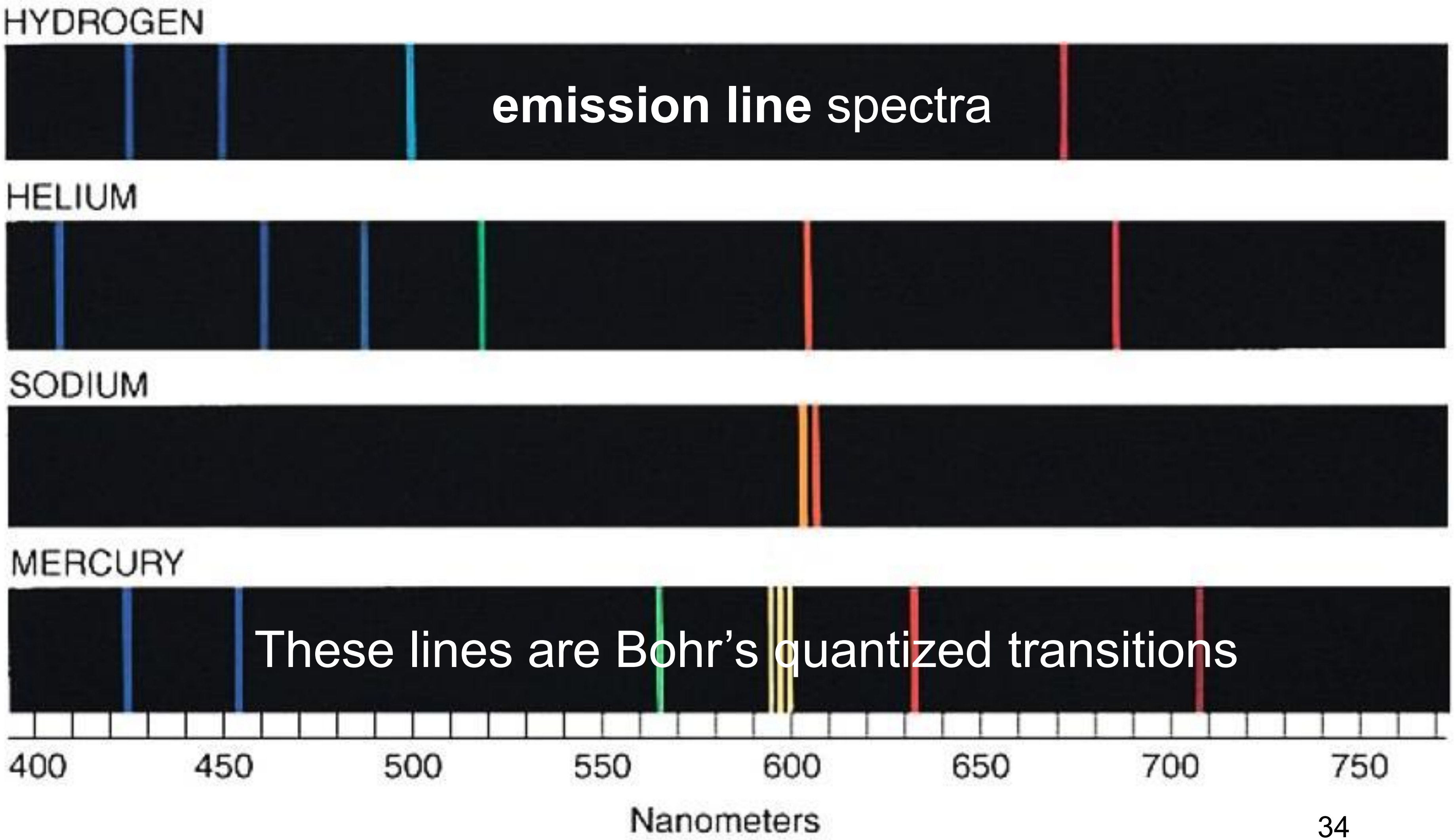
3C 273 was then associated with it’s optical counterpart, and **Maarten Schmidt** obtained an optical spectrum also using the 200” Hale Telescope.

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

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

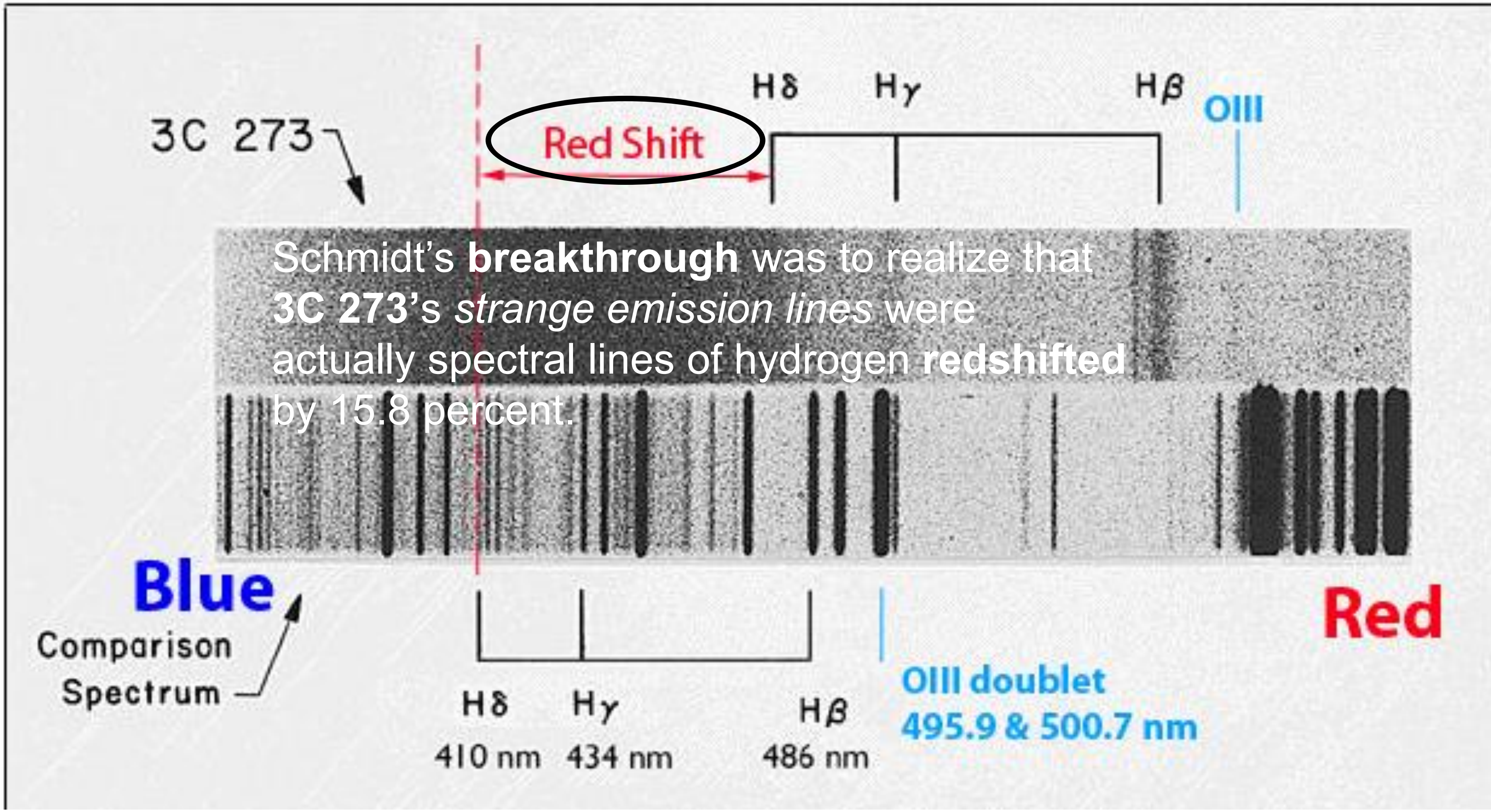
Spectra are like *fingerprints* uniquely identifying each atom

Atoms (molecules) spectra are distinctive.
Each **atom** has a **unique** and well known **spectra**.



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

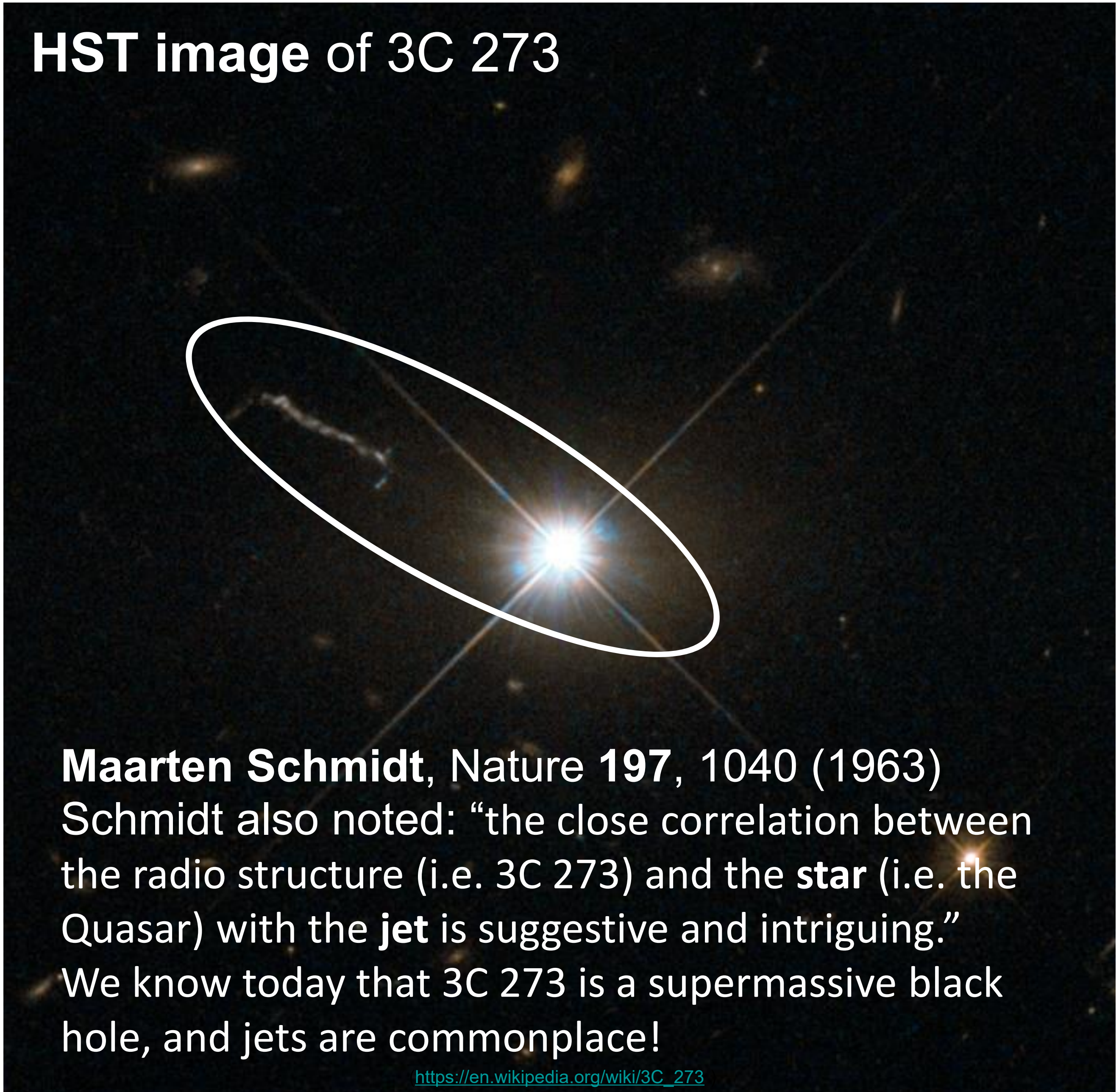
3C 273 *strange spectrum* was just an unexpected redshift



Schmidt's **breakthrough** was to realize that **3C 273**'s *strange emission lines* were actually spectral lines of hydrogen **redshifted** by 15.8 percent.

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

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

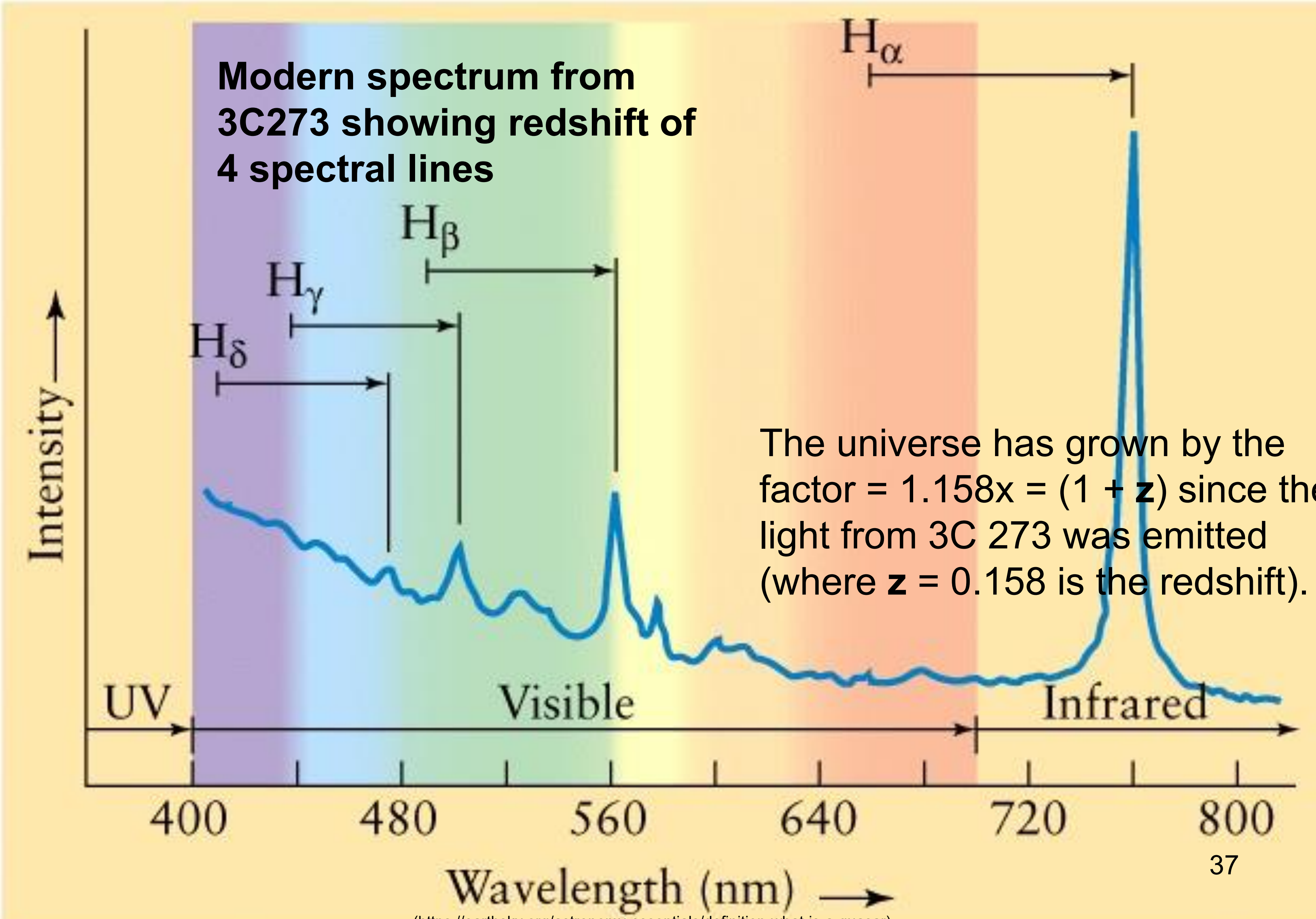


HST image of 3C 273

Maarten Schmidt, Nature **197**, 1040 (1963)
Schmidt also noted: "the close correlation between the radio structure (i.e. 3C 273) and the **star** (i.e. the Quasar) with the **jet** is suggestive and intriguing."
We know today that 3C 273 is a supermassive black hole, and jets are commonplace!

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

Unexpected redshift was from the expansion of the universe!



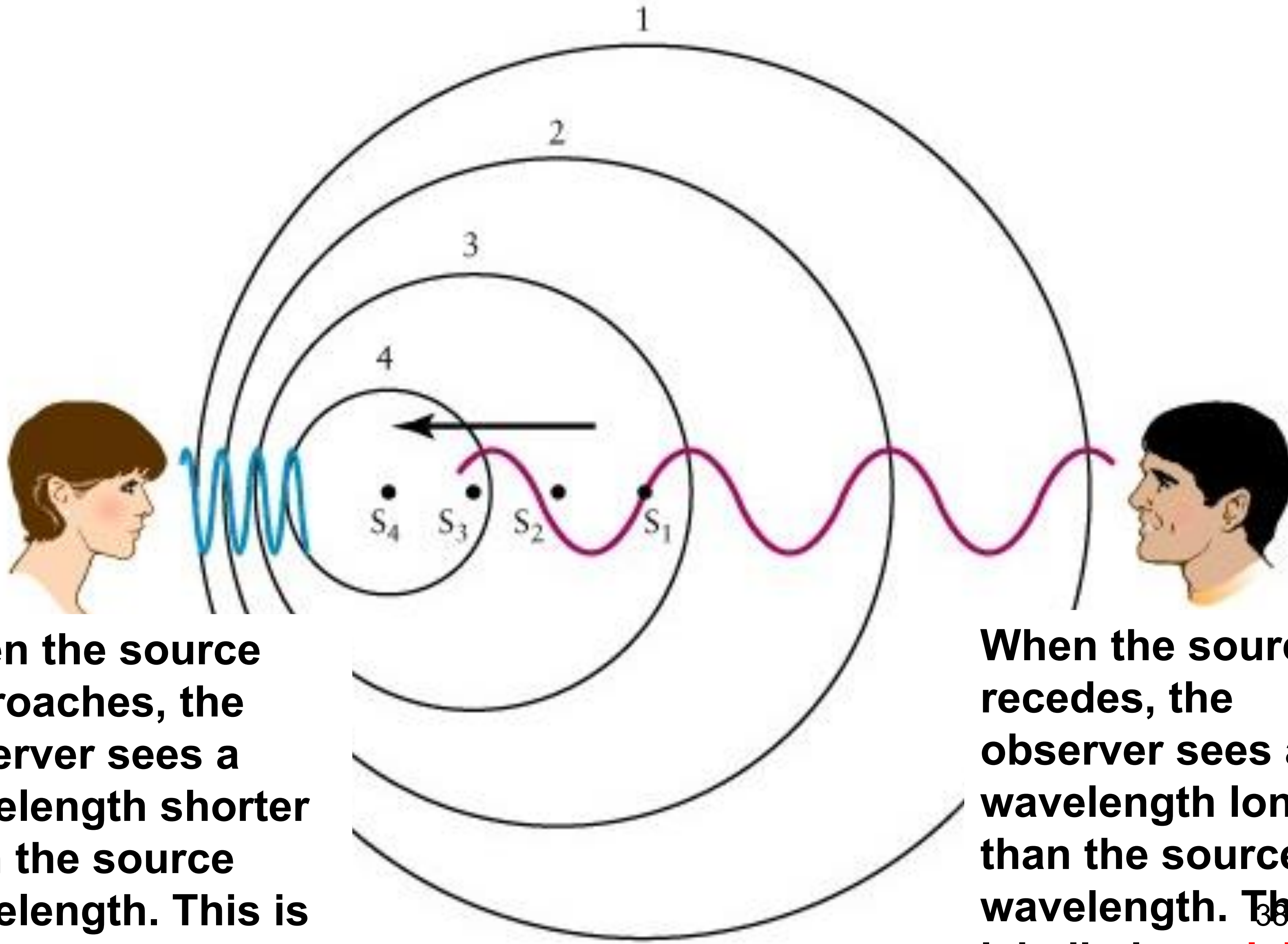
Modern spectrum from 3C273 showing redshift of 4 spectral lines

The universe has grown by the factor = 1.158x = (1 + **z**) since the light from 3C 273 was emitted (where **z** = 0.158 is the redshift).

(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 $\equiv (\lambda_{observed} - \lambda_{rest})/\lambda_{rest}$

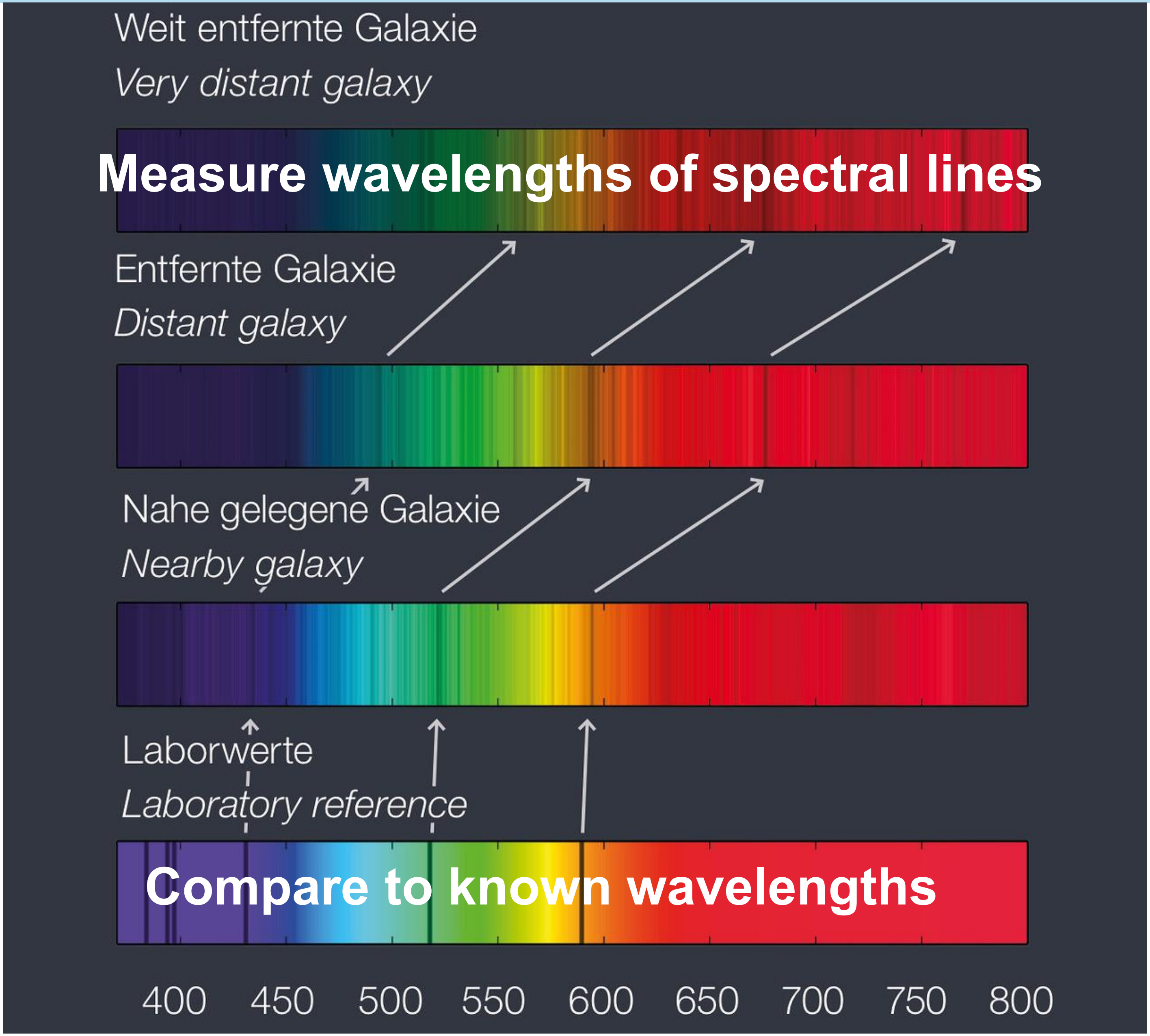
$\lambda_{observed}$ = observed **wavelength** (of light)

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?

