Review of
Astroparticle Physics experiments
(in Europe)

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Particle Astrophysics

Particle Astrophysics is the field that uses high energy (particle) physics techniques to study astrophysical processes

• Astronomer:
  • Extension of observation to all electromagnetic spectrum

• Astrophysicist:
  • Explanation of astrophysical processes $O(10^{26} \text{ m})$ with particle physics phenomena $O(10^{-17} \text{ m})$

• Particle Physicist (& Cosmologist):
  • Only possibility to access to extremely high energies (BigBang)

Particle Astrophysics ~ Cosmic Ray Physics

“Cosmic ray particles which we detect directly on earth, at the top of the atmosphere and in the interplanetary medium are the only high energy particles of genuinely cosmic origin which we can detect”

M.S.Longair *High Energy Astrophysics*
Underground Physics

- Physics in Underground Labs. developed during last 20 years with discoveries of great scientific impact.
- Screening of cosmic rays coming from space (one muon per cm$^2$ per minute in the earth surface).
- PROTON DECAY
- NEUTRINO PHYSICS
- DARK MATTER SEARCH
Underground Laboratories

![Graph showing the relationship between depth and muon flux for various underground laboratories. The graph indicates that the muon flux decreases exponentially with increasing depth. Notable laboratories include OROVILLE (USA), IMB (USA), SOUDAN (USA), KAMIOKA (Japan), BOULBY (UK), GRAN SASSO (Italy), HOMESTAKE (USA), SUDBURY (Canada), BAKSAN (Russia), ST. GOTHARD (Switzerland), FREJUS (France), and MONT BLANC (France). The graph highlights CANFRANC (SPAIN) as a significant point.]
International Somport road tunnel
Laboratorio Subterráneo de Canfran
• Astroparticle Physics European Coordination
  - Steering Committee
  - Peer Review Committee
• Formed by large funding agencies for APP in Belgium, Germany, France, Greece, UK, Italy, Netherlands, Portugal, Switzerland and Spain
• Further countries joined or are going to join: Finland, Ireland, Poland, Slovenia, Tchechia, Sweden, ...
ApPEC

ILIAS Networks, JRAs, Transnational Access DUA

KM3

ASPERA (ERANET; as ASTRONET)
  Web page
  Database
  Roadmap
ILIAS

~1200 scientists, budget ~10 M€

Networking Activities
(N2) Deep Underground science laboratories
(N3) Direct dark matter detection
(N4) Search on double beta decay
(N5) Gravitational wave research
(N6) Theoretical astroparticle physics

Joint Research Activities (R&D Projects)
(JRA1) Low background techniques underground
(JRA2) Double beta decay European observatory
(JRA3) Study of noise in gravitational wave detectors

Transnational Access Activities
(TA1) Access to the EU Deep Laboratories

www.ilias.in2p3/fr
"ASPERA"

- ERA-Net „Implementation of European Coordination in Astroparticle Physics“
- 2.8 M€, among others for:
  - Communication Structure
  - ApPEC secretariat
  - ApPEC web page
  - AppEC roadmap
  - Meetings
  - Support of bottom-up activities (like ILIAS)
  - Framework to direct part of the national resources of the agencies to transnational research programs

Has just been approved!
Programs running or in construction
European leadership

<table>
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<tr>
<th>NAME</th>
<th>TYPE</th>
<th>COST</th>
<th>AUTHORS</th>
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</table>

| Totals       | 364.65 | 1910 |

Table of European lead astroparticle programs whose funding is almost complete. The table contains the name of the program, its type, its cost in million Euros, the number of authors signing the publications, starting date, the aspera partners participating in it and the non-aspera partners.

350M€/5 years investments and 2000 physicists
6 questions* (Astroparticle physics)

1. What is the Universe made of?
2. Do protons have a finite life time?
3. What are the properties of neutrinos? What is their role in cosmic evolution?
4. What do neutrinos tell us about the interior of Sun and Earth, and about Supernova explosions?
5. What is the origin of cosmic rays? What is the view of the sky at extreme energies?
6. What is the nature of gravity? Can we detect gravitational waves? What will they tell us about violent cosmic processes?

