Outline

- The Extreme Universe: Science Case
- UHECRs
  - Latest News from Auger, HiRes and TA
    - Energy Spectra: GZK-Effect
    - Anisotropies: Search for Sources
    - Mass-Compos.: Puzzling Results
    - Photon Limits: Propagation and TopDown Tests
- Tests of Fundamental Physics
- Neutrino Astronomy
  - Latest Results from IceCube, ANTARES, Auger, ...
- Future Directions

Largely based on results presented at ICRC in Łódź, last week
All Particle Cosmic Ray Spectrum

**Equivalent c.m. energy** $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande (prel.)
- Tibet
- HiRes-MIA
- HiRes I
- HiRes II
- Auger SD 2008

Diffusion losses from Galaxis?

Galactic CRs?

Extragalactic CRs?

AGN?

Particle Energy (eV)

- HERA ($e$-$p$)
- RHIC (p-p)
- Tevatron (p-p)
- LHC (p-p)
Want LHC to accelerate protons up to $10^{20}$ eV ??

![Diagram showing cosmic ray spectrum and particle energies](image)
CR Absorption in CMB (GZK-Effect)

\[ E_p E_\gamma > (m_\Delta^2 - m_p^2) \]
\[ \Rightarrow E_{GZK} \approx 6 \cdot 10^{19} \text{ eV} \]

X-section is known, \( n_\gamma = 412/\text{cm}^3 \) is known

\[ \lambda_{free} = \frac{1}{n_\gamma \cdot \sigma_{p\gamma}} \approx 8 \text{ Mpc} \]

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**Greisen-Zatsepin-Kuz'min (1966)**

\[ p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \]
\[ \rightarrow n + \pi^+ \]
The GZK Horizon

90% of events from $x < D$; $dN/dE \sim E^{-2.7}$

90% of particles at $E > 80$ EeV come from within 100 Mpc

Harari et al.; astro-ph/0609294
• Sources of most energetic CRs need to be nearby
• Deflections in magnetic fields are moderately weak

→ Opportunity to identify sources by CR-Astronomy!
→ need to measure: direction, energy, particle-type

By-Products:
• Do Particle Physics at the Highest Energies,
e.g. pA and v- cross-sections
• Probe Fundamental Physics, e.g. Tests of LIV
• Learn about Cosmic Environments, e.g. B-FIELDS
HiRes Experiment (Dugway, Utah)

HiRes-I
21 mirrors
1 ring, full azimuth, 3°-17° elevation
Sample & Hold DAQ System

HiRes-II
42 mirrors
2 rings, full azimuth, 3°-31° elevation
FADC DAQ System
Took data: Dec. 1999-April 2006

Both:
5.1 m² mirrors, 16x16 PMTs

HR I+II data taking:
June 1997-April 2006
Auger Hybrid Observatory (Argentina)
Auger Hybrid Observatory (Argentina)

24 fluorescence telescopes...

...1600 Water Cherenkov tanks
Pierre Auger Observatory

1600 SD stations
(1.6 km spacing)
= 3000 km²
24 FD telescopes

Fully Operational since June 2008

Hybrid Detector of 3000 km²
Telescope Array (Utah)

- Fully Operational since March 2008
- 507 Plastic Scintillator Detectors cover ~700 km² (1.2km spacing)
- 3 Fluorescence Telescope Stations overlook the array.
- Utah, USA
  39.3 °N, 112.9 °W
  alt. 1400 m
Exposures @ ICRC 2009

As a fct of energy...

AGASA : HiRes : Auger
1 : 5 : 10

... and time
UHECR Energy Spectrum
Hybrid: More than Sum of the Two

**Surface Detector Based:**
+ High Statistics (24 hrs a day)
+ Simple geometrical exposure
  – Calibration of Energy from EAS-simul.

**Fluorescence Detector Based:**
+ High Resolution
+ Low energy threshold
+ Calibration by laboratory expt’s
  – about 15 % duty cycle
  – complicated aperture

**Hybrid Based:**
+ Well known calibration
+ Flat, well known aperture
+ Low energy threshold
Ground Array calibrated by Fluorescence Obs.

795 events
$E_{\text{max}} = 6 \cdot 10^{19} \text{ eV}$

Applied by Auger and Telescope Array

SD energy param. $\lg(S_{38}/\text{VEM})$

Energy from FD $\lg(E_{FD}/\text{eV})$

observed lateral particle density
Hybrid Energy Spectrum

Equivalent Centre of Mass Energy $\sqrt{s_{pp}}$ (TeV)

Transition Galactic $\rightarrow$ Extragalactic CRs?

max. energy of accel. or propagation?

