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Contribution to the Proceedings of the ESLAB Symposium on the Context and Status of Gamma-Ray Astronomy, Frascati, Italy, June 10-12, 1974

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ABSTRACT

Recent observations have now provided evidence for diffuse background gamma radiation extending to energies beyond 100 MeV. There is some evidence of isotropy and implied cosmological origin. Significant features in the spectrum of this background radiation have been observed which provide evidence for its origin in nuclear processes in the early stages of the big-bang cosmology and tie in these processes with galaxy formation theory. A crucial test of the theory may lie in future observations of the background radiation in the 100 MeV to 100 GeV energy range which may be made with large orbiting spark-chamber satellite detectors. A discussion of the theoretical interpretations of present data, their connection with baryon symmetric cosmology and galaxy formation theory and the need for future observations will be given.

1. Introduction

Since this is a symposium on the context and status of gamma-ray astronomy, it is perhaps an appropriate time and place to consider the evolution of our ideas in the recent past and where we should be going in the future, not only in important observational work such as the COS-B experiment, but also in the evolution of theoretical ideas and concepts. It may therefore be of interest to begin this presentation with a brief look backward before discussing the future. Such a look is, by its very nature, a subjective thing and this presentation is somewhat reflective particularly of the views of one of us (F.W.S.) who has has a rather longstanding interest in the subject of the existence and origin of the diffuse gamma-ray background radiation. With that warning and apology, let us consider the subject at hand.

2. Early Ideas and Motivations

Early interest in gamma-ray astronomy was stimulated by important discussions of the potential knowledge to be gained about high energy astrophysics by studying cosmic gamma-rays. Of particular significance was the discussion by Morrison (1958). Interestingly enough, Morrison's discussion of a possible gamma-ray background centered around antimatter annihilation as a prime source, this being in the context of the steady state cosmology. We are now coming again to focus our attention on antimatter annihilation as the prime source of the gamma-ray background radiation, this time in a different cosmological context (Stecker, Morgan, and Bredekamp, 1971; Stecker and Puget, 1972).

It must have been evident very early, in an implicit way that the only source of matter large enough to give a significant background of isotropic radiation of a truly astronomical nature is the universe itself. Therefore, the connection with cosmology has been clearly the prime motivation for interest in an isotropic background radiation since Morrison's paper.

Theoretical discussions of various types may be found in the literature long before the first solid observational evidence of the existence of a gamma-ray background.

The mechanisms listed by Morrison (1958) to be of possible significance in producing continuum radiation were synchrotron radiation, cosmic-ray electron bremsstrahlung, π^o-meson decay (from cosmic ray-nucleon interactions) and antimatter annihilation. To these four, one more mechanism, viz., Compton interactions between cosmic-ray electrons and starlight (Felten and Morrison, 1963) was added. It later became apparent when the 3K blackbody radiation was discovered that these photons would be orders of magnitude more numerous than starlight photons in intergalactic space as targets for cosmic-ray electrons and should thus be the prime Compton radiation generators of cosmological interest. That the significance of this was readily grasped is obvious from the plethora of independent suggestions made immediately after the discovery of the microwave background radiation (Felten 1965, Gould 1965, Hoyle 1965, Fazio, Stecker and Wright 1966, Felten and Morrison 1966). The relative weakness of intergalactic magnetic fields, evidenced by data on the non-thermal radio background, eliminated synchrotron radiation as a prime contender in generating the diffuse gamma-ray background so that four mechanisms were left

a) electron bremsstrahlung

b) electron-photon interactions (Compton effect)

c) cosmic-ray produced π^o-decay

d) decay of π^o-mesons from matter-antimatter annihilations

The first detection of a low energy gamma-ray background was from a detector aboard the Ranger 3 moon probe. The concluding remarks of Arnold et al. (1962) made about their data 12 years ago, still have bearing today:

"The continuum falls roughly as $E^{-2.4}$ up to 1 MeV and is essentially flat thereafter. The shape below 1 MeV is suggestive of a thick target bremsstrahlung spectrum. The shape above 1 MeV is puzzling; the absence of spectral data above 2.6 MeV precludes a unique unfolding of the instrument response. Nevertheless, attention is called to the unexpectedly high flux observed above 2.1 MeV."

Evidence for a diffuse background above 50 MeV was reported by Kraushaar and Clark (1962) from measurements on Explorer 11. The interpretation of Felten and Morrison (1963) that both the Ranger 3 and Explorer 11 results could be fitted reasonably well by a single power law of the type expected from Compton interactions seemed logical; the possible flattening above 1 MeV reported by Arnold, et al. shuffled off to relative oblivion for years to come and it was expected that data in the two energy decades between 1 and 100 MeV would exhibit nothing more exciting than a smooth power law spectrum as extrapolated from the sub-MeV ("X-ray") energies.

Theoretical attention was turned to the problem of galactic π^o-production by cosmic rays since the bremsstrahlung and compton production cross sections were well understood and the measurement of Kraushaar and Clark on Explorer 11 eliminated the large annihilation fluxes predicted by steady state cosmology and provided a serious blow to the steady state theory itself. Ginzburg and Syrovatsky (1963) made estimates of galactic π^o production based on a study by Greisen (1960) of π meson production in the earth's atmosphere. Pollack and Fazio (1963) calculated the production rate based on accelerator data. While attempts were made to detect a gamma-ray background with balloons (e.g. Häfner et al. 1963) balloon results remained ambiguous because of subtractions of large background correction from atmospheric secondary gamma-radiation. The observational situation remained relatively stagnant as observational gamma-ray astronomy took a back seat to X-ray astronomy until the classic OSO-3 experiment whose preliminary results were reported on by Clark, Garmire and Kraushaar (1968). While their most exciting results were about the detection of galactic gamma-rays, they also reported on a possible background flux at high galactic latitudes.

