Comparing analyses of E_o- determination methods on the MAKET ANI installation and primary energy spectra for $(H + He)$ and $(Si + Fe)$ nuclei groups in range of $3 \times 10^{14} eV \leq E_o < 10^{17} eV$

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An aim of this work is comparing analysis of primary energy spectra for the "light" $(H + He)$ and "heavy" $(Si + Fe)$ nuclei of primary cosmic rays (PCR), obtained from the MAKET ANI [1]-[3] data using two different methods of E_o determination [4],[5]. Both methods use the data bank of simulated events by CORSIKA 562(NKG, QGSJET) [6, 7] for the five primaries (H, He, O, Si, Fe) (10^6 events/nuc.) and zenith angles of incidence in the interval $0^o \div 50^o$.
Reference [4] gives a detailed description of the procedures for the determination of the mass and energy of primary particles using method [8], [9] of "Neural Network Mass Classification and Estimation" (NN). Applying this method the processing of the MAKET ANI data was carried out for the two classes of "light" $(H + He)$ and "heavy" $(Si + Fe)$ nuclei in PCR, and E_o and N_e - spectra have been constructed.
In [5] a description of E_o - determination method using $E(N_e)$ - dependencies (obtained from simulation data) for five θ bins, is given. The analogous investigations for the "light" $(H + He)$ and "heavy" $(Si + Fe)$ groups of nuclei have been carried out. The results are presented in this work and are compared with results obtained in [4].
During last quarter we decided to refuse the procedure of uniform division of zenith angles by $\Delta sec\theta$ because of an essential migration of events on θ at $\theta > 40^o$. At this θ - binning the width of the last, 5 - th bin, of θ is $\approx 3.5^o$ only, that is very insufficient at an $\approx 1.6^o$ accuracy of θ determination in the MAKET ANI installation.
At this time the following variant of the θ - binning is used: $(0^o \div 20^o; 20^o \div 28^o; 28^o \div 34^o; 34^o \div 39^o; 39^o \div 44^o)$. This corresponds approximately to the following differential thicknesses of the air absorber: $\Delta X_i \approx 45; 50; 50; 60; 70gcm^{-2}$, thus the slant depths in interval $700 \div 975g/cm^2$ have been changed.
The energy threshold in the simulation was set to $E^{thr} = 10^5 GeV$, and the ratio of events in the groups H/He and Si/Fe were taken in agreement with "normal" chemical composition ($36\%H, 25\%He$, $14\%O, 15\%Si, 10\%Fe$).
The investigations have been carried out in the following 2 variants:

1)In the primary E_o - spectra each nucleus species forms a "knee" in such a way that $E^{(knee)} \sim Z$, where Z is charge of the nucleus (diffusion model of the "knee" formation) [10, 11]). The "knee" positions and slopes of E_o - spectra in the regions below and above the "knee" were selected to achieve agreement of these characteristics between simulated and experimental "All Particles"- size spectra in each from five slant depths observed.
The recalculation from primary spectrum simulated with slope index $\gamma = -2$ to the spectrum with real indices was carried out by statistical weighting of events.

2)The Knee position of the E_o - spectrum is independent on the charge of the nucleus : $E^{(knee)} = 3 \times 10^{15} eV$, and spectral indices $\gamma = -2.75$ below the knee, and $\gamma = -3.1$ above the knee have been taken. These values were selected in analogy with var.1 .
In [13] a detailed description is given of the procedures accounting for the response of MAKET ANI

detectors in each individual simulated CORSIKA event .
In [5] the procedures considering the event migration from bin to bin in EAS size- and energy-spectra at the reconstruction of the shower parameters are described too.
In Figs.1(a,b) and 2(a,b) the N_e - spectra for $(H + He)$ and $(Si + Fe)$ groups in variants 1 and 2, and for five slant depths are shown. The shift of the Knee position in "light"- primaries spectra from $\approx 10^6$ for the vertical events to $\approx 5 \times 10^5$ for the last zenith-angle interval is evident.
In order to include also the maximum energies reached with the MAKET ANI, it is necessary to achieve an agreement of the intensities and shapes of E_o - spectra constructed for each slant depth with simulated as well as experimental data.
In Figs.3,4 the procedures of the investigations of the E_o - fluctuations as well as shape of the energy spectra for "light" and "heavy" nuclei at different θ are illustrated.
Figs.3(a), 4(a) show the normalized energy distributions for "vertical" events at different fixed values of N_e. The width of N_e bin(in log. scale) is set to $\Delta Log(N_e) = 0.1$.
In Figs.3(b), 4(b) the distributions of E_o at one fixed value of N_e for five θ intervals are shown.
Average E_o values of given distributions correspond to the given N_e.
The decrease of the E_o fluctuations with increasing N_e at fixed θ and the increase of them with depth at each fixed N_e are evident. This is also reflected in Figs. 3(c), 4(c) , where the standard deviations $\sigma_{Log(E)}$ (relative fluctuations of energy) for five slant depths as function of EAS size are shown. The marks of the θ intervals there are same as in Fig. 3(b).
From comparison of Figs. 3(c) and 4(c) it is seen that E_o fluctuations for "light" nuclei are essentially larger than for "heavy" nuclei. For events produced by "light" nuclei these fluctuations decrease from $\Delta E / < E > \approx 0.3$ at $Log(N_e) = 5$ to $\Delta E / < E > \approx 0.15$ at $Log(N_e) = 7$ for vertical showers, and from 0.6 to 0.4 at the same EAS size on the last slant depth. But for "heavy" nuclei in vertical showers we observe $\Delta E / < E > \approx 0.19$ at $Log(N_e) = 5$ and $\Delta E / < E > \approx 0.14$ at $Log(N_e) = 7$. The increasing of E_o fluctuations with slant depth in this case is not essential (only $\approx 5\%$ of rise with θ).
Figs.3(d), 4(d) show the differential energy spectra of "light" and "heavy" nuclei for each slant depth using the diffusion model for the knee formation. From these figures we find a good agreement of E_o - spectra intensities, slopes and knee positions for the first four slant depths. But on 5 - th depth a systematic reduction of the spectrum intensity is observed. A possible reason for this may be the low statistics in this θ - interval. By this cause only events with $\theta \leq 39^o$ for the construction of E_o - spectrum have been taken.
In Fig.5 the energy spectra of "light" and "heavy" primaries constructed in this way for variants 1 and 2 are shown. As it is seen from Fig.5(a), the difference in E_o - spectra shape in regions below and above the knee is not essential, but width of the knee region from the diffusion model as compared to variant 2 is larger $((E_{knee}^{(He)} / E_{knee}^{(H)} = 2)$. Because width of the knee region itself is composed $\Delta Log(E_o^{knee}) \approx 0.25 \div 0.3$, the knee from each individual nucleus separately is not observed.
For "heavy" nuclei (see Fig.5(b)) the difference in E_o - spectrum shapes between variant 1 and variant2 is not observed.
Using the determination of E_o from the experiment the $E(N_e)$ dependencies for both nuclei groups were obtained from distributions (constructed for all N_e and θ) as shown in Figs. 3(a,b), 4(a,b). Results are given in Figs.6,7. The same dependencies are obtained from experimental statistics using the (NN) - method, these results are shown too.
As it is seen from Figs.6,7 the primary energy for group $(Si + Fe)$ at fixed N_e and θ is larger by a factor of ≈ 2 than E_o for "light" nuclei.
From Fig.6 we deduce that an agreement of (NN) - method with CORSIKA for any N_e is observed only for vertical events. With increasing θ one recognizes a systematic rising of energy values obtained

