“Intro” to Particle Physics

Richard Jacobsson, CERN

Language of science

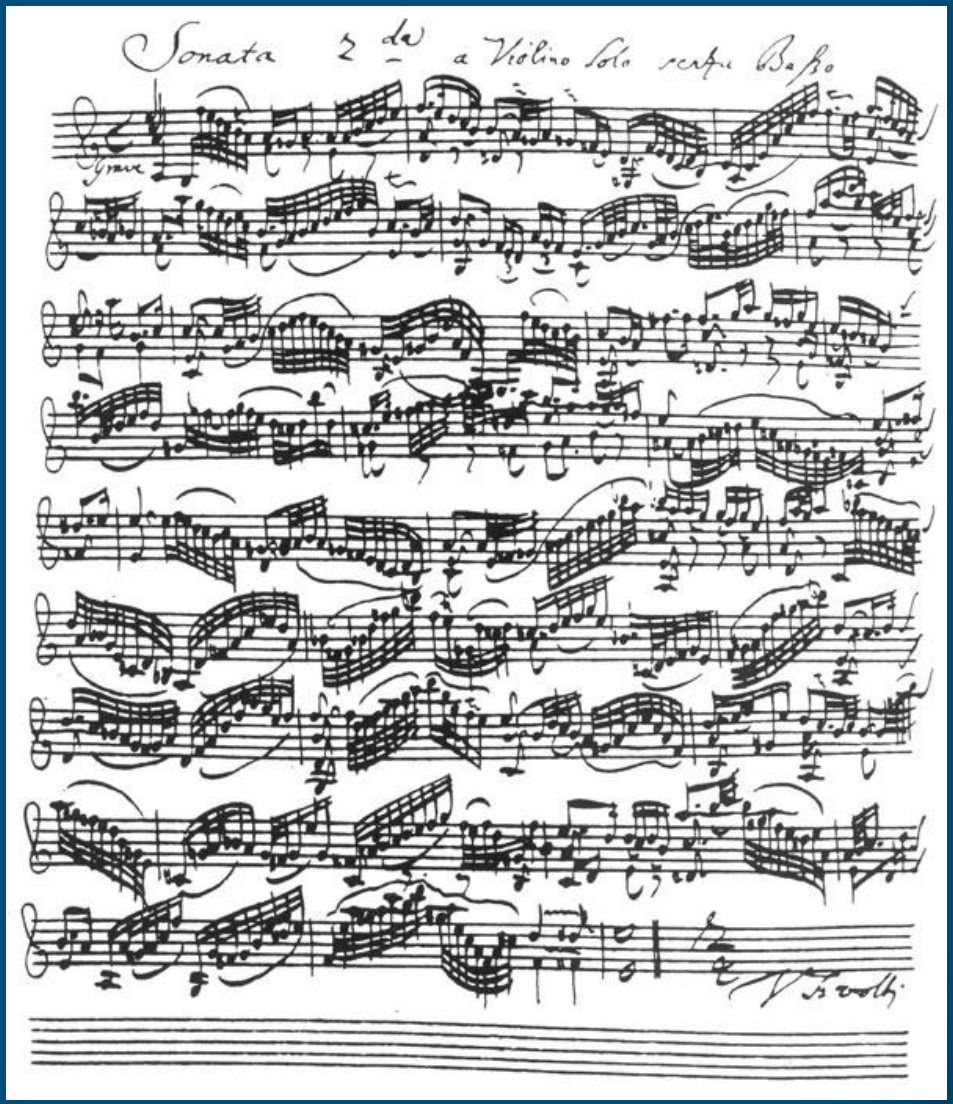
Universe at 0 K – 10^{15}K in one formula?

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \\
&\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - \\
&1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&\tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c^2_w}\bar{X}^0X^0H] + \\
&\tfrac{1-2c^2_w}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
&igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

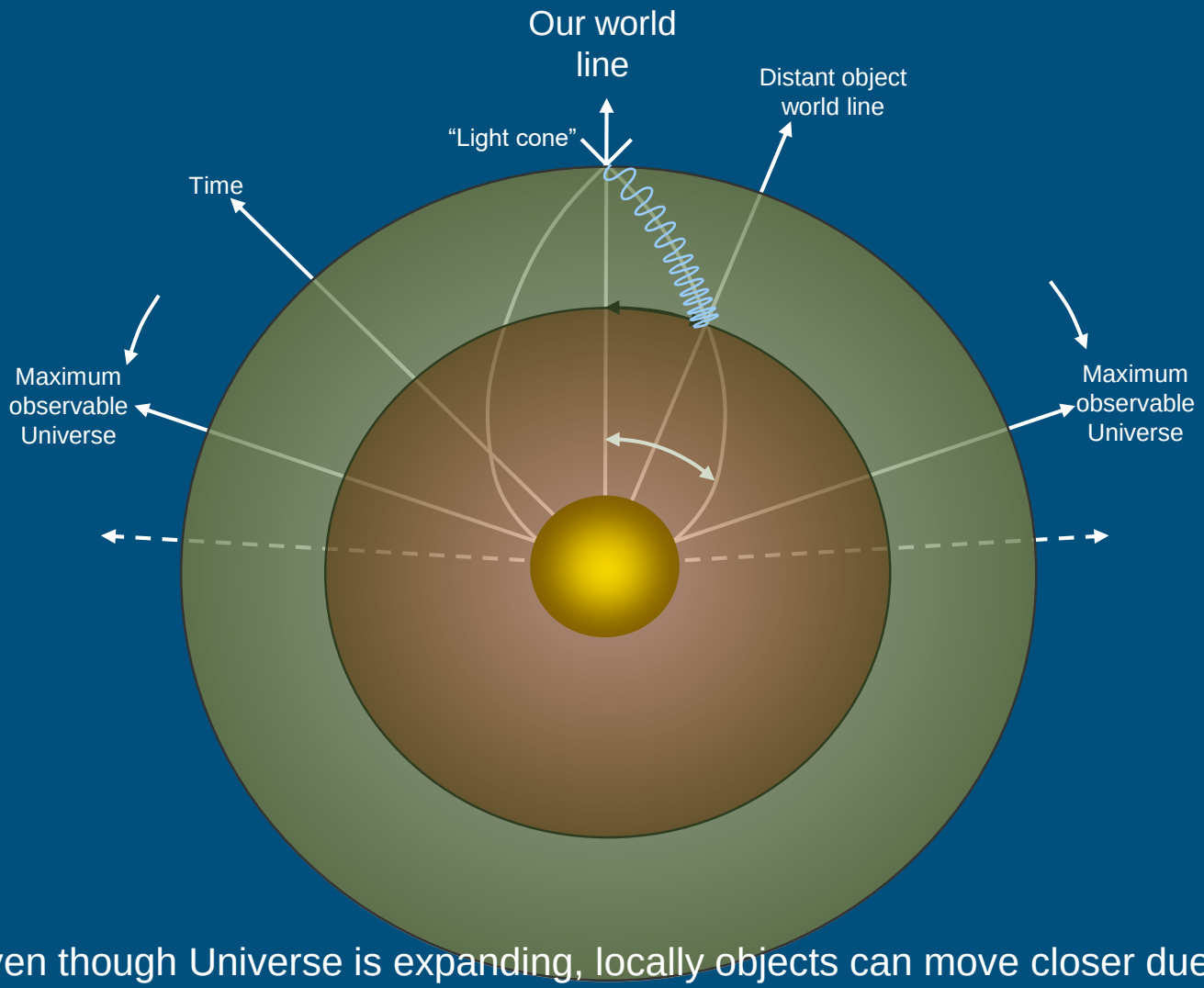
And a few more pages…

Language of science

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$



Expansion and the distorsion of the past



- Even though Universe is expanding, locally objects can move closer due to gravity
- Expansion rate depends on radiation, matter, curvature, cosmological constant

13 800 000 000 (billion) years

Age of the Universe = 3 x Age of Earth !

hic sunt dracones

BIG BANG

hic sunt dracones

Universe becomes transparent
380 000 y.
T= 3000 °C
Size 1/1000

First stars light up
100 million y.
T= 20 °C
Size 1/100

Galaxies form
500 million y.
T= -255 °C
Size 1/6

Expansion rate of the Universe starts to accelerate
~5 billion y.
T=-264 °C
Size 1/3

Birth of the Solar system
9 billion y.
T=-267 °C
Size 1/2

13 October 2016
13.7 billion y.
T=-270 °C
Size 1/1

Time ~zero
T= 100 000 000 000 000 000 000 000 000 000 000 °C

Size 0.000 000 000 000 000 000 000 000 000 000 000 010 m

13 800 000 000 (billion) years

Age of the Universe = 3 x Age of Earth !

hic sunt dracones

BIG BANG

hic sunt dracones

Laws of physics established here

Universe becomes transparent
380 000 y.
T= 3000 °C
Size 1/1000

First stars light up
100 million y.
T= 20 °C
Size 1/100

Galaxies form
500 million y.
T= -255 °C
Size 1/6

Expansion rate of the Universe starts to accelerate
~5 billion y.
T=-264 °C
Size 1/3

Birth of the Solar system
9 billion y.
T=-267 °C
Size 1/2

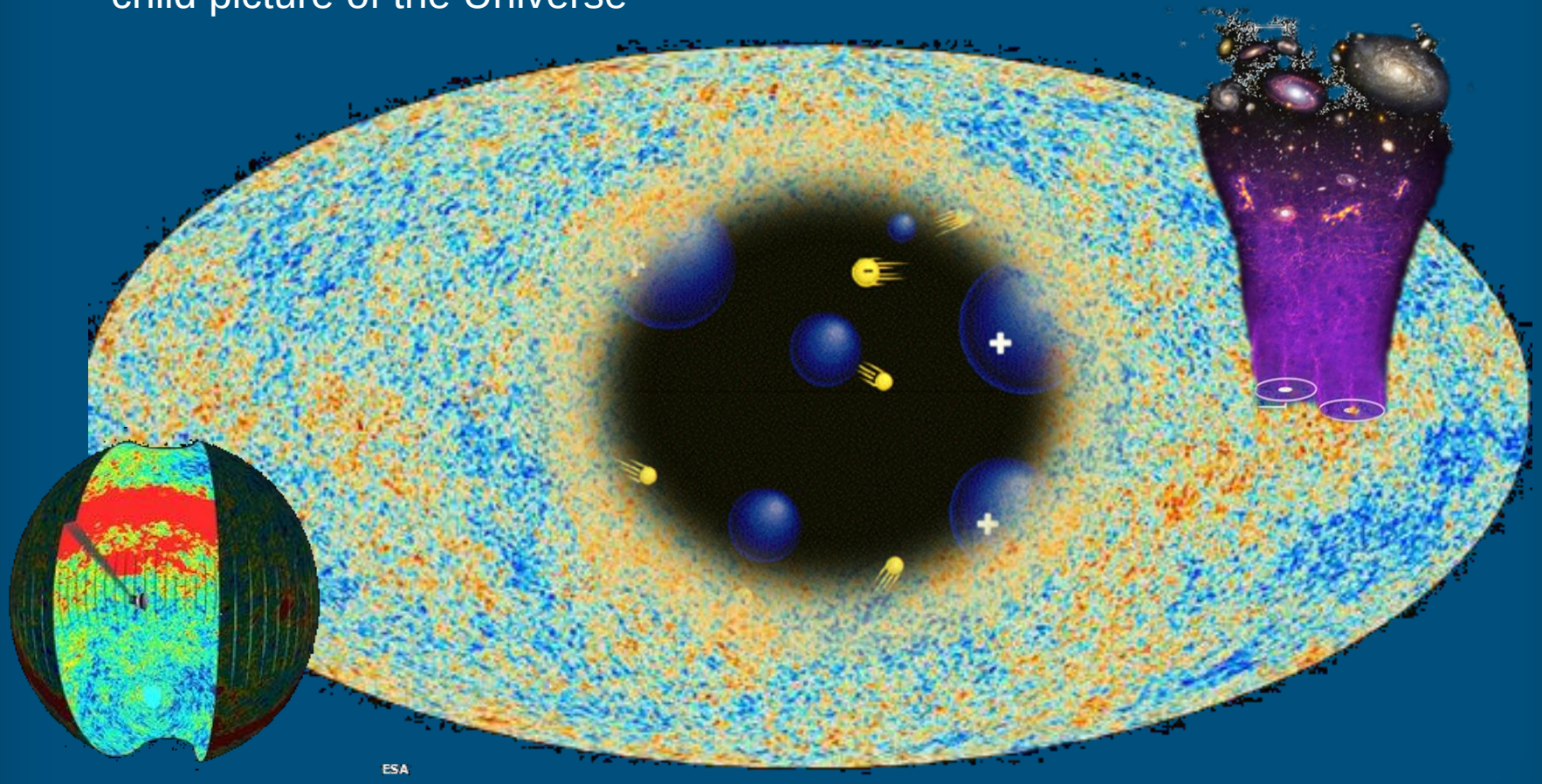
13 October 2016
13.7 billion y.
T=-270 °C
Size 1/1

