50 лет ИЯИ

Изучая Вселенную высоких энергий

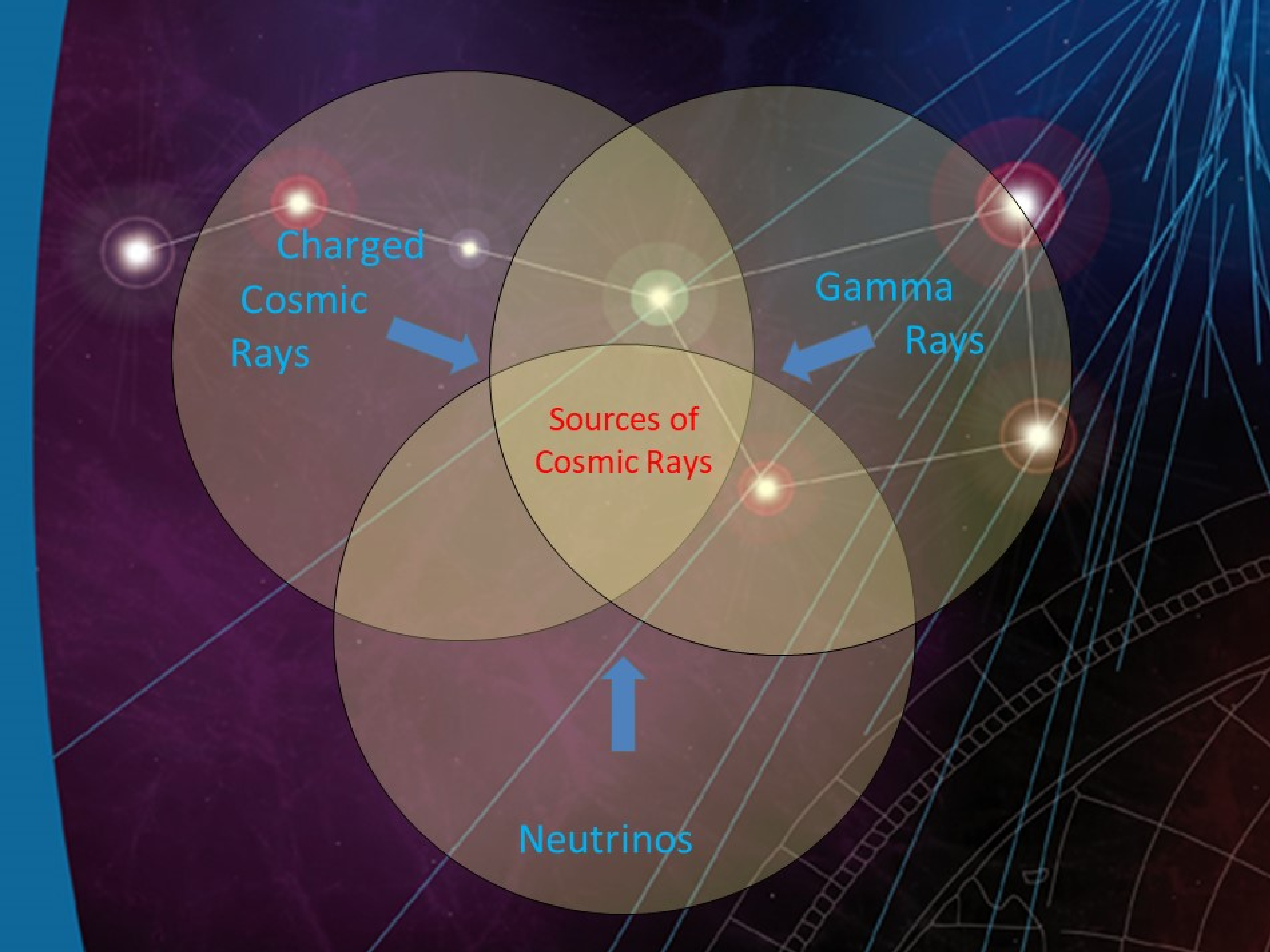
Christian Spiering

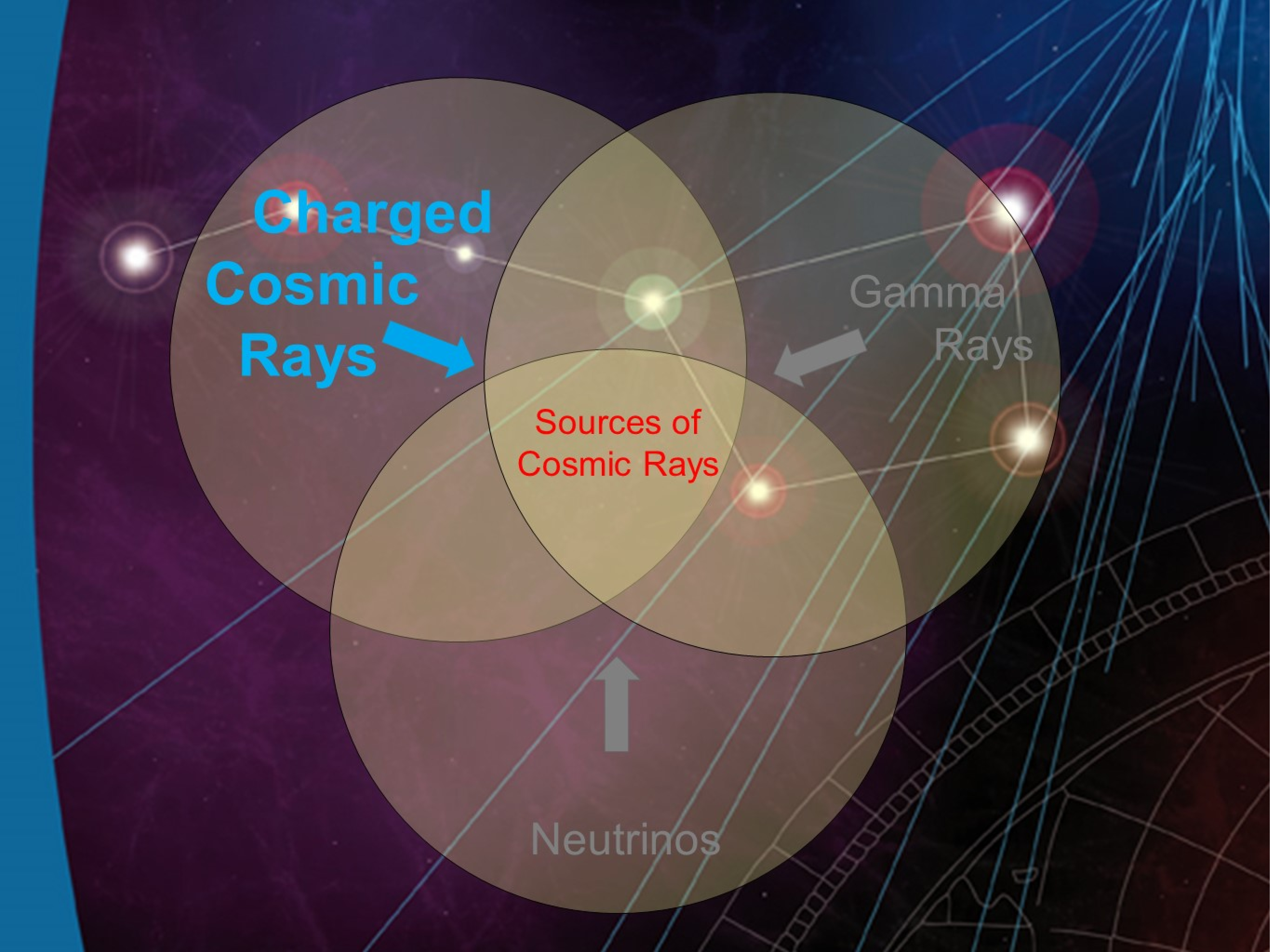
Fathers of cosmic ray/neutrino physics in INR

Моисей Александрович Марков

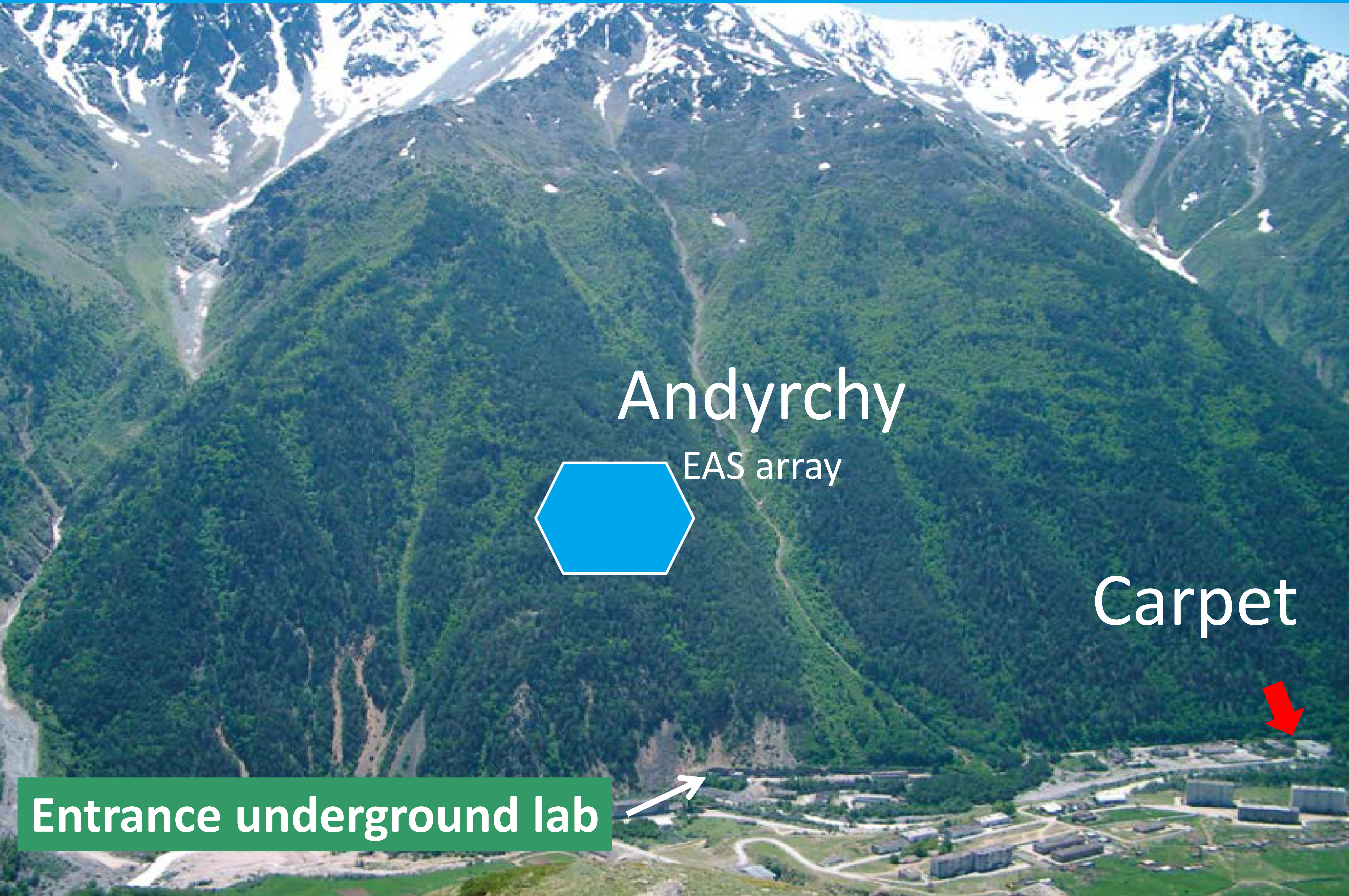
Георгий Тимофеевич Зацепин

Александр Евгеньевич Чудаков

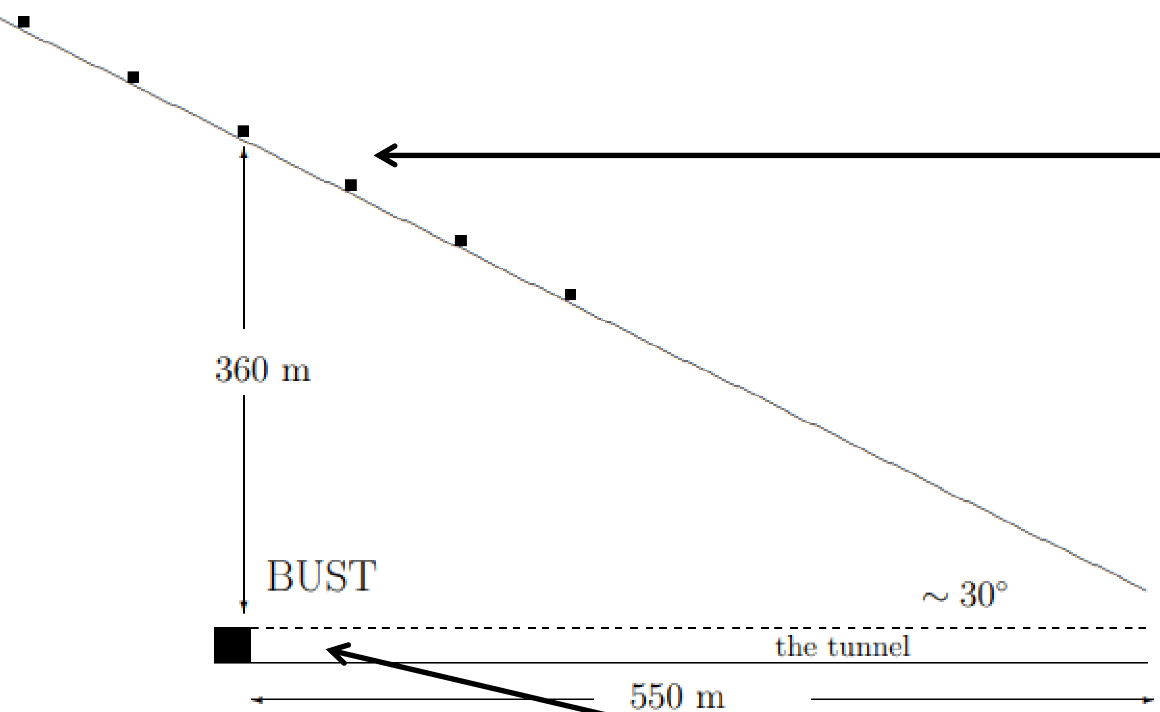

Charged Cosmic Rays
Gamma Rays
Sources of Cosmic Rays
Neutrinos


Charged Cosmic Rays
Gamma Rays
Sources of Cosmic Rays
Neutrinos

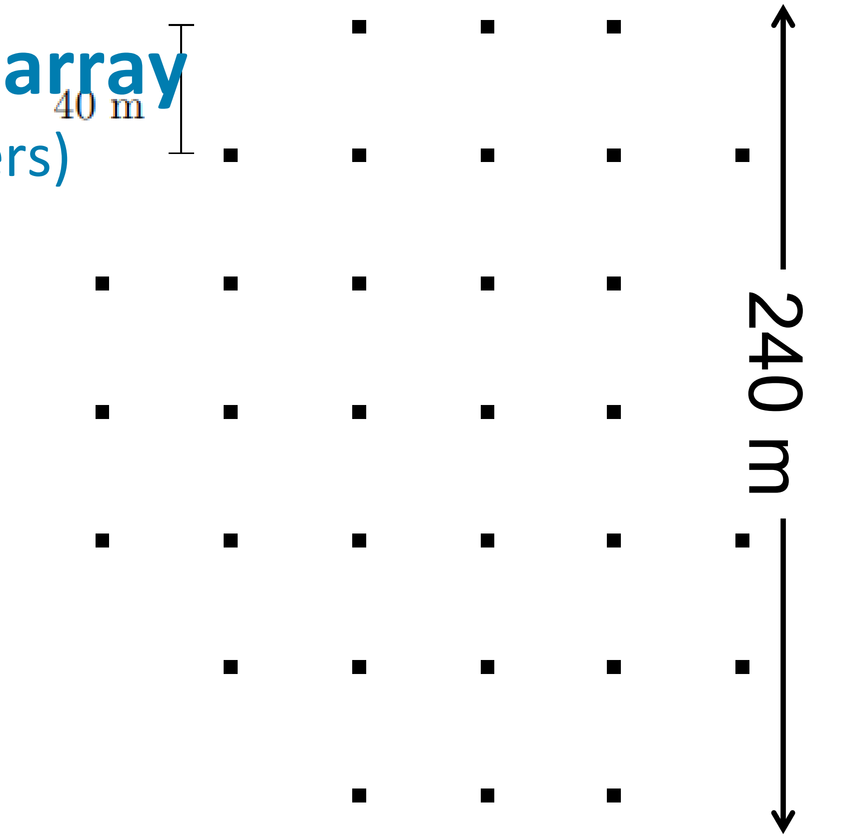
Baksan: Carpet, Andyrchy, BUST



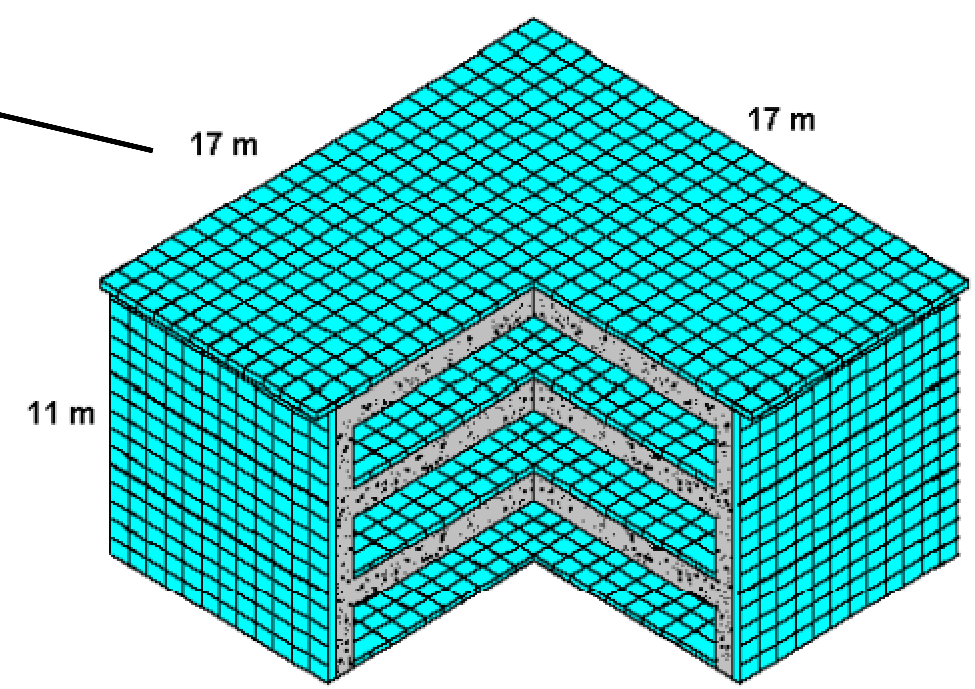
Baksan: Construction of BUST (1970s) and Andyrchy (1993)



- **Surface EAS array**
  (37 scint. Counters)



- **Underground detector BUST**
  (see talk of Leonid Bezrukov)



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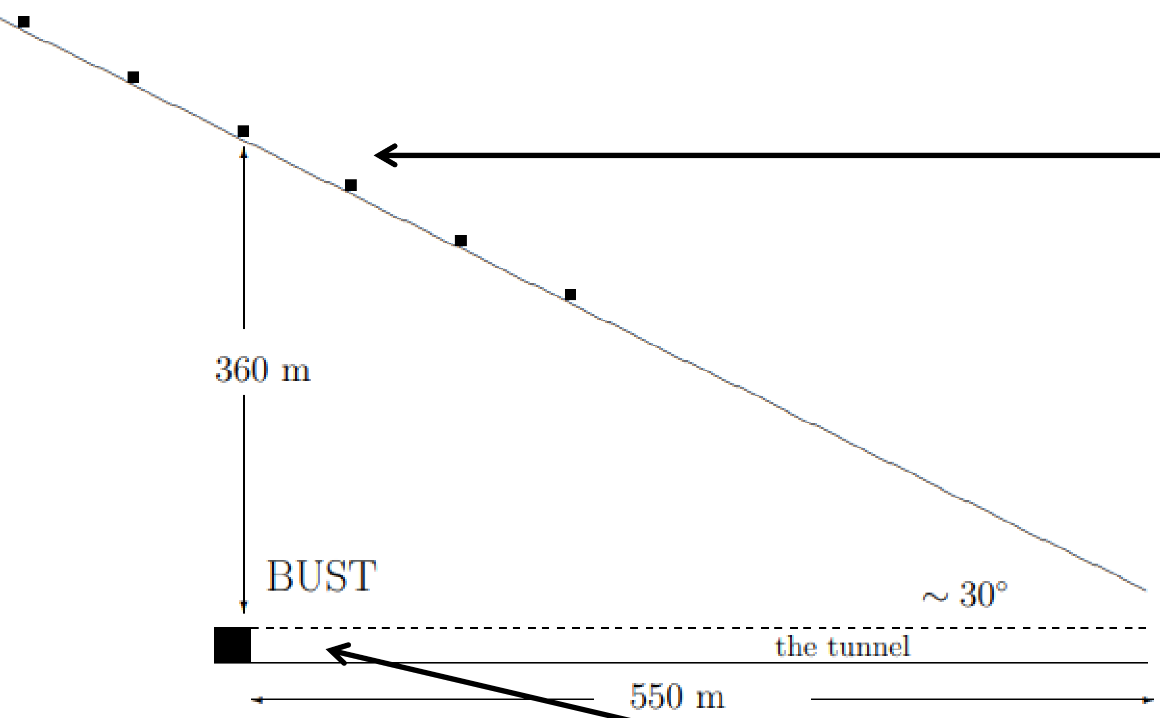

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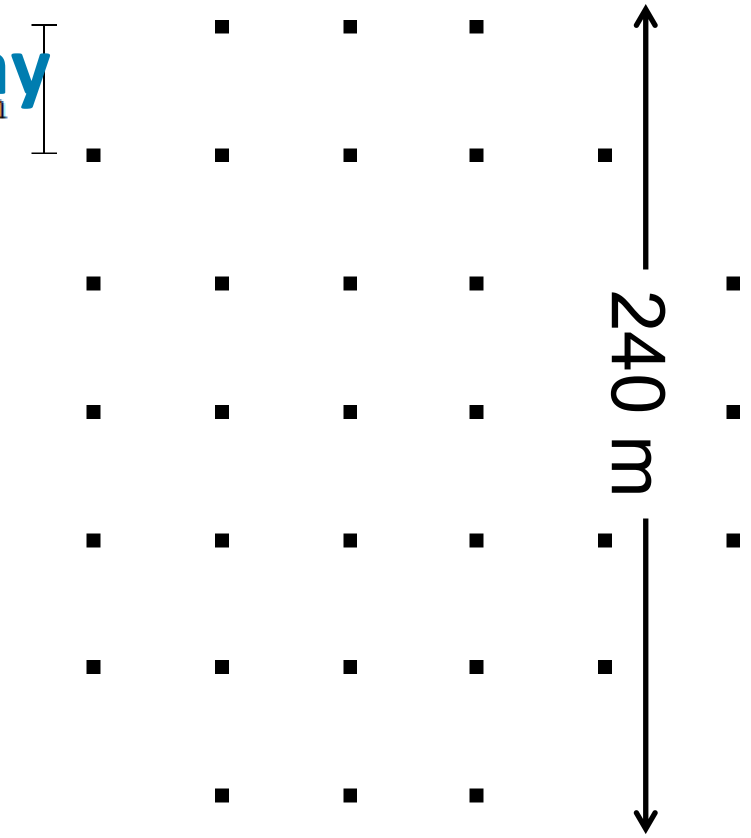

- **Underground detector BUST**
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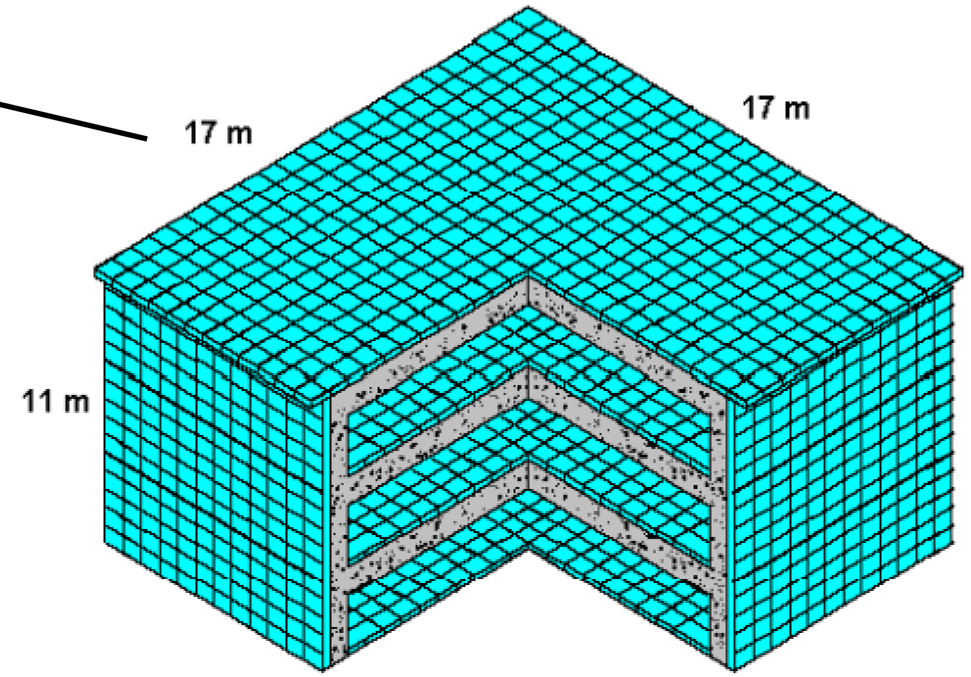
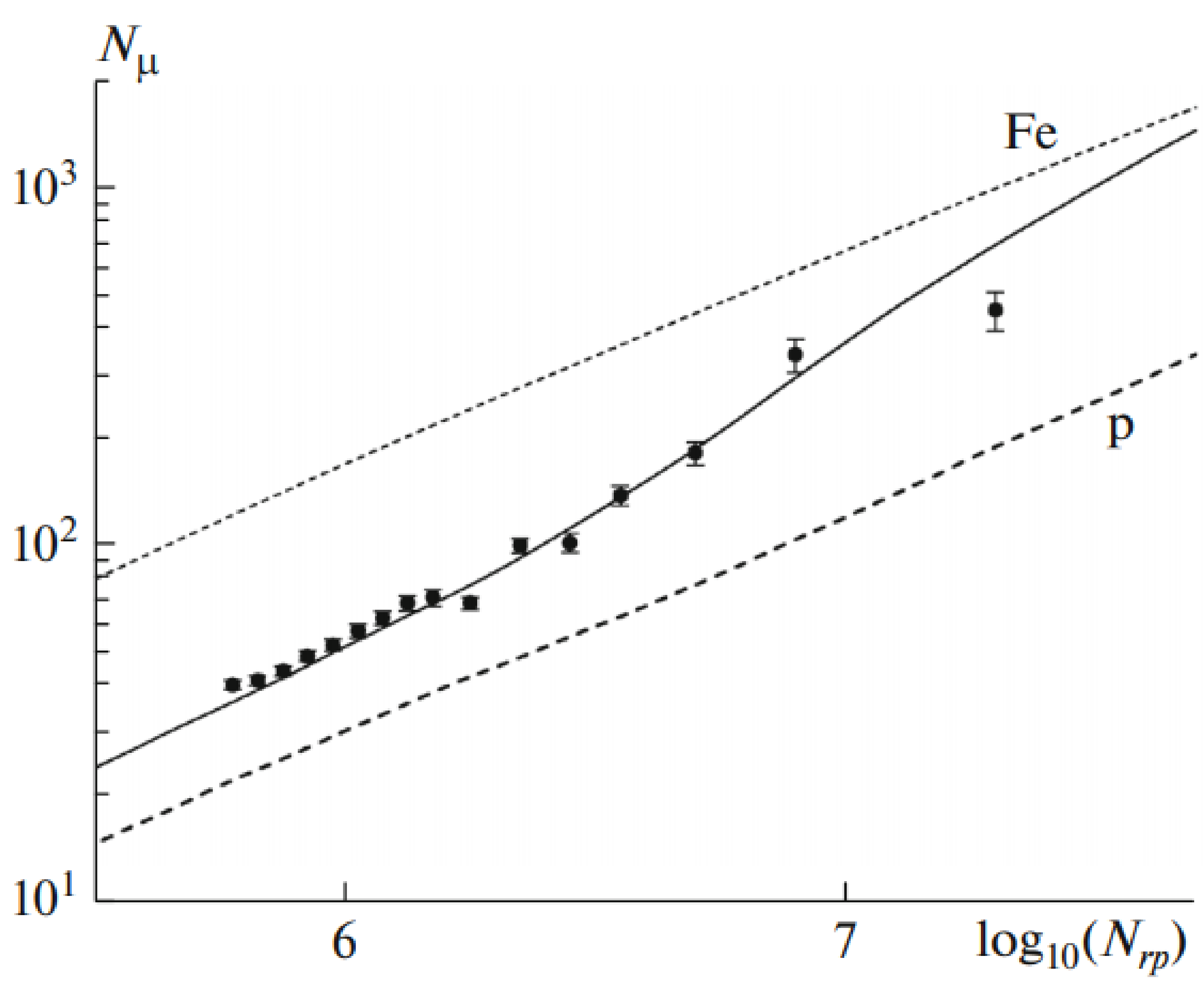


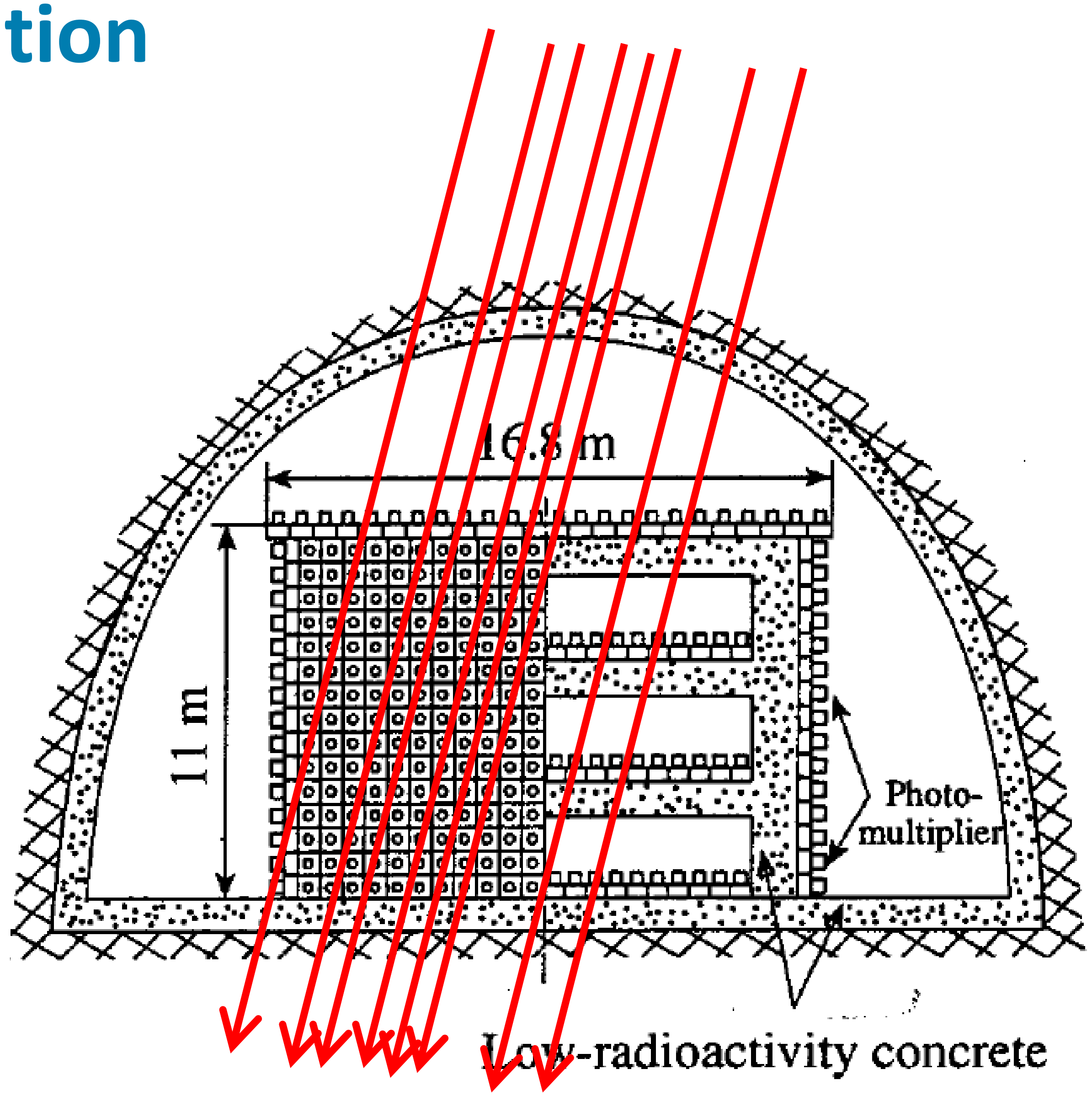
Study of spectrum and mass composition of cosmic rays with
Andyrchy EAS (shower)
+ BUST (muons)