by (NN) - method in ranges $5 \leq Log(N_e) < 5.7$, and $Log(N_e) > 6.6$. This may results in differences in the shapes E_o - spectra for different zenith angles. Denote, that step $\Delta Log(E_o) = 0.1$ (one division on ordinate axis) corresponds to changing the energy by 25%.
In case of "heavy" nuclei, the good agreement of (NN) with CORSIKA is observed only in the first and fourth θ interval, and for all angles $\theta \leq 39^o$ an agreement only at $6.2 \leq Log(E_o/GeV) < 7$ is observed.
For comparison, in Figs.8,9 the energy spectra for $(H + He)$ and $(Si + Fe)$ groups are shown constructed for different θ using the 2 different methods ((NN) and [5]) of E_o determination. As it is seen from Fig.8(a)(method [5]), a good agreement of E_o - spectra shape for the first 4 slant depths is observed. But in results of (NN) - method (see Fig.8(b)) the shift of E_o - spectral intensities with θ at $Log(E_o/GeV) \approx 6$ almost 3 times is observed. With increasing E_o this shift is decreased to ≈ 1.5 times at $Log(E_o/GeV) = 7$, and the energy spectrum for "light" primaries and, as consequence "All Particles" spectrum, constructed for $\theta \leq 39^o$ are unreliable.
A better agreement between the two methods is observed in the E_o - spectra constructed in case of the $(Si + Fe)$ group : in the region $6.3 < Log(E_o/GeV) < 7$ are no distortions in shape of (NN) energy spectra shape on first 4 depths. But one cannot analyse the energy spectrum for existence or abscence of the knee in the such a narrow energy interval. By some theoretical predictions [14] the knee position, for example, for the Fe nucleus is expected outside of this region, namely, at $Log(E_o/GeV) \approx 7.2$.
In Fig.10 the differential energy spectra for "All Particles", $(H + He)$ and $(Si + Fe)$ groups obtained by method [5] are compared with results of other experiments. From this figure it is seen, that "All Particles" E_o - spectrum from MAKET ANI data agrees with D I C E data in region below the knee $(E^{knee} \approx 3 \times 10^{15} eV)$. At larger energies the results from MAKET ANI practically coincide with those from KASCADE.
Comparing the energy spectra for "light" and "heavy" nuclei groups from MAKET ANI data (Fig. 10) one observes a "cross-over" of spectral intensities around "All Particles" (or "light" primaries) spectrum knee. At larger energies the contribution of of "heavy" nuclei is rised, i.e. chemical composition of PCR became heavier. In the "heavy" spectrum one identifies the knee at $Log(E_o/GeV) \approx 7.1$ and a flattering at $Log(E_o/GeV) > 7.3$. The last fact is in surprisingly good agreement with the prediction of [15].
At $Log(E_o/GeV) \approx 6.6$ a particularity in the "heavy" E_o - spectrum shape is observed too.
The comparison of N_e spectra for "All Particles", $(H + He)$ and $(Si + Fe)$ groups also is interesting. These spectra are shown in Fig.11. From the figure is can be deduced that the knee of the "heavy" nuclei spectrum is located at $Log(N_e^{knee}) \approx 6.6$, where the accuracy of N_e determination by MAKET ANI is high ($\approx 2 - 3\%$ [13]). From Fig.11 it is seen also, that traditional fitting of the N_e spectra presented here using two linear functions in the regions below and above the knee is almost impossible within the given statistical errors for all ranges of N_e .

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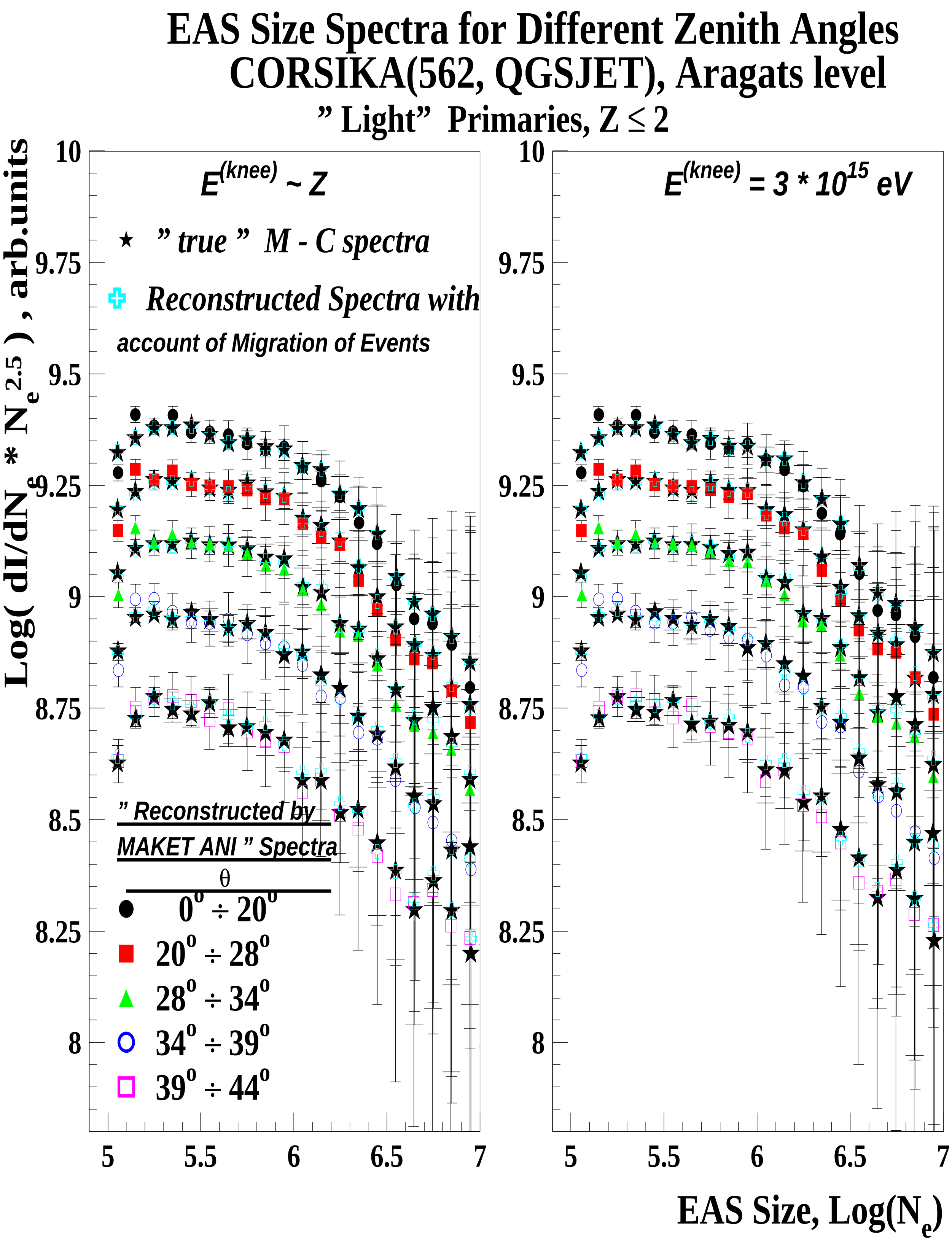


