COSMIC ANTIMATTER. MODELS AND OBSERVATIONAL BOUNDS

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This year is 80th anniversary of antimatter prediction (precisely: 80 years, 6 months, and 25 days).

Paul Dirac: maybe there exists a completely new universe made of antimatter? 110 year anniversary of Arthur Schuster (another British physicist) guess: there might be entire solar systems, made of antimatter and indistinguishable from ours (probably by light) but capable to annihilate and produce enormous energy. He believed that they were gravitationally repulsive. Now we know that antimatter surely exists but believe that there are very few antiparticles in the universe, except for antineutrinos.

The problem addressed below:

could galaxies or the Galaxy consist of matter with large clumps of antimatter?

Maybe Dirac and Schuster were right.

Both natural theory and existing observations allow for that. Based on works with C. Bambi, M. Kawasaki, N. Kevlishvili, A. Petrov, and J. Silk, published long ago (1993), very recently (2007, 2008), and some work in progress.

Stimulated by the observed low energy positrons in the Center and Halo(?) and by the missions for search of cosmic/galactic antimatter:

Existing: PAMELA, BESS, AMS.

Future: AMS-02 (2009), PEBS (2010), GAPS (2013) (according to P. Picozza, TAUP 2007) It is strongly believed that the universe is populated by matter and that

the observed antimatter is of secondary origin.

Observations and the simplest scenarios of baryogenesis support this assertion. THEORY (Sakharov, 1967)

1. Nonconservation of baryons. Predicted theoretically, demanded by inflation (no inflation with baryonic density equal to the measured one).

2. Breaking of symmetry between particles and antiparticles, i.e. of C and CP. Observed in experiment.

3. Deviation from thermal equilibrium. True in expanding universe.

Neither of the three is obligatory.

Theory nicely explains predominance of matter over antimatter (or vice versa). In the usual scenarios:

$$eta = rac{N_B - N_{ar{B}}}{N_\gamma} = const,$$

However a simple modification of existing baryogenesis mechanisms may lead to varying and even negative $\beta(x)$ and observations do not exclude that, at least now.

OBSERVATIONS:

Up to now no astronomically significant objects consisting antimatter have been observed. A little antiprotons and positrons in cosmic rays are most probably of secondary origin.

May the observed positron 0.511 MeV line from the galactic bulge and possibly from the halo be a signature of cosmic antimatter!?

Observational bounds:

In charge symmetric universe with separated matter and antimatter domains the nearest antimatter domain should be at $l_B > \text{Gpc}$ - efficient annihilation at an early stage, due to positive feedback, would create too many cosmic background photons (CdRG). No significant amount of antimatter is observed in the Galaxy.

Observed colliding galaxies or galaxies in the common cloud of intergalactic gas are dominated by the same kind of matter (or antimatter?). Fraction of antimatter Bullet Cluster $< 3 \times 10^{-6}$ (Steigman, 2008).

Nearest anti-galaxy could not be closer than at ~ 10 Mpc (Steigman, 1976), but still in our supercluster. The bounds presented above are true if antimatter makes the exactly same type objects as the OBSERVED matter.

For example, compact objects made of antimatter may escape observations and be almost at hand. **CONCLUDE:**

The universe looks predominantly baryonic with

 $\beta = (N_B - N_{\bar{B}})/N_{\gamma} = 6 \cdot 10^{-10}$

with $\beta \approx const$ at l > 10 Mpc (from CMB) and l > 1 Mpc (from BBN).

Standard baryogenesis "produce" one constant number β .

It is impossible to determine which of the plethora of the standard baryogenesis scenarios is realized having only one number.

Nonstandard models predict a function $\beta(x)$, which may be negative, and allow for observational verification. What to search: cosmic antinuclei, ${}^{4}He$ and heavier; antiprotons and positrons; violent phenomena from antistars and anticlouds, and some more. Secondary production of antimatter.

 Antiprotons and positrons by cosmic rays or violent stellar processes.
 DM annihilation or other particle physics processes.

3. PBH evaporation.

All above is a background against discovery of REAL cosmic antimatter.

