Detecting Anti-Matter with GLAST

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most pieces of talk from
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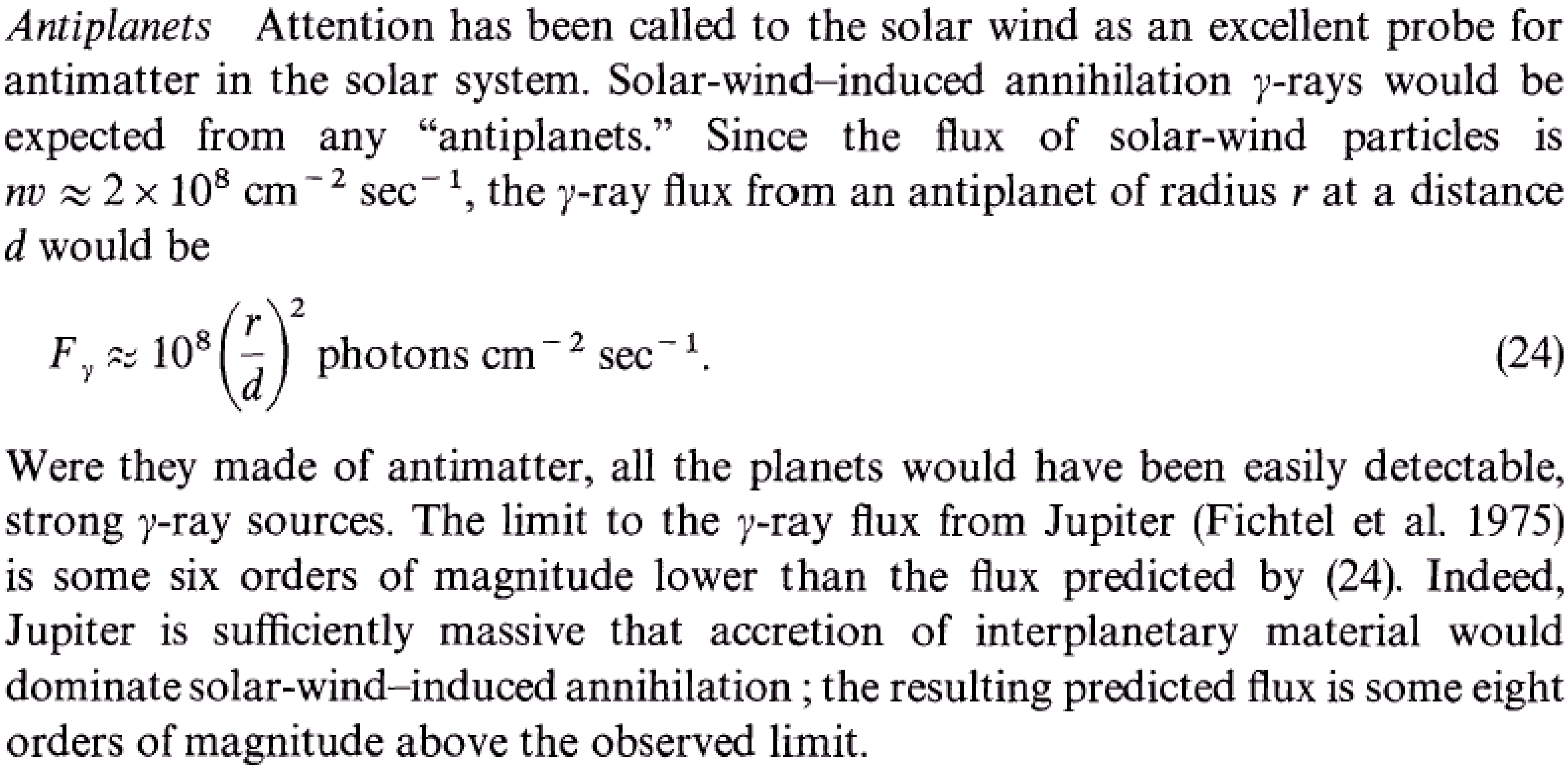
Outline

- **Inclusive γ spectrum from P- Pbar annihilation**
  - **Redshifted ($z<20$) annihilation spectrum is within GLAST energy range**
- **What spatial distributions of anti-matter might exist?**
  - **Experimentally**
    - No anti-planets in solar system (no solar wind glow, landers survived)
    - Low fraction of anti-stars in our galaxy (cosmics rays mostly matter)
    - Other galaxies in our cluster are the same as us (intergalactic medium doesn’t glow)
    - Any other clusters are either all matter or all anti-matter (intergalactic medium doesn’t glow)
  - **Maybe**
    - Equal numbers of matter galactic clusters and anti-matter gal clusters
    - GLAST might see the intercluster medium glowing or set a limit there on the (anti-matter density x matter density)

Antiplanets?



Antiplanets Attention has been called to the solar wind as an excellent probe for antimatter in the solar system. Solar-wind–induced annihilation γ-rays would be expected from any “antiplanets.” Since the flux of solar-wind particles is $nv \approx 2 \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, the γ-ray flux from an antiplanet of radius r at a distance d would be

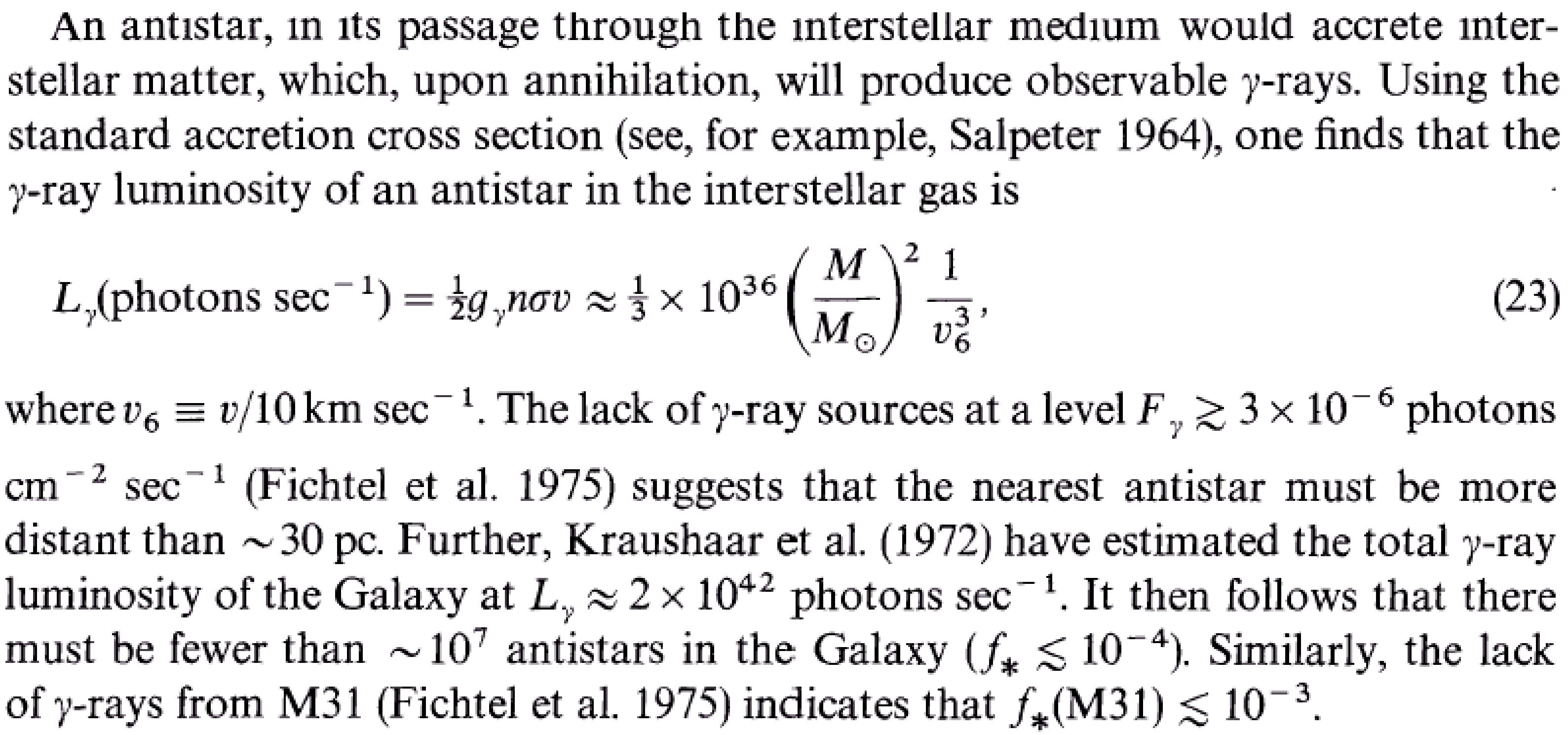
$$F_\gamma \approx 10^8 \left(\frac{r}{d}\right)^2 \text{ photons cm}^{-2}\ \text{sec}^{-1}. \tag{24}$$

