Physics 129 — Nuclear and Particle Astrophysics

Winter 2014 - TuTh 2:00-3:45 - ISB 231

Instructor: Joel R. Primack, Physics.
Office hours: Wednesdays 2-3:30 or by appointment, Office: ISB 318, Phone: 459-2580 Email: joel@ucsc.edu

The standard model of particle physics, general relativistic cosmology, the early universe and Big Bang nucleosynthesis, dark matter and structure formation, formation of heavy elements in stars and supernovae, neutrino oscillations, high energy astrophysics: cosmic rays and gamma ray astronomy. *Note:* This course is an upper division astrophysics course, and thus can be one of the three such courses that UCSC Astrophysics majors must take.

Tentative syllabus:

week	**topic**
1	Standard Model of particle physics
2	Special and general relativity in the universe
3	Conservtion rules and symmetries
4	The early universe and Big Bang nucleosynthesis
5	Dark matter and structure formation
6	Nuclear astrophysics, formation of elements in stars and supernovae
7	Neutrinos: production, detection, mass, oscillations
8	Nature and sources of high energy particles in the universe
9	Gamma ray astronomy
10	Future prospects and summary

Textbook: *Particle Astrophysics*, 2nd Edition, by D. H. Perkins (Oxford University Press, 2009) [ordered at Bay Tree Bookstore, available cheaper from Amazon, online at the UCSC Science Library]. I have put a number of relevant books on reserve at the Science Library.

There will be additional material presented in lectures and posted online, at http://physics.ucsc.edu/~joel/Phys129/

There will be regular problem sets, an in-class midterm, and a final exam. Students will be expected to be familiar with special relativity and quantum mechanics. Physics 101A or 102 is a prerequisite, and Physics 101B or more advanced courses will be helpful.

“Natural Units” = High Energy Physics Units $\boxed{\hbar = c = k_B = 1}$

These are especially appropriate for the hot early universe.

There is one fundamental dimension, which we can take to be mass or energy = $mc^2 = m$.

$$[\text{Energy}] = [\text{Mass}] = [\text{Temperature}] = [\text{Length}]^{-1} = [\text{Time}]^{-1}$$

$$1\ \text{GeV} = 1.78\text{x}10^{-24}\ \text{g} = 1.16\text{x}10^{13}\ \text{K} = 1.97\text{x}10^{-14}\ \text{cm}^{-1} = 6.58\text{x}10^{-25}\ \text{s}^{-1}$$

$$= 1.78\text{x}10^{-27}\ \text{kg} = 1.602\text{x}10^{-3}\ \text{erg} = 1.602\text{x}10^{-10}\ \text{J}$$

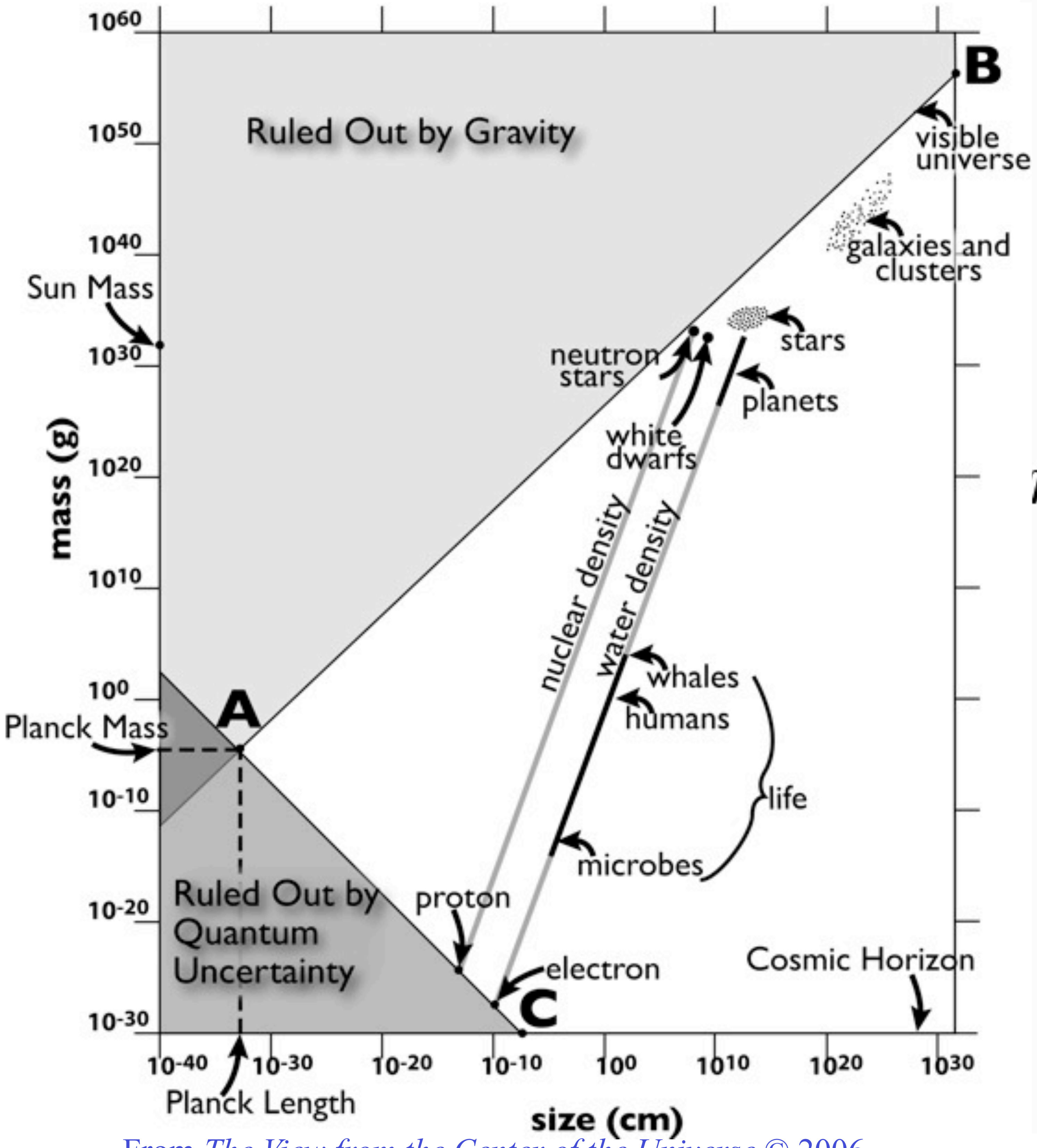
$1\ \text{eV} = 1.60\text{x}10^{-19}\ \text{J} = 1.16\text{x}10^{4}\ \text{K}$ $\quad (k_B = 1.38\text{x}10^{-16}\ \text{erg K}^{-1})$

$1\ \text{pc} = 3.26\ \text{lyr} = 3.09\text{x}10^{18}\ \text{cm}$

To add gravity to this scheme, we usually express it in terms of the Planck mass $\boxed{M_{\text{Pl}} = (\hbar c/G)^{1/2}} = 1.2 \times 10^{19}\ \text{GeV}/c^2$

For more conversion factors, see Appendix A of Kolb & Turner, *The Early Universe*, and Table 1.1 of Perkins, *Particle Astrophysics*.

The Wedge of Material Reality



From *The View from the Center of the Universe* © 2006

The Planck Length

$$l_{Pl} = \sqrt{\frac{hG}{2\pi c^3}} = 1.6 \times 10^{-33}\ \text{cm}$$

is the smallest possible length. Here h is Planck's constant

$$h = 6.626068 \times 10^{-34}\ \text{m}^2\ \text{kg / s}$$

The Planck Mass is

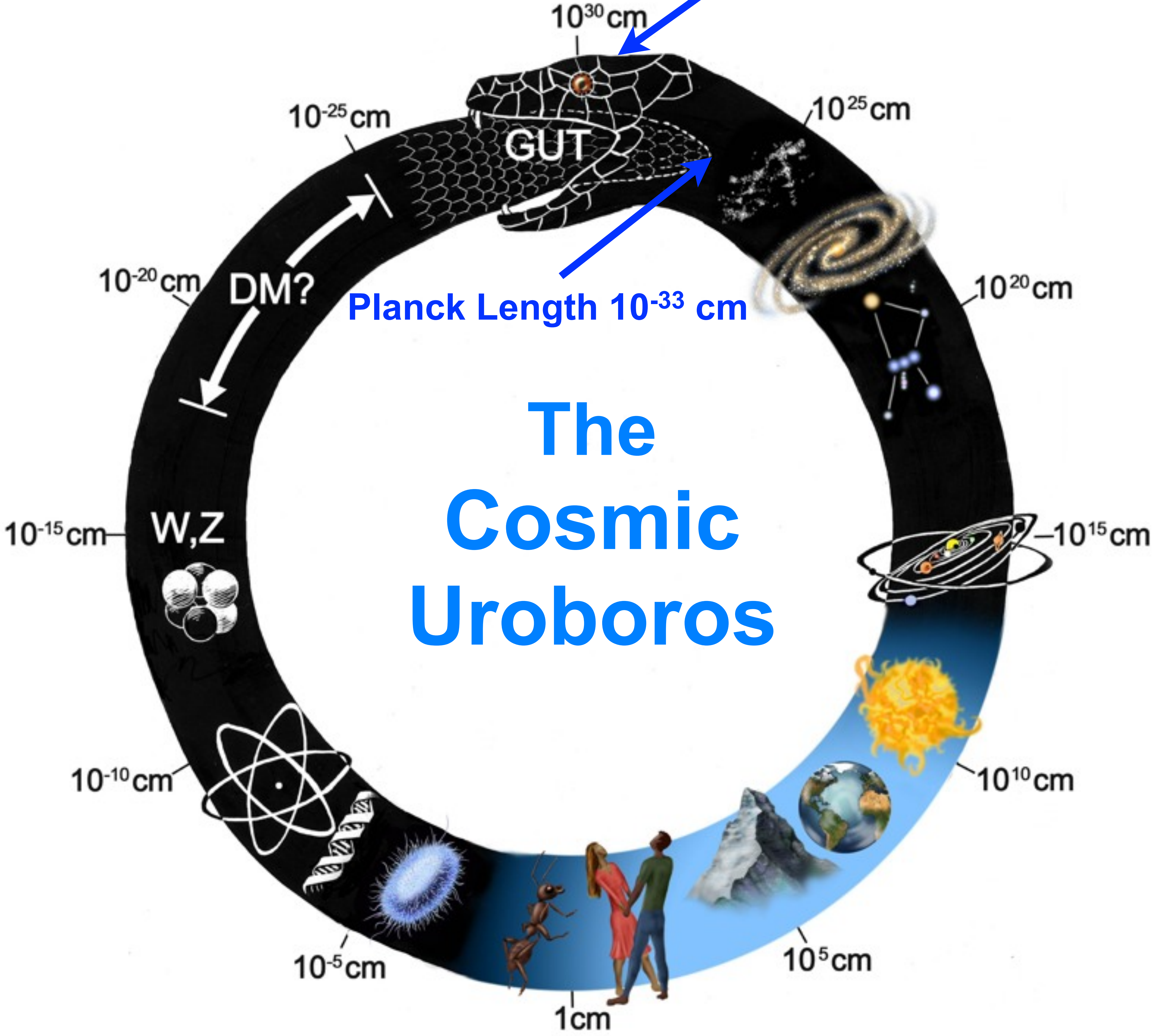
$$m_{Pl} = \sqrt{\frac{hc}{2\pi G}} = 2.2 \times 10^{-5}\ \text{g}$$

