

# Чувствительность малоразмерного чертенковского телескопа TAIGA-IACT с камерой на SiPM

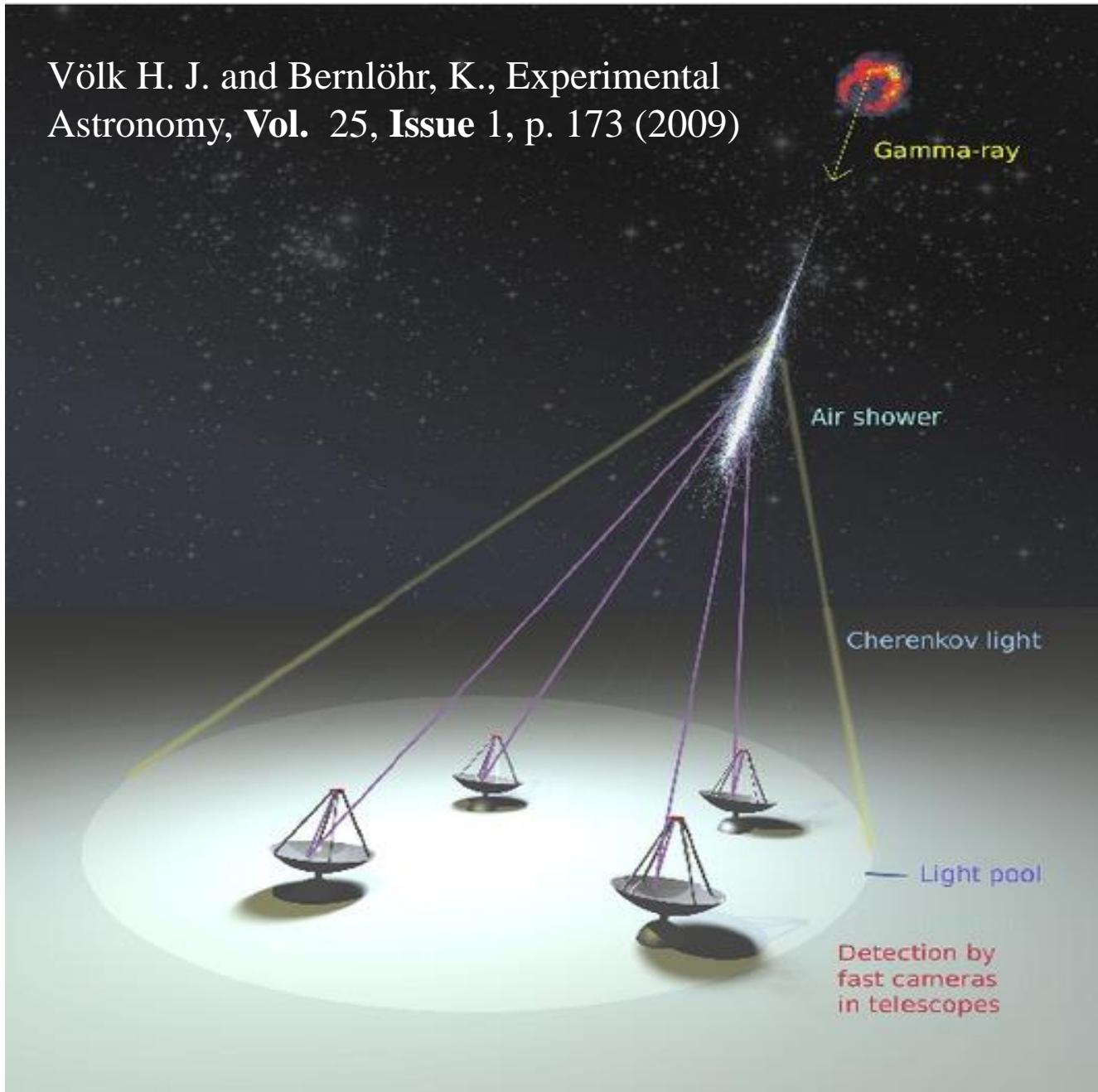
Е.Е. Холупенко, Д.В. Бадмаев, А.М. Красильщиков,  
А.С. Антонов, А.А. Богданов, Г.А. Репман,  
Ю.В. Тубольцев, Е.М. Хилькевич, Ю.В. Чичагов

ФТИ им. А.Ф. Иоффе  
(Санкт-Петербург)

исследование поддержано РНФ в рамках проекта 19-72-20045

# Принцип работы черенковского гамма-телескопа

Völk H. J. and Bernlöhr, K., Experimental Astronomy, Vol. 25, Issue 1, p. 173 (2009)



# Черенковский гамма-телескоп TAIGA-IACT



Авторы изображения: коллаборация TAIGA (Л.А. Кузьмичев и др.)

Один из элементов  
обсерватории TAIGA,  
расположенной в  
Тункинской долине  
(респ. Бурятия)

площадь зеркала  
 $\sim 10 \text{ m}^2$

порог регистрации  
гамма-событий  
 $\sim 1,5 \text{ ТэВ}$

3 телескопа уже  
работают + 1  
будет введен в  
2022 году + еще  
несколько в  
будущем

