ULTRA-HIGH ENERGY COSMIC RAYS
and
SUPERHEAVY LONG-LIVING PARTICLES

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and Igor I. Tkachev.

May 00!

PLAN.

1. INTRODUCTION (MOTIVATION).
2. TWO PUZZLES
   - SOLAR NEUTRINO DEFICIT
   - UHECR BEYOND GZK CUT-OFF
3. WHAT IS THE UHECR PUZZLE?
   - GZK CUT-OFF
   - CR PROPAGATION
   - NO SOURCES INSIDE GALAXY
   - ORIGIN EXPECTED EXTRAGALACTIC
   - RIGIDITY OF UHECR → DIRECT PROPAGATION
4. SOME EXPT-L RESULTS
5. SUPERHEAVY PARTICLES AS A SOURCE OF UHECR
6. OBSERVATIONAL SIGNATURES
7. CONCLUSIONS

Should CERN get involved in

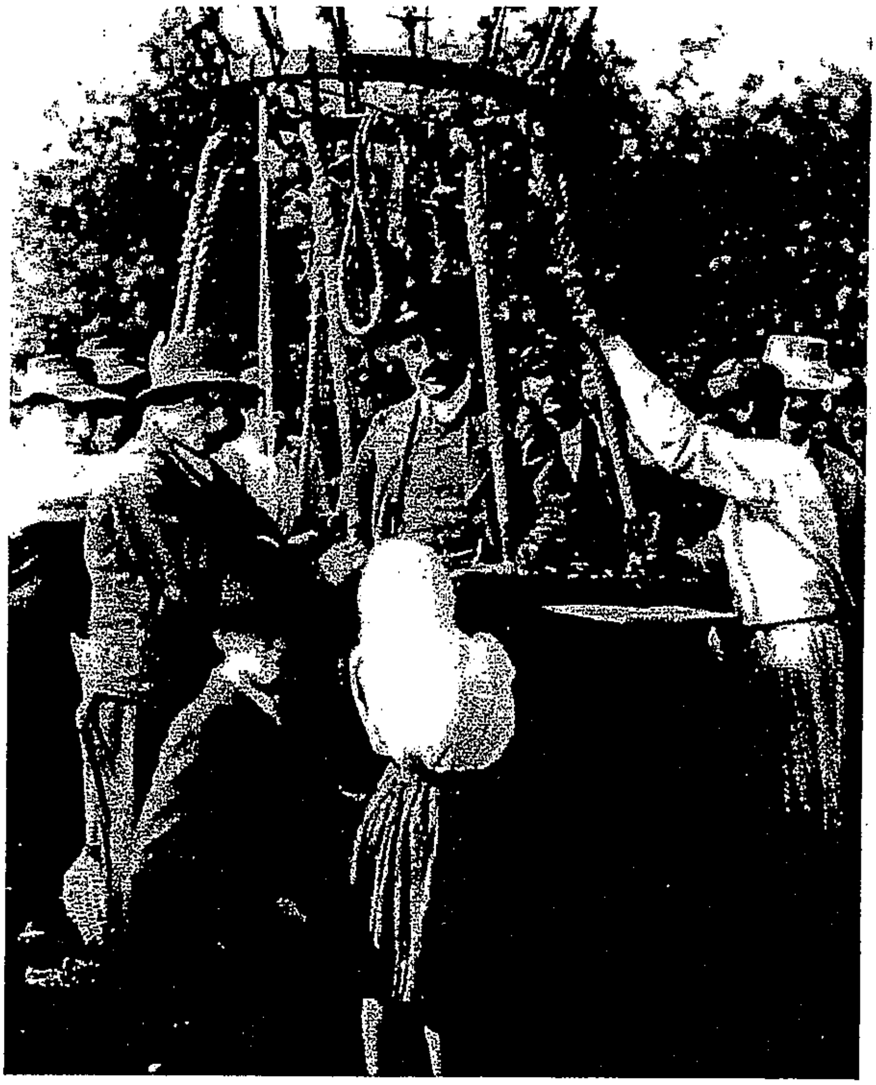
- charged-particle CR (< 1014 eV) ?
  no
- charged-particle CR (1014 - 1018 eV) ?
  maybe
- charged-particle CR (> 1018 eV) ?
  YES
- X-ray orbiting observatory ?
  maybe
- Gamma-ray satellites ?
  no
- TeV photons ?
  no
- solar neutrinos ?
  no
- atmospheric neutrinos ?
  YES
- ultra-high energy neutrinos ?
  maybe
- dark matter ?
  no
- gravitational waves ?
  YES

Dydak, F.

ATLAS.

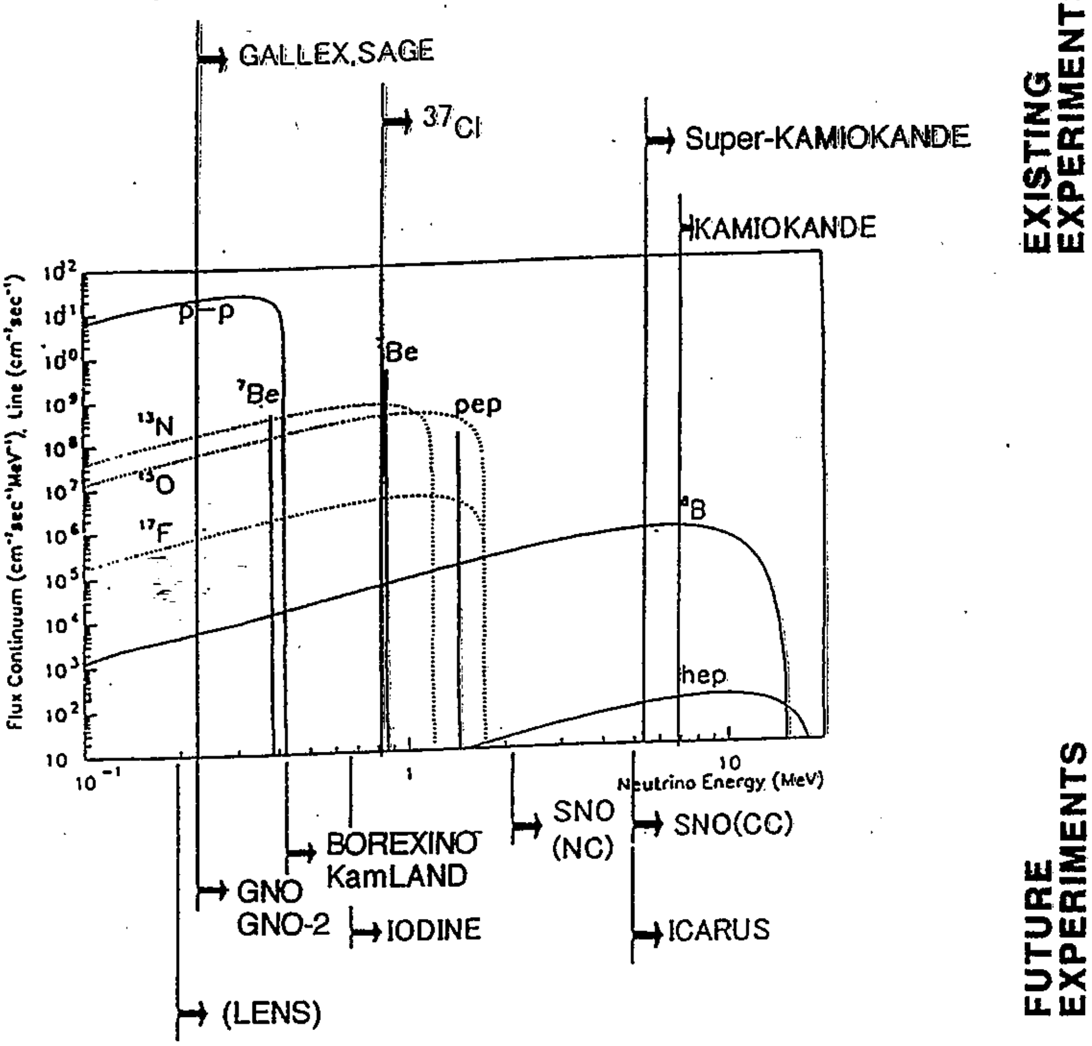
LHC.

1912



In a balloon at an altitude of 5000 meters, Victor Hess , the father of cosmic ray research, discovered "penetrating radiation" coming from space.

Solar Neutrinos



Results of Solar Neutrino experiments

experi-ment	method	flux	Data/SSM (BP98)
^{37}Cl	ν_e ^{37}Cl	2.56±0.23 SNU	0.33±0.03
GALLEX	ν_e ^{71}Ga	76±8 SNU	0.59±0.06
SAGE	ν_e ^{71}Ga	70±8 SNU	0.54±0.06
Kamiokande	ν e scat.	$(2.80 \pm 0.19 \pm 0.33) \times 10^{6}$ /cm^2/sec	0.54±0.07
Super-K.	ν e scat.	$(2.44 \pm 0.05\ {+0.09/-0.07}) \times 10^{6}$ /cm^2/sec	0.47±0.02

BP98: J.N.Bahcall et al., Phys. Lett. B433(1998)1.

A Timeline History of High-Energy Cosmic Rays

Hess discovered cosmic rays **1912**

1927 Cosmic rays seen in cloud chamber by Skobelzyn

Anderson discovered antimatter **1932**

1937 Discovery of muon

Auger discovered extensive air showers **1938**

1946 First air shower experiments

Discovery of charged pions and kaons **1947**

1949 Fermi's theory of cosmic rays

First 10^{20} eV cosmic ray detected **1962**

1966 Greisen and Zatsepin & Kuzmin propose GZK cutoff energy for cosmic rays

Fly's Eye detected highest-energy event ever **1991**

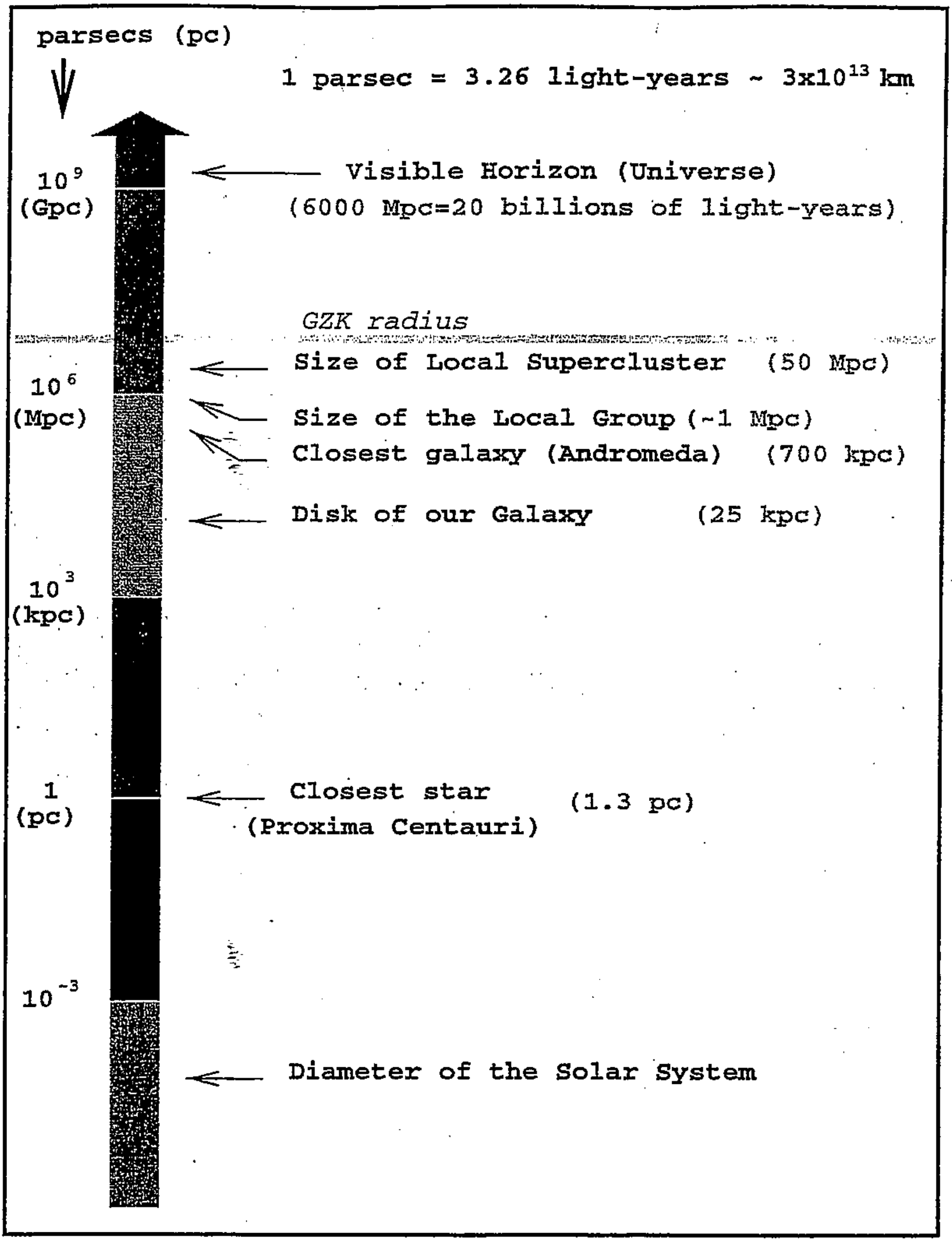
1994 AGASA high-energy event

HiRes expected to begin operation **2000**

Particle Physics Energy Scales

10^{21}	ZeV (zetta)	????	Region of sensitivity of the Pierre Auger project
10^{18}	EeV (exa)	Active galactic nuclei/ black holes	
		Pulsar/neutron stars	
10^{15}	PeV (peta)		
		Supernovae	
	←	Likely limit of human technology	
10^{12}	TeV (tera)	Synchrotrons	
10^{9}	GeV (giga)	Synchrocylotrons	
10^{6}	MeV (mega)	Electrostatic accelerators Nuclear reactors	
10^{3}	keV (kilo)	Schoolroom generator	
1	eV	$1 battery	

