INDEX

Abell 2218, 294	Bessel function/equation, 196, 235,
Acceleration of scale factor, 151	237-238, 243, 346
Acoustic oscillations	spherical, 419–420
qualitatively, 217	Big Bang Nucleosynthesis (BBN), 9–12, 62
tightly coupled limit of Boltzmann	binding energy, 63–65
equations, 224–227	light element abundances, 68-70
tightly coupled solutions, 227–230	neutron abundance, 65–68
Adiabatic perturbations, 142	Big Bang versus Steady State universe, 14
Analysis techniques	Binding energy, 63–65
Fisher matrix, 366, 368–375	Boltzmann equations
likelihood function, 337–344, 356–367	
	for annihilation, 59–62
mapmaking and inversion, 375–378	for baryons, 106–109
signal covariance matrix, 344–356	for cold dark matter, 102–106
systematics, 378–387	collisionless, for photons, 87–95
Angular correlation function, 261, 262–270	for harmonic oscillator, 85–87
Angular diameter distance, 35	initial conditions, 139–140
Anisotropic stress, 124	for photons, 100–101
Anisotropies, 14	polarization and, 320–323
acoustic oscillations, 224–230	tightly coupled limit of, 224–227
anisotropy spectrum, current, 242–248	unintegrated, 84
cosmic variance, 239–242	Borrill, Julian, 336
cosmological parameters, 248–255	Bose-Einstein distributions, 38, 41, 89
diffusion damping, 230–233	Bose enhancement, 59
free streaming, 234–239	
inhomogeneities to, 234–242	Cartesian coordinate system, 28
integrated Sachs-Wolfe (ISW), 238, 244,	Christoffel symbol, 29–30
245-248	metric for, 24
large scale, 223–224, 242–245	CDM. See Cold dark matter
overview, 217–223	Cepheid variables, 9
Sachs-Wolfe (SW) effect, 242-245	Chemical equilibrium, 62
small scale, 245–248	Chopping angle, 348
Annihilation, Boltzmann equation for,	Christoffel symbols, 29–30, 32, 298
59–62	for scalar perturbations, 118–119
Antenna temperature, 379	for tensor perturbations, 125–126
Atomic number, 63	for Friedman-Robertson-Walker metric,
Automated Plate Measuring (APM)	130
Survey, 43, 262, 267–269	
Survey, 43, 202, 201 203	Closed universe, 2
D 1 1 070	CMB. See Cosmic microwave background
Backgrounds, 379	CMBFAST, 216
Bandpowers, 341	Cold dark matter (CDM), 18
Baryon density, 10, 41–42, 253–254	beyond, 207–211
Baryons, 62	Boltzmann equation for, 102–106
Boltzmann equation for, 106–109	evolution equations, 185–189
-photon fluid, 216, 223–233	gravitational instability, 180–182
transfer function and, 208–209	growth function, 205–207
BBKS (Bardeen, Bond, Kaiser, and Szalay)	horizon crossing, 192–199
transfer function, 204–205, 274	large scales, 189–194

