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Full-Particle Modeling of a Small Size Cherenkov Gamma-Ray Telescope with a SiPM-based Camera

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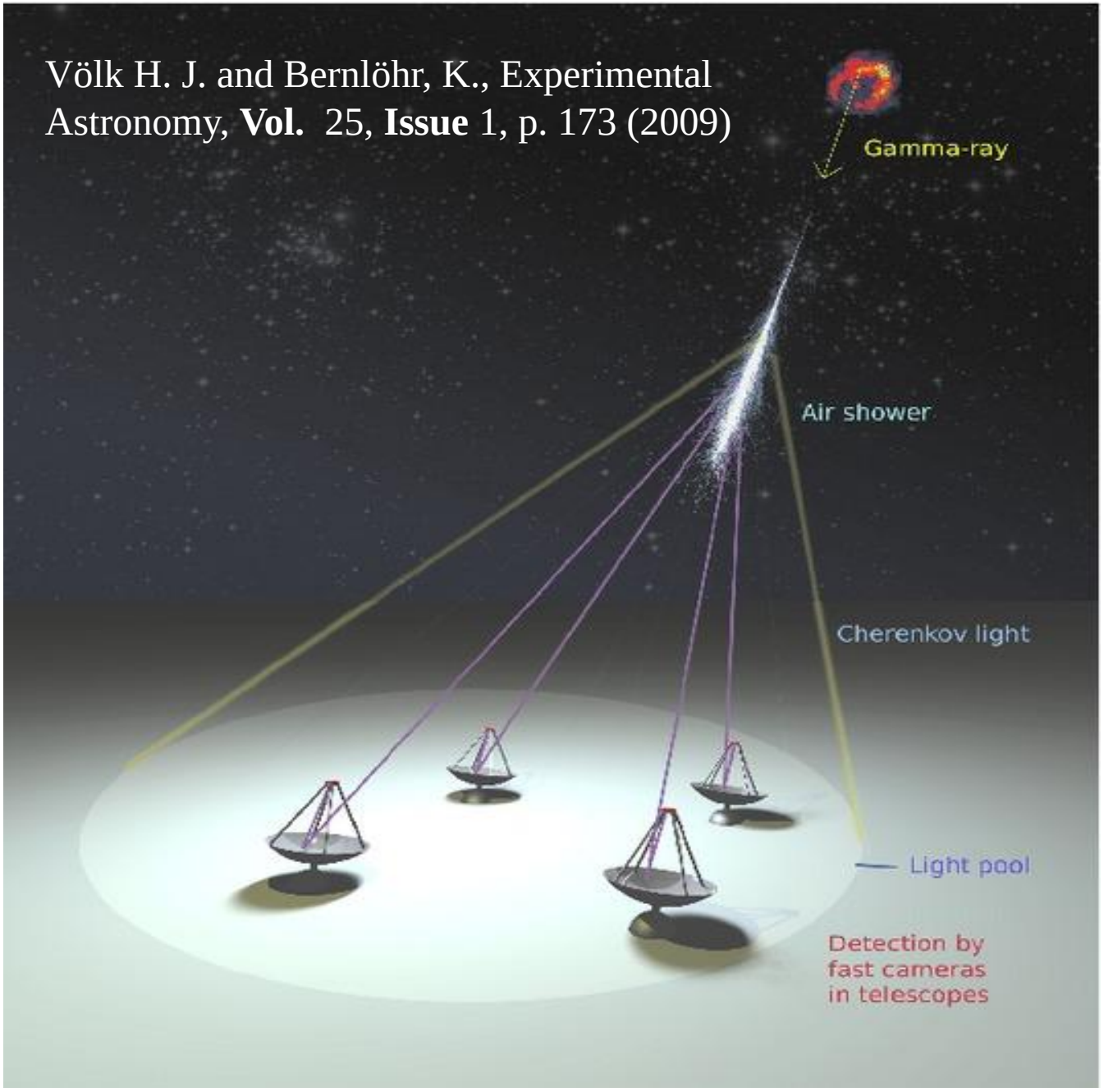
Principle of operation of ground-based Cherenkov telescopes



Cherenkov gamma-ray telescope TAIGA-IACT

Image credit: TAIGA project team, L.A. Kuzmichev et al.

Operated in the Tunka valley (Buryatiya, Russia) as an integral part of the TAIGA complex

mirror area
~ 10 m^2

threshold energy
~1.5 TeV

2 units in use + 1 to be deployed in 2021 + more to go

How could we modify a TAIGA-IACT unit?

1. Replace PMTs (Philips XP1911) with SiPMs (OnSemi MicroFJ-60035)

- PDE about two times higher
- Lower supply voltage
- Resistance to possible damages due to excess light
- Lightweight camera

2. Apply optical filters

- Suppression of the optical noise induced by the night sky background (NSB) would allow us to increase the duty-cycle (observations at moonlit nights)
- Increase the efficiency of gamma-hadron separation (measurements of the fraction of $\lambda<300$ nm near-UV emission of an EAS)

EAS and NSB simulations

EASs simulations: CORSIKA v. 7.7400 (D. Heck et al. 1998)
NSB simulations: TAIGA Soft (Kholupenko et al. 2020)

Place: Tunka valley, altitude is 675 m a.s.l. (atmosphere depth is about 950 – 960 g/cm^2), atmosphere model is 'winter mid-latitude atmosphere N3', wavelength range 200 – 700 nm, magnetic field is (H,Z)=(18.5, 57.7) μT

Only vertically incident primary particles were considered, impact parameter (distance from telescope position to the EAS axis) 120 m, primary particle energies 0.3162, 0.5, 0.7, 1.0, 3.162, 10.0, 31.62 TeV

