DEDICATED TO D.V. Sciama

PUZZLES IN ASTROPHYSICS IN THE PAST AND PRESENT

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FORMULA OF ASTROPHYSICAL DISCOVERIES:

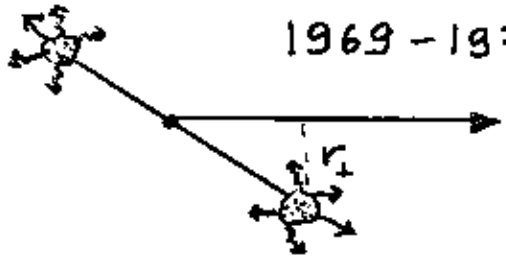
ALL GREATEST DISCOVERIES IN ASTROPHYSICS APPEARED UNPREDICTABLY; WHAT WAS PREDICTED WAS NOT DISCOVERED.

ASTROPHYSICAL PUZZLES AND DISCOVERIES

PHENOMENON	PUZZLE	PHYSICS DISCOVERY
QUASARS 1960	LARGE ENERGY PRODUCTION	BLACK HOLES
PULSARS 1967	PERIODIC SIGNAL	NEUTRON STARS, RELATIVISTIC ELECTRODYNAMICS
ATM AND SOLAR NEUTRINOS	NEUTRINO DEFICIT	NEUTRINO OSCILLATIONS
ν's FROM SN 1987A	GOOD AGREEMENT WITH BAD THEORY	GRAV COLLAPSE

GREATNESS OF FALSE DISCOVERIES

SUPERLUMINAL VELOCITIES



1969 - 1971 $V \gtrsim (4-6)c$

ASTROPHYSICS OF RELATIVISTIC OBJECTS

CYG X-3 SAGA

VHE ($\gtrsim 1$ TeV) AND UHE ($\gtrsim 0.1-1$ PeV) "gamma"-RADIATION WAS DETECTED IN 80s BY MANY DETECTORS:

KIEL, HAVERAH PARK, FLY'S EYE, AKENO, BAKSAN, TIEN-SHAN, OOTY, GULMARG, PLATEU ROSA, CRIMEA, DUGWAY, WHIPPLE ....

UNDERGROUND MUON SIGNAL WAS ALSO DETECTED:

NUSEX, SOUDAN, MUTRON

LESSON:

NOT TO TRUST "3σ DISCOVERIES", EVEN IF MANY DETECTORS OBSERVE THE EFFECT

THEORETICAL BENEFITS:

- HIGH ENERGY ASTROPHYSICS WITH NEW PARTICLES: THEIR PRODUCTION, DETECTION, AND GENERAL LIMITS. (cygnets: neutralinos, light gluinos, free gluons, dilambda hyperons and what not?)
- ACCELERATION IN BINARY SYSTEMS

VIOLATION OF LORENTZ-INVARIENCE (L.I.)

MOTIVATION:

- EXP DATA: PROBABLY NOT (?)
- IS SUPERWEAK L.I. BREAKING THEORETICALLY FEASIBLE? PROBABLY YES (!)
- DO WE SPOIL SPECIAL RELATIVITY AESTHETICALLY?

  BREAKING OF L.I. IMPLIES EXISTENCE OF THE ABSOLUTE LORENTZ FRAME.
  BUT IF L.I. VIOLATION IS VERY WEAK, ALL FRAMES ARE NEARLY EQUIVALENT.

SPONTANEOUSLY BROKEN L.I.

› EQUATIONS OF MOTION REMAIN LORENTZ-INVARIANT. THE VIOLATION SPONTANEOUSLY APPEARS IN THE SOLUTIONS.

- **L.I.**-BREAKING-SOLUTIONS ARE KNOWN IN STRING MODELS AND EXTRA DIMENSION MODELS (Colladay, Kostelecky 1995, Dvali, Shifman 1999, J. Ellis et al 1999)

STRING INTERACTIONS SET NONZERO VEV'S FOR LORENTZ TENSOR FIELDS, BREAKING THUS **L.I.** IN OUR FOUR-DIMENSIONAL WORLD. AFTER SSB THESE TERMS LOOK LIKE (Colladay and Kostelecky):

$$\mathcal{L}_{int} = \frac{\epsilon}{M^k} V_k \bar{\Psi} \Gamma(\gamma) (i\partial)^k \Psi$$

$K = 0, 1, 2 \ldots$, V_K = VEV's, $V_2 = \langle T_{00} \rangle$, Γ IS BUILD FROM γ'S. LARGE M (e.g. $M = M_{Pl}$) PROVIDES SMALLNESS OF LI VIOLATION

- SPONTANEOUSLY BROKEN **L.I.** MODIFIES DISPERSION RELATIONS (Coleman, Glashow 1997)
e.g. $\langle T_{00} \rangle = V^2 \longrightarrow p_\mu^2 - m^2 + \frac{\epsilon}{M^2} V^2 E^2 = 0$

- MODIFIED DISPERSION RELATIONS CHANGE THRESHOLDS OF REACTIONS (OBSERVABLE EFFECT)

e.g. $\underset{k_\mu}{\gamma} + \underset{k_\mu}{\gamma} \rightarrow \underset{p_\mu}{e^+} + e^-$ 

FROM $k_\mu + k'_\mu = p_\mu + p'_\mu$ AND $k'^2_\mu = 0$, $p_\mu^2 = m_e^2$

$$E_\gamma^{th} \approx \frac{m_e^2}{\varepsilon_\gamma}$$

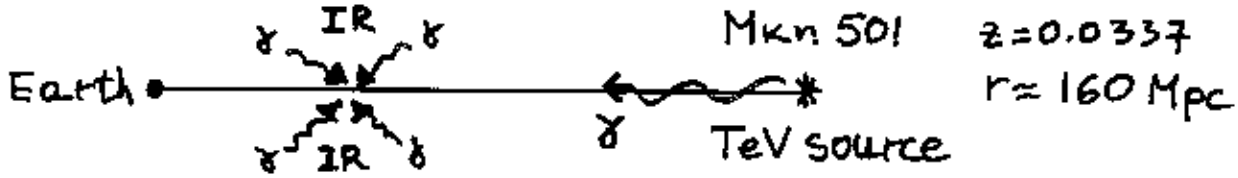
$p_\mu^2 = m_e^2 + \frac{\epsilon}{M^2} V^2 E^2$ SHIFTS THE THRESHOLD

OTHER ASTROPHYSICAL TESTS OF LI VIOLATION

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

1st puzzle:

ABSORPTION OF TeV GAMMA-RAYS: TeV GAMMA-RAY CRISIS?



$$\gamma + \gamma_{IR} \rightarrow e^+ + e^-$$

$E_\gamma \varepsilon_\gamma \sim 2 m_e^2$: $\lambda_{IR} \approx \frac{E_\gamma}{4 m_e^2} \approx 1.2 \frac{E_\gamma}{1\,TeV}\ \mu m$

$1\,TeV \lesssim E_\gamma \lesssim 20\,TeV \Rightarrow \quad 1\mu m \lesssim \lambda_{IR} \lesssim 20\mu m$

IR BCGR:

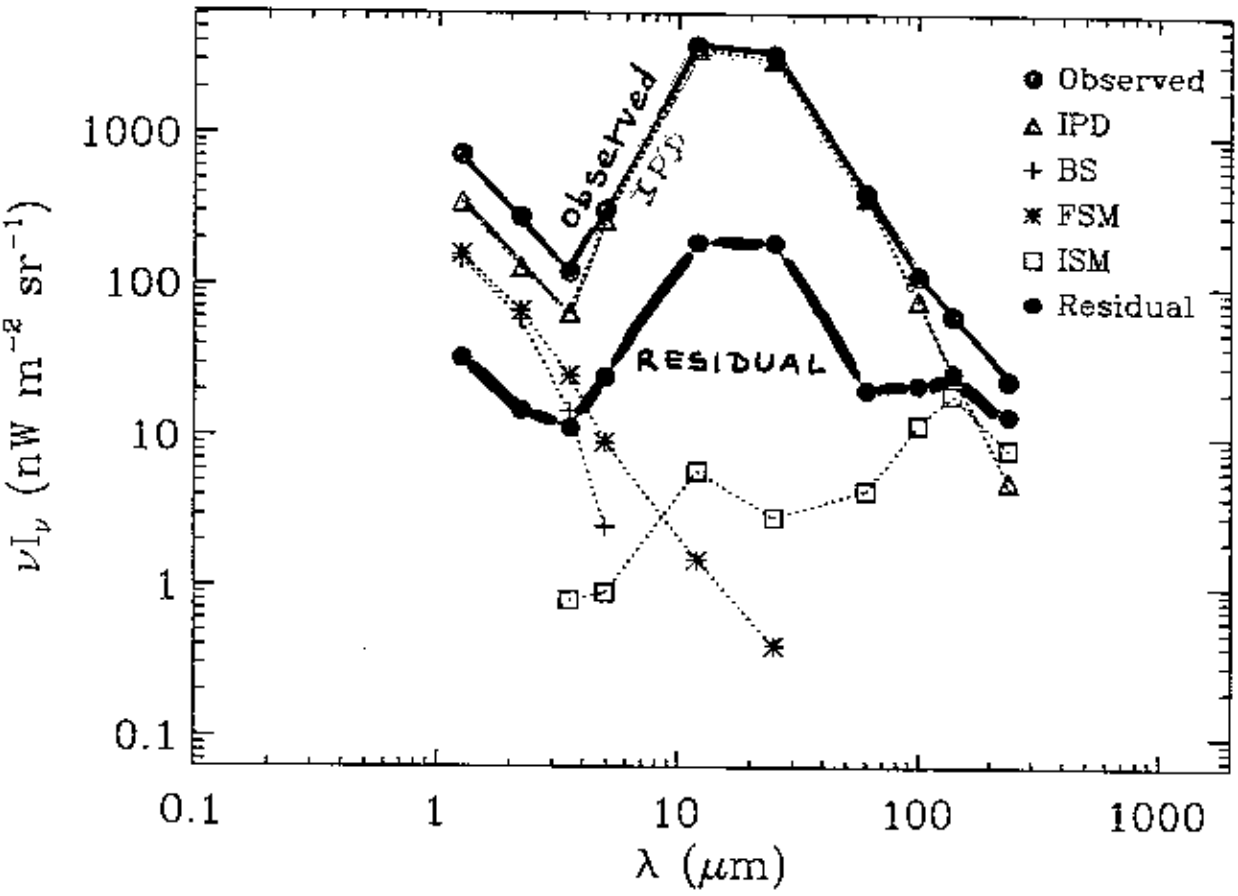
COBE DETECTORS: DIBRE (1.25-240μm), FIRAS (125-2000

ISOCAM $\sim 15\mu m$

CALCULATIONS: PRIMACK et al (high)

MALKAN AND STECKER (low)

