Status of the Yakutsk air shower array and future plans

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Outline

- Introduction
- Cosmic ray energy spectrum
- Mass composition
- Directional anisotropy
- Muonic component of extensive air showers
- Theory of particle acceleration at shocks
- Prospect of future upgrade
- Summary

The Yakutsk EAS array team (as of June 2021)

Scientific staff:

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Engineering staff:

E.A. Atlasov, N.G. Bolotnikov, N.S. Gerasimova, N.A. Dyachkovskiy, O.N. Ivanov, G.G. Struchkov, B.B. Yakovlev (7)

IT infrastructure & RnD unit:

I.A. Kellarev, I.V. Ksenofontov, N.I. Neustroev, A.S. Proshutinsky (4)

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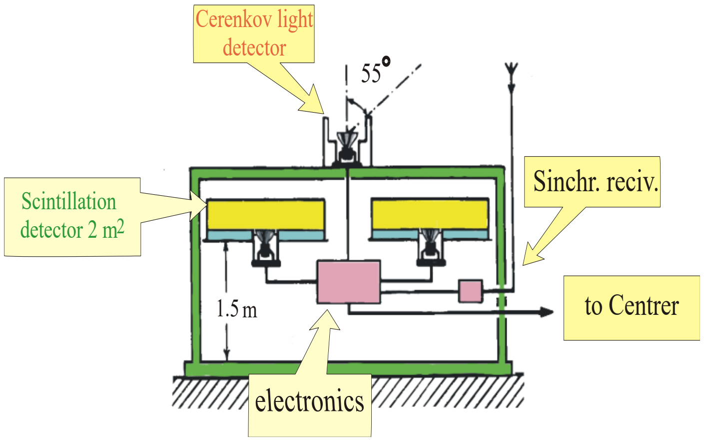
The Yakutsk array

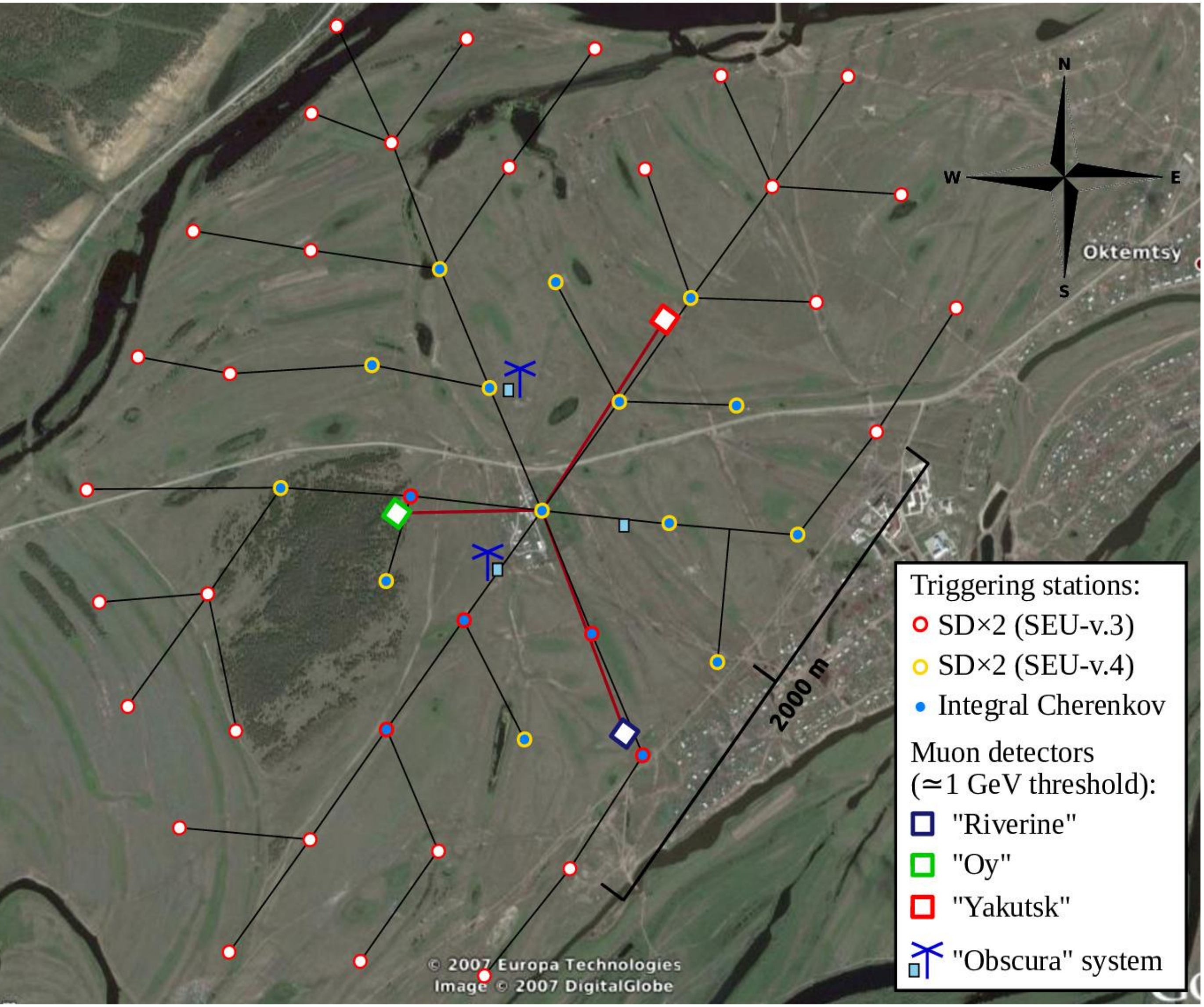
The Yakutsk extensive air showers array (YEASa) is a stationary research site, located in the Lena river valley 55 km south of Yakutsk (61.7◦ N, 129.4◦ E, ~100 m above the sea level).

The Yakutsk extensive air shower array studies cosmic rays of extremely high energies above 10 PeV (=10^{16} eV)

The Yakutsk Extensive Air Shower Array has been continuously operating for more than 50 years (since 1970) and up until recently it has been one of world's largest ground-based instruments aimed at studying the properties of cosmic rays in the ultra-high energy domain.

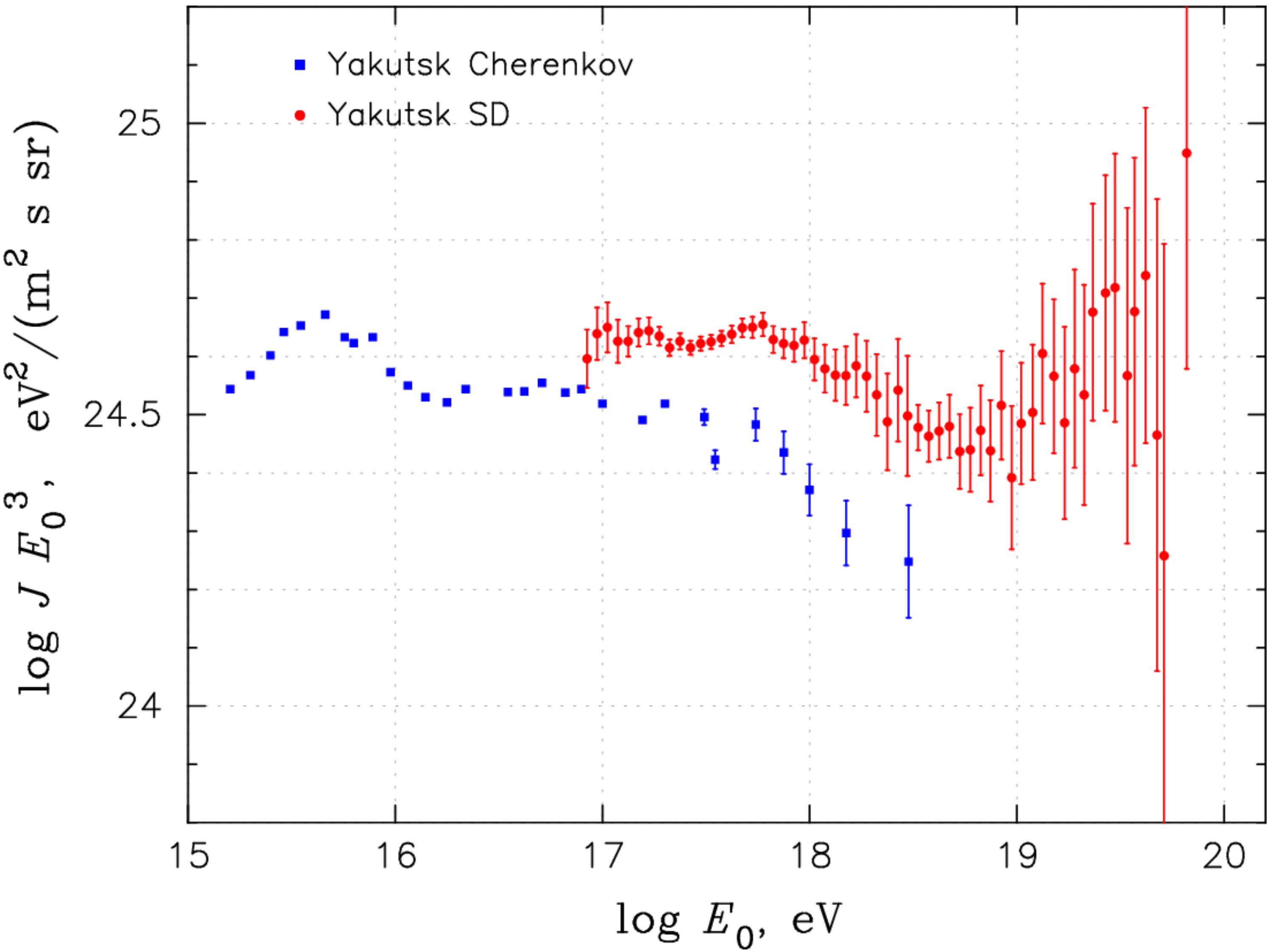


The Yakutsk array



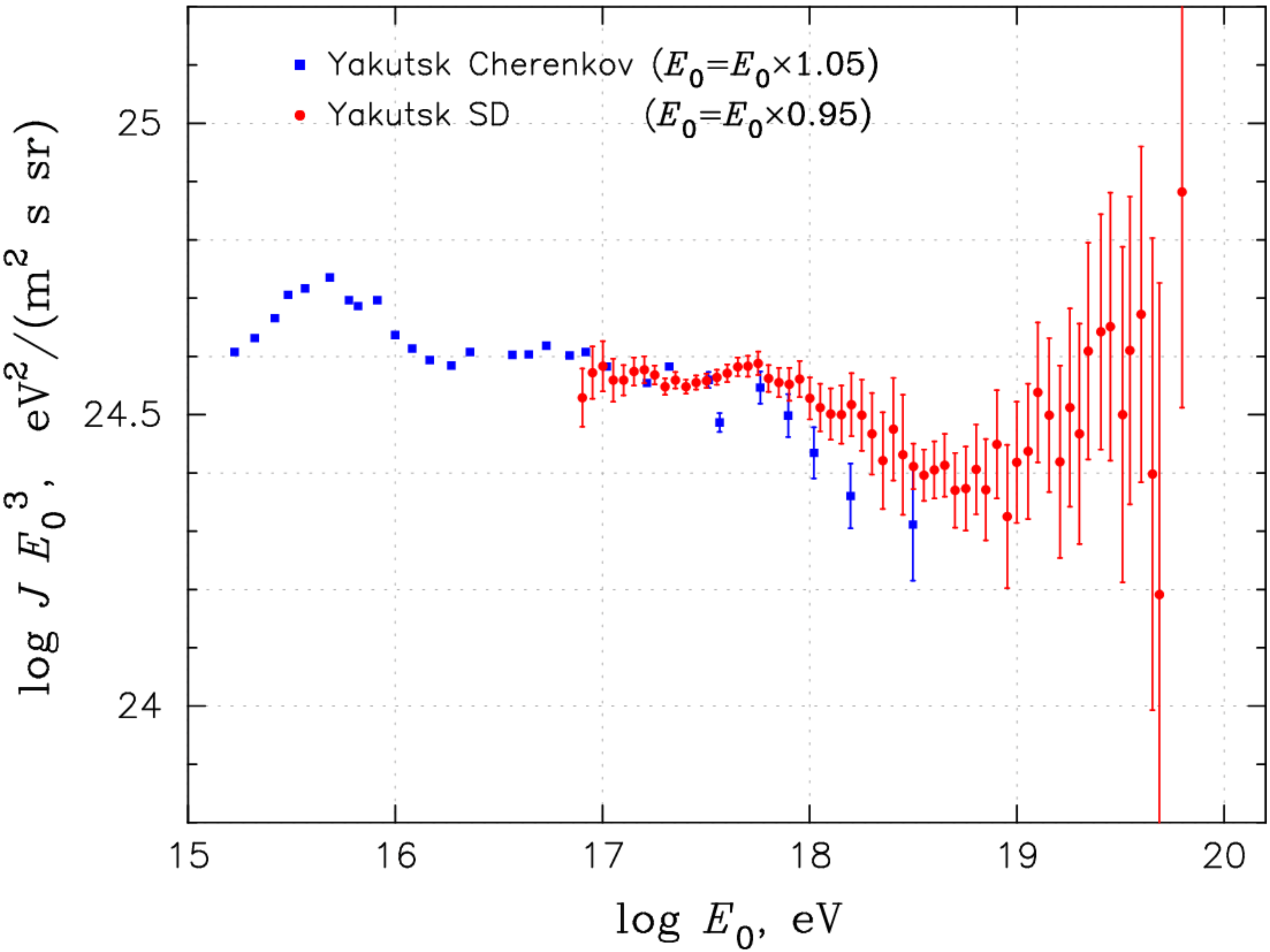
- Array area: 11 km^2 (18 km^2 before 1990)
- 49 stations equipped with scintillation counters
- 19 detectors of Cherenkov light
- 3 detectors of muons
- 3 detectors-*obscura*

