Cosmology: Historical Outline

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Whole History of Universe (1)

- Planck epoch, < 10^{-43} sec, particle energies reach Planck mass = 22 µg, where Compton wavelength = Schwarzschild radius. Primordial material, infinite? in extent, filled with various fields and “false vacuum”, unknown laws of physics, possibility that space and time have no (independent) meaning. Possible other “universes”.
- Grand Unification epoch, 10^{-43} to 10^{-36} sec. Gravitation separates from other 3 forces.
- Electroweak epoch, 10^{-36} to 10^{-12} sec. Phase transition, separation of strong nuclear force from electroweak.

Whole History of Universe (2)

- Inflation epoch, 10^{-36} to 10^{-32} sec. Some or all of primordial material inflates to make our observable Universe: calculable from guesses about various fields, Lagrangians, etc. Evidence from CMB.
- Produces initial conditions for classical physics: matter, antimatter, dark matter, all known particles, geometrically flat topology (due to inflation)?, dilution of magnetic monopoles (due to inflation), large scale uniformity, Gaussian fluctuations, etc….
- Reheating, after 10^{-32} sec. Inflatons decay, quarks and leptons form.
- Baryogenesis. No obvious reason why baryons > antibaryons. Quark-gluon plasma.

Whole History of Universe (3)

- Supersymmetry breaking, if there is supersymmetry?
- Quark epoch, 10^{-12} to 10^{-6} sec. Particles acquire mass by Higgs mechanism.
- Hadron epoch, 10^{-6} to 1 sec. Neutrinos decouple at 1 sec. Most antihadrons annihilate, 1 ppb hadrons left.
- Lepton epoch, 1 sec to 3 min. Antileptons annihilated.
- Nucleosynthesis, 3 to 20 min. Neutrons decay or stick to protons. D, He, 3He, Li. Depends on number of neutrinos.
- 1 year, $z = 10^{6.5}$, photon number fixed, CMB can have Bose-Einstein distribution with chemical potential if energy added
- $z=10^5$, equilibration slows, can mix CMB temperatures, "Comptonization" of energy added to CMB

Whole History of Universe (4)

- Matter domination, 70,000 yrs. Dark matter streaming, but charged particles are stuck to radiation field.
- Recombination, 240,000 - 310,000 yrs. Z=1089. Complex phenomena permit slight spectrum distortions, delays. Baryonic matter can stream. Blackbody CMB form preserved by adiabatic expansion.
- Dark ages, dark and ordinary matter move into potential wells, forming cosmic structure web as horizon scale grows and new forces are felt
- First luminous objects: Pop III stars (M=30 - 300 Msun), quasars, ?? At highest density peaks, z up to 50?. SNe detectable by JWST up to z = 10-20 depending on number density. Numerical simulations.
- Direct formation of black holes from pair-instability supernovae, M=200 Msun
- Growth of black holes, Eddington luminosity limit? Or more? Hiding baryons.

Whole History of Universe (5)

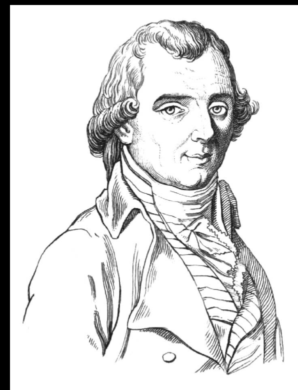
- Complex physics, star formation, proto-galaxy formation, enrichment of IGM and ISM, dust formation, galaxy mergers
- Formation of protogalaxies, 10^8 Msun, detectable by JWST?
- Reionization by hot stars, black holes, SNe, etc.: when & how? Electron optical depth to CMB about 10%. Peaks at z=11 (per WMAP), complete around z=6, observe with JWST
- Black holes grow, merge, and migrate to galactic centers? Gravitational radiation detectable by LISA?
- Gamma ray bursts from stars falling into black holes, or neutron star pairs, etc., with jets aimed at us?
- z=1, expansion slows galaxy mergers, star formation diminishes, quasar numbers decrease, major infalls to Milky Way stop, Milky Way takes present shape
- Sun and Earth form, 4.5 Gyr ago (z ~ 1/3), prompted by local SNe?

Whole History of Universe (6)

- Planets form from collisions of smaller bodies; Mars-sized object hits Earth and makes Moon; Pluto-sized object hits Mars and makes huge lowlands; heavy bombardment of Earth lasts for 0.5 Gyr
- Comets & asteroids? bring more water to hot Earth
- As soon as possible? (< 1 Gyr) life appears on Earth; biological molecules have preferred chirality; all current living things related
- Plate tectonics & big meteorites make frequent mass extinctions
- Mammals appear; dominant at 55 Myr ago
- Humans appear, 3 Myr ago; Homo sapiens sapiens, 0.2 Myr ago
- Humans want to know, what was that all about? What's next?
- Humans discover (signs of) life on other planets, t < 50 yrs
- Humans create artificial intelligence, t < 50 yrs
- Sun gets brighter, Earth too hot: 1 Gyr
- Andromeda Nebula collides with Milky Way, 5 Gyr
- Sun swallows Earth, then goes out: 7.6 Gyr
- Most stars go out: 100 Gyr
- Probably never: interstellar travel for living things

Major Observations

- Sky is dark - Olbers 1823; Kepler?
- Galaxies made of stars - Ritchey, 1917, nova in NGC 6946; supernova in M31, 1885; Cepheids in M31, Hubble, 1925
- Galaxies receding - V. M. Slipher, 1917
- Galaxy speeds proportional to distance - Hubble, 1929 $\Rightarrow$ expanding universe
- Deviations from Hubble flow $\Rightarrow$ masses of clusters; explain this!
- Universal helium abundance, traces of D, 3He, Li: $\Rightarrow$ primordial nucleosynthesis

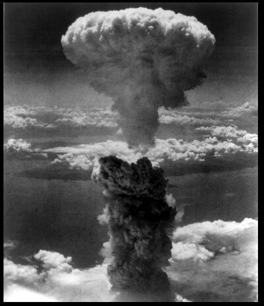


Relativity Tests

- Precession of Mercury: Einstein 1915
- Bending of Starlight: Eddington 1919; gravitational lenses
- Gravitational redshift: astrophysics, atomic clocks, GPS, Mossbauer effect
- Orbit of Moon, using laser retroreflectors
- Orbits of other planets
- Orbits of space probes (signs of deviations, but probably not gravitational)
- Binary pulsars, gravitational radiation
- GP-B, geodetic precession (parallel transport), and search for frame dragging (gravito-magnetism)

Particle & Nuclear Physics

- Elementary particle properties
  - Catalog, symmetries, masses, decays, reaction cross sections
  - Antimatter (predicted by Dirac, 1928)
  - Extra dimensions: isospin, strangeness, color, etc.
  - Proton decay?
- Nuclear physics
  - Isotope catalog
  - Reaction & decay rates
  - Nuclear energy levels (affect rates)