COBE/DIBRE IR DIFFUSE FLUX



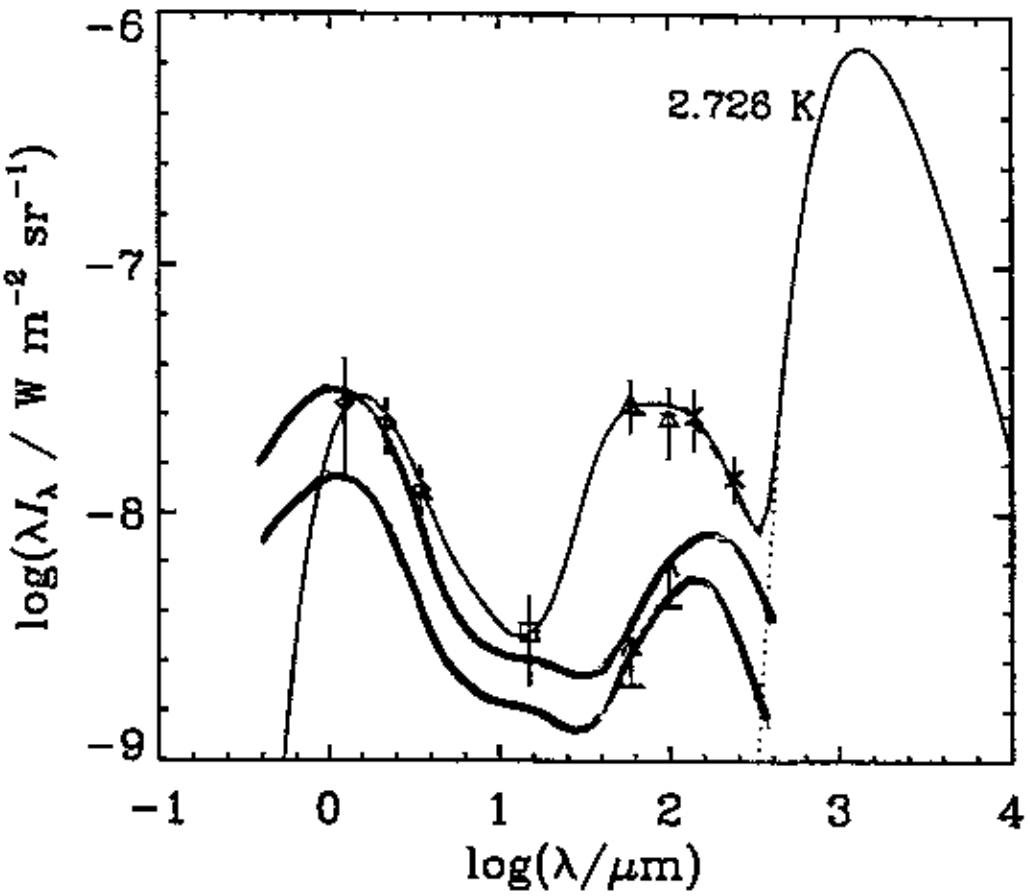
IPD - INTERPLANETARY DUST

ISM - INTERSTELLAR MEDIUM

FSM - FAINT GALACTIC SOURCES

IR DIFFUSE FLUX

COMPILATION BY PROTHEROE AND MEYER 2000



▲ COBE/DIBRE

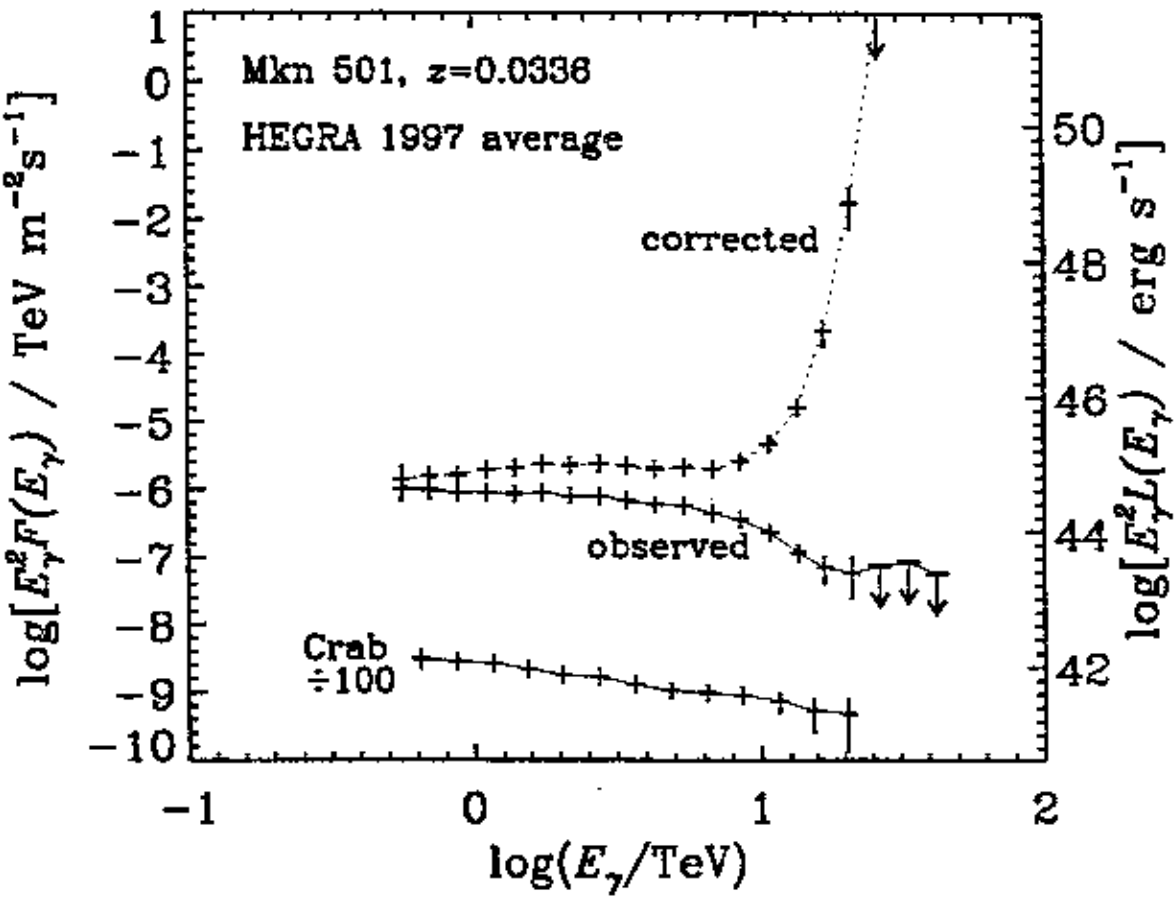
X COBE/FIRES

□ ISOCAM

— CALCULATIONS BY MALKAN AND STECKER

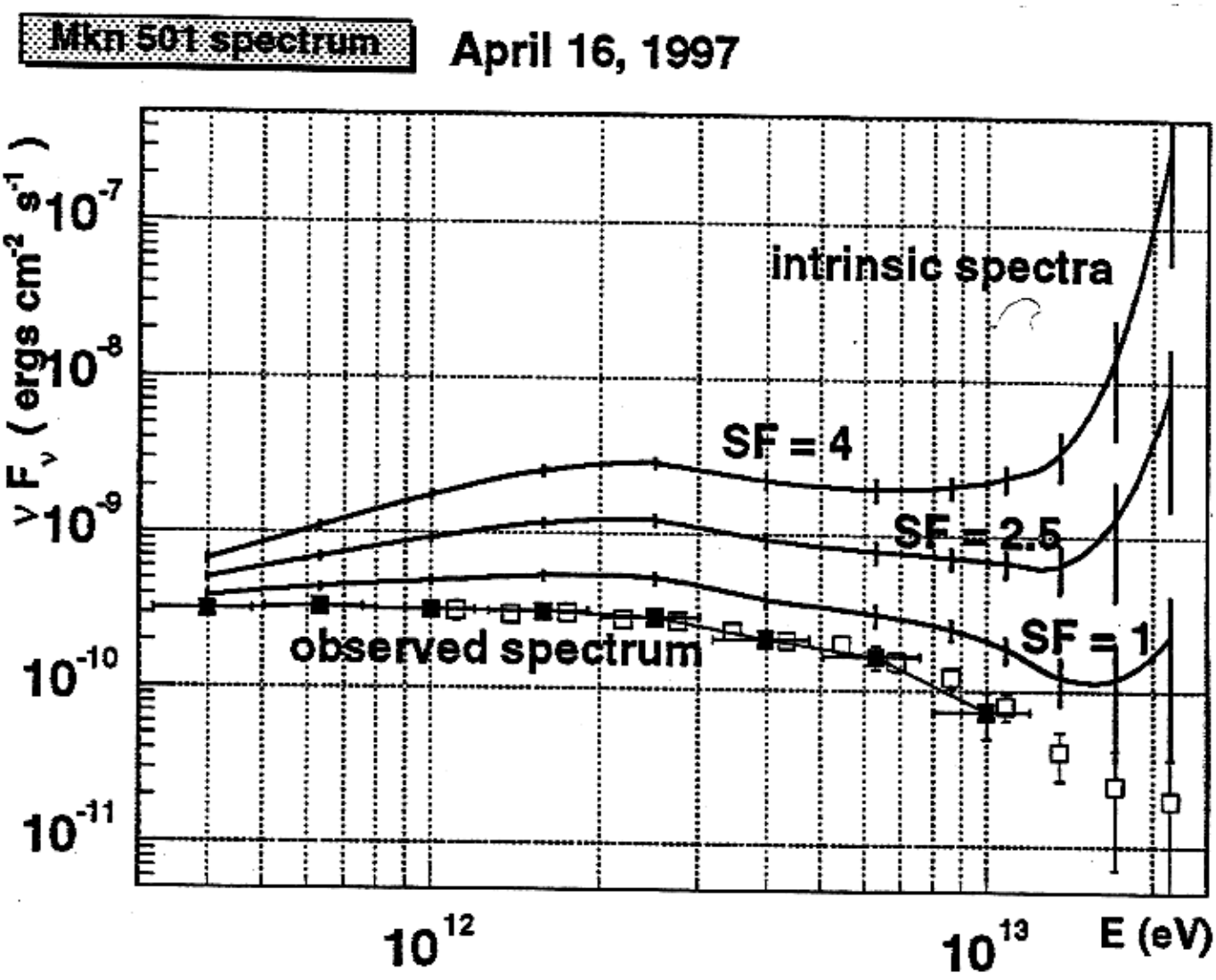
PRODUCTION GAMMA RAY SPECTRUM OF Mkn 501

(PROTHEROE, MEYER 2000)



PRODUCTION GAMMA RAY SPECTRUM OF Mkn 501

J. GUY et al 2000

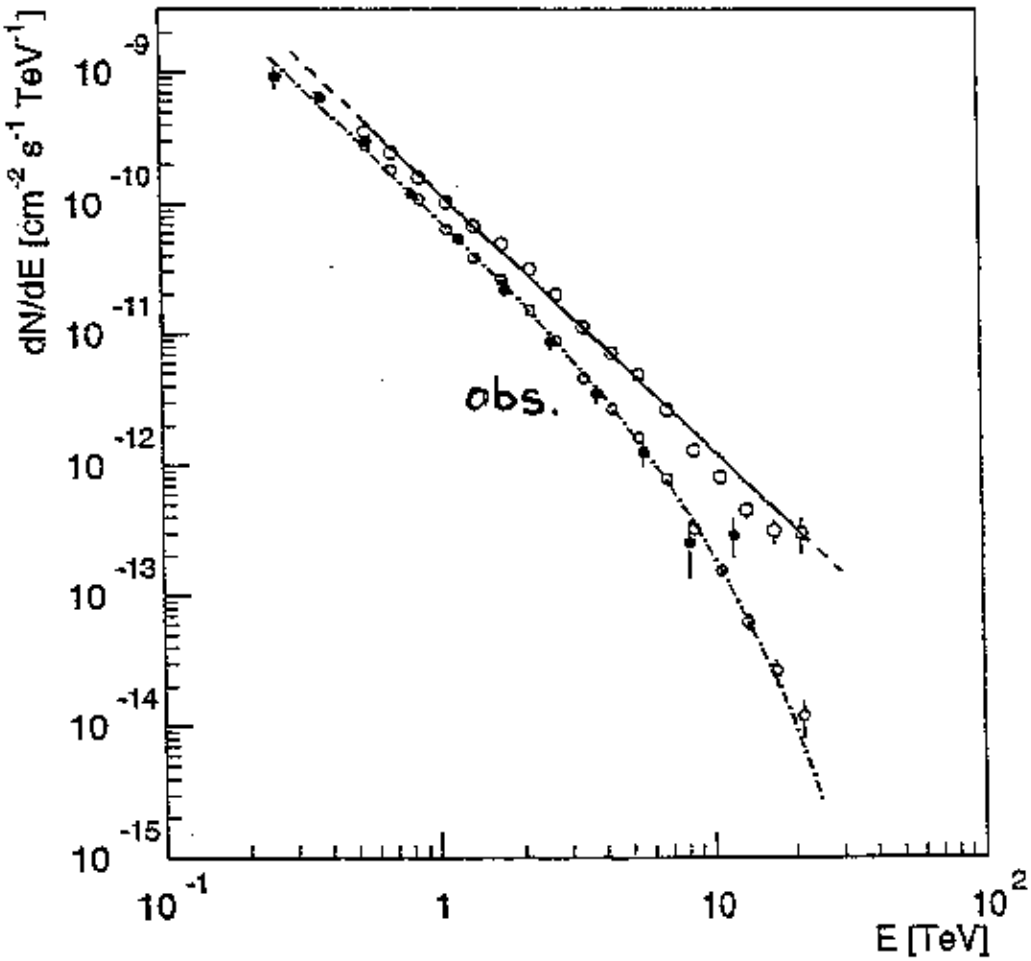


CURVE SF=1 - WITH IR FLUX AS CALCULATED BY PRIMACK ET AL FOR ΛCDM

FOR SF=2.5 AND SF=4 FLUX IS 2.5 AND 4 TIMES HIGHER

PRODUCTION GAMMA RAY SPECTRUM OF Mkn 501

STECKER 2000



WITH THE MALKAN-STECKER IR FLUX

CONCLUSIONS

- THERE IS SOME DISCREPANCY BETWEEN MEASURED IR BCGR AND ABSENCE OF TeV GAMMA RAY ABSORPTION.

