ULTRA-HIGH ENERGY COSMIC RAYS and SUPERHEAVY LONG-LIVING PARTICLES in the Universe.

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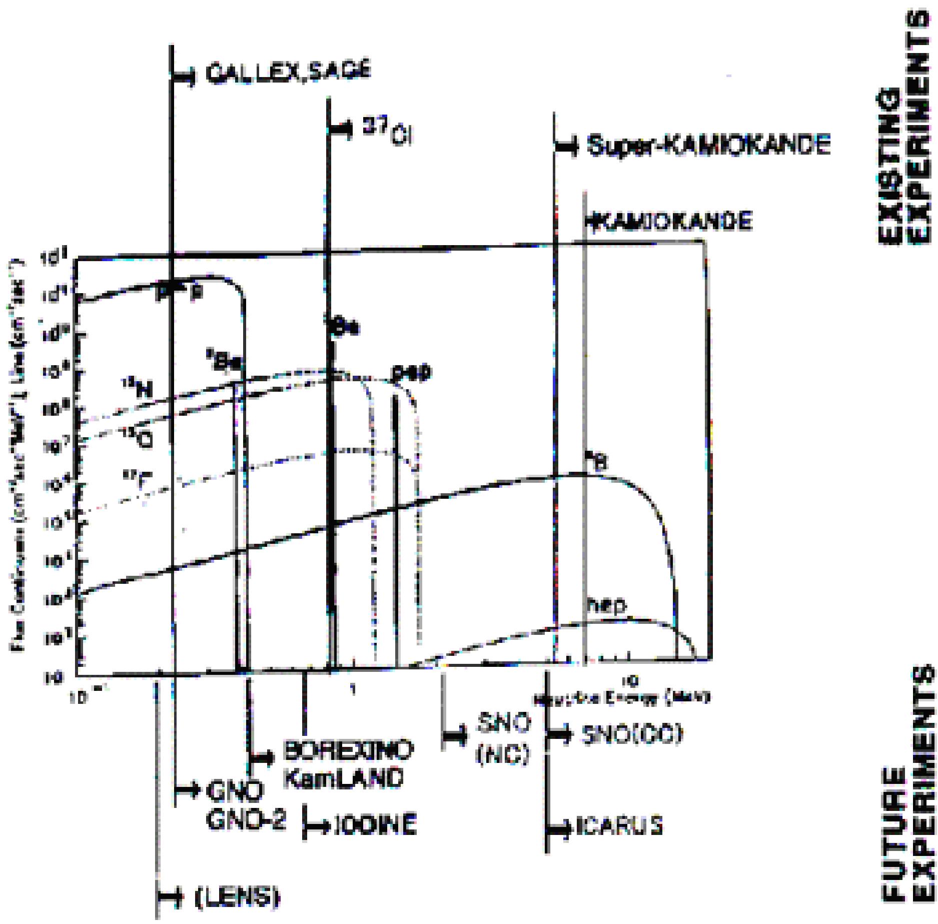
PLAN.

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

Solar Neutrinos



Results of Solar Neutrino experiments

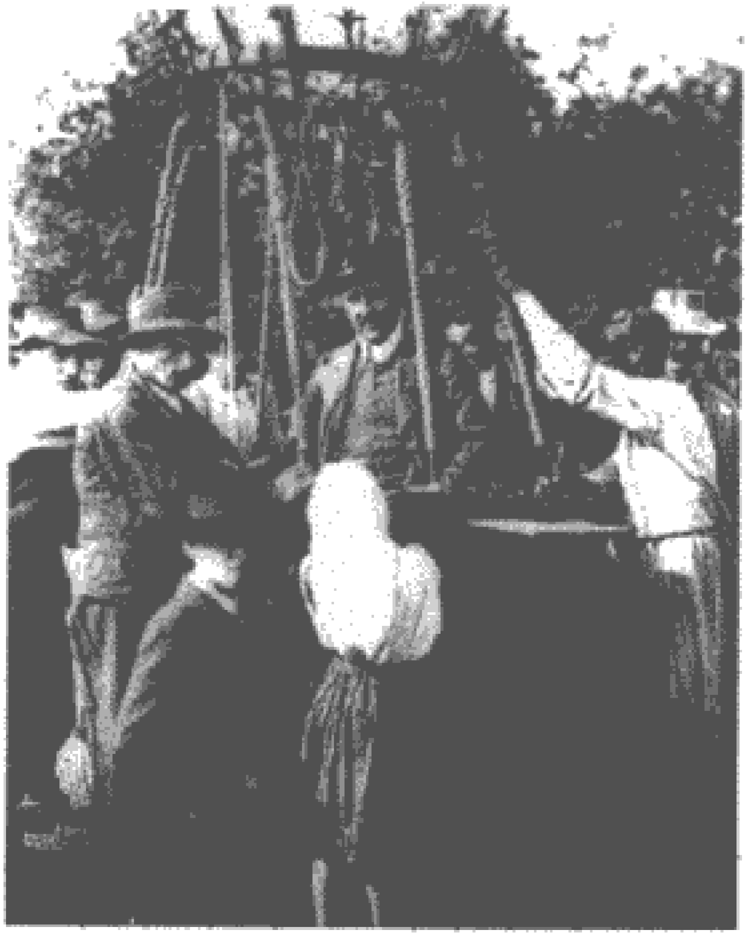
experi-ment	method	flux	Data/SSM (BP98)
^{37}Cl	ν_e ^{37}Cl	2.56±0.23 SNU	0.33±0.03
GALLEX	ν_e ^{71}Ga	76±8 SNU	0.59±0.06
SAGE	ν_e ^{71}Ga	70±8 SNU	0.54±0.06
Kamiokande	ν e scat.	$(2.80\pm0.19\pm0.33)\times10^6$ /cm²/sec	0.54±0.07
Super K	ν e scat.	$(2.44\pm0.05\ {+0.09/-0.07})\times10^6$ /cm²/sec	0.47±0.03