Astronomical Distance Scales



parsecs (pc)

1 parsec = 3.26 light-years ~ 3×10^{13} km

10^9 (Gpc)

Visible Horizon (Universe)

(6000 Mpc=20 billions of light-years)

GZK radius

Size of Local Supercluster (50 Mpc)

10^6 (Mpc)

Size of the Local Group (~1 Mpc)

Closest galaxy (Andromeda) (700 kpc)

Disk of our Galaxy (25 kpc)

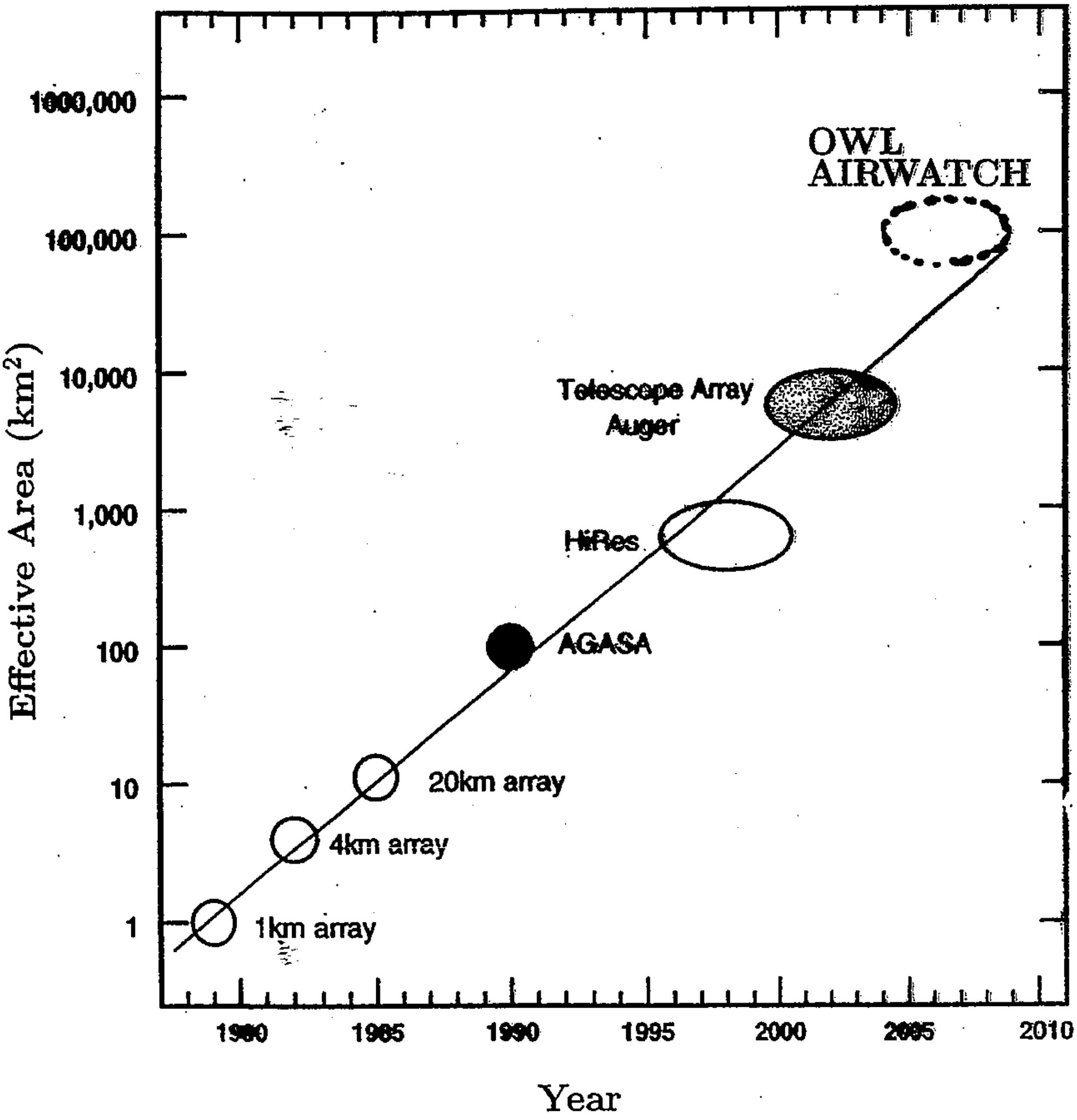
10^3 (kpc)

1 (pc)

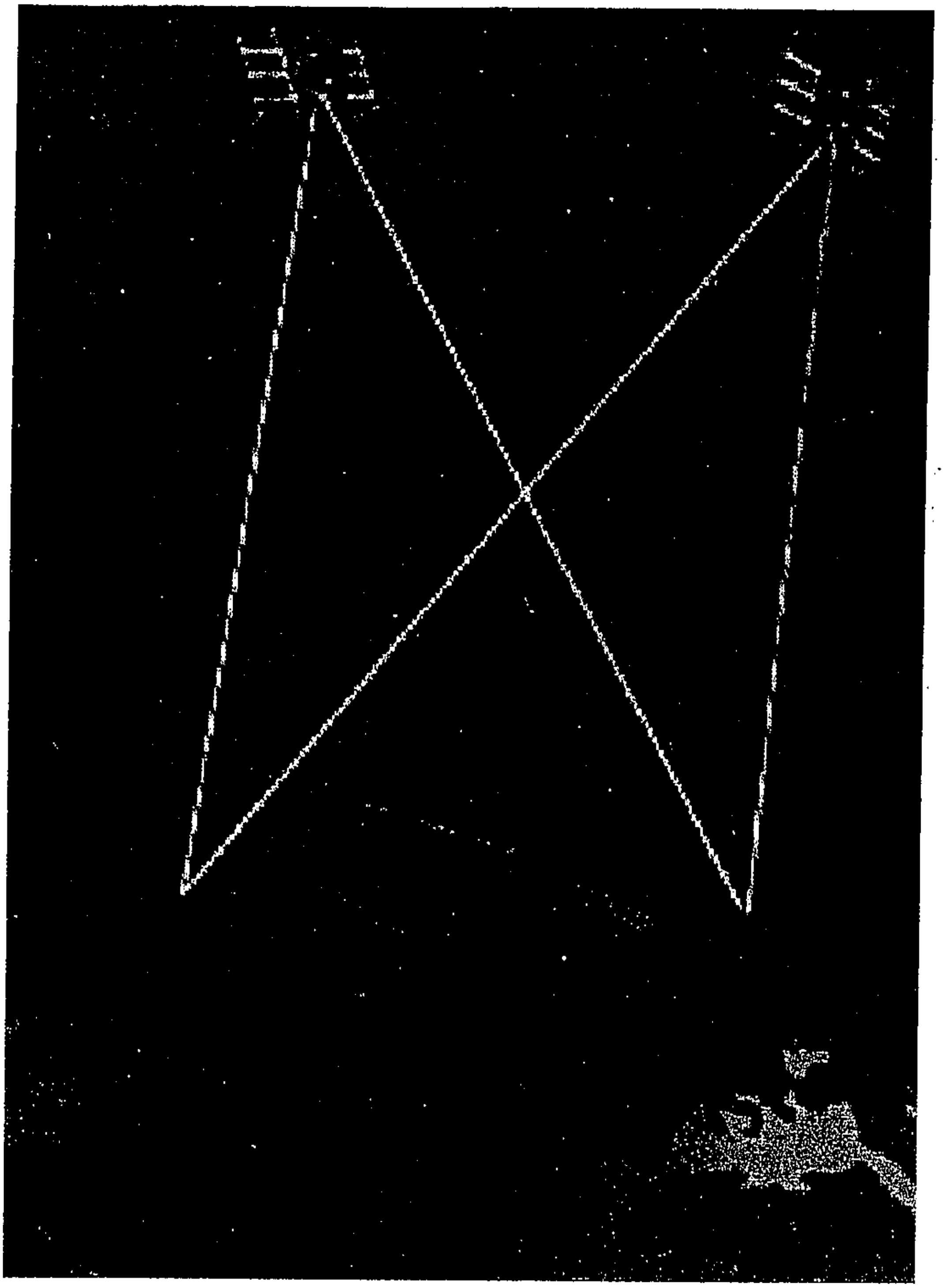
Closest star (Proxima Centauri) (1.3 pc)

10^{-3}

Diameter of the Solar System

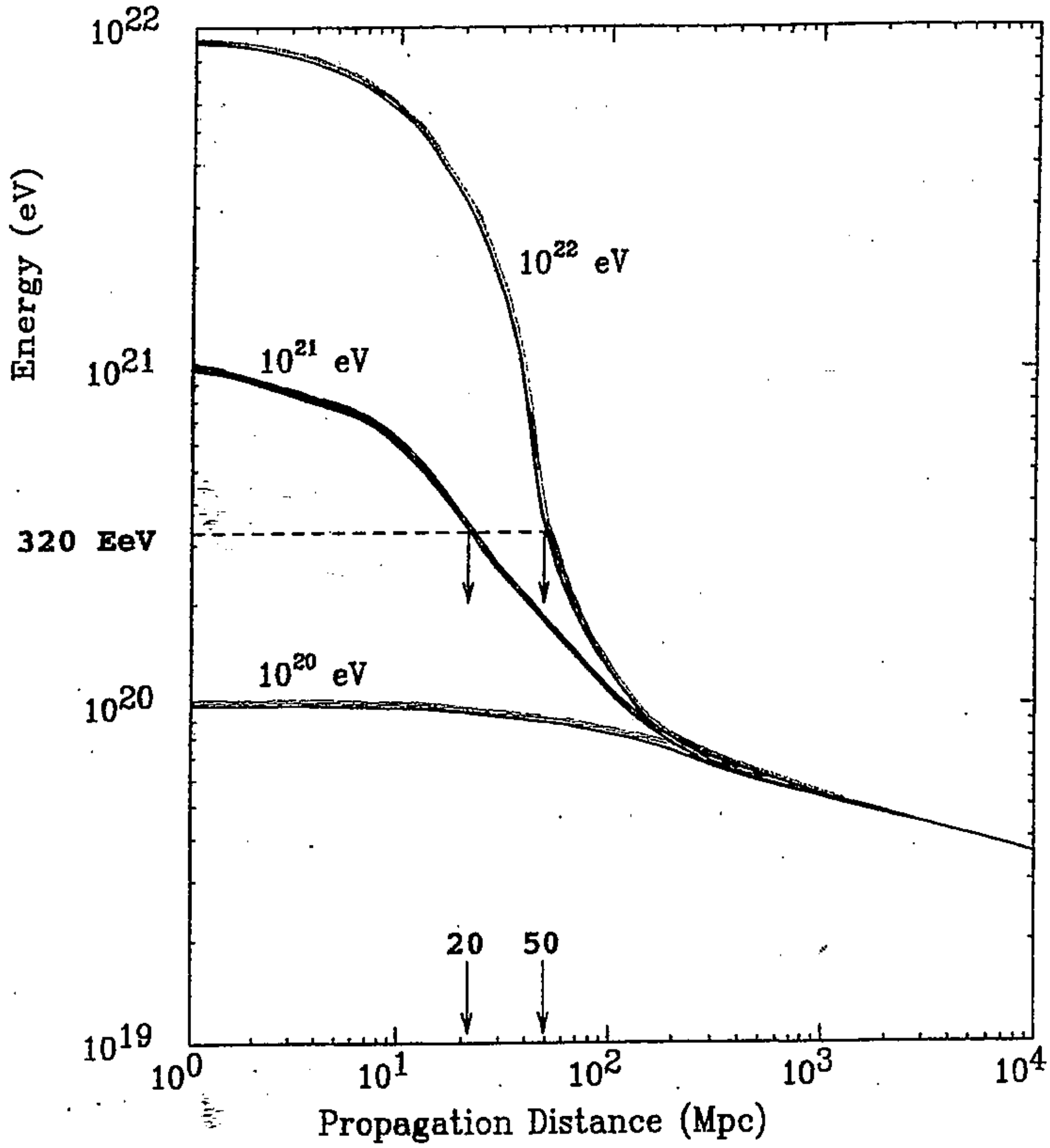

1000,000
100,000
10,000
1,000
100
10
1
Effective Area (km^2)
OWL
AIRWATCH
Telescope Array
Auger
HiRes
AGASA
20km array
4km array
1km array
1980
1985
1990
1995
2000
2005
2010
Year

OWL – AirWatch planned UHECR experiment



THE GZK CUTOFF

Energy at source



Energy attenuation of protons

Protons: photopion threshold @ ~50 EeV

Photons: pair production threshold @ ~200 TeV

Nuclei: photodisintegration above 50 EeV

Neutrinos: no problem!