Were they made of antimatter, all the planets would have been easily detectable, strong γ-ray sources. The limit to the γ-ray flux from Jupiter (Fichtel et al. 1975) is some six orders of magnitude lower than the flux predicted by (24). Indeed, Jupiter is sufficiently massive that accretion of interplanetary material would dominate solar-wind–induced annihilation; the resulting predicted flux is some eight orders of magnitude above the observed limit.

Plus, don’t forget that we’ve sent matter probes to several planets – didn’t immediately vaporize …

Anti-stars?

Could still be around today if annihilation Eddington-limited.



An antistar, in its passage through the interstellar medium would accrete interstellar matter, which, upon annihilation, will produce observable γ-rays. Using the standard accretion cross section (see, for example, Salpeter 1964), one finds that the γ-ray luminosity of an antistar in the interstellar gas is

$$L_\gamma(\text{photons sec}^{-1}) = \tfrac{1}{2} g_\gamma n\sigma v \approx \tfrac{1}{3}\times 10^{36}\left(\frac{M}{M_\odot}\right)^2 \frac{1}{v_6^3}, \quad (23)$$

where $v_6 \equiv v/10\,\text{km sec}^{-1}$. The lack of γ-ray sources at a level $F_\gamma \gtrsim 3\times 10^{-6}$ photons $\text{cm}^{-2}\,\text{sec}^{-1}$ (Fichtel et al. 1975) suggests that the nearest antistar must be more distant than ~ 30 pc. Further, Kraushaar et al. (1972) have estimated the total γ-ray luminosity of the Galaxy at $L_\gamma \approx 2\times 10^{42}$ photons sec^{-1}. It then follows that there must be fewer than $\sim 10^7$ antistars in the Galaxy ($f_* \lesssim 10^{-4}$). Similarly, the lack of γ-rays from M31 (Fichtel et al. 1975) indicates that $f_*(\text{M31}) \lesssim 10^{-3}$.

Note:

EGRET detected NO nearby galaxies (Eγ>100MeV), except LMC. Both LMC and our galaxy flux consistent with cosmic secondary production.

Direct Detection of Antimatter

– Anti- cosmic rays! Sufficiently energetic cosmic rays probably come to us from large region of galaxy => large volume sample.

When you look, you actually see lots of antimatter: positrons and antiprotons. More or less consistent with being secondaries from cosmic ray-ISM interactions. “Subtracting out” secondaries very messy business…

Can we get a cleaner signal? Look for $Z<-1$ cosmic rays!

Direct Detection II.

Why? Interaction between energetic C.R. and ISM nucleus like RHIC – make quark “soup/fireball.” Rough estimate for relative branching ratio between production of antiprotons and nuclei with mass M from Hagedorn (1973) theory:

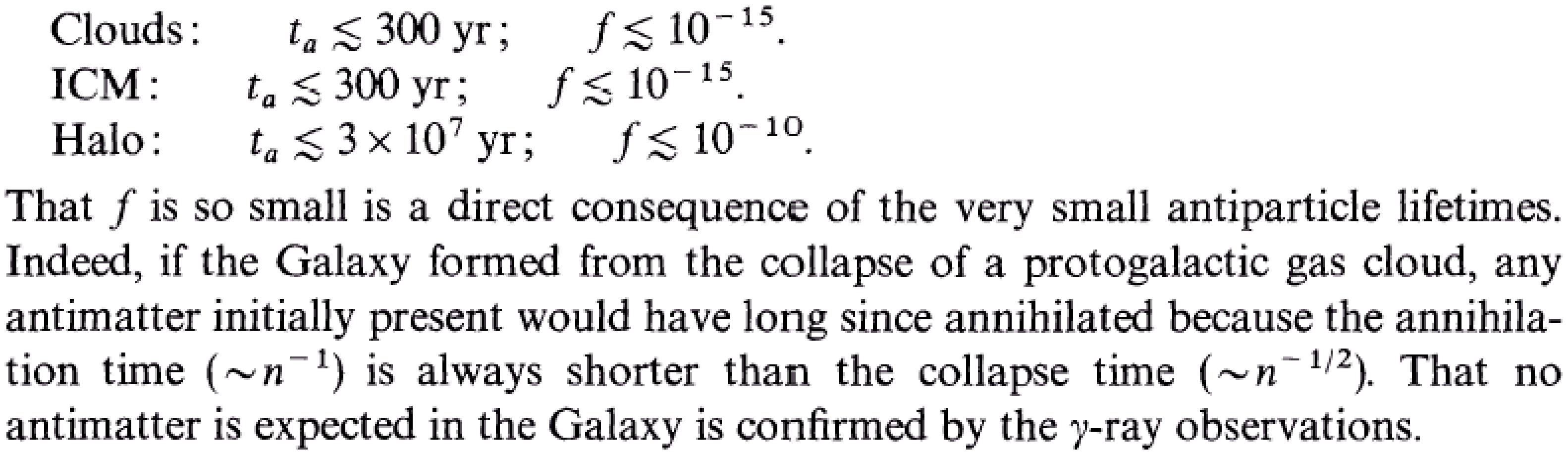
$$\bar{N}/\bar{p} \approx \exp\left[-2(M-M_p)c^2/kT_0\right], \text{ where } kT_0 \approx 160 \text{ MeV.}$$

Small, even for Z=-2! Estimates agree reasonably with actual measurements in this case.

If you see anti-nucleus, it’s not a cosmic ray secondary!
Case Z<-2 particularly exciting. Helium (and presumably anti-helium) can be made in Big Bang, but only way to get heavier elements is via nucleosynthesis in stars. So Z<-2 => anti-stars!

Cosmic rays leak out of galaxies (with highly unknown fraction) and intermediate energy ones can make it to us, so sufficiently sensitive detector (AMS?) could actually probe quite large volume of space.

Patches of galaxy with equal amounts of matter and antimatter at typical Galactic densities?



Clouds: $t_a \lesssim 300$ yr; $f \lesssim 10^{-15}$.
ICM: $t_a \lesssim 300$ yr; $f \lesssim 10^{-15}$.
Halo: $t_a \lesssim 3 \times 10^{7}$ yr; $f \lesssim 10^{-10}$.

That f is so small is a direct consequence of the very small antiparticle lifetimes. Indeed, if the Galaxy formed from the collapse of a protogalactic gas cloud, any antimatter initially present would have long since annihilated because the annihilation time ($\sim n^{-1}$) is always shorter than the collapse time ($\sim n^{-1/2}$). That no antimatter is expected in the Galaxy is confirmed by the γ-ray observations.