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

A Timeline History of High-Energy Cosmic Rays

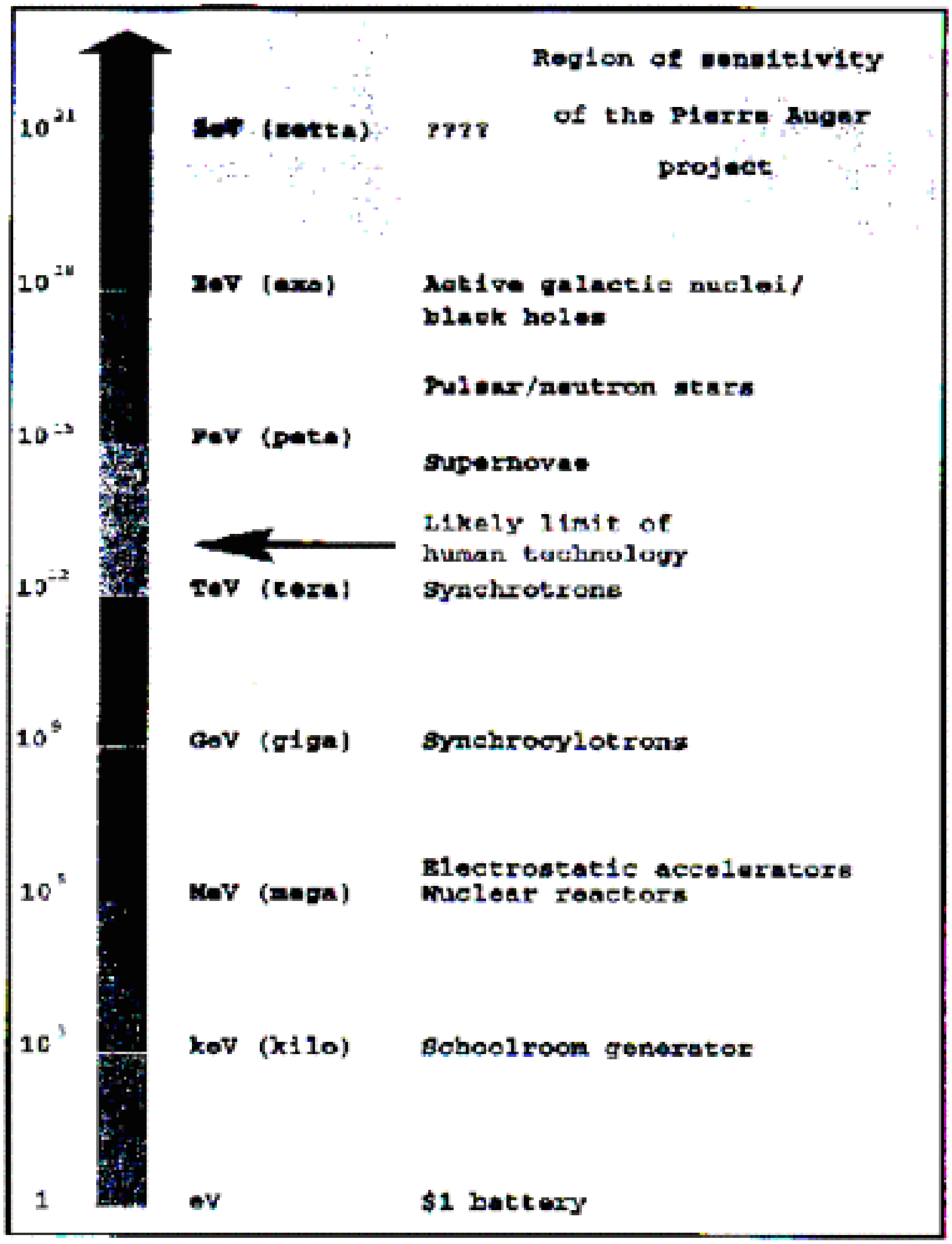
- **1912** Hess discovered cosmic rays
- **1927** Cosmic rays seen in cloud chamber by Skobelzyn
- **1932** Anderson discovered antimatter
- **1937** Discovery of muon
- **1938** Auger discovered extensive air showers
- **1946** First air shower experiments
- **1947** Discovery of charged pions and kaons
- **1949** Fermi's theory of cosmic rays
- **1962** First 10^{20} eV cosmic ray detected
- **1966** Greisen and Zatsepin & Kuzmin propose GZK cutoff energy for cosmic rays
- **1991** Fly's Eye detected highest-energy event ever
- **1994** AGASA high-energy event
- **2000** HiRes expected to begin operation

