

---

# Die Entdeckung des kosmischen Mikrowellenhintergrundes

---

Yvonne Kasper

**11. Januar 2019**

Fakultät Physik

## Inhaltsverzeichnis

1. Theorien zur Entstehung des Universums
  - Steady State Theory
  - Big Bang Theory
2. Entdeckung des kosmischen Mikrowellenhintergrundes
  - A. Penzias und R. Wilson
  - Die Holmdel Horn Antenne
  - Das eigentliche Messvorhaben
  - Probleme bei den Messungen
  - Entdeckung im Jahre 1964
3. Nachfolgende Experimente
  - COBE
  - BOOMERanG
4. Zusammenfassung und Ausblick geben

# Das Paper zur Entdeckung des kosmischen Mikrowellenhintergrundes

## “A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s” A. A. Penzias & R. W. Wilson in Astrophysical Journal, Vol. 142, p.419-421

No. 1, 1965 LETTERS TO THE EDITOR 419

high pressure, such as the neutron scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of  $2 \times 10^{10}$  gm/cm<sup>3</sup> is needed. Without a neutron-scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for cladding the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in cases of antineutrinos) greatly larger than the nucleus abundance. In this case, if the neutrino abundance were so great that three neutrons are degraded, the degeneracy would favor a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be  $\geq 10^7$ .

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the results of their measurements and in showing us the receiving system. We are also indebted for several helpful suggestions of Professor J. A. Wheeler.

R. H. DICKE  
P. E. FRIEDMAN  
D. J. BOLL  
D. T. WILKINSON

May 7, 1965  
PRINCETON PRINCETON LABORATORY  
PRINCETON, NEW JERSEY

### REFERENCES

- Alpher, E. A., Bethe, H. A., and Gamow, G. 1948, *Phys. Rev.*, **70**, 403.  
Alpher, E. A., Follis, J. W., and Herman, R. C. 1953, *Phys. Rev.*, **90**, 1347.  
Bondi, H., and Gold, T. 1948, *Proc. R. Soc. London*, **A201**, 51.  
Bunn, C., and Dicke, R. H. 1962, *Phys. Rev.*, **124**, 925.  
Dicke, R. H. 1962, *Phys. Rev.*, **124**, 930.  
Dicke, R. H., Peebles, E., Roll, D., and Wilkins, S. 1964, *Phys. Rev.*, **130**, 240.  
Einstein, A. 1916, *The Foundation of Relativity* (4th ed.), Princeton, N.J.: Princeton University Press, 191.  
Holtz, F. 1948, *ibid.*, **9**, 100, 372.  
Holtz, F., and Sachs, R. J. 1954, *Nature*, **208**, 1158.  
Lichtenberg, E. M., and Klebanow, I. M. 1963, *Adv. in Phys.*, **12**, 145.  
Gott, J. H. 1958, *La Structure de l'Univers et l'Antenne* (11th Solvay Conf. (Brussels-Edinburgh)), 145.  
Penzias, A. A., and Wilson, R. W. 1965, *unpublished communication*.  
Wheeler, J. A. 1958, *La Structure de l'Univers et l'Antenne* (11th Solvay Conf. (Brussels-Edinburgh)), 145.  
—, 1964, in *Relativity, Gravity and Cosmology*, ed. C. DeWitt and R. DeWitt (New York: Gordon & Breach).  
Zeldovich, Ya. B. 1962, *Soviet Phys.—JETP*, **14**, 1445.

### A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford Hill, Holmdel, New Jersey) in the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature, within the limits of our observations, isotropic, unpolarized, and

free from seasonal variations (July, 1964-April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkins (1965) in a companion letter in this issue.

The total antenna temperature measured at the zenith is 6.7° K of which 3.2° K is due to atmospheric absorption. The calculated contribution due to cosmic losses in the antenna and back-side response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzias and Wilson 1965). It employs a traveling-wave mixer, a low-loss (0.01-dB) comparison switch, and a liquid helium-cooled reference thermometer (Fertus 1965). Measurements were made by matching mutually between the antenna input and reference thermometer. The antenna, reference thermometer, and radiometer were well matched so that a round-trip return loss of more than 35 db existed throughout the measurement; thus errors in the measurement of the effective temperature due to impedance mismatch can be neglected. The estimated error in the measured value of the total antenna temperature is 0.2° K and causes largely from uncertainty in the absolute calibration of the reference thermometer.