The Compton (i.e. quantum) wavelength $l_C = \frac{h}{2\pi mc}$

equals the Schwarzschild radius $l_S \approx \frac{Gm}{c^2}$

when $m = m_{Pl} = 1.2 \times 10^{19}\ \text{GeV/c}^2$

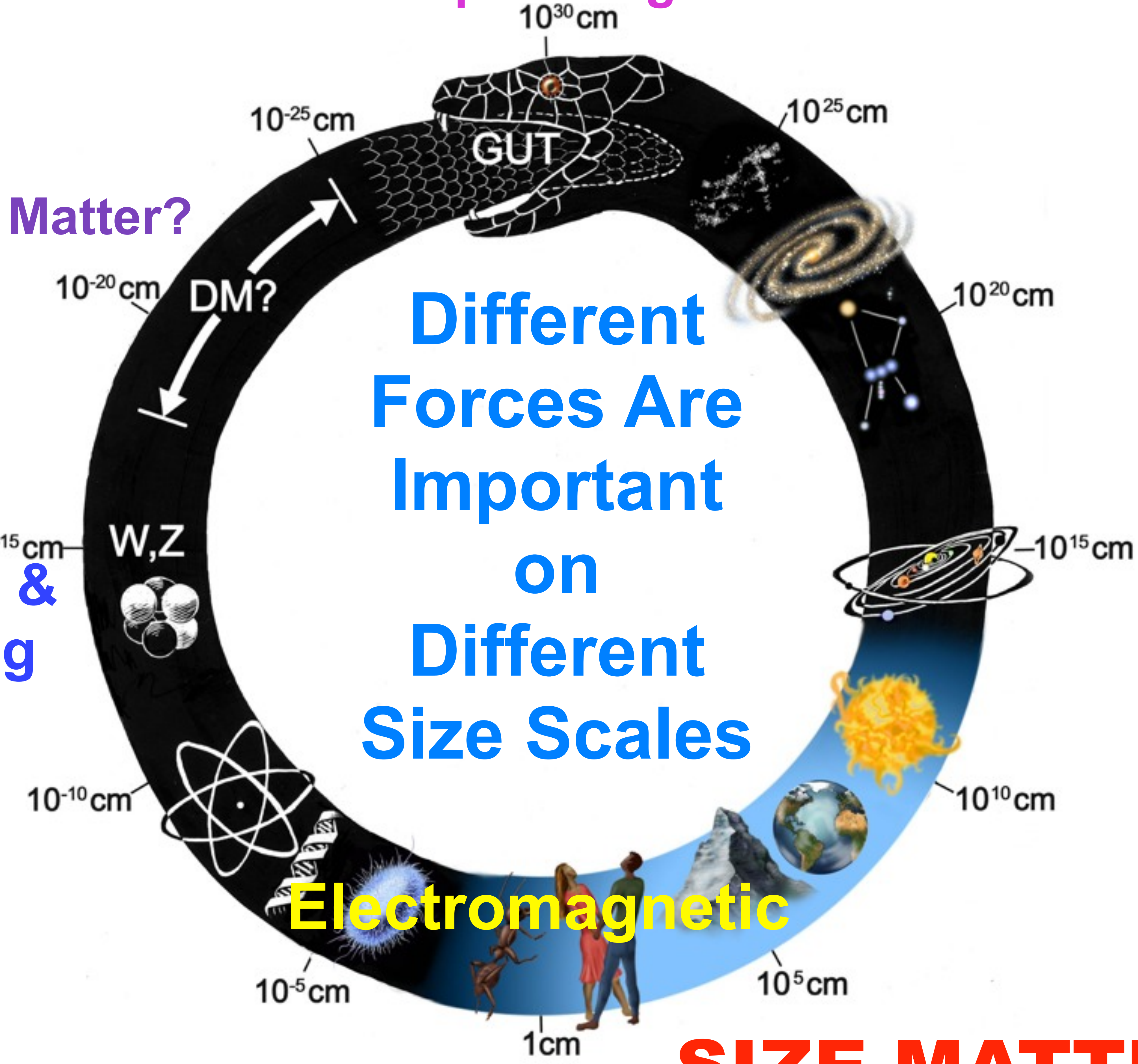
The Cosmic Uroboros



Cosmic Horizon 10^{29} cm

Planck Length 10^{-33} cm

Superstrings?



Dark Matter?

Weak & Strong

Different Forces Are Important on Different Size Scales

Electromagnetic

Gravitation

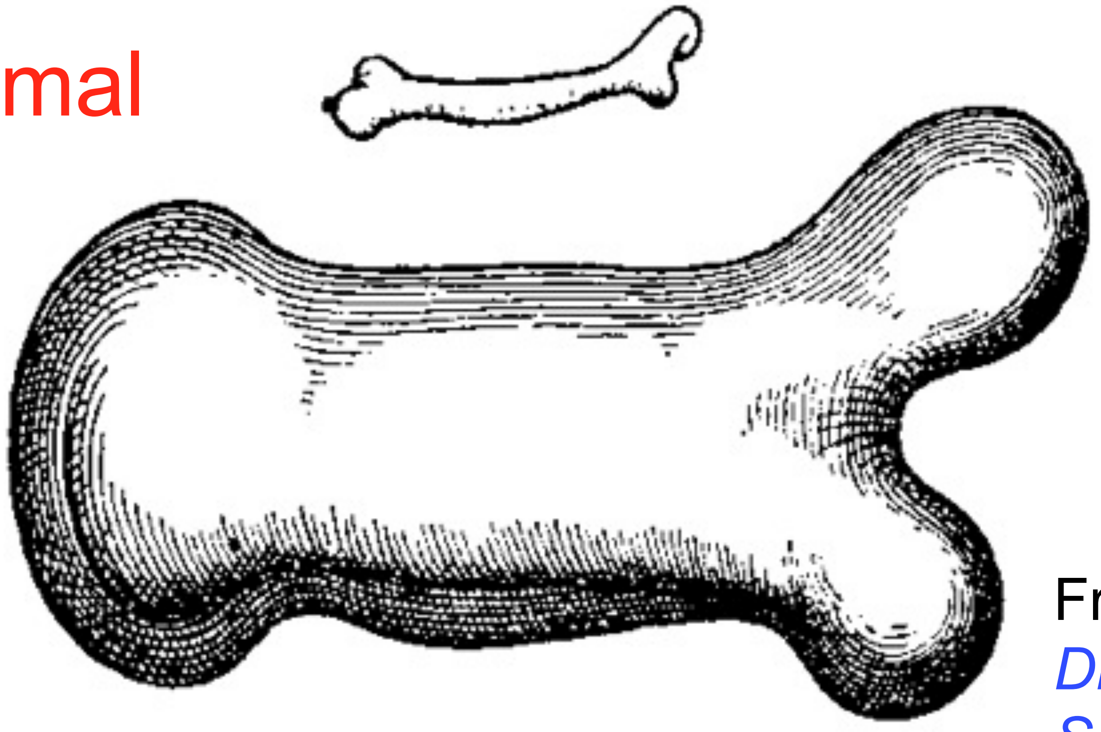
SIZE MATTERS!

SIZE MATTERS!

No animal could be 3 times its normal height and stay the same shape, simply scaled up.

If height increases 3 times,
strength of bones increases 3x3 = 9 times.
But weight increases 3x3x3 = 27 times.
Its weight would crush its bones!

That is why an elephant does not look like a large gazelle.