Time ~zero
T= 100 000 000 000 000 000 000 000 000 000 000 °C

Size 0.000 000 000 000 000 000 000 000 000 000 000 010 m

The Big Bang Afterglow

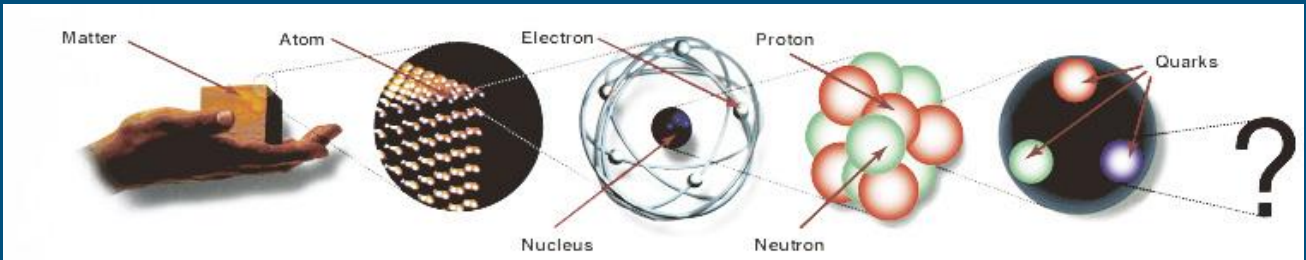
- Universe gets transparent at an age of 380 000 years!
- The Cosmic Microwave Background (CMB) is the first child picture of the Universe



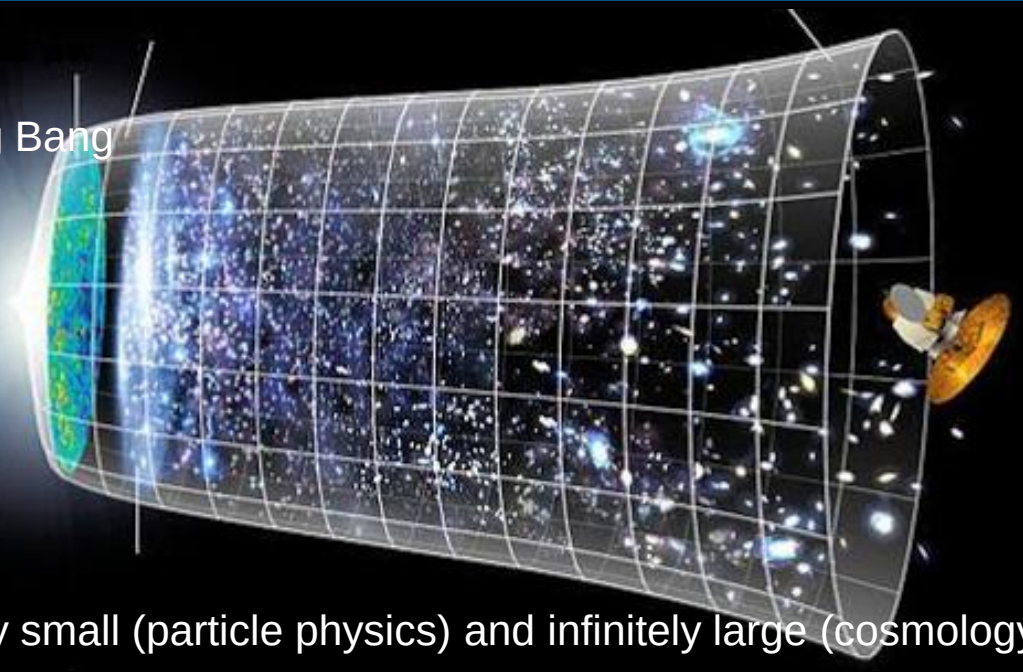
- What is behind the veil?

Particle Physics and Cosmology

- Quest to understand:
  - Fundamental constituents of matter - Matter particles
  - Interactions with which particles act on each other - Interactions
  - Particles propagating the interactions - Messenger particles



- Ultimately describe:
  - Birth of the Universe, the Big Bang
  - Passed and future Evolution

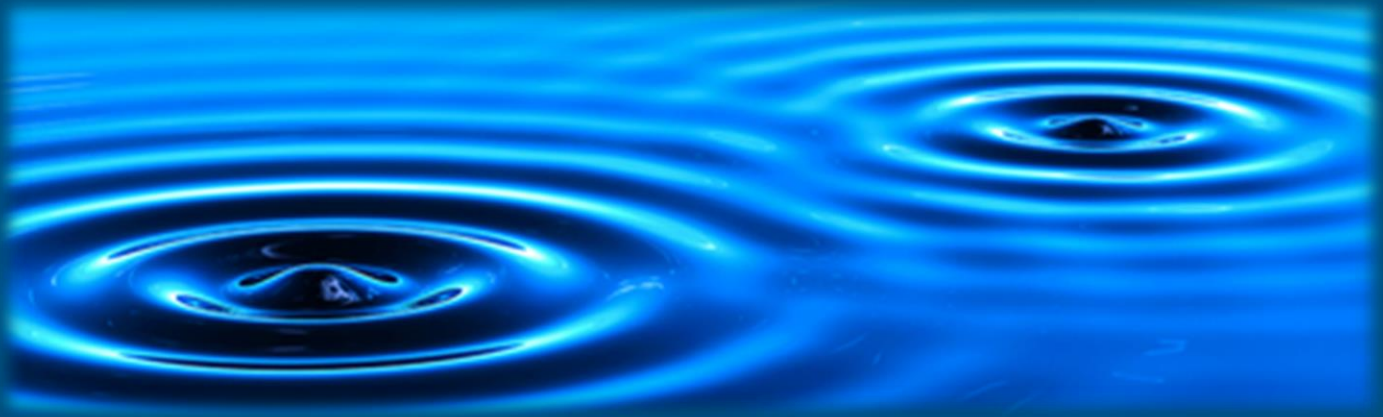


- Strong link between the infinitely small (particle physics) and infinitely large (cosmology)

What is a “fundamental particle”?

A “particle” is a propagation of a quantity of information (properties) perceived through the different interactions (~forces)!

- ➔ That is, particles are perceived differently depending on their properties
- ➔ Technically, in quantum field theory, a matter particle is represented by an excitation of a matter field, and interaction particles by excitation of a interaction field, very similar to the waves on a surface of water



What is the size of a particle?

➔ Analogy: “What is the size of piece of cotton?” ☺

➔ Depends on how much energy you apply to interact with it!

Heisenberg Uncertainty Principle

A tiny little complication though…. with astronomic consequences:

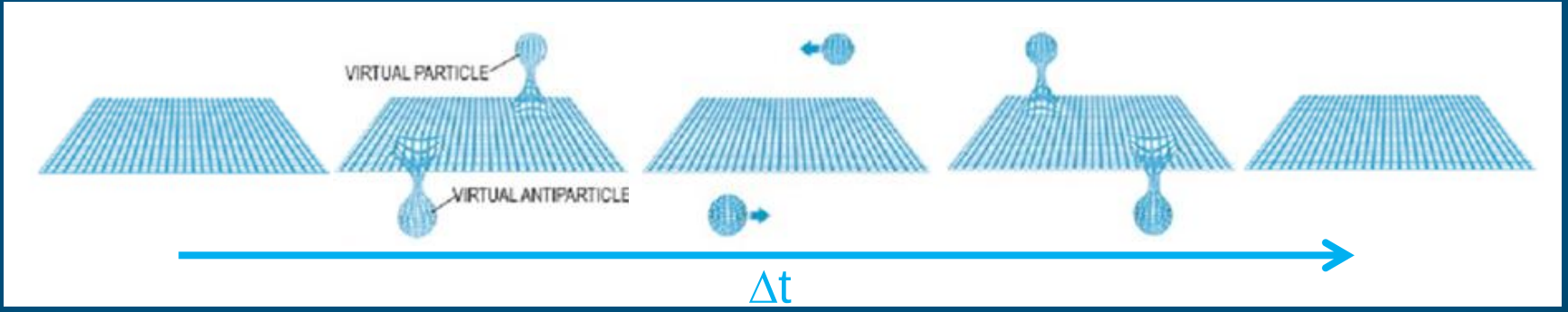
➔ Nature has built in an unavoidable intrinsic randomness:

$$\Delta p \Delta x \leq \frac{h}{2\pi} \qquad \Delta E \Delta t \leq \frac{h}{2\pi}$$

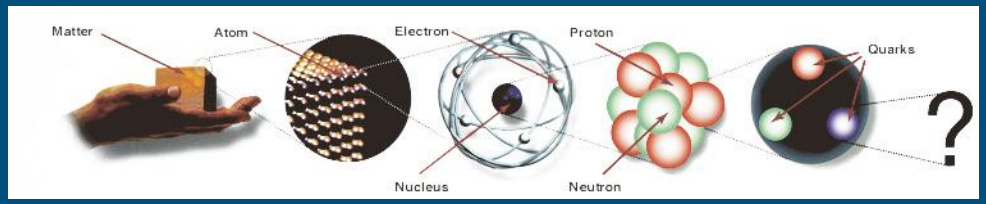
➔

$$\Delta E \leq \frac{h}{2\pi \Delta t}$$

- Vacuum fluctuation = vacuum polarization = virtual particle creation (many names..)



