COSMIC AND GALACTIC ANTIMATTER

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Based on works with C. Bambi, M. Kawasakik, N. Kevlishvili, A. Petrov, and J. Silk, published long ago (1993), recently (2007), work in progress, and some review.

Stimulated by the missions for search of cosmic/galactic antimatter:

Existing: PAMELA, BESS, AMS.

Future: AMS-02 (2009), PEBS (2010), GAPS (2013) (accoring to P. Picozza, TAUP 2007)

What to search:
cosmic antinuclei, ^4He and heavier;
antiprotons and positrons;
violent phenomena from antistars and anticlouds, and some more.

Does it make sense - any resonable chance to find it?

Mechanisms of antimatter creation:

1. Spontaneous CP-violation, makes 50:50, most probably excluded.

2. Spontaneous + explicite CP-violation, makes matter dominated universe, possibly excluded or strongly constrained.

3. Inhomogeneous baryogenesis with stochastic (dynamical) CP-violation, might make about 50:50 with all DM in compact matter/antimatter objects, allowed.

Secondary production of antimatter.

1. Antiprotons and positrons by cosmic rays or violent stellar processes.
2. DM annihilation.
3. PBH evaporation. May it be the source of positrons from Galactic center?

Main question for possible discovery:

Could galaxies or the Galaxy consist of matter with astronomically significant compact clumps of antimatter?

Both "natural" theory and existing observations allow for that.

Three parts:

I. Mechanism of antimatter creation which might be in the Galaxy.
II. Phenomenology, observational signatures and bounds.
III. Observed positrons from the galactic center. **Signatures of antimatter or some conventional mechanisms?**

Universe is predominantly baryonic (at least in our neighborhood):

$$\beta_B = N_B / N_\gamma = 6 \cdot 10^{-10}$$

But large fluctuations of β at small scales and even $\beta < 0$ (antimatter) are allowed theoretically and observationally.

Standard baryogenesis deals with one constant number β_B. Nonstandard models predict a function $\beta_B(x)$.

Up to now we have observed only matter and no antimatter, except for a little antiprotons and positrons most probably of secondary origin.
Observed positron 0.511 MeV line from the galactic bulge may be a signature of cosmic antimatter!?

Observational bounds:

In charge symmetric universe the nearest antimatter domain should be at $l_B >$ 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 at larger distances or galaxies in the common cloud of intergalactic gas are dominated by the same kind of matter (or antimatter?).

Nearest anti-galaxy could not be closer than at $\sim$10 Mpc (Steigman, Stecker), but still in our supecluster.

Annihilation of intergalactic gas inside antigalaxy:

$$\dot{N} = \sigma_{ann} v N_{gal} \langle n_p \rangle = 10^{47}/sec$$

where $\sigma_{ann} v = 10^{-15}$ **cm^3/s,**
$N_{gal} = 10^{67}$, $\langle n_p \rangle = 10^{-5}/\mathrm{cm}^3$.
Luminosity $L = 10^{43}\, erg/s$.
leads to flux on the Earth:
number: $\phi = 10^{-5}/\mathrm{cm}^2/\mathrm{s}$,
energy: $F = 10^{-3}\mathrm{MeV}/\mathrm{cm}^2/\mathrm{s}$.
(γ-bursts: $10^2\mathrm{MeV}/\mathrm{cm}^2/\mathrm{s}$).

The bounds presented above are true if antimatter makes the same type objectes as the OBSERVED matter.

Compact objects made of antimater may escape observations and be almost at hand.

Picture: the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects or PBH, plus subdominant 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:

