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SMR.1508 - 34

SUMMER SCHOOL ON PARTICLE PHYSICS

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ASTROPARTICLE PHYSICS

Lecture III

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UHECR: TOP-DOWN SCENARIOS

NOT MUCH SPACE IS LEFT: $E > 1 \cdot 10^{20}$ eV

GENERAL REQUIREMENTS

- TO EXPLAIN EVENTS AT $E > 1 \cdot 10^{20}$ eV
- TO EXPLAIN CORRELATIONS WITH BL Lacs

OVERVIEW

- NEW SIGNAL CARRIERS
  - STRONGLY INTERACTING NEUTRINOS (ν_{SI})
    (EXTRA DIMENSIONS, INSTANTON EFFECT)
  - LIGHT STABLE HADRONS (e.g. GLUINO)

  MOTIVATION:

  NO GZK CUTOFF, SMALL-ANGLE CLUSTERING,
  CORRELATION WITH BL Lacs

  DRAWBACKS:

  EXP STATUS AND FLUXES – FOR LIGHT GLUINOS
  THEORETICAL STATUS – FOR ν_{SI}

- Z-BURSTS
  (RESONANT Z-PRODUCTION: $\nu + \bar{\nu}_{DM} \to Z^0 \to$ hadrons)
  ELEM.-PARTICLE PHYSICS IS STANDARD (SM)

  $$E_\nu^{res} = \frac{m_Z^2}{2m_\nu} \gtrsim 1.8 \cdot 10^{22} \left(\frac{0.23}{m_\nu}\right) eV \text{ AND } E_p > 1.8 \cdot 10^{23} eV$$

  (needed for ν-production)

  - PROBLEM WITH SOURCES AND FLUXES:
    E-M CASCADE LIMIT $I_\nu(E) < \frac{c}{4\pi} \frac{\omega_{cas}}{E^2}$ EXCLUDES
    ASTROPHYSICAL SOURCES, TD and SHDM

- TOPOLOGICAL DEFECTS

  RELIABLE OBJECTS NATURALLY PRODUCED BY
  SYMMETRY BREAKING IN EARLY UNIVERSE.
  RELIABLE PRODUCTION OF HE PARTICLES
  MANY CANDIDATES: MONOPOLONIUM, MONOPOLES
  CONNECTED BY STRINGS, ORDINARY STRINGS,
  SUPERCONDUCTING STRINGS, CUSPS, VORTONS, NECKLACES
  MOST OF THEM ARE EXCLUDED OR DISFAVOURED

- **SUPERHEAVY DM**

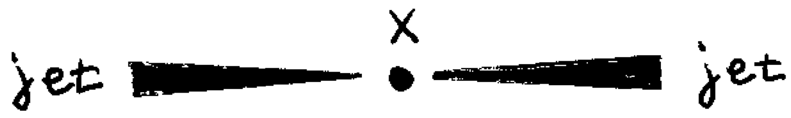
  QUASISTABLE PARTICLES WITH $M_X > 1 \cdot 10^{13}$ GeV PRODUCED AT INFLATION AND ACCUMULATED IN GALACTIC HALO.
  NO GZK CUTOFF

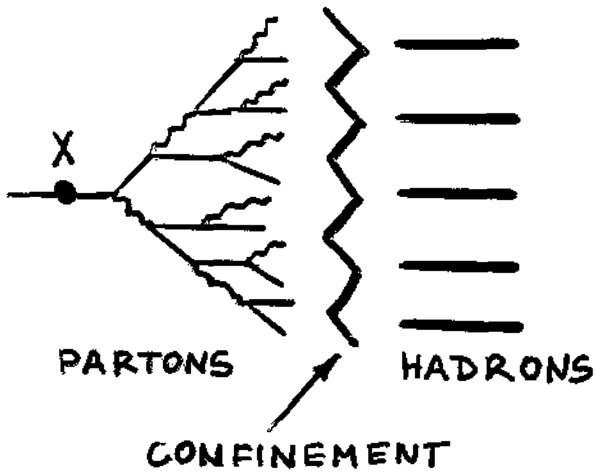
- **LORENTZ-INVARIANCE VIOLATION**

  ENERGY OF CMB PHOTON IN CM-SYSTEM IS $\Gamma \varepsilon_{CMB}$
  VIOLATION OF LORENTZ-INVARIANCE CAN RESULT IN SMALLER E_{CM} AND GZK CUTOFF IS SHIFTED.

- MOST RADICAL POSSIBILITY

X DECAY: ENERGY SPECTRUM





SPECTRUM IS DOMINATED BY ν'S AND γ'S

RATIO $\gamma/N \sim 2-3$

CALCULATION OF SPECTRUM

MC SIMULATION

TWO STEPS:

- PERTURBATIVE REGIME

$$x = \frac{2E}{M_X}, \quad Q_0 \sim 1\,\mathrm{GeV} \text{ (min virtuality)}$$

- HADRONIZATION

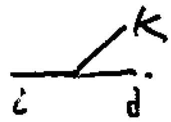
$$D_i^h(x, M_X) = \sum_{j=q,g} \int_x^1 \frac{dz}{z} D_i^j\left(\frac{x}{z}, M_X, Q_0\right) f_j^h(z, Q_0)$$

$f_j^h(x, Q_0)$ IS FOUND FROM $D_q^h(x, M_Z)$

DGLAP EVOLUTION

$$\partial_t D_i^h = \sum_j \frac{\alpha_s(t)}{2\pi} P_{ij} \otimes D_j^h\left(\frac{x}{z}, t\right)$$