3. Cosmology, Redshifts and Spectra

In the late 60's one of us (FWS), having made detailed thesis calculations of gamma-ray spectra from cosmic-ray producted secondary particles and from proton-antiproton annihilation (Stecker 1967), became interested in the effects cosmology might have on such spectra and on the implications of these effects for cosmology itself. Cosmic-ray π^o-decay was suspected to play a major role in generating galactic gamma-rays (Pollack and Fazio , 1963) and it remained a viable possibility for explaining the extragalactic background flux above 100 MeV. But if such interactions are occuring in intergalactic space now, why not in the distant past when gas and cosmic-ray densities were higher (in an expanding universe)? If so, large fluxes of extragalactic cosmic-rays (comparable to galactic fluxes) need not exist now to explain the 100 MeV background (Stecker 1968, 1969a). Also, the spectrum would be redshifted and would be softer than the galactic spectrum (Stecker 1969b). Similar ideas were being independently worked on by Ginzburg (1968) in the context of the Lamaitre cosmological model and by Rozental and Shukalov (1969) for the standard expanding universe model. In these models, various cosmological effects come into play to distort the spectrum from π^o-decay and redshift its characteristic peak from an energy of $m_\pi c^2/2 \sim 70$ MeV to lower energies (see extensive discussions in the monographs by Stecker (1971a) and Ozernoi, Prilutsky and Rozental (1973)). The result was the prediction of a possible enhancement in the gamma-ray background spectrum between 1 and 100 MeV deviating from the simple power law extrapolation of the X-ray background. At the time of these early predictions, there was only a single uncertain data point at 100 MeV obtained by the OSO-3 experiment which seemed as if it might be above the X-ray extrapolation (Stecker 1968). Figure 1, taken from Stecker and Silk (1969) showed these predictions for the gamma-ray background. Shortly thereafter, results on the background up to an energy of 6 MeV were reported by Vette et al. (1969, 1970) as obtained on the ERS-18 satellite which did indicate an enhancement above 1 MeV, recalling the earlier statement of Arnold, et al. The data of Vette, et al. gave support to the interpretation of a redshifted π^0-decay origin for the gamma-ray background, but with the surprizing implication of a burst of cosmic-rays produced at a redshift of $\sim$100 and it was speculated that such a large burst at such a high redshift might be connected with the galaxy formation process and protogalactic masses (protars) (Stecker 1969c, 1971b). Cosmological absorption effects expected at high redshifts were then examined by Rees (1969), Arons and McCray (1969), Fazio and Stecker (1970) and Stecker (1971a). Other implications of the "protar" hypothesis have recently been examined by Montmerle (1973, 1974).

4. Baryon Symmetric Cosmology

Early observations of gamma-radiation by Kraushaar and Clark (1962) had clearly indicated that if antimatter exists in the universe in large amounts, it must clearly be separated from matter so that the average annihilation rate is quite small. In 1969, Omnès suggested a baryon symmetric (equal amounts of matter and antimatter) cosmology based on a possible phase transition effect which could separate matter from antimatter at an early stage in the big-bang corresponding to nuclear density for the cosmic plasma. The phase transition effect was also studied by Aldrovandi and Caser (1972) and Cisneros (1973). Further work by Omnès (1972 and references therein) showed that the separate domains of matter and antimatter could grow to contain masses of the size of galaxies by the recombination epoch. This result has recently been refined by Aldrovandi et al. (1973).

It was to be expected that boundary-region annihilations in this picture would also produce redshifted π^o-decay radiation and absorption effects would cut off the resultant flux below 1 MeV. Therefore, Stecker, Morgan and Bredekamp (1971) were motivated to make a detailed calculation of the resultant diffuse background spectrum to be expected, and the results agreed fairly well with the observations then available. The encouraging enhancement in the 1 to 100 MeV range is partially due to the existence of a "gamma-ray window" in this energy range as shown in Figure 2. The results were encouraging enough for us to examine further the evolution of the Omnes cosmology for redshifts less than 10^3 (Stecker and Puget 1972). We then found several exciting implications

a) separate regions containing masses the size of galaxy clusters could be obtained.

b) turbulence produced by annihilation pressure could provide enough energy to trigger galaxy formation.

c) estimates obtained placed the galaxy formation stage at redshifts of the order of 60.

d) mean densities and angular momenta of galaxies could be estimated in this picture consistent with observation and related to the annihilation rates calculated by the model and implied by the observations.

The annihilation rate has been further examined by one of us (Puget 1973) and the galaxy formation model has been further refined by Dallaporta, Danese and Lucchin (1974). These later results have been encouraging as have the more recent data.

The general scheme of the galaxy formation model is shown in Figure 3. The observational implications of the model are outlined in Figure 4.

The calculated annihilation rate as a function of redshift z is shown in Figure 5 (Puget 1973). Further discussion of the gamma-ray spectrum calculations has been given previously (Stecker 1973).

5. Recent Data on the Diffuse Gamma-Ray Background

Since 1971, various groups have obtained data on the diffuse background radiation in the cosmologically critical region between 1 and 100 MeV, hopefully in some part stimulated by the theoretical calculations. These data have now defined a continuous background spectrum up to an energy of ∿200 MeV. They are summarized in Figure 6. Figure 7 shows a comparison of these data with the annihilation spectrum calculated by Stecker, Morgan and Bredekamp (1971) (see also the discussion of Stecker and Puget 1972). Determinations of isotropy have been made by Fichtel et al. (1973) at the higher energies and by Schönfelder and Lichti (1974) at the lower energies. We feel that the recent data tend to support the annihilation model.

Figure 8 shows the energy spectrum $J(E_\gamma) \equiv E_\gamma I(E_\gamma)$ of the background radiation between 10^{-3} and 200 MeV as based on the review paper of Schwartz and Gursky (1973) and the data shown in Figure 6. An extrapolation of the data between 30 keV and 1 MeV is shown by the dashed line. A strong deviation from the power law extrapolation expected historically is indicated. These data may be compared with Table 1 which summarizes the features expected from the four main production mechanisms mentioned earlier. Further discussion of these features and mechanisms has been recently given (Stecker 1973).

Growing evidence of an enhancement in the background flux has stimulated a variety of other theoretical models to explain these data ex post facto. We feel that these later attempts have problems of various degrees of seriousness ranging from "troublesome" to "physically impossible." Such models have been discussed previously (Stecker 1973) and more recent attempts will probably be discussed elsewhere in these proceedings and in the future (Stecker 1974). Suffice it to say here that we feel that the redshifted π^0-decay mechanisms seem to us the most likely explanation of the gamma-ray background spectrum.

6. Future Observational Tests

Having discussed the past evolution of our knowledge of the diffuse background and the present situation, we now turn toward the future. We feel theorists and cosmologists should be encouraged by the recent observational successes in the field. Likewise, it is to be hoped that the exciting theoretical implications of these studies will inspire new observational efforts. In the range around 1 MeV, a better understanding of intrinsic contamination and its minimization should enable a more confident determination of the energy spectrum to be made. But perhaps the new challenge lies in a study of the flux between 100 MeV and 100 GeV. It is in this energy range that critical tests may be made of the "protar" and annihilation hypotheses.

The first critical test lies in a study of the energy spectrum. Figure 9 shows the present range of the data, indicated by the shaded region, along with the extrapolated power-law spectrum (X) the annihilation spectrum (A) and the high energy form of the spectrum predicted for red-shifted cosmic-ray π^0-decay gamma-rays (CR). The annihilation spectrum should exhibit a sharp cutoff slightly below 1 GeV because the energy of the gamma-rays is limited by the rest energy available to them from baryon-antibaryon annihilations. A detailed discussion of this may be found in Stecker (1971a). The cosmic-ray produced spectrum, on the contrary, can continue up to higher energies with a steepening induced around 10 GeV by pair-production losses through interactions with the microwave background (Fazio and Stecker 1970). This steepening should amount to an increase of 0.5 in the spectral index for a closed Einstein-de Sitter universe and an increase of 0.75 in the spectral index for a low-density open universe (Stecker 1971a). It should be kept in mind that the cutoff in the annihilation spectrum may be somewhat obscured by the presence of other background radiations having relatively lower intensities below 200 GeV.