- IT MAY INDICATE TO OVERESTIMATED EXTRAGALACTIC FLUX IN COBE/DIBRE MEASUREMENTS DUE TO NON-SUFFICIENT SUBTRACTION OF GALACTIC AND INTERPLANETARY CONTRIBUTION.
  TO RESOLVE "CRISIS" EXTRAGALACTIC FLUX SHOULD BE REDUCED BY FACTOR 2.5 – 3.

- IN CONSERVATIVE APPROACH TeV GAMMA RADIATION FROM REMOTE GALAXIES IS A PROBE OF EXTRAGALACTIC IR BCGR.

- TEST OF **L.I.** BREAKING CAN BE RELIABLY PERFORMED USING GAMMA RADIATION WITH $E_\gamma \gtrsim 100$ TeV, WHICH IS ABSORBED ON 2.7K MICROWAVE RADIATION

2nd puzzle

ULTRA HIGH ENERGY COSMIC RAYS: IS NEW PHYSICS NEEDED?

PROBLEM:

UHE PARTICLES HAVE SMALL PATH-LENGTHS AS COMPARED WITH THE HUBBLE SCALE.

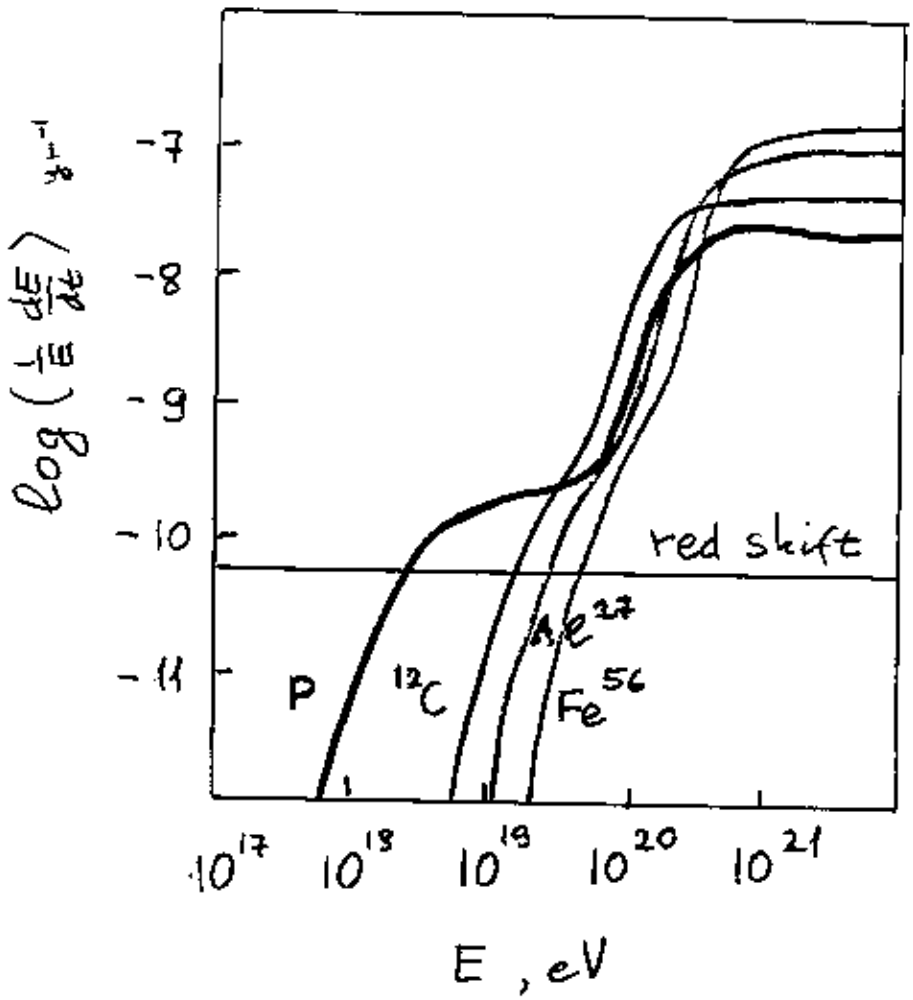
PROTONS: DUE TO $p + \gamma_{2.7K} \rightarrow N + \pi$ (GZK CUTOFF)
NUCLEI : DUE TO $A + \gamma_{2.7K} \rightarrow A + e^+ + e^-$
PHOTONS: DUE TO $\gamma + \gamma_{radio} \rightarrow e^+ + e^-$

OBSERVATIONS:

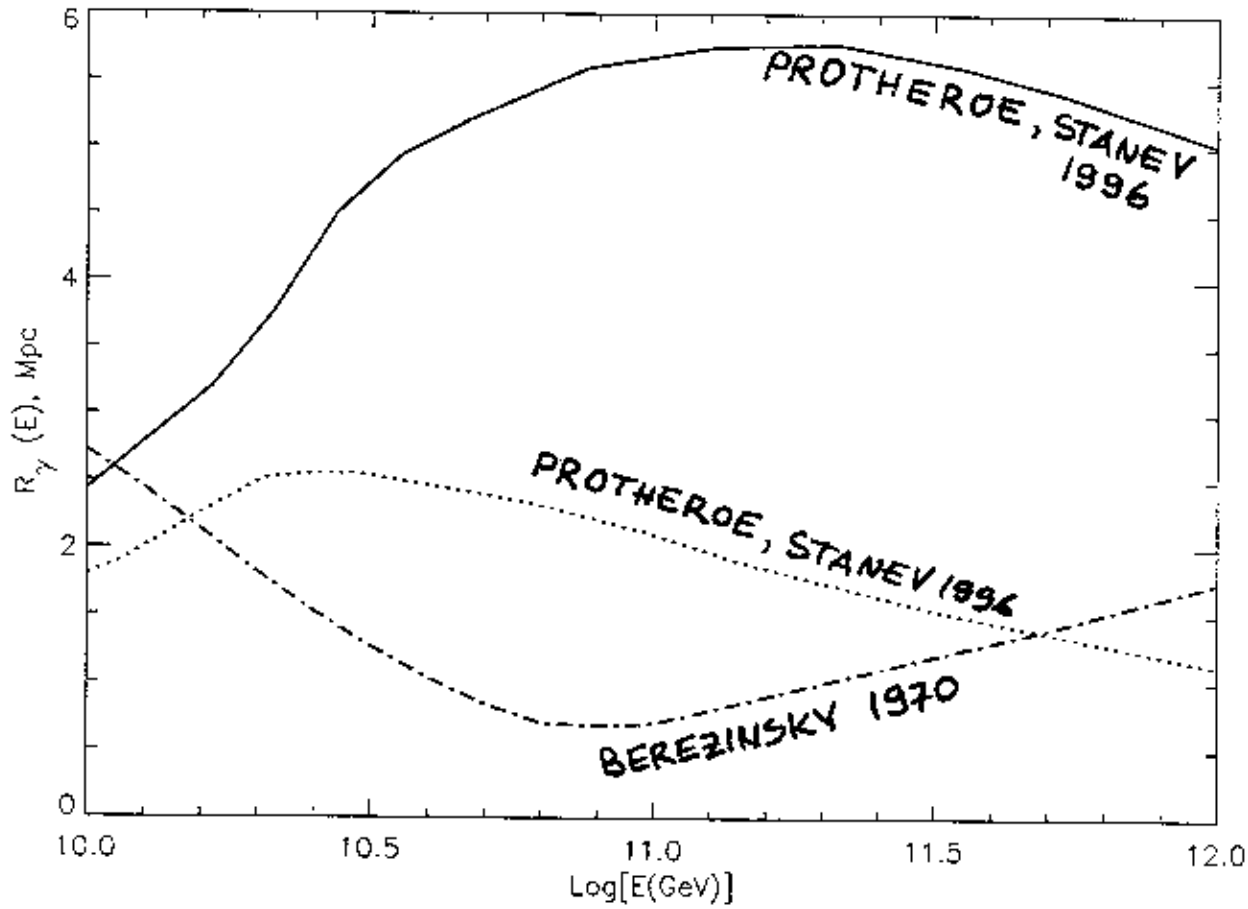
- NO CUTOFF IN THE SPECTRUM UP TO $2 \cdot 10^{20}$ eV
  STATISTICS OF AGASA
  $E \gtrsim 1 \cdot 10^{19}$ eV : ~600 events, $E \gtrsim 4 \cdot 10^{19}$ eV: 60 events,
  $E \gtrsim 1 \cdot 10^{20}$ eV: 8 events

