The standard model

(particles + cosmo)

Or:

100 a of QM, 50 a of SM

getting in and

getting out

K. Kajantie Hyytiälä, 22 March 2025

Tong: damtp.cam.ac.uk/user/tong/standardmodel.html
Willenbrock: hep-ph/0410370
Quevedo-Schachner: 2409.09211

Woit blog

Standard model is known since 1975 (ples) and 1983 (inflat cosmo)

Mi=0, chirality SSB

1973 1967 1947

$$U(3)^5 \rightarrow SU(3) \times SU(2) \times U(1) \qquad \Lambda CDM + \text{radiation}$$

$$g_3 \quad g_2 \quad g_1 \qquad 3$$

Masses/v, CKM $u\ c\ t\ d\ s\ b \quad \theta_{12}\ \theta_{23}\ \theta_{31}\ \delta \qquad 10$

Mass PMNS $e\ \mu\ \tau\ \nu_e\ \nu_\mu\ \nu_\tau \quad \bar{\theta}_{12}\ \bar{\theta}_{23}\ \bar{\theta}_{31}\ \bar{\delta} \qquad 10$

Lepton confinement? SU(2) is confining

$$m_H \qquad v \qquad \Lambda^{1/2} \sim H_0 \qquad 3$$

26 parameters, neutrino sector not fully known

Neutrino is left-handed, only ν_L in SM. Adding ν_R is BSM physics. Dark matter?

Biblical pic!

Inflationary FRW cosmology for $10^{-52} < a < 1$ 1980-

-+++

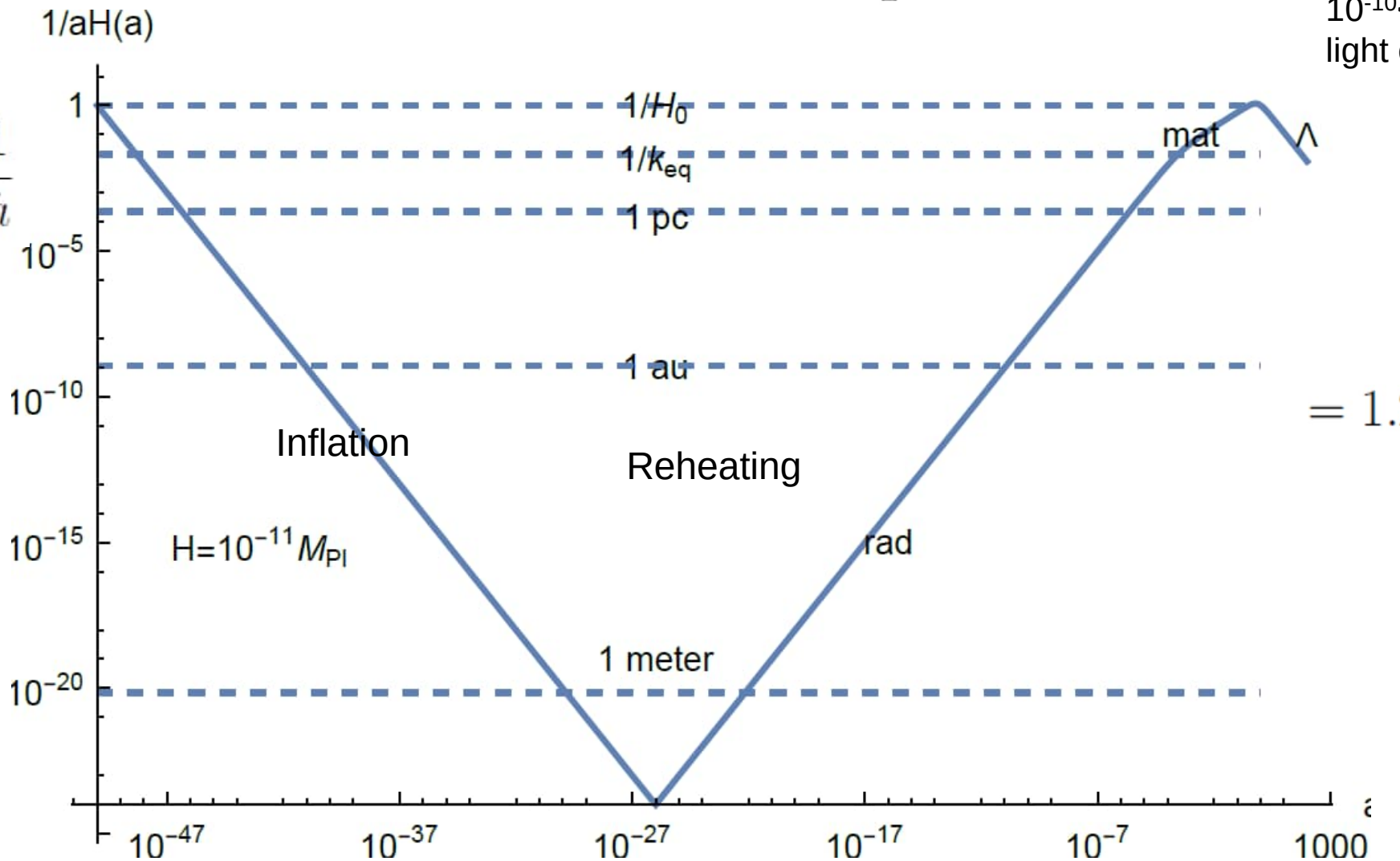
My first 8 cosmo lectures at Nordita CPH, May 1981

