

Index

- achronal, 193–195, 200–206
- action integral, 63–64, 66–68
- active gravitational mass, 62
- adiabatic index, 131, 378
- advanced time, 246, 258, 293
- Affine connection, 22–24, 36–37
- age of the universe, 316, 328–332, 341
- Ampere’s law, 146
- angle between two vectors, 17, 43
- angular momentum, 73, 160, 177, 182, 184, 271, 274, 288, 291, 296–300, 361, 372
- angular size, 319–320
- anti-de Sitter space, 230–233
- anti-symmetric tensor, 6, 147
- associated vectors, 13
- asymptotically flat, 109, 123, 216, 253, 256, 259, 271, 284, 293, 370, 371, 390
- asymptotically simple and empty, 216
- baryons, 72, 129, 305
- bending of light, 166–167, 176, 179, 370
- Bianchi identity, 38–39, 315, 327, 381
- Bianchi I-space, 237
- big bang, 158, 235, 305, 306, 327, 340–342
- Birkhoff’s Theorem, 77, 123–126
- birth of a star, 360–361
- black hole, 90, 109, 115–158, 182, 240, 248, 252–257, 261–304, 347, 361, 364, 370, 372, 373
- black hole merger, 157, 158
- boundary conditions, 118, 134, 166, 349, 351, 383
- boundary term, 66, 385, 387
- Boyer lindquist form, 279, 280, 281, 283, 290
- Brans–Dicke theory of gravity, 81
- brown dwarfs, 360
- Buchdahl limit, 137
- Buchdahl theorem, 137
- Cauchy horizon, 201–230, 205, 206
- Cauchy surface, 201, 202, 204, 205, 216, 227
- causal boundary points, 214
- causal curve, 188, 190–192, 195–198, 200, 201, 204, 206, 212–214, 216
- causal function, 210–217
- causal future, 188–190, 206–208
- causality, 187, 192, 196–198, 200, 293, 342, 378
- causality condition, 196, 197, 293, 378
- causally precedes, 188
- causally simple, 206–208
- Chandrasekhar Limit, 364, 366
- Christoffel symbols, 20–23, 31, 37, 44, 51, 53, 56, 64, 65, 117, 219, 313
- chronological future, 188, 193, 211
- chronological past, 188, 202
- chronologically precedes, 188
- closed universe, 311, 321, 333
- closest approach, 166, 168, 180, 181, 372
- comoving coordinate, 72, 237, 313
- compact, 22, 90, 121, 146, 172, 173, 182, 197, 204, 206, 361, 364, 376, 385,
- compactness, 157
- compression modulus, 378
- conformal diagram, 220, 224, 293
- conformal killing vectors, xx
- conformally related, 42, 43, 139, 175, 228, 237, 252
- conjugate tensor, 9
- connected, 16, 22, 187, 197, 216, 220, 222, 225, 256, 280
- conservation principle of energy, 160
- constant curvature, 32–36, 225, 226, 233, 234, 237, 310–312
- contorsion, 79
- contraction, 7, 50, 79, 80, 265, 361
- contravariant frame metric, 261
- contravariant tensor, 3, 4, 6, 13, 25, 98–101
- contravariant vector, 2–6, 8, 17, 23, 24, 26, 64, 95, 97, 100, 105, 386
- convective equilibrium, 349, 351
- coordinate singularity, 240, 246, 284, 285, 292
- Coriolis force, 54, 55
- cosmic background radiation, 305

cosmic microwave background radiation, 305
 cosmography parameters, 342–343
 cosmological constant, 66, 77, 79, 122–123, 132,
 225, 231, 334, 335
 cosmological inflation, 341–342
 cosmological principle, 309, 337–338, 342
 cosmological redshift, 316–318, 322
 covariant Derivative, 24–27, 29, 37, 39, 40, 44,
 59, 60, 63, 70, 77, 80, 97–99, 105, 265
 critical curve, 371
 critical density, 341, 359
 critical image, 371
 curvature radius, 311
 curvature tensor, 27–29, 32, 38, 39, 41–43, 49,
 50, 108
 cylindrically symmetric spacetime, 110–114

 dark energy, 306
 dark matter, 306
 DEC, 155
 deceleration parameter, 323, 329, 331, 332, 338,
 343
 deflection of light, 175, 179–181, 370
 density parameter, 341
 de Sitter line element, 132
 de Sitter universe, 238, 335–337
 directional tensor derivative, 100
 distinguishing, 210, 212–215
 Doppler shifts, 134, 306, 319
 Doran coordinates, 281
 dragging of inertial frames, 287, 288
 dual basis, 261
 dual tetrad, 261
 dust model, 328–334, 366–370