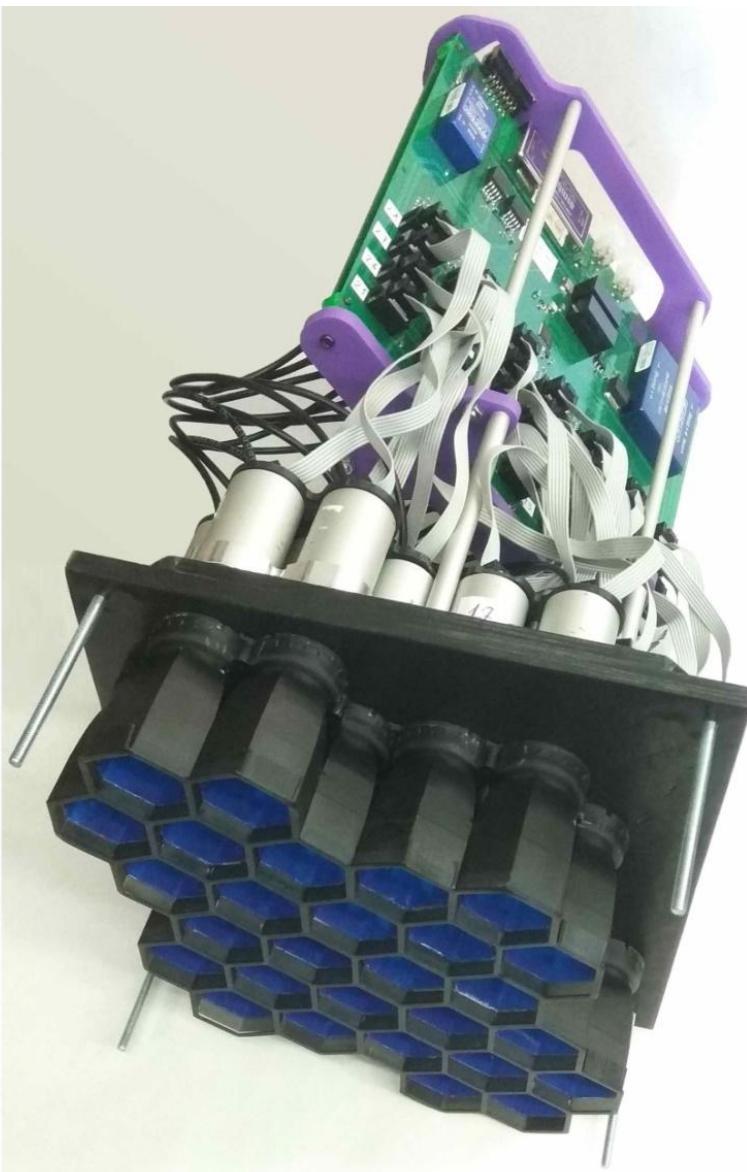
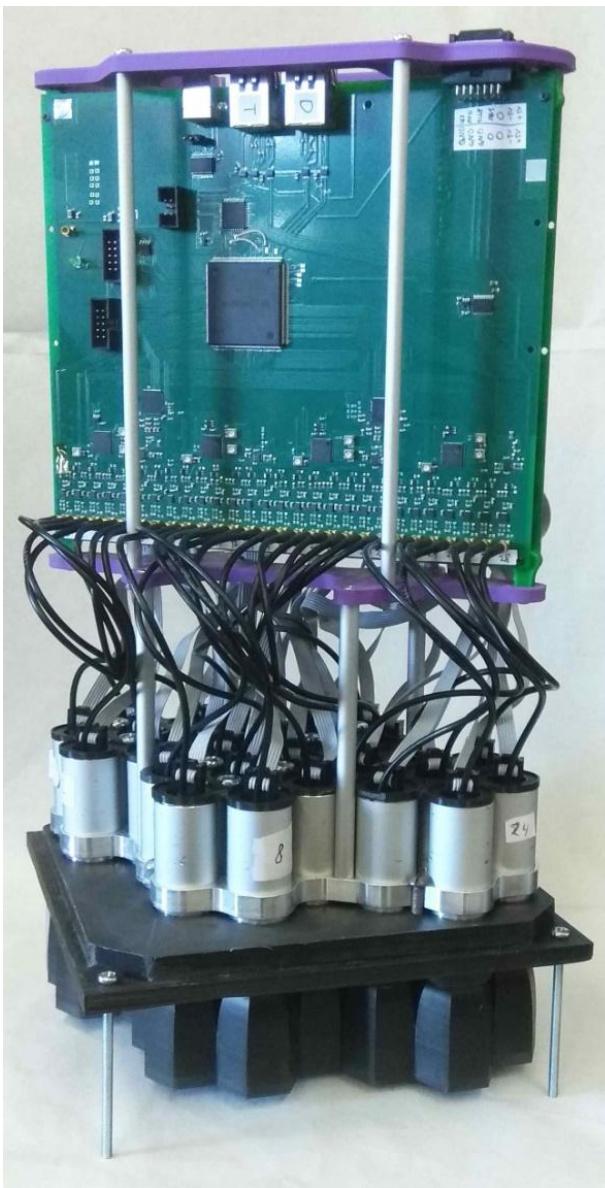
# Как можно улучшить характеристики телескопа TAIGA-IACT и создать перспективу для будущих IACT?

## 1. Заменить вакуумные ФЭУ на кремниевые фотоумножители (например, SensL/OnSemi MicroFJ-60035)

- улучшенная чувствительность (PDE)
- низкое напряжение питания и энергопотребление
- устойчивость к засветке
- сниженный вес детектора и камеры в целом

## 2. Использовать светофильтры

- увеличение экспозиций за счет подавление фона от ночного неба (NSB)
- улучшение гамма-адронной селекции сигнала от ярких источников за счет измерения доли излучения ШАЛ в ближнем УФ диапазоне ( $\lambda < 300$  nm)



Экспериментальный детекторный кластер на SiPM, разработанный в ФТИ  
(совместим с кластерами, ныне используемыми на TAIGA-IACT)  
2 комплекта светофильтров, интегрированных в конусы Уинстона

# Моделирование параметров телескопа в преддверии натурных испытаний

## EAS and NSB simulations

EASs simulations: CORSIKA v. 7.7400 (D. Heck et al. 1998)

NSB simulations: TAIGA Soft (Kholupenko et al. 2020)

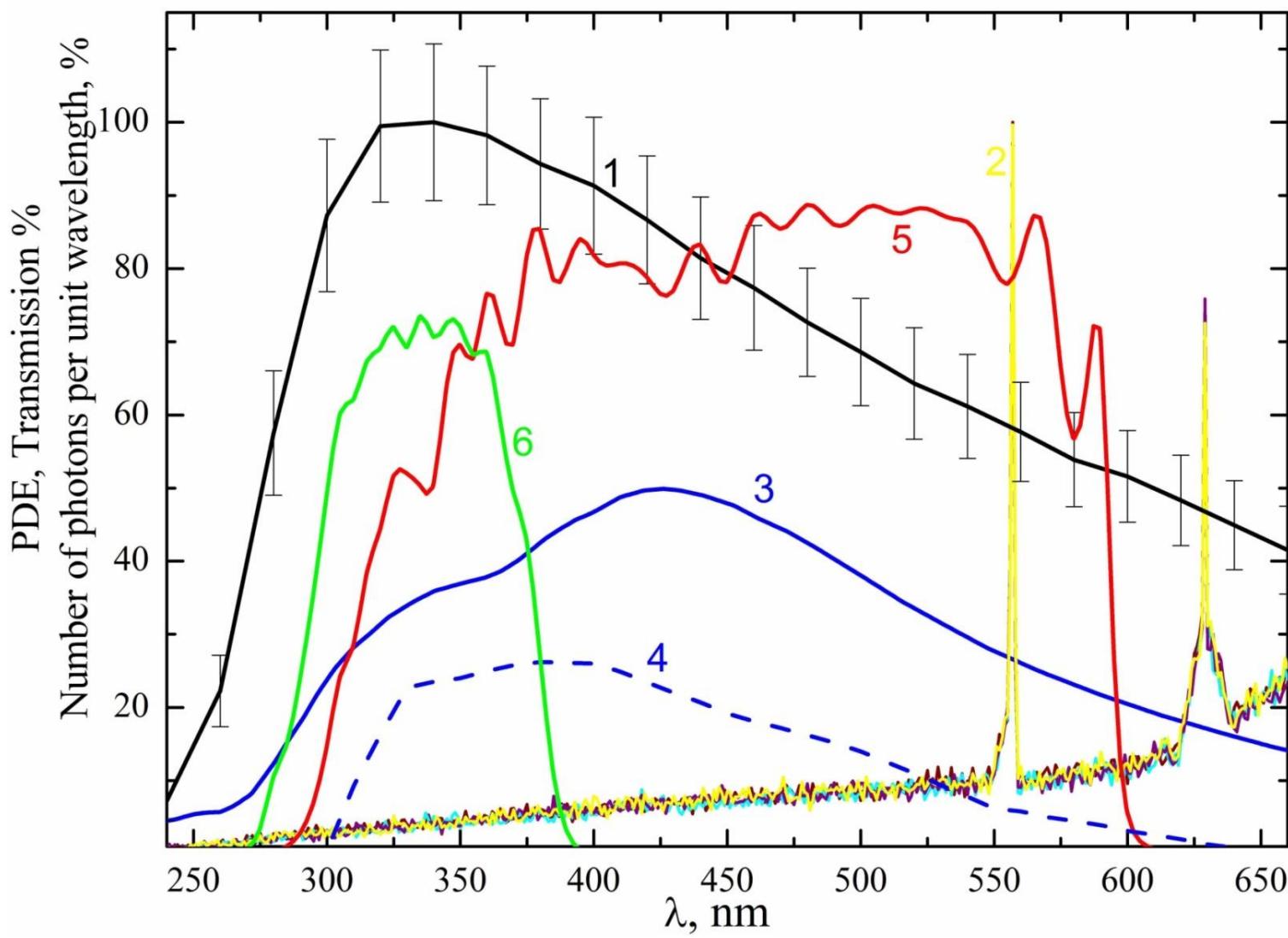
Place: Tunka valley, altitude is 675 m a.s.l. (atmosphere depth 950 – 960 g/cm<sup>2</sup>), atmosphere model is ‘winter mid-latitude atmosphere N3’, wavelength 200 – 700 nm, magnetic field (H,Z)=(18.5, 57.7) μT

