

## Index

- 4-vectors, 255, 685
- $\sigma_0$ , density parameter, 109, 114
- $\Omega$ -parameters, 109
  - evolution, 136
- $\chi^2$ 
  - and likelihood, 576
  - least squares, 568
- $\square$ , 275
- $\sigma_8$ , linear power spectrum amplitude, 641
- $\zeta(x)$  Riemann  $\zeta$ -function, 165, 454
- $q_0$ , 112, 115
- $t_{\text{eq}}$  time of matter-radiation equality, 143
- $y$  Sunyaev–Zel'dovich  $y$ -parameter, 470
- iid, independent and identically distributed, 547, 548, 692
- $z_{\text{eq}}$  redshift of matter-radiation equality, 143
- abundances
  - light elements, 182
- acceleration, 417
- affine parameters, 324
- age
  - cosmic, 433
  - look-back time, 139, 140
  - Universe, 38, 118, 120, 139
- Ames, Adelaide, 15
- anisotropies
  - large angular scales, 62
- anisotropy, 516
- annihilation
  - electron–positron, 172
- antimatter cosmology, 27
- Arago, François, 493
- atlases, maps, charts, 312
- averaging
  - Einstein field equations, 406
- back reaction, 405, 407
- BAO, 187, 202, 203, 662, 665
  - cosmology, 667
  - dark energy, 668
- Hubble parameter, 667
- observations, 665
- Baryonic Acoustic Oscillation, *see* BAO
- Bayes factor, 587
- Bayes theorem, 582
- Bayes, Thomas, 583
- Bayesian inference, 582
  - basics, 591
  - classifying priors, 596
  - comparing hypotheses, 586
  - empirical, 599
  - hierarchical Bayes, 601
  - hyper-parameters, 600
  - marginalising parameters, 598
  - mixed priors, 595, 600
  - multiple parameters, 589
  - priors, 584, 593
  - triplet, 594
- Bayesian statistics, 542
- Belinfante–Rosenfeld tensor, 279
- benchmark model, 130
- Berry step surface, 192
- Besso
  - Michele, 292, 342
- Bianchi I model, 363
  - Christoffel symbols, 363
- Bianchi identities, 335, 336, 338
- Big Bang theory, 3, 16, 27
- Birkhoff theorem, 372
- black hole mergers, 94
- blue sky, 505
- Boltzmann equation, 67
- Bose–Einstein distribution, 474
- Brans–Dicke theory, 344
- C-field, 29
- Cambridge 2C,3C survey, 33, 34
- catalogues
  - galaxy, 80
  - HMS, 16, 41
  - Messier, 5