Standard Particle Model

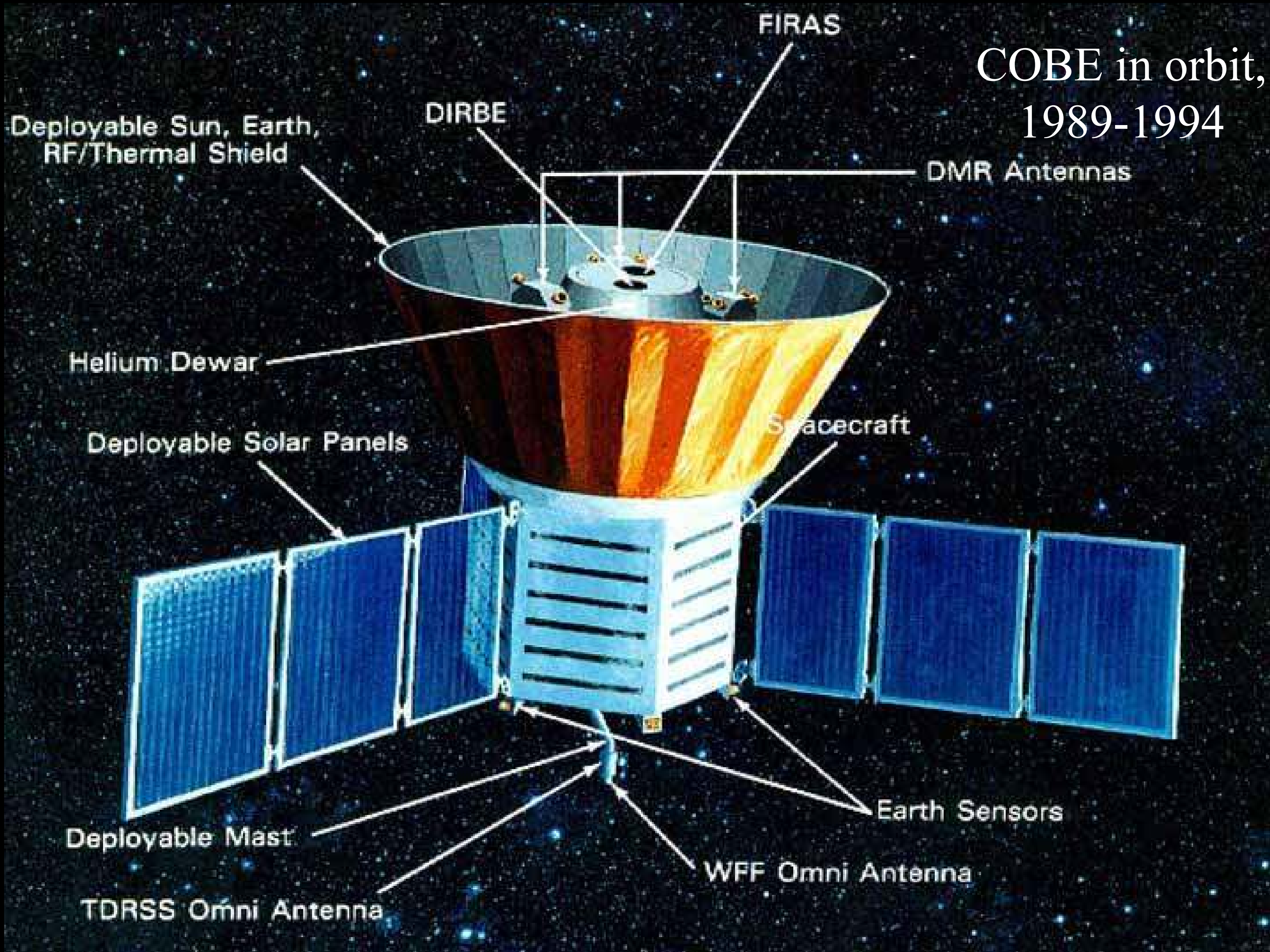
Leptons, plus gluons, photon, $W^{\pm}$, Z, Higgs boson, graviton(?), + antiparticles…