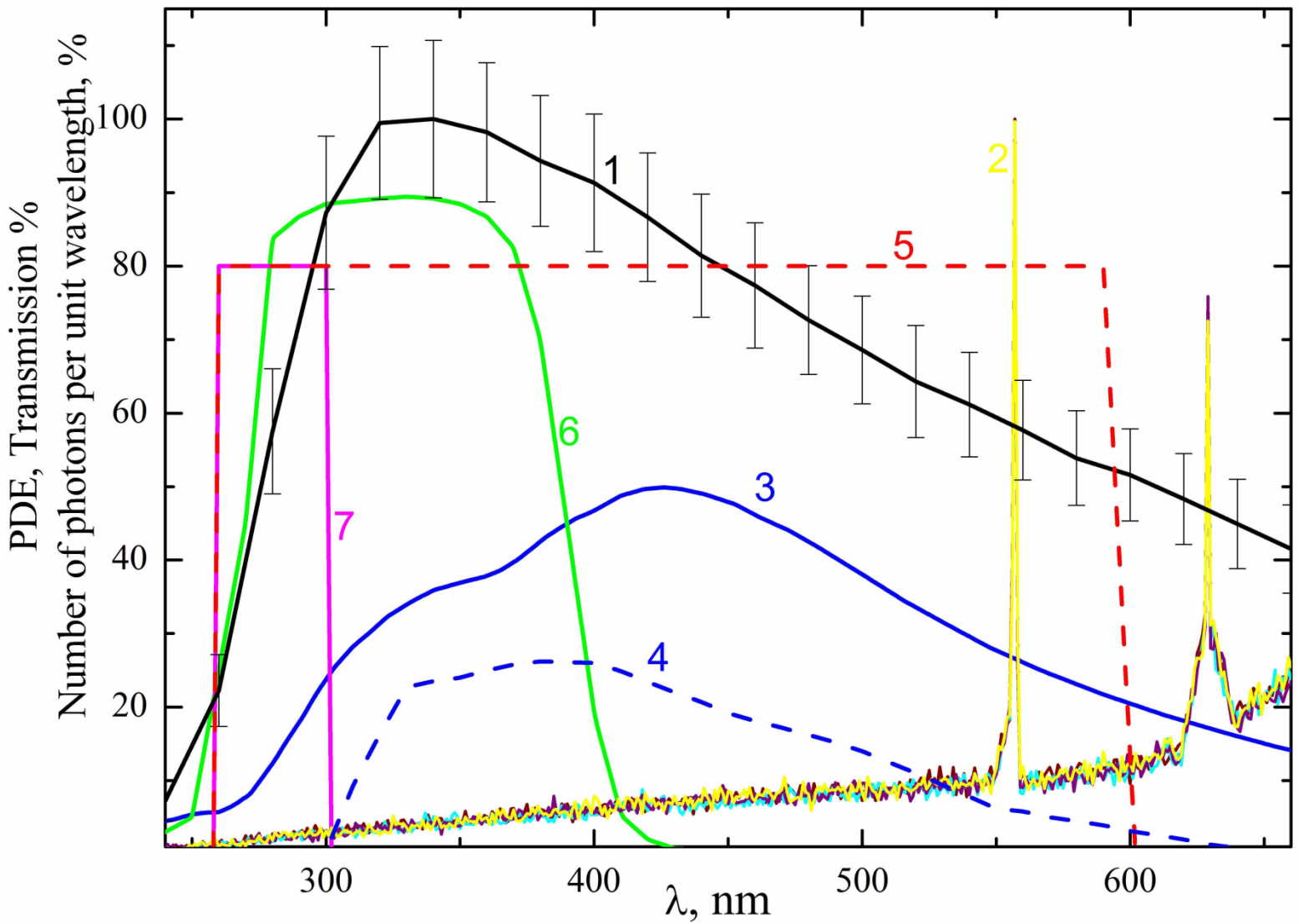
The total intensity of NSB in the range 300 – 600 nm is $3 \cdot 10^{12}$ ph$\cdot$m^{-2}s^{-1}ster^{-1}. Line of atomic oxygen at 557.7 nm is taken into account

Modeling of photon transport in the telescope

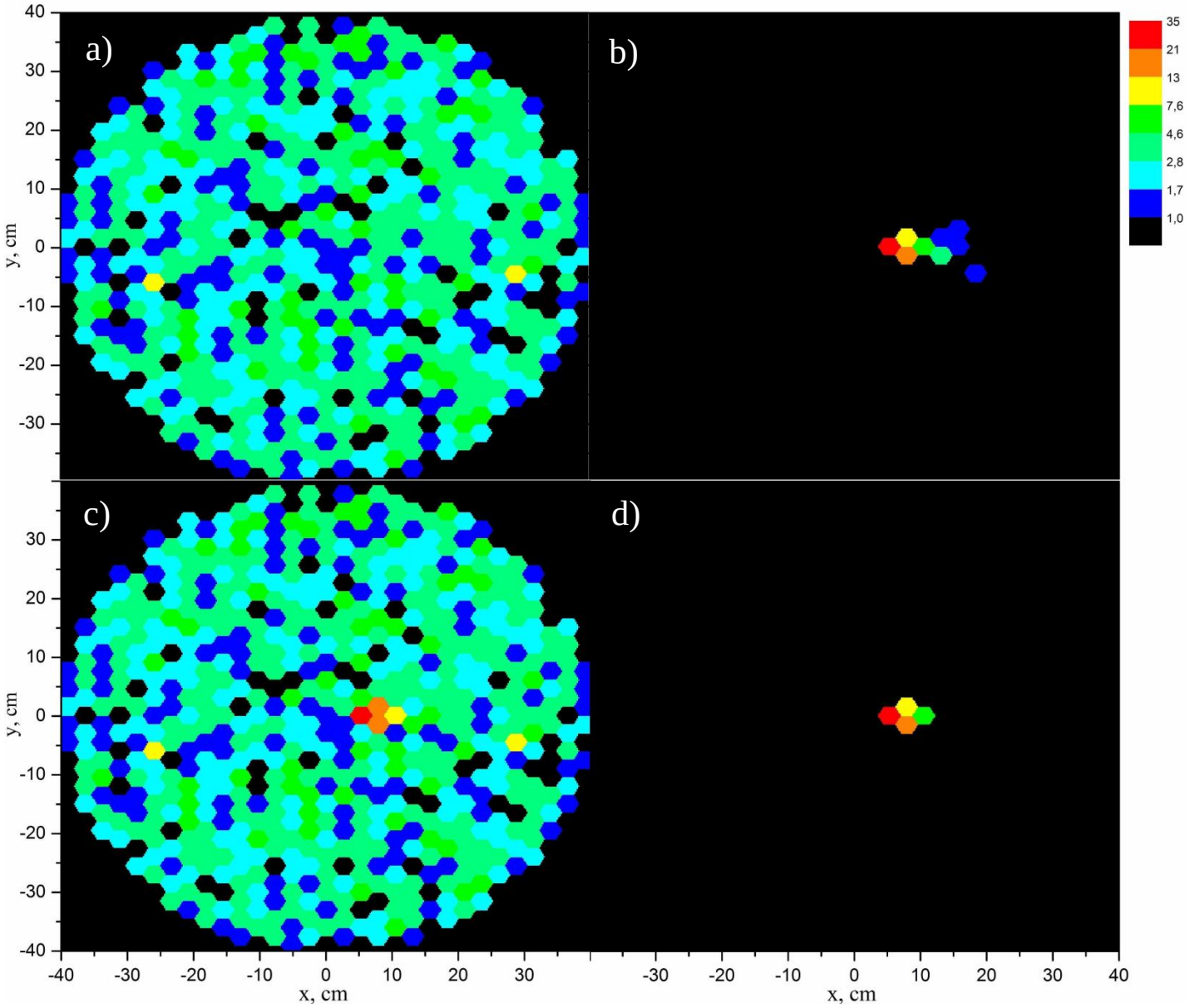
Modeling of telescope is performed with specially developed package, TAIGA Soft. Parameters: mirror area 9.6 m^2, field of view (FoV) 9.72^0, mirror albedo 0.9, cover glass transmission 0.9, Winston cone transmission 0.75, signal integration time-frame 15 ns