Energy spectrum of UHECRs



A.V. Glushkov, M.I. Pravdin, Yu.A. Egorov, A.A. Ivanov, S.P. Knurenko et al. PoS(ICRC2017)552.
Glushkov A.V., Pravdin, M.I. Saburov A.V. JETP, 2019. 128 415.

Energy spectrum of UHECRs



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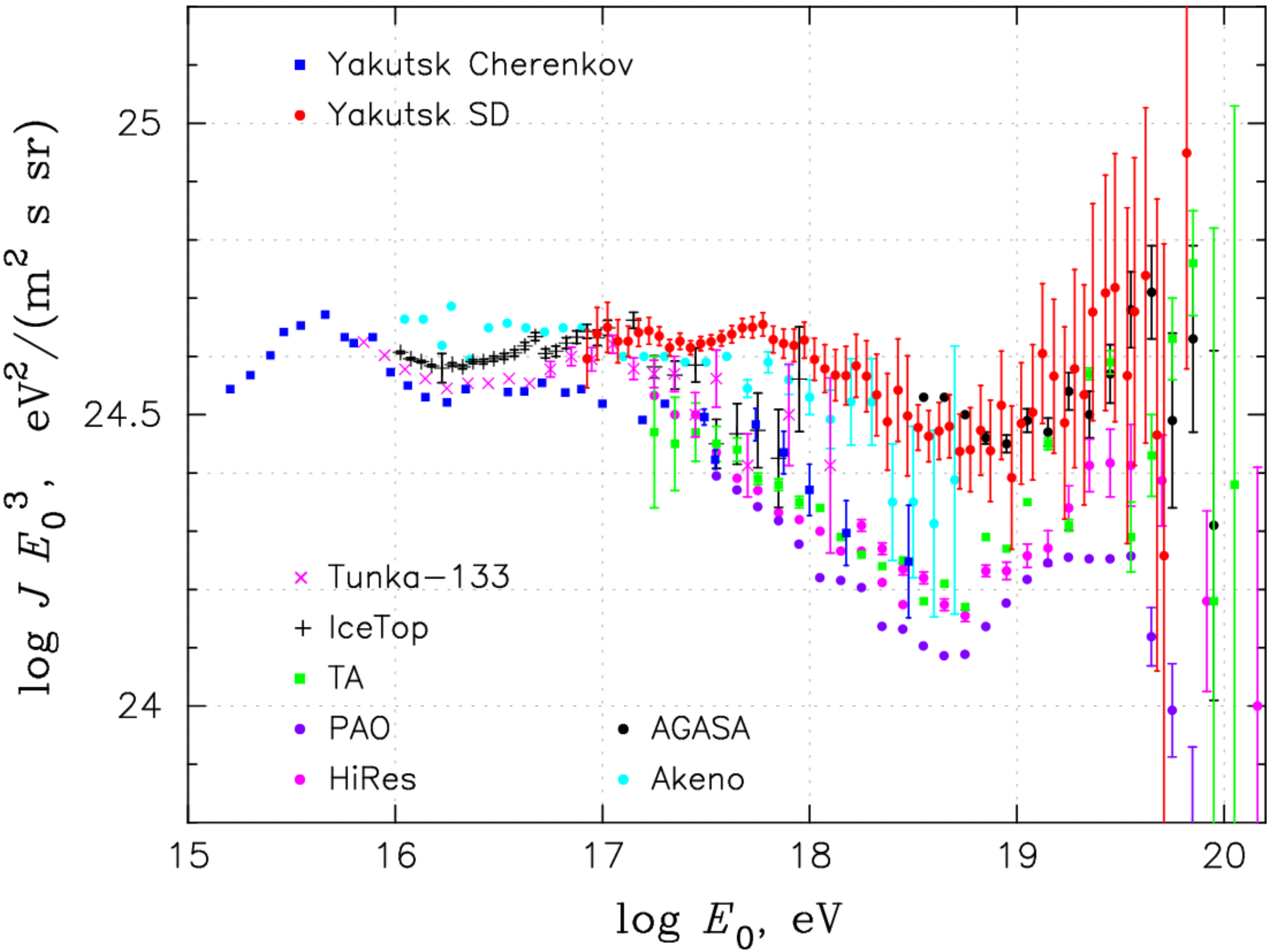

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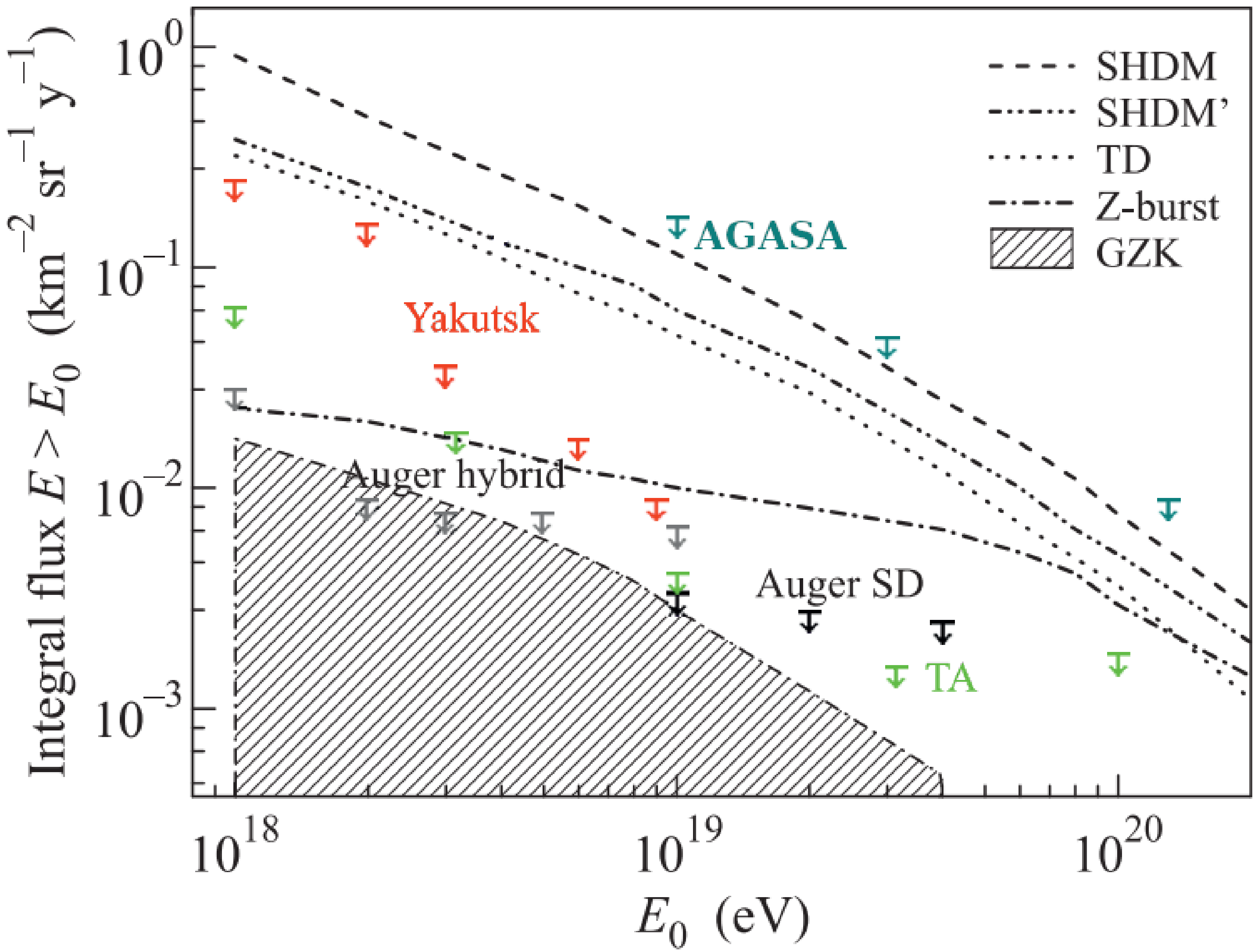
Glushkov A.V., Pravdin, M.I. Saburov A.V. JETP, 2019. 128 415.

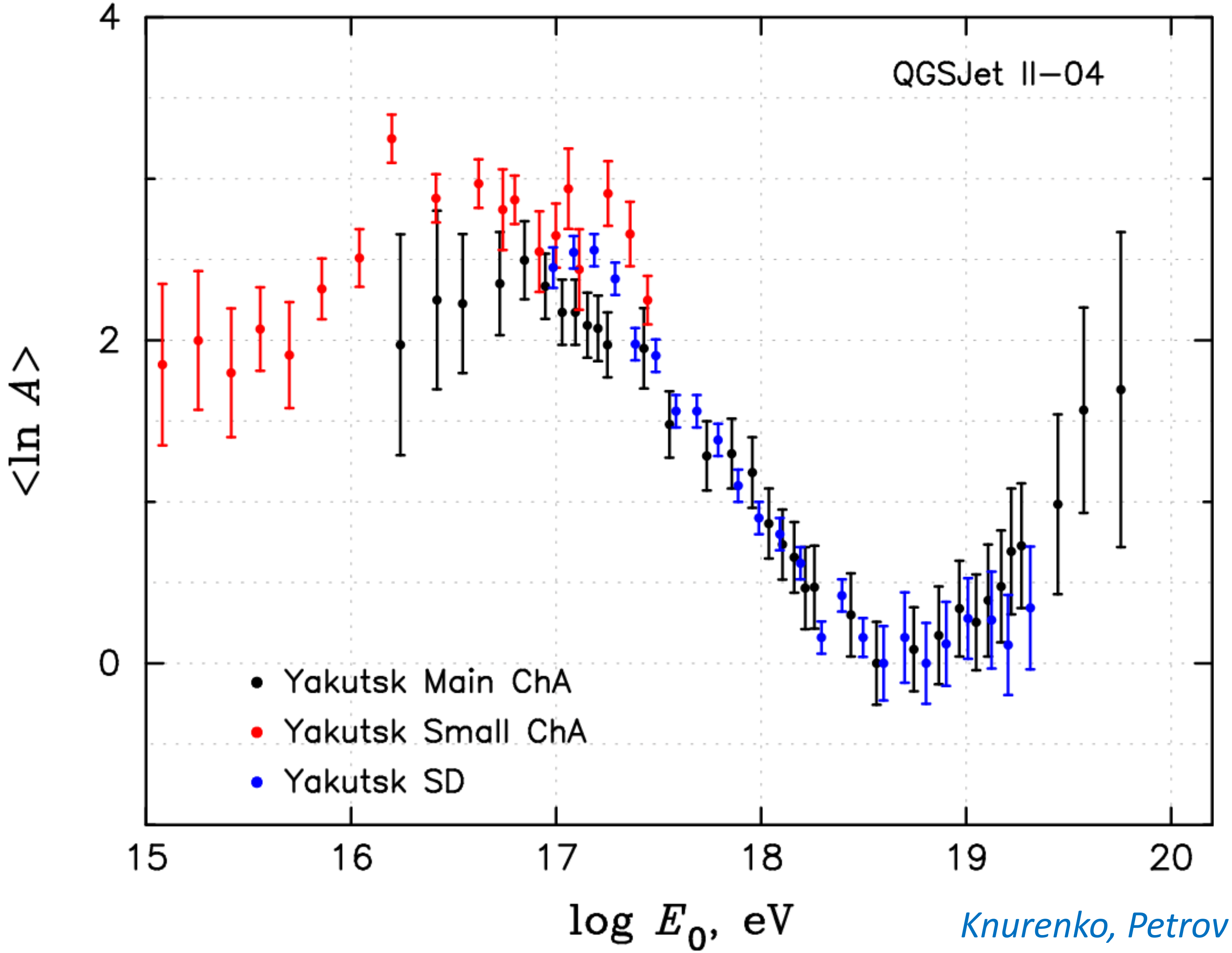
Search for UHE photon flux



S.P. Knurenko and I.S. Petrov, JETP Lett. ***107****, No. 11, pp. 676-683 (2018)*