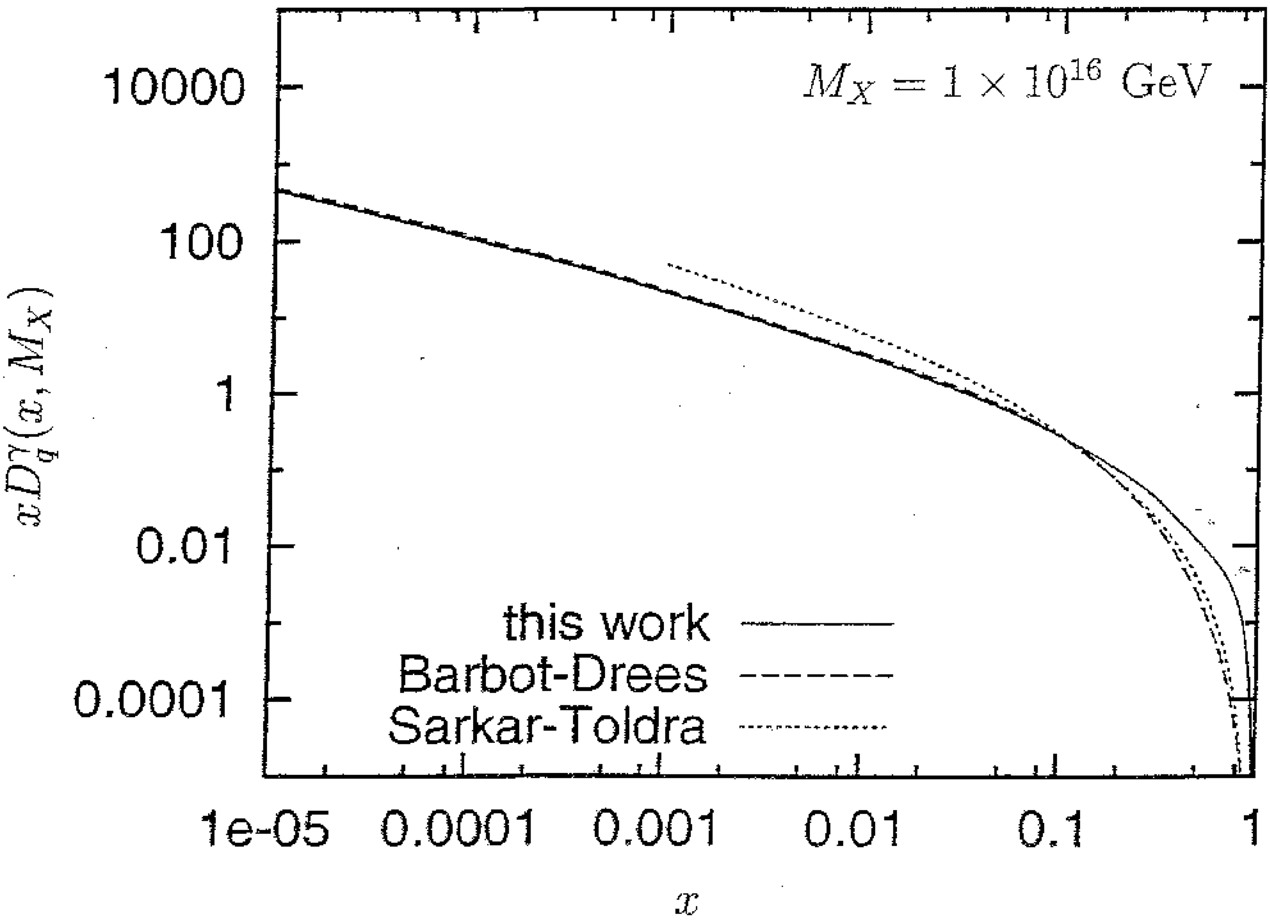
$t = \ln s/s_0$ $\quad$ P_{ij} IS SPLITTING FUNCTION



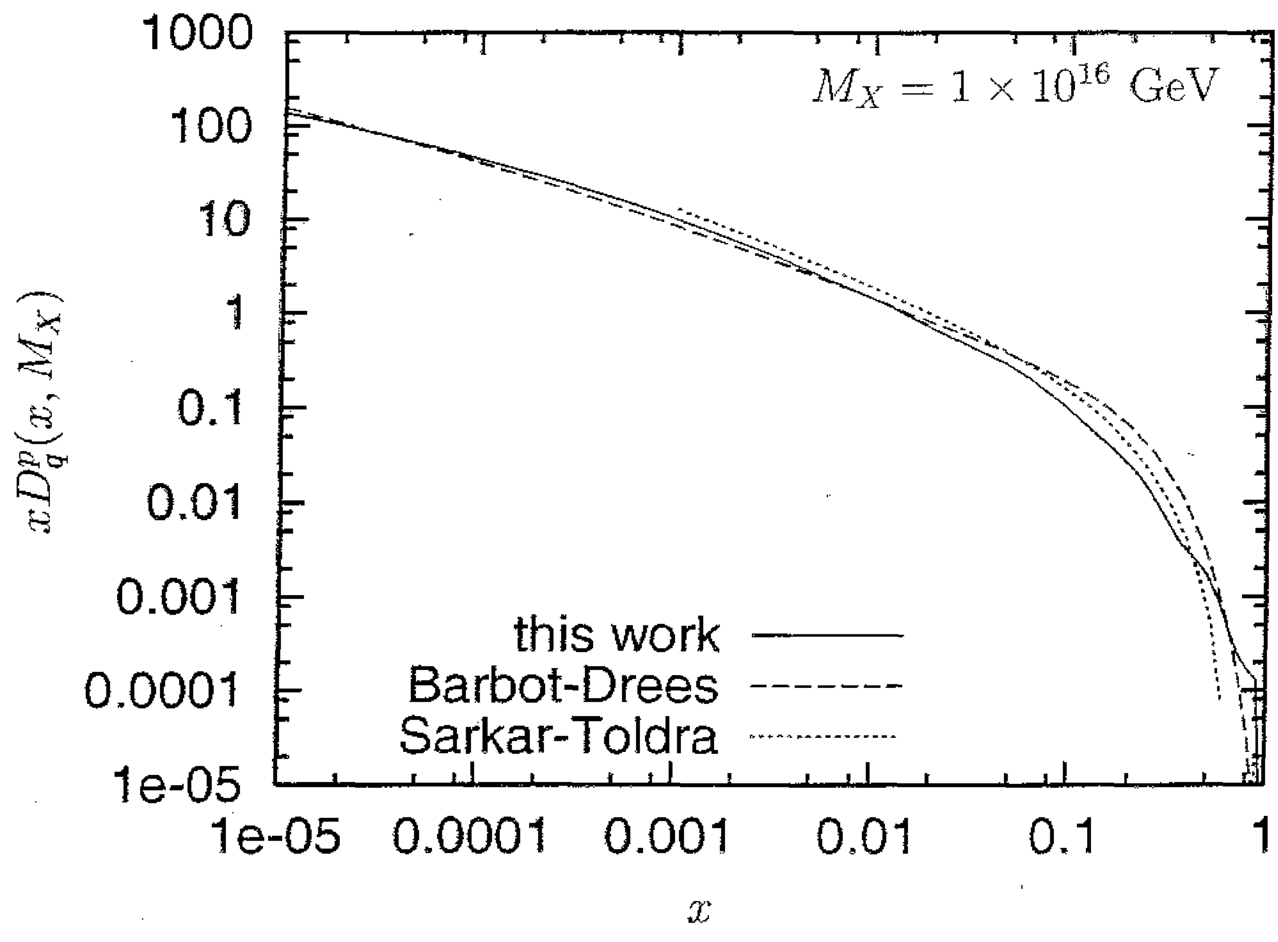
$$f \otimes g \equiv \int_z^1 \frac{dx}{x} f(x)\, g\left(\frac{x}{z}, t\right)$$