Cold doub motter (CDM) (Continued)	Damen's s
Cold dark matter (CDM) (Continued)	Damping
numerical results and fits, 203–205	diffusion/of perturbations of small scales,
small scales, 194–203	230–233
stages of evolution, 182–185	term, 227
standard versus Lambda, 185	Dark energy, 4, 47–50, 122, 210–211
sub-horizon evolution, 199–203	Dark matter, 14, 73–78
super-horizon solution, 189–192	See also Cold dark matter (CDM)
transfer function, 183, 203–205, 268	Decomposition theorem, 131–132
Collapse fraction, 284–285	Decoupling of photons, 72
Collisionless Boltzmann equation for	Density correlation function, 273–274
photons, 87–95	Deuterium measurements, 10–12
Comoving distance, 2, 34	Diffusion damping, 230–233
Comoving horizon, 34, 143, 146–150	Dirac delta function, 16, 59, 263–266
Comoving Hubble radius, 146–150	Distant observer approximation, 279
Compton scattering, 70, 95–100, 234,	Distances, 33–37
310–311	Distortion of images, gravitational, 293–296
Conformal Newtonian gauge, 88, 132,	Distortion tensor, 293, 302–303
134–135, 170	Distribution function, 38–39
Conformal time, 34, 100, 123, 143	Divergenceless tensor, 125
Conservation law, 37–38	Doppler formula, standard, 7, 9
Continuity equation, 37	Ti
Convergence, 300	Einstein, A., 1, 4, 293
Cosmic microwave background (CMB), 4,	Einstein equations, 32–33
13-14	components of, 121–124
See also Anisotropies	decomposition theorem, 131–132
Fisher matrix, 368–370	initial conditions, 140–142
foregrounds, 378–384	perturbed Ricci tensor and scalar,
likelihood function, 340–343	117-120
mode subtraction/contamination,	tensor perturbations, 129–131
384–387	transforming from one gauge to another,
window functions, 345–350	132–135
Cosmic time, evolution of scale factor with, 2–4	Einstein tensor, 32
Cosmic variance, 239–242	Ellipticity as an estimator of shear, 300–302
Cosmic variance, 259–242 Cosmic velocity field, 44, 270–274	Energy, evolution of, 37–40 Energy density, 2–3
Cosmological constant, 4, 47	baryons, 10, 41–42
power spectrum and, 210–211	dark energy, 47–50
anisotropies and, 254–255	matter, 42–44
Cosmological parameters, 248	matter-radiation equality, 50–51
baryon density, 253–254	neutrinos, 44–47
cosmological constant, 254–255	photons, 40-41
curvature density, 249–251	radiation, 4, 38
matter density, 255	Energy-momentum tensor, 32, 37–40, 121
normalization, 251	energy density, 152
reionization, 253	homogeneous part, 152
tensor modes, 253	pressure, 152
tilt, primordial, 252	Entropy density, 40
Coulomb scattering, 70	Euler equation, 37
Covariant derivative, 37	Expanding universe, 1–7
Cramer-Rao inequality, 367	See also Smooth expanding universe
Critical density, 3	Expansion rate, 4–5
numerical value for, 6	
Curvature density, 249–251	False vacuum, 152–154
Curvature of likelihood function, 365	Fermi-Dirac distributions, 38–39
Curvature perturbations, 170	Feynman rules, 97
Sarrata Porturbutotto, 110	20,

First-order perturbation equation, 94-95, Harrison-Zel'dovich-Peebles spectrum, 171, 104 185, 244-245, 421 Fisher matrix, 366 Heisenberg's principle, 38 CMB, 368-370 Higgs field, 152 forecasting, 371-375 Horizon crossing galaxy surveys, 370-371 large scales, 192-194 Flat universe, 2, 4 small scales, 195–199 age of, 5 Hubble constant, 8 evidence for, 249-251 Hubble diagram, 7-9 Flux, measuring, 35-36 Hubble rate, defined, 3, 5 Forecasting, 371–375 Hubble radius, 123 Foreground degradation factor (FDF), 383 comoving, 146-150 Foregrounds, 378–384 Fourier transform, 15, 100-101, 262-263, Indices, 27 420 Inflation, theory of, 18, 144 Free electron fraction, 70–71 negative pressure, 151 Free streaming, 234-239 origin of term, 147 Freeze-out, 74-75 scalar field and, 145 Friedmann equation, 3, 33 scalar field implementation, 151-155 Friedmann-Robertson-Walker (FRW) solution to horizon problem, 146-150 metric, 24, 26, 30, 89 Inhomogeneities to anisotropies, 234-242 Galaxy clusters, 282-287 beyond cold dark matter, 207-211 Galaxy power spectrum, 272 cosmic variance, 239-242 Galaxy surveys, 43, 261–263 evolution equations, 185-189 Fisher matrix, 370–371 free streaming, 234-239 likelihood function, 343-344 gravitational instability, 180-182 window functions, 350-354 growth function, 205-207 Gauges, 88 horizon crossing, 192-199 invariant variables, 134, 162, 169-170 large scales, 189-194 transforming from one to another, numerical results and fits, 203-205 132 - 135small scales, 194-203 Gaussian beam, 347-350 stages of evolution, 182-185 Gaussianity, 161 sub-horizon evolution, 199-203 General relativity, 23 super-horizon solution, 189-192 Einstein equations, 32-33 transfer function, 183, 203-205 geodesic equation, 28-31 Inhomogeneities, probes of metric, 24-27 angular correlations, 261-270 Geodesic equation, 28–31 galaxy clusters, 282-287 shear and, 296-300 Geometry, 2 peculiar velocities, 261-262, 270-271 peculiar velocities, direct measurements Grand Unified Theories, 145 Gravitational distortion of images, 293–296 of, 271-275 Gravitational instability, 180-182 redshift space distortions, 275-282 Initial conditions Gravity, metrics and, 25 Gravity waves, 130-131 comoving horizon, 143-144 detecting, 326-329 determining causes, 142-144 production, 155-162 Einstein-Boltzmann equations, 139-142 Green's function, 198, 227 gravity wave production, 155-162 Growth function, 171-172, 183, 205-207 inflation, 144-155 scalar perturbations, 162-170 Harmonic oscillator Integrated Sachs-Wolfe (ISW), 238, Boltzmann equation for, 85-87 244 - 248quantizing, 156-157 Invariant distance, 24 Harmonics, spherical, 418–419 Isocurvature perturbations, 142