Muons with BUST

…. for instance: mass composition of cosmic rays

Muon number as function of shower energy:



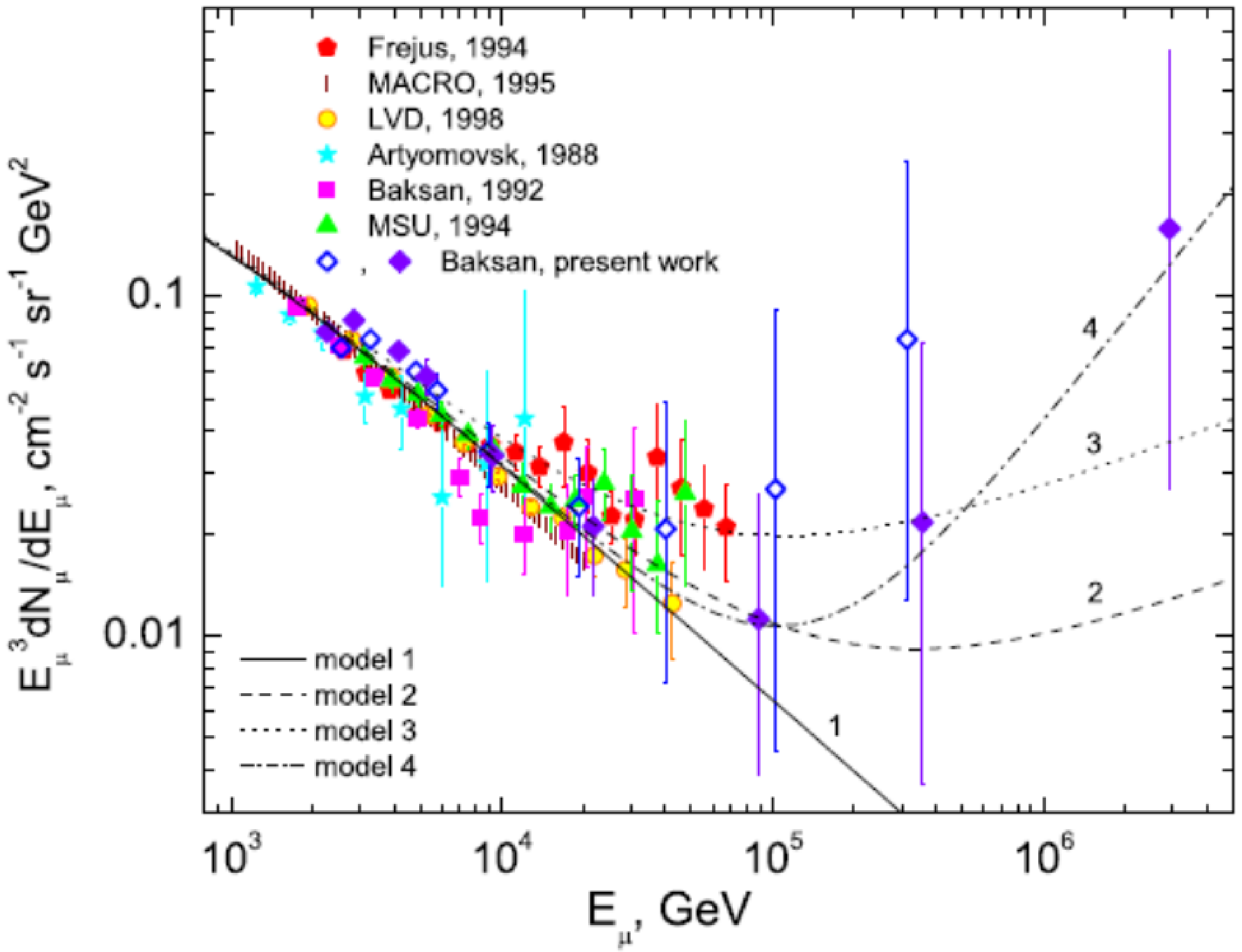


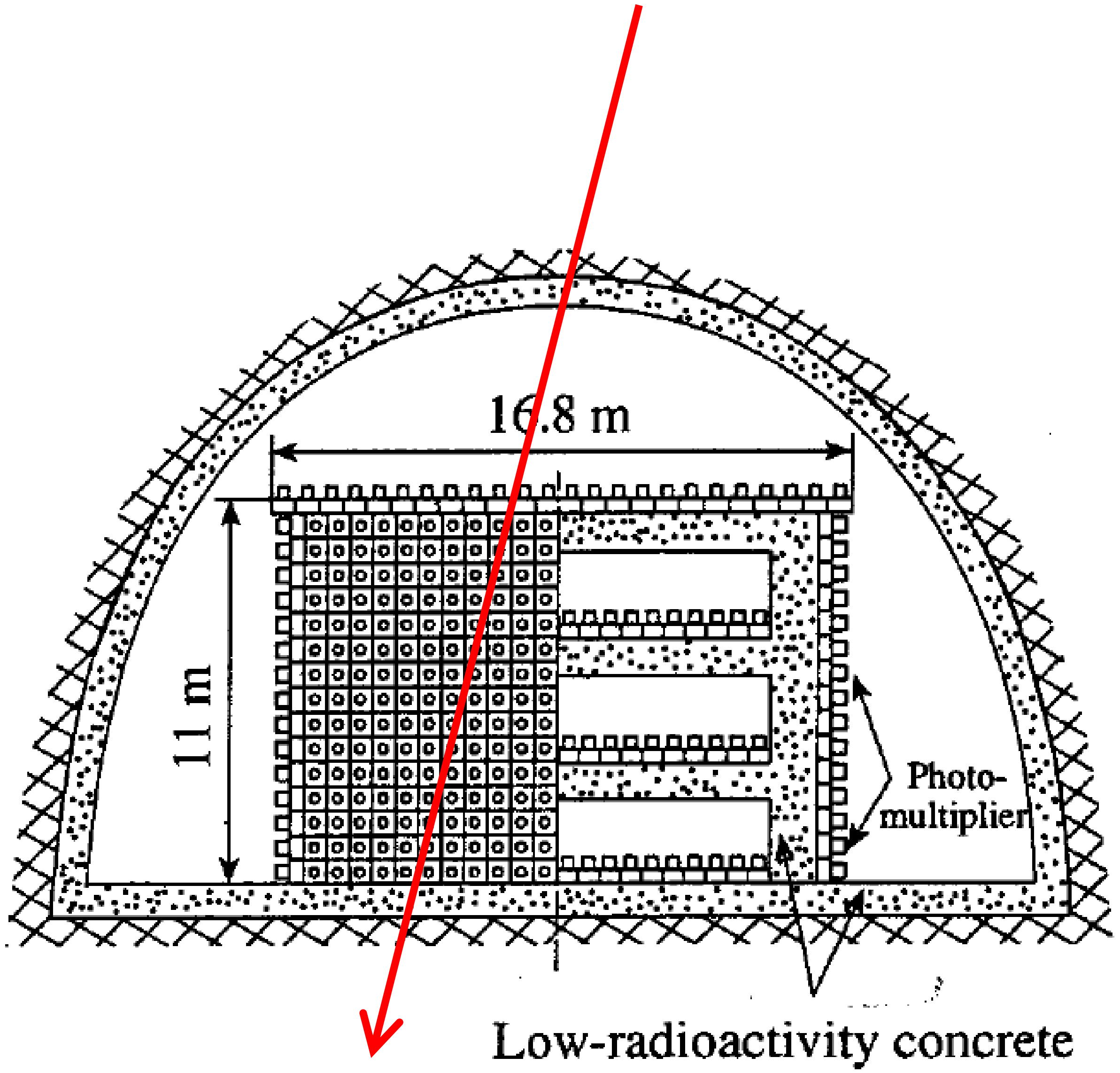
Muons with BUST

World leading results at that time

..... for instance

Muon cross section at high energies:





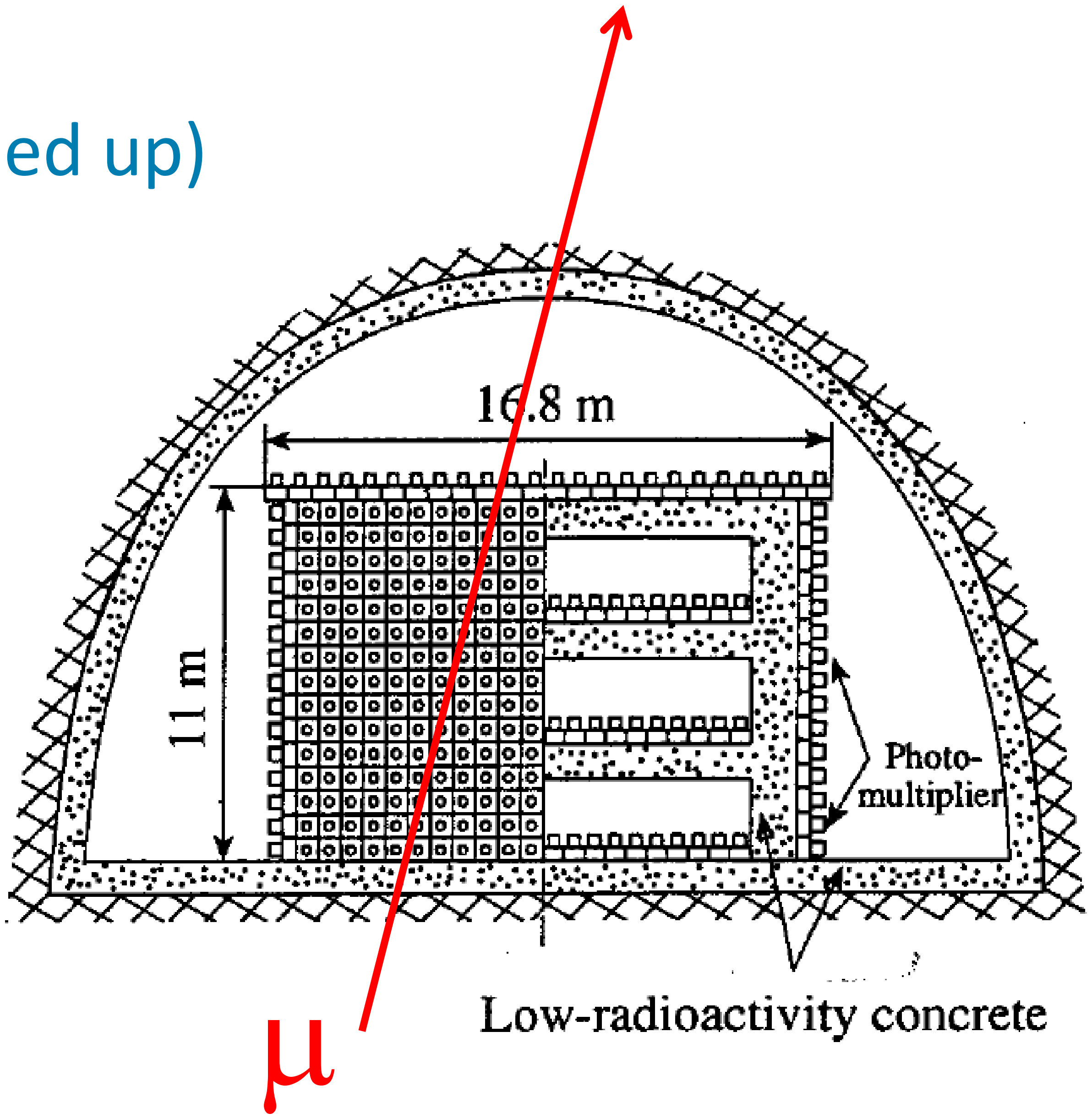
and many others ....

> GeV neutrinos with BUST

Leading player until mid 1990s

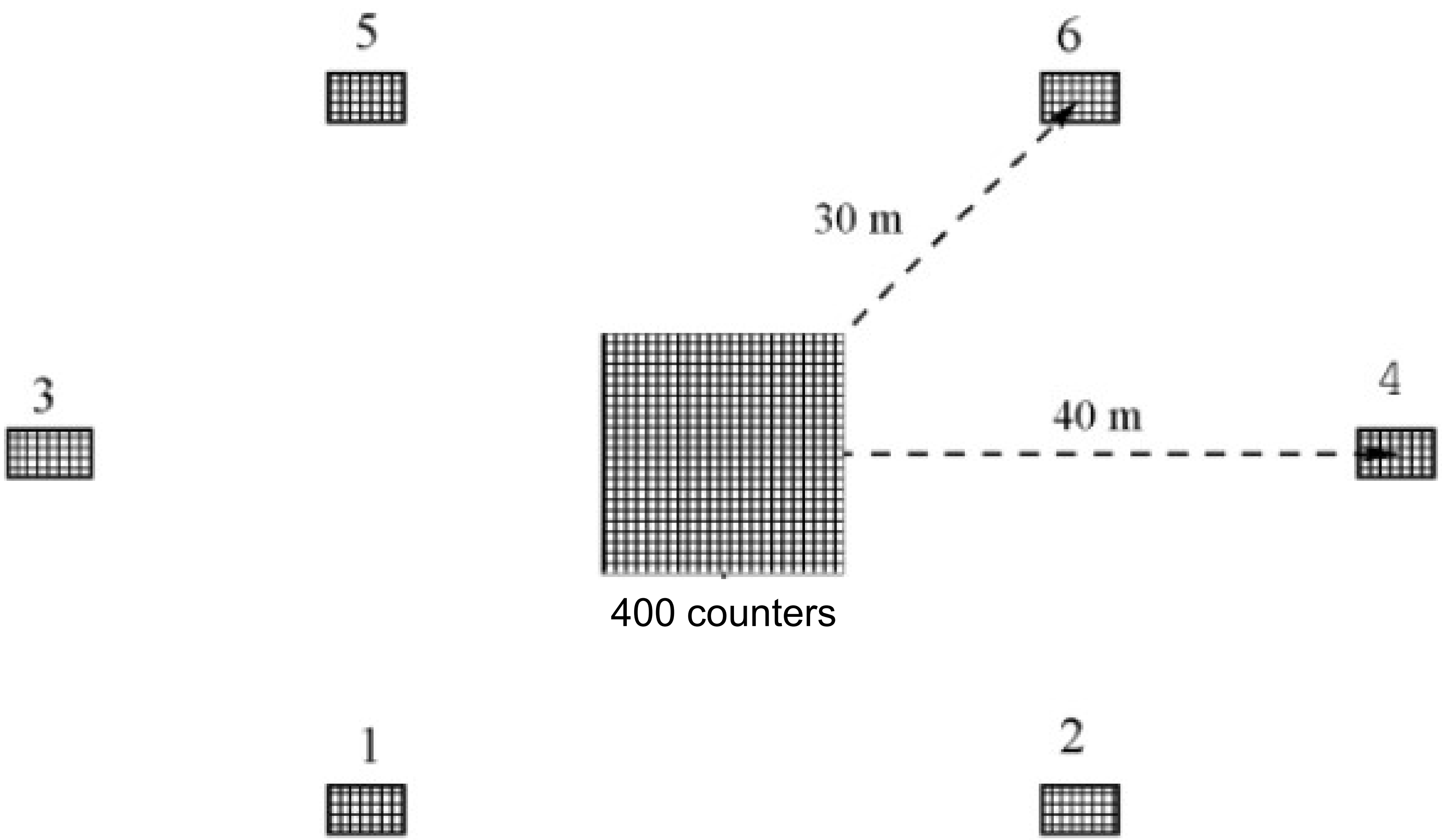
(then MACRO, Super-Kamiokande catched up)

- Limit on neutrino point sources
- Limits on neutrinos from dark matter annihilation in the Earth
- Constraints on oscillation parameters
- Search for neutrinos coinciding with GRB



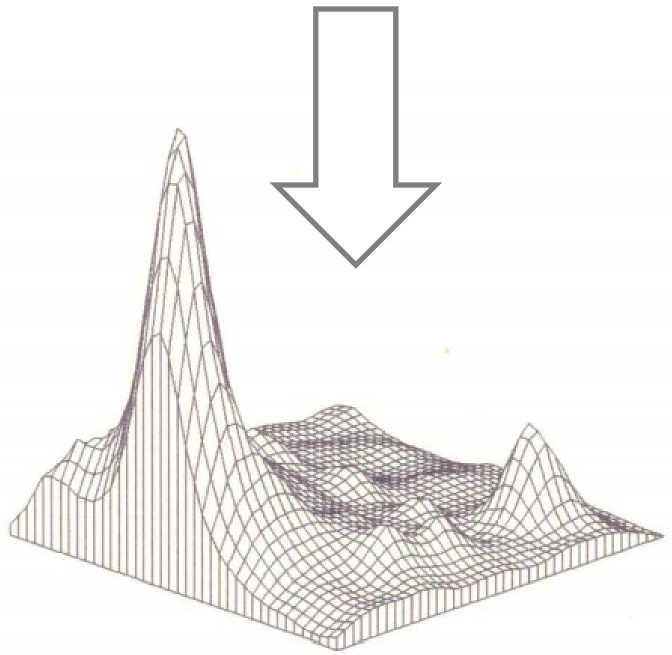
- Also: limits on magnetic monopoles + ...

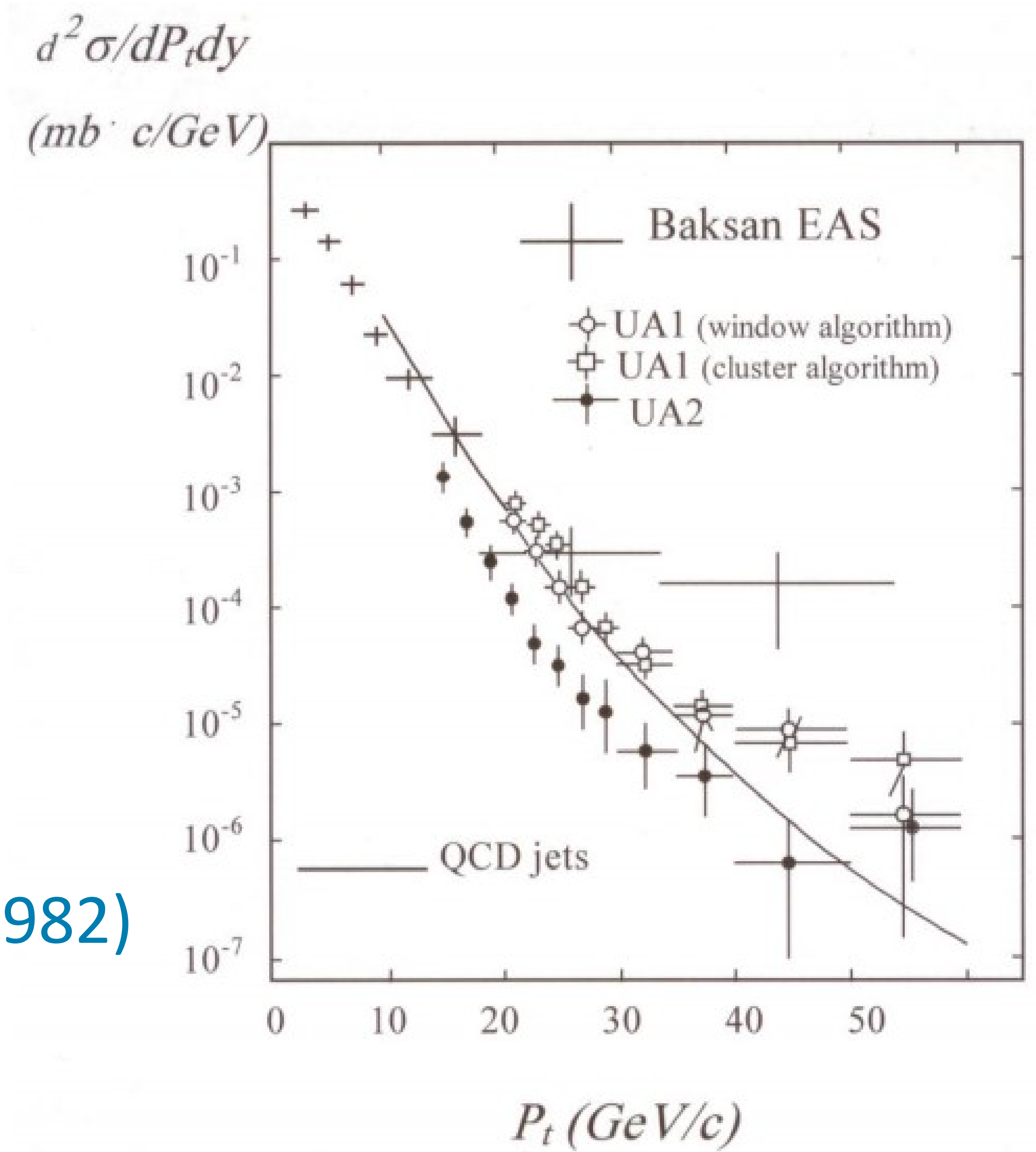
Baksan: Construction of Carpet in the 1970s



Carpet: early results

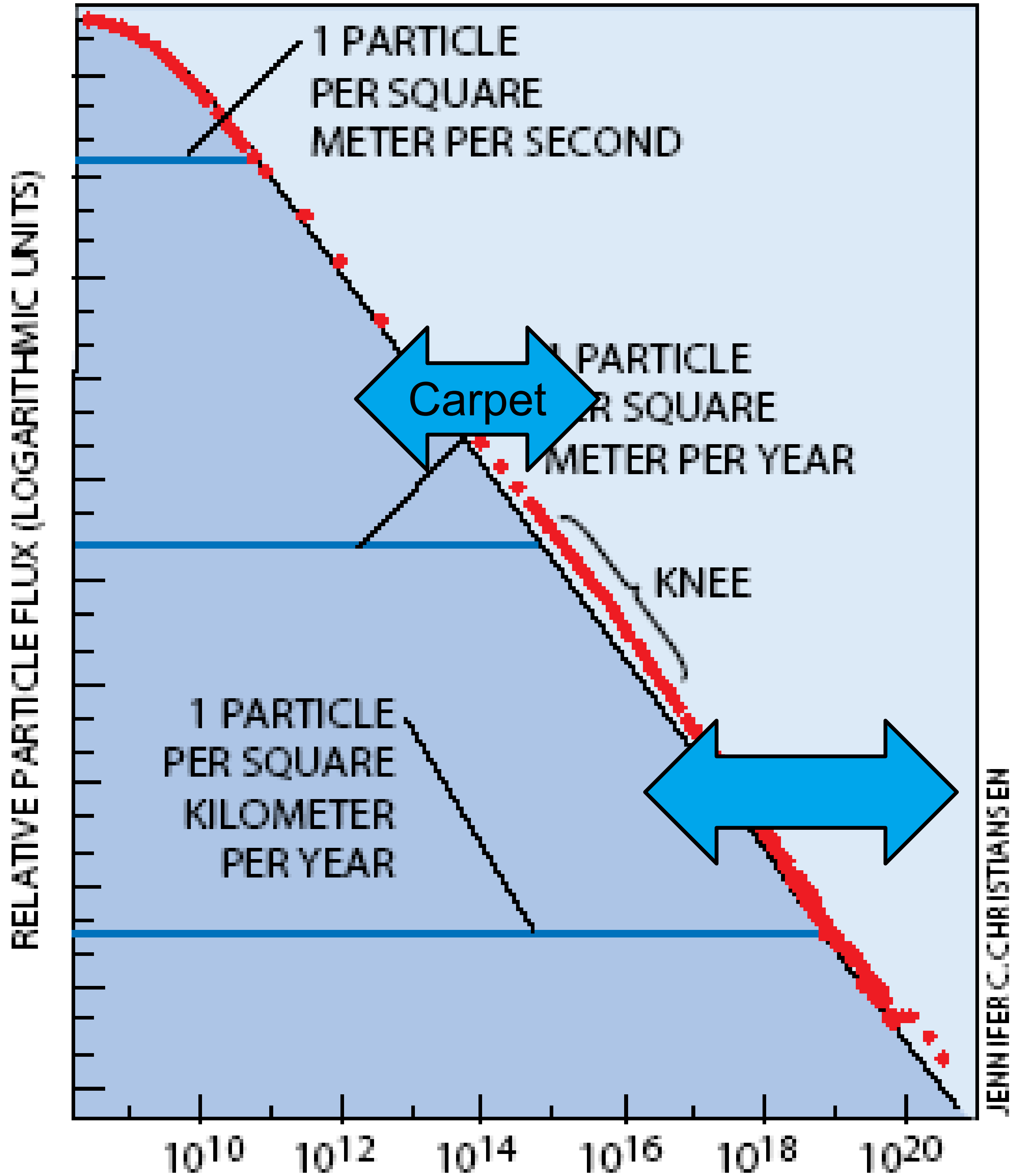
- **High-precision measurements of Extensive Air Showers (EAS)**
- **Multicore EAS and high-p_T interactions (from 1979 on)**



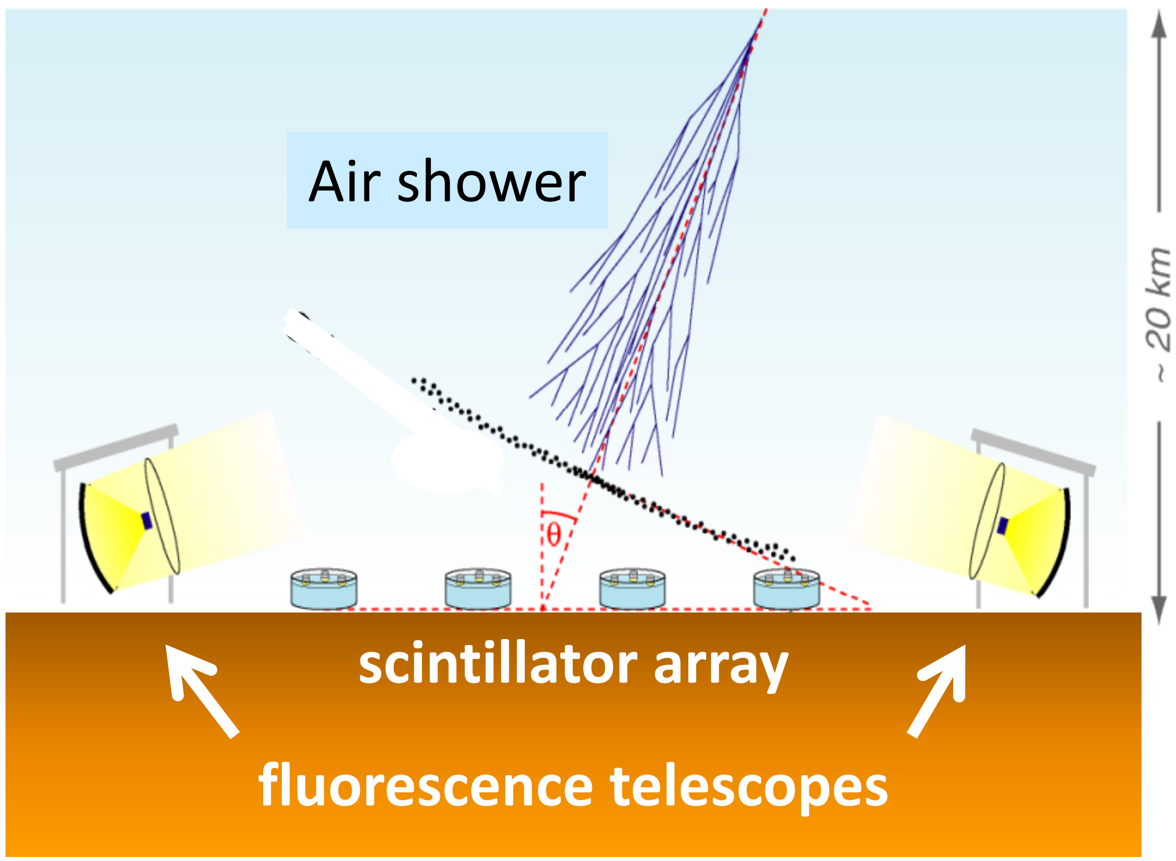


Cross section of high p_T events from Carpet (1981) and CERN (1982) compared to QCD calculations

The highest energies



- **Pierre Auger Observatory** (Argentina) **3000 km²**
- **Telescope Array** (Utah, USA) **700 km²**



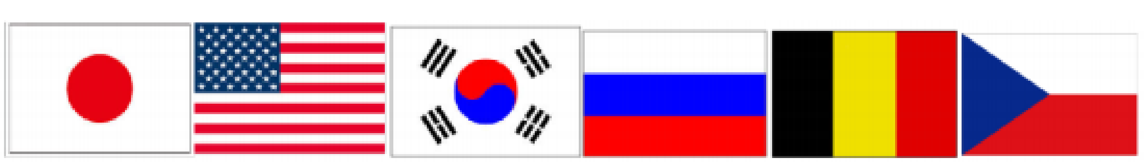
Telecsope Array with Low Energy Extension (TALE) and TA×4

TALE

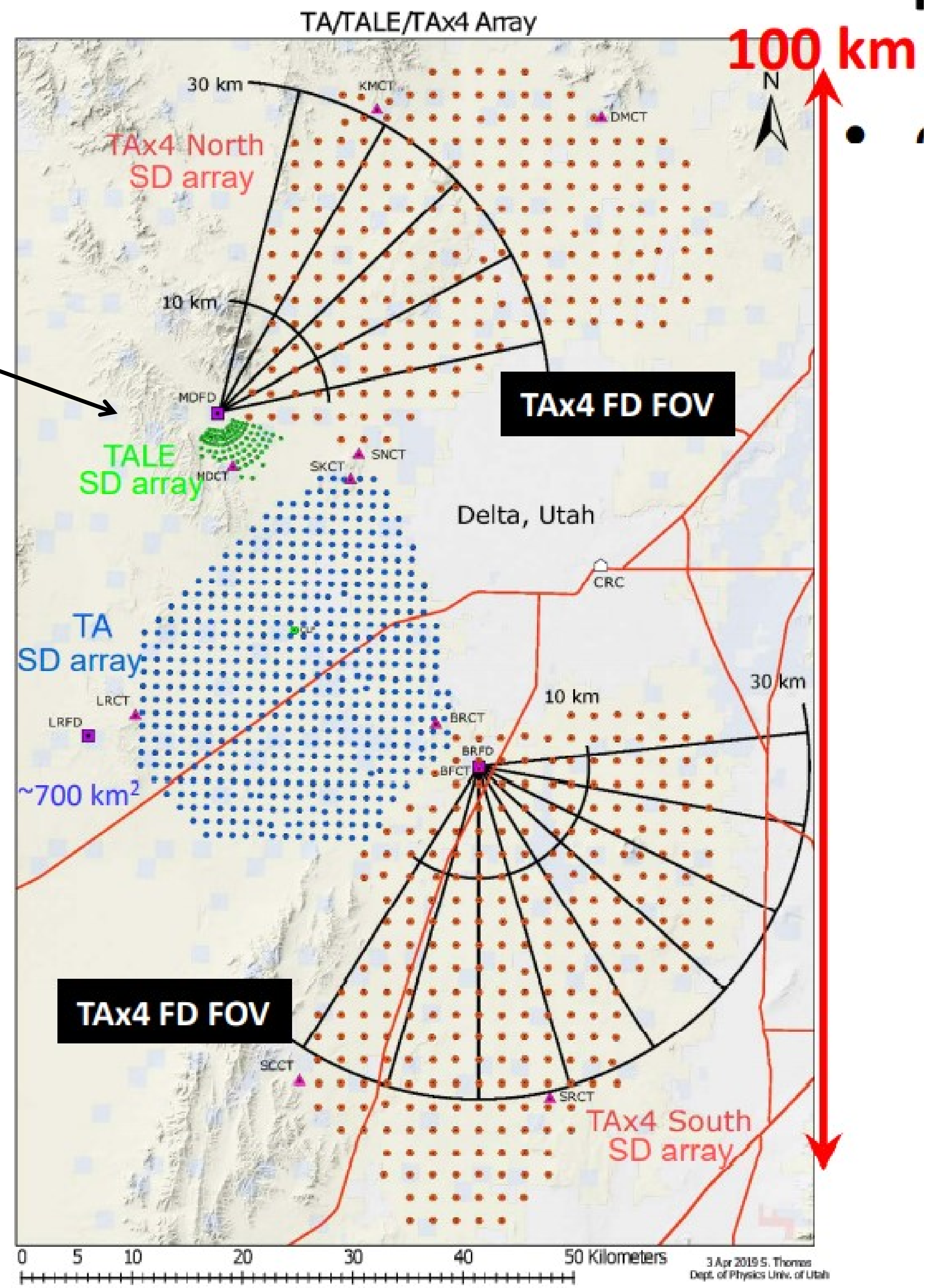
low threshold

TA×4

→ 3000 km², under construction



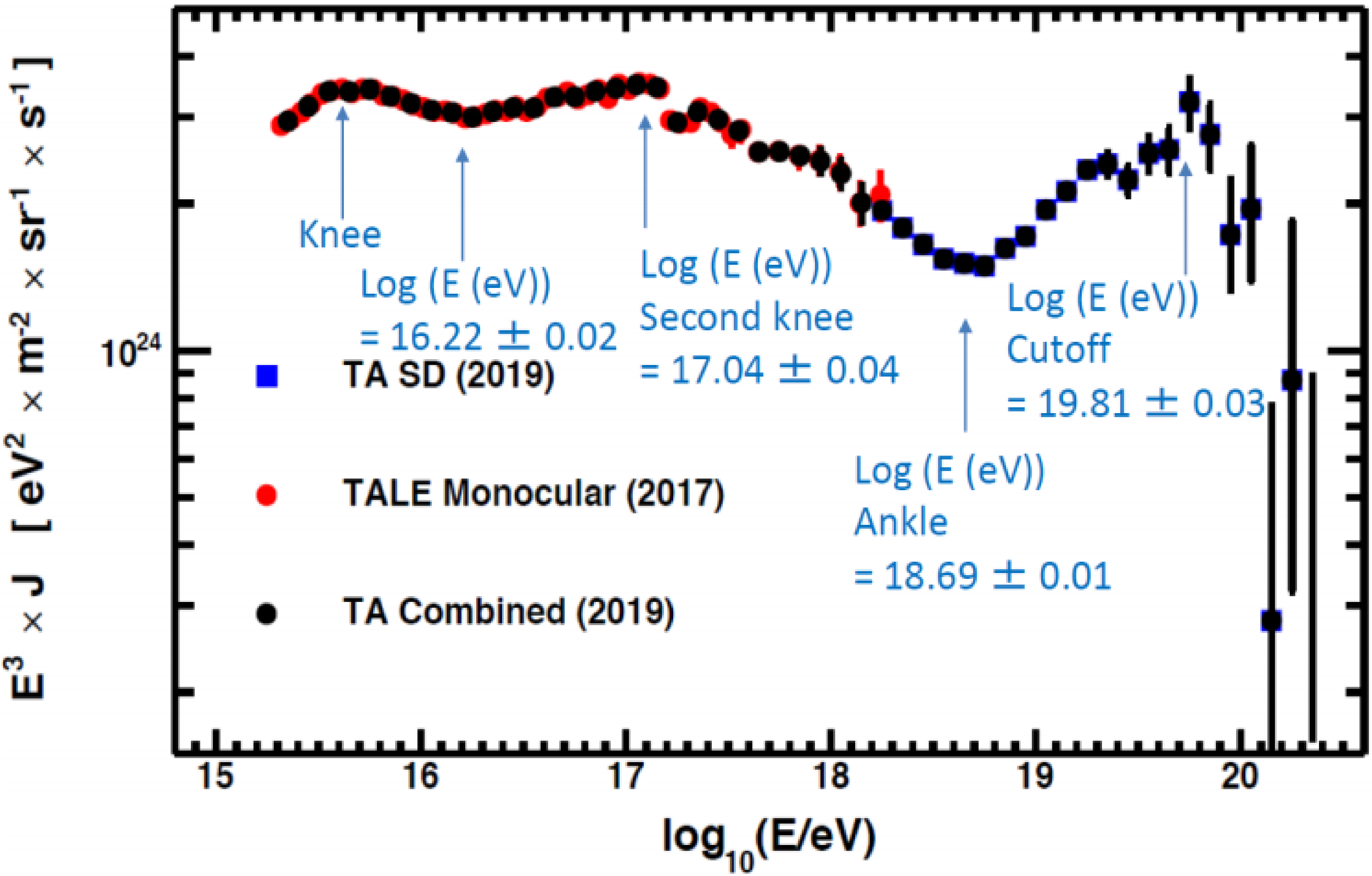
Japan, USA, Korea, Russia, Belgium, Czech