The contribution to the antenna temperature due to atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law. The result,  $3.2 \pm 0.2$ ° K, is in good agreement with published values (Hogg 1959; DeGruise, Hogg, Olm, and Sovell 1959; Olm 1961).

The contribution to the antenna temperature from cosmic losses is computed to be  $0.8^\circ \pm 0.4^\circ$  K. In this calculation we have divided the antenna into three parts: (1) two non-isotropic tapered approximately 1 m in total length which terminate between the 20-inch round output waveguide and the 6-inch-square antenna throat opening; (2) a double-coiled relay path located between these two tapers; (3) the antenna throat. Care was taken to de-ice and align joints between these parts so that they would not significantly increase the loss in the structure. Appropriate tests were made for leakage and loss in the relay joint with negative results.

The possibility of losses in the antenna horn due to imperfections in its surface was eliminated by means of a leakage test. Taping all the seams in the section near the throat and most of the others with aluminum tape caused no observable change in antenna temperature.

The backside response to ground radiation is taken to be less than 0.3° K for two reasons: (1) Measurement of the response of the antenna to a small transmitter located on the ground in its vicinity indicates that the average back-side level is more than 30 db below isotropic response. The horn-reflector antenna was pointed at the zenith for these measurements, and complete rotations in azimuth were made with the transmitter in each of ten locations using horizontal and vertical transmitted polarization from each position. (2) Measurements on smaller horn-reflector antennas at these laboratories, using perfect measuring sets on the antenna ranges, have consistently shown a back-side level of 30 db below isotropic response. Our larger antenna would be expected to have an even lower back-side level.

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be  $3.5^\circ \pm 1.0^\circ$  K at 4080 Mc/s. In connection with this result it should be noted that DeGruise et al. (1959) and Olm (1961) give total system temperatures at 5610 Mc/s and 2200 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

We are grateful to R. H. Dicke and his associates for fruitful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. A. R. Crawford, D. C. Hogg, and E. A. Olm in connection with the problems associated with this measurement.

No. 1, 1965 LETTERS TO THE EDITOR 421

*Now added in proof.*—The highest frequency at which the background temperature of the sky had been measured previously was 4080 Mc/s (Penzias-Yell and Shakeshaft, 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than  $\lambda^2$ . This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. PENZIAS  
R. W. WILSON

May 13, 1965  
BELL TELEPHONE LABORATORIES, INC.  
CRAWFORD HILL, HOLMDEL, NEW JERSEY

### REFERENCES

- Crawford, A. A., Bethe, H. A., and Hogg, D. C. 1962, *Rad. Environ. Tech.*, **4**, 495.  
DeGruise, R. W., Hogg, D. C., Olm, E. A., and Sovell, H. B. 1959, "Ultra-low Noise Receiving System for Satellite Space Communications," *Proceedings of the National Electronics Conference*, **15**, 291.  
Dicke, R. H., Peebles, P. J. E., Roll, D. C., and Wilkins, D. T. 1965, *Ap. J.*, **142**, 414.  
Hogg, D. C. 1959, *J. Appl. Phys.*, **30**, 1417.  
Penzias, A. A. 1961, *Rad. Environ. Tech.*, **4**, 481.  
Penzias, A. A., and Shakeshaft, R. B. 1962, *M.F.*, **14**, 16, 81.  
Penzias, A. A. 1965, *Rev. Sci. Instr.*, **36**, 58.  
Penzias, A. A., and Wilson, R. W. 1965, *Ap. J.* (in press).

### ERRATUM

In the paper "Stellar Evolution. I. The Approach to the Main Sequence" (*Ap. J.*, **141**, 991), the following corrections are to be made: page 993, line 1, replace "population" by "population"; page 991, line 18, delete the last word "energy"; page 999, line 1, replace "expanding" by "contracting"; page 1007, section heading "15—replace "8" by "9"; page 1007, line 1, replace "Figure 17" by "Figure 17"; page 1007, line 3, replace "equation (10)" by "equation (10)"; page 1008, line 8, replace "W. Z. Foster" by "W. A. Fowler".

June 5, 1965  
MICHIGAN STATE UNIVERSITY  
EAST LANSING, MICHIGAN

SCOTT JONES, JR.

**“A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s”**

A. A. Penzias und R. W. Wilson, Astrophysical Journal, Volume 142, 1965

“Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about  $3.5^{\circ}$  K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964-April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.”