Vertically incident primary particles, impact parameter (distance from the telescope to the EAS axis) varied from 0 to 960 m, primary particle energies 0.3162, 0.5, 0.7, 1.0, 3.162, 10.0, 31.62 TeV

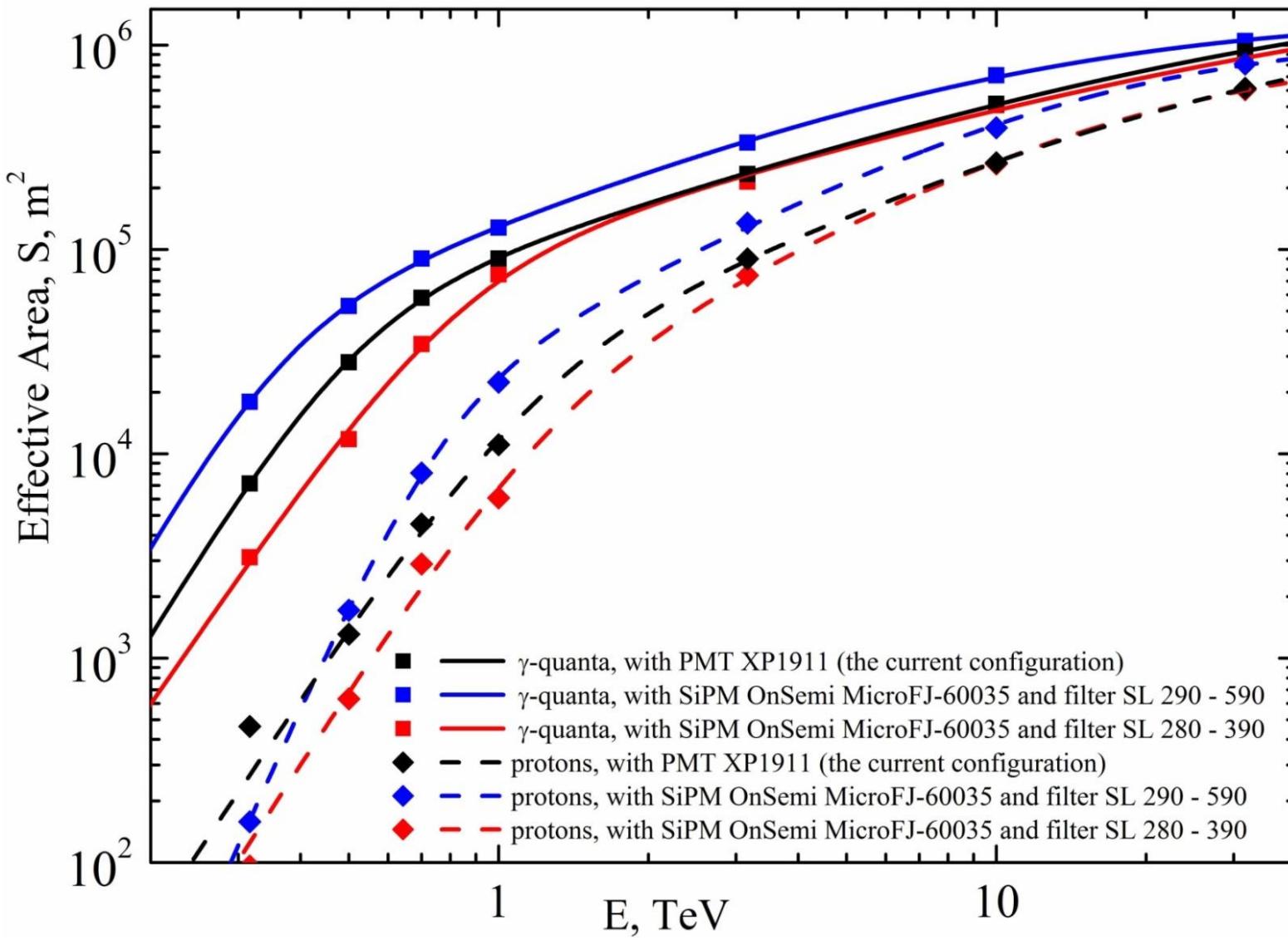
The total 300 – 600 nm NSB intensity  $3 \cdot 10^{12} \text{ ph} \cdot \text{m}^{-2} \text{s}^{-1} \text{ster}^{-1}$ . Lines of atomic oxygen at 557.7 nm and its doublet at 630-632 nm are taken into account

## Modeling of photon transport in the telescope

Modeling of a telescope is performed with a specially developed software package, “TAIGA Soft”. Parameters: mirror area 9.6 m<sup>2</sup>, field of view (FoV) 9.72°, mirror albedo 0.8, cover glass transmission 0.9, Winston cone transmission 0.7, signal integration time-frame 15 ns.

