Connections between the
Big and Small

Introduction to
31st SSI

John Ellis,
CERN

1 - Big-Bang Cosmology
2 - Particle Physics Beyond the Standard Model
3 - Density Budget of Universe
4 - Formation of Structures
5 - Candidates for Dark Matter
6 - New Physics in Ultra-High-Energy Cosmic Rays
寻找宇宙中最基本的粒子

LEP
LHC

S. Weinberg
A. Salam
S. Glashow
L. Maiani
J. Iliopoulos
G. 't Hooft

10^{15} \text{C}^0
10^{-10} \text{sec}

3 \text{ min}
6000 \text{C}^0

3 \text{C}^0 \text{ K}
15 \text{ billion years}

...
1. **Big-Bang Cosmology**

3 major pieces of evidence for Big Bang

1) **Present-day Hubble expansion**

- All distant objects in the Universe are receding from each other: \( \mathbf{v} = H \cdot d \)
- Velocity \( \rightarrow \) distance \( \leftarrow \)
- Hubble constant: \( H = h \cdot 100 \text{km/s/Mpc} \)
- \( h \approx 0.7 \)

- Expansion is homogeneous, isotropic
- Extrapolate backwards in time...

2) **Microwave background radiation** (~3 K)

- Relic of (re)combination of nuclei + electrons \( \rightarrow \) atoms
- \( T \approx 1000 \times T_{\text{MBR}} \)
- \( a \approx \frac{1}{1000} \times a_0 \)
- Scale size
- \( t \approx 10^6 \) y: best evidence for isotropy
- Extrapolate further back...

3) **Light element abundances**

- \( ^3\text{He}, ^4\text{He}, ^7\text{Li}, \ldots \)

- Consistent with nuclear "cooking"
- \( T \approx 10^8 \) to \( 10^9 \) K (0.1 to 1 MeV)
- \( t \approx (1 \text{ to } 100) \text{s} \)

and even earlier...
Cosmic Microwave Background

isotropic, thermal:

\[ T = 2.728 \text{ K} \]

dipole asymmetry:

\[ \Delta T = 3.353 \text{ mK} \]

perturbations:

\[ \Delta T = 18 \text{ \mu K} \]
Cosmic Microwave Background before WMAP

Angular scale in degrees

Temperature fluctuation $\delta T$ [μK]

Multipole $l$

(Tegmark)
Light - Element Abundances in Universe agree with calculations

Fraction of critical density

0.01  0.02  0.05

$^4\text{He}$ Mass fraction

$10^{-6}$  $10^{-5}$  $10^{-4}$

Number relative to H

$^3\text{He}$

$^7\text{Li}$

Baryon density $(10^{-31} \text{ g cm}^{-3})$

1  2  5

conventional matter $<<$ critical density

-$U$-
TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME

- **Quark era**
  - $\frac{n_e}{n_\gamma} \sim 10^{-9}$
- **Lepton era**
  - $e, \nu, \gamma$
  - $\frac{n_p}{n_\gamma} \sim 10^{-9}$
- **Photon era**
  - $T \sim t^{-1/2}$
  - $p, \alpha, e, \gamma$
- **Matter era**
  - $H, He$
  - $T \sim t^{-2/3}$
  - From 1 GeV to $10^{-3}$ eV

- $T \sim 200$ MeV
  - Quarks bind into hadrons
  - Carnage of quarks and antiquarks.
  - Universe opaque to colour.

- $t \sim 10^6$ s
  - Nuclear synthesis
  - Carnage of electrons and positrons

- $t \sim 10^6$ s
  - Atom formation
  - Universe transparent to light
  - "recombination"
Energy, Temperature, Time

during the expansion of the Universe

- expansion \Rightarrow cooling \quad T \sim \frac{1}{a} \quad \text{size}

- rate of expansion

\[ t \sim a^2 \sim \frac{1}{T^2} \]

age \quad \text{when particle masses negligible}

- the first second \iff high temperatures

1 sec. \sim 10^{10} \text{ K}

and high particle energies

\[ 10^{10} \text{ K} \sim 1 \text{ MeV} \quad \text{of electron mass} \sim \frac{1}{2} \text{ MeV} \]

\[ 10^{13} \text{ K} \sim 1 \text{ GeV} \quad \text{of proton mass} \sim 1 \text{ GeV} \]

- time-temperature relation:

\[ t \text{ (sec.)} \sim \frac{1}{T \text{ (MeV)}^2} \]

the history of the young Universe was dominated by elementary particles
TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME

From $1 \text{ GeV}$ to $10^{19} \text{ GeV}$

- **Planck era**
  - Vacuum phase transition.
  - The Grand Unified Symmetry is broken.