SPECTRA OF PHOTONS

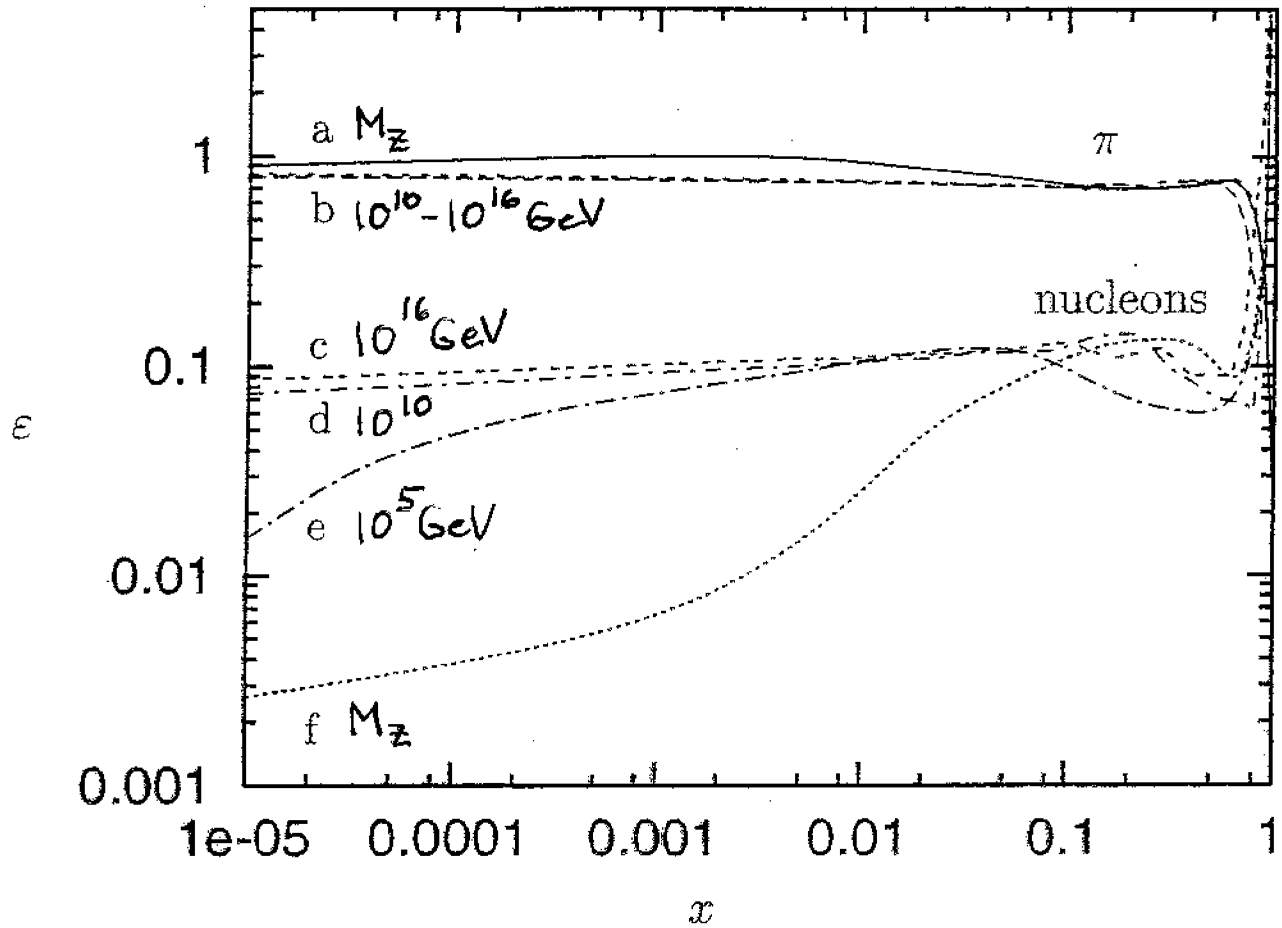
AT THE DECAY OF SH PARTICLE



SPECTRA OF PROTONS
AT THE DECAY OF SH PARTICLE



FRACTION OF PIONS AND NUCLEONS IN THE DECAY SPECTRA OF SH PARTICLES



Z-BURSTS

Fargion et al 1999
Weiler 1999

$$\nu + \bar{\nu}_{DM} \to Z^0 \to \text{hadrons}$$

$$E_0 = \frac{m_Z^2}{2 m_\nu} = 1.8 \cdot 10^{22} \left(\frac{0.23\,eV}{m_\nu}\right) \; eV$$

$$\sigma_{\nu f} = \frac{12\pi}{m_Z^2} \; \frac{\Gamma_\nu \Gamma_f}{(E_c - m_Z)^2 + \Gamma_t^2/4}$$

$$\gamma_Z = \frac{E_0}{m_Z} = \frac{m_Z}{2 m_\nu} = 2.0 \cdot 10^{11} \left(\frac{0.23\,eV}{m_\nu}\right)$$

$$\dot{n}_{Z^0} = 4\pi\, n_{\bar{\nu}_i} \int I_{\nu_i}(E)\, \sigma(E)\, dE = 4\pi \sigma_t\, n_{\bar{\nu}_i} I_{\nu_i}(E_0)\, E_0$$

$$\sigma_t = 48\pi f_\nu G_F = 1.29 \cdot 10^{-32}\, cm^2$$

$$f_\nu = \frac{\Gamma_\nu}{G_F m_Z^3} = 0.019$$

PROBLEMS OF Z-BURST MODELS

$$E_\nu = E_0 = 1.8 \cdot 10^{22} \left(\frac{0.23\,eV}{m_\nu}\right) \; eV$$

$$E_p > 20\, E_\nu = 3.6 \cdot 10^{23} \left(\frac{0.23\,eV}{m_\nu}\right) \; eV$$

IS TOO HIGH FOR ACCELERATION

DECAYS IN THE EXTRAGALACTIC SPACE (TD's, SUPERHEAVY DM PARTICLES) ARE ACCOMPANIED BY e-m CASCADE

$$I_\nu(E) < \frac{c}{4\pi}\frac{\omega_{cas}}{E^2}\,; \quad \omega_{cas} \leq 2 \cdot 10^{-6}\,\frac{eV}{cm^3} \;\; (\text{EGRET})$$

$$I_\nu(E_0) < \frac{c}{\pi}\,\omega_{cas}\frac{m_\nu^2}{m_Z^4}$$ IS TOO SMALL TO PRODUCE THE OBSERVED FLUX OF UHECR

$$\dot{n}_Z = 4\pi\sigma_t\, n_{\nu_i} I_\nu(E_0) \cdot E_0 \lesssim \sigma_t\, n_{\nu_i} c\, \omega_{cas}/E_0$$

$$\dot{n}_\gamma(E_\gamma) < \frac{E_0}{E_\gamma}\,\dot{n}_Z$$

$$F_\gamma(>E_\gamma) = \frac{1}{4\pi}\,\dot{n}_\gamma(E_\gamma) \cdot R_\gamma^{abs} = \frac{1}{4\pi}\sigma_t\, n_{\nu_i} R_\gamma^{abs}\;\frac{c\,\omega_{cas}}{E_\gamma}$$

