Lectures on radio astronomy: 4

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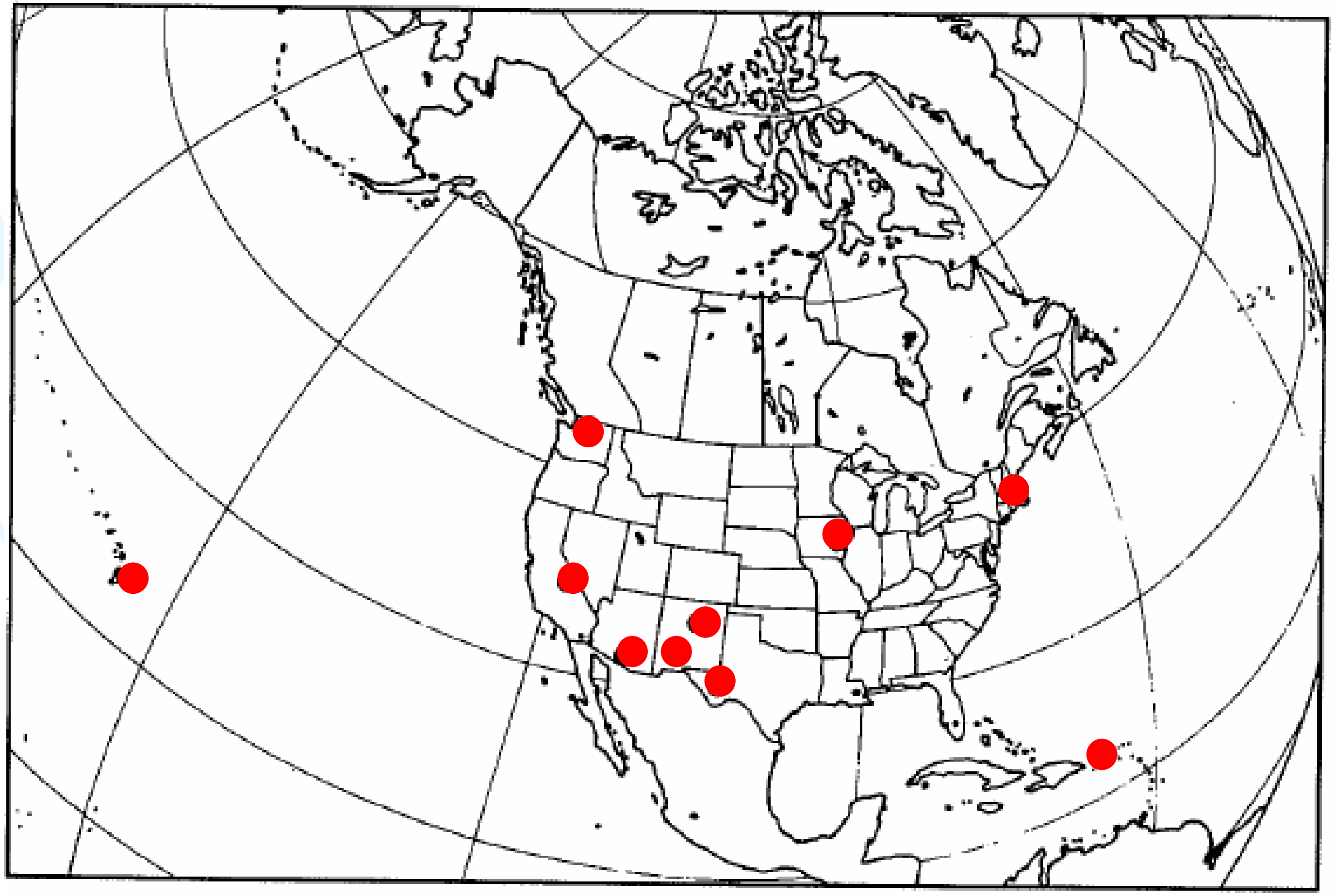
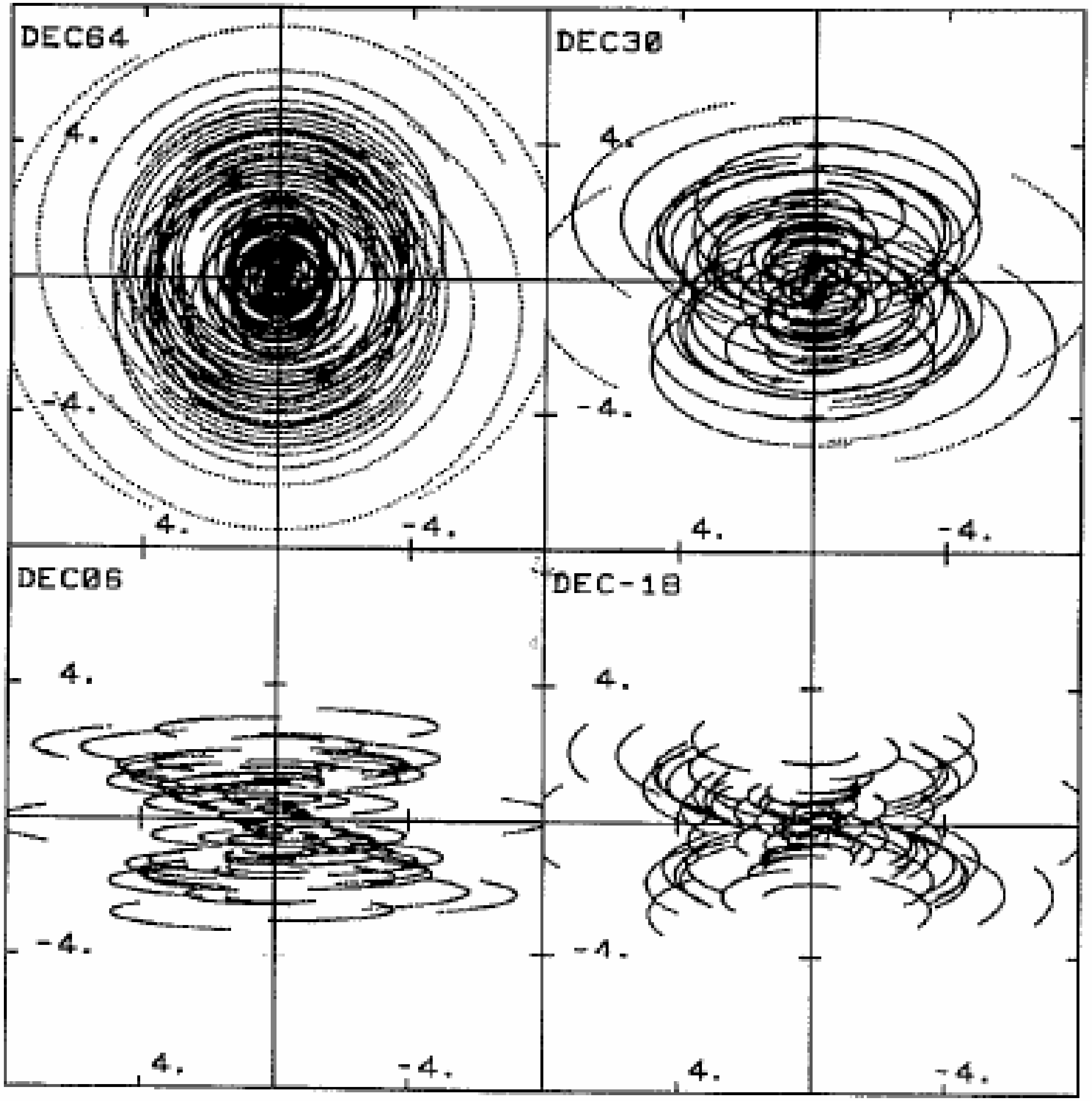
Frontier astronomy, future technology