EAS Size Spectra for Different Zenith Angles
CORSIKA(562, QGSJET), Aragats level
" Light" Primaries, Z ≤ 2
$E^{(knee)} \sim Z$
$E^{(knee)} = 3 * 10^{15}$ eV
" true " M - C spectra
Reconstructed Spectra with
account of Migration of Events
" Reconstructed by
MAKET ANI " Spectra
θ
$0^0 \div 20^0$
$20^0 \div 28^0$
$28^0 \div 34^0$
$34^0 \div 39^0$
$39^0 \div 44^0$
Log(dI/dN$_e$ * N$_e^{2.5}$) , arb.units
EAS Size, Log(N$_e$)

Figure 1:

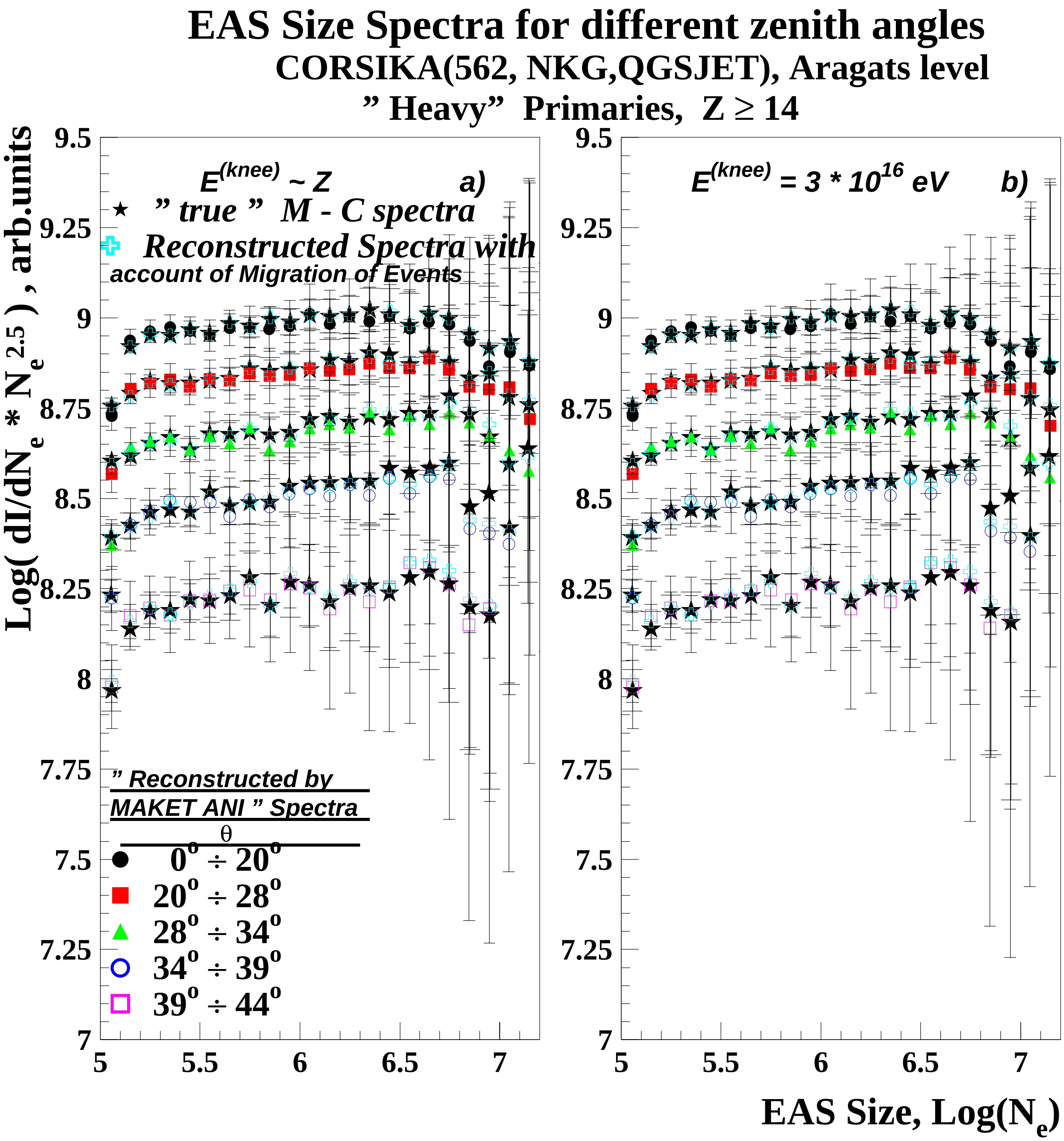
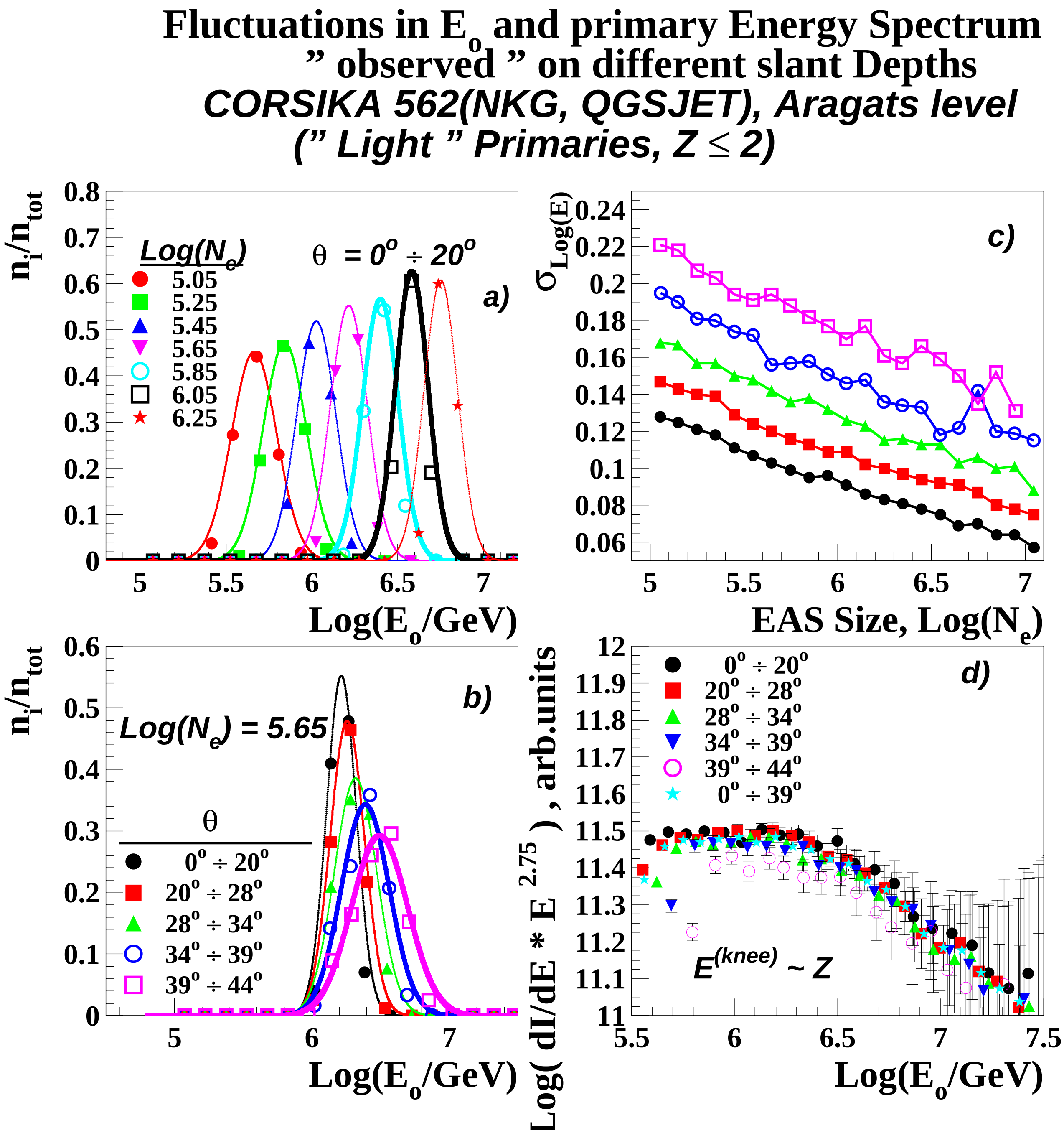

