20^{th} century cosmology

- **1920s – 1990s (from Friedmann to Freedman)**
  - **theoretical technology available, but no data**
  - **20^{th} century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
    - Discovery of the CMB 1965
    - Inflation 1981
    - CMB anisotropies: COBE ~1990

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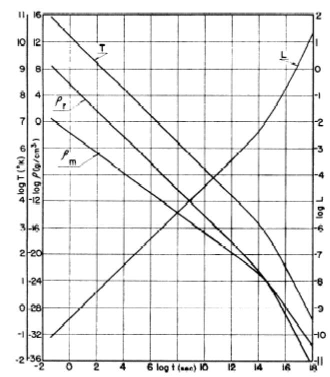
  - **20^{th} century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
    - Discovery of the CMB 1965
      - "smoking gun" for the Hot Big Bang model
      - now the main tool for precision cosmology (see later)

The Cosmic Microwave Background: Theory

- **Prediction of CMB trivial in Hot Big Bang model**
  - **hot, ionised initial state should produce thermal radiation**
  - **photons decouple when universe stops being ionised (last scattering)**
  - **expansion by factor *a* cools a blackbody spectrum from *T* to *T/a***
  - **therefore we should now see a cool blackbody background**
    - Alpher and Herman, 1949, “a temperature now of the order of 5 K”
    - Dicke et al., 1965, “<40 K”
      - note that the Alpher and Herman prediction had been completely forgotten at this time!

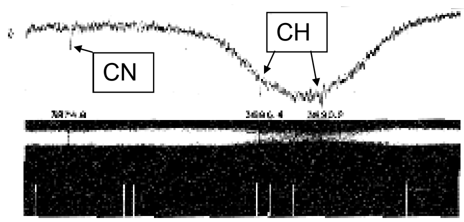


The Cosmic Microwave Background: Theory

- **Blackbody background radiation is a natural consequence of the *whole* universe having been in thermal equilibrium at *one* particular past time**
- **Continuous creation of radiation does not lead to a blackbody background**
  - **see photons from different distances, created at different times, with different redshifts**
  - **superposition of several blackbody spectra with different temperatures is not a blackbody**

The Cosmic Microwave Background: Observations

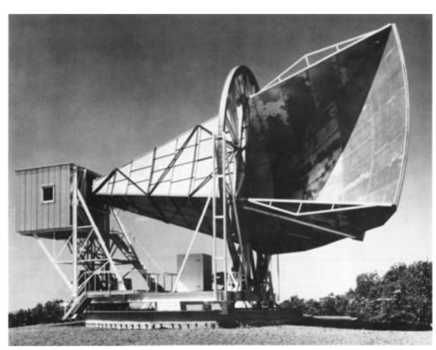
- **First seen in 1941 (yes, 1941)**
  - **lines seen in stellar spectra identified as interstellar CH and CN (Andrew McKellar, theory; Walter Adams, spectroscopy)**
  - **comparison of lines from different rotational states gave "rotational temperature" of 2-3 K**
  - **unfortunately Gamow et al. do not seem to have known about this**



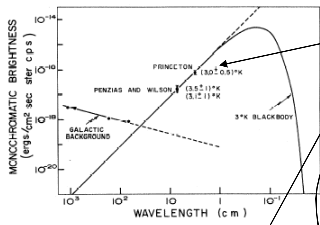
spectrum of ζ Oph, Mt Wilson coudé spec., Adams 1941

The Cosmic Microwave Background: Observations

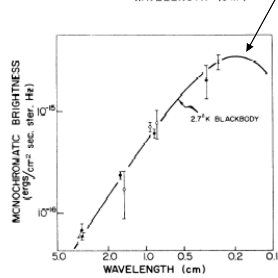
- **Discovered in 1965**
  - **Penzias and Wilson observe excess "antenna temperature" of 3.5±1.0 K from the Holmdel microwave horn**
  - **interpreted by Dicke et al. at Princeton**
    - they had independently rediscovered the prediction and were just about to start looking for the radiation!
  - **note: this is one point (not a blackbody spectrum!)**