Mechanisms of antimatter creation:

 Spontaneous CP-violation, makes exactly 50:50, most probably excluded.
 Spontaneous + explicit CP-violation, makes matter dominated universe, possibly excluded or strongly constrained.
 Inhomogeneous baryogenesis with stochastic (dynamical) or explicit CPviolation, might make about 50:50 or less with possibly all DM in compact (anti)objects, allowed. Two parts:

I. Mechanism of antimatter creation which might be in the Galaxy.II. Phenomenology, observational signatures and bounds. Forget theory. Picture: the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects or PBH, plus sub-dominant observed baryonic background, all created by the same baryogenesis mechanism.

The amount of antimatter may be much larger than that of the KNOWN baryons, but such "compact" (anti)baryons could escape observations through BBN and CMB and even make all DM. Observational restrictions on astronomically large but compact antimatter objects/domains, anti-stars, clouds, etc, are rather loose and strongly depend upon the type of the objects.

How a noticeable (even large) amount of anti-stars and/or (anti)black holes can be created without conflict with observations?

ANTI-CREATION MECHANISM

Affleck-Dine baryogenesis: SUSY condensate of baryonic charge along flat directions of the potential.

Normally it predicts very high

 $\beta = n_B/n_{\gamma} \sim 1$ and theoretical efforts are needed to diminish it.

However, if the window to flat direction is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$.

Phase transition of 3/2 order.

Affleck-Dine field χ with CW potential coupled to inflaton Φ :

 $U(\chi,\Phi) = \lambda_1 |\chi|^2 (\Phi - \Phi_1)^2 + \lambda_2 |\chi|^4 \ln(|\chi|^2/\sigma^2) + (m^2\chi^2 + h.c.).$

m may be complex but CP would be still conserved - "phase rotate" χ .

Last term breaks B-conservation. $J_{\mu}^{(B)} = i\chi^{\dagger}\partial_{\mu}\chi + h.c.,$ $B = J_{\star}^{(B)}$ is the angular momentum.



Evolution of the potential of χ as a function of the inflaton field Φ .

Probability for χ to reach a high value is determined by the diffusion equation (Starobinsky):

$$egin{aligned} &rac{\partial \mathcal{P}}{\partial t} = rac{H^3}{8\pi^2} \sum_{k=1,2} rac{\partial^2 \mathcal{P}}{\partial \chi_k^2} + \ &rac{1}{3H} \sum_{k=1,2} rac{\partial}{\partial \chi_k} \left[\mathcal{P} rac{\partial U}{\partial \chi_k}
ight] \end{aligned}$$

where $\chi = \chi_1 + i\chi_2$.

The effective mass behave as $m_{eff}^2 \approx m_0^2 + m_1^4 (t - t_1)^2$, when Φ passes through Φ_1 . Correspondingly the dispersion is:

 $\langle \chi^2
angle \sim \left[m_0^2 + m_1^4 (t - t_1)^2
ight]^{-1}$

Hence the bubble distributions over length and mass have log-normal form:

 $rac{dn}{dM} = C_M \exp\left[-\gamma \ln^2(M/M_0)
ight]$

where C_M , γ , and M_0 are constant parameters. A modification of this distribution by a power factor, M^{ν} , or, which is the same, by a log term in the exponent, $\exp(\kappa \ln M)$ leads to the same log-normal form of the distribution with some change of the parameter values.



Evolution of $|\chi|$ in the bubble. The phase is chaotic.



"Rotation" of χ due to non-sphericity of the potential and creation of $B \neq 0$.

"Rotation" of χ is transformed into baryonic number of quarks by B-conserving decays of χ . The magnitude of the baryon asymmetry inside the (B-balls), β and the bubble size are stochastic quantities. Initial phase is uniform in $[0, 2\pi]$, due to the large Hubble driving force, $H \gg m$.

The size of B-ball is determined by the remaining inflationary time.

 β could be as large as > 1, especially if χ decayed much after inflaton decay. In the simplest version of the model both positive and negative β are equally probable.

Background uniform baryon asymmetry with $\beta = 6 \cdot 10^{-10}$ and small regions with $|\beta| \sim 1$ of both signs are created with very simple and natural generalization of the standard AD scenario.

INHOMOGENEITIES.

Two kinds of density perturbations: 1. After formation of domains with large χ due to different equations of state inside and outside of the domains: nonrelativistic matter inside the bubbles and relativistic outside. If $\delta \rho / \rho = 1$ at horizon crossing, PBHs would be formed.

Horizon mass: $M_{hor} = 10^{38} g (t/sec)$. For $T = 10^8$ GeV the PBH mass would be 10^{16} g.