Mass composition of UHECRs

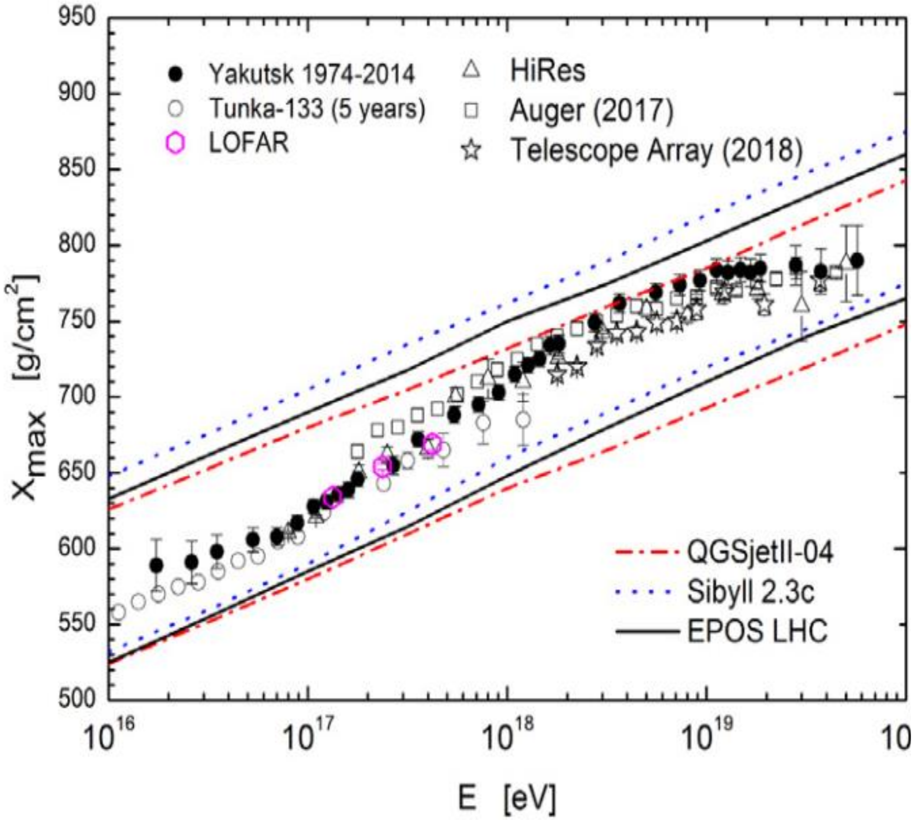
$$\langle lnA \rangle = \frac{X_{max}^{exp} - X_{max}^{p}}{X_{max}^{Fe} - X_{max}^{p}} \cdot lnA_{Fe}$$

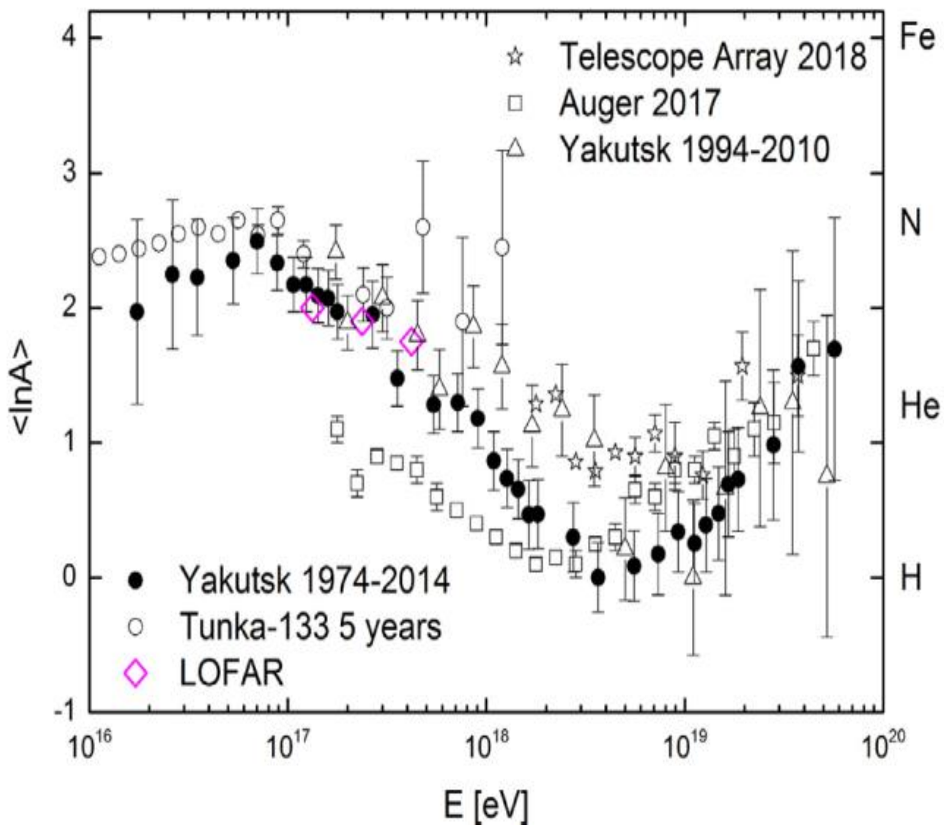


Knurenko, Petrov (2015, 2019);

Glushkov, Pravdin, Saburov (2018)

Mass composition of UHECRs

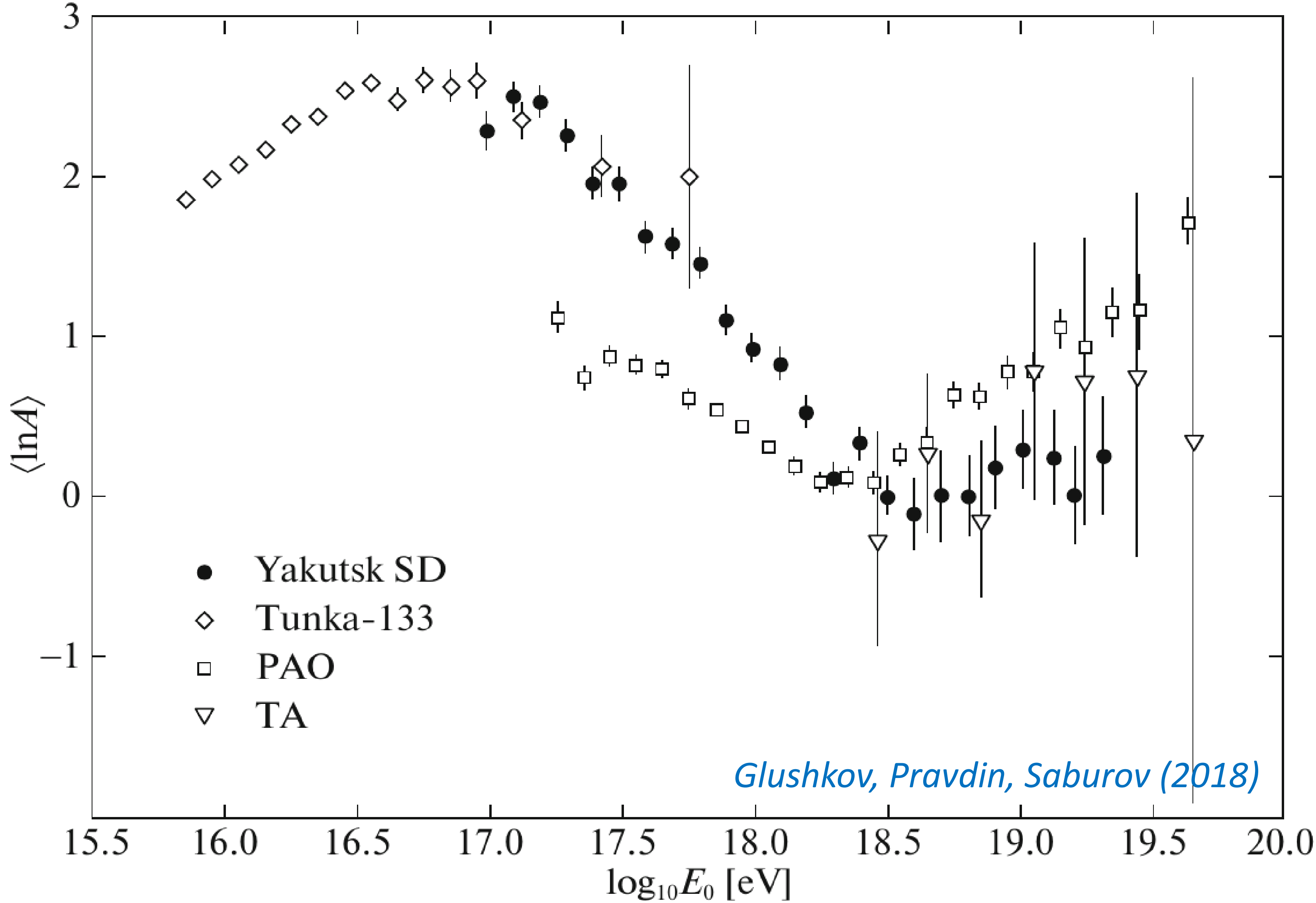




$$\langle lnA \rangle = \frac{X_{max}^{exp} - X_{max}^{p}}{X_{max}^{Fe} - X_{max}^{p}} \cdot lnA_{Fe}$$

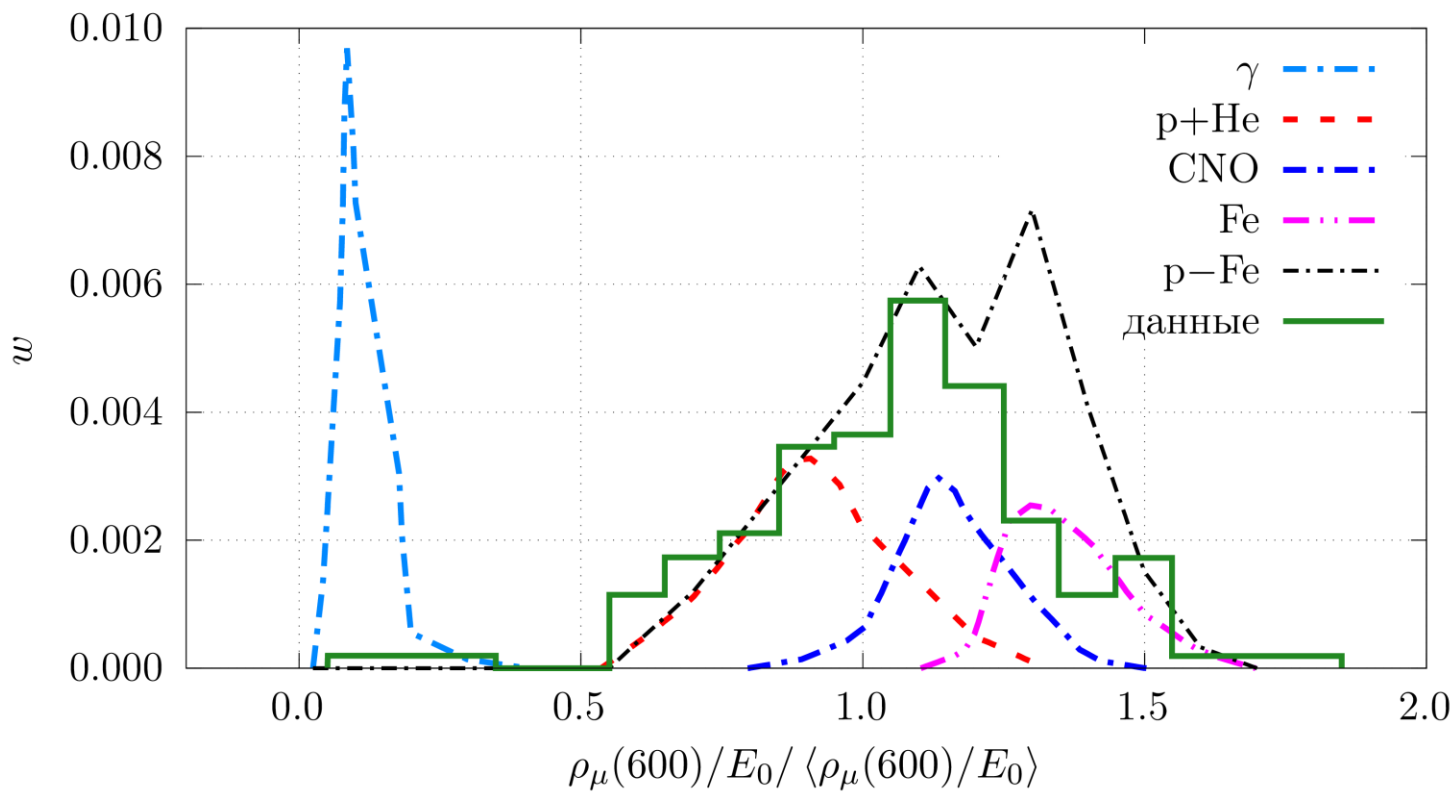
*S. Knurenko, I. Petrov, Advances in Space Research **64**, 2570-2577 (2019)*

