The Particle Physics–Cosmology connection

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November 2009: First collisions at the Large Hadron Collider (LHC)

The LHC: The Largest (27 km) & most powerful particle accelerator on earth

At the LHC, we collide protons at an unprecedented energy of $14 \times 10^{12}$ electron-Volt.

By studying the products of these collisions, we hope to discover new particles and push our understanding of the laws of physics to the smallest distant scales.

➡️ The LHC: A gigantic microscope
Going to higher energies allows to study finer details.

$L = 400 \text{ km}$

$L = 800 \text{ km}$
The elementary blocks of matter

- Matter is made of molecules ...
- Molecules are made of atoms ...
- Atoms are made of a nuclei and electrons ...
- Nuclei are made of protons and neutrons ...
- Protons and neutrons are made of quarks ...
Direct exploration of the Fermi scale has started

i.e distances $< 10^{-15}$ cm

main physics goal
at the LHC:

What is the mechanism of Electroweak Symmetry breaking?
what is the origin of the mass of elementary particles

in other words:

search for the Higgs Boson
The Standard Model of Particle Physics

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

The Higgs is the only remaining unobserved piece
and a portal to new physics hidden sectors
Light propagating in a medium is slowed down by its continuous interaction with the medium itself.

Think of the Higgs field as being a continuum medium embedding the whole universe. Particles interacting with it will undergo a similar “slow-down” phenomenon. Rather than slowing down however the interaction with the higgs medium gives them inertia \( \rightarrow \) mass.

\[
\nu \quad m \propto \lambda \nu
\]

The number \( \nu \) is a universal property of the higgs field background. The quantity \( \lambda \) is a characteristic of a particle moving in the higgs field. Particles which have a large \( \lambda \) will have a large mass.

[M. Mangano]
Electroweak Unification

**Electroweak Unification**

- Electromagnetism
- Weak force

**Diagram:**
- $\gamma$
- $W$
- $\gamma Z$
- $Z$

**HERA**
- $d\sigma/dQ^2$ (pb/GeV$^2$)
- $Q^2$ (GeV$^2$)
- neutral current
- charged current
- weak force
The Higgs selects a vacuum state by developing a non zero background value. When it does so, it gives mass to SM particles it couples to.

**The puzzle:**

We do not know what makes the Higgs condensate. We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.
Which Higgs?
Imagine what our universe would look like if electroweak symmetry was not broken

- Quarks and leptons would be massless
- Mass of proton and neutron (the strong force confines quarks into hadrons) would be a little changed
- Proton becomes heavier than neutron (due to its electrostatic self energy) → no more stable
- No hydrogen atom
- Very different primordial nucleosynthesis
- A profoundly different (and terribly boring) universe
What questions the LHC experiments will try to answer:

Does a Higgs boson exist?

If yes:
- is there only one?
- what are its mass, width, quantum numbers?
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed?
- what are its couplings to itself and other particles?
- Spin determination
- CP properties

If no:
  - be ready for
    - very tough searches at the (S)LHC (VLVL scattering, ...) or
    - more spectacular phenomena such as $W'$, $Z'$ (KK) resonances, technicolor, etc...
Most recent experimental successes in particle physics

- Top quark discovery
- Solar, atmospheric & terrestrial neutrino oscillations
- Direct CP violation in K mesons
- CP violation in B mesons
- Validation of quantum properties of Standard Model
- Observation of accelerated expansion of the universe
- Determination of the energy/matter content of the universe