Trigger Conditions

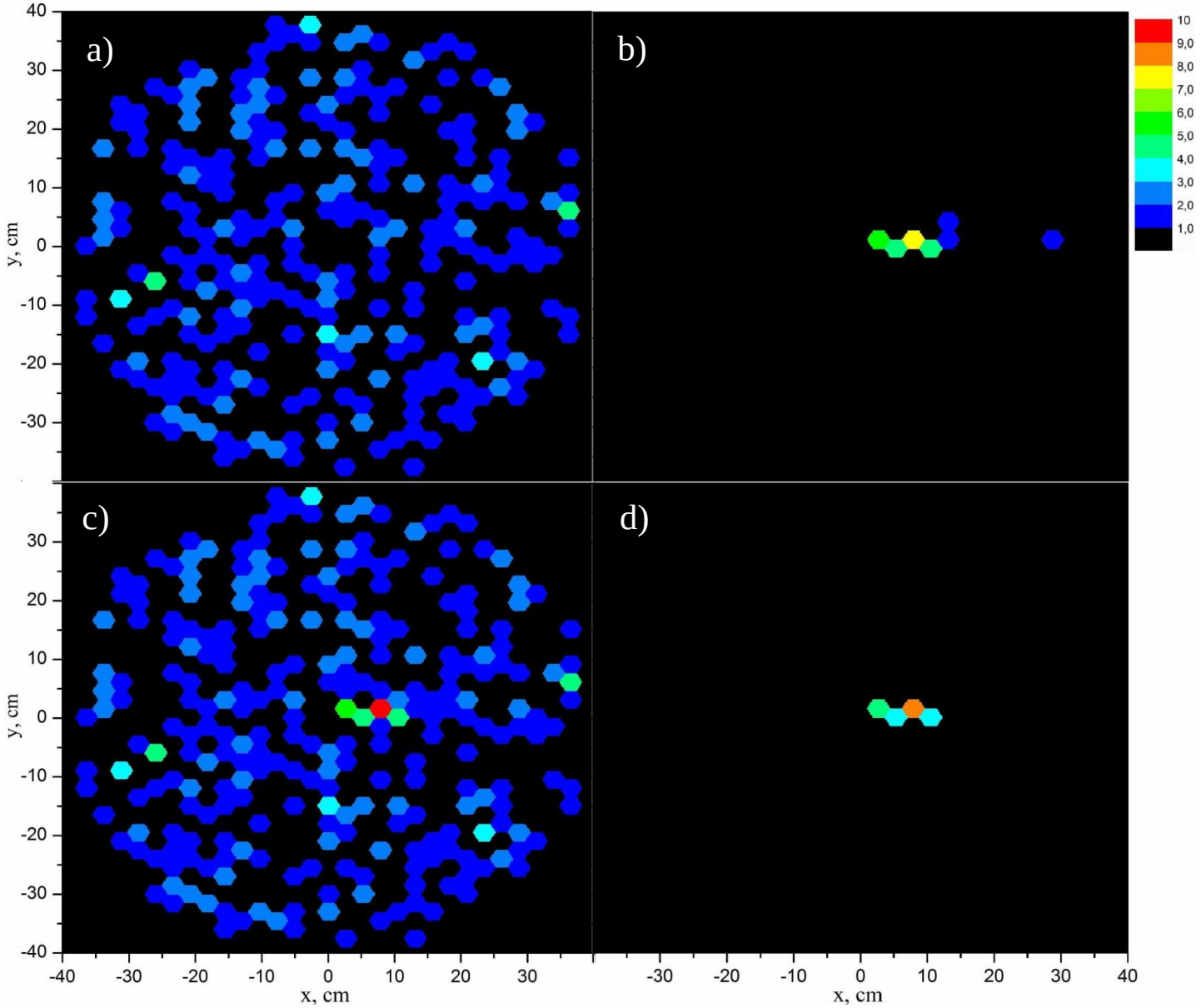
{n, N}: n determines threshold signal via $Q_{th}=Q_{NSB}+n\sigma_{NSB}$ (where Q_{NSB} is the mean signal generated by NSB, σ_{NSB} – its square deviation), N is the threshold number of neighboring bright pixels (i.e. pixels with signal $Q > Q_{th}$)