- **GUT era**
  - $\eta_p \neq \eta\bar{p}$
  - CP violation.

- **Quark era**
  - $\eta_p = \eta e$
  - Vacuum phase transition.
  - The W and Z bosons acquire a mass.

Inflation period somewhere between $10^{-44}$ and $10^{-34}$ s

(An artist view)

$T$ (GeV)

$t$ (s)

To be probed by LHC $10^{-12}$ to $10^{-10}$ s

$1\text{ GeV} \approx 10$
Tests of the Standard Model @ LEP

OPAL preliminary

- $e^+e^- \rightarrow \text{hadrons}$
- $e^+e^- \rightarrow \text{hadrons}; \ s'/s > 0.7225$
Roadmap to physics

2. Beyond the Standard Model

Open problems:

- **Standard Model**
  - **Unification**
    - Single framework for all gauge forces
    - Grand Unified Theory (GUT?)
  - **Flavour**
    - Why so many types of quarks? (Q?"
    - Weak mixing? G?
    - Composite? Extra symmetries?
  - **Mass**
    - Origin of particle masses
    - Higgs boson?
    - Why are masses so small?
    - Supersymmetry

- **Theory of Everything**
  - Include gravity
  - Reconcile it with quantum mechanics
  - Origin of space-time
  - Why 4 dimensions?
  - Superstring?
  - M theory?
Defects of the Standard Model

it agrees with all confirmed accelerator data

But

is theoretically very unsatisfactory:

no explanations for particle quantum f's

contains $\leq 19$ arbitrary parameters

3 gauge couplings $g_3, g_2, g_1$

$\Theta_3$

CP-violating vacuum angle

un tidy gauge structure: 3 independent group

6 quark masses $m_u, d, s, c, b, t$

3 charged-lepton masses $m_e, \mu, \tau$

3 "Cabibo" weak mixing angles $\alpha, \beta, \gamma$

CP-violating Kobayashi-Maskawa phase $\delta$

arbitrary Yukawa couplings

1 W mass

Higgs mass

$\mu_W, m_H$
as if that was not enough...

3 neutrino masses
3 neutrino mixing angles
3 CP-violating phases

without even talking about mechanism for \( \nu \) mass generation: more Higgs? heavy \( \eta \) ?...

and do not forget gravity:

1 Newton's constant
1 Cosmological "constant"

\( C_N = \frac{1}{G m_p} \)

is it? or \( V(\phi) \)?

also keep in mind:

\( m_\chi \)

inflation parameter

not Standard Model: %$\frac{\delta I}{I} \alpha \left( \frac{m_\chi}{m_p} \right)^2$%$ \sim 10^{-5} \gg \left( \frac{m_\nu}{m_p} \right)^2$

parameter for baryon asymmetry

not Standard Model: \( m_\chi > 90 \text{ GeV} \)
Where will New Physics Appear?
3 - Density Budget of the Universe

relative to critical density: \( \Omega_i = \frac{\rho_i}{\rho_{crit}} \)

- \( \Omega_{tot} \)
  Inflation suggests \( \Omega_{tot} = 1 \pm 0.1 \times 10^{-4} \) supported by CMB data WMAP

- \( \Omega_\gamma \)
  Nucleosynthesis suggests \( \Omega_\gamma = 0.04 \) insufficient to explain all of \( \rho_c \) WMAP

- \( \Omega_m \)
  Total matter density \( \Omega_m = 0.25 \) clusters, CMB suggest \( < 1 \) WMAP

- \( \Omega_{cdm} \)
  Cold Dark Matter \( \Omega_{cdm} \sim \Omega_m \)? structure formation theory suggests

- \( \Omega_{hdm} \)
  Hot Dark Matter \( \Omega_{hdm} h^2 \lesssim \frac{m}{10^{10}\text{eV}} \) structure formation theory suggests \( < \Omega_m \) atmospheric, solar \( \equiv \) small masses? WMAP

- \( \Omega \Lambda \)
  Cosmological Constant \( \Omega_\Lambda \sim 0.7 \) great opportunity for quantum gravity
The Size of the Universe

Why is the Universe so large?
\[ a \gg l_{pl} \sim 10^{-33} \text{cm} \]

Why is the Universe so old?
\[ t \gg t_{pl} \sim 10^{-43} \text{sec} \]

Why is its density so close to critical value?
\[ \rho \approx \frac{1}{10} \rho_{\text{crit}} \]

Why is geometry Euclidean?