Mass composition of UHECRs



Mass composition of UHECRs

$E_0 > 5 \times 10^{18}$ eV

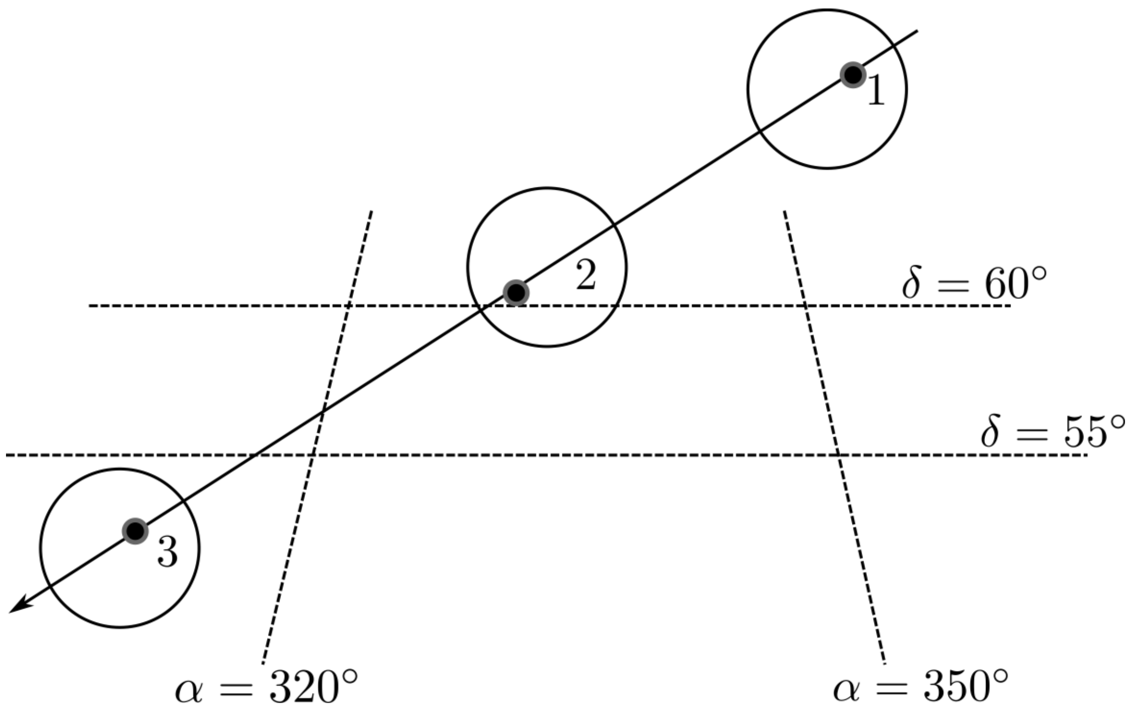


Data – relative abundance of muons in EAS recorded at the Yakutsk array.

(50 ± 10)% are protons and helium nuclei,
(32 ± 6) % - nuclei of carbon, nitrogen and oxygen,
(16 ± 8)% - nuclei of iron,
about 2% - gamma-rays of ultrahigh energies.

S. P. Knurenko and I. S. Petrov, Phys. Rev. D 102, 023036 (2020)

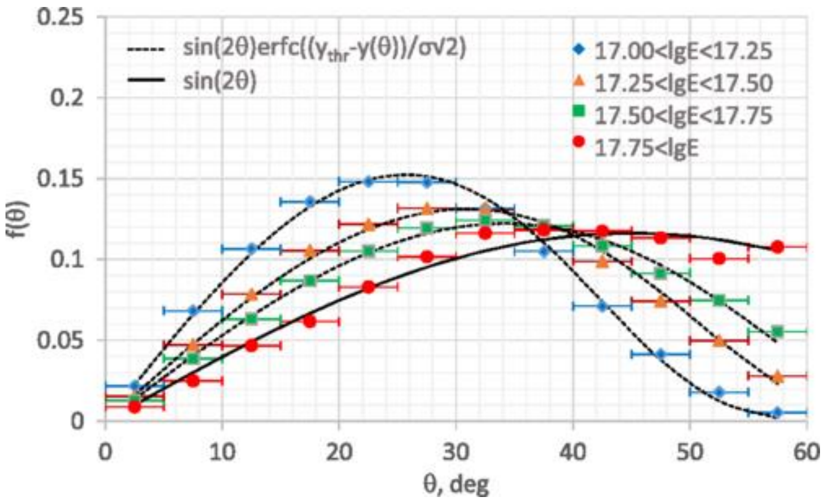
Observation of a Beam of Ultrarelativistic Particles

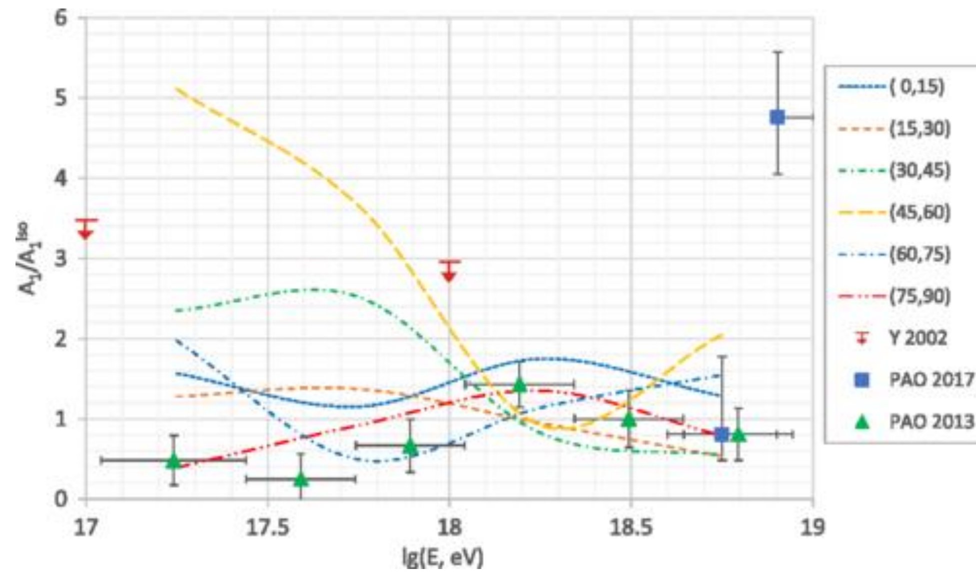


A short-term beam of CR particles with energies above 30 EeV was detected from a compact region of the sky

G. F. Krymsky, M. I. Pravdin, I. E. Sleptsov & A. D. Krasilnikov. Astronomy Lett. 45, 576–579 (2019)

Zenith angle distribution of cosmic ray showers

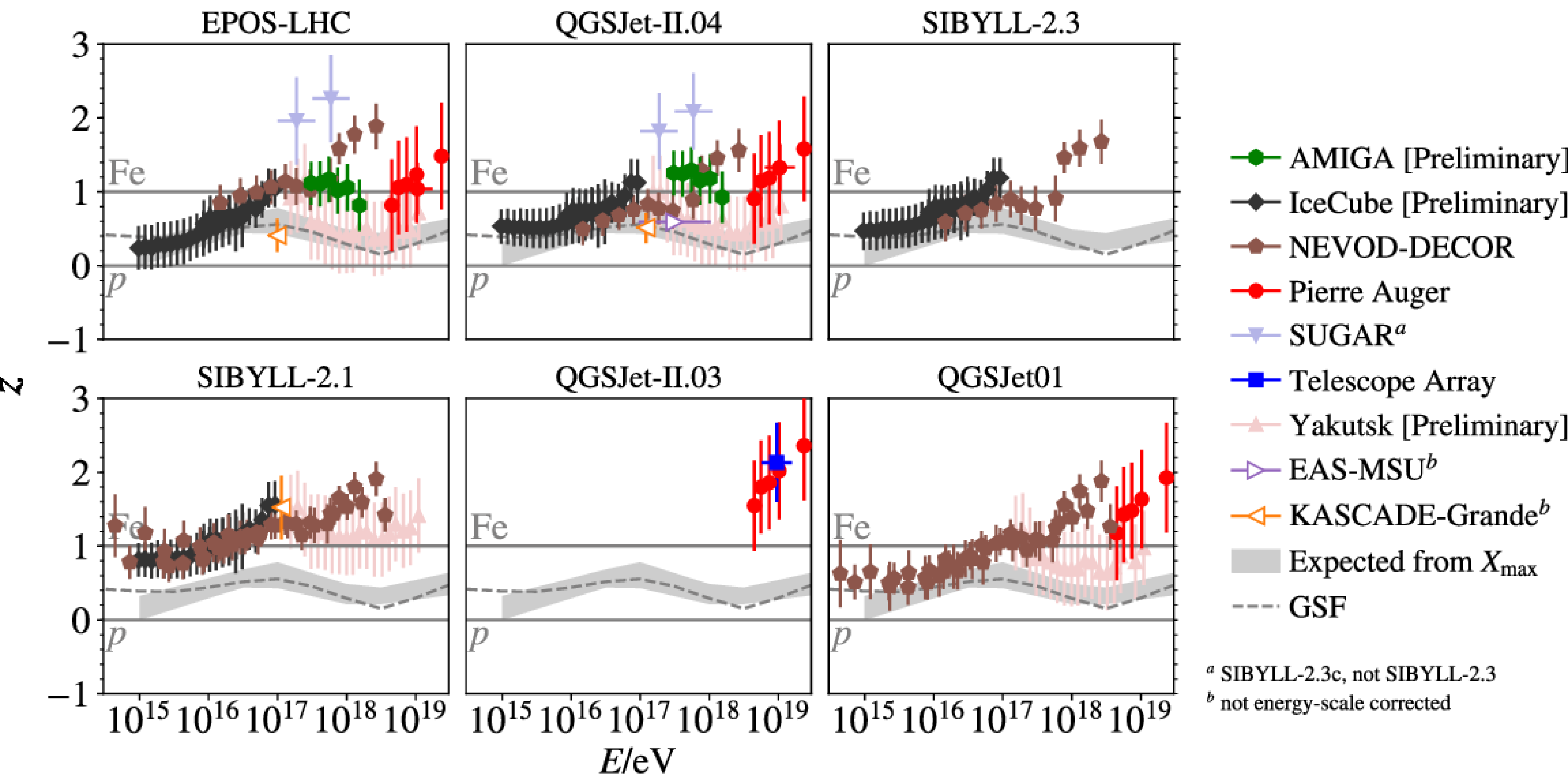




While the null hypothesis cannot be rejected with data from the Yakutsk array, an upper limit on the fraction of cosmic rays from a separable source in the uniform background is derived as a function of declination and energy.