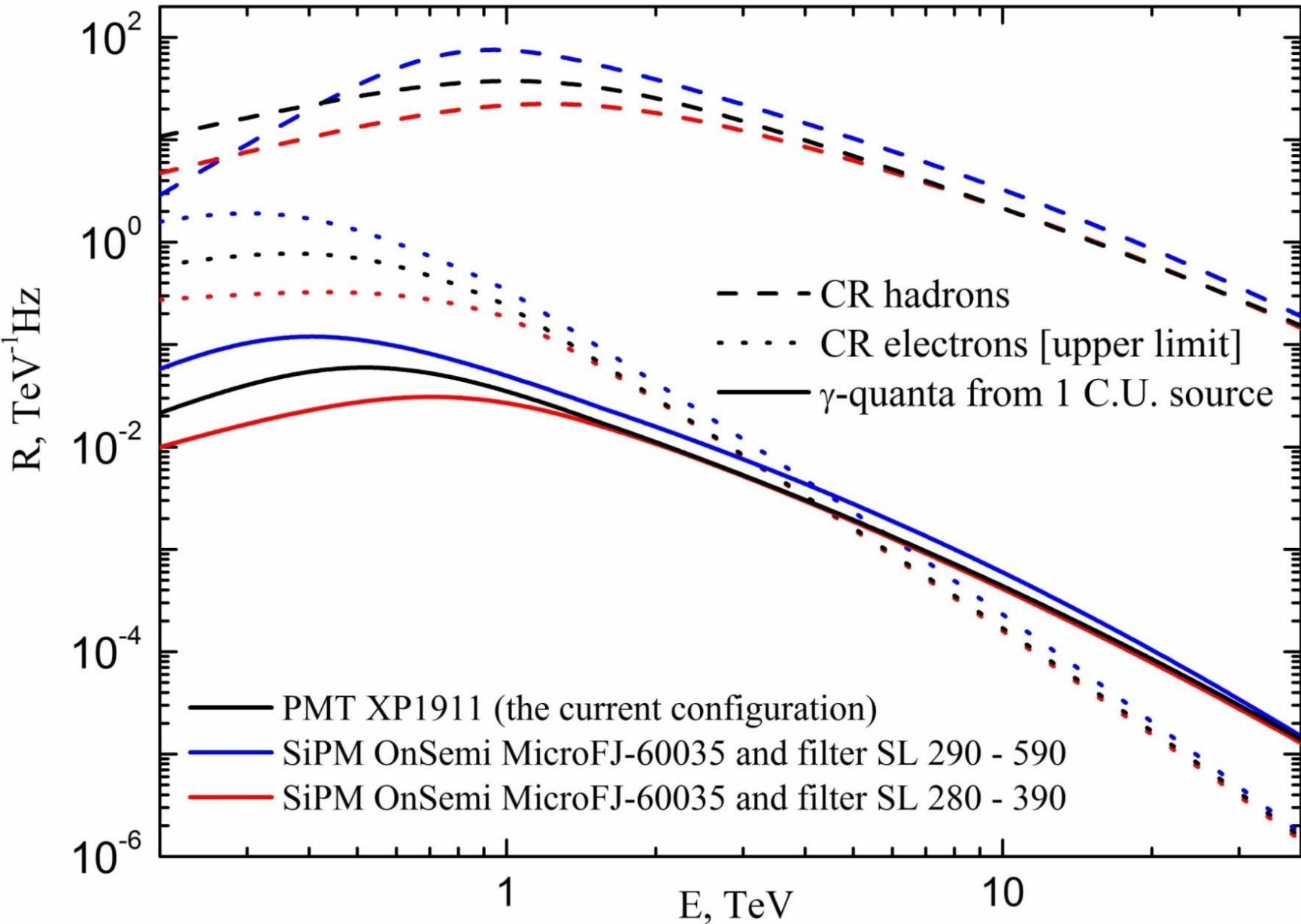


- 1) Черный : усредненный спектр черенковского излучения от ШАЛ от фотона с энергией 1 ТэВ
- 2) Желтый, голубой и др: 4 Монте-Карло реализации фона ночного неба
- 3) Синий сплошной: PDE SiPM OnSemi MicroFJ-60035
- 4) Синий штрих: PDE PMT XP1911
- 5) Красный: коэффициент пропускания фильтра “Фотооптик” SL 290 -- 590
- 6) Зеленый: коэффициент пропускания фильтра “Фотооптик” SL 280 -- 390

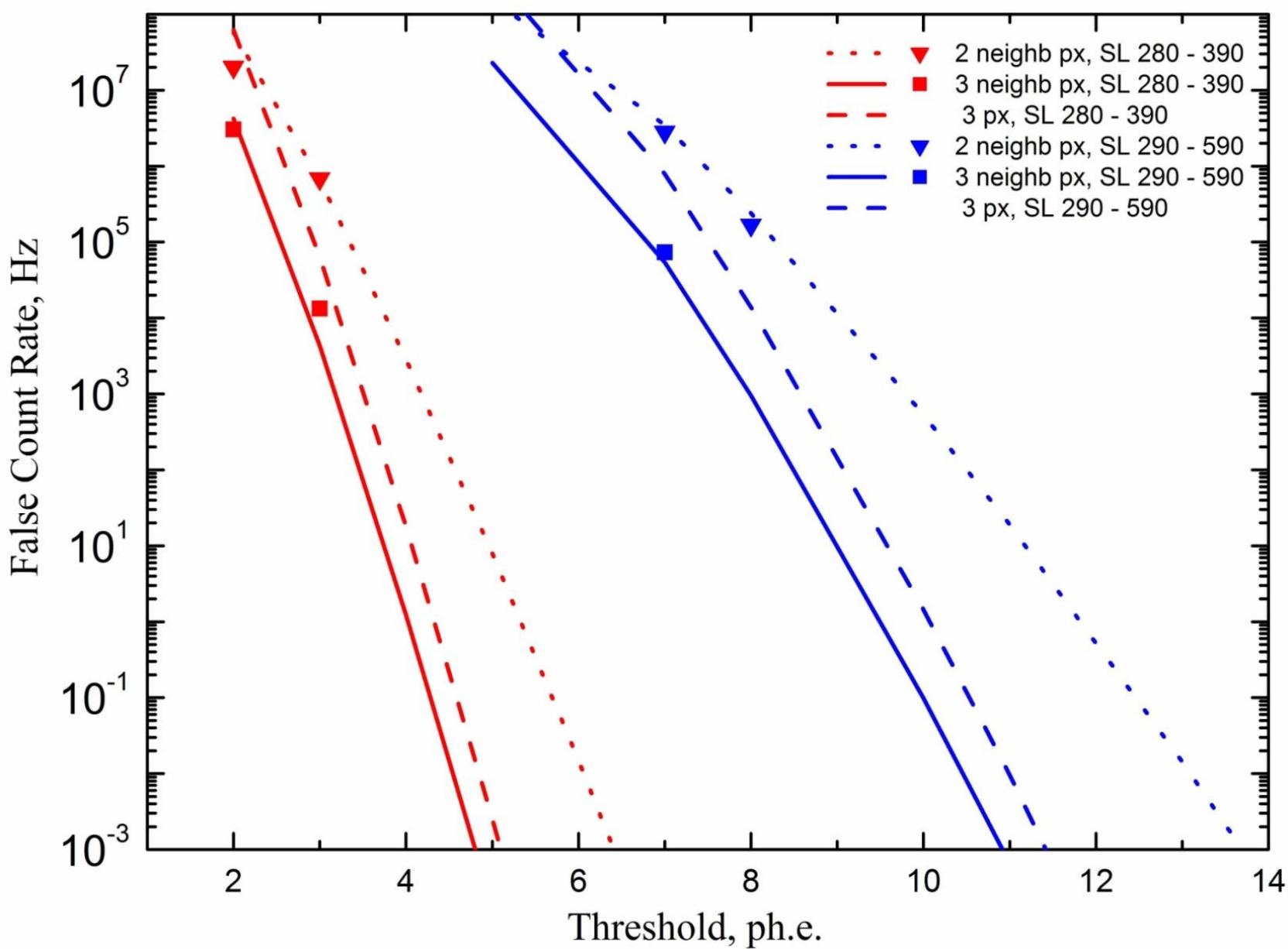


Модельная эффективная площадь камеры TAIGA-IACT по регистрации фотонов и протонов