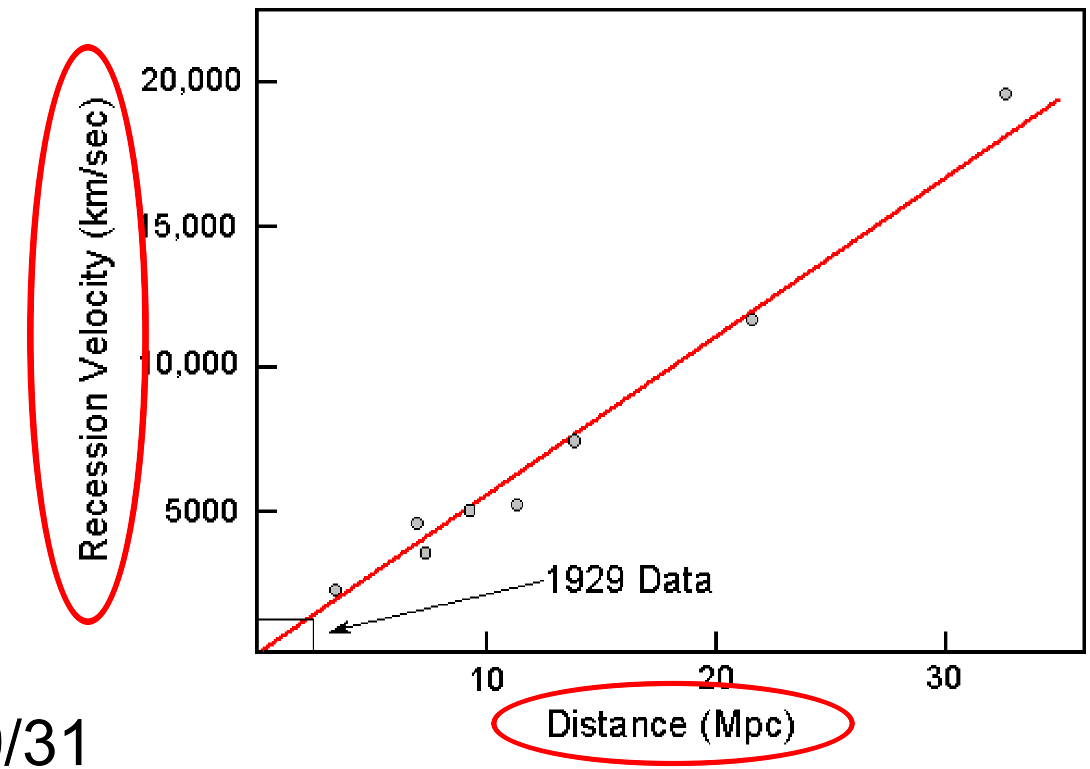


(https://supernova.eso.org/exhibition/1111/)

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**.

Hubble & Humason (1931)

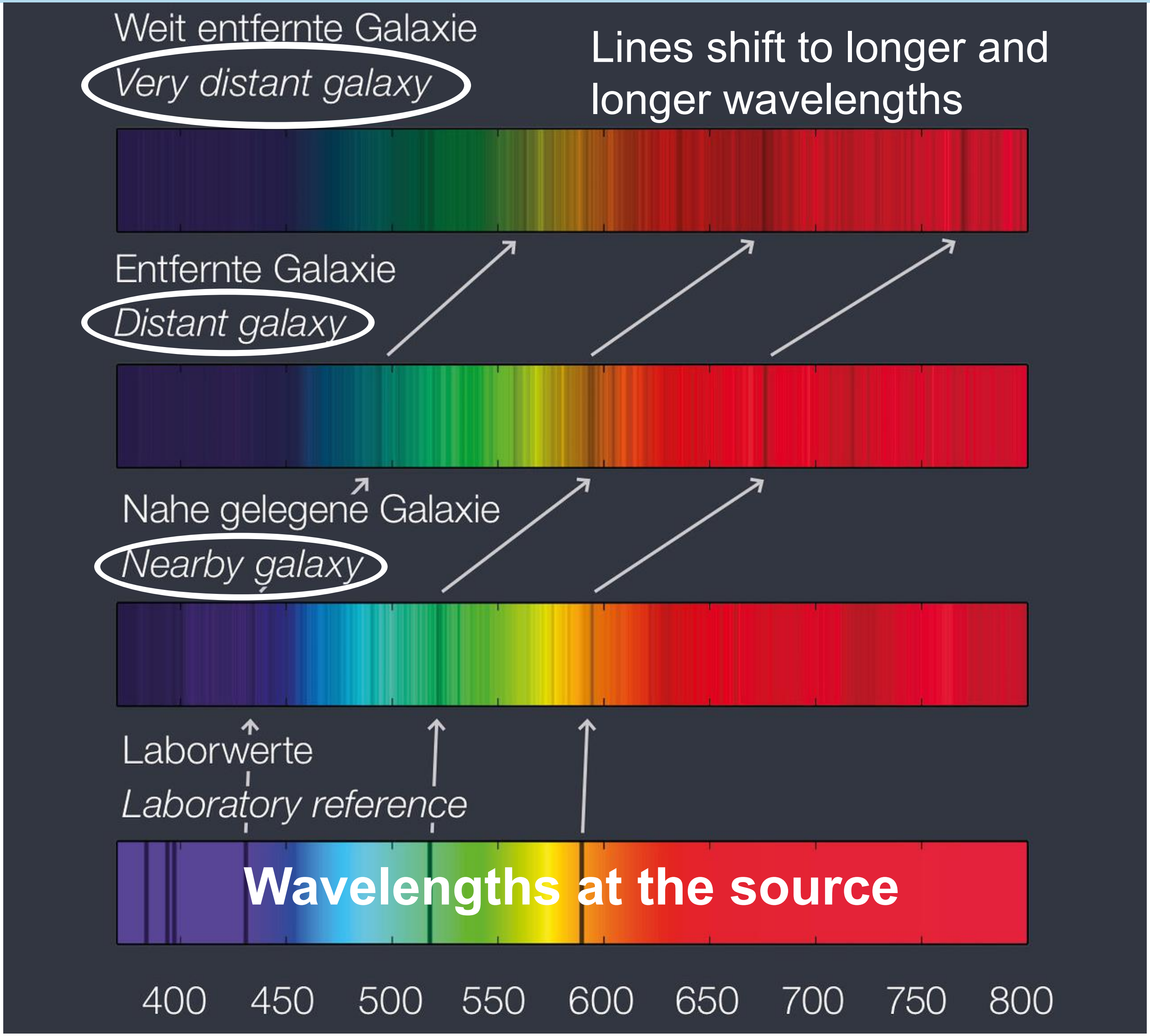


Edwin Hubble, 1929/31

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 moved 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

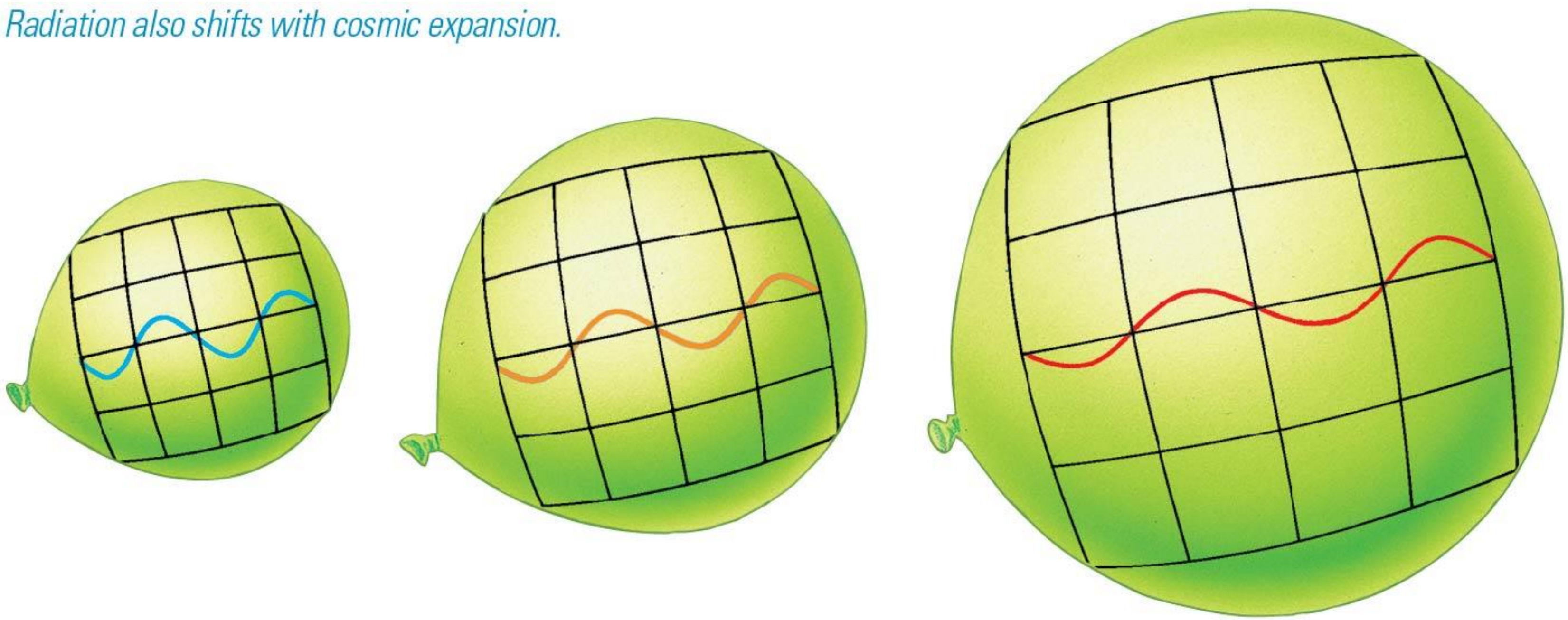
Hoyle used "**Big Bang**" for the first time in his “Nature of the Universe” talks, but **with derision**, to describe a theory on the origin of the universe that he didn't accept.

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

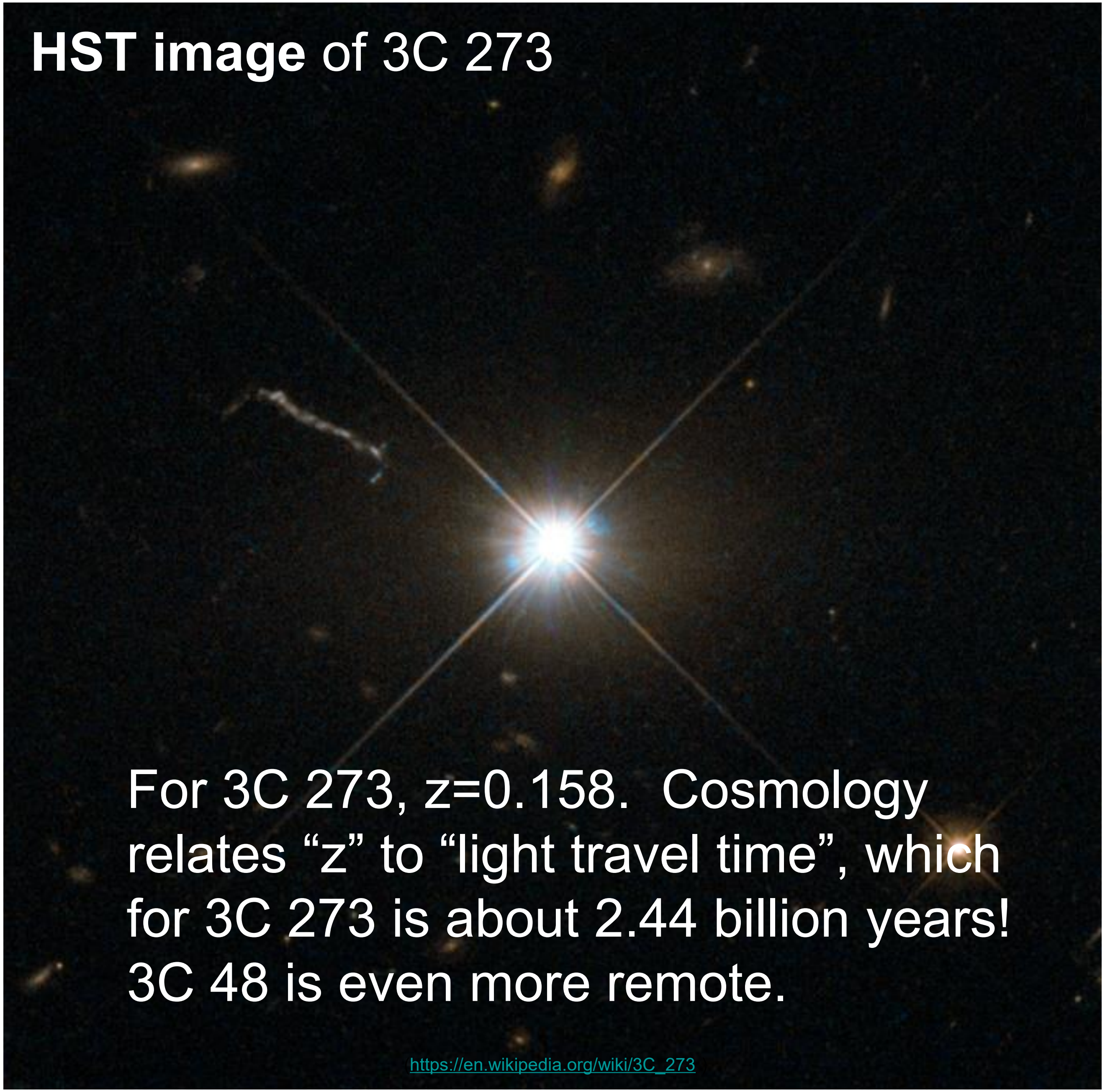
- As the universe expands so do the wavelengths of the light travelling through it!



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

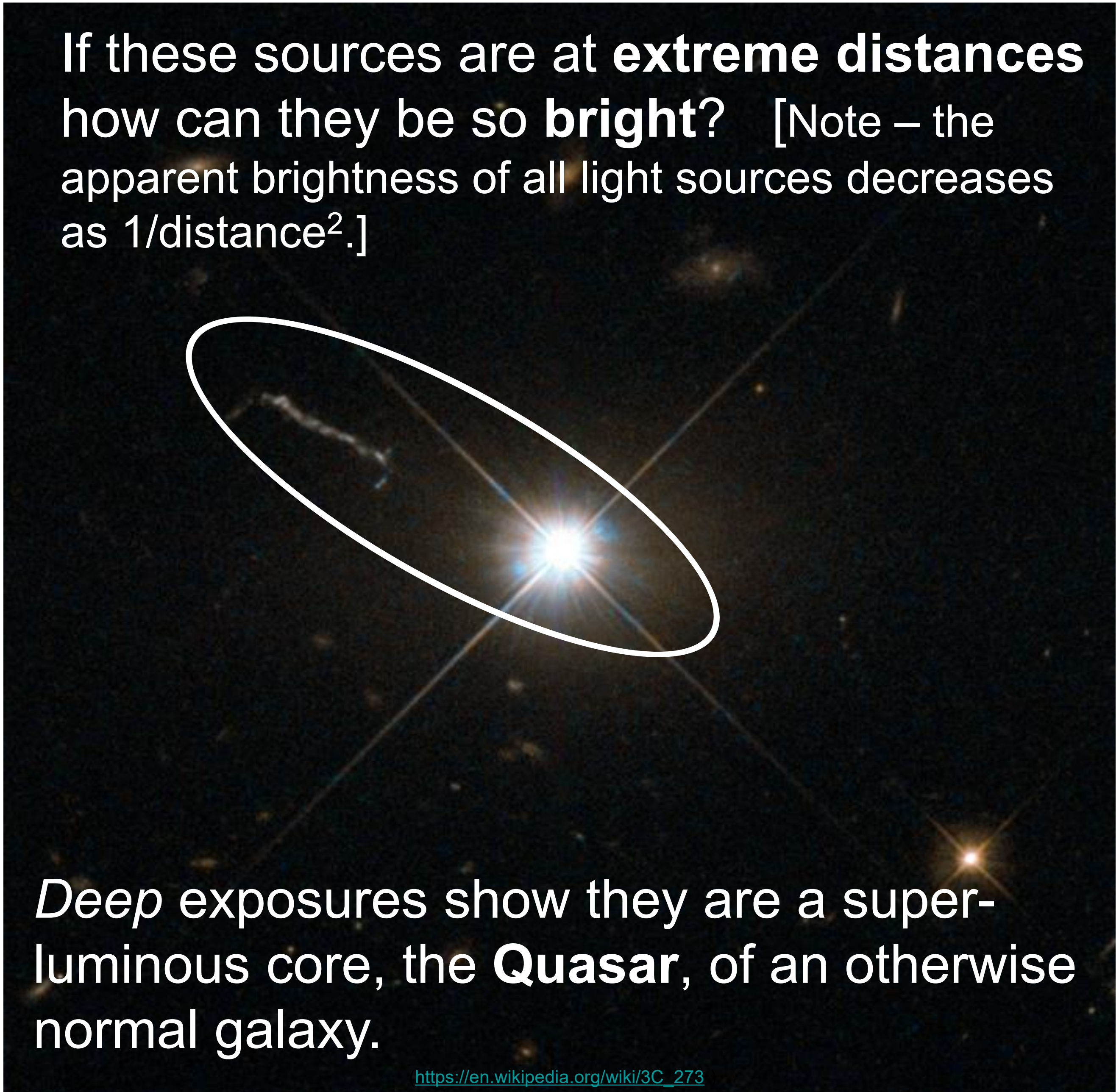
Because the **universe expansion scale factor** is also 1 + z, the universe (and the wavelengths of light) have grown by a factor of 1 + z since this light was emitted!

3C 48 and 3C 273 were at extreme distances



3C 48 and 3C 273 intrinsic luminosities were unimaginable

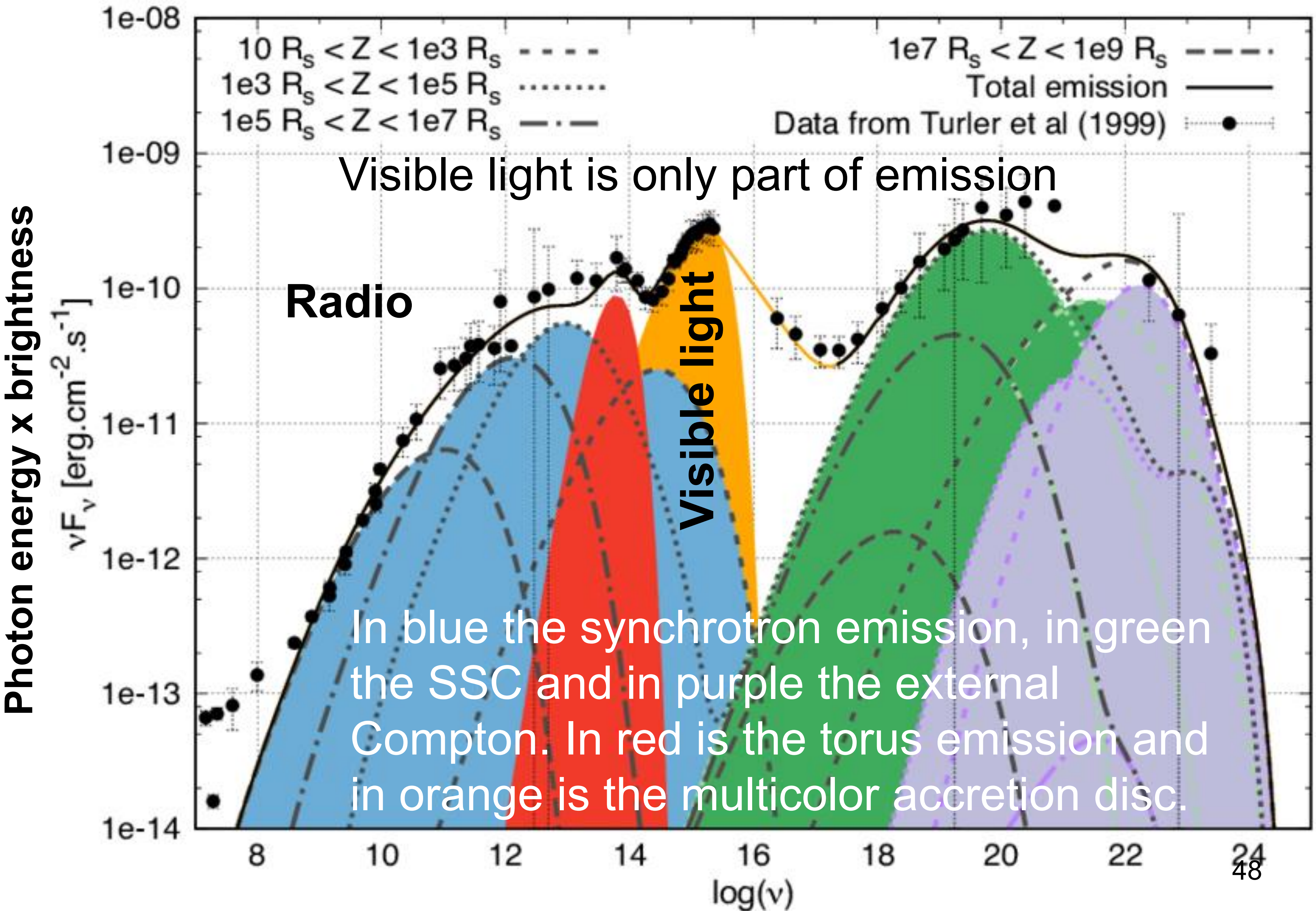
If these sources are at **extreme distances** how can they be so **bright**? [Note – the apparent brightness of all light sources decreases as 1/distance^2.]



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

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

Today we know Quasars as “flat spectrum” sources



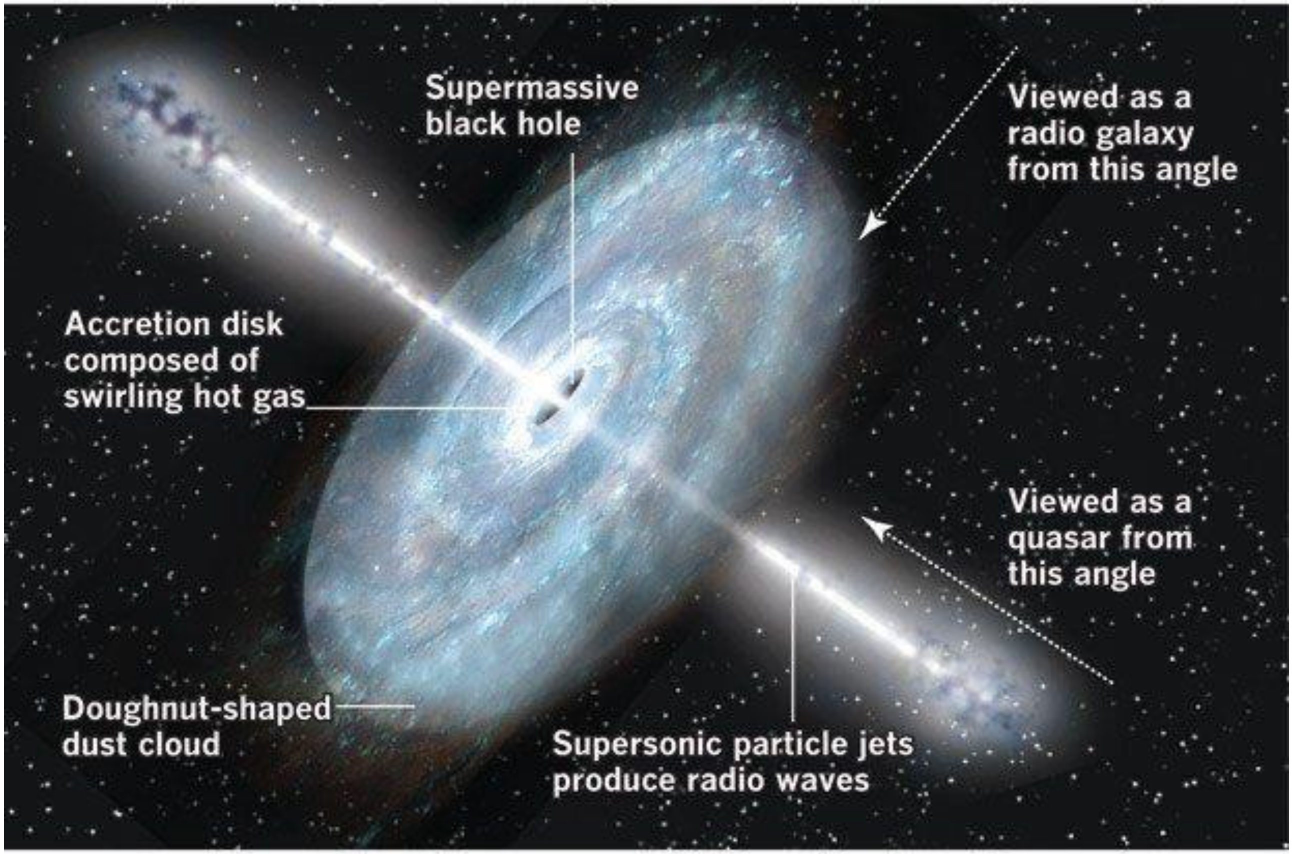
(https://www.researchgate.net/figure/SED-of-3C-273-modeling-compared-to-data-from-25-In-blue-the-synchrotron-emission-in_fig2_326810583)

Quasars are remote and thus existed in the early universe

Quasars are likely the most luminous objects in the universe!

Quasars are thought to be **super-massive Black Holes** actively **accreting matter**.