$$a \sim \frac{2.7\,\mathrm{K}}{T}$$

$10^{-10}<a<1$ is tested in light elem nucl synth

$$\frac{1}{a\,H(a)} = \frac{1}{\dot{a}}$$

Comoving Hubble



$$M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}}$$

$$= 1.22 \cdot 10^{19}\mathrm{GeV}/c^2$$

= 543kWh

Expansion factor a(t)

Cosmological constant

Empty slot for a constant term!

Expansion in $1/M_{Pl}$, eff theory

$$\int d^4x\sqrt{-g}\left[-\frac{\Lambda_2}{8\pi G}+\frac{R}{16\pi G}+a_1R^2+a_2R_{\mu\nu}R^{\mu\nu}+a_3\,8\pi G R^3+\dots\right]$$

$$H^2=\left(\frac{\dot a}{a}\right)^2=\frac{\Lambda_2}{3}+\frac{8\pi G}{3}\rho$$

Friedman 1922
Finds $H^{-1}_0 = 10^{10}$a

Sign of Λ_2 ! dS vs AntidS

$$\Lambda_2=3\Omega_\Lambda H_0^2 \quad H_0^{-1}=h^{-1}\,9.7781\,\mathrm{Ga}$$

2.72K = 0.235 meV !

$$\Lambda_4=\frac{\Lambda_2}{8\pi G}=\Omega_\Lambda\rho_{\rm cr}=0.7h^2(3.00\,\mathrm{meV})^4$$

CC is basically size or energy density of present Universe. Understanding it is understanding creation of U!

Btw, $R^U_{\rm Schw}=2GM_U=R_U=H_0^{-1}, \qquad S_U\sim(M_U/M_{Pl})^2\approx 10^{122}$

Particle physics around 1960

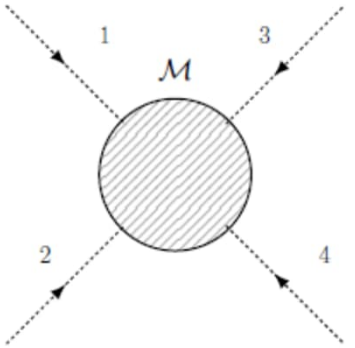
Ples: $e^-, \gamma, p, n, e^+, \pi, \mu^\pm, \quad K, \rho, \omega, \phi, N^\star, .., \nu = ?$

Theory: relativity, QM, QED with its divergences, Fermi theory (n decay) ,
no theory of strong interactions

Exp: New accelerators (Bevalac, Brookhaven, Cern), detectors (bubble chambers)
lots of new data (after 1965):

$$p + p \to p + \Delta^+ \to p + n + \pi^+ \qquad \pi^- + p \to \pi^0 + n$$

Need 2to2 scattering amplitude A(s,t) ~ A(energy, angle)



One had to do phenomenology: Regge poles, Veneziano model,
string theory…..

No advisors then. I found: Chew's bootstrap

Gamow - Teller – Los Alamos – Fermi – Geoffrey Chew – Gross - Wilczek

Idea: Maybe on could bootstrap the amplitude from general principles by assuming all particles are equal (nuclear democracy). Lots of them!

" Analyticity, unitarity and crossing symmetry as a theory of strong interaction dynamics"

(title of my licentiate thesis in 1962)

Total failure: even today with QCD known
there is no first principle way of computing A(s,t)

But, Chew's bootstrap led to a new (2020-) bootstrap:

Keep the same general principles, Lorentz (or Poincare), analyticity (causality), unitarity (prob < 1), locality (action contains A(x)B(x))

QG,quantum gravity, breaks locality (Black Holes!)