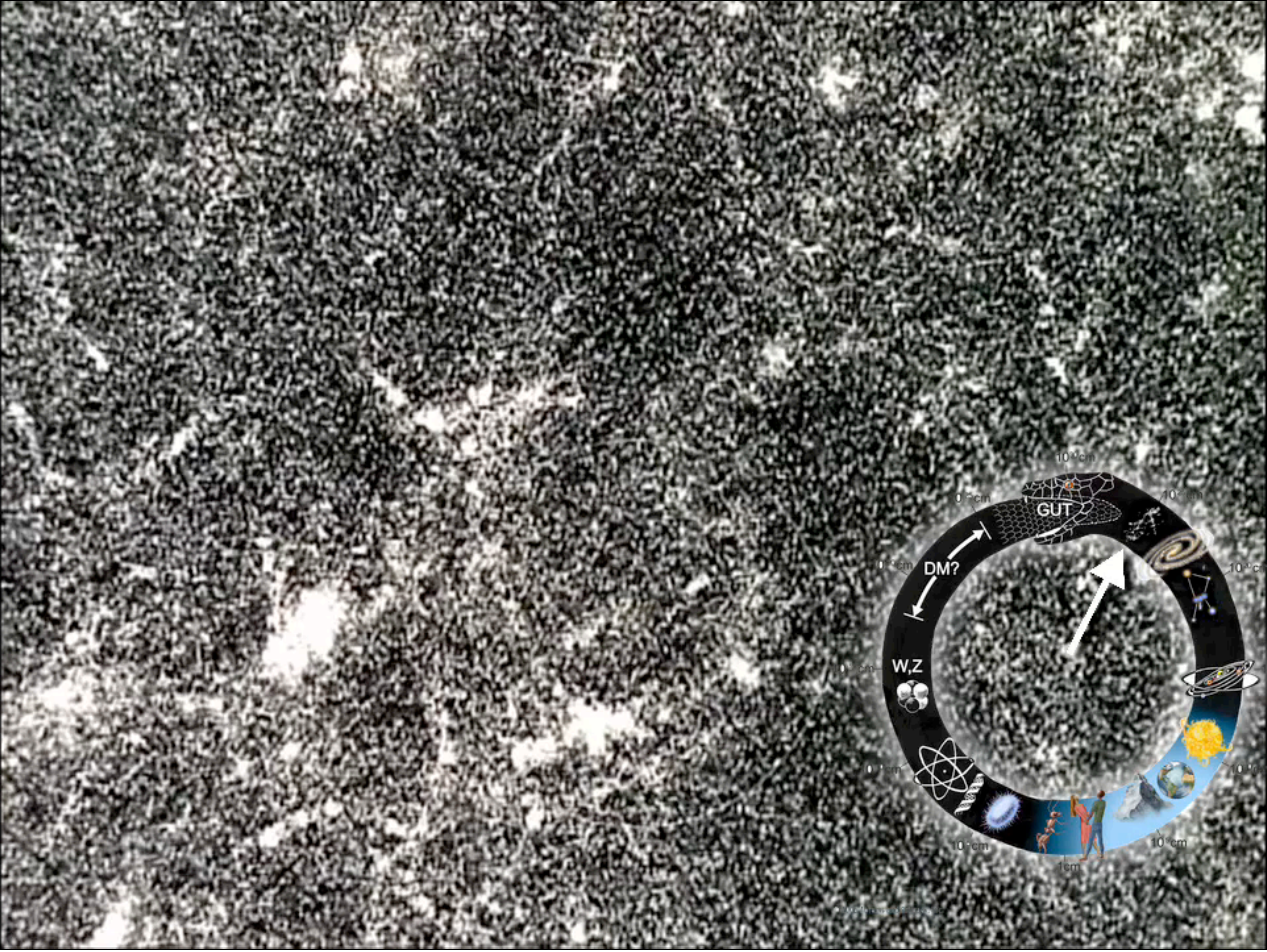


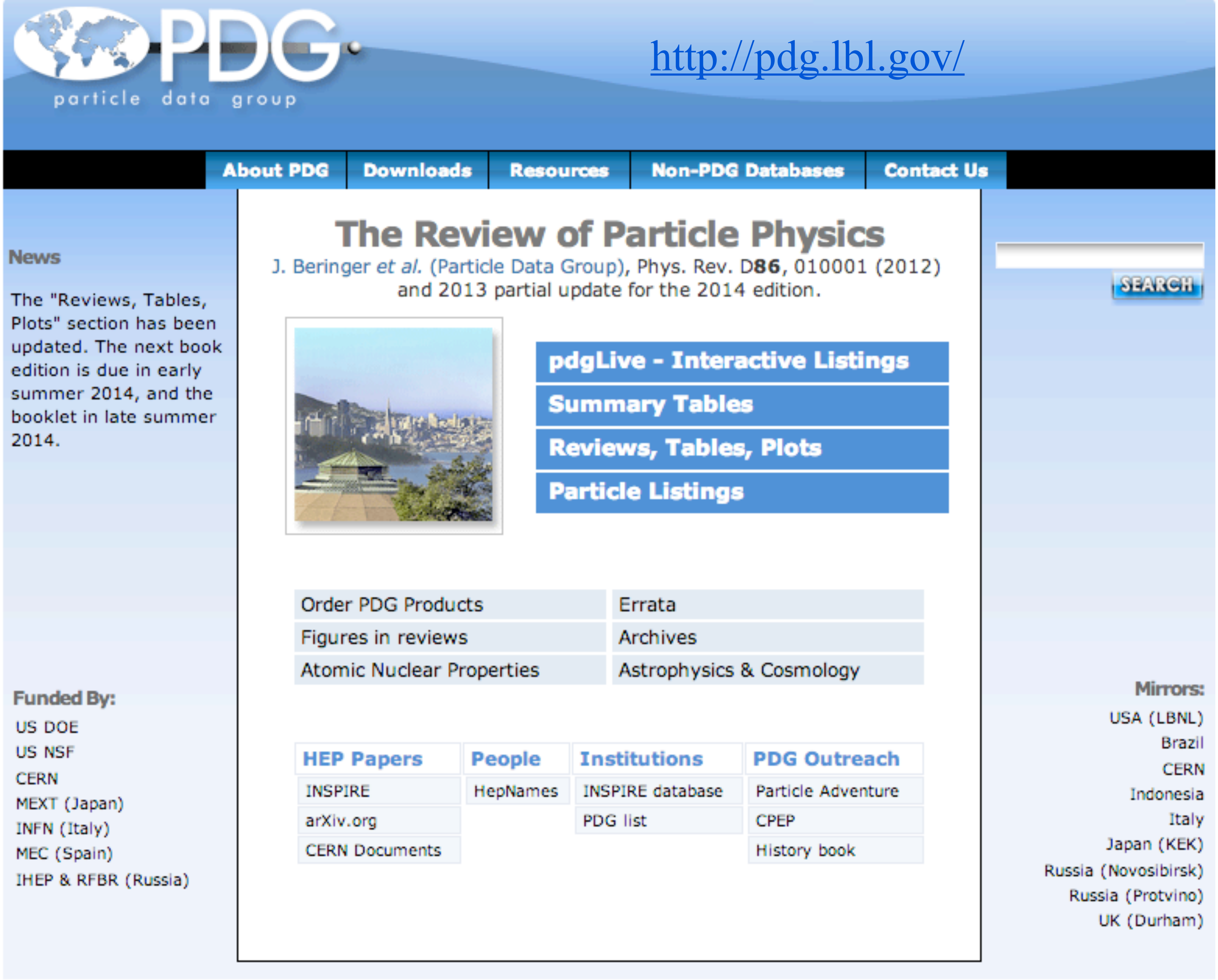
Bone of small animal

Bone of animal
3 times longer

From Galileo’s last book, *Discourses On Two New Sciences* (1638).

King Kong


GUT
DM?
W,Z
1cm



http://pdg.lbl.gov/

News

The "Reviews, Tables, Plots" section has been updated. The next book edition is due in early summer 2014, and the booklet in late summer 2014.

The Review of Particle Physics

J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012)
and 2013 partial update for the 2014 edition.

- pdgLive - Interactive Listings
- Summary Tables
- Reviews, Tables, Plots
- Particle Listings

Order PDG Products	Errata
Figures in reviews	Archives
Atomic Nuclear Properties	Astrophysics & Cosmology

HEP Papers	People	Institutions	PDG Outreach
INSPIRE	HepNames	INSPIRE database	Particle Adventure
arXiv.org		PDG list	CPEP
CERN Documents			History book

Funded By:

- US DOE
- US NSF
- CERN
- MEXT (Japan)
- INFN (Italy)
- MEC (Spain)
- IHEP & RFBR (Russia)

Mirrors:

- USA (LBNL)
- Brazil
- CERN
- Indonesia
- Italy
- Japan (KEK)
- Russia (Novosibirsk)
- Russia (Protvino)
- UK (Durham)

http://pdg.lbl.gov/

Order PDG products

- Particle Physics Booklet (320 pages)
- Review of Particle Physics (1526 pages; if you need more detailed information)
- Pocket Diary for Physicists

For **special requests only**, please contact:

In North or South America, Australia, and the Far East:

Via E-mail: pdg@lbl.gov
Via postal mail:
Particle Data Group, MS 50R6008
Lawrence Berkeley National Lab
One Cyclotron Road
Berkeley, CA 94720-8166 USA

In Europe, Africa, Middle East, India, Pakistan, Russia and all other countries:

Via Email: pdg-products@cern.ch
Via postal mail:
CERN Scientific Information Service
CH-1211 Geneva 23
Switzerland
At CERN: contact Library (bldg 52-1-52)

1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 2013 by P.J. Mohr (NIST). Mainly from the "CODATA Recommended Values of the Fundamental Physical Constants: 2010" by P.J. Mohr, B.N. Taylor, and D.B. Newell in Rev. Mod. Phys. **84**, 1527 (2012). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding fractional uncertainties in parts per 10^9 (ppb) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology). The full 2010 CODATA set of constants may be found at `http://physics.nist.gov/constants`. See also P.J. Mohr and D.B. Newell, "Resource Letter FC-1: The Physics of Fundamental Constants," Am. J. Phys. **78**, 338 (2010).

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	299 792 458 m s^{-1}	exact*
Planck constant	h	6.626 069 57(29)$\times10^{-34}$ J s	44
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 571 726(47)$\times10^{-34}$ J s	44
		= 6.582 119 28(15)$\times10^{-22}$ MeV s	22
electron charge magnitude	e	1.602 176 565(35)$\times10^{-19}$ C = 4.803 204 50(11)$\times10^{-10}$ esu	22, 22
conversion constant	$\hbar c$	197.326 9718(44) MeV fm	22
conversion constant	$(\hbar c)^2$	0.389 379 338(17) GeV^2 mbarn	44
electron mass	m_e	0.510 998 928(11) MeV/c^2 = 9.109 382 91(40)$\times10^{-31}$ kg	22, 44
proton mass	m_p	938.272 046(21) MeV/c^2 = 1.672 621 777(74)$\times10^{-27}$ kg	22, 44
		= 1.007 276 466 812(90) u = 1836.152 672 45(75) m_e	0.089, 0.41
deuteron mass	m_d	1875.612 859(41) MeV/c^2	22
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	931.494 061(21) MeV/c^2 = 1.660 538 921(73)$\times10^{-27}$ kg	22, 44
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 817 ... $\times10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0	$4\pi\times10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 5698(24)$\times10^{-3}$ = 1/137.035 999 074(44)†	0.32, 0.32
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3267(27)$\times10^{-15}$ m	0.97
(e^- Compton wavelength)/2π	$\bar{\lambda}_e = \hbar/m_e c = r_e\alpha^{-1}$	3.861 592 6800(25)$\times10^{-13}$ m	0.65
Bohr radius ($m_{\mathrm{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	0.529 177 210 92(17)$\times10^{-10}$ m	0.32
wavelength of 1 eV/c particle	$hc/(1\ \mathrm{eV})$	1.239 841 930(27)$\times10^{-6}$ m	22
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 692 53(30) eV	22
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 245 8734(13) barn	1.9
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 381 8066(38)$\times10^{-11}$ MeV T^{-1}	0.65
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 2605(22)$\times10^{-14}$ MeV T^{-1}	0.71
electron cyclotron freq./field	$\omega^e_{\mathrm{cycl}}/B = e/m_e$	1.758 820 088(39)$\times10^{11}$ rad s^{-1} T^{-1}	22
proton cyclotron freq./field	$\omega^p_{\mathrm{cycl}}/B = e/m_p$	9.578 833 58(21)$\times10^{7}$ rad s^{-1} T^{-1}	22
gravitational constant‡	G_N	6.673 84(80)$\times10^{-11}$ m^3 kg^{-1} s^{-2}	1.2×10^5
		= 6.708 37(80)$\times10^{-39}$ $\hbar c$ $(\mathrm{GeV}/c^2)^{-2}$	1.2×10^5
standard gravitational accel.	g_N	9.806 65 m s^{-2}	exact
Avogadro constant	N_A	6.022 141 29(27)$\times10^{23}$ mol^{-1}	44
Boltzmann constant	k	1.380 6488(13)$\times10^{-23}$ J K^{-1}	910
		= 8.617 3324(78)$\times10^{-5}$ eV K^{-1}	910
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(101 325 Pa)	22.413 968(20)$\times10^{-3}$ m^3 mol^{-1}	910
Wien displacement law constant	$b = \lambda_{\mathrm{max}}T$	2.897 7721(26)$\times10^{-3}$ m K	910
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 373(21)$\times10^{-8}$ W m^{-2} K^{-4}	3600
Fermi coupling constant**	$G_F/(\hbar c)^3$	1.166 378 7(6)$\times10^{-5}$ GeV^{-2}	500
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\mathrm{MS}}$)	0.231 26(5)††	2.2×10^5
$W^\pm$ boson mass	m_W	80.385(15) GeV/c^2	1.9×10^5
Z^0 boson mass	m_Z	91.1876(21) GeV/c^2	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	0.1185(6)	5.1×10^6

