Ground based cosmic ray experiments: results and perspectives

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INAF-OaTo & INFN Torino

11th Workshop on Science with the New generation of High Energy Gamma-ray Experiments

October 18-21, 2016 - Pisa, Italy
The experimental challenge

Galactic cosmic rays

extra-Galactic cosmic rays

J \times E^{2.5} [m^{-1} s^{-1} sr^{-1} eV^{1.5}]

all-particle knee

transition region

suppression region

post-ICRC2015

\begin{itemize}
  \item ARGO All analog
  \item Tibet QGS+HD
  \item Tibet QGS+PD
  \item GAMMA
  \item Tibet Sib+HD
  \item IceTop
  \item Kascade-Grande combined
  \item Kascade-Grande EPOS-LHC
  \item Kascade-Grande QGSJet04
  \item Yakutsk
  \item Telescope Array
  \item Pierre Auger
\end{itemize}
# The air shower detectors

<table>
<thead>
<tr>
<th>Array</th>
<th>( g \text{ cm}^2 )</th>
<th>Detector</th>
<th>( \Delta E \text{ [eV]} )</th>
<th>Area [km(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ARGO</strong></td>
<td>600</td>
<td>RPC hybrid (LLASHO)</td>
<td>( 0.3 - 5 \times 10^{15} )</td>
<td>0.0056</td>
</tr>
<tr>
<td><strong>Tibet-AS(\gamma)</strong></td>
<td>600</td>
<td>Scintillator/burst detector</td>
<td>( 1 - 200 \times 10^{15} )</td>
<td>0.0037 [0.5 phase III]</td>
</tr>
<tr>
<td><strong>EasTop</strong></td>
<td>820</td>
<td>scintillator/muon</td>
<td>( 1 - 100 \times 10^{15} )</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>GAMMA</strong></td>
<td>700</td>
<td>scintillator/muon</td>
<td>( 3 - 200 \times 10^{15} )</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>KASCADE</strong></td>
<td>1020</td>
<td>scintillator/muon</td>
<td>( 2 - 90 \times 10^{15} )</td>
<td>0.04</td>
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<tr>
<td><strong>CASA-MIA</strong></td>
<td>860</td>
<td>scintillator/muon</td>
<td>( 0.1 - 100 \times 10^{15} )</td>
<td>0.25</td>
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<tr>
<td><strong>Kascade-Grande</strong></td>
<td>1020</td>
<td>scintillator/muon</td>
<td>( 10^{16} - 10^{18} )</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>IceTop</strong></td>
<td>680</td>
<td>ice Cher. tanks</td>
<td>( 10^{16} - 10^{18} )</td>
<td>1</td>
</tr>
<tr>
<td><strong>Tunka</strong></td>
<td>900</td>
<td>unshielded PMTs</td>
<td>( 10^{15} - 10^{18} )</td>
<td>3</td>
</tr>
<tr>
<td><strong>Yakutsk</strong></td>
<td>1020</td>
<td>scintillator/unshielded PMTs</td>
<td>( 10^{15} - 10^{19} )</td>
<td>~40</td>
</tr>
<tr>
<td><strong>Telescope Array + TALE</strong></td>
<td>880</td>
<td>scintillator + fluorescence tel.</td>
<td>( 4 \times 10^{15} - 10^{20} )</td>
<td>700</td>
</tr>
<tr>
<td><strong>Auger + Infill</strong></td>
<td>840</td>
<td>water Cher. tanks fluorescence tel.</td>
<td>( 10^{17} - 10^{20} )</td>
<td>3000</td>
</tr>
</tbody>
</table>

**High altitude experiments**
- \( N_{\text{part}} \) ~ indip of composition
- close to maximum of EAS: low fluctuations
- energy resolution

**Sea level experiments**
- \( N_{\text{part}} \) ~ indip of composition
- EAS after maximum
- exploit longitudinal distribution differences for different primaries
- composition
The knee region

- Evidence for a proton knee at $E_k = (700 \pm 230)$ TeV at variance with $E_k(p) \sim E_k(\text{all-particle})$
- $\gamma$ from $(-2.56 \pm 0.05)$ to $(-3.24 \pm 0.36)$
- Compatible with JH2003 spectrum with proton knee at 1 PeV