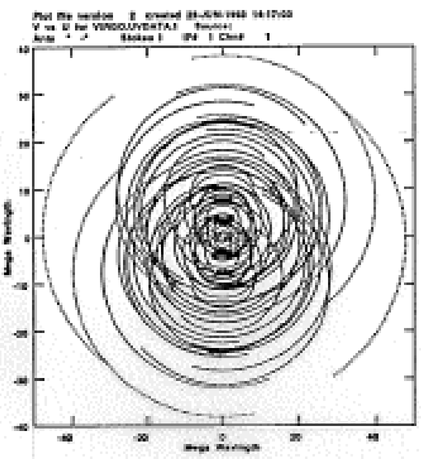
VLBA telescope locations

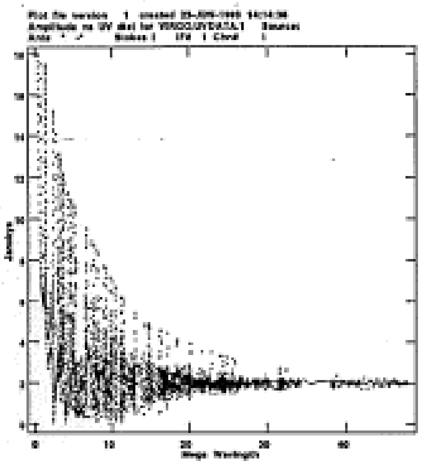


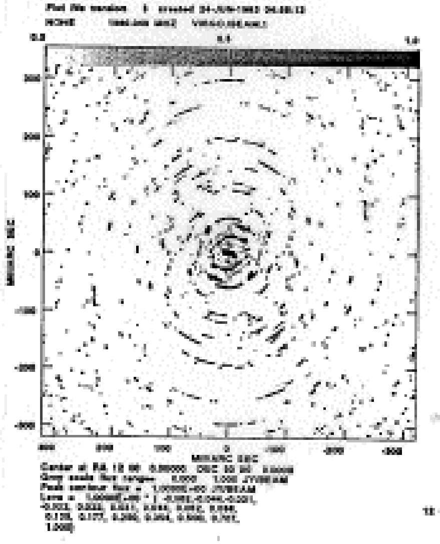
VLBA u,v-ellipses, different δ

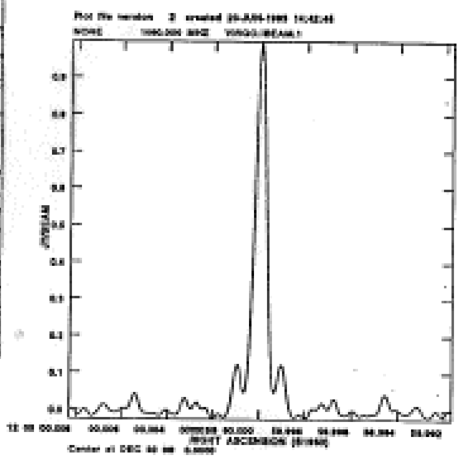


VLBA data on model source

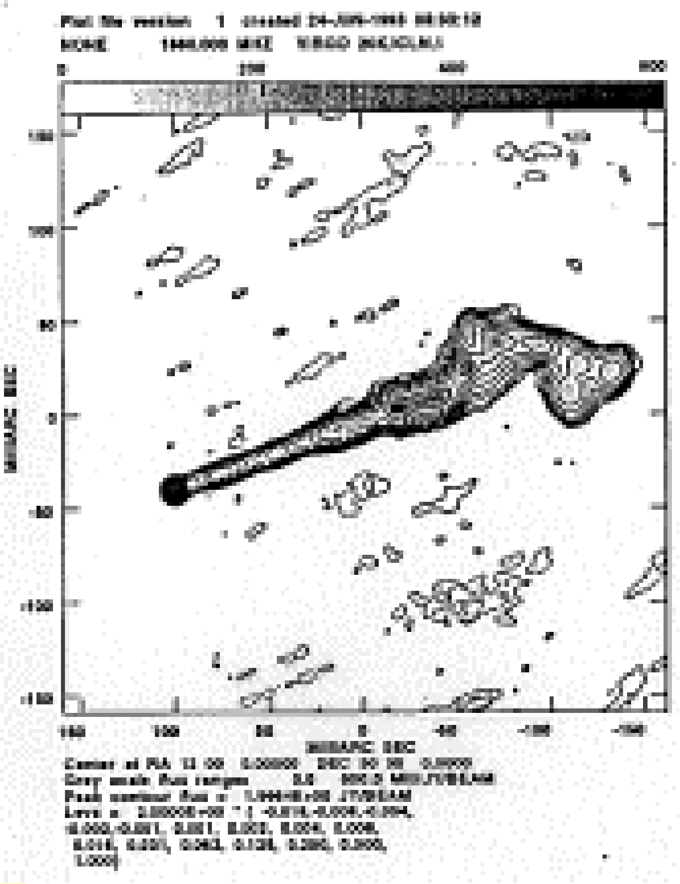


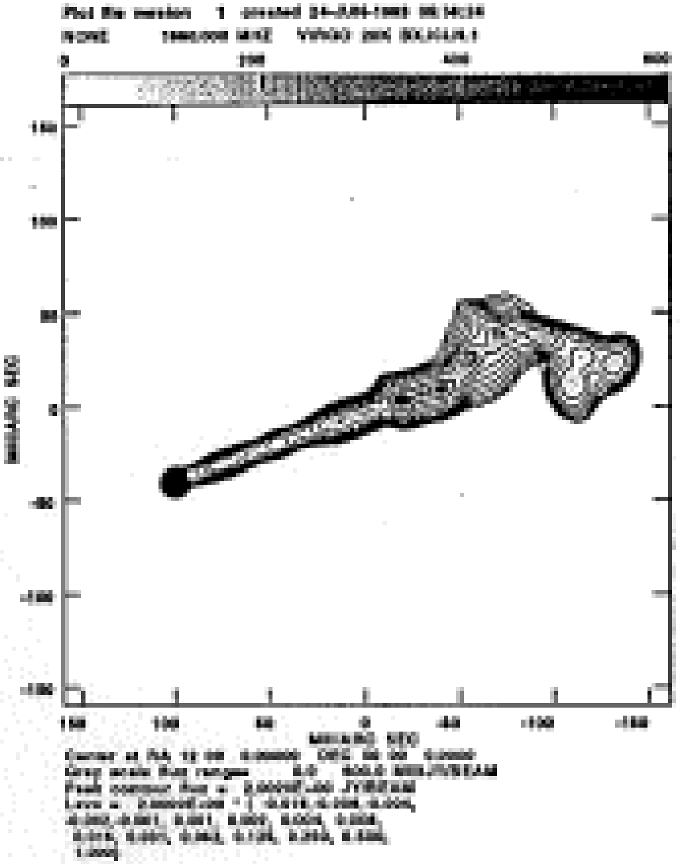




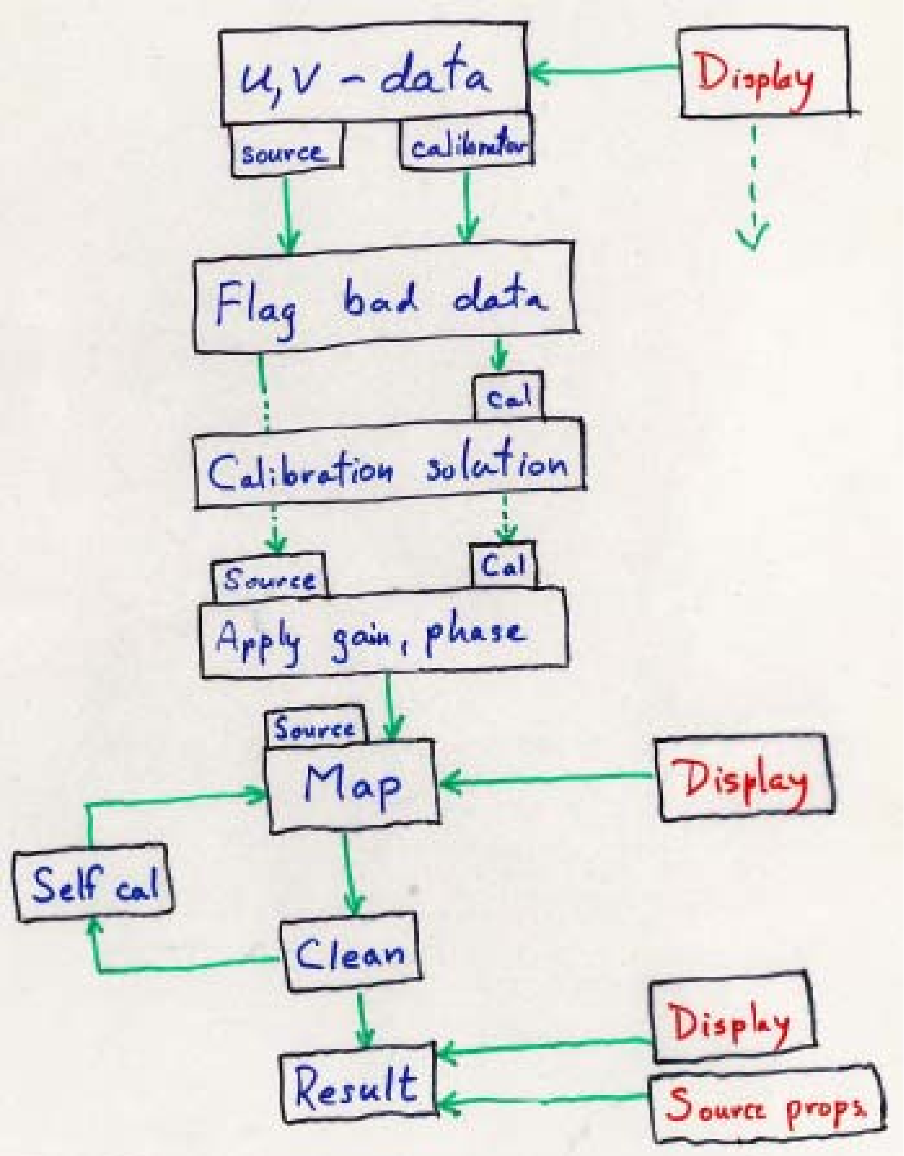


Raw & CLEANed map of Vir A

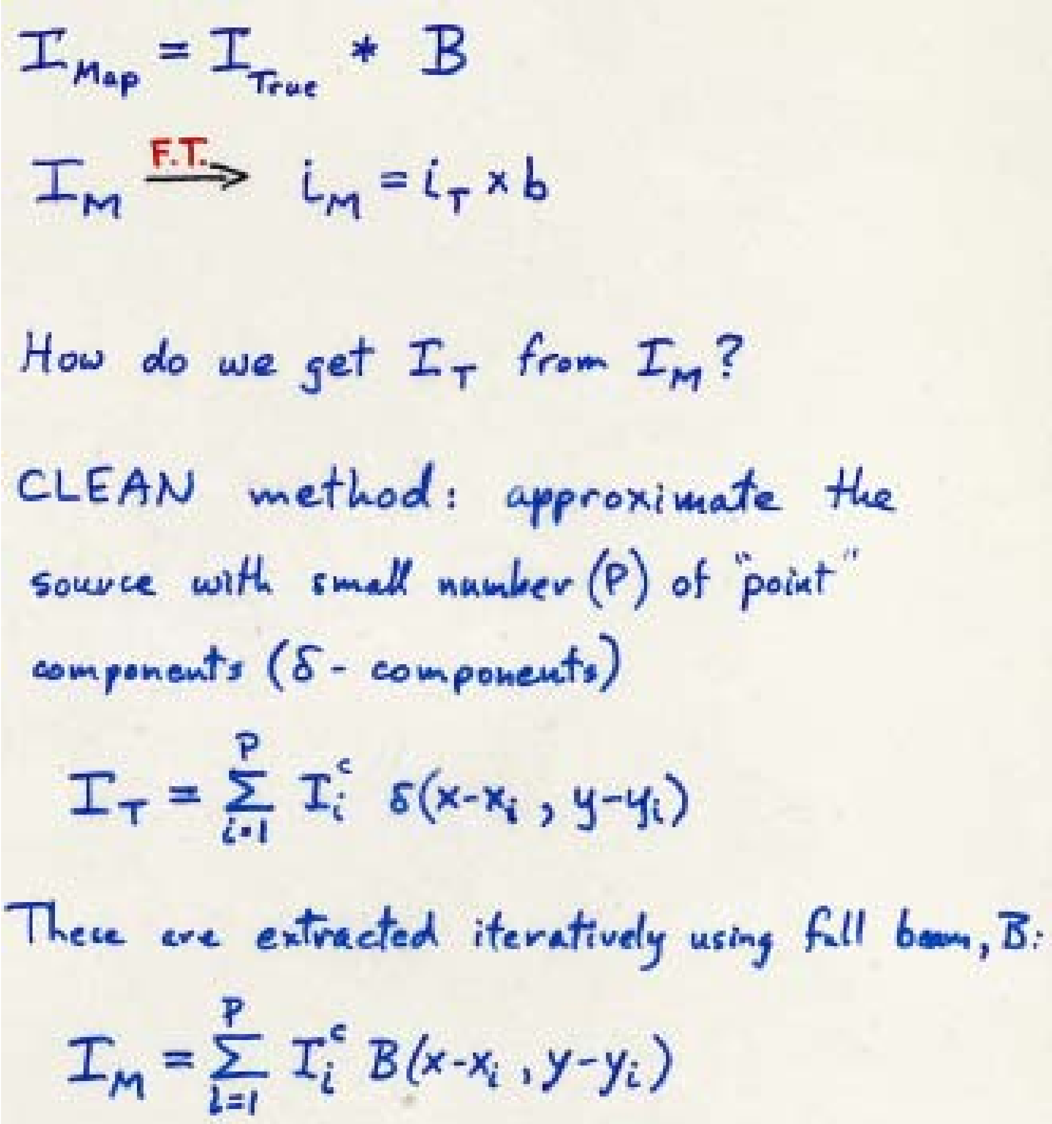




Data reduction block diagram



Deconvolution (Clean)



$$I_{Map} = I_{True} * B$$

$$I_M \xrightarrow{F.T.} i_M = i_T \times b$$

How do we get I_T from I_M?

CLEAN method: approximate the source with small number (P) of "point" components (δ- components)

$$I_T = \sum_{i=1}^{P} I_i^c \, \delta(x-x_i , y-y_i)$$

These are extracted iteratively using full beam, B:

$$I_M = \sum_{i=1}^{P} I_i^c \, B(x-x_i , y-y_i)$$

Let’s now look back at some great discoveries in radio

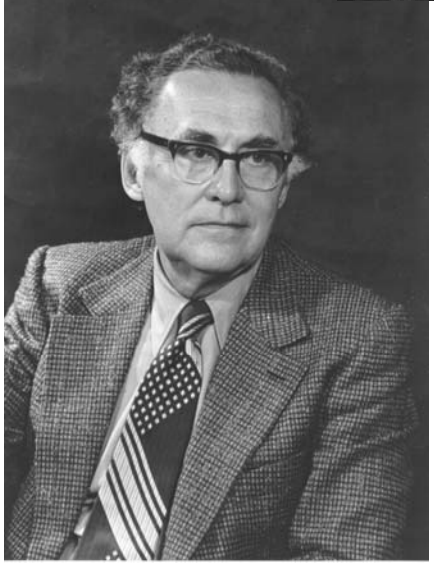
- Then we can consider some other prize-winning results in astronomy
- We can see what kinds of results appear to make the greatest impression
- Then list some of the great unsolved problems in astrophysics

Early work on supernovae was largely due to F. Zwicky & W. Baade

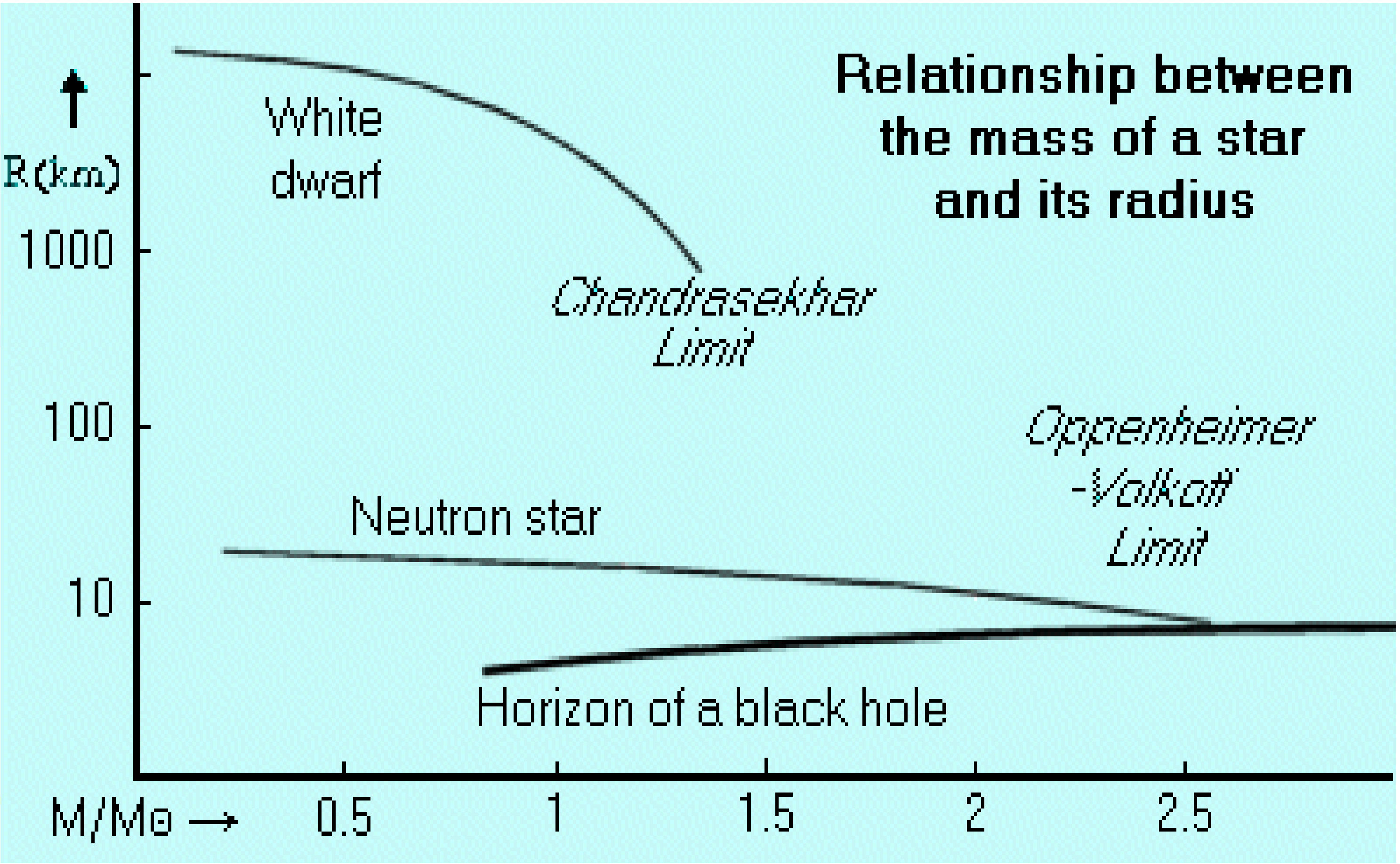
- They coined the term supernova (in 1931) and made the original type classifications (Type I, II, III, IV & V)
- Zwicky used a Schmidt (wide field) telescope at Palomar to discover 120 supernovae, a record