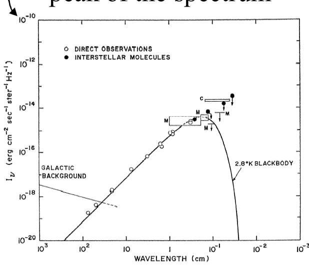


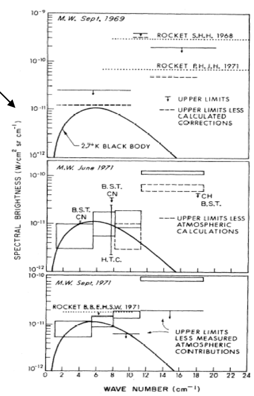
The Cosmic Microwave Background: Spectrum



Roll and Wilkinson, 1966: a second point
Boynton, Stokes and Wilkinson, 1968
Thaddeus, review 1972
Muehler and Weiss, 1973: first indications of radiation beyond the peak of the spectrum

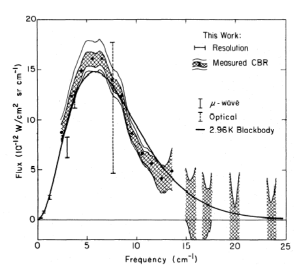




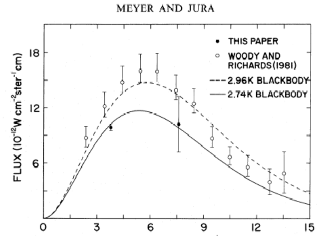


The Cosmic Microwave Background: Spectrum

- **Is the spectrum a blackbody?**
  - **Balloon measurements by Woody and Richards (1981) – no!**
    - higher temperature than the long wavelength measurements
    - spectrum more peaked
- **much theoretical interest, but data were simply wrong**
  - **CN measurements by Meyer and Jura, 1985**
    - temperature back to 2.74 K (not 2.96)
    - no evidence for non-blackbody

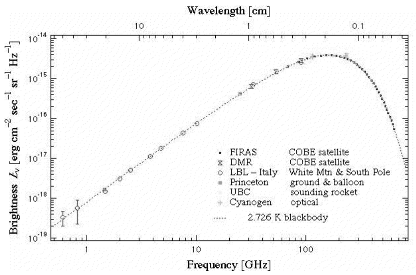


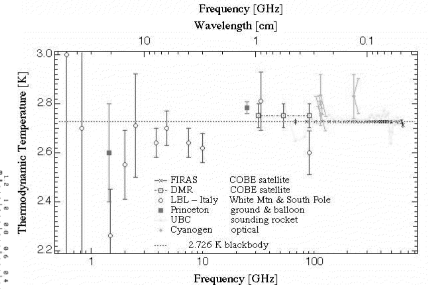
MEYER AND JURA



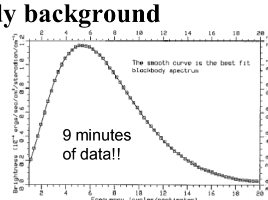
COBE

- **Launched November 1989**
- **After two years of data:**
  - **spectrum is a precise blackbody (no measurable deviations)**
  - ***T* = 2.725±0.002 K**
- **At this point all cosmological models other than Hot Big Bang are effectively dead**
  - **no other model expects this good a blackbody background**