Why is Universe so homogeneous?
on large scales
\[ c / T \lesssim 10^{-5} \]
Modus Operandi of Inflation
\[ \Omega = \frac{\text{density}}{\text{critical}} \]

- **Open Universe**
- **Closed Universe**
- **Flat Universe**

Graphs showing:
- **Open Universe** with a reference length increasing over time; \( \Omega < 1 \)
- **Closed Universe** with a reference length at a maximum; \( \Omega > 1 \)
- **Flat Universe** with a reference length increasing over time; \( \Omega = 1 \)

\textit{inflation}
Constraints on $\Omega_m, \Omega_{\Lambda}$

$\Omega_{\Lambda} = 1$

SN1a

CMB

$185 < l_{\text{peak}} < 209$

$\Omega_m$

(pre-WMAP)

(De Bernardis et al.: Nature 404, 955 (2000))
Cosmological Vacuum Energy?

indicated by high-redshift supernovae

Supernova Cosmology Project
Perlmutter et al. (1998)

$\frac{H_0 t_0}{63 \text{ km s}^{-1} \text{ Mpc}^{-1}} = 19 \text{ Gyr}$

Best fit age of universe: $t_0 = 14.5 \pm 1 \ (0.63/h) \ \text{Gyr}$

Best fit in flat universe: $t_0 = 14.9 \pm 1 \ (0.63/h) \ \text{Gyr}$
Cosmological "Constant"

apparently non-zero

opportunity for theoretical physics

calculate it!

\[ \Lambda = O \left( \frac{m_w}{m_p} \right)^8 \]

is it a constant?

could vary with time:

\[ \omega = \frac{p}{\rho} \]

\[ = -1 \text{ if constant} \]

observationally:

\[ \omega \leq -\frac{1}{2} \]

dynamical relaxation of vacuum energy?

quintessence: scalar field (Steinhardt et al.)

quantum gravity (S.E. + Mousotakis + Nanopoulos)
Content of Universe

in units of amount required to stop Big Bang expansion

ordinary matter ~ 2%
microwave background radiation,
abundances of light elements
dark matter ~ 30%?
vacuum energy ~ 70%?
much more photons than protons, electrons
microwave background also neutrinos
\[
\frac{N_p, e}{N_X} \sim 10^{-9} \text{ to } 10^{-10}
\]

why so little matter?
why any at all?
why no antimatter?
Cosmic-Ray $\bar{p}$ Measurements

![Graph showing the $\bar{p}/p$ ratio versus kinetic energy (GeV). The graph includes data points from various experiments such as BESS(95+97), BESS(93), CAPRICE, Golden et al., Bogomolov et al., Buffington et al., IMAX, PBAR, LEAP, and MASS2.](Image)
AMS (STS91 mission)

Assume $\text{He}$ and $\text{He}$ have the same spectrum up to 140 GV then $\text{He} / \text{He} < \sim 1.1 \times 10^{-6}$
Back to the beginning of the Universe

early Universe very hot
Temperature $(10^9 \text{ K}) \sim \sqrt{\text{age (seconds)}}$

high temperatures $\Rightarrow$ energetic particles
$\Rightarrow$ copious antimatter

**SUPPOSE** primordial soup had

$10^9 + 1$ quarks, $10^9$ antiquarks

as Universe cools, annihilation:

(matter + antimatter) $\Rightarrow$ radiation

odd quark left over of wallflower dance

| matter particle | $10^9$ radiation |

**WHERE** did matter-antimatter asymmetry come from?

was button pushed with this asymmetry?

anthropic principle?

or did laws of Nature generate asymmetry?
Conditions for generating matter asymmetry

need difference: matter ≠ antimatter
seen in laboratory

BREAK C symmetry
weak forces 1957

BREAK CP symmetry
kaons 1964

LOSE thermal equilibrium
otherwise effective T symmetry
of Boltzmann distributions: \( e^{-\Delta T} \)

POSSIBLE during phase transition:

Grand Unified Theory ⇒ strong, electroweak
probability \((X \rightarrow \bar{q}) \neq \text{probability} \((\bar{X} \rightarrow \bar{q})\).