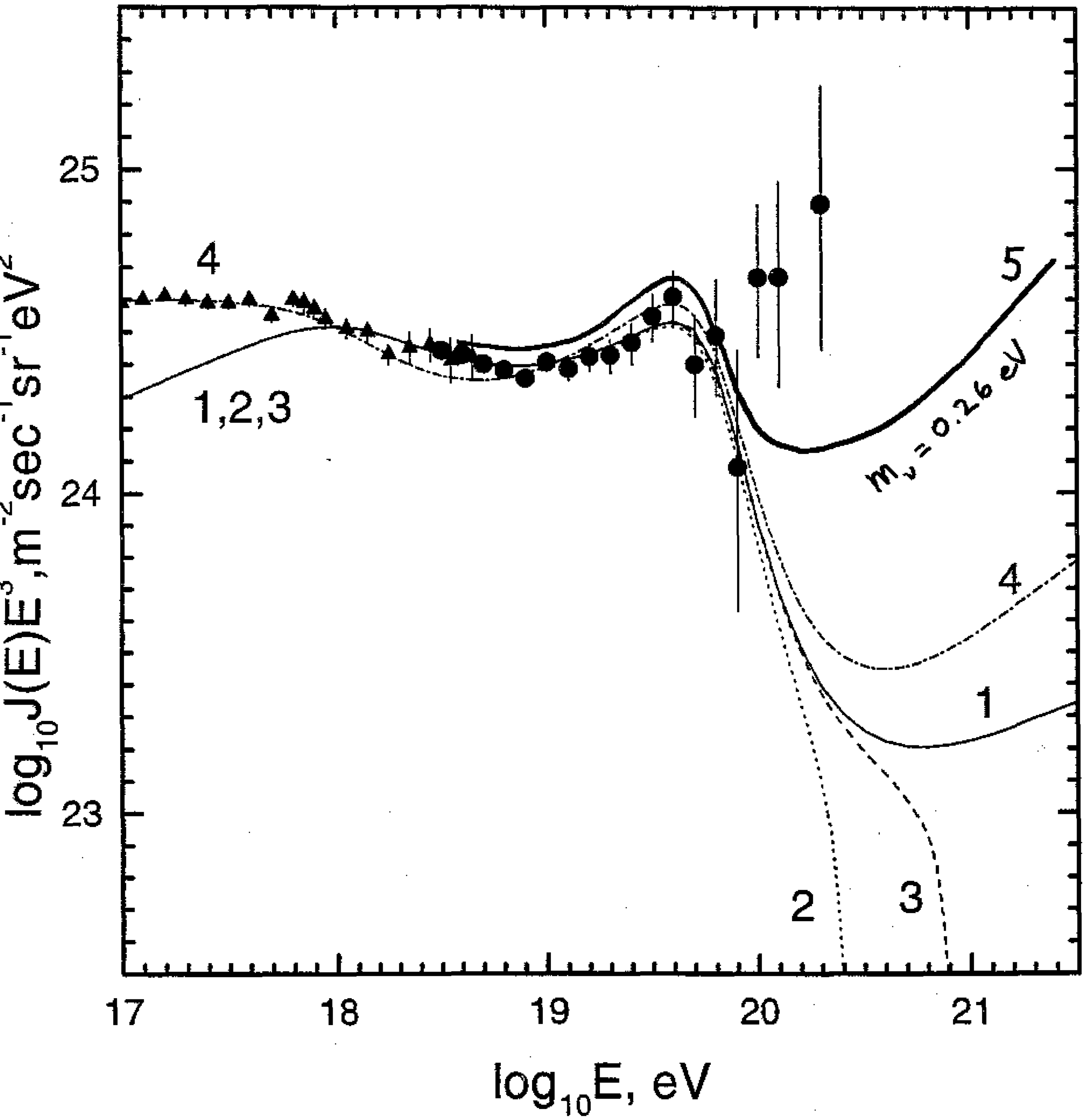
$$n_{\nu_i} = 56\ cm^{-3} \qquad R_\gamma^{abs} \leq 5\ Mpc \qquad E_\gamma = 8 \cdot 10^{19}\,eV$$

$$F_\gamma(>E_\gamma) \lesssim 5.9 \cdot 10^{-22}\ cm^{-2}s^{-1}sr^{-1}$$

i.e. 2 ORDERS OF MAGN LESS THAN OBSERVED

Z-BURSTS

Fodor, Katz, Ringwald 2001



TOPOLOGICAL DEFECTS

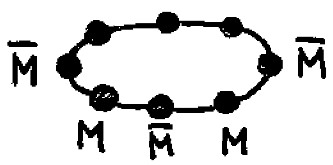
- SYMMETRY BREAKING IN EARLY UNIVERSE RESULTS IN PHASE TRANSITIONS (D.A. KIRZHNITZ 1972). THEY ARE ACCOMPANIED BY TOPOLOGICAL DEFECTS.

- DEPENDING ON SYMMETRY BREAKING, DEFECTS CAN BE IN FORM OF SURFACES (DOMAIN WALLS), LINES (STRINGS), AND POINTS (MONOPOLES).

TD OF INTEREST FOR UHECR

- MONOPOLES: $G \to H \times U(1)$
- ORDINARY STRINGS: $U(1)$ BREAKING
- MONOPOLES CONNECTED BY STRINGS: $G \to H \times U(1) \to H \times Z_n$

  e.g. NECKLACES $Z_n = Z_2$
- SUPERCONDUCTING STRINGS



PRODUCTION OF UHECR

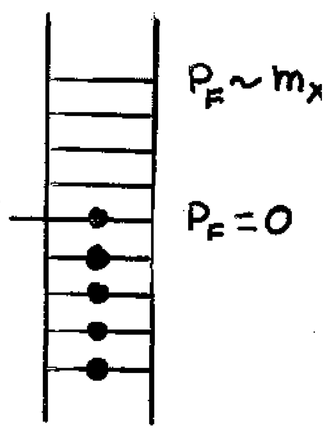
- ANNIHILATION OF MONOPOLES

  $M + \bar{M} \to$ PARTON CASCADE $\to$ PIONS $\to$ PHOTONS + NEUTRINOS

- SUPERCONDUCTING STRINGS

$$\frac{dP}{dt} = e\mathcal{E} \begin{cases} P = e\mathcal{E}t & P \sim m_X \\ J = e^2\mathcal{E}t & J \sim e m_X \end{cases}$$