For E>100 EeV, the source must be within ~50 Mpc

Propagation of UHECR Cosmic Rays

GZK cutoff

UHE protons (or neutrons) propagating in cosmic background loose energy colliding with γ's and producing particles. These reactions have threshold energy.

Most important is photopion production

$$\mathrm{E_{th}}(\mathrm{p}+\gamma \to \mathrm{N}+\pi) = \frac{(\mathbf{m_p}+\mathbf{m}_\pi)^2 - \mathbf{m_p^2}}{\mathbf{2E}_\gamma(\mathbf{1}-\mathbf{cos}\theta)}$$

$$\mathrm{E_{th}} \approx \frac{\mathbf{m_p m_\pi}}{\mathbf{2E}_\gamma} \approx \mathbf{5 \times 10^{19}\ eV} \left(\frac{\mathbf{2.7^\circ\ K}}{\mathbf{T}}\right)$$

This reaction has large cross section, being the largest at Δ resonance,

$$\sigma \sim \mathbf{130}\ \mu\mathbf{b} \approx \mathbf{1.3 \times 10^{-28} cm^2}$$

Density of CMB radiation is $n \sim 400\ \mathrm{cm}^{-3}$ → Mean free path:

$$\mathbf{L} = (\sigma \mathbf{n})^{-1} \approx \mathbf{2 \times 10^{25}\ cm} \approx \mathbf{6\ Mpc} \left(\frac{\mathbf{T}}{\mathbf{2.7^\circ K}}\right)^3$$

In each collision 20% of energy is lost.

The reaction $p+\gamma \to p+e^+e^-$ is subdominant. While it has smaller threshold (by a factor of $2m_e/m_\pi \sim 10^{-2}$), it also has smaller cross section.

UHE photons loose energy in $\gamma+\gamma \to e^+e^-$. Threshold is smaller by a factor $2m_e^2/m_\pi m_p \sim 10^{-5}$ compared to GZK cutoff energy.

Propagation of UHECR Cosmic Rays

- Magnetic “trap” can not confine a cosmic ray if the Larmor radius
$$R_{\mathrm{L}} \approx \left(\frac{E}{10^{19}\ \mathrm{eV}}\right)\left(\frac{3\ \mu\mathrm{G}}{B}\right) \times 3\ \mathrm{kpc}$$
exceeds the trap size. E.g. UHECR escape easily our Galactic disk.

- EHECR trajectories are not strongly bent by the extragalactic magnetic fields. Mean deflection angle is
$$\theta_{\mathrm{def}} < \left(\frac{R}{50\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{5 \times 10^{19}\ \mathrm{eV}}{E}\right) \times 4^{\circ},$$
here R is the distance to the source. Arrival directions of UHECR should point back to the source. Charged particle astronomy is possible.

- UHECR protons (or neutrons) propagating in the microwave background loose energy in photopion production, e.g., $p\gamma \rightarrow p\pi^0$. Threshold energy :
$$E_{\mathrm{cut}} \approx 5 \times 10^{19} \left(\frac{2 \times 10^{-4}\ \mathrm{eV}}{T}\right)\ \mathrm{eV}$$
The mean free path is ≈ 5 Mpc. In each collision 20% of energy is lost. Detection of 3×10^{20} eV proton would require source to be within ~ 50 Mpc.

Propagation of UHECR Cosmic Rays

Magnetic fields

UHE charged particles do not move straight in a magnetic field. Lorentz force:

$$\frac{\mathrm{dv}}{\mathrm{dt}} = \frac{\mathrm{Ze}}{\mathrm{E}}\ [\vec{\mathrm{v}} \times \vec{\mathrm{B}}]$$

- Magnetic "trap" can not confine a cosmic ray if the Larmour radius

  $$\mathrm{R_L} \approx \left(\frac{\mathrm{E}}{\mathrm{Z} \times 10^{19}\,\mathrm{eV}}\right)\left(\frac{3\,\mu\mathrm{G}}{\mathrm{B}}\right) \times 3\ \mathrm{kpc}$$

  exceeds the trap size. E.g. UHECR escape easily our Galactic disk.

- EHECR trajectories are not strongly bent by the extragalactic magnetic fields. Mean deflection angle is

  $$\theta_{\mathrm{def}} < \left(\frac{\mathrm{R}}{50\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{\mathrm{Z} \times 10^{20}\,\mathrm{eV}}{\mathrm{E}}\right) \times 2^\circ,$$

  here R is the distance to the source. Arrival directions of UHECR should point back to the source.

  Charged particle astronomy of UHECR is possible.

- Time delay in the extragalactic magnetic fields

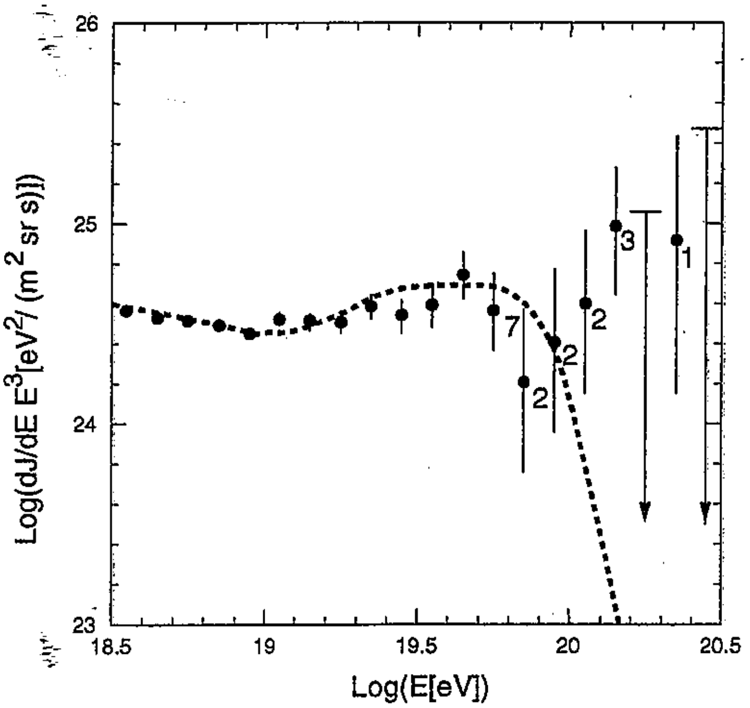
  $$\tau < \left(\frac{\mathrm{R}}{10\ \mathrm{Mpc}}\right)^{2}\left(\frac{\mathrm{Z} \times 10^{20}\,\mathrm{eV}}{\mathrm{E}}\right)^{2} \times 10^{3}\ \mathrm{yr}$$

The CR spectrum beyond GZK cutoff

Detection of 3×10^{20} **eV** proton would require sources to be contained within **50 Mpc.** Or, with uniform cosmological distribution there should be the GZK cut-off.

However, events above the cutoff were observed !

* Volcano Ranch	April 1962	100 EeV
* Haverah Park	1970 – 1980	3 events 100 EeV 1 event 120 EeV
* Yakutsk	May 1989	120 EeV
* Fly's Eye	October 1991	320 EeV
* AGASA	1990 – 1997	see the plot:

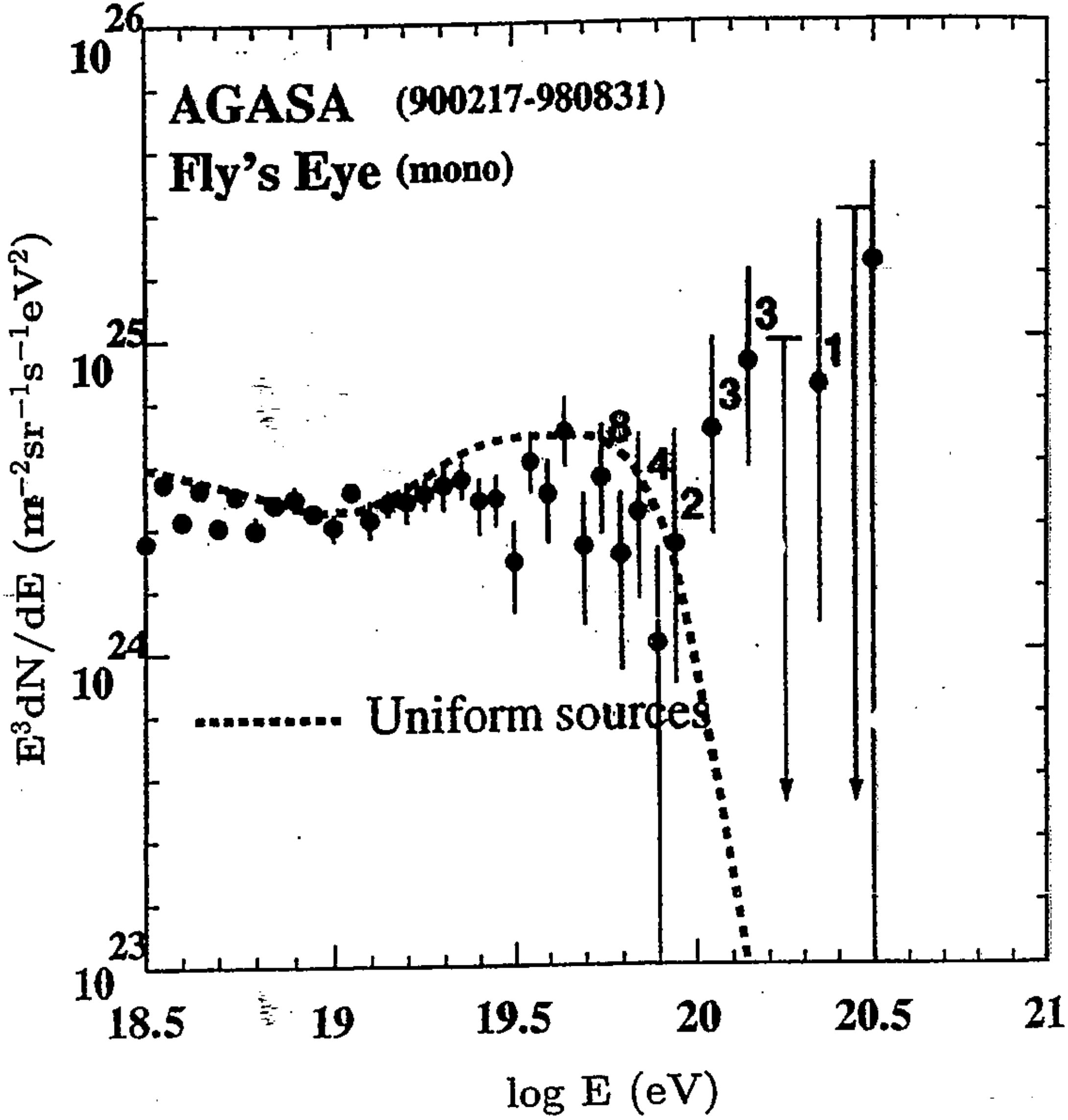


adapted from M. Takeda et al., Phys. Rev. Lett. 81, 1163-1166 (1998)