Electroweak Theory ⇒ electromagnetism

\[
\text{temperature} \sim 10^{15} \text{GeV} \sim 10^{18} \text{MeV} \sim 10^8 \text{GeV} \sim 10^5 \text{N}
\]

\[
\text{age} \sim 10^{-36} \rightarrow \text{range} \rightarrow \text{age} \sim 10^{-10} \text{s}
\]
1985 in Gorki
Density Perturbations

Quantum/thermal fluctuations in scalar field → different parts of Universe expand differently

Field energy $V \propto n^4$

Initial field value

Values in different regions of Universe → energy → particles

Gaussian random field of perturbations

$\frac{\delta \rho}{\rho}$ → Scale size

Similar magnitudes at different scale sizes wanted by astrophysicists (Harrison Zeldovich)

Magnitude $\propto$ value of field energy

$\left( \frac{\delta T}{T} \right) \propto \frac{\delta \rho}{\rho} \propto \mu^2 \xi_I$

Consistent with COBE data: $\frac{\delta T}{T} \approx 10^{-5}$

$\mu \approx 10^{16}$ GeV: GUT energy?
Structure Formation

density perturbation = embryonic potential well

cold dark matter particles (non-relativistic) fall in:

density contrast enhanced

hot dark matter particles (relativistic) escape:

suppress growth of small-scale perturbations

amplification of perturbation depends on rate of expansion of universe

sensitive to cosmological constant
Amplification of Primordial Perturbations

by gravitational instability acts within horizon

Cold Dark Matter

\frac{\delta \rho}{\rho}

\rightarrow\text{rayons coupled to radiation}

\rightarrow\text{rayons released}

\rightarrow\text{rayons pulled by Cold Dark Matter if no Cold Dark Matter}
Microwave Background + Large-Scale Structure

cosmological constant + cold dark matter

\[ \frac{\chi^2}{\text{dof}} = 1.9 \]

\[ \Omega_m = 0.5 \]

\( P(k) \ (h^{-1} \text{Mpc})^3 \)

\[ k \ (h \text{ Mpc}^{-1}) \]

(Gawiser + Silk)
Possible future data

Projected SDSS BRG

\[ P(k) \text{ (arbitrary norm.)} \]

- \[ m_\nu = 0 \text{ eV} \]
- \[ m_\nu = 1 \text{ eV} \]

\[ k \text{ (h Mpc}^{-1}) \]

W. Hu - Feb. 1998
COSMIC METALLIC LOOKS

NEW HIGHLIGHTER STICKS AND SPARTICLES

THE BODY SHOP
Why Supersymmetry?

Hierarchy Problem:

why is $m_W \ll m_P$?

$\frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_p^2}$

alternatively

why is $G_F \gg G_N$?

why is $V_{\text{quark}} \gg V_{\text{neutron}}$?

Set by hand?

what about quantum corrections?

\[
S m^2_{H,W} \approx O \left( \frac{\alpha}{\pi} \right) \Lambda^2 \gg m_W^2
\]

cut off $\Lambda \sim m_p$?

made naturally small by supersymmetry:

\[
S m^2_{H,W} \approx O \left( \frac{\alpha}{\pi} \right) (m_B^2 - m_F^2)
\]

\[
\leq m^2_{H,W} \text{ if } |m_B^2 - m_F^2| \ll 1 \text{ TeV}^2
\]

Low-energy supersymmetry
5 - Searches for Dark Matter Particles

Focus on neutralinos

- Annihilation in galactic halo
  \( \tilde{\chi} \tilde{\chi} \rightarrow l^+ l^- \tilde{\nu} \rightarrow \tilde{p}, e^+, \nu \) cosmic rays?
  \( \tilde{\chi} \rightarrow \text{galactic center} \)

- Annihilation in Sun or Earth
  \( \tilde{\chi} \) captured by elastic scattering, \( \Delta E \), \( \tilde{\chi} \tilde{\chi} \rightarrow \text{high energy} \) \( \sim \text{GeV} \)
  underground detectors: \( \nu \) or \( \mu \)

- Elastic Scattering in Laboratory
  \( \tilde{\chi}N \rightarrow \tilde{\chi}N \rightarrow \text{detectable recoil energy} \)
  \( E \approx \text{keV} \times \left( \frac{m_{\tilde{\chi}}}{4 \text{GeV}} \right) \)