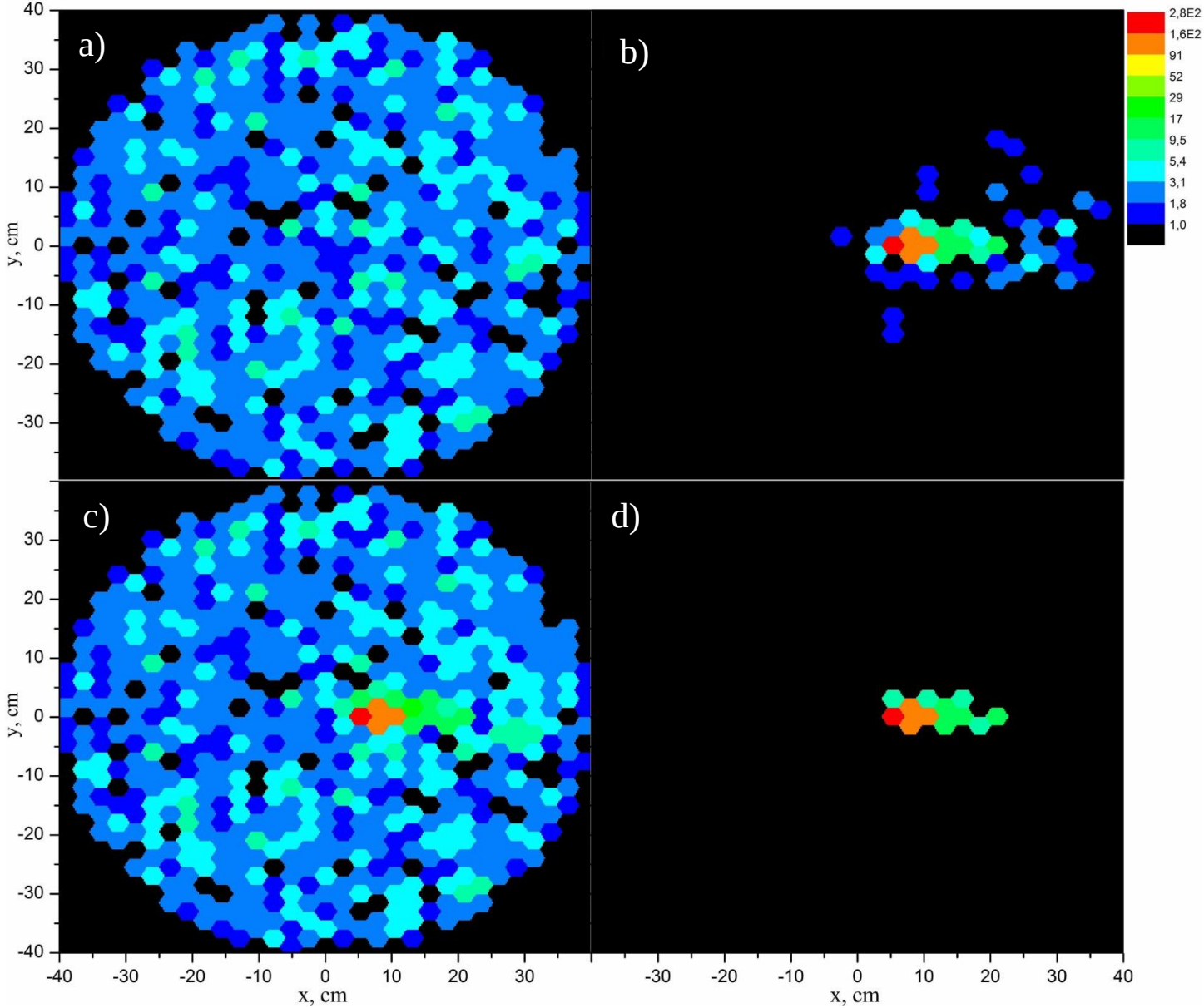
1) Mean spectrum (black curve) of Cherenkov radiation of EAS induced by 1 TeV gamma-quantum, normalized to 100% in maximum at wavelength of about 330 nm; 2) Four specific samples (yellow, purple, cyan, and wine curves) of Monte Carlo simulations of night sky background, based on data by Leinert et al. (1998), Benn & Ellison (1998), Mikhalev et al. (2001), Mikhalev & Medvedeva (2002). Profiles are normalized to 100% for maximal (among presented) value at wavelength 557 nm; 3) PDE of SiPM OnSemi MicroFJ-60035 - blue solid curve; 4) PDE of PMT XP1911 - blue dashed curve; 5) Transmission of model filter of main band 260 - 600 nm - red dashed curve; 6) Transmission of filter ZWB3 - green curve; 7) Transmission of model MUV-filter (260 - 300 nm) - magenta curve.