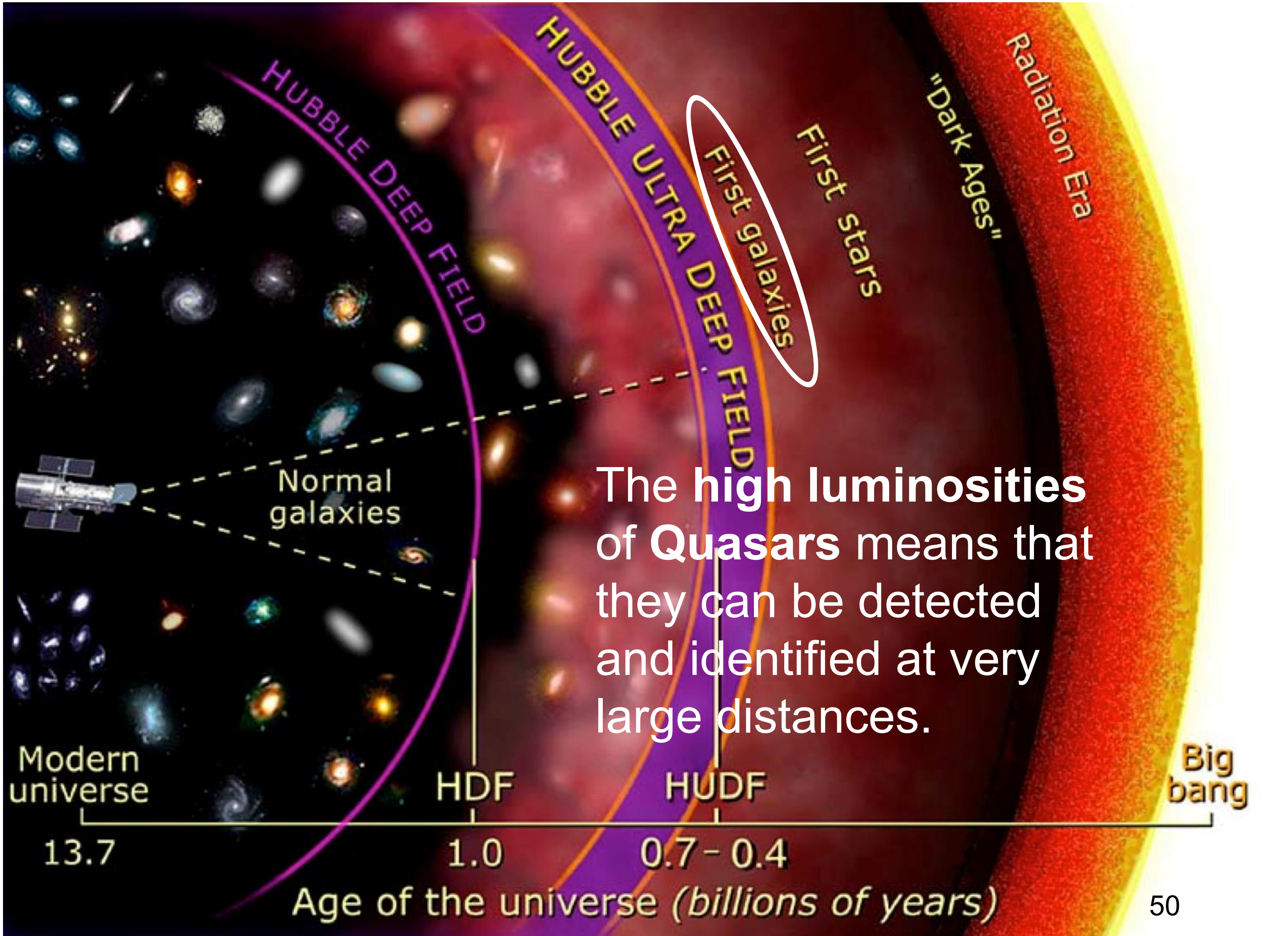
The luminous glow of a quasar is powered by the accumulation of matter into a giant black hole at the center of a galaxy.



Source: Nature. Graphics reporting by BRADY MACDONALD

LORENA IÑIGUEZ ELEBEE Los Angeles Times

Quasars should provide insights into the early universe



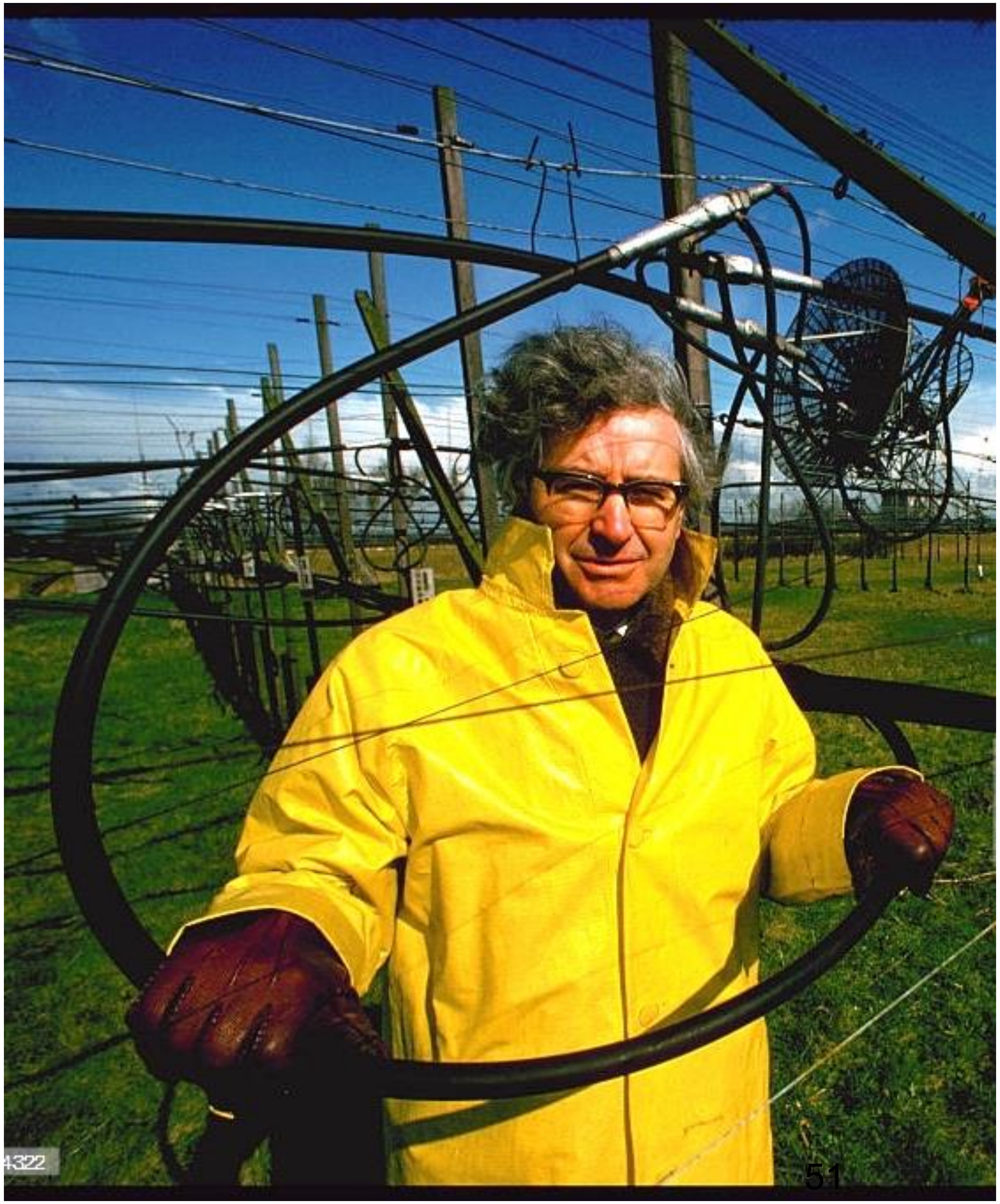
The **high luminosities** of **Quasars** means that they can be detected and identified at very large distances.

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

The hunt to find Quasars

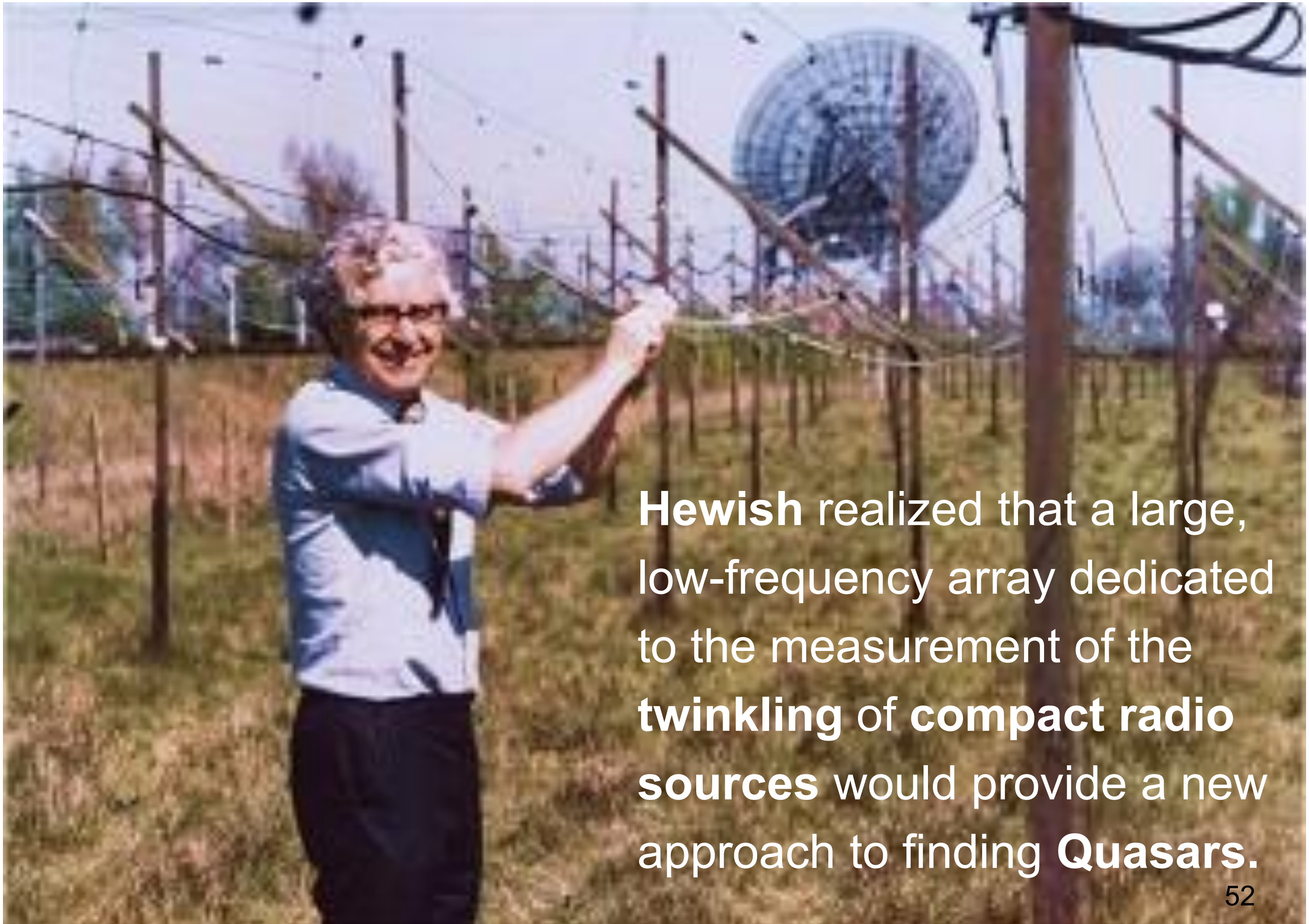
By 1964 a number of radio **Quasars** were known, some of these were **point-like**, *i.e.* had small angular sizes.

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"

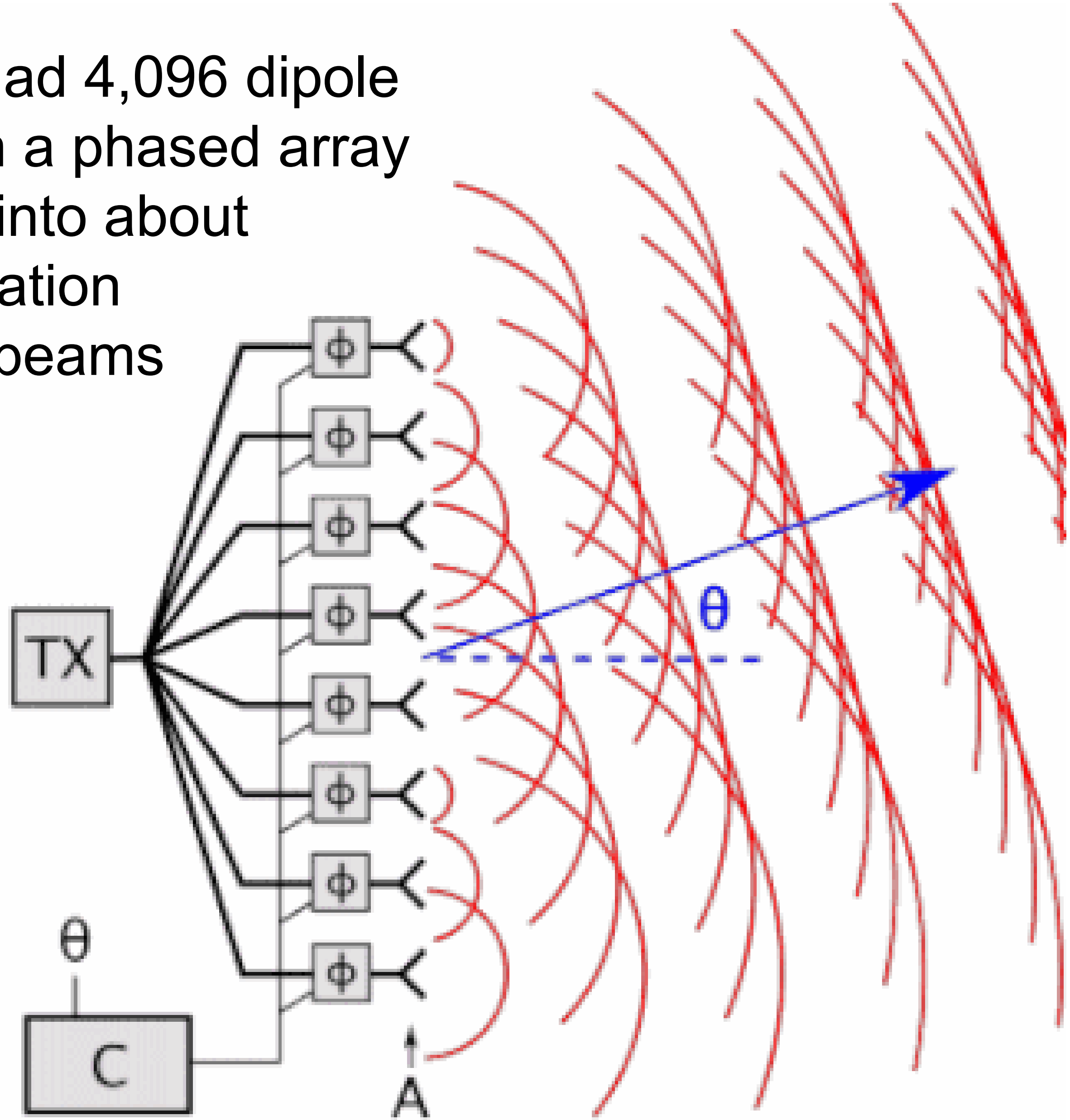


Hewish realized that a large, low-frequency array dedicated to the measurement of the **twinkling** of **compact radio sources** would provide a new approach to finding **Quasars.**

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 5°-in-declination directional-beams



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

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/)

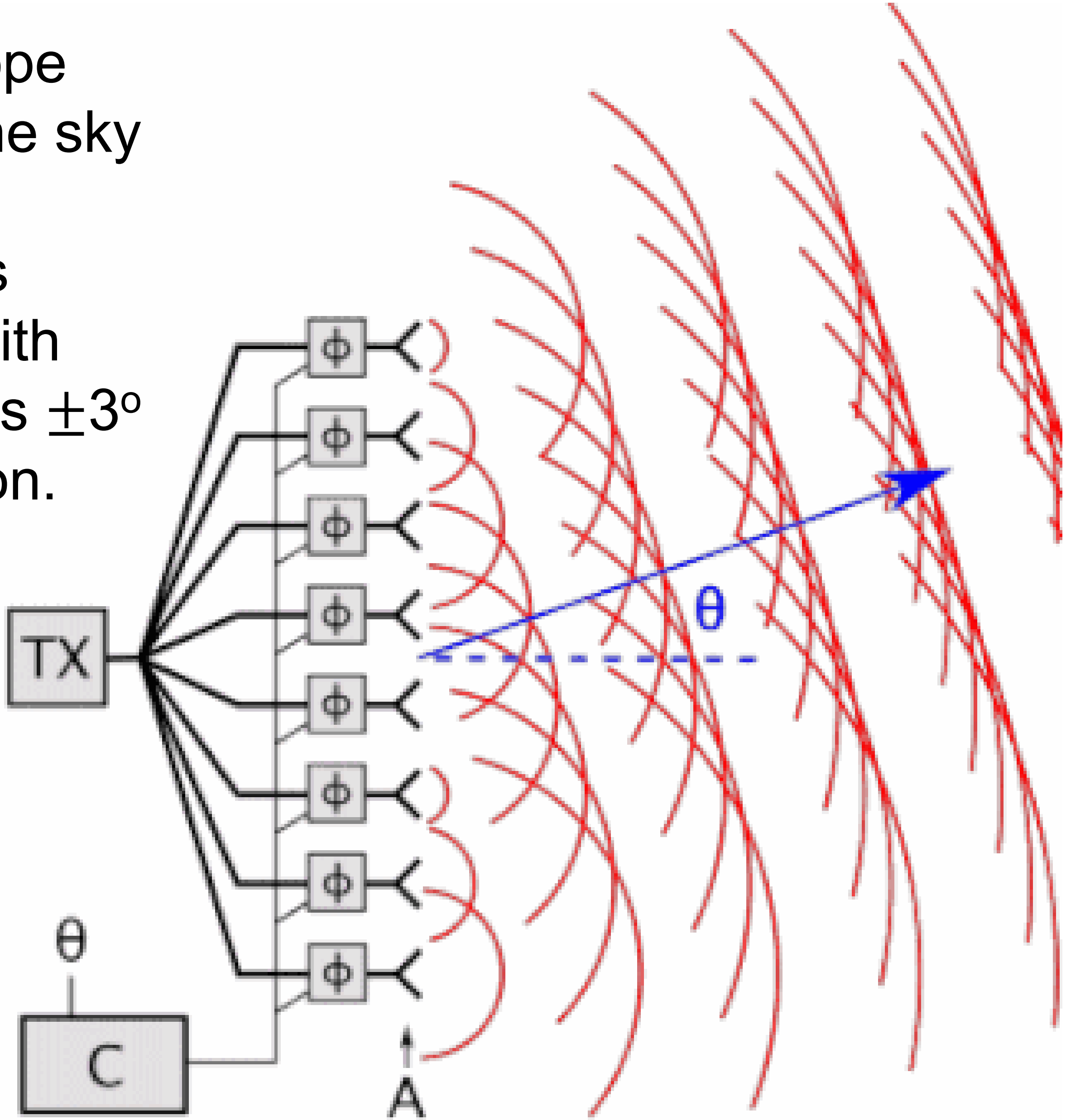
The telescope was commissioned during July 1967

The key aspect was to measure the **twinkling** (**time variations** of **brightness**) of the radio sources.

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 declination-beams were observed at any given time

The telescope observed the sky between declinations -8º to 44º with beam widths ±3º in declination.



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

Fortunately data were not digital, and computers inaccessible

Bell recalls: "The array 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)

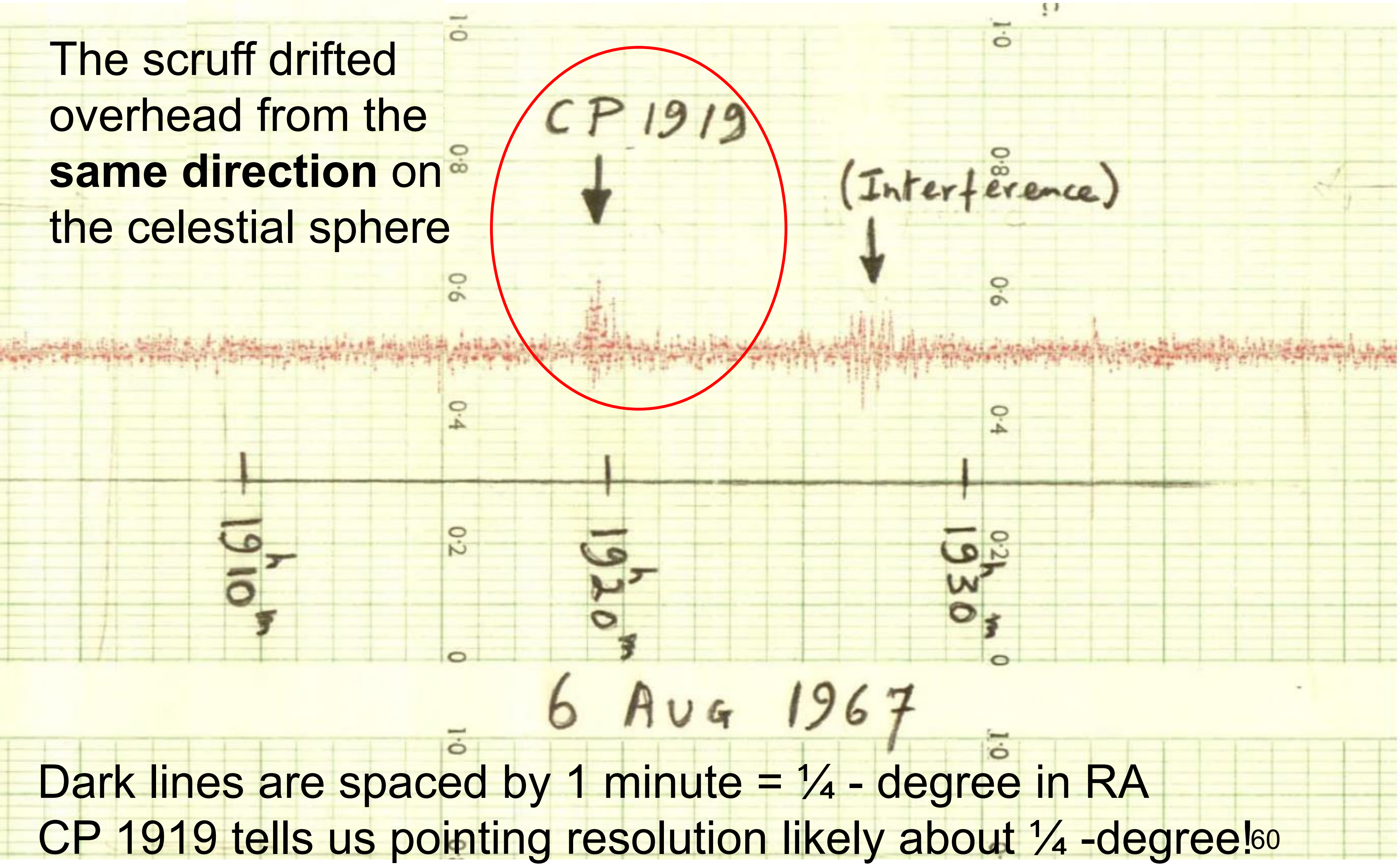
What is that *scruff* in the chart recording?

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)

The hunt to find 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.

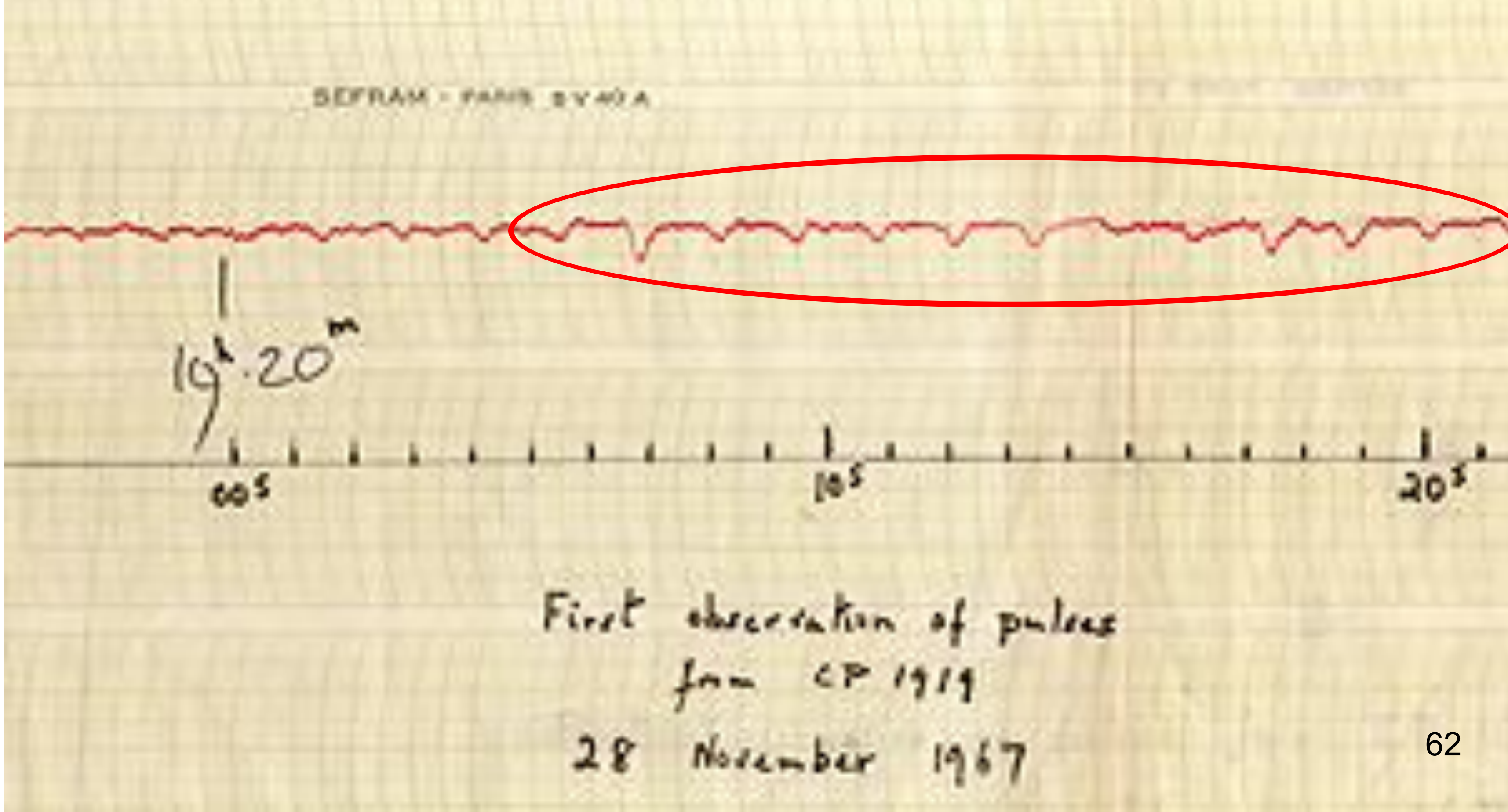
Towards the end of October 1967, when we had finished doing some special tests on 3C 273 and when we had at last our full complement of receivers and recorders, I started going out to the observatory each day to make the fast recordings.