1912

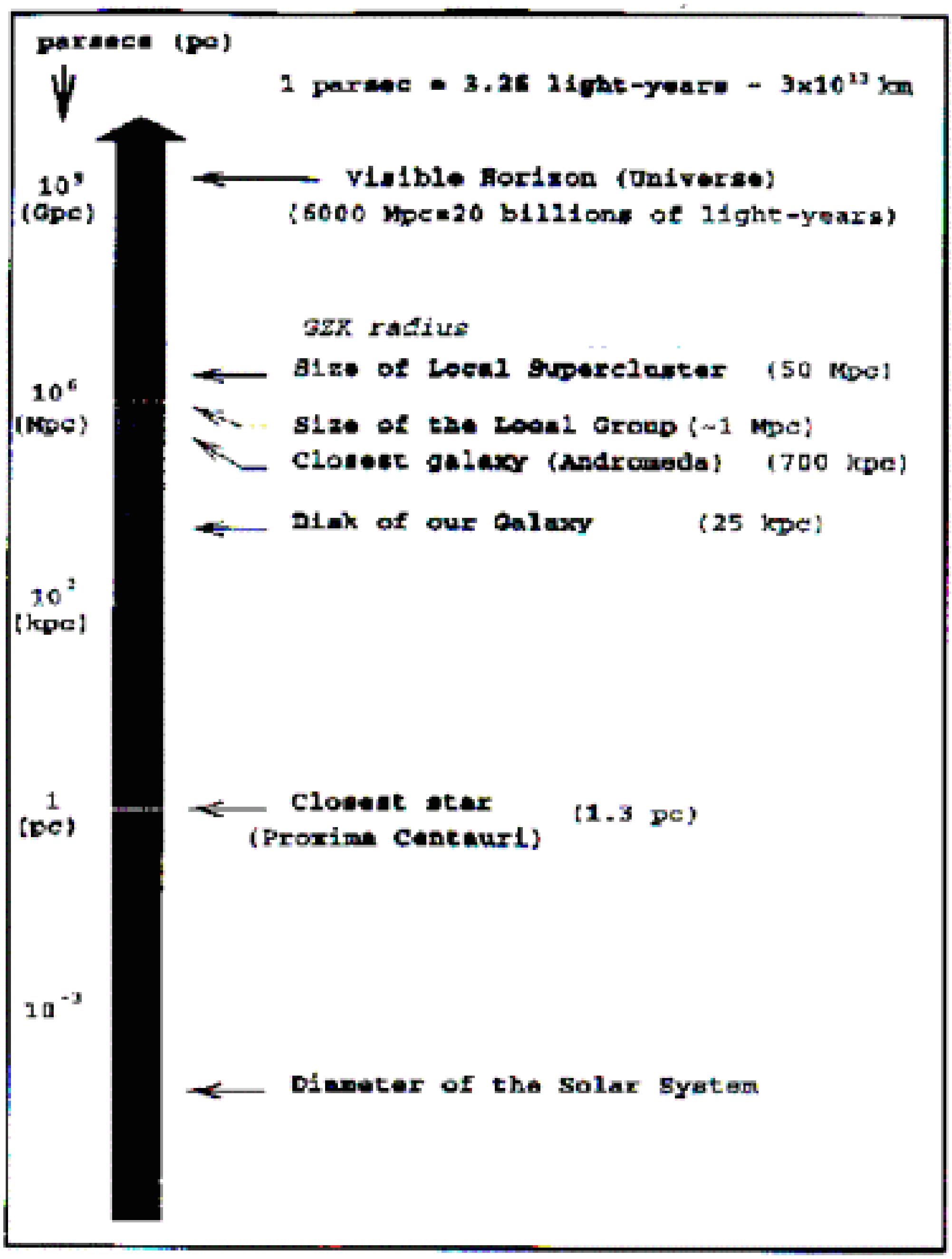


In a balloon at an altitude of 5000 meters, Victor Hess , the father of cosmic ray research, discovered "penetrating radiation" coming from space.