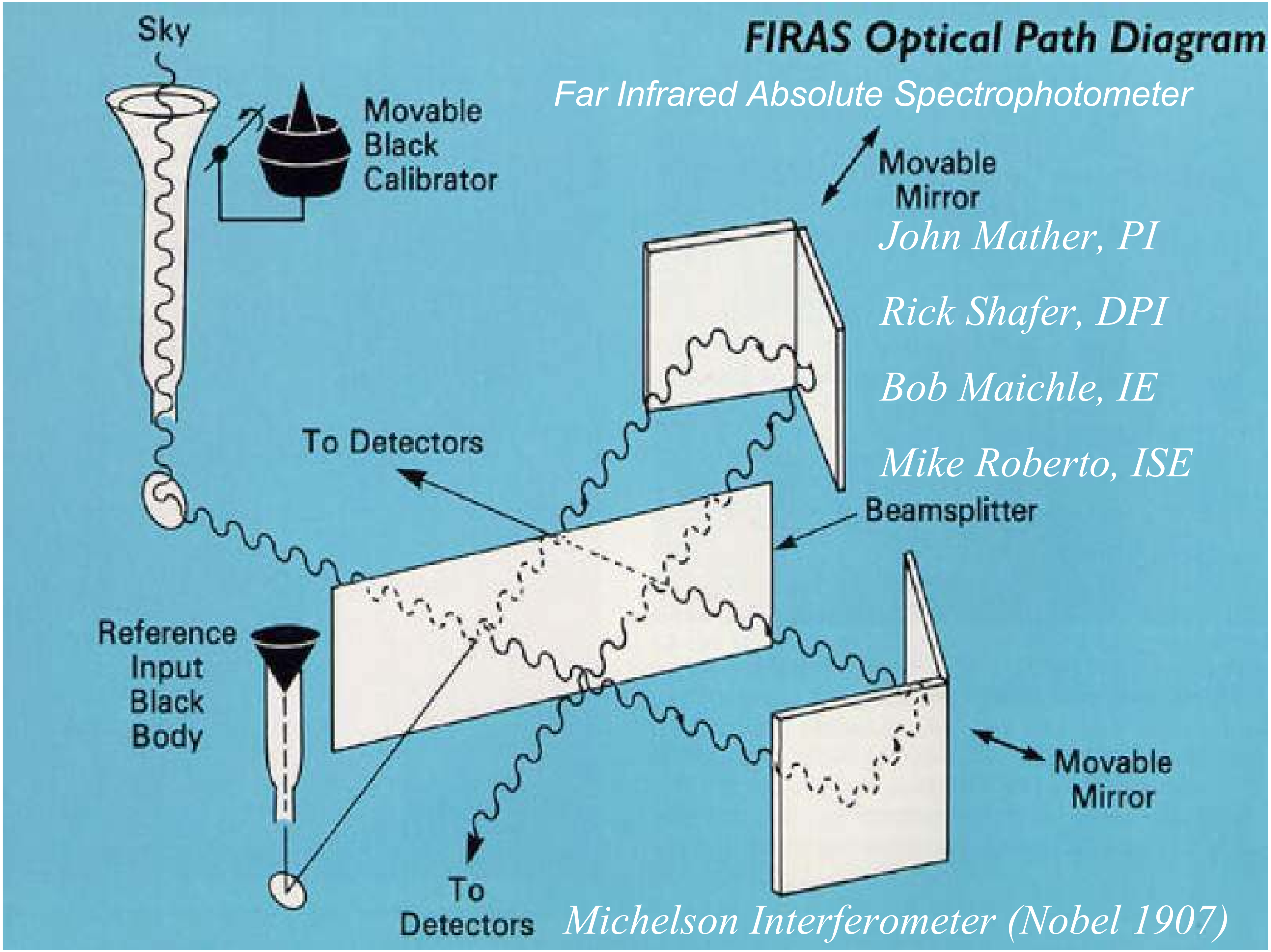
hadron = 3 quarks, meson = q+anti q

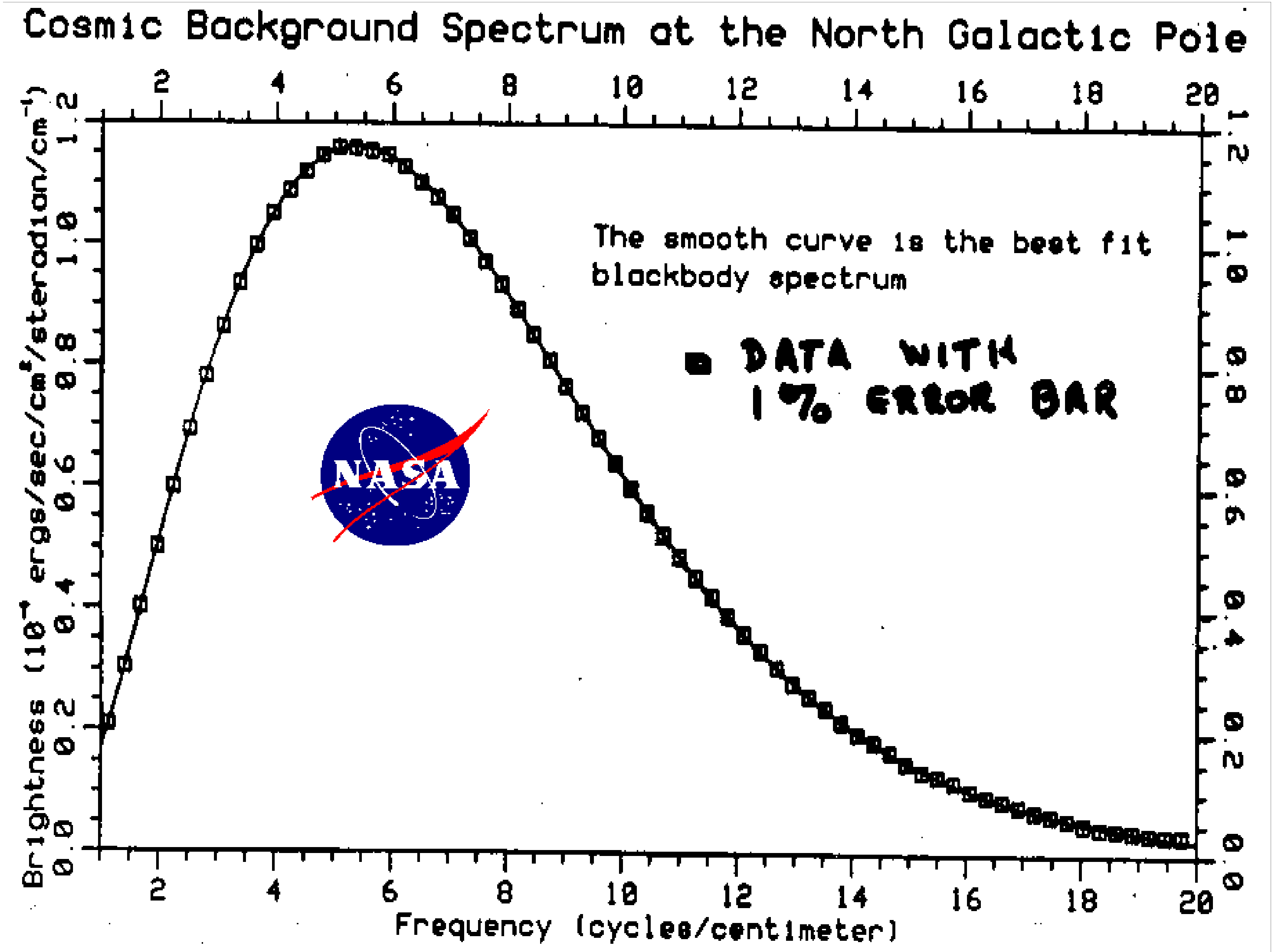
First generation	Second generation	Third generation
▪ electron: e^-	▪ muon: μ^-	▪ tau: τ^-
▪ electron-neutrino: ν_e	▪ muon-neutrino: ν_μ	▪ tau-neutrino: ν_τ
▪ up quark: u	▪ charm quark: c	▪ top quark: t
▪ down quark: d	▪ strange quark: s	▪ bottom quark: b

Cosmic microwave background (CMB)

- CMB has thermal spectrum $\Rightarrow$ Hot BB
- CMB has < 10^{-4} spectrum deviations $\Rightarrow$ no energy conversion after 1 year
- CMB roughly isotropic $\Rightarrow$ cosmic origin
  - Flatness problem, causality
- CMB dipole $\Rightarrow$ we're moving; explain that!
- CMB intrinsic anisotropy $\Rightarrow$ primordial density fluctuations from Sachs-Wolfe etc.
- CMB power spectrum and large scale clustering $\Rightarrow$ Λ CDM
- Polarization $\Rightarrow$ reionization epoch, optical depth


COBE in orbit,
1989-1994
FIRAS
DIRBE
Deployable Sun, Earth,
RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna


FIRAS Optical Path Diagram
Far Infrared Absolute Spectrophotometer
Sky
Movable Black Calibrator
Movable Mirror
John Mather, PI
Rick Shafer, DPI
Bob Maichle, IE
Mike Roberto, ISE
To Detectors
Beamsplitter
Reference Input Black Body
Movable Mirror
To Detectors
Michelson Interferometer (Nobel 1907)


Cosmic Background Spectrum at the North Galactic Pole
The smooth curve is the best fit blackbody spectrum
DATA WITH 1% ERROR BAR
Brightness (10⁻⁴ ergs/sec/cm²/steradian/cm⁻¹)
Frequency (cycles/centimeter)
NASA