Within 5 years, physics of neutron stars worked out

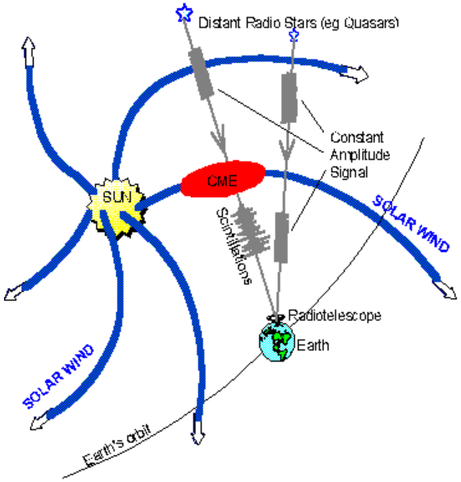
- Oppenheimer & Volkoff (1939):
  - Theory of the neutron star
    - Radius ≈ 10 km
    - Mass ≈ 1.4 M_{sun}
      density ≈ 10^{14} g/cm^3
      (1 grain weighs 10.000 tons)



They established a limit for the neutron star mass



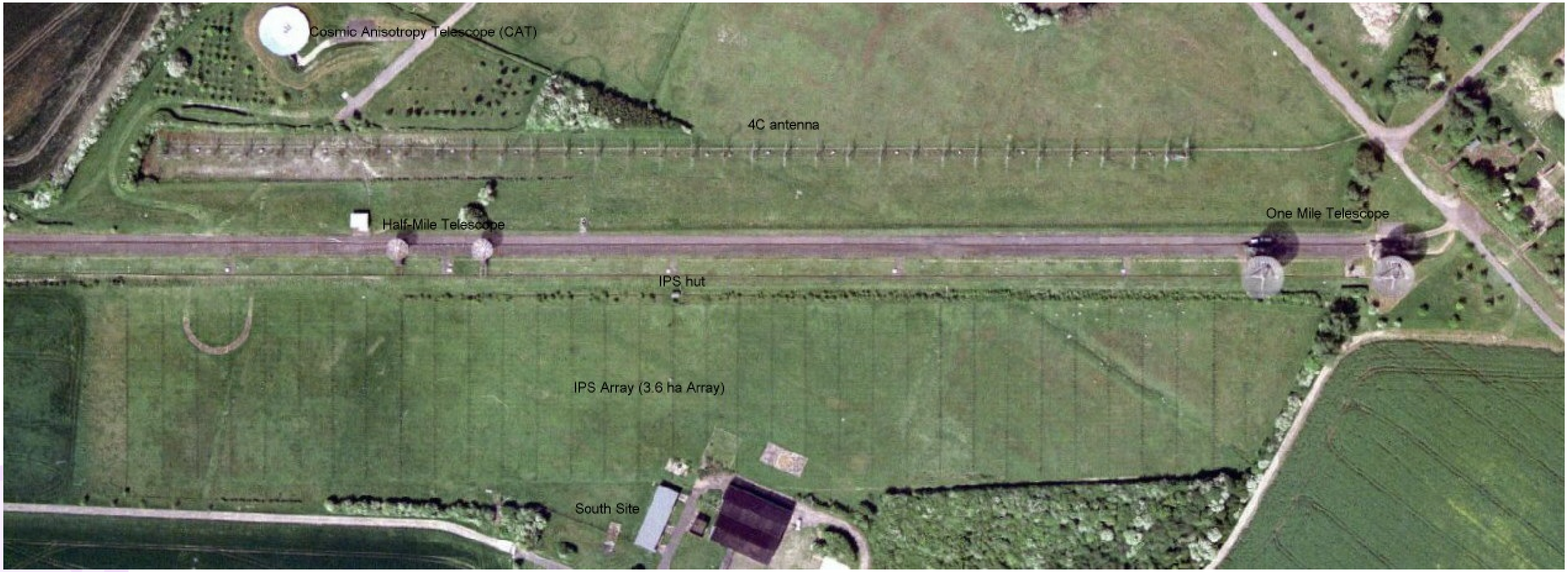
In 1960s, Tony Hewish studied scintillation of radio sources



His telescope: an array of dipoles at 80 MHz

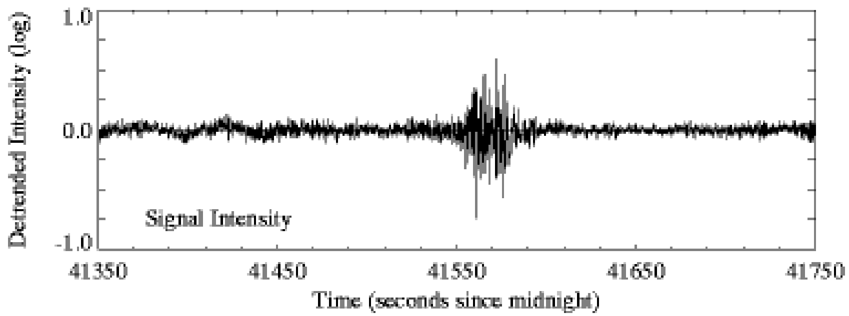
High time resolution (0.1 s) – large area needed (to get maximum signal)

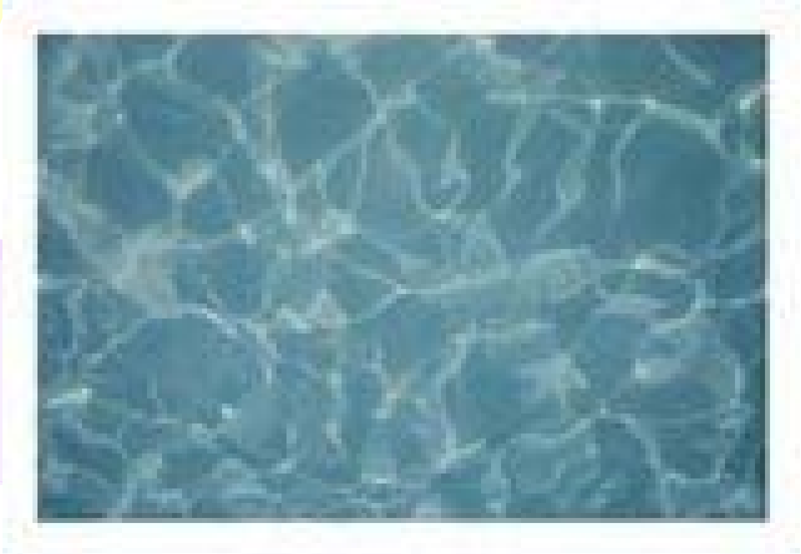
The Inter-Planetary Scintillation (IPS) array in Cambridge, UK



Total area: 3.6 hectares

Irregularities in ionized gas cause radio signal to vary rapidly





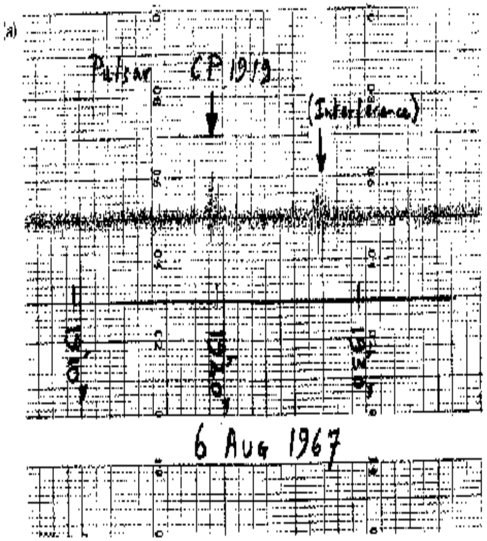
- Can happen in solar wind or ionosphere
- Result is ragged, fluctuating signal
- In atmosphere, cause of stars twinkling
- Similar to what water waves do to sunlight in pool
- Source must be more compact than irregularities (see pool on cloudy day)

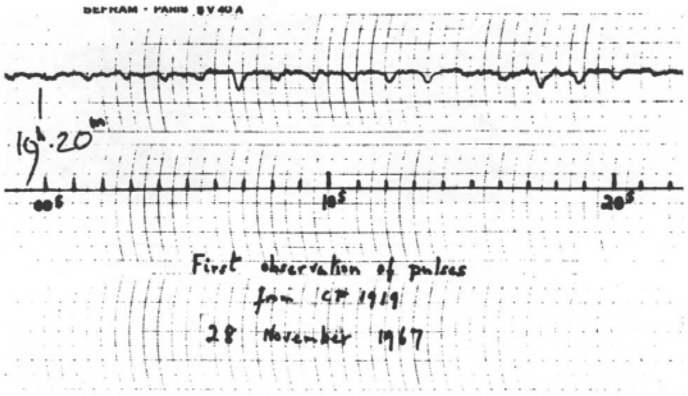
Hewish had an excellent Ph.D. student, Jocelyn Bell

- Jocelyn was a very careful worker, who wanted to understand her observations completely
- The signal was recorded on charts (30 m/day) which she examined
- In addition to signals from sources, had to worry about interference
- One source was strange: it looked unusual, but wasn’t interference
- She called it scruff. The source was in the wrong direction – scintillations shouldn’t be seen at night

Looked a bit like interference – to check, chart record was sped up

- Above is an early observation of pulsar CP1919, also with example of interference
- In August this source was a nighttime object
- In the sped up record, in Nov., see a series of pulses, about 2 seconds apart
- They first thought it was instrumental, they checked everything, and carried out several experiments
- What you hear: 0.7 s





"I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart." (Deflections are down).

Some of the experiments tried

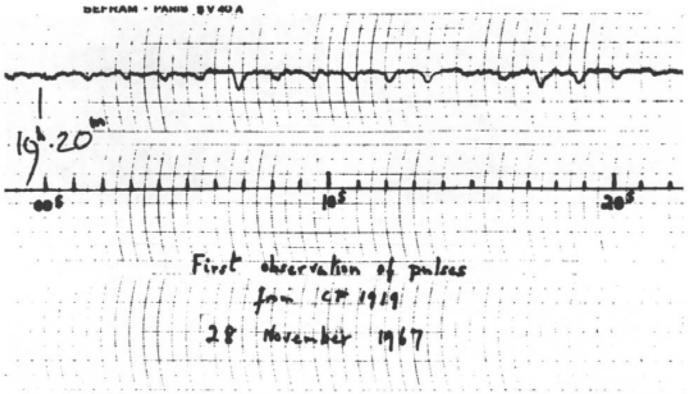
- Space is filled with ionized gas, causing radio waves to slow down at longer wavelengths. They found that longer wavelength pulses had an extra delay, as expected
- Perhaps the signals were from intelligent life in space. Life should be on a planet circling a star – should see motion from planet in Doppler shift. They found Doppler shift – of the Earth moving around the Sun
- The group didn’t know what to do – how to publish what they didn’t understand?