Perturbations with $\delta \rho / \rho < 1$ might still make PBH due to subsequent matter accretion.

If PBH had not formed, perturbations did not rise and even might disappear after χ decay (???)

Standard approach.

The energy density inside the bubble evolves as:

$$ho_{inside}=rac{
ho_r^{in}}{x^4}+rac{
ho_{nr}^{in}}{x^3}=rac{
ho_r^{in}}{x^4}\left(1+\epsilon x
ight)$$

where $x = a/a_{in}$ is the ratio of the running cosmological scale factor to its initial value.
Solving the Friedmann equation

$$\left(rac{\dot{x}}{x}
ight)^2=rac{8\pi}{3m_{Pl}^2}\left(rac{
ho_r^{in}}{x^4}+rac{
ho_{nr}^{in}}{x^3}
ight)$$

In conformal time $d\eta = dt/a(t)$:

$$a=a_{eq}\left(2\eta+\eta^2
ight)$$

where $a_{eq} = a_{in}/\epsilon$ is the value of the scale factor when the energy densities of relativistic and nonrelativistic matter inside the bubble become equal and $\eta = \tau a_{in}/(4t_{in}\epsilon)$. At matter radiation equilibrium $\eta \sim 1$. Gravitational potential Φ with the initial condition $\Phi(\eta = 0) = 0$ is:

$$\Phi = rac{\eta}{5} \, rac{\eta^2 + 6\eta + 10}{(\eta+2)^3} \, rac{\delta S}{S}$$

where

$$\frac{\delta S}{S} = \frac{3}{4} \frac{\delta \rho_r}{\rho_r} - \frac{\delta \rho_{nr}}{\rho_{nr}}$$

NB: the entropy perturbations are not small because $\delta \rho_{nr} / \rho_{nr} = 1$.

Density perturbations are related to the potential through the equation

 $\Delta\Phi - 3\mathcal{H}\left(\Phi' + \mathcal{H}\Phi\right) = 4\pi G_N a^2 \delta
ho,$

where the Laplacian term in the l.h.s. can be neglected for large wave length of perturbations. Thus

 $\delta
ho /
ho \simeq 2 \Phi.$

At MD stage, for $\eta \gg 1$, the density perturbations tend to a constant value:

$$\left.rac{\delta
ho}{
ho}
ight|_{MD}=-rac{2}{5}rac{\delta S}{S}pproxrac{2}{5}$$

At RD stage the perturbations rise linearly with η :

$$\left.\frac{\delta\rho}{\rho}\right|_{RD} = -\frac{\eta}{2}\frac{\delta S}{S} \approx \frac{\eta}{2}$$

At some moment field χ should decay into relativistic matter and after that both inside and outside the bubble equations of state would be identical, those of relativistic matter, $p = \rho/3$. After decay the developed density perturbations would stay constant. These results are not valid for large perturbations. The system is simple and the answer should be known. 2. Second period of $\delta \rho$ generation after the QCD phase transition at $T \sim 100$ MeV when quarks made nonrelativistic protons. BH masses from a few M_{\odot} to $10^{6-7}M_{\odot}$.

Compact objects (not BH) with smaller masses could be formed too.

Initial inhomogeneous χ and/or β led to large isocurvature perturbations. The amplitude of such perturbations is restricted by CMBR at about 10% level, but the bounds from CMBR are valid at much larger wave lengths. Formation of (anti-)black holes: relative density perturbations, when enter horizon, should be of order unity.

 $r_B=rac{\delta
ho}{
ho}=rac{eta n_\gamma m_p}{(\pi^2/30)g_*T^4}pprox 0.07etarac{m_p}{T}.$

The mass inside horizon

 $M_{hor} \approx m_{Pl}^2 t \approx 10^5 M_{\odot}(t/sec),$

where $(T/MeV)^2 (t/sec) \approx 1$.

Anti-BH may be surrounded by antiatmosphere if β slowly decreases. Mass spectrum, log-normal:

$$rac{dN}{dM} = C \, exp \left[-\gamma \, ln^2 \left(rac{M}{M_1}
ight)
ight]$$

C, γ , and M₁ are unknown parameters. If $M_1 \sim M_{\odot}$ some of these high β bubbles might form stellar type objects and early black holes.

If they are black holes and/or evolved, now dead or low luminosity, stars, they could make (all?) cosmological dark matter.

Subsequent accretion is not accounted for.