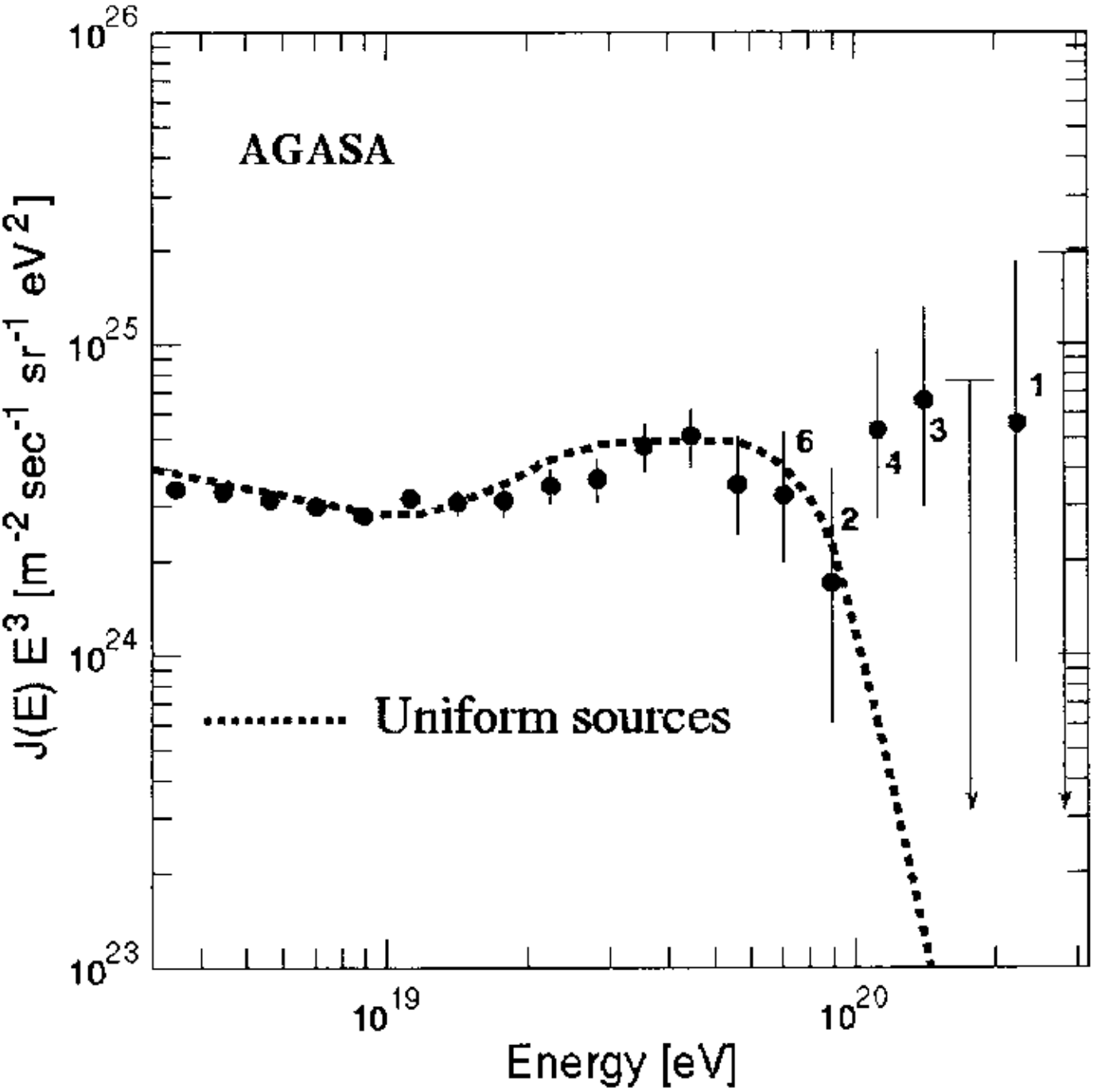
- NO ANISOTROPY ASSOCIATED WITH GALACTIC PLANE

ENERGY LOSSES ON MICROWAVE RADIATION



ABSORPTION OF UHE GAMMAS ON RADIO BACKGROUND




AGASA
Uniform sources
J(E) E^3 [m^{-2} sec^{-1} sr^{-1} eV^2]
Energy [eV]
10^{26}
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
1
2
3
4
6

IS ENERGY DETERMINATION OF THE SHOWERS CORRECT ?

DIFFERENT METHODS OF MEASUREMENTS:

- HAVERAH PARK: JOINT SIGNAL FROM CASCADE PARTICLES AND MUONS, S_{600}
- YAKUTSK: CASCADE PARTICLES, MUONS AND CHERENKOV RADIATION FROM ATM (CALORIMETRIC CALIBRATION)
- FLY'S EYE: FLUORESCENT LIGHT FROM ATM
- HIRES: THE SAME
- AGASA: CASCADE PARTICLES AND MUONS, S_{600}

UNCERTAINTIES IN ENERGY DETERMINATION IS 20-30%

FE HIGHEST ENERGY EVENT

$$E = (3^{+0.36}_{-0.54}) \cdot 10^{20}\ eV$$

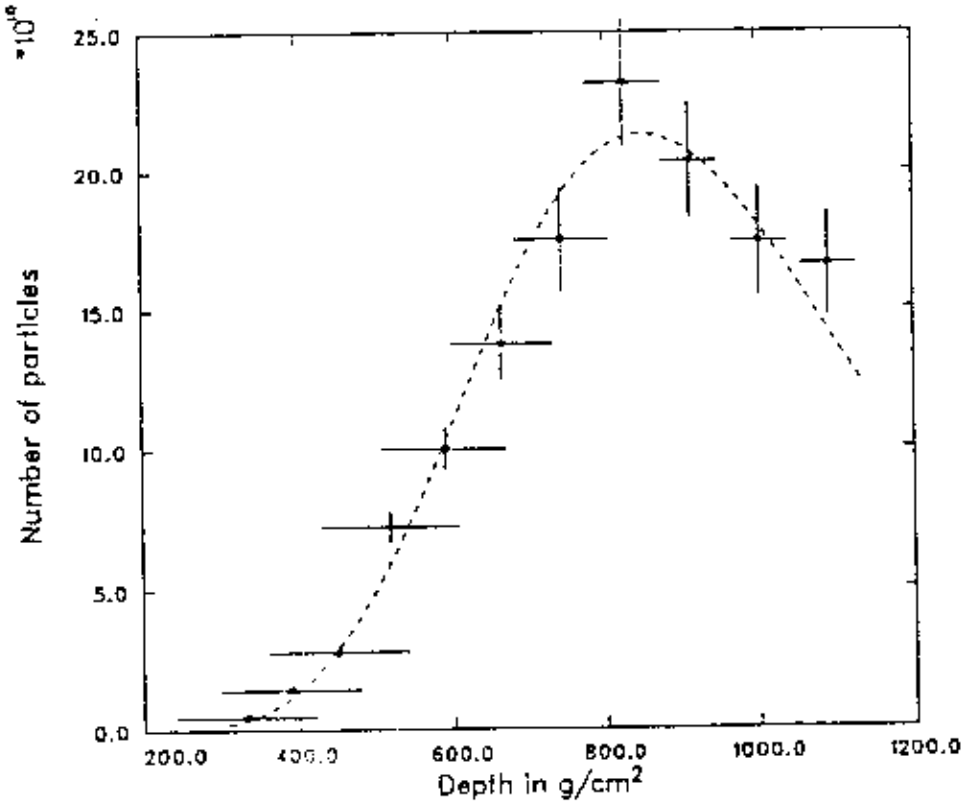
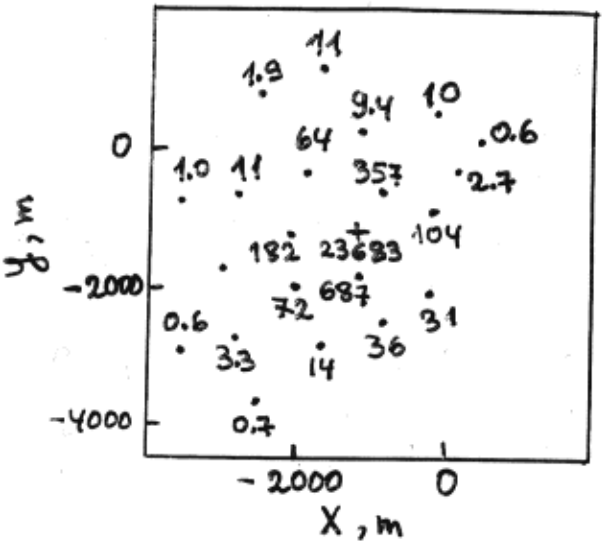


FIG. 12. – Shower profile for the most energetic event observed by the Fly's Eye detector.