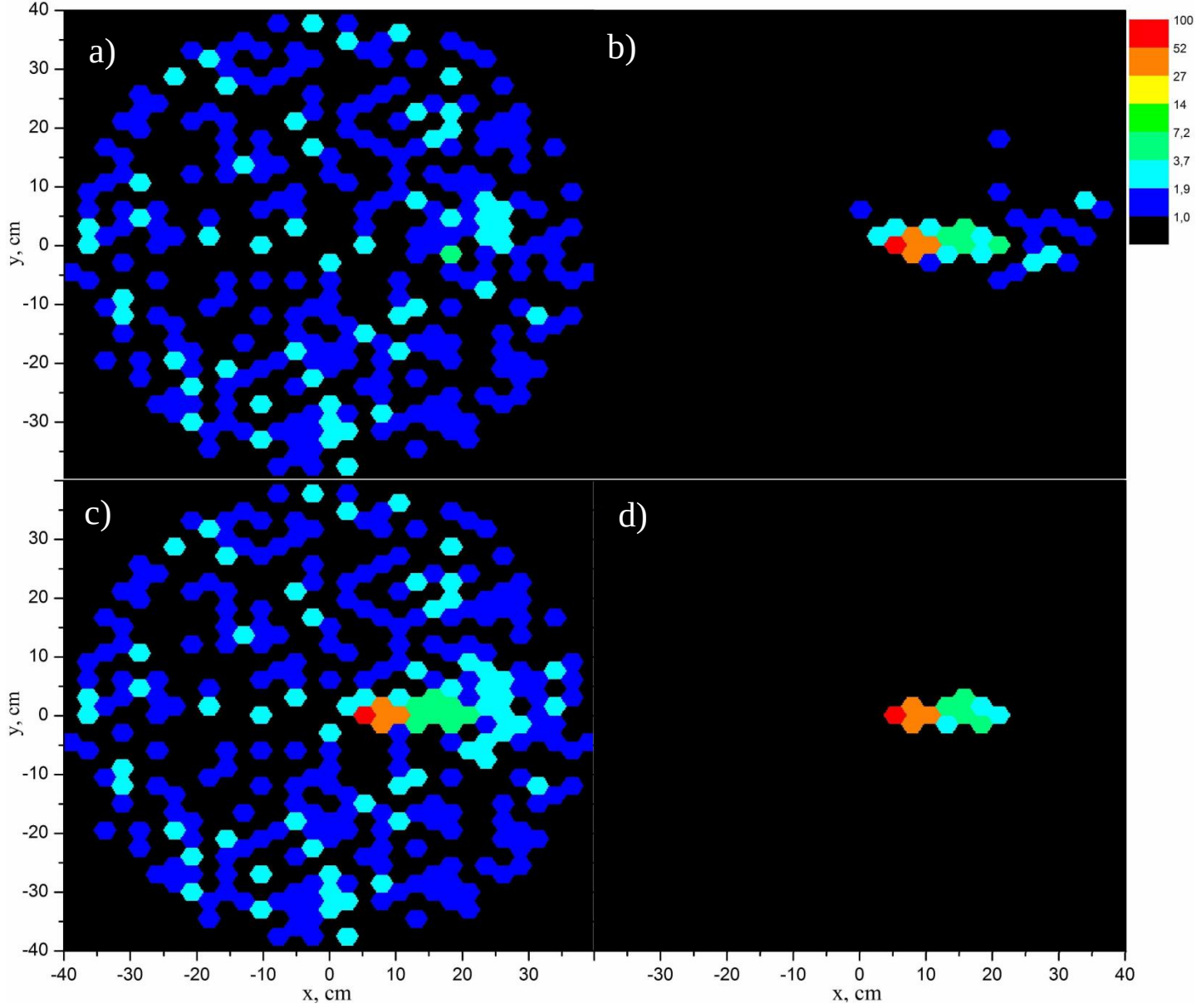
Model TAIGA-IACT camera images with a main band filter (260 - 600 nm): a) night sky background (NSB) noise; b) signal generated by Cherenkov radiation at 120 m from axis of EAS induced by a vertically incident 0.3 TeV gamma-quantum c) sum of (a) and (b) ; d) image (c) after cleaning



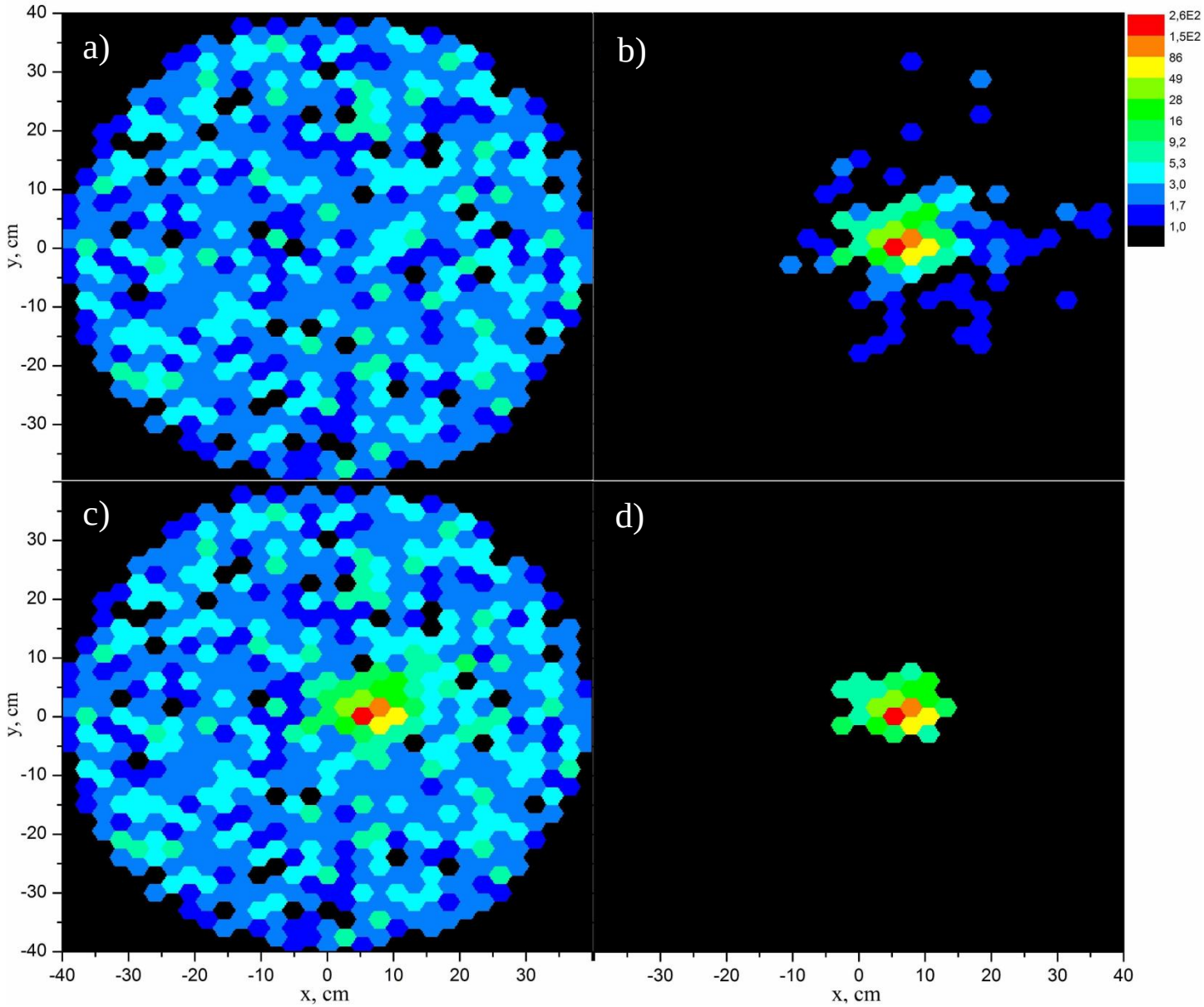
Model TAIGA-IACT camera images with a ZWB3-filter (270 - 400 nm): a) night sky background (NSB) noise; b) signal generated by Cherenkov radiation at 120 m from axis of EAS induced by a vertically incident 0.3 TeV gamma-quantum c) sum of (a) and (b) ; d) image (c) after cleaning