Jacobian, 278

Karhunen-Loève method, 356–362 Kernel, of the angular correlation function, 266 Kinetic agailibrium, 60

Kinetic equilibrium, 60

Kronecker delta, 27

Lambda Cold Dark Matter (Λ CDM), 185 Large-scale anisotropies, 223–224, 242–245 Large scales, inhomogeneities, 189–194 Legendre polynomials, 110, 225, 234–235, 265, 280, 346, 418

Light element abundances, 9–10, 68–70 Lightest supersymmetric partner (LSP), 77–78

Likelihood function CMB, 340–343 curvature of, 365 galaxy surveys, 343–344 simple example, 337–340

Likelihood function, estimating the Karhunen-Loève method, 356–362 quadratic estimator, 362–367 Linear growth rate dimensionless, 270 Luminosity distance, 9, 36–37

Mapmaking and inversion, 375–378 Marginalizing, 374–375

Mass

determination for clusters, 285–286 gravitational distortion of images, 293–296

Massive compact halo objects (MACHOs), 294

294
Massless particle, geodesic equation and, 31
Mass-to-light ratios, 42
Matrices, writing of, 27
Matter density, 42–44, 255

Matter-radiation equality, 50–51

Maxwell-Boltzmann distribution, 87

Meszaros equation, 201–203

Matter power spectrum, 272

Metric, 24–27, 87, 151 Microlensing, 294

Microfensing, 294

Minkowski space-time, 25-26

Mode subtraction/contamination, 384–387 MSAM experiment, beam pattern for, 345

Negative pressure, 151
Neumann function, 196
Neutrinos, 44–47, 62
transfer function and massive, 209–210
Neutron abundance, 65–68

Newton-Raphson method, 363–365

Newton's constant, 3, 6, 32 Newton's equation, for oscillator motion, 86 Newton's law, generalization of, 28 Nonrelativistic Compton scattering, 96 Nonrelativistic matter, 3 energy density of, 4, 42–44 Nonrelativistic particles, 62 Normalization, anisotropy spectrum, 251

Nuclear statistical equilibrium (NSE), 62

One-point function, 282 Open universe, 2, 249–251 Overdots, use of, 30, 100

Pauli blocking, 59, 95
Peculiar velocities, 261–262, 270–271
direct measurements of, 271–275
Pencil beam survey, 353–354
Phase space elements, number of, 38
Photons, 40–41, 62
See also Anisotropies
Boltzmann equation for, 100–101
collisionless Boltzmann equation for, 87–95

decoupling of, 72 effects of Compton scattering, 95–100

Physical constants, 415–416

Physical distance, 34

Plane wave, polarization from a single, 313–320

Poisson's equation, 184 Polar coordinates, 24, 28 Polarization

Boltzmann equation, 320–323 power spectra, 323–326 quadrupole and the Q/U decomposition, 310–313

from a single plane wave, 313–320

Positive curvature, 2

Positrons, 62

Power spectrum, 16, 159, 183–185 matter versus galaxy, 272

polarization, 323–326 weak lensing, 302–310

Press-Schechter formalism, 283–287

Projection operator, 123, 131

Proper time, 25

Python experiment, 360-362

Quadratic estimator, 362–367 Quadrupole moments, 300 Q/U decomposition, 310–313 Quintessence, 47