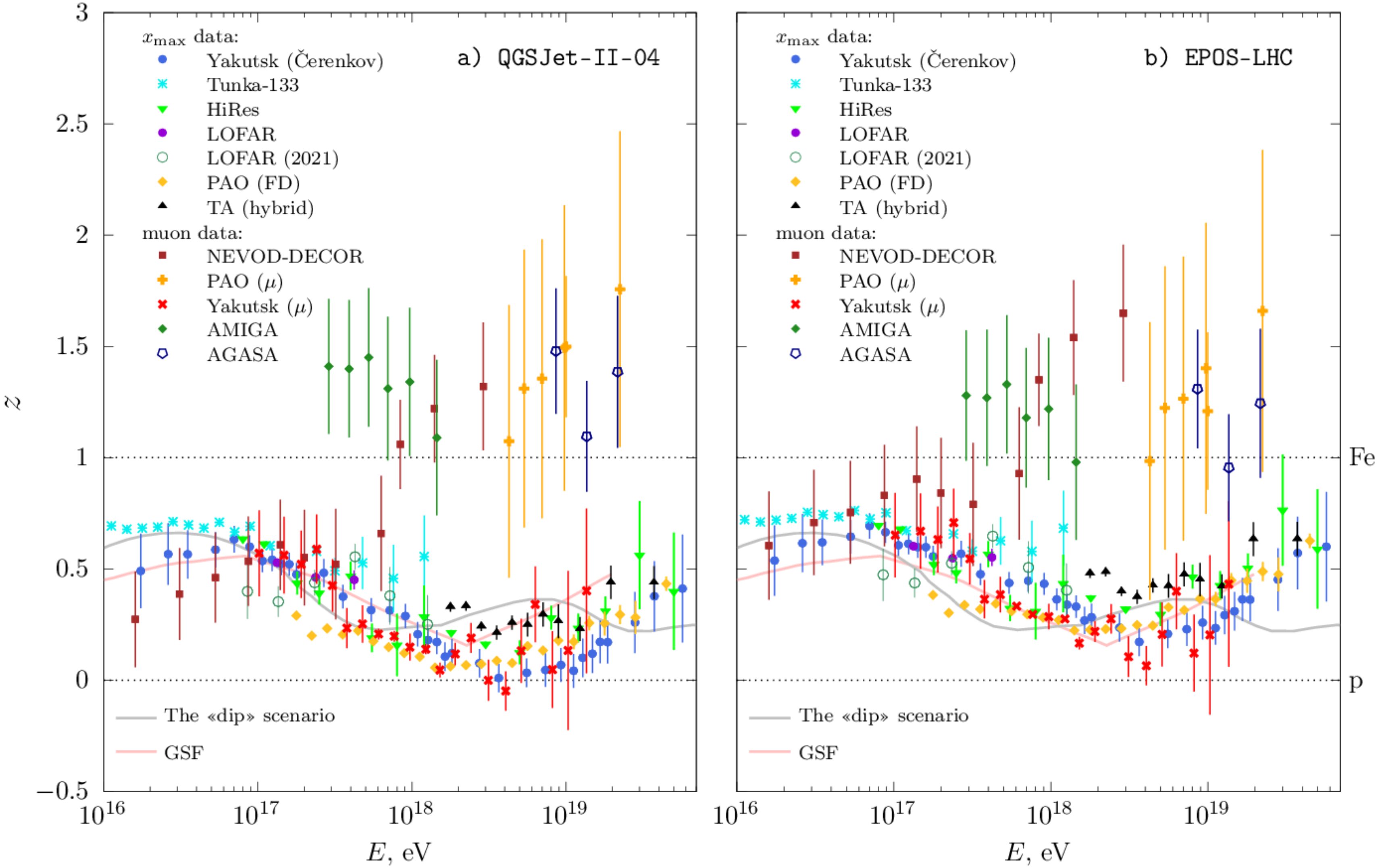
A. A. Ivanov Phys. Rev. D **97**, 083003, (2018)

Muon component



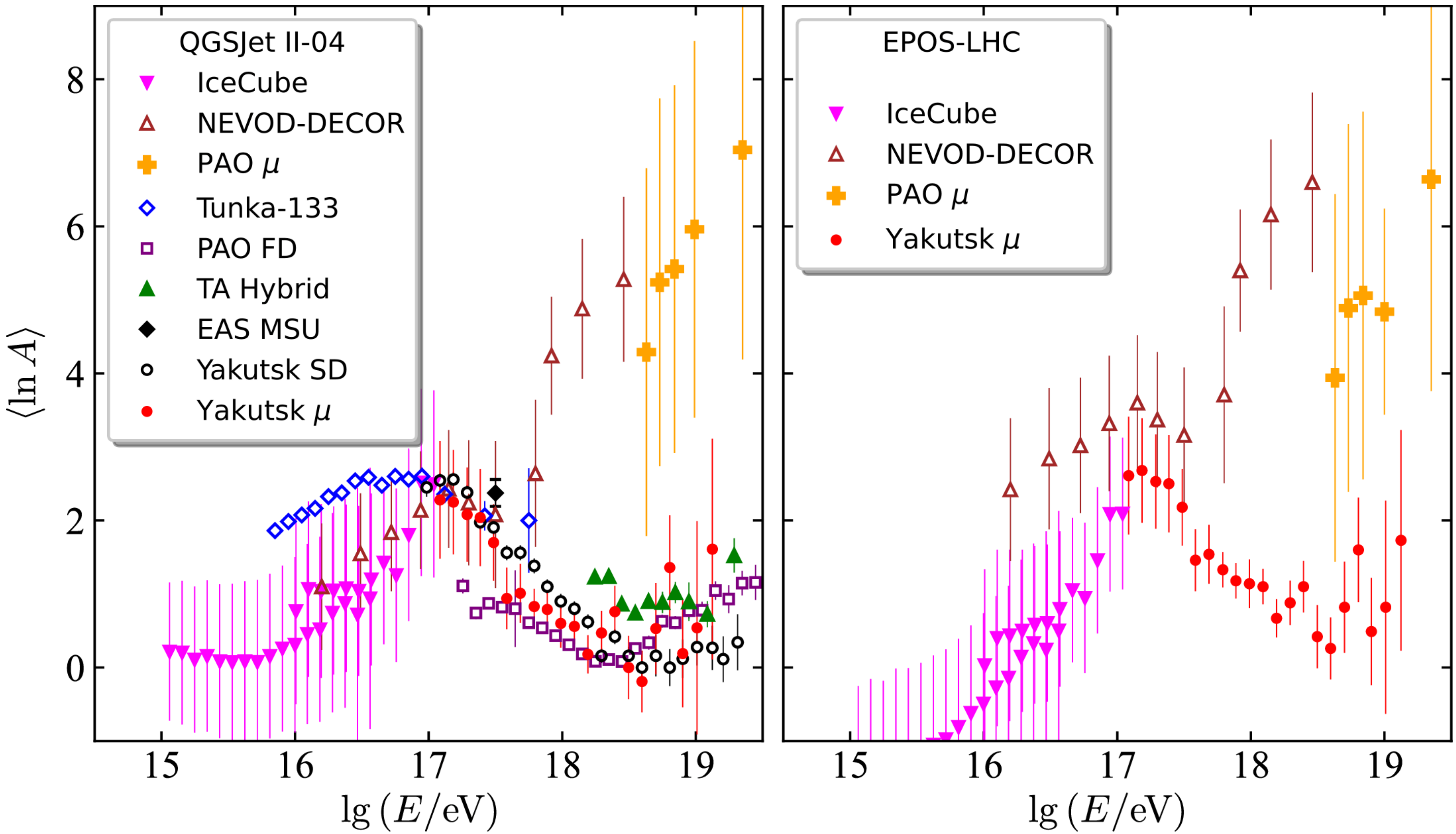
$$z = \frac{\ln N_\mu^{\rm exp} - \ln N_\mu^{\rm p}}{\ln N_\mu^{\rm Fe} - \ln N_\mu^{\rm p}},$$

Muon component



Glushkov A.V., Saburov A.V. JETP Lett. 2019. 109. P.559.

Muon component



Glushkov A.V., Saburov A.V. JETP Lett. 2019. 109. P.559.

Theory of CR Acceleration in Supernova Remnants and in AGNs

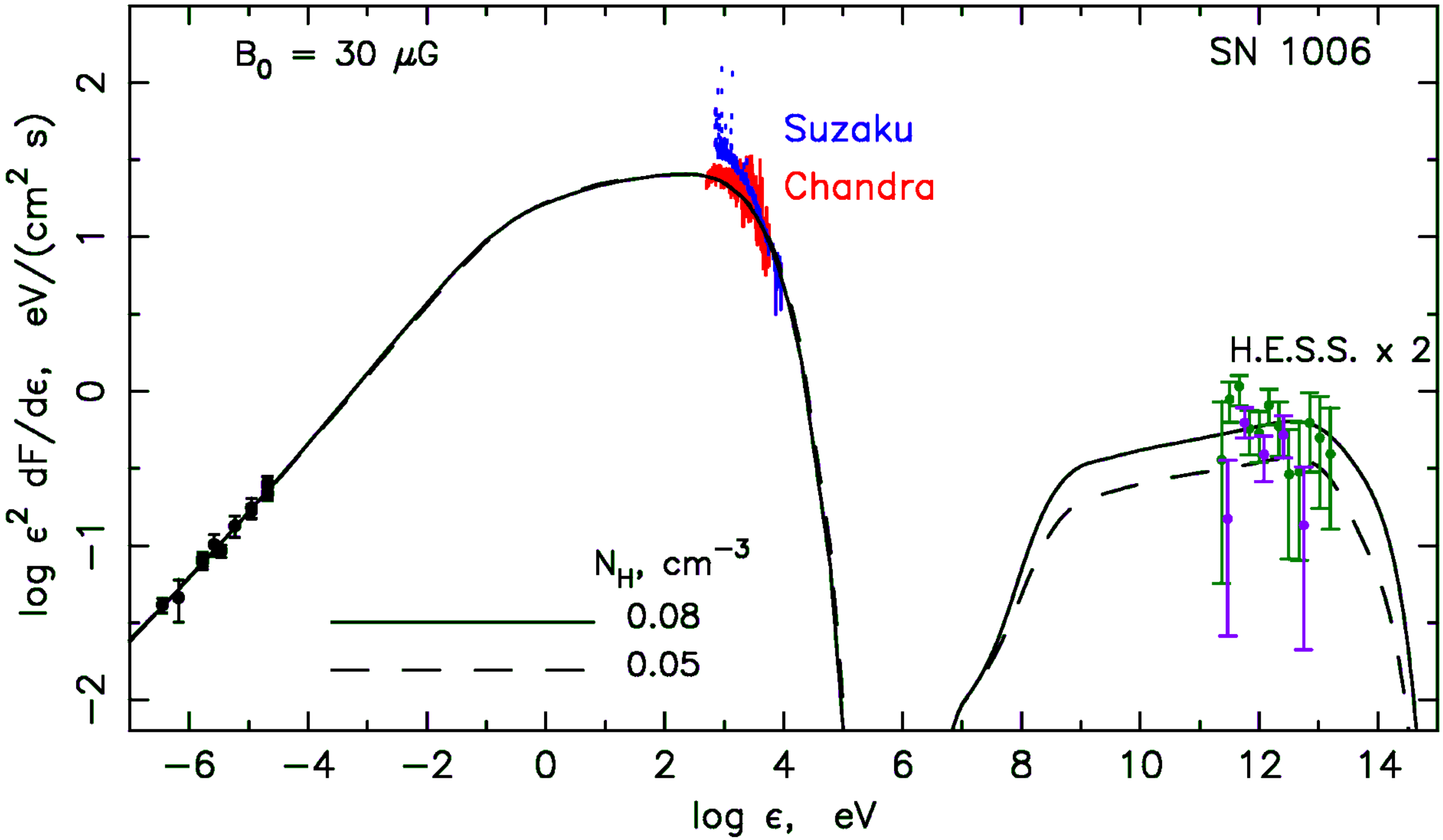
A numerical method for study the diffusive shock CR acceleration process (*Krymsky 1977*) in the SNR, the evolution of remnants and the properties of their nonthermal radiation has been developed (*Berezhko, Ksenofontov 1996*).