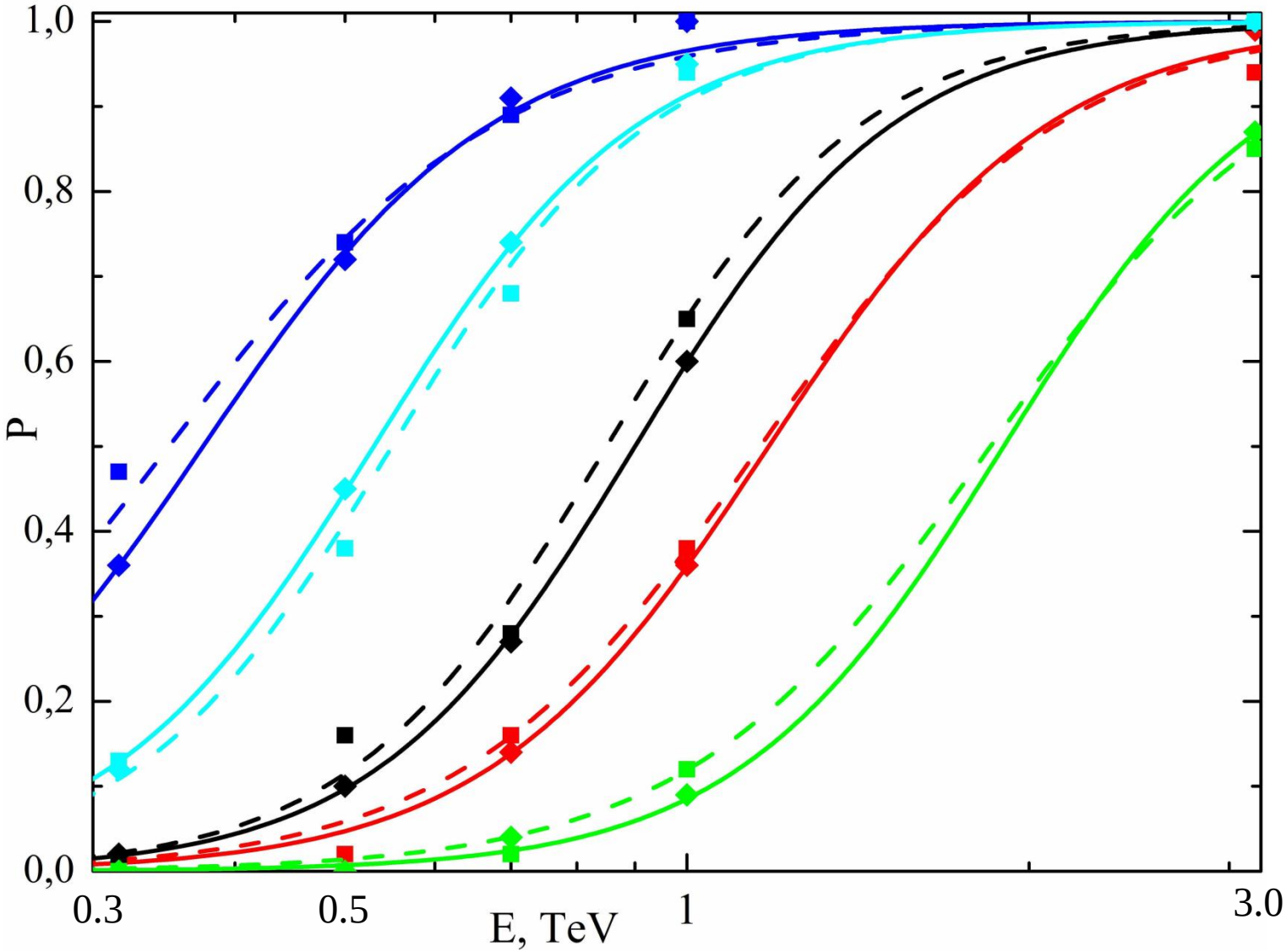
Example images formed in camera with using main band filter (260 - 600 nm): a) night sky background (NSB) noise; b) original useful signal generated by Cherenkov radiation at distance of 120 m from axis of EAS induced by vertically incident gamma-quantum of energy 3 TeV c) sum of images (a) and (b) - the model of real signal; d) image (c) after cleaning;