*"Science is the art of replacing unimportant questions that can be answered by important ones which cannot" Edward B. Ferguson Jr. 1976.
1) What is the Universe made of?

- 3 main experimental questions of today:
  - What is the mechanism of inflation?
    - From WMAP to PLANCK(2008) and beyond ex. SAMPAN(2020)
  - What is the equation of state of dark energy?
    - From a ground program to space ex.SNAP/DUNE(2015)
  - What is the nature of dark matter particles?
    - One ton observatory of dark matter particles based on bolometers or noble liquids (2011)

- Of the 3 questions
  - The last is definitively included in the roadmap
  - The inclusion of the second is under discussion in ApPEC and in the CERN Strategy group
  - The first is considered in other roadmaps (ASTRONET) with participation of the astroparticle community
Detection of Dark Matter

- **Direct detection**
  - CDMS-II, Edelweiss, DAMA,

- **Indirect detection**
  - SuperK, AMANDA, ICECUBE, Antares, etc

Complementary techniques are getting into the interesting region of parameter space.
Dark matter, Detection methods

WIMP: elastic scattering on detector nucleus

$< 1 \text{evt} / \text{kg} / \text{day}$ ⇒
- Deep underground
- Low radioactivity of materials
- Discrimination against radioactive background

Nuclear (vs. electronic) recoil discrimination: event by event or statistical
# NaI scintillation experiments

<table>
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<tr>
<th>EXPERIMENT AND SITE</th>
<th>M (Kg)</th>
<th>E_{\text{Thr}} (KeV)</th>
<th>B (c/KeV Kg day) (Average) Before PSD</th>
<th>OBSERVATIONS</th>
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<td>DAMA LNGS</td>
<td>9 x 9.70</td>
<td>2</td>
<td>1<del>1.5 (at 2-3 KeV) 1.5</del>2 (at 3-6 KeV) 0.5 (at 2.5 KeV) BESt CRYSTAL</td>
<td>Annual modulation effect reported along four annual cycles (4s) 5th and 6th cycles soon Phys. Lett. B450 (99)448, ibid B480 (2000) 23 COMPLETED</td>
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<td>ELEGANT Oto Cosmo</td>
<td>670</td>
<td>4-5</td>
<td>8-10 (at Threshold)</td>
<td>Old set-up upgraded. Large BKG from $^{210}$Pb (10 mB/Kg)</td>
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<td>ANAIS LSC, Canfranc Prototype running</td>
<td>PROTOTYPE 10.7 FINAL SET 10 x 10.7</td>
<td>2</td>
<td>$\sim$1.5 (at 4-10 KeV)</td>
<td>107 Kg intended for ann. mod. search. Old set upgraded plus new radiopure crystals. Preliminary 1200 Kg day. R+D in course In operation Phase I.</td>
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<td>NAIAD (Boulby)</td>
<td>SET OF 48→56kg (8 crystals)</td>
<td>2</td>
<td>$\sim$6-10 (4-20 keV)</td>
<td>Set of NaI encapsulated and unencapsulated In operation.</td>
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<td>LIBRA IN DAMA LNGS</td>
<td>250</td>
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<td></td>
<td>Set of NaI crystals. R+D on detector radiopurity crystals from ultrapure powders (DAMA-ST.GOBAIN). In operation.</td>
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</table>
DAMA: Final results

Exposure 107731 Kg day (approx. 300 Kg year)

ANNUAL MODULATION MODEL INDEPENDENT RESULT

Residual of the rate versus time, for the energy interval 2 to 6 keV

\[ A \cos \omega (t - t_0), \ t_0=152.5 \text{ d}, \ T=1 \text{ y} \]  
(continuous line)

Fitted (all parameters free):

\[ A = (0.0200 +/- 0.0032) \text{ counts/keV/kg/day} \]
\[ t_0 = (140 +/- 22) \text{ d} \]
\[ T = (1.00 +/- 0.01) \text{ y} \]
Annual modulation effect
Model for Neutralino Galactic Halo:

$\rho_{\text{local}} \sim 0.3 \text{ GeV/cm}^3$, $v/c \sim 10^{-3}$, $m_\chi \sim 100 \text{ GeV}$

$\Rightarrow$ flux $10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$!
Detect Dark Matter to see it is there.