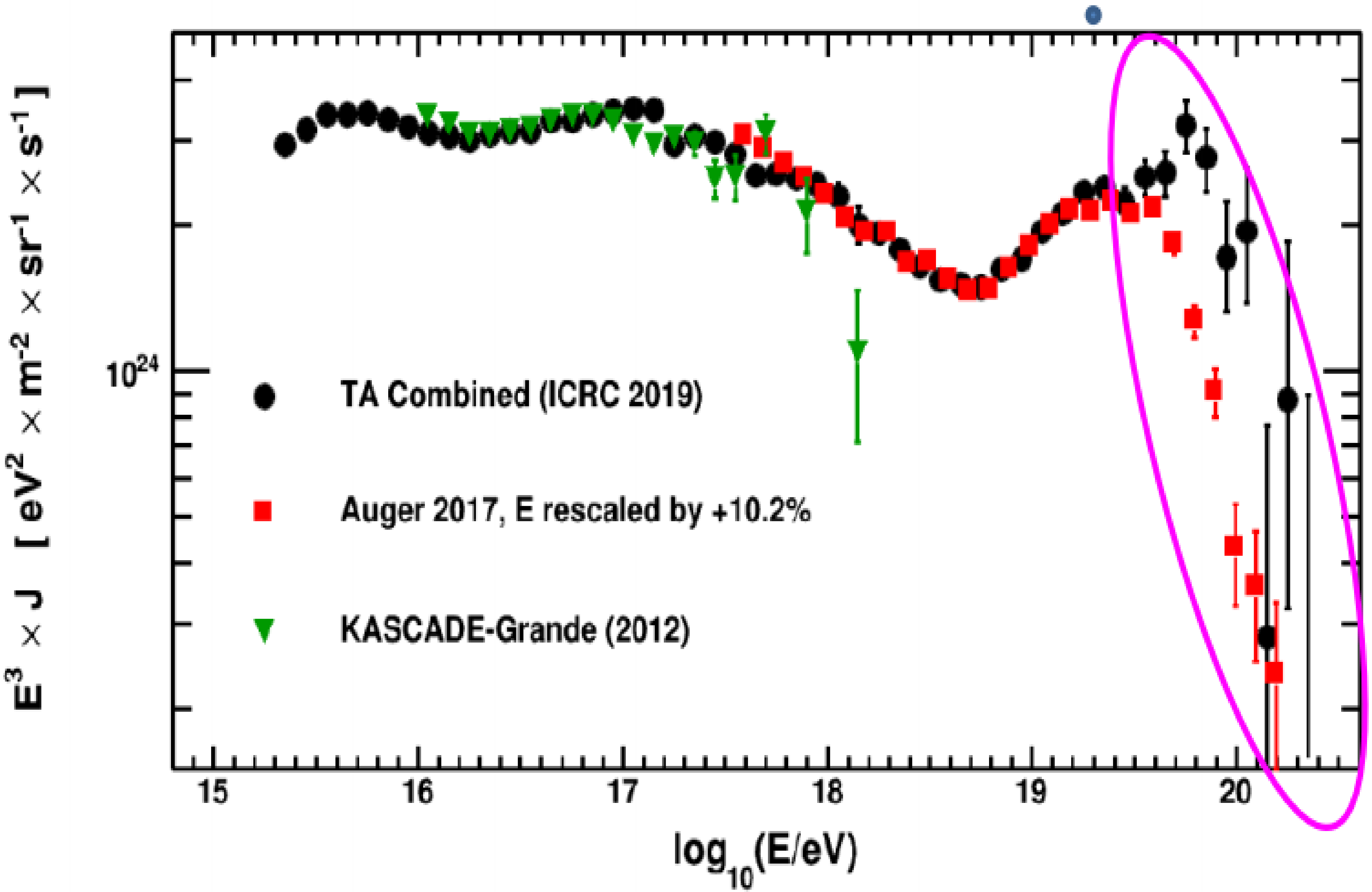
Where is the cut-off? GZK or power limit?