$X \to$ PARTON CASCADE $\to$ PIONS $\to \gamma + \nu$



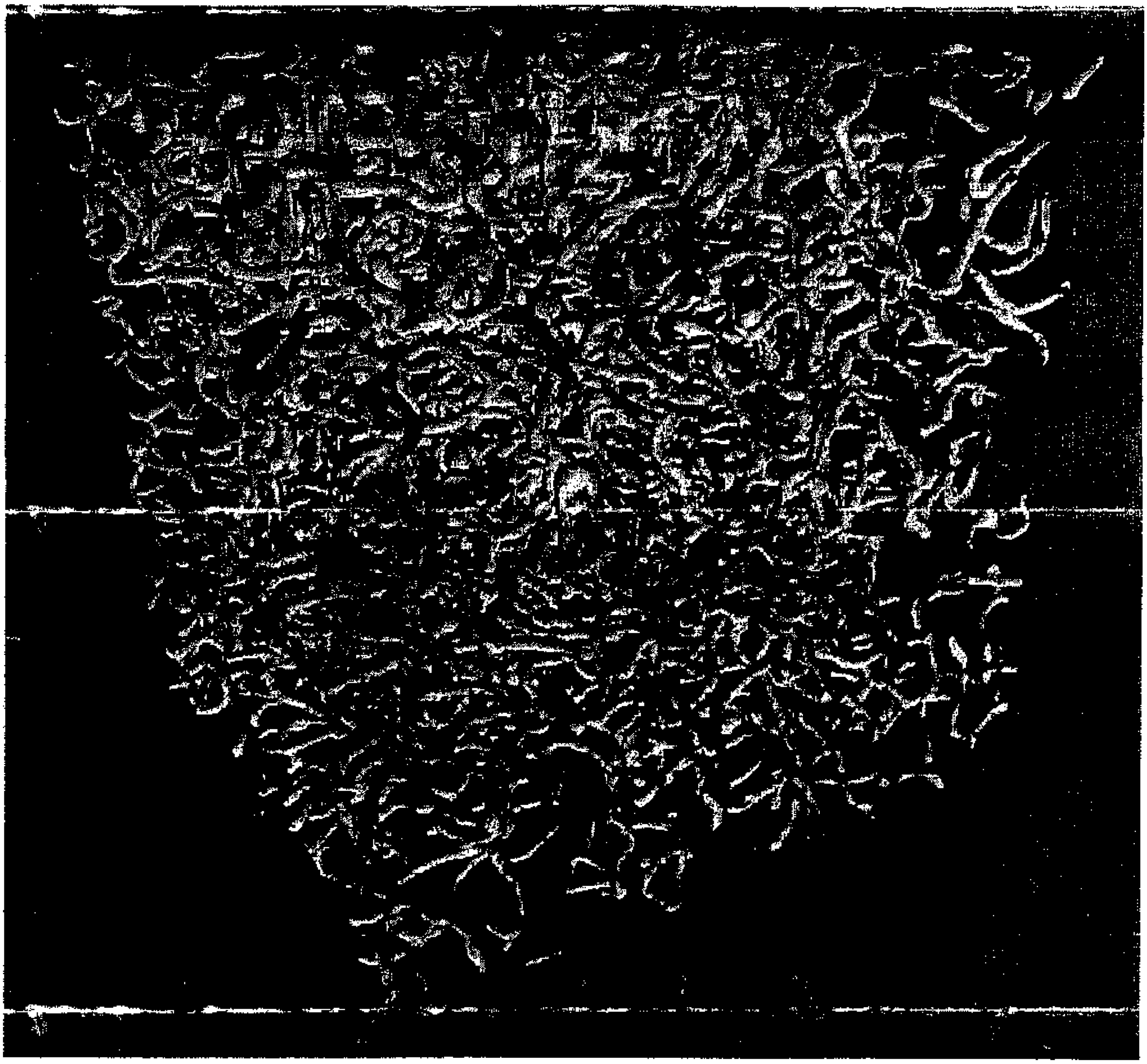


Figure 1. When a body of water freezes over, ice begins forming in many places independently. As the frozen areas grow, they create irregular boundaries between areas of crystalline ice that have different orientations. Phase transitions in the early universe can likewise create topological defects, as regions of space where the transition has proceeded independently run up against each other. The author discusses the possibility that today's universe may, as a result, be riddled with high-energy, gravitationally powerful filaments of primordial material called cosmic strings. Above, a simulation shows a step in the evolution of one region of the universe, in which cosmic strings form from a random initial distribution of phases of a hypothetical field called a Higgs field. (Image above courtesy of Paul Shellard, Cambridge University.)

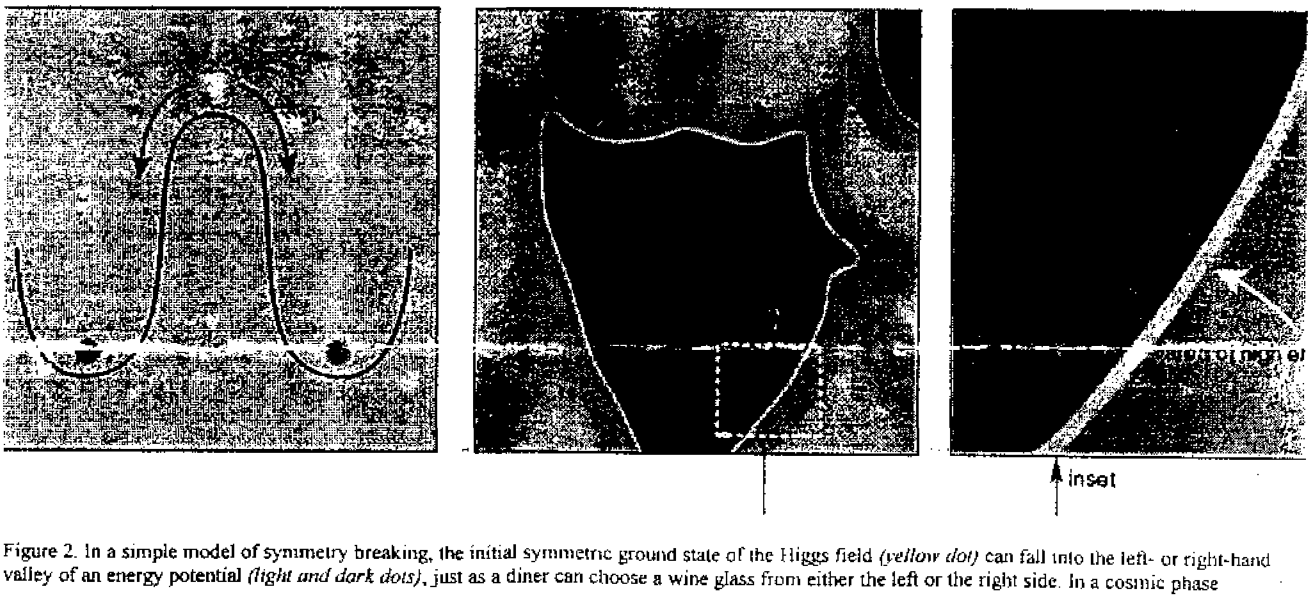


Figure 2. In a simple model of symmetry breaking, the initial symmetric ground state of the Higgs field *(yellow dot)* can fall into the left- or right-hand valley of an energy potential *(light and dark dots)*, just as a diner can choose a wine glass from either the left or the right side. In a cosmic phase