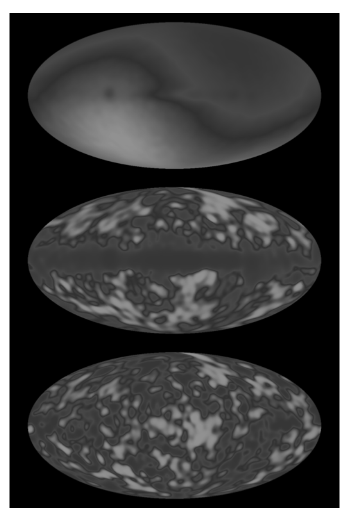


Mather et al., *ApJ* **354** (1990) L37



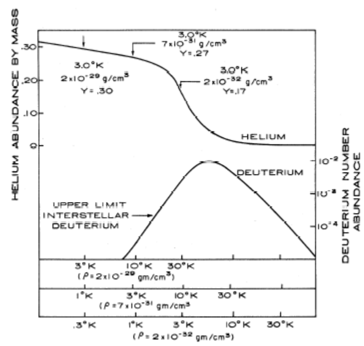
CMB Structure

- **COBE saw:**
  - **a dipole anisotropy of 0.1%**
    - we are moving relative to the CMB rest frame
  - **random anisotropies of ~10^{-5}**
    - these represent density fluctuations in the early universe
    - COBE's angular resolution was not good, so it mapped only very large-scale fluctuations (~10°)
      - – superclusters, not galaxies
- **revisit this later in the course**



Observations & the Hot Big Bang

- **Predictions of Hot Big Bang model ~mid 1960s**
  - **background radiation (“smoking gun”)**
    - discovered by accident in 1965, but about to be found on purpose!
  - **age of universe ≤ $1/H_0$**
    - reasonably OK by this time
    - discovery of quasars helped establish evolution
  - **primordial deuterium and helium abundance**
    - calculated by Jim Peebles, 1966
- **Really a set of models, so need to measure parameters**



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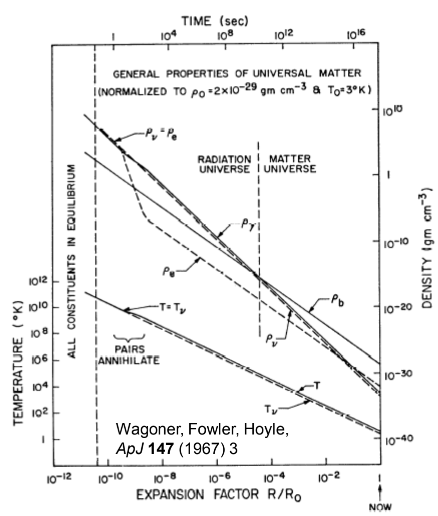
Big Bang Nucleosynthesis

- **First detailed calculations by Wagoner, Fowler and Hoyle**
- **Basic principles**
  - **at very high energies neutrons and protons interconvert:** $p + e^- \leftrightarrow n + \nu$
  - **neutron:proton ratio given by** $\exp(-\Delta mc^2/kT)$ **where** Δm **is the neutron-proton mass difference and** T **is the temperature at which the neutrinos “freeze out” (~**10^{10} **K)**
  - **this is ~1:5**



Wagoner, Fowler, Hoyle, *ApJ* **147** (1967) 3

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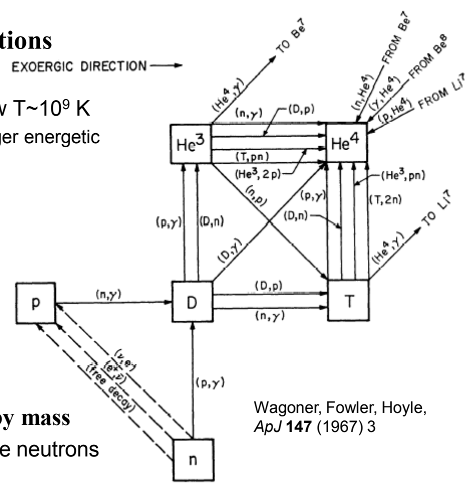
Big Bang Nucleosynthesis

- As universe cools, start fusion reactions
  - $p + n \leftrightarrow d + \gamma$
    - deuterium starts to build up below $T \sim 10^9$ K
      - background photons are no longer energetic enough for back reaction
  - $d + p \rightarrow {}^3He + \gamma$
    $d + n \rightarrow {}^3H + \gamma$
    $d + d \rightarrow {}^3H + p$ or ${}^3He + n$
  - various reactions then lead to ${}^4He$ (and a bit of ${}^7Li$)
- eventually every neutron winds up in ${}^4He$
  - ${}^4He$ fraction ~1:8 by number, 1:2 by mass
    - actually rather less because some neutrons decay