- Power index for light spectrum steeper wrt all-particle one: $E_k(\text{light}) < E_k(\text{all})$
- Heavy component dominates the all particle knee

Data

<table>
<thead>
<tr>
<th>Data</th>
<th>$\sigma(E)$</th>
<th>$\sigma_{\text{sys}}$ (E scale)</th>
<th>$\sigma_{\text{sys}}$ (flux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td>25%</td>
<td>-9.7%</td>
<td>-28%</td>
</tr>
<tr>
<td>Analog</td>
<td>15%</td>
<td>5%</td>
<td>20%</td>
</tr>
</tbody>
</table>
The knee region - old results

- Light knee around few PeV
- Harder spectrum for heavier nuclei: indication for $E_k \propto Z$
- Old models, lower resolution

- All-particle knee $\sim 4 \times 10^{15}$ eV
- p knee around few PeV, heavier knee not visible (no statistics)
- If Peters cycles, $E_k(\text{Fe})$ must be found at $\sim Z \times E_k(p) \sim 7-10 \times 10^{16}$ eV

Similar results in Casa-MIA, Gamma experiments
The transition region

- \textbf{(heavy+medium) component knee} \sim 10^{16.88} \text{ eV} \textit{compatible with previous result}
- \textbf{light component hardening} \sim 10^{17.08} \text{ eV}, \Delta \gamma = 0.46 \textit{(from -3.25 to -2.79)} \rightarrow 5.8\sigma: \textit{start of the transition?}
The transition region

**IceTop**

- KG features confirmed in both standalone and combined analysis
- Light spectra steeper
- Problem with iron component?

Systematics: +9.6% -12.5%
(dominant effect light yield in the in-ice detectors)

**Tunka**

- Features in agreement with KG experimental results
- Agreement with TALE spectrum between $2 \times 10^{17}$ and $10^{18}$ eV
- Knee: $p$, $He$
- Heavy knee at $\sim 7 \times 10^{16}$ eV
- EG light component growing above $4-5 \times 10^{16}$ eV
The UHE region

Telescope Array

- Knee for the heavy component \( \sim 7 \times 10^{16} \) eV
- EG light component growing \( > 4-5 \times 10^{16} \) eV

- 4.8 orders of magnitude spectrum, 4 spectral features
- thanks to TALE, a clear 2nd knee is visible at \( 10^{17.2} \) eV and a low energy ankle appears around \( 10^{16.25} \) eV
The UHE region

Pierre Auger Observatory

- composition meas. extended to $\sim 10^{17}$ eV thanks to HEAT
- detector unfolded

- ankle observed at $E_{\text{ankle}} = 4.8 \times 10^{18}$ eV
- cut-off clearly observed ($>20\sigma$ significance).

$E_{1/2} = (2.48 \pm 0.01) \times 10^{19}$ eV
• **data better reproduced with a mixed composition**

• p fraction increases to >60% at the ankle, drops near $10^{19}$ eV, maybe rising again at higher energies —> but EG according to anisotropy limits!

• no significant contribution of Fe
The UHE region - interpretation

- Pure proton, $E > 10^{18.2}$ eV
- Injection spectrum $E^{-\gamma}$, $E_{\text{max}} = 10^{21}$ eV
- Source density $(1 + z)^m$ (per comoving unit volume)
- Energy losses with CMB and IRB.
- Propagation code: TransportCR [checked by CRPropa]
- no magnetic fields

Telescope Array

- identical sources homogeneously distributed
- Injection of H, He, N, Fe
- injection spectrum
  \[
  \frac{dN_{\text{diff}}}{dE} = \left\{ \frac{J_0 p_i}{E} \right\} \gamma \exp \left(1 - \frac{E}{Z_i R_{\text{cut}}}\right), \quad E/Z_i < R_{\text{cut}}
  \]
  \[
  \frac{dN_{\text{diff}}}{dE} = \left\{ \frac{J_0 p_i}{E} \right\} \gamma \exp \left(1 - \frac{E}{Z_i R_{\text{cut}}}\right), \quad E/Z_i > R_{\text{cut}}
  \]
- Photodis. cross section + EBL (far IR)
- Propagation code: CRPropa, SimProp
- no magnetic fields