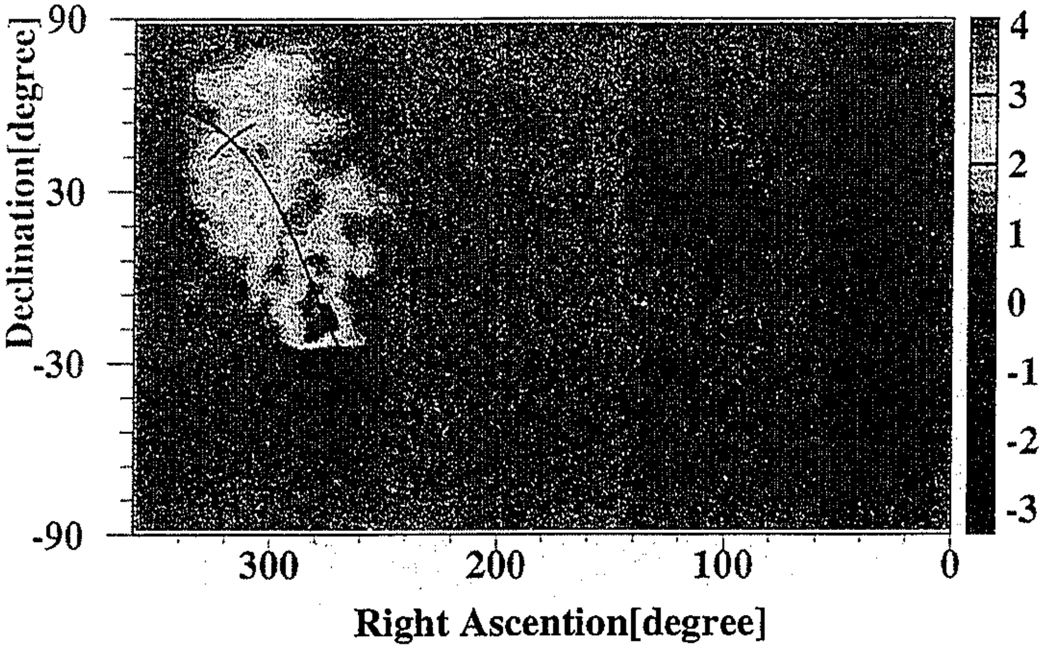
The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe.

No candidate sources are found in the directions of all $E > 10^{20}$ eV events.

There is no chance that these events are artefacts.


AGASA (900217-980831)
Fly's Eye (mono)
$E^3 dN/dE$ ($m^{-2}sr^{-1}s^{-1}eV^2$)
10^{26}
10^{25}
10^{24}
10^{23}
18.5
19
19.5
20
20.5
21
log E (eV)
Uniform sources
8
4
2
3
3
1

Anisotropy of cosmic rays with energies around 10^{18} eV



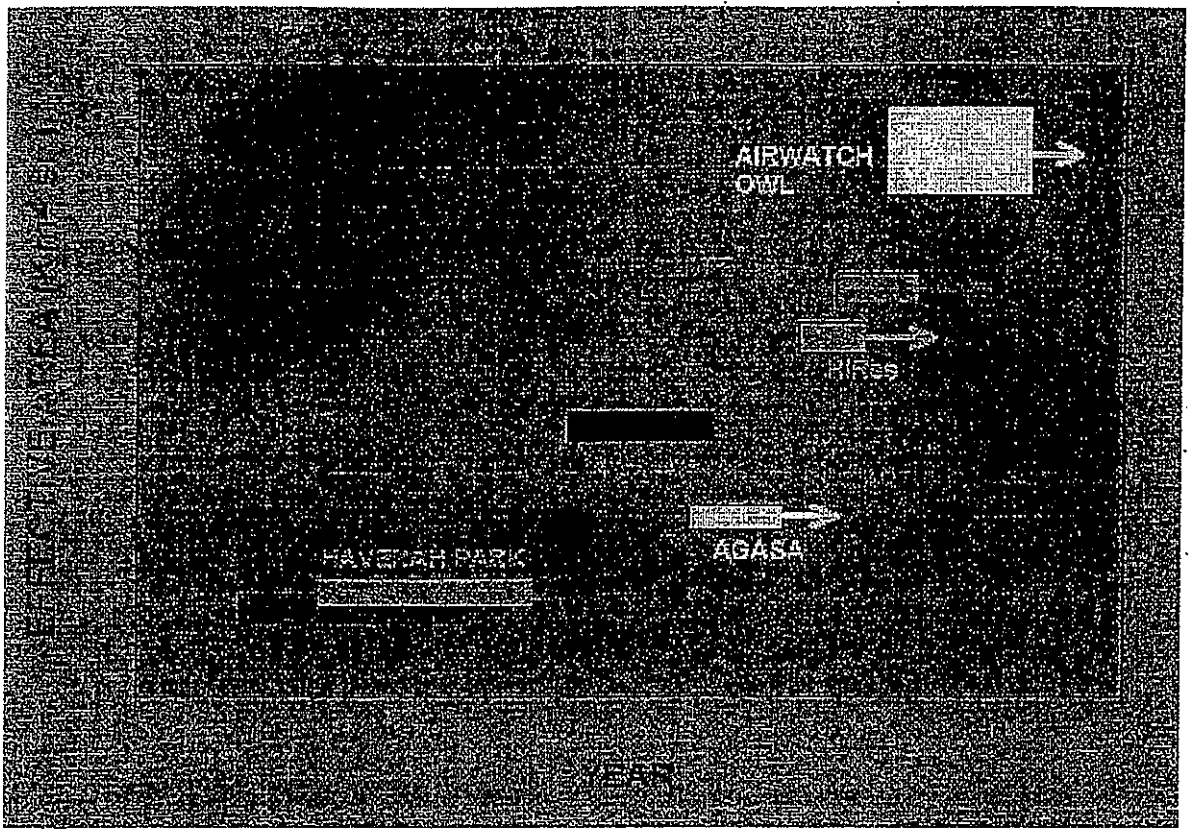
Excess near the Galactic Center region: 4.5σ

Excess from the direction of Cygnus region: 3.9σ

Deficit in direction of Galactic anti-Center : -4.0σ

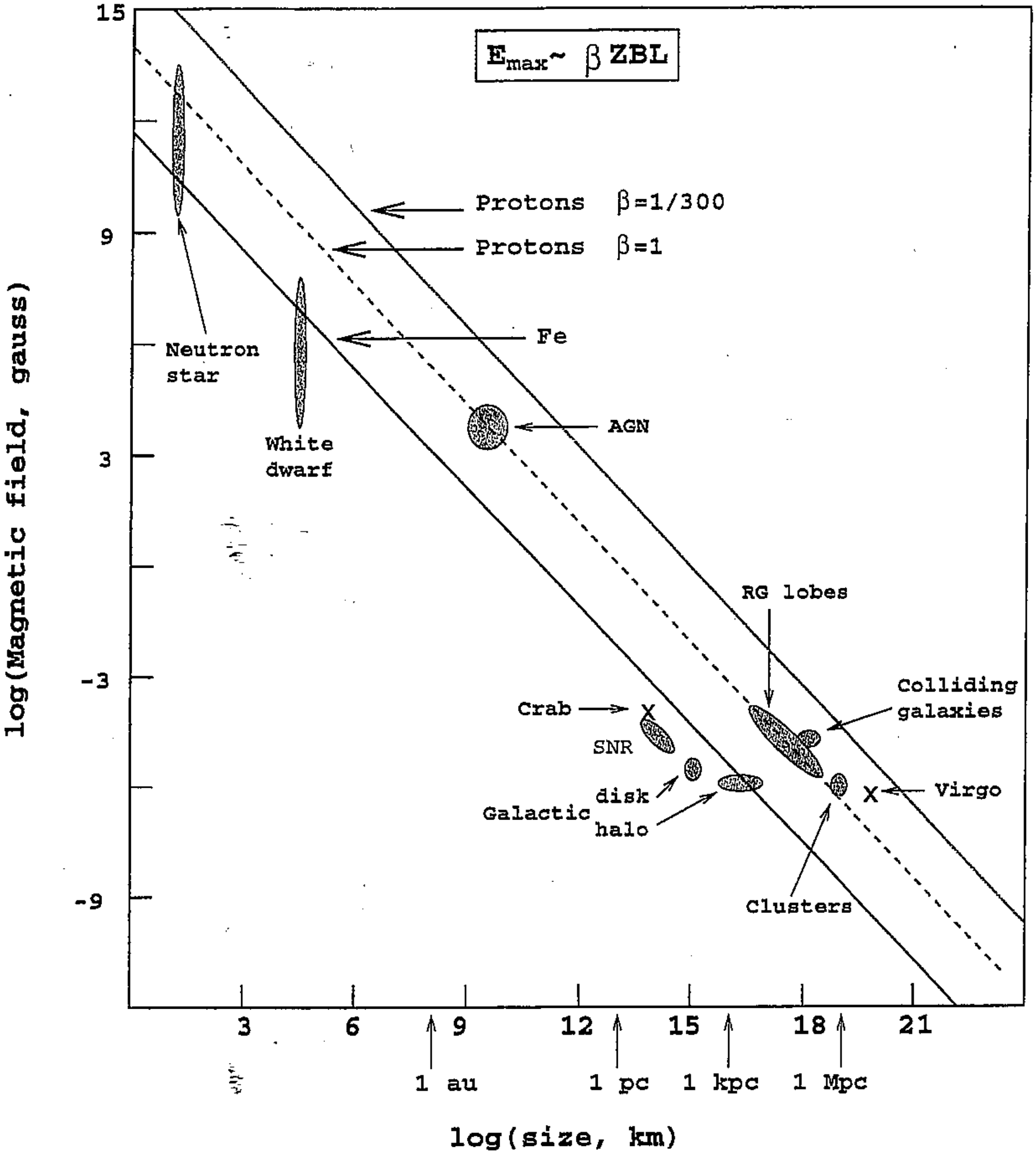
adapted from N. Hayashida, et al, AGASA collaboration

Growth of detection capabilities with time



Volcano Ranch (USA)	Scintillators
Haverah Park (GB)	Water Cherenkov
Yakutsk (Russia)	Scintillators + Atmospheric Cherenkov
Fly's Eye (USA)	Atmospheric fluorescence
Akeno (Japan)	Scintillators + μ detectors
Auger (Int)	Scintillators + Atmospheric fluorescence
Telescope Array (Japan)	Atmospheric fluorescence
OWL-AirWatch (Int)	Atmospheric fluorescence

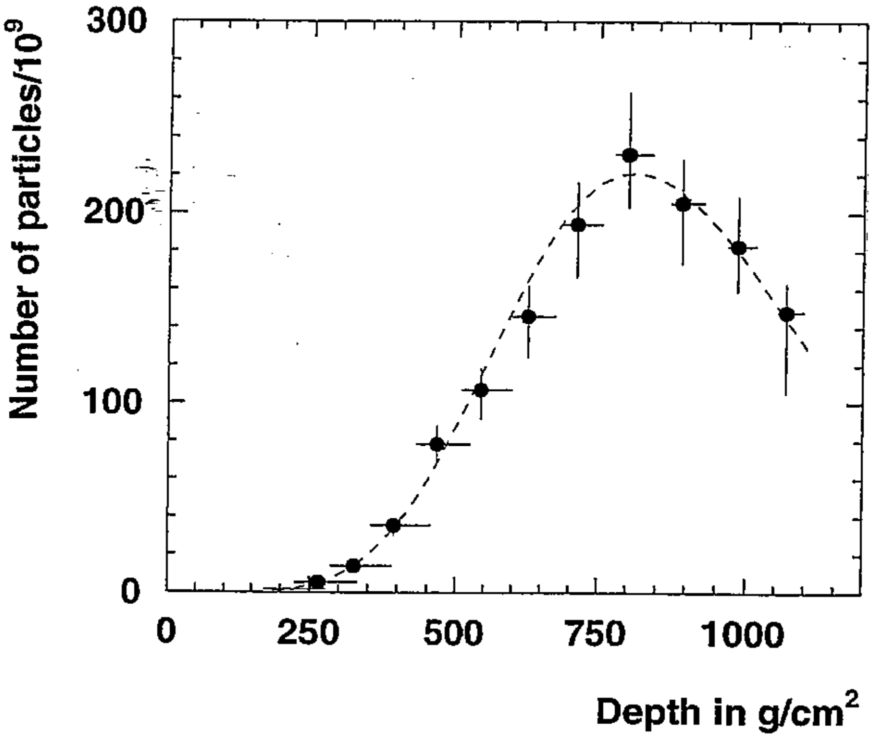
Hillas-plot (candidate sites for E=100 EeV)