EAS Size Spectra for different zenith angles
CORSIKA(562, NKG,QGSJET), Aragats level
" Heavy" Primaries, Z ≥ 14
E(knee) ~ Z
a)
" true " M - C spectra
Reconstructed Spectra with
account of Migration of Events
" Reconstructed by
MAKET ANI " Spectra
θ
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
E(knee) = 3 * 10^16 eV
b)
Log(dI/dNe * Ne^2.5) , arb.units
EAS Size, Log(Ne)
9.5
9.25
9
8.75
8.5
8.25
8
7.75
7.5
7.25
7
5
5.5
6
6.5
7

Figure 2:



Fluctuations in E$_o$ and primary Energy Spectrum
" observed " on different slant Depths
CORSIKA 562(NKG, QGSJET), Aragats level
(" Light " Primaries, Z ≤ 2)
a)
n_i/n_{tot}
Log(N$_e$)
5.05
5.25
5.45
5.65
5.85
6.05
6.25
θ = 0° ÷ 20°
Log(E$_o$/GeV)
b)
n_i/n_{tot}
Log(N$_e$) = 5.65
θ
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
Log(E$_o$/GeV)
c)
$\sigma_{Log(E)}$
EAS Size, Log(N$_e$)
d)
Log(dI/dE * E$^{2.75}$) , arb.units
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
0° ÷ 39°
E$^{(knee)}$ ~ Z
Log(E$_o$/GeV)

Figure 3:

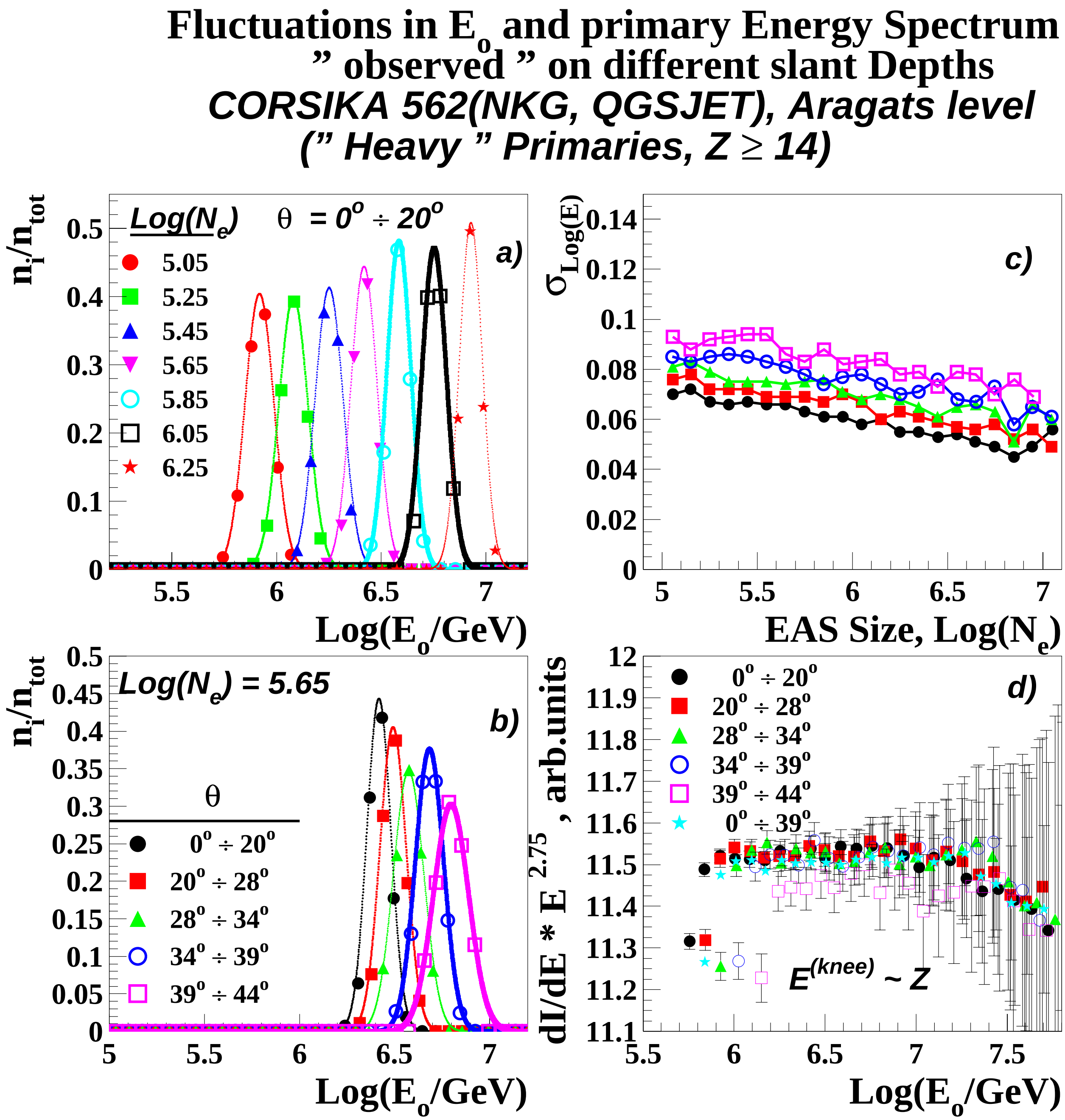

Fluctuations in E_o and primary Energy Spectrum
" observed " on different slant Depths
CORSIKA 562(NKG, QGSJET), Aragats level
(" Heavy " Primaries, Z ≥ 14)
a)
Log(N_e)
θ = 0° ÷ 20°
5.05
5.25
5.45
5.65
5.85
6.05
6.25
n_i/n_tot
Log(E_o/GeV)
c)
σ_Log(E)
EAS Size, Log(N_e)
b)
Log(N_e) = 5.65
θ
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
d)
dI/dE * E^2.75, arb.units
0° ÷ 39°
E^(knee) ~ Z

Figure 4:

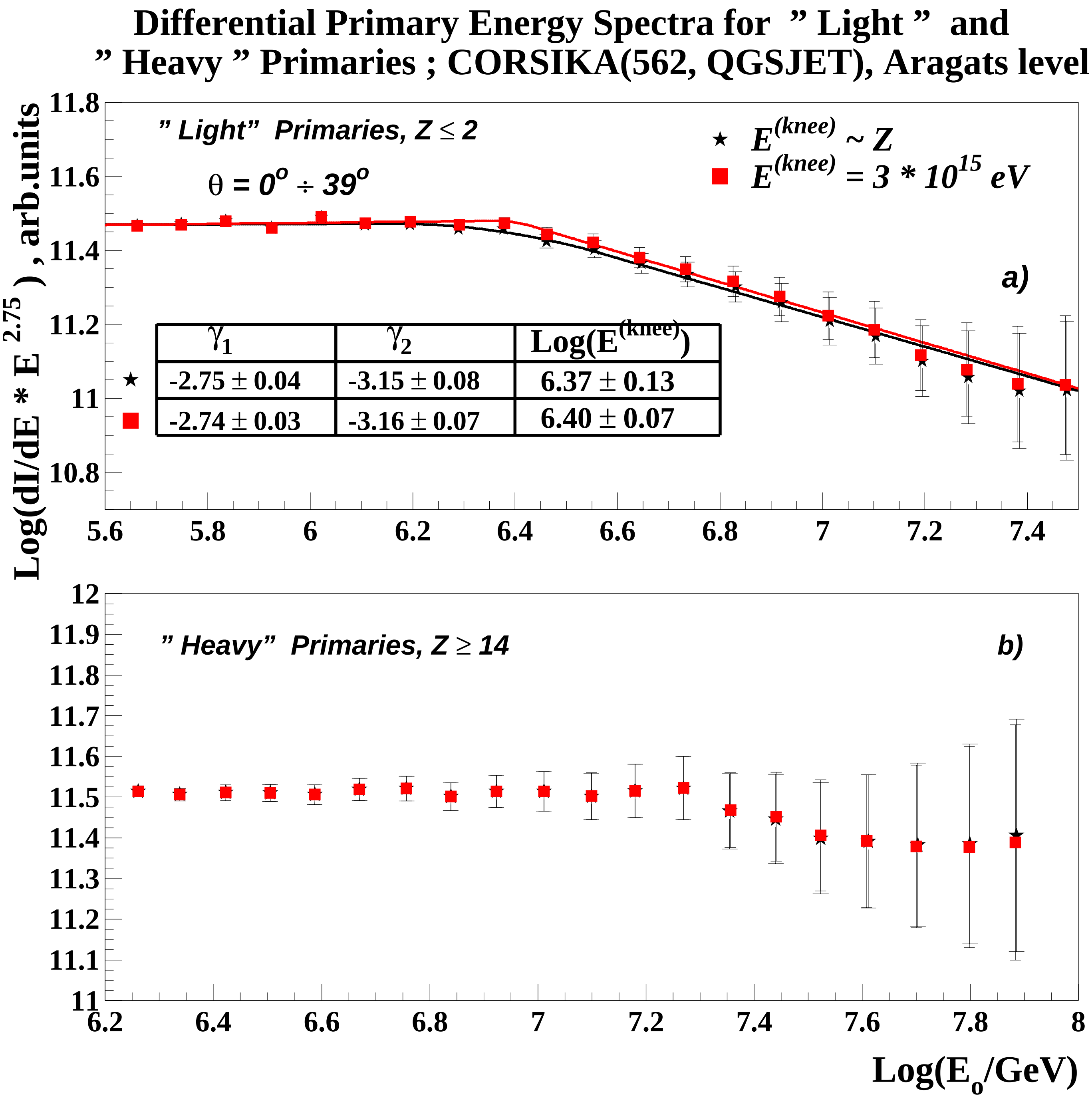

Differential Primary Energy Spectra for " Light " and
" Heavy " Primaries ; CORSIKA(562, QGSJET), Aragats level
" Light" Primaries, Z ≤ 2
θ = 0° ÷ 39°
E^(knee) ~ Z
E^(knee) = 3 * 10^15 eV
a)
γ1
γ2
Log(E^(knee))
-2.75 ± 0.04
-3.15 ± 0.08
6.37 ± 0.13
-2.74 ± 0.03
-3.16 ± 0.07
6.40 ± 0.07
Log(dI/dE * E^2.75) , arb.units
" Heavy" Primaries, Z ≥ 14
b)
Log(E0/GeV)

Figure 5:

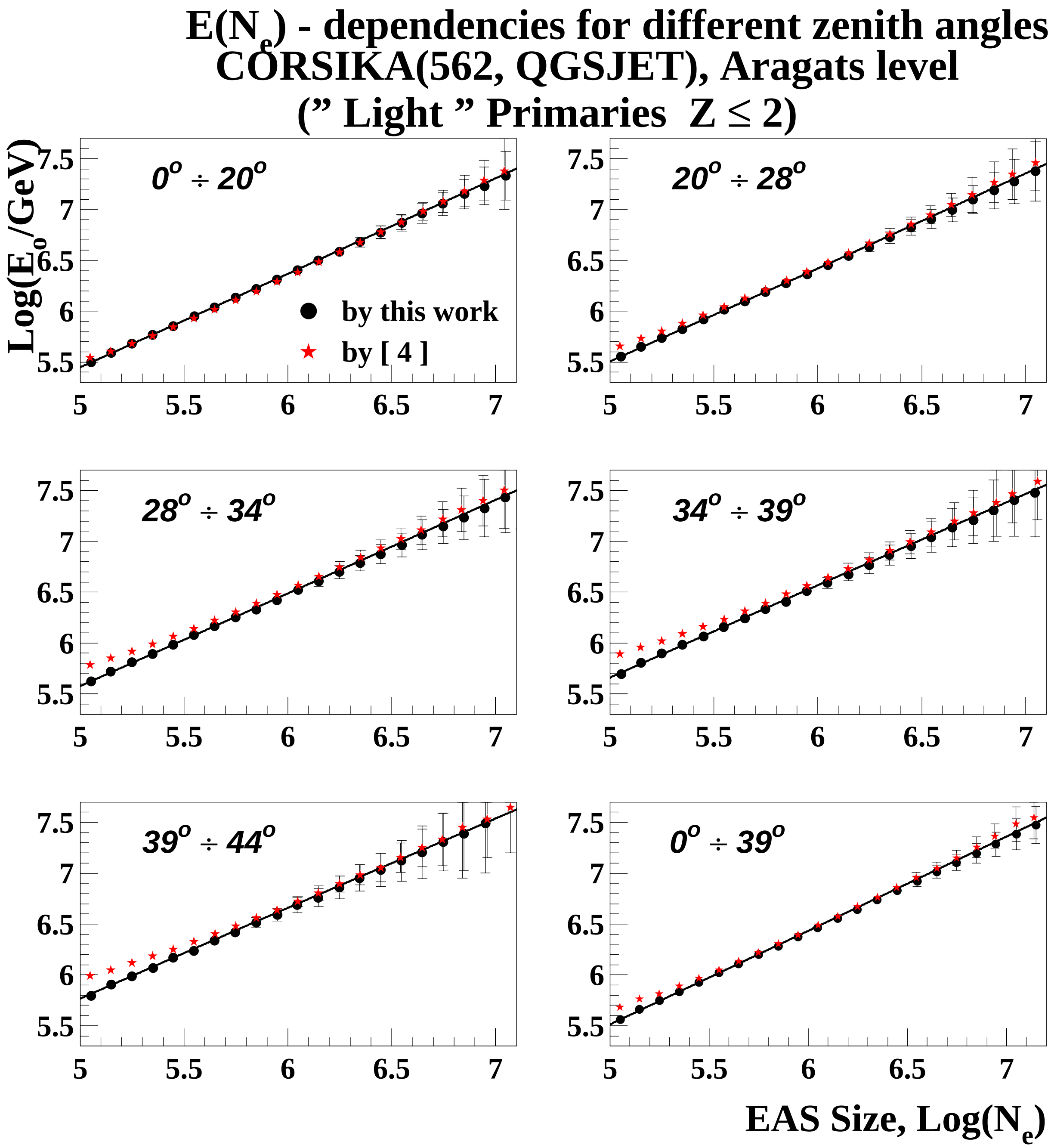

E(Ne) - dependencies for different zenith angles
CORSIKA(562, QGSJET), Aragats level
(” Light ” Primaries Z ≤ 2)
Log(E0/GeV)
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
0° ÷ 39°
by this work
by [4]
EAS Size, Log(Ne)