Fundamental constituents of matter (?)



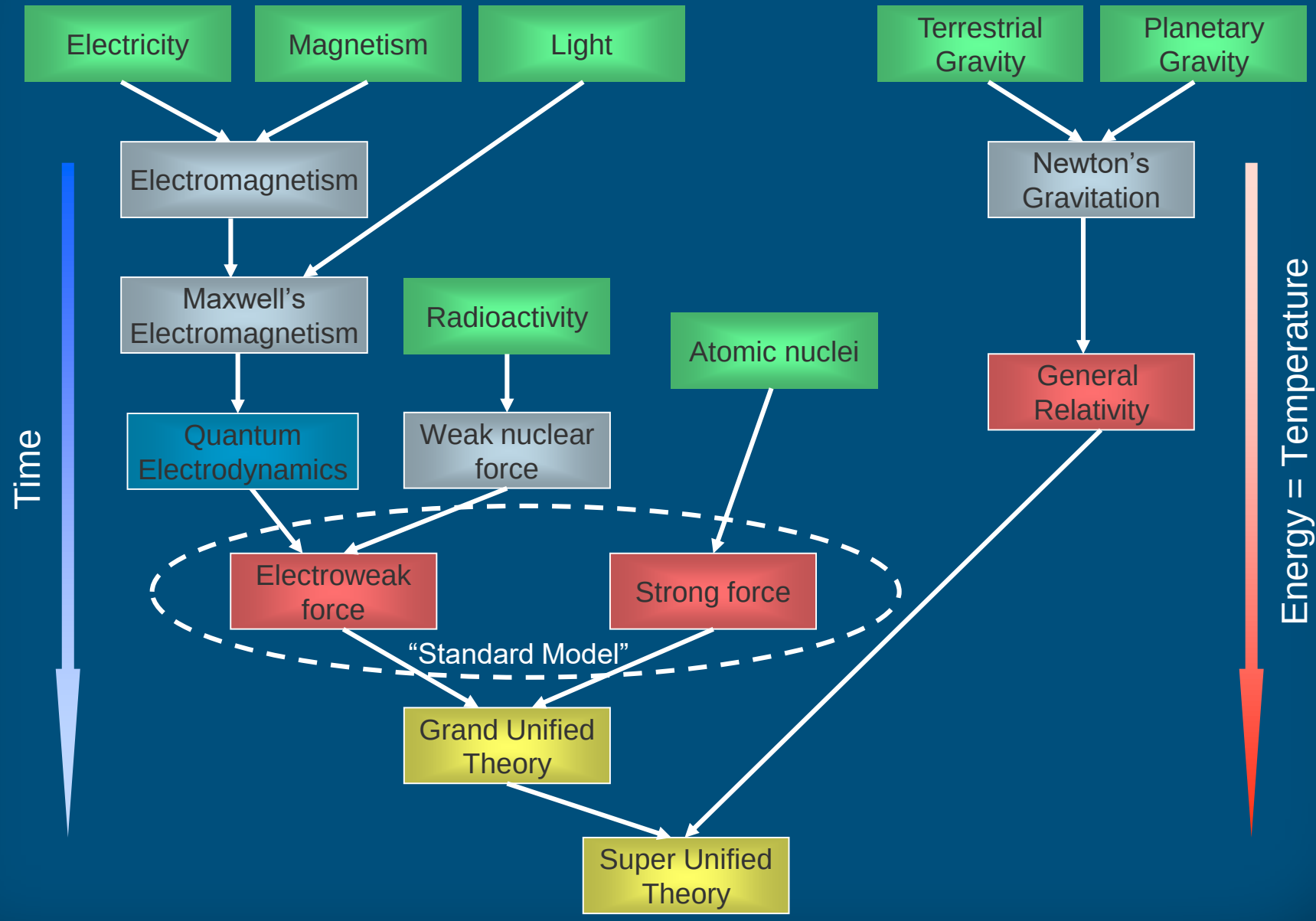
Today's periodic system of the fundamental building blocks

	Quarks		Leptons	
Generation 3	t Top	b Bottom	τ Tau	ν_τ Tau-neutrino
Generation 2	c Charm	s Strange	μ Muon	ν_μ Muon-neutrino
Generation 1	u Up	d Down	e Electron	ν_e Electron-neutrino

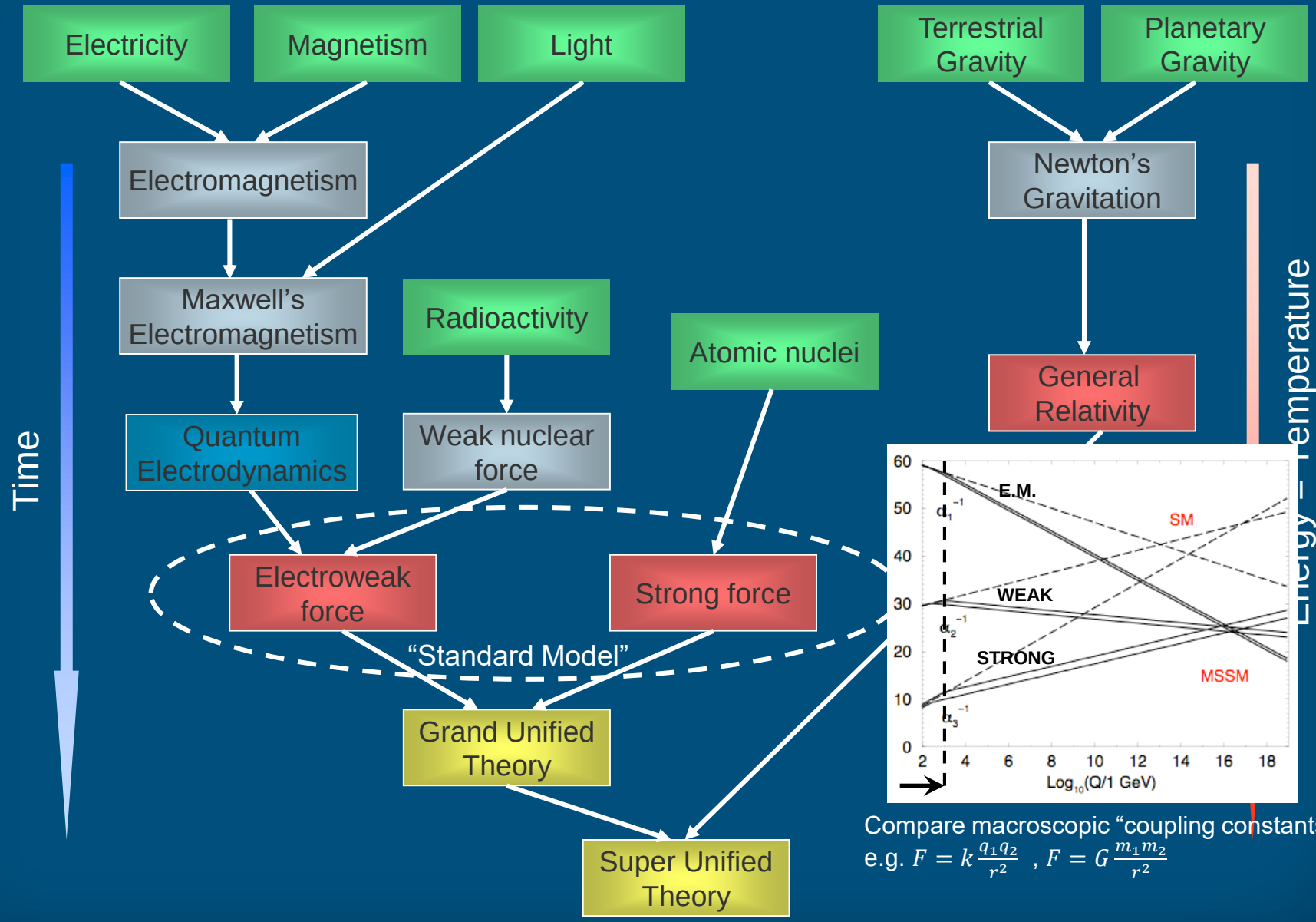
And as many types of anti-particles!

- Note the mass of the fundamental particles
  - 80 kg of human body / $m_{p/n}$(~1.6x10^{-27}kg) * $\Sigma m_{uud/udd}$(~2*10^{-29}kg) = ~1 kg….?
  - .. Rest is kinetic energy and interaction (binding) energy

Interactions (~"forces") and "Unification"

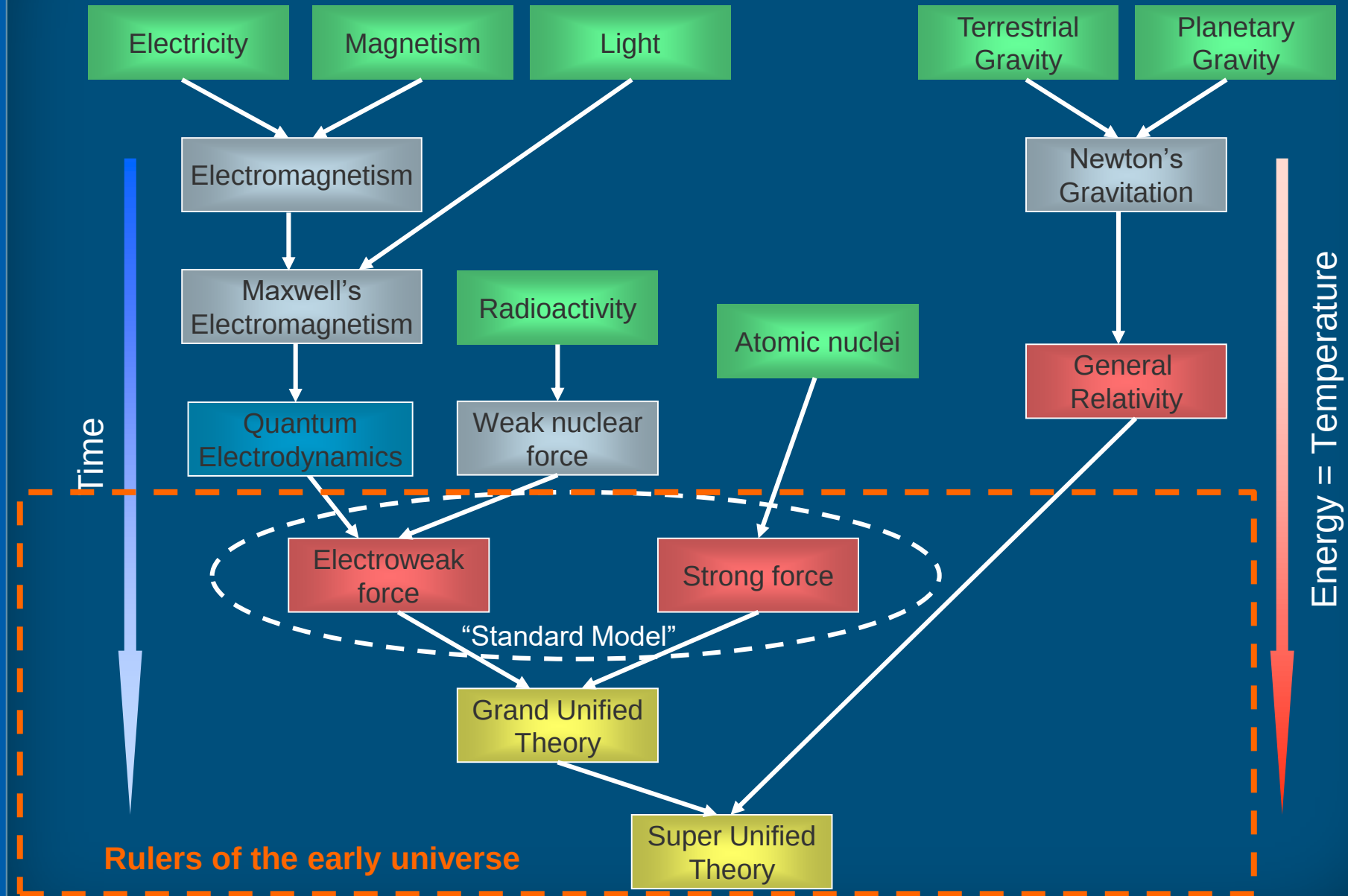


Interactions (~"forces") and "Unification"