$p + \gamma_{3K}$

TA SD, TALE FD, TA Combined

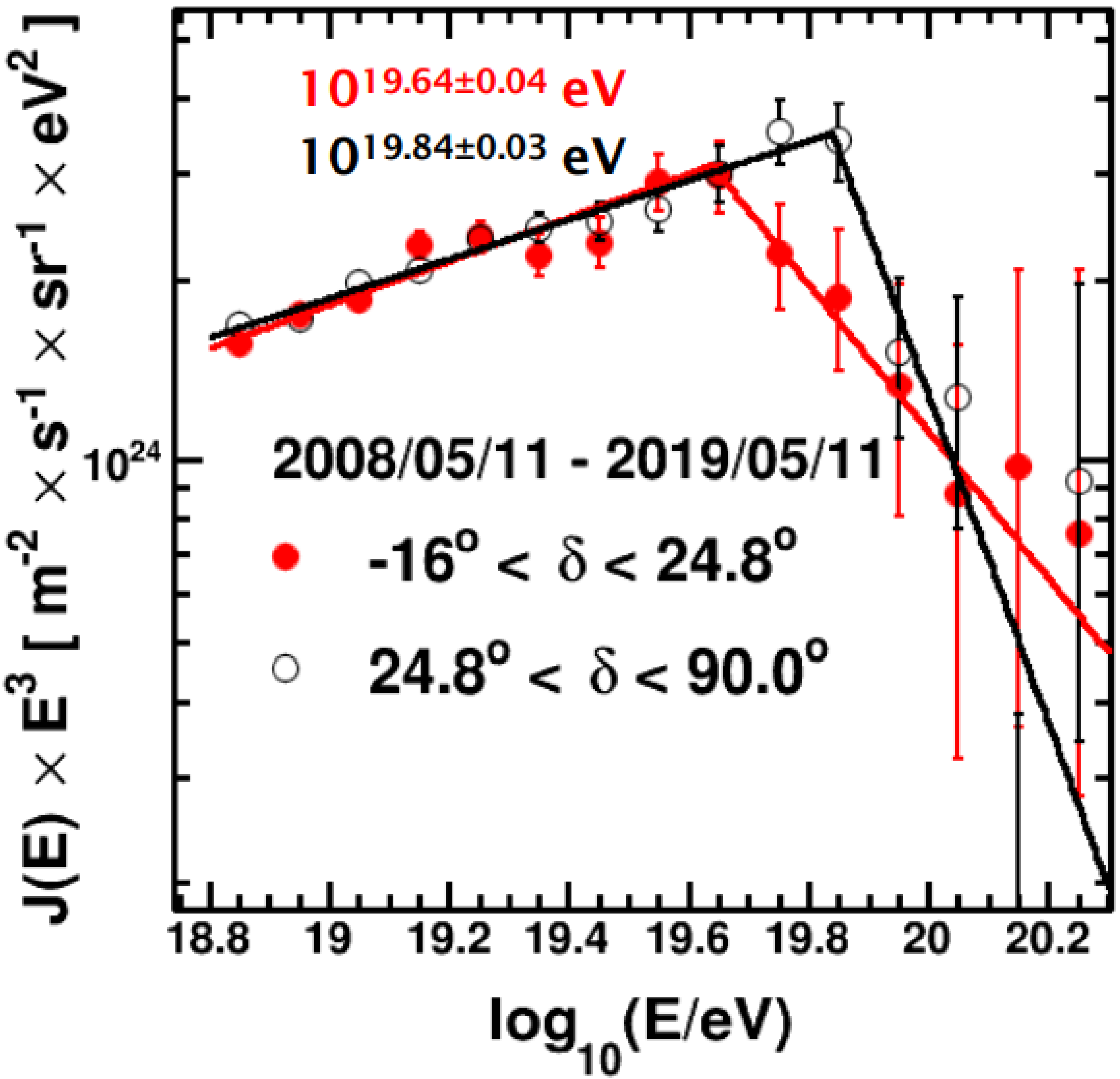


Where is the cut-off? TA vs. Auger



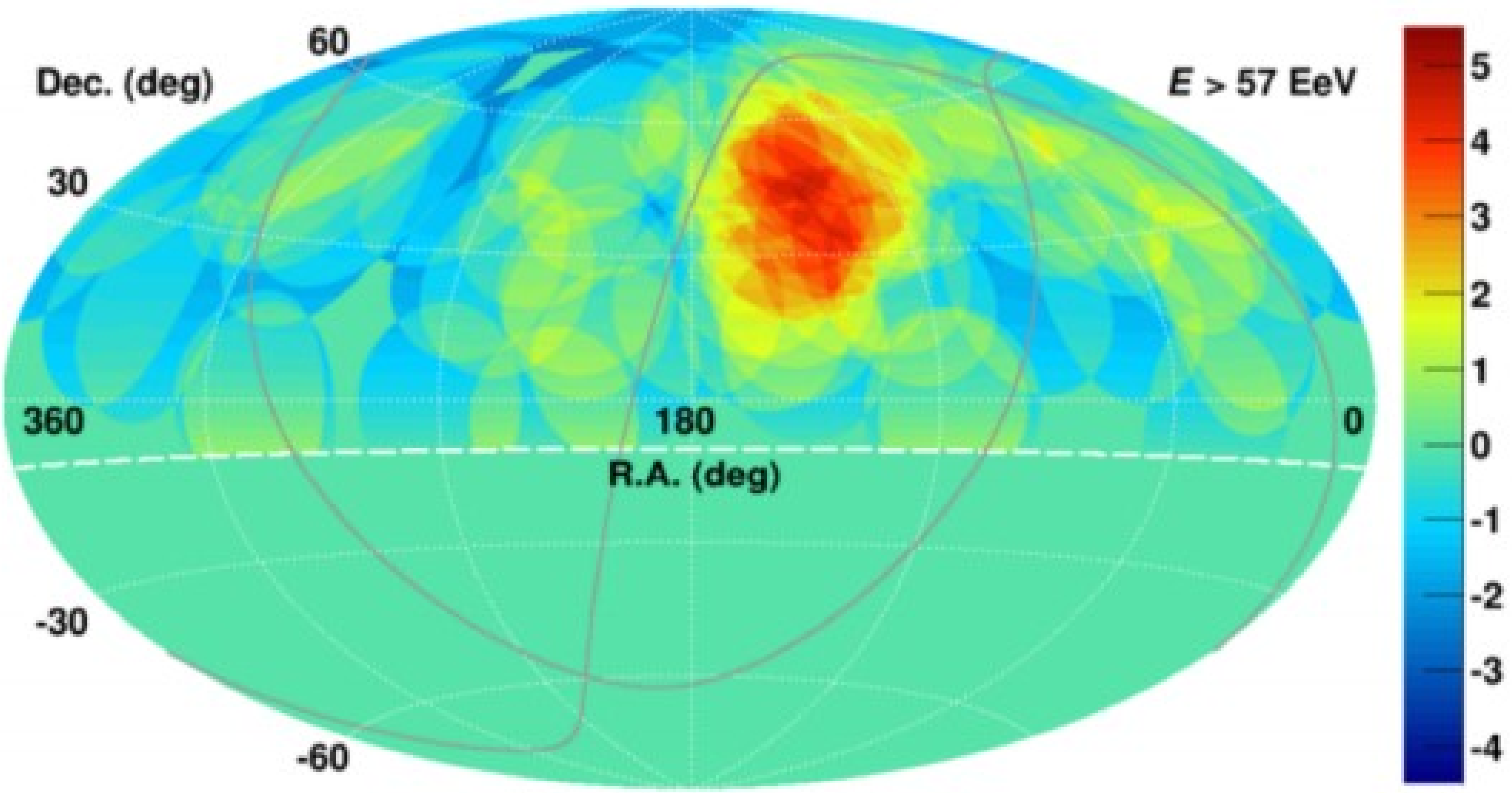
Where is the cut-off? TA vs. Auger

11 years of TA SD data



The hot spot 2013

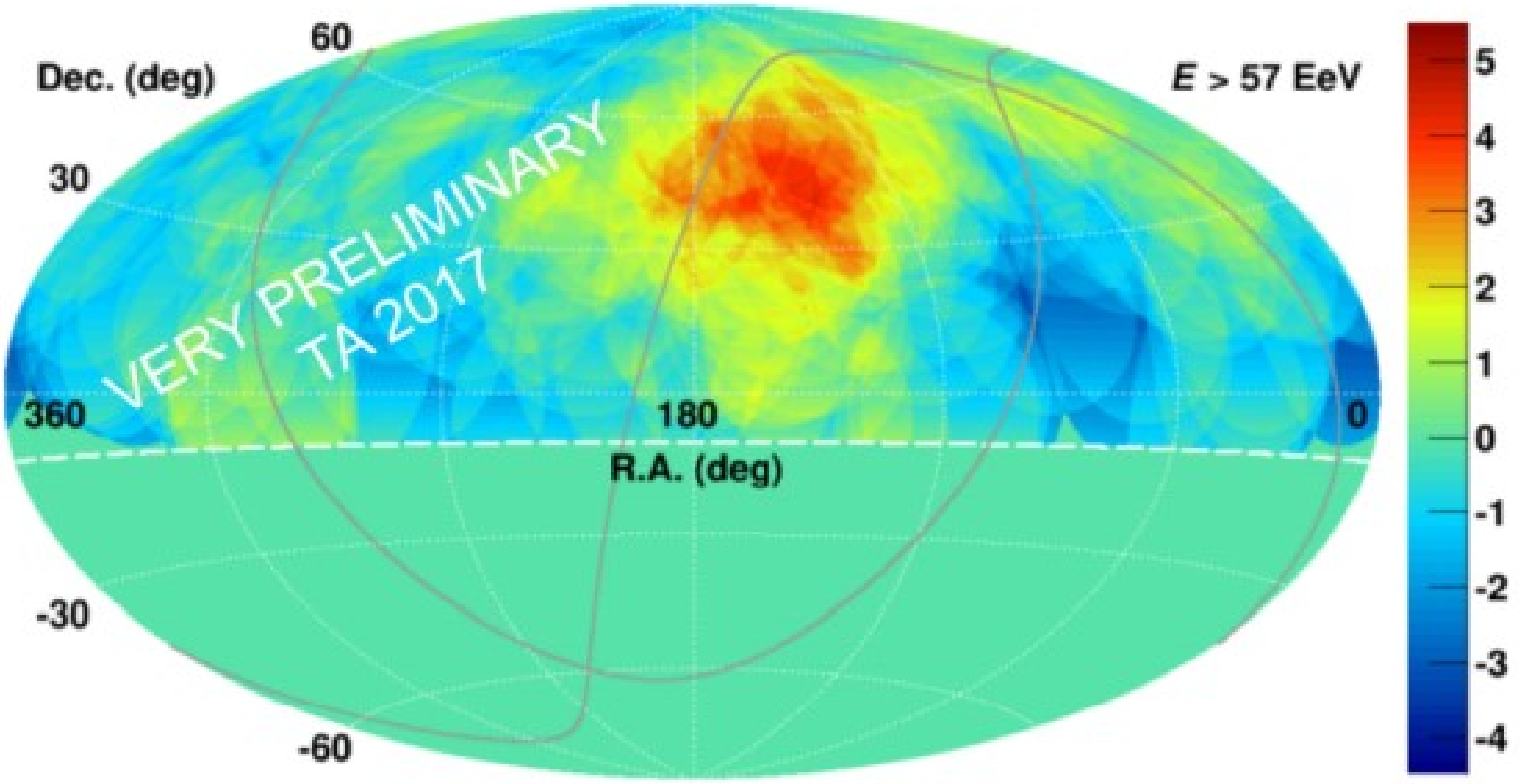
E>57 EeV - Years 1-5 excess map



Total events: 72

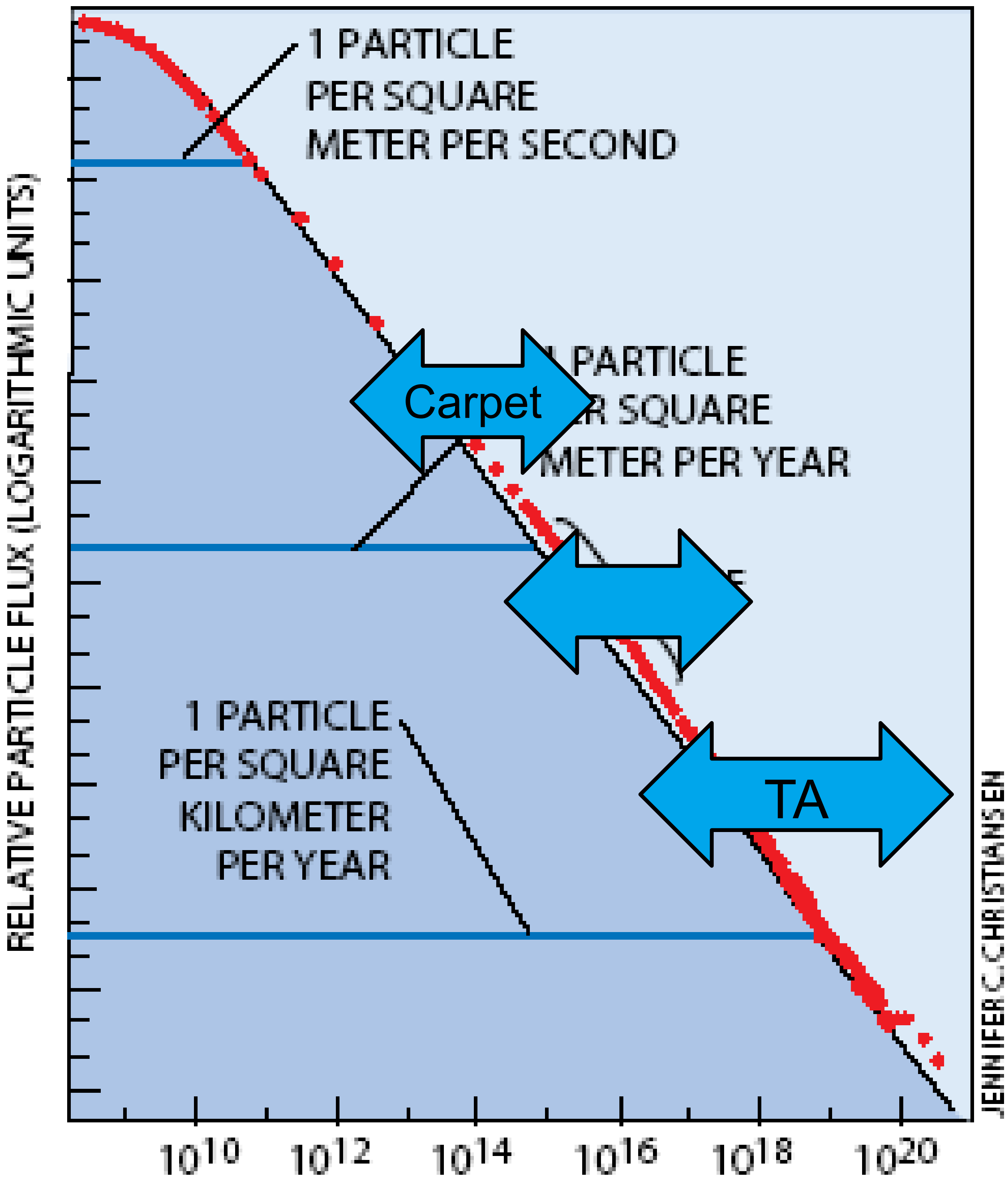
The hot spot 2017

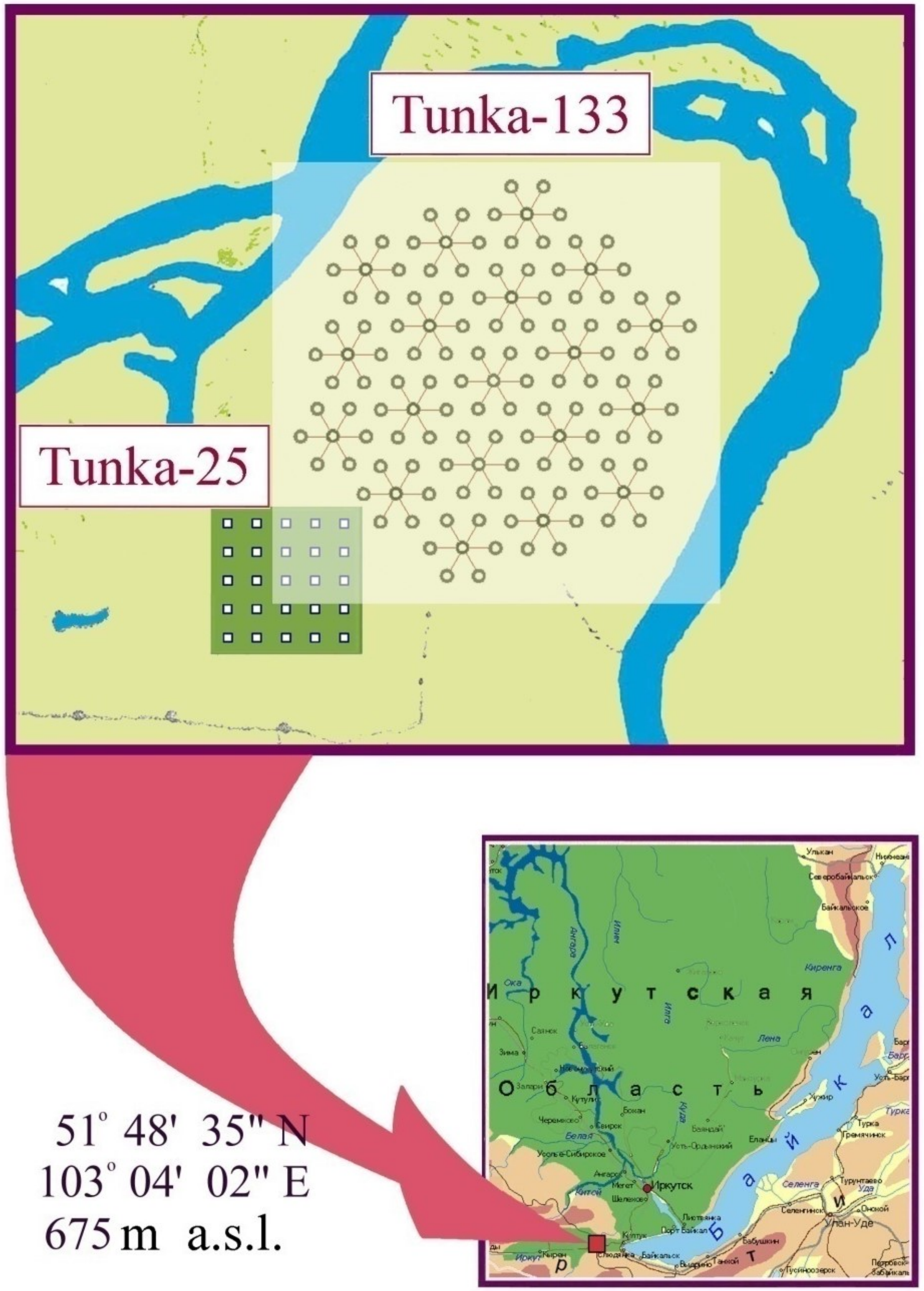
E>57 EeV - Years 1-9 excess map



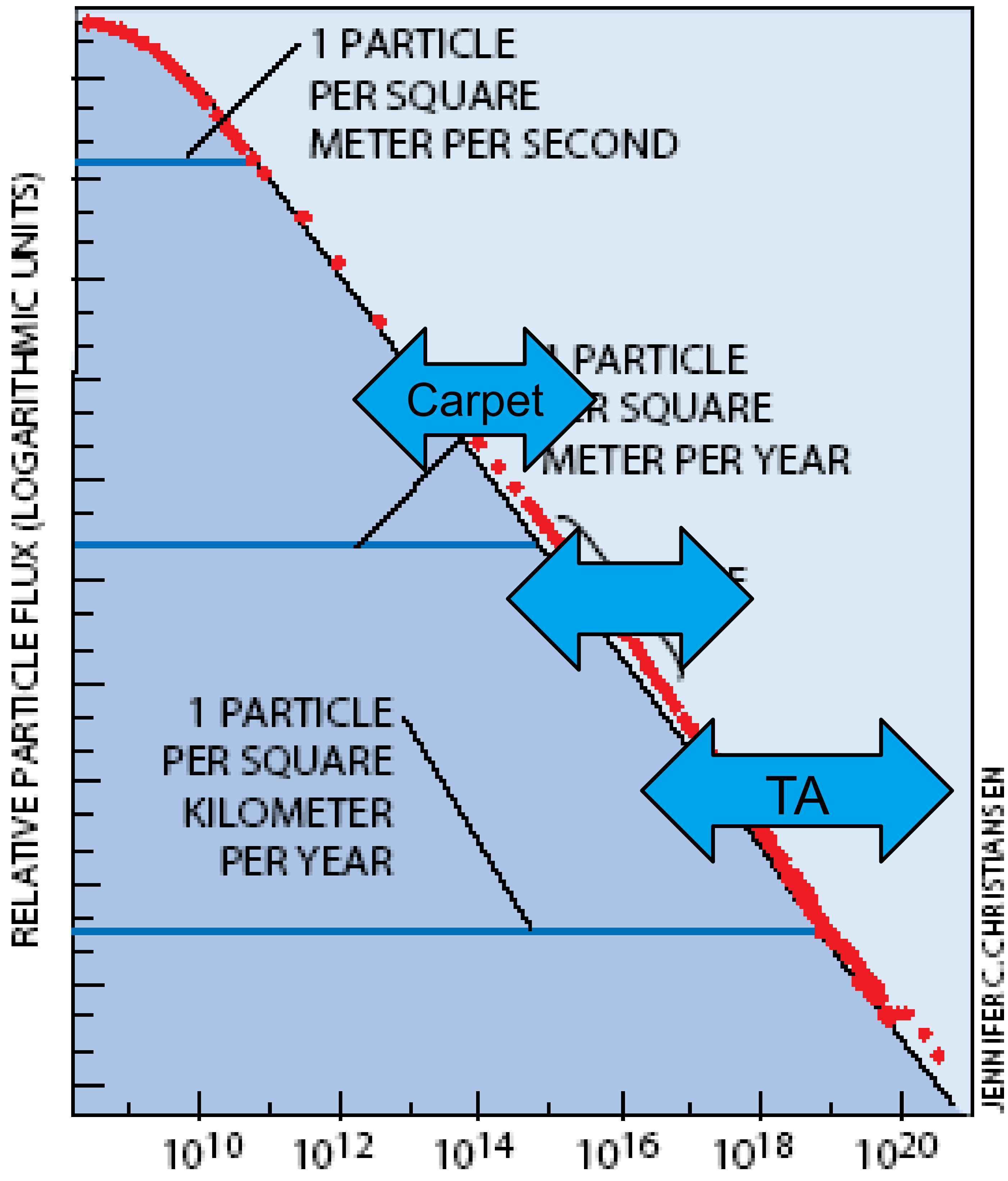
Total events: 143

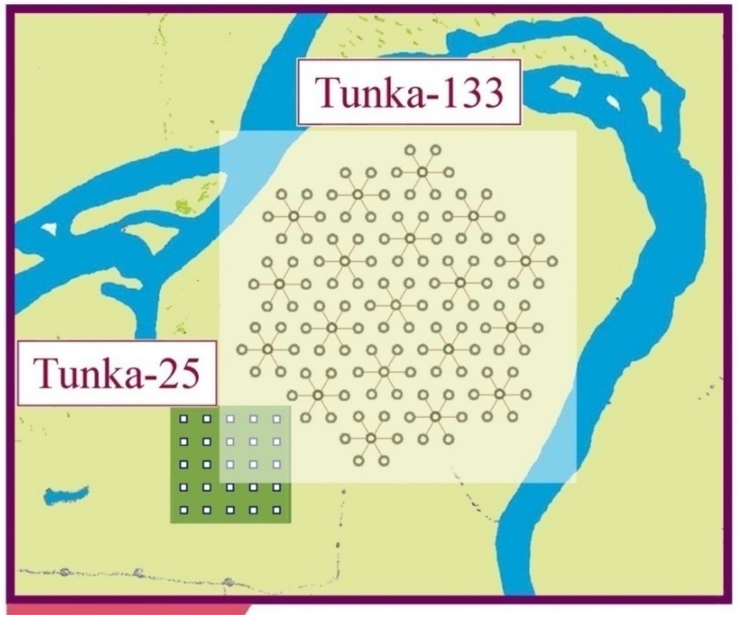
Galactic cosmic rays

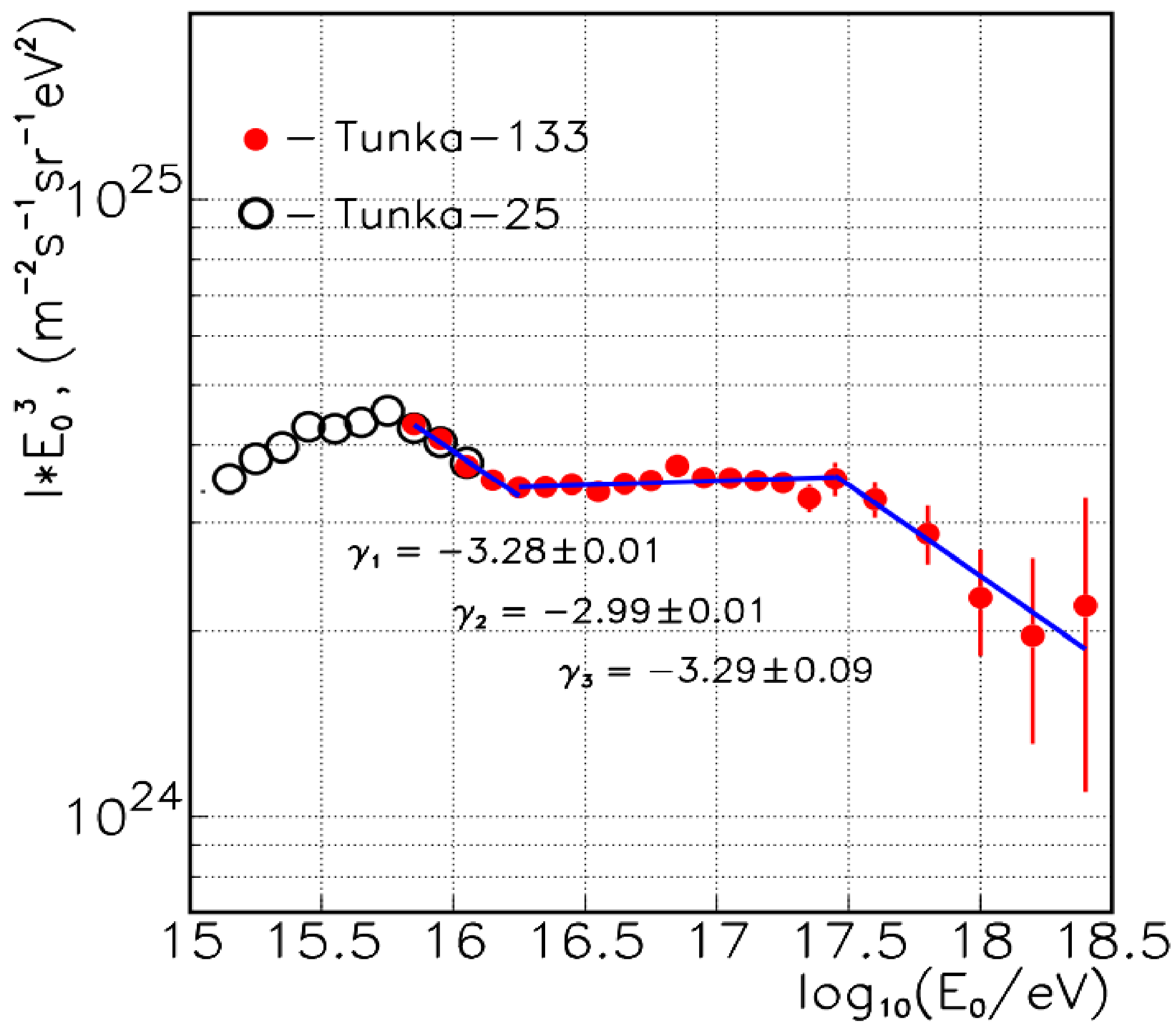


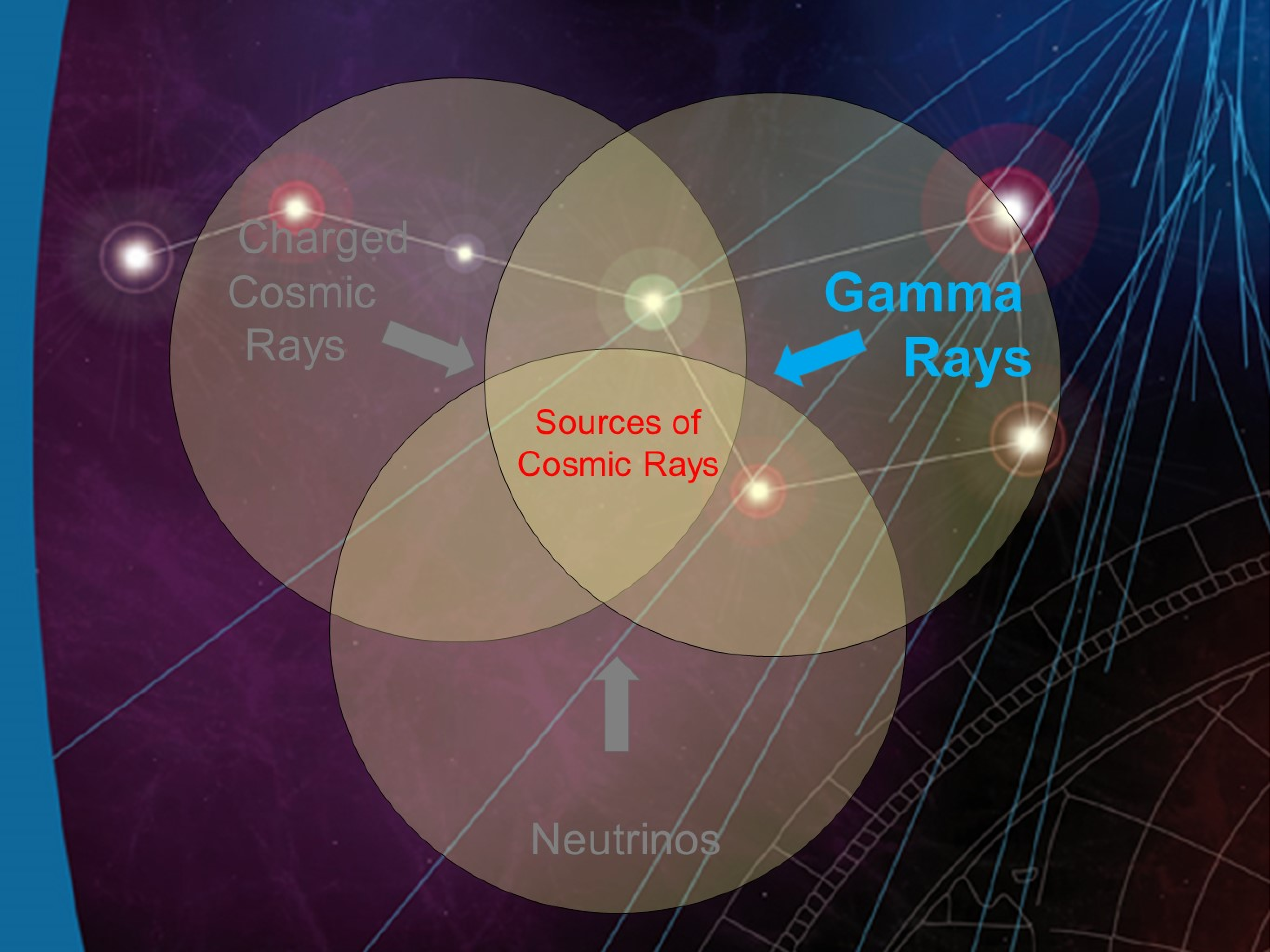


Galactic cosmic rays








Charged Cosmic Rays
Gamma Rays
Sources of Cosmic Rays
Neutrinos

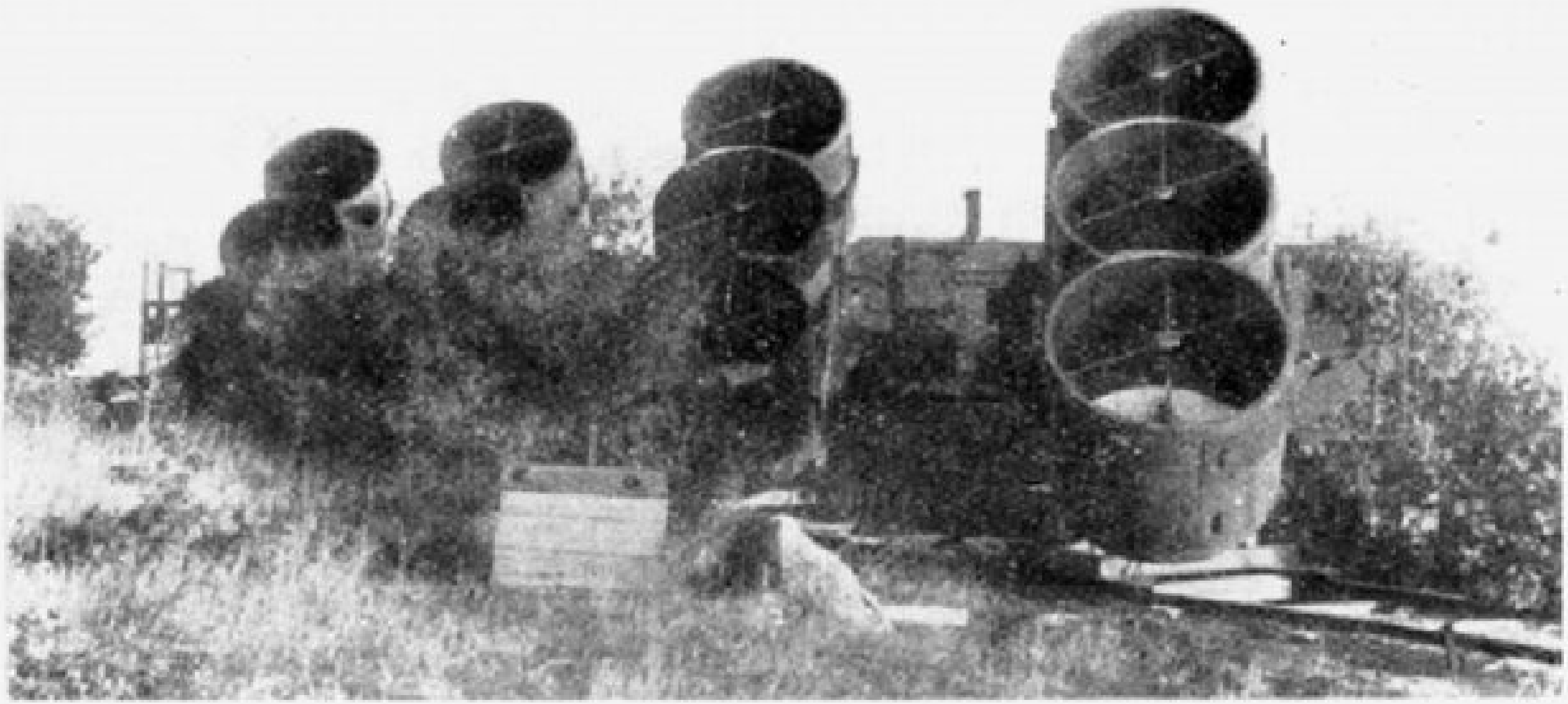
Alexander Chudakov, Georgi Zatsepin

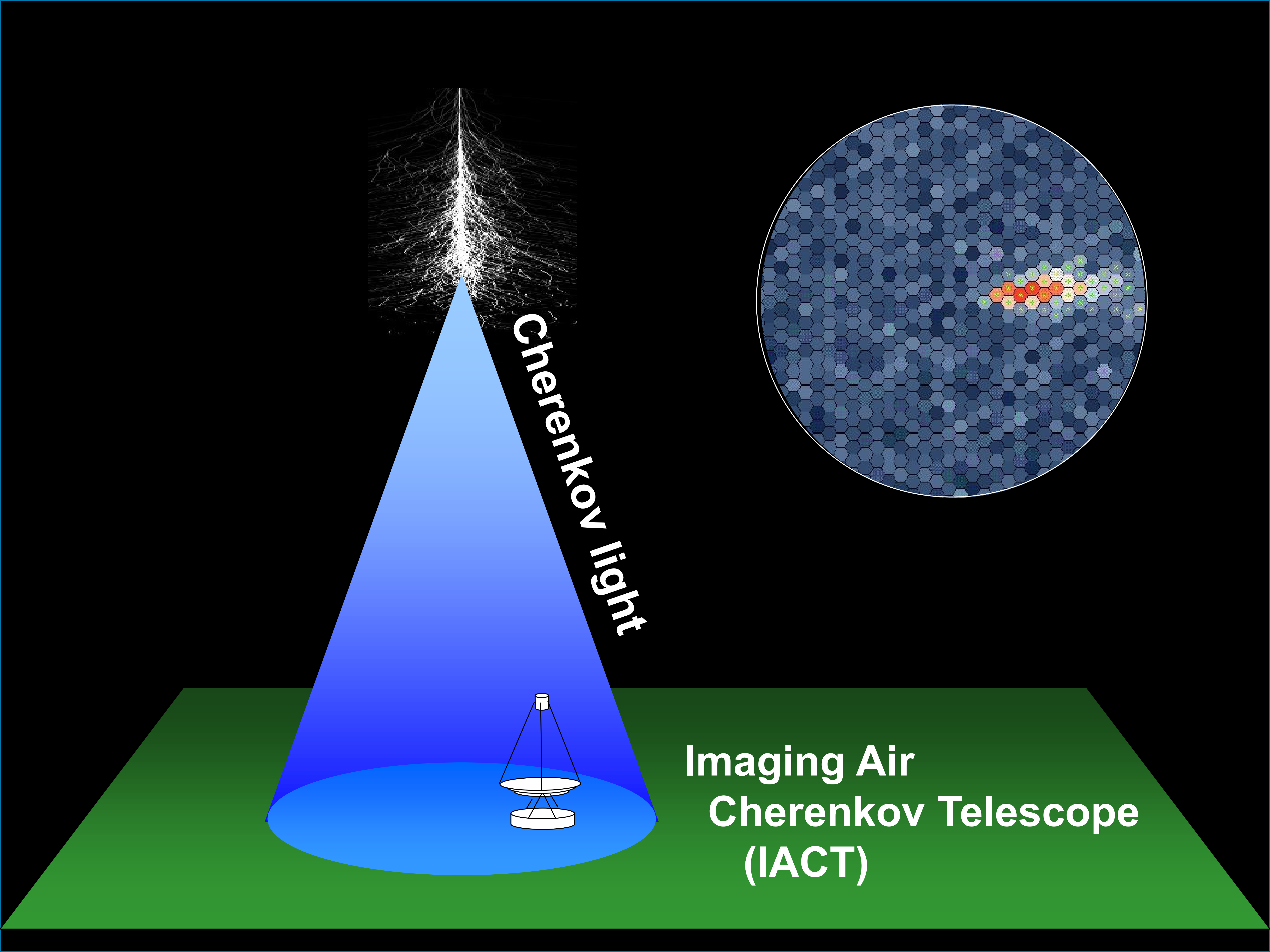
1961

Search for CR sources
with gamma-ray showers
in the atmosphere

Alexander Chudakov

Crimea, 1961-1965: SNR, radio galaxies





Cherenkov light
Imaging Air
Cherenkov Telescope
(IACT)

3rd generation Imaging Air Cherenkov Telescopes

1989:	1 Source
1996:	3 Sources
2005:	80 Sources
2015:	150 Sources

Where are the PeVatrons?

- **IceCube: neutrinos with E > 500 TeV**
- **The parent hadrons should have energies >> 1 PeV („PeVatrons“)**

- **There MUST be gamma rays of ~PeV !**
- **Mean free path for PeV gamma rays ~ 10 kpc → can only come from our own Galaxy**

TAIGA in Siberia

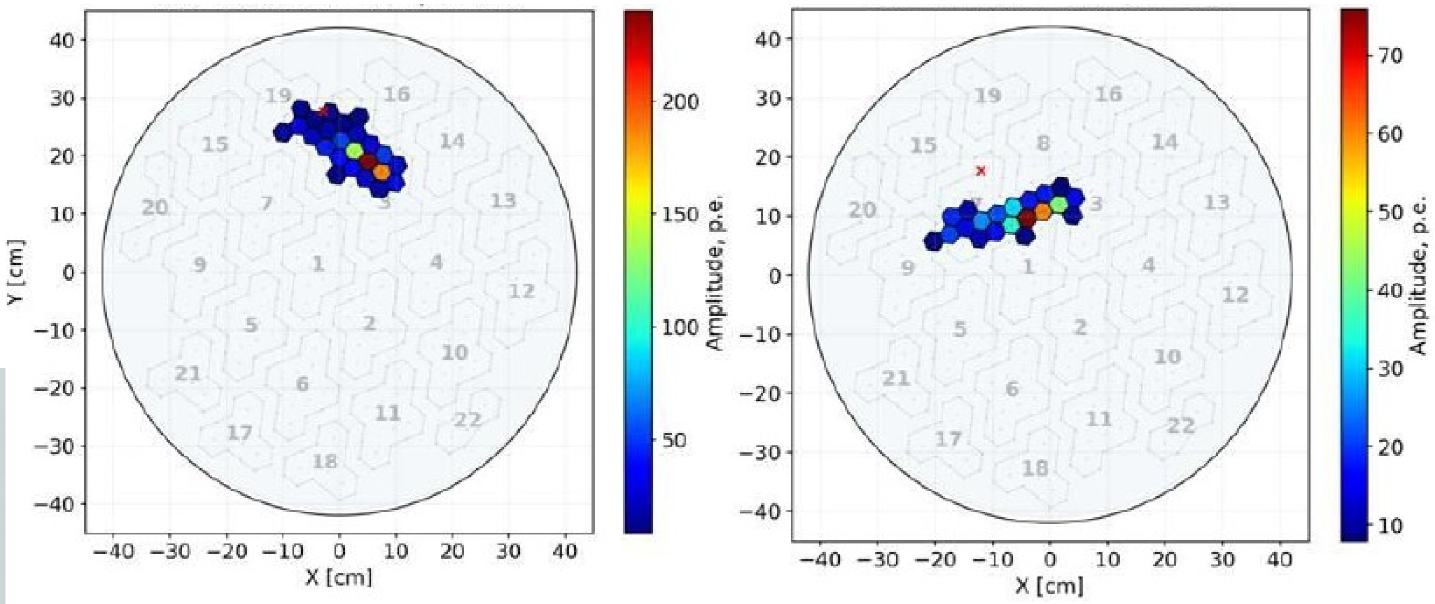
DESY Zeuthen, KIT Karlsruhe
MPI Munich, Univ. Hamburg

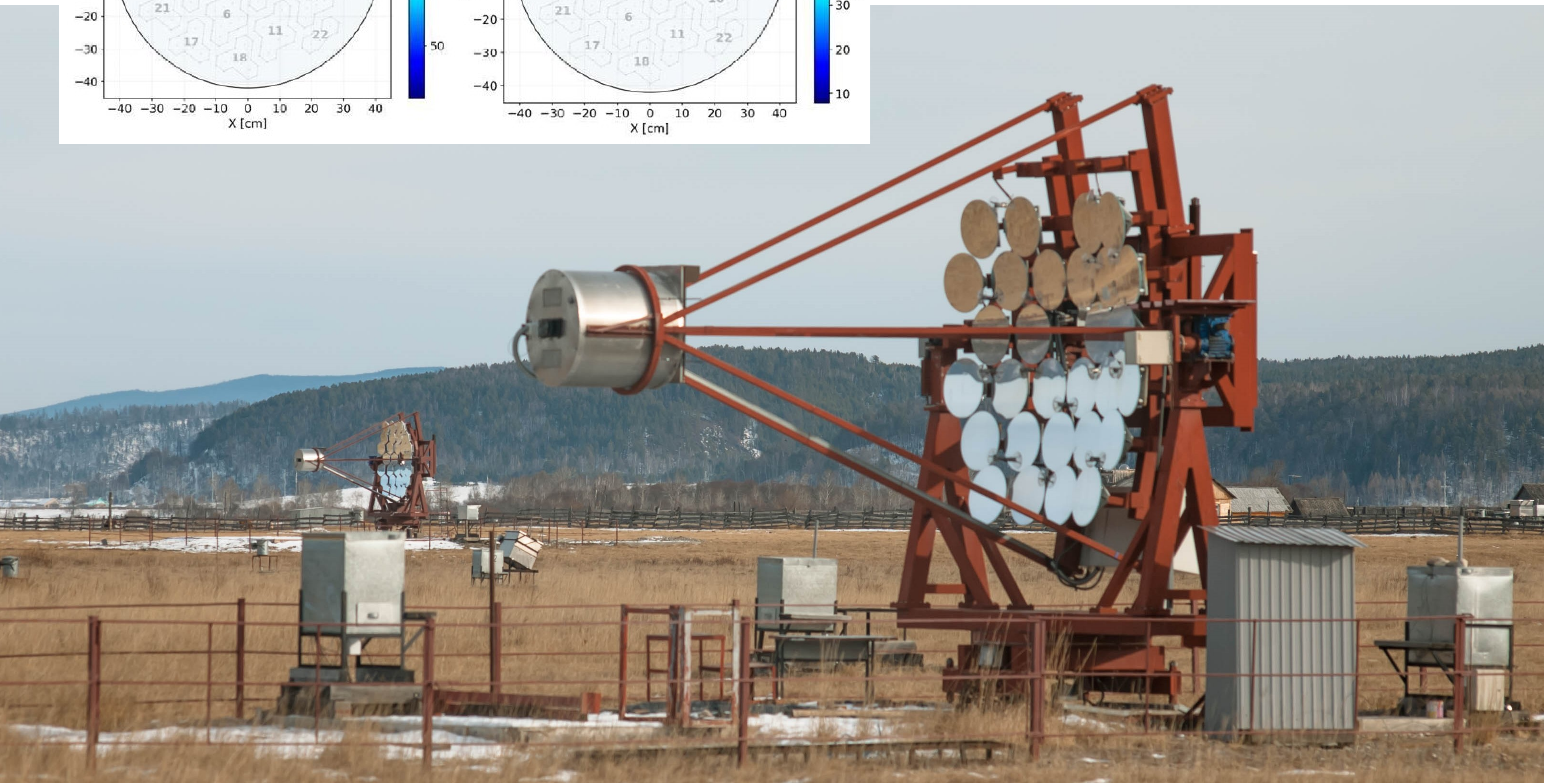
Combination of

120 wide angle timing detectors

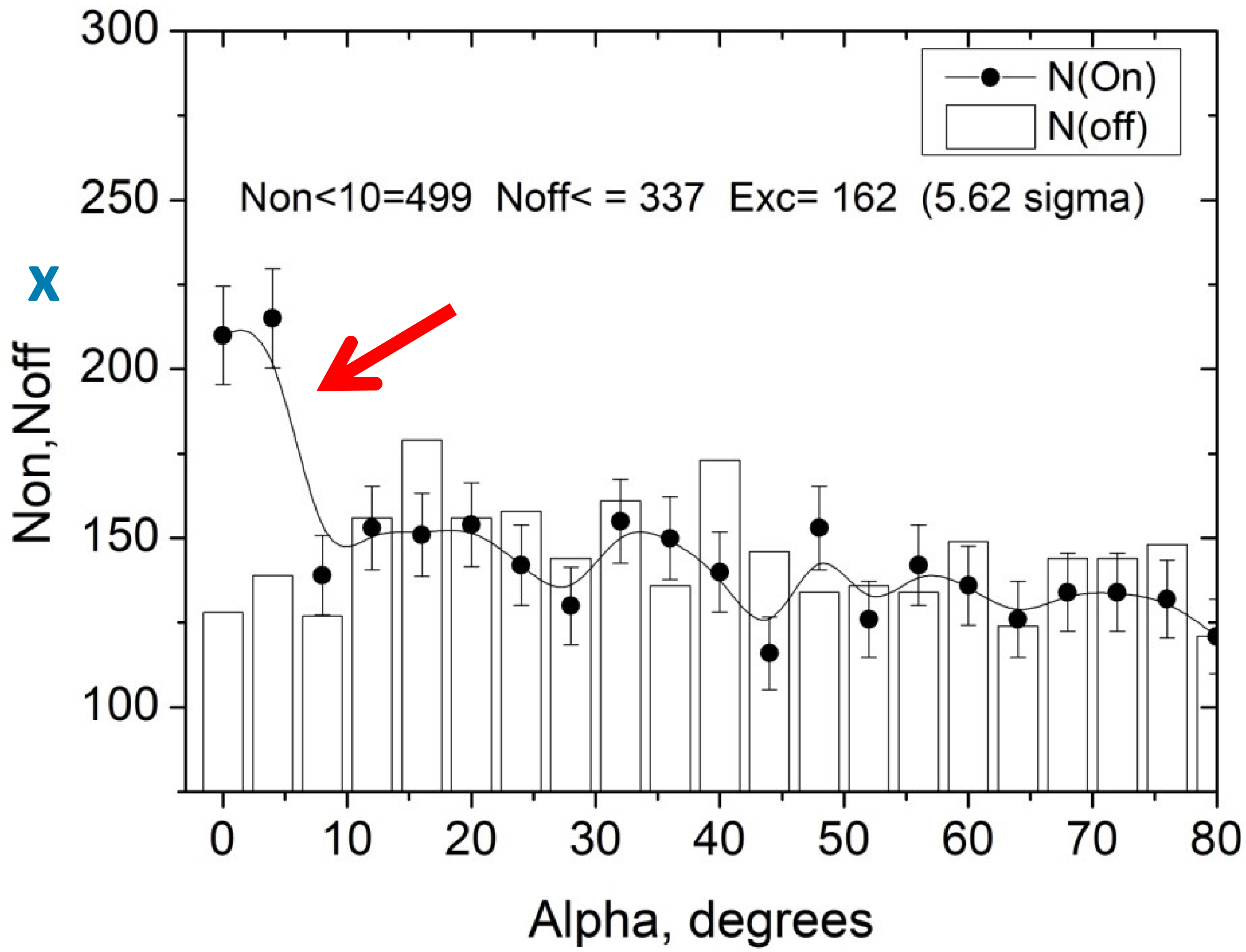
3 small Imaging Telescopes

Stereoscopic operation of the 2 installed IACTs





TAIGA: The Crab at low and high energies



Crab 5-50 TeV, one IACT,
~6σ at 5-50 TeV

(preliminary)

Also seen at > 50 TeV (HiSCORE + one IACT)

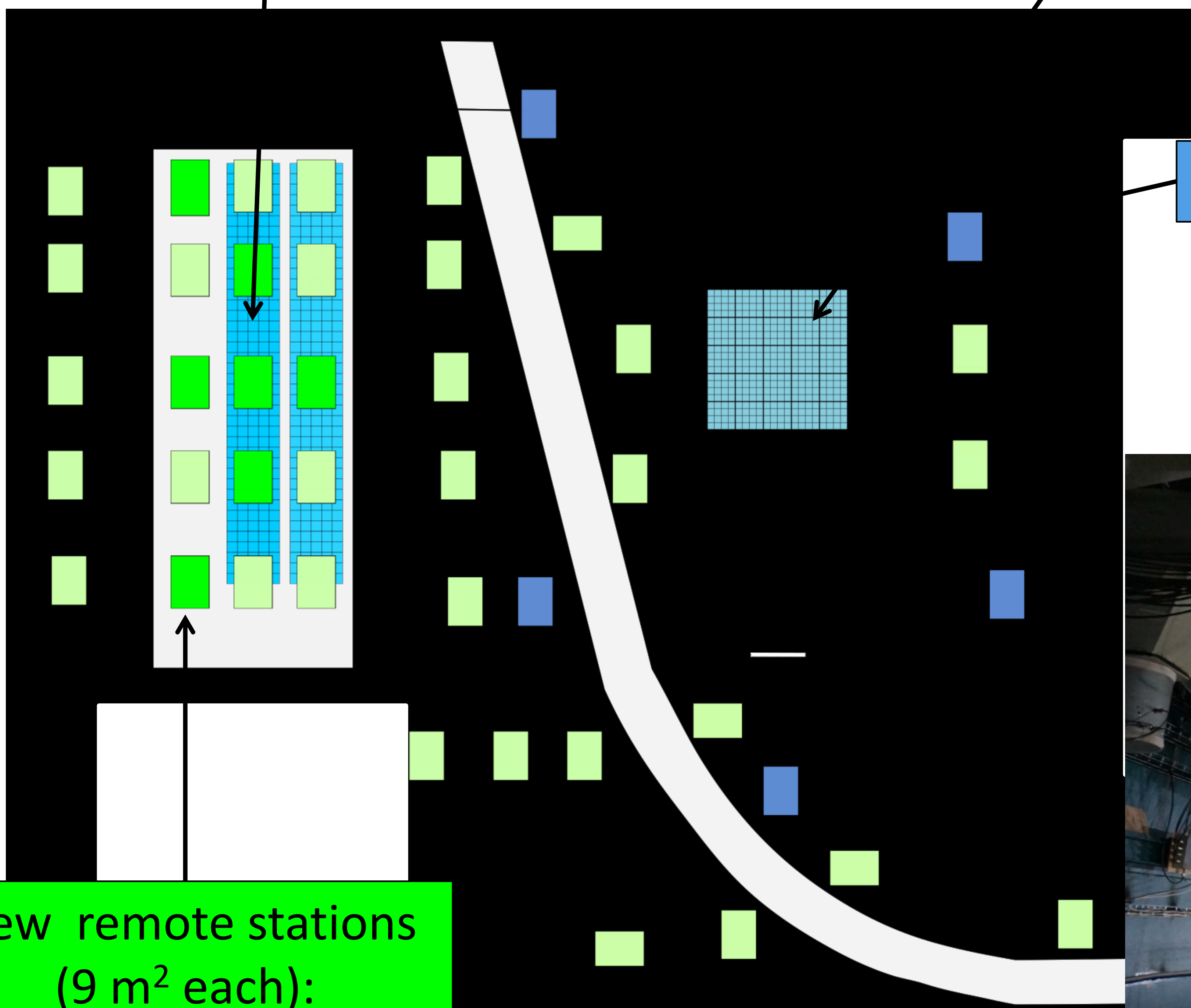
+2 more sources ….