Nevertheless:
We’re lacking the understanding of 95% of the energetic content of the universe
We don’t understand 96% of the energy budget of the universe.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2 \Omega_b h^2$</td>
<td>$2.258^{+0.057}_{-0.056}$</td>
<td>Expansion rate</td>
</tr>
<tr>
<td>$1 - n_s$</td>
<td>$0.0079 &lt; 1 - n_s &lt; 0.0642$ (95% CL)</td>
<td>Fraction of the total energy density in &quot;dark energy&quot;</td>
</tr>
<tr>
<td>$C_{220}$</td>
<td>$5763^{+38}_{-40}$</td>
<td>Fraction of the total energy density in matter</td>
</tr>
<tr>
<td>$d_A(z_*)$</td>
<td>$14116^{+160}_{-163}$ Mpc</td>
<td>Age of the universe</td>
</tr>
<tr>
<td>$h$</td>
<td>$0.710 \pm 0.025$</td>
<td></td>
</tr>
<tr>
<td>$k_{eq}$</td>
<td>$0.00974^{+0.00041}_{-0.00040}$</td>
<td></td>
</tr>
<tr>
<td>$\ell_*$</td>
<td>$302.44 \pm 0.80$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_b$</td>
<td>$0.0449 \pm 0.0028$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c$</td>
<td>$0.222 \pm 0.026$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.734 \pm 0.029$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>$0.1334^{+0.0056}_{-0.0055}$</td>
<td></td>
</tr>
<tr>
<td>$r_s(z_d)$</td>
<td>$153.2 \pm 1.7$ Mpc</td>
<td></td>
</tr>
<tr>
<td>$r_s(z_d)/D_v(z = 0.35)$</td>
<td>$0.1153^{+0.0038}_{-0.0039}$</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>$1.719 \pm 0.019$</td>
<td></td>
</tr>
<tr>
<td>$A_{SZ}$</td>
<td>$0.97^{+0.68}_{-0.97}$</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.088 \pm 0.015$</td>
<td></td>
</tr>
<tr>
<td>$\theta_*$</td>
<td>$0.5952 \pm 0.0016$ °</td>
<td></td>
</tr>
<tr>
<td>$z_{dec}$</td>
<td>$1088.2 \pm 1.2$</td>
<td></td>
</tr>
<tr>
<td>$z_{eq}$</td>
<td>$3196^{+134}_{-133}$</td>
<td></td>
</tr>
<tr>
<td>$z_*$</td>
<td>$1090.79^{+0.94}_{-0.92}$</td>
<td></td>
</tr>
<tr>
<td>$1 - n_s$</td>
<td>$0.037 \pm 0.014$</td>
<td></td>
</tr>
<tr>
<td>$A_{BAO}(z = 0.35)$</td>
<td>$0.463^{+0.021}_{-0.020}$</td>
<td></td>
</tr>
<tr>
<td>$d_A(z_{eq})$</td>
<td>$14281^{+158}_{-161}$ Mpc</td>
<td></td>
</tr>
<tr>
<td>$\Delta^2_R$</td>
<td>$(2.43 \pm 0.11) \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>$H_0$</td>
<td>$71.0 \pm 2.5$ km/s/Mpc</td>
<td></td>
</tr>
<tr>
<td>$\ell_{eq}$</td>
<td>$137.5 \pm 4.3$</td>
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</tr>
<tr>
<td>$n_s$</td>
<td>$0.963 \pm 0.014$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02258^{+0.00057}_{-0.00056}$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_{\Lambda} h^2$</td>
<td>$0.1109 \pm 0.0056$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.266 \pm 0.029$</td>
<td></td>
</tr>
<tr>
<td>$r_{hor}(z_{dec})$</td>
<td>$285.5 \pm 3.0$ Mpc</td>
<td></td>
</tr>
<tr>
<td>$r_s(z_d)/D_v(z = 0.2)$</td>
<td>$0.1922^{+0.0072}_{-0.0073}$</td>
<td></td>
</tr>
<tr>
<td>$r_s(z_*)$</td>
<td>$146.6^{+1.5}_{-1.6}$ Mpc</td>
<td></td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.801 \pm 0.030$</td>
<td></td>
</tr>
<tr>
<td>$t_0$</td>
<td>$13.75 \pm 0.13$ Gyr</td>
<td></td>
</tr>
<tr>
<td>$\theta_*$</td>
<td>$0.010388 \pm 0.000027$</td>
<td></td>
</tr>
<tr>
<td>$t_*$</td>
<td>$379164^{+5187}_{-5243}$ yr</td>
<td></td>
</tr>
<tr>
<td>$z_d$</td>
<td>$1020.3 \pm 1.4$</td>
<td></td>
</tr>
<tr>
<td>$z_{reion}$</td>
<td>$10.5 \pm 1.2$</td>
<td></td>
</tr>
</tbody>
</table>
Nucleosynthesis