- Inelastic Scattering
  \( \tilde{\chi}N \rightarrow \tilde{\chi}(N^* \rightarrow N \tilde{\chi}) \)
  de-excitation + recoil energy: small rate
Gamma-Ray Spectra

in supersymmetric benchmark scenarios

uncertain concentration in galactic centre

\[
\Phi_\gamma (E_{\text{thr}}) \text{ (cm}^{-2}\text{s}^{-1})
\]

\[
E_{\text{thr}} \text{ (GeV)}
\]

EGRET \quad solid: A B C D E F G

AMS/\gamma \quad dashed: H I J K L M

AGILE

STACEE/CELESTE

VERITAS

GLAST

MAGIC

ARGO-YBJ

HESS, LANGAROO

J.E. Feng, Fosel, Mather, Olive
Annihilation in Sun (Earth)

- Capture of relic particle due to recoil energy loss
  hyperbolic orbit \Rightarrow elliptic orbit
  perihelion < solar (radius)
  gee earth?

- Repeated scattering, energy loss
  \Rightarrow quasi-isothermal distribution

- Population control by annihilation
  \( XX \rightarrow \gamma + \ldots \) evaporation negligible for \( m_X > \) few (GeV)

- High-energy solar neutrinos (from core of Earth)
  \( E_\nu \geq 5 \) (eV)
  vulnerable to MSW?!

- Detect directly or via \( \mu \) production
$\kappa \kappa \rightarrow \nu \rightarrow \mu$

annihilation inside the Sun

$\bar{\nu}_e \rightarrow \mu$
Direct Detection of Dark Matter

scattering of nucleus in laboratory:
recoil energy \( E \approx m_x v^2 \approx \text{keV} \)

interaction mediated by exchanges of:

![Diagram of interactions]

too important types of interaction:

- spin-dependent:
  matrix element \( \propto \) quark contributions to proton spin: \( M \sim \sum_i \Delta q_i \cdot c_i \)
  not coherent: important for small nuclei

- spin-independent:
  matrix element \( \propto \) quark contributions to proton mass: coherent, important for heavy nuclei
prospects for dark matter search

Spin-Independent Elastic Scattering

in supersymmetric benchmark scenarios

(J.E. Feng, Festi, Matchev, Olive)
Energy at source

**THE GZK CUTOFF**

![Graph showing energy attenuation of protons]

Energy attenuation of protons:
- **Protons**: photopion threshold @ ~50 EeV
- **Photons**: pair production threshold @ ~200 TeV
- **Nuclei**: photodisintegration above 50 EeV
- **Neutrinos**: no problem!

For E>100 EeV, the source must be within ~50 Mpc.
Fig. 14. Energy spectrum determined by AGASA and the exposure with zenith angles smaller than 45° up until July 2001. (Open circles: well contained events; Closed circles: all events) The vertical axis is multiplied by $E^3$. Error bars represent the Poisson upper and lower limits at 68% confidence limit and arrows are 90% C.L. upper limits. Numbers attached to the points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error. The uncertainty in the exposure is shown by the shaded region.
Fig. 14. $E^2$ times the UHE Cosmic Ray Flux. Results from the HiRes-I and HiRes-II detectors, and the AGASA experiment are shown. Also shown is a fit to the data assuming a model, described in the text, of galactic and extragalactic sources.
Ultra-high-Energy Cosmic Rays
Possible Mechanisms

'Bottom-up'

acceleration by astrophysical sources:

gyromagnetic radius:
\[ R \sim 10^{17} \left( \frac{E}{10^{20}\text{eV}} \right) \left( \frac{m_\gamma}{B} \right) \]

size of cosmic 'accelerator'

upper limit on attainable energy
\[ E \leq 10^{18} \left( \frac{R}{1\text{kpc}} \right) \left( \frac{B}{\mu G} \right) \text{eV} \]

finite time?
energy losses, ...

catalogue of possible sources \( \Rightarrow \) GRBs

'Top-down'

GUT-scale physics \( \Rightarrow \) energetic particles

e.g. topological defects

metastable relic particles

expect anisotropy
clustering?
Hillas-plot (candidate sites for $E=100$ EeV)
Top-Down Fit to UHECR Data

$\log_{10} E^3 J(E) \ (eV^2 m^2 s^{-1} sr^{-1})$

- AGASA
- Akeno 1 km²
- Stereo Fly's Eye
- Haverah Park
- Yakutsk

$\log_{10} E (eV)$
Copernicus:

We do not live at the centre of the Universe

Modern astrophysicists:

We are not made of the same stuff as most matter in the Universe

The challenge: prove it!