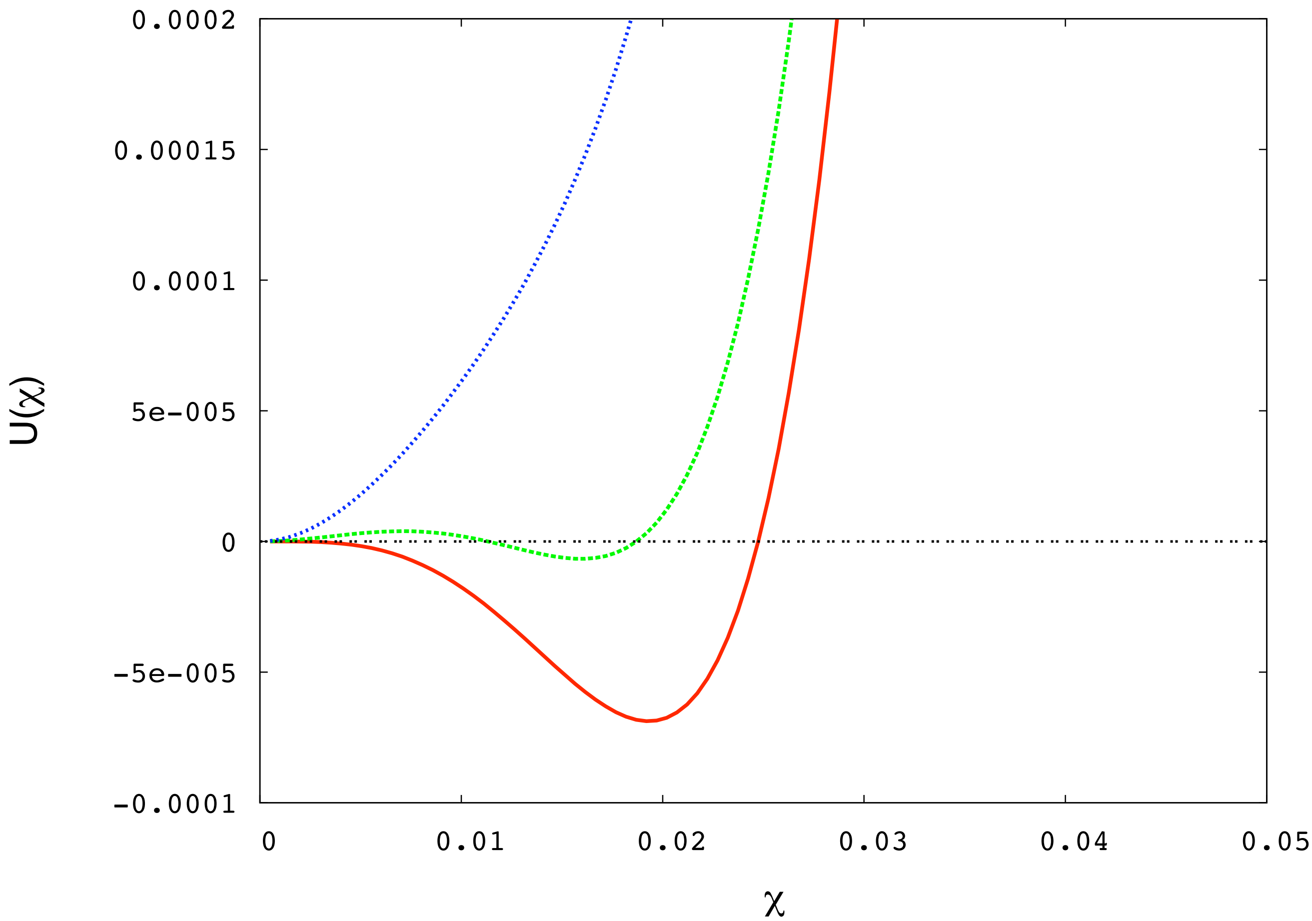
$$U(\chi, \Phi) = \lambda_1 |\chi|^2 (\Phi - \Phi_1)^2 + \lambda_2 |\chi|^4 \ln\left(|\chi|^2/\sigma^2\right) + \left(m^2 \chi^2 + h.c.\right).$$

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

Last term breaks B-conservation.

$J_\mu^{(B)} = i\chi^\dagger \partial_\mu \chi + h.c.,$

$B = J_t^{(B)}$ 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):

$$\frac{\partial \mathcal{P}}{\partial t} = \frac{H^3}{8\pi^2} \sum_{k=1,2} \frac{\partial^2 \mathcal{P}}{\partial \chi_k^2} +$$

$$\frac{1}{3H} \sum_{k=1,2} \frac{\partial}{\partial \chi_k} \left[\mathcal{P} \frac{\partial U}{\partial \chi_k} \right]$$