Bose-Einstein Distribution - 1994

Energy release or conversion in the redshift range $10^5 < z < 3 \times 10^6$ produces a Bose-Einstein distribution, where the Planck law is modified by a dimensionless chemical potential μ (Zeldovich & Sunyaev 1970):

$$S_\mu(\nu;\, T,\, \mu) = \frac{2hc^2\nu^3}{e^{x+\mu} - 1}\,, \tag{4}$$

where $x = hc\nu/kT$, and ν is measured in cm^{-1}. The linearized deviation of S_μ from a blackbody is the derivative of equation (4) with respect to μ:

$$\frac{\partial S_\mu}{\partial \mu} = \frac{-T_0}{x}\,\frac{\partial B_\nu}{\partial T}\,. \tag{5}$$

The current FIRAS result is $\mu = -1 \pm 4 \times 10^{-5}$, or a 95% CL upper limit of $|\mu| < 9 \times 10^{-5}$. This result and

Compton Distortion - 1994

6.3. *Compton Distortion*

Energy release at later times, $z < 10^5$, produces a Comptonized spectrum, a mixture of blackbodies at a range of temperatures. In the case of nonrelativistic electron temperatures, this spectrum is described by the Kompaneets (1957) equation, parameterized by the value of y (Zeldovich & Sunyaev 1969):

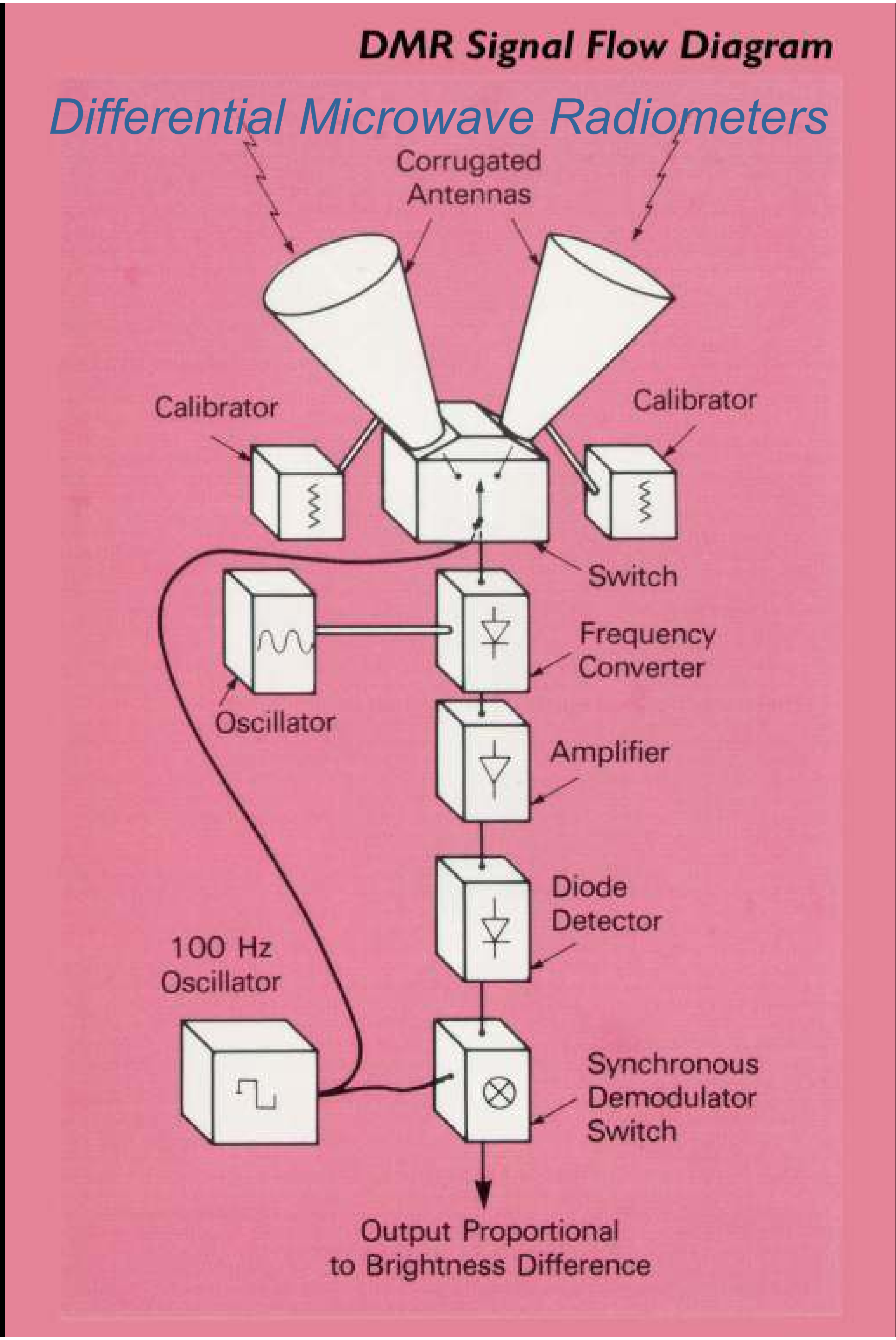
$$y = \int \frac{k(T_e - T_\gamma)}{m_e c^2} \, d\tau_e \, , \qquad (6)$$

where T_e, T_γ, and τ_e are the electron temperature, the CMBR photon temperature, and the optical depth to electron Compton scattering, respectively. The distortion will be of the form (Zeldovich & Sunyaev 1969)

$$\frac{\partial S_y}{\partial y} = T_0 \left[x \coth\left(\frac{x}{2}\right) \right] - 4 \, \frac{\partial B_\nu}{\partial T} \, . \qquad (7)$$

Typo!