- CDM, 45
- Cepheid variables, 84
- Christoffel connection, 311
  - 3-space, 415
- Christoffel symbol
  - diagonal metric, 361
  - first kind, 319
  - quick calculation, 361
  - second kind, 320
  - trace, 320
- Christoffel symbols, 319
  - static weak field, 395
- Bianchi I, 363
- diagonal metric, 361
- Robertson–Walker, 368
- spherical symmetry, 370
- CMB, 451
  - $y$ -parameter, 470
  - aftermath, 77
  - anisotropy, 516
  - anisotropy measurements, 63
  - antenna temperature, 456
  - black-body intensity, 455
  - Bremssstrahlung, 459, 469
  - Compton cooling, 466
  - Compton wavelength, 502
  - conservation of energy, 461
  - data processing, 606
  - dipole component, 62
  - dipole source, 65
  - discovery, 16, 48, 52
  - double Compton scattering, 468
  - electron–photon scattering, 463
  - equilibrium photon gas, 457
  - fireball phase, 459
  - free-free, 469
  - impact, 77
  - maps and correlations, 609
  - mass energy density, 462
  - non-cosmological origin, 58
  - photoionisation, 479
  - Planck distribution, 453
  - Planck law, 452, 456, 461
  - polarisation, 491
  - power spectrum, 529
  - power spectrum peaks, 73
  - quadrupole component, 62
  - radiation drag, 465
  - radiation energy density, 455
  - radiative recombination, 479
  - Rayleigh scattering, 495, 502
  - Rayleigh–Jeans law, 456
  - re-ionisation, 488
  - recombination, 476, 482
  - relativistic gas dynamics, 461
  - renaissance in cosmology, 48
  - Saha formula, 477
  - sky maps, 69
  - specific heat, 462
  - spectral distortions, 473
  - spectral radiation intensity, 452
  - temperatures, 456
  - the Eddington limit, 466
  - Thomson cross-section, 500
  - Thomson scattering, 459, 464, 468, 485, 495, 499, 505
  - visibility function, 488
  - Wein law, 456
  - CMB anisotropies
    - benchmark parameters, 640
    - cosmic signature, 66
    - curvature of Universe, 643
    - derived parameters, 642
    - evidence for dark matter, 68
    - history, 61
    - Hubble constant, 642
    - internal parameters, 643
    - models fitting, 643
    - power spectrum, 66
      - damping tail, 638
      - features, 636
      - peaks, 636
  - CMB experiments
    - history, 635
  - COBE, 85
  - COBE satellite, 69, 70
  - comoving coordinates, 364
  - conformal
    - time, 126
  - conformal tensor,  $C_{abcd}$ , 339
  - conformal transformation
    - Robertson–Walker, 391
  - congruences, 412
  - connection, 317
  - conservation laws, 275
  - contravariant representation, 314
  - coordinate systems, 238
  - coordinates
    - co-moving, 387
    - conventions, 248
    - hyper-spherical, 388
    - isotropic, 388
    - light-cone, null, 260
    - Newtonian, 99
    - non-orthogonal, 249
    - normal, 321
  - correlation function
    - sphere, 698
  - cosmic eras, 159
  - cosmic evolution, 35
  - cosmic expansion, 656
    - discovery, 9

- cosmic microwave background radiation - see CMB, 451  
cosmic periods, 159  
  speculative, 159  
cosmic structure, 81  
  formation, 66  
cosmic web, 82  
cosmological constant, 20, 43, 44, 144, 349  
  Friedmann equations, 369  
cosmological models, 19  
  de Sitter, 376  
  de Sitter static, 20  
  Einstein de Sitter, 21  
  Einstein static, 20, 375  
  FLRW, 10  
  geometry, 411  
  Milne, 21, 23  
  Newtonian, 97  
cosmological parameters, 114, 634  
  benchmark model, 640  
  non-CMB determination, 638  
cosmology  
  model, 79  
  numerical, 78  
covariant derivative, 317, 327  
covariant representation, 314  
curvature  
  extrinsic and intrinsic, 423  
  fine tuning, 136  
  Gaussian, 424, 426  
  intrinsic and extrinsic, 306  
  length scale, 111  
curvature scalar, 338  
curvature tensor  
  extrinsic, 425  
curves, integral, 412  
  
dark energy, 30, 44, 68, 86, 130, 132, 144, 350, 641,  
  643, 646, 657  
BAO, 668  
  quintessence, 215  
dark matter, 45, 86  
data models, 628  
  Gaussian, 629  
data processing, 606  
  cleaning, 610  
  COBE, 607  
  data acquisition, 610  
  foreground separation, 611  
  Planck, 607  
  WMAP, 607  
data reconstruction, 613, 619  
  additional constraints, 623  
  cleaning, 613  
  HEALPix, 615  
  least squares, 631  
  MAP, 628, 630  
model fitting, 532  
SMICA, 614  
spatial Weiner filter, 632  
with noise, 622  
without noise, 621  
data regularisation, 626  
statistical, 628  
  Tikhonov, 626  
de Rham wave operator, 353  
de Sitter effect, 12, 20, 379  
de Sitter, Willem, 10  
deceleration parameter, 51  
density fields  
  random, 190  
derivative  
  covariant, 317  
  Lie, 317  
deuterium, 38, 50  
dissipative processes, 285  
distance  
  angular diameter, 440  
  comoving, 437  
  concept, 24  
  cosmic, 434  
  instantaneous physical, 436  
  luminosity, 444  
  modulus, 113  
  proper, 125, 245, 389  
  standard ruler, 444  
distribution  
  Dirichlet, 601  
  exponential, 692  
  Fermi–Dirac, 164  
  gamma, 693  
  Poisson, 692  
distributions  
   $\chi^2$ , 694  
distributions, statistical, 691  
DMR, 72  
Doppler effect, 24, 61, 244  
  