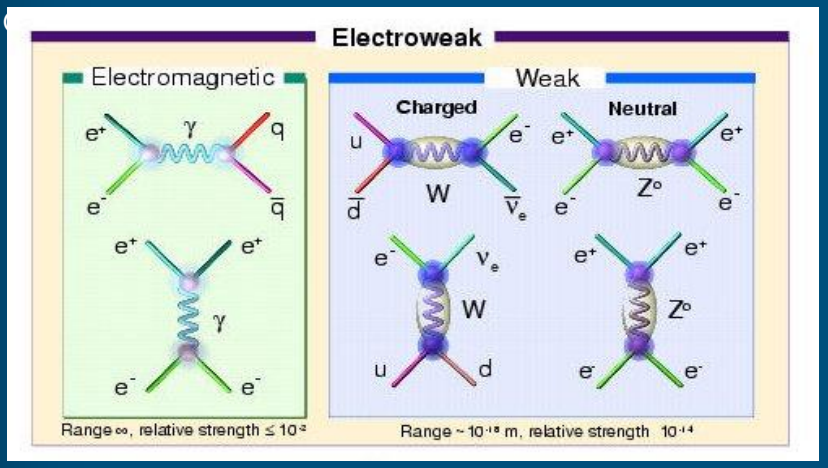


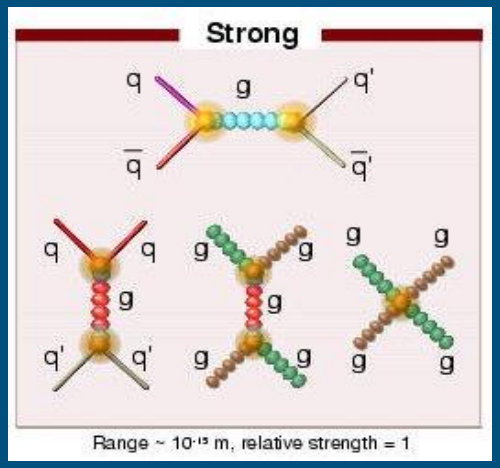
Compare macroscopic "coupling constants", e.g. $F = k\frac{q_1 q_2}{r^2}$, $F = G\frac{m_1 m_2}{r^2}$

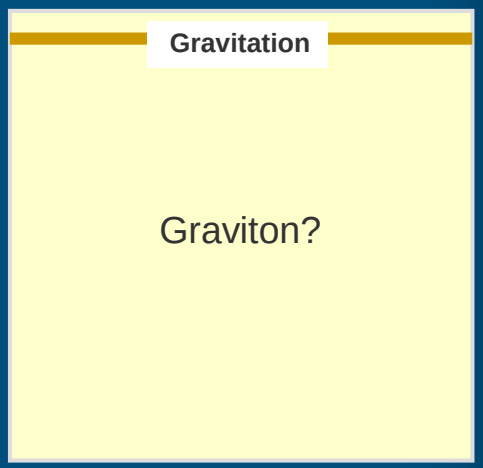
Interactions (~"forces") and "Unification"



Interactions mediators between particles

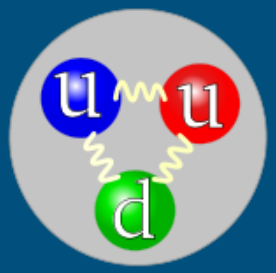




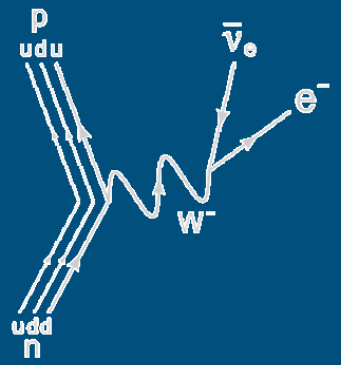


Hadrons

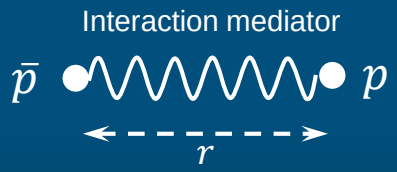
Baryons



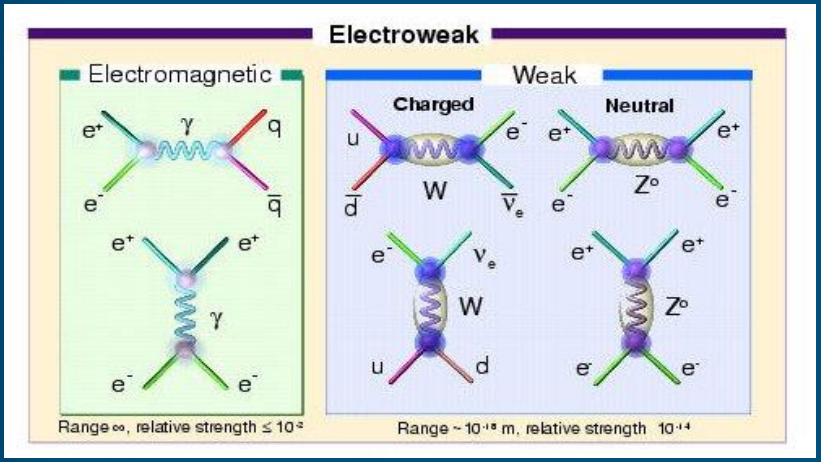
Mesons

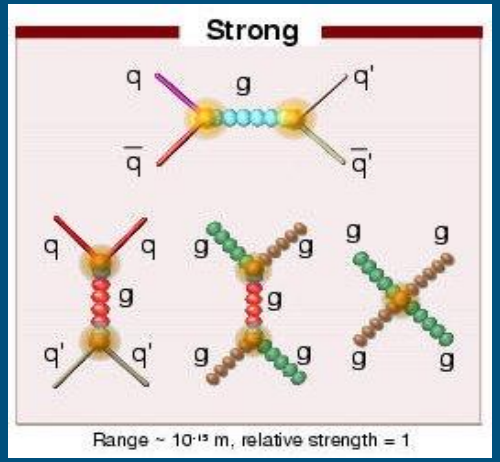


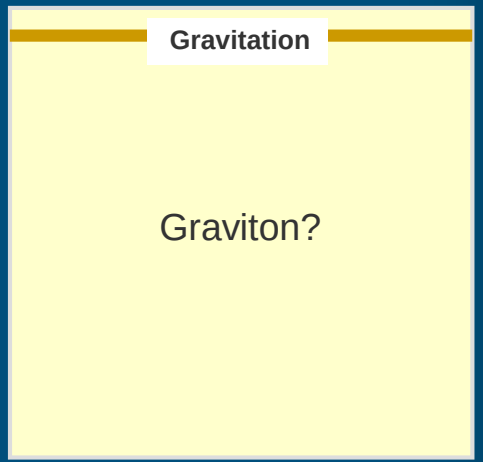
But hey, something weird is going on!
Example, particle – antiparticles at rest:



Interactions between particles

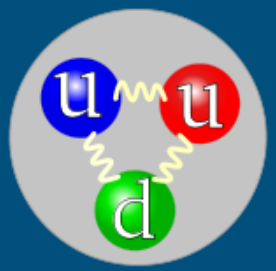




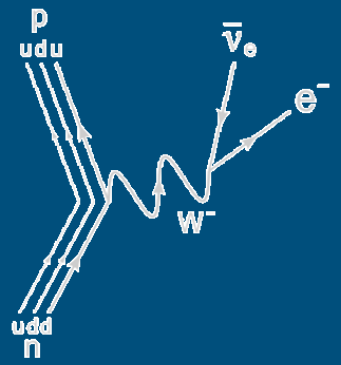


Hadrons

Baryons

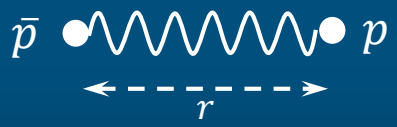


Mesons



But hey, something weird is going on!
Example, particle – antiparticles at rest:

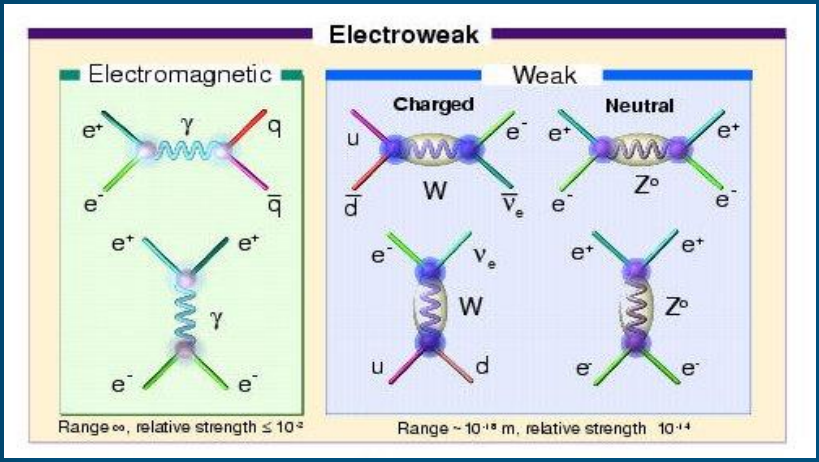
Interaction mediator (e.g. photon)