The results are $y = -1 \pm 6 \times 10^{-6}$. There is some depen-



George Smoot

Chuck Bennett

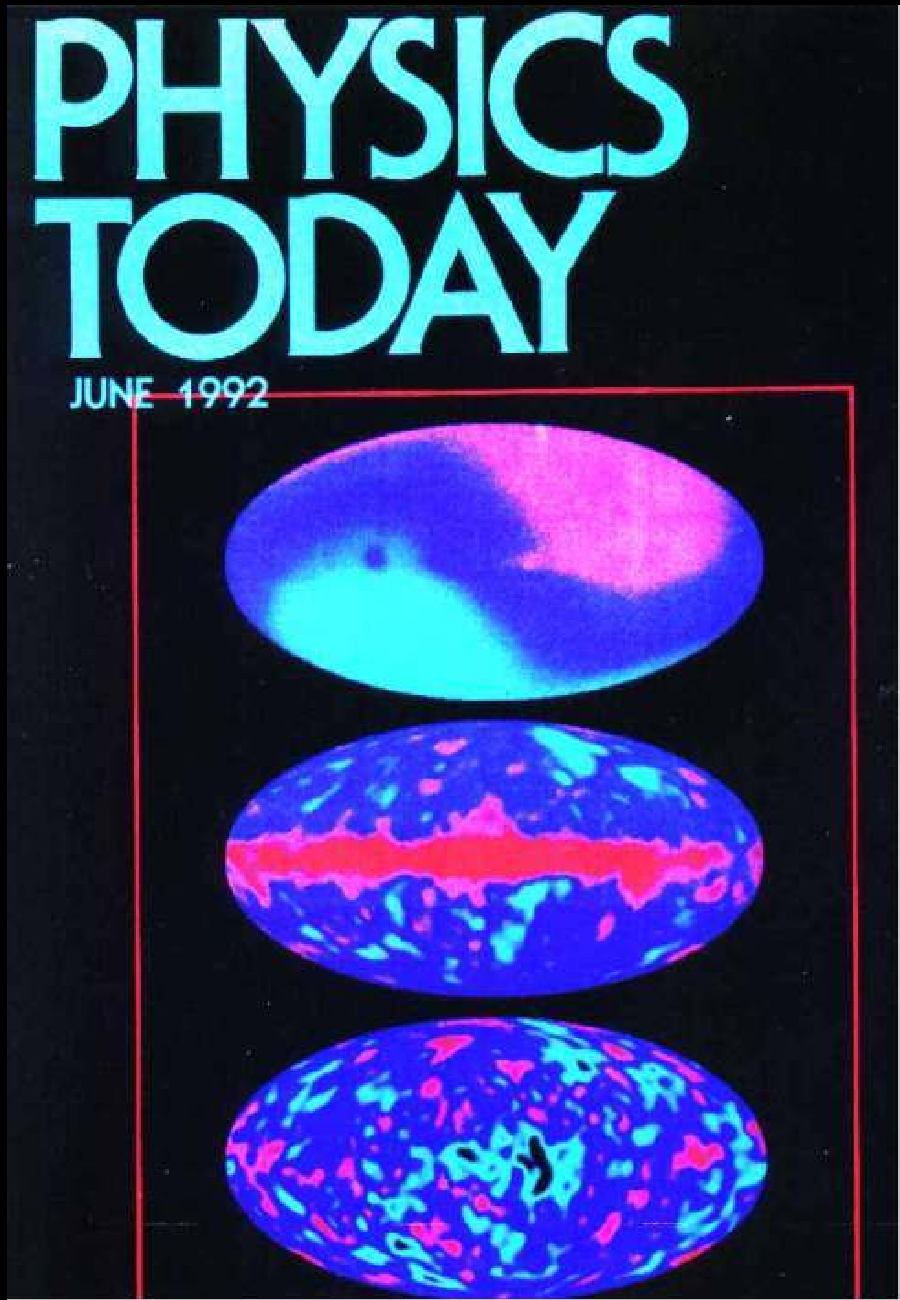
Bernie Klein

Steve Leete

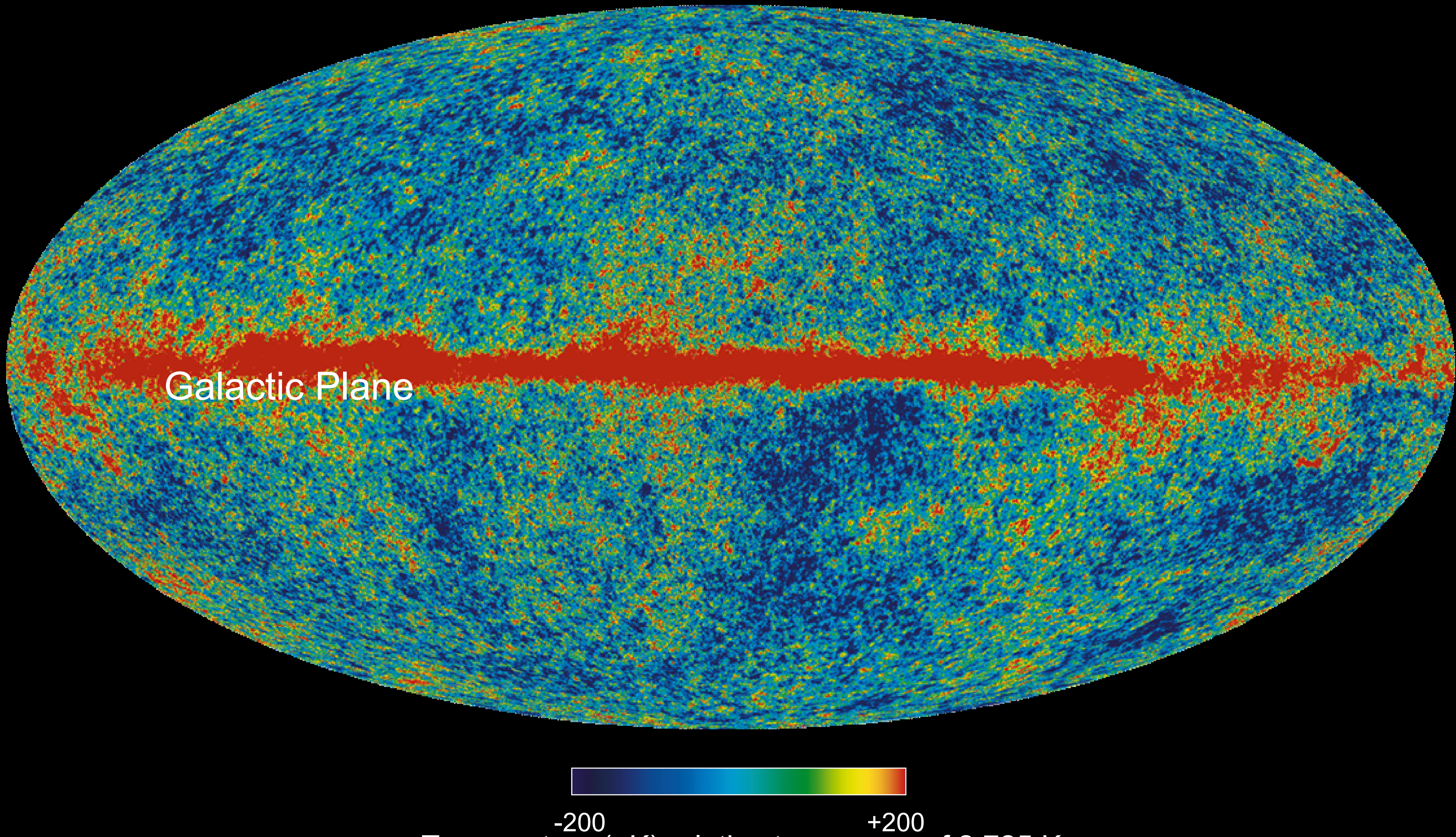
Sky map from DMR,
2.7 K +/- 0.003 K

Doppler Effect of Sun's motion removed (v/c = 0.001)

Cosmic temperature/density variations at 389,000 years, +/- 0.00003 K (part in 100,000)