- It was shown that the process of CR acceleration by a supernova shock wave is characterized by high enough efficiency.

- The theory explains most of the observed properties of the nonthermal radiation of well-known supernova remnants SN 1006, SN Tycho, SN 1987A and others.

- Based on a detailed study of the process of diffusive shock acceleration of CR in SNRs, it was found that SNRs are the main source of galactic CRs up to ~ 10^{17} eV

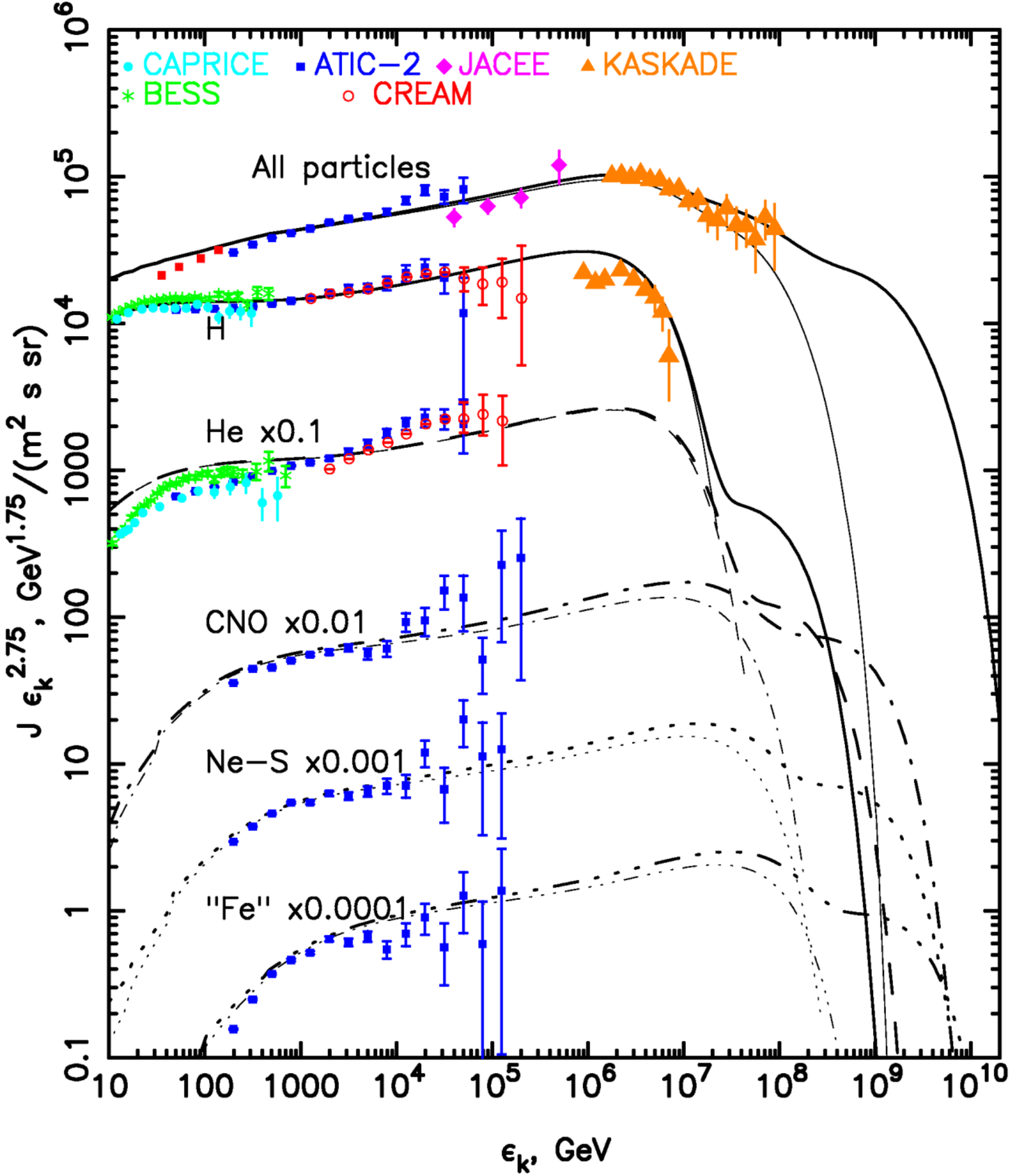
Overall nonthermal spectra



NE polar cap and **SW polar cap**

may have somewhat different densities. Agree with H.E.S.S. overall.

N_H ≈ 0.05 /cc from thermal X-rays (Acero et al. 2007)



SN Ia + SN IIb

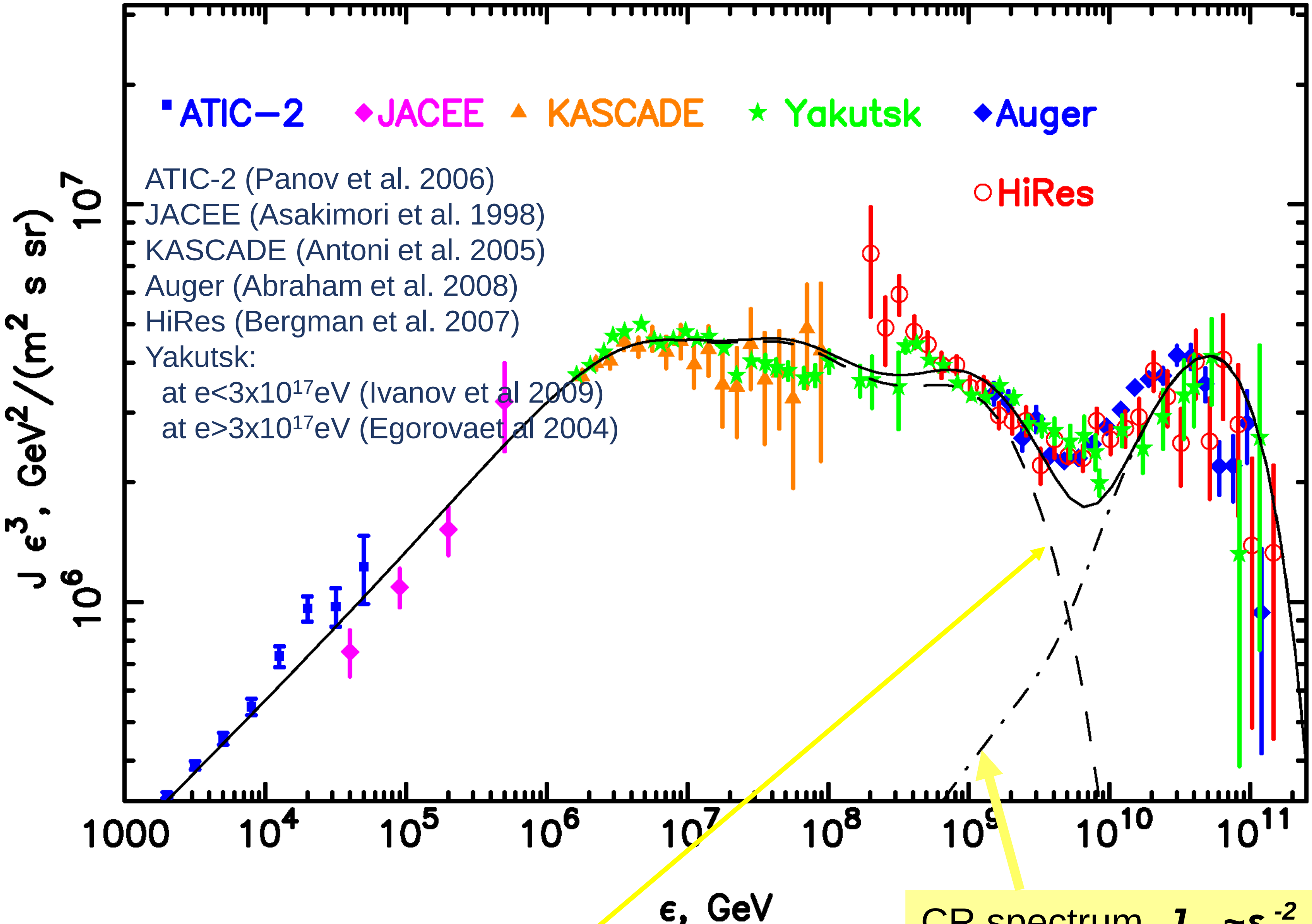
SN IIb :

$E_{SN} = 3\times10^{51}$ erg

RSG wind:

Energy spectrum of CRs

Ankle scenario

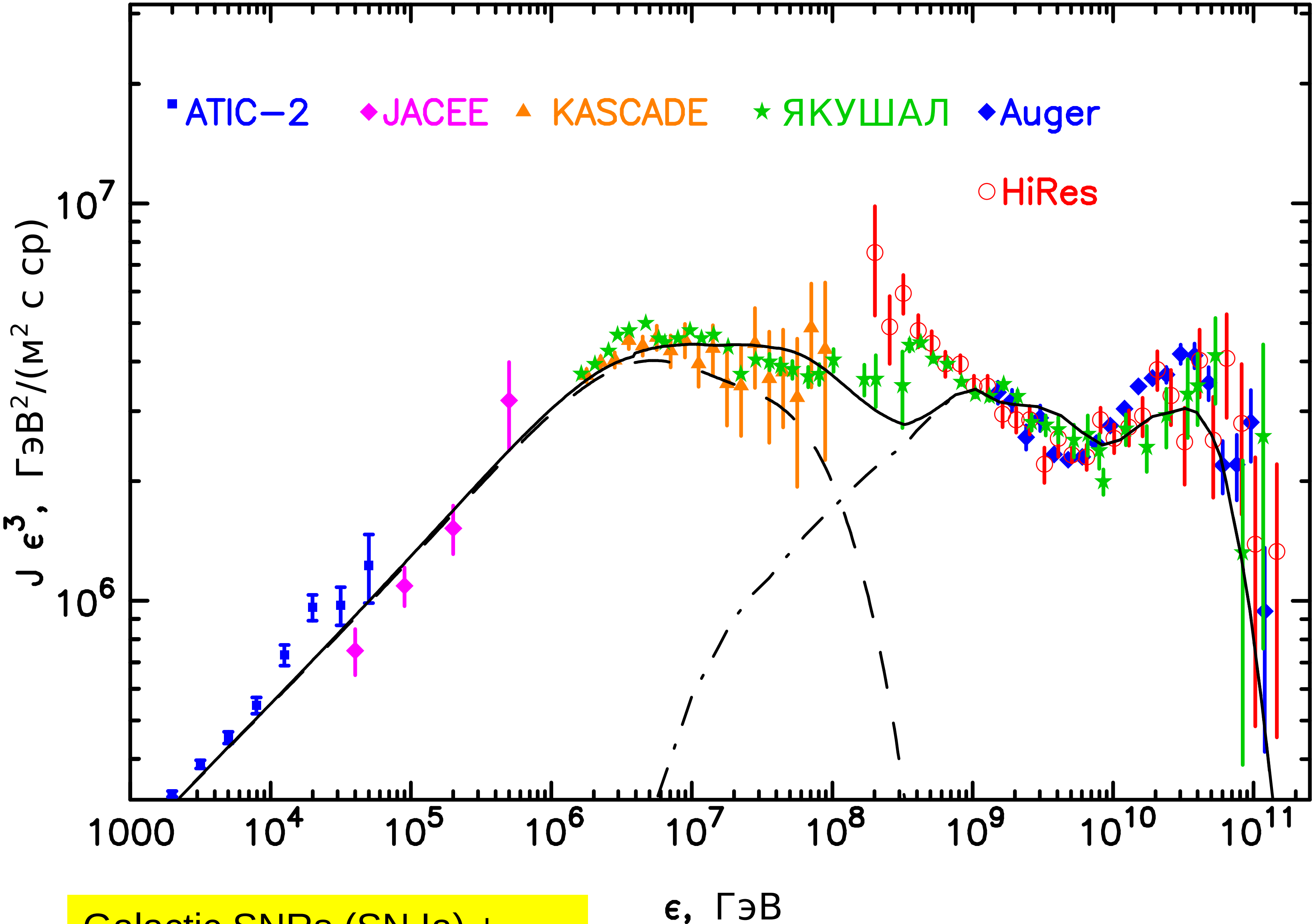


CR from SNRs:
SN Ia + SN IIb

CR spectrum $J_{EG} \sim \varepsilon^{-2}$
from extragalactic sources
(*Berezinsky et al.2006*)