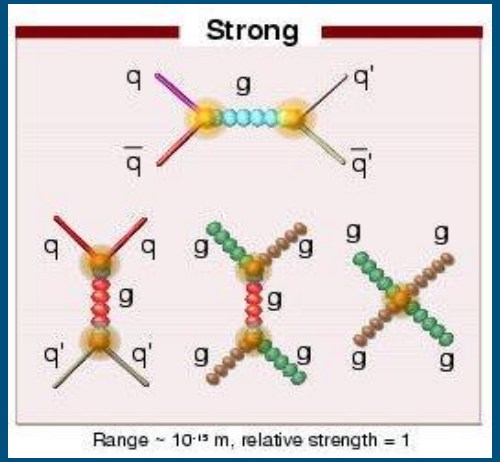


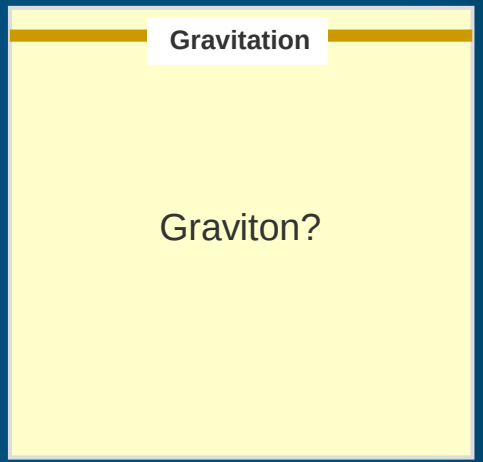
Massless force carrier

$$\Delta E \Delta t \sim E_{int} \frac{r}{c} \leq \frac{h}{2\pi}$$

Interactions between particles

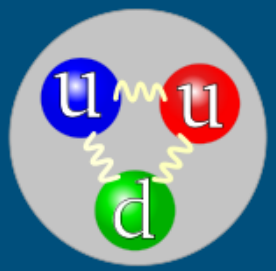




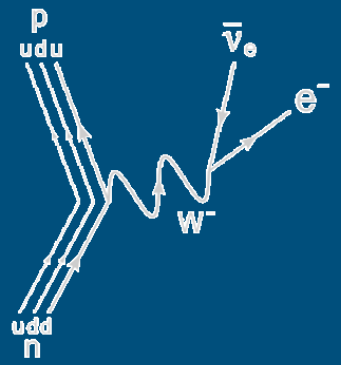


Hadrons

Baryons

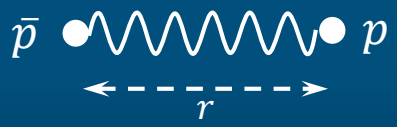


Mesons



But hey, something weird is going on!
Example, particle – antiparticles at rest

Interaction mediator (e.g. Z^0)



Massive force carrier

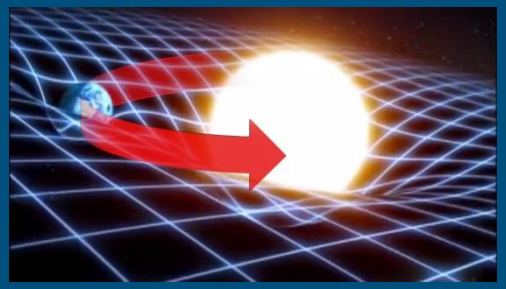
$$\Delta E \Delta t \sim (E_{int} + \langle E_{mass} \rangle) \frac{r}{c} \leq \frac{h}{2\pi}$$

What's so difficult about gravity?

- It's very weak (why so weak!?) and affects the space itself in which it acts…

…that is:

1. Gravity couples to energy and mass and curves space

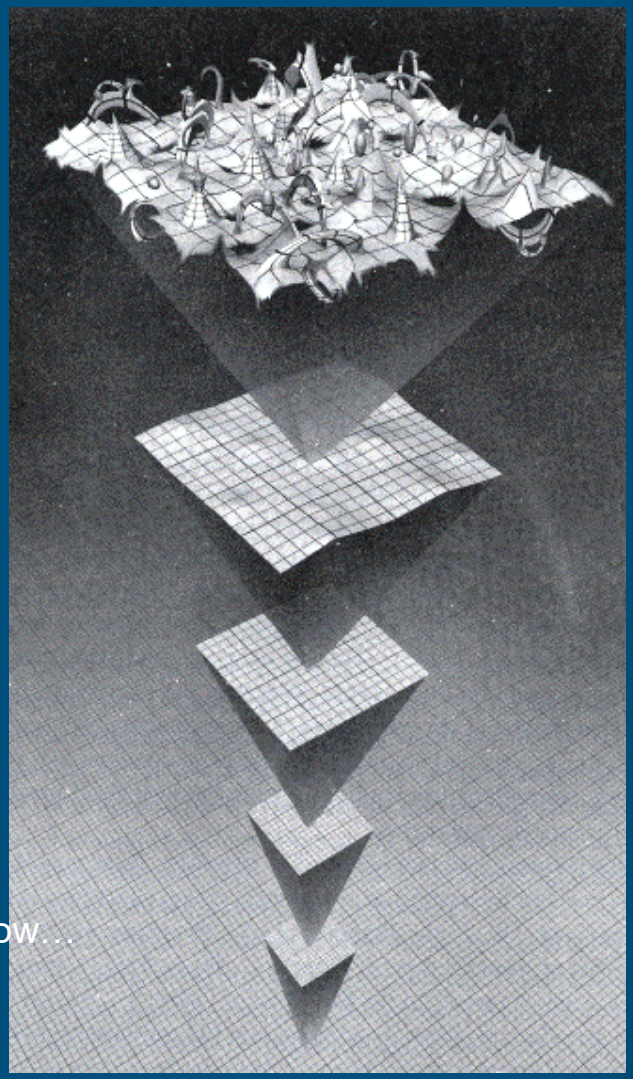


2. Vaccum fluctuations produces virtual mass and virtual energy

3. Gravity will curve space further

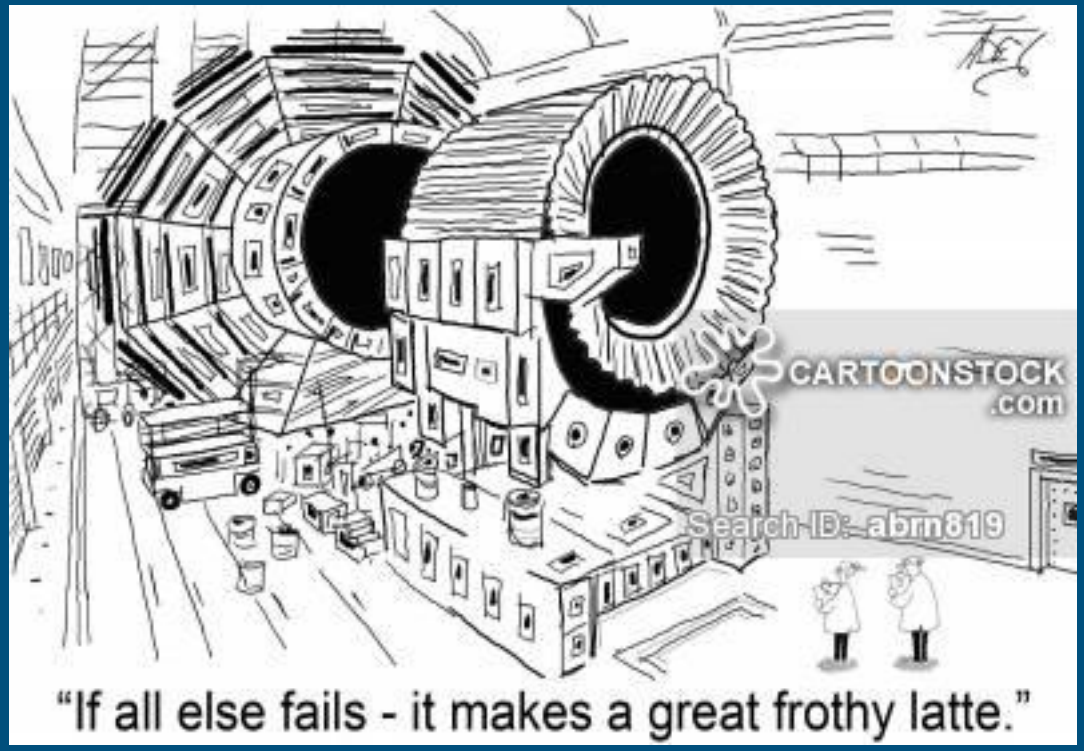
4. The smaller the distances (time-scales),
   the more virtual energy is available,
   the more gravity couples,
   the more the space is curved….
   Leads to infinities…

➔ No way to make a self-consistent quantum gravity theory up to now…

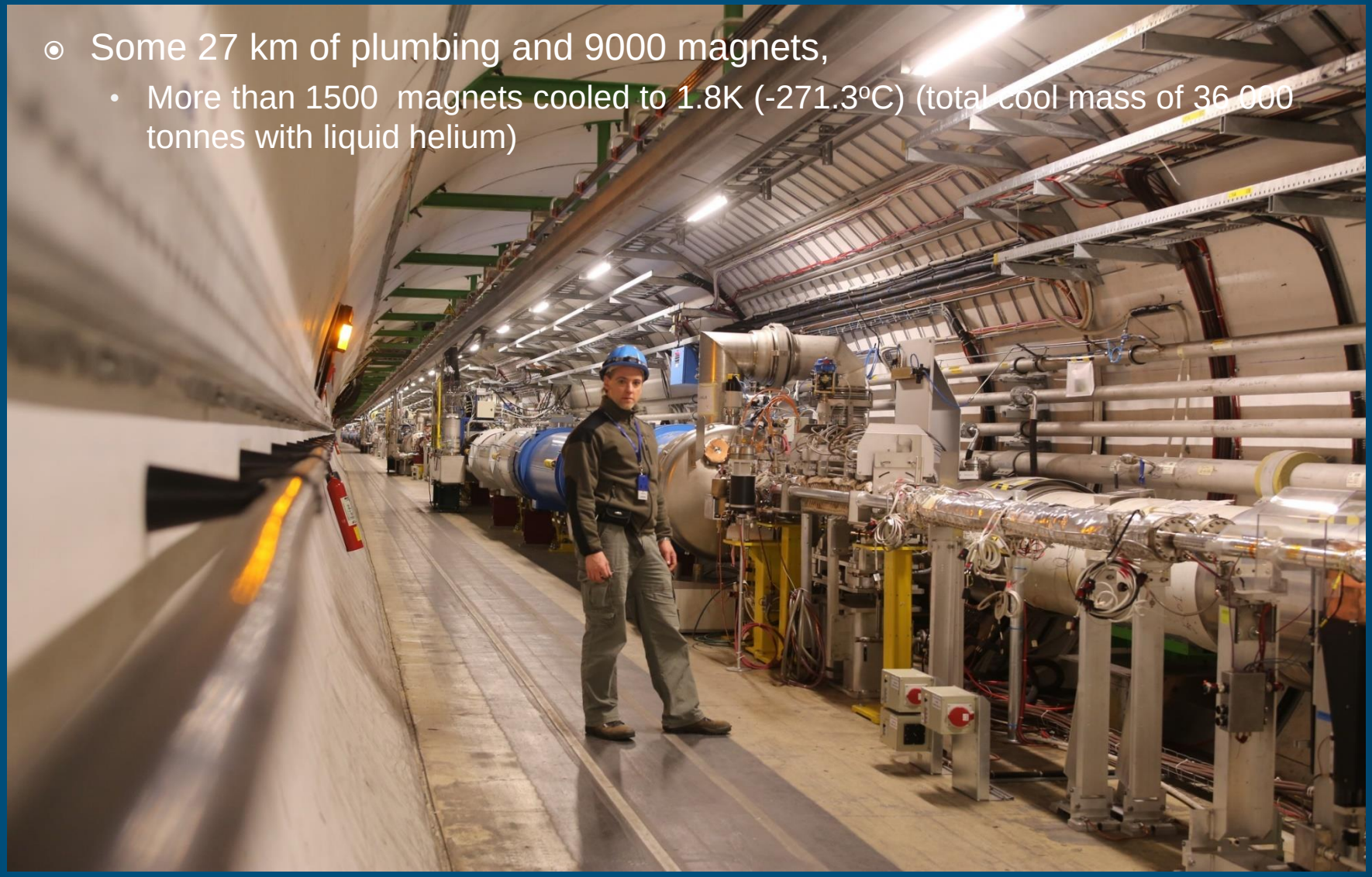


Back to Earth again!