Formation of structures

protons and neutrons

Inflation

BIG BANG

Key:
- $q$: quark
- $g$: gluon
- $e$: electron
- $m$: muon
- $n$: neutrino
- $W$,$Z$: bosons
- $\gamma$: photon
- $\nu$: neutrino
- $\bar{\nu}$: antineutrino
- $m_\text{matter}$: dark matter relicts
- $m_\text{cosmic}$: cosmic microwave radiation

Timeline:
- $10^{-44}$ s
- $10^{-37}$ s
- $10^{-12}$ s
- $10^{-9}$ s
- $10^{-6}$ s
- $10^{-5}$ s
- $10^{-4}$ s
- $3 \times 10^5$ yr
- $10^9$ yr
- Today

Accelerators:
- CERN-LHC
- FNAL-Tevatron
- BNL-RHIC
- CERN-LEP
- SLAC-SLC

High-energy cosmic rays

Possible dark matter relics

Cosmic microwave radiation visible

Formation of structures

2.7 $\times 10^{-10}$ (Kelvin)

2.3 $\times 10^{-13}$ (GeV)
Time Since Big Bang

- **Present**: Human observe the cosmos.
- **1 billion years**: First galaxies form.
- **500,000 years**: Atoms form; photons fly free and become microwave background.
- **3 minutes**: Fusion ceases; normal matter is 75% hydrogen, 25% helium by mass.
- **0.001 seconds**: Matter annihilates antimatter.
- **10^-10 seconds**: Electromagnetic and weak forces become distinct.
- **10^-38 seconds**: Strong force becomes distinct, perhaps causing inflation of universe.
- **10^-43 seconds**: Planck Era

Major Events Since Big Bang

- **Stars, galaxies and clusters (made of atoms and plasma)**
- **Atoms and plasma (stars begin to form)**
- **Plasma of hydrogen and helium nuclei plus electrons**
- **Protons, neutrons, electrons, neutrinos (antimatter rare)**
- **Elementary particles (antimatter common)**
- **Elementary particles**

**Era of Nucleosynthesis**

- **3 minutes**
- **0.001 seconds**
- **10^-16 seconds**
- **10^-38 seconds**
- **10^-43 seconds**

**Era of Nuclei**

- **500,000 years**
- **3 minutes**
- **0.001 seconds**
- **10^-10 seconds**
- **10^-38 seconds**
- **10^-43 seconds**

**Era of Atoms**

- **500,000 years**
- **3 minutes**
- **0.001 seconds**
- **10^-10 seconds**
- **10^-38 seconds**
- **10^-43 seconds**

**Era of Galaxies**

- **1 billion years**
- **500,000 years**
- **3 minutes**
- **0.001 seconds**
- **10^-10 seconds**
- **10^-38 seconds**
- **10^-43 seconds**

**Particle Era**

- **0.001 seconds**
- **10^-10 seconds**
- **10^-38 seconds**
- **10^-43 seconds**

**GUT Era**

- **10^-43 seconds**

**Planck Era**

- **10^-43 seconds**

**Neutron - Proton - Electron - Neutrino - Antiproton - Antineutrino - Antielectron - Quarks**
2 major observations unexplained by the Standard Model

- **the Dark Matter of the Universe**
  
  Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects

  15% baryonic matter (1% in stars, 14% in gas)

  85% dark unknown matter

- **the (quasi) absence of antimatter in the universe**

  baryon asymmetry: \( \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10} \)

  \( \rightarrow \) observational need for new physics

  \( \rightarrow \) what does this have to do with the electroweak scale?
galaxy rotation curves

\[ M(r) \propto \frac{v^2 r}{G_N} \]
gravitational lensing

Galaxy Cluster Abell 2218
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08
The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales.

DM properties are well-constrained (gravitationally interacting, long-lived, not hot, not baryonic) but its identity remains a mystery.