The other test lies in possible angular fluctuations in the background radiation at a few hundred MeV. Such fluctuations may be expected from annihilation radiations since annihilations take place mainly at the boundaries of regions containing galaxy clusters at present (redshift zero). On the contrary, metagalactic cosmic-ray induced radiation may be more uniform in nature.

In order to accomplish these observational tests, experimenters are challenged to build more sensitive detectors to study the relatively small fluxes of photons expected at the higher energies. Better angular resolution is clearly needed. The challenges may not be easy ones, but the results can be rewarding in shedding more light on the nature of the universe in which we live.

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TABLE 1

MECHANISM	γ-RAY SPECTRUM CHARACTERISTICS		
	SINGLE INTERACTION	GALACTIC SPECTRUM	COSMOLOGICAL SPECTRUM
COMPTON INTERACTIONS	FLAT AT TYPICAL COSMIC-RAY ENERGIES PEAKED TOWARD HIGH PHOTON ENERGY AT ULTRAHIGH ENERGIES. (KLEIN-NISHINA THEORY)	POWER-LAW ROUGHLY $I(E_\gamma) \sim E_\gamma^{-2}$ RELATION BETWEEN EXPONENTS $\Gamma_c = (\Gamma_e + 1)/2$	POWER-LAW ROUGHLY $I(E_\gamma) \sim E_\gamma^{-2}$ RELATION BETWEEN EXPONENTS $\Gamma_c = (\Gamma_e + 1)/2$
BREMSSTRAHLUNG INTERACTIONS	FLAT AT RELATIVISTIC ENERGIES. PEAKED TOWARD LOW PHOTON ENERGY AT NON-RELATIVISTIC ENERGIES.	POWER-LAW ROUGHLY $I \sim E_\gamma^{-3}$ $\Gamma_b = \Gamma_e$ (RELATIVISTIC) $\Gamma_b = (\Gamma_e + 1)$, NON-REL.	POWER-LAW WITH POSSIBLE CHANGES OF EXPONENT AT ~ 0.04, ~ 1, and ~ 3.5 MeV.
NEUTRAL PION PRODUCTION (INELASTIC COSMIC-RAY INTERACTIONS)	FLAT AND SYMMETRIC AROUND $m_\pi c^2/2$ ON A LOG E_γ GRAPH (FOR DECAY OF A SINGLE PION)	MAXIMUM AT $m_\pi c^2/2$. NEARLY FLAT NEAR MAXIMUM AND SYMMETRIC ON A LOG E_γ GRAPH. POWER-LAW ROUGHLY $I \sim E_\gamma^{-3}$ ABOVE A FEW HUNDRED MeV.	MAXIMUM IS REDSHIFTED TO SOME ENERGY BETWEEN ~ 1 AND ~ 70MeV. (NOTE: $m_\pi c^2/2 \simeq 70$ MeV). POWER-LAW AT HIGHER ENERGIES.
NEUTRAL PION PRODUCTION IN MATTER-ANTIMATTER ANNIHILATION.	FLAT AND SYMMETRIC AROUND $m_\pi c^2/2$ ON A LOG E_γ GRAPH (FOR DECAY OF A SINGLE PION)	EXPECT NONEXISTENT	SPECTRUM POWER-LAW BETWEEN ~ 5 AND ~ 50 MeV, TURNS OVER BELOW 5 MeV AND FALLS OFF MORE SHARPLY ABOVE 50 MeV.

FIGURE CAPTIONS

Figure 1 Early predictions of the diffuse gamma-ray background spectrum given by Stecker and Silk (1969). The expected power-law flux, according to the Compton hypothesis of Felten and Morrison (1963) is indicated by the dashed line. Red-shifted cosmological cosmic-ray pion decay spectra for two maximum redshifts (z_{max}) were shown to predict enhancements in the background spectrum between 1 and 100 MeV. $Z_{max} = 100$ corresponding to the epoch of galaxy formation was considered the extreme case. Calculations were based on an $E^{-2.5}$ cosmic-ray spectrum which later had to be steepened to $E^{-2.7}$ to fit the observational data.

Figure 2 The redshift at which the universe becomes opaque to photons given as a function of observed gamma-ray energy. Gamma-rays originating at all redshifts below the curve can reach us unattenuated with the energy indicated. The two curves on the left side of the figure are for attenuation by Compton scattering with intergalactic electrons having the densities indicated and for pair production and are based on the calculations of Arons and McCray (1969). The right-hand curve results from attenuation of gamma-rays by interactions with the microwave blackbody radiation and is based on the discussion of Fazio and Stecker (1970).

Figure 3 Outline of the galaxy formation theory of Stecker and Puget (1972).

Figure 4 Observational implications of baryon symmetric cosmology.

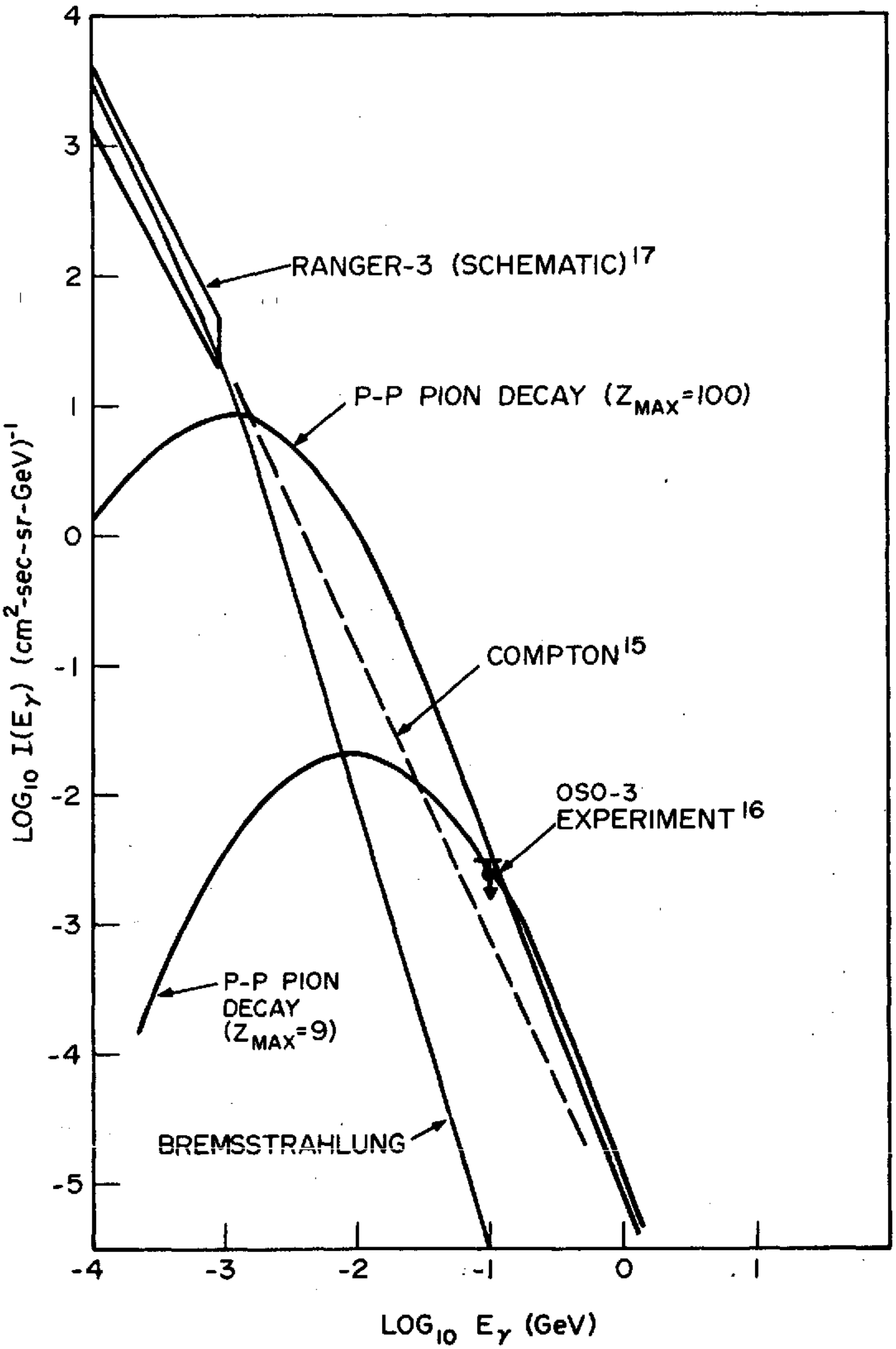
Figure 5 Matter-antimatter annihilation rate as a function of redshift based on the discussion of Puget (1973).