FIGURES

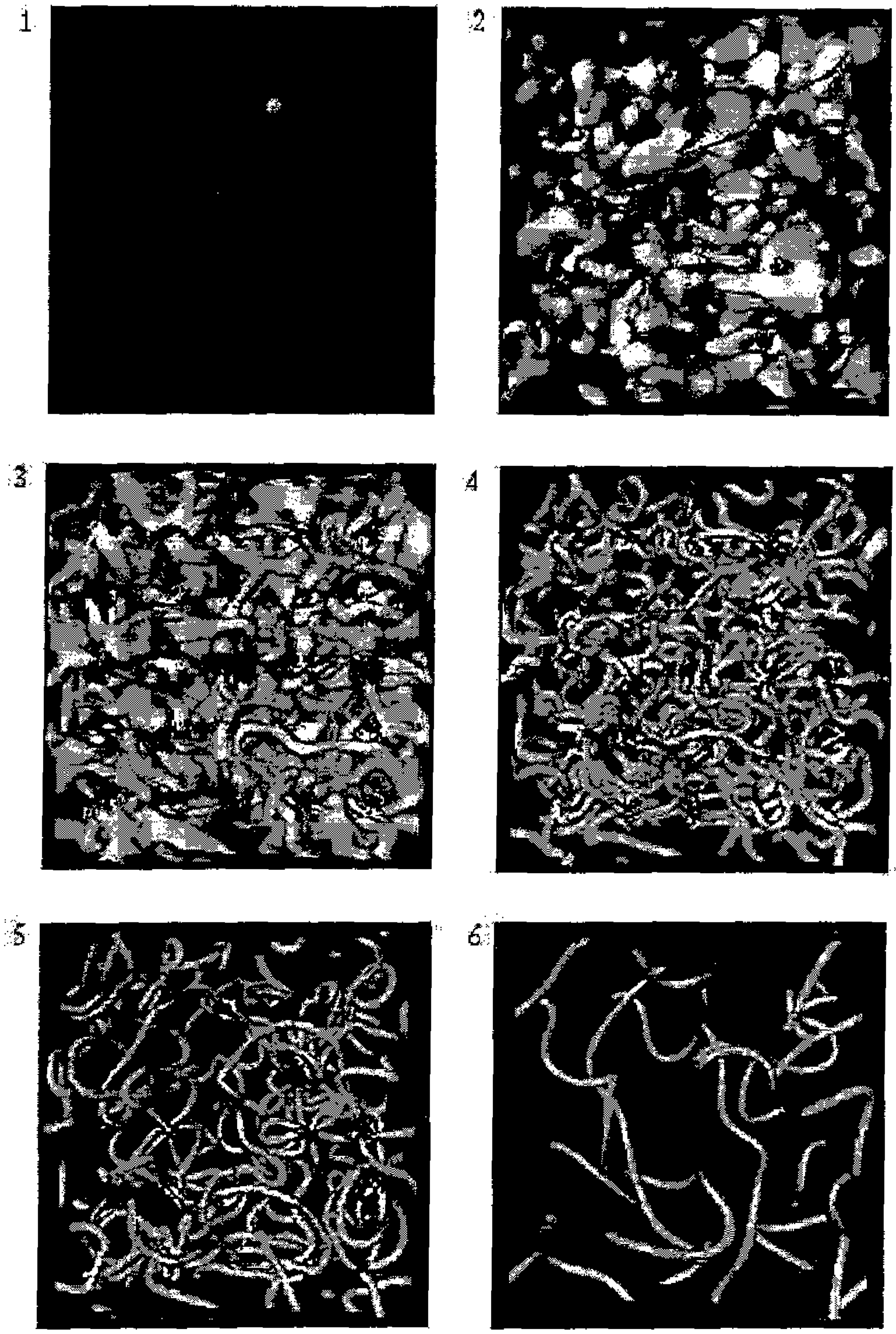
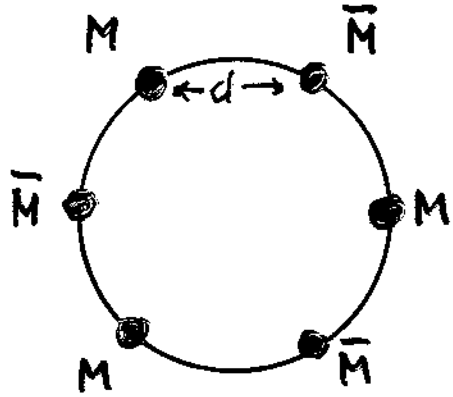


FIG. 1. String network formation in the Abelian-Higgs model using gradient flow (diffusive) evolution. Given random initial phases, a symmetry-breaking phase transition occurs, strings form and then begin to evolve in a scale-invariant manner (the correlation length is $L \propto t^{1/2}$). This dissipative evolution is used to create the initial configuration for a string network with a specified L for subsequent relativistic evolution.

NECKLACES

$$G \to H \times U(1) \to H \times Z_2$$

SYMM BREAKING SCALE η_m $\quad\quad$ η_s



$$m \sim 4\pi\eta_m/e \qquad \mu \sim 2\pi\eta_s^2$$

$$r = \frac{m}{\mu d}$$

$$\dot{n}_X \sim \frac{r^2\mu}{t^3 m_X}$$

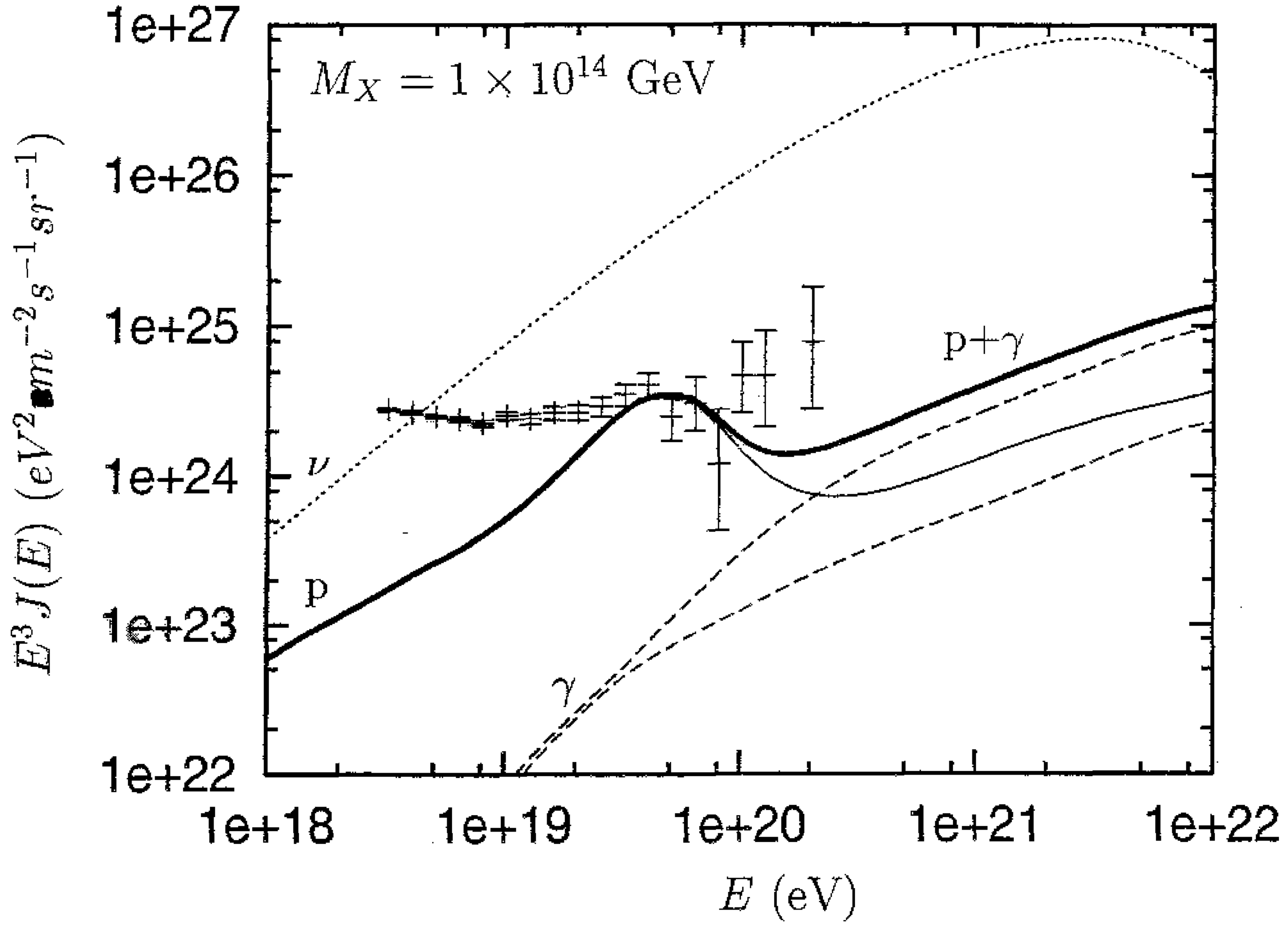
$$\omega \sim m_X t \dot{n}_X \sim r^2 \frac{\mu}{t^2}$$

$$\omega_{cas} = \frac{3}{4} f_\pi r^2 \frac{\mu}{t_0} \lesssim 2 \cdot 10^{-6} \frac{eV}{cm^3} \quad \text{(EGRET)}$$