π = 3.141 592 653 589 793 238 e = 2.718 281 828 459 045 235 γ = 0.577 215 664 901 532 861

1 in ≡ 0.0254 m 1 G ≡ 10^{-4} T 1 eV = 1.602 176 565(35) × 10^{-19} J kT at 300 K = $[38.681\ 731(35)]^{-1}$ eV

1 Å ≡ 0.1 nm 1 dyne ≡ 10^{-5} N 1 eV/c^2 = 1.782 661 845(39) × 10^{-36} kg 0 °C ≡ 273.15 K

1 barn ≡ 10^{-28} m^2 1 erg ≡ 10^{-7} J 2.997 924 58 × 10^9 esu = 1 C 1 atmosphere ≡ 760 Torr ≡ 101 325 Pa

1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 2013 by P.J. Mohr (NIST). Mainly from the "CODATA Recommended Values of the Fundamental Physical Constants: 2010" by P.J. Mohr, B.N. Taylor, and D.B. Newell in Rev. Mod. Phys. **84**, 1527 (2012). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding fractional uncertainties in parts per 10^9 (ppb) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology). The full 2010 CODATA set of constants may be found at `http://physics.nist.gov/constants`. See also P.J. Mohr and D.B. Newell, "Resource Letter FC-1: The Physics of Fundamental Constants," Am. J. Phys. **78**, 338 (2010).

(Bottom of Table 1)

$\pi = 3.141\ 592\ 653\ 589\ 793\ 238$	$e = 2.718\ 281\ 828\ 459\ 045\ 235$	$\gamma = 0.577\ 215\ 664\ 901\ 532\ 861$

$1\ \text{in} \equiv 0.0254\ \text{m}$	$1\ \text{G} \equiv 10^{-4}\ \text{T}$	$1\ \text{eV} = 1.602\ 176\ 565(35) \times 10^{-19}\ \text{J}$	kT at 300 K $= [38.681\ 731(35)]^{-1}$ eV
$1\ \text{Å} \equiv 0.1\ \text{nm}$	$1\ \text{dyne} \equiv 10^{-5}\ \text{N}$	$1\ \text{eV}/c^2 = 1.782\ 661\ 845(39) \times 10^{-36}\ \text{kg}$	$0\ ^\circ\text{C} \equiv 273.15\ \text{K}$
$1\ \text{barn} \equiv 10^{-28}\ \text{m}^2$	$1\ \text{erg} \equiv 10^{-7}\ \text{J}$	$2.997\ 924\ 58 \times 10^9\ \text{esu} = 1\ \text{C}$	$1\ \text{atmosphere} \equiv 760\ \text{Torr} \equiv 101\ 325\ \text{Pa}$

* The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is $\sim 1/128$.

‡ Absolute lab measurements of G_N have been made only on scales of about 1 cm to 1 m.

** See the discussion in Sec. 10, "Electroweak model and constraints on new physics."

†† The corresponding $\sin^2\theta$ for the effective angle is 0.23155(5).

2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised November 2013 by D.E. Groom (LBNL). The figures in parentheses after some values give the 1-σ uncertainties in the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

The values and uncertainties for the cosmological parameters depend on the exact data sets, priors, and basis parameters used in the fit. Many of the derived parameters reported in this table have non-Gaussian likelihoods. Parameters may be highly correlated, so care must be taken in propagating errors. (But in multiplications by h^{-2} *etc.* in the table below, independent errors were assumed.) Unless otherwise specified, cosmological parameters are from six-parameter fits to a flat ΛCDM cosmology using CMB data alone: *Planck* temperature + WMAP polarization data + high-resolution data from ACT and SPT [2]. For more information see Ref. 3 and the original papers.

(Bottom of Table 2)

baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^\ddagger 0.02207(27)\, h^{-2} = {}^\dagger 0.0499(22)$	[2,3]
cold dark matter density of the universe	$\Omega_{cdm} = \rho_{cdm}/\rho_{crit}$	$^\ddagger 0.1198(26)\, h^{-2} = {}^\dagger 0.265(11)$	[2,3]
100 × approx to r_*/D_A	$100 \times \theta_{MC}$	$^\ddagger 1.0413(6)$	[2,3]
reionization optical depth	τ	$^\ddagger 0.091^{+0.013}_{-0.014}$	[2,3]
scalar spectral index	n_s	$^\ddagger 0.958(7)$	[2,3]
ln pwr primordial curvature pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger 3.090(25)$	[2,3]

1. Physical Constants

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	$299\,792\,458\ \mathrm{m\ s^{-1}}$	exact*
Planck constant	h	$6.626\,069\,57(29)\times10^{-34}\ \mathrm{J\ s}$	44
Planck constant, reduced	$\hbar \equiv h/2\pi$	$1.054\,571\,726(47)\times10^{-34}\ \mathrm{J\ s}$	44
		$= 6.582\,119\,28(15)\times10^{-22}\ \mathrm{MeV\ s}$	22
electron charge magnitude	e	$1.602\,176\,565(35)\times10^{-19}\ \mathrm{C} = 4.803\,204\,50(11)\times10^{-10}\ \mathrm{esu}$	22, 22
conversion constant	$\hbar c$	$197.326\,9718(44)\ \mathrm{MeV\ fm}$	22
conversion constant	$(\hbar c)^2$	$0.389\,379\,338(17)\ \mathrm{GeV^2\ mbarn}$	44
electron mass	m_e	$0.510\,998\,928(11)\ \mathrm{MeV}/c^2 = 9.109\,382\,91(40)\times10^{-31}\ \mathrm{kg}$	22, 44
proton mass	m_p	$938.272\,046(21)\ \mathrm{MeV}/c^2 = 1.672\,621\,777(74)\times10^{-27}\ \mathrm{kg}$	22, 44
		$= 1.007\,276\,466\,812(90)\ \mathrm{u} = 1836.152\,672\,45(75)\ m_e$	0.089, 0.41
deuteron mass	m_d	$1875.612\,859(41)\ \mathrm{MeV}/c^2$	22
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	$931.494\,061(21)\ \mathrm{MeV}/c^2 = 1.660\,538\,921(73)\times10^{-27}\ \mathrm{kg}$	22, 44
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	$8.854\,187\,817\ldots\times10^{-12}\ \mathrm{F\ m^{-1}}$	exact
permeability of free space	μ_0	$4\pi\times10^{-7}\ \mathrm{N\ A^{-2}} = 12.566\,370\,614\ldots\times10^{-7}\ \mathrm{N\ A^{-2}}$	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	$7.297\,352\,5698(24)\times10^{-3} = 1/137.035\,999\,074(44)^{\dagger}$	0.32, 0.32
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,3267(27)\times10^{-15}\ \mathrm{m}$	0.97
(e^- Compton wavelength)/2π	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	$3.861\,592\,6800(25)\times10^{-13}\ \mathrm{m}$	0.65
Bohr radius ($m_{\mathrm{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	$0.529\,177\,210\,92(17)\times10^{-10}\ \mathrm{m}$	0.32
wavelength of 1 eV/c particle	$hc/(1\ \mathrm{eV})$	$1.239\,841\,930(27)\times10^{-6}\ \mathrm{m}$	22
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	$13.605\,692\,53(30)\ \mathrm{eV}$	22
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	$0.665\,245\,8734(13)\ \mathrm{barn}$	1.9
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\,381\,8066(38)\times10^{-11}\ \mathrm{MeV\ T^{-1}}$	0.65
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\,451\,2605(22)\times10^{-14}\ \mathrm{MeV\ T^{-1}}$	0.71
electron cyclotron freq./field	$\omega^e_{\mathrm{cycl}}/B = e/m_e$	$1.758\,820\,088(39)\times10^{11}\ \mathrm{rad\ s^{-1}\ T^{-1}}$	22
proton cyclotron freq./field	$\omega^p_{\mathrm{cycl}}/B = e/m_p$	$9.578\,833\,58(21)\times10^{7}\ \mathrm{rad\ s^{-1}\ T^{-1}}$	22
gravitational constant‡	G_N	$6.673\,84(80)\times10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$	1.2×10^5
		$= 6.708\,37(80)\times10^{-39}\ \hbar c\ (\mathrm{GeV}/c^2)^{-2}$	1.2×10^5
standard gravitational accel.	g_N	$9.806\,65\ \mathrm{m\ s^{-2}}$	exact
Avogadro constant	N_A	$6.022\,141\,29(27)\times10^{23}\ \mathrm{mol^{-1}}$	44
Boltzmann constant	k	$1.380\,6488(13)\times10^{-23}\ \mathrm{J\ K^{-1}}$	910
		$= 8.617\,3324(78)\times10^{-5}\ \mathrm{eV\ K^{-1}}$	910
molar volume, ideal gas at STP	$N_A k(273.15\ \mathrm{K})/(101\,325\ \mathrm{Pa})$	$22.413\,968(20)\times10^{-3}\ \mathrm{m^3\ mol^{-1}}$	910
Wien displacement law constant	$b = \lambda_{\mathrm{max}}T$	$2.897\,7721(26)\times10^{-3}\ \mathrm{m\ K}$	910
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	$5.670\,373(21)\times10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$	3600
Fermi coupling constant**	$G_F/(\hbar c)^3$	$1.166\,378\,7(6)\times10^{-5}\ \mathrm{GeV^{-2}}$	500
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\mathrm{MS}}$)	$0.231\,26(5)^{\dagger\dagger}$	2.2×10^5
$W^\pm$ boson mass	m_W	$80.385(15)\ \mathrm{GeV}/c^2$	1.9×10^5
Z^0 boson mass	m_Z	$91.1876(21)\ \mathrm{GeV}/c^2$	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	$0.1185(6)$	5.1×10^6