Figure 6 Observational data on the gamma-ray background energy spectrum. The highest energy point of Vette, et al. (1970), shown with a dashed line, and possibly the neighboring point are now thought to be erroneously high due to an inefficiency in the anticoincidence circuit of their detector which should not significantly affect the points at lower energies (Vette, private communication).

Figure 7 A comparison of the data given in Figure 6 with the annihilation model discussed by Stecker, Morgan and Bredekamp (1971) and Stecker and Puget (1972).

Figure 8 Energy flux spectrum of the X-ray and gamma-ray background based on Schwartz and Gursky (1973) and the data given in Figure 6. The straight diagonal line indicates an extrapolation of the 30 keV to 1 MeV spectrum.

Figure 9 Predicted energy flux spectra from the annihilation model (A) and cosmic ray (protar) model (CR) as discussed in the text. Also shown is the scatter area covered by the observational data (shaded) and the extrapolated X-ray background spectrum (X). The two curves shown for the CR spectrum above 7 GeV are for closed (Einstein-de Sitter) and open universes as discussed in the text (Stecker 1971a).


RANGER-3 (SCHEMATIC) 17
P-P PION DECAY (Z MAX =100)
COMPTON 15
OSO-3
EXPERIMENT 16
P-P PION
DECAY
(Z MAX =9)
BREMSSTRAHLUNG
LOG10 I(Eγ) (cm2-sec-sr-GeV)-1
LOG10 Eγ (GeV)
4
3
2
1
0
-1
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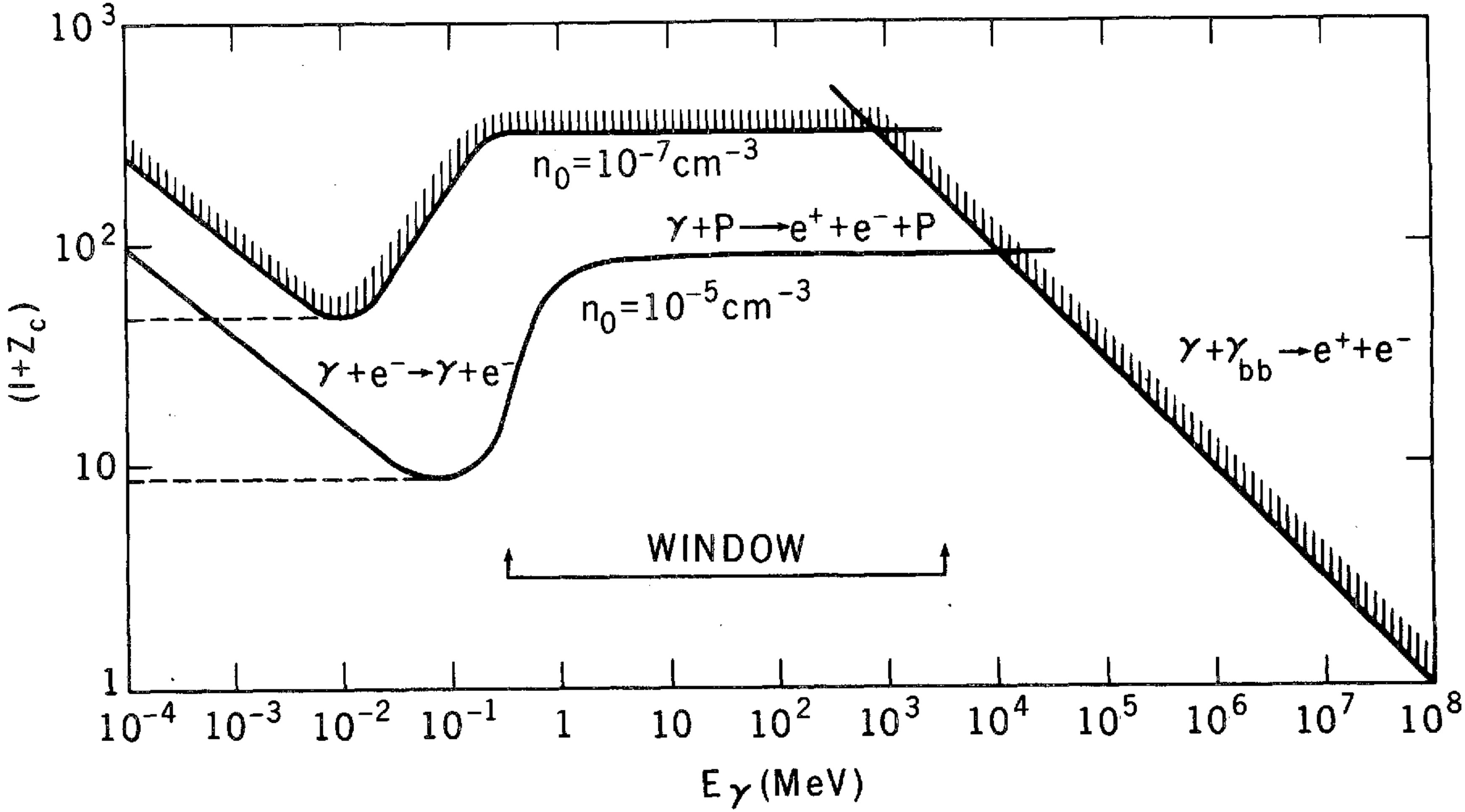
REDSHIFT AT WHICH THE UNIVERSE BECOMES OPAQUE TO PHOTONS