## 2 Theorien zur Entstehung des Universums

### Steady State Theory

- Sir James Jeans, 1928
- Sir Fred Hoyle, 1948
- Sir Hermann Bondi, 1948
- Thomas Gold, 1948
- Albert Einstein, 1931

### Big Bang Theory

- Alexander Friedmann, 1929
- Georges Lemaître, 1927
- George Gamow 1940er
- Ralph Alpher
- Robert Herman

## Steady State Theorie

- bekannt seit dem 13. Jahrhundert
- beruht auf dem (perfekten) kosmologischen Prinzip
  - Universum ist homogen
  - Universum ist isotrop
  - (auch zeitliche homogen)
- Expansion des Universums
- kontinuierliche Erzeugung von Materie ( $\propto 2$  Wasserstoffatome pro  $\text{m}^3$  pro  $10^9$  Jahre)
- Dichte bleibt erhalten

Liefert keine Erklärung zur Existenz des kosmischen Mikrowellenhintergrundes.

→Die meisten Physiker sind heute von der Urknalltheorie überzeugt.

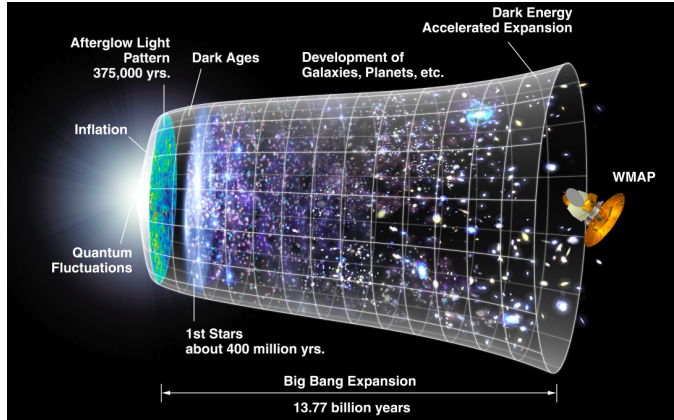


Abbildung 1: Bildrechte: NASA / WMAP Science Team

## George Anthony Gamow

- Geboren 4. März 1904 in Odessa
- Studium von 1922 bis 1929 in Leningrad
- unter anderen unter Alexander Friedmann (Leningrad), Max Born (Göttingen) und Nils Bohr (Kopenhagen)
- 1933 endgültige Flucht in die USA



Abbildung 2: Bildrechte: Serge Lachinov



## Gamow's Fireball

"The Elements were cooked in less time than it takes to boil an egg."

-George Gamow

- 99 % der Elemente im interstellarem Raum sind Wasserstoff (75%) und Helium(24%)
- Gamow beschäftigt sich 1946 mit der Frage woher die Elemente kommen
- Seine Idee: Das frühe Universum war eine heiße, dichte "Suppe", genannt:
- "YLEM":
  - Protonen
  - Neutronen
  - Elektronen
  - thermale Strahlung

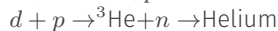
## Kochrezept

- Rezept für Helium:

1.  $p + n \rightarrow$  Deuterium + Strahlung

- $T < 10^9 \text{K}$  notwendig

2.  $d + n \rightarrow {}^3\text{H} + p \rightarrow \text{Helium}$



- $T > 10^7 \text{K}$  notwendig

3. für schwerere Elemente: weitere Protonen und Neutronen hinzufügen

- Problem: Alle Protonen und Neutronen würden zu Deuterium werden

- Lösung: Variation der Dichte des Universums

- Universum dehnt sich aus
- "Suppe verdünnt sich"
- Prozess stoppt

Zusammengefasst:

- Temperaturen bis zu 100mal heißer als die der Sonne
- Dichte fast 20fach so gering wie die der Sonne
- Strahlungsdominant
- Frage: Was passierte mit dem Feuerball?

■ Antwort:

1. Ausdehnung um  $a^3 = \frac{V_0}{V_1} = \frac{\rho_0}{\rho_1}$

2. Kühlung auf  $T_1 = \frac{10^9 \text{K}}{a} = 5 \text{K}$

Das 1948 von Alpher, Bethe und Gamow veröffentlichte Paper findet keine Aufmerksamkeit.