$\pi = 3.141\,592\,653\,589\,793\,238$ $\mathrm{e} = 2.718\,281\,828\,459\,045\,235$ $\gamma = 0.577\,215\,664\,901\,532\,861$

1 in $\equiv$ 0.0254 m 1 G $\equiv 10^{-4}$ T 1 eV $= 1.602\ 176\ 565(35)\times10^{-19}$ J kT at 300 K $= [38.681\ 731(35)]^{-1}$ eV

1 Å $\equiv$ 0.1 nm 1 dyne $\equiv 10^{-5}$ N 1 eV/$c^2 = 1.782\ 661\ 845(39)\times10^{-36}$ kg 0 °C $\equiv$ 273.15 K

1 barn $\equiv 10^{-28}$ m^2 1 erg $\equiv 10^{-7}$ J $2.997\ 924\ 58\times10^9$ esu = 1 C 1 atmosphere $\equiv$ 760 Torr $\equiv$ 101 325 Pa

Physical quantity	Name of unit	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
Derived units with special names		
plane angle	radian	rad
solid angle	steradian	sr
frequency	hertz	Hz
energy	joule	J
force	newton	N
pressure	pascal	Pa
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T
luminous flux	lumen	lm
illuminance	lux	lx
celsius temperature	degree celsius	°C
activity (of a radioactive source)*	becquerel	Bq
absorbed dose (of ionizing radiation)*	gray	Gy
dose equivalent*	sievert	Sv

2. Astrophysical Constants and Parameters

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	exact[4]
Newtonian gravitational constant	G_N	$6.673\,8(8) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1,5]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,93(7) \times 10^{19}$ GeV/c^2 $= 2.176\,51(13) \times 10^{-8}$ kg	[1]
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,20(10) \times 10^{-35}$ m	[1]
standard gravitational acceleration	g_N	$9.806\,65$ m s	exact[1]
jansky (flux density)	Jy	10^{-26} W m^{-2} Hz^{-1}	definition
tropical year (equinox to equinox) (2011)	yr	$31\,556\,925.2$ s $\approx \pi \times 10^7$ s	[6]
sidereal year (fixed star to fixed star) (2011)		$31\,558\,149.8$ s $\approx \pi \times 10^7$ s	[6]
mean sidereal day (2011) (time between vernal equinox transits)		$23^{\mathrm{h}}\,56^{\mathrm{m}}\,04\overset{\mathrm{s}}{.}090\,53$	[6]
astronomical unit	au	$149\,597\,870\,700$ m	exact [7]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,581\,49 \times 10^{16}$ m $= 3.262\ldots$ ly	exact [8]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,077(2)$ km	[9]
Solar mass	$M_\odot$	$1.988\,5(2) \times 10^{30}$ kg	[10]
Solar equatorial radius	$R_\odot$	$6.9551(4) \times 10^8$ m	[11]
Solar luminosity	$L_\odot$	3.828×10^{26} W	[12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,055\,94(2)$ mm	[13]
Earth mass	$M_\oplus$	$5.972\,6(7) \times 10^{24}$ kg	[14]
Earth mean equatorial radius	$R_\oplus$	$6.378\,137 \times 10^6$ m	[6]
luminosity conversion (deprecated)	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{\mathrm{bol}}}$ W	[15]
		(M_{bol} = absolute bolometric magnitude = bolometric magnitude at 10 pc)	
flux conversion (deprecated)	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_{\mathrm{bol}}}$ W m^{-2}	from above
		(m_{bol} = apparent bolometric magnitude)	
ABsolute monochromatic magnitude	AB	$-2.5\,\log_{10} f_\nu - 56.10$ (for f_ν in W m^{-2} Hz^{-1}) $= -2.5\,\log_{10} f_\nu + 8.90$ (for f_ν in Jy)	[16]
Solar angular velocity around the Galactic center	Θ_0/R_0	30.3 ± 0.9 km s^{-1} kpc^{-1}	[17]
Solar distance from Galactic center	R_0	$8.4(6)$ kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16)$ km s^{-1}	[17]
local disk density	ρ_{disk}	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	[19]
local dark matter density	ρ_χ	canonical value 0.3 GeV/c^2 cm^{-3} within factor 2–3	[20]
escape velocity from Galaxy	v_{esc}	498 km/s $< v_{\mathrm{esc}} <$ 608 km/s	[21]
present day CMB temperature	T_0	$2.7255(6)$ K	[22,23]
present day CMB dipole amplitude		$3.355(8)$ mK	[22,24]
Solar velocity with respect to CMB		369(1) km/s towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,24]
Local Group velocity with respect to CMB	v_{LG}	627(22) km/s towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,24]
entropy density/Boltzmann constant	s/k	$2\,891.2\ (T/2.7255)^3$ cm^{-3}	[25]
number density of CMB photons	n_γ	$410.7 (T/2.7255)^3$ cm^{-3}	[25]
baryon-to-photon ratio	$\eta = n_{\mathrm{b}}/n_\gamma$	$6.05(7) \times 10^{-10}$ (CMB)	[26]
		$5.7 \times 10^{-10} \le \eta \le 6.7 \times 10^{-10}$ (95% CL)	[26]
present day Hubble expansion rate	H_0	$100\ h$ km s^{-1} Mpc^{-1} $= h \times (9.777\,752$ Gyr$)^{-1}$	[29]
scale factor for Hubble expansion rate	h	$0.673(12)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26}\,h^{-1}$ m $= 1.37(2) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51}\,h^{-2}$ m^2 $= 6.3(2) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\mathrm{crit}} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\ M_\odot$Mpc^{-3} $= 1.878\,47(23) \times 10^{-29}\,h^2$ g cm^{-3} $= 1.053\,75(13) \times 10^{-5}\,h^2$ (GeV/c^2) cm^{-3}	
number density of baryons	n_{b}	$2.482(32) \times 10^{-7}$ cm^{-3}	[2,3,27,28]
		$(2.1 \times 10^{-7} < n_{\mathrm{b}} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	$\eta \times n_\gamma$

SI prefixes

10^{24}	yotta	(Y)
10^{21}	zetta	(Z)
10^{18}	exa	(E)
10^{15}	peta	(P)
10^{12}	tera	(T)
10^{9}	giga	(G)
10^{6}	mega	(M)
10^{3}	kilo	(k)
10^{2}	hecto	(h)
10	deca	(da)
10^{-1}	deci	(d)
10^{-2}	centi	(c)
10^{-3}	milli	(m)
10^{-6}	micro	(μ)
10^{-9}	nano	(n)
10^{-12}	pico	(p)
10^{-15}	femto	(f)
10^{-18}	atto	(a)
10^{-21}	zepto	(z)
10^{-24}	yocto	(y)

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

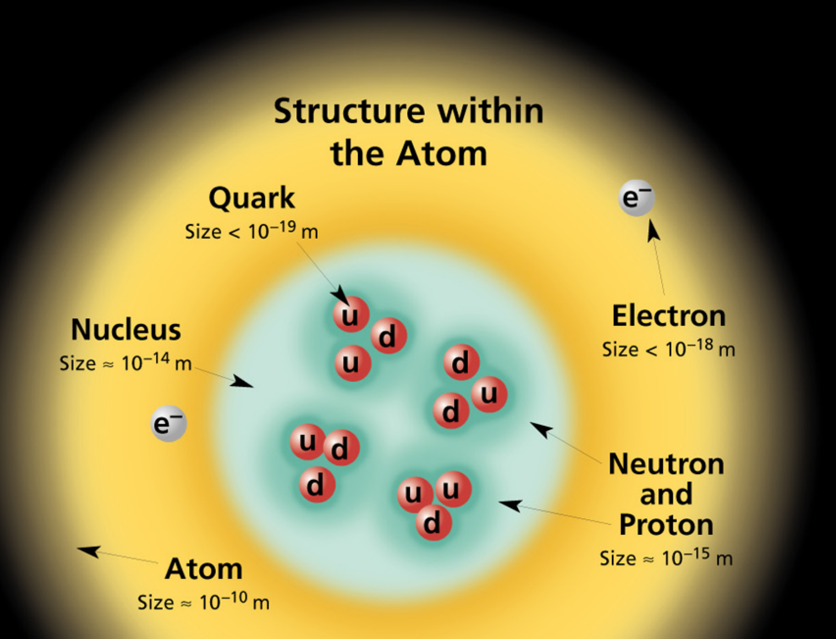
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

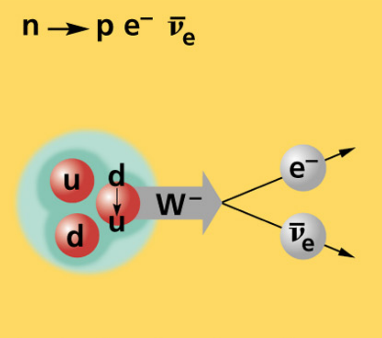
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

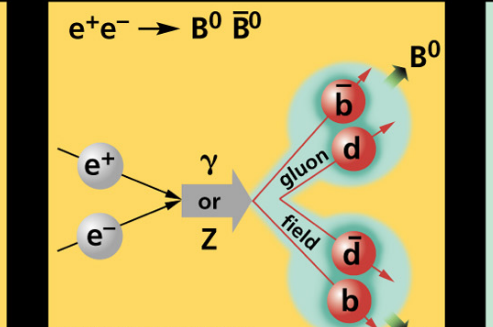
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

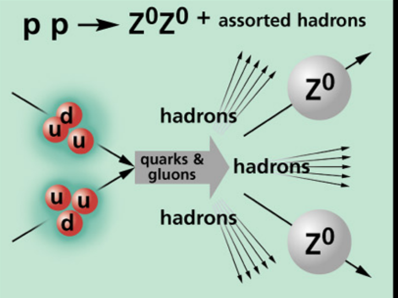
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

http://CPEPweb.org

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\text{x}10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