Faraday Rotation

- View polarized light (eg: non-thermal synchrotron sources)
- Line of sight passes through a galaxy or cluster
- Rotation of polarization $\sim \int \left[n(e^-) - n(e^+) \right] B_{\|} \, dl$
- Rotation is seen along lines of sight that pass through galaxies and clusters.
- Therefore:
  - Amount of Matter .NE. Amount of Anti-matter (along these lines of sight)

Emission from Clusters

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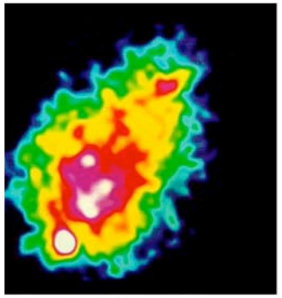


X-Ray

X-ray emitting clusters of galaxies are of great value. If the X-rays are the thermal-bremsstrahlung emission of a hot ($T \approx 10^8$ °K) intracluster gas (see, for example, Gunn & Gott 1972), then the X-ray luminosity is

$$L_x(\text{erg sec}^{-1}) \approx 1.4 \times 10^{-23} T_8^{1/2} \int n^2 \, dV, \tag{19}$$

where $T_8 \equiv 10^{-8} T(°\text{K})$. If this gas contained a fraction f of antimatter, the γ-ray luminosity would be

$$L_\gamma(\text{photons sec}^{-1}) \approx 3 \times 10^{-14} \frac{f}{T_8^{1/2}} \int n^2 \, dV. \tag{20}$$

A limit to f may be derived from the measured X-ray flux $F_x(\text{erg cm}^{-2}\ \text{sec}^{-1})$ and the limit to the γ-ray flux $F_\gamma(\text{photons cm}^{-2}\ \text{sec}^{-1})$.

$$f \lesssim \frac{T_8}{2} \left(\frac{F_\gamma}{10^9 F_x} \right). \tag{21}$$

For the Perseus cluster, Kellogg et al. (1973) found $10^9 F_x \approx 0.8$, whereas Niel et al. (1972) set $F_\gamma < 4 \times 10^{-5}$, so that $f_{\text{Per}} < 2.5 \times 10^{-5}$. Similarly, for the Virgo cluster, one finds $10^9 F_x \approx 0.4$ (Kellogg et al. 1973), whereas $F_\gamma < 1 \times 10^{-6}$ (Fichtel et al. 1975), which implies $f_{\text{Vir}} < 1.2 \times 10^{-6}$. Indeed, Kellogg et al. (1973) have observed an additional 16 X-ray emitting Abell clusters with $10^9 F_x \gtrsim 0.04$. The γ-ray flux from such clusters would be

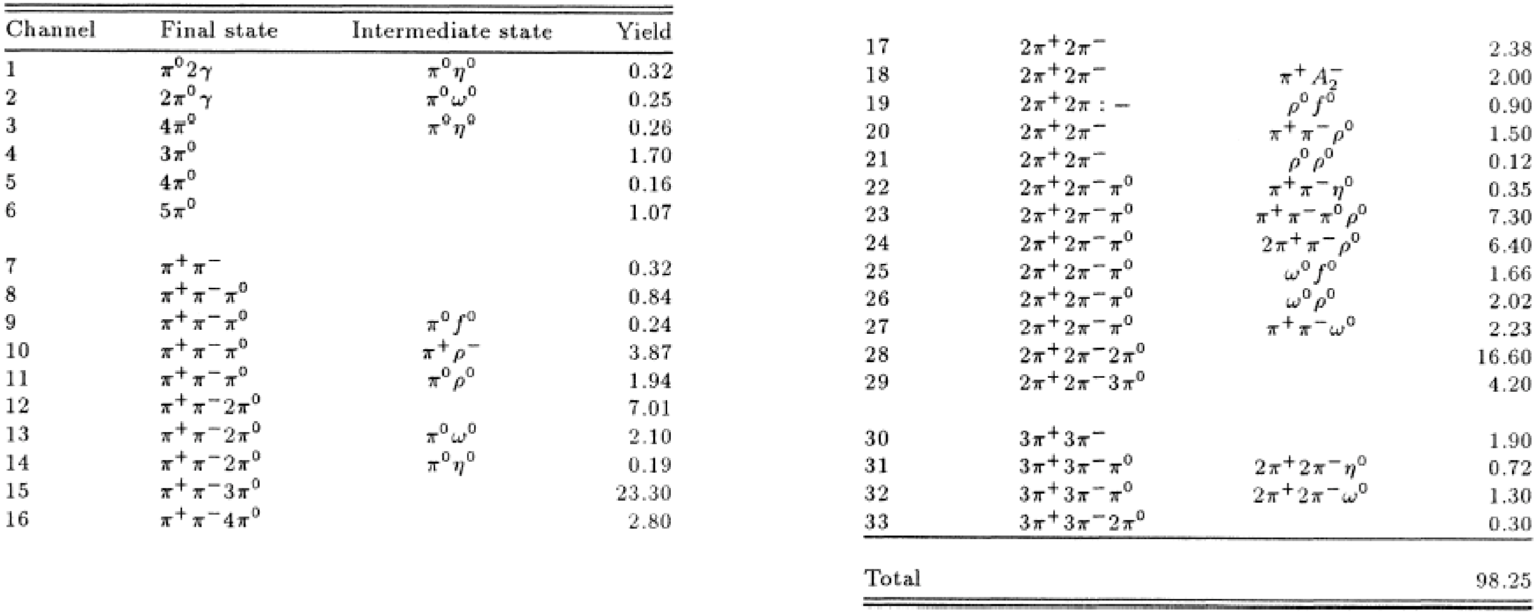
$$F_\gamma \gtrsim 0.08 \frac{f}{T_8} \approx 10^{-1} f \text{ photons cm}^{-2}\ \text{sec}^{-1}. \tag{22}$$

Where Could Anti-Matter Still Be?

- **A cluster of galaxies could be entirely matter or entirely anti-matter.**
- **Some gas from each cluster would extend into the voids between clusters.**
- **GLAST can look for annihilation of gas in the voids that has leaked from different sex clusters.**
- **GLAST can see …. or set a limit on the**