The picture from astrophysical and cosmological observations is getting more and more focussed.

\[ \Omega_{DM} \approx 0.22 \]

\( \rightarrow \) Fraction of the universe’s energy density stored in dark matter:

The “Bullet cluster”: lensing map versus X-ray image.
Matter power spectrum

- Intergalactic hydrogen clumping
- Gravitational lensing
- Cluster abundance
- Cosmic microwave background
- SDSS galaxy clustering

Scale (millions of lightyears)

Density fluctuations

Power spectrum for CDM

matter-radiation equality

$\Gamma = \Omega_m h = 0.4$

$\Gamma = \Omega_m h = 0.2$

$\Gamma = \Omega_m h = 0.1$
Neutrinos

Collisionless damping

CDM
HDM

hot dark matter

cold dark matter

\[ P(k) \left[ \text{h}^{-3} \text{Mpc}^3 \right] \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^0 \]

\[ k \left[ \text{h Mpc}^{-1} \right] \]

\[ \Omega_{\text{CDM}} = 0.7; \quad \Omega_{\text{HDM}} = 0.3 \]

\[ \Omega_{\text{CDM}} = 1 \]

\[ \Omega_{\text{HDM}} = 1 \]
Why can’t dark matter be explained by the Standard Model?

Matter

- quarks
- leptons

<table>
<thead>
<tr>
<th>Generation</th>
<th>Particle</th>
<th>$\Omega$ (%)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Baryons</td>
<td>4 - 5</td>
<td>cold</td>
</tr>
<tr>
<td>II</td>
<td>Neutrinos</td>
<td>&lt; 2</td>
<td>hot</td>
</tr>
<tr>
<td>III</td>
<td>Dark matter</td>
<td>20 - 26</td>
<td>cold</td>
</tr>
</tbody>
</table>

Forces

- charged/unstable
- baryonic
- massless

radius of circle is proportional to the mass

contribution to the energy budget of the universe
Dark Matter Candidates $\Omega \sim 1$

- WIMP
  - KK photon ($s=1$)
  - KK neutrino ($s=1/2$)
  - neutralino ($s=1/2$)
  - sneutrino ($s=0$)
  - branon ($s=0$)
- sterile neutrino ($s=1/2$)
- axino ($s=1/2$)
- axion ($s=0$)
- gravitino ($s=3/2$)
- KK graviton ($s=2$)
- Thermal relic
- SuperWIMP
- Condensate
- Gravitationally produced or at preheating

Logarithmic scale for mass/M GeV and cross-section/σ int pb.
In Theory Space

Peccei-Quinn
  - axion
  - majoron

(almost) Standard Model
  - sterile neutrino

Technicolor & Composite Higgs
  - technifermion

SU(2)-ntuplet
  - heavy fermion

GUT
  - wimpzillas

Supersymmetry
  - neutralino
  - axino
  - gravitino
  - sneutrino

Extra Dimensions
  - Kaluza-Klein photon
  - Kaluza-Klein neutrino
  - Kaluza-Klein graviton
  - branon

WIMP thermal relic
superWIMP
condensate
gravitational production or at preheating
Dark matter candidates: two main possibilities

- very light & only gravitationally coupled (or with equivalently suppressed couplings) → stable on cosmological scales

**Sizable (but not strong) couplings to the SM** → symmetry needed to guarantee stability

**Thermal relic:** $\Omega h^2 \propto 1/\langle \sigma_{\text{anni}} v \rangle$

\[ \sigma \sim \alpha^2/m^2 \]

⇒ $\langle \sigma_{\text{anni}} v \rangle = 0.1 \text{ pb}$

The "WIMP miracle"

**Production mechanism is model-dependent,**
depends on early-universe cosmology

ex: meV scalar with $1/M_{\text{Pl}}$ couplings (radion)

Production mechanism is very general, does not depend on early universe cosmology, only requires the reheat temperature to be $\geq m/25$ (= weak requirement)

**Dependence on reheat temperature**

an alternative: superWIMPs (where most often the above calculation is still relevant since SuperWIMPs are produced from the WIMP decay)

ex: gravitino, KK graviton
The “WIMP miracle”

\[ \Omega h^2 \propto \frac{1}{\langle \sigma_{anni} v \rangle} \]

\[ \langle \sigma_{anni} v \rangle = 0.1 \text{ pb} \]

\[ \sigma \sim \alpha^2/m^2 \]

\[ \Rightarrow m \sim 100 \text{ GeV} \]
Dark Matter and the Fermi scale

Fraction of the universe’s energy density stored in a stable massive thermal relic:

\[ \Omega_{DM} \approx \frac{0.2 \text{ pb}}{\sigma_{anni}} \]

\[ \rightarrow \] a particle with a typical Fermi-scale cross section \( \sigma_{anni} \approx 1 \text{ pb} \) leads to the correct dark matter abundance.