 Eddington–Finkelstein coordinates, 245–248, 251,
 258, 266, 268, 270, 272, 274, 279, 281,
 292–293, 303
 Eddington–Finkelstein form of Kerr solution,
 279
 edgeless, 194, 195, 206
 edge of a set, 195
 effective gravitational mass, 129
 Einstein–de Sitter model, 328, 329
 Einstein gravitational constant, 90
 Einstein–Hilbert action, 64, 77, 82
 Einstein line element, 140
 Einstein–Maxwell field equation, 69
 Einstein–Rosen bridge, 145
 Einstein space, 29, 30, 32, 33
 Einstein static space, 236, 237

Einstein static universe, 133, 134, 222, 223, 227,
 228, 232, 236, 335
 Einstein tensor, 39–41, 62–63, 226, 386, 388
 electromagnetic field strength tensor, 147, 148
 electromagnetism, 63, 68, 146
 embedding, 144, 145
 Emden’s equation, 351
 equation of continuity, 70, 147, 348
 equation of energy transfer, 349
 equation of thermal equilibrium, 349
 equivalence principle, 37, 61, 62
 ergosphere, 286–288, 297, 298
 ergosurface, 285, 287
 Euler–Lagrange equation, 46–47, 177, 290,
 384, 385
 event horizon, 121, 122, 145, 150, 157, 228, 229,
 247, 248, 253–257, 285, 287, 289, 290, 293,
 296, 299, 301, 336, 338–339, 371, 373
 event horizon telescope, 157
 extendible, 196
 exterior solution, 87, 117–123
 extremal Kerr black hole, 286
 extremal Reissner–Nordström black hole, 151
 extrinsic curvature, 379–381, 385

 first integral, 48, 52–54, 57, 65, 160, 175, 290, 291
 flatness problem, 341, 342
 flat space, 20, 29, 32, 70, 75, 125, 140–142, 168,
 175, 226, 233, 236, 241, 280
 flat universe, 311, 321, 328
 four directional covariant derivatives, 265
 frame metric, 261–264
 full domain of dependence, 201
 fundamental tensor, 12, 20, 25, 27, 28, 63, 92,
 101, 228, 283, 284
 future Cauchy development, 200
 future Cauchy horizon, 201, 202
 future causal function, 211
 future-directed time-like curve, 188, 190, 199,
 211, 214, 215
 future distinguishing, 210, 213
 future domain of dependence, 200, 201, 205
 future end point, 195, 214–216
 future event horizon, 229, 230
 future inextendible, 196, 214
 future infinity, 228, 236
 future null infinity, 220, 223, 224
 future (past) k-ideal point, 215
 future (past) o-ideal point, 215
 future set, 190, 193, 194, 214
 future time-like infinity, 223–225