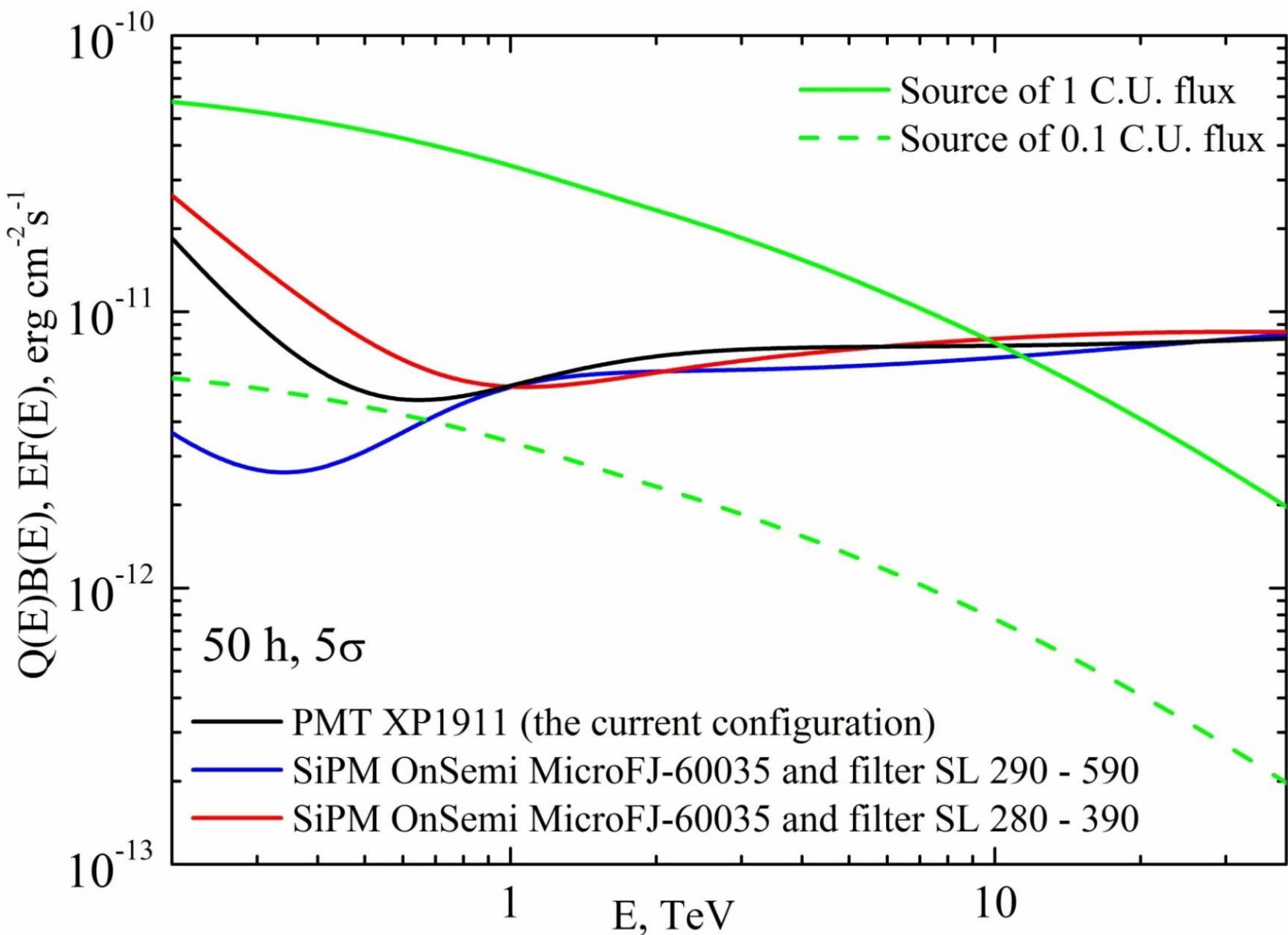
- 1) черный: текущая конфигурация камеры (PMT XP1911)
- 2) синий: камера на SiPM OnSemi MicroFJ-60035 с фильтром SL 290 -- 590
- 3) красный: камера на SiPM OnSemi MicroFJ-60035 с фильтром SL 280 -- 390



Модельные дифференциальные скорости счета различных конфигураций камеры  
TAIGA-IACT для различных типов первичных частиц



Модельные скорости счета в модифицированной камере TAIGA-IACT, вызванные фоновыми фотонами от ночного неба (NSB) и их послеимпульсами, для различных типов триггеров



Модельная чувствительность камеры TAIGA-IACT.  
C.U. = Crab Unit,  $Q(E)$  – фактор селекции ( $\sim 1.2\text{-}3.0$ ).

# Вывод

Порог регистрации космического гамма-излучения с TAIGA-IACT  
при использовании детекторов на кремниевых фотоумножителях  
может быть снижен до 0,3-0,8 ТэВ

(в зависимости от фильтра и приемлемого уровня погрешности)

Спасибо за внимание!







The effective area of a Cherenkov telescope can be defined as

$$S^{MC}(E) = 2\pi \int_0^{\infty} P(E, r) r dr, \quad (1)$$

where  $P(E, r)$  is the probability to detect a primary particle of energy  $E$ , at a distance  $r$  from EAS axis. This probability has been estimated within a Monte Carlo approach described in [11].

To describe the dependence of the telescope effective area on energy the following formula has been used:

$$S(E) \simeq S_0 \left( \frac{E}{E_0} \right)^a \left[ 1 + \left( \frac{E}{E_0} \right)^b \right]^{-1} \left[ 1 + \left( \frac{E}{E_1} \right)^{a-b} \right]^{-1}, \quad (2)$$

where  $S_0$ ,  $E_0$ ,  $a$ ,  $b$  are the approximation parameters, determined by minimization of the standard deviation, given as

$$\sigma = \left( \frac{1}{n_{max}} \sum_{n=1}^{n_{max}} \left[ \frac{S(E_n)}{S_n^{MC}} - 1 \right]^2 \right)^{1/2}, \quad (3)$$

where  $S_n^{MC}$  is the effective area value calculated by full-particle (Monte Carlo, MC) methods at energy  $E_n$ . Part of the formula (2) determining the functional dependence at low energies ( $\lesssim 10$  TeV) is well known (e.g. [25, 26]) and an additional factor (the last term in square brackets) takes into account the influence of finiteness of the telescope's field of view, which leads to limitation of the effective area at high values of energy ( $\gtrsim 30$  TeV). For gamma-quanta, the MC modeling and approximation has been done over  $n=7$

Table 1: Parameters of effective area approximation according to the formula (2)

Configuration, Primary Particle	$S_0$ , m <sup>2</sup>	$E_0$ , TeV	$E_1$ , TeV	a	b	$\sigma$ , %	$\delta$ , %
PMT XP1911							
No filter							
{2 neighb. px, 10 ph.e.}							
Gamma-quantum	$6.1798 \cdot 10^4$	0.5106	39.7372	4.0704	3.2649	1.3	2.4
SiPM OnSemi MicroFJ-60035							
Filter SL 290 – 590							
{3 neighb. px, 10 ph.e.}							
Gamma-quantum	$5.4711 \cdot 10^4$	0.3616	10.4358	4.426	3.4577	1.8	2.9
SiPM OnSemi MicroFJ-60035							
Filter SL 280 – 390							
{3 neighb. px, 4 ph.e.}							
Gamma-quantum	$9.8943 \cdot 10^4$	0.8185	59.57	3.6058	2.8785	6.8	11
PMT XP1911							
No filter							
{2 neighb. px, 10 ph.e.}							
Proton	$3.7116 \cdot 10^4$	1.191	39.528	3.6929	2.6594	4.6	9
SiPM OnSemi MicroFJ-60035							
Filter SL 290 – 590							
{3 neighb. px, 10 ph.e.}							
Proton	$2.4245 \cdot 10^4$	0.7879	15.2022	5.4607	4.1693	3.4	4.5
SiPM OnSemi MicroFJ-60035							
Filter SL 280 – 390							
{3 neighb. px, 4 ph.e.}							
Proton	$2.7041 \cdot 10^4$	1.2763	20.6882	3.8311	2.553	11.4	24

A point source of 1 Crab Unit (C.U.) flux placed at zenith was chosen as a reference source of gamma-rays. Its spectral flux [ $\text{TeV}^{-1}\text{m}^{-2}\text{s}^{-1}$ ] can be approximated as:

$$\frac{dF_\gamma}{dE} = A_\gamma \left( \frac{E}{E_\gamma} \right)^{-\beta_{0\gamma} - \beta_{1\gamma} \ln(E/E_\gamma)}, \quad (8)$$

where  $\{A_\gamma = 3.85 \cdot 10^{-7} \text{ TeV}^{-1}\text{m}^{-2}\text{s}^{-1}, E_\gamma = 1 \text{ TeV}, \beta_{0\gamma} = 2.51, \beta_{1\gamma} = 0.10423 \text{ at } E \leq 1.543 \text{ TeV}\}$  (in this range the fit from [31] is used<sup>2</sup>), and  $\{A_\gamma = 2.35 \cdot 10^{-9} \text{ TeV}^{-1}\text{m}^{-2}\text{s}^{-1}, E_\gamma = 7 \text{ TeV}, \beta_{0\gamma} = 2.79, \beta_{1\gamma} = 0.1 \text{ at } E > 1.543 \text{ TeV}\}$  (in this range the fit from [32] is used).