a compelling coincidence (the “WIMP miracle”)
Work out properties of new degrees of freedom

The stability of a new particle is a common feature of many models

mass spectrum, interactions

dark matter candidates

relic abundance

detection signatures & rates
Producing Dark Matter at LHC = "Missing Energy" events

Dark matter candidate

Missing energy

hadronic jets

leptons

what is seen in the detector

Events / 1fb

ATLAS

Missing energy from dark matter

SM BG

SU3

Standard Model background

0 100 200 300 400 500 600 700 800 900 1000

0 1 10 100 1000

Missing $E_T$ [GeV]
LHC: not sufficient to provide all answers

LHC sees missing energy events and measures mass for new particles

but what is the underlying theory?
Spins are difficult to measure (need for e+ e- Linear Collider)

Solving the Dark Matter problem requires

1) detecting dark matter in the galaxy (from its annihilation products)
2) studying its properties in the laboratory
3) being able to make the connection between the two

Need complementarity of particle astrophysics (direct/indirect experiments) to identify the nature of the Dark Matter particle
Because they interact so weakly, Wimps drifting through the Milky Way pass through the earth without much harm.

Just a few Wimps are expected to collide elastically upon terrestrial nuclei, partially transferring to them their kinetic energy.

Direct detection consists in observing the recoiled nuclei.
WIMP indirect detection

WIMP Dark Matter Particles
\( E_{\text{CM}} \sim 100 \text{GeV} \)

\( \chi \)

\( W^-/Z/q \)

\( \gamma \)

\( \pi^0 \)

\( \gamma \)

\( \pi^+ \)

\( \mu^+ \)

\( e^+ \)

\( \nu_\mu \)

\( \nu_e \)

\( \pi^- \)

\( \mu^- \)

\( e^- \)

\( \nu_\mu \)

\( \nu_e \)

\( + \) a few \( p/\bar{p}, d/\bar{d} \)

Anti-matter

Gamma-rays

Neutrinos

smoking gun: gamma-ray line from direct anni into \( \gamma\gamma \) or \( \gamma Z \)

gamma-ray spectra (Inert doublet model)

Log\((E_\gamma)\) vs Log\((E_\gamma \text{ [GeV]})\)

IDM: NFW, \( \Delta \Omega \sim 10^{-3}, \sigma_{E_\gamma} = 7\%

EGRET: \( \Delta \Omega = 2 \times 10^{-3} \)

50 GeV, boost \( \sim 10^4 \)

70 GeV, boost \( \sim 100 \)

GLAST sensitivity

HESS: \( \Delta \Omega = 10^{-2} \)
Seeing the light from Dark Matter

- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don’t require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)
The Dark Matter Decade

Huge experimental effort towards the identification of Dark Matter

- **Indirect**
  - Antimatter
  - Neutrinos
  - Gamma Rays
  - Signature of Annihilation in space

- **Direct**
  - Elastic Scattering signature in underground labs

- **Collider experiments**
  - Missing Energy signature in high energy accelerators

The Dark Matter Decade

- Neutrino Telescopes
- Gamma-ray Telescopes (ACTs)
- Gamma-ray Telescopes (non-ACTs)
- Direct Detection Exps.
- Colliders

G. Bertone, 24 Oct. 2007
Matter Anti-matter asymmetry:

The universe we live in is made of matter (fortunately for us)

Where has the antimatter gone?
At the scale of the solar system: no concentration of antimatter otherwise its interaction with the solar wind would produce important source of $\gamma$'s visible radiation.

At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\bar{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as $p + p \rightarrow 3p + \bar{p}$.

At the scale of galaxy clusters: we have not detected radiation coming from annihilation of matter and antimatter due to $p + \bar{p} \rightarrow \pi^0 \ldots \rightarrow \gamma\gamma$.