- Gauge freedom, 381
- Gauss–Bonnet gravity, 77
- Gauss divergence theorem, 85, 384, 386
- generalized Kronecker delta, 9–11
- generalized TOV, 128, 376
- geodesically complete, 248, 259
- geodesic coordinate, 37, 38, 63, 386
- geodesic deviation, 49
- geodesic equation, 45, 47–48, 50–58, 61, 89, 106, 110, 133, 154, 308, 338, 367, 372
- geodesics, 45–60, 133, 159, 160, 162, 166, 173, 175, 197, 216–217, 220, 224, 228, 229, 232, 242, 246–248, 252, 254, 258, 279, 290–293, 298, 307, 308, 317, 319, 367
- giant star, 346, 347
- globally hyperbolic, 204–207, 216
- gravitational collapse, 358, 359, 361, 366
- gravitational lensing, 369, 370–371
- gravitational redshift, 171–173
- gravitational mass, 119, 129, 156, 253
- gravitational time delay, 180
- gravitational wave, 92–94, 157, 158, 265, 305
- Hamilton–Jacobi approach, 183
- Hausdorff, 22, 187, 195
- Hawking radiation, 295–296
- Hilbert term, 385, 386
- homogeneity, 307–310, 314, 342
- homothetic vectors, 111
- horizon problem, 342
- horizons, 122, 145, 151, 249, 251–254, 256, 257, 259, 265, 271, 284–287, 289, 290, 293, 295, 298–303, 341, 371
- H-R diagram, 345, 346, 347
- Hubble’s constant, 312, 313, 319
- Hubble’s law, 312–313, 315, 318–319
- hydrostatic equilibrium, 129, 347, 348, 350
- hypersurface, 109, 121, 122, 138, 139, 144, 145, 197, 233, 241, 285, 286, 290, 307, 309, 310, 379, 380, 381, 383, 385, 387, 389, 390, 391, 392, 393
- ideal boundary points, 214, 215
- impact parameter, 371, 372, 373
- indecomposable future set, 214
- indecomposable past set, 214
- inertial mass, 62
- infinitesimal mapping, 95, 96
- initial data problem, 381
- inner horizon, 253, 254, 256, 257, 285, 286, 293
- inner product, 7, 28, 42, 297
- invariant, 4, 6, 7, 8, 12, 13, 15, 23, 25, 26, 30, 42, 61, 63, 77, 82, 83, 95, 110, 115, 196, 284
- invariant energy, 156
- isentropic, 130
- isometric mapping, 101
- isometry, 225, 233, 237
- isothermal configuration, 351
- isotropic coordinates, 138–146
- isotropy, 129, 238, 307–310, 314, 342, 378
- Jerk, 343
- Kerr black hole, 272, 280, 285–288, 297, 298, 300, 302
- Kerr charged black hole metric, 278, 279
- Kerr metric, 267, 271, 273, 274, 276, 279, 281, 283, 284, 286, 288, 289, 290, 293, 297
- Kerr–Newmann metric, 269, 276
- Kerr–Newmann solution, 274–276
- Kerr parameter, 273, 275, 278
- Kerr–Schild Cartesian coordinate, 282
- Kerr solution, 271, 272–274, 279–284, 286, 292–293, 299, 301, 302
- Kerr spacetime, 271, 280, 282–294
- Kerr uncharged black hole solution, 278
- Killing equation, 101–109
- Killing horizon, 290
- Killing vectors, 102, 109, 225, 284, 287–289, 290, 297, 298
- Klein–Gordon Equation, 71, 72, 75, 182, 384
- Kronecker delta, 2, 5, 9–11
- Kruskal–Szekeres coordinates, 248–253, 256
- Kruskal–Szekeres diagram, 251
- Lagrangian, 45, 53, 63, 64, 67–69, 71, 72, 74–76, 79, 80, 82, 148, 159, 160, 175, 177, 181, 242, 290, 291
- Lagrangian density, 69, 74, 75
- Lagrangian formulation, 381, 383–390
- Lane–Emden function, 351–353
- lapse, 381, 392, 393
- laws of black hole thermodynamics, 301–304
- Lemaitre coordinates, 125
- Lerk, 343
- Levi Civita tensor, 18–20
- Lie derivative, 95–114, 380, 392
- Lie derivative of a covariant and contravariant tensor, 98–101
- Lie derivative of a contravariant vector, 97
- Lie derivative of a covariant vector, 97
- Lie derivative of a scalar, 96