Produce Dark Matter in accelerator experiments to see what it is.
Higher dimension models (eg. 6D SO(10)) not included
Definitively not exhaustive neither p channels nor n decay...
3) ¿Qué sabemos de los neutrinos?

- Existen 3 neutrinos ligeros (LEP): \( N_\nu = 2.994 \pm 0.012 \)
- Son mucho más ligeros que sus compañeros leptónicos cargados (¿por qué?):

<table>
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<tr>
<th>( \nu )</th>
<th>( E )</th>
<th>( \nu )</th>
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<tr>
<td>( e )</td>
<td>511 keV</td>
<td>( \nu_e )</td>
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<td>( \mu )</td>
<td>106 MeV</td>
<td>( \nu_\mu )</td>
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<tr>
<td>( \tau )</td>
<td>1.78 GeV</td>
<td>( \nu_\tau )</td>
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- Existe un déficit de neutrinos solares, atmosféricos, reactores y aceleradores: evidencia de oscilación de neutrinos \( \Rightarrow \) son masivos
- Los autoestados de masa y débiles son diferentes \( \Rightarrow \) oscilaciones
- Oscilaciones de neutrinos es la primera indicación de física más allá del Modelo Estándar
The Neutrino mass

Experimental detection of neutrino oscillations

⇓

Neutrinos have got mass

How large is $m(\nu_e)$, what is the mass hierarchy?

1. Tritium $\beta$-decay
   \[ m(\nu_e)^2 = -0.6 \pm 2.2 \pm 2.1 \text{ eV}^2 \quad \text{Mainz} \]
   \[ \Rightarrow m(\nu_e) \leq 2.3 \text{eV (95\%)} \]

2. $0\nu\beta\beta$-decay
   \[ \langle m(\nu_e) \rangle \approx 0.4 \text{ eV} \quad \text{to be confirmed} \]

3. $\nu$-Oscillations
   \[ 7.3 \cdot 10^{-5} \text{eV}^2 < \Delta m_{12}^2 < 9.3 \cdot 10^{-5} \text{eV}^2 \quad \text{solar} \]
   \[ 1.6 \cdot 10^{-3} \text{eV}^2 < \Delta m_{23}^2 < 3.6 \cdot 10^{-3} \text{eV}^2 \quad \text{atm.} \]
   \[ \Rightarrow \text{There is a } \nu \text{ with } m_{\nu_i} \geq 0.009 \text{eV and one with } m_{\nu_j} \geq 0.05 \text{eV} \]

4. Cosmology
   \[ \sum m_{\nu_i} \leq 0.7 \text{eV} \]
Tritium $\beta$-decay

Tritium $\beta$ Decay: $^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu_e$

Superallowed
$E_0 = 18.6 \text{ keV}$
$t_{1/2} = 12.3 \text{ a}$

$$dN/dE = K \ F(E,Z) \ p \ E_{\text{tot}} \ (E_0-E_e) \ \sum |U_{ei}|^2 \ [ (E_0-E_e)^2 - m(\nu_i)^2 ]^{1/2}$$

$$m(\nu_e)^2 = \sum_{i=1}^{3} |U_{ei}|^2 \ m(\nu_i)^2$$

![Graph showing energy spectrum and rate vs energy for tritium decay](image)
Large number of even-even nuclei undergo double-beta decay, but not single-beta decay

Standard Model process of $2\nu\beta\beta$ is also allowed of course

Enrichment procedure in place for about 10 isotopes

You do not search for peaks in unknown places: you always know where to look

Q value of the decay is well known (difference in mass between two isotopes)

\[
\langle m_r \rangle = |c_3^2 c_2^2 m_1 + s_3^2 c_2^2 e^{i\phi_2} m_2 + s_2^2 e^{i\phi_3} m_3|
\]

\[
^{76}\text{Ge} \rightarrow ^{76}\text{Se} + e^- + e^- + (\nu + \nu)
\]
Double beta decay

Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
\[ \Gamma(2\nu) = 100 \times \Gamma(0\nu) \]

76Ge example

Sum Energy for the Two Electrons (MeV)

\[ Q_{\beta\beta} \]

Endpoint Energy
The High Energy Universe

Neutrinos

Charged Cosmic Rays

Gammas
• Ultra-high energy cosmic rays
• high energy photons
• Neutrinos
• Gravitational waves
Neutrino Sources

There are many sources of neutrinos, “natural” and “artificial”:

1) “Fission neutrinos”: bombs and reactors. (\( \sim 10^{11} \text{ cm}^{-2}\text{s}^{-1} \))
2) Accelerator neutrinos. (\( \sim 10^{6} \text{ cm}^{-2}\text{s}^{-1} \))
   These have been the standard HEP \( \nu \)-sources since the 60’s:
   a) “Classical” (K, \( \pi \) decay)
   b) Beam Dump (\( \nu_\tau \) just discovered)
   c) Future Hadron Machines
   d) Future Muon-Colliders (\( \nu \)-factories)
3) Solar neutrinos. (\( \sim 10^{11} \text{ cm}^{-2}\text{s}^{-1} \))
4) Atmospheric neutrinos. (\( \sim 10 \text{ cm}^{-2}\text{s}^{-1} \))
5) Supernova neutrinos.
6) Other astrophysical sources.
7) Big-bang neutrinos (the ultimate challenge).
Neutrino sources

Natural sources

- Sun
- Atmosphere
- Supernovas
- BigBang

Detected

Artificial sources

- Accelerators
- Reactors, Bombs

Undetected
Solar Neutrinos

• The flux of solar neutrinos is calculated in the framework of the Standard Solar Model, J. Bahcall et al. The model assumes hydrostatic and thermal equilibrium
luminosity = rate of energy production:

\[ L = 3.846 \times 10^{26} \text{ watts} \]

• The luminosity is directly related to the total \( \nu_e \) flux. There are several fusion reaction chains, but they all amount to:

\[ 4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e \ (Q=24.68 \text{ MeV}) \]

• The \( e^+ \)s (with \( e^- \)) give \( \gamma\gamma \). Assuming that \( \gamma \)'s and kinetic energy (except that of the \( \nu \)'s) go to heat, the heat production per reaction is

\[ W = Q + 4m_e c^2 - \langle E\nu's \rangle = 26.1 \text{ MeV} \]

• The total number of \( \nu_e \)'s produced by the Sun is then:

\[ N_\nu = 2 \frac{L}{W} = 1.8 \times 10^{38} \nu_e \cdot \text{s}^{-1} \]

• Flux on Earth surface = \( 6.4 \times 10^{10} \nu_e/\text{cm}^2\text{s} \) !!!

• (day and night)
A) The pp cycle

\[ p + p \rightarrow ^3H + e^+ + \nu_e \]

99.6%  \[ p + e^- + p \rightarrow ^3H + \nu_e \]

0.4%

\[ ^2H + p \rightarrow ^3He + \gamma \]

85%

\[ ^3He + ^3He \rightarrow ^4He + 2p \]

15%

\[ ^3He + ^4He \rightarrow ^7Be + \gamma \]

99.87%

\[ ^7Be + e^- \rightarrow ^7Li + \nu_e \]

15%

\[ ^7Li + p \rightarrow ^4He \]

E_\nu < 0.42 \text{ MeV}

E_\nu = 1.44 \text{ MeV}

E_\nu < 18.8 \text{ MeV}

E_\nu = 0.86 \text{ MeV (90%)}

E_\nu = 0.38 \text{ MeV (10%)}

E_\nu < 15 \text{ MeV}

B) The Carbon-Nitrogen-Oxygen Cycle (CNO-cycle)

\[ p + ^{15}N \rightarrow ^{12}C + ^4He \]

\[ p + ^{12}C \rightarrow ^{13}N + \gamma \]

\[ ^{13}N \rightarrow ^{13}C + e^+ + \nu_e \]