## Entdeckung durch Robert W. Wilson und Arno A. Penzias



## Robert Woodrow Wilson

- geboren am 10. Januar 1936 in Houston
- studierte an der Rice University und dem California Institute of Technology
- unter anderen bei Sir Fred Hoyle
- Mitarbeit an der Konstruktion eines Interferometers
- Doktorarbeit über die Helligkeit der Milchstraße mittels Interferometrie (31 cm)
- ab 1963 bei Bell Laboratories in Holmdel, New Jersey

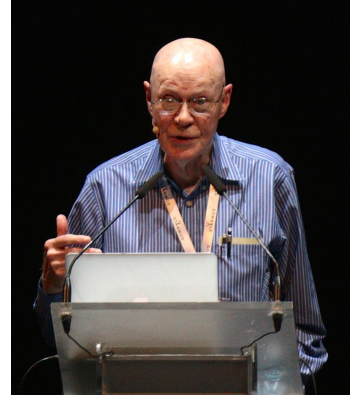


Abbildung 4: Bildrechte: Victor R. Ruiz

## Arno Allen Penzias

- geboren am 26. April 1933 in München
- 1940 flieht die Familie in die USA, New York City
- studierte ab 1951 am City College of New York, zunächst mit Hauptfach Chemie, später Wechsel zu Physik
- Doktorarbeit über das Vorkommen von Wasserstoff in der Milchstraße
- ab 1962 bei Bell Laboratories

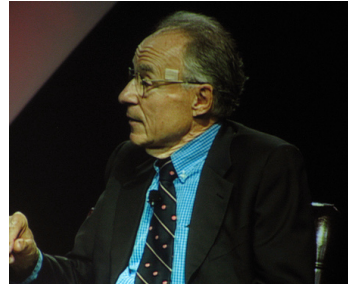


Abbildung 5: Bildrechte: Kartik Jayan

## Bell Laboratories

- 1925 gegründet als Forschungs- und Entwicklungseinheit von Western Electric
- Arbeiten für Bell Telephone Company, die US Regierung und Grundlagenforschung
- seit dem 9 Nobelpreise

### Meilensteine:

- Nachweis von Beugung von Elektronen an Kristallen
- Entdeckung von Radiostrahlung aus der Mitte unserer Galaxie
- Entwicklung des ersten Bipolartransistors
- erster Helium-Neon-Laser
- Entdeckung des kosmischen Mikrowellenhintergrundes
- Entwicklung von CCD-Sensoren
- Ursprung der Programmiersprache C und C++

## Ziele

1. Vermessung von CasA bei 4080 Mc/s
2. Verbesserung der Untergrundrate bei der Vermessung der Milchstraße
3. Suche nach atomarem Wasserstoff in galaktischen Clustern



## Technik

- Horn-Reflektorantenne aus Aluminium
- 15 m lang
- 6m x 6m Antennenapertur
- Seitenwände bilden gute Abschirmung
- ideal für Messung schwacher Signale

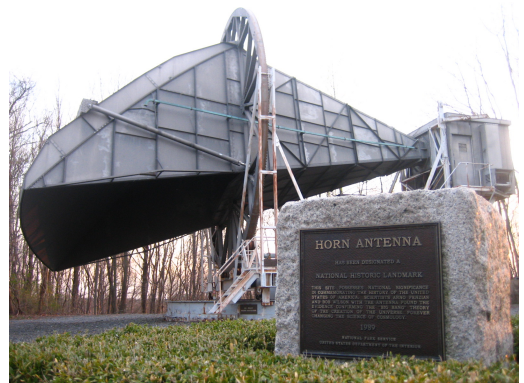


Abbildung 6: Bildrechte: Fabio J.

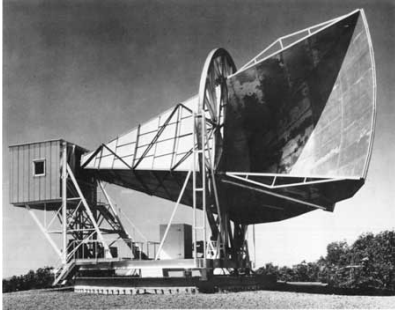


Abbildung 7: Bildrechte: NASA

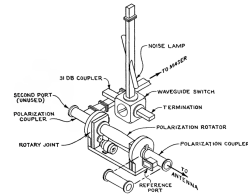


Abbildung 8: Measurement of the Flux Density of CAS a at 4080 Mc/s., Penzias, A. A. and Wilson, R. W., in Astrophysical Journal, vol. 142, p.1149