(matter density)*(antimatter density) in the voids

P-Pbar Atoms Branching Ratios



Channel	Final state	Intermediate state	Yield
1	$\pi^0 2\gamma$	$\pi^0\eta^0$	0.32
2	$2\pi^0\gamma$	$\pi^0\omega^0$	0.25
3	$4\pi^0$	$\pi^0\eta^0$	0.26
4	$3\pi^0$		1.70
5	$4\pi^0$		0.16
6	$5\pi^0$		1.07
7	$\pi^+\pi^-$		0.32
8	$\pi^+\pi^-\pi^0$		0.84
9	$\pi^+\pi^-\pi^0$	$\pi^0 f^0$	0.24
10	$\pi^+\pi^-\pi^0$	$\pi^+\rho^-$	3.87
11	$\pi^+\pi^-\pi^0$	$\pi^0\rho^0$	1.94
12	$\pi^+\pi^- 2\pi^0$		7.01
13	$\pi^+\pi^- 2\pi^0$	$\pi^0\omega^0$	2.10
14	$\pi^+\pi^- 2\pi^0$	$\pi^0\eta^0$	0.19
15	$\pi^+\pi^- 3\pi^0$		23.30
16	$\pi^+\pi^- 4\pi^0$		2.80
17	$2\pi^+ 2\pi^-$		2.38
18	$2\pi^+ 2\pi^-$	$\pi^+ A_2^-$	2.00
19	$2\pi^+ 2\pi : -$	$\rho^0 f^0$	0.90
20	$2\pi^+ 2\pi^-$	$\pi^+\pi^-\rho^0$	1.50
21	$2\pi^+ 2\pi^-$	$\rho^0\rho^0$	0.12
22	$2\pi^+ 2\pi^-\pi^0$	$\pi^+\pi^-\eta^0$	0.35
23	$2\pi^+ 2\pi^-\pi^0$	$\pi^+\pi^-\pi^0\rho^0$	7.30
24	$2\pi^+ 2\pi^-\pi^0$	$2\pi^+\pi^-\rho^0$	6.40
25	$2\pi^+ 2\pi^-\pi^0$	$\omega^0 f^0$	1.66
26	$2\pi^+ 2\pi^-\pi^0$	$\omega^0\rho^0$	2.02
27	$2\pi^+ 2\pi^-\pi^0$	$\pi^+\pi^-\omega^0$	2.23
28	$2\pi^+ 2\pi^- 2\pi^0$		16.60
29	$2\pi^+ 2\pi^- 3\pi^0$		4.20
30	$3\pi^+ 3\pi^-$		1.90
31	$3\pi^+ 3\pi^-\pi^0$	$2\pi^+ 2\pi^-\eta^0$	0.72
32	$3\pi^+ 3\pi^-\pi^0$	$2\pi^+ 2\pi^-\omega^0$	1.30
33	$3\pi^+ 3\pi^- 2\pi^0$		0.30
Total			98.25

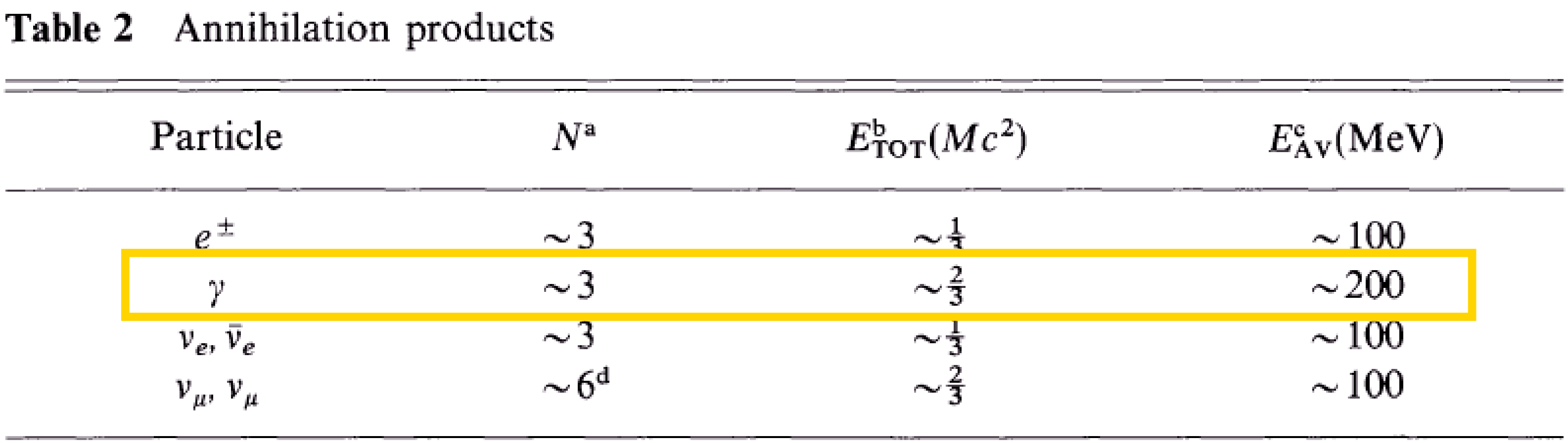


Table 2 Annihilation products

Particle	N^{a}	$E^{\mathrm{b}}_{\mathrm{TOT}}(Mc^2)$	$E^{\mathrm{c}}_{\mathrm{AV}}(\mathrm{MeV})$
$e^\pm$	~ 3	$\sim\frac{1}{3}$	~ 100
γ	~ 3	$\sim\frac{2}{3}$	~ 200
$\nu_e, \bar{\nu}_e$	~ 3	$\sim\frac{1}{3}$	~ 100
ν_μ, ν_μ	$\sim 6^{\mathrm{d}}$	$\sim\frac{2}{3}$	~ 100

Inclusive γ Spectrum from P-Pbar Atoms

Phys Lett B, 182, 405-408 (1986) Backenstoss, etal.