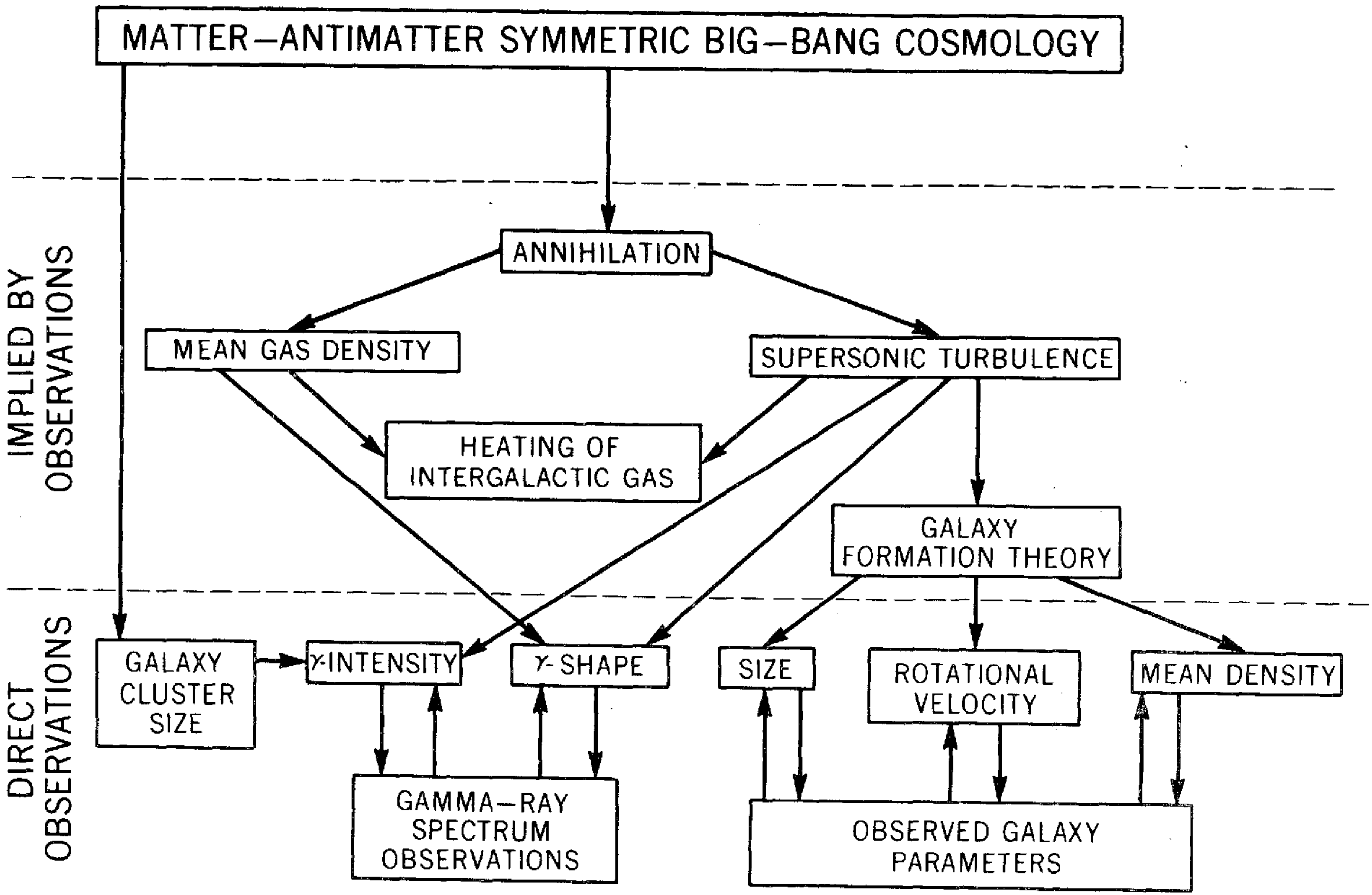
GENERAL SCHEME OF MODEL

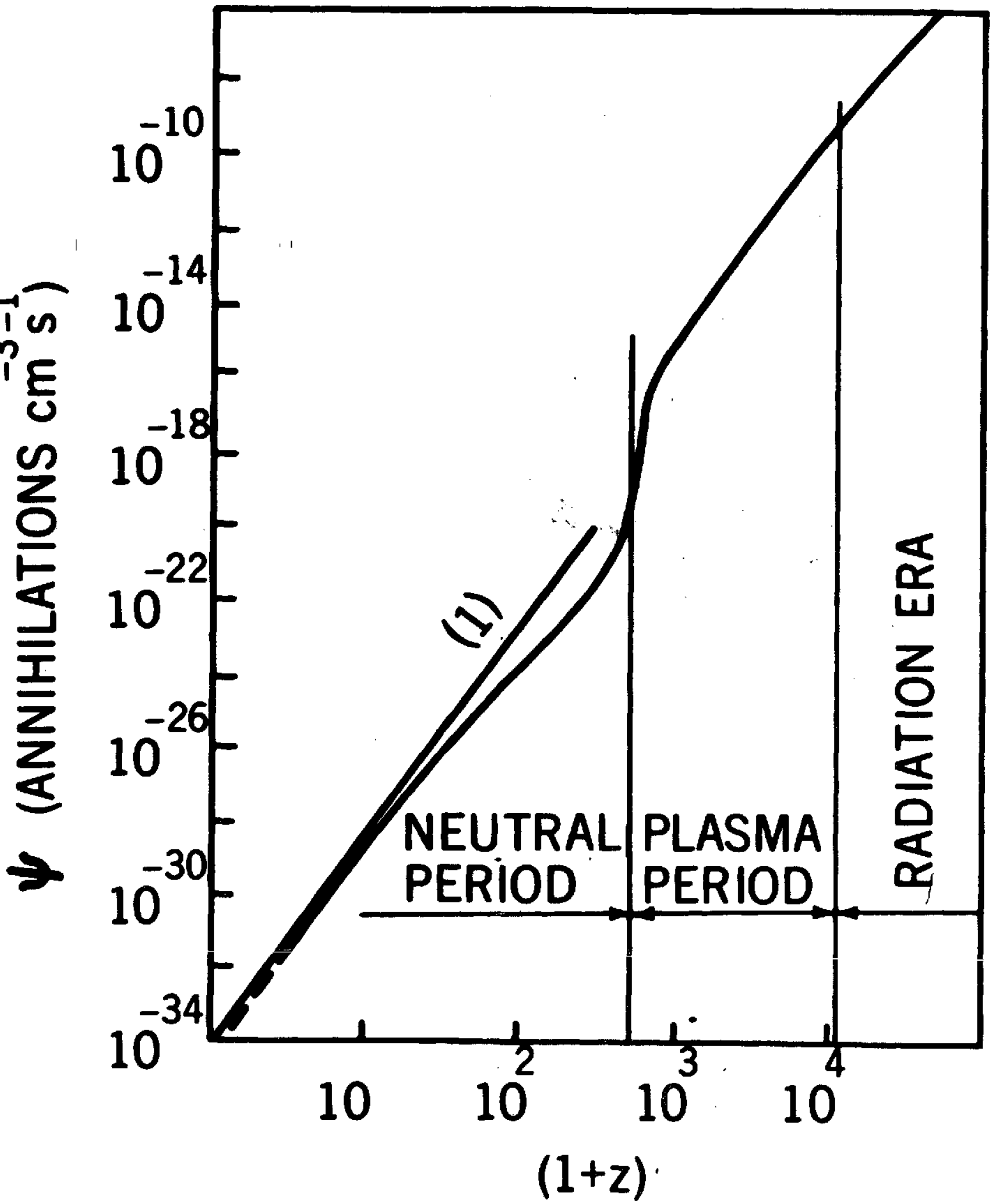
- MATTER AND ANTIMATTER EXIST IN EQUAL AMOUNTS IN SEPARATE REGIONS.
- MIXING OCCURS ALONG BOUNDARY REGIONS OF THICKNESS $\sim\lambda_A$.
- RESULTING RAPID HEATING OF PLASMA WITHIN A DISTANCE $\sim\lambda_X$ OF BOUNDARY BY ANNIHILATION PRODUCTS PRODUCES EXPANSION AWAY FROM BOUNDARY.
- RESULTING EXPANSION OF PLASMA INDUCES HIGH-VELOCITY GAS MOTIONS.
- DURING THE NEUTRALIZATION ERA (POSSIBLY EVEN SOMEWHAT BEFORE) GAS MOTIONS BECOME TURBULENT ($\sim 500 \leq Z \leq \sim 3000$).
- WHEN GAS GOES FROM PLASMA TO ATOMIC STATE ($\sim 400 \leq Z_N \leq \sim 600$):