- $\frac{1}{2}$  ft. radius }  $\rightarrow$  diameter  $10^{\circ}$   
 }  $\rightarrow$  radius  
 }  $\rightarrow$  odd half load  
 }  $\rightarrow$  odd  
 odd half load }  $\rightarrow$  odd load + 0.5  
 }  $\rightarrow$  Antenna  $\begin{matrix} 5 \times 45^{\circ} \\ 6 \times 0^{\circ} \end{matrix}$
- BDT 11:15  
 12 radio 12:15  
 13 radio 13:15  
 14 radio 14:15  
 15 radio 15:15  
 16 radio 16:15  
 17 radio 17:15  
 18 radio 18:15  
 19 radio 19:15  
 20 radio 20:15  
 21 radio 21:15  
 22 radio 22:15  
 23 radio 23:15  
 24 radio 24:15  
 25 radio 25:15  
 26 radio 26:15  
 27 radio 27:15  
 28 radio 28:15  
 29 radio 29:15  
 30 radio 30:15  
 31 radio 31:15  
 32 radio 32:15  
 33 radio 33:15  
 34 radio 34:15  
 35 radio 35:15  
 36 radio 36:15  
 37 radio 37:15  
 38 radio 38:15  
 39 radio 39:15  
 40 radio 40:15  
 41 radio 41:15  
 42 radio 42:15  
 43 radio 43:15  
 44 radio 44:15  
 45 radio 45:15  
 46 radio 46:15  
 47 radio 47:15  
 48 radio 48:15  
 49 radio 49:15  
 50 radio 50:15  
 51 radio 51:15  
 52 radio 52:15  
 53 radio 53:15  
 54 radio 54:15  
 55 radio 55:15  
 56 radio 56:15  
 57 radio 57:15  
 58 radio 58:15  
 59 radio 59:15  
 60 radio 60:15  
 61 radio 61:15  
 62 radio 62:15  
 63 radio 63:15  
 64 radio 64:15  
 65 radio 65:15  
 66 radio 66:15  
 67 radio 67:15  
 68 radio 68:15  
 69 radio 69:15  
 70 radio 70:15  
 71 radio 71:15  
 72 radio 72:15  
 73 radio 73:15  
 74 radio 74:15  
 75 radio 75:15  
 76 radio 76:15  
 77 radio 77:15  
 78 radio 78:15  
 79 radio 79:15  
 80 radio 80:15  
 81 radio 81:15  
 82 radio 82:15  
 83 radio 83:15  
 84 radio 84:15  
 85 radio 85:15  
 86 radio 86:15  
 87 radio 87:15  
 88 radio 88:15  
 89 radio 89:15  
 90 radio 90:15  
 91 radio 91:15  
 92 radio 92:15  
 93 radio 93:15  
 94 radio 94:15  
 95 radio 95:15  
 96 radio 96:15  
 97 radio 97:15  
 98 radio 98:15  
 99 radio 99:15  
 100 radio 100:15  
 101 radio 101:15  
 102 radio 102:15  
 103 radio 103:15  
 104 radio 104:15  
 105 radio 105:15  
 106 radio 106:15  
 107 radio 107:15  
 108 radio 108:15  
 109 radio 109:15  
 110 radio 110:15  
 111 radio 111:15  
 112 radio 112:15  
 113 radio 113:15  
 114 radio 114:15  
 115 radio 115:15  
 116 radio 116:15  
 117 radio 117:15  
 118 radio 118:15  
 119 radio 119:15  
 120 radio 120:15  
 121 radio 121:15  
 122 radio 122:15  
 123 radio 123:15  
 124 radio 124:15  
 125 radio 125:15  
 126 radio 126:15  
 127 radio 127:15  
 128 radio 128:15  
 129 radio 129:15  
 130 radio 130:15  
 131 radio 131:15  
 132 radio 132:15  
 133 radio 133:15  
 134 radio 134:15  
 135 radio 135:15  
 136 radio 136:15  