CERN LEAR stopping Pbar beam in liquid hydrogen. BGO γ detector

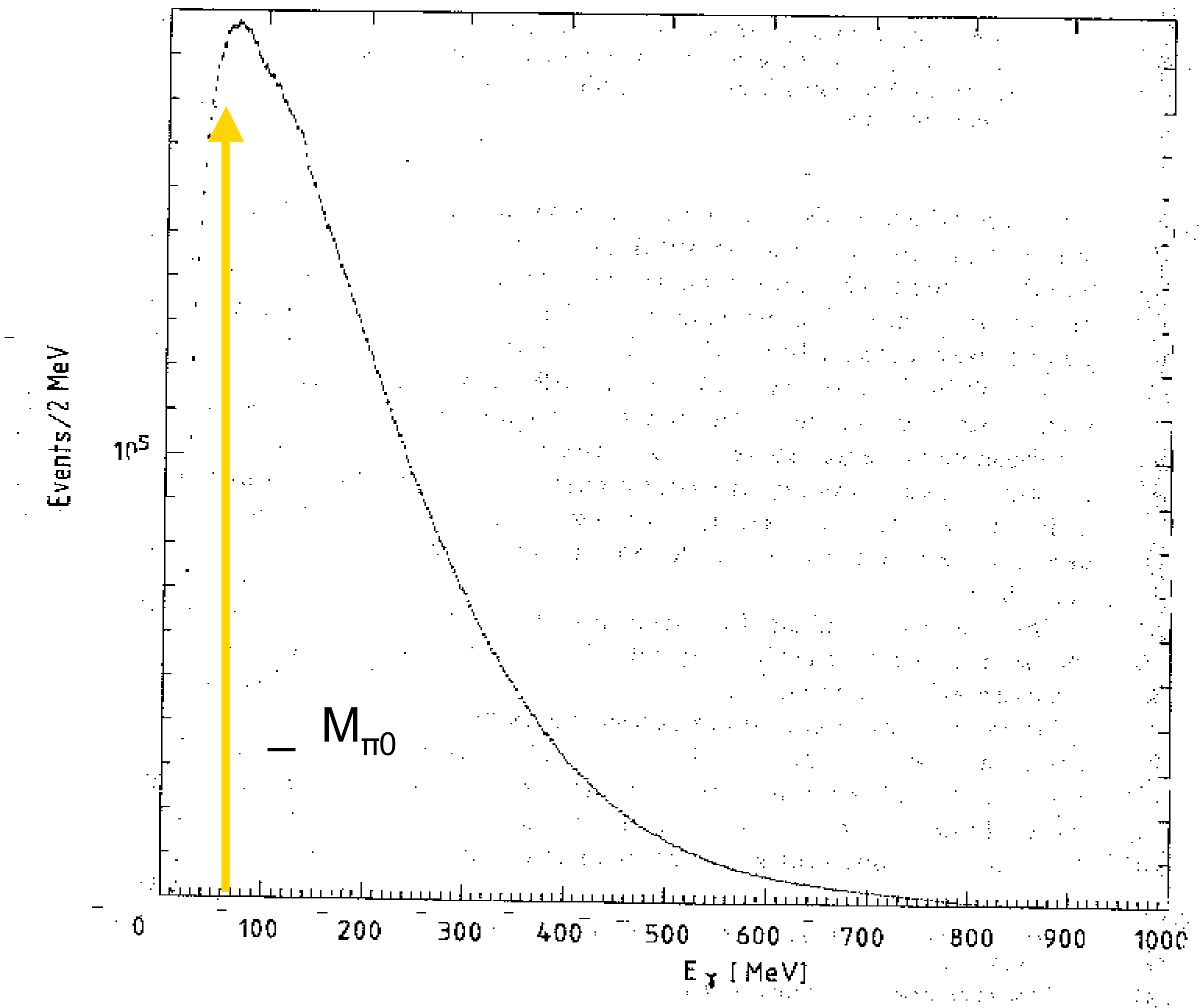


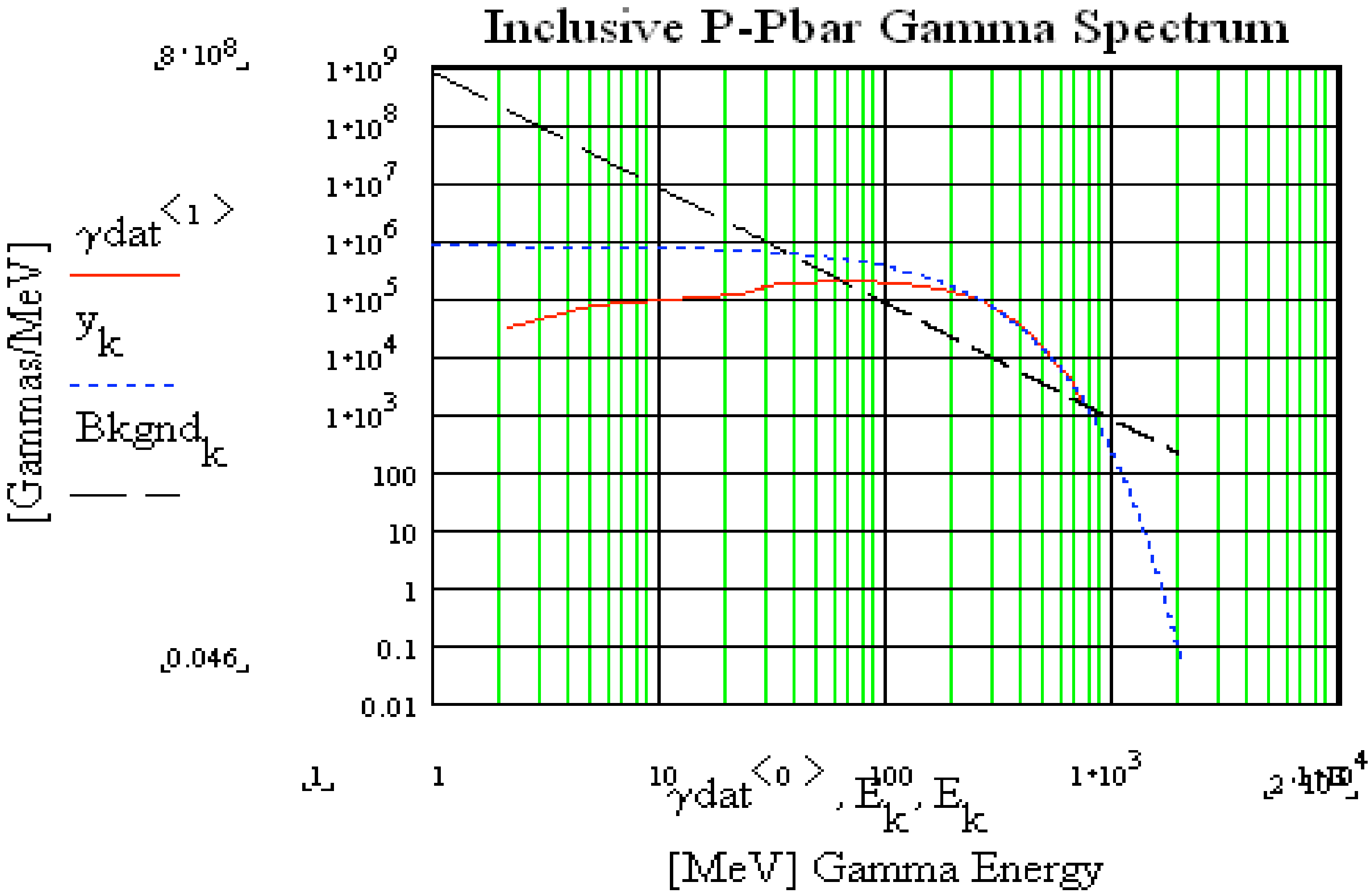
Fig. 1. γ-spectrum from p$\bar{p}$ annihilations at rest in liquid hydrogen. The spectrum contains 23.95×10^6 γ's.

Searching for Exp Decaying γ Spectrum on a Power Law Background

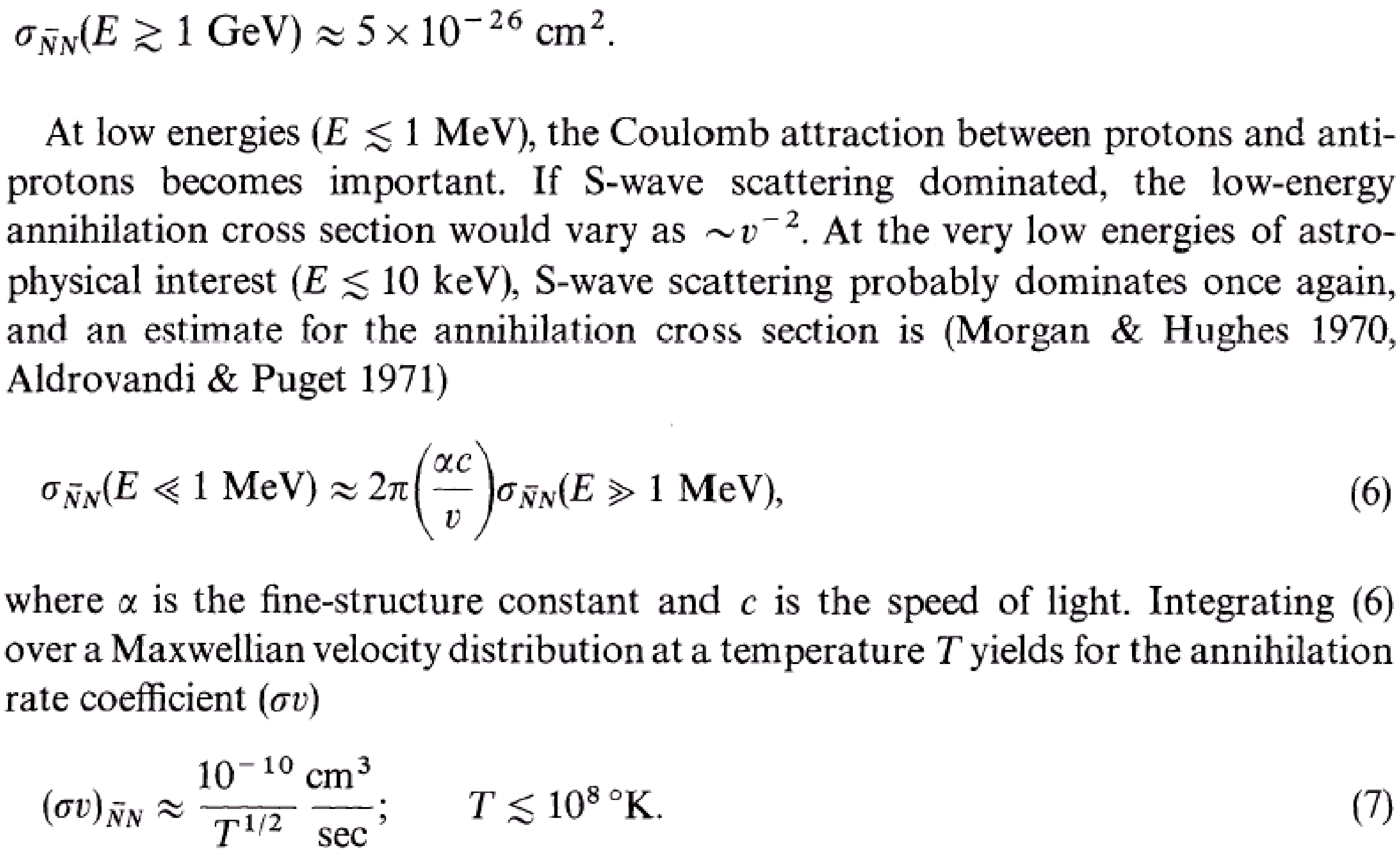
Relative heights of Bkgnd and Annihilation Spectrum are random - not yet calculated.