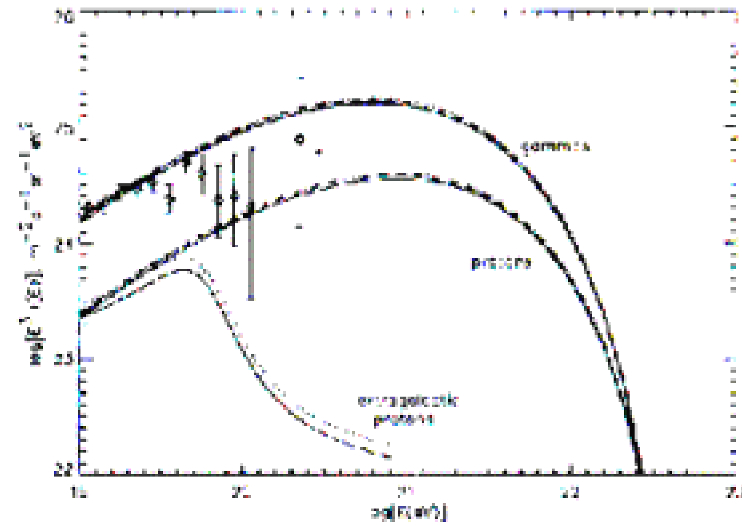
Particle Physics Energy Scales



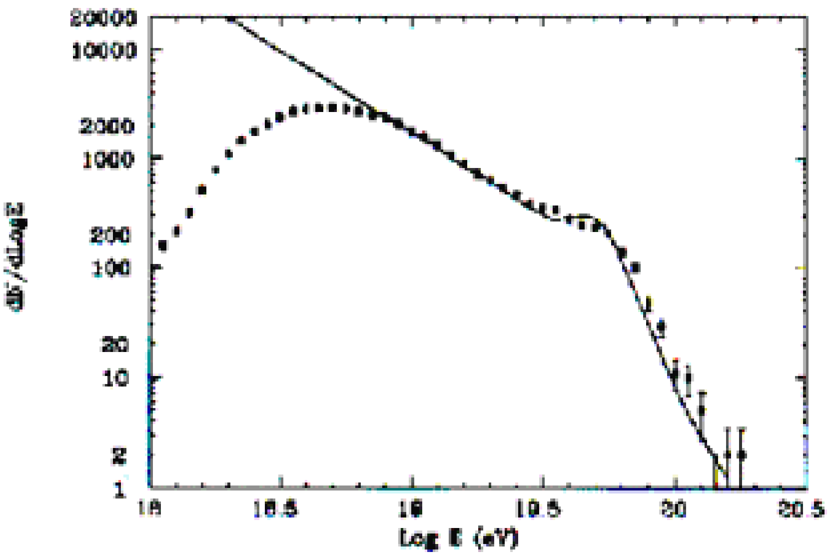
Astronomical Distance Scales



Statistics: Present and Future



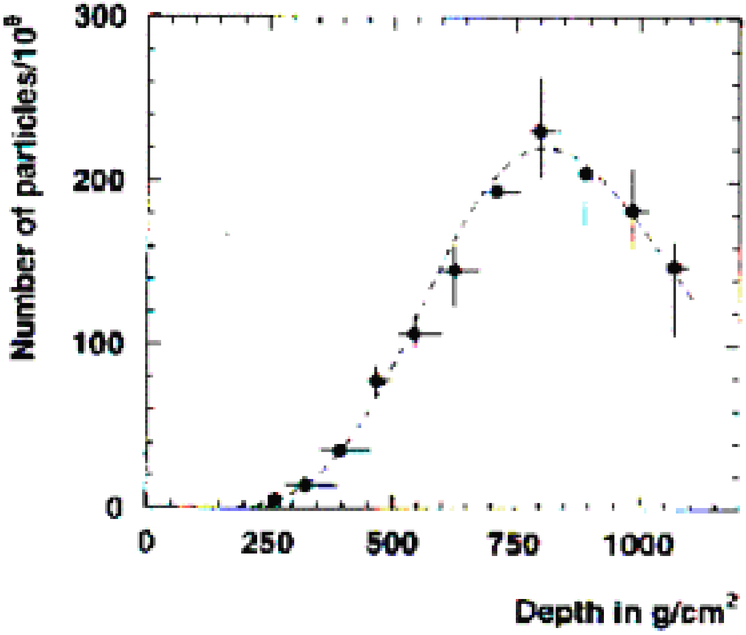
AGASA data versus X-particles decay scenario



Auger Design Report versus Astrophysics scenario

Highest Energy Event

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

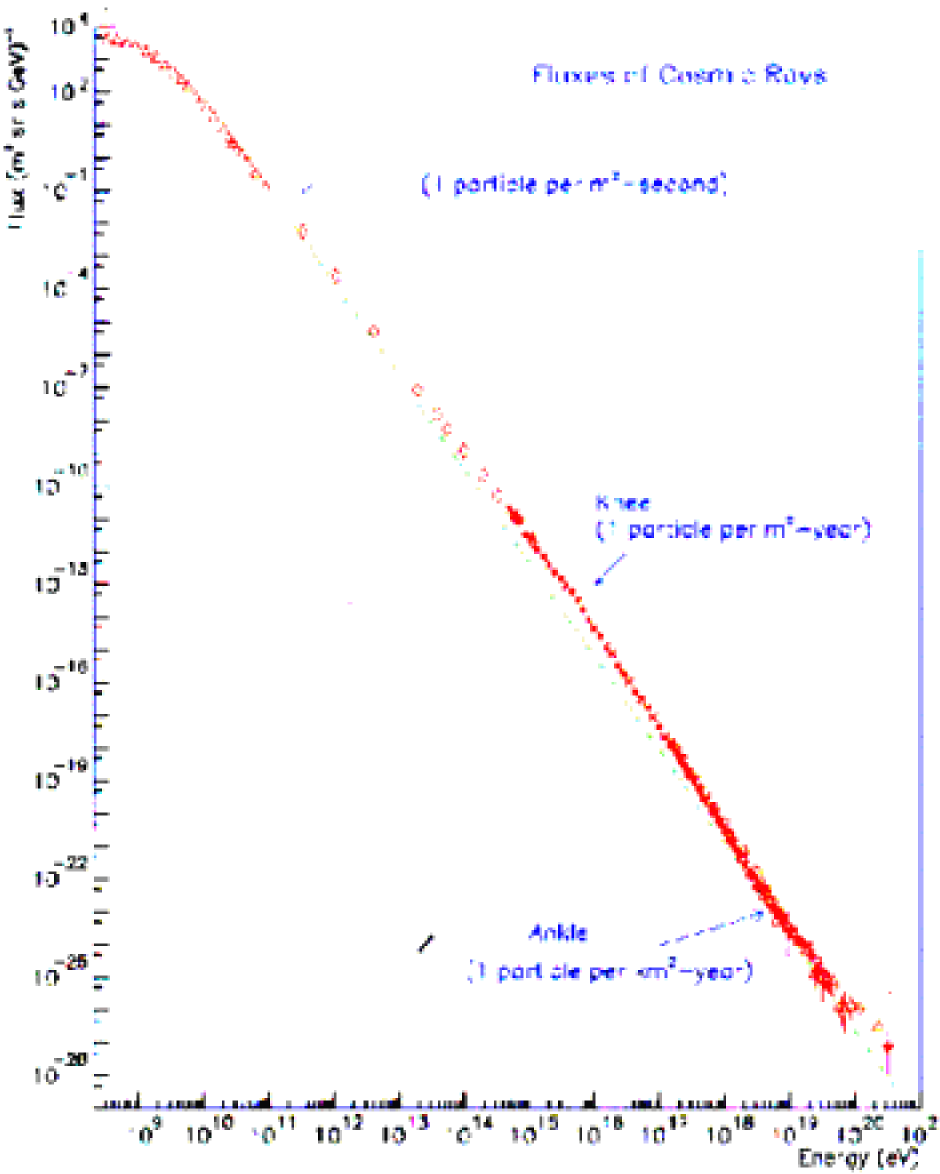


The number of particles in the cascade at the maximum is more than 200 billion.