 137 radio 137:15  
 138 radio 138:15  
 139 radio 139:15  
 140 radio 140:15  
 141 radio 141:15  
 142 radio 142:15  
 143 radio 143:15  
 144 radio 144:15  
 145 radio 145:15  
 146 radio 146:15  
 147 radio 147:15  
 148 radio 148:15  
 149 radio 149:15  
 150 radio 150:15  
 151 radio 151:15  
 152 radio 152:15  
 153 radio 153:15  
 154 radio 154:15  
 155 radio 155:15  
 156 radio 156:15  
 157 radio 157:15  
 158 radio 158:15  
 159 radio 159:15  
 160 radio 160:15  
 161 radio 161:15  
 162 radio 162:15  
 163 radio 163:15  
 164 radio 164:15  
 165 radio 165:15  
 166 radio 166:15  
 167 radio 167:15  
 168 radio 168:15  
 169 radio 169:15  
 170 radio 170:15  
 171 radio 171:15  
 172 radio 172:15  
 173 radio 173:15  
 174 radio 174:15  
 175 radio 175:15  
 176 radio 176:15  
 177 radio 177:15  
 178 radio 178:15  
 179 radio 179:15  
 180 radio 180:15  
 181 radio 181:15  
 182 radio 182:15  
 183 radio 183:15  
 184 radio 184:15  
 185 radio 185:15  
 186 radio 186:15  
 187 radio 187:15  
 188 radio 188:15  
 189 radio 189:15  
 190 radio 190:15  
 191 radio 191:15  
 192 radio 192:15  
 193 radio 193:15  
 194 radio 194:15  
 195 radio 195:15  
 196 radio 196:15  
 197 radio 197:15  
 198 radio 198:15  
 199 radio 199:15  
 200 radio 200:15  
 201 radio 201:15  
 202 radio 202:15  
 203 radio 203:15  
 204 radio 204:15  
 205 radio 205:15  
 206 radio 206:15  
 207 radio 207:15  
 208 radio 208:15  
 209 radio 209:15  
 210 radio 210:15  
 211 radio 211:15  
 212 radio 212:15  
 213 radio 213:15  
 214 radio 214:15  
 215 radio 215:15  
 216 radio 216:15  
 217 radio 217:15  
 218 radio 218:15  
 219 radio 219:15  
 220 radio 220:15  
 221 radio 221:15  
 222 radio 222:15  
 223 radio 223:15  
 224 radio 224:15  
 225 radio 225:15  
 226 radio 226:15  
 227 radio 227:15  
 228 radio 228:15  
 229 radio 229:15  
 230 radio 230:15  
 231 radio 231:15  
 232 radio 232:15  
 233 radio 233:15  
 234 radio 234:15  
 235 radio 235:15  
 236 radio 236:15  
 237 radio 237:15  
 238 radio 238:15  
 239 radio 239:15  
 240 radio 240:15  
 241 radio 241:15  
 242 radio 242:15  
 243 radio 243:15  
 244 radio 244:15  
 245 radio 245:15  
 246 radio 246:15  
 247 radio 247:15  
 248 radio 248:15  
 249 radio 249:15  
 250 radio 250:15  
 251 radio 251:15  
 252 radio 252:15  
 253 radio 253:15  
 254 radio 254:15  
 255 radio 255:15  
 256 radio 256:15  
 257 radio 257:15  
 258 radio 258:15  
 259 radio 259:15  
 260 radio 260:15  
 261 radio 261:15  
 262 radio 262:15  
 263 radio 263:15  
 264 radio 264:15  
 265 radio 265:15  
 266 radio 266:15  
 267 radio 267:15  
 268 radio