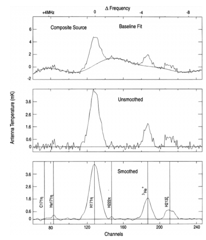
Wagoner, Fowler, Hoyle, *ApJ* **147** (1967) 3

Big Bang Nucleosynthesis

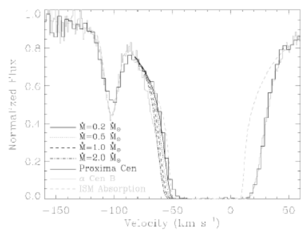
- Final yields of ${}^2H$, ${}^3He$, ${}^4He$ and ${}^7Li$ depend on
  - the neutron lifetime (measured in lab)
    - 885.7±0.8 s (PDG, 2004)
  - the number of neutrino species (measured in e^+e^-)
    - because in radiation dominated era $H^2 \propto \rho_{rel} = \rho_\gamma + N_\nu \rho_\nu$
    - 2.984±0.008 (combined LEP experiments)
  - *H* (measured by HST, WMAP)
    - 72±8 km/s/Mpc (HST), 70.1±1.3 km/s/Mpc (WMAP)
  - baryon density (i.e. number density of protons+neutrons)

Light elements: observations

- **Helium 4**
  - **measure in spectra of Pop. II stars**
  - **also produced in stars: big correction factors**
- **Helium 3**
  - **measured in radio (spin flip of $^{3}He^{+}$ at 3.46 cm)**
- **Deuterium**
  - **lines can be separated from ^{1}H**
  - **currently best measured isotope**
- **Lithium 7**
  - **measure in spectra**
  - **also produced by cosmic rays, and destroyed by stars**
  - **results are currently not concordant**



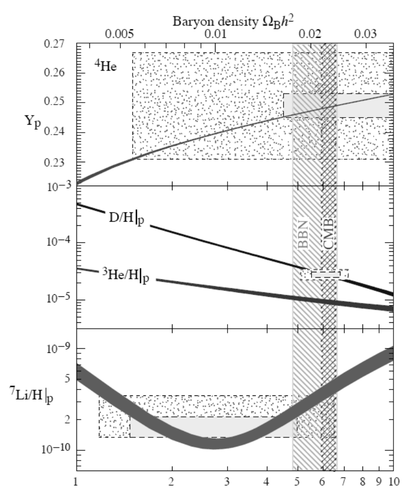
Bania et al., *ApJSS* **113** (1997) 353



Linsky, Sp. Sci. Rev. **106** (2003) 49

Big Bang Nucleosynthesis

- **Current abundances**
  Fields and Sarkar, PDG 2008
  - D/H = (2.84±0.26) × 10^{-5}
  - ^{7}Li/H = (1.23±0.06) × 10^{-10}
    - but could be factor of 2 higher
  - Y = 0.249±0.009
  - ^{3}He is only measured in our Galaxy – systematics too high to be useful
- **^{7}Li somewhat inconsistent**
  - **but may be destroyed in the early universe or in stars**
  - **D/H is consistent with WMAP Ω_b**



Case for the Hot Big Bang

- **The Cosmic Microwave Background has an isotropic blackbody spectrum**
  - **it is extremely difficult to generate a blackbody background in other models**
- **The observed abundances of the light isotopes are reasonably consistent with predictions**
  - **again, a hot initial state is the natural way to generate these**
- **Many astrophysical populations (e.g. quasars) show strong evolution with redshift**
  - **this certainly argues against any Steady State models**

Outstanding Problems

- **Why is the CMB so isotropic?**
  - **horizon distance at last scattering << horizon distance now**
  - **why would causally disconnected regions have the same temperature to 1 part in 10^5?**
- **Why is universe so flat?**
  - **if $\Omega \neq 1$, Ω evolves rapidly away from 1 in radiation or matter dominated universe**
  - **but CMB analysis (later!) shows $\Omega = 1$ to high accuracy – so either $\Omega \equiv 1$ (why?) or Ω is fine tuned to very nearly 1**
- **How do structures form?**
  - **if early universe is so very nearly uniform**

→ inflation