Pierre Auger Observatory

- data compatible with pure proton model
- $\gamma = 2.18 - 0.14 + 0.08$ (stat.+sys.)
- suppression due to GZK cutoff

- hard injection ($\gamma \sim 1$) and low cutoff ($R_{\text{cut}} < 10^{18.7}$ eV) favoured
- $\gamma \sim 2$ strongly disfavoured by $X_{\text{max}}$ distribution width
The UHE region - PAO and TA comparison

Energy spectrum
- very good agreement for $E_{\text{ankle}}$
- different interpretation for the suppression
- difference not due to different declination

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$E_{\text{ankle}}$ (EeV)</td>
<td>$5.2 \pm 0.2$</td>
<td>$4.8 \pm 0.1 \pm 0.8$ (syst)</td>
</tr>
<tr>
<td>$E_{1/2}$ (EeV)</td>
<td>$60 \pm 7$</td>
<td>$24.7 \pm 0.1 \pm 8.2 \pm 3.4$ (syst)</td>
</tr>
<tr>
<td>$\Delta E / E$</td>
<td>21%</td>
<td>14%</td>
</tr>
</tbody>
</table>

PAO Composition in TA reconstruction chain:
- TA reconstruction of events simulated according to PAO $X_{\text{max}}$ distribution
- average $X_{\text{max}}$ agrees within uncertainties

**TA cannot distinguish between “proton” or “Auger mixed” composition with the current level of uncertainties**
Multimessengers

From primary p and heavy nuclei production, acceleration and propagation, we can expect neutral primaries

\[ \gamma \]
- p pair production
- pion photo production (\(E_\gamma \sim 0.1E_p\))
- neutron decay
- top-down models
- in EM cascades by pair production, inverse Compton scattering

Travel distance \(\sim 4.5/\text{EeV Mpc}\)

Galactic + EG

\[ \eta \]
- pp interaction near the source
- pion photo production (\(E_\gamma \sim 0.8E_p\))
- neutron decay
- neutron decay

\(\tau \sim 886\) s
Travel distance \(\sim 9.2/\text{EeV kpc}\)

Galactic sources only

\[ \nu \]
- pion photo production (UHE) (\(E_\nu \sim 0.05E_p\))
- interactions within the sources (PeV)
- interaction with relic \(\nu\) (Z-burst)
- top-down mechanisms

unattenuated

Up to cosmological distances
Protons near the ankle produce photons ~ 1 EeV: can we find them?
- as the energy flux in TeV γ rays exceeds 1 eV cm\(^{-2}\) s\(^{-1}\) for some sources (CenA, GC) with this energy spectrum, we expect similar flux at EeV (as sources with spectrum \(\sim E^{-2}\) put the same energy flux/decade)

No point sources of EeV photons is found.
For \(d\phi/dE \sim E^{-2}\)
\[\phi_\gamma < 0.25 \text{ eV cm}^{-2} \text{ s}^{-1}\]
well below expectations

**No Galactic sources of protons IF**
- they are not transient
- they do not emit in jets towards Earth
- they are too faint


No candidates found:
For an \(E^{-2}\) neutron spectrum
\[0.083 \text{ eV cm}^{-2} \text{ s}^{-1}\]

[Aab et al., ApJL 789 (2014) L34]
Photon flux

VHE

- new upper limits from Kascade-Grande
- the limits on TeV to PeV diffuse γ-ray flux can set constraints on the galactic or EG origin of the IceCube excess

[K. Feng et al., ICRC2015]

UHE

- top-down models highly disfavoured
- first constraints to the most optimistic predictions for cosmogenic photon fluxes
- 4 times lower or 2 order of magnitude fluxes are predicted for p or Fe primaries if $\gamma_{inj} \sim -2$ and $E_{max} \sim 10^{21}$ eV at the sources
- observations cover both hemispheres