Ausgeschlossene Quellen:

- Strahlung aus der Atmosphäre
- Störsignale von NYC
- Tauben in der Antenne
- Atombombentest
- und viele mehr

## Tauben und Atombomben

Anekdoten zur Lösung der Probleme im Video von Robert Wilson. (Harvard-Smithsonian Center for Astrophysics: 50 Years After the Discovery of the Big Bang!) ab 41:10  
<https://www.youtube.com/watch?v=V6rUi65qLqc>

## Identifikation

- Penzias führt Telefonat mit Bernard Burke
- Burke empfiehlt Robert Henry Dicke aus Princeton
- Penzias spricht mit Dicke
- “Boys, we’ve been scooped”
- Treffen initiiert
- zwei eigenständige Paper
- Nobelpreis für Penzias und Wilson in 1978
- “for their discovery of cosmic microwave background radiation”



Abbildung 10: Bildrechte: National Academies Press

## Nachfolgende Messungen

- homogene, isotrope, unpolarisierte Strahlung gefunden bei 3,5 K
- theoretische Berechnungen von Sachs und Wolf (1967) sagen Anisotropien voraus

Die Entdeckung stieß eine Reihe an weiteren Experimenten zur Untersuchung des kosmischen Mikrowellenhintergrundes los:

- weitere Untersuchungen mit erdgebundenen Instrumenten
  - Hinweis auf Schwarzkörperspektrum
  - Problem: Atmosphärische Absorption
- Satellitengebundene Messungen
  - COBE
  - (W)MAP
  - Planck
- Ballongebundene Instrumente
  - BOOMERanG
  - MAXIMA

## COBE

- The **C**osmic **B**ackground **E**xplorer
- von 1989 bis 1993

### Ziele:

- Messung der hohen Frequenzen des Spektrums
- Messung der Anisotropien
- Messung von diffuser Infrarotstrahlung

### Drei Instrumente:

- **F**ar **I**nfra**R**ed **A**bsolute **S**pectrophotometer
- **D**ifferential **M**icrowave **R**adiometer
- **D**iffuse **I**nfra**R**ed **B**ackground **E**xperiment

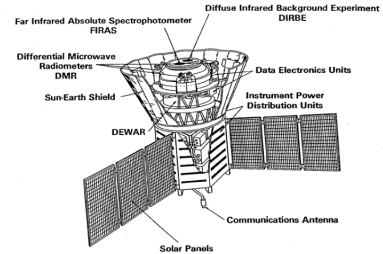


Abbildung 11: aus Boggess et al. (1992)



## Far InfraRed Absolute Spectrophometer

Ziel:

- Vermessung des Schwarzkörperspektrums
- Wellenlängenbereich 0,1 mm - 10 mm

Ergebnis:

- perfektes Schwarzkörperspektrum

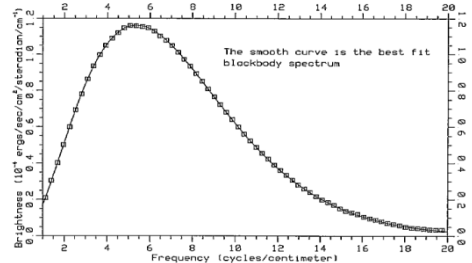


Abbildung 12: aus Mather et al. 1990

## Differential Microwave Radiometer

Ziel:

- Suche nach Anisotropien
- Wellenlängen: 3 mm, 6 mm, 10 mm
- Winkelauflösung von  $7^\circ$

Ergebnis:

- $T = 2,728 \text{ K}$
- Temperaturfluktuationen von Größenordnung  $10^{-5}$

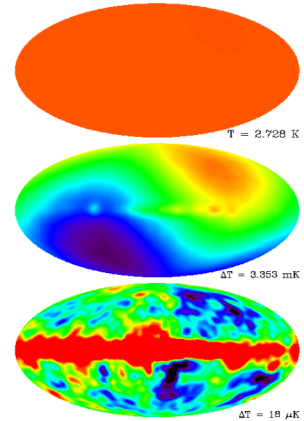


Abbildung 13: aus Smoot et al. 1992

Nobelpreis in 2006

“for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation”



Abbildung 14: George Smoot, Bildrechte: Michael Höfner



Abbildung 15: John Mather, Bildrechte: Christopher Michel

## BOOMERanG

- **B**alloon **O**bservations **O**f **M**illimetric **E**xtragalactic **R**adiation **and** **G**eophysics
- von 1998 bis 2003

- 1998 Start von McMurdo Station in der Antarktis
- 42000 m hoch
- kosten günstiger als Satellit
- Polarwirbel sorgt für Rückkehr zum Startpunkt



Abbildung 16: Bildrechte: BOOMERanG collaboration

Ergebnisse:

- Vermessung der Anisotropien mit höherer Genauigkeit
- Geometrie des Universums ist flach



Abbildung 17: Bildrechte: BOOMERanG collaboration

## Zusammenfassung und Ausblick

### Zusammenfassung:

- zufällige Entdeckung des kosmischen Mikrowellenhintergrundes von Penzias und Wilson in 1964
- Beweis der Urknalltheorie
- präzise Vermessung

### Ausblick:

- theoretische Vorhersage des Neutrino hintergrundes bei 1,9 K
- zeitlich vor dem kosmischen Mikrowellenhintergrund
- Messung schwierig