On the tail of the distribution very heavy BH may be created, $M_{BH} \sim 10^7 M_{\odot}$.

A mechanism of early quasar formation with evolved chemistry - one of the mysteries of the standard model. Superheavy PBH are seeds for structure formation!? Nonrelativistic baryonic matter starts to dominate inside the bubble at

 $T = T_{in} \approx 65 \,\beta \,\mathrm{MeV}$

Mass inside a baryon-rich bubble at the radiation dominated stage is

 $M_B \approx 2 \cdot 10^5 \, M_{\odot} (1 + r_B) \left(\frac{R_B}{2t}\right)^3 \, \left(\frac{t}{\text{sec}}\right)$

Mass density at onset of MD stage:

 $\rho_B \approx 10^{13} \beta^4 \text{ g/cm}^3.$

EVOLUTION IN THE EARLY UNI-VERSE

Bubbles with $\delta \rho / \rho < 1$ but with

$M_B > M_{Jeans}$

at horizon would decouple from cosmological expansion and form compact stellar type objects or lower density clouds.

Which anti-objects could survive against early annihilation?

For $M_B \sim M_{\odot}$:

 $\rho_B = \rho_B^{(in)} (a_{in}/a)^3 \approx 6 \cdot 10^5 \text{ g/cm}^3$

and $R_B \approx 10^9$ cm; temperature when $M_J = M_{\odot}$:

 $T \approx T_{in} (a_{in}/a)^2 \approx 0.025 \text{ MeV}.$

Similar to **RED** GIANT core. External pressure could be larger then the internal one. Three processes of energy release:

1. Cooling down because of high internal temperature, $T \sim 25$ keV.

2. Annihilation of surrounding matter on the surface.

3. Nuclear reactions inside.

1. Cooling time is determined by photon diffusion:

 $t_{diff} pprox 2 \cdot 10^{11} \sec\left(rac{M_B}{M_\odot}
ight) \left(rac{\sec}{R_B}
ight) \left(rac{\sigma_{e\gamma}}{\sigma_{Th}}
ight)$

Thermal energy stored inside B-ball

 $E_{therm}^{(tot)} = 3TM_B/m_N \approx 1.5 \cdot 10^{50} \mathrm{erg}$

Luminosity: $L \approx 10^{39}$ erg/sec. If $\Omega_{BB} = 0.25$, then thermal keV photons would make $10^{-4} - 10^{-5}$ of CMBR, red-shifted today to background light. 2. Nuclear helium burning, (similar to red giant): $3He^4 \rightarrow C^{12}$, however with larger T by factor ~ 2.5. Since $L \sim T^{40}$, life-time would be very short. Total energy influx would be below 10^{-4} of CMBR if $\tau < 10^9$ s.

Could it lead to B-ball explosion and creation of solar mass anti-cloud?

3. Annihilation on the surface.

(Anti)proton mean free path before recombination is small:

$$l_p = rac{1}{(\sigma n)} \sim rac{m_p^2}{lpha^2 \, T^3} = 0.1 \, cm \, \left(rac{MeV}{T}
ight)^3$$

After recombination the number of annihilation on one B-ball per unit time:

$$\dot{N}=10^{31}V_p\left(\frac{T}{0.1~eV}\right)^3\left(\frac{R_B}{10^9~cm}\right)^2,$$

gives about 10^{-15} of CMBR.

EARLY SUMMARY:

1. Compact anti-objects mostly survived in the early universe, especially if they are PBHs.

2. A kind of early dense stars might be formed with initial pressure outside larger than that inside.

3. Such "stars" may evolve quickly and, in particular, make early SNs, enrich the universe with heavy

(anti)nuclei and re-ionize the universe.

4. Energy release from stellar like objects in the early universe is small compared to CMBR.

5. Not dangerous for BBN since the volume of B-bubbles is small.

One can always hide any undesirable objects into black holes.

More detailed calculations are necessary.

ANTIMATTER IN CONTEMPORARY UNIVERSE

Forget theory (but still use it as a guiding principle).

Possible astronomical objects:

- 1. Gas clouds of antimatter.
- 2. Isolated antistars.
- 3. Anti stellar clusters.
- 4. Anti black holes.
- 5. What else?

WHERE:

Inside galaxies or outside galaxies? Inside galactic halos or in intergalactic space?

Consider all the options.

New part: unusual compact objects, e.g. dead or half dead stars, (anti)BH with (anti)atmosphere.