The employed estimate of spectral intensity [ $\text{TeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{ster}^{-1}$ ] of cosmic ray electrons is described by the following formulas [25, 29]:

$$J_e = \begin{cases} A_{1e} \left( \frac{E}{E_e} \right)^{-1} \left[ 1 + \left( \frac{E}{E_{1e}} \right)^{\beta_{1e}} \right]^{-1}, & E \leq E_e \\ A_{2e} \left( \frac{E}{E_e} \right)^{-\beta_{2e}}, & E > E_e \end{cases}, \quad (7)$$

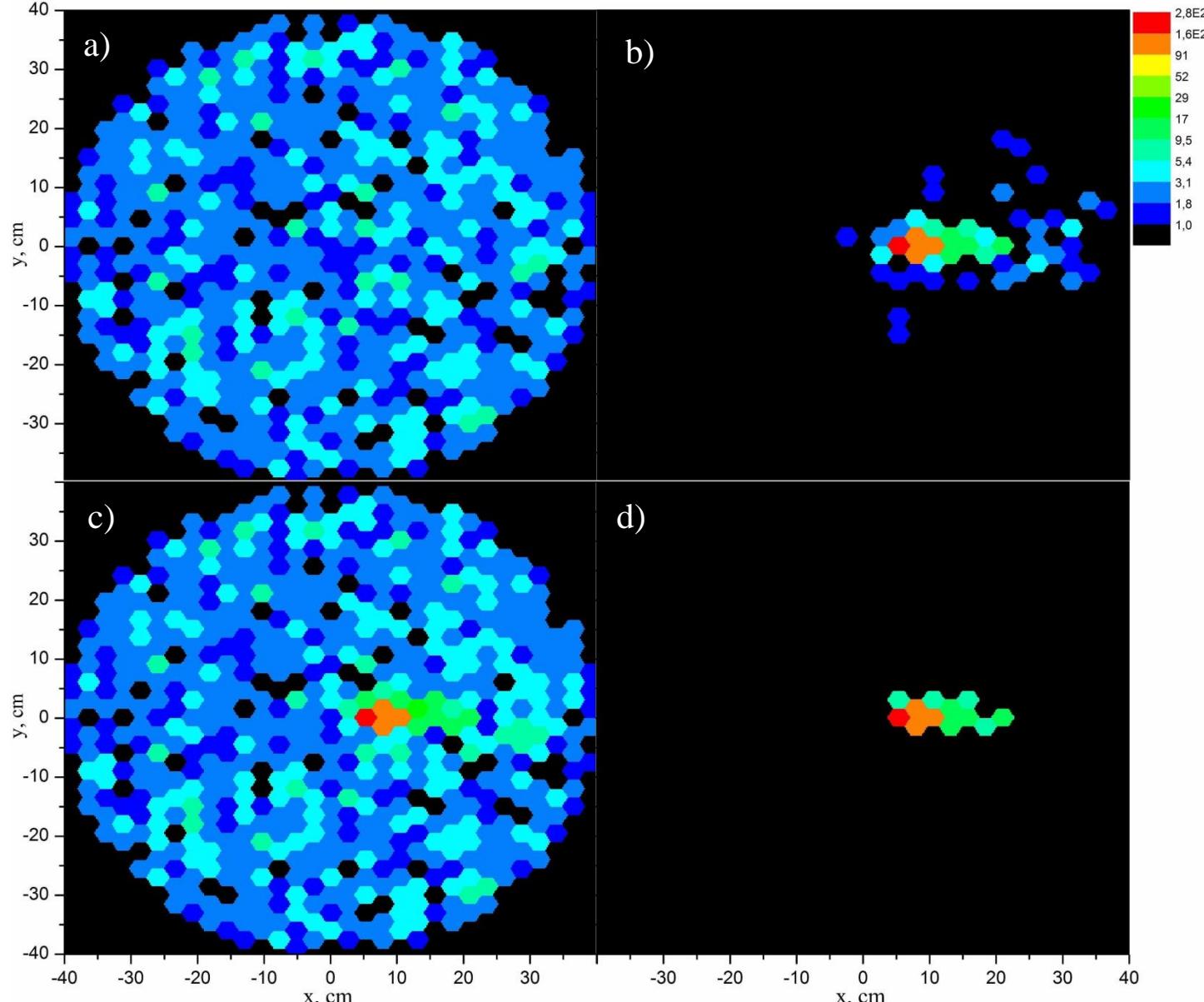
where  $E_e = 1 \text{ TeV}$ ,  $A_{1e} = 13.6 \text{ TeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{ster}^{-1}$ ,  $E_{1e} = 5 \cdot 10^{-3} \text{ TeV}$ ,  $\beta_{1e} = 2.2$ ,  $A_{2e} = 1.17 \cdot 10^{-4} \text{ TeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{ster}^{-1}$ ,  $\beta_{2e} = 3.9$ . At low energies ( $E \lesssim 0.5 \text{ TeV}$ ) this spectrum is in a very good agreement with that reported by [30].

Table 2: The integral count rates,  $R$  [Hz]