Red=Digitized annihilation measurements Blue=const*exp(-E/120) Black=const*E^-2

Don't forget to move the red curve to the left by the factor Z+1



Cross section



$$\sigma_{\bar{N}N}(E \gtrsim 1\ \mathrm{GeV}) \approx 5 \times 10^{-26}\ \mathrm{cm}^2.$$

At low energies ($E \lesssim 1$ MeV), the Coulomb attraction between protons and antiprotons becomes important. If S-wave scattering dominated, the low-energy annihilation cross section would vary as $\sim v^{-2}$. At the very low energies of astrophysical interest ($E \lesssim 10$ keV), S-wave scattering probably dominates once again, and an estimate for the annihilation cross section is (Morgan & Hughes 1970, Aldrovandi & Puget 1971)

$$\sigma_{\bar{N}N}(E \ll 1\ \mathrm{MeV}) \approx 2\pi\left(\frac{\alpha c}{v}\right)\sigma_{\bar{N}N}(E \gg 1\ \mathrm{MeV}), \tag{6}$$

where α is the fine-structure constant and c is the speed of light. Integrating (6) over a Maxwellian velocity distribution at a temperature T yields for the annihilation rate coefficient (σv)

$$(\sigma v)_{\bar{N}N} \approx \frac{10^{-10}}{T^{1/2}}\frac{\mathrm{cm}^3}{\mathrm{sec}}; \qquad T \lesssim 10^8\ {}^\circ\mathrm{K}. \tag{7}$$

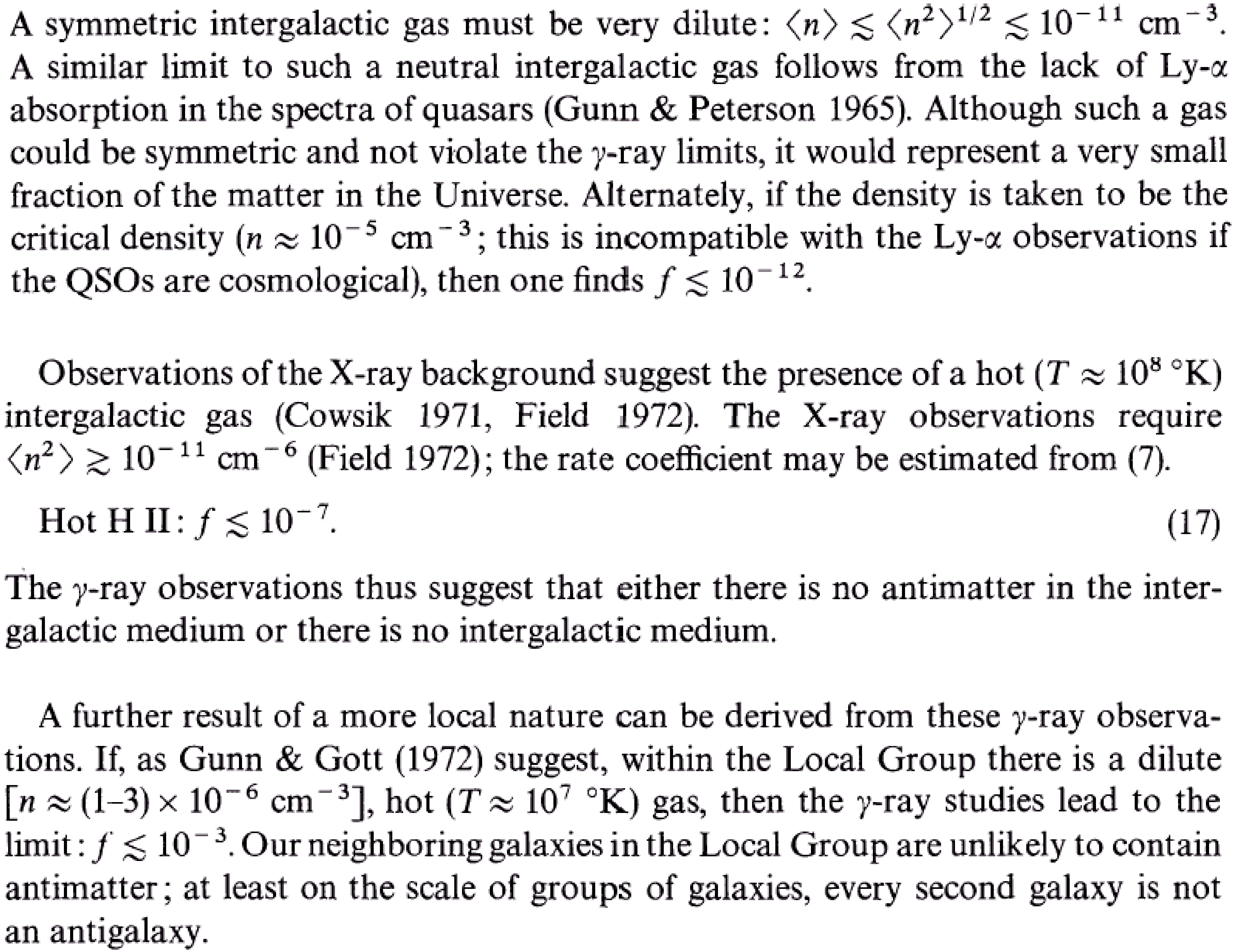
For low temperatures ($T \lesssim 10^4$ °K) the $\bar{\mathrm{H}}$-H annihilation cross section is large ($\sigma_{\bar{\mathrm{H}}\mathrm{H}} \gtrsim 10^{-16}$ cm^2) and the rate coefficient may be estimated:

$$10^{-10} \lesssim (\sigma v)_{\bar{\mathrm{H}}\mathrm{H}} \lesssim 10^{-9} \frac{\mathrm{cm}^3}{\mathrm{sec}}; \qquad 10 \lesssim T(°\mathrm{K}) \lesssim 10^4. \tag{8}$$

In terms of the mean squared intergalactic gas density $\langle n^2 \rangle$, the antimatter fraction f, and the annihilation rate coefficient σv, S may be written as[8]

$$S = f \langle n^2 \rangle (\sigma v). \tag{15}$$

[cm^3/sec]



A symmetric intergalactic gas must be very dilute: $\langle n \rangle \lesssim \langle n^2 \rangle^{1/2} \lesssim 10^{-11}$ cm^{-3}. A similar limit to such a neutral intergalactic gas follows from the lack of Ly-α absorption in the spectra of quasars (Gunn & Peterson 1965). Although such a gas could be symmetric and not violate the γ-ray limits, it would represent a very small fraction of the matter in the Universe. Alternately, if the density is taken to be the critical density ($n \approx 10^{-5}$ cm^{-3}; this is incompatible with the Ly-α observations if the QSOs are cosmological), then one finds $f \lesssim 10^{-12}$.