SEPARATION OF NECKLACES $D \sim \frac{t_0}{\sqrt{r}}$

$$D \sim \left(\frac{3 f_\pi \mu}{4 t_0^2 \omega_{cas}}\right)^{1/4} t_0 > 10 \left(\frac{\mu}{10^6 GeV^2}\right)^{1/4} kpc$$

NECKLACES



$M_X = 1 \times 10^{14}$ GeV
1e+27
1e+26
1e+25
1e+24
1e+23
1e+22
1e+18
1e+19
1e+20
1e+21
1e+22
E (eV)
$E^3 J(E)$ $(eV^2 m^{-2} s^{-1} sr^{-1})$
ν
p
p+γ
γ

UHECR FROM SUPERHEAVY DM

- PRODUCTION AT POST-INFLATION EPOCHS
  (i) VARIATY OF MECHANISMS AT PREHEATING
  (ii) PRODUCTION BY TIME-VARYING GRAVITATIONAL FIELD
  NO COUPLING WITH INFLATON, X CAN BE STERILE!
  PARTICLE MASS m_X COUPLES TO EXPANDING METRIC

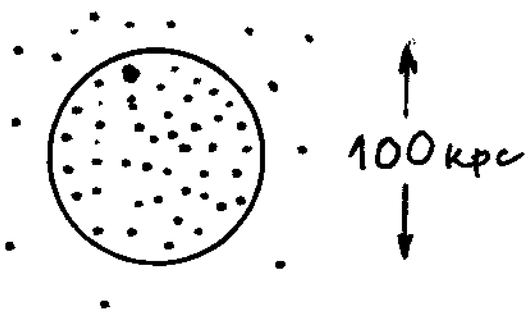
$$\mathcal{L} \sim \frac{1}{2} \xi R X^2$$

$\xi = \frac{1}{6}$ CONFORMAL COUPLING

CREATION OCCURS WHEN $H(t) \sim m_X$,
SINCE $H(t) \lesssim m_\varphi \sim 10^{13}$ GeV, $m_X \lesssim 10^{13}$ GeV
e.g. $m_X \sim 2-3 \cdot 10^{13}$ GeV RESULTS IN $\Omega_X h^2 \sim 0.1$

- LIFETIME $\tau_X > 10^{10}$ yr
  e.g. DISCRETE-GAUGE SYMMETRY PROTECTION
  MANY PARTICLE CANDIDATES

- ACCUMULATION IN THE HALO

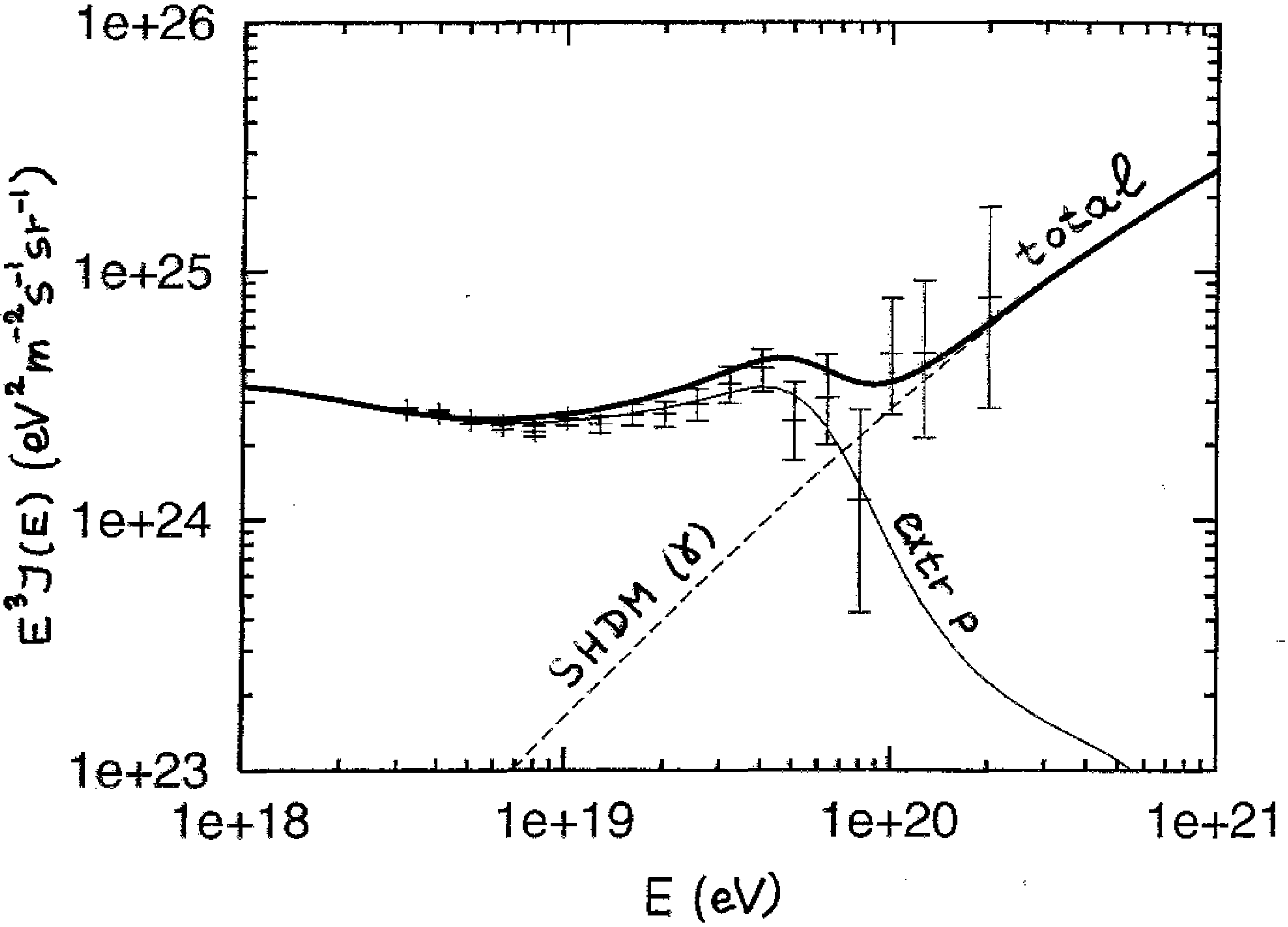


$$\frac{n_X^{halo}}{n_X^{extr}} = \frac{\rho_{CDM}^{obs}}{\Omega_{CDM} \rho_{cr}} \approx 2.1 \cdot 10^5$$

NO GZK CUTOFF!

- CALCULATED ANGULAR CLUSTERING AGREES WITH DATA.
- PREDICTIONS:
  PRIMARIES ARE γ's, ANISOTROPY

SHDM



1e+26
1e+25
1e+24
1e+23
1e+18
1e+19
1e+20
1e+21
E (eV)
total
SHDM (γ)
extr p

OBSERVATIONAL CONSEQUENCES

- SH RELIC PARTICLES ARE ACCUMULATED IN THE GALACTIC HALO ($n_X^{halo}/n_X^{ext} \sim 10^5$) AND THUS UHECR PRODUCED AT THEIR DECAYS HAVE NO GZK CUTOFF.

- UHE PHOTONS (FROM $\pi^0 \to 2\gamma$) HAVE FLUX $\sim$ 2 TIMES HIGHER THAN NUCLEONS.