OBSERVATIONAL SIGNATURES

- 1. Gamma background.
- 2. Excessive antiprotons.
- 3. Positrons.
- 4. Antinuclei.

5. Compact sources of gamma radiation.

Antimatter search:

BESS, Pamella, and AMS have not found anything, maybe the future ones will? More difficult:

- 1. Photon polarization.
- 2. Neutrino versus antineutrino. SK?

Two types of objects:

1. Gas clouds.

2. Compact stellar-like objects.

Gas of antimatter: mean free path of protons l_p is larger than the size of the (anti)cloud, $l_c \equiv l_B$.

$$l_p = rac{1}{\sigma_{tot} n_{ar{p}}} = 10^{24} \, cm \, \left(rac{cm^{-3}}{n_{ar{p}}}
ight) \, \left(rac{barn}{\sigma_{tot}}
ight)$$

Compact (stellar type) objects: $l_p < l_B$.

If $n_{\bar{p}} >> n_p$, then it is possible that for B-ball smaller than $l_{gal} = 3 - 10 \ kpc$ both limiting cases can be realized: volume annihilation $l_{free} > l_B$ - clouds; surface annihilation $l_{free} < l_B$, compact stellar-like objects. Impact on BBN.

If $\beta \equiv \eta \gg 10^{-9}$, light (anti)element abundances would be anomalous: much less anti-deuterium, more anti-helium. Look for clouds with anomalous chemistry. However, with 50% probability it may be the normal matter with anomalous n_B/n_γ .

If such a cloud or compact object is found, search for annihilation there. Volume annihilation, if $l_{free}^p > l_c$:

 $\dot{n}_p = v \sigma_{ann} n_p n_{ar{p}}$

Total number of annihilation: $\dot{N}_p = 4\pi l_c^3 \dot{n}_p/3.$ Total number of \bar{p} in the cloud: $N_{\bar{p}} = 4\pi l_c^3 n_{\bar{p}}/3.$ Low density or small clouds would not survive in a galaxy. It would disappear during

$$au=10^{15}~sec~\left(rac{10^{-15}cm^3/s}{\sigma_{ann}v}
ight)\left(rac{cm^{-3}}{n_p}
ight),$$

if supply of protons from galactic gas is sufficient.

They could survive in the halo.

Proton flux into an anti-cloud:

$$F=4\pi l_c^2 n_p v=10^{35} sec^{-1}\left(rac{n_p}{cm^3}
ight)\left(rac{l_c}{pc}
ight)^2$$

Total number of \bar{p} in the cloud: $N_{\bar{p}} = 4\pi l_c^3 n_{\bar{p}}/3.$

Flux is sufficient to destroy the anticloud in 10^{17} sec if:

$$\left(rac{n_{ar{p}}}{cm^3}
ight)\left(rac{l_c}{pc}
ight) < 3\cdot 10^4$$

The luminosity for volume annihilation:

$$L_{\gamma}^{(vol)} \approx 10^{35} rac{\mathrm{erg}}{\mathrm{s}} \left(rac{R_B}{0.1 \, \mathrm{pc}}
ight)^3 \ \left(rac{n_p}{10^{-4} \, \mathrm{cm}^{-3}}
ight) \left(rac{n_{ar{p}}}{10^4 \mathrm{cm}^{-3}}
ight).$$

Flux on the Earth at d=10 kpc: $10^{-7}\gamma/s/cm^2$ or $10^{-5}Mev/s/cm^2$, to be compared with cosmic background $10^{-3}/MeV/s/cm^2$. Compact stellar type objects, $l_s \gg l_{free}$, surface annihilation - all that hits the surface annihilate.

Gamma-radiation from $\bar{p}p \rightarrow pions$ and $\pi^0 \rightarrow 2\gamma ~(E_{\pi} \sim 500 \text{ MeV})$ and from e^+e^- -annihilation originating from π^{\pm} -decays and from the "original" positrons in the B-ball.

Total luminosity, $L = 2m_p \cdot 4\pi \, l_s^2 \, n_p v$:

$$L_{tot} \approx 10^{27} \frac{erg}{sec} \left(\frac{n_p}{cm^3}\right) \left(\frac{l_s}{l_{\odot}}\right)^2$$

Fraction into gamma-rays is about 20-30%.