Carpet-2 → Carpet-3 100 – 10,000 TeV

Muon Detector: plastic scintillator counters, 410 m^2, $E_\mu \geq 1$ GeV

400 liquid scintillation counters (200m^2)

5 remote stations (9 m^2 each)



New remote stations (9 m^2 each):
9 scintill. counters - ready to work

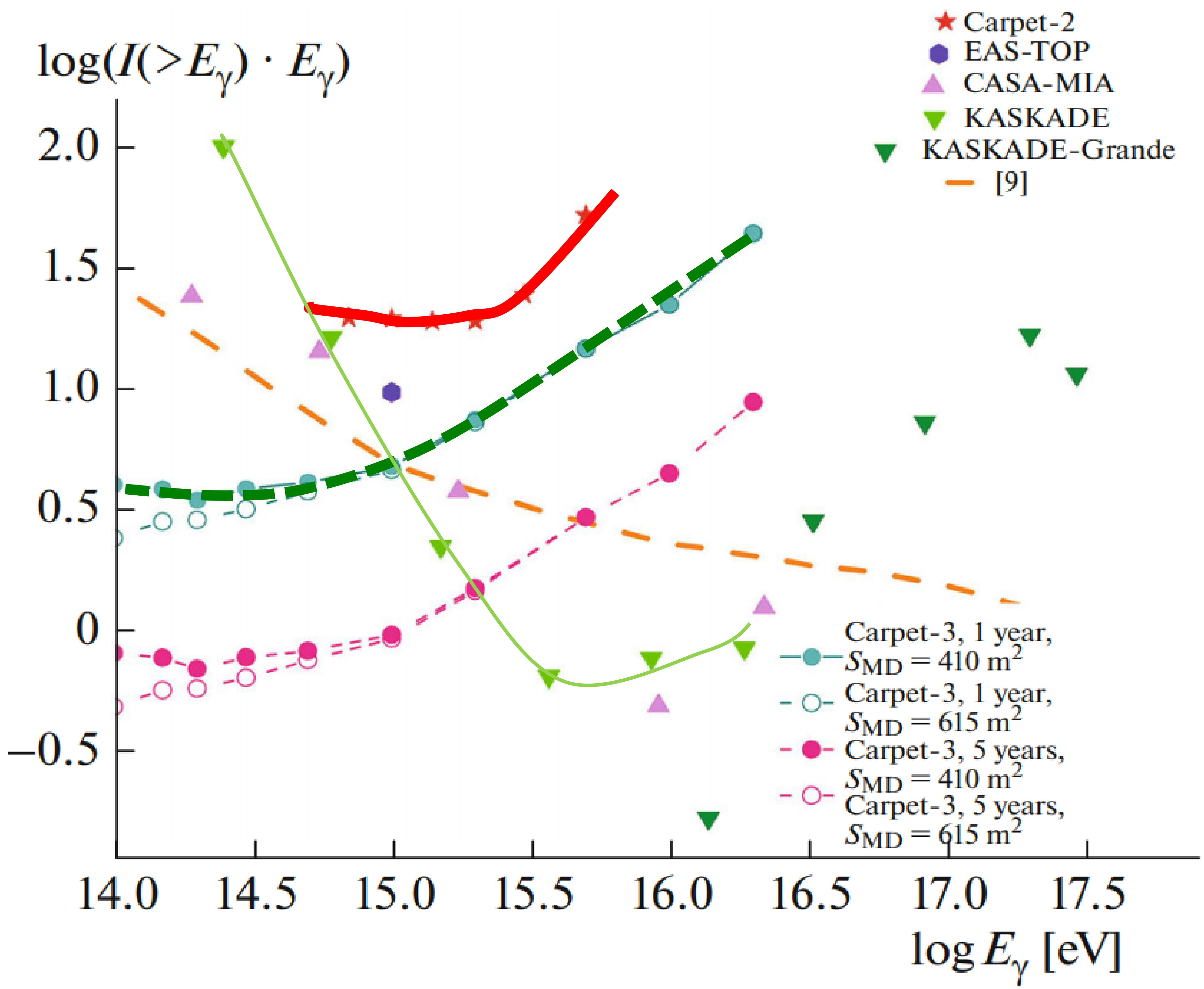
Future remote stations - ready to work by end of 2021

1st tunnel of muon detector

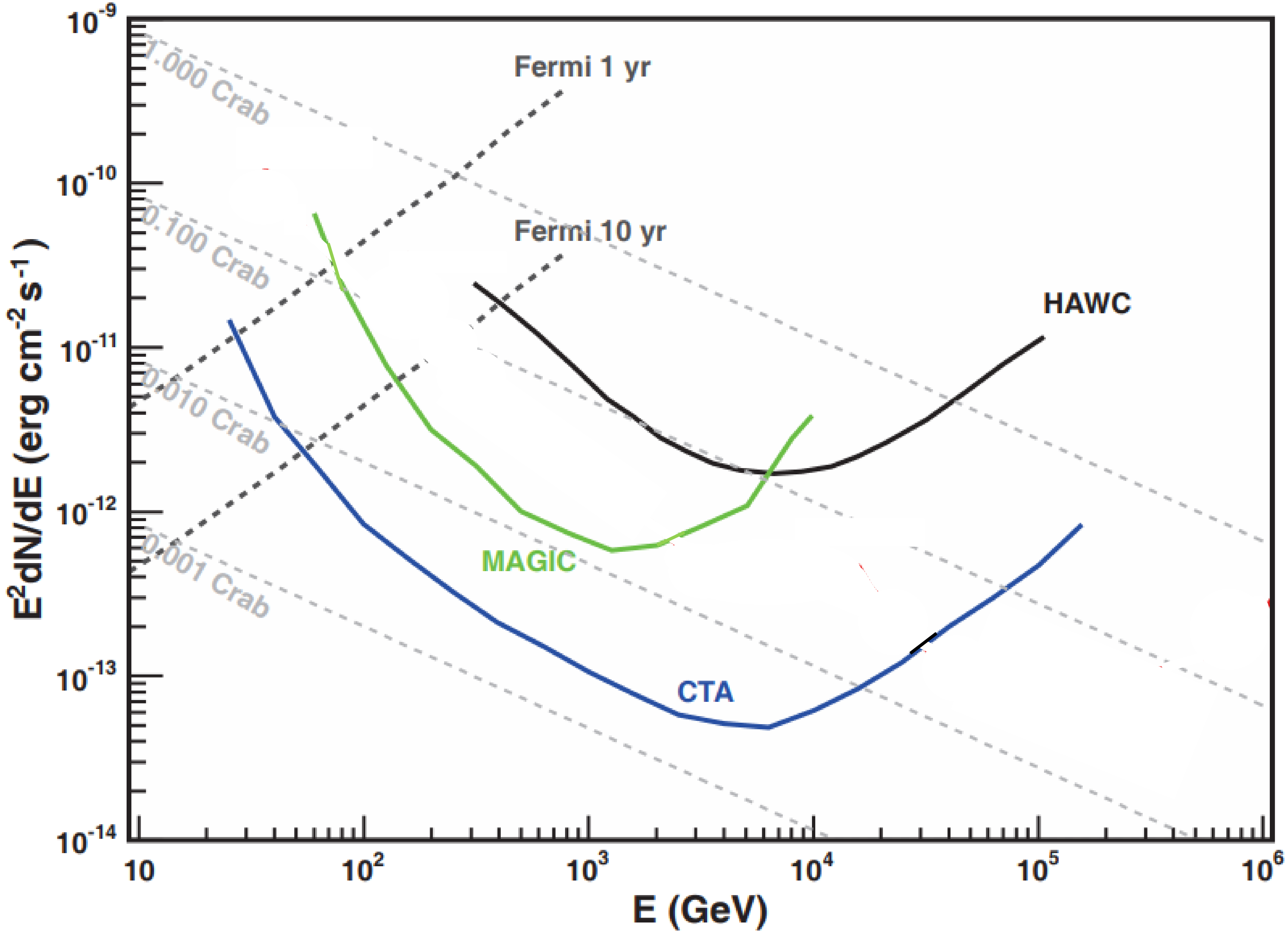
175 m² → 410 m² → 615 m²

Carpet-2 100 – 10,000 TeV, diffuse γ flux

Search for muon-poor showers: Limits on the diffuse γ flux

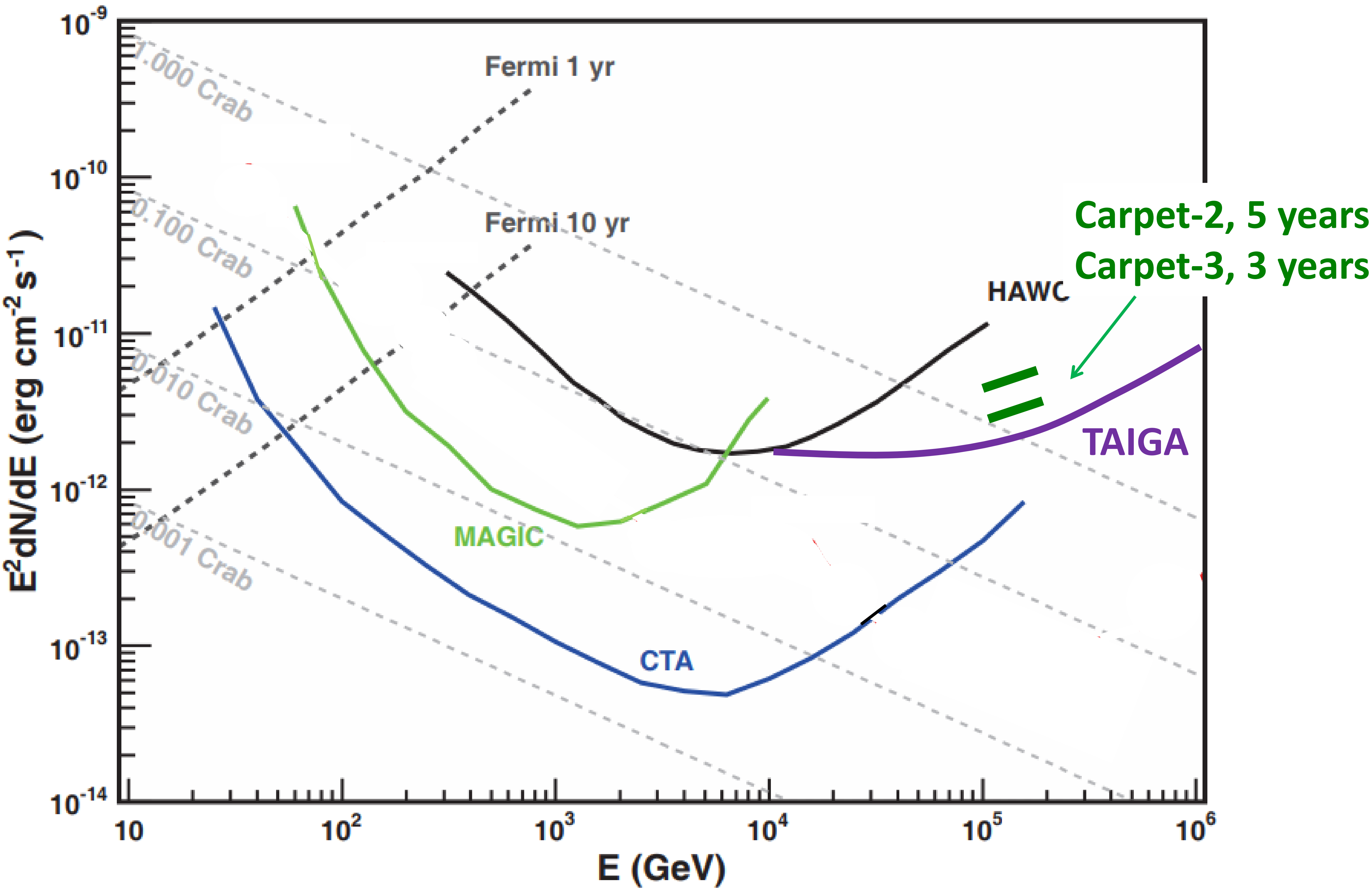


Detection potential for point sources (>5σ)



Detection potential (>5σ)

curves for TAIGA/Carpet inserted by C.S. !



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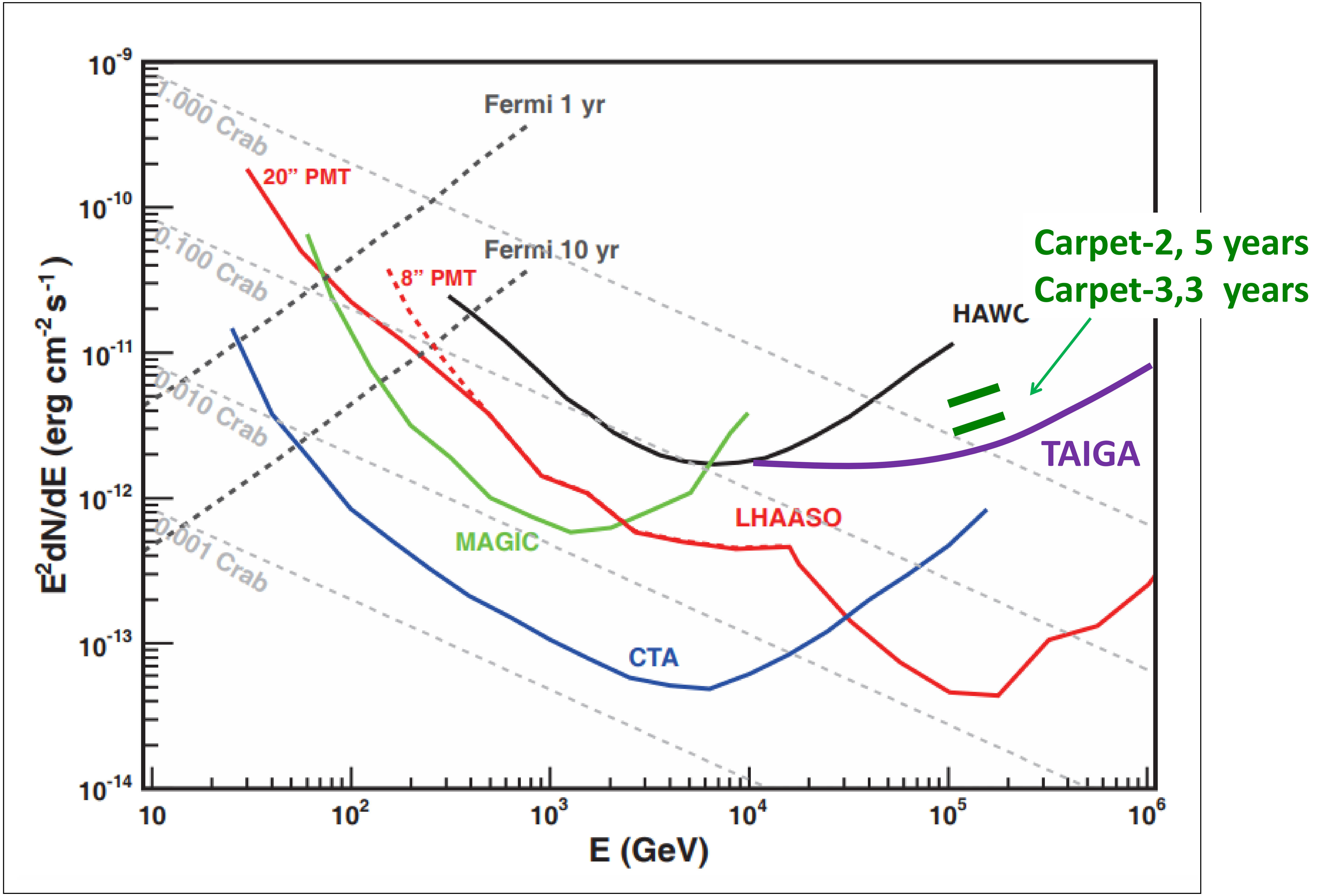
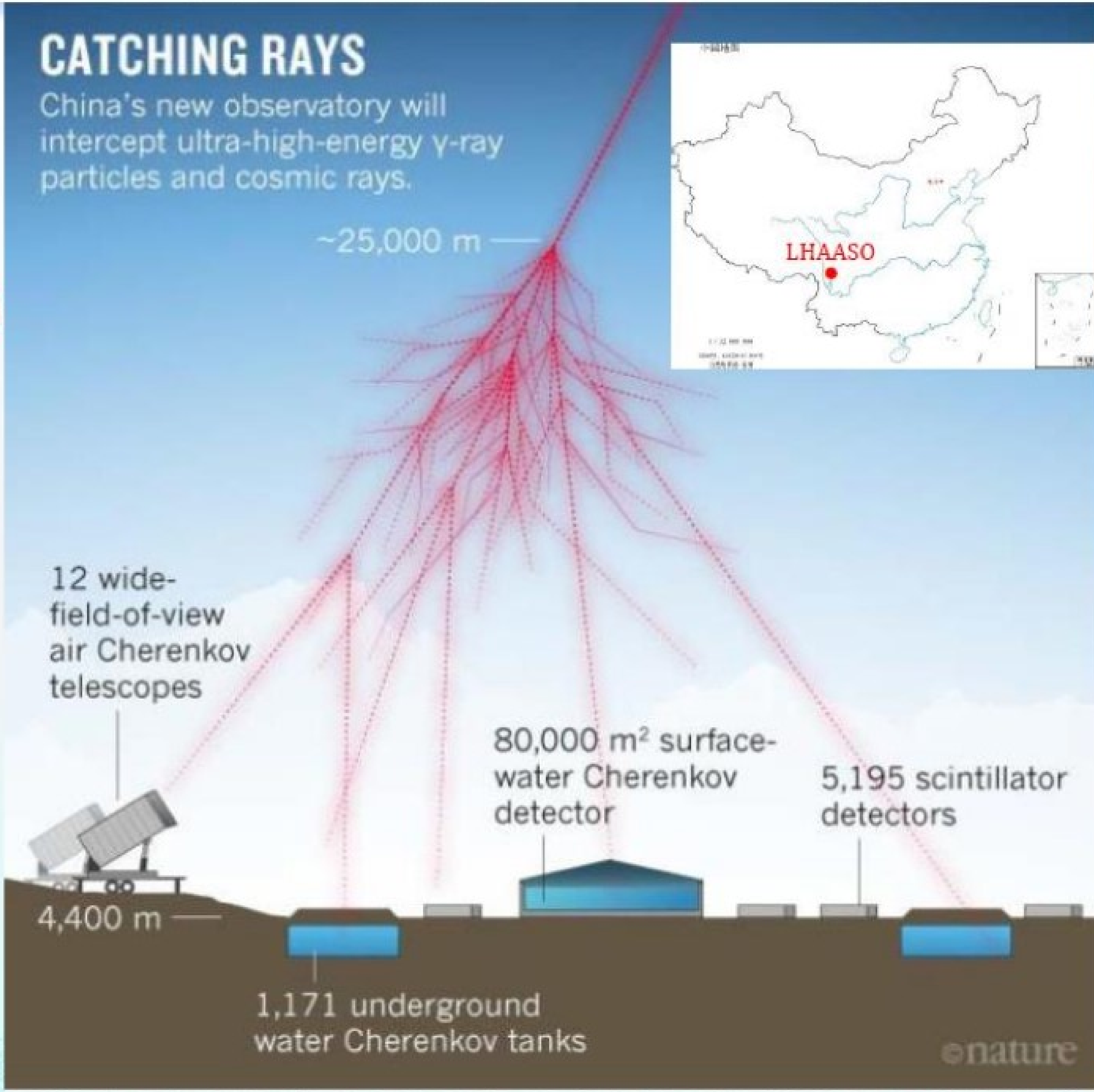


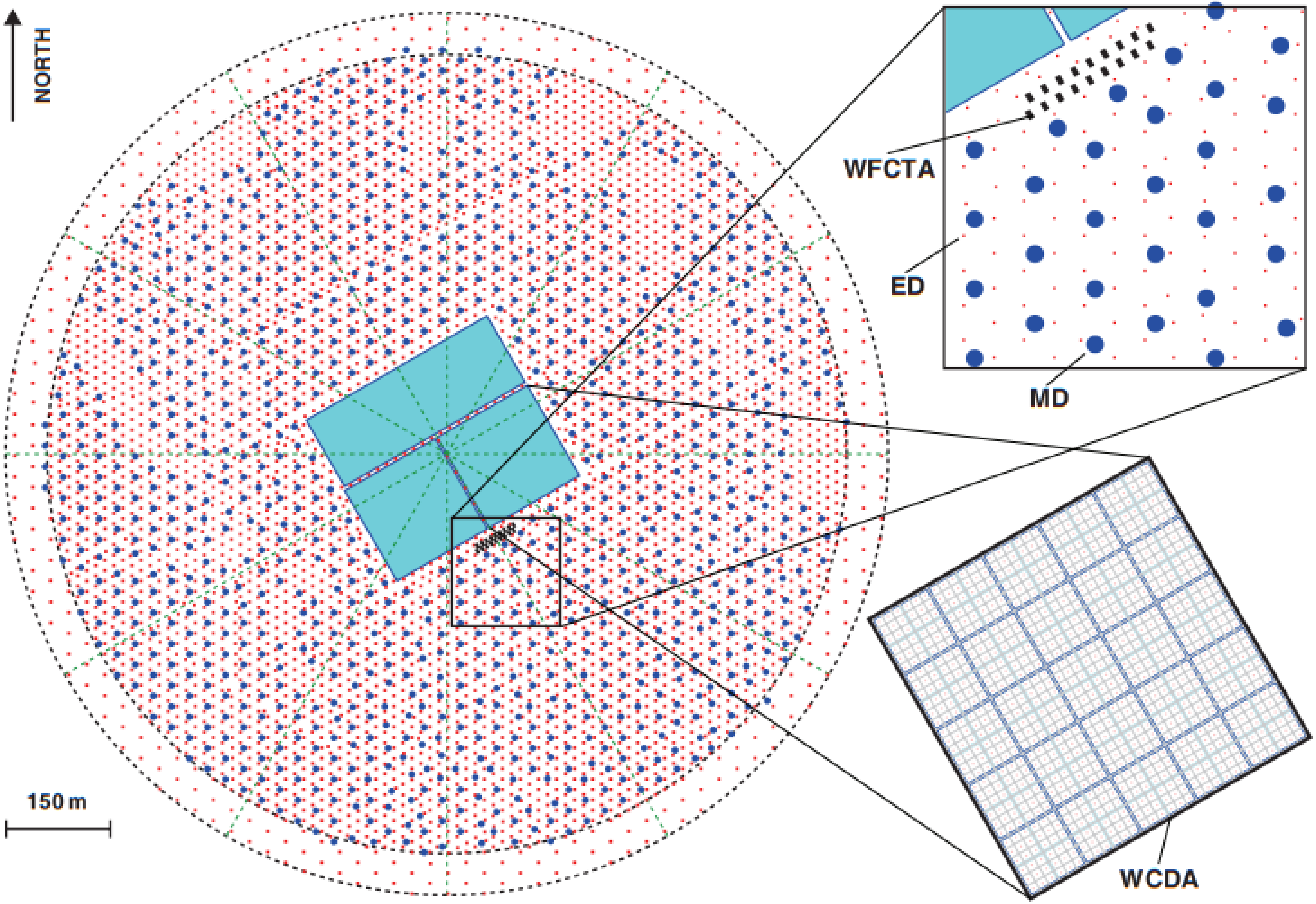
LHAASO
高海拔宇宙线观测站

LHAASO

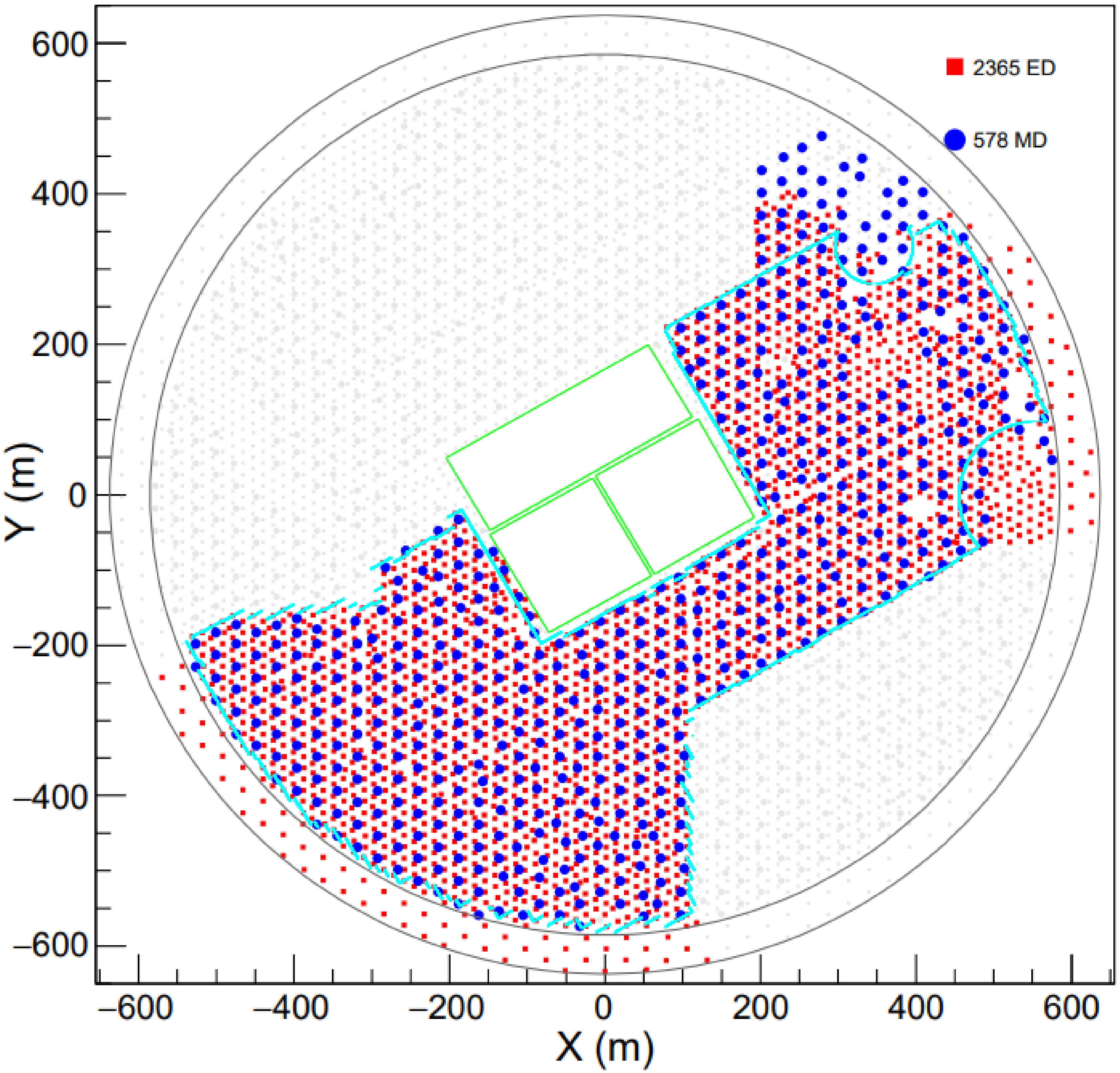
in the eyes of reporters from Nature



LHAASO

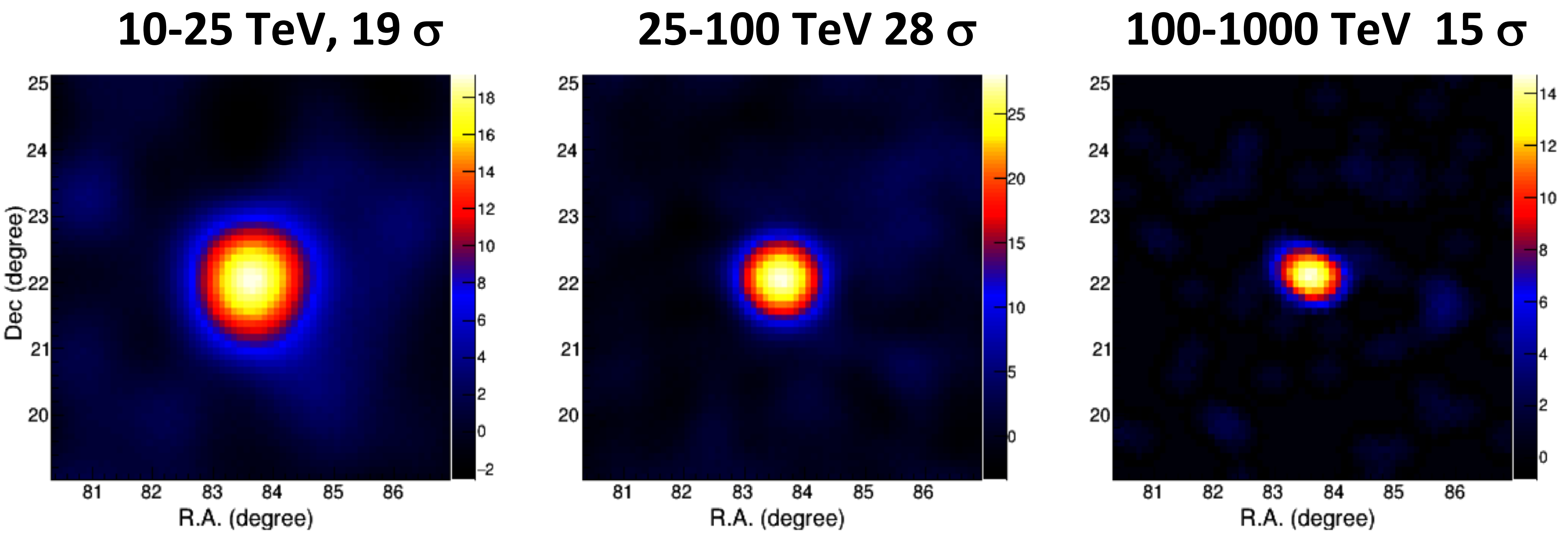


LHAASO: first results



Crab Nebula and first PeVatrons

Crab Nebula



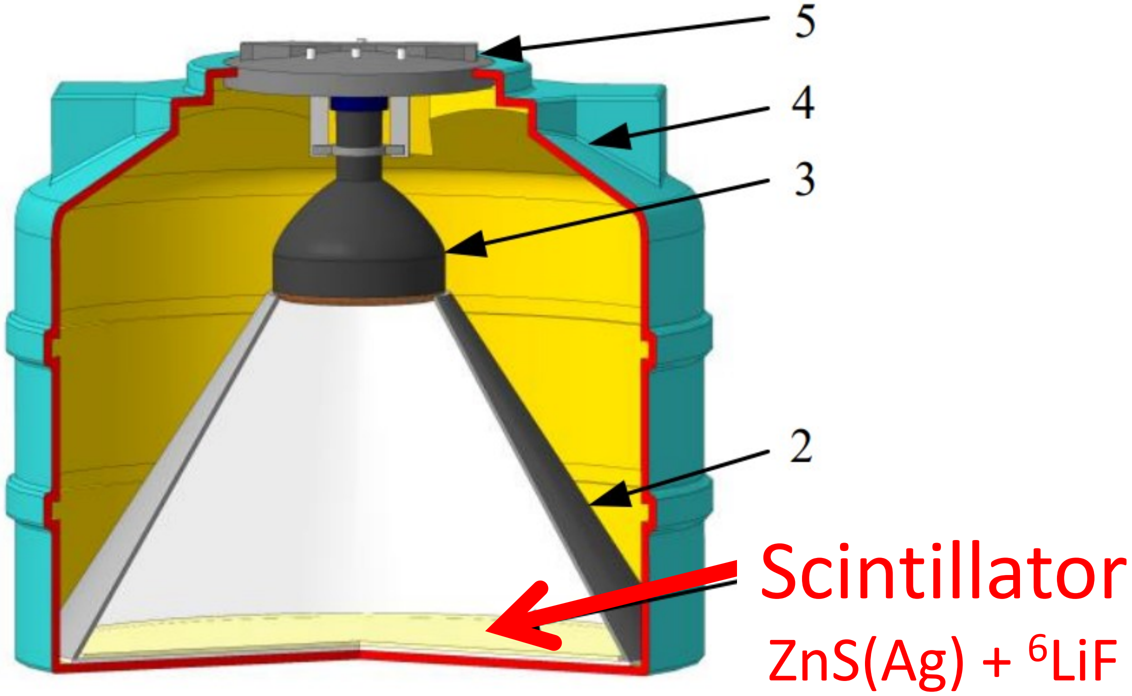
Plus 10 other sources, including one reported with <u>maximum energy 1.14 PeV</u> !

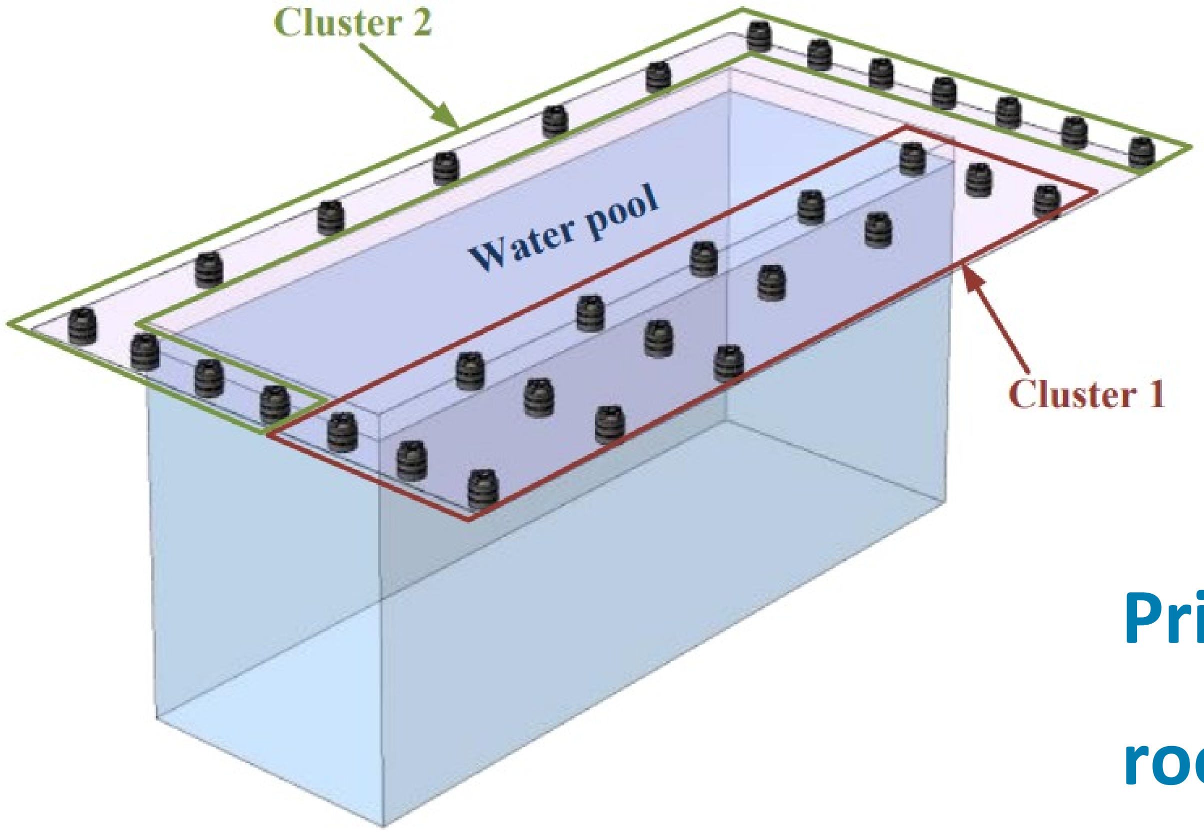
→ **LHAASO spoeksperson „The Galaxy is full of PeVatrons“**

Start of a new era in gamma astronomy?

PRISMA counters in LHAASO Yu. V. Stenkin et al.