CR Energy (eV)


Auger 2009

Auger @ ICRC09
Comparison HiRes - Auger

$J / (A \times E^{2.6})^{-1}$ vs $\log_{10}(E/eV)$

- **HiRes Stereo**
- **Auger**

Energy [eV]

$10^{18}$ $10^{19}$ $10^{20}$
Comparison HiRes - Auger

differences compatible with 25\% uncertainty of energy scale

Energy [arb. units]

-1 -0.5 0 0.5 1 1.5 2

\[ J / (B \times E^{2.6}) -1 \]

○ HiRes Stereo \((k_E=0.75)\)

or

● Auger \((k_E=1.25)\)
Comparison with Astrophys. Models

$$\phi(E) \propto E^{-\beta} \cdot (1 + z)^m$$

- Simple models fit data surprisingly well
- Constraining models needs composition measurement
UHECR
Anisotropies
Auger Sky above 60 EeV

**27 events as of November 2007**
(with Verón-Cetty-Verón catalogue)

**58 events now**
(with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).

<10⁻⁵ samples of isotropic distr’s give higher LL than data
However ...

Auger correlation strength with VCV dropped from \( \sim 70\% \) to \( \sim 40\% \) (still, isotropy excluded at \( >99\% \)).

HiRes Sky plot of Northern Sky
10 evts above 57 EeV
(42 EeV on Auger scale)
compatible with isotropy

TA sees 3 correlated events out of 4 measured ones
Galactic Magnetic Fields are important

✧ Does GMF disturb the expected correlation of the highest energy cosmic rays (HECRs) with their sources (even if HECRs are mainly protons)?
✧ Can there be differences between Southern and Northern sky?
✧ Can HECRs obtain information on GMF?
✧ 0.2-0.3 µG near solar system; but mG parallel to galactic disk found

- four basic models for GMF

- S-parity: no reversals between spiral arms
- A-parity: reversals between spiral arms

Correlations at 3-5° scale possible except for AS-structure models in northern sky
Centaurus A appears interesting

Central AGN core now also seen by HESS and FERMI-LAT

H.E.S.S. @ ICRC09

Cen A brightest radio source; d~ 3.5 Mpc

Auger @ ICRC09

Data
Isotropic

12 events within 18°
2.7 expected
2% chance prob.
UHECR Composition
Composition from $X_{\text{max}}$ observations

Performed by HiRes, Auger and TA

Example: Auger Hybrid

$E_{\text{tot}} = \int_{0}^{\infty} \frac{dE}{dX} dX$

Analysis of stereo data: $\sigma(X_{\text{max}}) = 20-25 \text{ g/cm}^2$
Composition from Xmax

- Ankle region: light composition
- Higher Energies: Auger - mixed; HiRes - light (but within systematic uncertainties)

Expts: ~15-20 g/cm² syst. error
**Surprise: Very Small Fluctuations of $X_{\text{max}}$!**

Auger @ ICRC 2009

Observed Fluctuations suggest Fe-dominance at $E > 3 \cdot 10^{19} \text{ eV}$!
Hints for increasing X-Section?

All these data are based on cosmic ray measurements!
Search for Photons
Motivation for Photon Search

- Acceleration of nuclear primaries + photo-disintegration in CMB during propagation
  → expect small fraction of photons

- Non-acceleration models (decay/annihilation of primordial relics; Super-Heavy Dark Matter)
  → expect large fraction of photons

- Z-Burst Models: interaction of EHE-ν’s with cosmogenic ν’s
  → sensitive to ν-mass and detection of cosmogenic ν’s

- Tests of fundamental physics
  → Lorentz-invariance Violation (LIV)
  → smoothness of space-time

Very good γ-Hadron Discrimination by X_{max} Measurements
Photon Upper Limits vs Predictions

Motivation

Data set and selection

Photon upper limits vs predictions

Confirmation of previous constraints on non-observation models

Threshold energy [eV]

Photon fraction

Top Down & SHDM Models largely ruled out

GZK photons

Auger Hybrid

Auger SD

SHDM, TD, Z Burst: Gelmini et al. '05
SHDM': Ellis et al. '06
GZK: Gelmini et al. '07

Auger 09
Yakutsk 09

HP: Ave et al. '00 & '02
A1: Shinozaki et al. '02
A2: Risse et al. '05
AY: Rubtsov et al. '06
Y: Glushkov et al. '07

Auger SD:
Auger Collaboration '08

HP: Ave et al. '00 & '02
A1: Shinozaki et al. '02
A2: Risse et al. '05
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Y: Glushkov et al. '07

Auger Hybrid:
Auger Collaboration '09
Tests of Fundamental Physics
Lorentz Invariance Violation (I)

- LIV related to structure of space time near Planck scale
- Vacuum Cherenkov Radiation $\rightarrow$ expect strong E-losses absence $\rightarrow$ best presently existing SEM-Parameters *
- Particle dependent maximum $c_j \rightarrow$ GZK-effect altered** $p + \gamma \rightarrow p + \pi$

\[ c_i - c_j = \frac{\epsilon_i - \epsilon_j}{2} \equiv \delta_{ij}. \]

\[ \delta_{\pi p} = 10^{-22} \ldots 3 \cdot 10^{-24}, 0 \]