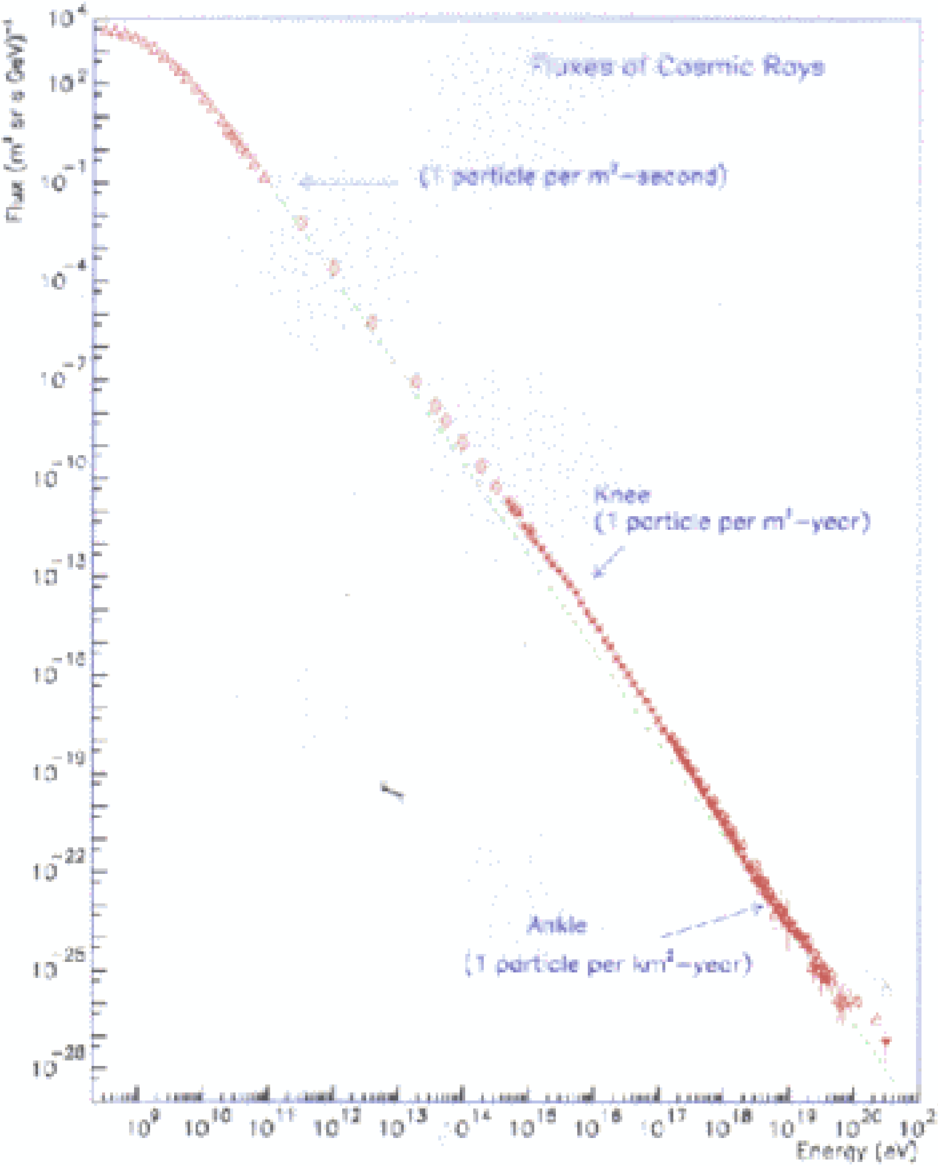
Primary particle had more kinetic energy than a well-hit rock.

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



Global Spectrum of Cosmic Rays

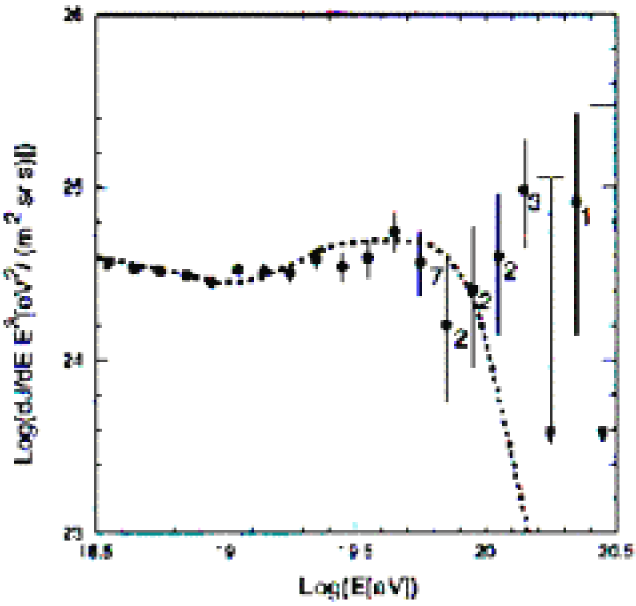


The CR spectrum beyond GZK cutoff

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.

NEW PHYSICS ?!

Solutions of the puzzle were considered with the aid of:

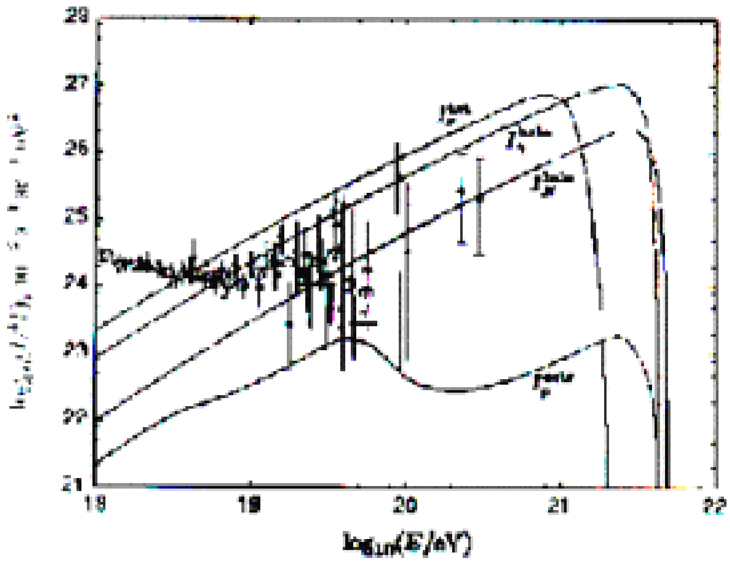
- Particle which is immune to CMBR but produces normal air shower.
- Topological Defects:
  - Strings.

    Superconducting strings.