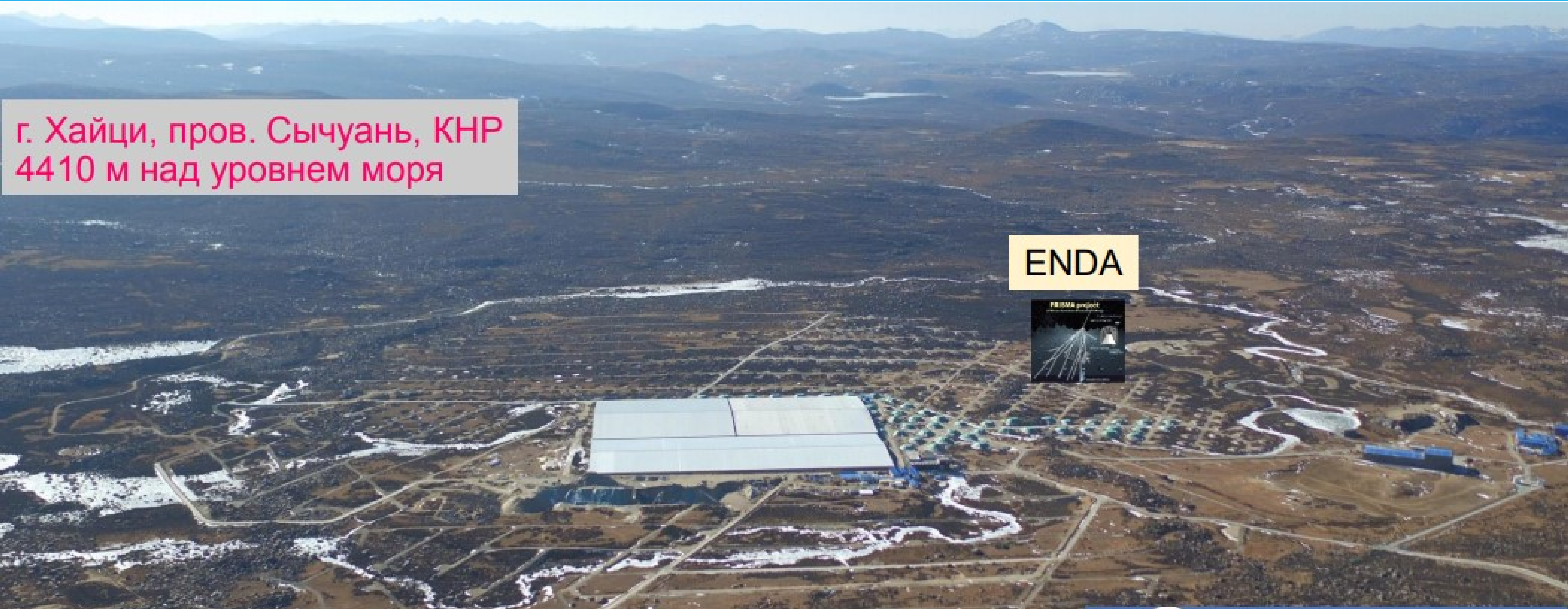
- **Measure the hadron component through thermal neutrons** (plus electrons)
- **Thin scintillator sensitive to thermal neutrons and charged particles**
- **400 detectors over 100 × 100 m²**

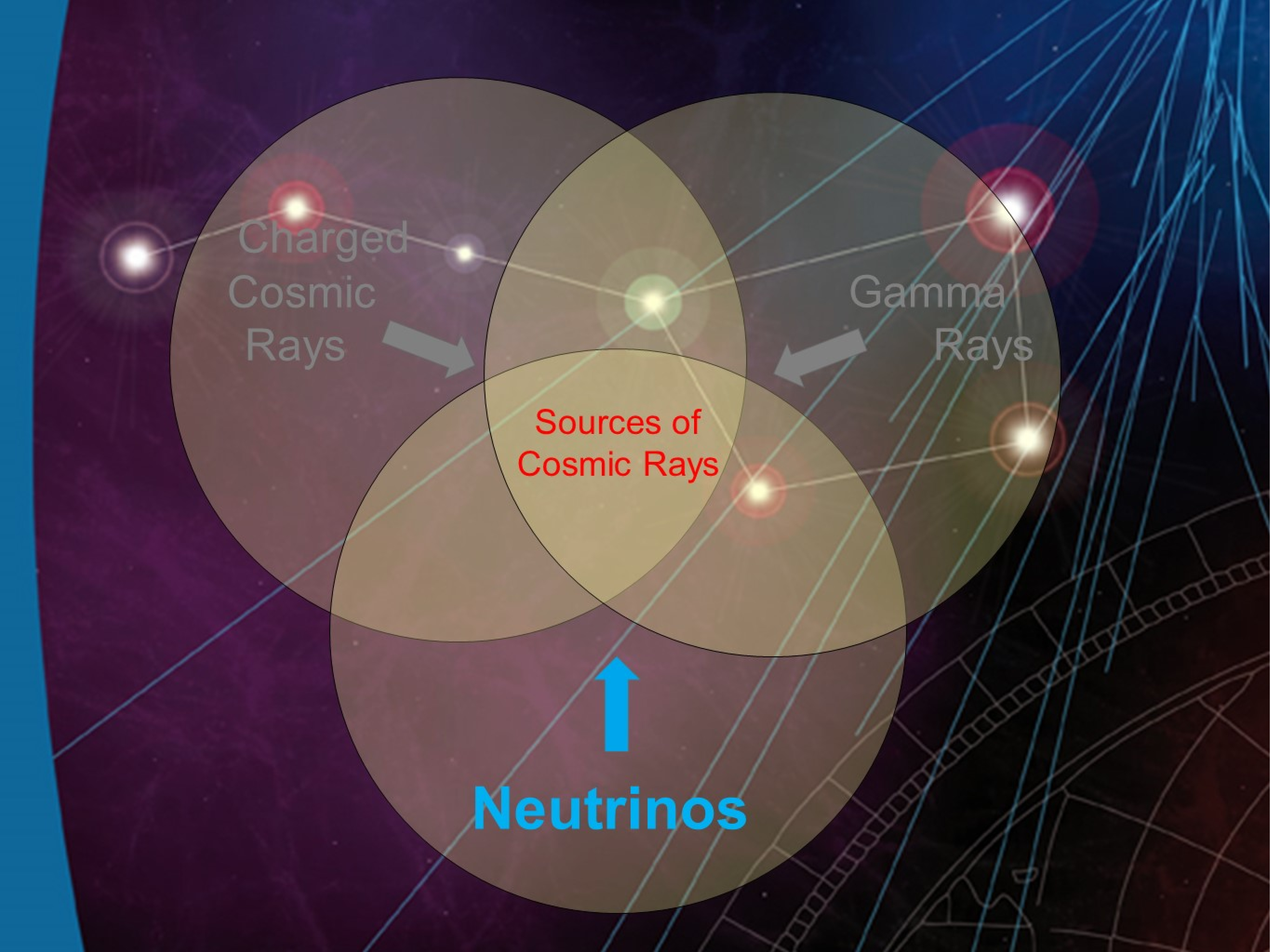




Principle of PRISMA operating on the roof of NEVOD (MEPhI)

ENDA – Electron-Neutron Detection Array




Charged
Cosmic
Rays
Gamma
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Sources of
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Neutrinos

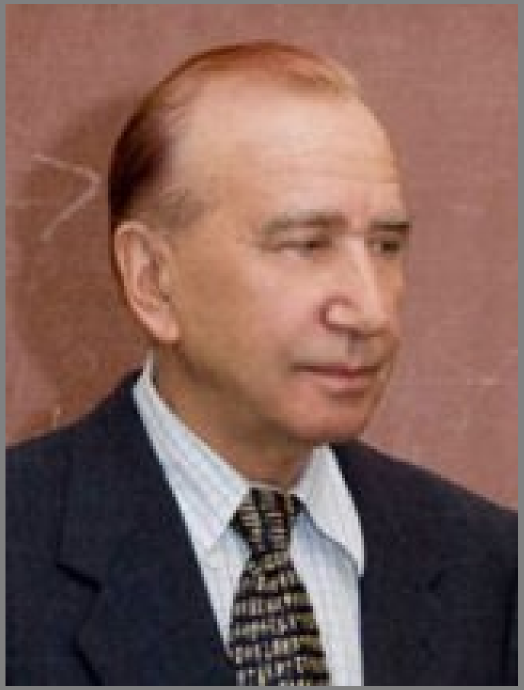
Moisej Markov

1960

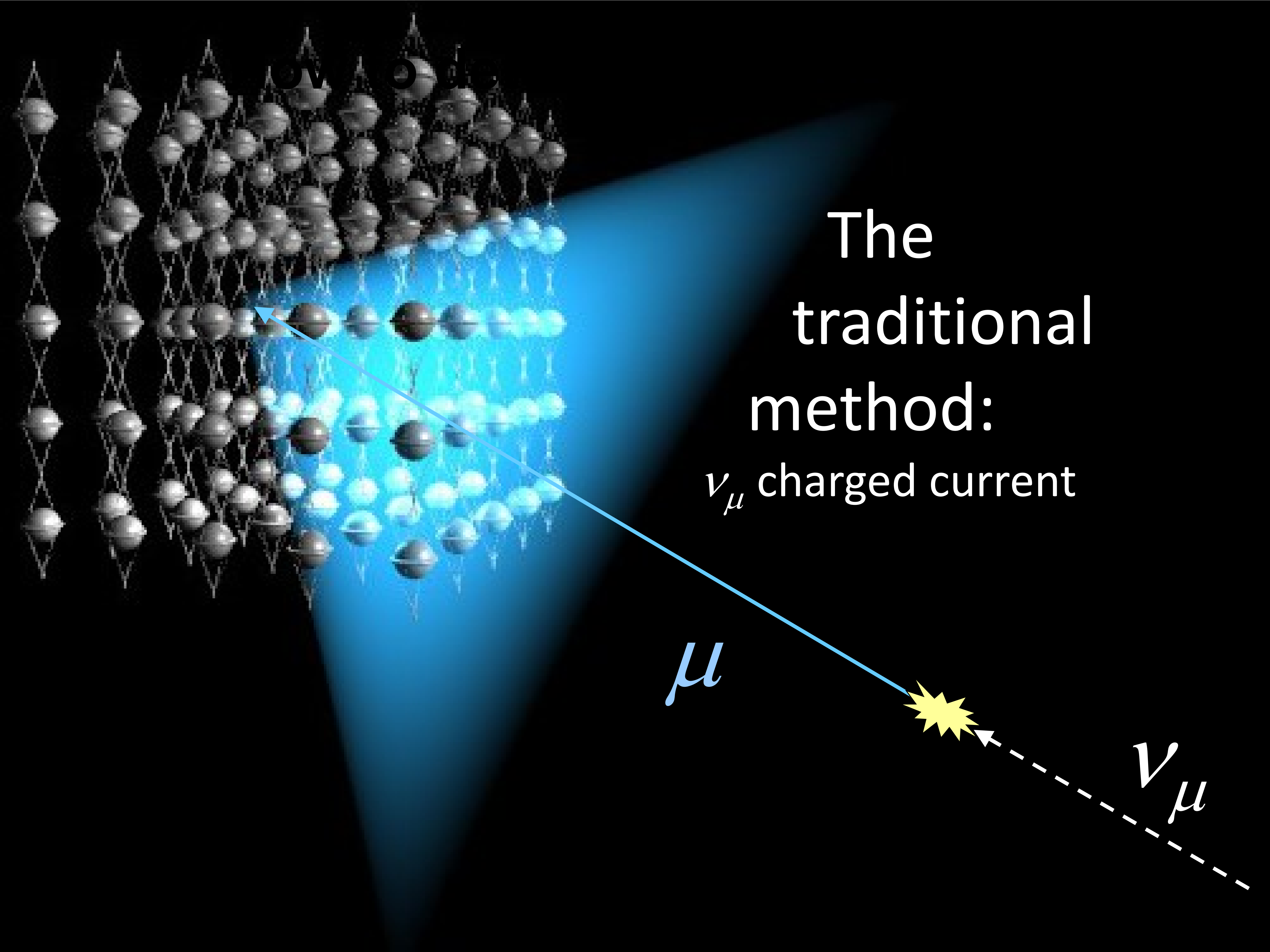
Proposal to detect C-light from charged particles in open water

Moisej Markov

Igor Zheleznykh



Proposal to detect C-light from charged particles in open water


The traditional method:
ν_μ charged current
μ
ν_μ

From atmospheric to cosmic neutrinos

1961

Markov & Zhelesnykh and Zatsepin & Kuzmin publish first reliable flux calculations for atmospheric neutrinos

1965

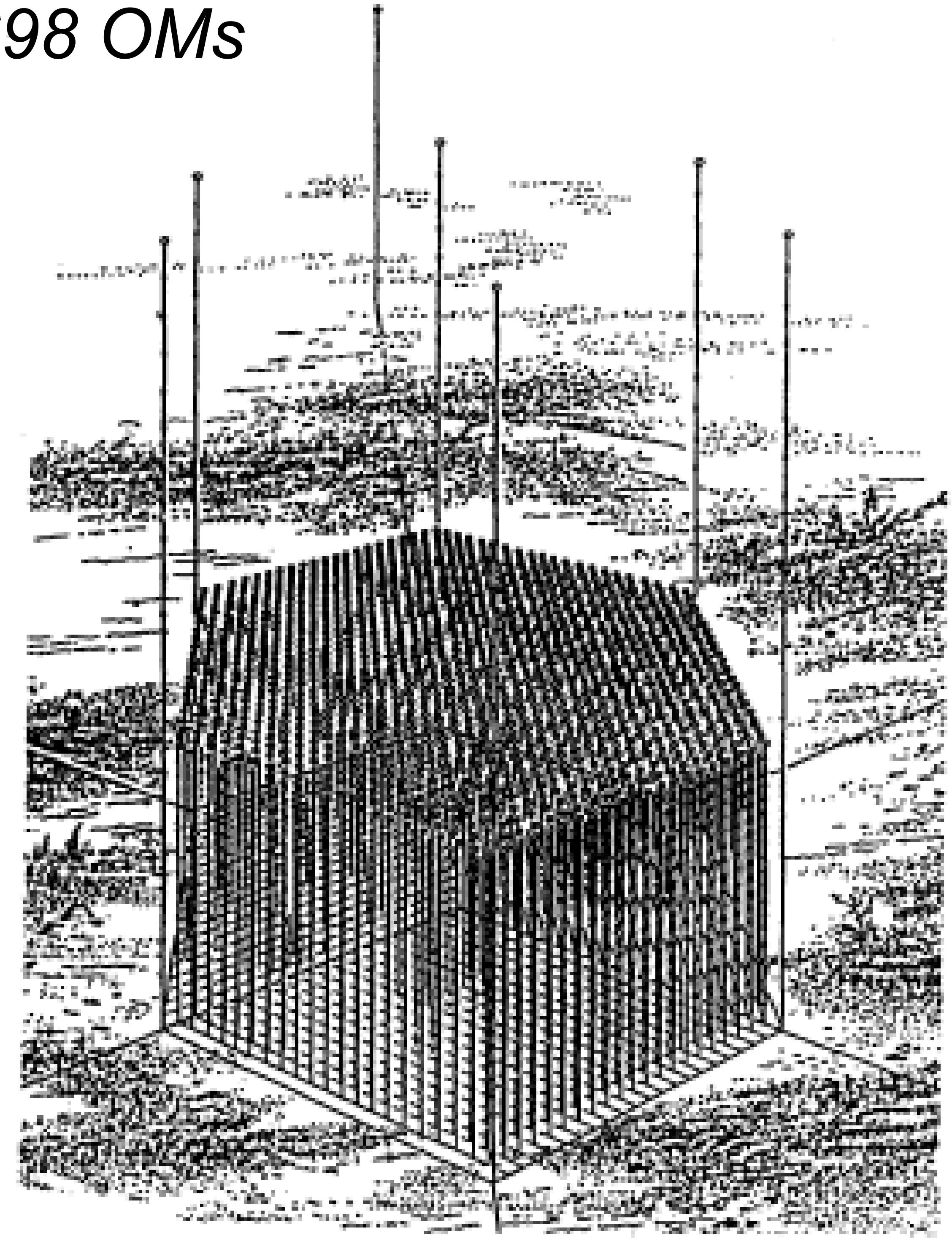
Discovery of atmospheric neutrinos in underground detectors (South Africa, India)

1969

Berezinsky & Zatsepin calculate neutrino flux from GZK process p + γ_{3K}

DUMAND (Pacific close to Hawaii)

1978: 1.26 km³
22,698 OMs



- Conceptually strong participation of USSR
- *Chudakov, Petrukhin, Bezrukov, Berezinsky, …*
- End of Soviet participation 1980

1980
Exploration Baikal

1995:

- Experiment terminated

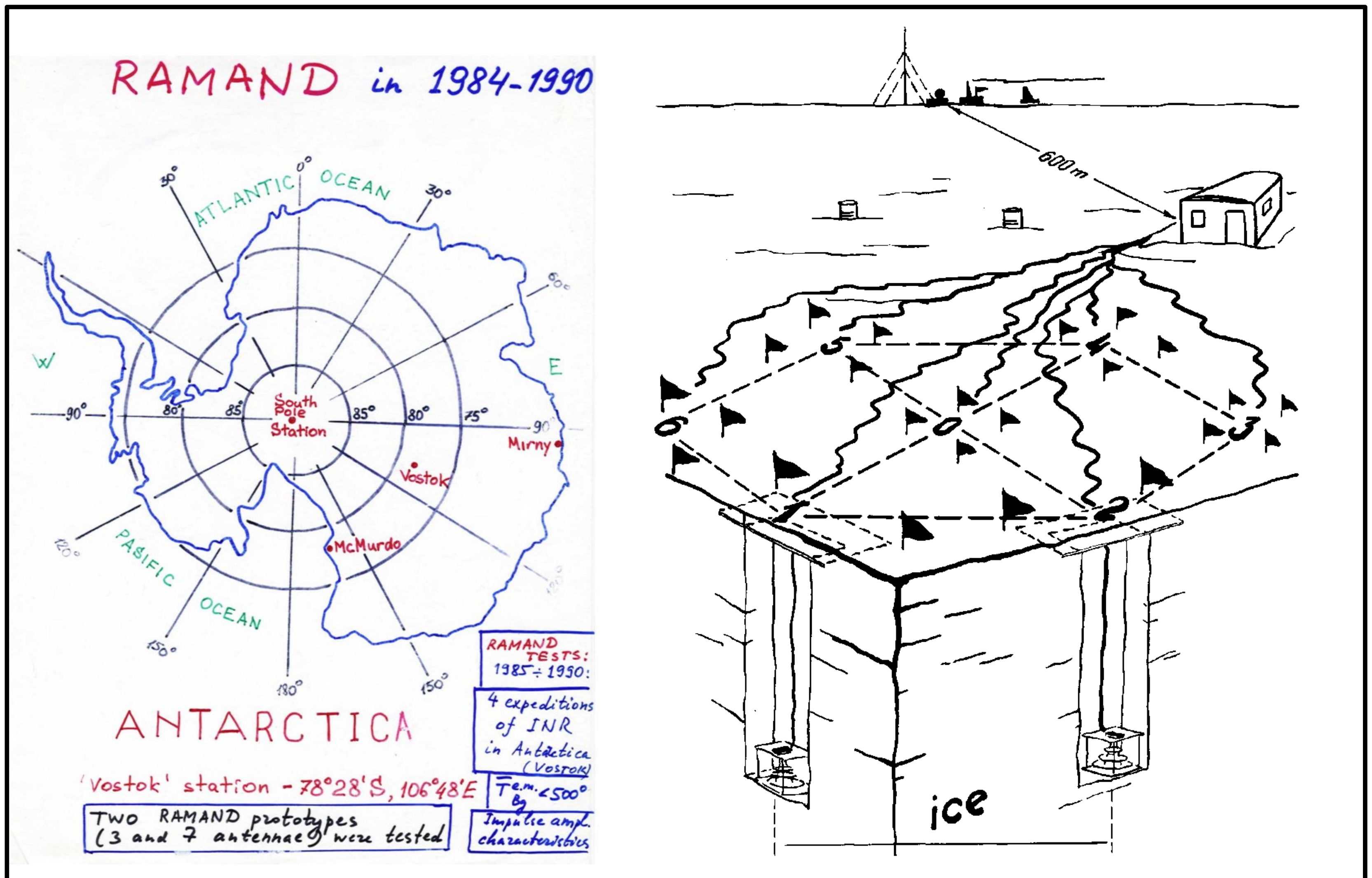
New Methods for >100 PeV (I. Zhelesnykh)

- **Radio Neutrino Detection in Antarctica (RAMAND)**
- **Radio Neutrino Detection with radio telescopes**
- **Hydro-Acoustical Neutrino Detection**

New Methods for >100 PeV (I. Zhelesnykh)

- <u>Radio Neutrino Detection in Antarctica (RAMAND)</u>
- Radio Neutrino Detection with radio telescopes
- Hydro-Acoustical Neutrino Detection

RAMAND:



Now being realized as future part of IceCube !

New Methods for >100 PeV (I. Zhelesnykh)

- Radio Neutrino Detection in Antarctica (RAMAND)
- Radio Neutrino Detection with radio telescopes
- Hydro-Acoustical Neutrino Detection

Radio-astronomy method for detecting neutrinos and other elementary particles of superhigh energy

R. D. Dagkesamanskiĭ and I. M. Zheleznykh
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow; Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 10 August 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **50**, No. 5, 233–235 (10 September 1989)

The possibility of using radio telescopes to detect the radiation of electron-photon and hadron cascades generated in the interactions of neutrinos and other particles of superhigh energy ($\gtrsim 10^{20}$ eV) with the moon and other celestial objects is discussed.

Kalayazhin 64-m radio telescope

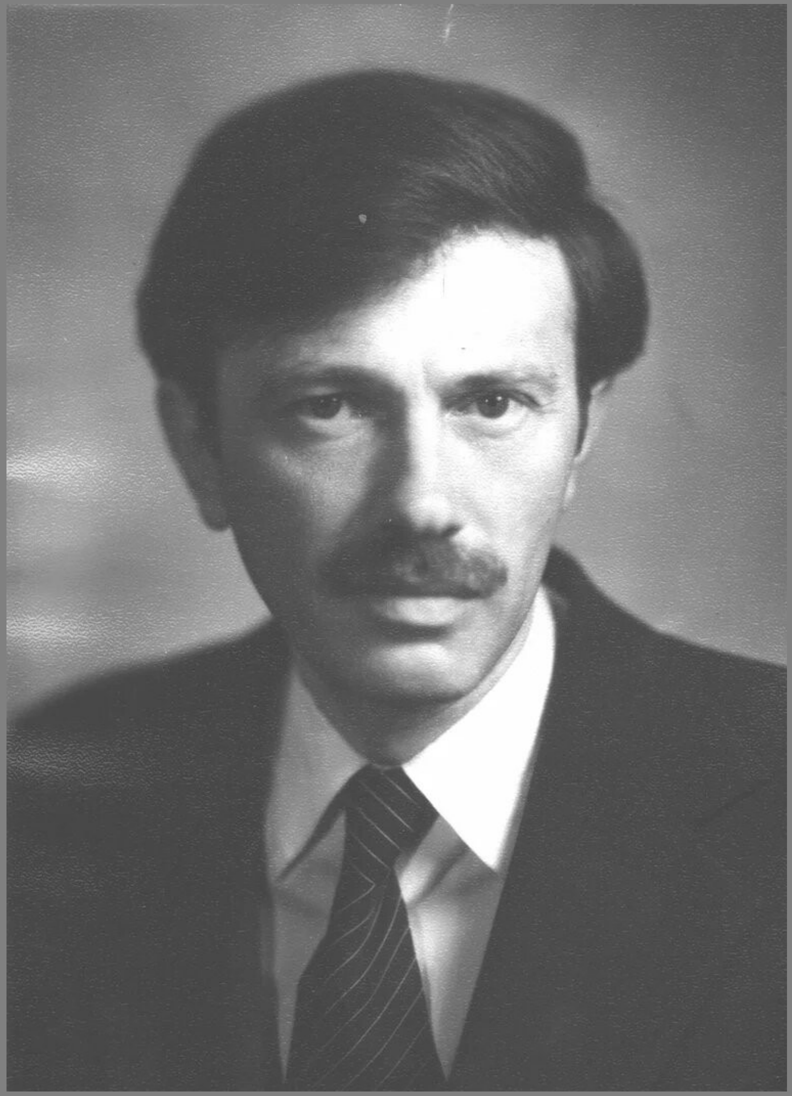
→ upper limits on ν flux at > EeV

1980

Alexander Chudakov proposes Lake Baikal as testbed for a future neutrino telescope

October 1980

Foundation of the Laboratory of High Energy Neutrino Astrophysics (Lake Baikal)



Григорий Владимирович Домогацкий

Lake Baikal

- **Ice as a stable platform for deployment**
- **Crystal-clear water**
- **Sufficient depth**

- Ice as a stable platform for deployment
  → develop technology!
- Crystal-clear water
  → explore!
- Sufficient depth
  → test!

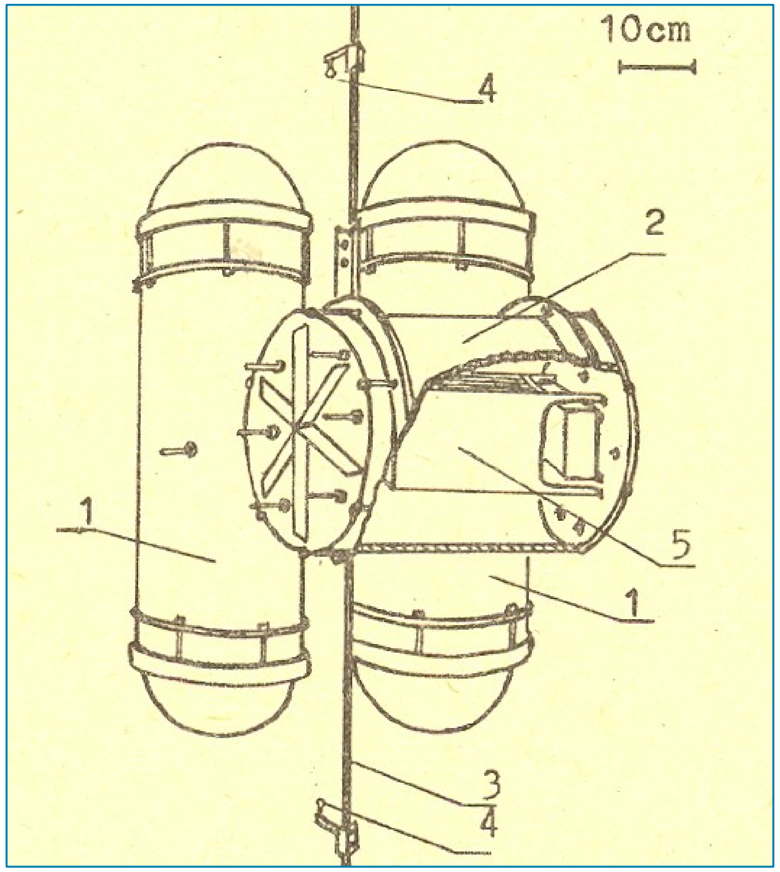
Lake Baikal: the 1980s

- **1984: first stationary string**

  Muon flux measurement

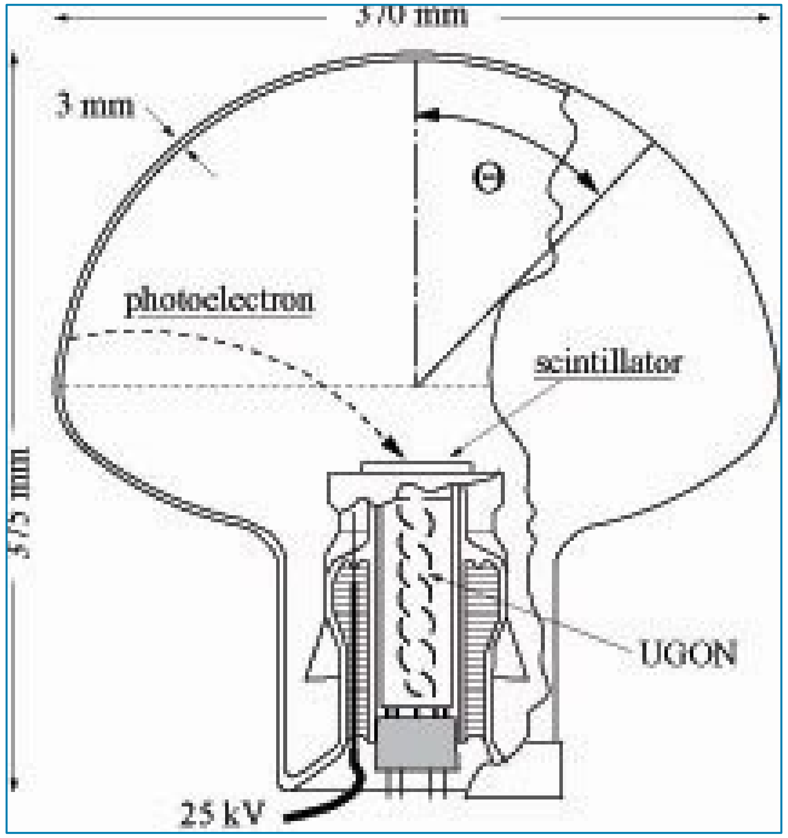
- **1986: second stationary string (Girlyanda 86)**

  Limits on GUT magnetic monopoles



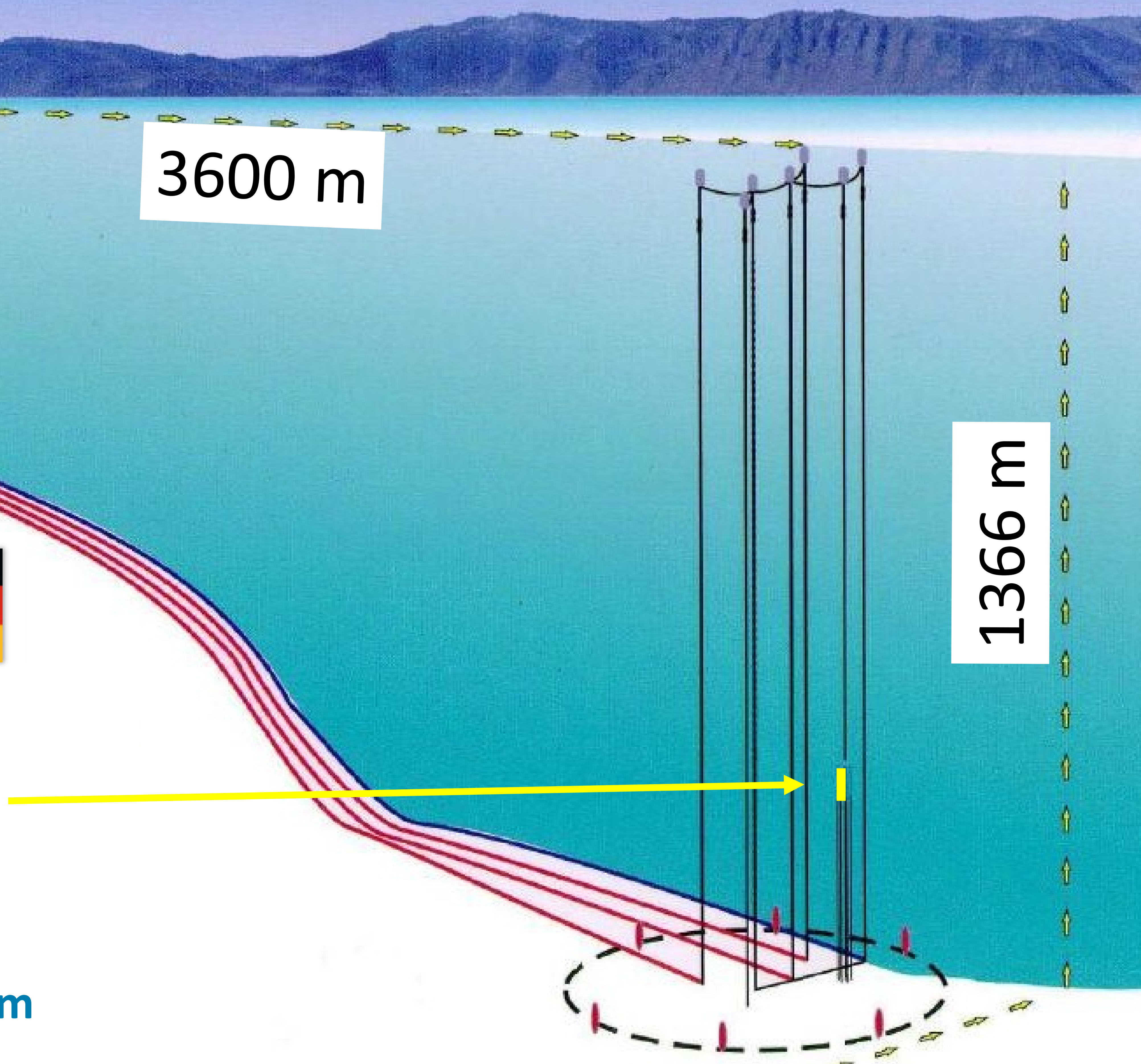
- **Development of a Russian smart phototube (Quasar)**