* Klinkhamer, Risse; PRD77, 016002
** Coleman, Glashow; PRD59, 116008
Lorentz Invariance Violation (II)

LIV $\rightarrow$ may modify photon dispersion relation

$$\omega^2 = k^2 + m^2 + \xi_n k^2 (k/M_{Pl})^n$$

$\rightarrow$ affect the threshold for $e^+ e^-$ pair production

$\rightarrow$ $p + \gamma_{CMB} \rightarrow \Delta \rightarrow n + \pi^0 \rightarrow \gamma \gamma \rightarrow e^+ e^-$

cascading of UHE photons suppressed

expect significant photon fraction above $\sim 10^{19}$ eV

$$\xi_1 \leq 2.4 \times 10^{-15}$$

$$\xi_2 \geq -2.4 \times 10^{-7}$$

7 orders of magnitudes better than previous limits!
Neutrino Astronomy
ν-Telescope Projects

ANTARES+NEMO+NESTOR: Joint effort for km$^3$-scale detector KM3NeT

AMANDA/IceCube
Principle of Neutrino Detection

Water or Ice

\[ \nu_\mu \rightarrow \mu n \text{ reaction} \]

\[ \mu \text{ recoil cascade} \]

Time & position of hits

PMT amplitudes

\[ \mu (\sim v) \text{ trajectory} \]

Energy
IceCube at South-Pole

South Pole Station Building

Astronomy Sector

IceCube

skiway

2000 mtrs down

AMANDA
IceCube Observatory

Remaining: 22 IceCube Strings
5 DeepCore Strings
→ complete in January 2011
Antares

- Detector at 2500 m depth
- Site 40 km SSE of Toulon
- 40 km data cable
- Counting room La Seyne-sur-Mer
All-sky map (6 months IceCube 2008, 40 strings)

Northern hemisphere
TeV - PeV
Background: atmospheric neutrinos

Southern hemisphere
PeV - EeV
Background: atmospheric muons
Reduced by $10^{-5}$ using energy cut

175.5 days livetime,
6796 up-going events,
10981 down-going events
Hottest location at r.a. = 114.95°, dec. = 15.35°
Pre-trial $-\log_{10}(p\text{-value}) = 4.43$

all-sky p-value is 61% $\rightarrow$ not significant
Point Sources limits/sensitivities

- **AMANDA 7 yr**
- **40-string Discovery Potential**: $5\sigma$ in 50% of trials
- **ANTARES**
- **80-string Sensitivity**: Based on 40-string analysis

40 string results preliminary
Diffuse Neutrino Fluxes

IceCube atm. $\nu$

Integral limits (E^{-2} flux) from Baikal, Amanda IceCube

Auger

WB bound

GZK

C. Spiering
Neutrino Absorption in Earth

Earth becomes 'opaque' above $E_\nu \geq 100$ TeV

$E_\nu = 1$ GeV

$E_\nu = 1$ PeV

$E_\nu = 100$ PeV

Nadir Angle $\theta$ (rad)

v-shadow factor $S$: $1/2\pi \frac{dS}{d\cos \theta}$

based on

CTEQ3-LDA

CTEQ4-DIS Parton distr.

MRS-D'

nach Gandhi et al., Fermilab-Pub-98-087-T
EeV Neutrinos by Horizontal EAS

Only a neutrino can induce a young horizontal shower!

ν → em → μ

ντ → h

~30 atm

shower front

after 1 atm

electromagn. cascade

after 3 atm

hard muons
+ 20% electrons in equil. with muons

'old' showers (h)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

EeV Neutrinos by Horizontal EAS

Only a neutrino can induce a young horizontal shower!
Askaryan Effect gives rise to coherent radio emission (verified e.g. @ SLAC)

Huge volumes can be observed
Assuming \( \nu \) flavour \( e:\mu:\tau = 1:1:1 \), several astrophysical models are excluded, while cosmogenic neutrinos are in reach!
Future Directions
**UHECRs**

**GZK-effect established**
- Filter to nearby sources
  - But: steep spectrum above 60 EeV requires huge apertures

**UHECR-Astronomy** around the corner
- CR sources will be identified,
  - better knowledge of magn. fields required ➔ projects with astronomers

Want to measure spectra/composition of individual sources

Study *fundamental physics*, particle physics, exotics

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**Auger-North + JEM-EUSO**

**New techniques**
Radio observation of EAS may reduce costs
UHE-ν‘s

Present results from **UHECR** suggests a few ν’s year/km³

→ If sources are seen, another undisputable proof for CR-accelerators
First 2 years of IceCube should tell...

SN-explosion in Galaxy or LMC → hundreds of ν’s would be seen
Competative Dark-Matter limits come for free

**km3net + New Techniques**

**km3net** large enough?
Acoustic a/o Radio techniques very attractive for huge volume instrumentation; but applicability to be proven...
Moon Regolith serves as $\nu$-Target

First observations performed already
Will be fully exploited by LOFAR
Very exciting time also for Astroparticle Physics