This version of the Hillas plot is due to M. Boratav

Highest Energy Event

$$E = 3 \times 10^{20}\ \mathrm{eV} \quad \text{or} \quad 50\,\mathrm{J}$$

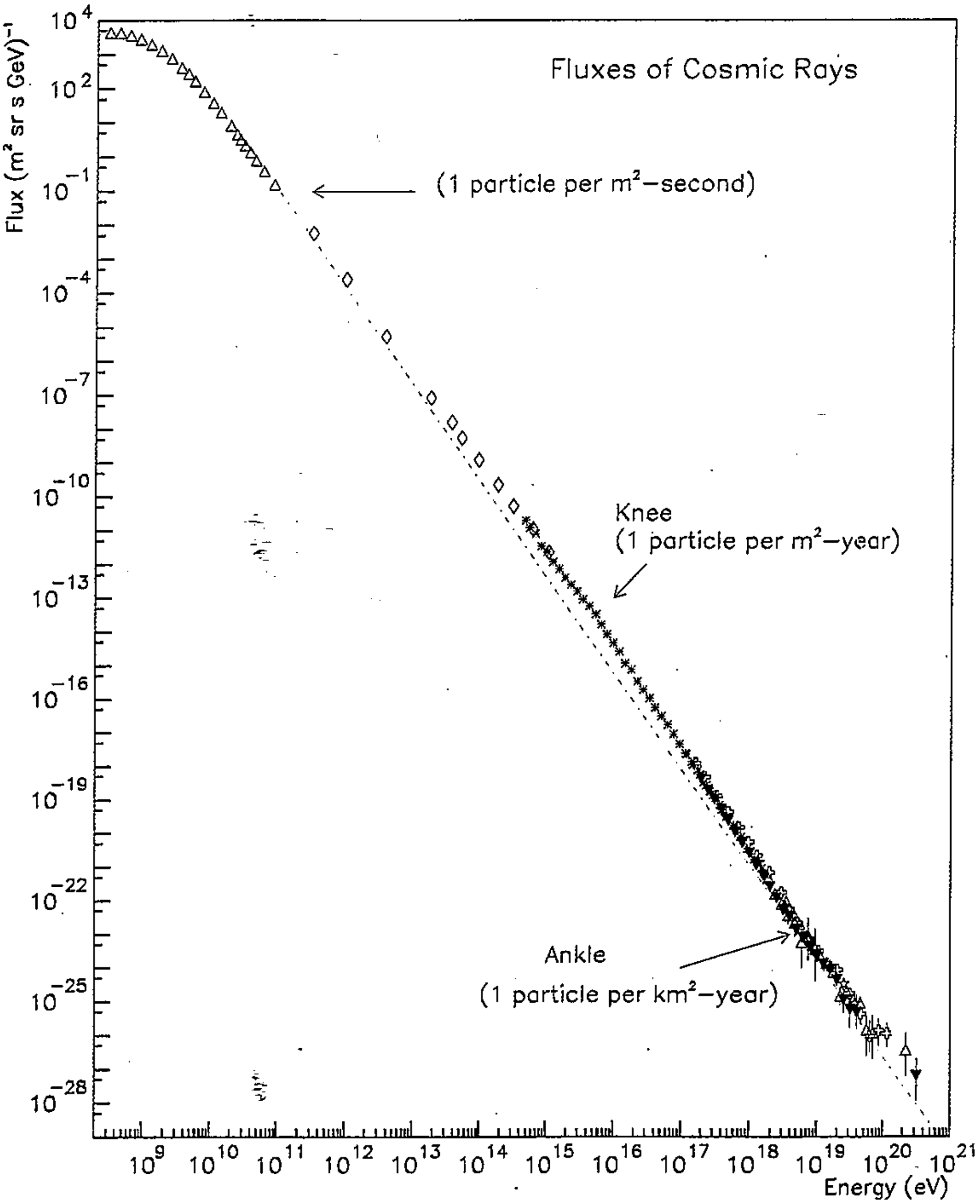


The number of particles in the cascade at the maximum is more than 200 billion.

Primary particle had more kinetic energy than a well-hit rock.

This is what you would see if someone ran through the atmosphere at the speed of light holding a 4 watt blue lightbulb.

Global Spectrum of Cosmic Rays

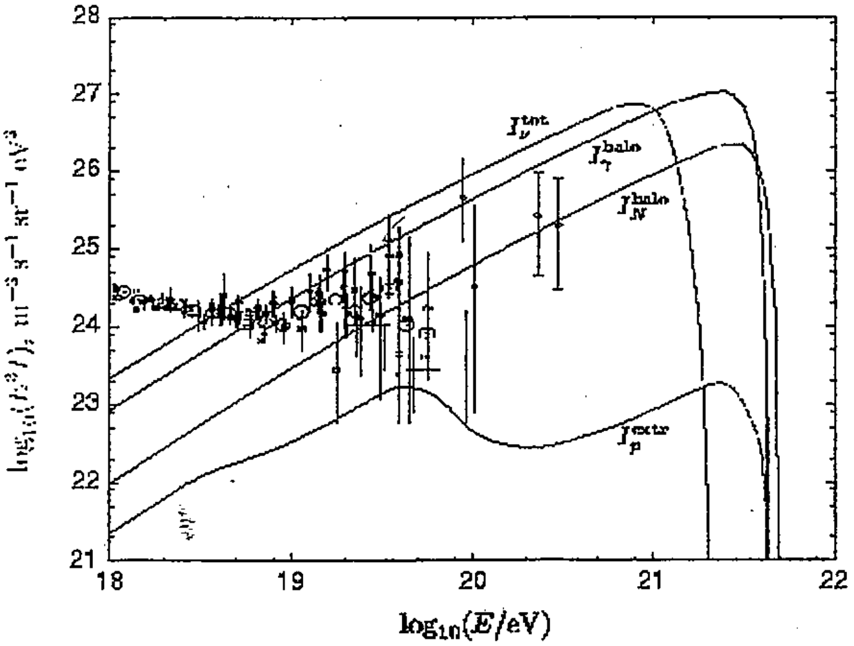


NEW PHYSICS ?!

Solutions to the puzzle were considered with the aid of:

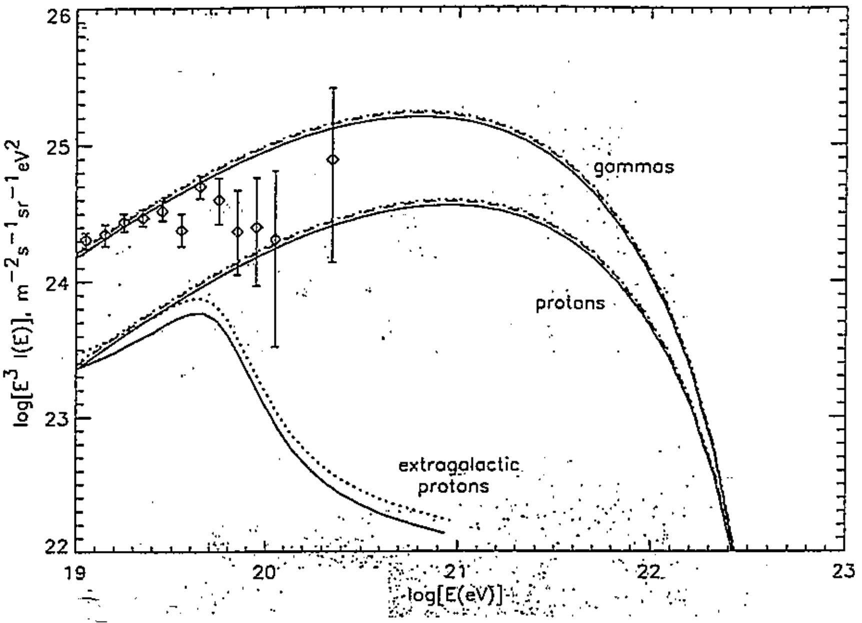
- Particle which is immune to CMBR but produces normal air shower.
- Topological Defects:
  - Strings.
  - Superconducting strings.
  - Networks of monopoles connected by strings.
  - Magnetic monopoles.
- Heavy quasistable relic particles.

Particle has to be HEAVY, $m_X > 10^{12}$ GeV.

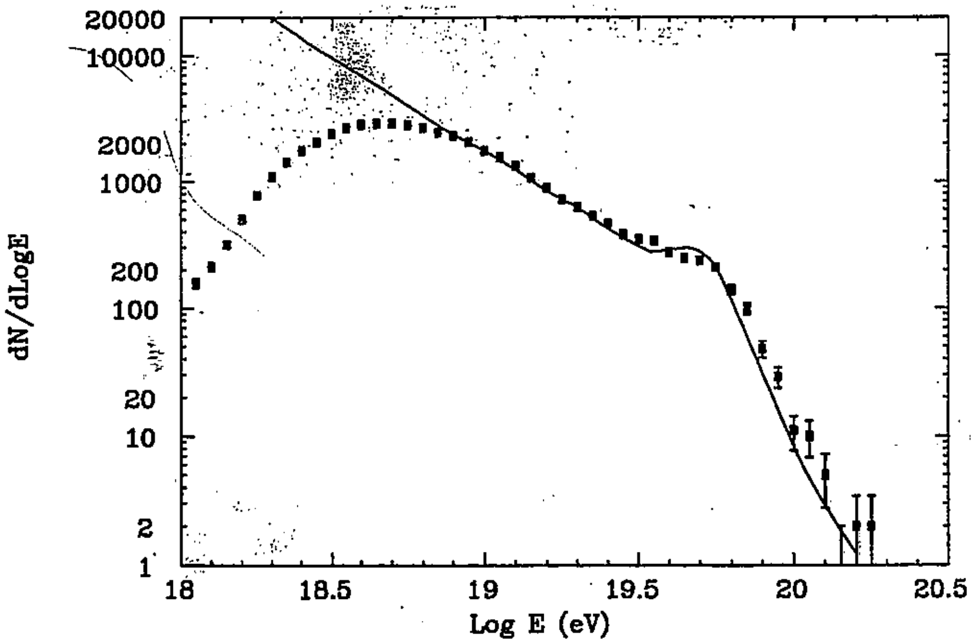


The fluxes shown were obtained for $m_X = 10^{13}$ GeV and $(\Omega_X/\Omega\mathrm{CDM})(t_0/\tau_X) = 5 \times 10^{-11}$, V. Berezinsky, astro-ph/9801046.

Statistics: Present and Future



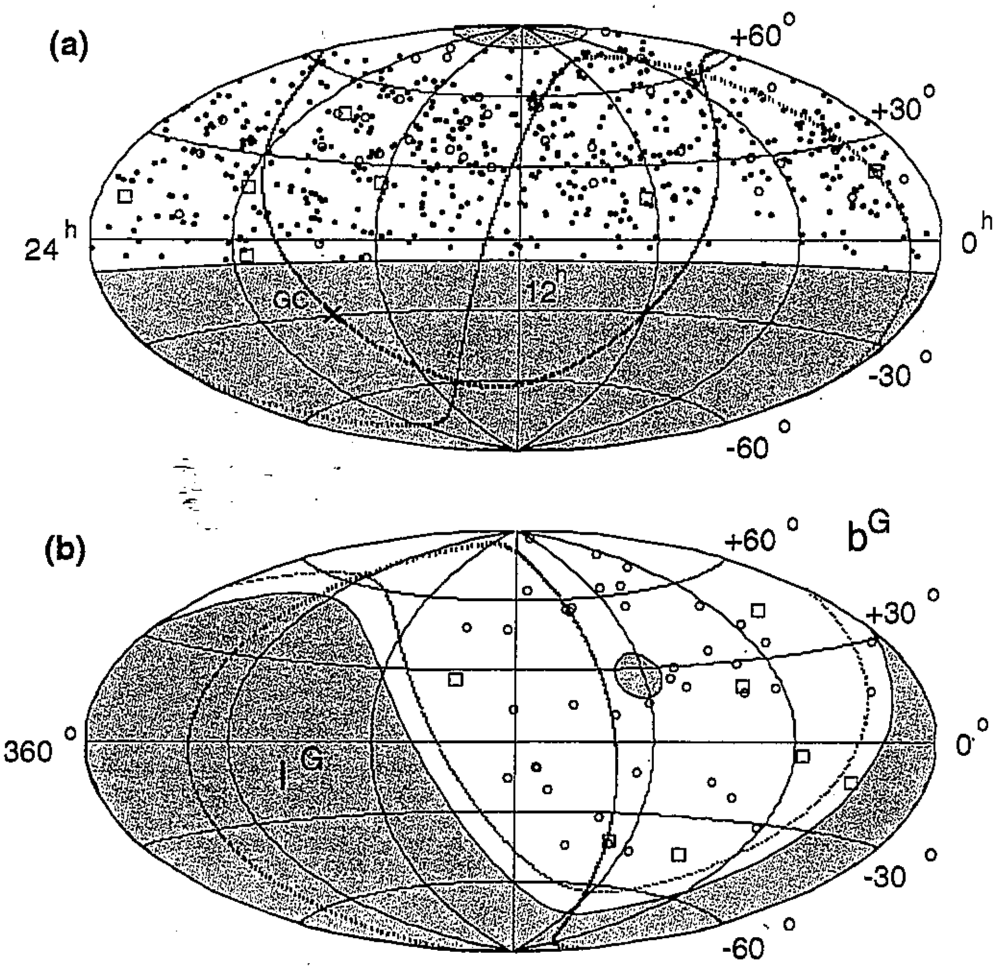
AGASA data versus X-particles decay scenario