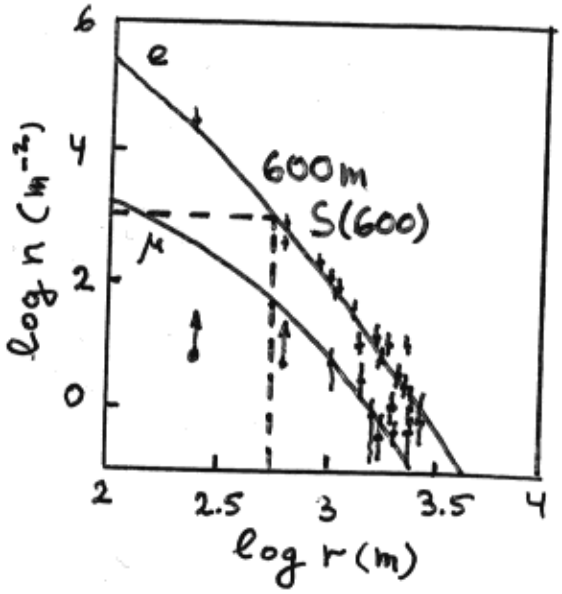
THE AKENO EVENT

$$E = (1.7 - 2.6) \cdot 10^{20}\ eV$$

* The core in the center of the "Akeno Branch"



$E_{eV} = 2 \cdot 10^{17} S(600)$



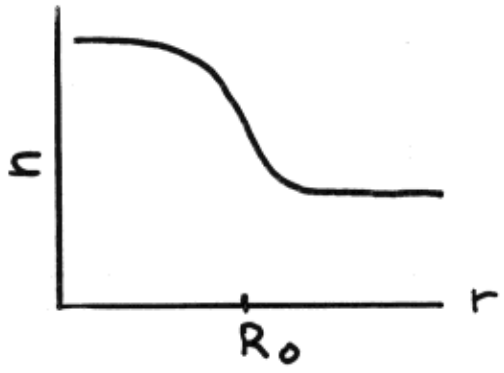
* Both electron and muon components are measured

* Zenith angle 22.9°

ASTROPHYSICAL SOLUTIONS

- AGN AND GRBs: CLASSICAL GZK CUTOFF

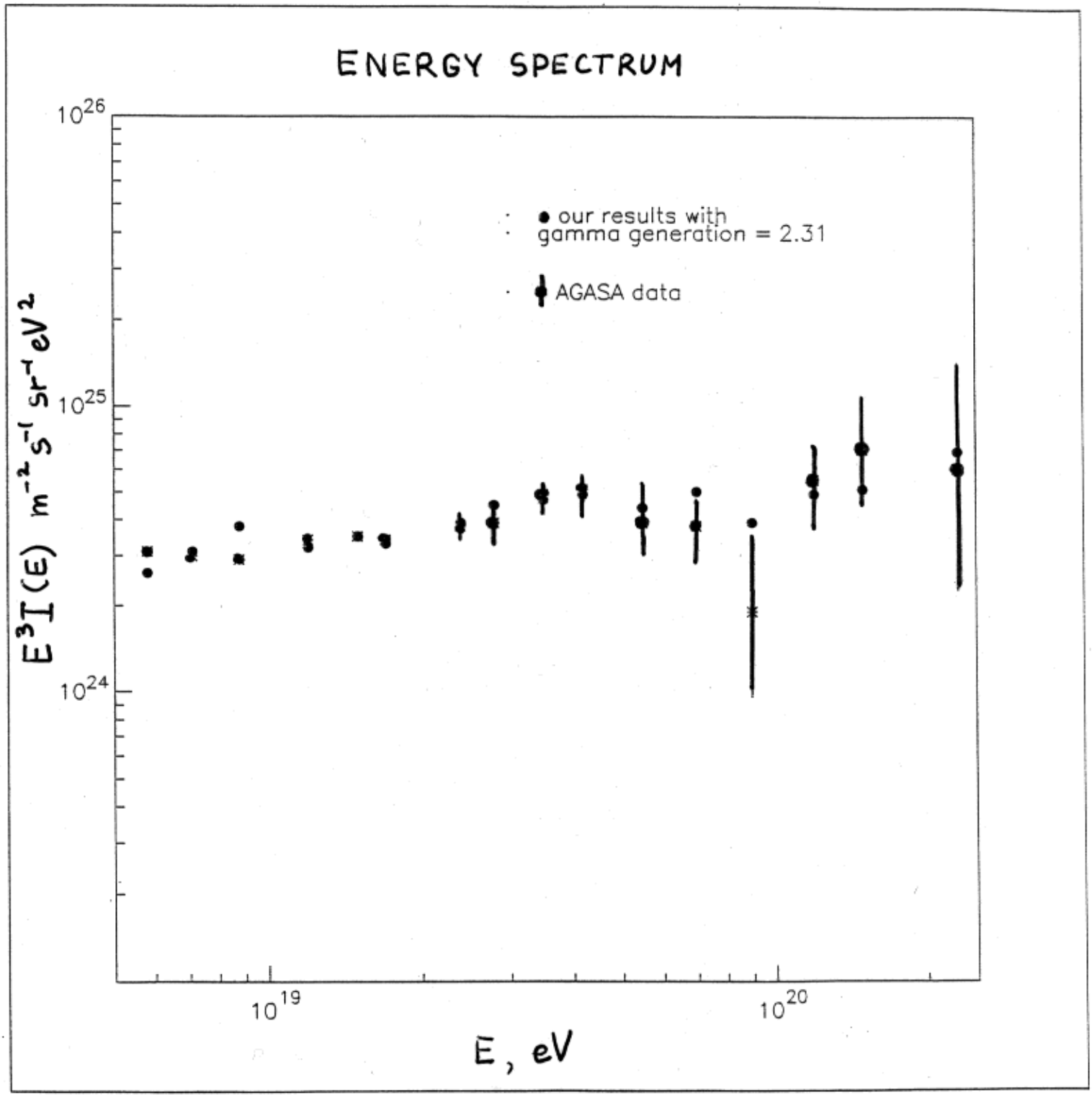
- SPACE DENSITY OF UHECR SOURCES IS LOCALLY ENHANCED BY FACTOR 30-100.