\[ p + ^{13}C \rightarrow ^{14}N + \gamma \]

\[ p + ^{15}N \rightarrow ^{16}O + \gamma \]

\[ p + ^{16}O \rightarrow ^{17}F + \gamma \]

\[ ^{17}F \rightarrow ^{17}O + e^+ + \nu_e \]

\[ p + ^{17}O \rightarrow ^{14}N + ^4He \]

\[ ^{15}O \rightarrow ^{15}N + e^+ + \nu_e \]
Solar Neutrino Experiments

**GALLEX RESULTS**

Combined Result (SR1-SR65): 77.5 $\pm$ 6.2 (stat) $^{+4.3}_{-4.7}$ (sys)

SSM prediction : 129 SNU

SAGE : 66.7 $^{+7.1+5.4}_{-6.8-5.7}$ SNU

GALLEX : 77.5 $^{+7.6}_{-7.8}$ SNU
Solar Neutrino Experiments

Simple algebraic equations can be set to obtain independently the different contributions to the solar neutrino flux.
**SNO (Canadá)**

- **CC** \( \nu_e + d \Rightarrow p + p + e^- \)
- **ES** \( \nu_x + e^- \Rightarrow \nu_x + e^- \)
- **NC** \( \nu_x + d \Rightarrow p + n + \nu_x \)

**En ausencia de oscilaciones:**

\[ \Phi_{CC} = \Phi_{NC} = \Phi_{ES} \]

\( (x \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}) \)

\[ \Phi_{CC} = \phi_e = 1.76^{+0.06}_{-0.05} \text{(stat)}^{+0.09}_{-0.09} \text{(sys)} \]

\[ \Phi_{ES} = \phi_e + 0.15 \cdot \phi_{\mu\tau} = 2.39^{+0.24}_{-0.23} \text{(stat)}^{+0.12}_{-0.12} \text{(sys)} \]

\[ \Phi_{NC} = \phi_e + \phi_{\mu\tau} = 5.09^{+0.44}_{-0.43} \text{(stat)}^{+0.46}_{-0.43} \text{(sys)} \]

**Flujo total medido igual al predicho**

\( \nu_e \) parecen transformarse en \( \nu_\mu, \nu_\tau \)

---

**SNO: Sudbury neutrino observatory (Canadá)**

- 1 KT D\(_2\)O
- 9500 PMT’s
- 12 m diámetro (bola ext.)
- 1.7 KT H\(_2\)O tanque interno
- 5.4 KT H\(_2\)O tanque externo
Oscilaciones $\nu_\mu \rightarrow \nu_\tau$

SK observa un déficit de $\nu_\mu$

Análisis ángulo cenital

Máxima oscilación

Análisis L/E

1.5x10$^{-3}$ eV$^2 < \Delta m^2 < 3.4 \times 10^{-3}$ eV$^2$
$\sin^22\theta > 0.02$ at 90% CL

Best Fit:
$\sin^22\theta = 1.02$
$\Delta m^2 = 2.1 \times 10^{-3}$ eV$^2$
$\chi^2 = 174.9/177$ dof
$\chi^2 = 465/179$ dof for no osc

1.9x10$^{-3}$ eV$^2 < \Delta m^2 < 3.0 \times 10^{-3}$ eV$^2$
$\sin^22\theta > 0.90$ at 90% CL

Best Fit:
$\sin^22\theta = 1.02$
$\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$
$\chi^2 = 37.7/40$ dof

90% contour from full dataset
Oscilaciones (ν-solares)

\[ \Delta m^2 \quad (\text{eV}^2) \]

- zona excluida (reactores)
- señal observada (neutrinos solares)

\[ \sin^2 2\theta \]

\[ v_e \rightarrow v_x \]
Oscilaciones ($\nu$-atmosféricos)

\[
\Delta m^2 (\text{eV}^2) \quad \text{vs.} \quad \sin^2 2\theta
\]

- Zona excluida (aceleradores)
- Señal observada (neutrinos atmosféricos)
Neutrinos are responsible for the core cooling and, ultimately, for the supernova explosion.