To be humorous, they called the source LGM 1

- About this time, Jocelyn thought that since the signal looked real, there might be another LGM
- She went back and looked through the records, and found another bit of "scruff"
- It was winter, and night, but she saw the source would soon pass through the telescope beam
- Again a series of pulses

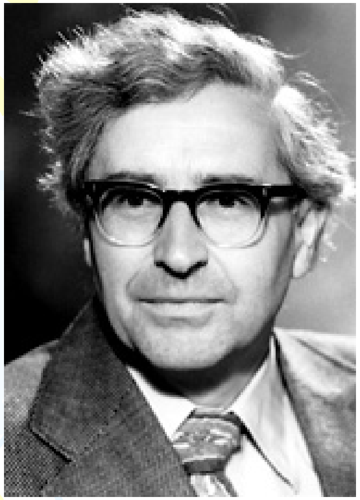
The discovery was published in *Nature* in 1968

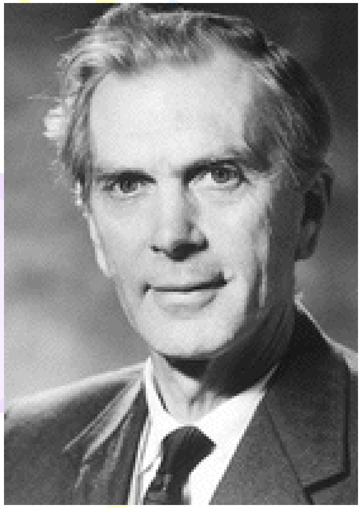
- By that time, four pulsing radio sources had been found
- Periods were around 1 second, objects had to be small – a compact star
- At the end of a special discussion in London, it was concluded, “so it seems the little green men have become white dwarfs”
- But WD idea was short lived



“I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart.” (Deflections are down).

For discovery of pulsating radio sources, Hewish shared the 1974 Nobel Prize

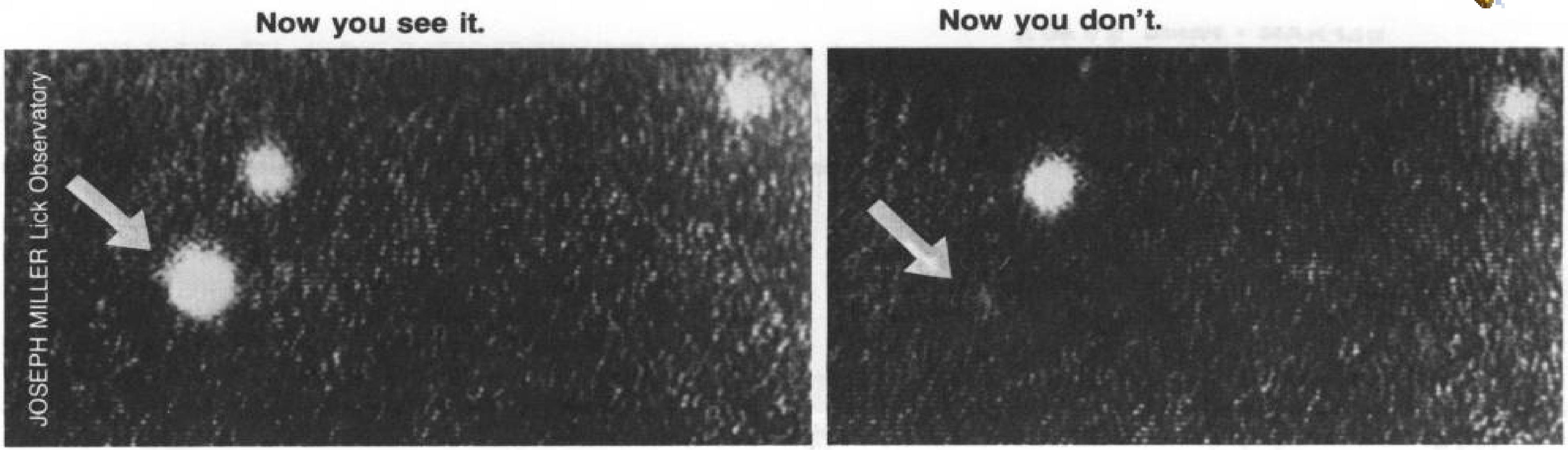




- Sir Martin Ryle, Hewish's colleague, received the other half
- The pulsing sources were soon called pulsars
- An early suggestion, by T. Gold, that the pulsars are rapidly spinning neutron stars, was quickly accepted. In particular, some pulsars spun too rapidly to be WDs
- Zwicky's idea was confirmed, although the first pulsars were not associated with supernova remnants

Two stars near center of Crab Nebula, one known to have nebula’s motion

It was shown that this star turns on and off 30 times per second



Now you see it.

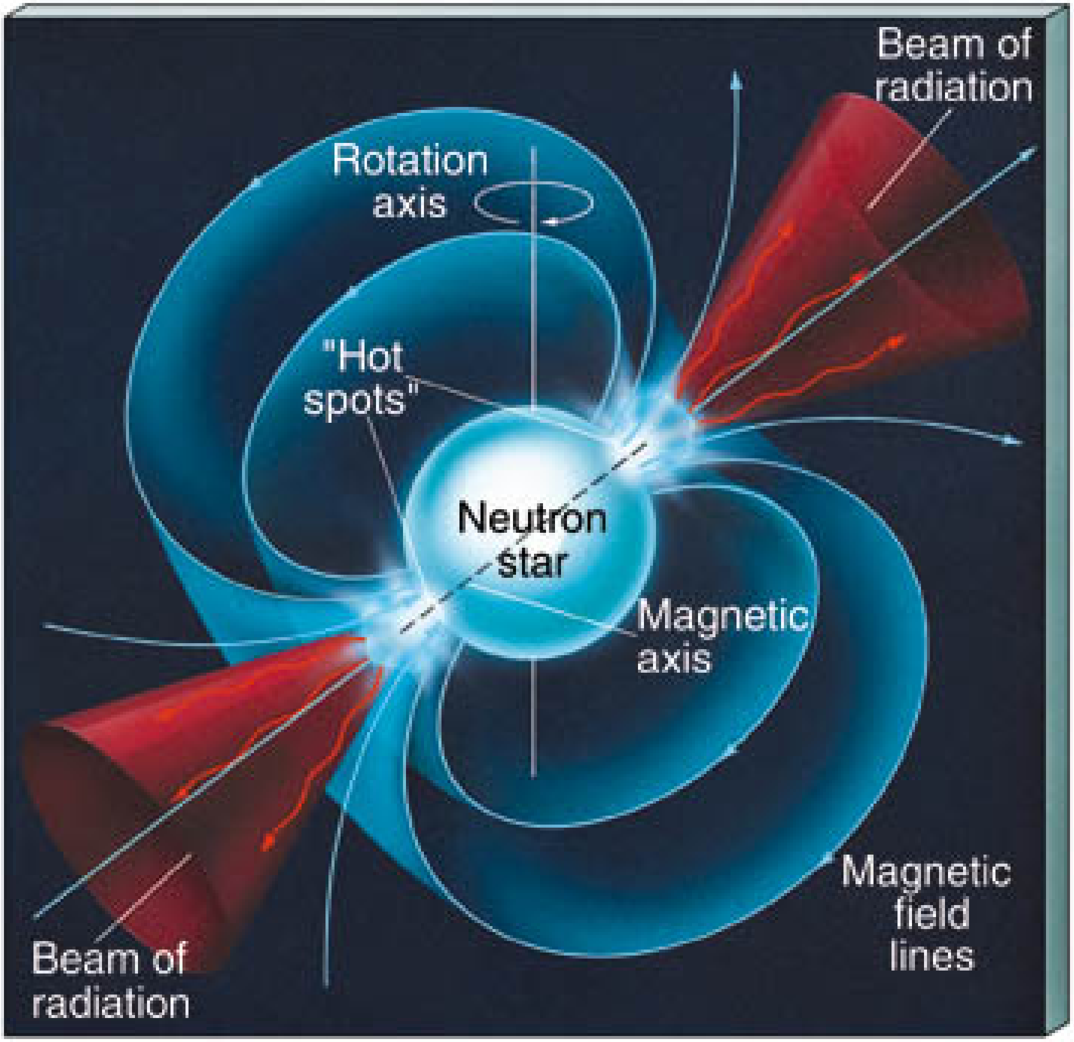
Now you don't.

JOSEPH MILLER Lick Observatory

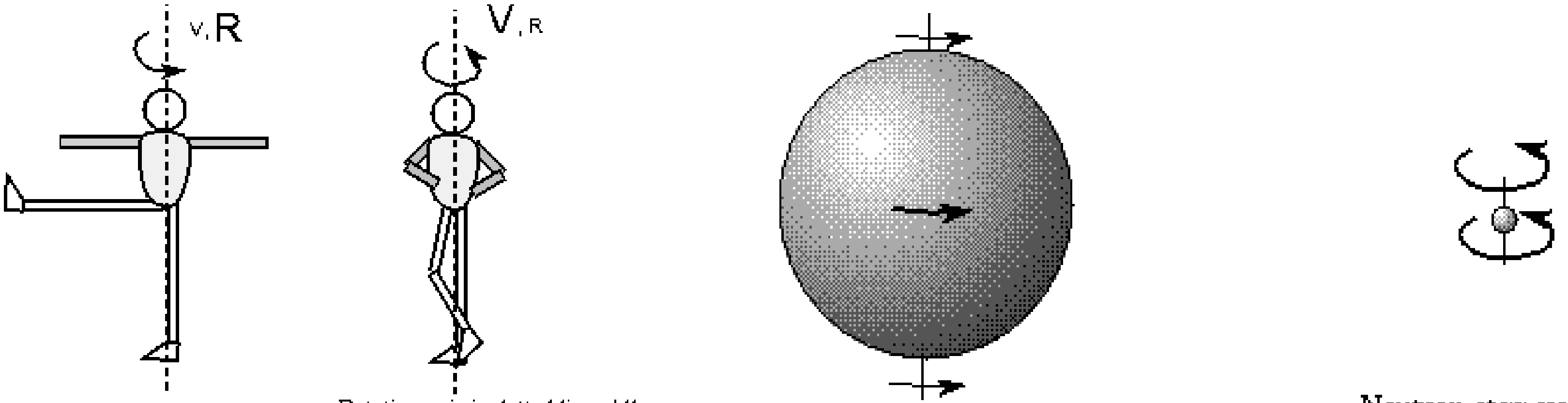
The pulsar discovered later in the Crab nebula blinking on and off 30 times per second.

- Crab Nebula: 950 yr old Supernova Remnant (SNR)
- There's an older one associated with the Vela SNR
- It's 10,000 yr old, pulses come 11 times/second

Rotating magnetic field produces emission, seen every rotation period



The rapid rate of spin comes from conservation of angular momentum



Rotation axis is dotted line. Part of body mass is far from rotation axis. Spinning slowly (v is small).

Rotation axis is dotted line. All of body mass is close to rotation axis. Spinning quickly (v is large).

Angular momentum BEFORE = Angular momentum AFTER

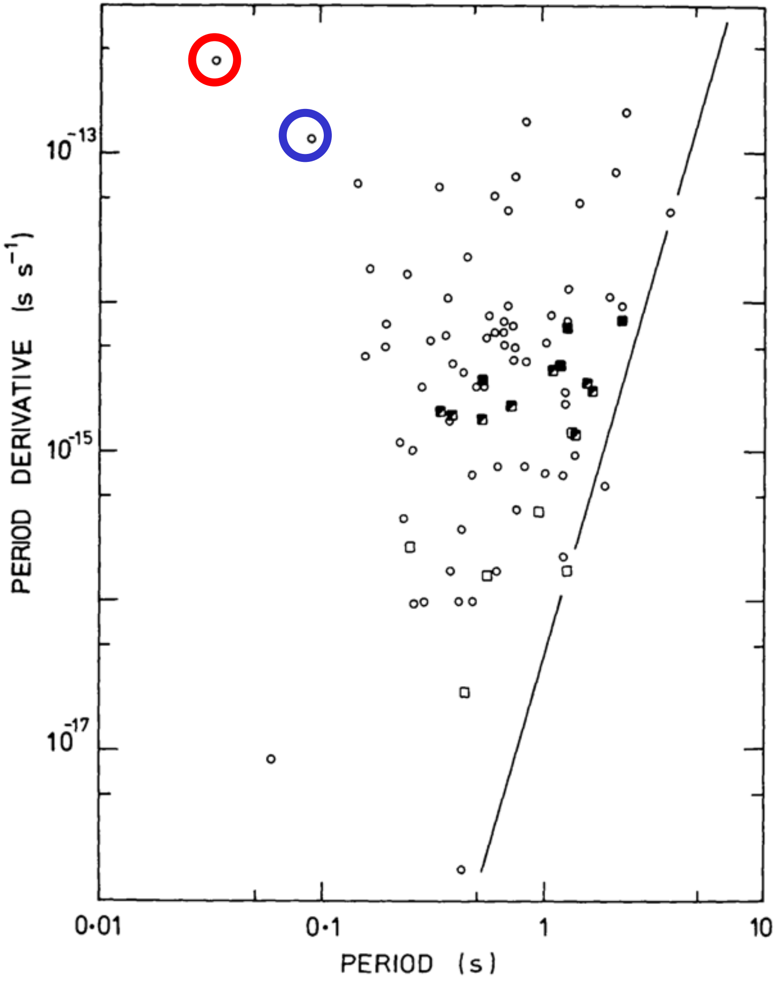
Regular star: Large size and slow spin. Weak magnetic field.