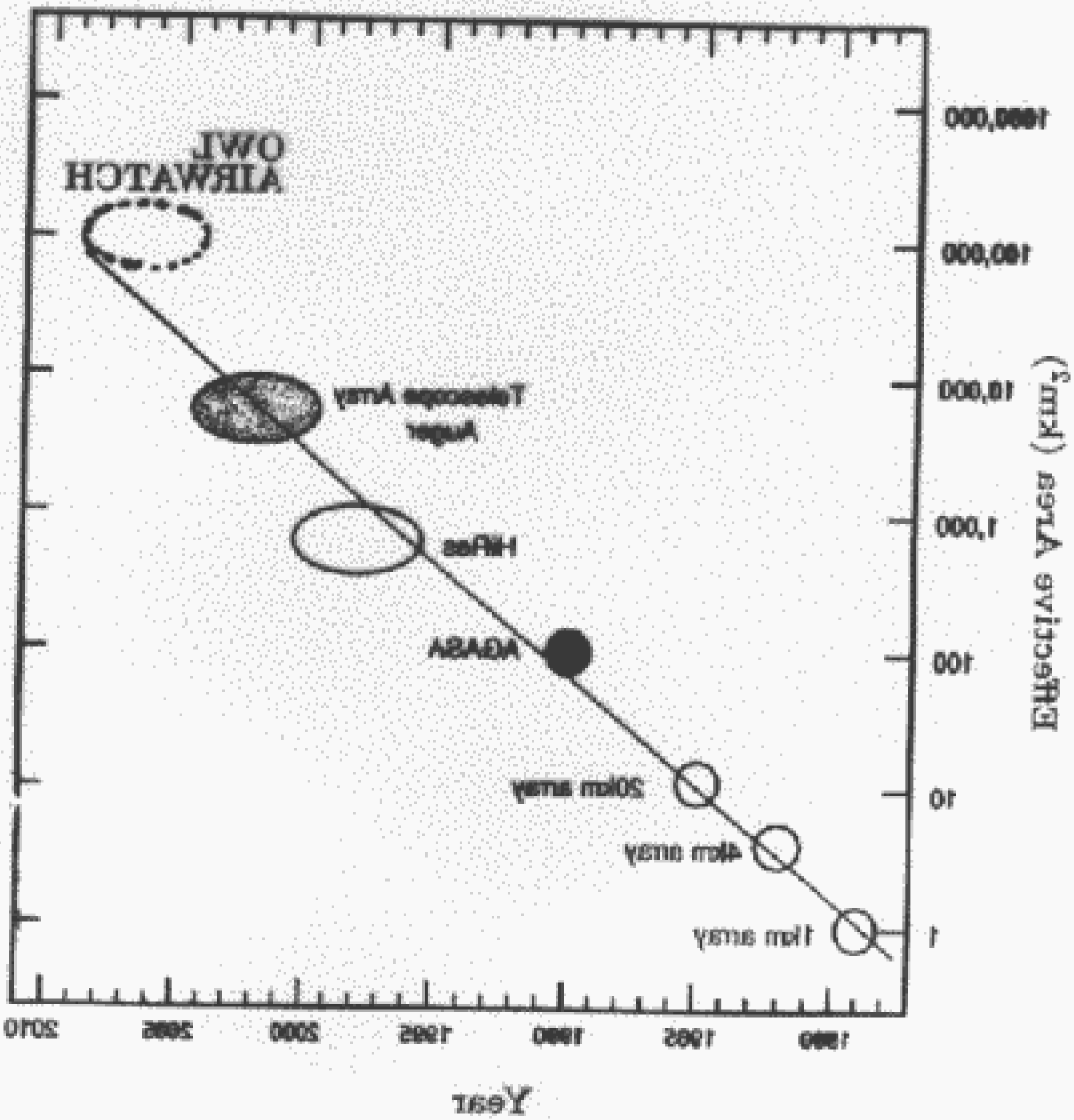
    Networks of monopoles connected by strings.

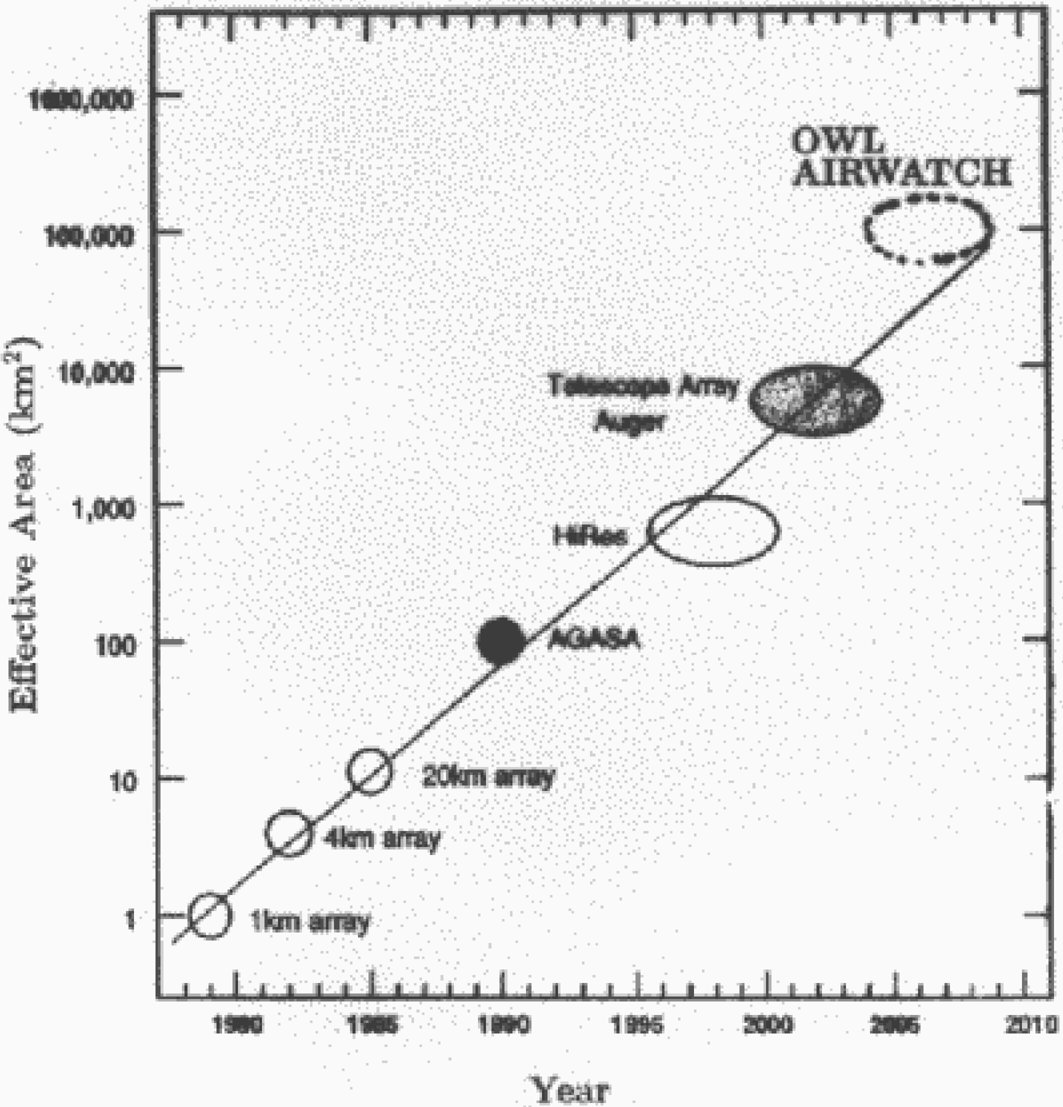
    Magnetic monopoles.
- Heavy quasistable relic particles.