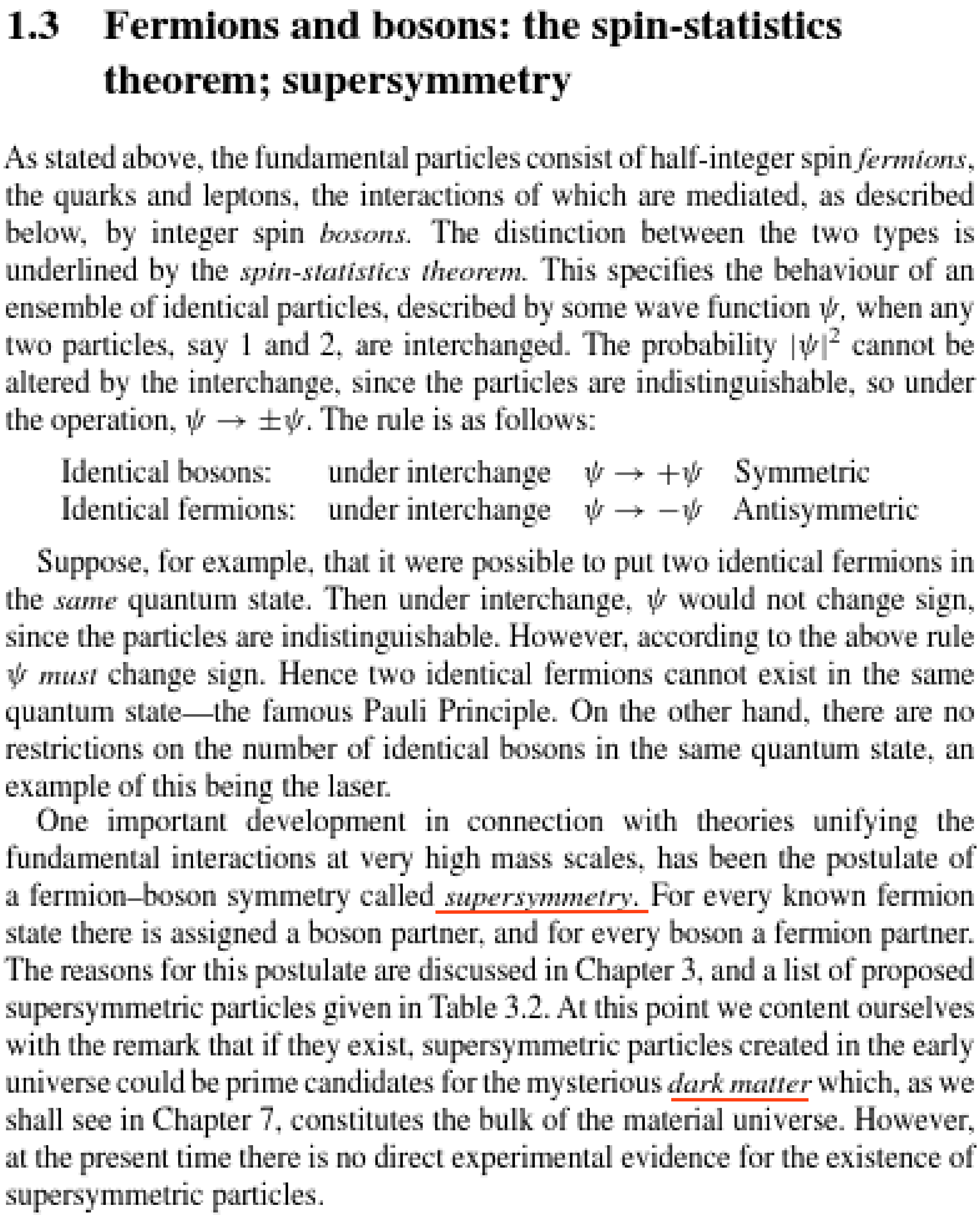
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.



1.3 Fermions and bosons: the spin-statistics theorem; supersymmetry

As stated above, the fundamental particles consist of half-integer spin *fermions*, the quarks and leptons, the interactions of which are mediated, as described below, by integer spin *bosons*. The distinction between the two types is underlined by the *spin-statistics theorem*. This specifies the behaviour of an ensemble of identical particles, described by some wave function ψ, when any two particles, say 1 and 2, are interchanged. The probability $|\psi|^2$ cannot be altered by the interchange, since the particles are indistinguishable, so under the operation, $\psi \to \pm\psi$. The rule is as follows:

Identical bosons:	under interchange	$\psi \to +\psi$	Symmetric
Identical fermions:	under interchange	$\psi \to -\psi$	Antisymmetric

Suppose, for example, that it were possible to put two identical fermions in the *same* quantum state. Then under interchange, ψ would not change sign, since the particles are indistinguishable. However, according to the above rule ψ *must* change sign. Hence two identical fermions cannot exist in the same quantum state—the famous Pauli Principle. On the other hand, there are no restrictions on the number of identical bosons in the same quantum state, an example of this being the laser.

One important development in connection with theories unifying the fundamental interactions at very high mass scales, has been the postulate of a fermion–boson symmetry called *supersymmetry*. For every known fermion state there is assigned a boson partner, and for every boson a fermion partner. The reasons for this postulate are discussed in Chapter 3, and a list of proposed supersymmetric particles given in Table 3.2. At this point we content ourselves with the remark that if they exist, supersymmetric particles created in the early universe could be prime candidates for the mysterious *dark matter* which, as we shall see in Chapter 7, constitutes the bulk of the material universe. However, at the present time there is no direct experimental evidence for the existence of supersymmetric particles.

From D. Perkins, *Particle Astrophysics*, 2nd Edition (2008)

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

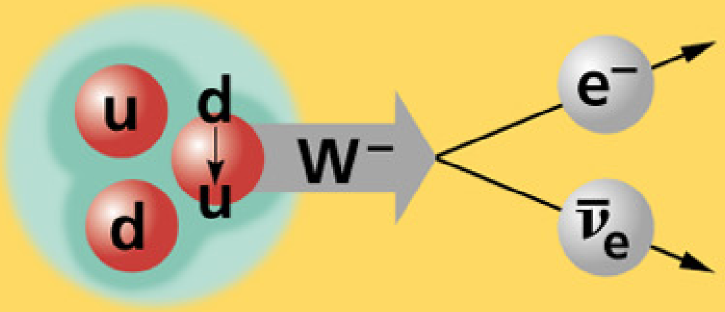
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

PROPERTIES OF THE INTERACTIONS

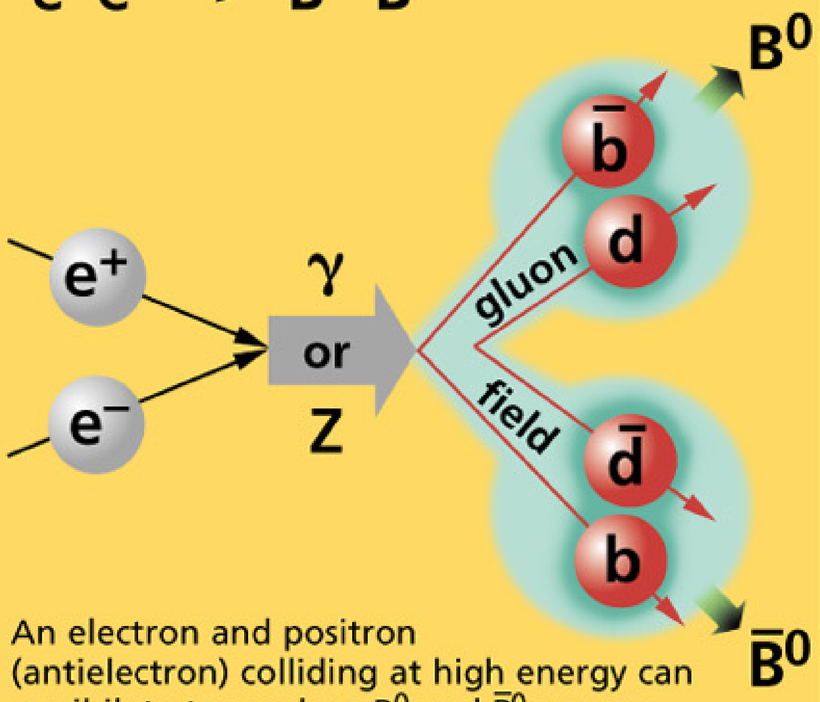
Property / Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for **two u quarks at:** 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for **two protons in nucleus**	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

$n \rightarrow p\, e^-\, \bar{\nu}_e$



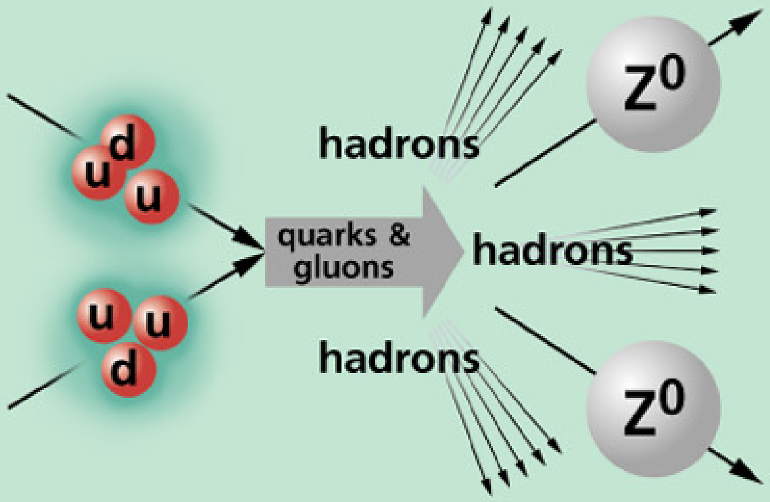
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