  L. Bezrukov, B. Lubsandorzhiev



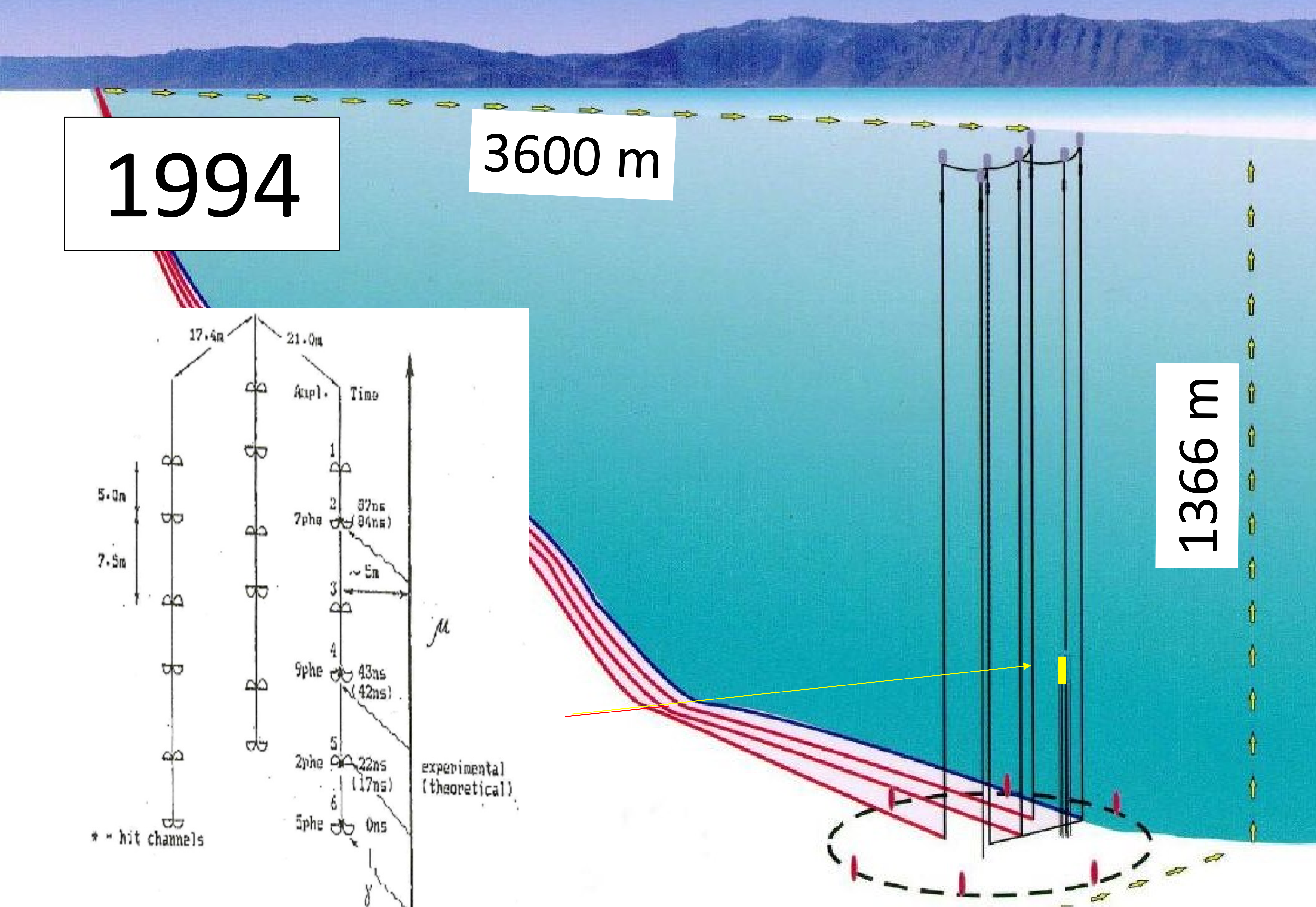
1993 – 1998: construction of NT200

The pioneer: NT200 in Lake Baikal



- 8 strings
- 192 PMTs
- Height 72 m
- Diameter 42 m

The first underwater neutrino events

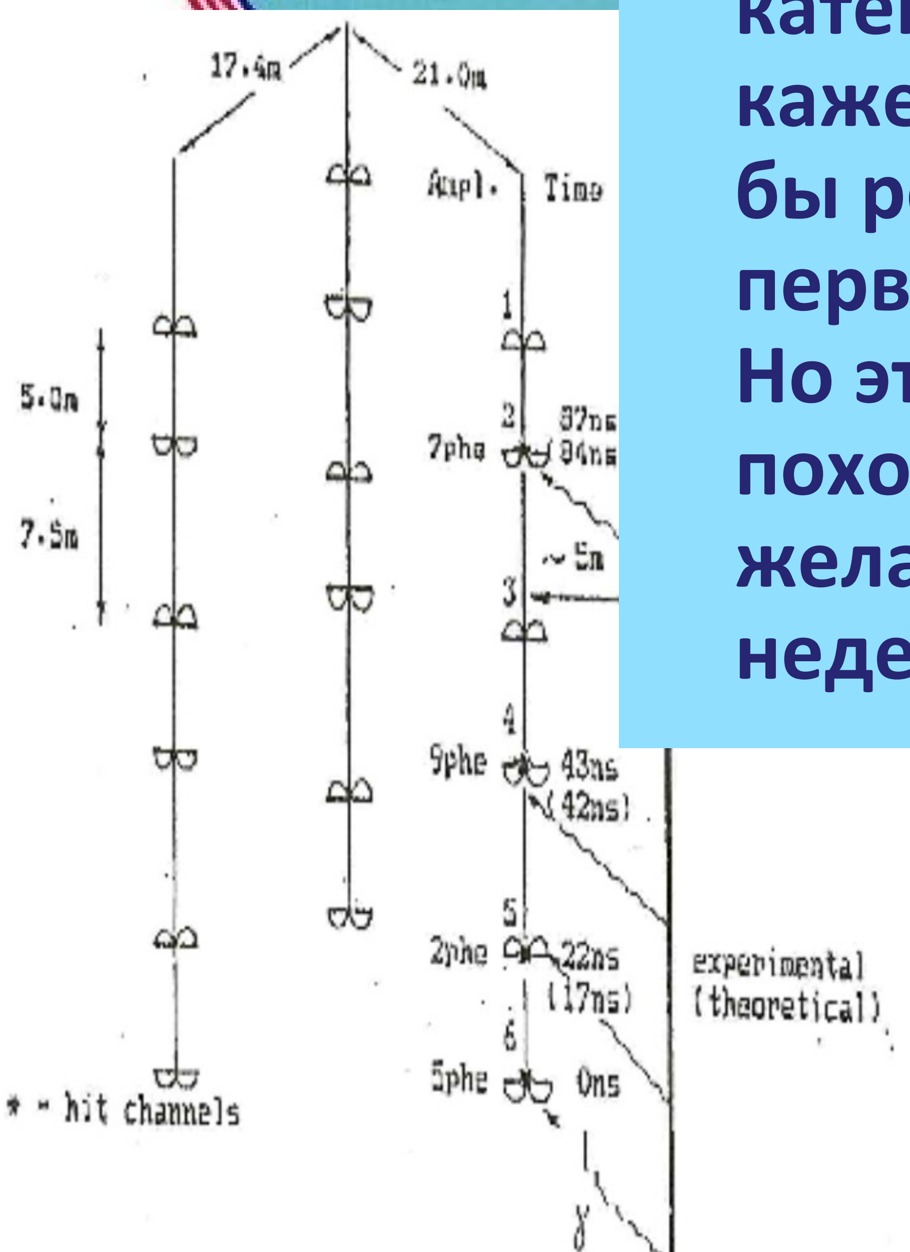


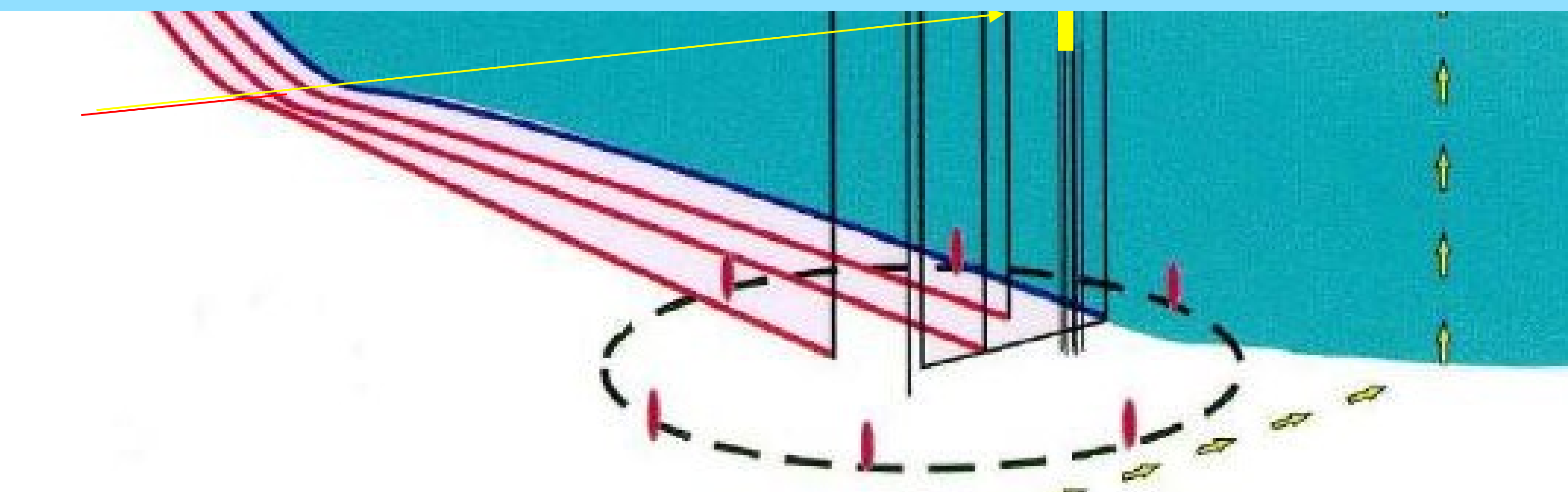
The first underwater neutrino events

1994

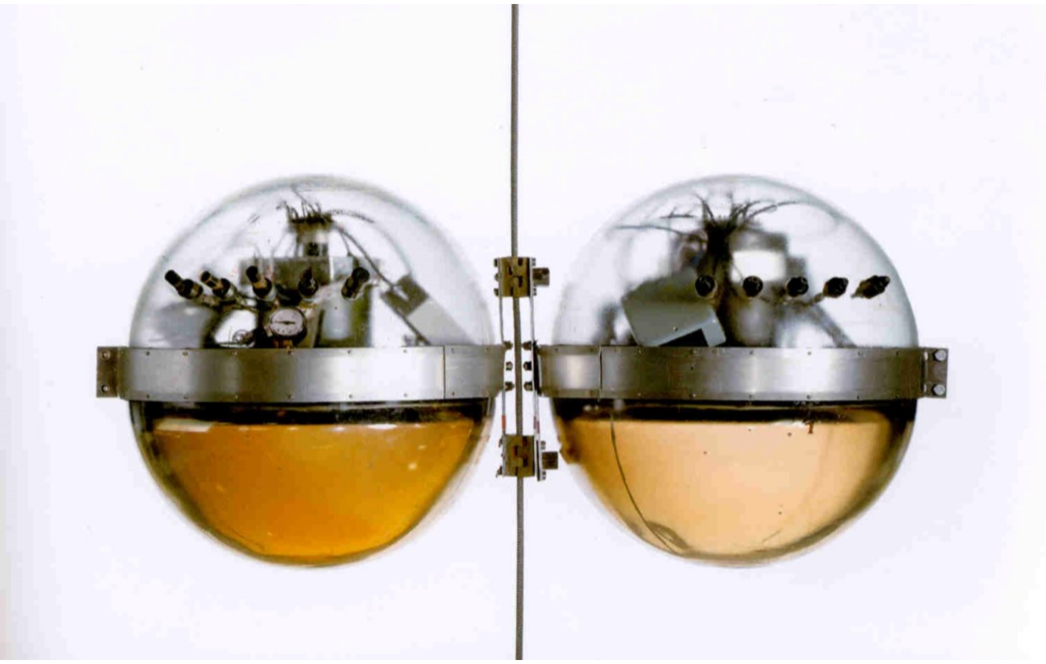
Telefax G.V.Domogatsky to C. Spiering:

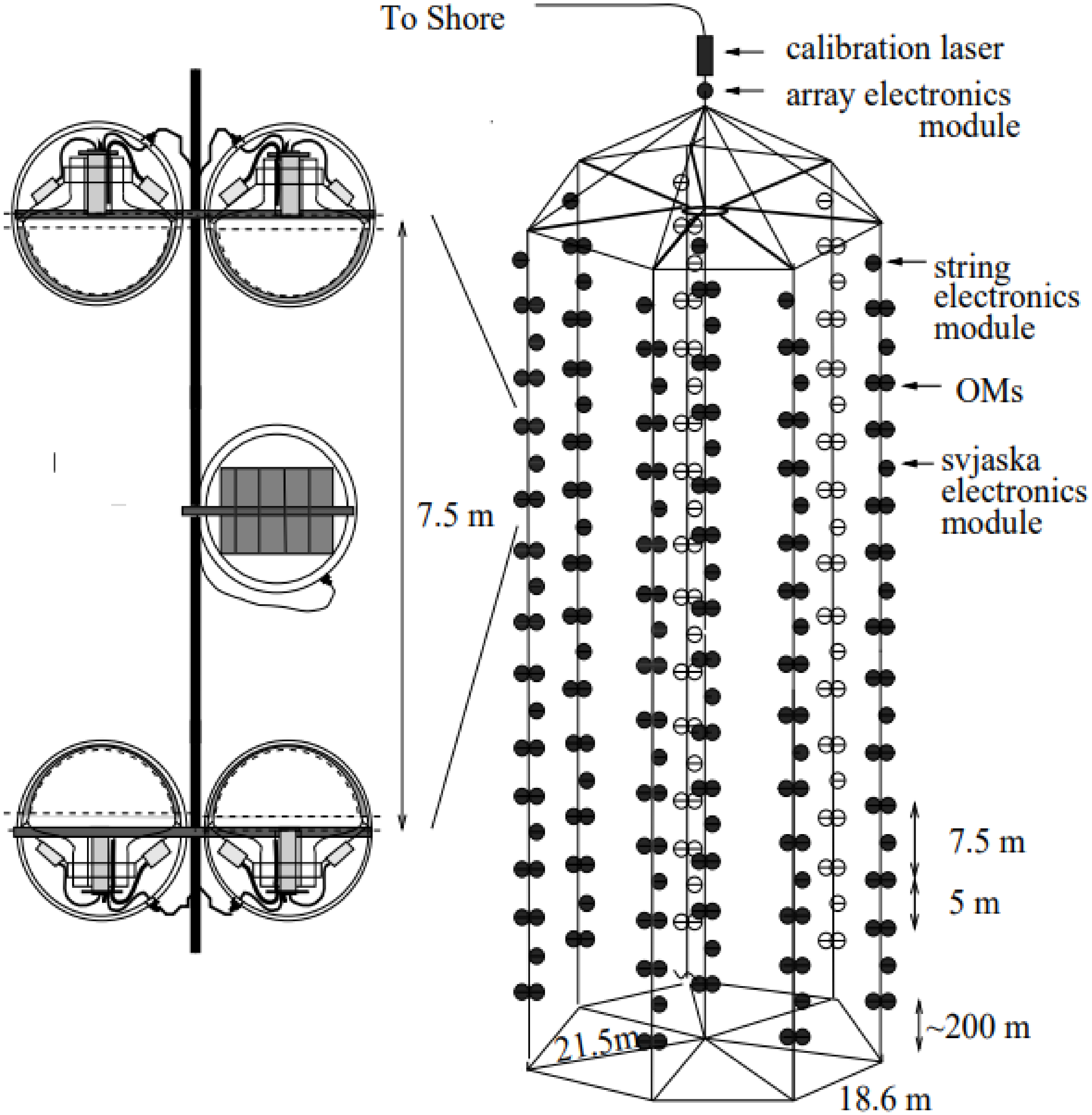
„ Дорогой Кристиан, сначала самое интересное: При анализе данных 1994ого года одно событие категорически сопротивляется всем тестам, и кажется это нейтрино. Естественно, я не хотел бы решать, декларируем ли мы это событие как первое ясное нейтрино в подводном детекторе. Но это можно называть очень на нейтрино похожем событием, и мне кажется, что очень желательно сообщить об этом через 2 или 3 недели достаточно широкой общественности."





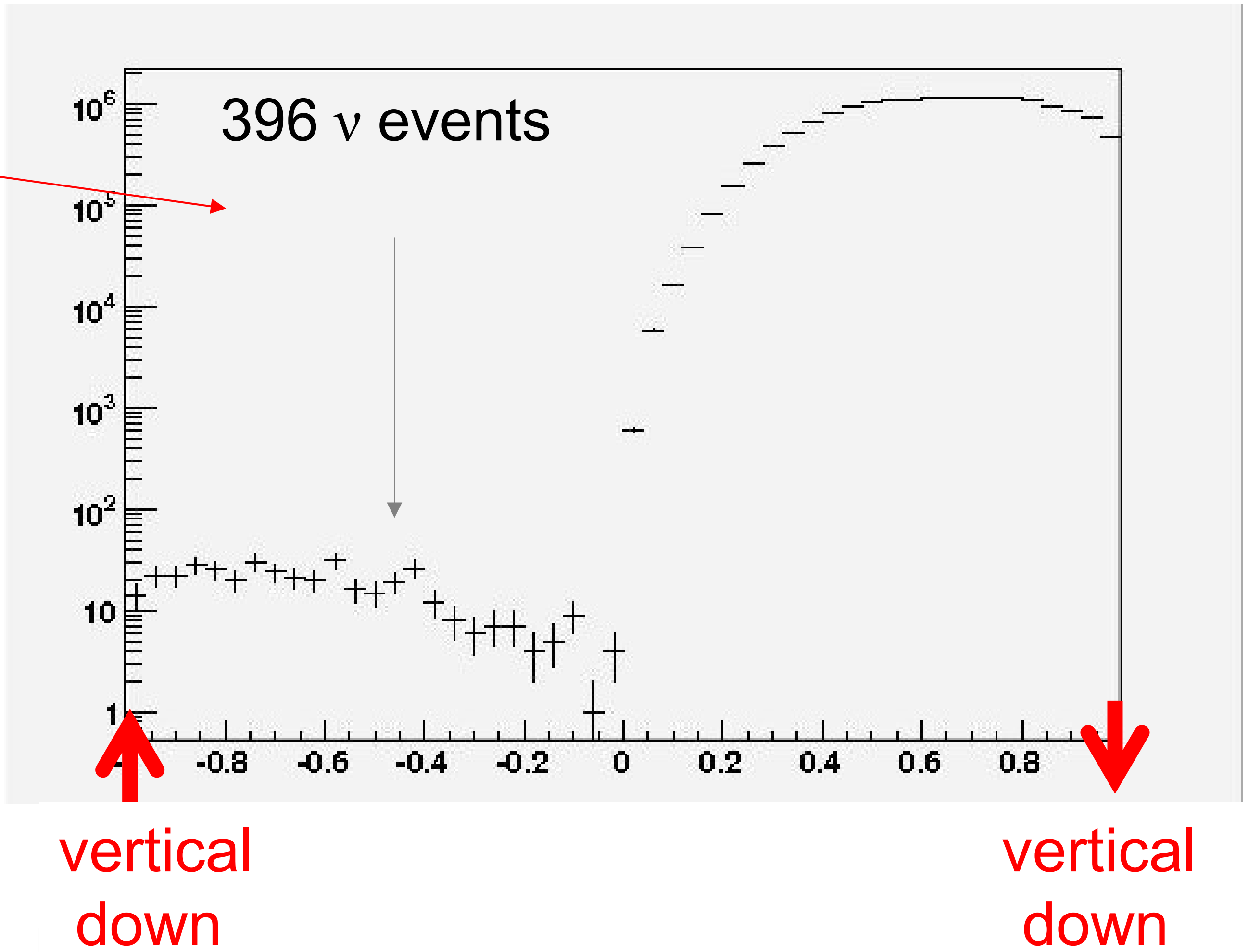
NT200




To Shore
calibration laser
array electronics module
string electronics module
OMs
svjaska electronics module
7.5 m
7.5 m
5 m
~200 m
21.5m
18.6 m

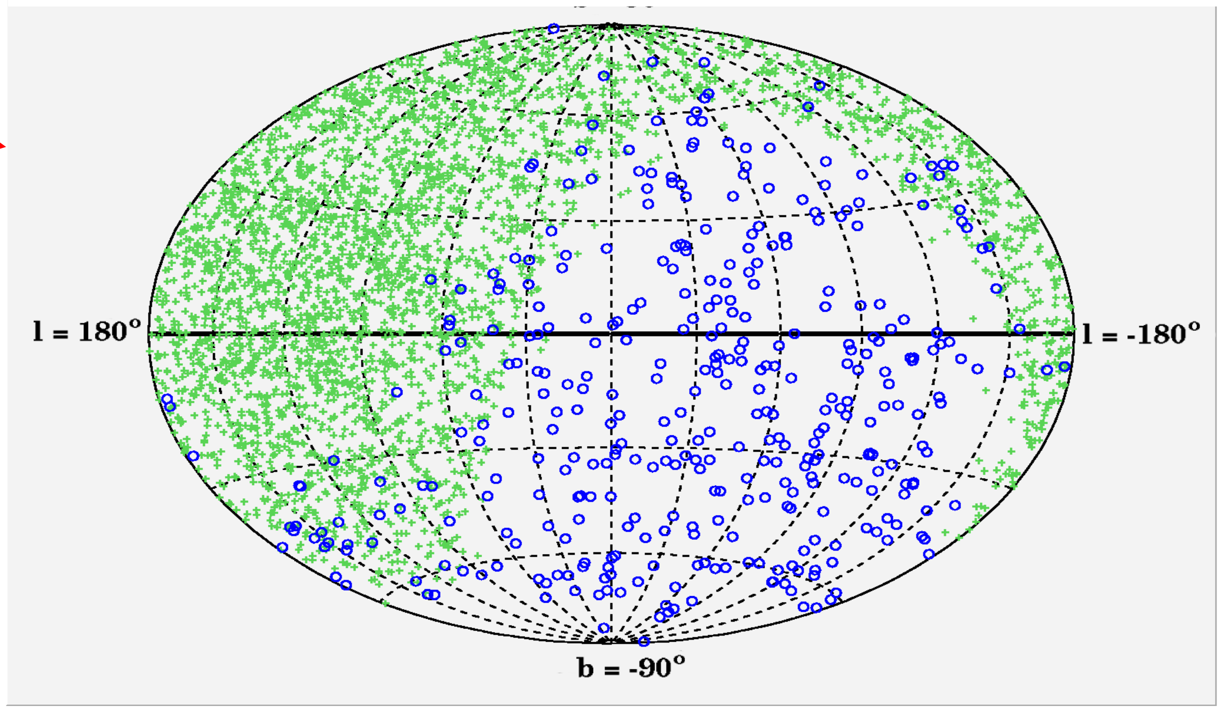
NT200: results

- Atmospheric neutrinos



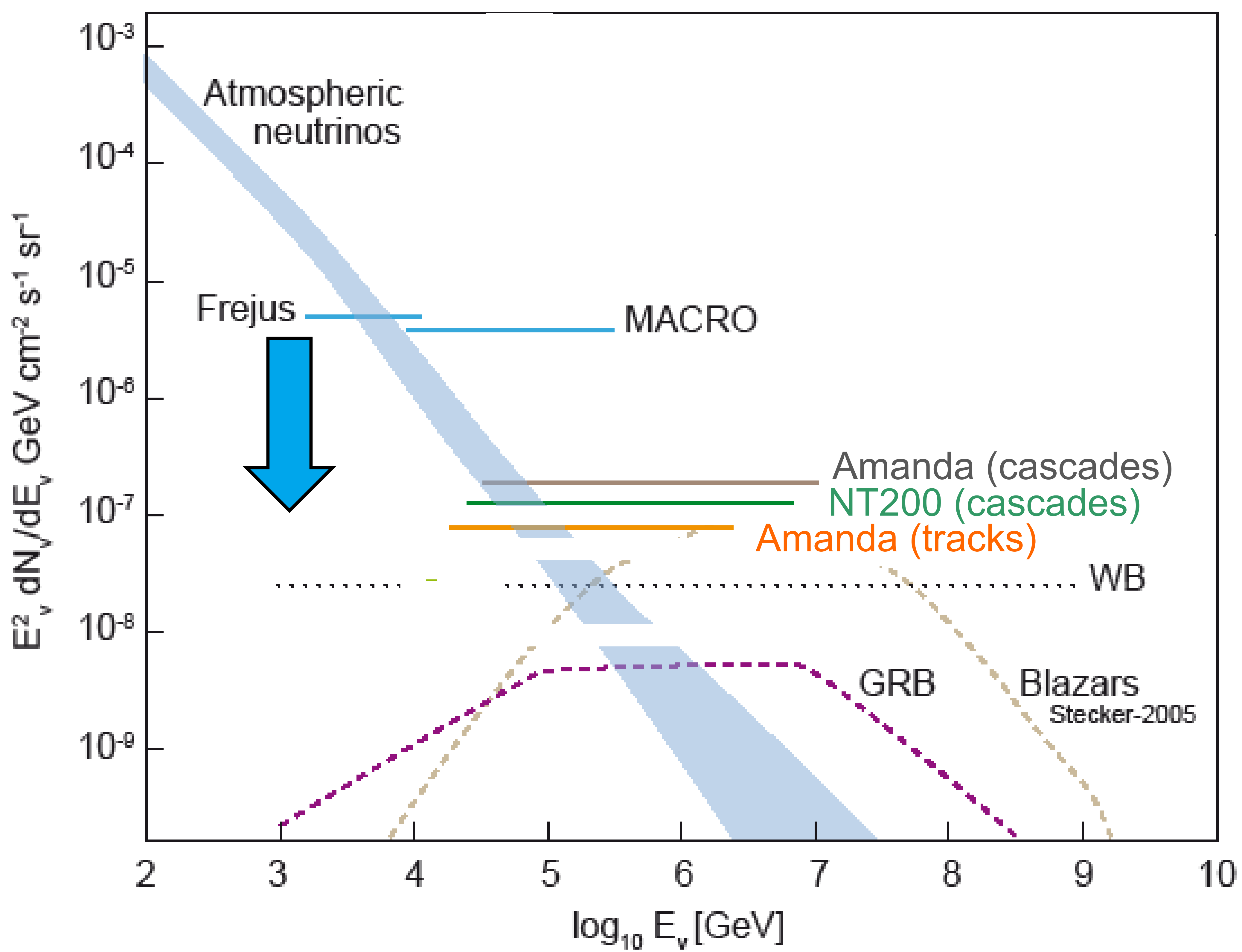
- WIMP search
- Diffuse neutrino fluxes
- Skymap

Amanda 4 years
Baikal 4 years

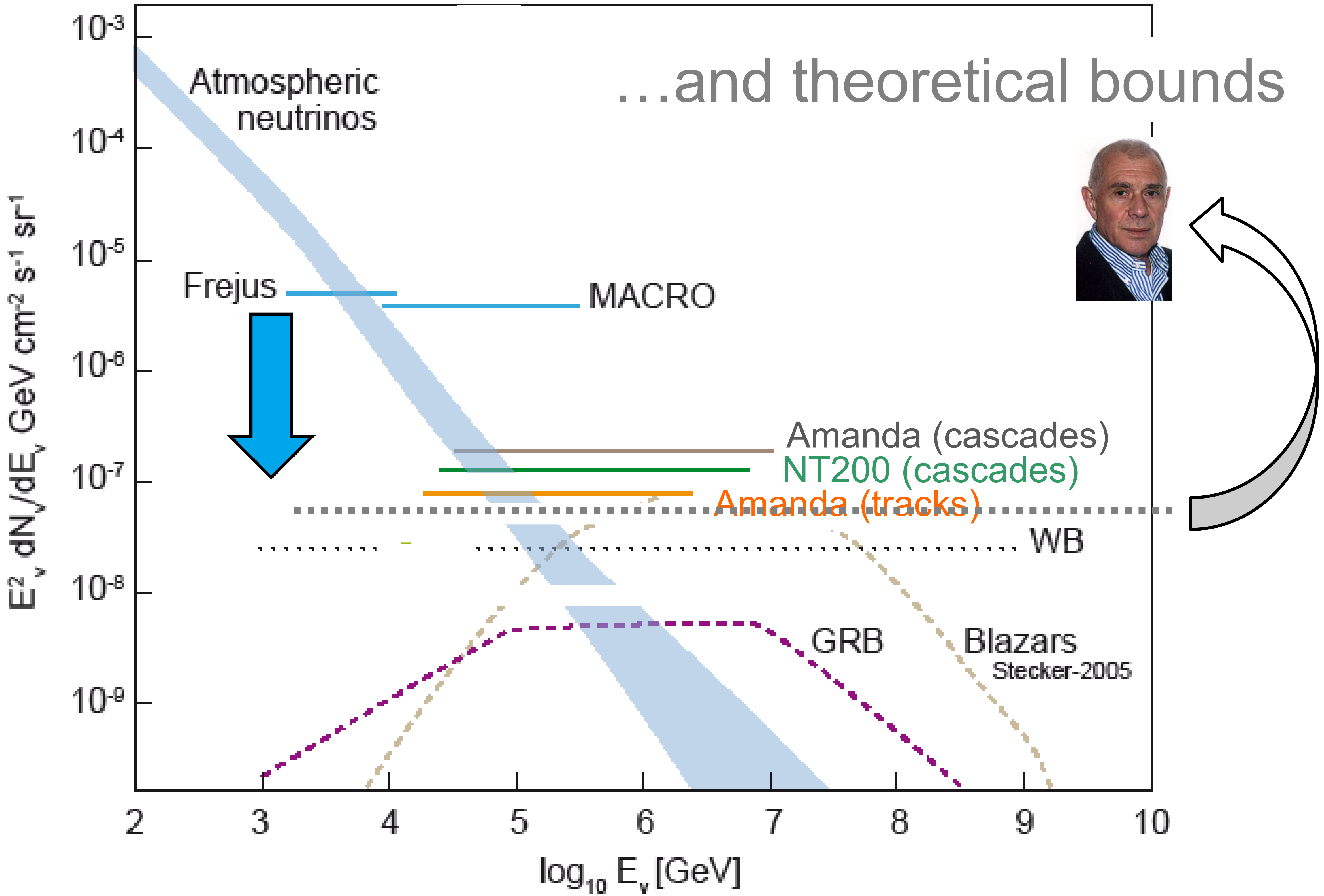


- Magnetic monopoles

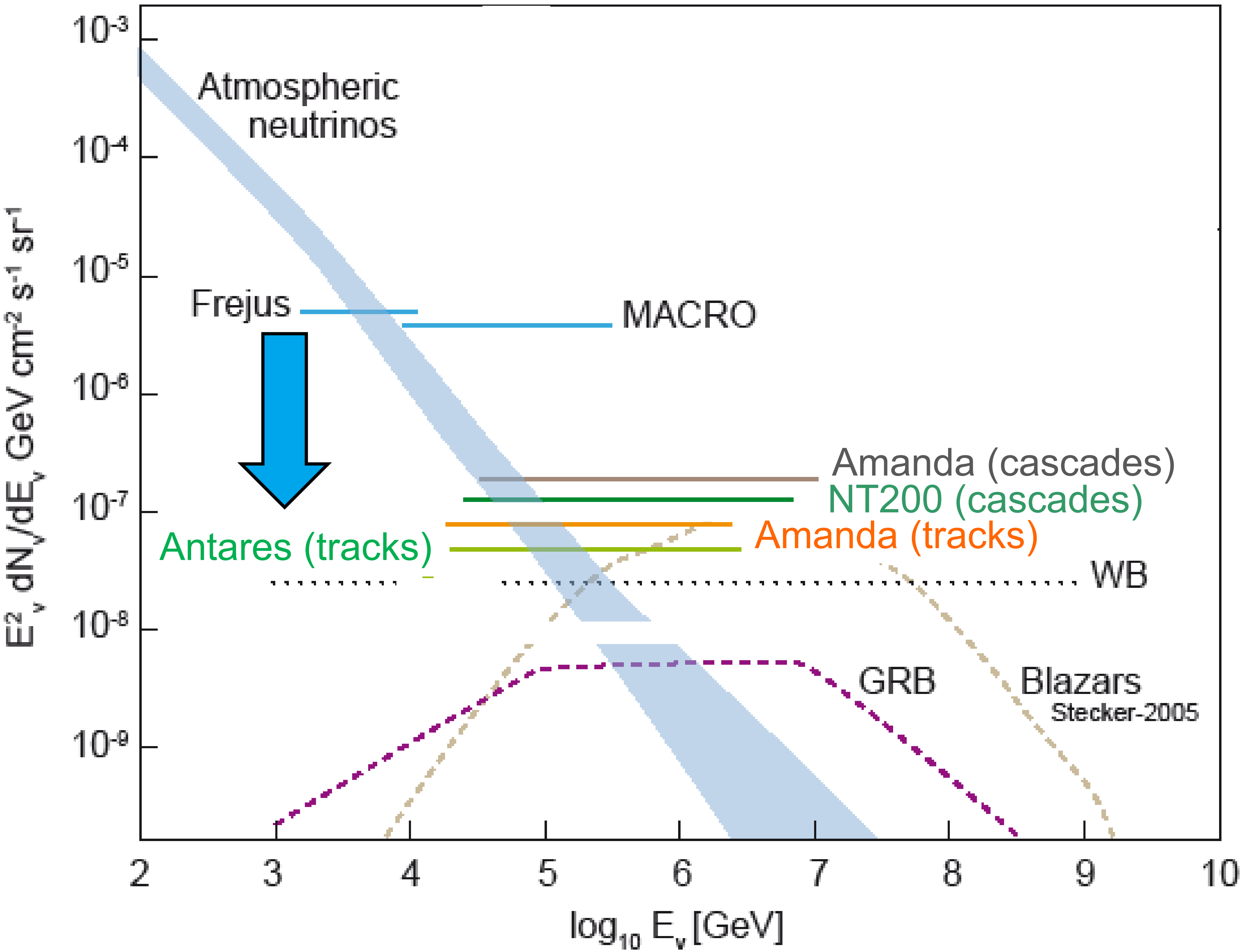
Limits on the diffuse flux (2003)