[C. Bleve et al., arXiv:1509.03732]
**ν detection in EAS arrays**

- maximum sensitivity where cosmogenic ν flux peaks
- first EAS detector reaching factor ~4 below WB
- strong constraints to models with proton primaries and strong evolution with redshift

Auger data do not yet constrain neutrinos from heavy primaries
- search limited by exposure

[A.Aab et al., PRD91 (2015) 092008]
Neutrinos and UHECRs

- HE extraGal. neutrinos can be produced by protons of $10^{15}$-$10^{17}$ eV
- sources of UHECRs >50 EeV can produce also lower energy CRs

Different analyses are employed to investigate the possible correlations between 318 UHECRs in Auger+TA with IceCube neutrino events

But

- if suppression of UHECRs flux due to GZK, maybe just a % fraction of HE neutrinos come from the same (nearby) sources producing UHECRs
- if burst-like sources, neutrinos arrive long before UHECRs, correlation not feasible
- sources producing HE neutrinos could be unable to produce UHECRs

\[\text{all results below 3.3}\sigma\]

with IC cascades:
correlation analysis: $p$ $5\times10^{-4}$, at angular scale $\sim22^0$

higher correlations in the region of TA hot spot an close to the Supergalactic Plane (PAO warm spot)

[IceCube, TA, Auger Coll., JCAP 01 (2016) 037]
UHEv follow-up of GW events

GW150914 & GW151226
- merger of binary black holes
- 3 and 1 M⊙ released in GW
- D_GW ~ 410 and 440 Mpc
- position few 100 deg²

[NSIG & Virgo Coll., PRL116 (2016) 061102 and 241103]

Em counterpart improbable, but
- Fermi GBM: transient source at 50 keV, 0.4s delay wrt GW150914 [V.Connaughton, arXiv:1602.07352]
- different models predict UHE neutrino production

Example:

UHECRs and neutrinos from BH-mergers

Transient sources can provide an environment for production and acceleration of UHECRs,

✓ rare transients (~ 1 Gpc⁻³ yr⁻¹) could be enough to produce a dense population
✓ BH mergers should be surrounded by metal-rich debris and able to accelerate heavy nuclei

Auger neutrino selection
- evt +/- 500 s around GW evt
- evt +1 day after GW evt (GRB afterglow in UHE ν)

No UHE neutrino candidate found
Limits on radiated energy in UHEv (declination dependent) at E>10¹⁷ eV
- < (0.5, 3) M⊙ released from both GW150914 and GW151126
- first limit in EAS

[Auger Coll., arXiv:1608.07378, subm.PRD]

Constraints from Pierre Auger:
- limit on source number density
  [P.Abreu et al., JCAP 1305 (2013) 009]
- heavier composition at UHE
  [A.Aab et al., PRD90 (2014) 122006]
The current view

experimental findings

protons

Fe

GCR

GCR

EGCR

factor 26

3 \times 10^{16} \text{ eV}

8 \times 10^{16} \quad 10^{17} \quad 3 \times 10^{16} \text{ eV}

Transition

UHECRs

[S. Thoudam et al., arXiv:1605.03111]
Conclusion

**Galactic Cosmic Rays**
- all experiments see the *all-particle knee* ~3-4 PeV
- ARGO, Tibet: proton knee at ~700 TeV
- Kascade-Grande, Tunka: $E_{\text{knee}}(p) \sim 3 \times 10^{15}$ eV and $E_{\text{knee}}(\text{Fe}) = 26 \times E_{\text{knee}}(p) \sim 80$ PeV

but
- analysis based on indirect extraction of information from EAS: strong dependence on models of hadronic interactions
- different definition of elemental groups
- difficult evaluation of systematic uncertainties

**Open issues**
Revision of ideas about particle acceleration up to PeV?
Is there an additional component of GCRs?

**Transition region and above**
- Kascade Grande: $E_{\text{knee}}(\text{Fe}) \sim 8 \times 10^{16}$ eV, light hardening $\sim 10^{17}$ eV
- IceTop measurements up to $\sim 10^{17}$ eV: too large fraction of iron
- constraints on elemental fractions from Auger $> 6 \times 10^{17}$ eV
- PAO, TA good agreement in the ankle region, **different interpretation of suppression**
- PAO, TA **different conclusion on composition**, but agreement within systematics
- constraints from Auger LSA UL