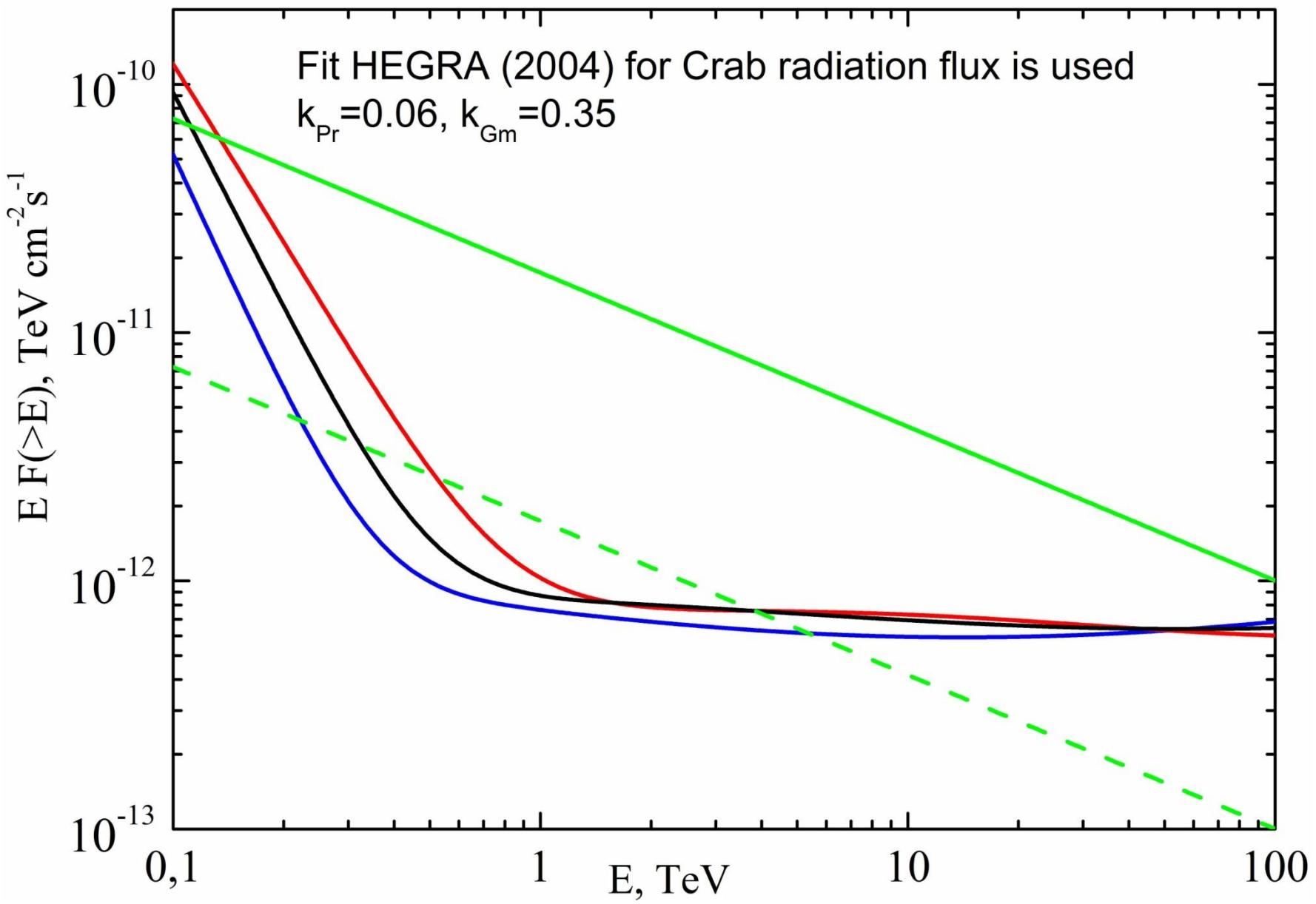
Primary Particle → Configuration ↓	Protons	Electrons	Gamma-Quanta	NSB
PMT XP1911				
No filter				
{2 neighb. px, 10 ph.e.}	138	0.6	0.08	–
SiPM OnSemi MicroFJ-60035				
Filter SL 290 – 590				
{3 neighb. px, 10 ph.e.}	212	1.2	0.13	0.1
SiPM OnSemi MicroFJ-60035				
Filter SL 280 – 390				
{3 neighb. px, 4 ph.e.}	106	0.4	0.06	1.23

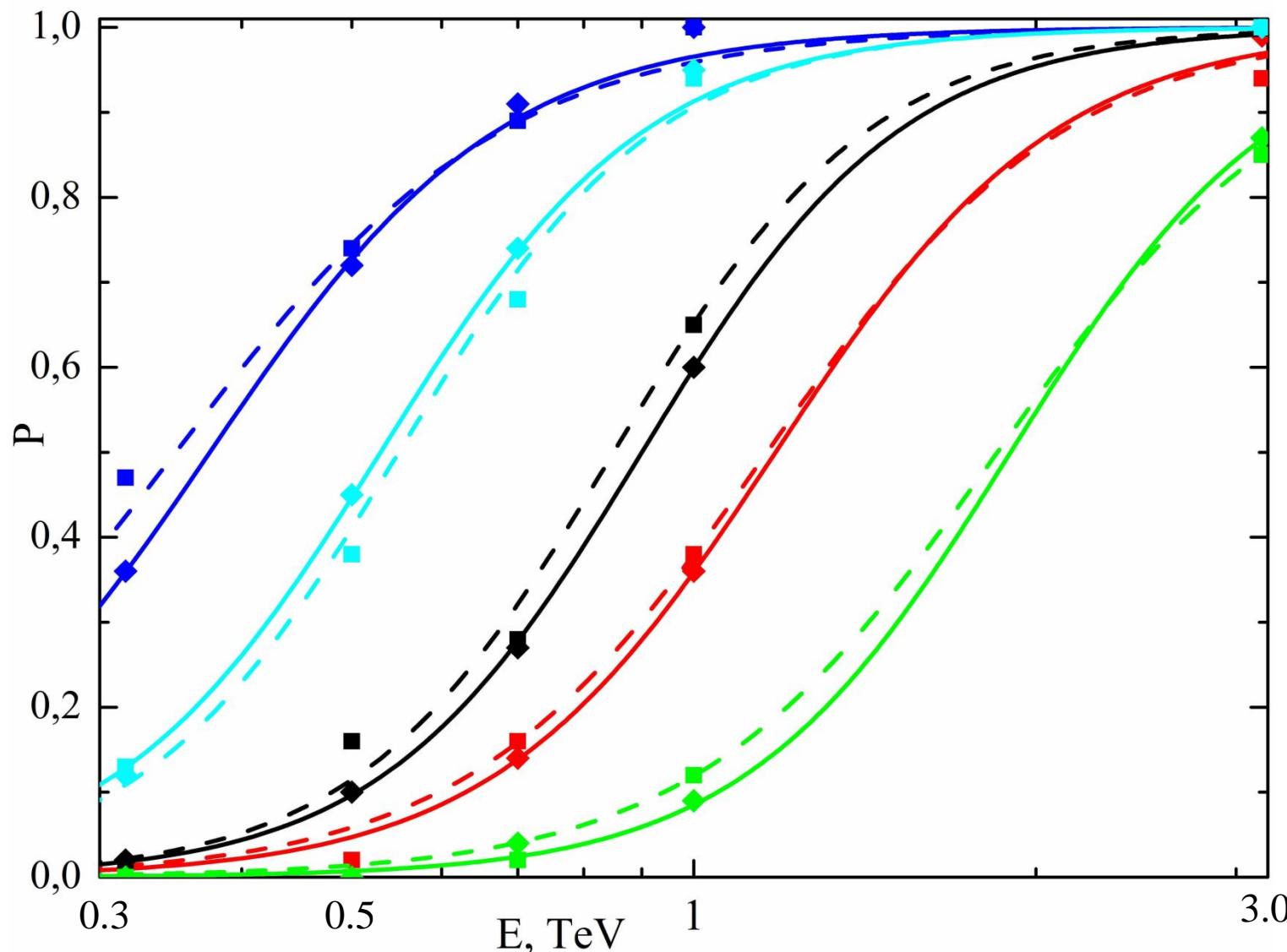
Table 3: The modeled threshold detection energy,  $E_{\text{th}}$  [TeV]

Primary Particle → Configuration ↓	Protons	Electrons	Gamma-Quanta
PMT XP1911			
No filter			
{2 neighb. px, 10 ph.e.}	1.02	0.37	0.52
SiPM OnSemi MicroFJ-60035			
Filter SL 290 – 590			
{3 neighb. px, 10 ph.e.}	0.94	0.3	0.41
SiPM OnSemi MicroFJ-60035			
Filter SL 280 – 390			
{3 neighb. px, 4 ph.e.}	1.21	0.43	0.71