Neutron star: very small size and very fast spin. STRONG magnetic field.

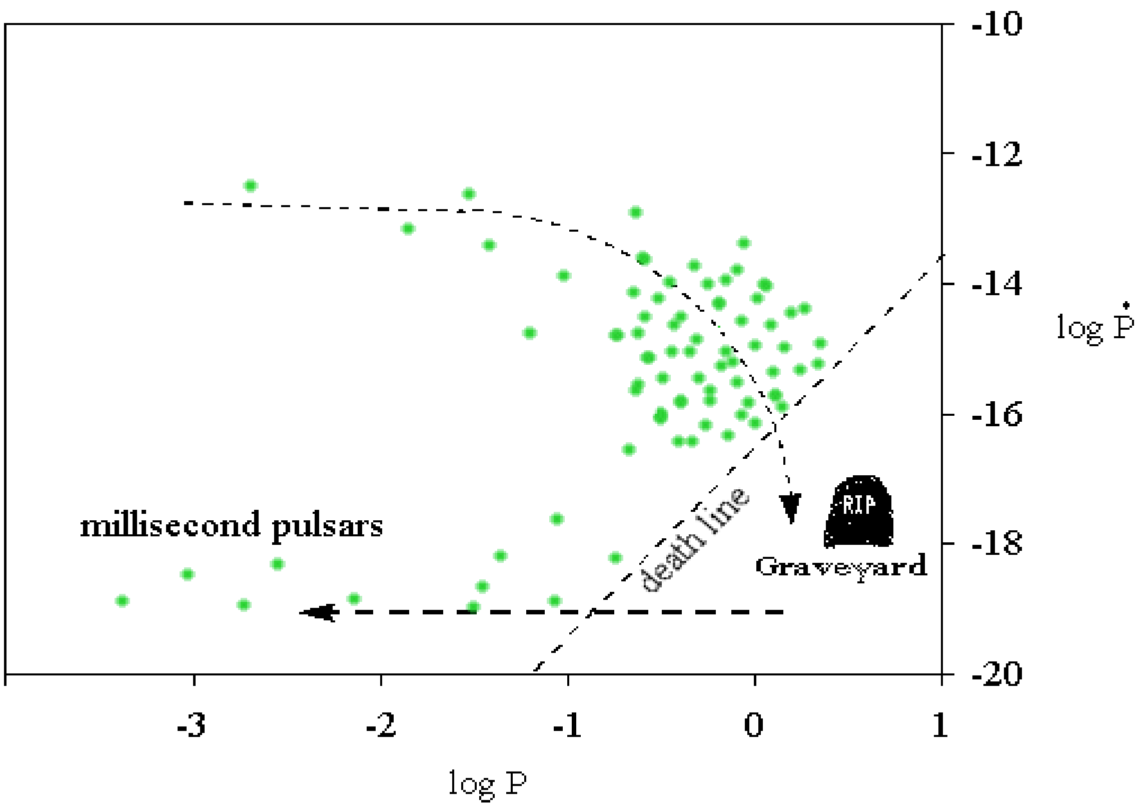
- Pulsars slow down with time – they lose energy
- Neutron stars have a very strong magnetic field
- The field of the original star is drawn in during the collapse, and greatly magnified – from 10 G or so to 10^{12} G

The pulsar period (P) vs. period change (Ṗ) provides evolutionary sequence

- Until 1980, P - Ṗ plot was like this
- Pulsars move from left to right
- Crab Nebula & Vela pulsars are youngest
- Past line on right, pulsed emission turns off

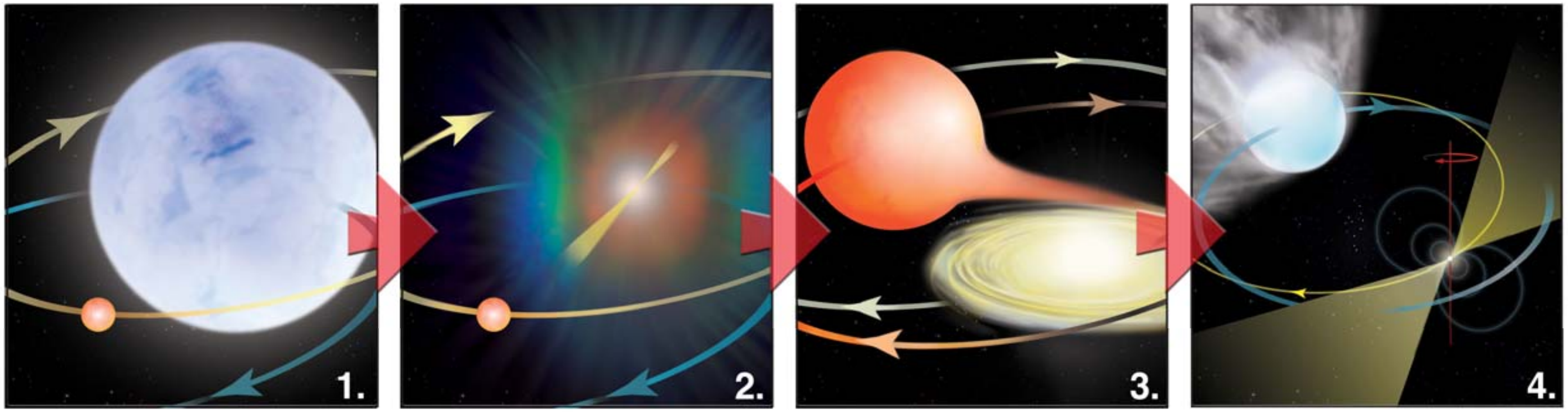


When pulsar spins too slowly, emission stops – it enters the graveyard

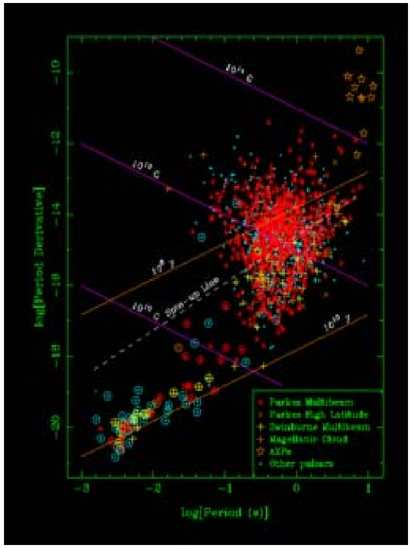


But if it has a companion, there can be life after death

Material from companion can spin up old pulsar, so it pulses again



- Magnetic field decreases dramatically
- Result: very fast (millisecond – ms) pulsar
- ms pulsars are most accurate clocks we know of



Millisecond pulsars: fastest known

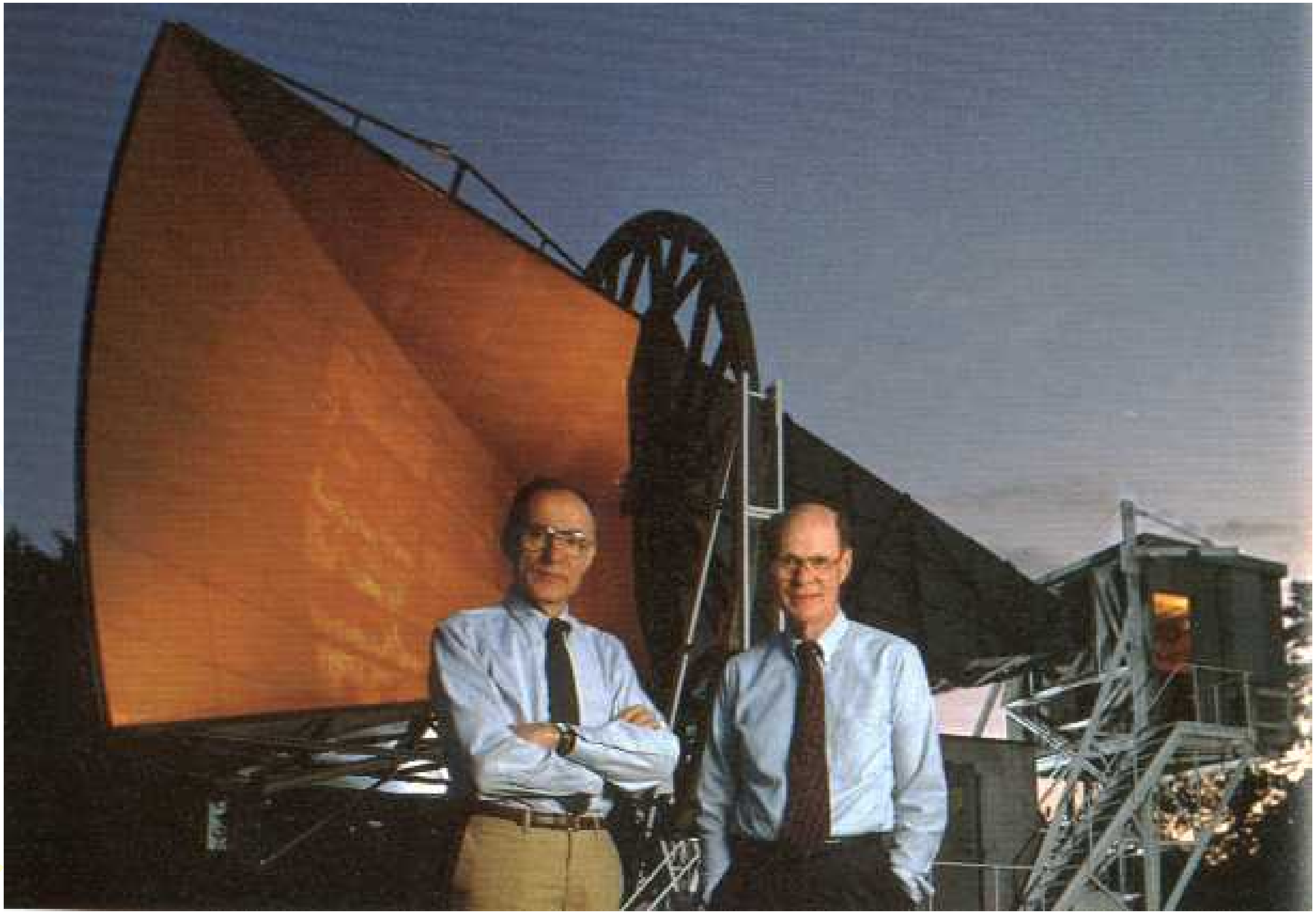
- And they make the best clocks
- Here is the recently discovered pulsar PSR J0437-4715
- It rotates at a rate of 174 times a second

- Think that’s fast? There’s a faster one
- Long known as *the* ms-pulsar, PSR B1937+21 rotates near the maximum possible rate
- Its period is very precisely known: 0.00155780644887275 seconds, or 716 rotations each second

From the very tiny to the largest structures: the whole universe

- Until the 1960s, cosmology saw a battle between two diametrically opposed ideas
- Everyone agreed that the universe is expanding
- Obviously there had been a **Big Bang**
- Not necessarily so, said the opposing camp: we could be in a **Steady State** with matter creation (Bondi, Gold & Hoyle)

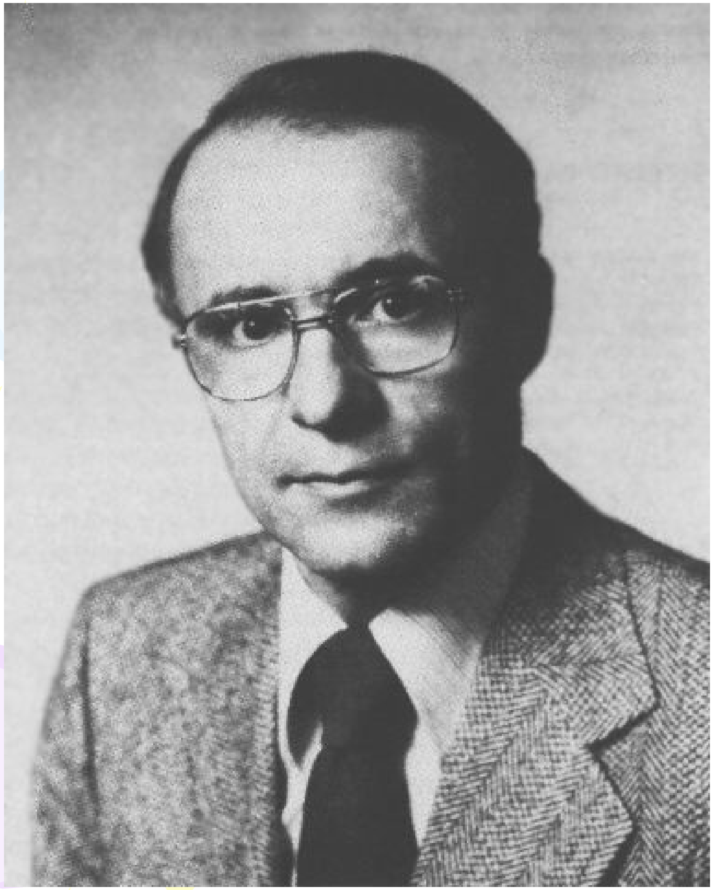
Penzias & Wilson were calibrating their antenna, but had a problem