Auger Design Report versus Astrophysics scenario

Arrival directions of cosmic rays with energies above $10^{19.0}$ eV

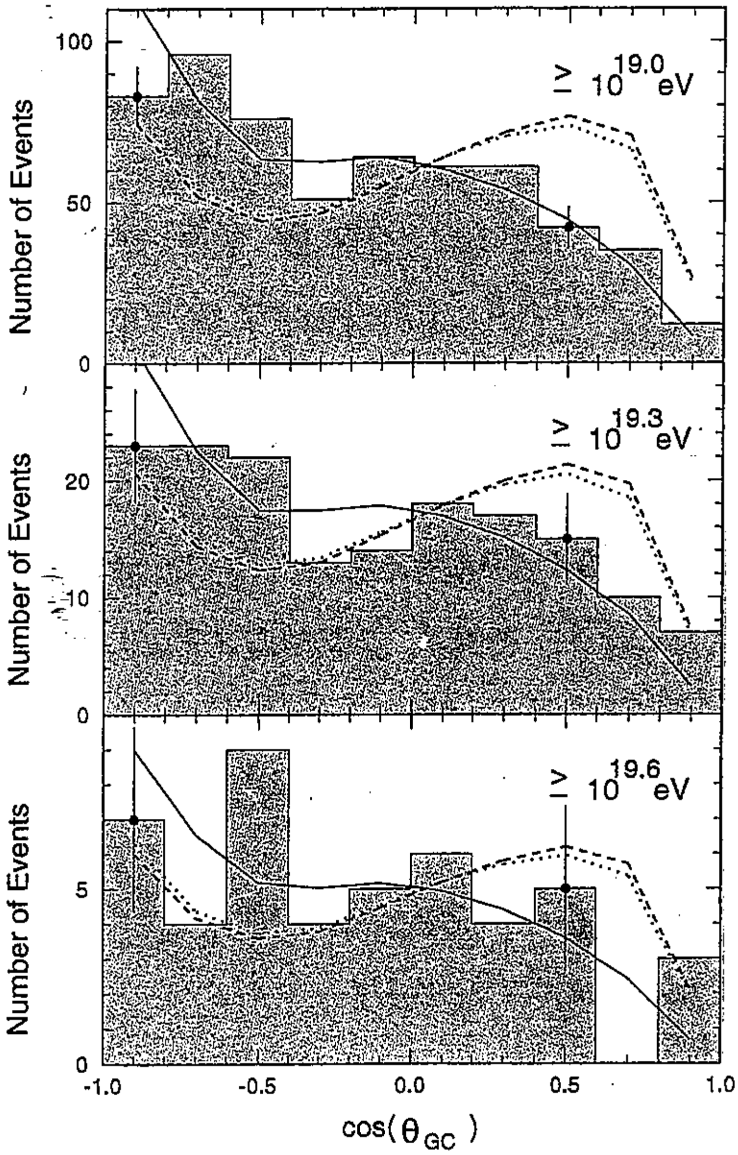
in (a) equatorial and (b) galactic coordinates



Dots, open circles, and open squares represent cosmic rays with energies of (1 - 4) × 10^{19} eV, (4 - 10) × 10^{19} eV, and $\geq 10^{20}$ eV, respectively.

The galactic plane is shown by the red curve.
The supergalactic plane is shown by the blue curve.
"GC" designates the galactic center.

Anisotropy of cosmic rays with energies > 10^{19} eV



θ_{GC} is the opening angle between the cosmic-ray direction and the galactic center direction.
The solid curve indicates expectation for isotropic flux.
Dashed and dotted curves indicate the distribution expected for two different dark matter halo models.

adapted from M. Takeda. et al. AGASA collaboration

SUPERHEAVY PARTICLES.

ULTRA-HIGH ENERGY COSMIC
RAYS (UHECR):
A WINDOW TO EARLY
(POST-INFLATIONARY) EPOCH
of the UNIVERSE

V.K. and V. RUBAKOV
'97

HEAVY LONG-LIVING, $\tau \gtrsim t_0$,
PARTICLES MAY CONSTITUTE
(a SUBSTANTIAL FRACTION of) CDM.
SO, UHECR and CDM MAY BE RELATED.

RANGE OF PROPERTIES OF DECAYING
X-PARTICLES.

1. ASSUMING SIZEABLE HADRONIC COMPONENT (JETS), THE FLUX OF PROTONS (NEUTRONS) OR γ'S OF ENERGY E ON THE EARTH:

$$\frac{dF}{d\ln E} = \frac{1}{4\pi}\,\frac{n_x}{\tau_x}\,R_{p,\gamma}\,N_j\,\frac{dN_{p,\gamma}(E)}{d\ln E} \qquad (1)$$

N_j - NUMBER OF JETS, n_X - NUMBER DENSITY
$R_{p,\gamma}$ - DISTANCE TO X-PARTICLE, τ_X - LIFETIME
$\frac{dN}{d\ln E}$ - FRAGMENTATION FUNCTION

TAKE $N_j \sim 1-10$

$dN/d\ln E \sim 10-100$

$R \lesssim 100$ Mpc

$E \sim (\text{a few}) \cdot 10^{10}$ GeV.

2. SECOND RELATION :

$$m_X \langle n_X \rangle = \Omega_X \rho_{crit} \qquad (2)$$

$$\Omega_X \lesssim 1$$

TAKE $n_X \sim \langle n_X \rangle$.

IN ORDER TO PRODUCE CR OF ENERGIES $E \gtrsim (\text{a few}) \cdot 10^{11}$ GeV,

$$m_X \gtrsim 10^{13} \text{ GeV}.$$

NOW, FROM (2) FIND a BOUND FOR DENSITY-TO-ENTROPY RATIO :

$$n_X / s \lesssim 10^{-21} \qquad (3)$$

TO PRODUCE THE OBSERVED FLUX OF UHECR, KEEPING IN MIND

$$\tau_X \gtrsim 10^{10} \text{ yr} , \qquad (4)$$

OBTAIN

$$n_X / s \gtrsim 10^{-33} \qquad (5)$$

THEN, FROM (3) and (5)

$$\tau_X \lesssim 10^{22} \text{ yr} \qquad (6)$$

TWO PROBLEMS:

I. <u>WHAT MIGHT BE THE PARTICLE PHYSICS MECHANISM RESPONSIBLE FOR LONG BUT FINITE LIFETIME OF SUPERHEAVY PARTICLES</u>?

II. <u>HOW TO PRODUCE A PROPER AMOUNT OF SUPERHEAVY PARTICLES</u>?

- TURN FIRST TO I.

WE HAVE TO EXPLAIN

$$10^{10}\,\text{yr} \lesssim \tau_X \lesssim 10^{22}\,\text{yr}$$

PERTURBATIVE MECHANISMS IRRELEVANT.
SO, ONE HAS TO EXPLORE
NON-PERTURBATIVE PHENOMENA.
EXAMPLE: INSTANTON INDUCED TRANSITIONS

IF INSTANTONS ARE RESPONSIBLE

$$\tau_X \sim m_X^{-1} \cdot \exp(4\pi/\alpha_X) \qquad (7)$$

WHERE α_X – COUPLING CONSTANT OF RELEVANT (SPONTANEOUSLY BROKEN) GAUGE SYMMETRY.

FROM

$$10^{10}\,yr \lesssim \tau_X \lesssim 10^{22}\,yr$$

ONE FINDS

$$\alpha_X = \frac{1}{10} - \frac{1}{12} \rightarrow \text{VERY LARGE!} \qquad (8)$$

- AN ILLUSTRATION: A TOY MODEL

- $SU(2)_X \otimes SM$
  $\hookrightarrow$ BROKEN AT HIGH SCALE
  CONVENTIONAL q's and ℓ's CARRY NON-TRIVIAL $SU(2)_X$ QUANTUM NUMBERS

- TWO LEFT-HANDED $SU(2)_X$ FERMIONIC DOUBLETS X and Y and 4 RH SINGLETS. ALL SINGLETS UNDER $SU(2)_L \times SU(3)_c$ OF SM.

- AFTER $SU(2)_X$ BREAKS DOWN
  X and Y ACQUIRE LARGE MASSES
  X and Y CARRY DIFFERENT GLOBAL QUANTUM NUMBERS
  LIGHTEST X and Y ARE PERTURBATIVELY STABLE.

- $SU(2)_X$ INSTANTONS INDUCE EFFECTIVE INTERACTIONS VIOLATING GLOBAL Q-NUMBERS OF X and Y.

- LET $m_X > m_Y$

$$X \rightarrow Y + \text{quarks} + \text{leptons} \qquad (11)$$

LIGHTEST OF X and Y MAY BE RESPONSIBLE FOR CD and PROCESS (11) → FOR UHECR.

NOW TURN TO THE PROBLEM II.

- II. <u>HOW TO PRODUCE A PROPER AMOUNT OF SUPERHEAVY PARTICLES IN THE EARLY UNIVERSE?</u>

THERE ARE TWO WAYS.

- THERMAL PRODUCTION. V.K. and V. Rubakov '97
- NON-THERMAL PRODUCTION (VACUUM FLUCTUATIONS)

V.K. and Tkachev '98
CHUNG et al '98

1. THERMAL PRODUCTION.

ONE NEEDS $T_{reheat} < m_X$.

THEN
$$n_X / s \cong const \cdot \exp(-2 m_X / T_r)$$
$$const \sim 10^{-3}.$$

AS THE DOMINANT SUPPRESSION COMES FROM exp( ), ONE FINDS
$$T_r = \left(\frac{1}{20} - \frac{1}{35}\right) m_X$$
$$T_r \sim 10^{11} - 10^{13} \text{ GeV}$$

THIS MIGHT BE REALISTIC IN SOME SCENARIOS OF INFLATION
HOWEVER, IF $T_r \lesssim 10^{10}$ GeV ONE HAS UNDERPRODUCTION!

- 2. NON-THERMAL PRODUCTION.

MATTER CREATION
IN THE EARLY RAPIDLY
EXPANDING UNIVERSE

V.K. and I. Tkachev
'98, '99
Chung, Kolb, Riotto
'98

NON-THERMAL

SHP CAN BE CREATED IN EARLY UNIVERSE BY SEVERAL MECHANISMS.
AMONG THOSE ARE:

1. NON-EQUIL. "THERMAL" PRODUCTION IN SCATTERING &/OR DECAY PROCESSES IN PRIMORDIAL PLASMA.
2. PRODUCTION DURING DECAY OF INFLATON OSCILLATIONS ("PREHEATING").
3. DIRECT GRAVITATIONAL PRODUCTION FROM VACUUM FLUCTUATIONS DURING INFLATION (59, 19, 60).

TWO LATTER MECHANISMS: PARTICLE CREATION IN EXTERNAL, TIME VARYING, BACKGROUND.

HOWEVER, WHILE OUTCOME OF 2nd MECHANISM IS HIGHLY DEPENDENT ON STRENGTH OF INTERACTION OF X FIELD TO INFLATON, NO COUPLING (E.G., TO INFLATON OR PLASMA) IS NEEDED IN 3rd MECHANISM, WHERE TEMPORAL CHANGE OF METRIC IS THE SINGLE CAUSE FOR PARTICLE PRODUCTION.

EVEN STERILE PARTICLES ARE PRODUCED which MIGHT BE RELEVANT FOR LONG-LIVING SUPERHEAVY PARTICLES.