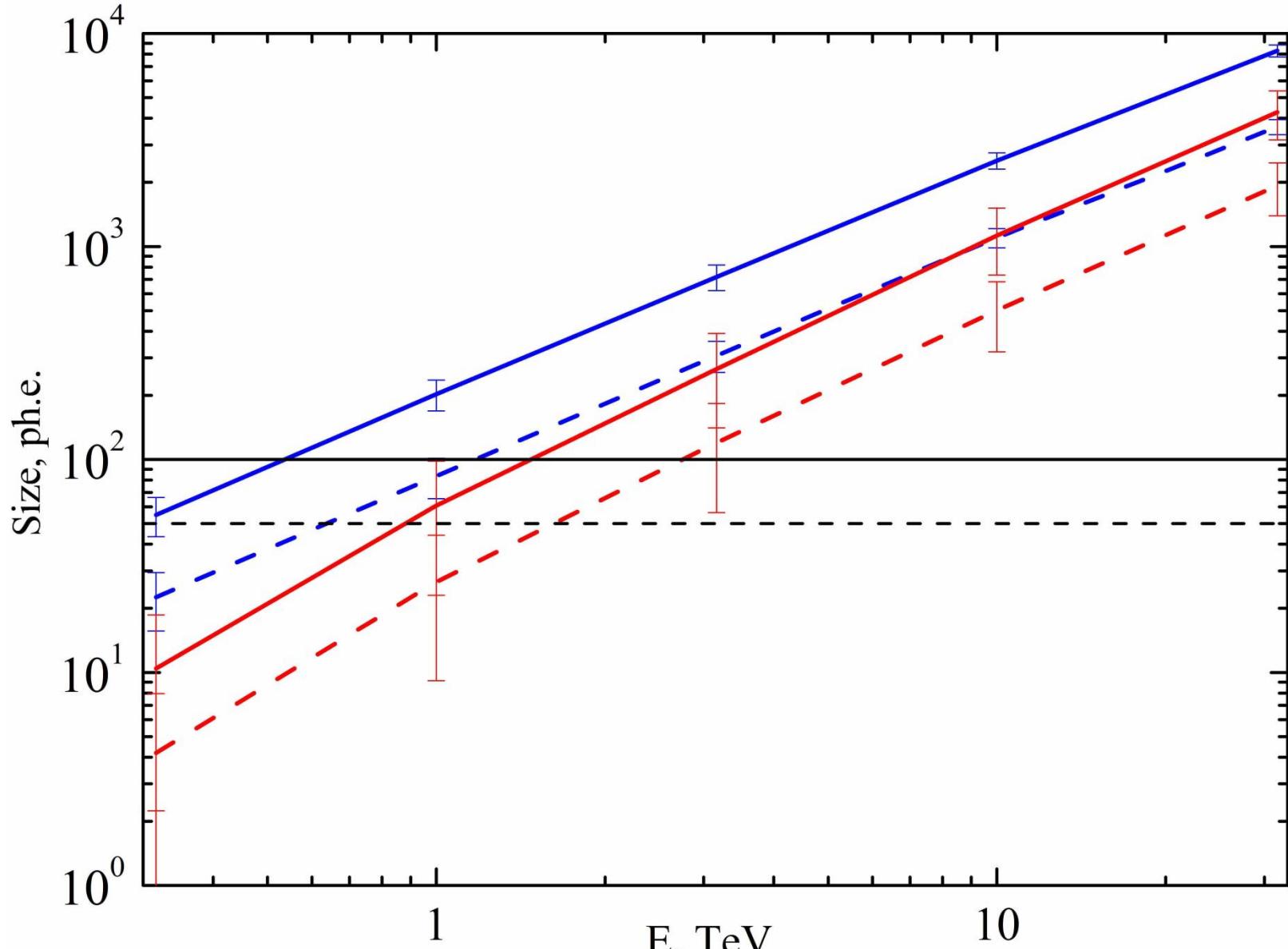


Example images formed in camera with using main band filter (260 - 600 nm): a) night sky background (NSB) noise; b) original useful signal generated by Cherenkov radiation at distance of 120 m from axis of EAS induced by vertically incident gamma-quantum of energy 3 TeV c) sum of images (a) and (b) -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

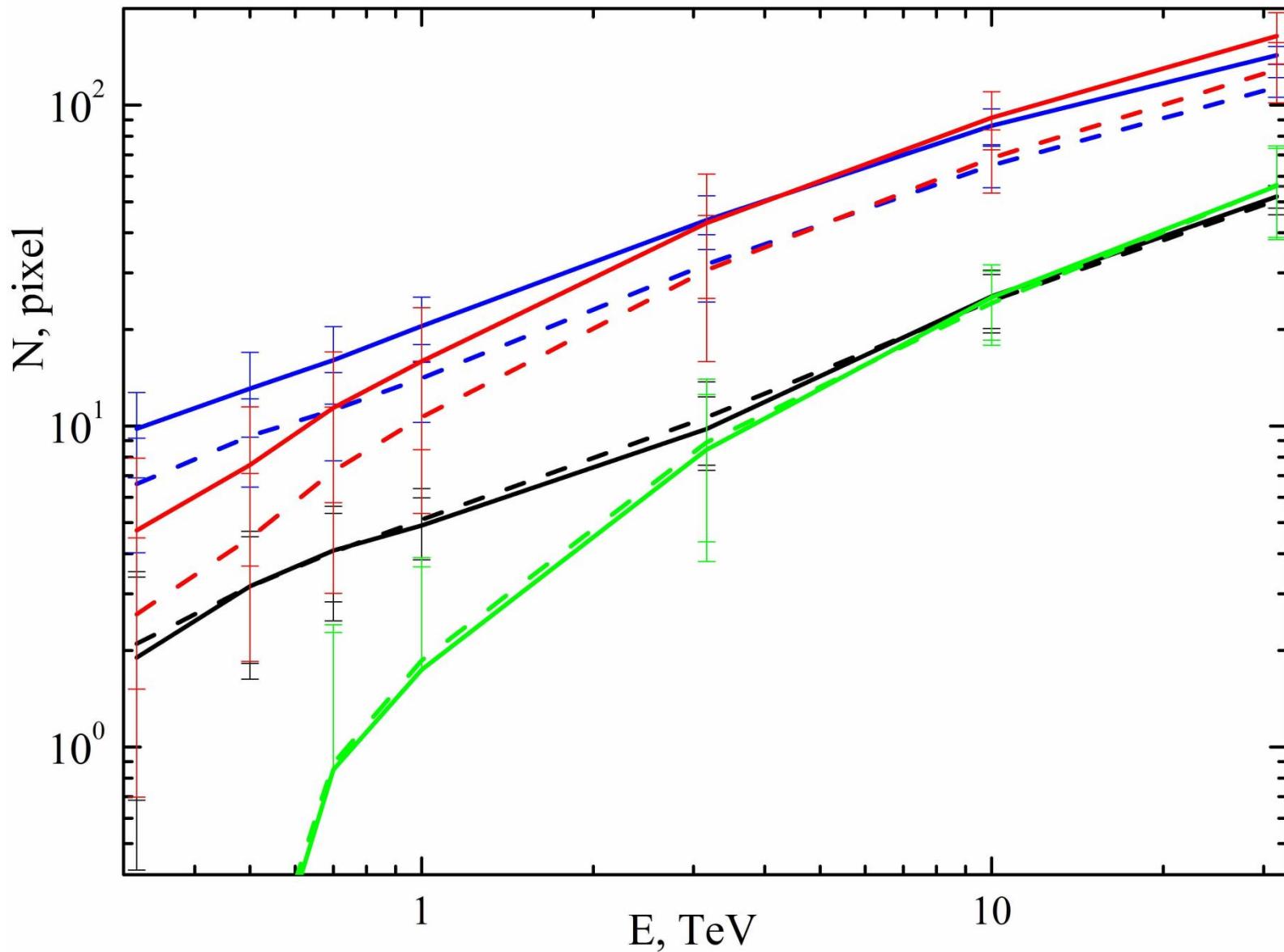




The triggering probability at distance of 120 m from axis of EASs induced by vertically incident primary particles. Results of calculations with using main band filter (260 - 600 nm) are shown by rhombuses, corresponding fits - by solid curves. Results of calculations with using ZWB3-filter (270 - 400 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).