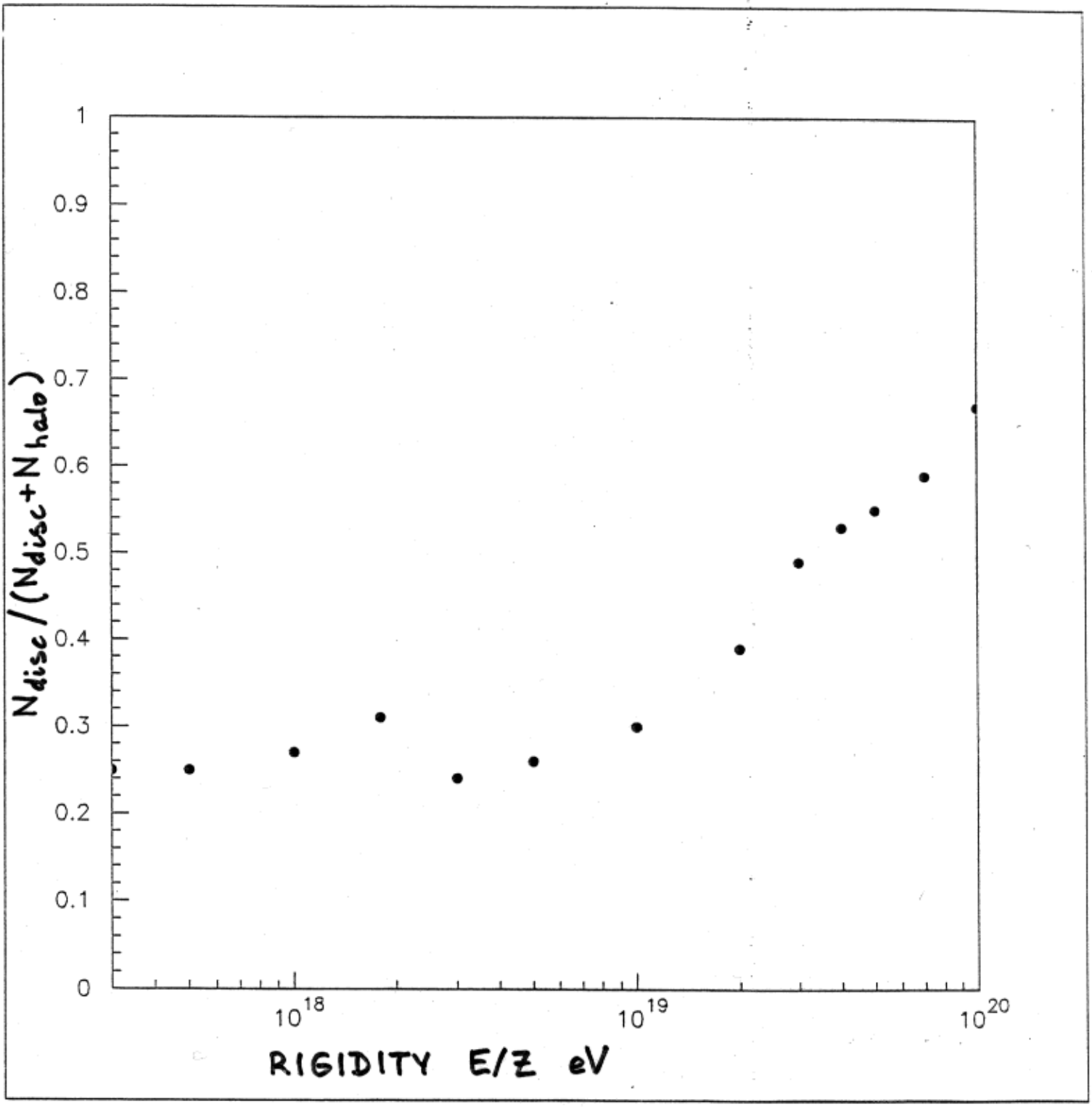
$R_0 \sim 10\text{-}30$ Mpc

- MAGNETIC FOCUSING FROM VIRGO (M 87)

- UHE PRIMARIES ARE GALACTIC IRON NUCLEI.
  PROBLEM: HIGH FRACTION OF EVENTS FROM DISC.


ENERGY SPECTRUM
10^{26}
10^{25}
10^{24}
$E^3 I(E)$ $m^{-2} s^{-1} sr^{-1} eV^2$
our results with
gamma generation = 2.31
AGASA data
10^{19}
10^{20}
E, eV

FRACTION OF DISC EVENTS



SOLUTIONS WITH NEW PHYSICS

- SUPERHEAVY DARK MATTER ($X \to$ hadrons)

  $M_X > 10^{12}$ GeV , $\tau_X > 10^{10}$ yr

  NO RADICALLY NEW PHYSICS INVOLVED

- RESONANT NEUTRINOS

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

  TOO HIGH FLUX OF PRIMARY NEUTRINOS IS NEEDED

- TOPOLOGICAL DEFECTS

  RELIABLE PHYSICS , WEAK GZK CUTOFF

- NEW PARTICLES

  STRONGLY INTERACTING NEUTRINOS , LSP (GLUEBALLINO), MONOPOLES ....

- LORENTZ INVARIANCE VIOLATION

  MOST RADICAL PROPOSAL

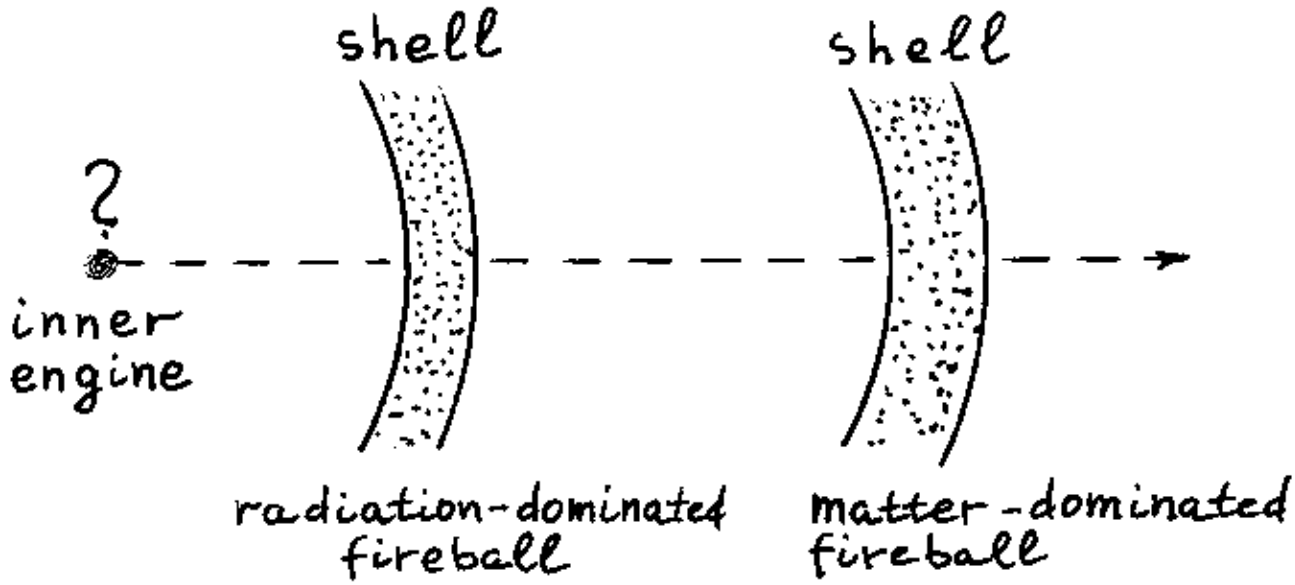
3d puzzle

SOURCES OF GRBs

- GRBs WERE DISCOVERED (UNPREDICTABLY) IN 1973 (PUBLICATION) BY VELA SATELLITES DESIGNED FOR DETECTING OF NUCLEAR TESTS.
- THERE WERE ~500 GRBs DETECTED BY MORE THEN A DOZEN SPACECRAFTS, WITH A CONCLUSION THAT THE SOURCES ARE GALACTIC NEUTRON STARS.
- BATSE (1992) DATA SHOWED THE COSMOLOGICAL ORIGIN OF GRBs.
- BEPPO-SAX (1997) DETECTED AFTERGLOW DUE TO WHICH A HOST GALAXY WITH IDENTIFIED REDSHIFT ($z = 0.835$) WAS FOUND.

HYDRODINAMICS OF GRBs

1. FIREBALL



radiation-dominated fireball

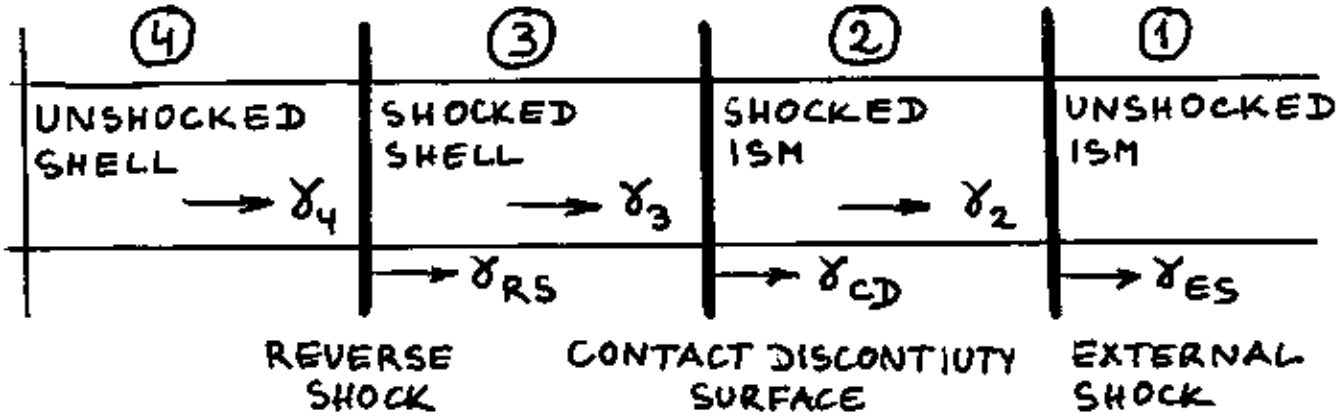
matter-dominated fireball

e^+, e^-, γ, barions

LORENTZ-FACTOR: $\gamma \sim R$ $\qquad \gamma \simeq \eta$

$M_b = E_{tot}/\eta \qquad \eta \sim 300-1000$

2. HYDRODINAMICS



3. AFTERGLOW

STARTS WHEN THE SHELL BEGINS ITS SLOWDOWN

$$R_{AG} = \left(\frac{3 E_{tot}}{4\pi n_{ISM} m_H c^2 \gamma^2} \right)^{1/3} \sim 10^{17} \text{ cm}$$

WHAT THE INNER ENGINE MUST EXPLAIN?