The asymmetry between matter and antimatter is characterized in terms of the baryon to photon ratio,

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The number of photons is not constant over the universe evolution. At early times, it is better to compare the baryon density to the entropy density since the $n_B/s$ ratio takes a constant value as long as B is conserved and no entropy production takes place. Today, the conversion factor is

$$\frac{n_B - n_{\bar{B}}}{s} = \frac{\eta}{7.04}$$
Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

\[ \eta \equiv \frac{n_B - n_B}{n_\gamma} \]

\[ \sim 6 \times 10^{-10} \]

The great annihilation

10,000,000,001
Matter

10,000,000,000
Anti-matter

1
(us)
Counting baryons is difficult because only some fraction of them formed stars and luminous objects. However, there are two indirect probes:

1) **Big Bang Nucleosynthesis predictions depend on the ratio** $n_B / n_\gamma$

Many more photons than baryons delays BBN by enhancing the reaction $D \gamma \rightarrow pn$

2) **Measurements of CMB anisotropies**

probe acoustic oscillations of the baryon/photon fluid

The amount of anisotropies depend on $n_B / n_\gamma$
The abundance of light elements (deuterium, helium, lithium) strongly depends on the amount of protons and neutrons in the primordial universe.

at $t<1$ s

\[
\begin{align*}
    n + \nu_e & \leftrightarrow p + e^- \\
    n + e^+ & \leftrightarrow p + \nu_e \\
    n & \leftrightarrow p + e^- + \bar{\nu}_e
\end{align*}
\]
Primordial nucleosynthesis

- $p + n \rightarrow D + \gamma$
- $D + n \rightarrow ^3H + \gamma$
- $D + p \rightarrow ^3He + \gamma$
- $D + D \rightarrow ^3H + p$
- $D + D \rightarrow ^3He + n$
- $D + D \rightarrow ^4He + \gamma$
- $^3H + p \rightarrow ^4He + \gamma$
- $^3He + n \rightarrow ^3H + p$
- $^3He + n \rightarrow ^4He + \gamma$
- $^3H + D \rightarrow ^4He + n$
- $^3He + D \rightarrow ^4He + p$
- $^3He + ^3He \rightarrow ^4He + 2p$
- $^4He + D \rightarrow ^6Li + \gamma$
- $^4He + ^3H \rightarrow ^7Li + \gamma$
- $^4He + ^3He \rightarrow ^7Be + \gamma$
- $^6Li + n \rightarrow ^7Li + \gamma$
- $^6Li + p \rightarrow ^7Be + \gamma$
- $^7Li + p \rightarrow ^4He + \gamma$
- $^7Be + n \rightarrow ^7Li + p$
- $^7Be + e^- \rightarrow ^7Li + \gamma$
Primordial abundances versus $\eta$

Dependence of the CMB Doppler peaks on $\eta$

(CMB temperature fluctuations)

$\eta = 10^{-10} \times \left\{ 6.28 \pm 0.35, 5.92 \pm 0.56 \right\}$

Baryons: only a few percents of the total energy density of the universe

$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$
How much baryons would there be in a symmetric universe?

Nucleon and anti-nucleon densities are maintained by annihilation processes

\[ n + \bar{n} \longleftrightarrow \pi + \pi \longleftrightarrow \gamma + \gamma + \ldots \]

Which become ineffective when

\[ \Gamma \sim n_N/m_{\pi}^2 \sim H \]

Leading to a freeze-out temperature

\[ T_F \sim 20 \text{ MeV} \]

\[ \frac{n_N}{s} \approx 7 \times 10^{-20} \]
Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation
   (we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation × Parity) violation
   (we need to prefer matter over antimatter)

3) Loss of thermal equilibrium
   (we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature -- particles & antiparticles have the same mass, so no asymmetry can develop)

\[ \Gamma(\Delta B > 0) > \Gamma(\Delta B < 0) \]
In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions.

Need for

- Long-lived particles decays out of equilibrium
- first-order phase transitions
Why can’t we achieve baryogenesis in the Standard Model?