- *proton dip, ankle, mixed composition models are the main alternatives*

**Open issues**
can we dismiss the dip model?
is the suppression due to propagation or source effects?

multimessengers needed
Example: the dip model

**Signatures**
- ✓ proton composition
- ✓ ankle and $E_{1/2}$
- ✓ measure of the cosmogenic $\nu$ flux
- ✓ measure of the diffuse $\gamma$ flux

**Serious problems**
- ✓ Auger composition (~40% p below ankle)
- ✓ hard spectra and low cutoff suggested by Auger spectrum+comp
- ✓ measure of the cosmogenic $\nu$ flux (IceCube)

Multi-messenger approach to break the degeneracy wrt models of the spectrum alone and to reach conclusion independent of composition

UHECR spectrum from TA + IceCube limit on cosmogenic neutrinos

[J.Heinze et al., arXiv:1512:05988]

Test of dip model: UHECRs $>10^{19}$ eV are EG protons with a 3D parameter space scan

[$\nu_{\text{injection}}, E_{\text{max}}(p), \text{source evolution parameter } m$]

- the minimum “TA allowed” cosmogenic $\nu$ flux is in tension with IceCube upper limit at more than 95% CL
- hard spectra, strong source evolution and low $E_{\text{max}}(p)$ are favored wrt the GZK scenario
- the proton dip model is strongly challenged
Future - 1

hybrid Tibet experiment
- high accuracy in the light spectrum determination between 50 TeV and 10 PeV accurately..
- energy resolution at 1 PeV better than 12%
- expected systematics on the flux ~30% (mostly from hadr.int.model dependence)

IceTop-2
- 10 km³ in-ice array with 10 km² IceTop-2 on top
- energy range increased by a factor 3
- coincident events increased by factor 50
- 100 km² veto EAS array (muon LDF)

LLHASO
- 1 km² hybrid array at 4410 m asl
- gamma ray astronomy
- cosmic rays from 300 GeV to 1 PeV
- Cherenkov+fluorescence telescopes

Tunka-Grande
- Tunka-133 + 228 detectors of Kascade-Grande + 152 underground muon detectors
- 19 stations
- 228 detectors (0.64 m²) on the surface
- 152 detectors underground (muons detectors, total area 100 m²)
Future -2

**AugerPrime** [arXiv:1604.03637]

- ✓ Origin of the flux suppression and mass composition at UHE
- ✓ Proton contribution >10% above $6 \times 10^{19}$ eV, particle astronomy?
- ✓ Explore particle physics beyond the reach of LHC
  by
- ✓ Extension of the composition measurements into the extreme energy range above $5 \times 10^{19}$ eV
- ✓ Increase of data quality (timing, dynamic range…)
- ✓ Extension of FD on-time

**TAx4** [E.Kido, UHECR2016]

- ✓ Origin of the flux suppression and mass composition at UHE
- ✓ Confirm the hot spot with $>5\sigma$ significance
- ✓ Search for point sources
- ✓ Extension of statistics for composition at UHE
- ✓ Flux limits on UHE $\gamma$ and $\nu$

500 additional scintillato counters, 2.08 km spacing + 2 new FD
~3000 km$^2$ area
BACKUP SLIDES
Large Scale Anisotropy

- Low amplitudes over a wide range of energy: hint for a crossover between GCRs and EGCRs;
- Around 1 EeV, the isotropy hints to an extragalactic origin of CRs;
- Indication for LSA
  - At E>8 EeV from Auger: dipole amplitude 7.3±1.5% pointing to (a,d)=(95°±13°,-39°±13°)
  - In a joint analysis Auger-TA at E>10 EeV: 6.5±1.9% with (a,d)=(93°±24°,-46°±18°)
Small Scale Anisotropy

Auger
- $r = 1^\circ - 30^\circ$, $\Delta r = 1^\circ$
- $E = 40 - 80$ EeV, $\Delta E = 1$ EeV