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.”

(http://www.bbc.co.uk/radio4/features/science-discovery/jocelyn-bell-burnell)



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

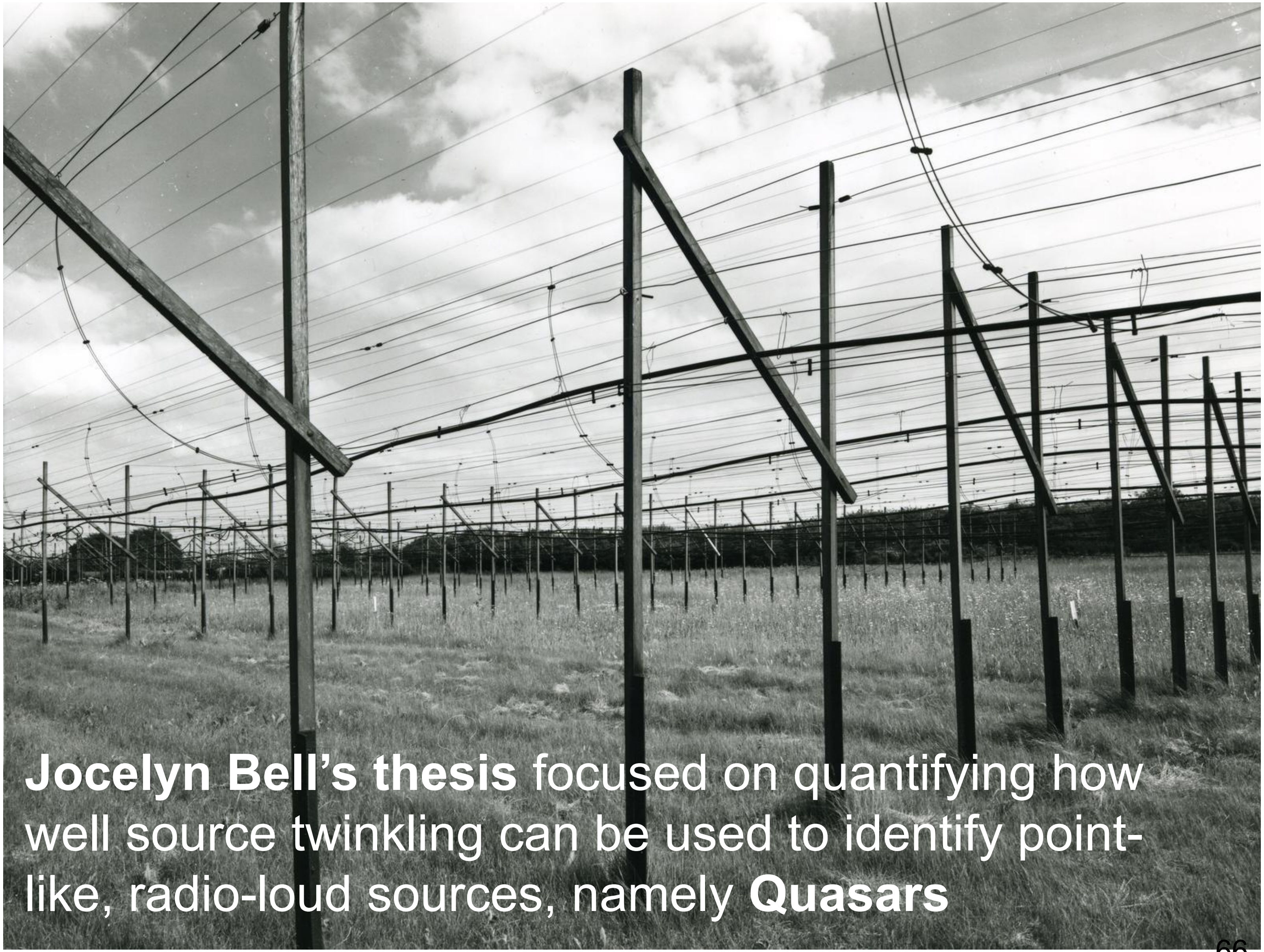
(Reprinted from Nature, Vol. 218, No. 5137, pp. 126–129, April 13, 1968)

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?



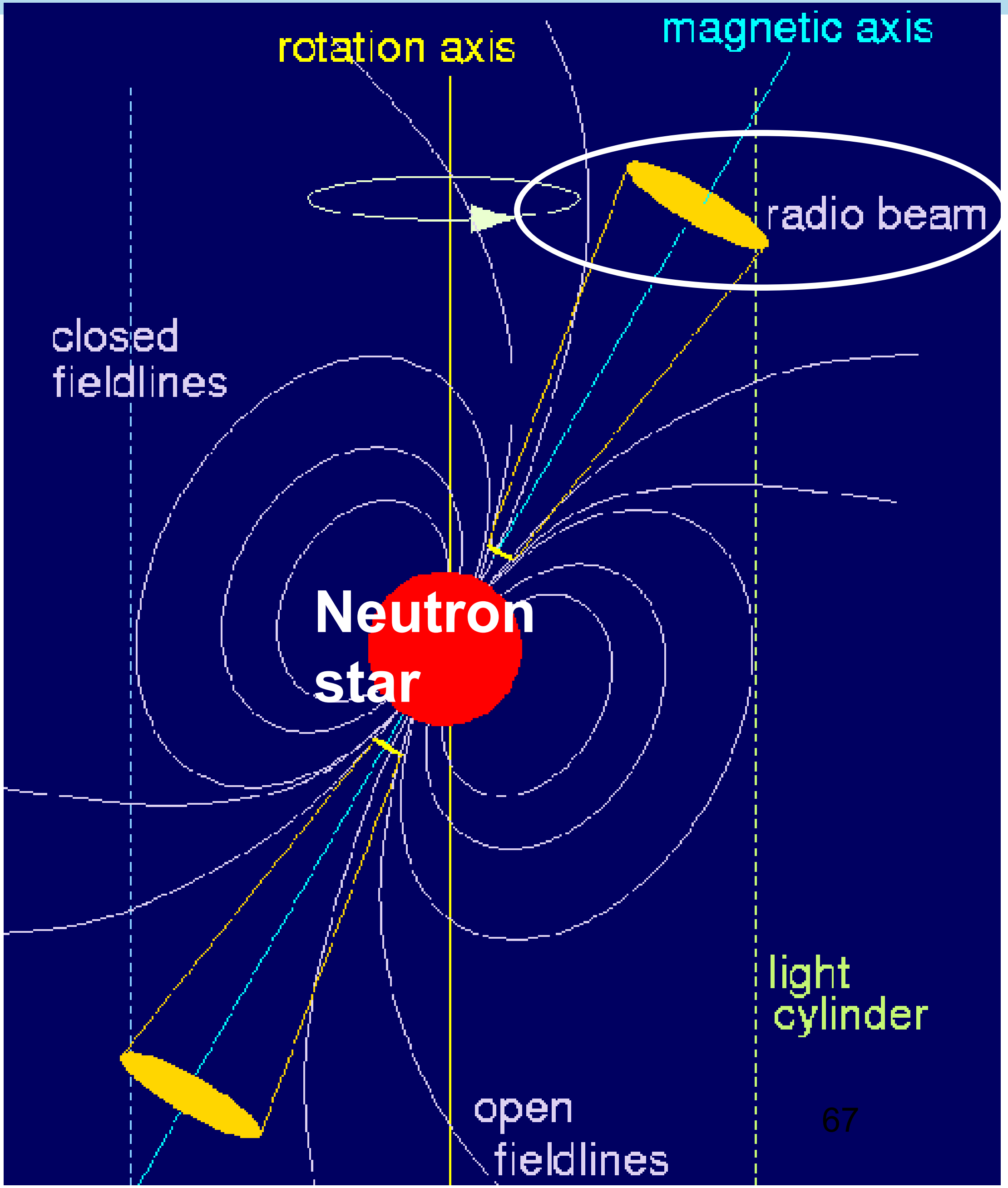
(https://www.nature.com/articles/s41550-017-0323-x?platform=hootsuite and https://collection.sciencemuseumgroup.org.uk/objects/co8105496/parts-from-the-cambridge-interplanetary-scintillation-array-radio-telescope-instrument-component)

Pulsar's explained one year later

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

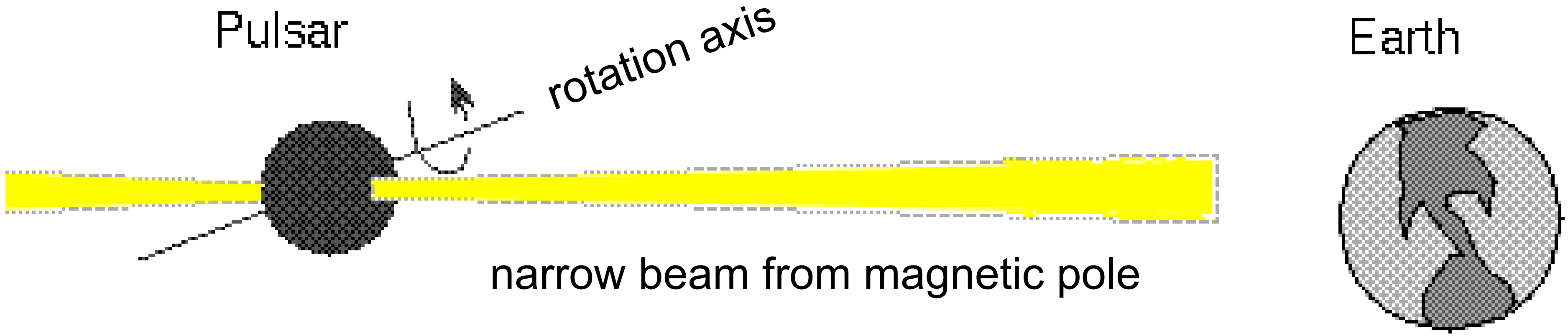
Neutron stars' intense, rotating, magnetic fields result in **radio beams**.

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



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

From scruff to pulsar to neutron star



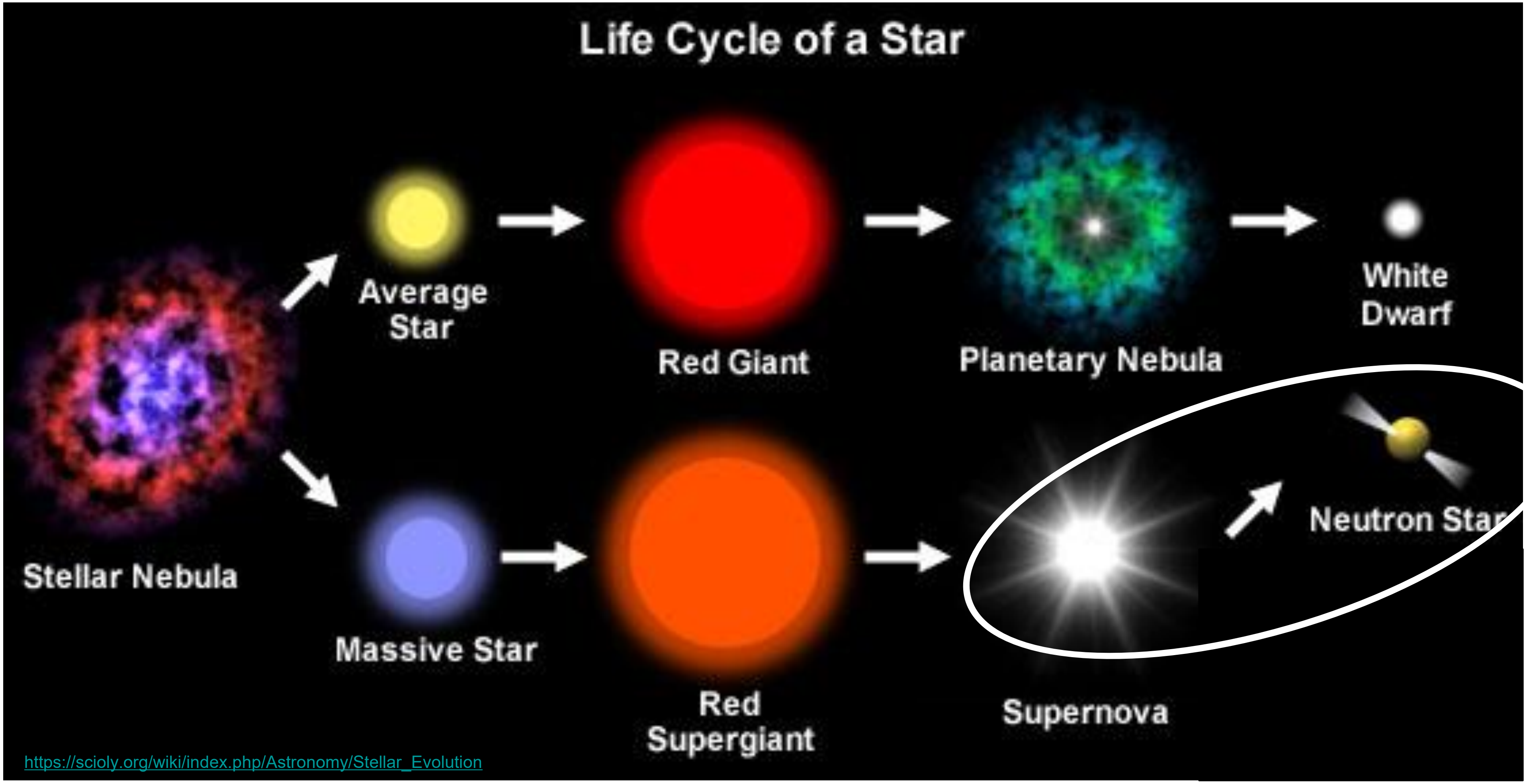
If the narrow synchrotron beam passes over the Earth, we see the neutron star flash on and off like a lighthouse beam does for ships at sea.

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

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



1st Nobel Prize in astronomy/astrophysics

The Nobel Prize in Physics 1974

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

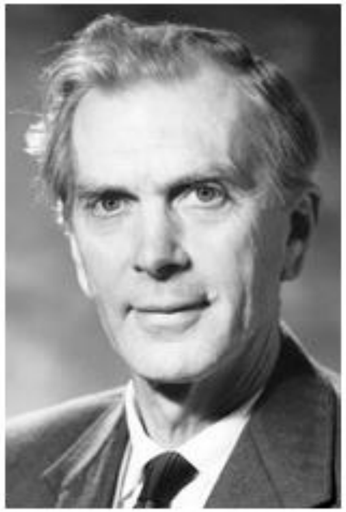


Photo from the Nobel Foundation archive.

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)

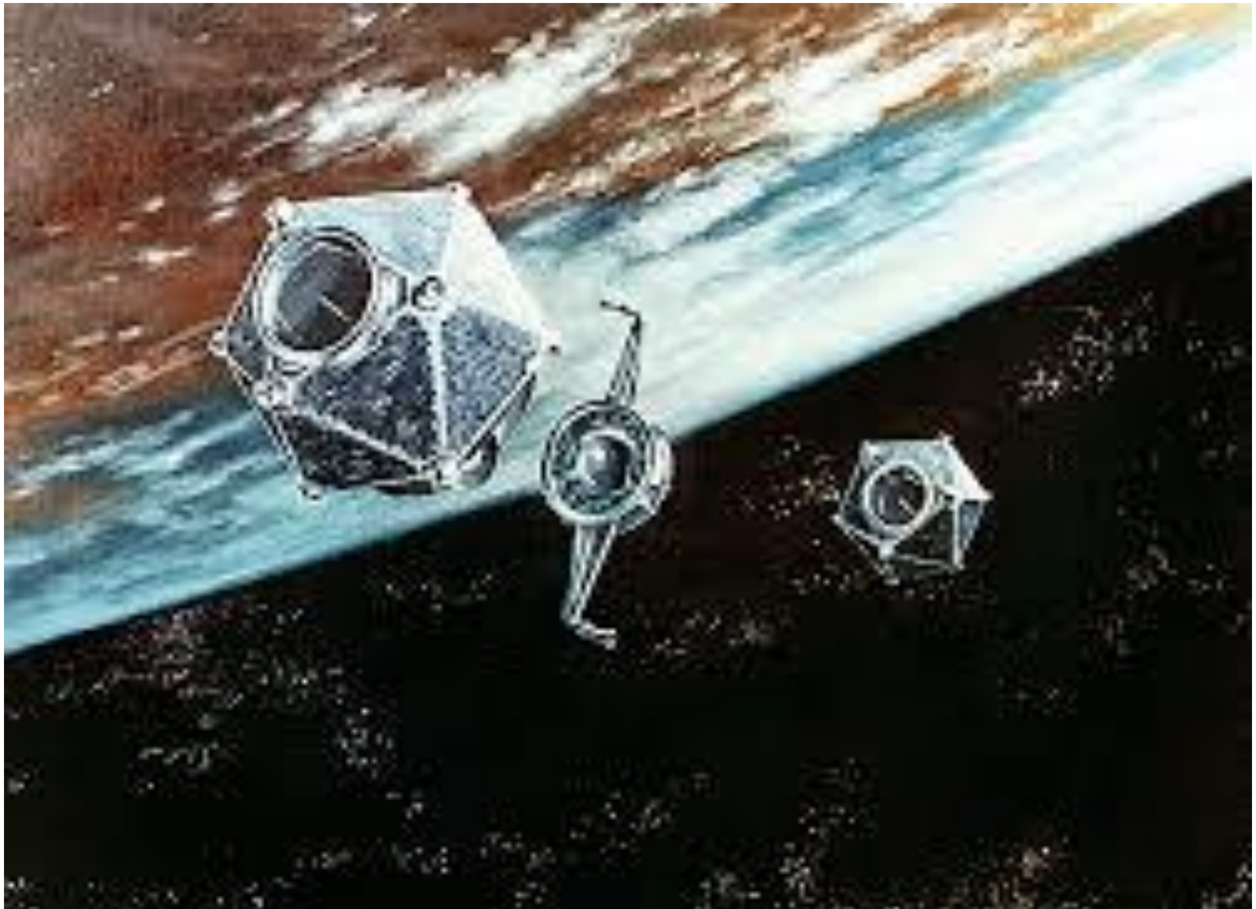
"*The $3 million award recognizes not only Bell Burnell's 1967 discovery of the weird, fast-spinning stellar corpses known as pulsars but also her scientific leadership in the 50 years since then.*"

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

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)

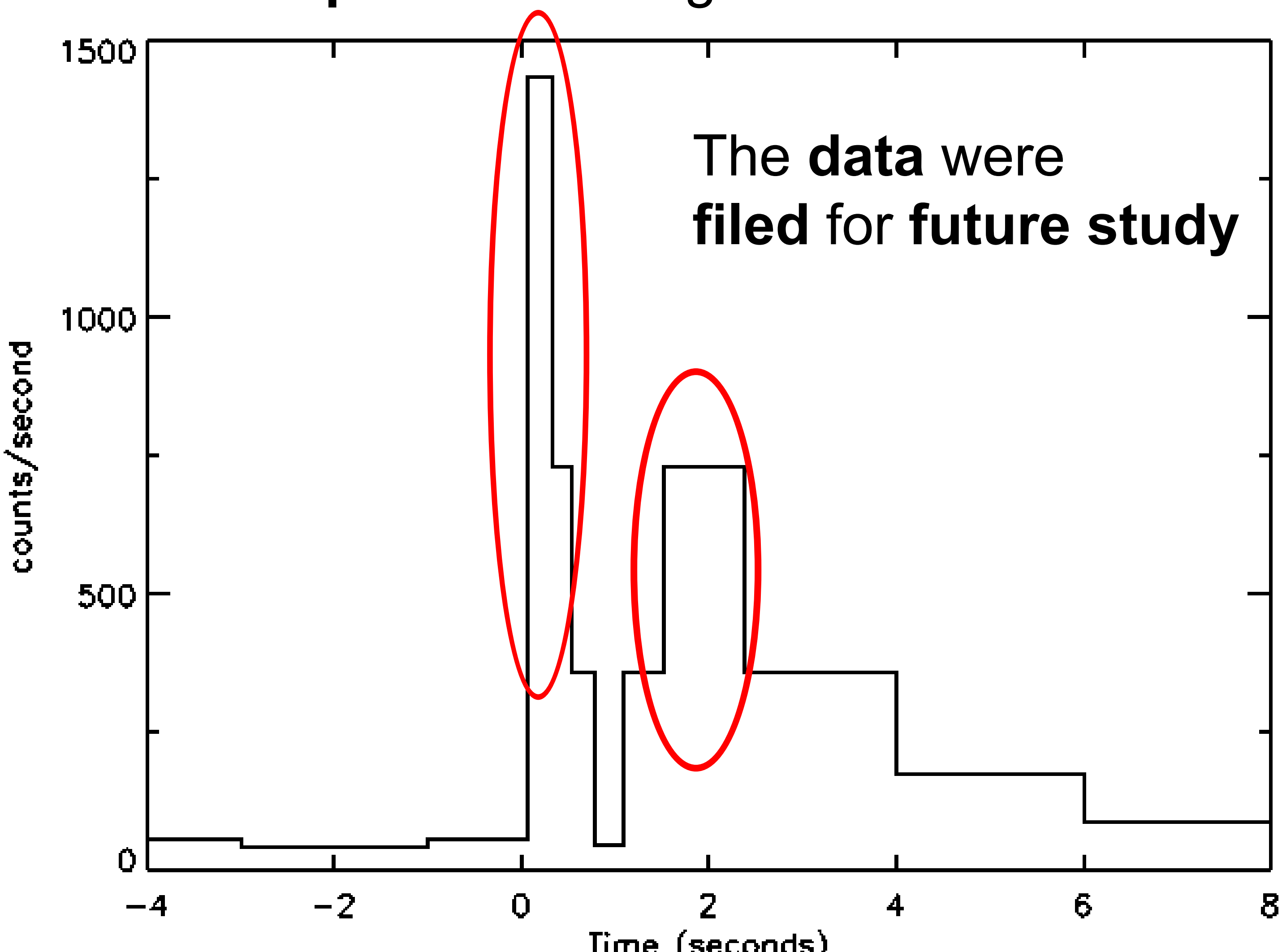
Suddenly our knowledge of the universe changed

- On **July 2, 1967**, at 14:19 UTC, the Vela 4 and Vela 3 satellites detected a **flash 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.

Burst of gamma-rays was observed over several seconds

The signal detected by the Vela satellites had neither the intense initial flash nor the gradual fading.
It had **two distinct peaks** in the light curve.