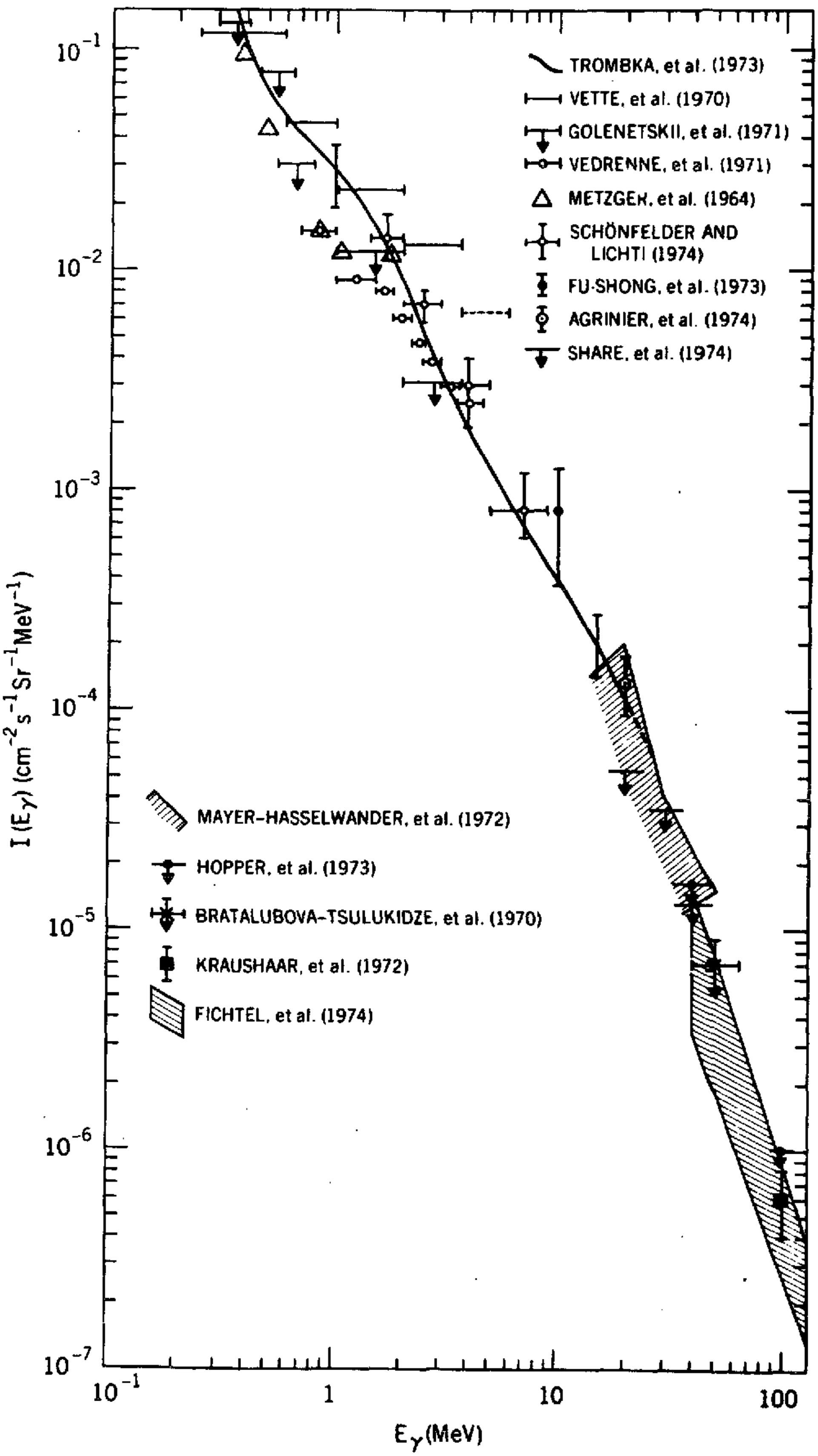
  A) DUE TO DECOUPLING OF MATTER FROM RADIATION FIELD, VISCOSITY DROPS BY ALMOST 8 ORDERS OF MAGNITUDE AND SOUND VELOCITY DROPS BY FOUR ORDERS OF MAGNITUDE.

  B) THIS CAUSES TURBULENCE TO BECOME SUPERSONIC AND TO EXTEND THE EDDY SPECTRUM DOWN TO A SCALE OF THE ORDER OF 10^{-3}pc.