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



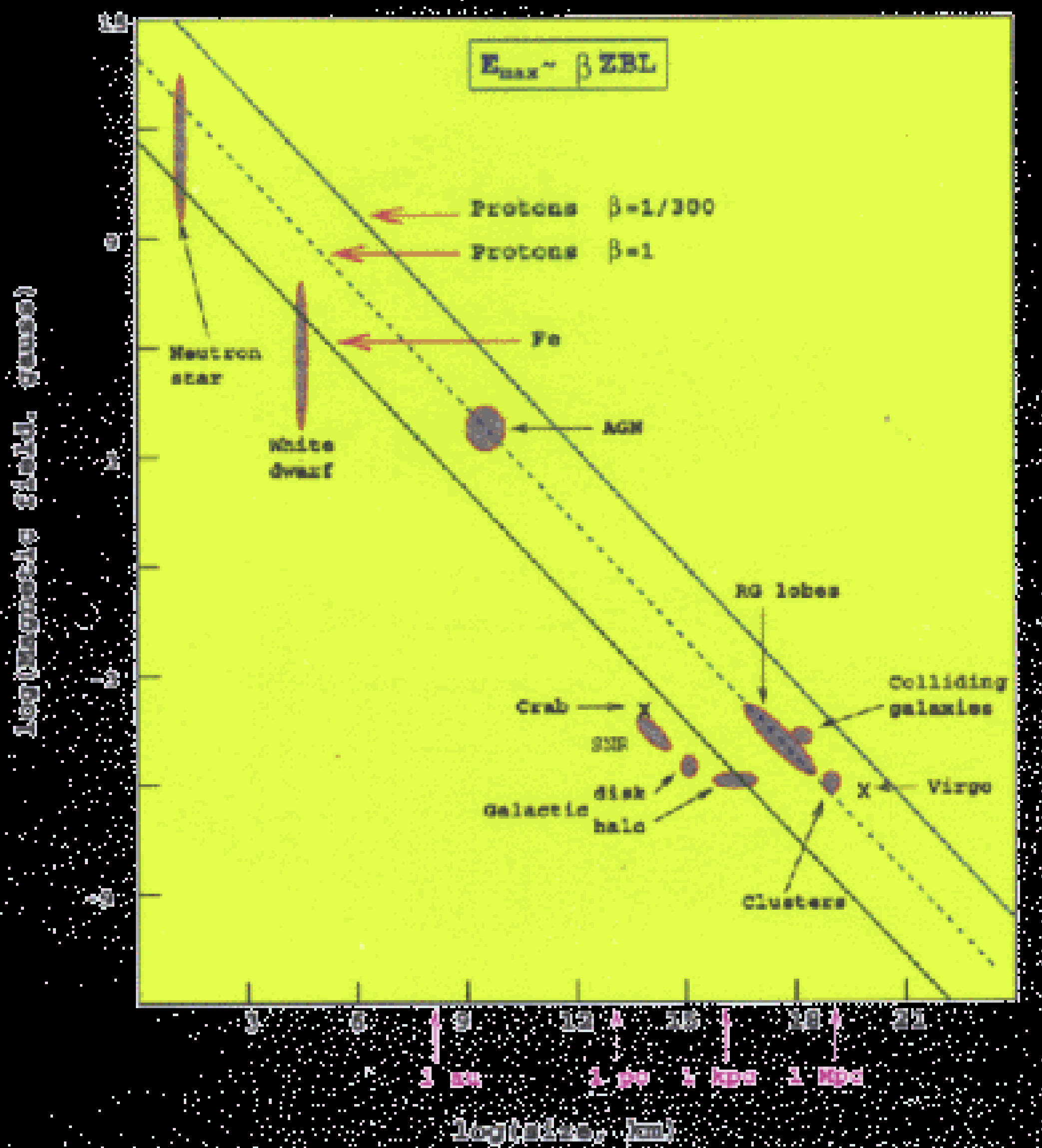
The fluxes shown were obtained for $m_X = 10^{13}$ GeV and $(\Omega_X/\Omega CDM)(t_0/\tau_X) = 5 \times 10^{-11}$, V. Berezinsky, astro-ph/9801046.