The **data** were **filed** for **future study**

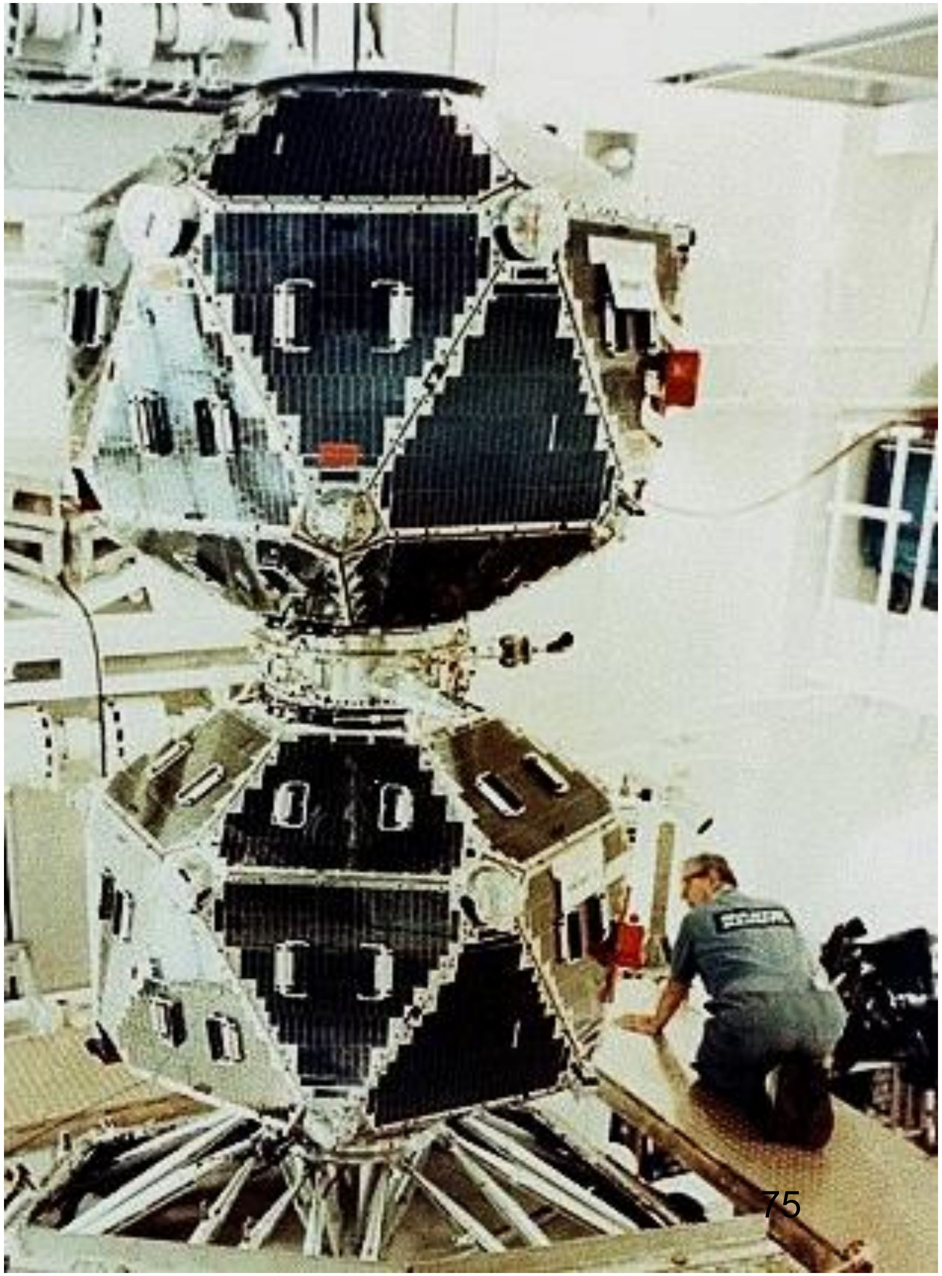
(https://heasarc.gsfc.nasa.gov/grbcat/about.html)

Vela 5 was launched on May 23, 1969

With **higher 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



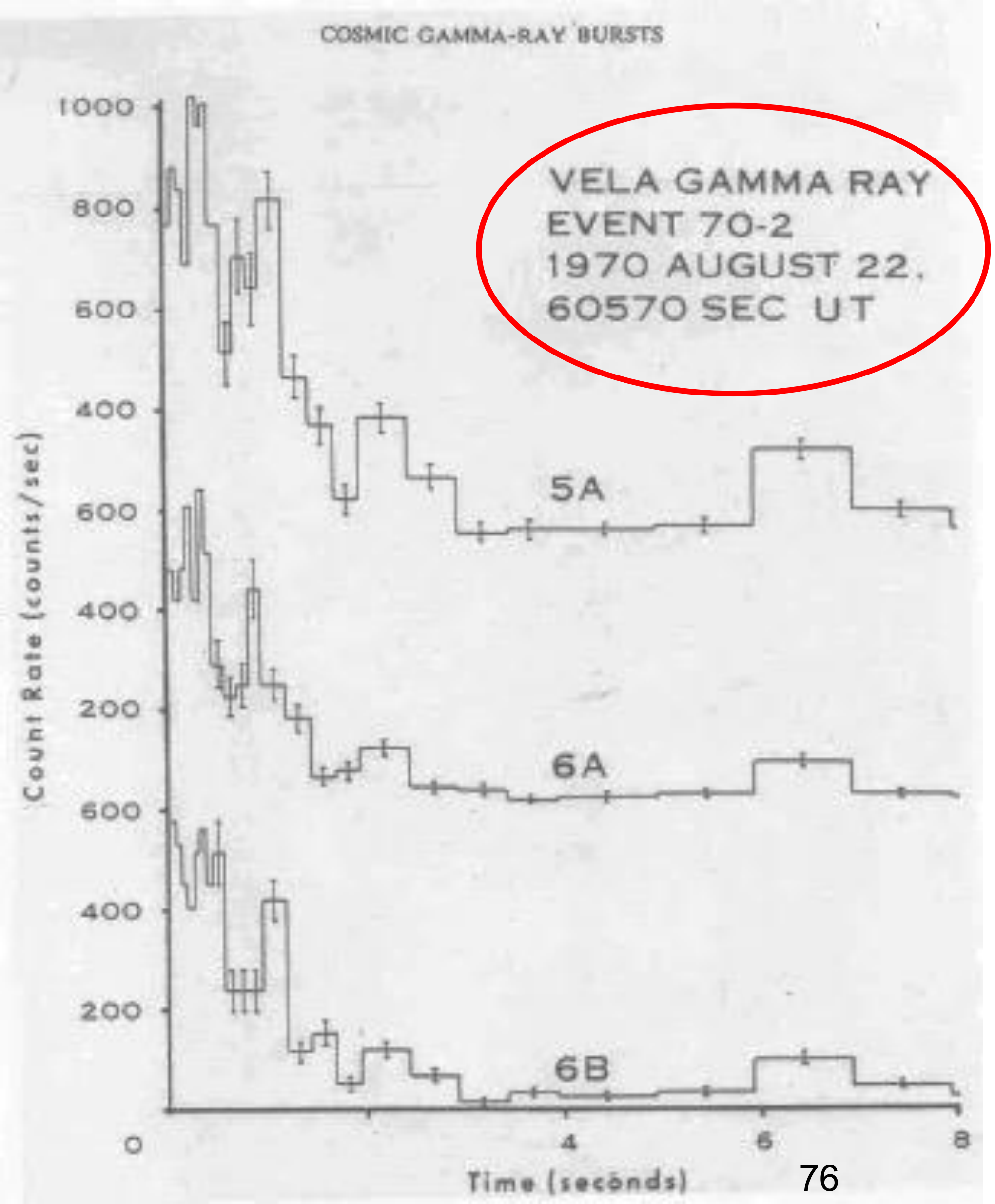
(https://en.wikipedia.org/wiki/Vela_(satellite))

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 **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 not 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 unrecognized.   Likely too unexpected.

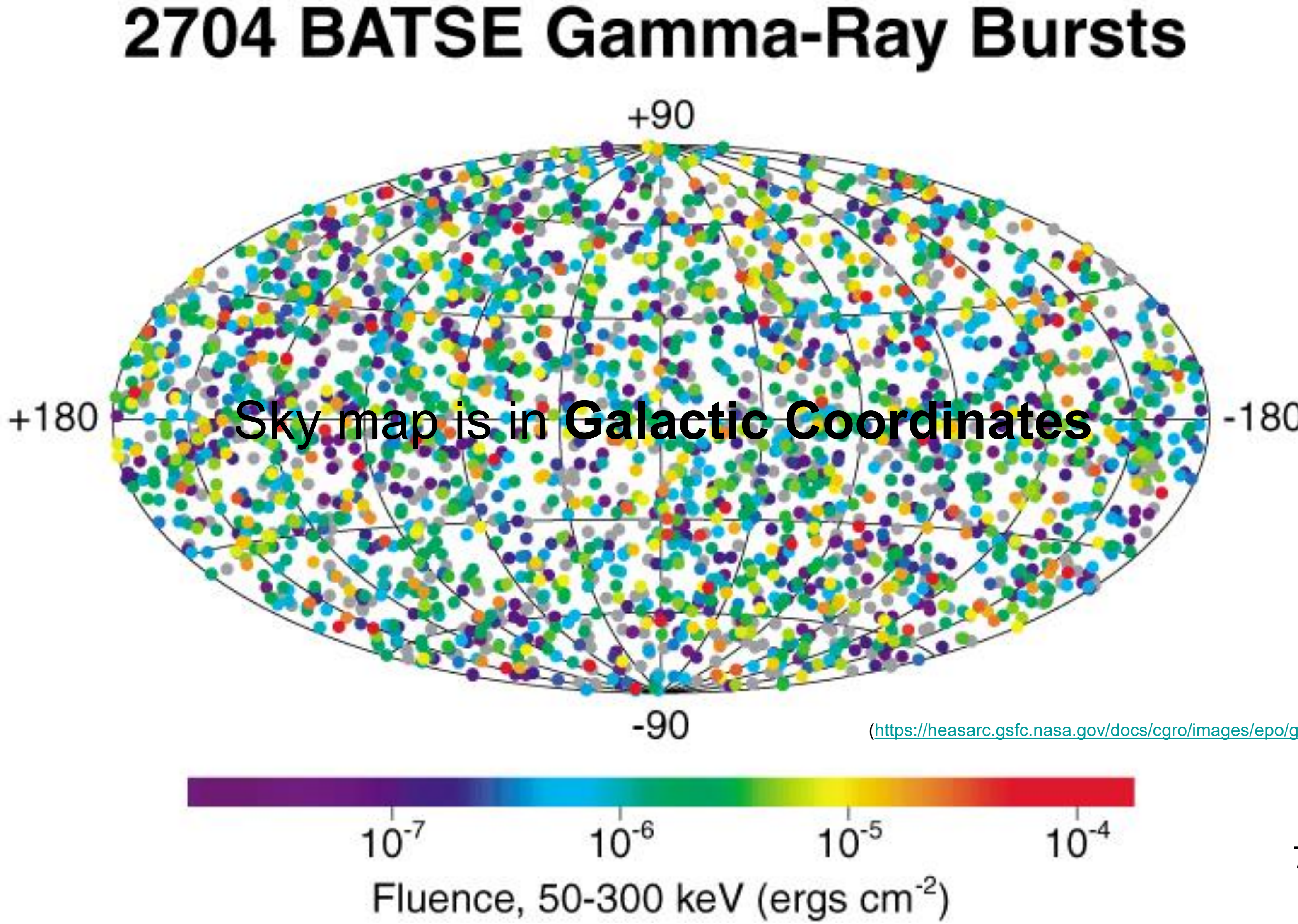
Gamma-ray bursts were just "**too unexpected**".

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*

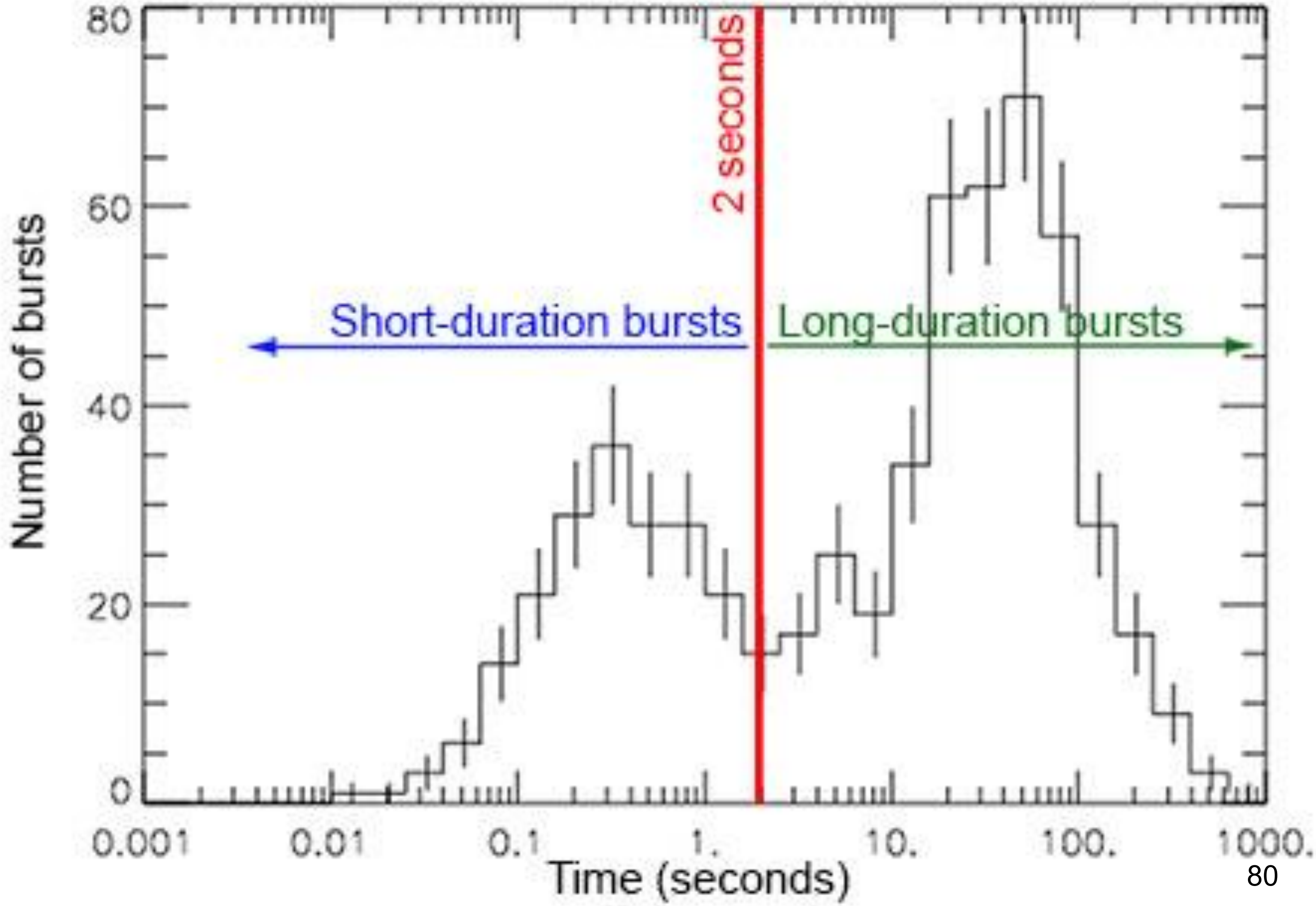
Today the uniform distribution of Gamma Ray Bursts **exclude** our galaxy and support an **extra-galactic** origin.



Sky map is in **Galactic Coordinates**

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

Gamma-ray bursts likely in 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.

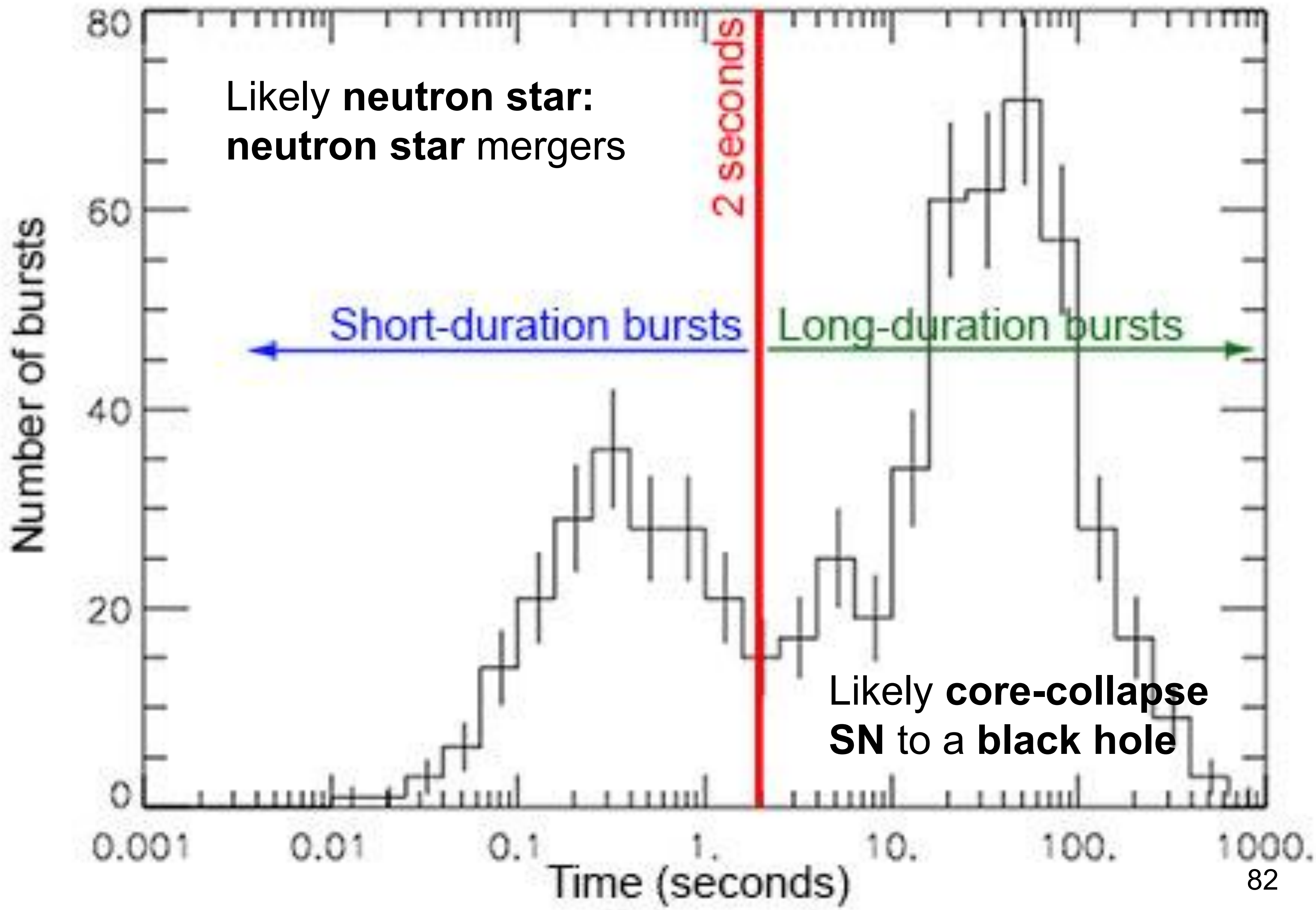
- By comparing photographs taken on May 8 and 9, 1997, one object was found to have increased in brightness.

- 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** >= 0.835, placing the burst at a distance of at least 6.6 billion light years: definitely **extra-galactic**!

- Like Quasars, something seen from that **distance** must be **extremely unusual**!

Gamma-ray bursts remain a “hot” topic

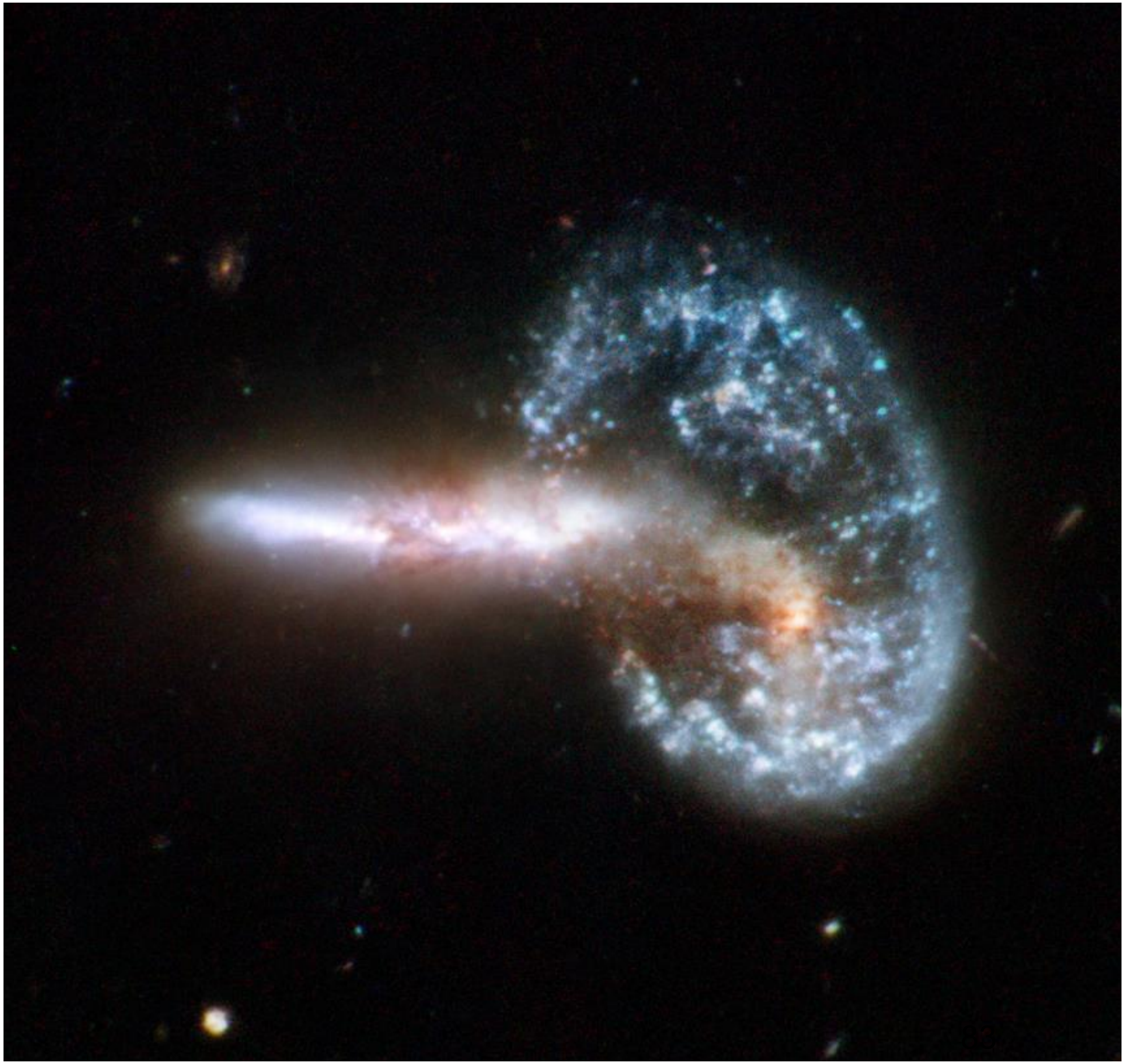


(https://gammaray.msfc.nasa.gov/batse/grb/duration/)

What were Arp's *peculiar galaxies* all about?

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)

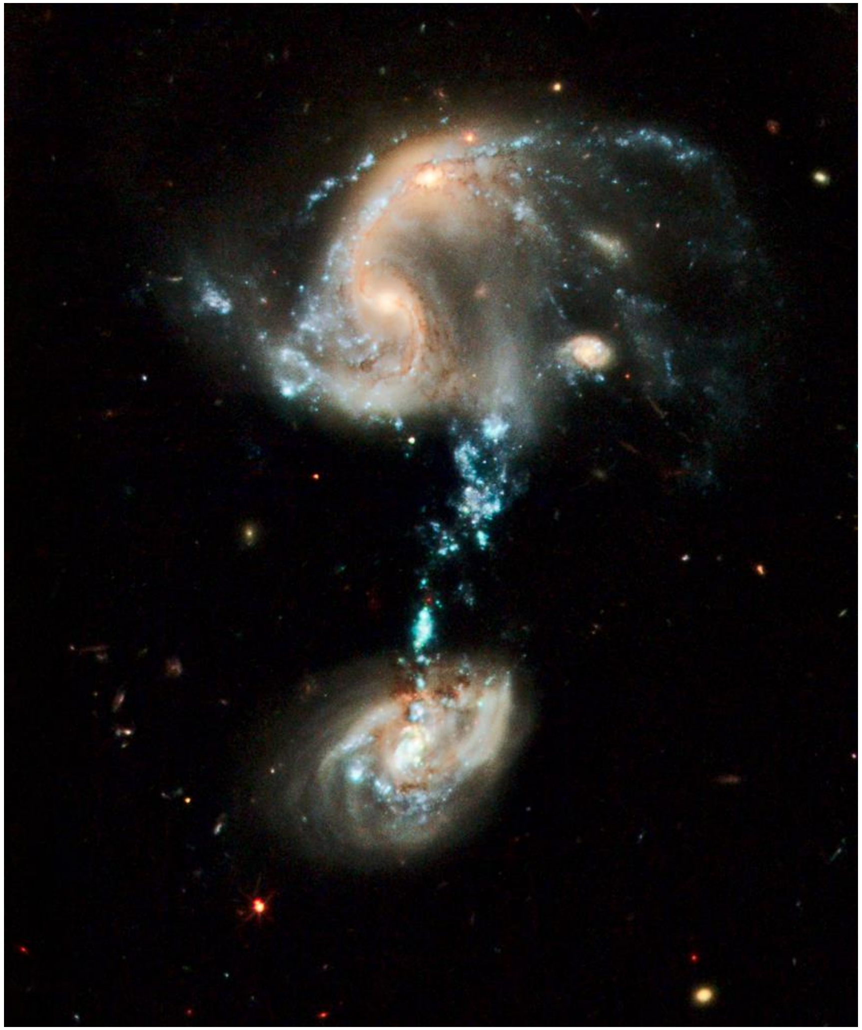
Arp had ready access to the 200” Hale telescope

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.