Experimenting with the Big Bang



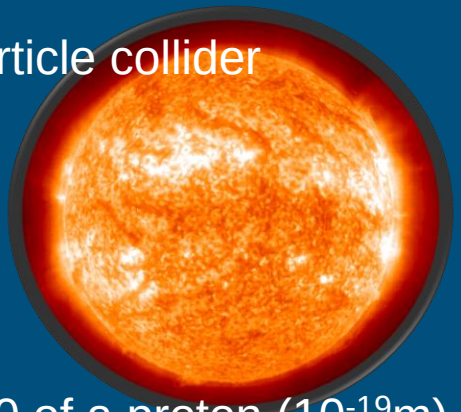
Large Hadron Collider



- Some 27 km of plumbing and 9000 magnets,
  - More than 1500 magnets cooled to 1.8K (-271.3°C) (total cool mass of 36 000 tonnes with liquid helium)

Large Hadron Collider

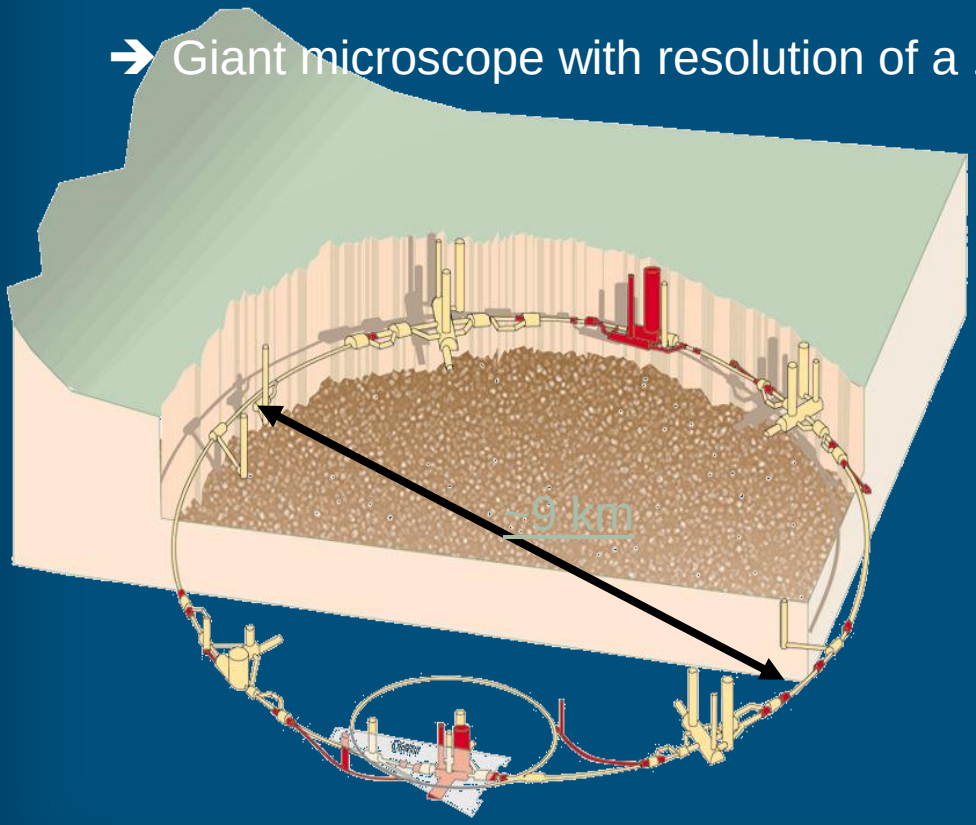
Large Hadron Collider (LHC) is a 27 km long particle collider

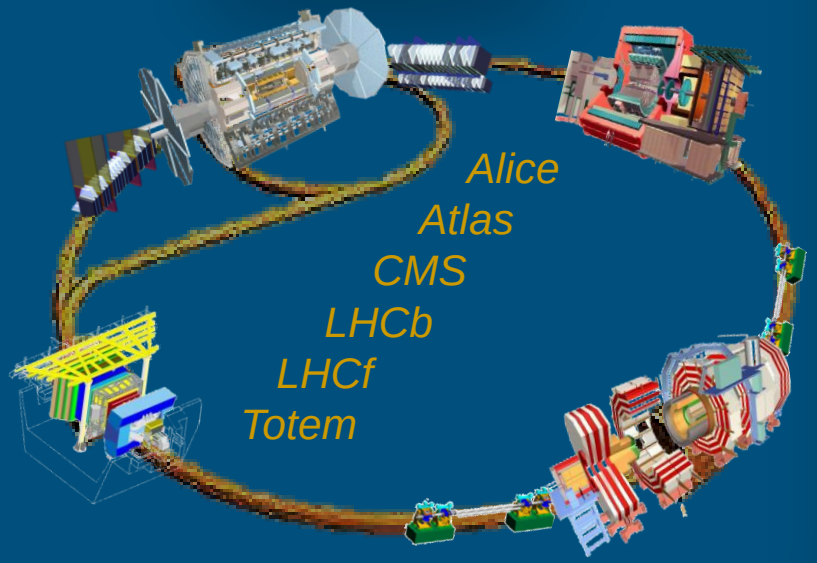


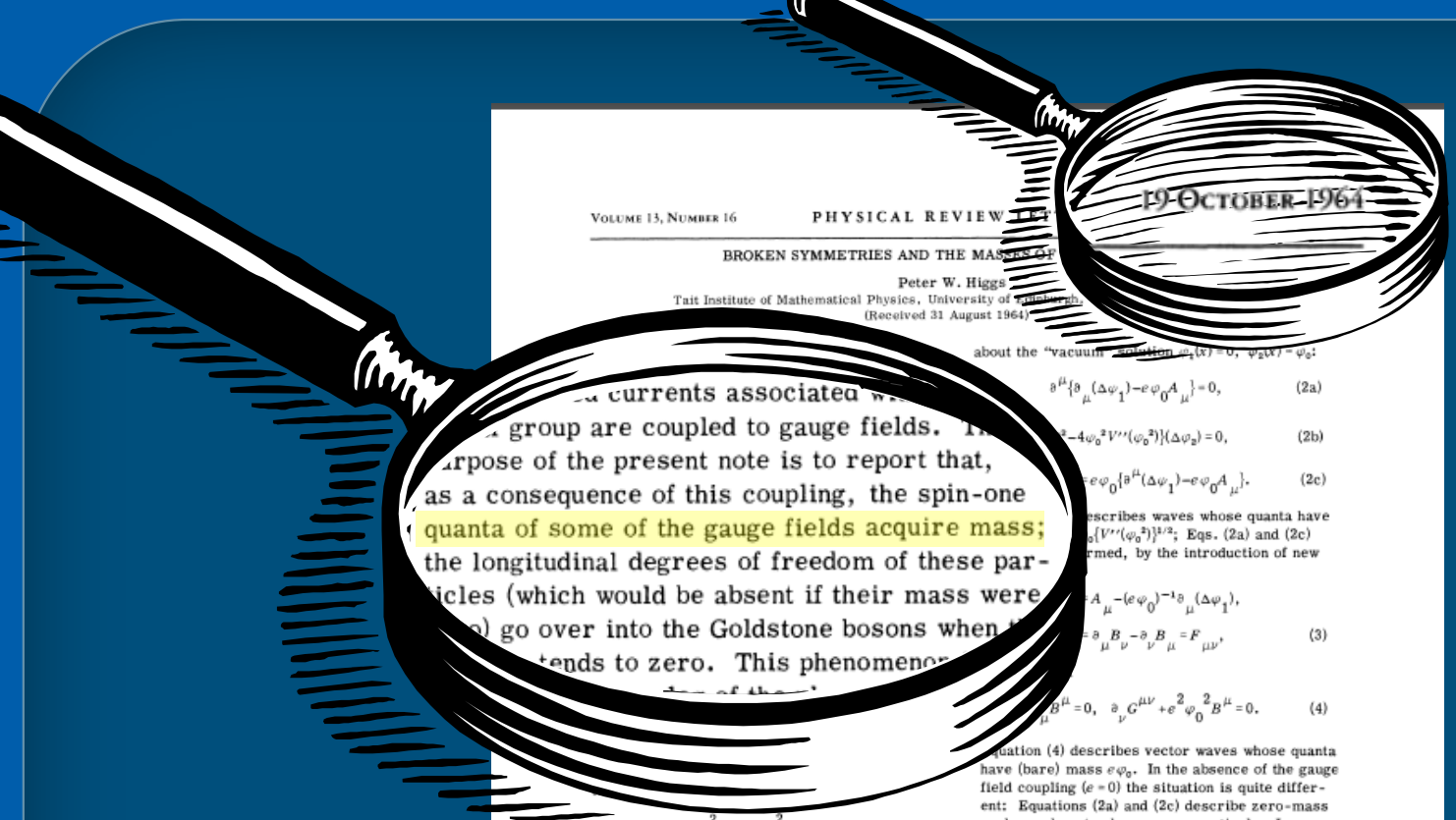
➔ *Recreate* conditions at “small scale”:

- Temperature 10^{16} K that is 1 000 000 000 x
- 0.00000000001 second after Big Bang (10^{-11}s)

➔ Giant microscope with resolution of a 1/10000 of a proton (10^{-19}m)







VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh

(Received 31 August 1964)

currents associated w
group are coupled to gauge fields. T
rpose of the present note is to report that,
as a consequence of this coupling, the spin-one
quanta of some of the gauge fields acquire mass;
the longitudinal degrees of freedom of these par-
icles (which would be absent if their mass were
) go over into the Goldstone bosons when t
tends to zero. This phenomenon

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2+\varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu.$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2)=0$, $V''(\varphi_0^2)>0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \quad (2a)$$

$$\partial^\mu\partial_\mu(\Delta\varphi_2) - 4\varphi_0^2 V''(\varphi_0^2)(\Delta\varphi_2) = 0, \quad (2b)$$

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \quad (2c)$$

escribes waves whose quanta have
$_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c)
rmed, by the introduction of new

$$= A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

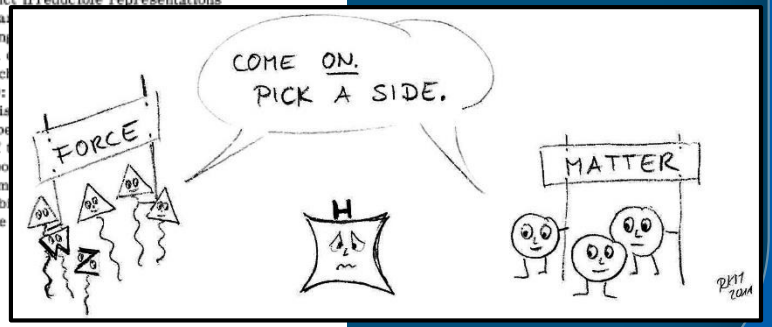
$$= \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \quad (3)$$