- ANISOTROPY DUE TO NON-CENTRAL POSITION OF THE SUN IN THE HALO.

  TWO DISTRIBUTIONS OF **DM** IN HALO:

  ISO: $$\rho(R) = \frac{\rho_0}{1 + (R/R_c)^2}$$

  NFW: $$\rho(R) = \frac{\rho_0}{R/R_s\,(1 + R/R_s)^2}$$

(i) PREDICTIONS FOR EXISTING ARRAYS

V.B. and A.MIKHAILOV 1998

G.A.M.TANCO and A.A.WATSON 1998

(ii) RATIO GC/AC

V.B., P.BLASI, A.VILENKIN 1998

BENSON, SMIALKOWSKI, WOLFENDALE 1998

WITHIN $\theta = 20^\circ$ THIS RATIO IS 3 - 10 FOR DIFFERENT MODELS: PROBLEM FOR THE AUGER DETECTOR.

- ANGULAR CLUSTERING DUE TO CLUMPINESS OF HALO

VIOLATION OF LORENTZ INVARIANCE (LI)

MOTIVATION:

- EXP DATA: PROBABLY NOT (?)
- IS SUPERWEAK **LI** BREAKING THEORETICALLY FEASIBLE
  PROBABLY YES (!)
- ABSOLUTE LORENTZ FRAME AND **LI** BREAKING.

  BREAKING OF **LI** IMPLIES EXISTENCE OF THE ABSOLUTE LORENTZ FRAME.

  DOES EXISTENCE OF THE ABSOLUTE FRAME IMPLY THE VISIBLE **LI** BREAKING?

  e.g. EXISTENCE OF THE FRAME WHERE CMBR IS ISOTROPIC?

  NO, IF WE TAKE INTO ACCOUNT THE INTERACTION WITH MICROWAVE PHOTONS.

SPONTANEOUSLY BROKEN LI

- EQUATION OF MOTION REMAIN LORENTZ INVARIANT
- VIOLATION OCCURS SPONTANEOUSLY IN SOLUTIONS, e.g. DUE TO VEV's.

$$\mathcal{L}_{int} = \frac{\epsilon}{M^2} \bar{\Psi} \gamma_\mu \partial_\nu \Psi T_{\mu\nu}$$

Ψ IS FIELD OF VISIBLE SECTOR,
$T_{\mu\nu}$ IS SUPERHEAVY FIELD FROM HIDDEN SECTOR

STRING INTERACTION SET NONZERO VEV FOR T_{00}

$$\langle T_{00} \rangle = V^2,$$

PRODUCING LORENTZ-NONINVARIANT VACUUM CONDENSATE ANALOGUE OF CMBR

SPONTANEOUSLY BROKEN **L.I.** AND MODIFIED DISPERSION RELATIONS

$$\mathcal{L} = \frac{1}{2} i \bar{\Psi} \gamma_\mu \overleftrightarrow{\partial_\mu} \Psi - m \bar{\Psi} \Psi + \mathcal{L}_{int}$$

e.g. $\mathcal{L}_{int} = \frac{\epsilon}{M^2} T_{\mu\nu} \bar{\Psi} \gamma_\mu \partial_\nu \Psi$

DIRAC EQUATION

$$\left(i \gamma_\mu \partial_\mu - m - \frac{\epsilon}{M^2} T_{\mu\nu} \gamma_\mu \partial_\nu \right) \Psi = 0$$

AFTER SSB $\langle T_{00} \rangle = V^2$ ASSOCIATE KLEIN-GORDON EQ:

$$\left(\partial_\mu^2 - m^2 + \frac{\epsilon}{M^2} V^2 \partial_0^2 \right) \Psi = 0$$

IN MOMENTUM SPACE $i\partial_\mu \rightarrow P_\mu$

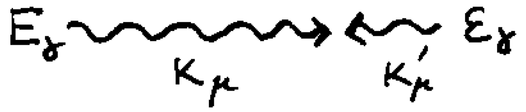
$$P_\mu^2 - m^2 + \frac{\epsilon}{M^2} V^2 E^2 = 0$$

THUS, **L.I.** BREAKING RESULTS IN THE MODIFIED DISPERSION RELATION (COLEMAN, GLASHOW 1997)

MODIFIED DISPERSION RELATIONS AND THRESHOLD OF REACTIONS.

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$E_\gamma \quad \varepsilon_\gamma \quad E_e \quad E_e' \qquad E_\gamma >>> \varepsilon_\gamma$$



$$K_\mu + K_\mu' = P_\mu + P_\mu'$$

$$K_\mu^2 + K_\mu'^2 + 2K_\mu K_\mu' = P_\mu^2 + P_\mu'^2 + 2P_\mu P_\mu'$$

IN CASE $K_\mu^2 = K_\mu'^2 = 0$ AND $P_\mu^2 = P_\mu'^2 = m_e^2$

$$(E_\gamma \varepsilon_\gamma)^{1/2} \gtrsim m_e$$

IN CASE OF MODIFIED DISPERSION RELATIONS

$$P_\mu^2 = E_e^2 - \vec{P}^2 \approx m_e^2 + \epsilon \frac{V^2}{M^2} E^2$$

WHEN $E > M m_e / V$ THRESHOLD IS SHIFTED

OTHER ASTROPHYSICAL TESTS OF SPECIAL RELATIVITY

- CONSTANCY OF LIGHT VELOCITY (e.g. IN GRBs). J. Ellis et al 1999
- HE PHOTON DECAY. S. GLASHOW 1997
- VACUUM CHERENKOV RADIATION. S. GLASHOW 1997

CONCLUSIONS

- OBSERVED UHECR SPECTRA AT $1\cdot 10^{18} - 8\cdot 10^{19}$ eV HAVE SIGNATURES OF INTERACTION OF EXTRAGALACTIC PROTONS WITH CMB IN THE FORM OF THE DIP (DUE TO $p+\gamma_{CMB} \to p+e^{+}+e^{-}$) AND OF THE BEGINNING OF THE GZK CUTOFF. THE CORRELATION WITH BLLacs INDICATE AGN AS UHECR SOURCES.

- NOT MUCH SPACE IS LEFT TO "EXOTIC" PHYSICS. UHECR PROBLEM IS REDUCED TO THE EVENTS AT $E > 1\cdot 10^{20}$ eV. EXCESS OF THE AGASA EVENTS OVER PREDICTED GZK CUTOFF IS AN INDICATION TO A NEW PHYSICS. IN 2 YEARS AUGER DATA WILL CLARIFY THE SITUATION.

- THREE TOP-DOWN MODELS (TD, SHDM AND Z-BURSTS) PREDICT PHOTON DOMINANCE AT $E \geq 1\cdot 10^{20}$ eV. THIS PREDICTION WILL BE TESTED BY AUGER

- SPECTRUM SHAPE ($F(E) \sim E^{-1.9}$) IS NOW A SIGNATURE OF SHDM MODEL. THIS PREDICTION IS IN AGREEMENT WITH THE AGASA EXCESS.

- SHDM MODEL PREDICTS ANISOTROPY CENTERED BY GC. THIS PREDICTION WILL BE TESTED BY AUGER LOCATED IN SOUTHERN HEMISPERE.

THERE IS A CHANCE OF DISCOVERY OF NEW FUNDAMENTAL PHYSICS IN UHECR!