They had carefully measured their antenna, and found excess power

- Sources of outside radiation, expressed as temperature, were: atmosphere (T_{atm}), electrical resistance loss in antenna (T_{loss}), radiation from ground (T_{gnd}) & sky (T_{sky})
- They measured or calculated, $T_{\text{atm}}=2.3\pm0.3$ K, $T_{\text{loss}}=0.9\pm0.4$ K, $T_{\text{gnd}}<0.1$ K; $T_{\text{sky}} \approx 0$ (expected)
- So, looking straight up, expected T_{A} was: $T_{\text{A}} = T_{\text{atm}}+T_{\text{loss}}+T_{\text{gnd}}+T_{\text{sky}}=2.3+0.9+<0.1+0=3.2$ K
- They found $T_{\text{A}} = 6.7$ K, so $T_{?} = 3.5$ K remained

They tried everything they could think of; the mystery signal remained

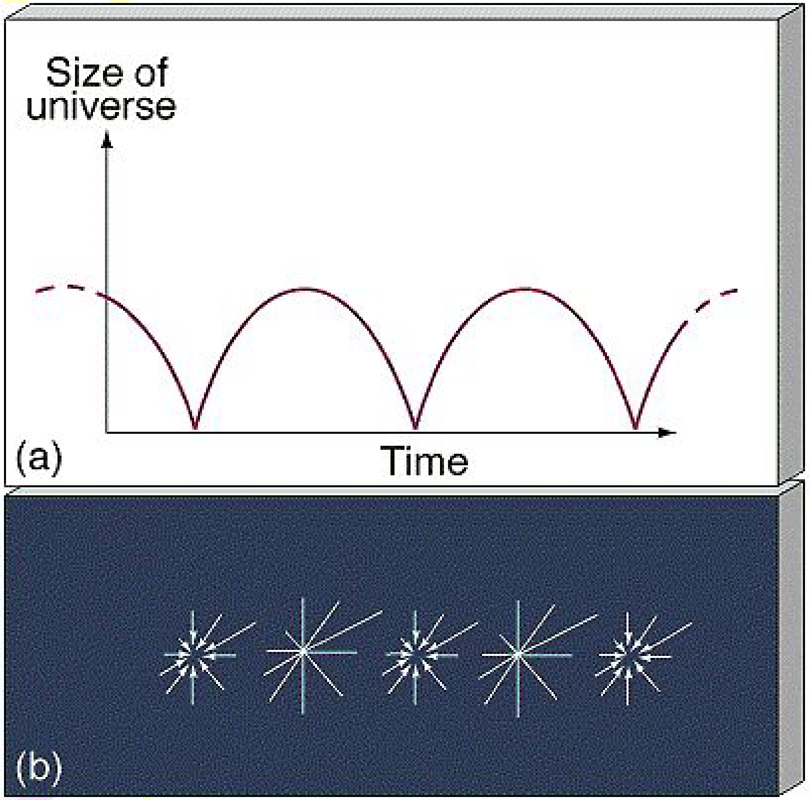


- Penzias had a telephone conversation with MIT radio astronomer Bernie Burke
- He mentioned the problem of the unexplained noise signal
- Burke had heard about an idea of Robert Dicke, which predicted background radiation
- Dicke was at Princeton, just down the road

Robert H. Dicke was a physicist who contributed much to radio technique

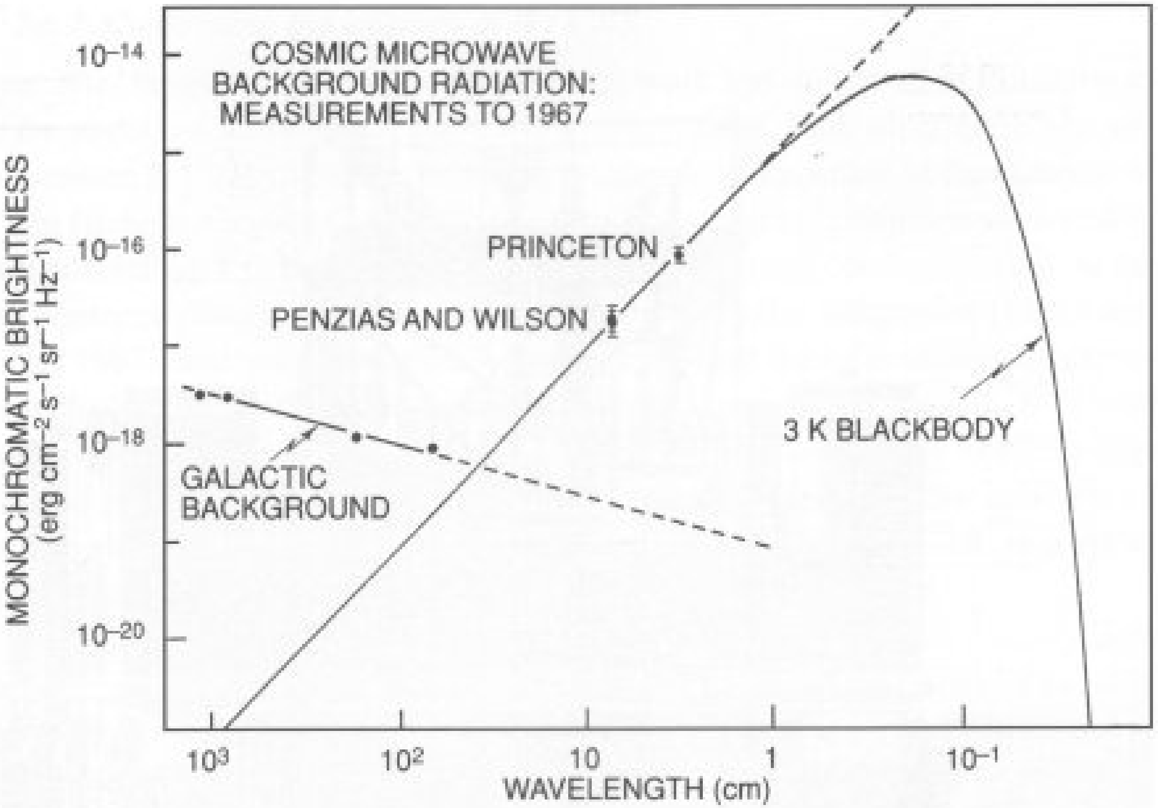
- His idea to stabilize the output of a radio telescope receiver by comparing it with a reference (“Dicke switch”) is used to this day – and was used by Penzias & Wilson
- He measured atmospheric radio emission before 1946 and had set a limit to the sky brightness (and probably could have measured it)

Dicke’s motivation was a cosmological model he preferred



- Dicke liked an oscillating universe, with expansion followed by contraction, and repeated big bangs
- We happen to be in one of the expansion phases, with remnant radiation
- When he heard from Penzias & Wilson of their detection, he told his students, "Boys, we've been scooped."

Here's what they found

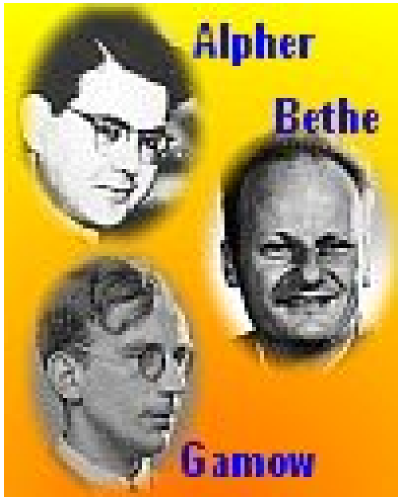


A second measurement of the CBR at 3.0 cm (Roll and Wilkinson, 1966) confirms the discovery of a thermal background and refines the value for T_0.

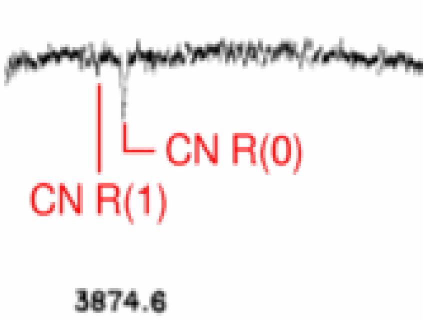
But there had already been a prediction of the effect

Alpher, Bethe & Gamow predicted synthesis of Helium in Big Bang

- Ralph Alpher, Gamow's PhD student, calculated how much hydrogen would be converted to helium in the very early hot phase after the big bang
- The result, 10% He, agreed well with what astronomers found
- Gamow, with his sense of humor, added Bethe's name *in absentia*, and ever since the paper has been called, αβγ



Stranger yet, the CMB had already been measured, accidentally



- In 1940, A. McKellar observed CN absorption lines in the spectra of bright stars, and found that the line strengths indicated an excitation temperature of 2.3 K. The effect was unexplained at the time
- The potential importance of this discovery was not realized for many years

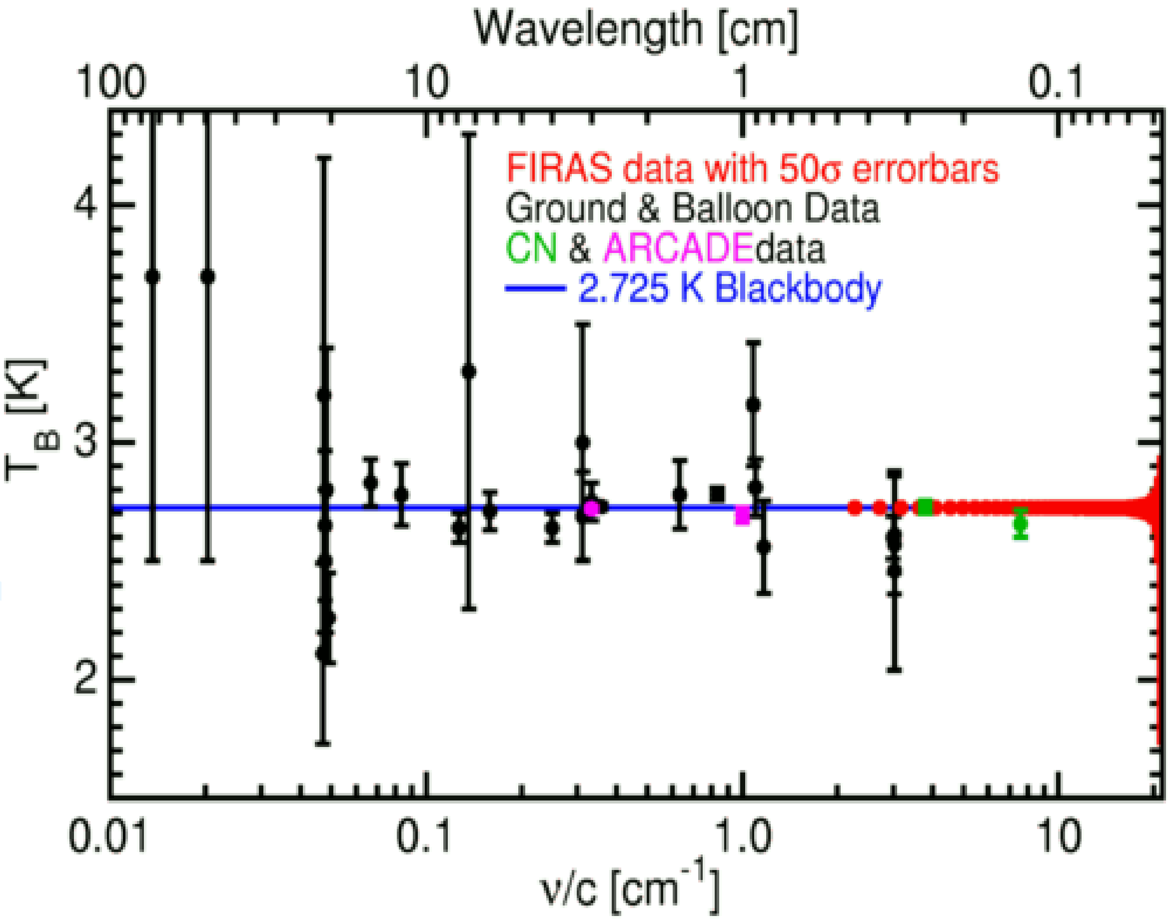
There is much irony in this early history of CMB