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \quad (4)$$

quation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e=0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

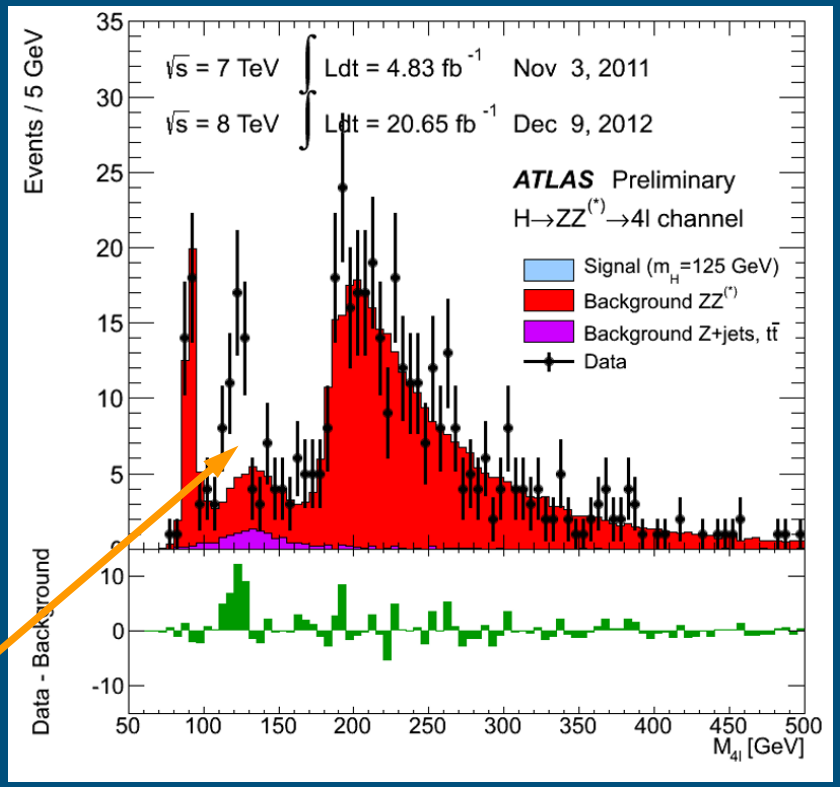
When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scala
field always belon
tion.[6] The model
est is that in whic
octet under SU(3):
ity of two nonvanis
ues, which may be
$I_3=0$ members of
massive scalar bo
numbers; the rem
scalar octet comb
components of the

508



Higgs appears in 2011 - 2012

- Most fundamental role of Higgs is to stop matter particles from being obliged to move at speed of light on early Universe!



- ~1 - 5 Higgs per minute without us knowing!.... O(1 million) at production in total!
  - ATLAS+CMS: 1400 Higgs events after selection cuts
- Mass of the Higgs is equivalent to the total mass of 130 protons!

The Big Questions

Observations in Cosmology

- Event horizon problem
- Flatness
- Density variation which lead to star and galaxy formation
- Natural constants
- The missing antimatter
- The missing matter – Dark Matter
- Universe expansion rate is accelerating today – Dark Energy

Observations in particle physics

- Tiny neutrino mass and oscillations

Hints from particle physics theory

- Stability of Higgs mass
- Structure of matter and interactions
- Unification of interactions
- Why no CP violation in strong interaction
- Gravity

➔ Which extension to the Standard Model??

Prejudice…: "Universe is fine-tuned by chance or *driven* by obligation?"

The Big Questions

Observations in Cosmology

- Event horizon problem
- Flatness
- Density variation which lead to star and galaxy formation
- Natural constants
- The missing antimatter
- The missing matter – Dark Matter
- Universe expansion rate is accele

Observations in particle ph

- Tiny neutrin

Hints fr

- nteractions
- teractions
- CP violation in strong interaction
- Gravity

➔ Which extension to the Standard Model??

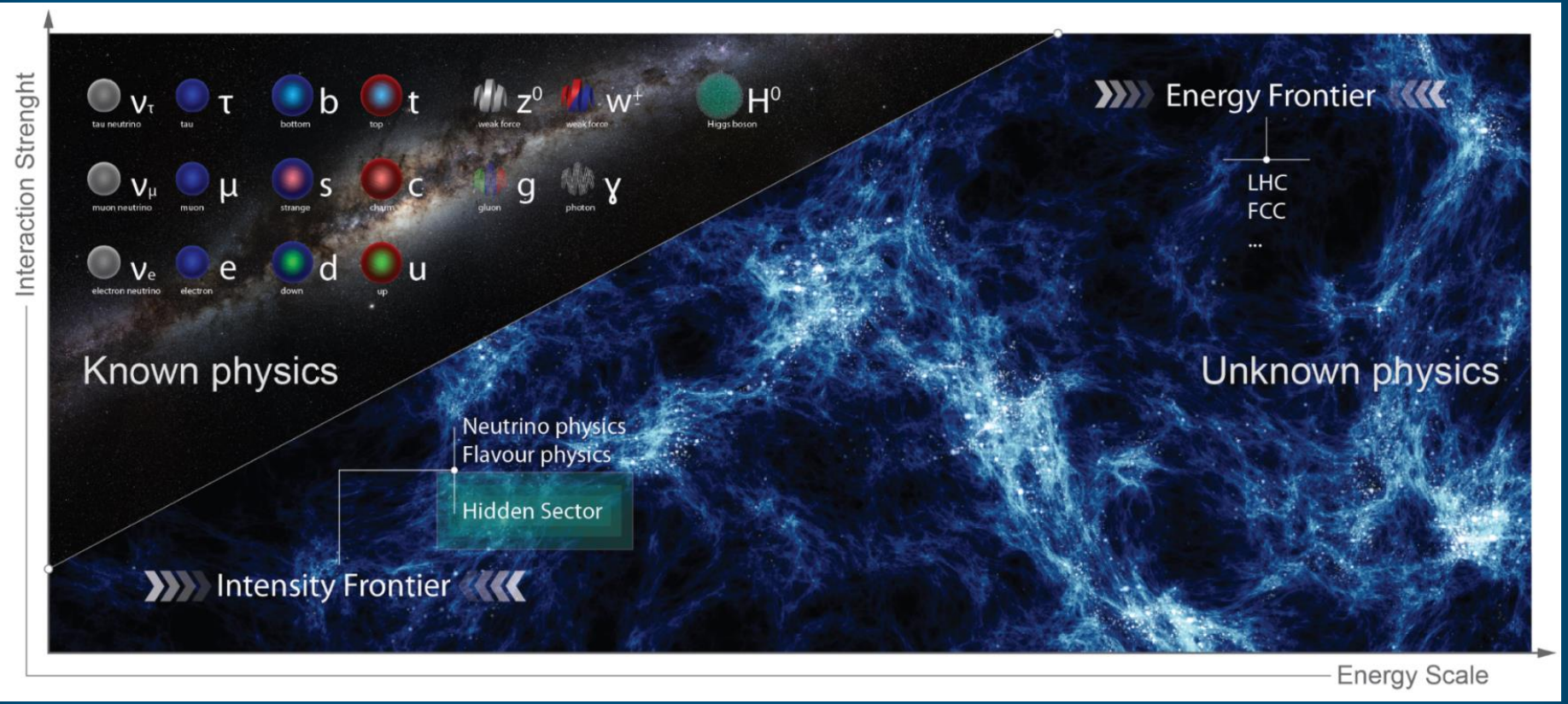
We need New Physics!
(i.e. new particles and interactions)

Prejudice…: "Universe is fine-tuned by chance or *driven* by obligation?"

Energy – intensity frontier

- What are the alternatives? "New particles" can hide in two ways:

Very massive OR very weakly coupled



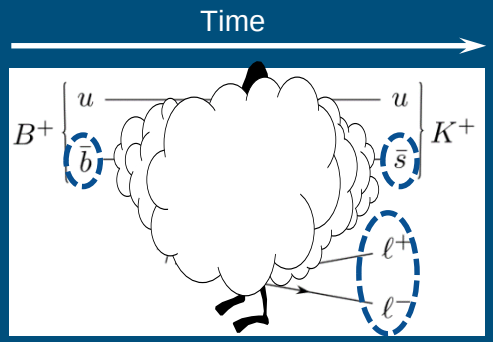
Precision measurements

Recipe:

- Choose processes which are rare and calculable to high precision in SM
  - Indirectly find evidence for New Physics as discrepancy from SM prediction!
  - Virtual effects allow probing energies much higher than the E_{cms} of the LHC

Example B meson decays to lepton pairs:

$$R_K = \frac{BR(B^+ \to K^+ e^+ e^-)}{BR(B^+ \to K^+ \mu^+ \mu^-)}$$



Precision measurements

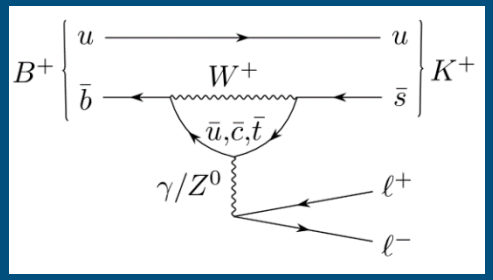
Recipe:

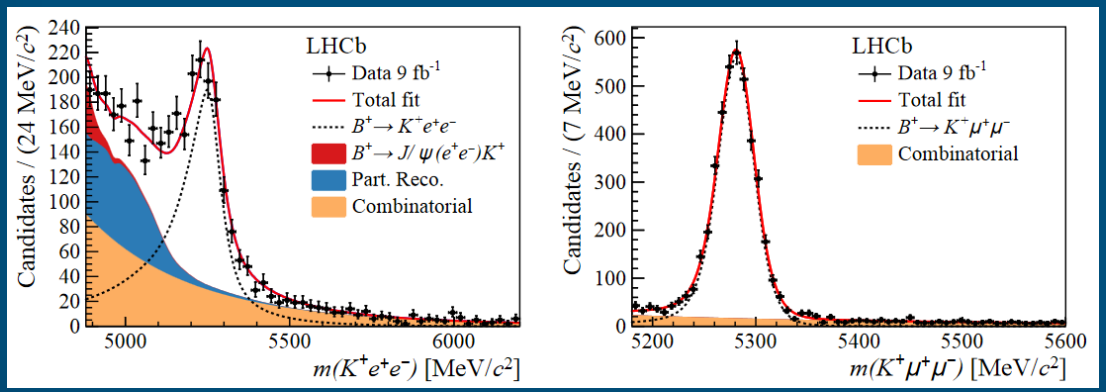
- Choose processes which are rare and calculable to high precision in SM
  - Indirectly find evidence for New Physics as discrepancy from SM prediction!
  - Virtual effects allow probing energies much higher than the E_{cms} of the LHC