Eddington, Arthur, 12, 21  
Einstein equations  
  classic solutions, 373  
  de Sitter solution, 381  
  higher dimensional spaces, 381  
  Robertson–Walker, 386  
  Schwarzschild solution, 382  
  solutions, 358  
  weak field, 400  
Einstein field equations, 98, 340  
Einstein tensor  $G_{ab}$ , 338, 341, 358  
  spherical symmetry, 371  
Einstein Universe, 44  
Einstein, Albert, 10, 291  
Einstein–Besso correspondence, 342  
Einstein–Hilbert action, 354

- electrodynamics, 261
- electromagnetic field
  - energy momentum tensor, 689
  - Faraday tensor, 686
  - Lagrangian, 688
  - potentials, 686
- electromagnetic field tensor, *see* Faraday tensor
- electromagnetic potential
  - curved spacetime, 352
- electromagnetism, 685
- energy–momentum tensor, 268, 276, 341, 350
  - canonical, 275
  - electromagnetic field, 266
  - fluids, 281
  - physics, 281
- entropy
  - equation, 167
  - flux (classical), 287
  - gravitational, 170
  - Müller–Israel–Stewart, 170
- Entwurf theory of gravitation, 291
- equation
  - energy, 145
  - Friedmann, 147
- equation of state, 123
- evidence for dark matter
  - CMB anisotropies, 68
- expansion
  - accelerated, 220
  - exponential, 215
  - isentropic, 168
- expansion factor, 104
- expansion law, 24
- expansion rate, 136, 418
- expansion, cosmic, 11
- Føllesdal, Dagfinn, 585
- factor ordering, 353
- Faraday tensor, 263, 353
- fermions
  - cosmic, 163
- field
  - electromagnetic, 278
  - scalar, 276
- field equations, 97
- fine tuning problem, 214
- FIRAS, 71
- fireball, 55
- first Cambridge catalogue, 31
- Fisher information matrix, 560
  - multivariate, 554
  - univariate, 554
- flatness problem, 149, 213
- fluid approximation, 282
- Fourier modes, 192
- free particle motion, 323
- freeze-out temperature, 176, 178
- frequentist statistics, 544
- Friedmann equations, 367
- Friedmann, Alexander, 10, 21
- galaxy
  - clusters, 88
  - rotation curves, 82, 87
- galaxy clustering, 44
- galaxy correlation function, 663
- galaxy evolution, 43
- galaxy formation, 79
- gambler's odds, 585
- gamma-ray bursts, 658
  - spectra, 661
- Gamow, George, 17, 49
- gauge
  - de Donder condition, 397
  - longitudinal, Newtonian, conformal, 408
  - Lorenz, 263, 686
  - transverse traceless, 400
- gauge transformations, 397
- Gauss–Codacci equations, 426
- Gaussian random field, 191
- general relativity, 19, 290
  - action principles, 354
  - cosmology, 9, 16
  - scalar fields, 355
  - solar system orbits, 343
- general relativity test
  - asteroids, 345
- general relativity tests
  - GPS systems, 348
  - gravitational redshift, 347
  - perihelion of Mercury, 342
  - post-Newtonian gravitation, 348
  - solar eclipse 1919, 346
- geodesic, 271
  - deviation, 329
  - timelike, 328
- geodesic deviation, 337
- geodesics, 312, 323
  - null, 326
  - variational approach, 271
- geodesics, timelike, 325
- geometrodynamics, 298, 342
- geometry
  - Euclidean, 299
  - non-Euclidean, 301
  - space-time, 299
- gravitation
  - weak, 394
- gravitation theory, 293
- gravitational instability, 187
- gravitational lensing, 83
- gravitational waves, 86, 400
  - detection, 88
- FLRW background, 405