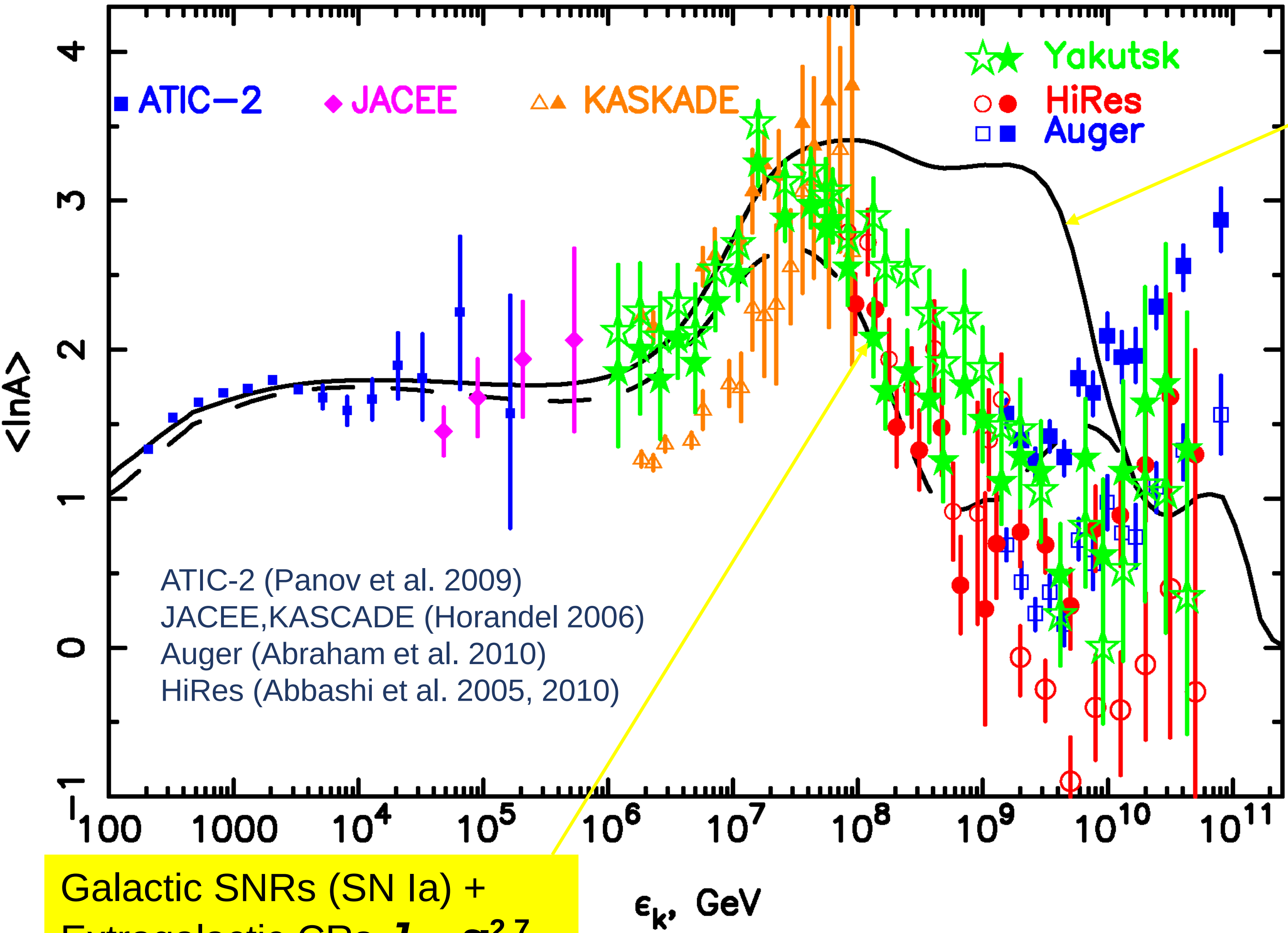
Energy spectrum of CRs

Dip scenario



Galactic SNRs (SN Ia) +
Extragalactic CRs $\boldsymbol{J \sim \varepsilon^{-2.7}}$

Mean logarithm of CR atomic number

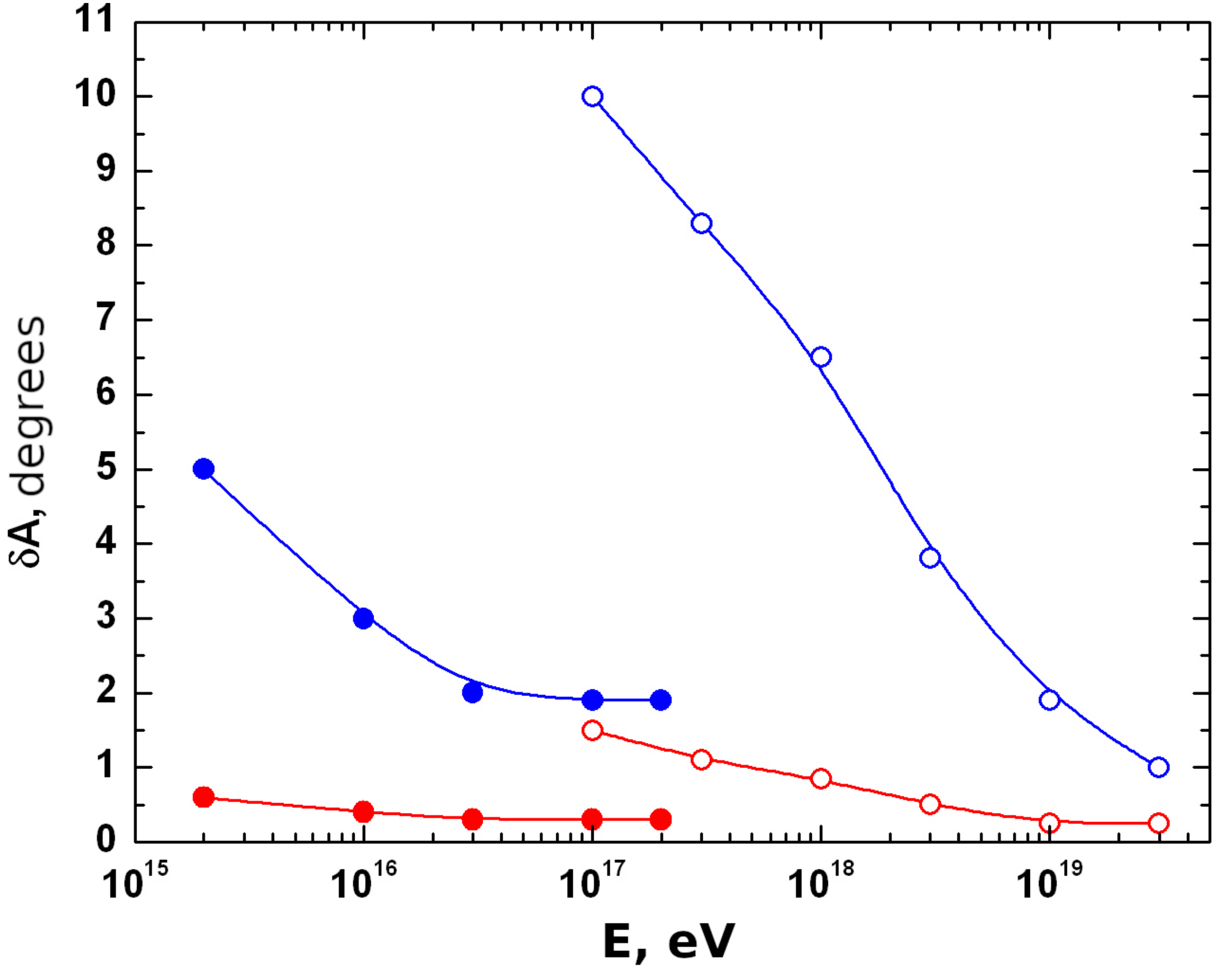


Galactic SNRs:
SN Ia + SN IIb

Galactic SNRs (SN Ia) +
Extragalactic CRs $J \sim \varepsilon^{-2.7}$

Prospect of the future upgrade

Improve the accuracy of EAS arrival direction reconstruction (by factor 5)



EASv3 DAQ: 100 ns resolution
SEU-v.3
estimated $\theta\Delta$=6.5°;
$\Delta\varphi$ = 15°

EASv4 DAQ: 10 ns resolution
SEU-v.4:

FPGA-based DAQ system 6.25 ns res.
estimated $\Delta\theta$ = 0.8°;
$\Delta\varphi$ = 2.1°

Prototype of the online monitoring system

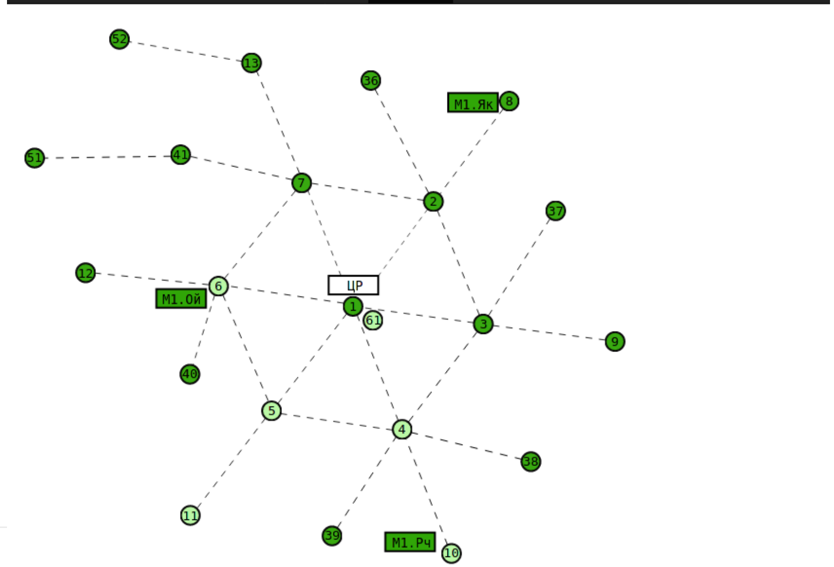
Ойский подвал М1.Ой

Посмотреть записи в журнале
Тип каналов: EASV3 и EASV4
Количество ЭСН: 3
Количество детекторов: 10

ЭСН	ЦС/ПОРТ	Линк	Канал	Данные EASv4	Шаг RC	RC
41	24	OK	656 D9 ШАЛ/М1.Ой 9-й детектор	OK		
			660 D10 ШАЛ/М1.Ой 10-й детектор	OK		
40	26	OK	640 D1 ШАЛ/М1.Ой 1-й детектор	OK		
			644 D2 ШАЛ/М1.Ой 2-й детектор	OK		
			648 D3 ШАЛ/М1.Ой 3-й детектор	OK		
			652 D4 ШАЛ/М1.Ой 4-й детектор	OK		
11	25	OK	176 D5 ШАЛ/М1.Ой 5-й детектор	OK		
			180 D6 ШАЛ/М1.Ой 6-й детектор	OK		
			184 D7 ШАЛ/М1.Ой 7-й детектор	OK		
			188 D8 ШАЛ/М1.Ой 8-й детектор	OK		