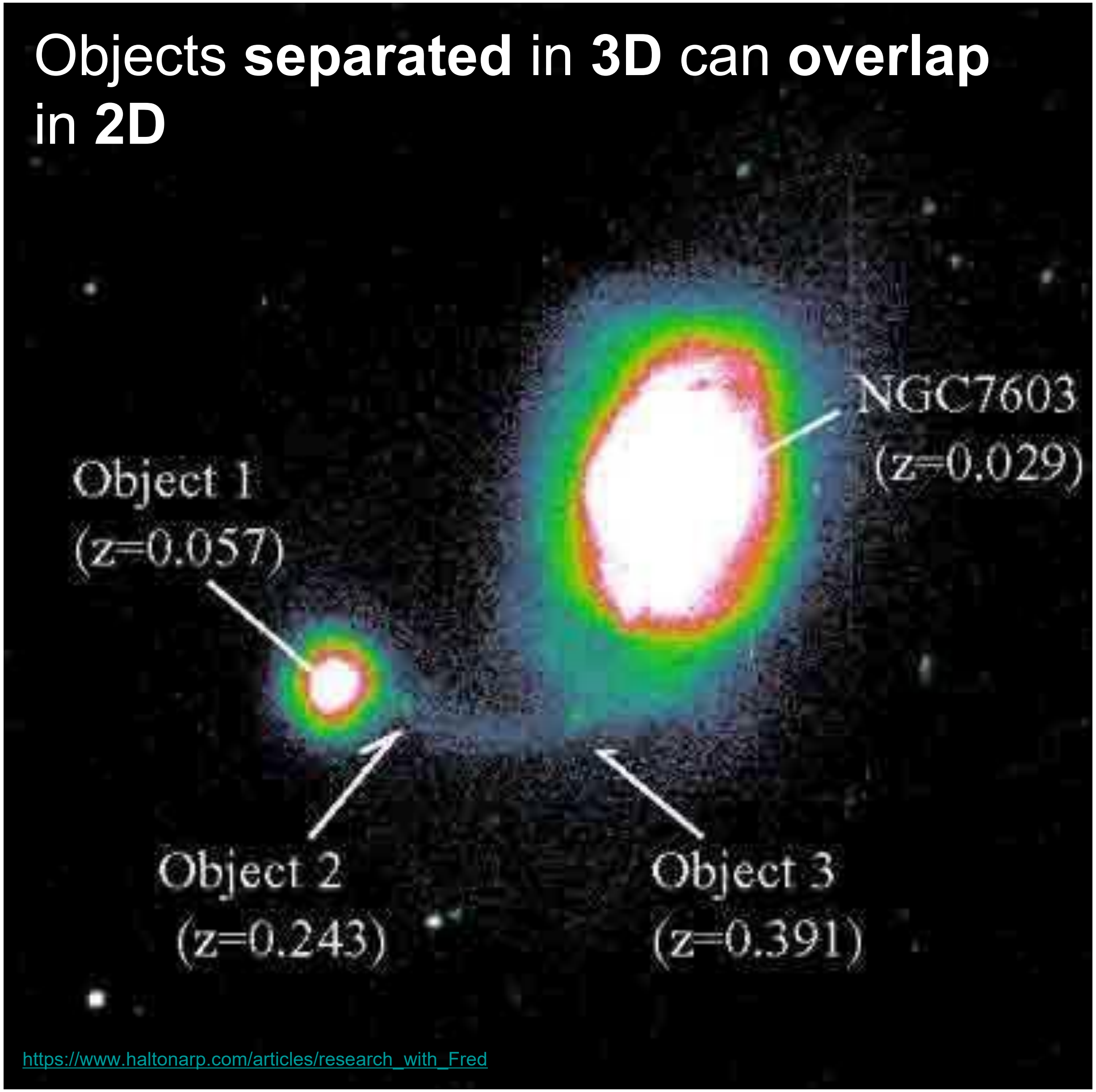


(https://en.wikipedia.org/wiki/Atlas_of_Peculiar_Galaxies)

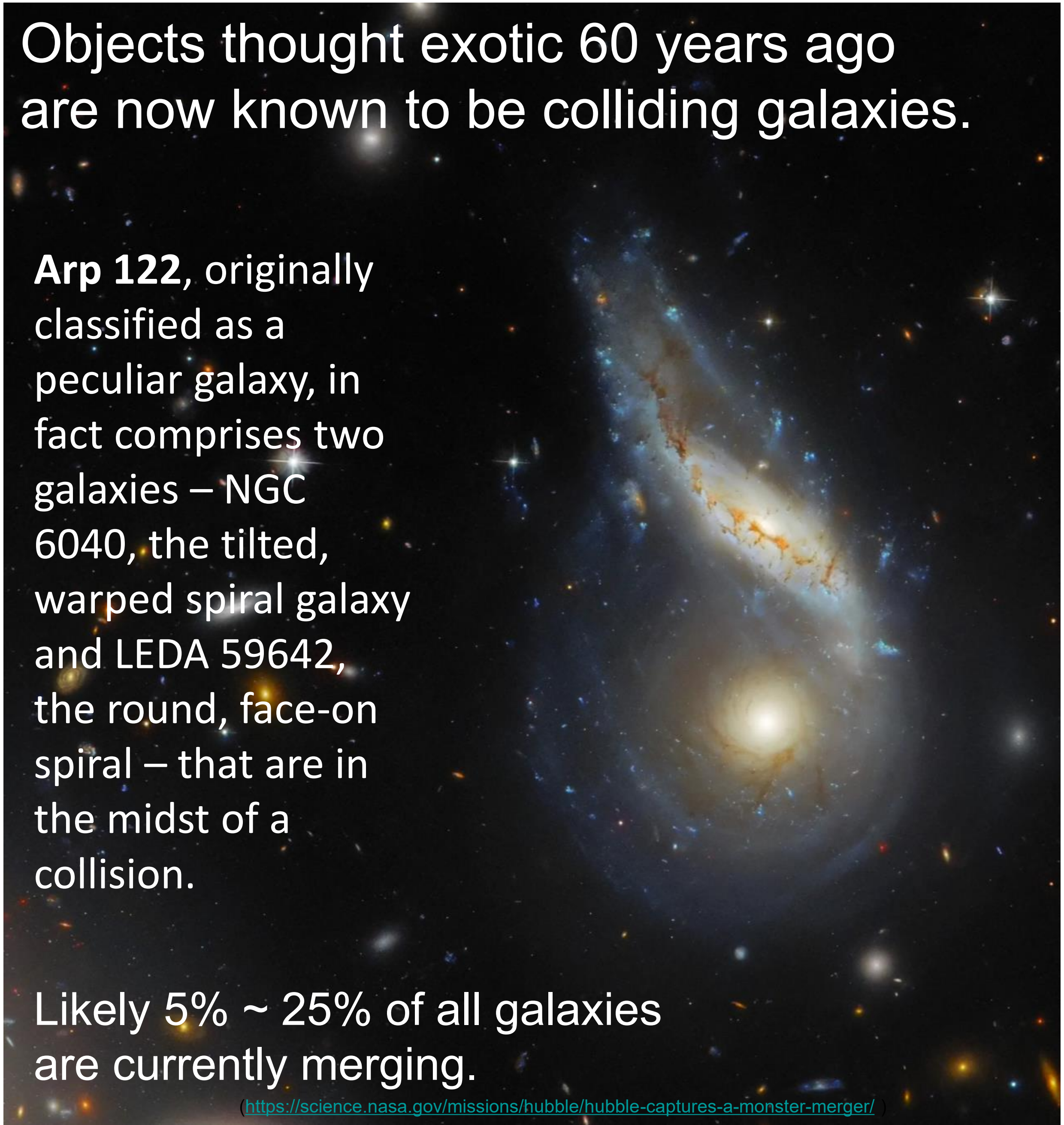
Is there truly a *Redshift Controversy*? Likely no.

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*.



And today galaxy collisions are known to be common place



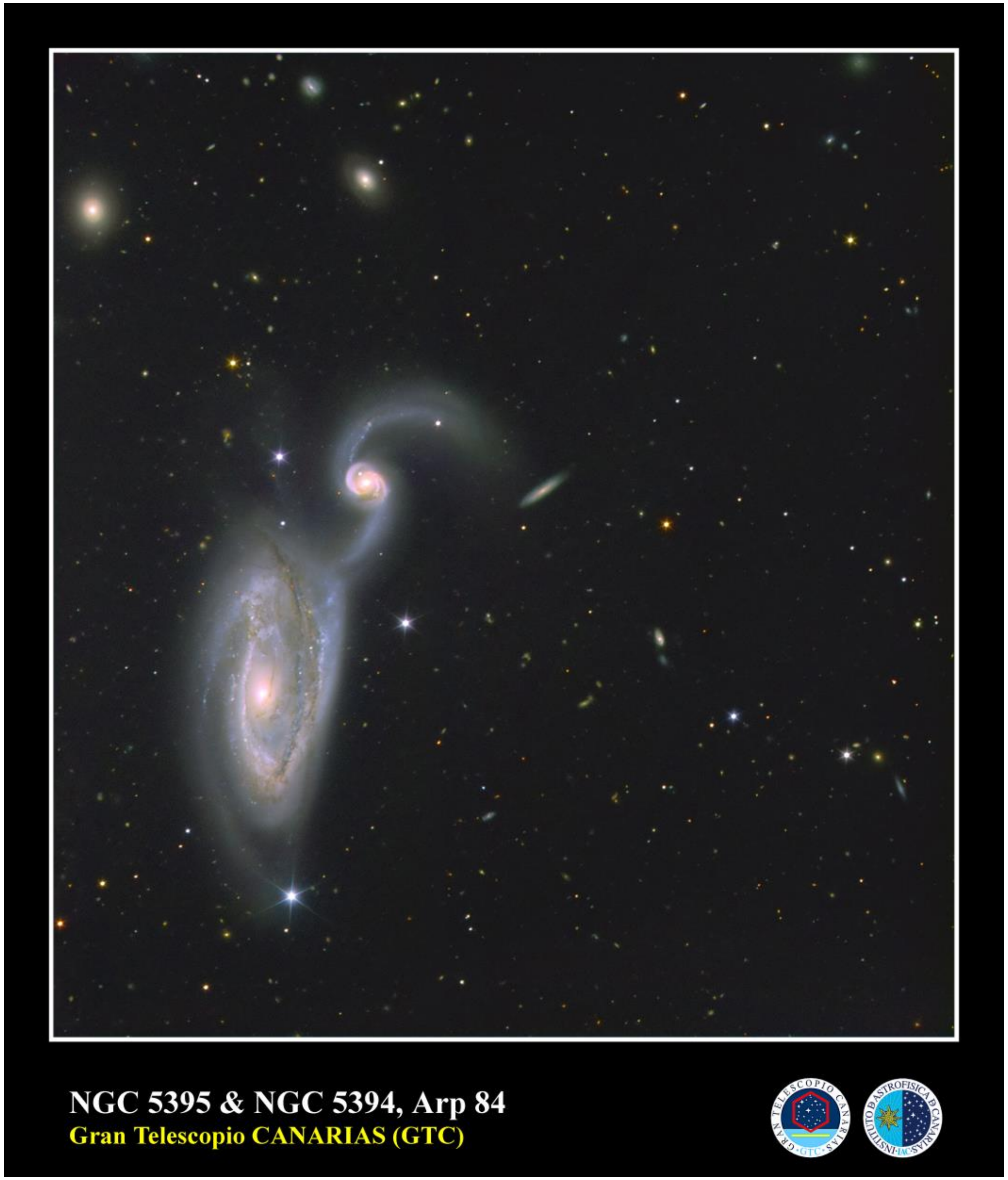
Objects thought exotic 60 years ago are now known to be colliding galaxies.

Arp 122, originally classified as a peculiar galaxy, in fact comprises two galaxies – NGC 6040, the tilted, warped spiral galaxy and LEDA 59642, the round, face-on spiral – that are in the midst of a collision.

Likely 5% ~ 25% of all galaxies are currently merging.

(https://science.nasa.gov/missions/hubble/hubble-captures-a-monster-merger/)

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

- **Quasars**: 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

- **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.

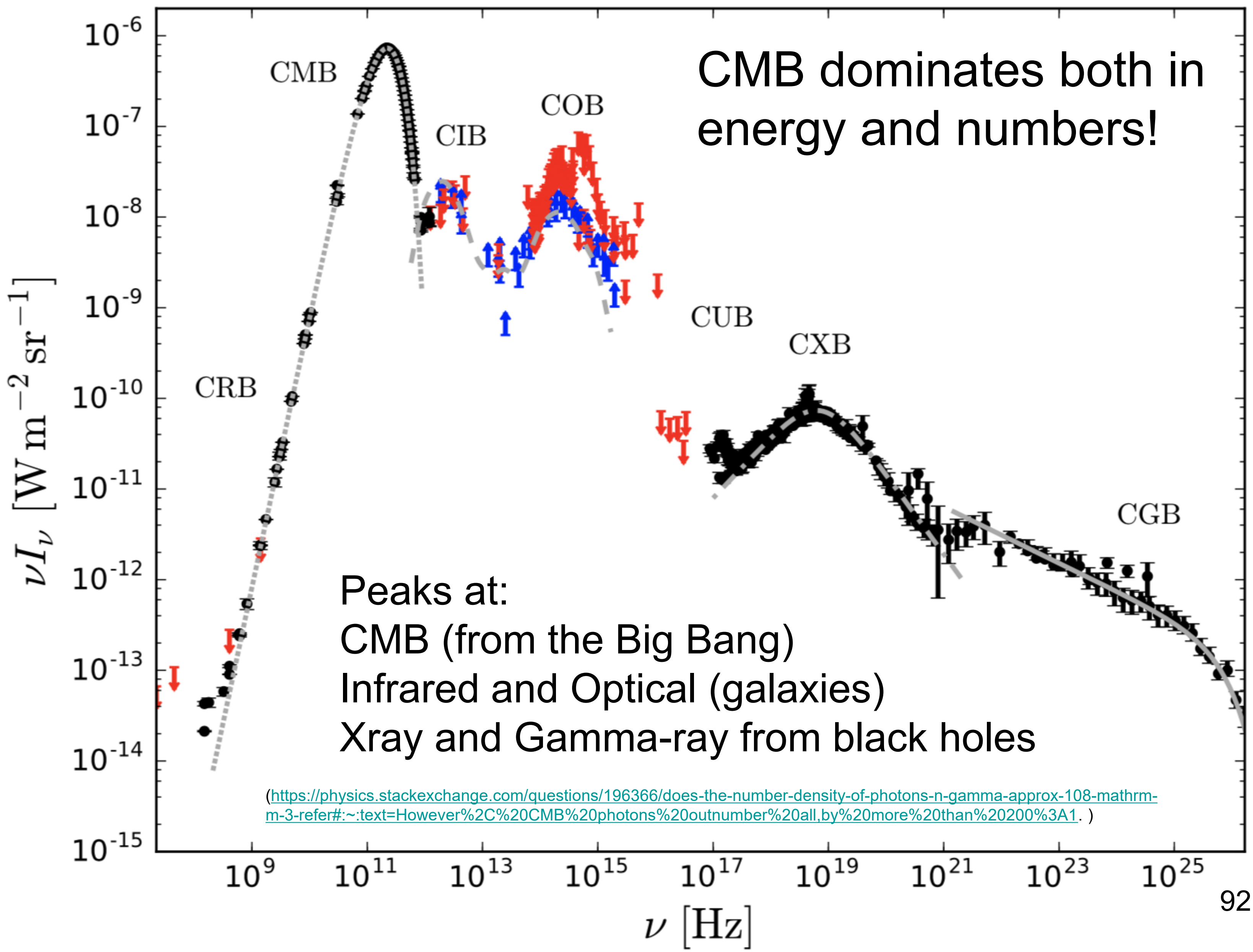
Isn't it nice to be lucky!

Thank you

John Matthews
Professor of Physics
U. of New Mexico
1 (505) 948-3241
johnm@unm.edu

Backup slides

Energy weighted flux of photons in the universe



CMB dominates both in energy and numbers!

Peaks at:
CMB (from the Big Bang)
Infrared and Optical (galaxies)
Xray and Gamma-ray from black holes

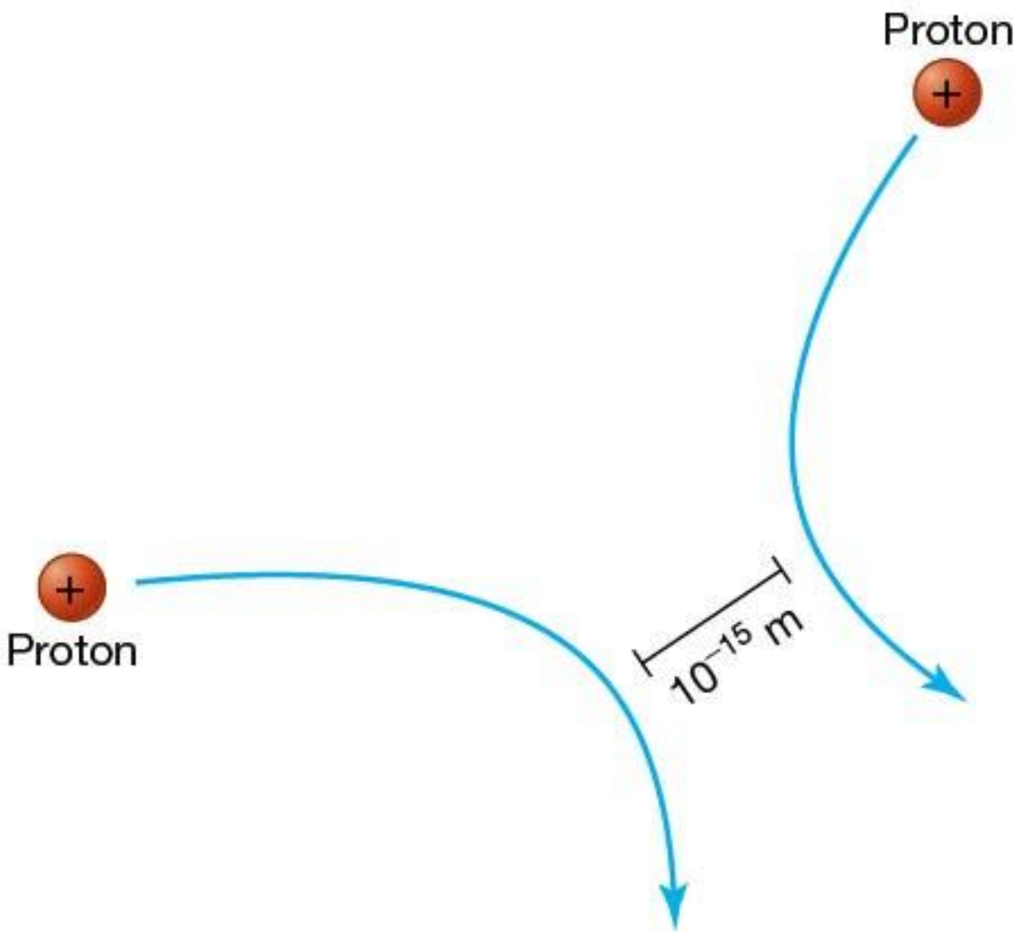
(https://physics.stackexchange.com/questions/196366/does-the-number-density-of-photons-n-gamma-approx-108-mathrm-m-3-refer#:~:text=However%2C%20CMB%20photons%20outnumber%20all,by%20more%20than%20200%3A1.)

Nuclear fusion requires nuclei to touch

Nuclei are **positively charged**, and **like-charges repel**.

For **nuclear fusion** to occur, like-charged nuclei must get close enough to **fuse**.

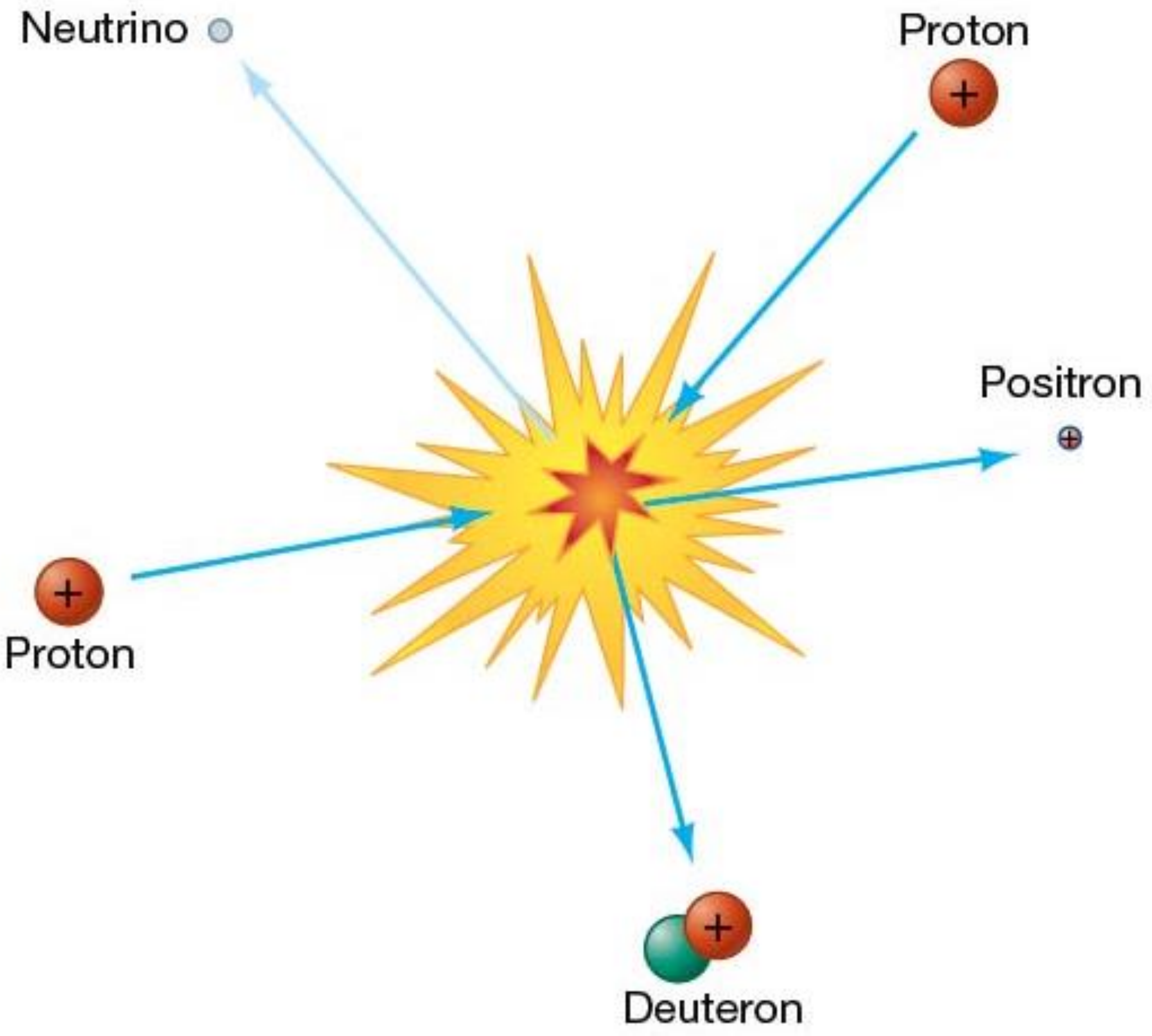
This will only happen when the nuclei have **very high velocities**.



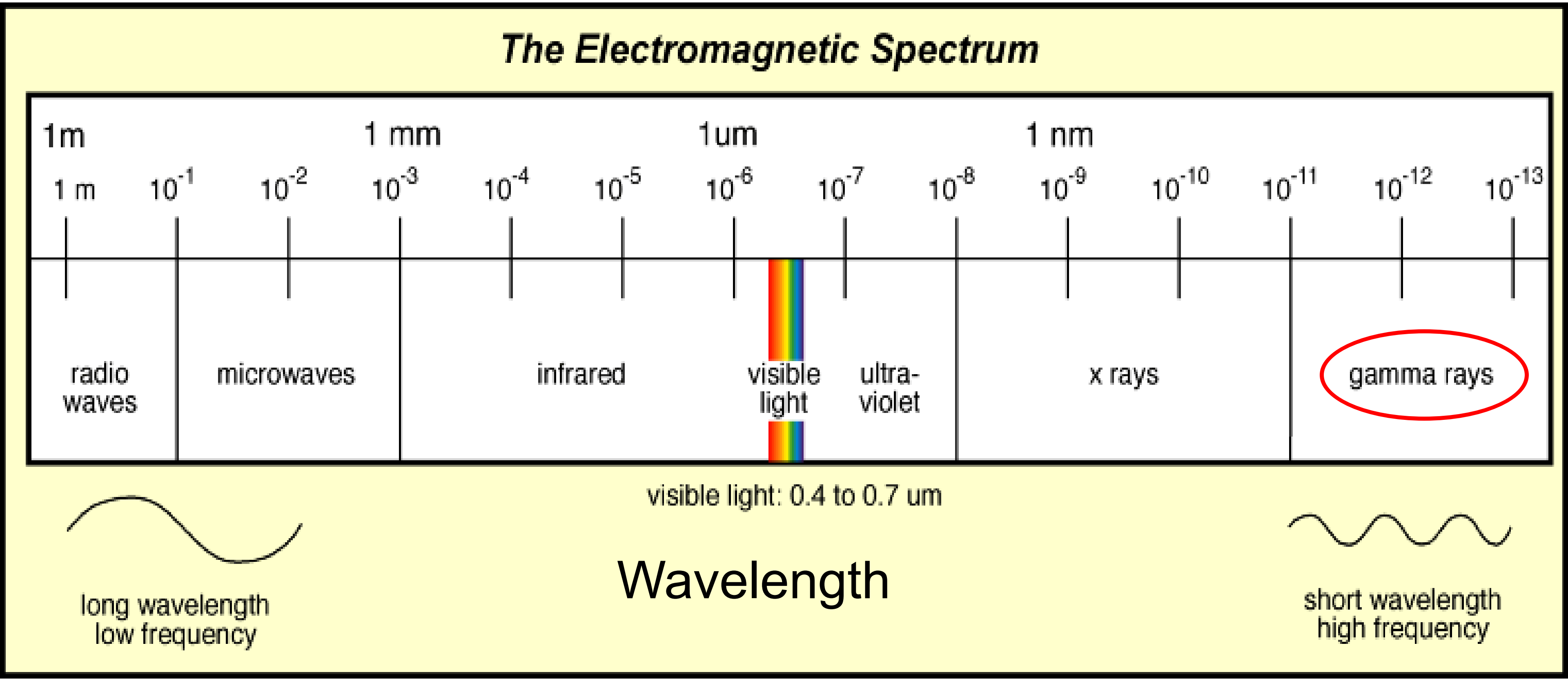
High velocities are at very high temperatures

The **higher** the **temperature** the higher the **velocities**.