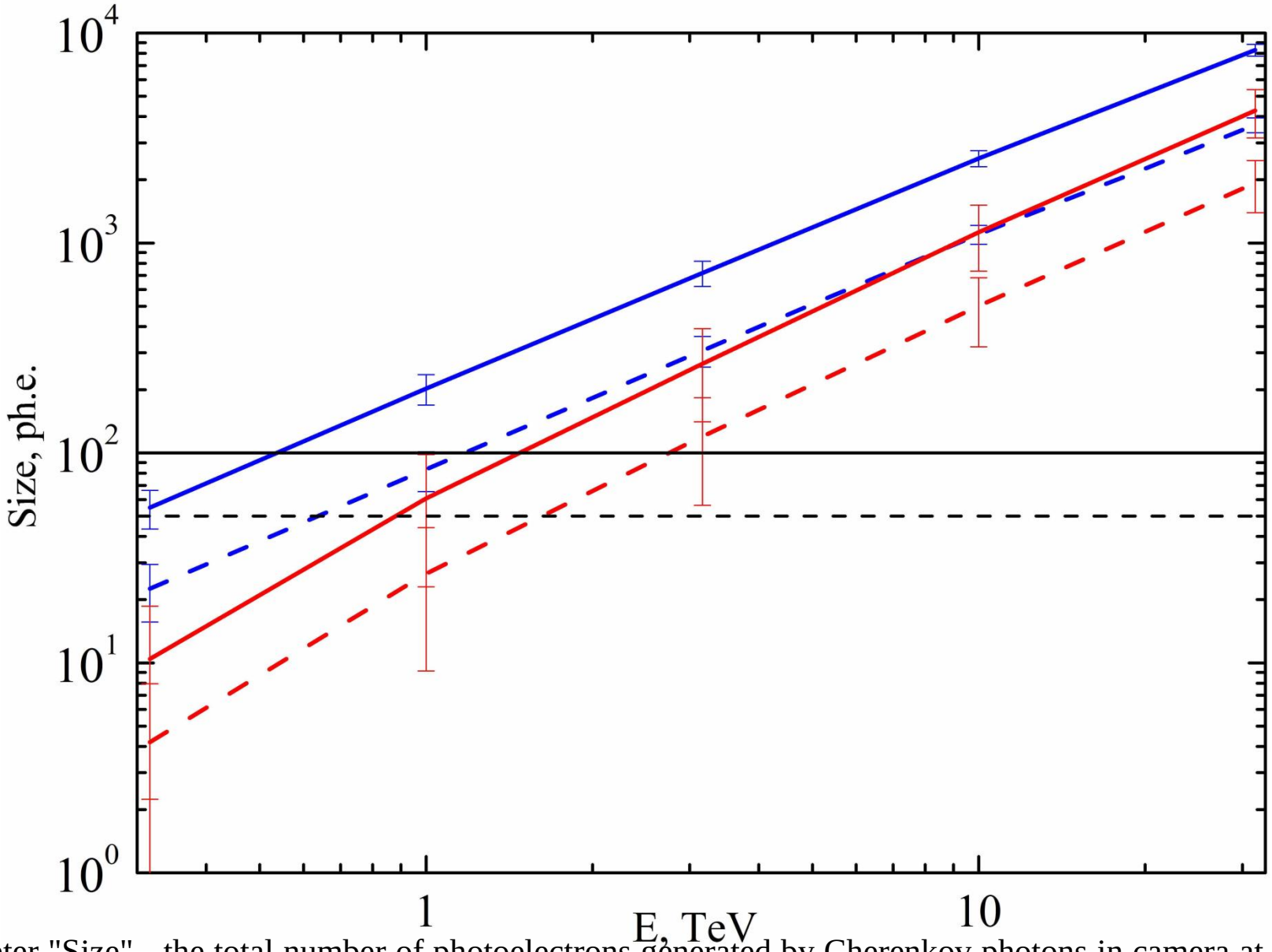
Example images formed in camera with using ZWB3-filter (270 - 400 nm): a) night sky background (NSB) noise; b) original useful signal generated by Cherenkov radiation at distance of 120 m from axis of EAS induced by vertically incident gamma-quantum of energy 3 TeV c) sum of images (a) and (b) - the model of real signal; d) image (c) after cleaning;