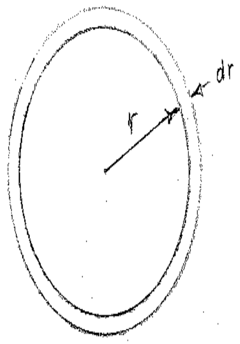
Observations of the X-ray background suggest the presence of a hot ($T \approx 10^8$ °K) intergalactic gas (Cowsik 1971, Field 1972). The X-ray observations require $\langle n^2 \rangle \gtrsim 10^{-11}$ cm^{-6} (Field 1972); the rate coefficient may be estimated from (7).

$$\text{Hot H II}: f \lesssim 10^{-7}. \tag{17}$$

The γ-ray observations thus suggest that either there is no antimatter in the intergalactic medium or there is no intergalactic medium.

A further result of a more local nature can be derived from these γ-ray observations. If, as Gunn & Gott (1972) suggest, within the Local Group there is a dilute [$n \approx (1\text{–}3) \times 10^{-6}$ cm^{-3}], hot ($T \approx 10^7$ °K) gas, then the γ-ray studies lead to the limit: $f \lesssim 10^{-3}$. Our neighboring galaxies in the Local Group are unlikely to contain antimatter; at least on the scale of groups of galaxies, every second galaxy is not an antigalaxy.

Annihilation Flux Seen at Earth



[cm³] Volume of shell

) From shell:

$$dFlux = \frac{(4\pi r^2 dr)\, S}{4\pi r^2} \qquad S \left[\frac{\#\ \text{photons}}{\text{cm}^3\ \text{sec}}\right]$$

[cm²] Each emitting volume element distributes its γs over this area

$$= S\, dr$$

for z~20

$$Flux = \int_0^R S\, dr = SR \qquad \text{where } R \sim 10^{10}\ \text{Lyrs} = 10^{28}\ \text{cm}$$

$$\text{Extra Galactic Diffuse Bkgnd Flux } (E_\gamma > 20\ \text{MeV}) \sim \left(\frac{100\ \text{MeV}}{20\ \text{MeV}}\right) 1.5\times10^{-5} / \text{cm}^2\ \text{sec}$$

GLAST Proposal

$$= 7.5 \times 10^{-5} / \text{cm}^2\ \text{sec}$$

3) Assume GLAST sees no annihilation above this

$$7.5\times10^{-5} \geq 3 \cdot f \cdot \langle n^2 \rangle\, 10^{-10} \frac{\text{cm}^3}{\text{sec}}\, 10^{28}\ \text{cm}$$

$$\boxed{\langle n^2 \rangle \leq \frac{1.5\times10^{-23}}{f}}$$

GLAST will set a limit like this

$n = \left[\frac{\#\ \text{protons}}{\text{cm}^3}\right]$ in voids

$f = \left[\begin{matrix}\text{fraction of} \\ \text{antimatter}\end{matrix}\right] = 1$ for 50% matter 50% antimatter

Can you Separate Baryons from Anti –Baryons in standard large scale structure formation scenarios?

Cohen, de Rujula, & Glashow

NO!

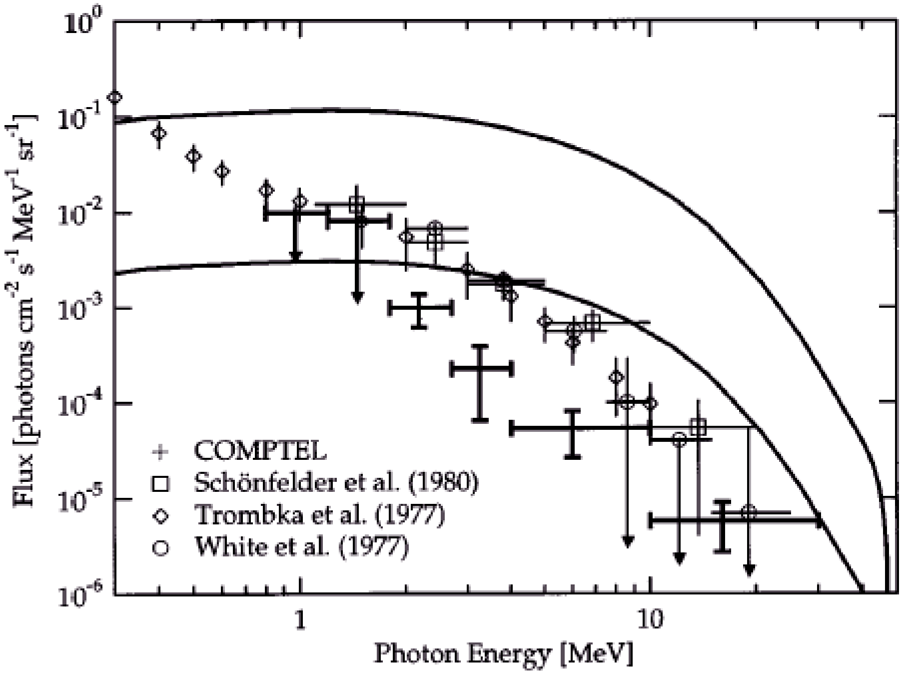
Theory Stuff

- Can baryons and anti-baryons be separated into massive different sex regions (eg: future clusters) at the time of baryogenisis?
  - NO. Such a statistical fluctuation very unlikely

- Any small (<15 Mpc) (l > 1400 in CMBR plot) density fluctuations get wiped out by Silk damping before recombination (at z=1000).

- So… must hypothesize a new force that pushes baryons and anti-baryons apart into volumes of space that are now >15 Mpc. The matter (or antimatter) in each of these large volumes then collapses to form a single sex galactic cluster.

Put in by hand an equal number of matter and antimatter domains.
Cohen, de Rujula, & Glashow 1998



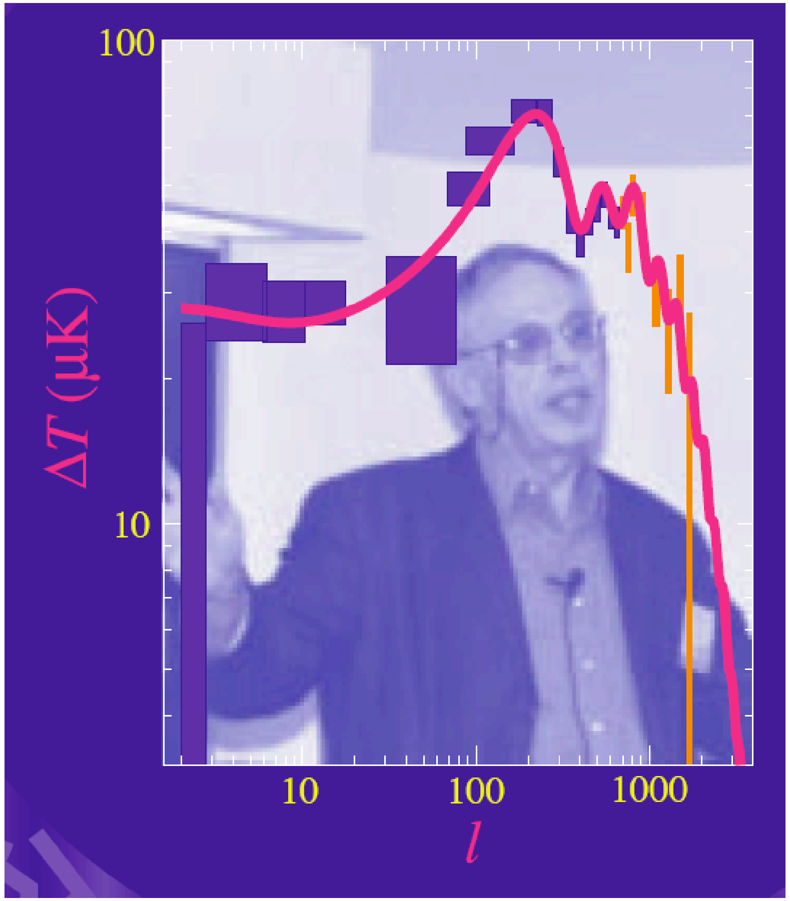
The points are extragalactic diffuse gamma-ray background measurements. The curves are a calculation of the annihilation between matter and antimatter in the redshift interval 20<z<1000. The upper cureve is for a domain size d=20 Mpc and the lower curve is for a domain size d=1 Gpc.