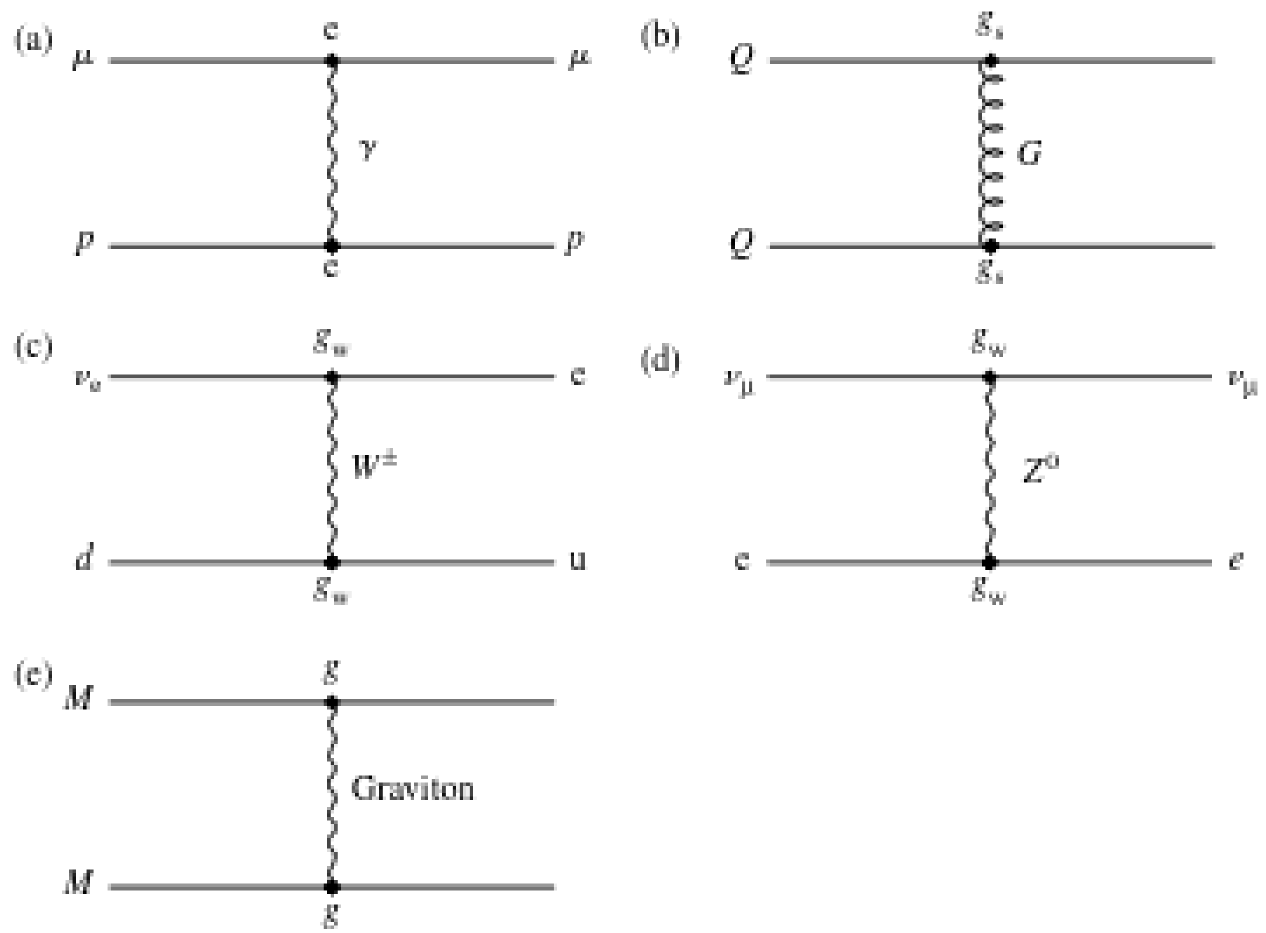
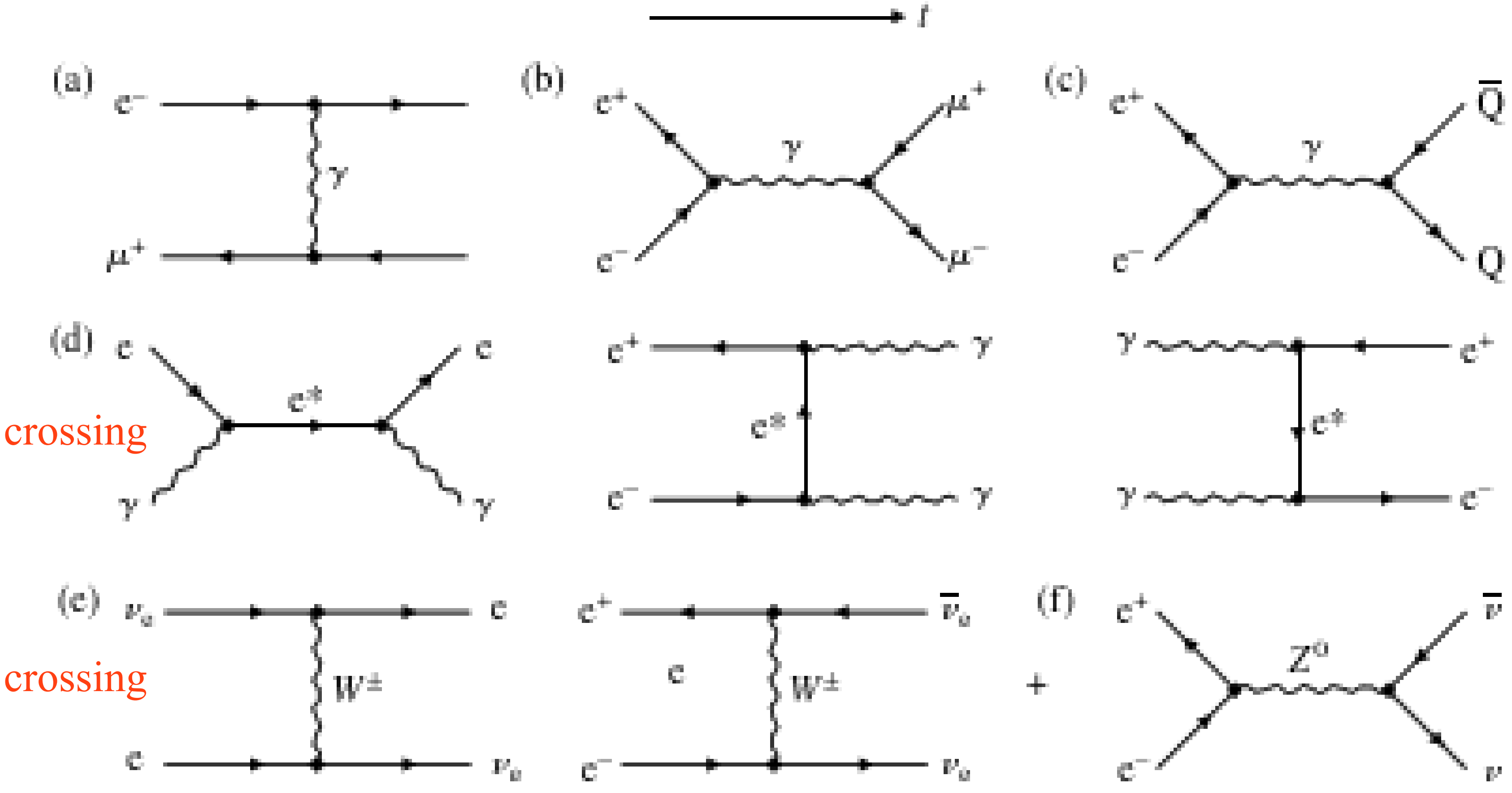


Fig. 1.3 Diagrams representing examples of single quantum-exchange processes in electromagnetic, strong, weak, and gravitational interactions. (a) The electromagnetic interaction between a muon μ and proton p, *via* photon (γ) exchange with coupling e. (b) The strong interaction between quarks Q *via* gluon (G) exchange with coupling g_s. (c) The weak interaction involving charged W boson exchange, transforming an electron-neutrino ν_e to an electron e, and a neutron (quark composition *ddu*) to a proton (*duu*). (d) The weak interaction involving neutral Z boson exchange, showing a muon–neutrino ν_μ scattering from an electron, e. In both (c) and (d), the couplings have been denoted g_w, but there are different numerical coefficients (of order unity) associated with the W and Z exchanges, as described in Chapter 3. (e) Gravitational interaction between two masses M, mediated by graviton (g) exchange. For macroscopic masses, multiple graviton exchanges will be involved.