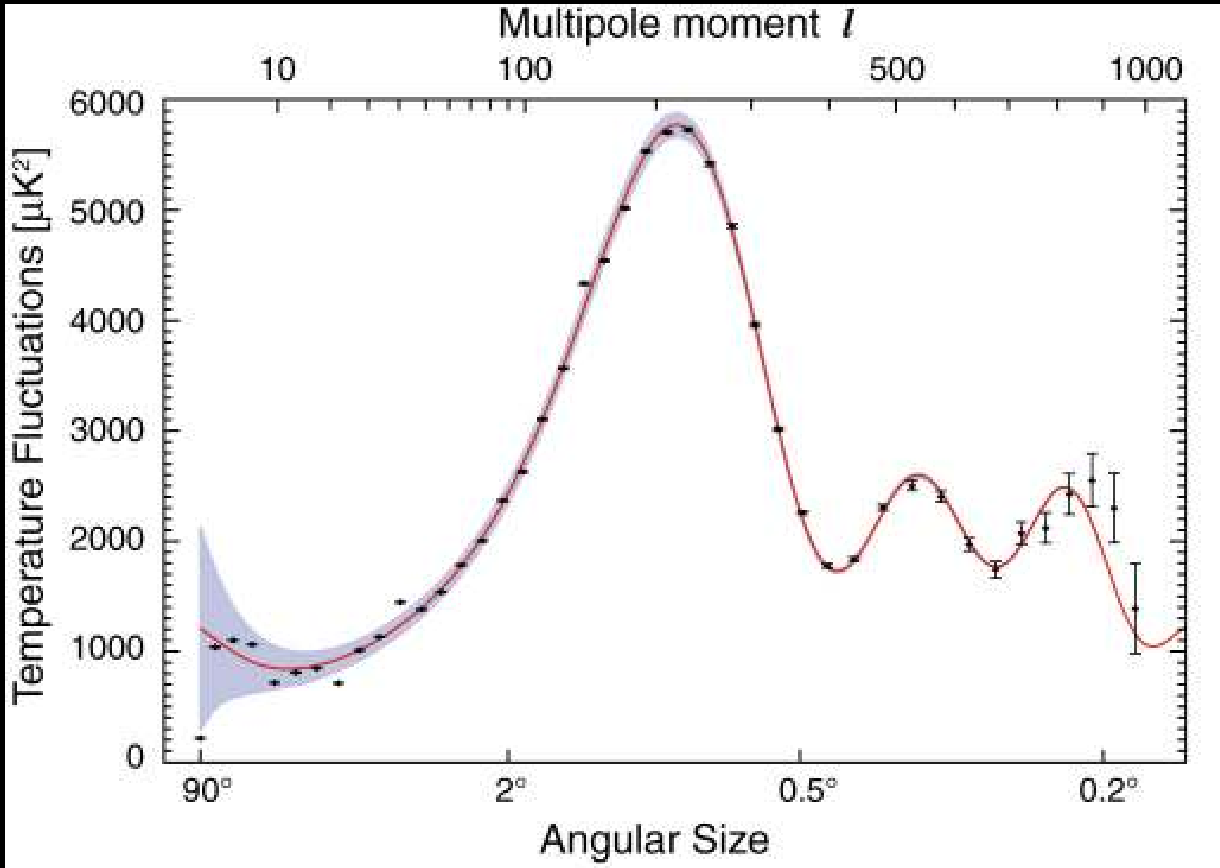


The Universe at age 389,000 years as seen by Wilkinson Microwave Anisotropy Probe (3 years of data)