- Gamow, proponent of the big bang, ignored the CN result
- Hoyle, in a review of a book by Gamow (where the background temperature was estimated to be 11 K) viewed the CN value of 2.3 K as disproving Gamow’s Big Bang
- In 1950, the Nobel-Prize winning spectroscopist G. Herzberg said the CN result had “only a very restricted meaning"

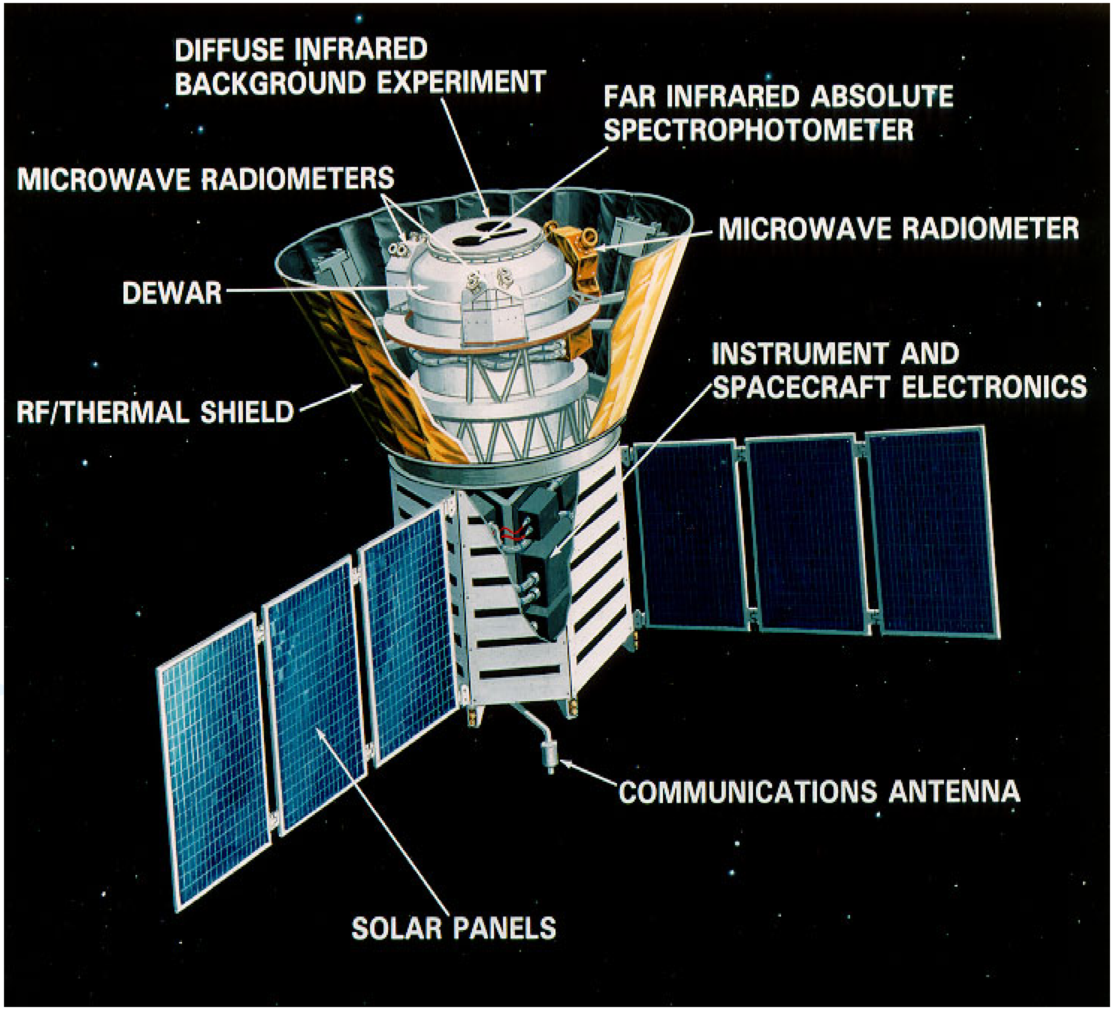
There were several strange errors of omission in the CMB story

- Dicke forgot, it seems, his wartime measurement of atmospheric emission, and limit of T_{sky}<20 K
- He also later acknowledged the oversight of not referring to the result from Gamow's group
- Penzias & Wilson say little about the possible cosmological implications of their detection, referring to Dicke et al. They didn't really believe in it, though it got them a Nobel Prize
- What if Dicke hadn't first published his oscillating universe idea?

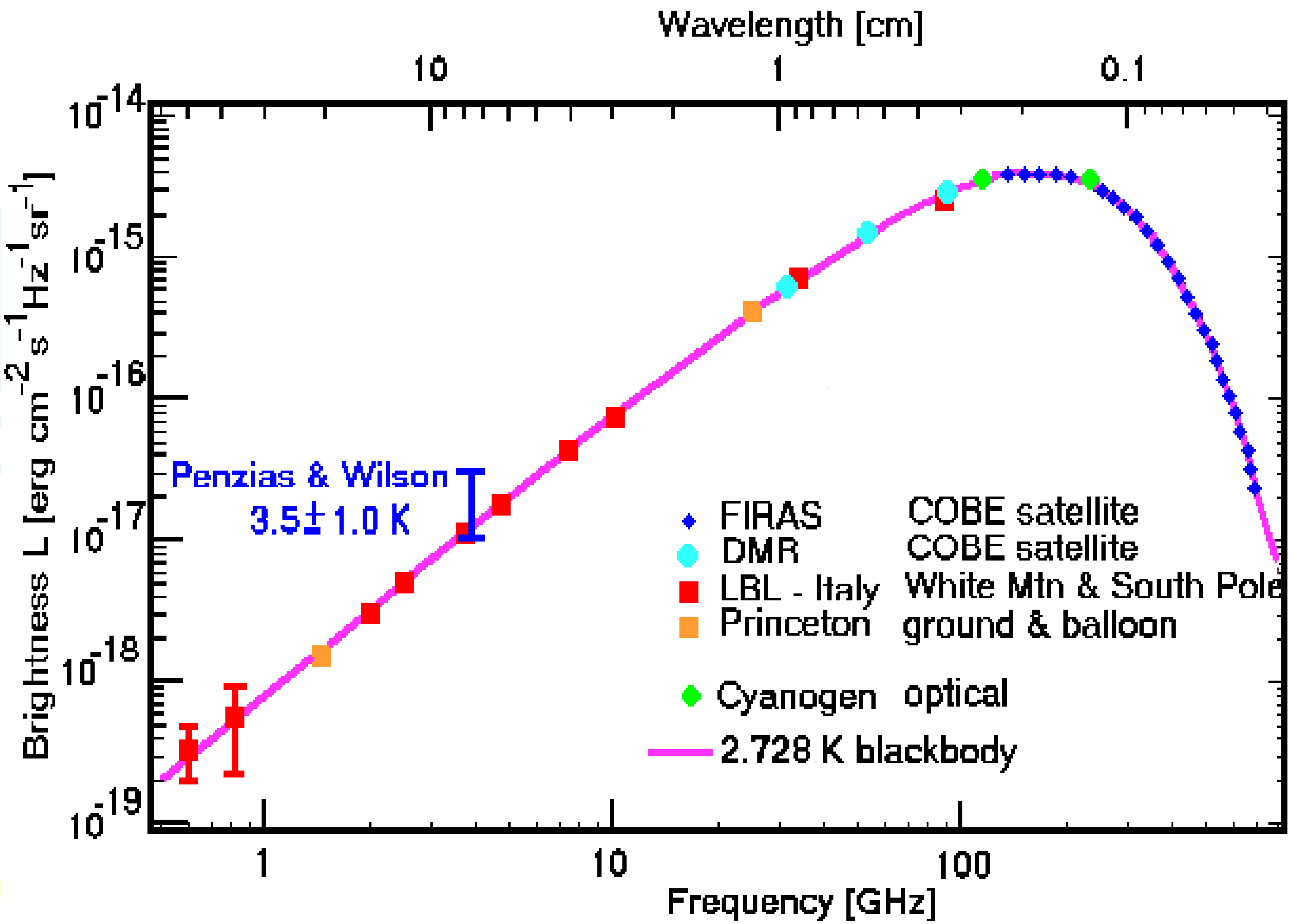
Overview of many of the CMB temperature measurements



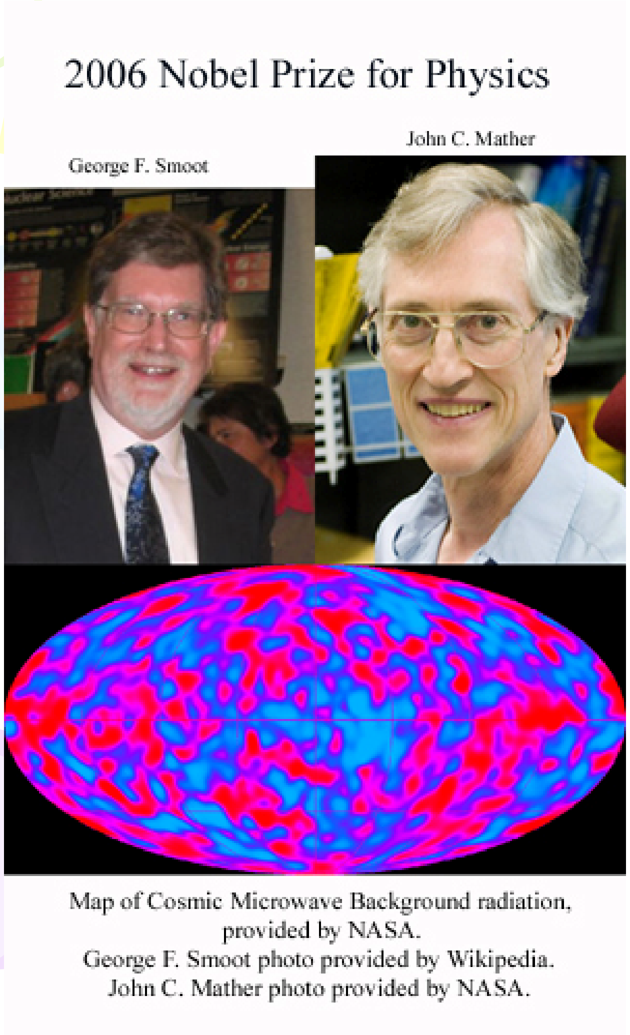
One of the biggest advances: the COBE satellite



COBE measured the average temperature over the whole sky…

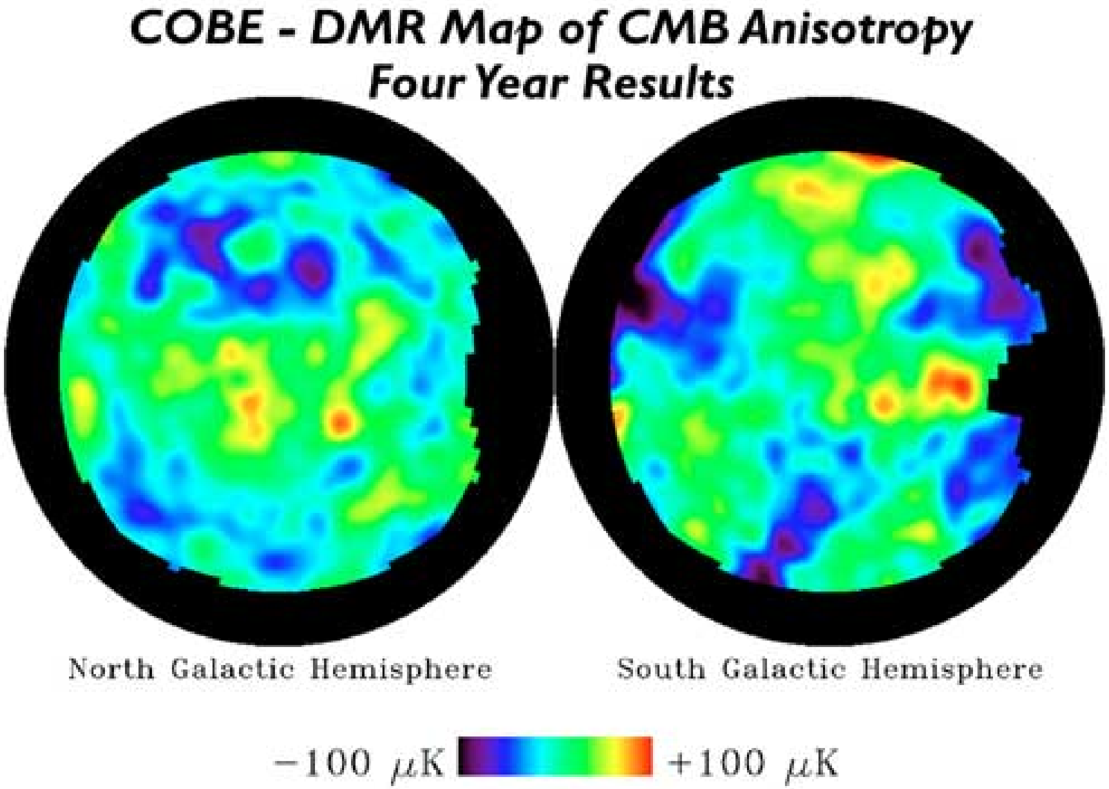


For the COBE work, Smoots & Mather shared the 2006 physics Nobel Prize



2006 Nobel Prize for Physics

Map of Cosmic Microwave Background radiation, provided by NASA.
George F. Smoot photo provided by Wikipedia.
John C. Mather photo provided by NASA.