crossing

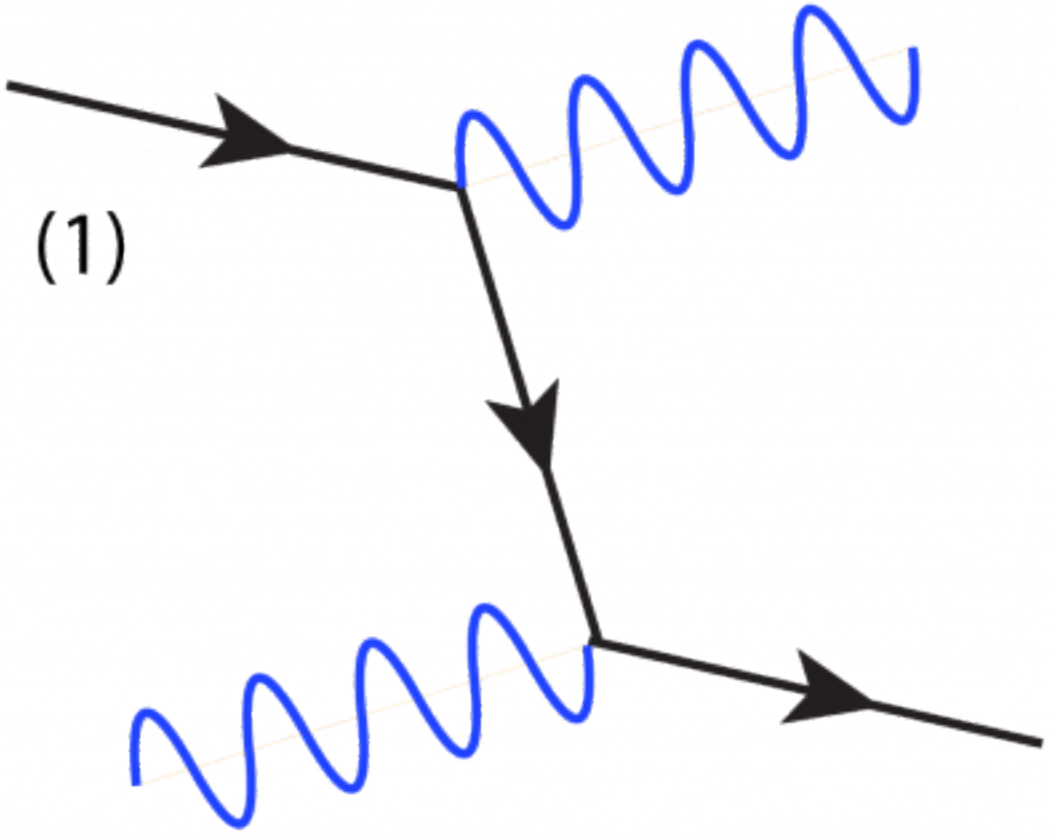
crossing

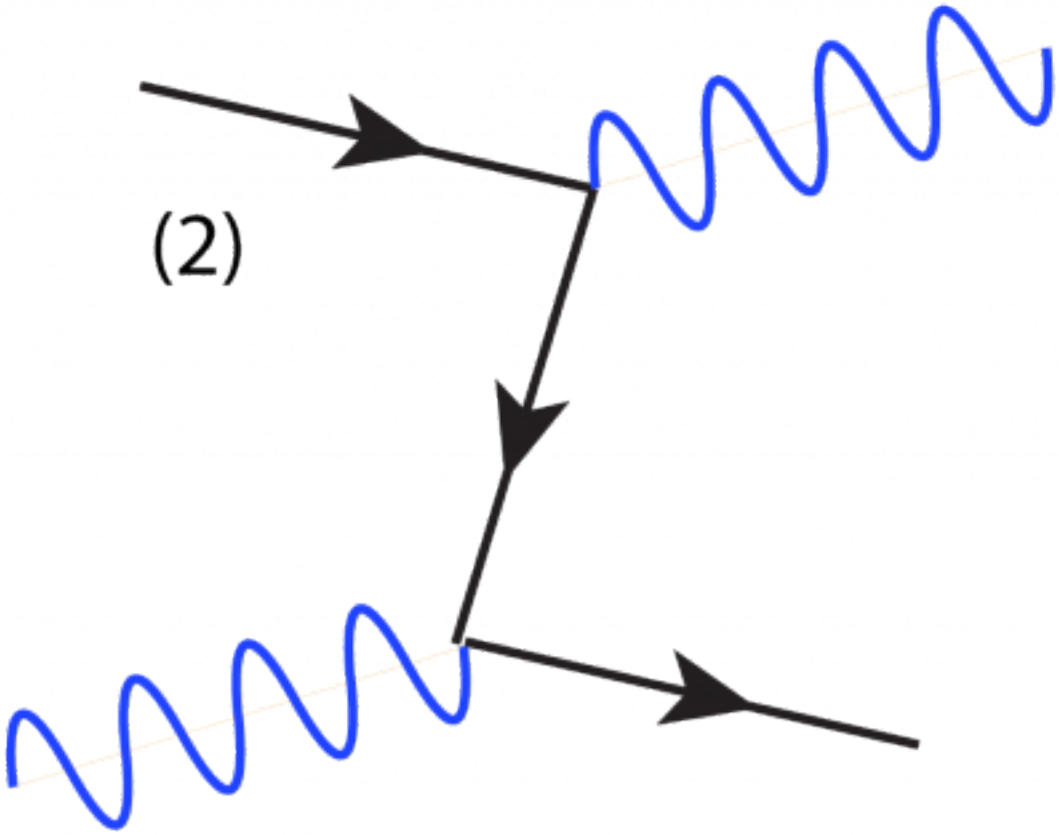
Fig. 1.9 Feynman diagrams for various elementary two-body to two-body reactions. In these diagrams. Time flows from left to right. The convention is that right-pointing arrows denote particles, while left-pointing arrows denote antiparticles. Diagrams (a) to (d) refer to electromagnetic interactions, and (e) and (f) to weak interactions. (a) $e^-\mu^+ \to e^-\mu^+$; (b) $e^+e^- \to \mu^+\mu^-$; (c) $e^+e^- \to Q\bar{Q} \to$ hadrons; (d) $e\gamma \to e\gamma$, $e^+e^- \to \gamma\gamma$, $\gamma\gamma \to e^+e^-$; (e) $\nu e \to \nu e$; (f) $e^+e^- \to \nu\bar{\nu}$.

From D. Perkins,
Particle Astrophysics,
2nd Edition (2008)

Feynman Diagrams for Compton Scattering

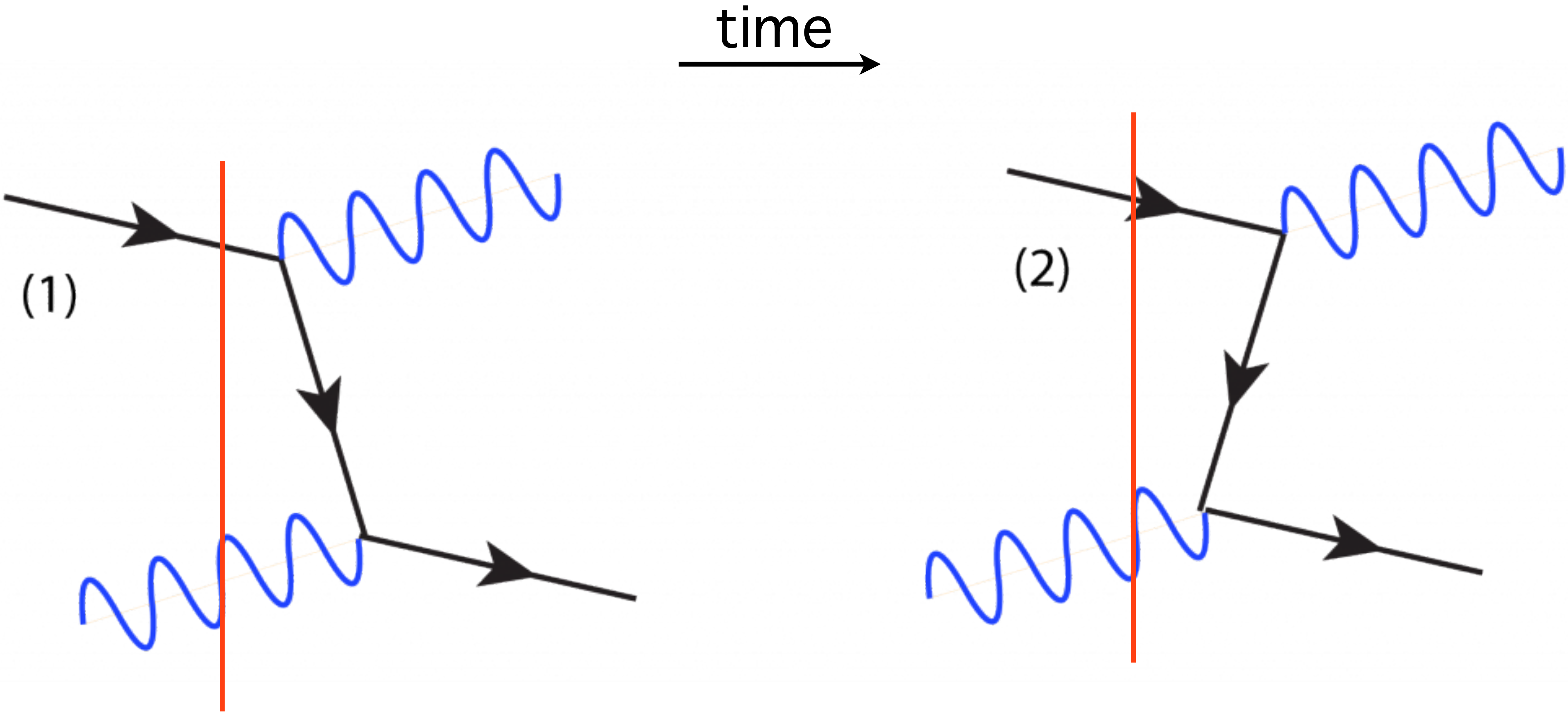
time →


(1)


(2)

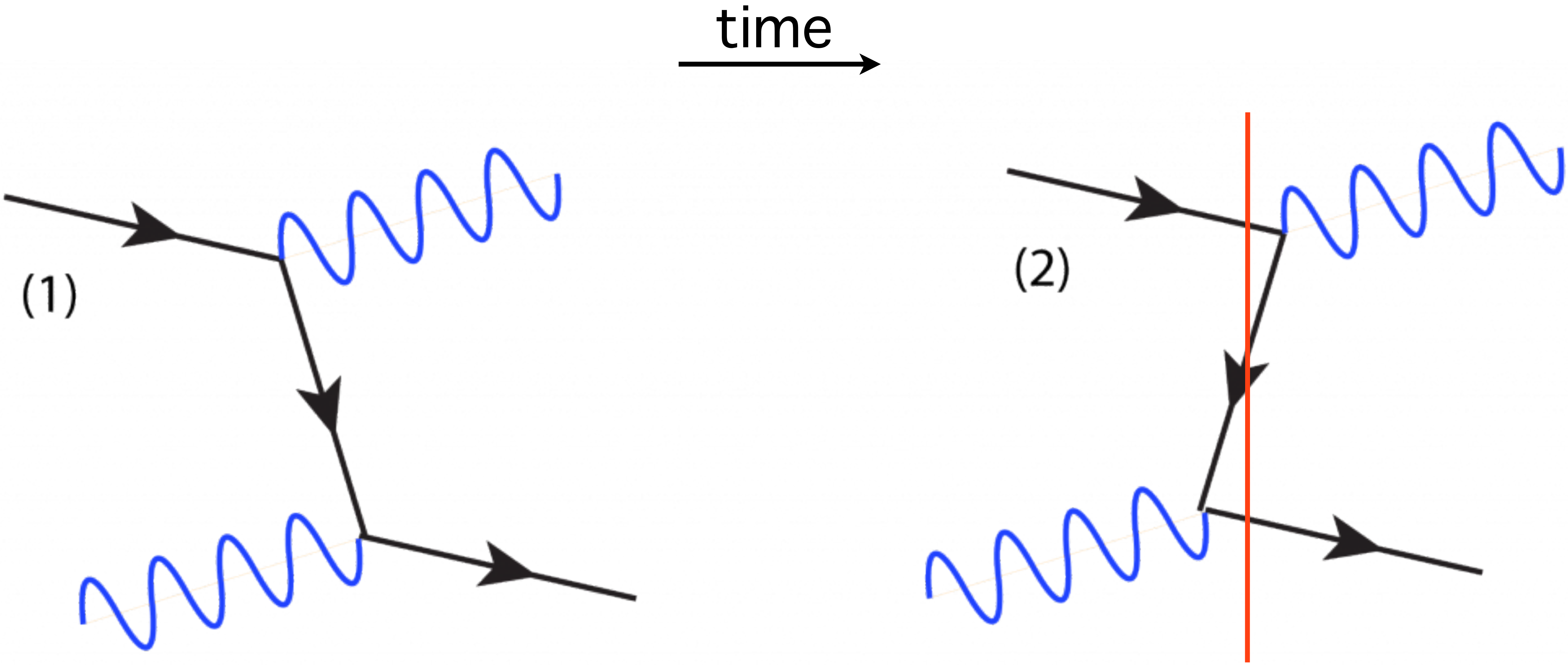
Feynman diagrams always have to include both time orders of the absorption and emission of the photons, since there is no way to tell which order actually happens.

Feynman Diagrams for Compton Scattering



Before the interaction (and also after it) there is one electron (e-) and one photon.

Feynman Diagrams for Compton Scattering



At this time, the line going backwards in time must correspond to a positron (e+), since otherwise one e- would have turned into three e-, violating charge conservation.

Quark Feynman Diagrams for Hadronic Reactions