OWL
AIRWATCH
Telescope Array
Auger
HiRes
AGASA
20km array
4km array
1km array
Effective Area (km²)
Year



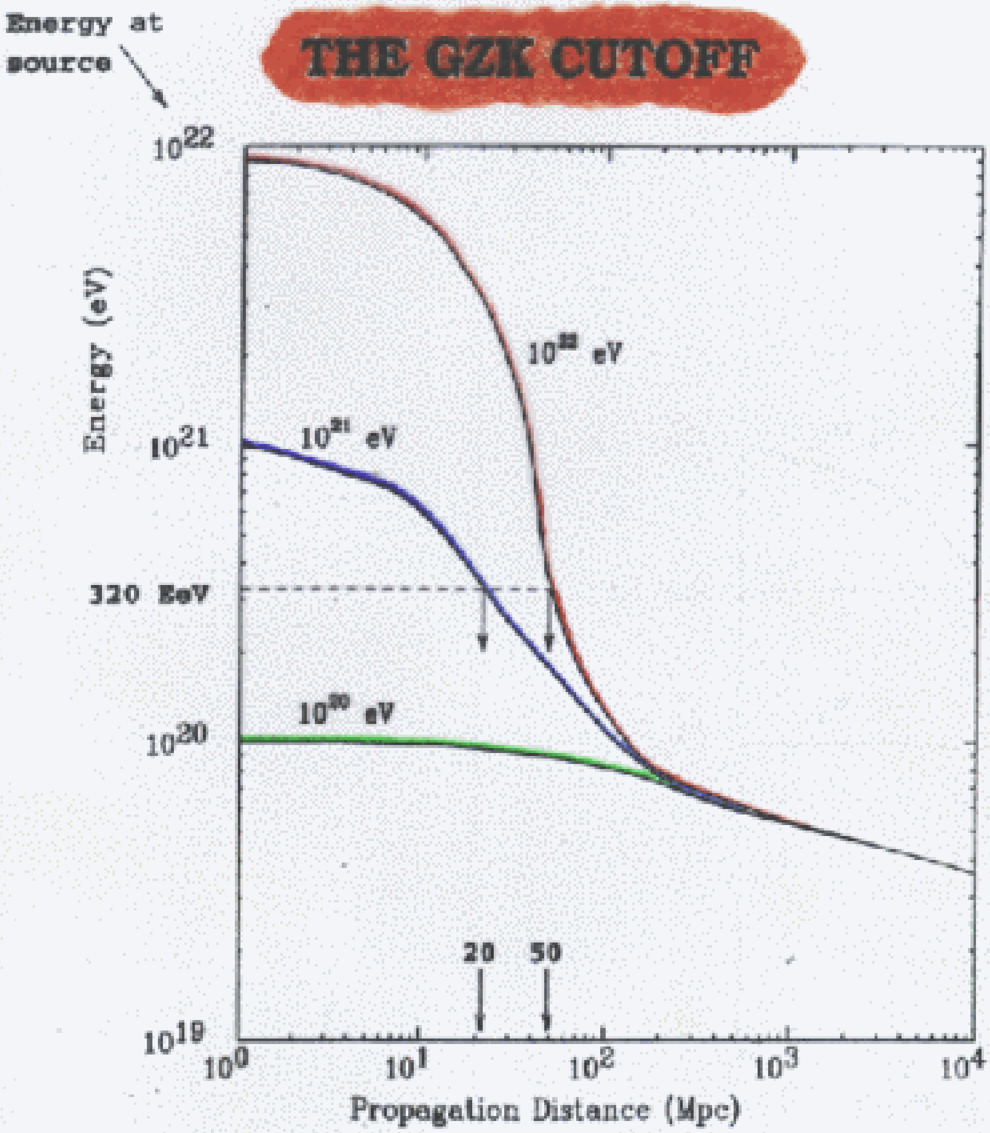
OWL
AIRWATCH
Telescope Array
Auger
HiRes
AGASA
20km array
4km array
1km array
1000,000
100,000
10,000
1,000
100
10
1
Effective Area (km²)
1980
1985
1990
1995
2000
2005
2010
Year

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



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

THE GZK CUTOFF



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

SUPERHEAVY PARTICLES.

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

BEREZINSKY et al '97.
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:

$$\frac{dF}{d\ln E} = \frac{1}{4\pi} \frac{n_X}{\tau_X} R_{p,\gamma} N_j \frac{dN_{p,\gamma}(E)}{d\ln E} \quad (1)$$

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)

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

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

II. HOW TO PRODUCE A PROPER AMOUNT OF SUPERHEAVY PARTICLES?

- TURN FIRST TO I. V.K. u Rubakov

WE HAVE TO EXPLAIN

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

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

$$\alpha_x = \frac{1}{10} - \frac{1}{12} \rightarrow \text{VERY LARGE!}$$

(!)

AN ILLUSTRATION: A TOY MODEL

- $SU(2)_X \otimes SM$
  - ⟶ 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 $m_X > m_Y$

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

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

NOW TURN TO THE PROBLEM II.

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

THERE ARE TWO WAYS.

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

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

1. THERMAL PRODUCTION.

ONE NEEDS $T_{reheat} < m_X$.

THEN

$$n_X / s \simeq const \cdot \exp(-2 m_X / T_r)$$

$$const \sim 10^{-3}.$$

AS THE DOMINANT SUPPRESSION COMES FROM exp( ),

ONE FINDS

$$T_r = \left(\frac{1}{20} - \frac{1}{35}\right) m_X$$

$$T_r \sim 10^{11} - 10^{13}\ GeV$$

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

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, <u>NO</u> 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.

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).

X-particle can be a thermal relic. However, strong constraints on reheating temperature (e.g. $T_r < 10^9$ in supergravity) 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.

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 [illegible] '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, TKACHEV. '00

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.