Summary

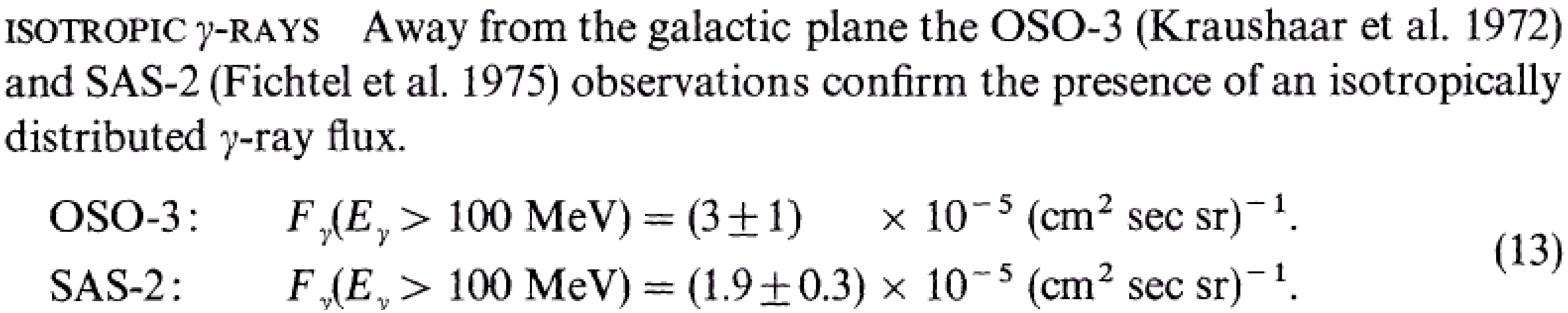
- Theorist conclusion (Paolo):
  - Antimatter gone before nucleosynthesis epoch => null searches (but you never know…)
- Experimenter conclusion (Gary):
  - Look for annihilation photons coming from the voids
  - See it… or set a density^2 limit

Silk Damping

No structure (with Void_Size_today < 15 Mpc) at recombination

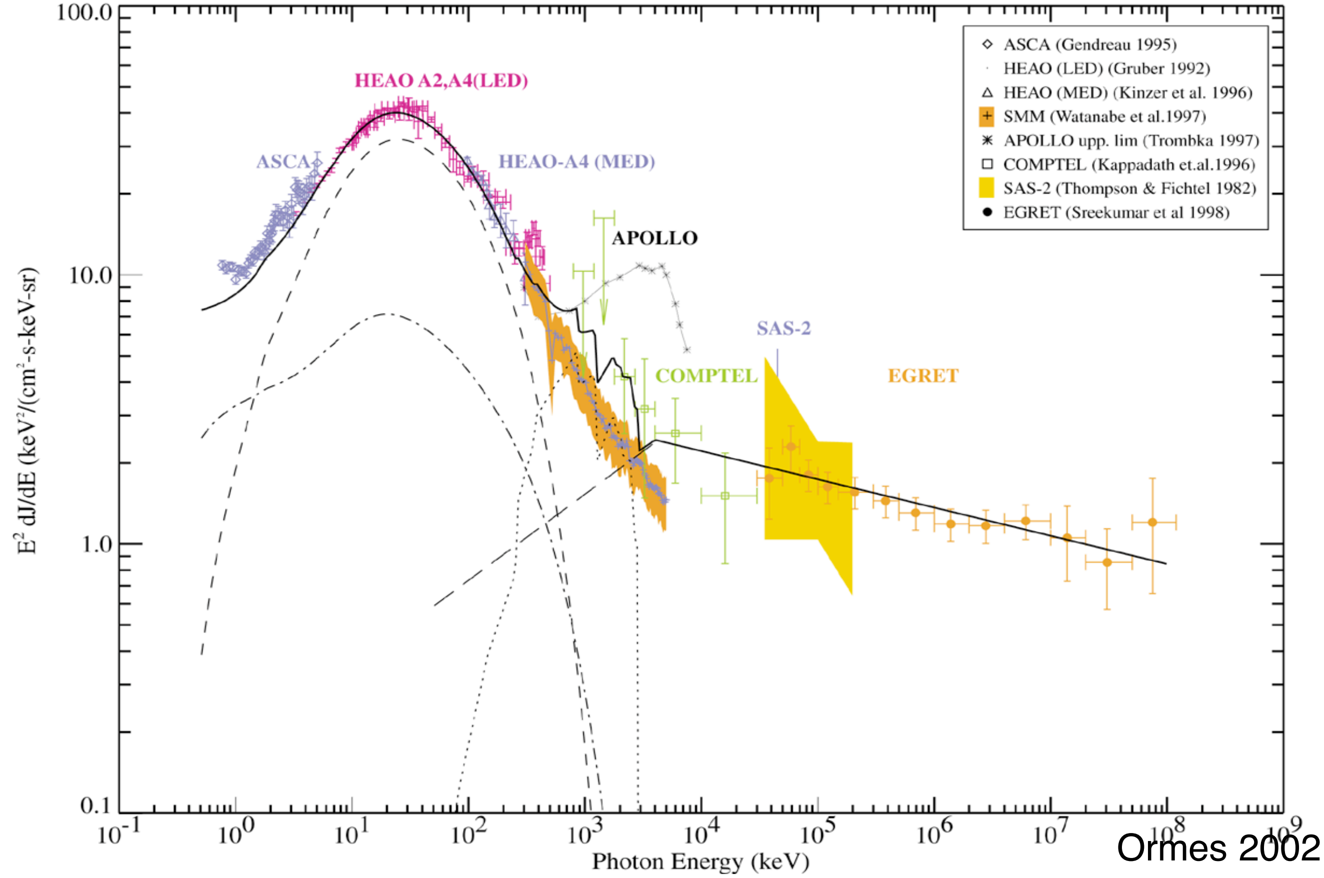


Diffuse Gamma-Rays = Upper Limit for Annihilation



ISOTROPIC γ-RAYS Away from the galactic plane the OSO-3 (Kraushaar et al. 1972) and SAS-2 (Fichtel et al. 1975) observations confirm the presence of an isotropically distributed γ-ray flux.

$$\begin{aligned} &\text{OSO-3:} \quad F_\gamma(E_\gamma > 100\ \text{MeV}) = (3 \pm 1) \times 10^{-5}\ (\text{cm}^2\ \text{sec sr})^{-1}. \\ &\text{SAS-2:} \quad F_\gamma(E_\gamma > 100\ \text{MeV}) = (1.9 \pm 0.3) \times 10^{-5}\ (\text{cm}^2\ \text{sec sr})^{-1}. \end{aligned} \tag{13}$$



Ormes 2002, GLAST presentation