Actually detected in 1987 by the Kamiokande-II and IMB detectors from Supernova 1987A.
SN1987 A neutrinos

![Graph showing energy (MeV) vs. time (sec) for KAM II and IMB experiments.](image-url)
## Antares: Scientific scope

<table>
<thead>
<tr>
<th>Low Energy</th>
<th>Medium Energy</th>
<th>High Energy</th>
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<tbody>
<tr>
<td>10 GeV &lt; $E_\nu$ &lt; 100 GeV</td>
<td>10 GeV &lt; $E_\nu$ &lt; 1 TeV</td>
<td>$E_\nu$ &gt; 1 TeV</td>
</tr>
</tbody>
</table>

- **$\nu$ oscillations**
  - (Observation of first oscillation minimum)

- **Neutralino search**
  - Self-annihilation at center of Earth, Sun, Galaxy
  - \( \chi \chi \rightarrow X \rightarrow \nu \)

- **$\nu$ from (extra-)galactic sources**
  - SN remnants, AGN, GRB, ...
Pointlike sources

Wide range of predictions of neutrino fluxes for pointlike sources

<table>
<thead>
<tr>
<th>EGRET source</th>
<th># of sources</th>
<th>ANTARES</th>
<th>AMANDA</th>
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</thead>
<tbody>
<tr>
<td>All</td>
<td>271</td>
<td>89%</td>
<td>43%</td>
</tr>
<tr>
<td>AGN</td>
<td>94</td>
<td>86%</td>
<td>52%</td>
</tr>
<tr>
<td>Pulsars</td>
<td>5</td>
<td>100%</td>
<td>40%</td>
</tr>
<tr>
<td>Unidentified:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gal. Plane</td>
<td>55</td>
<td>93%</td>
<td>36%</td>
</tr>
<tr>
<td>Off Gal. Plane</td>
<td>116</td>
<td>90%</td>
<td>40%</td>
</tr>
<tr>
<td>Observ.</td>
<td></td>
<td>source dep.</td>
<td>100%</td>
</tr>
</tbody>
</table>

GRB’s

ANTARES will keep all its data within ±100 secs of a GRB warning signal.
5) Cosmic Rays Spectrum

- >12 orders in Energy
- >30 orders in Flux
- Power Law \( \Phi = \Phi_0 E^{-\gamma} \)

\( E < 10^{15} \) \( \gamma \sim 2.7 \) Galactic

\( 10^{15} < E < 10^{19} \) \( \gamma \sim 3.0 \)

\( E > 10^{19} \) \( \gamma \sim 2.8 \) Extragalactic
Cosmic Ray Spectrum - Ankle

- Ultra High Energy Cosmic Rays $E \sim 10^{20}$ eV
  - Spectral index back to $\sim -2.8$
  - Macroscopic energy (50 J)
  - AGN most likely sources
    - No one found $< 100$ Mpc
- GZK cutoff
  - Universe becomes opaque because of interaction with CMB photons
  
  $\gamma_{2.7K} \to \Delta^+ \to p + \pi^0 \to n + \pi^+$

  $\lambda_i = \frac{1}{\rho_{CMB} \sigma}$
  
  $E_{th} = \frac{M_p \, m_{\pi}}{2 \, q \, \gamma} = \frac{4.26}{y} \times 10^{20}$ eV

  $q_c \, y kT$

- GZK cutoff
  - Universe becomes opaque because of interaction with CMB photons

  $\gamma_{2.7K} \to \Delta^+ \to p + \pi^0 \to n + \pi^+$

  $\rho_{CMB} = 400 \text{ cm}^{-3}$
  
  $\sigma = 2 \times 10^{-28} \text{ cm}^{-2}$

  10 Mpc is comparable to size of galaxy cluster

  No cutoff implies sources of UHECR are nearby

- Greisen, Phys. Rev. Lett 16 (1966) 748
Cosmic Ray Composition

- 98% nuclei
  - 87% protons
  - 12% He
  - 1% heavier elements
- All elements present up to Uranium
- Atoms reach heliosphere fully ionized
- 2% electrons and positrons
  - Steeper spectra at top of the atmosphere
  - \( \frac{e^+/(e^+e^-)}{~0.2 (~1 \text{ GeV}) ~0.1(2 \text{ GeV})} \)
Cosmic Ray Composition