Extremely high temperatures — **over 10 million Kelvin (K)** are needed for **H fusion** in the Sun — to overcome the repulsion.



What's that all about? Light is more than visible wavelengths



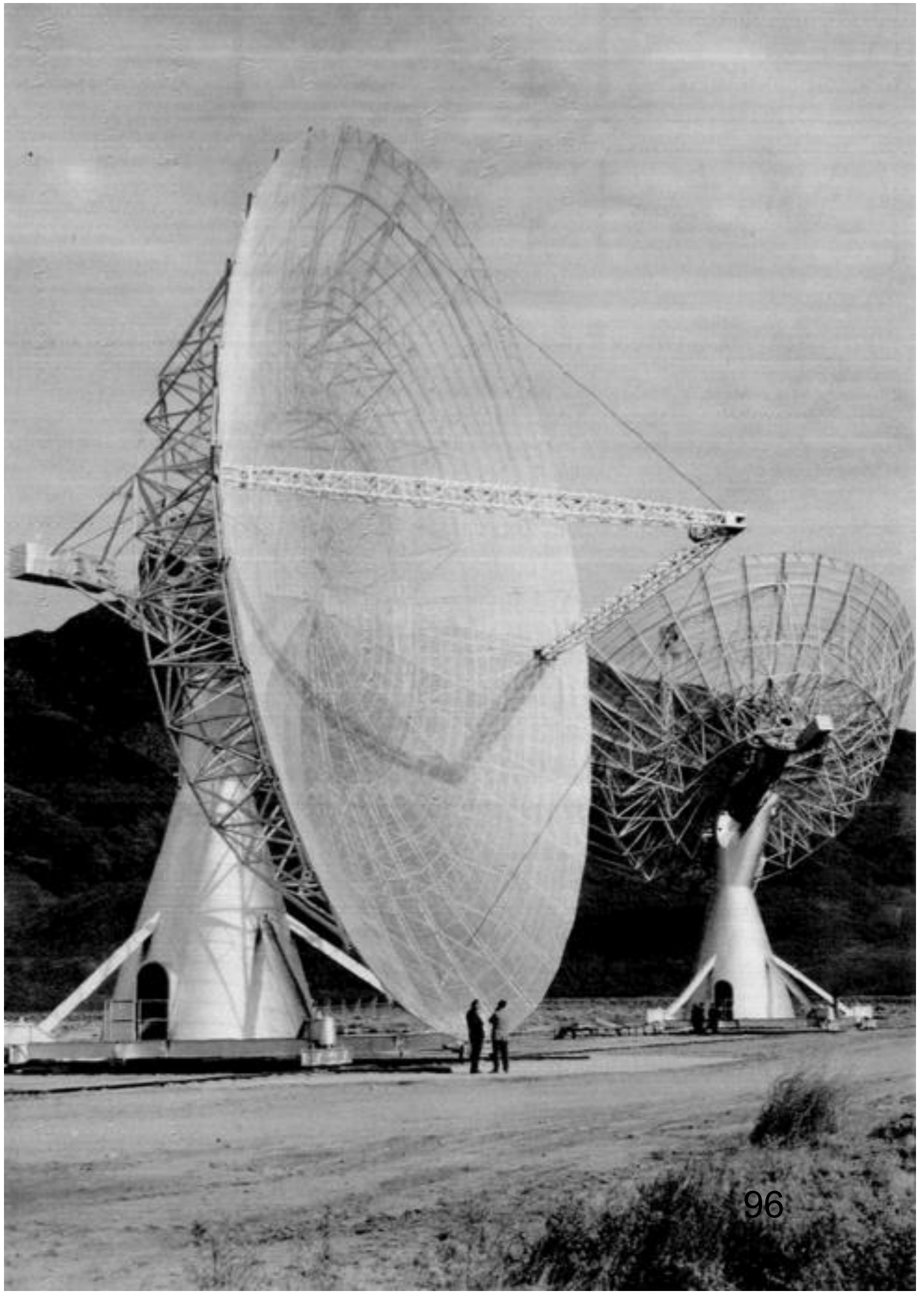
Gamma-rays have the **shortest wavelength.**
Humans emit light with **peak intensity** at a wavelength of about 0.29cm/310 (K) = 9.35 x 10^{-6} m ~ **10 μm** (Wien's law).

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

Improved angular precision was the game changer

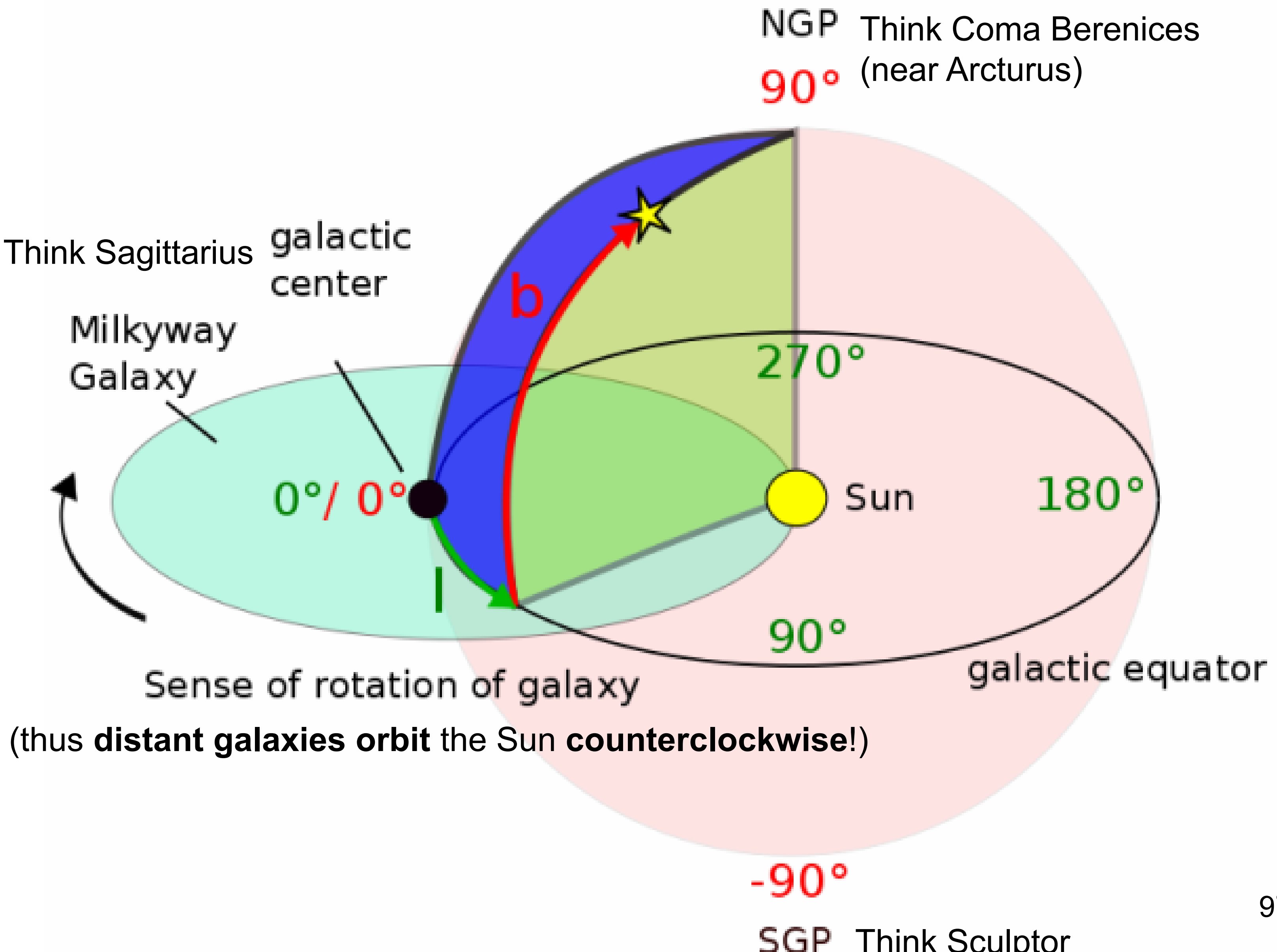
Owen's Valley Radio Observatory radio source positions were accurate up to 10-seconds of arc (**Jesse Greenstein** 1961)

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)

Galactic coordinates (l, b): Sun centered right-hand system

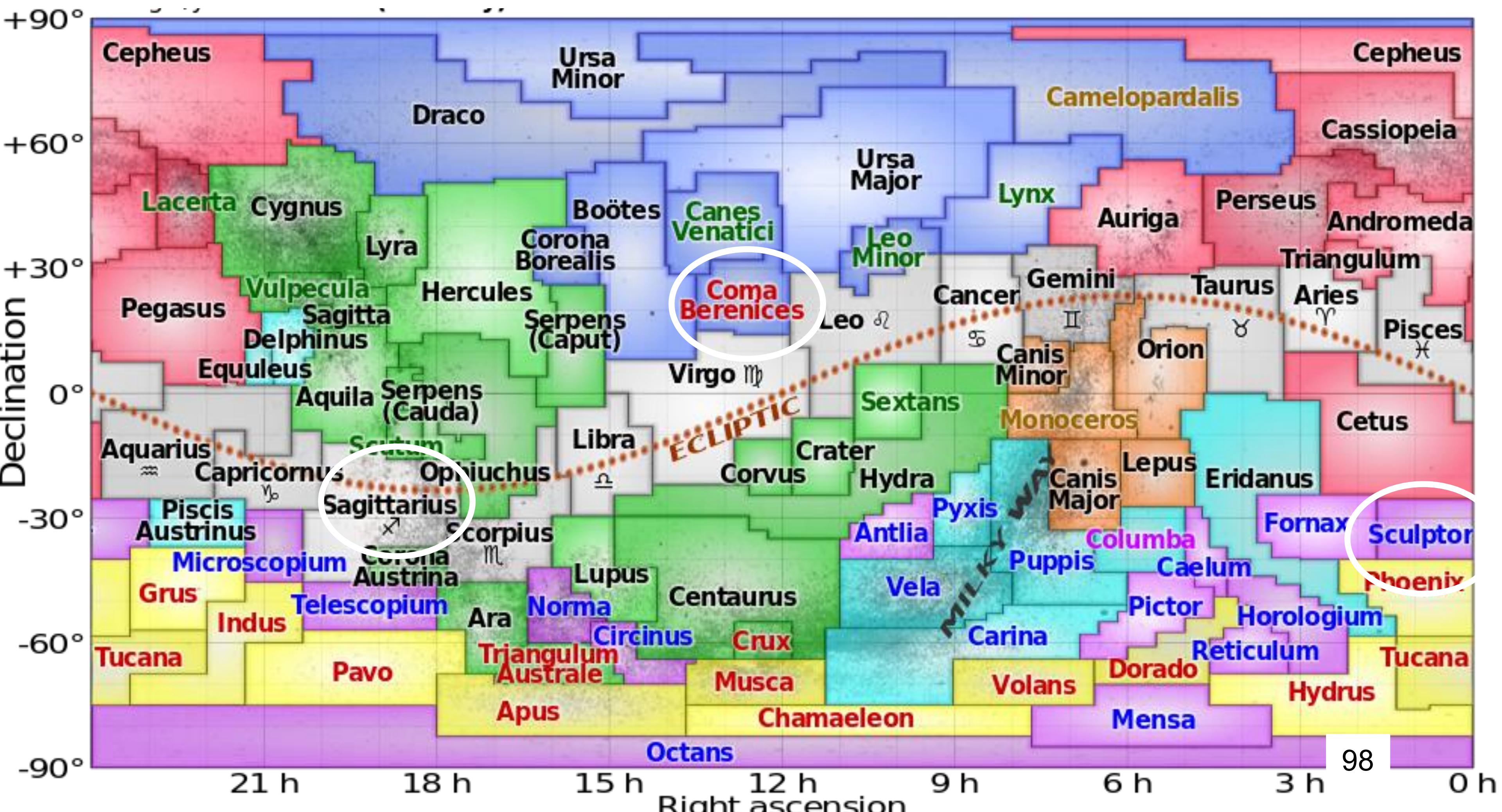


(thus **distant galaxies orbit** the Sun **counterclockwise**!)

(https://auger.org/education/Auger_Education/galacticcoordinates.html)

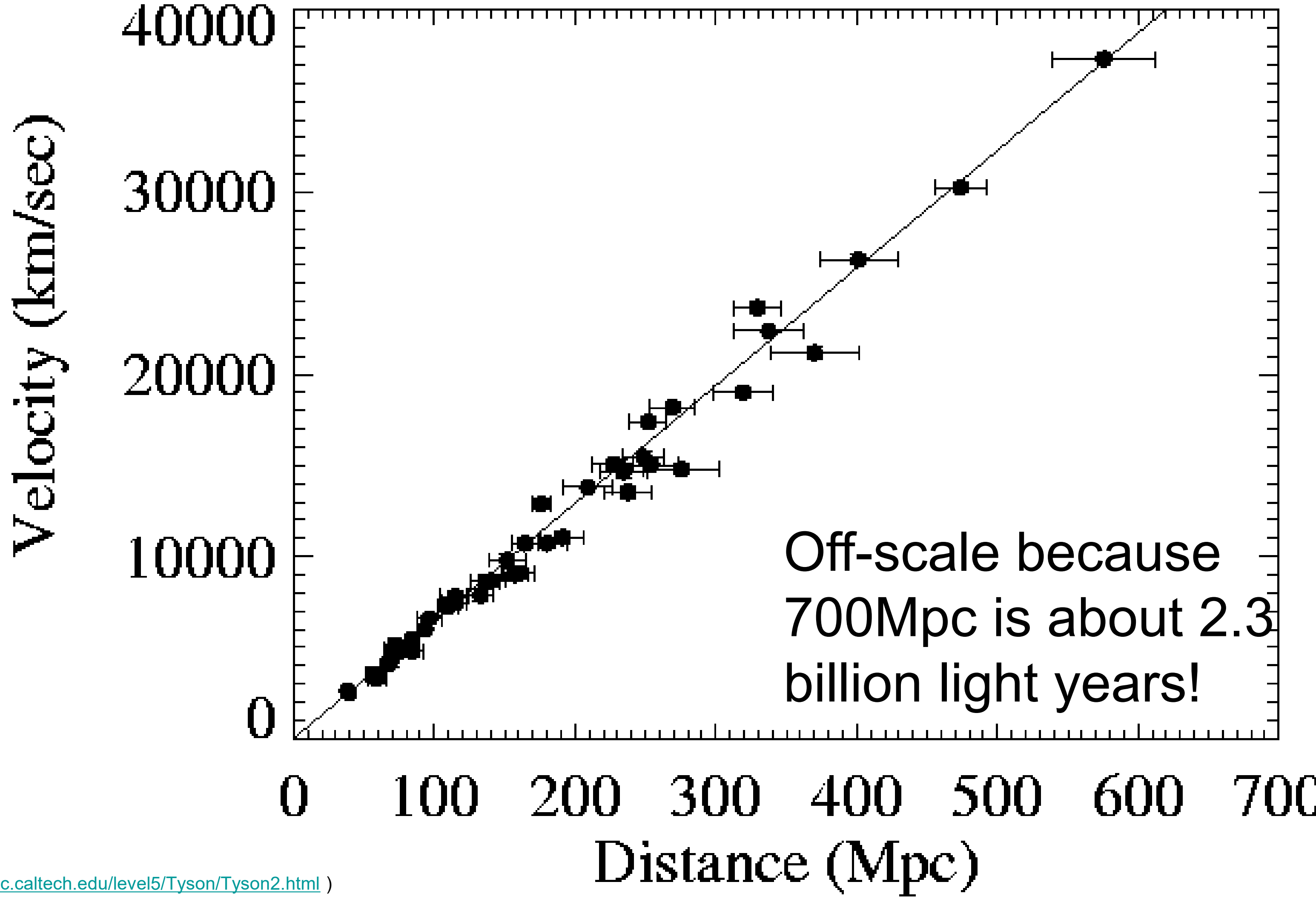
The entire sky is divided into 88 (modern day) constellations

- Today this is mostly for convenience: think how we use the fact that the continental US is divided into 48 states!



Maarten Schmidt’s observation was off-scale

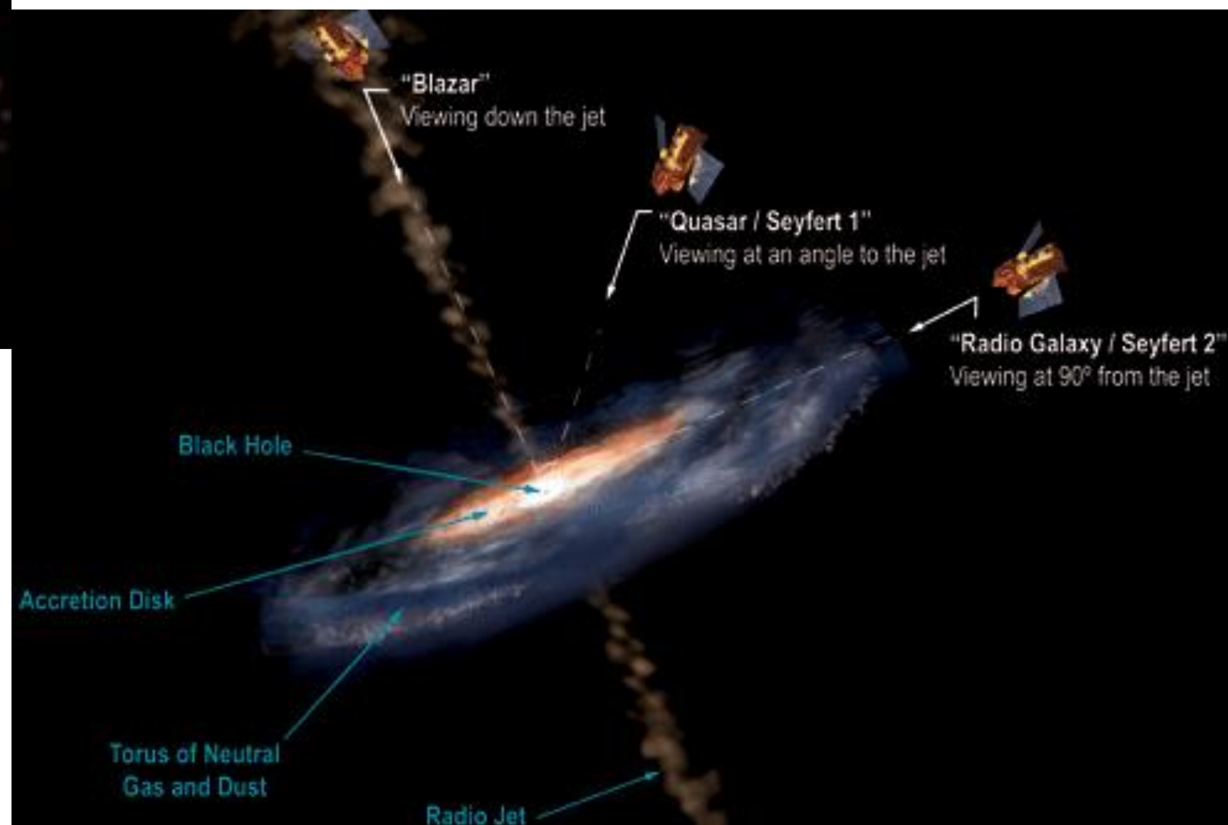
3C 273’s 15.8% **redshift** means that **3C 273** was receding from us at 15.8% the speed of light (47,400 km/sec). This is **off-scale** even with this modern Hubble relation plot!



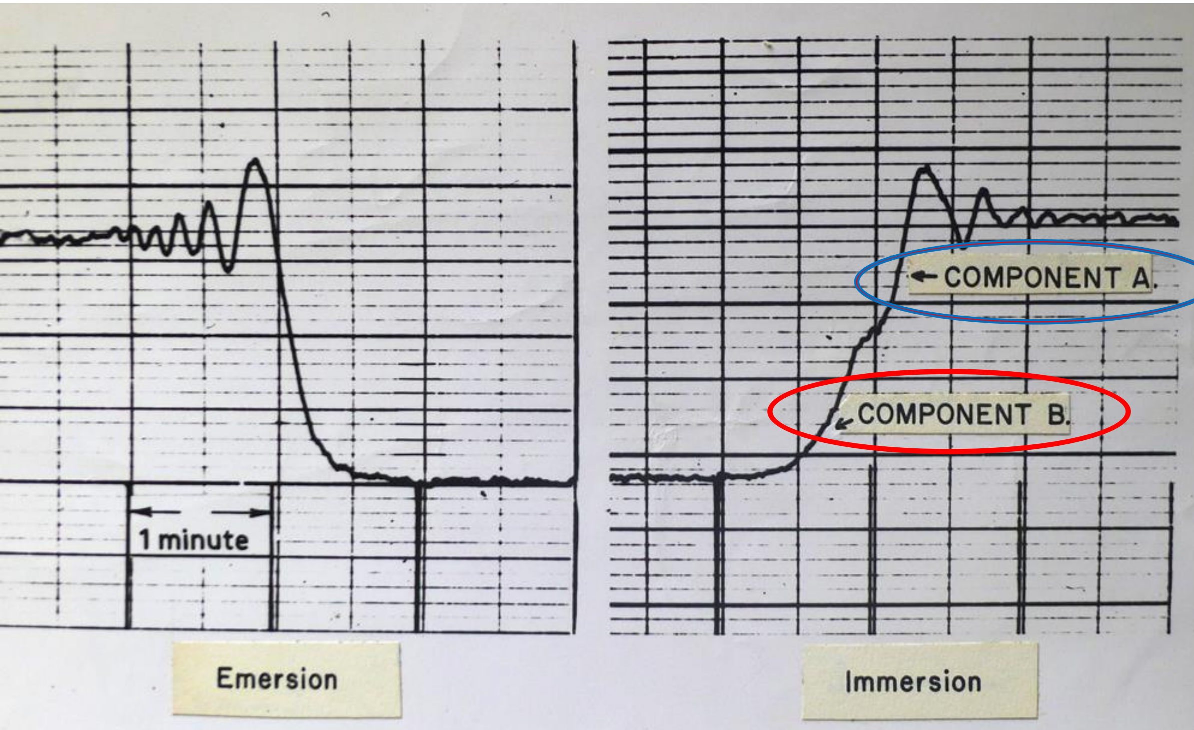
(https://ned.ipac.caltech.edu/level5/Tyson/Tyson2.html)

Possible model for Quasars

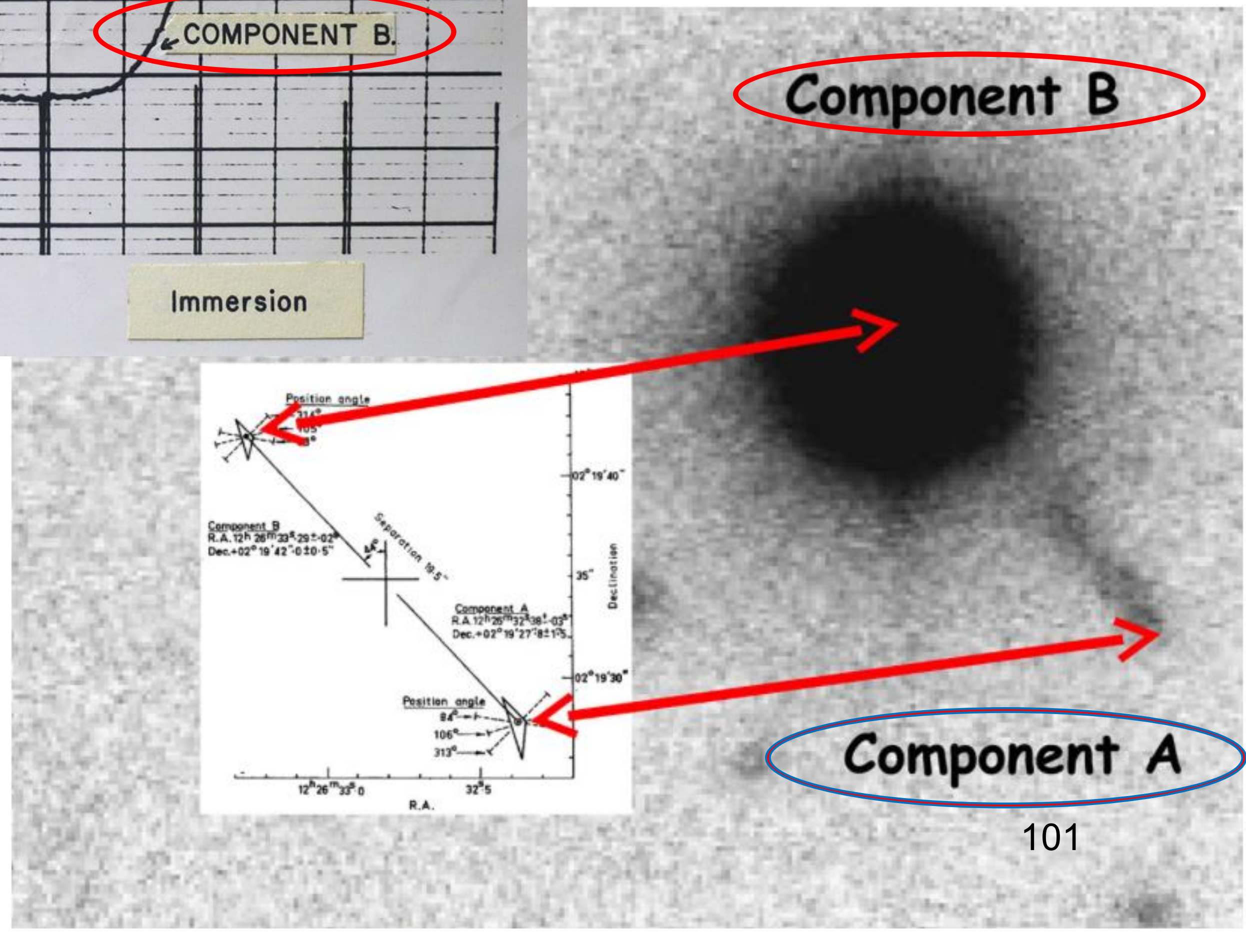
Quasars are thought to be super-massive Black Holes in a period of "peak" mass acquisition …
(Top left): X-ray image of Quasar
(Bottom right): artist sketch of typical model of super-massive Black Holes



Curiously Quasar jet structure likely seen in lunar occultation



(https://pdfs.semanticscholar.org/fa62/38493cc03edf23a208cbcd13c52421c1c6b3.pdf)



Amazingly the 1962 lunar occultation suggested a 2 component: **core + radio lobe (jet) structure.**

First page of Nature paper …

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 gala‹y, and may be associated with oscillations of white dwarf or neutron stars.