- history, 89
- Joe Weber, 89
- Minkowski space, 399
- polarisations, 401
- tensor to scalar ratio, 223
- gravity
  - Einstein's, 101
  - Newtonian, 100
- Great Schism, 541
- Grossman, Marcel, 291
- growth factor, 196
- GUT, 211
- hadron period, 161
- Harrison–Zel'dovich spectrum, 216
- heavy elements, 38
- helium, 50
  - production, 178
- Herschel, William, 5
- Hessian matrix, 550
- Hilbert, David, 292
- histograms
  - $\chi^2$ , 581
  - normal approximation, 580
  - Poisson approximation, 580
- history
  - 1945–1995, 19
  - emerging relativity, 19
- Holmberg radius, 87
- horizon
  - event, 128
  - inflation, 227, 230
  - particle, 127
- horizon problem, 212
- Hubble constant, 43, 51, 110, 112
- Hubble diagram, 13, 112
  - galaxy evolution, 41
- Hubble parameter, 435, 667
- Hubble space telescope, 84
- Hubble, Edwin, 7, 9, 13
- Humason, Milton, 12, 14, 16
- hypothesis testing, 574, 591
  - confidence intervals, 571
  - estimation, 570
  - Fisher Z-transform, 577
  - frequentist, 567
  - least squares, 568
  - loss function, 570
  - $p$ -value, 571
  - risk, 571
- indices, up & down, 313
- inertial frame, 240
- inference
  - Bayesian, 582
- inflation, 79, 208
  - chaotic, 224
- large field, 224
- new, 212
- perturbations, 229
- scalar, tensor modes, 228
- small field, 225
- tests, 223
- inflaton field, 215, 217, 218
- information
  - Fisher, 554
  - score, 555
  - two dimensions, 557
- inhomogeneities
  - primordial, 57
- inhomogeneous models
  - $\Lambda$ CDM, 198
  - averages, 405
  - evolution, 187
  - growing and oscillatory solutions, 201
  - growth factor, 198
  - growth rate, 196
  - growth rate alternative formulations, 198
  - growth rate approximations, 198
  - predictions, 189
  - zero pressure, 196
- inverse square law
  - modifications, 101
- James–Stein estimator, 565
- Jeans length, 199, 201
- Kasner Universe, 367
- Killing vector, 334
- Klein–Gordon equation, 277, 355
- Kompaneets equation, 467
- Kretschmann scalar, 338
- Lagrange field equations, 273
- Lagrangian
  - relativistic motion, 270
- Lagrangian coordinates, 195
- Lagrangians, 276
- Larmor's power equation, 496
- Larmor, Joseph, 496
- Leavitt, Henrietta, 7, 8
- Lemaître, Georges, 10, 21
- lepton period, 162
- Lie derivative, 332
- light
  - background, 58
  - propagation, 103
- light-cone, 125
- light propagation, 428
  - curved space, 433
  - redshift, 375
- LIGO, *see* gravitational waves, 401
- likelihood, 547
  - conditional, 552