B is violated

C and CP are violated

but which out-of-equilibrium condition?

no heavy particle which could decay out-of-equilibrium

no strong first-order phase transition

Electroweak phase transition is a smooth cross over

Also, CP violation is too small (suppressed by the small quark masses, remember there is no CP violation if quark masses vanish)
Conclusion:

The Standard model of Particle Physics is incomplete: It cannot explain the dark Matter nor the matter-antimatter asymmetry of the universe

New Physics is needed!
Which physics beyond the Standard Model?
ordinary matter is made of fermions which are tied to each other by bosons
Interactions between particles

Elementary particles interact with each other by exchanging gauge bosons.
Theories of grand unification

One single type of matter
One single fundamental interaction
Supersymmetry

Fermions

particles of matter

fermions repel each other

Bosons

particles of force

bosons can pile up
String Theory

Atom
- electrons + nucleus

Nucleus
- quarks

(Super)String

(Hair)
- $10^{-35}$ m

(observable universe)
- $10^{-10}$ m

(Earth)
- $10^{-17}$ m

$10^{-35}$ m
Extra Dimensions

String theories are (well) defined only in spacetime with 10 or 11 dimensions. These extra dimensions are assumed to be curled up.
2010: A new era starts for particle physicists
Back to Mick’s question: “How do we know?”

TODAY

- Dark Energy: 72%
- Dark Matter: 23%
- Atoms: 4.6%
- Neutrinos: 10%
- Photons: 15%
- Atoms: 12%

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

History of the Universe

Key:
- W, Z: bosons
- γ: photon
- q: quark
- g: gluon
- t: top quark
- e: electron
- µ: muon
- ν: neutrino
- n: atom
- b: baryon
- l: ion
- S: star
- G: galaxy
- M: black hole
- E: electron
- T: tau

Accelerators:
- CERN-LHC
- FNAL-Tevatron
- BNL-RHIC
- SLAC-SLC

Possible dark matter candidates:
- Inflation
The Milky Way: One galaxy among hundreds of billions of galaxies in our universe.
Our universe: some hundreds of billions of galaxies

A distribution which reflects the effect of gravity

Stars \subseteq \text{galaxies} \subseteq \text{galaxy groups} \subseteq \text{galaxy clusters} \subseteq \text{superclusters}

the largest known structures
The main characteristic of our universe: homogeneous & isotropic at large scales (>100 Mpc)

The observable universe: ~ 3000 Mpc (1 Mpc ≈ 3.26 × 10^6 light-years ≈ 3 × 10^{24} cm)

at scales < 100 Mpc: very inhomogeneous structure (galaxies, clusters, super-clusters)
The material of the universe is not distributed at random but there is a structure on the very largest scales.

Matter has condensed into filaments, super-clusters, and clusters of galaxies. Numerical simulations of the evolution of the primordial evolution of matter enable to determine the history of some 20 millions of galaxies.
Property 1: Universe is homogeneous and isotropic:

It looks the same whatever the position of the observer is or whatever the direction being observed is.

no preferred position, no center

Cosmic microwave background anisotropies:

\[ \frac{\delta T}{T} \sim 0.001\% \]
property 2: the universe is expanding

spectral lines from distant galaxies are shifted towards the red end of the spectrum

1929: Edwin Hubble

The velocity of recession of a galaxy is proportional to its distance from us

The amount of shift depends on the apparent brightness and hence on the distance

Doppler Effect

\[ \lambda' = \lambda \sqrt{\frac{1 + v/c}{1 - v/c}} \]
The universe was denser and hotter in the past

Expansion dilutes the number of particles and “stretches” the wavelength of photons, i.e. decreases their frequency -> redshift
Big Bang theory

Einstein Equation:

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]

The Robertson-Walker metric, characterized by the "scale factor" \( a(t) \)

Expansion rate:

\[ H = \frac{\dot{a}}{a} \]

Space-time is curved by the presence of matter/energy.
Friedmann Equation:

\[ H = \sqrt{\frac{8\pi G \rho}{3}} \]

What is the value of \( \rho \)?
3 epochs dominated by different forms of energy

1. Rad dominated
   $R \sim t^{1/2}$ thermal bath
   $R < 10^{-4}$, $t < 10^4$ yrs

2. Matter dominated
   $R \sim t^{2/3}$ struc. forms
   $t \sim 10^4$ yrs – $10^{10}$ yrs

3. Dark Energy
   $R \sim e^{Ht}$
   accelerated expansion
   $t > 10^{10}$ yrs
Relativistic degrees of freedom

The graph shows the evolution of relativistic degrees of freedom ($g_*$) with temperature ($T$) over time. The x-axis represents temperature in GeV, while the y-axis represents $g_*$.