Radiation, 2

Rayleigh-Jeans limit, 381–382 general relativity, 23-33 Recombination, 70–73 Sound horizon, 228 Reddening correction, 385 Space-time dimensions, 25-26 Redshift space distortions, 275–282 Spatially flat slicing, 132, 162, 169-170 Redshift surveys, problems with, 261 Species-dependent equilibrium number Redshift z, 7–9 density, 61 Reionization, 253 Spherical Bessel functions, 419-420 Relativistic particles Spherical harmonics, 239-240, 418-419 decoupled, 62 Standard candle, 8-9, 48 in equilibrium, 62 Standard Cold Dark Matter (sCDM), 185, Relativity, theory of, 1 197, 267 Riccati equation, 75 Standard Model, going beyond the, 14-19 Ricci scalar, 32–33, 117 Steady State universe, Big Bang versus, 14 finding, 120 Stimulated emission, 95 Ricci tensor, 32, 117 Sub-horizon evolution, 199-203 for scalar perturbations, 119-120 Sunvaev-Zeldovich distortion, 285 for tensor perturbations, 127-129 Super-horizon perturbations, 164-168 Riemann zeta function, 421 Super-horizon solution, 189-192, 223 Supersymmetry, 77 Sachs-Wolfe (SW) effect, 242-245, 421 Symbols, list of, 422-425 integrated (ISW), 238, 244-248 Synchronous gauge, 88, 132 Saha equation, 62, 71 Systematic errors Scalar field, inflation and, 145, 151-155 foregrounds, 378-384 Scalar perturbations, 88 mode subtraction, 384-387 Christoffel symbols for, 118–119 decomposition theorem, 131-132 Temperature, 4 gauges, 132-135 antenna, 379 inflation, 162-170 thermodynamic, 381 Ricci tensor for, 119-120 Tensor modes, 253 around smooth background, 162-164 Tensor perturbations, 88, 124 spatially flat slicing, 132, 162, 169-170 Christoffel symbols for, 125-126 super-horizon, 164-168 decomposition theorem, 131-132 Scale factor Einstein equations for, 129-131 defined, 2 gauges, 132-135 evolution of, with cosmic time, 2-4 inflation, 157-162 rates as a function of, 6-7 quantizing the harmonic oscillator, Scale-free spectrum, 171 158 - 162Scale-invariant spectrum, 171 Ricci tensor for, 127-129 Semianalytic techniques, 283 Thermodynamic temperature, 381 Shear Tightly coupled limit of Boltzmann ellipticity as an estimator of, 300-302 equations, 224–227 geodesic equation and, 296-300 Tightly coupled solutions, 227–230 Signal covariance matrix, 344 Tilt, primordial, 252 CMB window functions, 345–350 Tracelessness, 125 galaxy survey window functions, 350-354 Transfer function, 183, 203–205, 268 summary, 354-356 baryons and, 208-209 Sloan Digital Sky Survey (SDSS), 14, 43, cosmological constant and, 210-211 266, 336 massive neutrinos and, 209-210 Slow roll models, 154–155, 172 Transformation matrix, 28–29 Small scale anisotropies, 245–248 Two Degree Field Galaxy Redshift Survey, Small scale inhomogeneities, 194-203 14, 43-44, 336 Smooth expanding universe Two-point function, 16, 272, 303 cosmic inventory, 40-51 distances, 33-37

Underdensity, 219

evolution of energy, 37-40

Variable cosmological constant, 47 Variable Lambda, 47 Vector perturbations, 88, 125 Vectors, 24 Velocity correlation function, 272–273 Visibility function, 72, 233, 236–237 Volume limited survey, 351–353

Weak lensing, 286
ellipticity as an estimator of shear,
300–302
gravitational distortion of images,
293–296
power spectrum, 302–310

Weakly interacting massive particle (WIMP), 73–74
Window functions
CMB, 345–350
galaxy survey, 350–354
WKB approximation, 227

X-ray temperatures, 285

Zero-order distribution function, 89, 103 Zero-order equation, 93–94