- exponential process, 545
- formal definition, 547
- histograms, 578
- information, 553
- invariance, 552
- marginal, 552
- marginalised, 598
- maximum, 549
- maximum likelihood, 559
- maximum likelihood linear regression, 560
- model, 541
- multivariate Gaussian, 562
- ratio, 591
- relationship to  $\chi^2$ , 576
- likelihood estimation, 603
- line element
  - Minkowski, 246
- linear regression, 567
- local group, 61, 65
  - motion, 65
- Lorentz force, 261
- Lorentz group, 255
- Lorentz invariance, 244, 288
- Lorentz transformation
  - addition of velocities, 254
  - space-time interval, 254
- Lundmark, Knut, 12
- Mach's principle, 297
  - CMB, 61
- magnitude, 113
  - absolute, 113
- matrix notation, 247
- Maxwell equations, 261, 494
  - systems of units, 676
- Maxwell, James, 494
- metric
  - diagonal, 361
  - signature, 249
  - spherical symmetry, 369
  - static spherically symmetric, 371
  - static weak field, 394
- metric tensor, 304
- Milky Way, 6
- Minkowski space, 237, 246
  - coordinates, 359
  - metric, 259
  - particle dynamics, 257
  - Rindler coordinates, 360
- N-body simulations, 80
- nebulae, 5, 6
- neutrino cosmology, 182
- neutron decay, 176
- Newtonian gravity, 325
  - anomalies, 100
- Newtonian models
- as GR surrogates, 102
- cosmological constant, 140
- dark energy, 130
- dust, 105
- Einstein de Sitter, 117
- inflation, 208, 215, 216
- light propagation, 125
- relativistic surrogate, 121, 122
- two components, 150
- with pressure, 121
- with radiation, 123
- zero pressure, 130
- Newtonian theory
  - limitations, 237
- Noether's theorem, 219
- Noether, Emmy, 275
- Nordström's gravity theory, 350
- normal distribution
  - multivariate, 562
  - univariate, 558, 691
- nuclear physics, 26
- nuclear processes, 174
- nuclear reactions, 179
- nucleosynthesis, 17, 37, 39, 50, 55, 79, 154, 177
- nuisance parameter, 552
- parallel transport, 317, 328
- parameter
  - acceleration, 114
  - deceleration, 137
  - density, 109, 114, 132, 135
  - Hubble, 114
- particle physics, 155
  - color, 161
- peculiar velocity, 25
- perfect cosmological principle, 29
- perfect fluid, 283
- perturbations
  - adiabatic, 199
  - averaging, 405
  - Fourier modes, 192
  - Fourier representation, 192
  - gas pressure, 199
  - Gaussian random field, 191
  - horizon, 227
  - inflation, 229
  - radiation pressure, 200
  - relativistic models, 407
  - super-horizon, 409
- photon : baryon ratio, 458
- physical constants, 675
- Planck
  - FFP6, 613
  - full focal plane simulations, 613
- Planck satellite, 85
- Planck time, 217
- Planck units, 217