Luminosity is so small because annihilation takes place in a small shell on the surface. Stellar wind:

$$\dot{M}=10^{12}Wg/sec$$

where $W = \dot{M} / \dot{M}_{\odot}$.

If all "windy" particles annihilate, the luminosity per star:

 $L = 10^{33} W \ erg/sec.$

Number density of antinuclei is bounded by the density of "unexplained" \bar{p} and the fraction of antinuclei in stellar wind with respect to antiprotons.

It may be the same as in the Sun but if antistars are old and evolved, this number must be much smaller.
Heavy antinuclei from anti-SN may be abundant but their ratio to \bar{p} can hardly exceed the same for normal SN.

Explosion of anti-SN would create a large cloud of antimatter, which should quickly annihilate producing vast energy - a spectacular event.

However, most probably such stars are already dead and SN might explode only in very early galaxies or even before them.

COSMIC POSITRONS.

Gravitational proton capture by an antistar is more efficient than capture of electrons. Antistar is neutralized by forced positron ejection.

It would be most efficient in galactic center where n_p is large.

0.511 MeV line must be accompanied by wide spectrum ~ 100 MeV radiation.

EXOTIC EVENTS

Similar mass star-antistar collision, γ -bursters (???):

$$\Delta E \sim 10^{48} \, erg \, \left(rac{M}{M_{\odot}}
ight) \left(rac{v}{10^{-3}}
ight)^2$$

Annihilation pressure pushes the stars apart. Collision time ~ 1 sec. Radiation is emitted in the narrow disk but not jet. Collision with red giant: compact antistar travels inside creating an additional energy source. Change of color and luminosity(?).

 $\Delta E_{tot} \sim 10^{38}$ erg and $\Delta t \sim$ month.

Transfer of material in binary system - hypernova (!?) explosion. Photon polarization: e.g. e^+ are predominantly "right handed", the same is transferred to bremsstrahlung. Antineutron decays create left-handed e^- .

SN explosion: first burst of ν from SN and $\bar{\nu}$ from anti-SN.

DARK MATTER

made out of high B compact objects, black holes or dead (anti)stars.

Normal CDM with new features:

1. DM "particles" have different masses. 2. Very heavy ones with $M > 10^6 M_{\odot}$ should exist and may be seeds of structure formation. Lighter stellar type objects populate galactic halos as usual CDM.



Other bounds on PBP=DM see:

I. Reviews by Carr.

II. More recent:

1. N. Afshordi, P. McDonald, D. N. Spergel, astro-ph/0302035;

2. J. Yoo, J. Chaname, A. Gould, astro-ph/0306437;

3. N. Seto, A. Cooray, astro-ph/0702586.

Results strongly depend upon the mas spectrum.

No stars are observed in the halo. It means that all high B compact objects are already dead stars. Stellar wind is absent. However, annihilation of background protons on the surface should exist.

OBSERVATIONAL BOUNDS.

I. Stellar wind:

 $\mathbf{N}_{\mathbf{\bar{S}}}/\mathbf{N}_{\mathbf{S}} \leq 10^{-6} \mathbf{W}^{-1},$

from the total galactic luminosity in 100 MeV photons, $L_{\gamma} = 10^{39} erg/s$ and from the flux of the positron annihilation line $F \sim 3 \cdot 10^{-3}/cm^2/s$. $W \ll 1$ is natural to expect because the primordial antistars may be already evolved. **II.** Antihelium-helium ratio:

 $N_{ar{S}}/N_{S} = (ar{H}e/He) \le 10^{-6},$

if the antistars are similar to the usual stars, though most probably not.

Signatures in favor: 0.511 MeV photon line from galactic center and from galactic halo!?

CONCLUSION

1. The Galaxy may possess a noticeable amount of antimatter.

2. Theoretical predictions are vague and model dependent.

3. Not only ${}^{4}H\bar{e}$ is worth to look for but also heavier anti-elements. Their abundances should be similar to those observed in SN explosions. 4. Regions with an anomalous abundances of light elements are suspicious that there may be anti-elements.

5. A search of cosmic antimatter has nonvanishing chance to be successful. 6. Dark matter made of BH, anti-BH, and dead stars is a promising candidate. There is a chance to understand why $\Omega_{\rm B} = 0.05$ is similar to $\Omega_{\rm DM} = 0.25$. 7. Detection of $\overline{\nu}$ in the first burst from anti-SN explosion.

8. Measurement of polarization of synchrotron radiation (?).

THE END