Derive constraints for new amplitudes: Start from low energy amp; (e.g.,graviton-graviton) how is its behavior at higher E constrained? 2011.02802, 2011.02957 Useful results!

Maybe string theory will experience the same fate; after 50 years of intense work of O(1000) scientists, no physics results. In 50 years it will be resuscitated in a new disguise which will produce useful results!?

String theory ("the only game in town") was by its proponents hailed as a revolution which would give the SM and many other SMs (multiverse). Failure so far, world is not supersymmetric nor 10 dim

Gauge/Gravity duality, an outgrowth of ST, is an approximate method for solving strongly coupled field ths

As a Nordita fellow in 1963-64
I found a good advisor;

Gunnar Källén, Lund
1926-13.10.1968 Hannover

Plane crash, piloted
by GK himself

QED: $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}[i\gamma^{\mu}(\partial_{\mu} - ieA_{\mu}(x)) + m]\psi(x)$

RADIATIVE CORRECTIONS TO *e-p* SCATTERING COINCIDENCE EXPERIMENTS

BY

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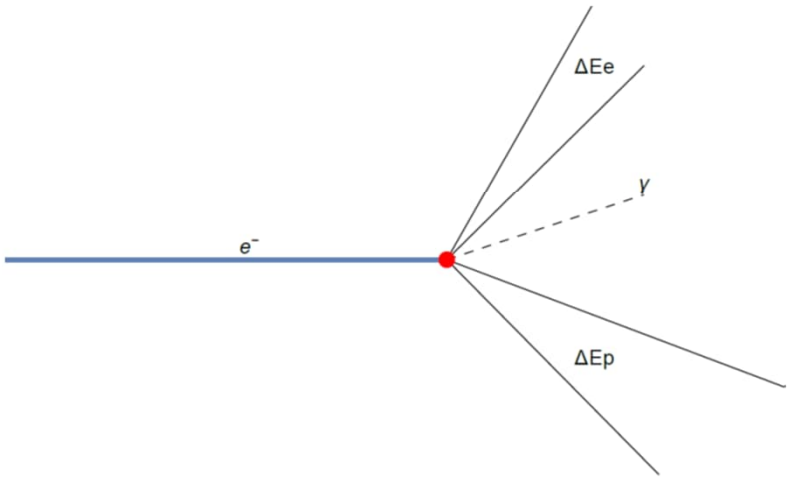

Very messy kinemacs
I ended up writing a
textbook ”Particle
Kinematics, in 1972

Landau pole!

In 1972 papers like this:
started appearing

Asymptotically free
(perturbative UV)
QCD was discovered

Regge poles, reaction
amplitudes were forgotten

Field theory even for
strong interactions!
Confinement?

686

CALT 68-409
AEC RESEARCH AND
DEVELOPMENT REPORT

Advantages of the Color Octet Gluon Picture*

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California Institute of Technology, Pasadena, California 91109

Phys. Letters 47B, 365 (73

ABSTRACT

It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang-Mills gauge model based on colored quarks and color octet gluons.

18. XII. 1973

SM evolved from zero to full bloom in about 1960 - 1980

Experiment: Constantly improving accelerator technology (strong focusing, colliding beams)
New data at 1 GeV – 1000 GeV
CMB, Pulsars, neutrino counting in He, Li,,, cosmo synthesis

Theory: Relativistic quantum field theory, physics of c and h, fully understood Not yet G!

Qualitative progress has seemingly stalled

Building bigger and bigger accelerators seems to be ended; dominant theory ideas, supersymmetry, extra dimensions, string theory, seem to be failures

Main difficulty: Planck scale is awfully far: 10^{3+12+4} GeV

We are at 1 TeV = 10^3 GeV
Hints of phenomena at $10^{12...16}$ GeV
Still 10^4 to Planck

Desert? Want: physics of c, h, G

Crisis? In no way: meaningful difficult problems waiting for solution, new exp/obs data

With SM complete in 1975 one could start an entirely new field, hot and dense QCD, experimentally studied in heavy ion collisions
Quark matter 1983 in Brookhaven really exploded the field. QM84 in Helsinki was actually 83 but the great interest in US (idea of RHIC!) forced shift to BNL

More generally, this became study of elementary particle matter, the $T_{\mu\nu}$ in Einstein
How this evolved in Finland is outlined in mv.helsinki.fi/home/kajantie/hiukkasaine1960-2023.pdf

Much more difficult now that the field is so mature, half a century old

I wonder is Fermi could help us with some theoretical and experimental ideas:

Pauli 1900-1958. Dangerous profession? Bethe 06-05

Fermi's (1901-1954) scientific descendants with Nobel

T. D. Lee(57), Segré, Chamberlain(59), Bethe(67), James Cronin (80),
Rubbia(84), Schwartz, Steinberger(88), Jerome Friedman(90),
Gross, Wilczek(04), Thouless(16)

Scientific genealogy can be studied in;

academictree.org/physics (get a position in a genealogic tree, somewhat disorganised)

genealogy.math.ndsu.nodak.edu (get one table with all immediate descendants, well organised)

Witten:

Name	School	Year	Descendants
Axelrod, Scott	Princeton University	1991	1
Bagger, Jonathan	Princeton University	1983	1
Bar-Natan, Dror	Princeton University	1991	10
Beasley, Christopher	Princeton University	2005	3
Crnkovic, Cedomir	Princeton University	1987	
Gukov, Sergei	Princeton University	2001	5
Kachru, Shamit	Princeton University	1994	17
Rangamani, Mukund	Princeton University	2002	1
Sharpe, Eric	Princeton University	1998	7
Silverstein, Eva	Princeton University	1996	29
Thompson, A	Princeton University	1988	
Vafa, Cumrun	Princeton University	1985	54
Wen, Xiao-Gang	Princeton University	1987	43

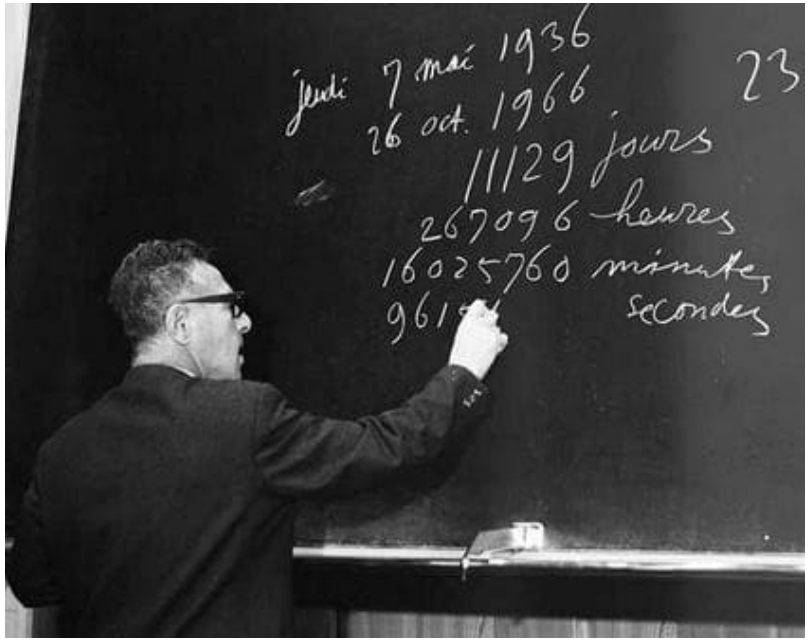
One memory from my time at CERN:

Wim "the human computer" Klein

1912-1986

At CERN/TH 1958-1976 as a computer

Unbelievable mental computational abilities



73rd root of a 500 digit number in 2min43s

Was murdered by an unknown in 1986 in Amsterdam

Getting out: SM in the future

Open questions with no foreseeable answer:

Numerical values of SM parameters. Why do fermion masses vary by 175GeV/meV ~ 10^{14} ?
Absolutely no idea of m_μ/m_e etc. The chain matter-molecules-atoms-nuclei-nucleons-quarks has ended

Group structure SU(3)xSU(2)xU(1) from where? 3 colors, 3 flavors constrained by physics (Pauli, Anomalies
3+3+1 has been tried

Confinement? Prove mathematically that in a theory of rigorously massless gluons the lowest state has a nonzero mass (the Clay Institute 1M$ ”gap problem”)
At finite T for pure glue there is an order parameter for confinement, none for quarks. So maybe confinement is not absolute for quarks
Note also that confinement radius $1/\Lambda$ for SU(3) is 1 fm but ~ 4000 km for weak SU(2)

QG= Quantum Gravity = ? Study black holes from close distance. One can say a lot in effective QG for E << M_{Pl}

$$S_{\mathrm{EFT}} \simeq \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R + a_1R^2 + a_2R_{\mu\nu}R^{\mu\nu}\right]$$

Open questions with a foreseeable answer:

Dark matter, desert up to M_{Pl}
Right handed neutrinos
Sterile neutrinos
Nonpert formulation of SM

3. and 4-Higgs coupling, exotic hadrons, nucleon structure down to very small momenta (EIC), first stars and bhs (J Webb S T)

No end of progress in sight!