- LIGO, 158
- limit curve, 196
- limit point, 191, 195, 196, 204, 208
- linearized gravity, 85–94
- Lorentz–Gauge condition, 93, 94
- luminosity distance, 306, 322–324, 333, 334, 338
- Mach’s principle, 61, 62
- magnification of image, 371
- magnitude of a vector, 59, 60
- magnitudes, 345
- main sequence stars, 345, 347, 357, 360, 361
- manifold, 22, 23, 81, 95, 100, 110, 111, 187, 201, 216, 217, 219, 220, 225, 248, 252, 379, 383, 385, 390, 391
- matter dominant era, 327
- maximal extension, 248, 293–294
- Maxwell’s corrections, 146
- Maxwell’s equation, 146, 147, 148
- microlensing, 370
- Minkowski flat metric, 236
- Minkowski spacetime, 150, 187, 191, 196, 197, 205, 206, 216, 219–226, 229, 236, 248, 250, 251, 252, 282
- mixed tensor, 5, 7, 25, 27, 29, 39, 100, 126
- naked singularities, 254, 257, 286, 296
- NEC, 155, 378
- neucleons, 305
- neutron star, 119, 121, 158, 347, 361, 364–366
- Newman–Penrose formalism, 264
- Newtonian cosmology, 315–316
- Newtonian gravity, 85–87, 88, 161
- Newtonian limit of Einstein field equation, 88–90
- Newtonian stars, 129–138
- Noether’s theorem, 73
- non-null geodesic, 48
- non-rotating black hole solution, 278
- non-singular, 150, 215, 246, 249, 252, 261
- null geodesic, 48, 52, 55, 57, 159, 160, 166, 175, 191, 197, 216, 220, 224, 232, 241, 242, 246, 247, 248, 252, 254, 258, 279, 290–293, 317, 318, 319, 338
- null hypersurfaces, 285
- null tetrad, 261–276, 278, 303
- null veiltrad, 270, 276
- number count, 320–322
- Olber’s paradox, 324–326
- open hyperbolic model, 331
- open universe, 311, 321, 331, 333
- Oppenheimer–Snyder model, 366
- orthogonal vectors, 17–18
- outer horizon, 254–256, 285, 286, 287, 299
- outer product, 6, 7
- Painleve–Gullstrand form, 121, 282
- paracompact, 22, 187
- parallel transport, 23, 24
- parity of image, 371
- particle horizon, 229, 338, 339
- passive gravitational mass, 62
- past Cauchy horizon, 201
- past causal function, 211
- past-directed causal curve, 212, 213
- past-directed time-like curve, 188, 202
- past distinguishing, 210, 212
- past domain of dependence, 201
- past event horizon, 229, 230
- past inextensible, 195, 200, 203, 204
- past infinity, 228, 236
- past null infinity, 220, 223, 224, 237
- past set, 193, 214
- past time like infinity, 222, 224
- Pauli exclusion principle, 362
- Penrose diagram, 220, 224, 225, 232, 235–238, 252–254, 256, 259
- Penrose process, 297–301
- perfect cosmological principle, 337–338
- perihelion motion, 161–166
- perihelion precession, 177–179
- photon sphere, 372–374
- Poisson equation, 85, 86, 90–92
- polytropic, 351, 352, 355, 358, 363, 365
- precession of the perihelion, 161–166
- principal congruence of null geodesics, 292
- principle of conservation of angular momentum, 160
- principle of covariance, 61, 62, 68
- proper distance, 183, 319, 322, 338, 339
- proper indecomposable future set, 214
- proper indecomposable past set, 214
- proper radial distance, 143, 144
- Proxima Centauri, 307
- quantum fluctuations, 296
- quarks, 305