- ENERGY RELEASE
  MAXIMUM ENERGY RELEASE (GRB 990123, $z=1.7$) IS $\mathcal{E}_{iso} = 4 \cdot 10^{54}$ erg, TYPICAL $\mathcal{E}_{iso} \sim 10^{52} - 10^{53}$ erg.
  BEAMING FACTOR $f_B = \Omega/4\pi$ DIMINISHES IT, BUT INCREASES $\dot{N}_{GRB} \sim 600\ yr^{-1}$

- GRB RATE $\dot{N}_{GRB}(S)$

- GRB DURATIONS $5\,ms \lesssim T_{GRB} \lesssim 1000\,s$
  AND DISTRIBUTION $\dot{N}_{GRB}(T)$

- SHORT-TIME STRUCTURE OF THE PULSE ($T \sim$ a few ms)

- BARYON CONTAMINATION $\eta \sim 300 - 1000$

ASTROPHYSICAL GRB ENGINES

1. BINARY NEUTRON-STAR MERGERS

Narayan, Paczynski, Piran 1992
Janka et al 1999

VIRTUE: NUMERICAL CALCULATIONS

PROBLEMS:

- NEED FOR STRONG COLLIMATION: $\mathcal{E}_{iso} < 10^{51}$ erg
- SHORT DURATIONS: $T_{GRB} \sim 0.1$ s
- LARGE BARYON CONTAMINATION

2. HYPERNOVA Paczynski 1997

ROTATING BH WITH STRONG MAGN FIELD $B \sim 10^{15}$ G.
ROTATION ENERGY OF BH ($E \sim 10^{54}$ erg) IS MAGNETICALLY TRANSFERRED TO DISC.
THE OUTER PARTS OF THE DISC ARE ACCELERATED TO RELATIVISTIC VELOCITIES.

VIRTUES:

- LARGE T_{GRB}
- LARGE $\mathcal{E}_{GRB} \sim 10^{54}$ erg

PROBLEMS:

- NO NUMERICAL CALCULATIONS (LARGE γ ?)
- LARGE BARYON CONTAMINATION

3. SUPRANOVA Vietri, Stella 1998

MASSIVE NEUTRON STAR STABILIZED BY ROTATION

- SMALL BARYON CONTAMINATION
- NO NUMERICAL CALCULATIONS

ELEMENTARY PARTICLE SOLUTION:

SUPERCONDUCTING STRINGS AS GRB ENGINES.

BABUL, PACZYNSKI, SPERGEL 1987

PACZYNSKI 1988

V.B., HNATYK, VILENKIN 2000

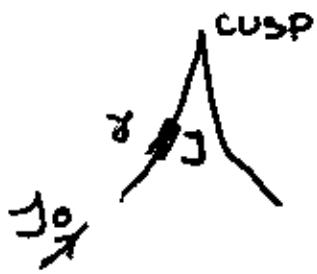
STRINGS ARE ONE-DIMENSIONAL TOPOLOGICAL DEFECTS
WHICH ARE PRODUCED BY SSB $\langle \varphi \rangle = \eta$

$$\alpha \equiv K_{grav} G \eta^2 \qquad K_{grav} \sim 50$$

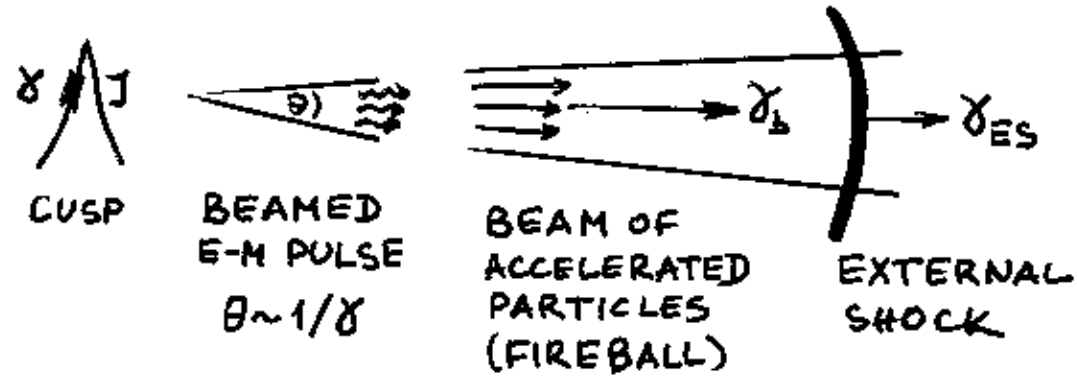
NETWORK OF STRINGS AND LOOPS AT EPOCH t:
MEAN LENGTH OF A LOOP: $\ell \sim \alpha t$
SPACE DENSITY OF LOOPS: $n_\ell \sim \frac{1}{\alpha t^3}$

IN MANY MODELS LOOPS ARE SUPERCONDUCTING (WITTEN 1985)
WITH ELECTRIC CURRENT INDUCED BY MAGNETIC FIELD
AS: $J_0 \sim e^2 B \ell$

LOOPS OSCILLATE PERIODICALLY ($T_\ell \sim \ell/2$)
AND ONE POINT, CUSP, REACHES $V \simeq C$ EACH PERIOD



GRBs FROM CUSPS



$$\frac{d\mathcal{E}_{em}}{d\Omega} \sim K_{em} J_0^2 \ell / \theta^3 \quad , \quad K_{em} \sim 10$$

$$\theta \sim 1/\gamma$$

DURATION OF CUSP EVENT: $\tau_{cusp} = \frac{\ell}{2\gamma^3} \sim \tau_{GRB}$

FLUENCE: $S = (1+z) \frac{d\mathcal{E}_{em}}{d\Omega} \frac{1}{d_L^2(z)}$

RATE: $d\dot{N}_{GRB} \sim \nu(t)\, dV(z)\, d\Omega$

$$\nu(t) \sim 1/\alpha t^4 \quad , \quad d\Omega = \tfrac{1}{2}\theta d\theta$$

RESULTS

- $\dot{N}_{GRB}(>S) \sim 3 \cdot 10^2 S_{-8}^{-2/3} B_{-7}^{4/3}$ yr^{-1}
- $\tau_{GRB}^{min} \sim 3 \alpha_{-8}^4 B_{-7}^2$ ms ; $\tau_{GRB}^{max} \sim 10^3$ s
- SHORT-TIME STRUCTURE DUE TO WIGGLES

PARAMETERS

$\alpha \sim 10^{-8}$ $(\xi \sim 10^{14}$ GeV$)$, $B \sim 10^{-7}$ G, $z_{max} \simeq 4$

PROBLEM

RATE OF GRBs FROM GALAXIES IS VERY LOW.

CUSPS CAN BE RESPONCIBLE FOR SUBSET OF SHORT BURSTS

CONCLUSIONS

- TeV GAMMA-RAY CRISIS IS BASED ON COBE/DIBRE IR DATA. THE EXTRAGALACTIC COMPONENT MAY BE OVERESTIMATED DUE TO ISUFFICIENT SUBTRACTION OF GALACTIC AND INTERPLANETARY CONTRIBUTION.

- THE ABSENCE OF GZK CUTOFF IN UHECR SPECTRUM SEEMS TO BE RELIABLY ESTABLISHED.
  THE SOLUTION OF THIS PROBLEM NEEDS SOME EXOTIC ASTROPHYSICS OR NEW PHYSICS.

- GRB ENGINE IS ESSENTIALLY UNKNOWN.
  THE ASTROPHYSICAL ENGINE WITH ENERGY OUTPUT UP TO $\mathcal{E}_{iso}^{max} = 4 \cdot 10^{54}$ erg, LARGE INTERVAL OF GRB DURATIONS $5\,\text{ms} \lesssim T_{GRB} \lesssim 1000\,\text{s}$ etc, IS DIFFICULT TO CONSTRUCT.
  IT COULD BE THAT NEW PHYSICS IS NEEDED FOR REALISTIC MODELS (SUPERCONDUCTING COSMIC STRINGS?)