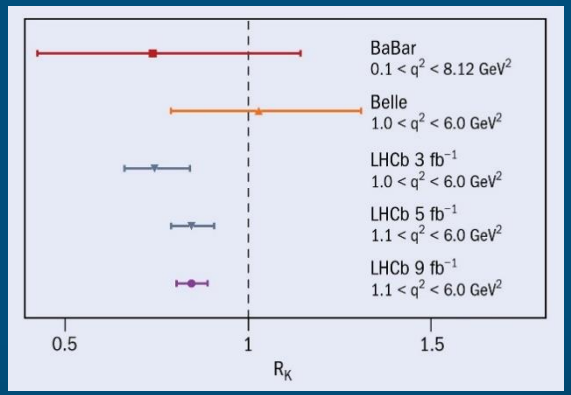
B meson decays to lepton pairs:

$$R_K = \frac{BR(B^+ \to K^+ e^+ e^-)}{BR(B^+ \to K^+ \mu^+ \mu^-)}$$

Lepton Universality (LU)
Expected to be ~unity in SM







Precision measurements

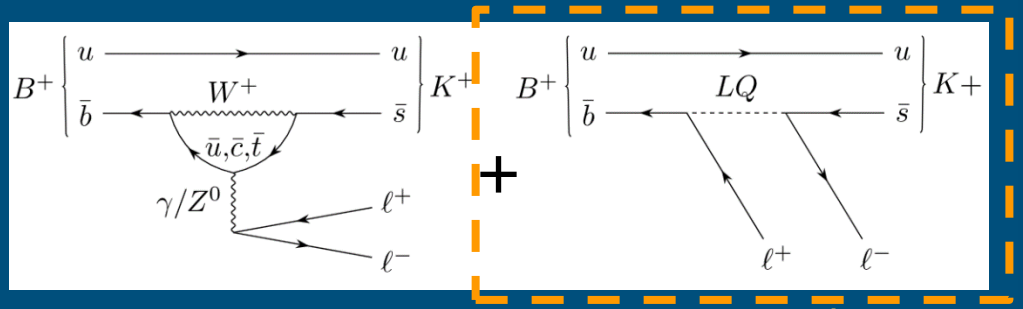
Recipe:

- Choose processes which are rare and calculable to high precision in SM
  - Indirectly find evidence for New Physics as discrepancy from SM prediction!
  - Virtual effects allow probing energies much higher than the E_{cms} of the LHC

B meson decays to lepton pairs:

$$R_K = \frac{BR(B^+ \to K^+ e^+ e^-)}{BR(B^+ \to K^+ \mu^+ \mu^-)}$$

E.g. lepto-quarks

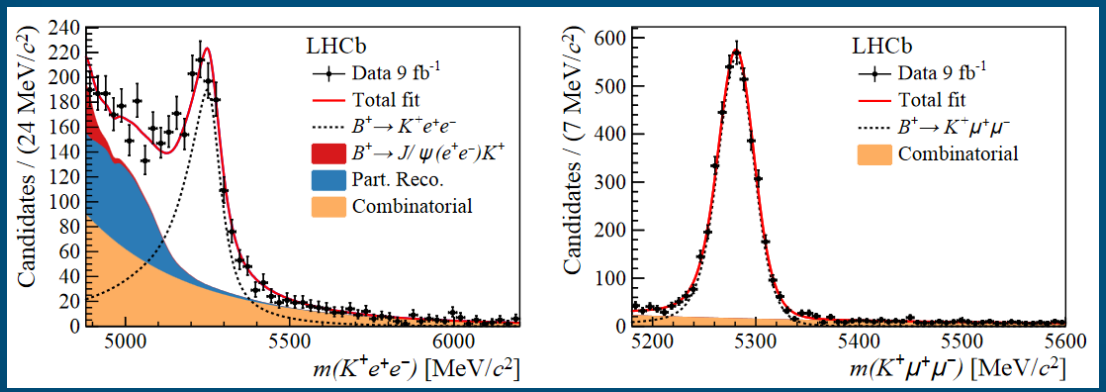


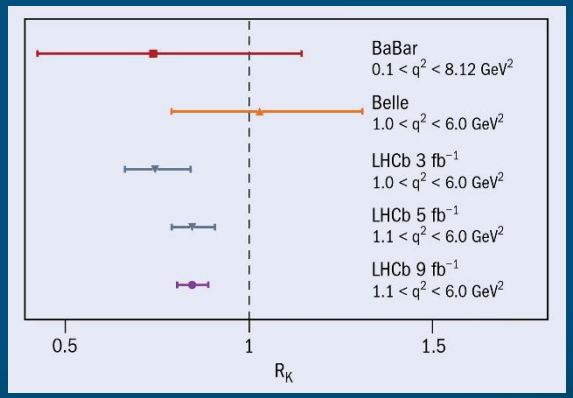
Lepton Universality Violation?

$$\text{“}R_K^{exp} = R_K^{SM} + R_K^{NewPhysics}\text{”}$$

R_K^{NP} contribution from New Physics

Analysis based on 1000 0000 0000 0000 measured b-decays!

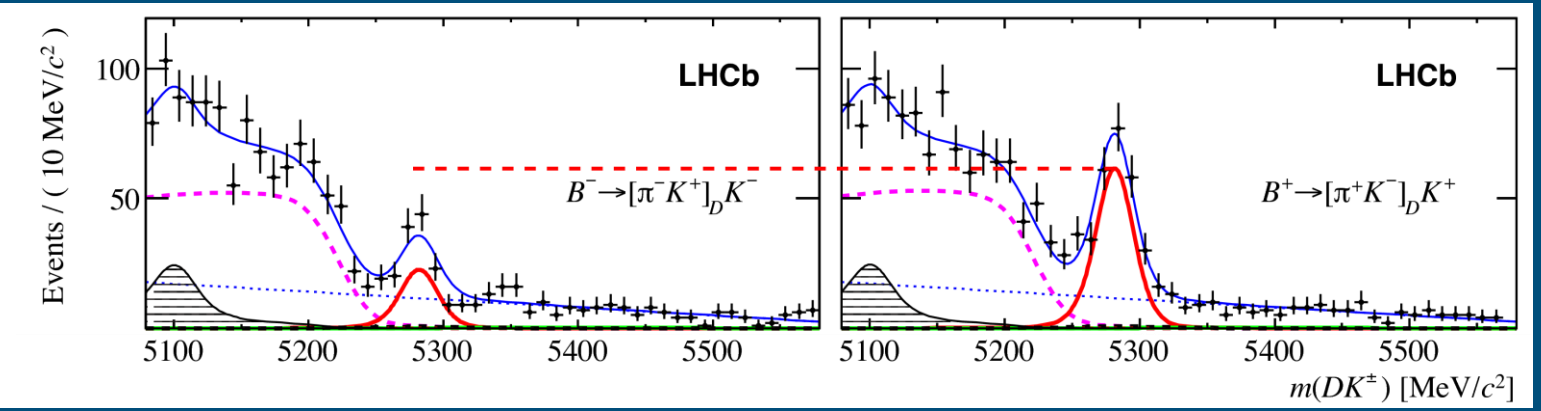




Example: missing anti-matter

- <u>"Baryon asymmetry" of the Universe</u>
  - Big Bang Nucleosynthesis and Cosmic Microwave Background $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim 6 \times 10^{-10}$
  - ➔ How did this happen?!

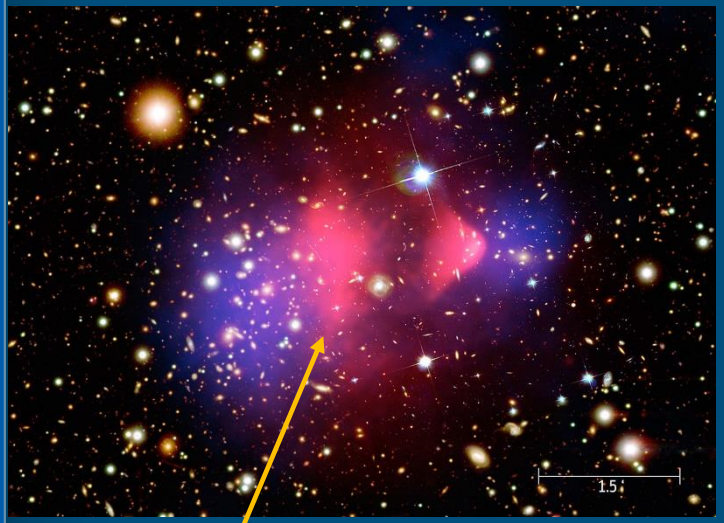
- "Manifestations" of CP violation: Matter-antimatter differs
  - Production rate
  - Decay rate
  - Mass
  - Lifetime
  - Current CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!



Establishing Dark Matter – direct observation

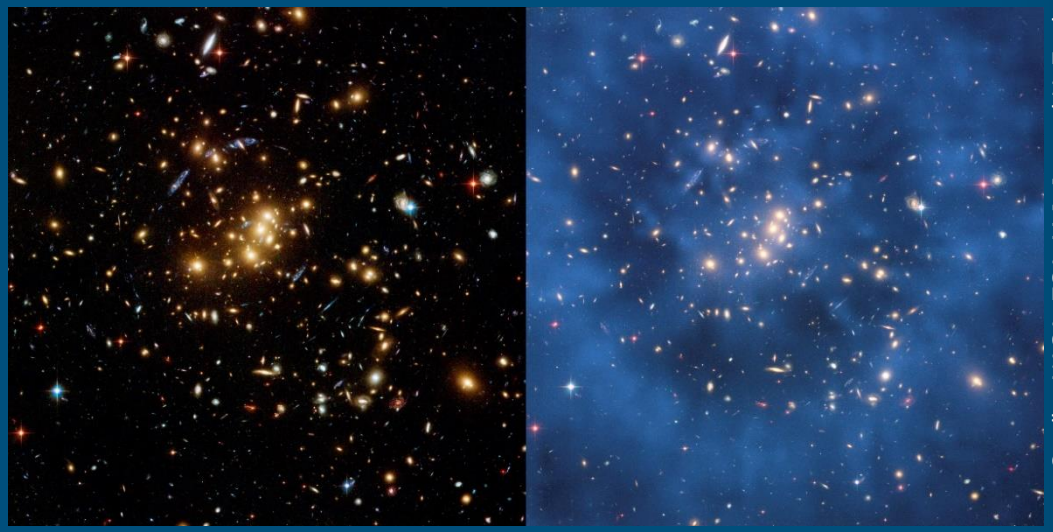
- Tracing DM: Gravitational lensing confirms previous observations (2003)

Bullet galaxy clusters (2003)



https://arxiv.org/abs/astro-ph/0608407

Galaxy cluster Cl 0024+17 (ZwCl 0024+1652)



Credits: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

Collision between two galaxy clusters

- In red, X-ray emitting plasma = dominant baryonic mass (5-15%)
- In blue, reconstruction of total mass distribution from lensing

Dark Matter remains around galaxy clusters (1-2% of mass) undisturbed

➔ Almost collisionless

➔ Very different density profile and dynamics from ordinary matter!
Why does it form a halo?

➔ Independent limits on Dark Matter self-interaction, and interaction with ordinary matter

➔ Explore with accelerators!!

More questions?

Buon apetit !


"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."