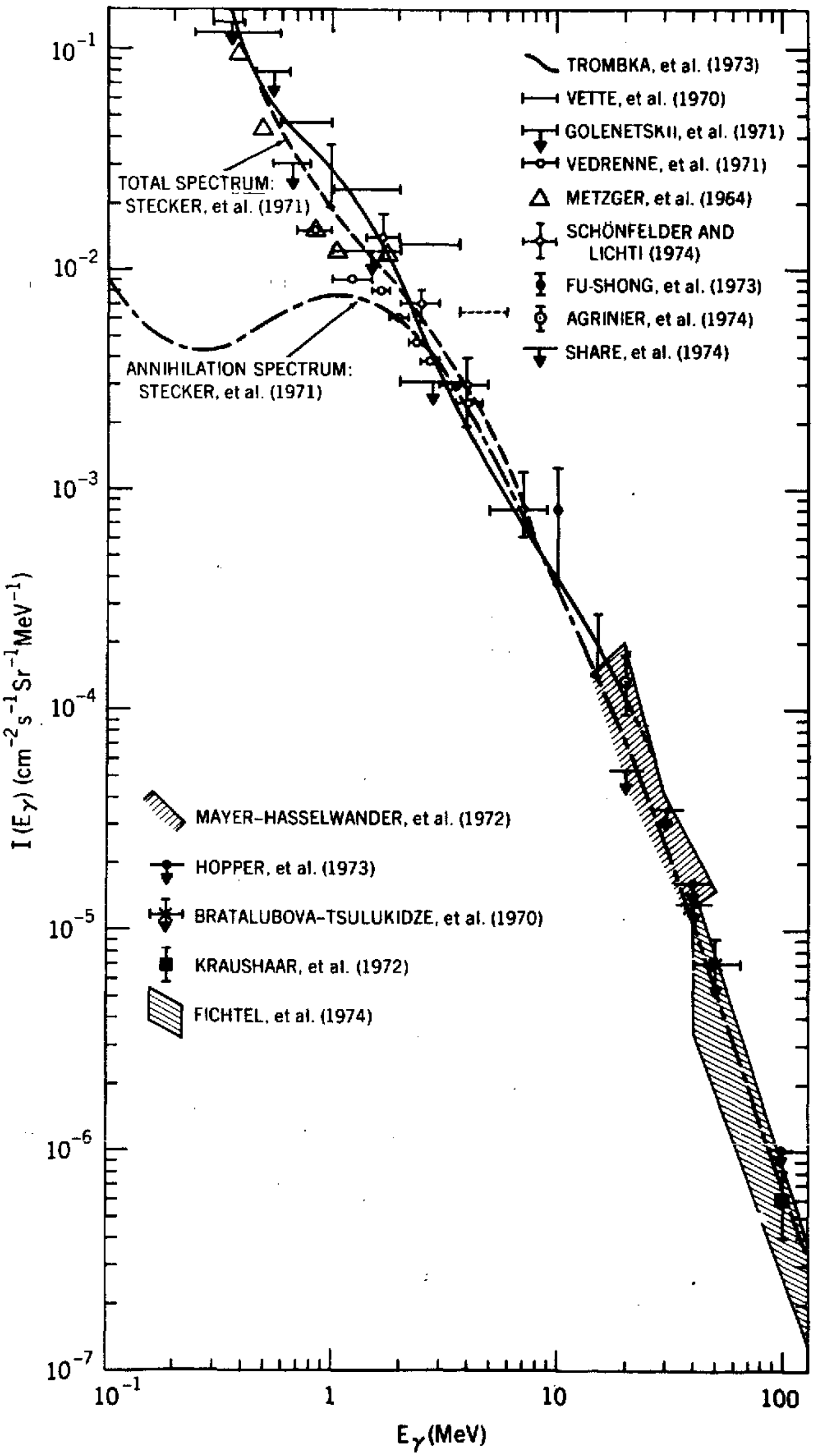
  C) THE SUPERSONIC TURBULENCE INDUCES DENSITY FLUCTUATIONS $\Delta\rho/\rho \sim 1$ OVER THE WHOLE RANGE OF EDDY SCALES.
- AT A REDSHIFT OF $\frac{2}{15}Z_N$ OR ABOUT 60, VIRIAL THEOREM BECOMES SATISFIED FOR BINDING OF GAS CLOUDS INTO PROTOGALAXIES DUE TO DENSITY FLUCTUATIONS INDUCED BY SUPERSONIC TURBULENCE.