- plasma
  - cosmic, 156
- Poisson equation, 98
- polarisation, 491, 533
  - circular, 507
  - elliptical, 509
  - linear, 506
  - spinor representation, 511
  - Stokes parameters, 508
- power spectrum
  - angular, 695
  - normalised, 230
  - sphere, 698
  - tilt, running, 231
- precision cosmology, 634, 645
  - cosmological parameters, 634
- pressure
  - negative, 30
- principle
  - covariance, 298
- principle of equivalence, 295, 342, 352
- prior
  - informative, 597
  - scale invariant, 594
- proper distance, *see* distance
- proper time, 247
- pulsar
  - binary, 90, 102
- quantum chromodynamics, 161
- quark, 161
- quasars, 16, 34
  - catalogue, 36
- quintessence, 215
- radiation
  - black body, 58
  - relic, 57
- radiation era, 55
- radio astronomy, 26
- radio source counts, 31
- Raychaudhuri equation, 411, 419
- Rayleigh–Jeans law, 60
- re-ionisation, 488
- recession velocity, 25, 103
- recombination, 56, 78
  - sound horizon, 443
- redshift, 24
  - controversy, 35
  - cosmological, 429
  - de Sitter space, 378, 432
  - interpretation, 15
  - relativistic, 430
  - Robertson–Walker metric, 432
  - survey, 80
- Relikt-1, 69, 84
- Ricci tensor, 338, 353
- Riemann tensor, 334, 426
  - Kretschmann scalar, 338
- Riemannian geometry, 309
- Riemannian manifold, 310, 311, 316
- Riemannian space, 301, 308
- risk, 570
- Robertson–Walker metric, 22, 32, 367, 386, 435
  - Christoffel symbols, 368
  - Ricci tensor, 368
- Robertson–Walker Universe
  - last scattering surface, 391
  - particle horizon, 390
- Robertson, Howard P., 10, 21
- Sachs–Wolfe effect, 516
  - derivation, 521
  - recombination, 516
- scalar field, 276
- scalars, vectors, tensors, 308
- scale factor, 106
- score, (Fisher), 555
- Shapley, Harlow, 15
- signal to noise ratio, 632
- Slipher, Vesto, 11, 12
- slow rolling approximation, 221
- Solutions GR
  - (anti) de Sitter, 385
  - Bianchi I, 363
  - de Sitter, 376
  - Einstein de Sitter, 381
  - Einstein static, 375
  - FLRW, 367, 386
  - Kasner Universe, 367
  - Kottler, 385
  - LTB, 402
  - Minkowski Space, 359
  - Schwarzschild, 382
  - spherical symmetry, 369
- sound speed, 443, 637
  - adiabatic, 201
- space-time
  - geometry, 307
  - visualisation, 305
- space-time curvature, 305, 351
- special relativity
  - Minkowski Space, 237
- species
  - relativistic, 170
- Sphere, analysis, 695
- standard candle, 113
- statistics
  - Cramér–Rao–Frechet lower bound, 563
  - efficiency, 555
  - James–Stein estimator, 565
  - sufficient, 559
- steady state theory, 16, 27, 39, 350
- structure

- formation, 57  
summation convention, 248, 308, 314  
*Sunyaev–Zel'dovich effect* *see* (SZE)  
kinetic, 537  
thermal, 536  
supernova cosmology, 646  
model fitting, 653  
parameter determination, 654  
supernovae, 45, 84  
calibration, 650  
distance indicator, 648  
MLCS and stretch, 652  
SZE, 474  
kinetic, 474, 537  
thermal, 474, 535  
tangents and projections, 416  
temperature fluctuations  
correlation, 526  
cosmic variance, 528  
multipoles, 525  
tensor  
expansion, 418  
projection, 260  
projection ( $h^{ab}$ , 413  
projection ( $h_{ab}$ ), 416  
shear, 418  
vorticity, 418  
tensor density, 313  
tensor to scalar ratio, 223  
tensor, definition, 315  
tensors  
as matrices, 682  
Theorema Egregium, 425  
thermal history, 154  
thermodynamics, 166  
Thomson scattering  
Stokes parameters, 510  
time  
conformal, 389  
cosmic, 446, 447  
proper, 245  
time-like curve  
acceleration, 328  
tired light, 12  
torsion, 322  
transformation  
4-vector, 242  
Galilean, 240  
Lorentz, 241, 252  
units, 673  
conversions, 675  
Gaussian, 676  
GeV, 678  
Planck, 677  
SI and cgs, 673  
Universe  
thermal history, 55  
vacuum, 288  
variance stabilisation, 576  
Fisher Z-transform, 577  
linear models, 576  
vectors  
as matrices, 682  
velocity  
addition, 243  
velocity–distance relationship, 12  
Virgo cluster, 65  
Virgo supercluster, 61  
voids, 81  
weak field equations, 396  
weak interactions, 175  
Wheeler, John A., 298, 341, 342, 585  
WMAP, 85  
y-parameter, 536  
zodiacal light, 61, 62