Закрыть

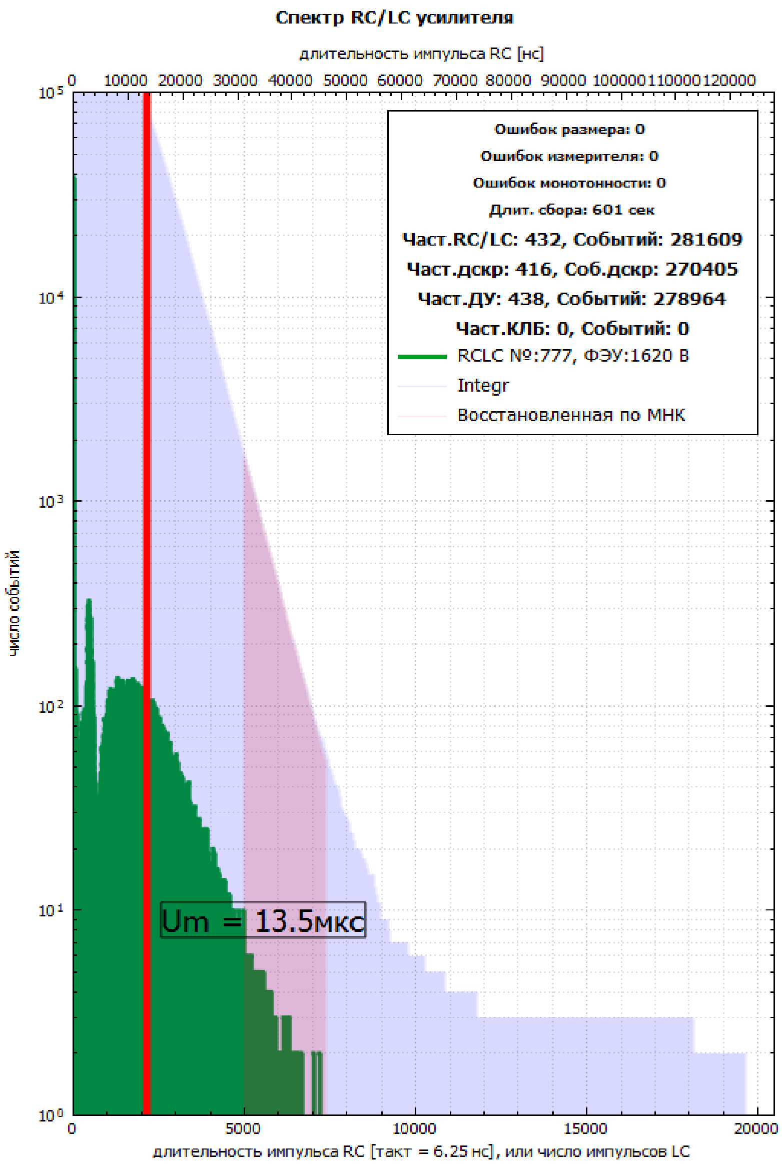
Карта Мониторинг База данных Управление



Общее состояние установки

Станция	ЭСН	КОНФ. ЦСПОРТ	РАБ. ЦСПОРТ	Линк	Канал	Данные EASv4 / Конфигурация	Уровень одной в микросекундах время экспоз. 10 мин.	Частота RC	Частота с динодным соб.	Шаг RC	RC
1	23	[0:1]	[0:1]	OK	368 L ШАЛ/ст.1/АК1-левый	OK/OK	12.89	445.92	358.80	27.14	081
					376 R ШАЛ/ст.1/АК2-правый	OK/OK	13.44	535.98	372.95	27.61	067
2	1	[0:7]	[0:7]	OK	16 L	OK/OK	12.12	470.87	414.18	26.5	084

Detector electronics



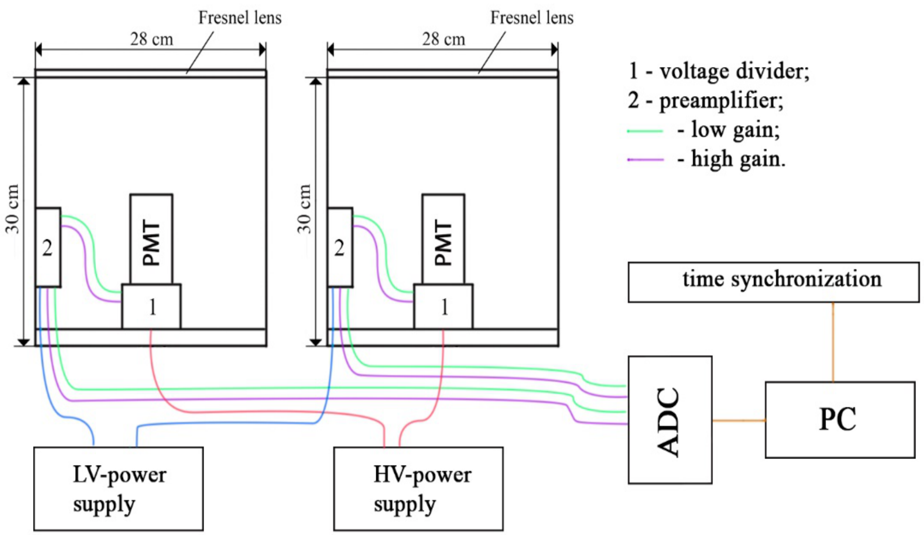
Current Station Electronics Unit v.3 (SEU-v.3):
- amplitude resolution (RC-signal): ≥1 μs
- timing resolution: ≥100 ns

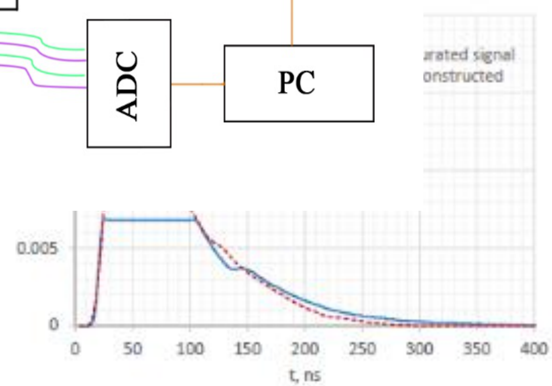
Station Electronics Unit v.4 (SEU-v.4):
FPGA-based multi-functional unit (data collection + timing +calibration),
- amplitide resolution (RC-signal): 6.25 ns
- timing resolution: ≥ 6.25 ns
- dynamic compensation of delays in timing channel

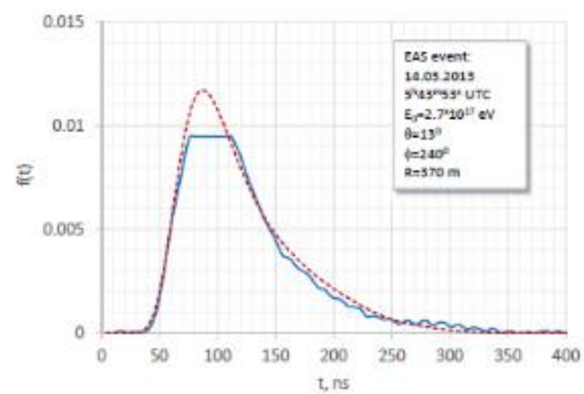
Planned:
Station Electronics Unit v.4.1 (SEU-v.4.1):
SEU-v.4 +
+ pulse shape recording
+ integral Cherenkov detectors with improved accuracy

System of fast Cherenkov detectors (ChID-2)

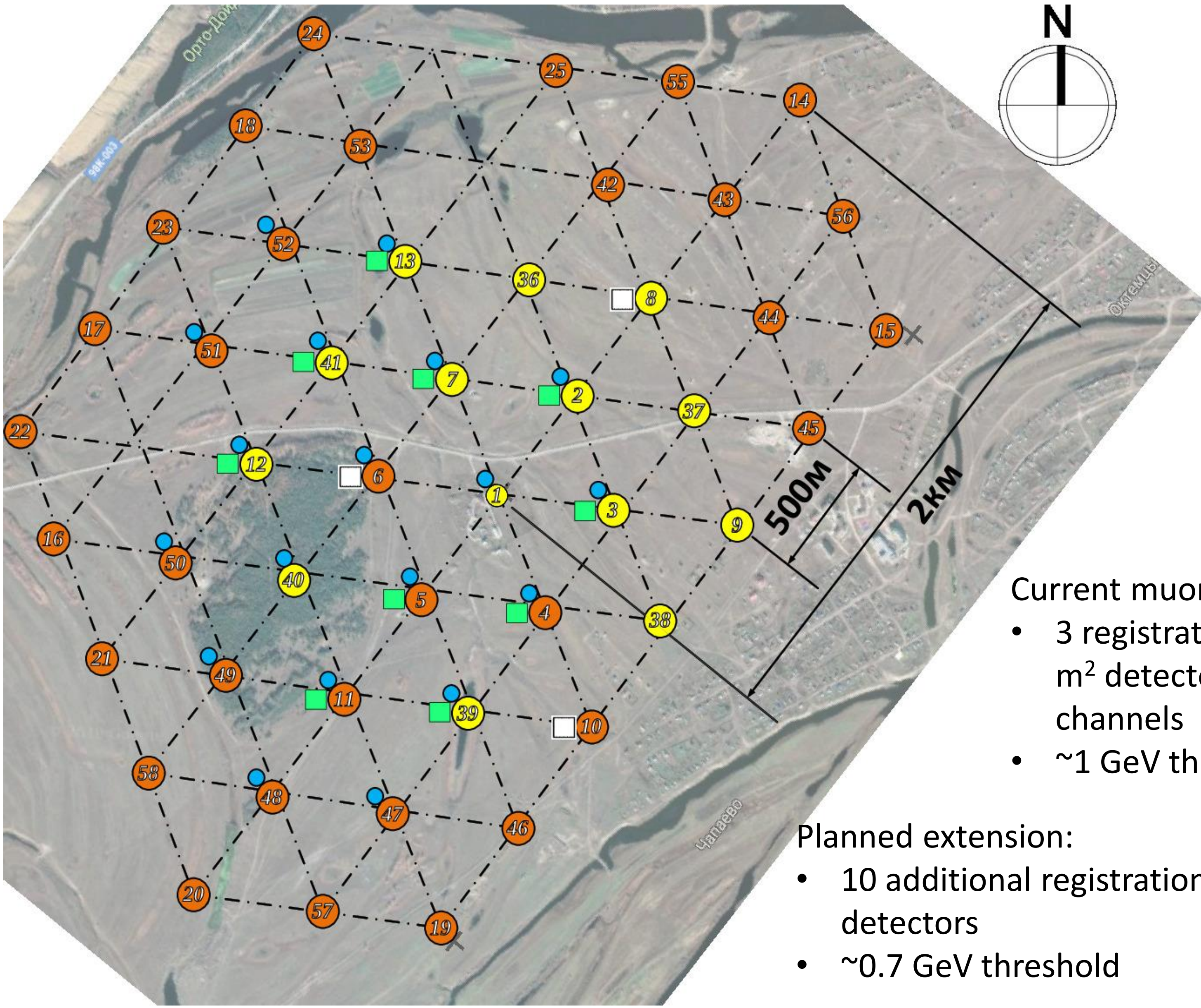
- Complementing the main Cherenkov grid
- Reduced aperture: less affected by antropogenic light pollution
- Frensel lense+fast PMT / ADC, ~2.5 ns front resolution
- Portable design: easily reconfigurable
- Field test: prototype setup x 4 detectors, saturated pulse reconstruction







Extension of the muon array



Current muon setup:

- 3 registration points ×10 2-m^2 detectors, 10 independent channels
- ~1 GeV threshold

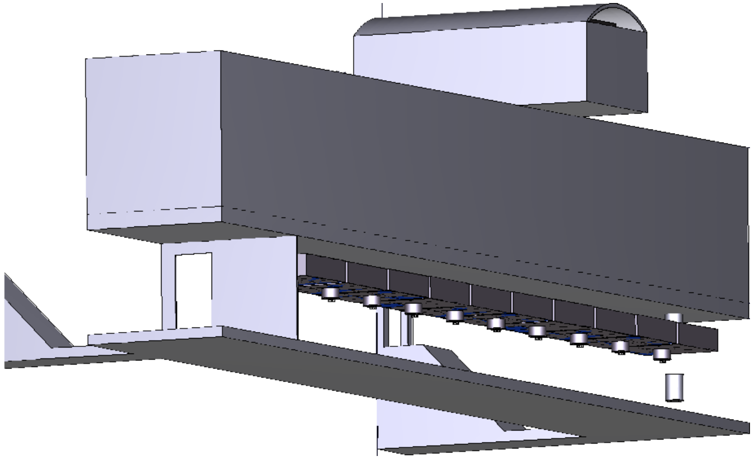
Planned extension:

- 10 additional registration points ×2 2-m^2 detectors
- ~0.7 GeV threshold

Extension of the muon array

Calibration telescope project:

- SD station above the “Oy” muon registration point
- Background muons selection
- Clarify / confirm the detector response to the muon component in EAS



Plans:

- Detailed detector simulations (SD, muon): CORSIKA + GEANT4
- Test detectors response
- Clarify / confirm the resolution
- *Test measured muon content*

Summary

- The Yakutsk Extensive Air Shower Array has been continuously operating for more than 50 years.
- At present the array area is about 11 km^2
- The cosmic-ray flux obtained from surface array data can be agreed with that measured using only the Cherenkov detectors adjusting the energy only by 5%
- Different methods of measuring composition of UHECR give a well agreed results.
- Mass composition derived from muon measurements is agree as well as with the other X_{max} based measurements, as well as with GSF and theoretical models.
- Extensive modernization of EAS is going on.