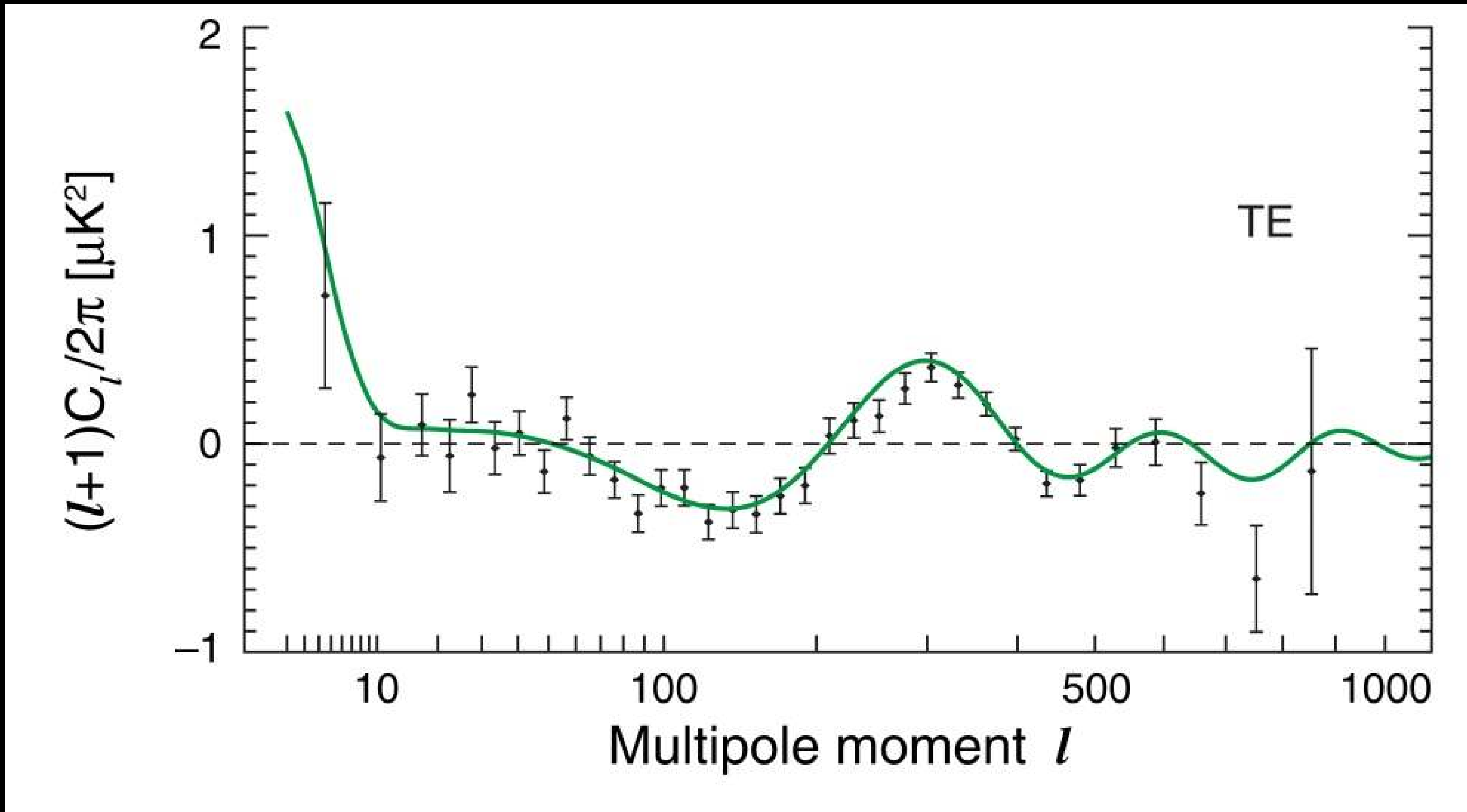


Temperature (μK) relative to average of 2.725 K

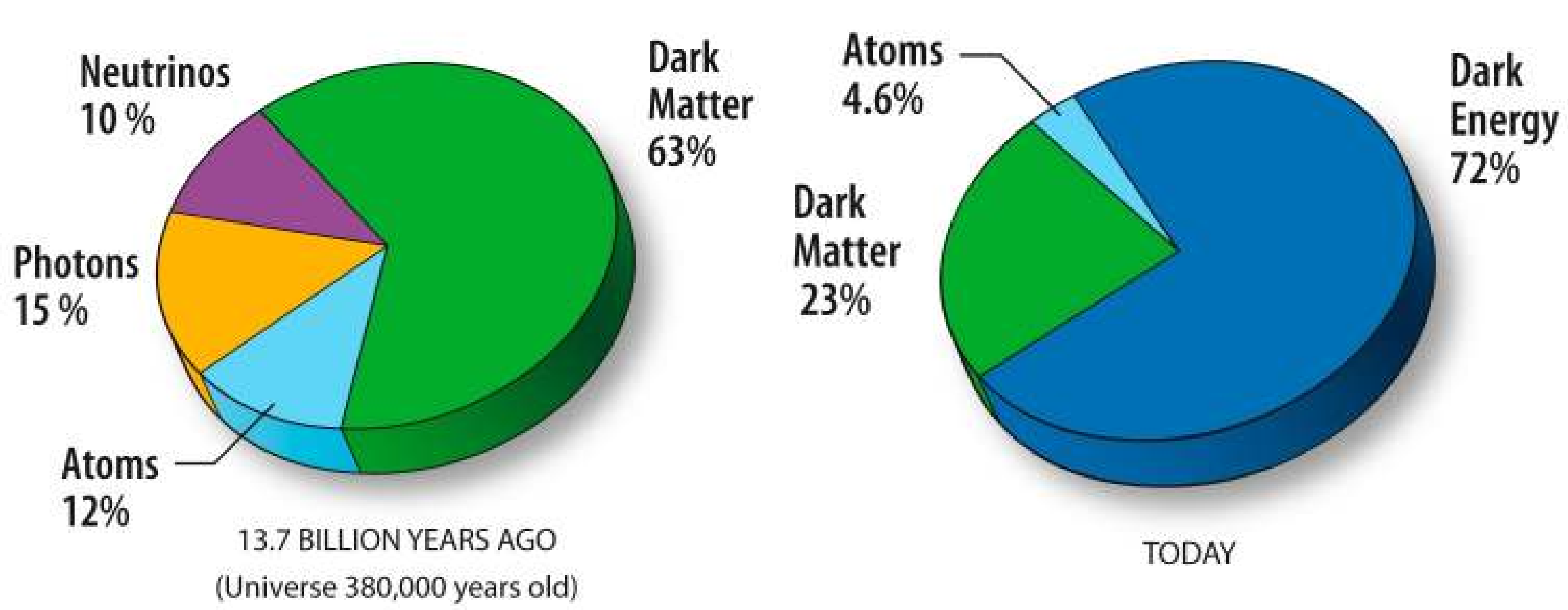
Power Spectrum



WMAP T-E correlation ⇒ τ



Changing Mix of Mysteries



- Photon and neutrino fractions diminish
- Dark Energy fraction grows with time

Distance scales $\Rightarrow$ Dark Energy

- Supernovae
  - Distance vs. redshift, acceleration
- Baryon Acoustic Oscillations
  - Horizon at decoupling $\Rightarrow$ natural ruler imprinted on CMB and galaxy distributions, observable vs. redshift
- Clustering versus redshift $\Rightarrow$ fit to theory
- Weak lensing $\Rightarrow$ mass distributions, mostly dark matter, versus time

Dark Matter evidence

- Galaxy clustering: Zwicky (1933)
- Galaxy rotation curves: Rubin et al. (1960's)
- Big Bang Nucleosynthesis (implies baryon number)
- Gravitational lensing, strong (multiple images) & weak (galaxy distortion)
- Very few dark point masses: nothing hiding (microlensing limits on MACHO's, massive compact halo objects)
- Baryonic inventory (stars, gas, hot IGM)
- X-ray temperatures of bound gas clouds $\Rightarrow$ potential well depth
- CMB power spectra $\Rightarrow$ fits to theory of structure
- Neutrino mass limits $\Rightarrow$ they're not the DM
- Lab searches $\Rightarrow$ what the DM is not

Galaxy properties

- Luminosity functions: how many of everything
- Shapes: irregular, spiral, elliptical (depends on wavelength, types of stars selected) ⇒ Hubble tuning fork diagram
- Correlations of shapes, spins, luminosities, etc. ⇒ phenomenological tests of theory
- Clustering ⇒ test of growth concepts
- Spectra: star classes, numbers ⇒ test of star formation history
- Dust blockage ⇒ test of details, very important to understanding structure
- Spin directions ⇒ test of exotic hypotheses of magnetic fields
- Presence of AGN, correlation of BH mass with bulge mass
- GRB's versus z
- Streams, tails, dynamical groups ⇒ history of merging
- Bulge, halo, thick, thin disks ⇒ history of formation
- Spiral arms and bars, velocity distributions ⇒ orbital dynamics

“Re”-ionization

- CMB polarization with WMAP
- Lyman alpha forest
- Gunn-Peterson test
- “Blue-dropout” galaxies
- Highest redshift galaxies, QSO’s: wide field surveys, selection criteria (colors, narrow band excess Ly alpha)

Major Theories

- Special Relativity: c = constant independent of observer motion
- Gravitation: GR from Equivalence Principle $\Rightarrow$ curved space-time
- Quantum mechanics: Fourier transforms, waves everywhere
- Particles: symmetries, classes, QED, QCD, standard model
- Inflation: scalar etc. fields in early Universe
- Big Bang Nucleosynthesis: detailed computations
- Decoupling - linear theory of perturbation growth
- Anthropic principle
- Complicated things - theory & simulations
  - Re-ioinization
  - Galaxies
  - Stars
  - AGN, GRB, black hole merging

Gravitation

- Newton, 1687: problem at infinity, but Birkhoff theorem, 1923 $\Rightarrow$ parallelism with GR, many useful approximations
- Einstein's GR, 1916, with/without Λ
  - Metric of homogeneous universe derivable from symmetry: Friedmann-Robertson-Walker
  - What's the source term $T_{\mu\nu}$? Vacuum energy? Was Albert right?
  - Parametrized post-Newtonian alternatives
  - Not renormalizable for quantum mechanics: QED approach doesn't work
- Kaluza-Klein theory, 1921: GR + EM in 5 dimensions (one compact)
- MOND, modified Newtonian dynamics
  - First order, e.g. Milgrom
  - Relativistic versions, e.g. Bekenstein
- Conformal, 4th order derivatives, L = (Weyl Tensor)^2, potentially renormalizable, e.g. Mannheim
- Etc. etc….