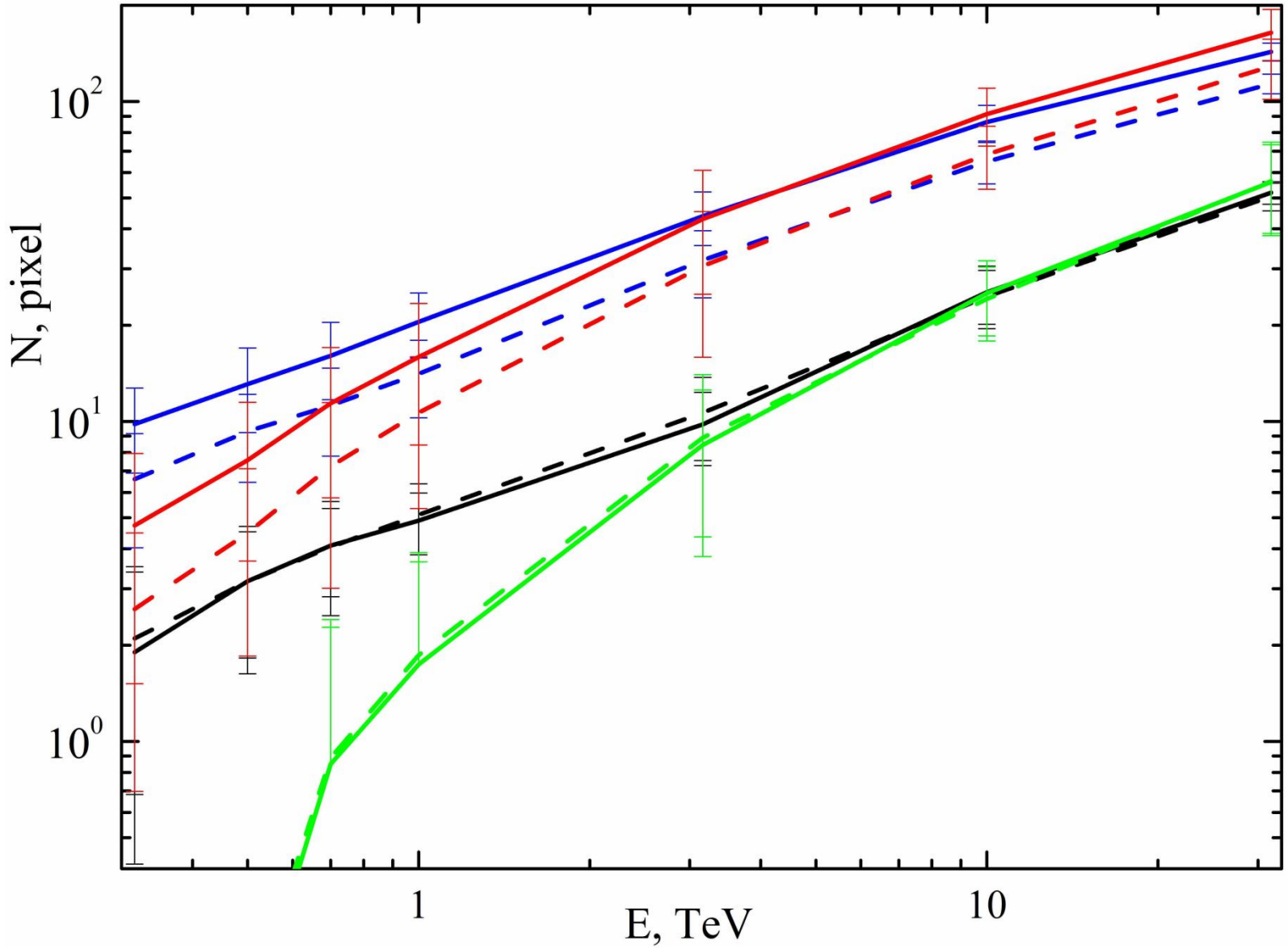
Example images formed in camera with using main band filter (260 - 600 nm): a) night sky background (NSB) noise; b) original useful signal generated by Cherenkov radiation at distance of 120 m from axis of EAS induced by vertically incident proton of energy 10 TeV c) sum of images (a) and (b) - the model of real signal; d) image (c) after cleaning;



The triggering probability at distance of 120 m from axis of EASs induced by vertically incident primary particles. Results of calculations with using main band filter (260 - 600 nm) are shown by rhombuses, corresponding fits - by solid curves. Results of calculations with using ZWB3-filter (270 - 400 nm) are shown by squares, corresponding fits - by dashed curves. Registration probabilities of events induced by gamma-quanta are shown by blue color for N_{th}=3, cyan - for N_{th}=4, black - for N_{th}=5. Registration probabilities of events induced by protons are shown by red color for N_{th}=3, green - for N_{th}=5.



Parameter "Size" - the total number of photoelectrons generated by Cherenkov photons in camera at distance of 120 m from axis of EASes induced by vertically incident gamma-quanta (blue curves) and protons (red curves). Dependencies of "Size" obtained with using main band filter (260 - 600 nm) are shown by solid color curves, and with using ZWB3 filter (270 - 400 nm) - by dashed color curves. Threshold values are shown by black color: the level of 100 ph.e. is shown by solid curve, 50 ph.e. - dashed curve.



The total number of illuminated pixels (blue curves correspond to events induced by gamma-quanta, red ones - by protons) and the number of non-isolated bright pixels (the signal in which exceeds the threshold value, black curves correspond to events induced by gamma-quanta, green ones - by protons) at registration on distance of 120 m from the EAS axis. Solid curves correspond to calculations using the main band filter (260 - 600 nm), dashed curves - ZWB3 filter (270 - 400 nm).

Simulation Summary

Noise level: 2.6±1.6 ph.e./pix for the main band filter (260 – 600 nm)
0.55 ±0.74 ph.e./pix for the ZWB3 filter (270 – 400 nm)

False count rate

Filter	n	$[Q_{th}+1]$, ph.e.	N	$\approx R_{false}$, Hz
Main	4	10	3	10^2
Main	4	10	4	0.3
Main	4	10	5	10^{-3}
Main	5	11	3	1.2
Main	5	11	4	10^{-3}
Main	5	11	5	10^{-6}
ZWB3	4	4	3	$2.6 \cdot 10^4$
ZWB3	4	4	4	$6 \cdot 10^2$
ZWB3	4	4	5	14
ZWB3	5	5	3	34
ZWB3	5	5	4	0.1
ZWB3	5	5	5	$2 \cdot 10^{-4}$

Current false count rate at TAIGA-IACT is ~10^2 Hz

Triggering threshold energy at n=4

Particle	Filter	N	$\approx E_{th}$, TeV
gamma	Main	3	0.28
gamma	Main	4	0.44
gamma	Main	5	0.76
gamma	ZWB3	3	0.20
gamma	ZWB3	4	0.46
gamma	ZWB3	5	0.72
p	Main	3	0.91
p	Main	5	1.56
p	ZWB3	3	0.82
p	ZWB3	5	1.28

These triggers can be used for bright events (e.g. GRB) by simple measurement of excess

Current value of threshold energy at TAIGA-IACT is ≈1.5 TeV

"Size" threshold energy

Particle	Filter	$Size_{th}$	$\approx E_{Size}$, TeV
gamma	Main	100	0.54
gamma	Main	50	0.3
gamma	ZWB3	100	1.17
gamma	ZWB3	50	0.64
p	Main	100	1.5
p	Main	50	0.88
p	ZWB3	100	2.76
p	ZWB3	50	1.63

Current value of $Size_{th}$ at TAIGA-IACT is 100 ph.e.

At HEGRA it was at 40 ph.e.

Conclusion

The threshold of a TAIGA-IACT-like telescope with SiPM-based camera can be as low as 0.3 – 0.8 TeV (depending on filter, trigger, cleaning algorithm and the acceptable level of uncertainty)

Even under strict selection criteria which would ensure a high quality of the EAS images, the threshold would be twice as low as currently achieved at TAIGA-IACT

Thank you for your attention!