- CR chemical composition similar to Solar system abundances
  - Li, Be, B, F enriched
  - Sc, Ti, V, Cr, Mn enriched
- Apart from Li, these ions are not primordial nor produced in stars
  - Produced by spallation reactions in interstellar medium
- Composition points to stellar origin
  - Odd products more frequent in thermonuclear reactions in stars
  - C, N, O and Fe peaks compatible with thermonuclear chains in stars
- Li, Be, B energy spectra steeper than C or O
  - At higher energies less fragmentation

ACE News#83  http://www.srl.caltech.edu/ACE/ACENews
GCR.
Data taken at Solar minimum Aug 1997-Apr 1998
H-He  BESS  170 MeV/nuc
$^3$Li-$^{28}$Ni  CRIS  170 MeV/nuc
$^{29}$Cu-$^{30}$Zn  CRIS  150-550 MeV/nuc

Solar system.
Photospheric spectroscopy
CI Chondritic meteorites
Exp. techniques in HE cosmic rays

First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Measurement of Cherenkov light with telescopes

Some of the particles reach the ground

Measurement with scintillation counters

Measurement of low-energy muons with scintillation or tracking detectors

Measurement of high-energy muons deep underground

Measurement of particles with tracking detectors (with drift chambers or streamer or Čerenkov tubes)

Measurement of fluorescence light (Fly’s Eye)
Pierre Auger Observatory

How UHECR are accelerated?

• Why are they not attenuated by CMB?
• What is their composition?
• Are they decay products of new particles?

Detection of ground particles by an array of 1600 Cherenkov water tanks with spacing of 1.5 km, (total surface of 3000 km²)
Detection of fluorescence light induced by the shower in the atmosphere.
Currently 2/3 deployed, end 2007.
First conclusive results mid-2007
Pierre Auger Observatory

• Apparatus
  - Total surface 3000 km²
  - 1600 round Water-Cerenkov detectors
    • 11.3m² x 1.2m in a 1.5 km array
  - 24 fluorescence detectors in 4 stations
    • 12 m² mirrors
    • 440 PM
  - Combines strengths of both techniques

• Physics
  - UHECR spectra and composition E>10¹⁹ eV
    • Independent measurement techniques allow control of systematic
    • Reliable energy and angle measurement
    • Primary mass measured in complementary
HE Cosmic Rays

HiRes
AGASA
AUGER
Second generation $\gamma$ telescopes

- MAGIC (2004)
- HESS (2003)
- VERITAS (2006)
Microquasar (MAGIC)
ISS
Dimensions 110 x 90 m
Weight 450 t
Orbit 51.6°
Altitude 400 km
AMS-02 Spectrometer

- Superconducting Magnet
- Silicon Tracker
- Scintillator System
- Transition Radiation Detector
- Ring Imaging Cerenkov
- Electromagnetic Calorimeter

Weight: 6 t
Power: 2 kW

Acceptance: 0.45 m²sr
AMS-02 Antimatter Sensitivity

In 3 years AMS will collect $10^9$ He with $E \lesssim 1$ TeV
Understand the spectra and composition of cosmic ray particles,

Are there cosmic antiparticles?

Are there dark matter decay products?

In order to search for new physics one must first understand the CR in our galaxy
6) What is the nature of Gravity? Can we detect gravitational waves? What will they tell us about violent cosmic processes?

- Now: GEO-600, VIRGO (+ upgrades)
- > 2010: Adv VIRGO (within budget), Adv LIGO
- > 2014 LISA in space
- > 2015: Large underground interferometer
  - Understand mergers, pulsars, supernova, stochastic background
  - Move from astrophysics to cosmology
  - Tests of General relativity
ApPEC Roadmap (GW Detectors Summary)
Conclusions

Astroparticle Physics is becoming an attractive discipline in Science

ApPEC coordination fruitful

Lot of experiments in progress

Lot of work to do

Still many important questions to be answered