Quantum Mechanics

- Quantum Electrodynamics
- Quantum Chromodynamics
- Standard Model
- QM of isolated (closed) system (e.g. the Universe)
  - Not your grandfather's QM!
  - Decoherence
  - James Hartle, e.g.: http://arxiv.org/abs/gr-qc/9210006; or Murray Gell-Mann, or Bryce DeWitt

Quantum Gravity: “Theory of Everything”

- Kaluza-Klein theory: GR + EM, one compact dimension
- Renormalization problem: self-energy infinities, divergence at high E
- Effective field theory for low energies
- Hawking radiation
- Gravitons
- String theory (from quark confinement) $\Rightarrow$ gravitons
- Vacuum energy
- M-theory (branes)
- Supersymmetry
- The Universe in a Helium Droplet, Grigori Volovik, http://ltl.tkk.fi/wiki/images/b/bf/Volovik-book.pdf . Condensed matter shows amazing parallels to GR.

Inflation Theory: solve horizon, flatness, magnetic monopole problems

- A. Guth; Starobinsky. 1980.
- Precursors from Sato, Shafi, Kazanas
- Linde, Albrecht, Steinhardt…
- Many more…
- One (or more) scalar (& tensor?) fields
- Hypothetical Lagrangians…
- Symmetry breaking, false vacuum decays…
- Predict primordial gravitational waves?
- Possibility of multiple, self-reproducing universes

Big Bang Nucleosynthesis

- Alpher & Gamow, 1948
  - Neutron capture matches abundances of the elements
  - But, bottleneck: no stable isotope of M=5 or 8 $\Rightarrow$ No carbon, and only traces of D, He-3, Li-7
  - Heavier elements from stars: Burbidge, Burbidge, Fowler, & Hoyle, 1957 review paper
- Historical review:
  - http://arXiv.org/abs/astro-ph/9903300
- Results sensitive to baryon abundance, and number of neutrino types $\Rightarrow \Omega_b h^2 \sim 0.02$
- Tutorial by Ned Wright:
  - http://www.astro.ucla.edu/~wright/BBNS.html

Decoupling Physics: Amazing Agreement

- Moment of transparency: t = 380,000 years, z ~ 1000, T ~ 2700 K, from Saha equation (much colder than 13.6 eV because of low density)
- Multiple fluids: protons, alpha particles, electrons, photons, dark matter (cold? warm? hot?), neutrinos
- Are initial fluctuations adiabatic or isothermal?
- Approximately scale-invariant fluctuations from Big Bang
- Linear approximations: all perturbation amplitudes small
- Geometry of universe, including dark energy
- Causal propagation of information
  - Super-horizon issues?
- Sound waves: original music of the spheres
- Preferred scale: horizon size at decoupling
- Tiny spectrum deviations due to non-equilibrium
  - LiH, trapping of Lyman alpha (Sunyaev et al.)

Decoupling effects

- Rapid neutralization, few % of age
- Residual ionization, very small, per Saha equation, but delayed due to huge optical depths in lines
- Dark matter was free to move before baryon decoupling, modified primordial power spectrum
- Preferred spatial scale: horizon size at decoupling $\Rightarrow$ amplification, first acoustic peak, imprinted “rulers”
- Bounces $\Rightarrow$ harmonics
- “Silk” Damping $\Rightarrow$ reduced amplitudes of small scales relative to primordial level
- Quadrupole seen by electron at decoupling $\Rightarrow$ linear polarization seen now, possibility to detect B-mode due to primordial gravitational waves, tensor fields

Anthropic Principle

- Anti-Copernican principle
- Of all possible universes, if ours weren't like this, we wouldn't be here to notice
- We *are* in a special time and place in this universe: Earth is good, the Sun's still here, we had time for life to evolve, we didn't die off
- "If things had been different before, they would be different now"
- Limited predictive power (so far)
- Infinite discussion power

Complicated Things "Gastrophysics"

- Everything becomes nonlinear
  - Cf: Einstein - "Everything should be made as simple as possible, but not one bit simpler."
- Complexity grows from energy flows, not limited by 2nd law of Thermodynamics
- NEGATIVE SPECIFIC HEAT due to gravitation: take energy out, things go faster!!
- Simulation required
- Observation required
- Radically different phenomena as parameters change
- Occam's Razor is NOT a reliable guide
- If something is not forbidden, it is required (will occur somewhere)
- Applies to everything we see (except CMB?)
- Have fun!! This is astronomy!!

11 Big Questions

- Quarks to Cosmos report: http://www.nap.edu/catalog.php?record_id=10079
- What is dark matter?
- What is the nature of dark energy?
- How did the universe begin?
- Did Einstein have the last word on gravity?
- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?

11 Big Questions

- How do cosmic accelerators work, and what are they accelerating?
- Are protons unstable?
- What are the new states of matter at exceedingly high density and temperature?
- Are there additional space-time dimensions?
- How were the elements from iron to uranium made?
- Is a new theory of matter and light needed at the highest energies?

More pretty big questions

- How do black holes form, grow, merge, radiate, and end up in the centers of galaxies? Which comes first? How would we know?
- How do AGN work?
- How do GRB’s work?

First Stars

- What were they?
- What happened to them?
- How did they enrich the intergalactic medium?
- Did they suppress future star formation?
- Did they re-ionize the universe?
- Can we see them?

More pretty big questions

- Any problem with the cosmic structure? Are the voids empty enough?
- When we measure the dark energy versus time, what will we do then? No theories here…
- Is all the dark matter cold?
- When did the dust form?
- When could life form?
- Are we alone?

More pretty big questions

- Why are the CMB quadrupole and octupole so small, and seem non-random? Trans-horizon stuff? Universe topology?
- Intergalactic (or primordial) magnetic fields?
- Intergalactic stars?
- Dark matter in galaxies?
- Where are all the baryons?
- Neutrino mass?

More pretty big questions

- How do galaxies form?
- How does light get out of them?
- When do they get dusty?
- How does the IGM get enriched?
- What’s the history of the Milky Way?

Key online resources

- Ned Wright cosmology tutorial: http://www.astro.ucla.edu/~wright/cosmolog.htm
- Ned's list of other sites: http://www.astro.ucla.edu/~wright/cosmo_sites.html
- Wayne Hu home page: http://background.uchicago.edu/~whu/
- Wikipedia
- Scholarpedia

Some good books

- Modern Cosmology: Scott Dodelson
- The Extravagant Universe: Robert Kirshner
- The Cosmic Century: Malcolm Longair
- The Very First Light, John Mather & John Boslough, 1996, 2008 (September)
- Principles of Physical Cosmology: Jim Peebles
- Endless Universe: Paul Steinhardt
- Cosmology (no pictures); The First Three Minutes: Steven Weinberg
- Cosmic Catastrophes: J. Craig Wheeler