RESULTING ABUNDANCE IS QUITE INDEPENDENT OF NATURE OF PARTICLES.

X-particle can be a thermal relic. However, strong constraints on reheating temperature (e.g. $T_r < 10^9$ in suprgravity) may rule out this possibility.

GRAVITATIONAL CREATION OF MATTER FROM THE VACUUM

Some part of matter which we (may be) are observing today could have been created right from the vacuum. No coupling (e.g. to the inflaton or plasma) is needed. The time varying metric of the cosmological background will do the job.

This happens naturally and without fine-tuning. All one needs are stable (very long-living) X-particles with the mass of order of the inflaton mass, $m_X \approx 10^{13}$ GeV. This was noticed by Chung, Kolb and Riotto (1998) who conjectured that such X-particles may constitute dark matter today ($\Omega_X \sim 1$), and by Kuzmin and Tkachev, (1998) who conjectured that the decays of these X-particles may produce observed mysterious Ultra High Energy ($E > 10^{11}$ GeV) Cosmic Rays events ($10^{-12} < \Omega_X < 1$).

Inflationary stage is not required to produce superheavy particles from the vacuum. Rather, the inflation provides a cut off in excessive production of heavy particles which would happen in the Friedmann Universe if it would start from the initial singularity.

THE BASIC FORMALISM.

HEAVY SCALAR FIELD χ:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) + \frac{1}{2}(D_\mu \chi)^2 - \frac{1}{2}(M^2 - \xi R)\chi^2 - \frac{g^2}{2}\phi^2\chi^2$$

$V(\phi)$ – inflaton

$V(\phi) = m_\phi^2 \phi^2/2$ or $\lambda \phi^4/4$

$m_\phi^2/M_{Pl}^2 \sim 10^{-12}$ or $\lambda \sim 10^{-13}$.

$\xi = 0$ MINIMAL COUPLING

$\xi = 1/6$ CONFORMAL COUPLING

FERMIONS $(1/2)$ CONFORMALLY COUPLED TO GRAVITY.
COUPLING TO INFLATON $V_{1/2} = g\phi\bar{\chi}\chi$.
CONFORMAL METRIC $ds^2 = a(\eta)^2(d\eta^2 - dx^2)$.

CHOOSE $\varphi \equiv \phi\, a(\eta)$

$X \equiv \chi\,(a(\eta))^S$,

$S = 1$ and $3/2$

SCALARS FERMIONS

$\tau \equiv m\eta$.

QUANTUM FIELDS IN CLASSICAL BACKGROUNDS.

REAL SCALAR FIELD. THE FOURIER EXPANSION:

$$X(\tau, x) = \sum_k \left[X_k(\tau)\, a_k + X_k^*(\tau)\, a_{-k}^\dagger \right] e^{ikx}$$

$$[a_k, a_k^\dagger] = 1.$$

MODE FUNCTIONS $\chi_k \equiv \chi_k(\tau)$ OF A SCALAR (BOSE) FIELD ARE SOLUTIONS OF OSCILLATOR EQUATIONS

$$\chi_k'' + \omega_k^2(\tau)\chi_k = 0 \qquad (4)$$

WITH THE TIME DEPENDENT FREAQUENCY:

$$\omega_k^2(\tau) = k^2 + \frac{a''}{a}(6\xi - 1) + m_\chi^2 a^2 + 4q\phi^2$$

$$' \equiv d/d\eta \, , \quad m_\chi^2 = \frac{M_X^2}{m^2} \, , \quad q \equiv \frac{g^2\phi^2(0)}{4m^2}$$

$\phi(0)$ – value of INFLATON FIELD WHEN IT STARTS TO OSCILLATE (CORRESPONDS TO $\varphi(0) = 1$).

Etc.

LET THERE WAS SOME ADIABATIC TIME INTERVAL: $|\omega_k'|/\omega_k^2 \ll 1$. VACUUM $a_k|0\rangle = 0$

DURING ADIABATIC EVOLUTION → NO CHANGE IN PARTICLE NUMBER DENSITY.

BUT AFTER UNDERGOING SOME NON-ADIABATIC PERIOD THERE IS SOME.

FOURIER COEFFICCENTS RELATED TO EACH OTHER:

$$a_k^{out} = \alpha_k a_k + \beta_k^* a_k^\dagger .$$

INITIAL VACUUM STATE AT LATE TIMES CONTAINS PARTICLES ← BOGOLYUBOV '58.

$$\langle 0| a_k^{\dagger out} a_k^{out} |0\rangle = |\beta_k|^2 .$$

TECHNICALLY EASIER TO FIND BOGOLYUBOV COEFFICIENTS BY DIAGONALIZING HAMILTONIAN of X.

ONE FINDS:

$$|\beta_k|^2 = \frac{|\chi_k'|^2 + \omega^2 |\chi_k|^2 - 2\omega}{4\omega}$$

WHERE MODE FUNCTIONS ARE SOLUTIONS OF (4). with INITIAL (VACUUM) CONDITIONS

$$\chi_k(0) = \omega^{-1/2} \quad \chi_k'(0) = -i\omega\chi_k .$$

②. SPIN $\frac{1}{2}$ FERMIONS.

MODE FUNCTIONS OF FERMION FIELD SATISFY OSCILLATOR EQUATION WITH COMPLEX FREQUENCY

$$\chi_k'' + (\omega_k^2 - i\, m_{eff}')\chi_k = 0$$

REAL PART OF FREQUENCY IS GIVEN BY $\omega_k^2 = k^2 + m_{eff}^2$

$$m_{eff} = m_\chi a + \sqrt{q} \cdot \varphi$$

CHOOSE $\chi_k(0) = \sqrt{1 - \frac{m_{eff}}{\omega}}$; $\chi_k'(0) = -i\omega\chi_k$.

ONE HAS PER ONE SPIN STATE

$$|\beta_k|^2 = \frac{\omega - m_{eff} - Im(\chi_k \chi_k^{*\prime})}{2\omega}$$

FINALLY, NUMBER DENSITY OF X CREATED BY TIME VARYING BACKGROUND

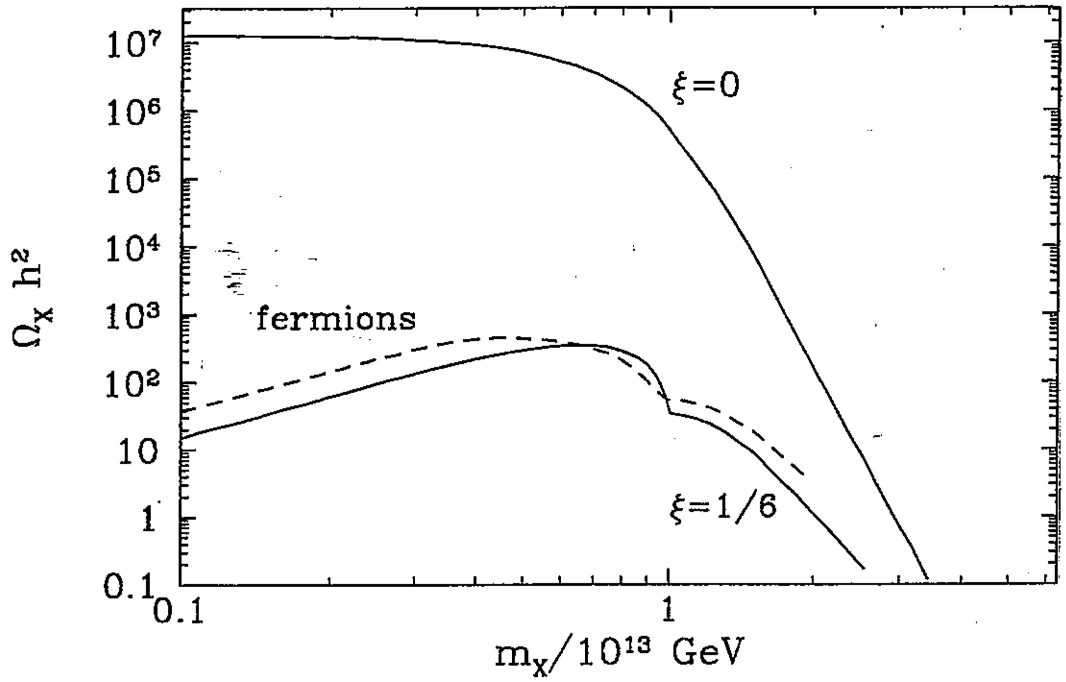
$$n_\chi = \frac{1}{2\pi^2 a^3} \sum_s \int |\beta_k|^2 k^2 dk .$$

THIS IS FOR PARTICLES ONLY.

INFLATIONARY COSMOLOGY

There is no singularity and Hubble constant is limited, $H < m_\phi$, in inflationary cosmology.

Production of particles with $m_X > H \sim 10^{13}$ GeV is suppressed.



adapted from I. Tkachev and V. Kuzmin Phys. Rev. D59 (1999) 123006

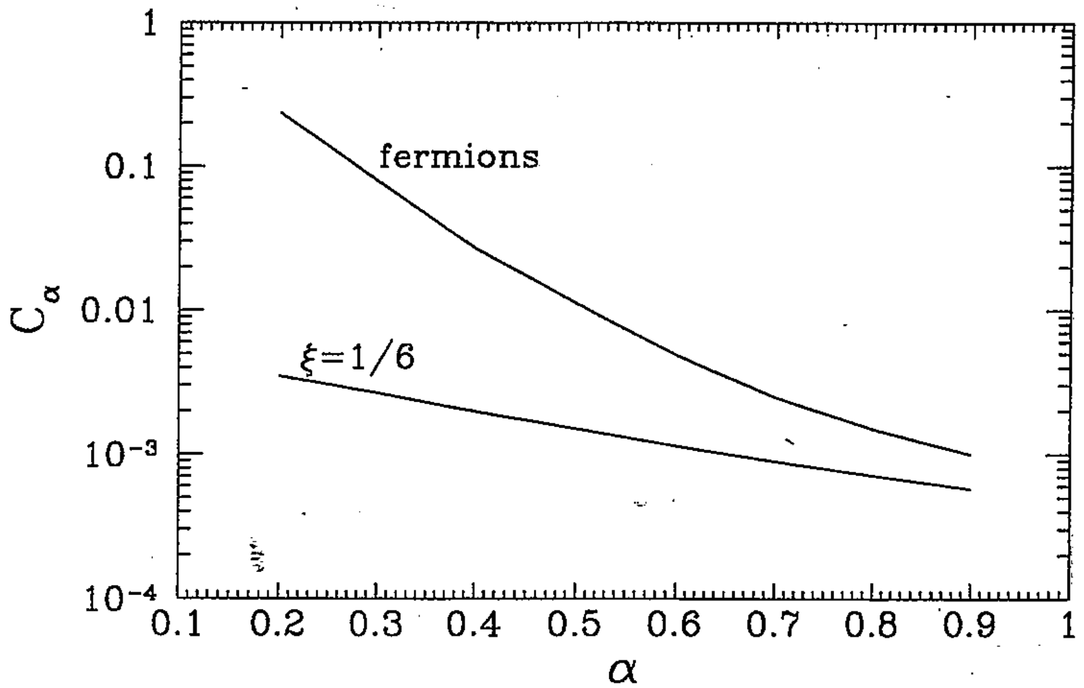
Present day ratio of the energy density in X-particles to the critical energy density

It is the particle mass which couples the system to the background expansion and serves as the source of particle creation. Therefore we expect

$$n_X \propto m_X^3 a^{-3}$$

at late times when particle creation diminishes. In Friedmann cosmology, $a \propto (mt)^\alpha \propto (m/H)^\alpha$ the anticipated formulae can be parameterized as

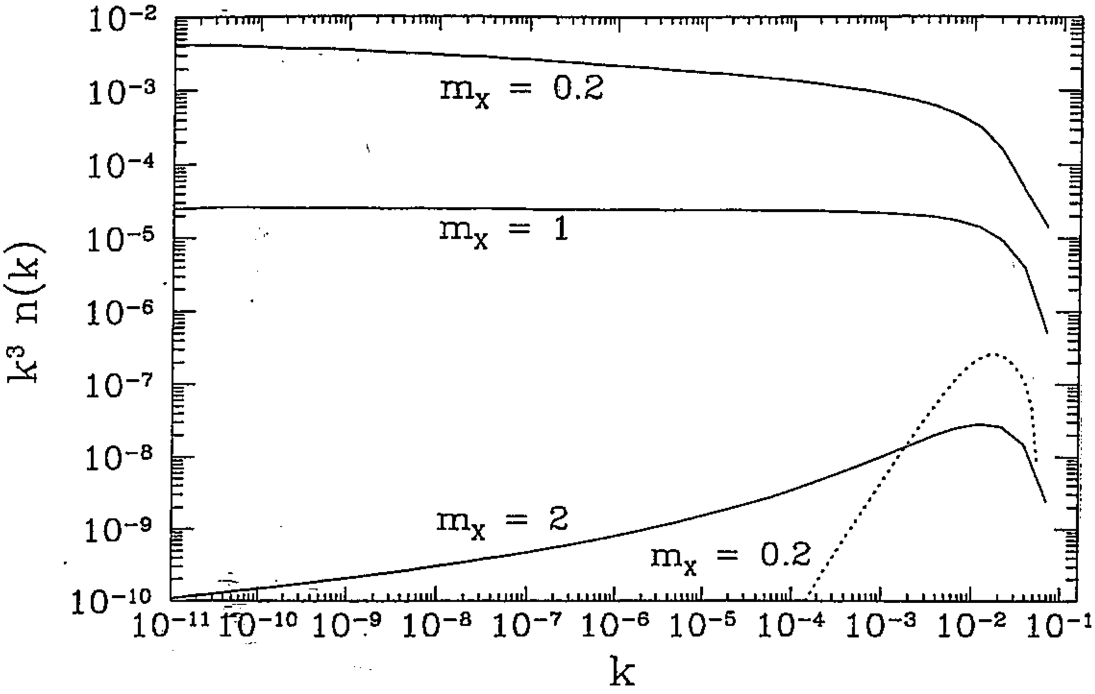
$$n_X = C_\alpha m_X^3 \left(\frac{H}{m_X}\right)^{3\alpha}$$



adapted from I. Tkachev and V. Kuzmin Phys. Rev. D59 (1999) 123006

Stable particles with $m_X > 10^9$ GeV will overclose the Universe.