Key features include:

- **All SM Particles**
- **Quark/Hadron**
- **$e^\pm$ pairs**
- **$\gamma$/neutrinos**

The graph illustrates the transition from different particle states as temperature changes.
The 2.7 K Cosmic Microwave Background

The peak position depends on $\Omega_{\text{tot}}$

the relative height between the first two peaks depends on $\Omega_b$
At last scattering the particle horizon was only \( \sim 100 \text{ Mpc} \), subtending an angle of about 1 degree. Why then are the large number of causally disconnected regions on the sky at the same temperature?
To allow causal contact over the whole of the region observed at last scattering requires a universe that expanded “faster than light” near $t=0$

=> phase of accelerated expansion known as the inflationary universe
The universe is larger than our observable horizon! Regions that we see now as widely separated in opposite directions in the sky were much closer together before inflation and could have been in direct contact, solving the horizon problem.
Back to dark Energy

- 70% dark energy
- 25% dark matter
- 5% ordinary matter
How are we led to the conclusion that there is some “dark energy”?

1) Postulate a cosmological model

- Friedmann-Lemaitre-Robertson-Walker metric (Friedmann) equation
  - energy content $\rho = \rho_M + \rho_R + \rho_\Lambda + ...$

2) Calculate observables

3) compare with observations: Supernovae, galaxies (distribution of matter density fluctuations/power spectrum), galaxy clusters (mass, redshift, structure), gravitational lensing (measurement of deflection angles is affected by the presence of dark energy)

-> No possible “fit” of the cosmological model if $\rho_\Lambda = 0$.

-> The “fit” gives the value of the “cosmological constant”:
  $\rho_\Lambda = (10^{-4} \text{ eV})^4$
the expansion rate $H$ is a key-quantity

$$H^2(z) = H_0^2 \left[ (1 - \Omega_{\text{TOTAL}})(1 + z)^2 + \Omega_M (1 + z)^3 + \Omega_R (1 + z)^4 + \Omega_w (1 + z)^{3(1+w)} \right]$$

- **Hubble’s constant**
  - CMB
  - (background radiation)
- **curvature**
  - LSS
  - (distribution of structures at large scales)
- **matter**
  - CMB
- **radiation**
  - CMB
- **dark energy**
  - $H(z)$
Evidence for Dark Energy

Astier et al. (2006)
SNLS
Einstein-de Sitter: spatially flat matter-dominated model (maximum theoretical bliss)

Supernovae (SNe1a)

1) Use Standard candles
2) Measure luminosity and redshift
3) make an hypothesis on the cosmological model
4) compare observations and model

$\Lambda$CDM

\[
\rho_\Lambda = (10^{-4} \text{ eV})^4
\]

-> The “fit” leads to the value of the `cosmological constant' $\rho_\Lambda = (10^{-4} \text{ eV})^4$
value deduced from observations:
\[ \rho_\Lambda = (10^{-4} \text{ eV})^4 = 10^{-16} \text{ eV}^4 \]

expected (theoretical) value: \( \sim 10^{120} \) times the observed value
\[ \Lambda = M_{\text{Planck}} \rightarrow \rho_\Lambda = 10^{112} \text{ eV}^4 \]
\[ \Lambda = \text{TeV} \rightarrow \rho_\Lambda = 10^{48} \text{ eV}^4 \]
Future plans

$h(z)$

- $d_L(z)$
  - supernova
  - clusters
- $d_A(z)$
  - baryon osc.
  - strong lensing
  - weak lensing
- $V(z)$
  - clusters
  - strong lensing

Growth of structure

$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho \delta_k = 0$

Test gravity

- solar system
- millimeter scale
- accelerators
- $P(k,z)$
The coincidence problem (the “why now?” problem)
Questions ?
Some web sites

http://www.universeadventure.org/
http://map.gsfc.nasa.gov/universe/index.html
http://www.aip.org/history/cosmology/