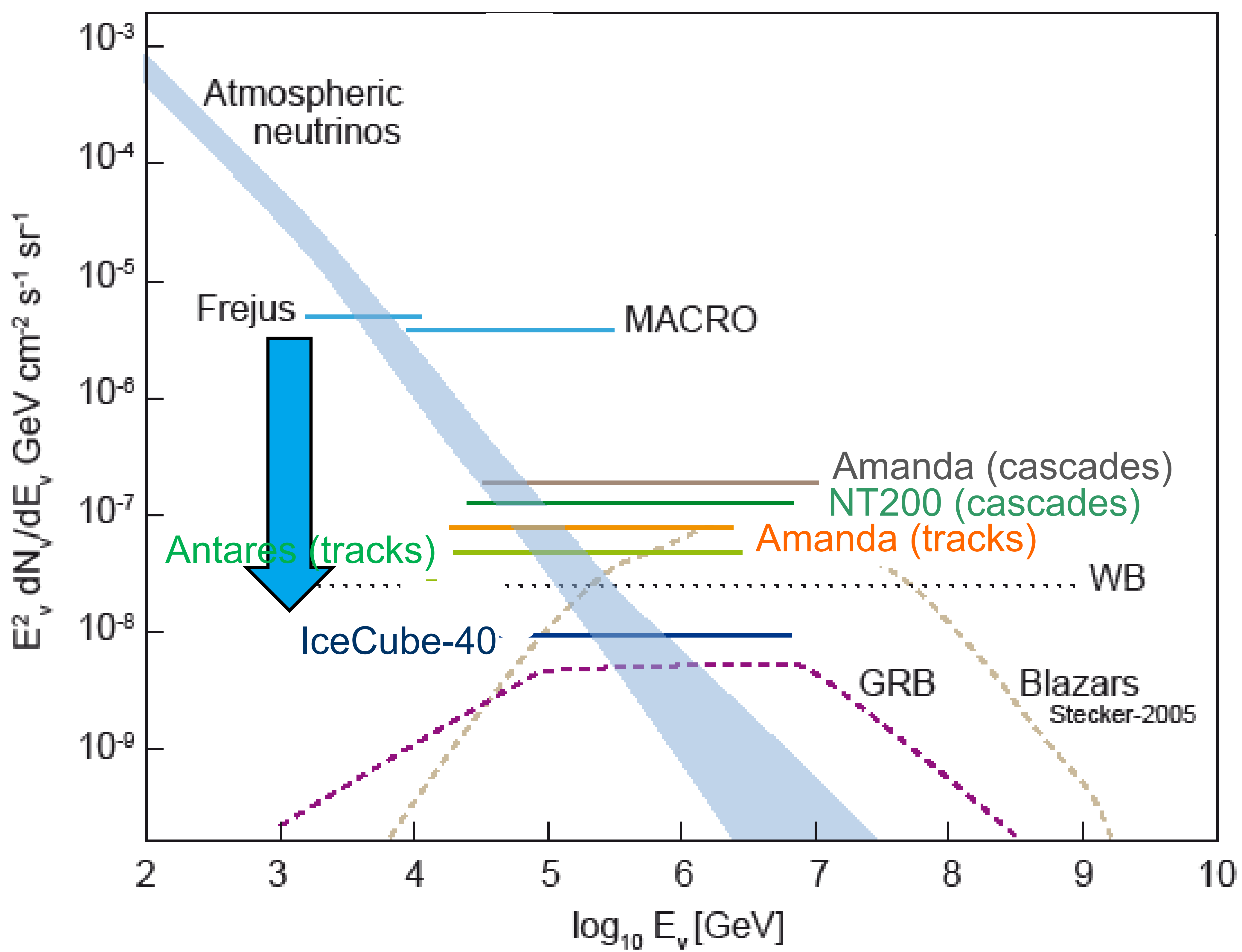
Limits on the diffuse flux (2003)



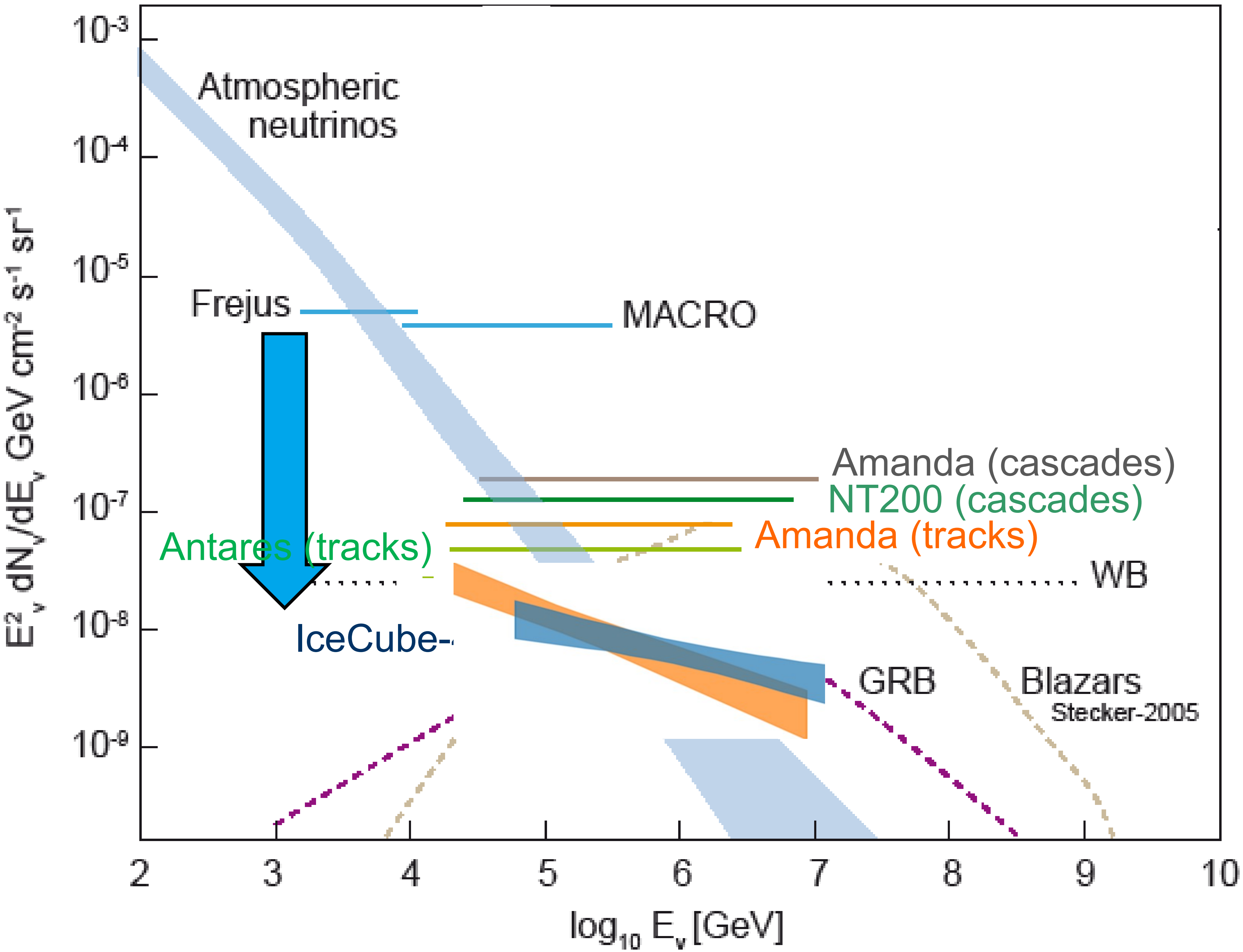
Limits on the diffuse flux (2007)



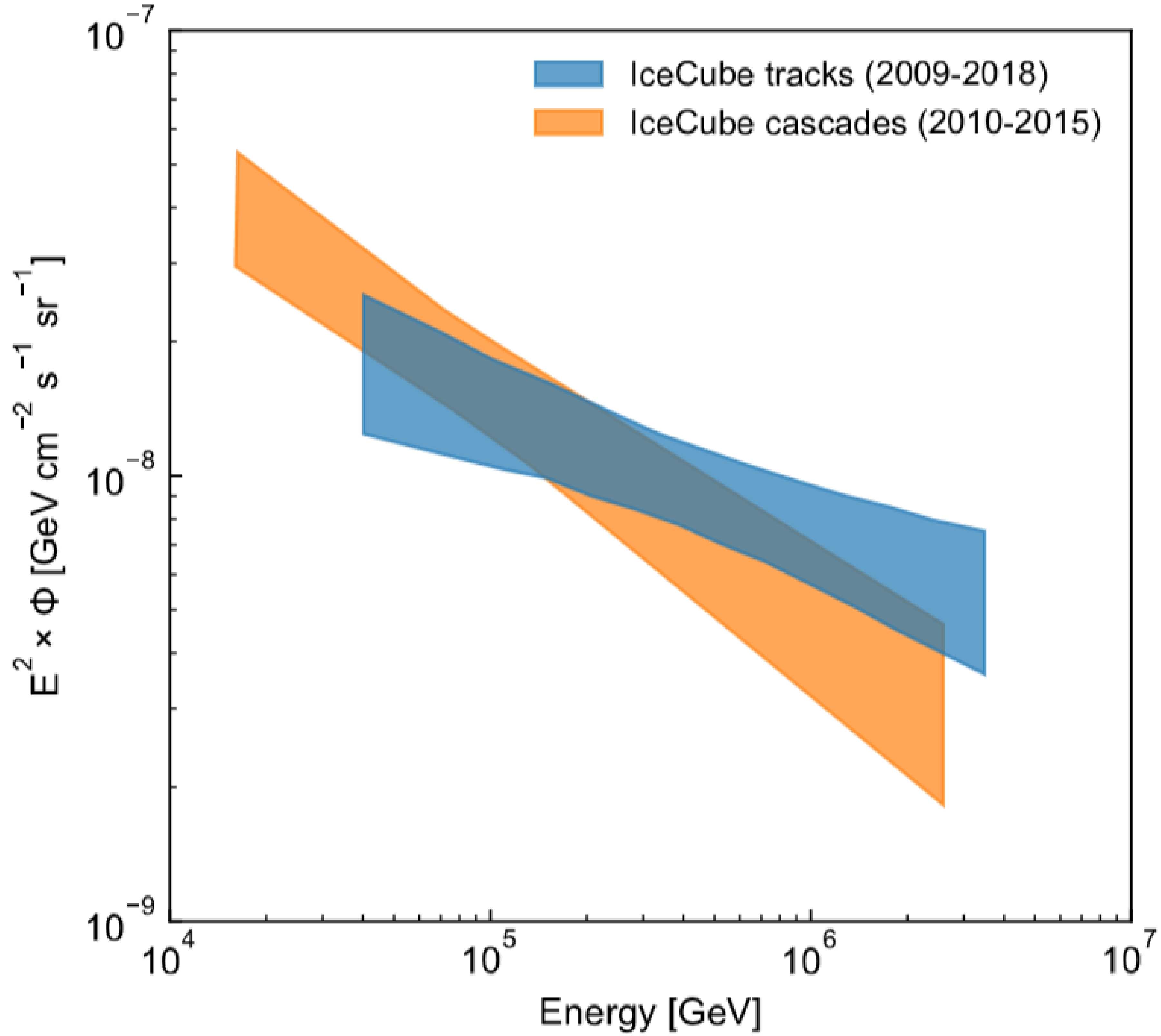
Limits on the diffuse flux (2008)



Size of the diffuse flux (2018)



Diffuse flux of cosmic neutrinos



Where do we stand?

- **Cosmic high-energy ν discovered**
  - **Remaining uncertainties on spectrum**
  - **No steady point sources with >3.5 σ identified up to now, but some individual sources are in reach**
  - **Excluded GRB, Blazars, …. as sole source of our cosmic events**
  - **But: exciting correlation with active galaxies with radio jets** (A. Plavin, Y. Kovalev, Yu. Kovalev, and S.Troitsky, 2020) !

Where do we stand?

- Need experiments with complementary systematics and better angular resolution (i.e. water, not ice)
- Need experiments at the Northern Hemisphere (better view of Galaxy)

GVD Baikal

KM3NeT (Mediterranean Sea)

Back to the 1990s and Lake Baikal


У600

From C. Spiering (2000):
„Охота за нейтрином в самом глубоком озере мира“

Не ясно, будет ли играть Байкалский телескоп на концерте будущих больших нейтринних телескопов основной мотив или только боковую мелодию.

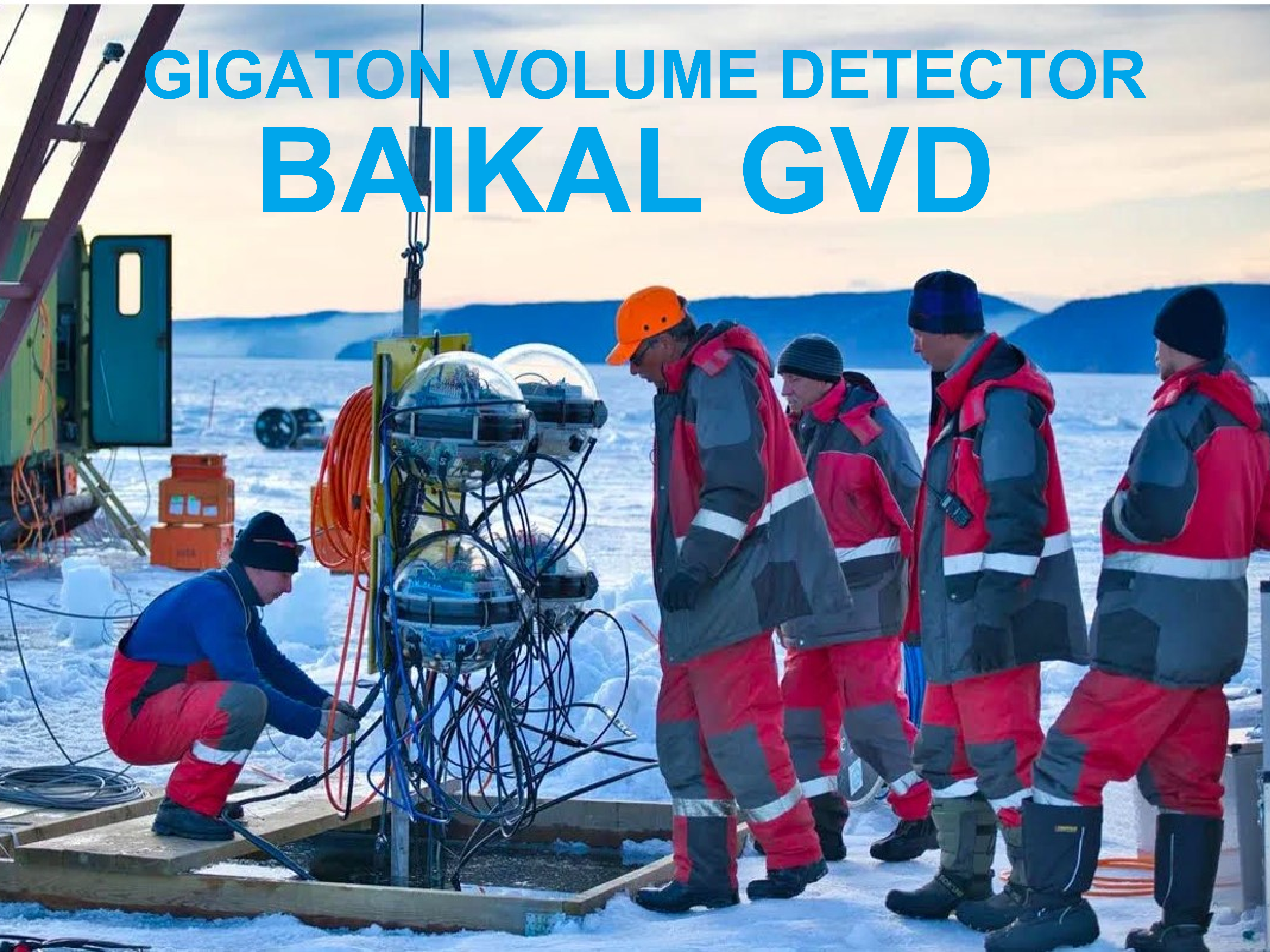
....

Но какой бы далнейшая дорога ни была, будет ли во всем мире один или 2 супер-телескопа: 106ой километр с его неприметным деревянным домом был значительным местом происшествия этого процесса.

Не ясно, будет ли играть Байкалский телескоп на концерте будущих больших нейтринних телескопов основной мотив или только боковую мелодию.

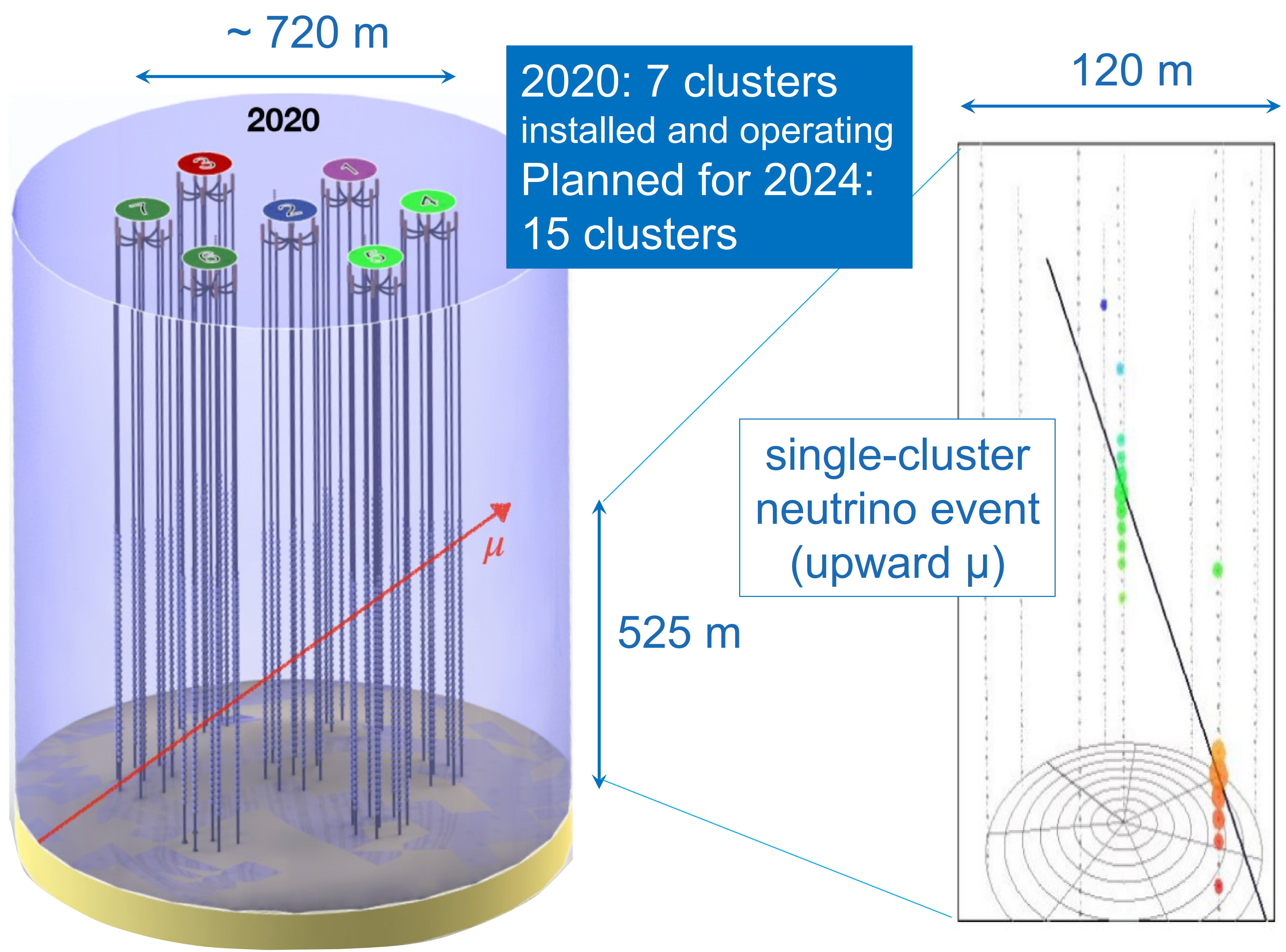
Now we know the answer:

Baikal GVD


GIGATON VOLUME DETECTOR
BAIKAL GVD

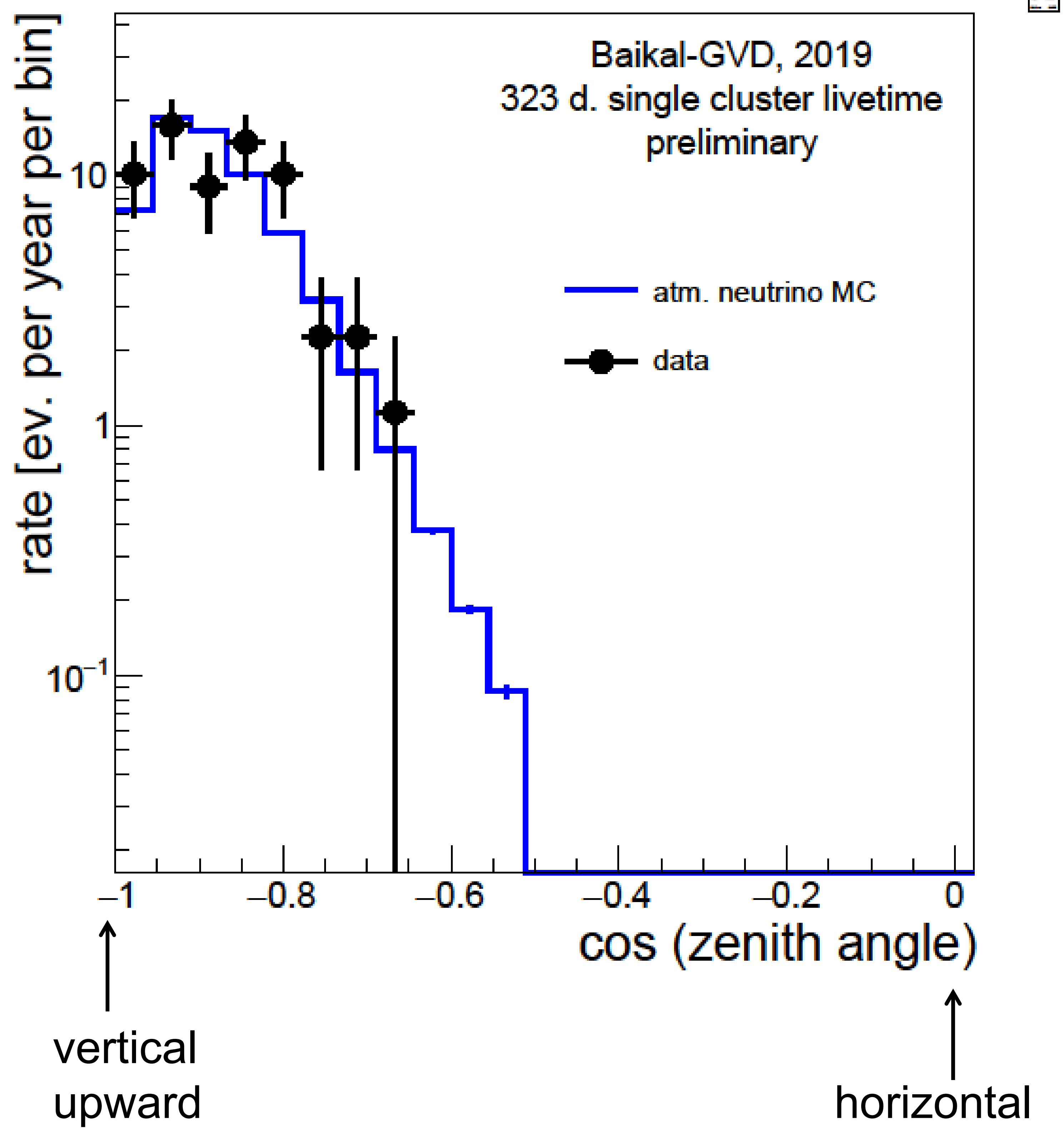
10 institutes

~ 70 members


~ 720 m
2020
3
1
7
2
4
6
5
μ
2020: 7 clusters
installed and operating
Planned for 2024:
15 clusters
120 m
single-cluster
neutrino event
(upward μ)
525 m

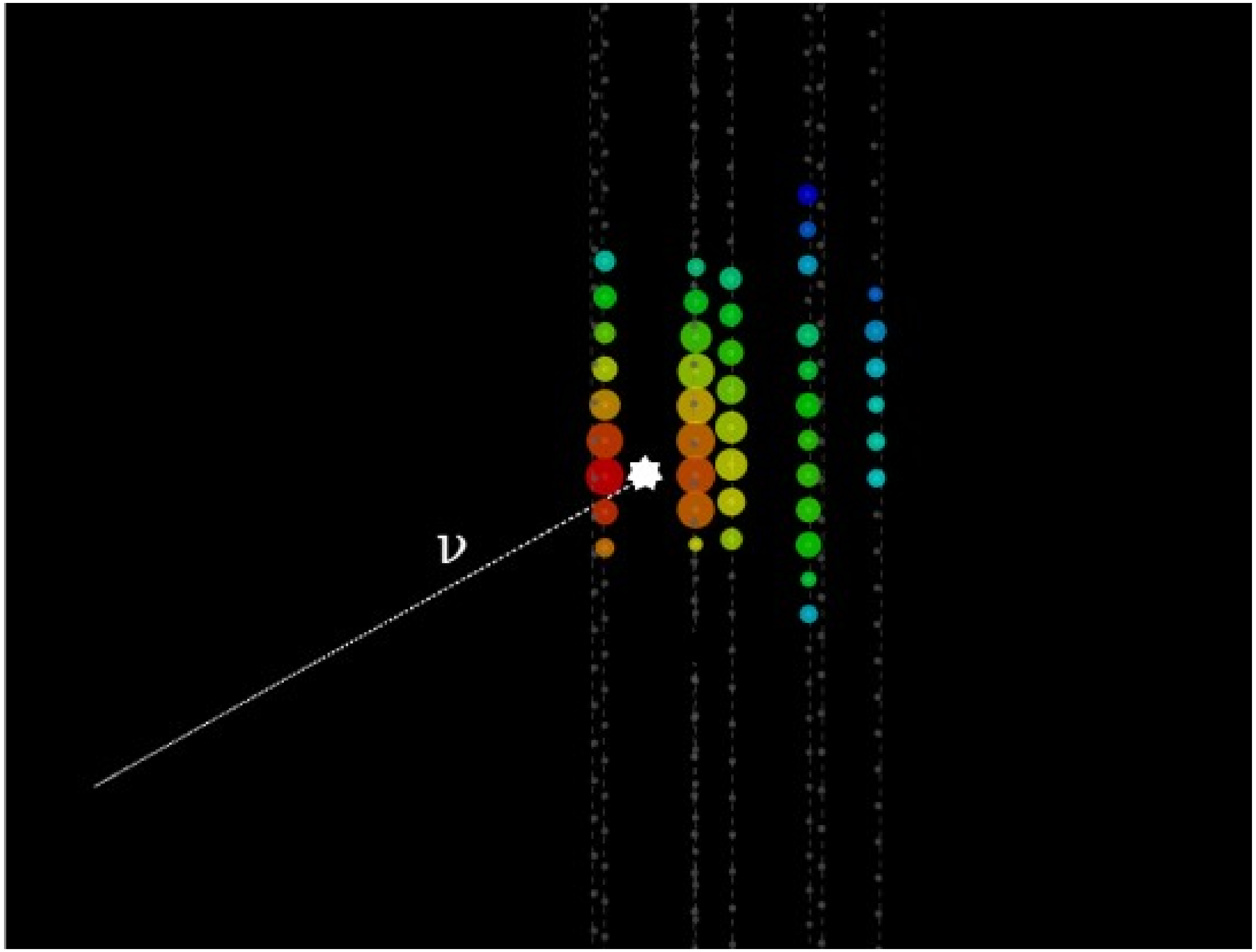
Baikal GVD: examples of first results

Upward going tracks from muon neutrino interactions



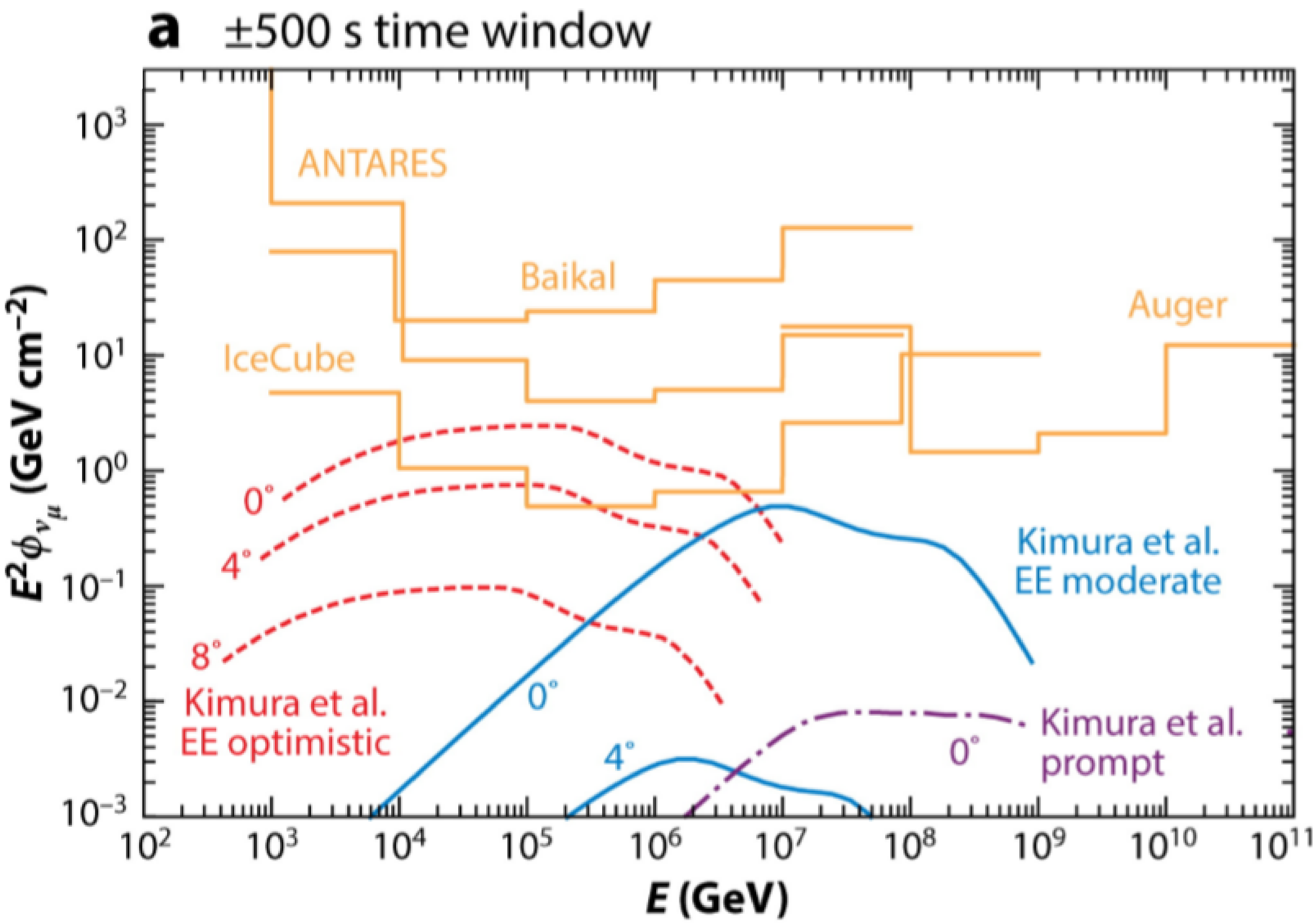
Baikal GVD: examples of first results

The first clear cascade event from the interaction of an upward moving electron- or tau-neutrino at the 100 TeV scale (91±10) TeV



Baikal GVD: examples of first results

See "SEARCH FOR HIGH-ENERGY NEUTRINOS FROM BINARY NEUTRON STAR MERGER GW170817 WITH ANTARES, ICECUBE, AND THE PIERRE AUGER OBSERVATORY"



Summary

INR has a great record in high-energy astronomy

e.g.

- pioneering Baikal neutrino telescope
- cosmic ray experiments at Baksan

Many basic ideas came from INR physicists

e.g.

- underwater neutrino detection
- air shower detection via Cherenkov light
- GZK effect
- ...

INR has a bright future with forefront experiments !

- **Neutrinos:** Baikal GVD
- **Cosmic Rays:** Telescope Array
- **Gamma Rays:** LHAASO

Thank you to my Baikal colleagues for guiding my first steps in neutrino astronomy and for being friends since 33 years!


Bair Shoybonov