SPECTRUM



Spectrum of created particles in a model with massive inflaton for several choices of the mass of scalar X-particle with the minimal coupling (solid lines) and the conformal coupling (dotted line). Masses and momenta are given in units of the inflaton mass.

Magnitude of the density fluctuations induced in the process of X particle creation can correspond to the observable on the horizon scale, and be responsible for fluctuations in CMBR if $m_X/m \approx 2$ and $\Omega_X \approx 1$.

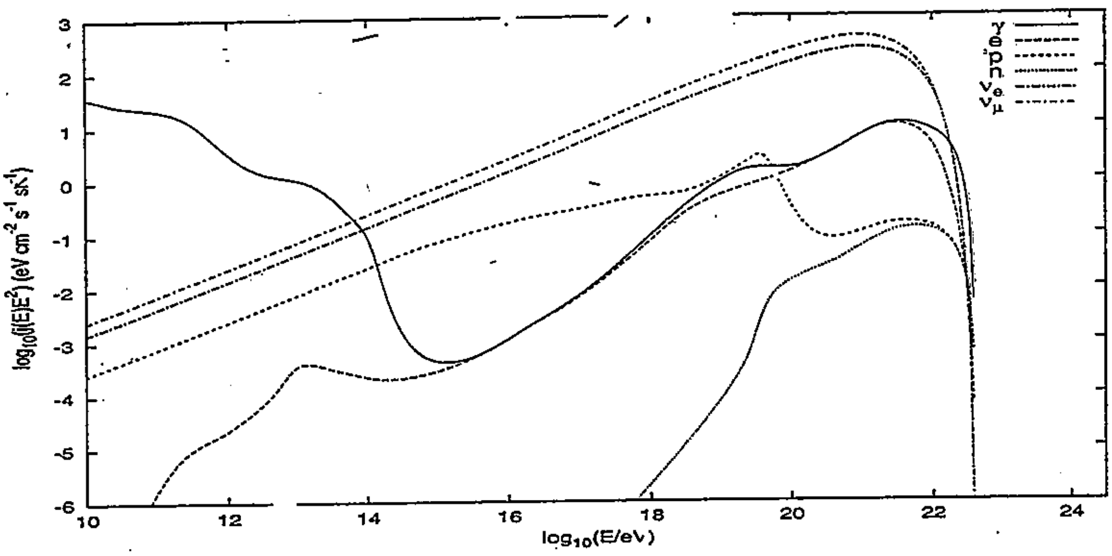


FIG. 3. UHECR spectra near the boundary of our Galaxy in the top-down model with $p = 1$, $M_X = 10^{23}$eV and constant EGMF $B = 10^{-12}$G, assuming decay mode $X \rightarrow qq$. The spectra are normalized to the observed flux at energy 10^{20}eV.

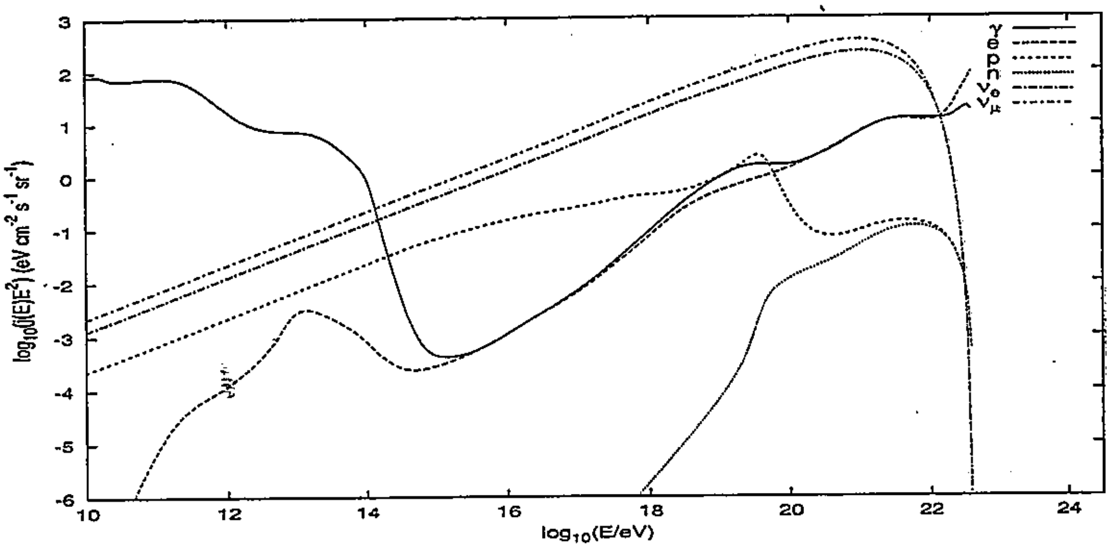


FIG. 4. Same as fig. 3 but for the decay mode $X \rightarrow qe$.

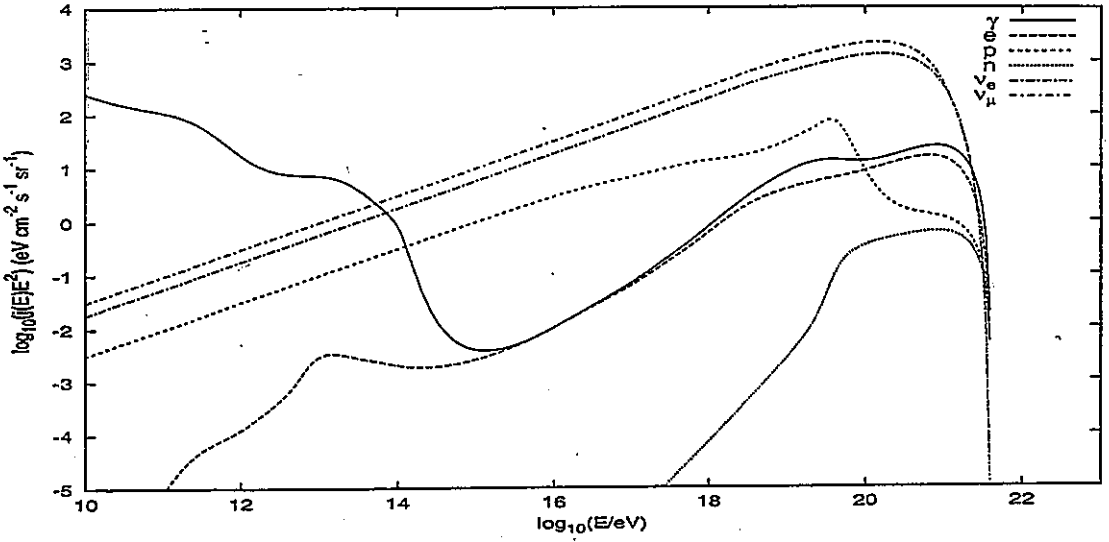


FIG. 1. Extra-galactic component of the spectra in the model of long-living X-particles with $\tau = 10^9 t_0$ (t_0 is the age of Universe) and the decay mode $X \to qq$. The strength of EGMF is $B = 10^{-12}$G. Synchrotron losses in the Galaxy are not taken into account (see comments in Sect. V).

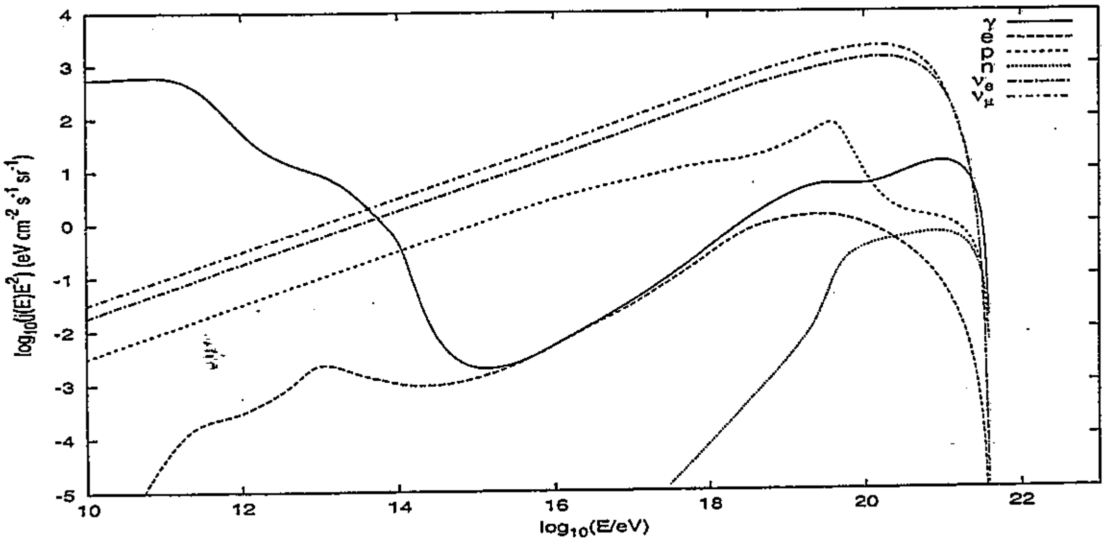


FIG. 2. Same as fig. 1 but for $B = 10^{-10}$G.

OBSERVATIONAL SIGNATURES OF UHECR ORIGINATING FROM X-PARTICLE DECAYS.

1. CLUSTERING IN GALAXIES

BERESINSKY, KACHELRIESS,
VILENKIN '97

UHECR FROM DECAYING X-PARTICLES IN OUR GALAXY CONSTITUTE THE BULK OF THE TOTAL (GALACTIC + EXTRAGALACTIC) FLUX OF UHECR

2. ANISOTROPY OF UHECR > 20%

DUBOVSKY, TINYAKOV
[redacted] '98
BEREZINSKY '99

3. LARGE (PREDOMINANT) FRACTION OF γ's DUE TO FRAGMENTATION

4. IF X ARE CLUMPED (VERY PLAUSABLY) UHECR WILL EXHIBIT CONSIDERABLE AMOUNT OF DOUBLETS (TRIPLETS).

DUBOVSKY,
TINYAKOV, '00
TKACHEV.

GENERAL CONCLUSIONS.

1. THE CONCEPT OF SUPERHEAVY LONG-LIVING PARTICLES AS SOURCES OF UHECR IS QUITE VIABLE FROM BOTH COSMOLOGICAL AND PARTICLE PHYSICS POINT OF VIEW.

2. THE CONCEPT HAS CLEAR EXPERIMENTAL SIGNATURES AND WITH BETTER STATISTICS MIGHT BE EITHER CONFIRMED OR RULED OUT. (A GOOD FEATURE!)

3. MORE STATISTICS IS NEEDED! NEW GENERATION OF EXPERIMENTAL ARRAYS FOR REGISTRATION OF EXTENSIVE AIR SHOWERS ARE IN TURN.

THANK YOU.