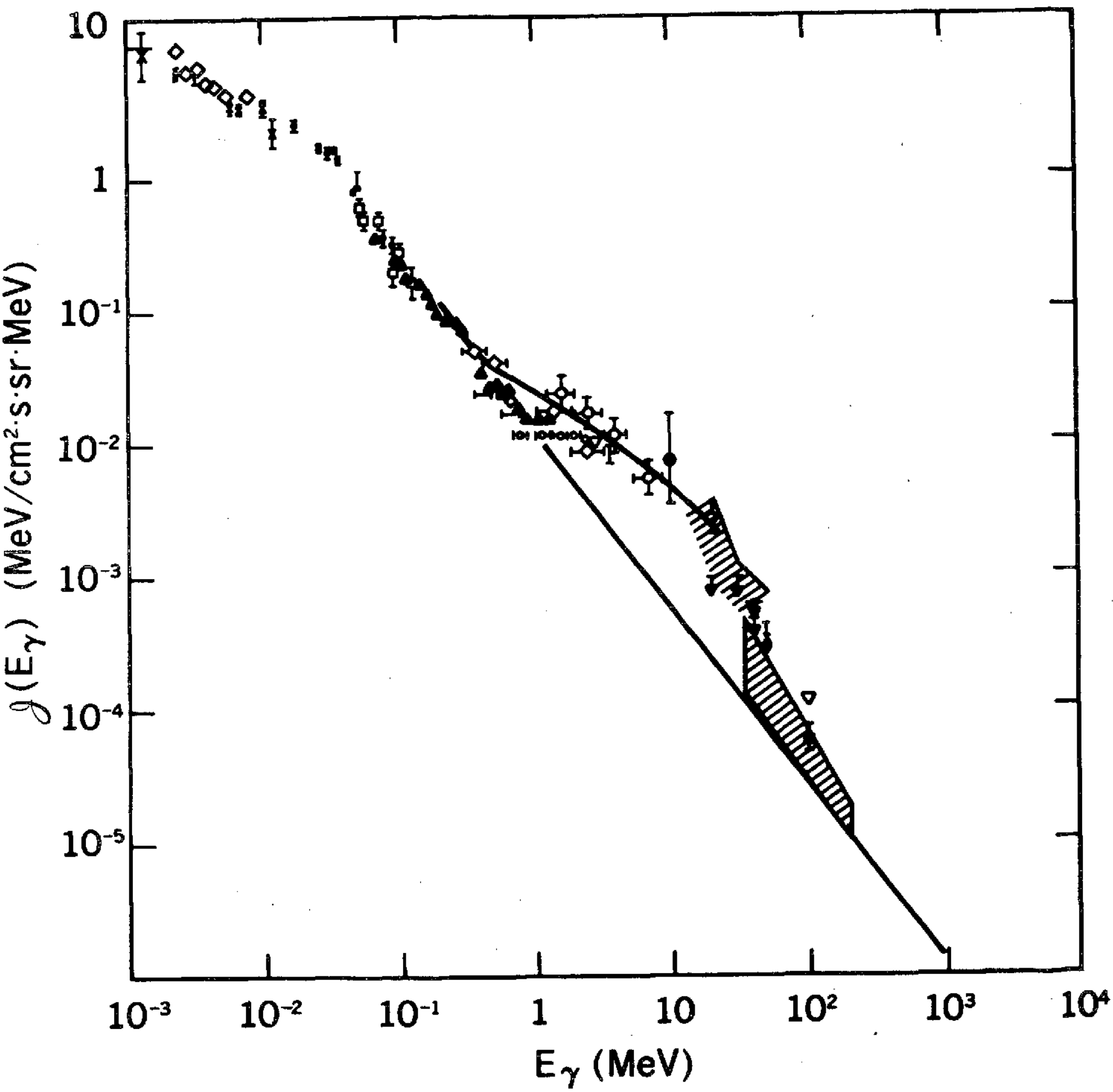

MATTER–ANTIMATTER SYMMETRIC BIG–BANG COSMOLOGY
IMPLIED BY OBSERVATIONS
ANNIHILATION
MEAN GAS DENSITY
SUPERSONIC TURBULENCE
HEATING OF INTERGALACTIC GAS
GALAXY FORMATION THEORY
DIRECT OBSERVATIONS
GALAXY CLUSTER SIZE
γ-INTENSITY
γ-SHAPE
SIZE
ROTATIONAL VELOCITY
MEAN DENSITY
GAMMA–RAY SPECTRUM OBSERVATIONS
OBSERVED GALAXY PARAMETERS


ψ (ANNIHILATIONS cm^{-3} s^{-1})
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-26}
10^{-30}
10^{-34}
(1)
NEUTRAL PERIOD
PLASMA PERIOD
RADIATION ERA
10
10^2
10^3
10^4
(1+z)

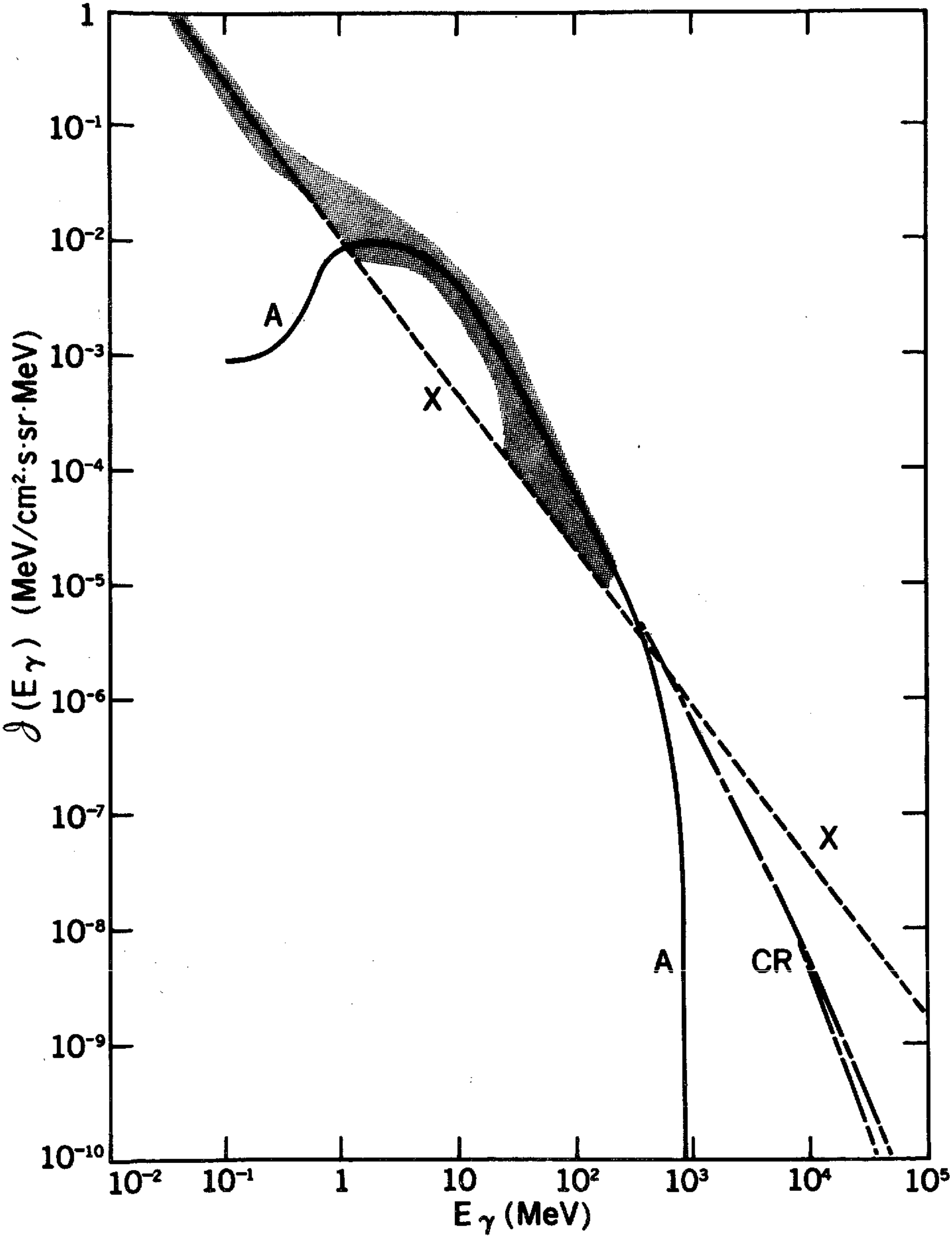


TROMBKA, et al. (1973)
VETTE, et al. (1970)
GOLENETSKII, et al. (1971)
VEDRENNE, et al. (1971)
METZGER, et al. (1964)
SCHÖNFELDER AND LICHTI (1974)
FU-SHONG, et al. (1973)
AGRINIER, et al. (1974)
SHARE, et al. (1974)
MAYER-HASSELWANDER, et al. (1972)
HOPPER, et al. (1973)
BRATALUBOVA-TSULUKIDZE, et al. (1970)
KRAUSHAAR, et al. (1972)
FICHTEL, et al. (1974)
$I(E_\gamma)$ ($cm^{-2} s^{-1} Sr^{-1} MeV^{-1}$)
E_γ(MeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-1}
1
10
100


TROMBKA, et al. (1973)
VETTE, et al. (1970)
GOLENETSKII, et al. (1971)
VEDRENNE, et al. (1971)
METZGER, et al. (1964)
SCHÖNFELDER AND LICHTI (1974)
FU-SHONG, et al. (1973)
AGRINIER, et al. (1974)
SHARE, et al. (1974)
TOTAL SPECTRUM: STECKER, et al. (1971)
ANNIHILATION SPECTRUM: STECKER, et al. (1971)
MAYER-HASSELWANDER, et al. (1972)
HOPPER, et al. (1973)
BRATALUBOVA-TSULUKIDZE, et al. (1970)
KRAUSHAAR, et al. (1972)
FICHTEL, et al. (1974)
I (E$_\gamma$) (cm^{-2}s^{-1}Sr^{-1}MeV^{-1})
E$_\gamma$(MeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-1}
1
10
100



10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$J(E_\gamma)$ (MeV/cm²·s·sr·MeV)
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
E_γ (MeV)



1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
𝒥(E γ) (MeV/cm²·s·sr·MeV)
A
X
X
A
CR
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵
E γ (MeV)