- quintessence, 76
- quotient law, 7–9
- radar echo delay, 168–170
- radial caustic, 371
- radiation model, 339–341
- Raychaudhuri equation, 50–60, 234, 235
- reciprocal tensor, 9
- redgiant star, 346, 347
- redshift, 157, 171–173, 240, 286, 312, 316–323, 326, 333, 334, 338, 343
- reflecting, 209, 381
- regular point, 214, 256
- Reissner–Nordström black hole, 150, 151, 269, 293
- Reissner–Nordström line element, 141, 142, 255, 274
- Reissner–Nordström metric, 141, 142, 150, 253, 254, 268, 269, 271, 274, 276
- Reissner–Nordström solution, 150, 151, 216, 253–259, 274–276, 280
- Retarded time, 153, 220, 246
- Ricci scalar, 30–32, 44, 76, 77, 79, 80, 117, 226, 230, 266, 385
- Ricci tensor, 29–30, 31, 43, 44, 80, 82, 92, 93, 117, 225, 265, 266, 312, 314, 386
- Riemann–Christoffel curvature tensor, 28, 29
- Riemannian connection, 26
- Riemannian geometry, 36–37, 77
- Riemannian space, 12, 27, 29, 30, 32, 37, 42, 45, 111
- Riemann tensor, 42, 44, 82, 219, 226, 310
- Ritter’s theorem, 355–357, 363
- Robertson–Walker metric, 233, 235, 309–312
- Robertson–Walker spaces, 233–235
- rotating black hole solution, 276–279, 303
- scalar wave equation, 182
- scale factor, 111, 237, 238, 311, 315–318, 320, 322, 328, 329, 332–334, 336, 341, 342, 343
- Schwarzschild black hole, 150, 151, 240, 269
- Schwarzschild interior solution, 126–127, 136, 137
- Schwarzschild line element, 118, 121, 139, 145, 240, 248, 272, 284, 368
- Schwarzschild metric, 119, 121, 123, 125, 126, 139, 140, 150, 152, 162, 176, 240, 245, 246, 249, 251, 266, 267, 272, 273, 274, 279, 282
- Schwarzschild radius, 119, 120, 240, 242, 243, 248, 369, 273
- Schwarzschild solution, 77, 117–122, 123, 136, 145, 175, 240–241, 248, 252, 253, 254, 272–274, 280, 283, 378
- Schwarzschild spacetime, 124, 144, 145, 159–185, 241–245, 271
- SEC, 155, 378
- self energy, 156
- singularities, 150, 187, 215, 226, 240, 243, 254, 255, 284–286, 296, 371, 377
- skew-symmetric tensor, 5–6, 11
- snap, 343
- space like vector, 16–17, 128, 155, 261–263
- spatial infinity, 223, 224
- spectral shift, 312
- spherically symmetric line element, 115–116
- spherically symmetric metric, 118, 122, 126, 176, 303, 373
- spherically symmetric spacetime, 109–110, 144, 182, 312, 371–378
- spiral galaxy, 306, 345
- stably causal, 198–200, 204
- static limit, 286–289
- static spacetimes, 108–109
- static universe, 133, 134, 140, 222, 223, 227, 228, 232, 236, 316, 335
- stationary, 108–109, 271, 280, 284, 287, 301
- stationary limit surface, 287, 297
- stationary observer, 288–290
- stationary spacetimes, 109
- strong equivalence principle, 61
- strong field limit, 370, 373
- strong lensing, 370
- strongly causal, 197, 200, 216
- surface gravity, 156, 301–303, 345
- surface gravity of Kerr solution, 301
- surface redshift, 157
- surfaces of infinite redshift, 286
- symmetric tensor, 5, 6, 11, 34, 62, 147, 380
- tangential caustic, 371
- teleparallel theory, 79
- terminal indecomposable future set, 214
- terminal indecomposable past set, 214
- tetrad, 78–79, 261–263, 265, 272, 275, 277, 303, 304
- time-like curve, 188–190, 193–203, 208–212, 214–215, 231, 293

- time orientable, 187–188
Tolman–Oppenheimer–Volkoff equation, 127–129, 350
torsion scalar, 79
torsion tensor, 79
tortoise coordinates, 183, 245, 246, 249, 250, 258
twelve spin coefficients, 265

vacuum energy, 305, 327, 328, 341
vacuum solution, 61, 77, 122–123, 225, 240, 389
Vaidya metric, 152, 153
velocity of sound, 130, 378
Vierbein, 261

weak field limit, 89, 161, 175, 372
weak lensing, 370
weak principle of equivalence, 61
Weitzenböck's connection, 79
Weyl gravity, 82–83
Weyl postulate, 307–308, 326
Weyl scalar, 265–266
Weyl tensor, 41–44, 82, 226, 265–266
Weyl transformation, 43–44
white dwarf, 119, 121, 173, 346–347, 361–365

zero angular momentum observer, 288
zeroth law, 301, 303