TA
- $r = 15^\circ - 35^\circ$, $\Delta r = 5^\circ$
- $E = 57$ EeV


[K.Kawata et al., POS (ICRC2015) 276]

- $r = 12^\circ$, $E = 54$ EeV
- $n_{\text{obs}}/n_{\text{exp}} = 14/3.23$
- pre-trial $\rightarrow$ 4.3 $\sigma$
- post-trial $P = 69$

detectable with Jem-Euso and Klipve at 5$\sigma$ with $>300$ events

[D.Semikoz, arXiv:1601.06363]
Direct + indirect measurements

From CREAM, ATIC, PAMELA, AMS:
Spectral index for p different from other nuclei
Spectra at >TeV harder than at lower energy

models for composition
exploit the normalisation to direct measurements

T. Gaisser et al., Front. Phys. 8(6) (2013) 748
• no indication of a declination-dependent flux
• differences between Auger and TA in the suppression region not explained
• the differences found between the measurements in two separate declination bands are compatible with the variations expected from a dipolar modulation of the flux.
 detection in EAS arrays

Muon-poor shower selection

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Position</th>
<th>$[\delta_{\text{min}}, \delta_{\text{max}}]$</th>
<th>Zenith</th>
</tr>
</thead>
<tbody>
<tr>
<td>KASCADE</td>
<td>49.0°N, 8.4°E</td>
<td>[14°, 84°]</td>
<td>&lt; 35°</td>
</tr>
<tr>
<td>EAS-TOP</td>
<td>42.5°N, 13.5°E</td>
<td>[7°, 78°]</td>
<td>&lt; 35°</td>
</tr>
<tr>
<td>GAMMA</td>
<td>40.5°N, 44.2°E</td>
<td>[10°, 71°]</td>
<td>&lt; 30°</td>
</tr>
<tr>
<td>UMC</td>
<td>40.2°N, 112.8°W</td>
<td>[0°, 80°]</td>
<td>&lt; 40°</td>
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<tr>
<td>CASA-MIA</td>
<td>40.2°N, 112.8°W</td>
<td>[−20°, 90°]</td>
<td>&lt; 60°</td>
</tr>
<tr>
<td>Milagro</td>
<td>35.9°N, 106.7°W</td>
<td>[−14°, 86°]</td>
<td>&lt; 50°</td>
</tr>
<tr>
<td>Tibet</td>
<td>30.1°N, 90.5°E</td>
<td>[−20°, 80°]</td>
<td>&lt; 50°</td>
</tr>
<tr>
<td>HEGRA</td>
<td>28.7°N, 17.9°W</td>
<td>[−6°, 64°]</td>
<td>&lt; 35°</td>
</tr>
<tr>
<td>GRAPES-3</td>
<td>11.4°N, 76.7°E</td>
<td>[−14°, 36°]</td>
<td>&lt; 25°</td>
</tr>
<tr>
<td>IceCube</td>
<td>South Pole</td>
<td>[−90°, −60°]</td>
<td>&lt; 30°</td>
</tr>
</tbody>
</table>

Exploit observable differences between $\gamma$ and hadrons

- $\gamma$ EAS develop deeper in atmosphere: larger $X_{\text{max}}$
- $\gamma$ EAS look young: larger rise time, smaller radius of curvature

Exp. data

$\gamma$-rays

KASCADE

UHE

VHE

FD

SD

Hybrids

Antonella Castellina

Ground based cosmic ray experiments: results and perspectives

21 October 2016
Fraction of time in one day GW150914 & GW15126 are visible in the Earth-skimming & Downward-going channels.

Constraints are declination-dependent.

Physics goals of AugerPrime

Origin of the suppression

Sensitivity to proton fraction
significance of tagging scenarios with and without 10% protons (ref. scenario 1, no uncertainties due to hadronic interaction models included)
Physics goals of AugerPrime

Set of 454 Auger data: \( E > 4 \times 10^{19} \text{ eV} \), random \( X_{\text{max}} \) according to scenario I.

10% protons added, \( \frac{1}{2} \) coming from AGNs within \( 3^\circ \)

**\( \nu \) and \( \gamma \)**

Improvement in
- exposure
- low energy trigger
- hadronic bckg rejection

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