In July 1967, a large radio telescope operating at a frequency of 81·5 MHz was brought into use at the Mullard Radio Astronomy Observatory. This instrument was designed to investigate the angular structure of compact radio sources by observing the scintillation caused by the irregular structure of the interplanetary medium[1]. The initial survey includes the whole sky in the declination range $-08° < \delta < 44°$ and this area is scanned once a week. A large fraction of the sky is thus under regular surveillance. Soon after the instrument was brought into operation it was noticed that signals which appeared at first to be weak sporadic interference were repeatedly observed at a fixed declination and right ascension; this result showed that the source could not be terrestrial in origin.

Systematic investigations were started in November and high speed records showed that the signals, when present, consisted of a series of pulses each lasting $\sim 0{\cdot}3$ s and with a repetition period of about 1·337 s which was soon found to be maintained with extreme accuracy. Further observations have shown that the true period is constant to better than 1 part in 10^7 although there is a systematic variation which can be ascribed to the orbital motion of the Earth. The impulsive nature of the recorded signals is caused by the periodic passage of a signal of descending frequency through the 1 MHz pass band of the receiver.

The remarkable nature of these signals at first suggested an origin in terms of man-made transmissions which might arise from deep space probes, planetary radar or the reflexion of terrestrial signals from the Moon. None of these interpretations can, however, be accepted because the absence of any parallax shows that the source lies far outside the solar system. A preliminary search for further pulsating sources has already revealed the presence of three others having remarkably similar properties which suggests that this type of source may be relatively common at a low flux density. A tentative explanation of these unusual sources in terms of the stable oscillations of white dwarf or neutron stars is proposed.

Position and Flux Density

The aerial consists of a rectangular array containing 2,048 full-wave dipoles arranged in sixteen rows of 128 elements. Each row is 470 m long in an E.–W. direction and the N.–S. extent of the array is 45 m. Phase-scanning is employed to direct the reception pattern in declination and four receivers are used so that four different declinations may be observed simultaneously. Phase-switching receivers are employed and the two halves of the aerial are combined as an E.–W. interferometer. Each row of dipole elements is backed by a tilted reflecting screen so that maximum sensitivity is obtained at a declination of approximately $+30°$, the overall sensitivity being reduced by more than one-half when the beam is scanned to declinations above $+90°$ and below $-5°$. The beamwidth of the array to half intensity is about $\pm\frac{1}{2}°$ in right ascension and $\pm 3°$ in declination; the phasing arrangement is designed to produce beams at roughly 3° intervals in declination. The receivers have a bandwidth of 1 MHz centred at a frequency of 81·5 MHz and routine recordings are made with a time constant of 0·1 s; the r.m.s. noise fluctuations correspond to a flux density of $0{\cdot}5 \times 10^{-26}$ W m^{-2} Hz^{-1}. For detailed studies of the pulsating source a time constant of 0·05 s was usually employed and the signals were displayed on a multi-channel 'Rapidgraph' pen recorder with a time constant of 0·03 s. Accurate timing of the pulses was achieved by recording second pips derived from the *MSF* Rugby time transmissions.

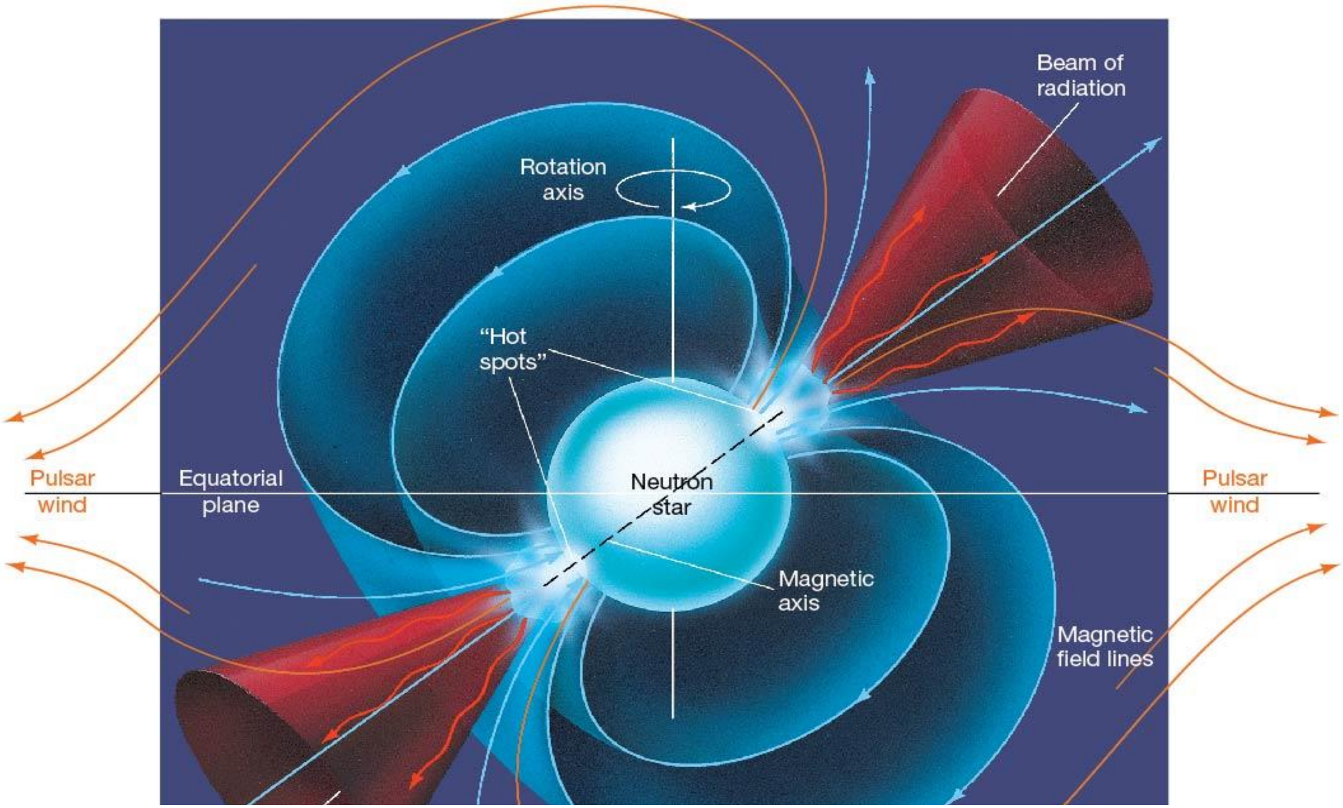
A record obtained when the pulsating source was un-

Pulsars: 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.**

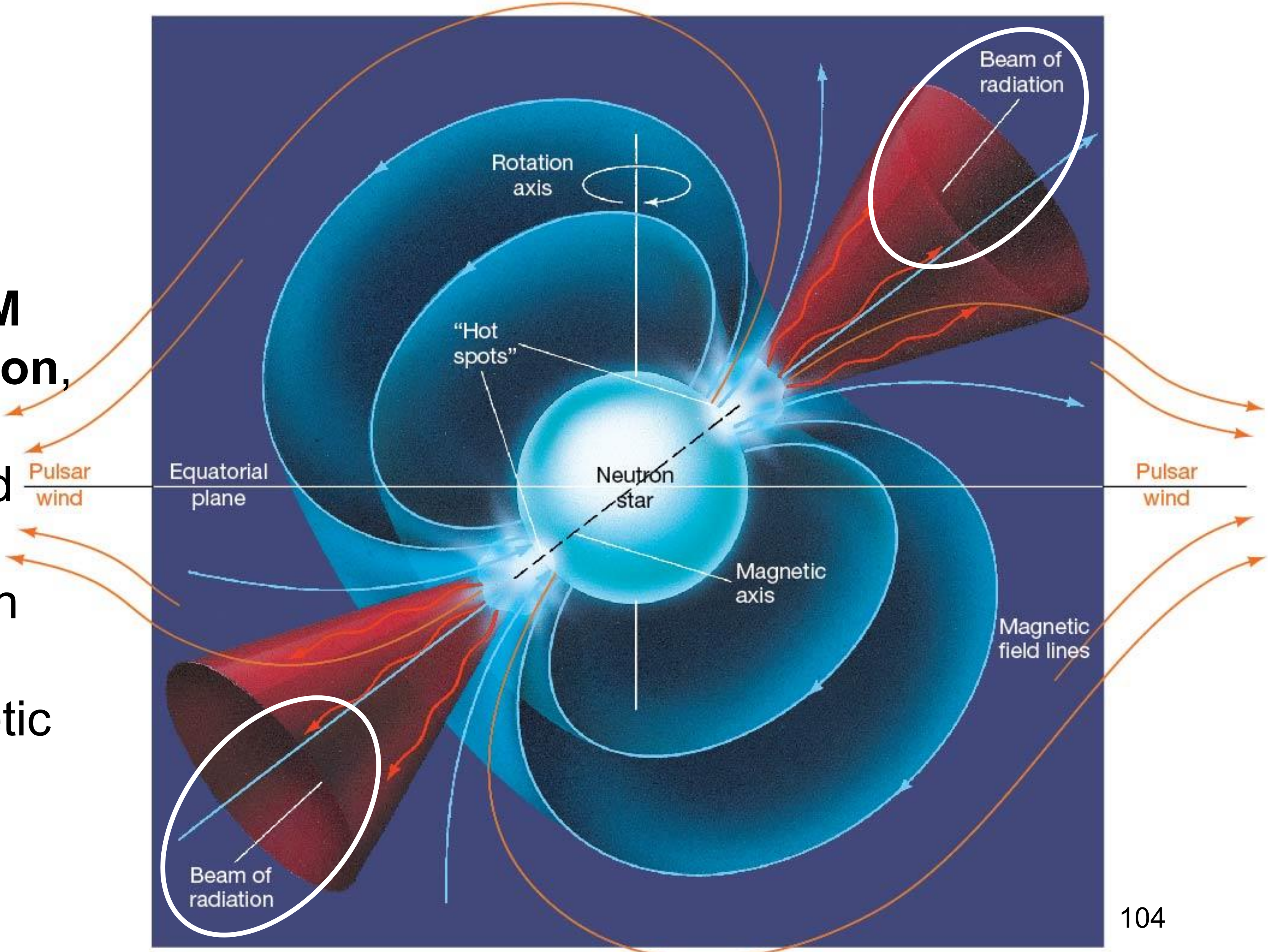
.



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

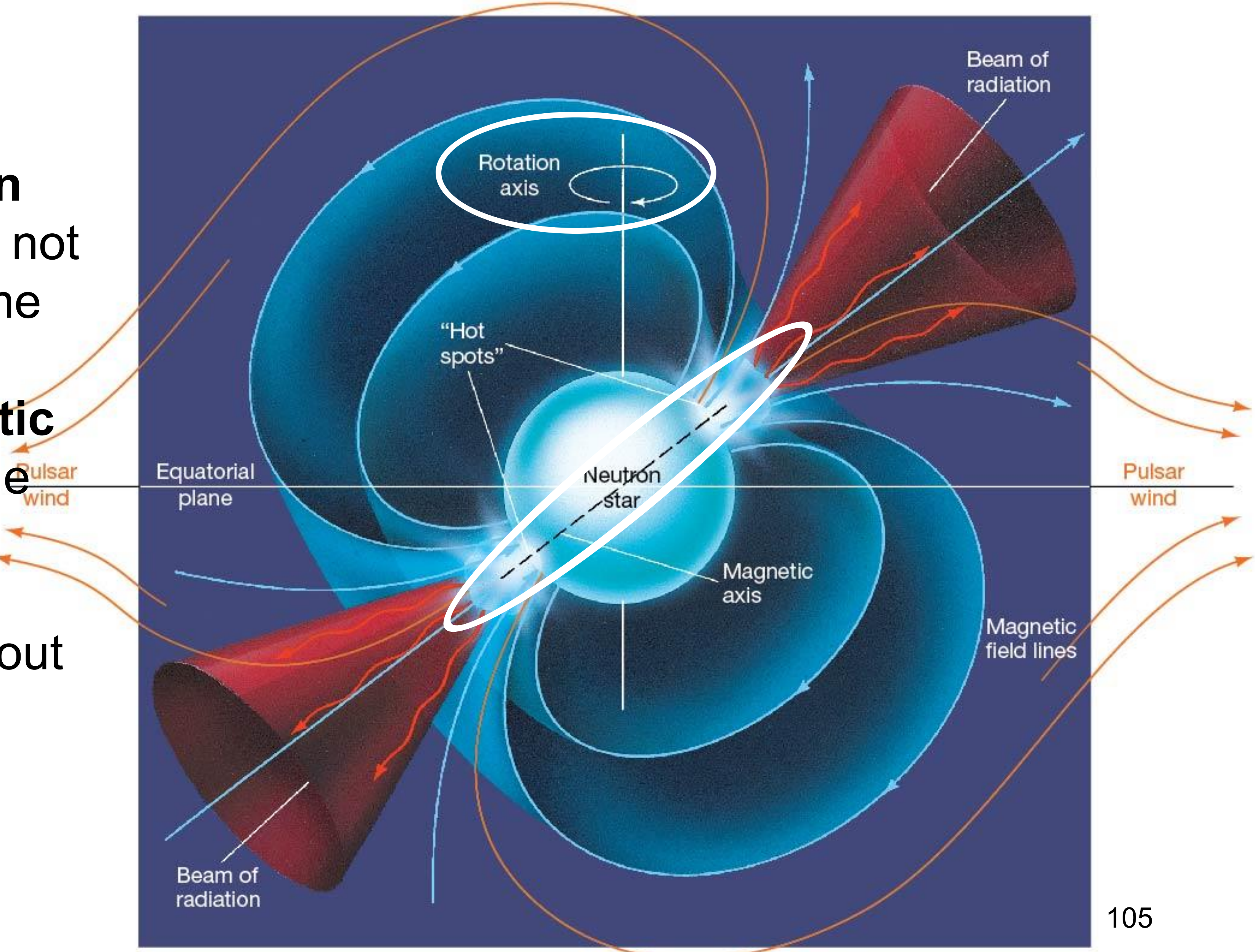
Pulsars: neutron stars emit beamed radiation

Strong **jets** of matter, and **EM radiation**, are emitted at the neutron star's magnetic poles



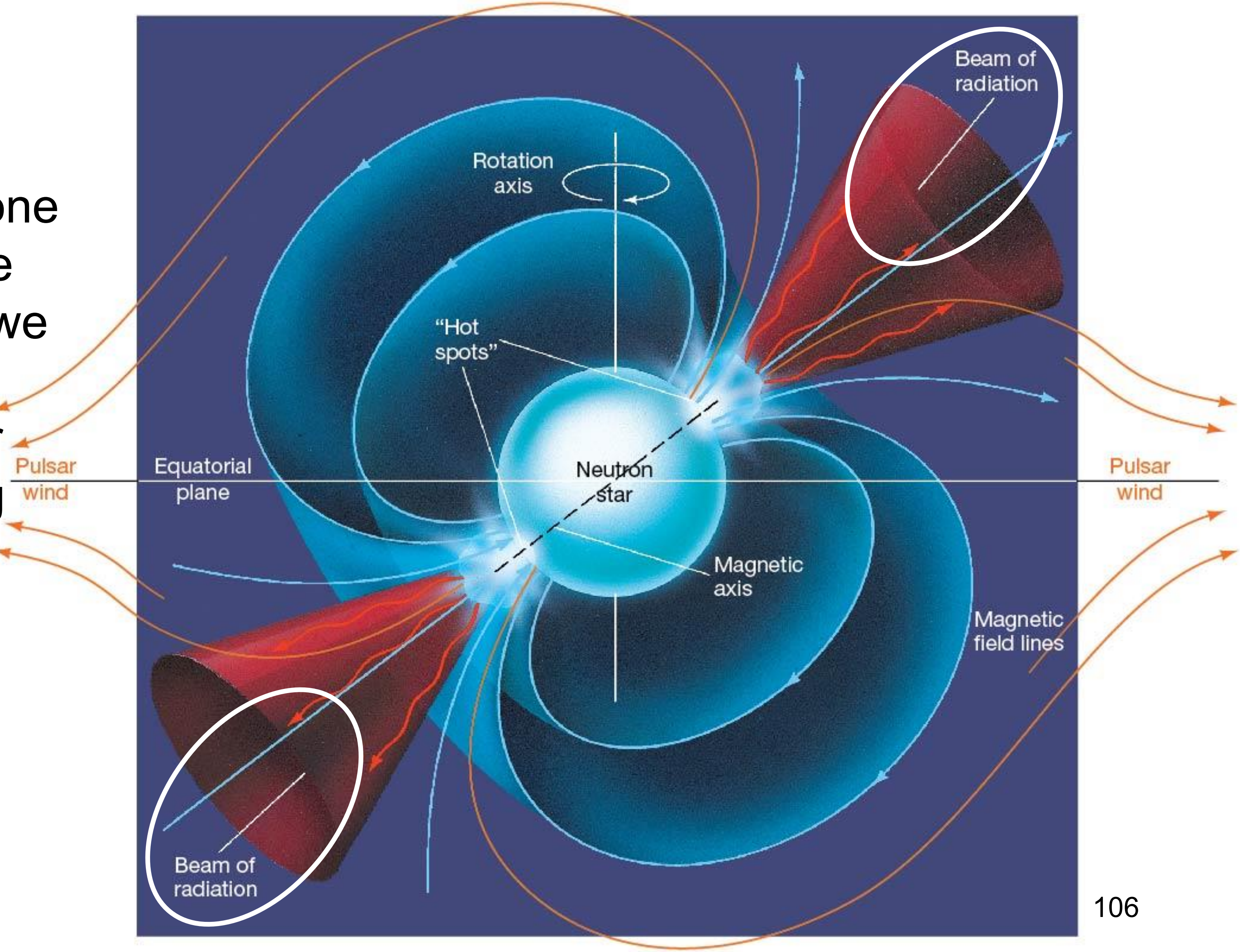
Pulsars: beamed radiation sweeps across the Celestial Sphere

If the **rotation axis,** is not the same as the **magnetic axis**, the (two) beams sweep out circular paths.

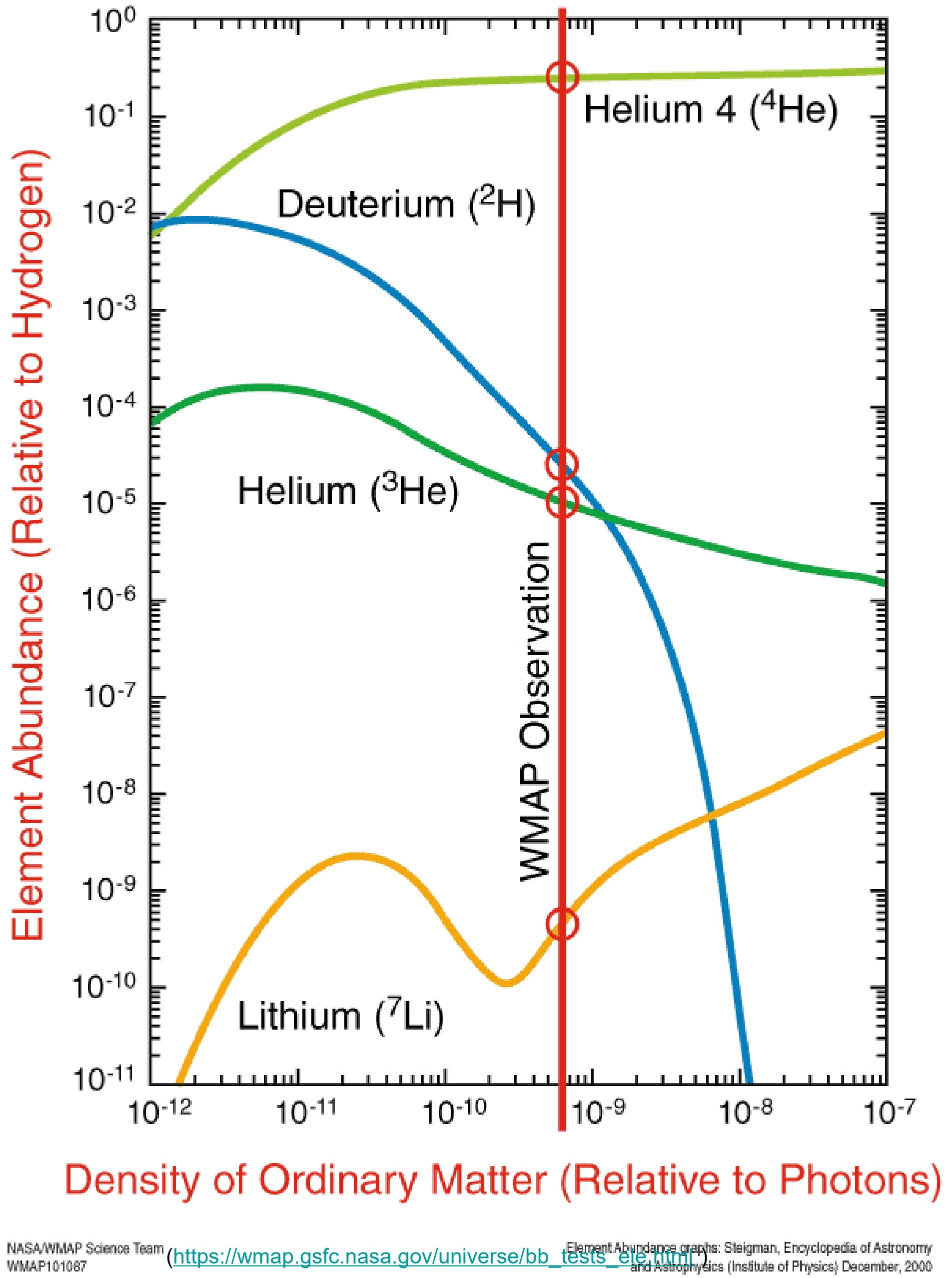


Pulsars: radio pulse when the beam sweeps across the Earth

If Earth lies in one of those paths, we will see the star blinking on, and off.



CMB constrained 6 x 10^{-10} also requires a huge flux of photons



(https://wmap.gsfc.nasa.gov/universe/bb_tests_ele.html)