Figure 6:

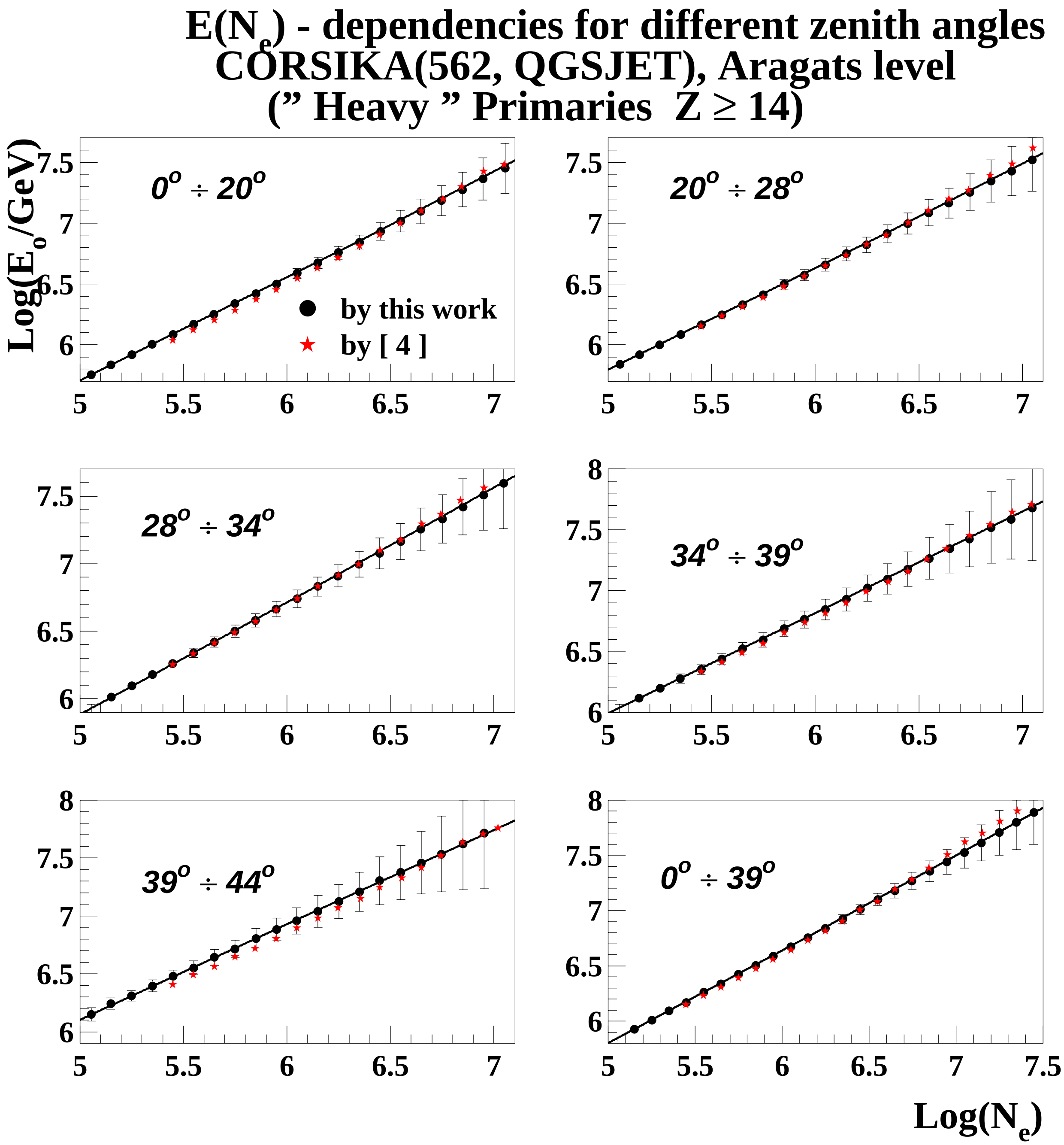

E(N_e) - dependencies for different zenith angles
CORSIKA(562, QGSJET), Aragats level
(” Heavy ” Primaries Z ≥ 14)
Log(E_0/GeV)
Log(N_e)
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
0° ÷ 39°
by this work
by [4]

Figure 7:

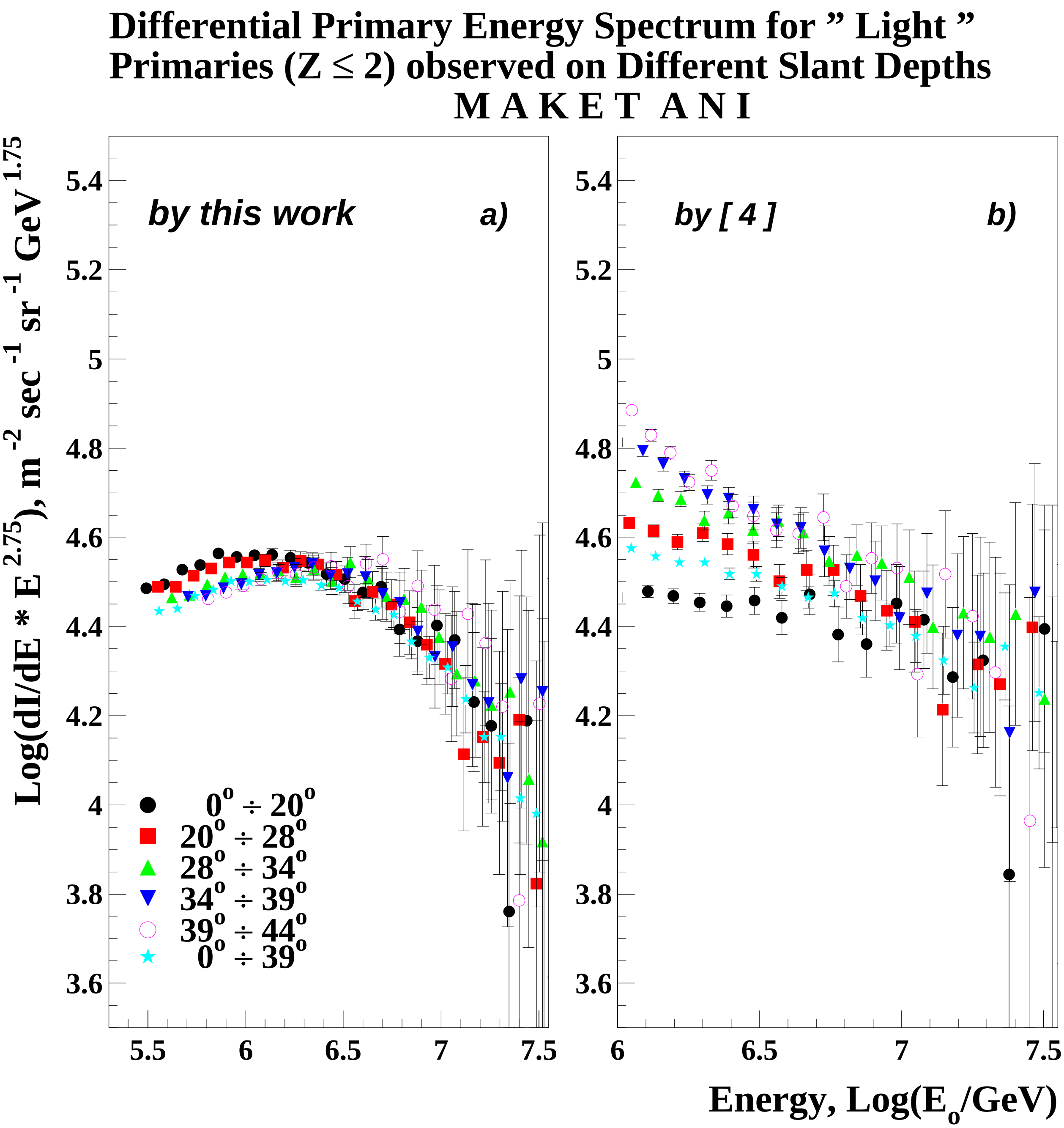

Differential Primary Energy Spectrum for " Light "
Primaries (Z ≤ 2) observed on Different Slant Depths
M A K E T A N I
by this work
a)
by [4]
b)
Log(dI/dE * E 2.75), m -2 sec -1 sr -1 GeV 1.75
Energy, Log(E0/GeV)
0° ÷ 20°
20° ÷ 28°
28° ÷ 34°
34° ÷ 39°
39° ÷ 44°
0° ÷ 39°

Figure 8:

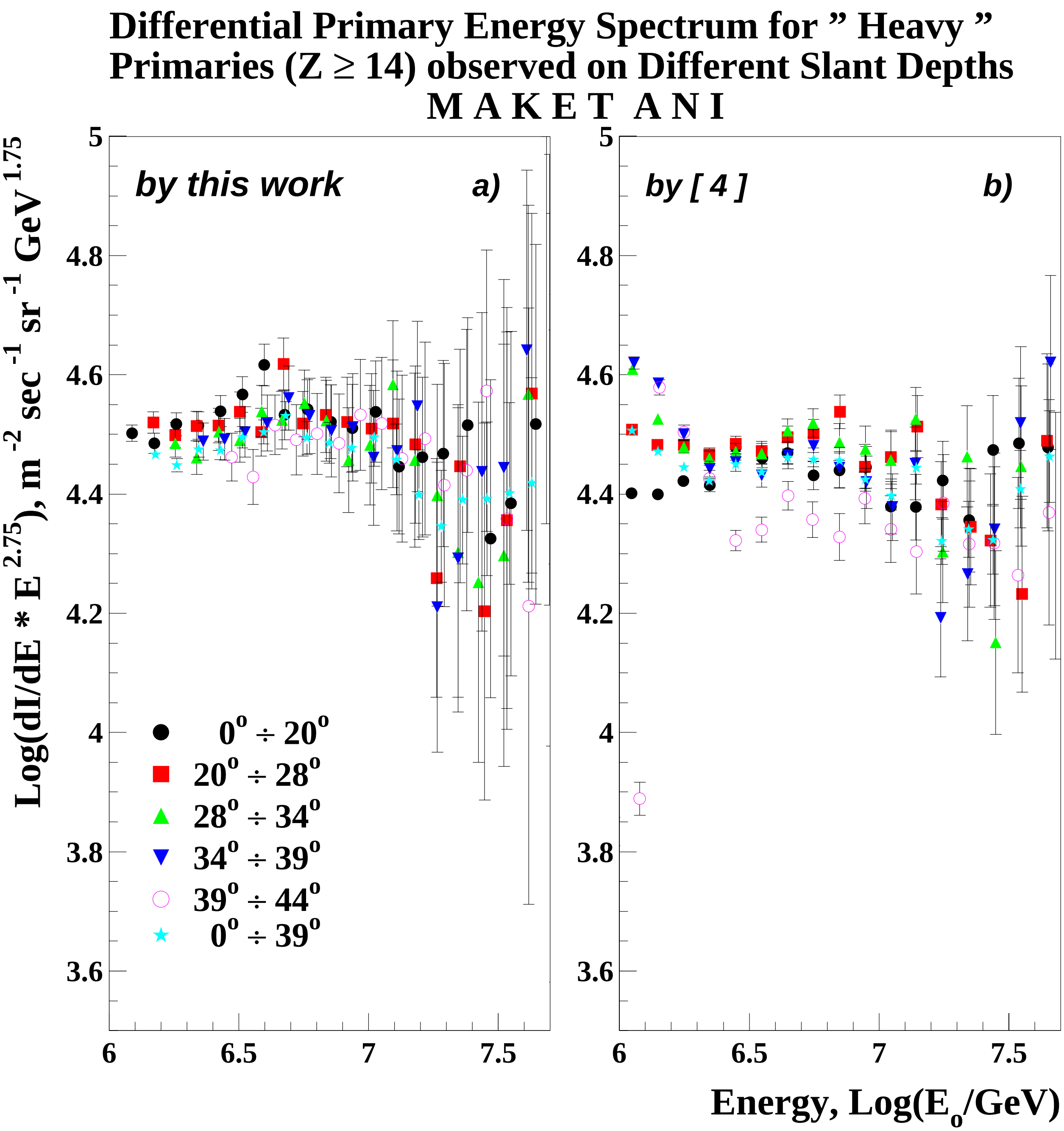

Differential Primary Energy Spectrum for " Heavy " Primaries (Z ≥ 14) observed on Different Slant Depths
M A K E T A N I
by this work
a)
by [4]
b)
Log(dI/dE * E 2.75), m -2 sec -1 sr -1 GeV 1.75
Energy, Log(Eo/GeV)
0o ÷ 20o
20o ÷ 28o
28o ÷ 34o
34o ÷ 39o
39o ÷ 44o
0o ÷ 39o

Figure 9:

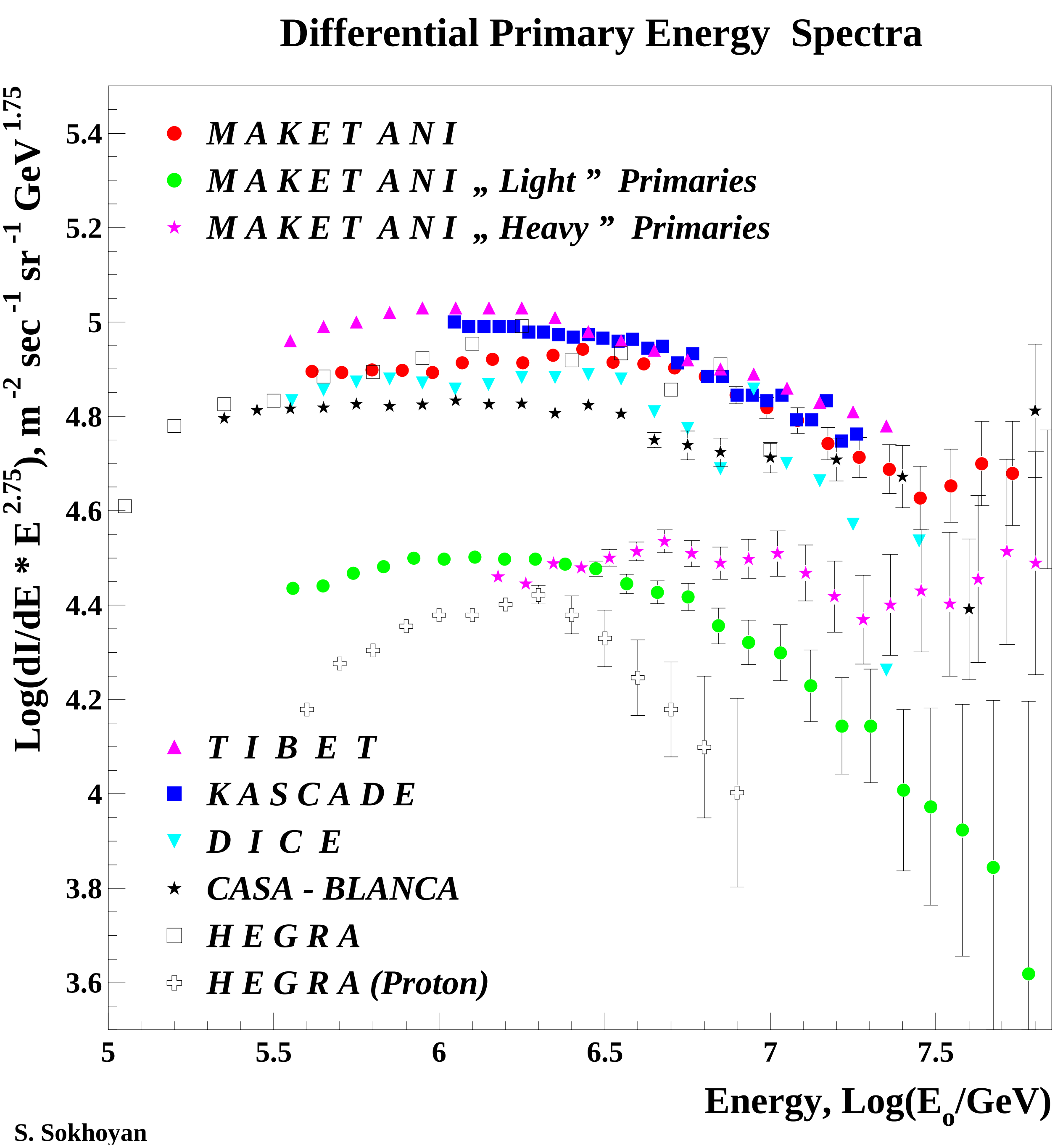
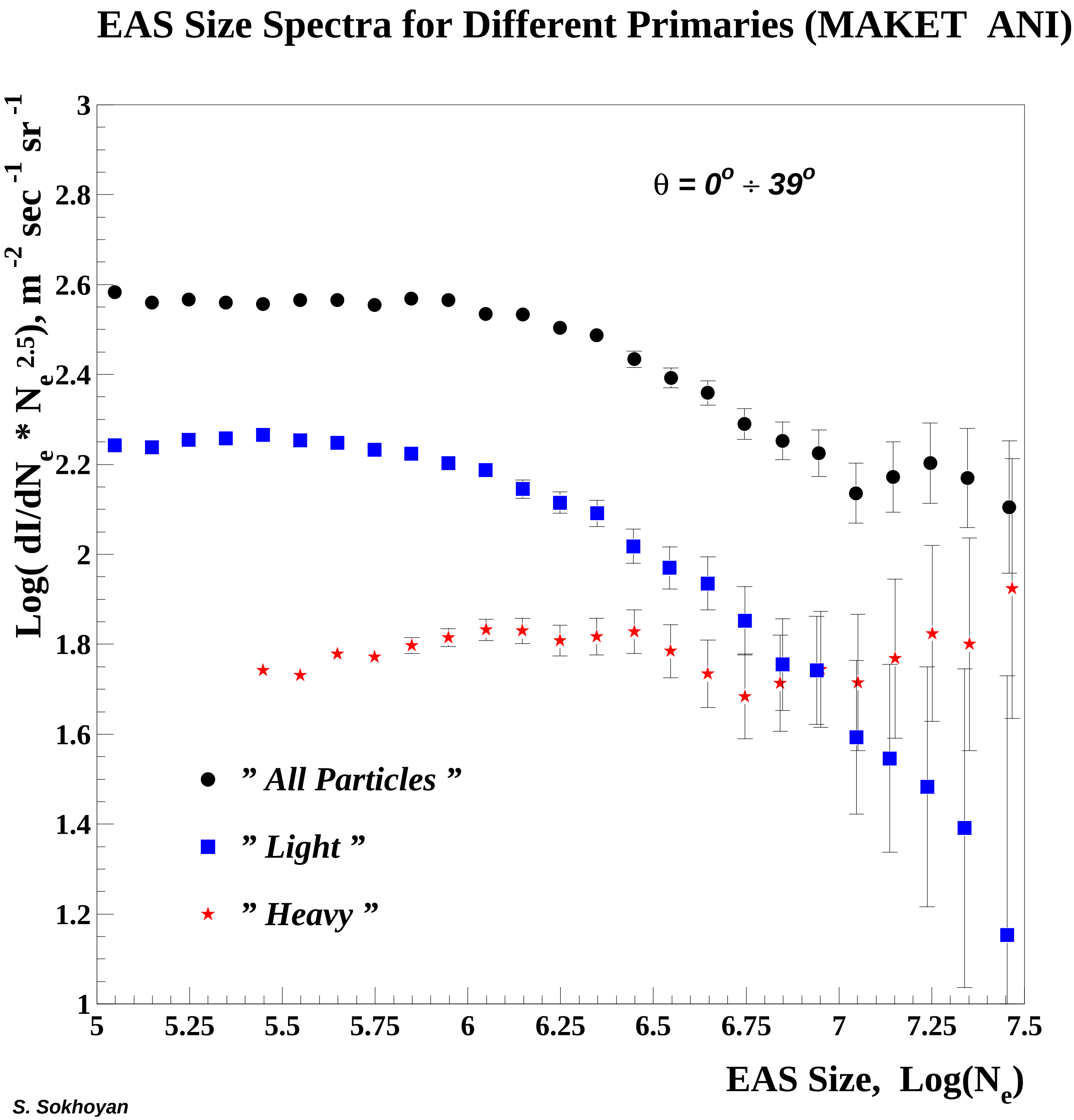

Differential Primary Energy Spectra
Log(dI/dE * E 2.75), m -2 sec -1 sr -1 GeV 1.75
M A K E T A N I
M A K E T A N I „ Light ” Primaries
M A K E T A N I „ Heavy ” Primaries
T I B E T
K A S C A D E
D I C E
CASA - BLANCA
H E G R A
H E G R A (Proton)
5.4
5.2
5
4.8
4.6
4.4
4.2
4
3.8
3.6
5
5.5
6
6.5
7
7.5
Energy, Log(Eo/GeV)
S. Sokhoyan

Figure 10:



EAS Size Spectra for Different Primaries (MAKET ANI)
θ = 0° ÷ 39°
Log(dI/dNe * Ne 2.5), m -2 sec -1 sr -1
” All Particles ”
” Light ”
” Heavy ”
EAS Size, Log(Ne)
S. Sokhoyan

Figure 11: