Contents

Preface *page* ix

1 The basics of neutrino physics 1
- 1.1 The electroweak Standard Model 2
- 1.2 Spontaneous symmetry breaking and fermion masses 5
- 1.3 The basic properties of neutrinos: interactions, masses and oscillations 9
  - 1.3.1 Neutrino interactions in the low energy limit 9
  - 1.3.2 Dirac and Majorana masses 16
  - 1.3.3 The seesaw mechanism 22
  - 1.3.4 Flavour oscillations in vacuum 25
  - 1.3.5 Flavour oscillations in matter 30
- 1.4 Neutrino experiments 35
  - 1.4.1 Oscillation experiments and three-neutrino mixing 35
  - 1.4.2 Oscillation experiments and sterile neutrinos 40
  - 1.4.3 Neutrino mass scale experiments 42
  - 1.4.4 Dirac or Majorana? Neutrinoless double-β decay 46
- 1.5 Nonstandard neutrino–electron interactions 50

2 Overview of the Standard Cosmological Model 53
- 2.1 The homogeneous and isotropic universe 55
  - 2.1.1 The dynamics of expansion 55
  - 2.1.2 Distances in the universe 65
- 2.2 Statistical mechanics in the expanding universe 70
  - 2.2.1 The relativistic Boltzmann equation 70
  - 2.2.2 When equilibrium holds 80
- 2.3 The expansion stages 83
  - 2.3.1 Inflation 83

2.3.2 Radiation and matter domination 87
2.3.3 Λ (or dark energy) domination 92
2.4 A first look at photon and neutrino backgrounds 95
2.4.1 Photon decoupling and the formation of the cosmic microwave background 95
2.4.2 The cosmic neutrino background 98

3 Neutrinos in the early ages 106
3.1 The baryon number of the universe 107
3.2 Sakharov conditions 109
3.3 C, CP, *B*, out of equilibrium and all that 112
3.3.1 C and CP violation 112
3.3.2 Baryon and lepton number violation 113
3.3.3 Relating baryon and lepton numbers 119
3.3.4 The out-of-equilibrium decay scenario 121
3.4 Basics of leptogenesis 125
3.4.1 Standard leptogenesis and Majorana neutrinos 126
3.4.2 Leptogenesis and neutrino oscillation: Two right-handed neutrinos 131

4 Neutrinos in the MeV age 134
4.1 Neutrino decoupling 135
4.2 Neutrino oscillations in the expanding universe 143
4.2.1 Effective matter potentials 143
4.2.2 Density matrix formalism 145
4.2.3 Flavour oscillations and relic neutrino distortions 152
4.2.4 Flavour oscillations and relic neutrino asymmetries 154
4.2.5 Active–sterile oscillations 160
4.3 Big Bang nucleosynthesis 166
4.3.1 Neutron–proton chemical equilibrium 170
4.3.2 The nuclear network 173
4.3.3 Light-element observations 176
4.3.4 Theory vs. data 180
4.4 Bounds on neutrino properties from Big Bang nucleosynthesis 181
4.4.1 Extra relativistic degrees of freedom 183
4.4.2 Relic neutrino asymmetries 185
4.4.3 Nonstandard neutrino electromagnetic properties and interactions 189
4.4.4 Sterile neutrinos and Big Bang nucleosynthesis 193

5 Neutrinos in the cosmic microwave background epoch 198
5.1 Cosmic microwave background anisotropies 199
5.1.1 Overview 199
5.1.2 Perturbation equations 201
5.1.3 Adiabatic and isocurvature modes 208
5.1.4 Power spectra and transfer functions 211
5.1.5 Acoustic oscillations 213
5.1.6 Temperature anisotropies 220
5.1.7 Polarization anisotropies 233
5.1.8 Tensor perturbations 234
5.2 Neutrino perturbations 236
5.2.1 Perturbation equations 236
5.2.2 Neutrino isocurvature modes 240
5.2.3 Adiabatic mode in the presence of neutrinos 242
5.2.4 Free-streaming length 244
5.2.5 Linear evolution of neutrino perturbations 248
5.2.6 Practical implementation and approximations 249
5.3 Effects of neutrinos on primary cosmic microwave background anisotropies 253
5.3.1 How can decoupled species affect the cosmic microwave background? 253
5.3.2 Effects of massless neutrinos 255
5.3.3 Effects of massive neutrinos 262
5.3.4 Effects of interacting neutrinos 266
5.4 Bounds on neutrinos from primary cosmic-microwave-background anisotropies 267
5.4.1 Cosmic microwave background and homogeneous cosmology data sets 267
5.4.2 Neutrino abundance 268
5.4.3 Neutrino masses 271

6 Recent times: neutrinos and structure formation 273
6.1 Linear matter power spectrum 274
6.1.1 Neutrinoless universe with cold dark matter 275
6.1.2 Neutrinoless universe with cold dark matter and baryons 284
6.1.3 Impact of massless neutrinos 290
6.1.4 Impact of hot dark matter 293
6.1.5 Impact of warm dark matter 312

6.2 Nonlinear matter power spectrum 317
6.2.1 N-body simulations 317
6.2.2 Analytic approaches 323
6.3 Impact of neutrinos on secondary cosmic microwave background anisotropies 324
6.3.1 Late integrated Sachs–Wolfe effect 324
6.3.2 Cosmic microwave background lensing 327
6.4 Observing the large-scale structure 328
6.4.1 Galaxy and cluster power spectrum 329
6.4.2 Cluster mass function 331
6.4.3 Galaxy weak lensing 332
6.4.4 Cosmic microwave background lensing 334
6.4.5 Lyman alpha forests 334
6.4.6 21-cm surveys 335
6.5 Large-scale structure bounds on neutrino properties 335
6.5.1 Active neutrino masses 335
6.5.2 Neutrino abundance and light sterile neutrinos 339
6.5.3 Nonstandard properties of active neutrinos 342
6.5.4 Heavy sterile neutrinos (warm dark matter) 344

7 Cosmological neutrinos today 348
7.1 The ultimate dream: detecting cosmological neutrinos 349
7.1.1 Scatterings: $G_{\rm F}^2$ effects are too small 349
7.1.2 The order $G_{\rm F}$ interactions and the Stodolsky effect 350
7.1.3 Massive neutrinos and β-decaying nuclei 354
7.2 Beyond the ultimate dream: neutrino anisotropies in the sky 359
7.2.1 Neutrino last scattering surface 359
7.2.2 Massless neutrinos 359
7.2.3 Massive neutrinos 360

References 362
Index 375