COBE - DMR Map of CMB Anisotropy
Four Year Results

CMB and neutron stars have each earned 2 Nobel Prizes

- 1978: Penzias & Wilson, CMB discovery
- 2006: Smoots & Mather for accurate CMB temperature and anisotropy
- 1974: Hewish for pulsars/neutron stars
- 1993: Hulse & Taylor for binary pulsar and test of general relativity

Nobel Prize-winning astronomy by category

Radio:

- 1974, Ryle (aperture synthesis)
- 1974, Hewish (pulsars)
- 1978, Penzias & Wilson (CMB)
- 1993, Hulse & Taylor (binary pulsar)
- 2006, Smoots & Mather (CMB)

X-rays:

- 2002, Giacconi (discovery of X-rays)

More prize-winning astronomy by category

Neutrino astronomy:

- 2002, Davis & Koshiba (discovery)

Theoretical astrophysics:

- 1967, Bethe (nuclear physics of stars)
- 1983, Chandrasekhar (white dwarf limit)
- 1983, Fowler (element synthesis in stars)

What does this tell us about top discoveries in the past?

- Radio has done quite well (5/10)
- “New” fields (radio, neutrinos, X-rays) did well
- Observation does better than theory (7/10)
- No “classical” (optical) awards
- Theory in areas of nuclear physics (neutrinos also) – similar to “classical” physics prizes

If this can be a guide, few of the radio results could have been anticipated

- Neutron stars *were* predicted, but no one knew how to observe them
- Pulsars were therefore unpredicted, CMB also (though Gamow & Dicke had the right idea)
- Binary pulsar & GR use not predicted
- CMB “ripples” were expected
- Ryle’s work logical extension

Most of the “observational” prizes arose from surveys

- So, what should we survey for? Here are some “big” topics of today
- ms pulsar around black hole: GR test
- Detect gravitational radiation directly
- Polarization of CMB
- Epoch of Reionization: high-z HI
- Nature of dark matter/energy
- Find earth-like planets/find ET life

A fairly typical receiver of some years ago

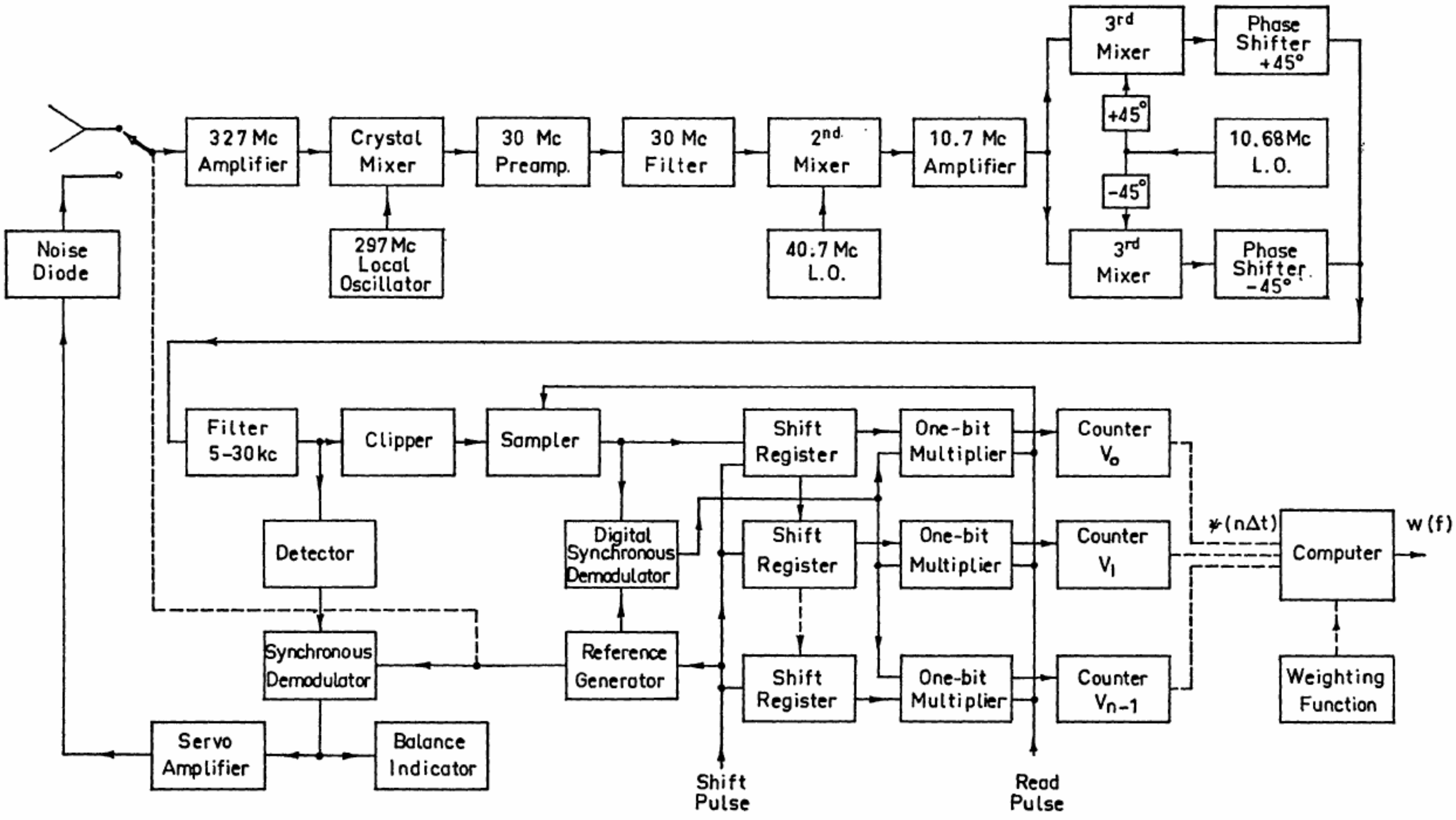


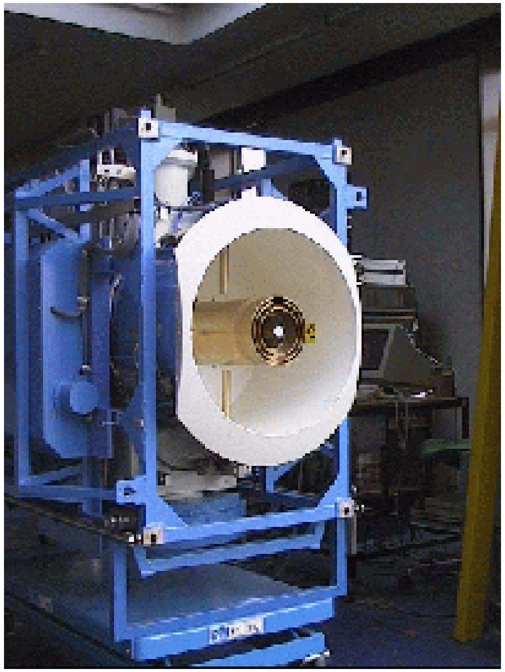
FIG. 10. Digital autocorrelation receiver for deuterium line measurements (41).

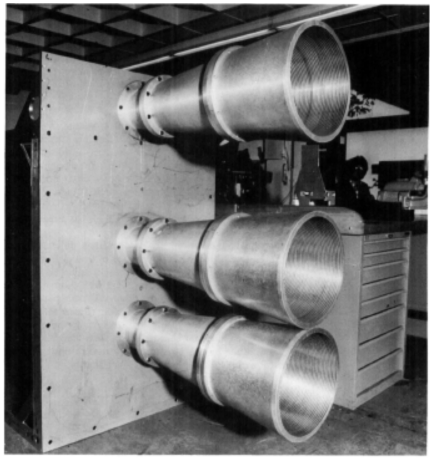
What are the technical frontiers of radio astronomy?

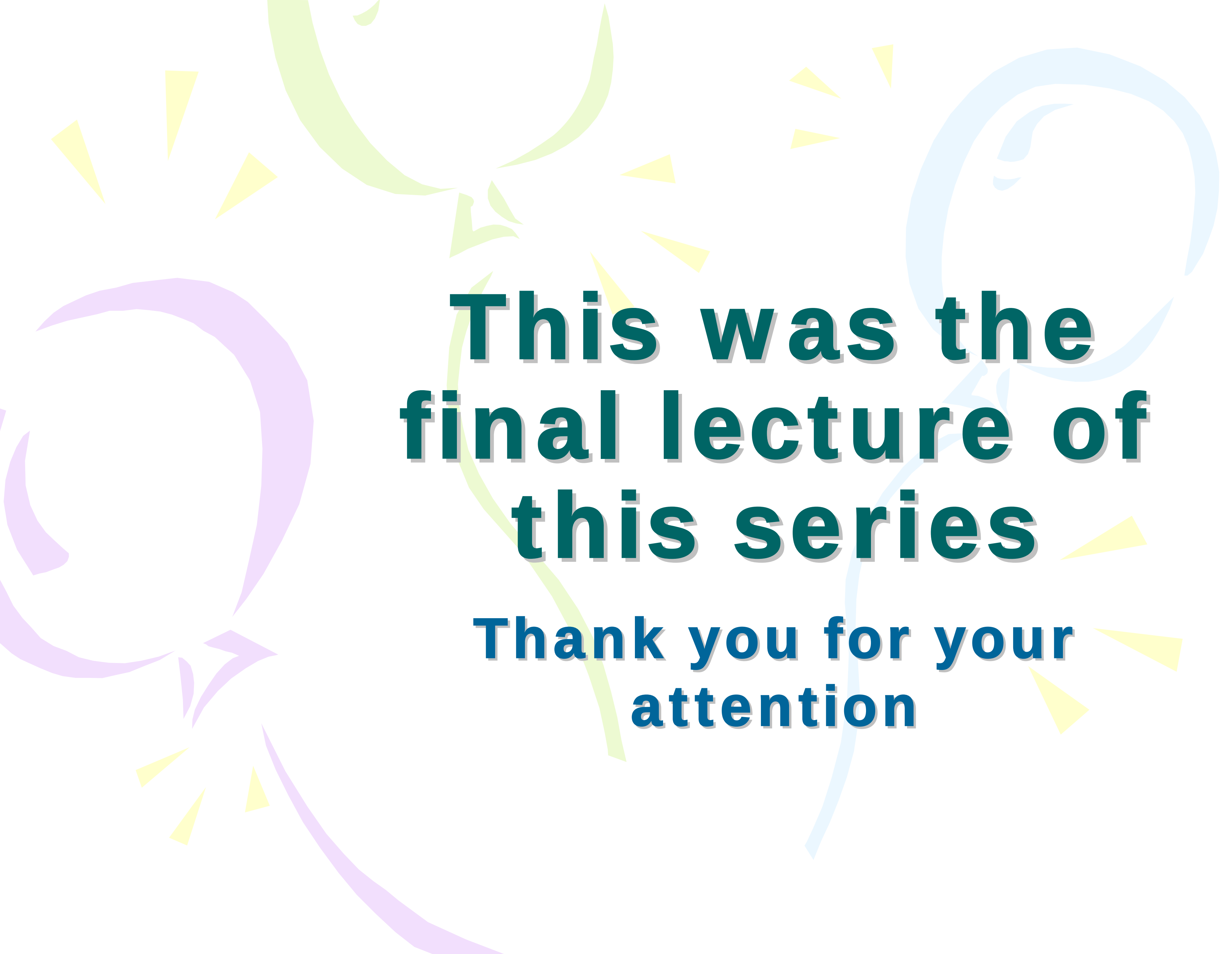
- A recent “white paper” makes some interesting observations:
- Although astronomers sometimes develop their own equipment, usually
- State-of-the-art components come from consumer products
- We often design systems too complex
- Leads to delay & cost overruns

White paper also suggests

- Get away from complex hardware
- Replace metal with silicon, analogue with digital and copper with glass fiber
- Digitize as soon as possible
- For wide bandwidth, make use of optical fibers as much as possible







This was the final lecture of this series

Thank you for your attention