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

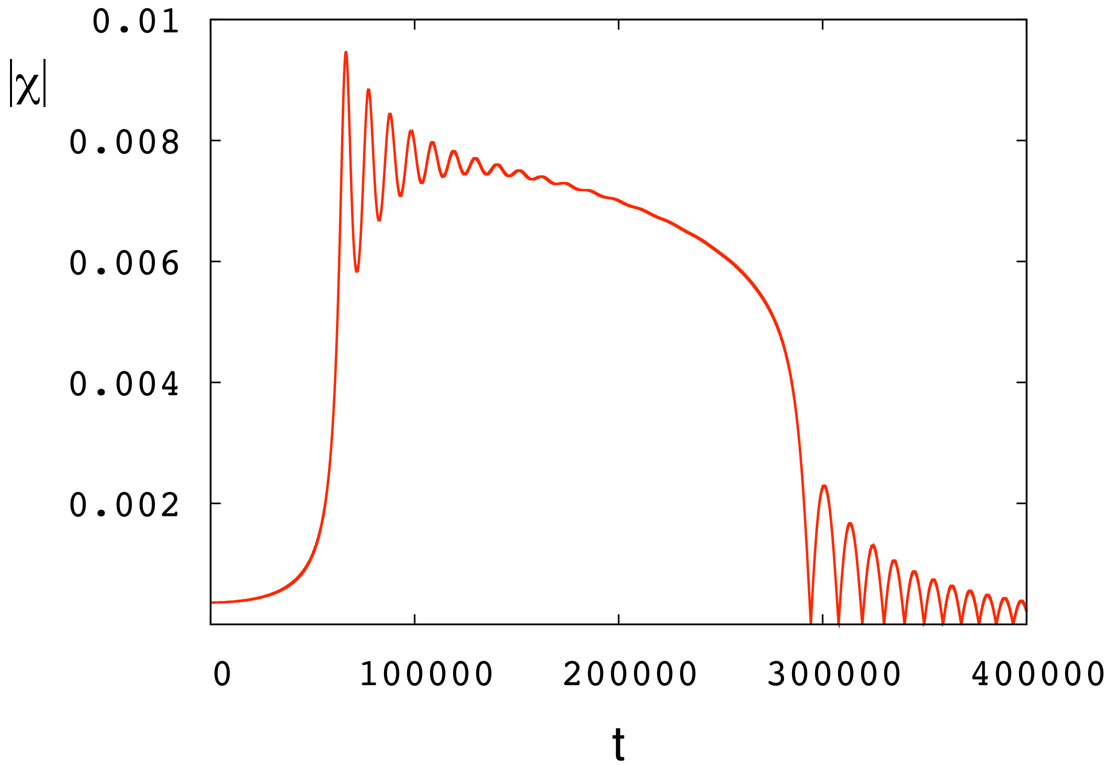
The effective mass behave as $m_{eff}^2 \approx m_0^2 + m_1^4(t - t_1)^2$, when Φ passes through Φ_1. Correspondingly the dispersion is:

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

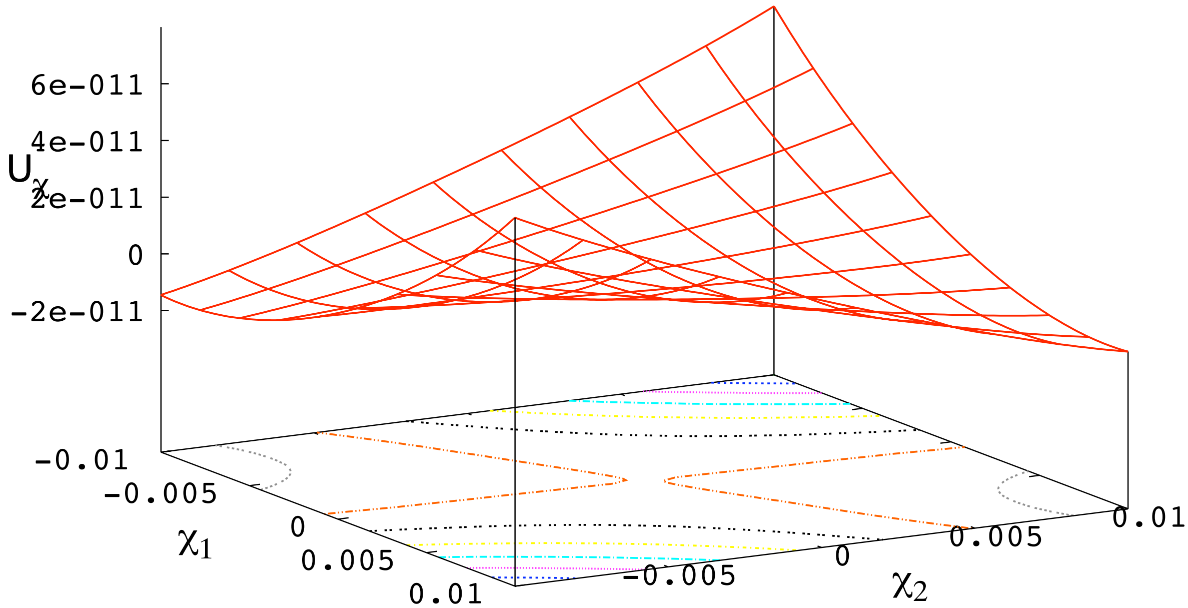
Hence the bubble distributions over length and mass have log-normal form:

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

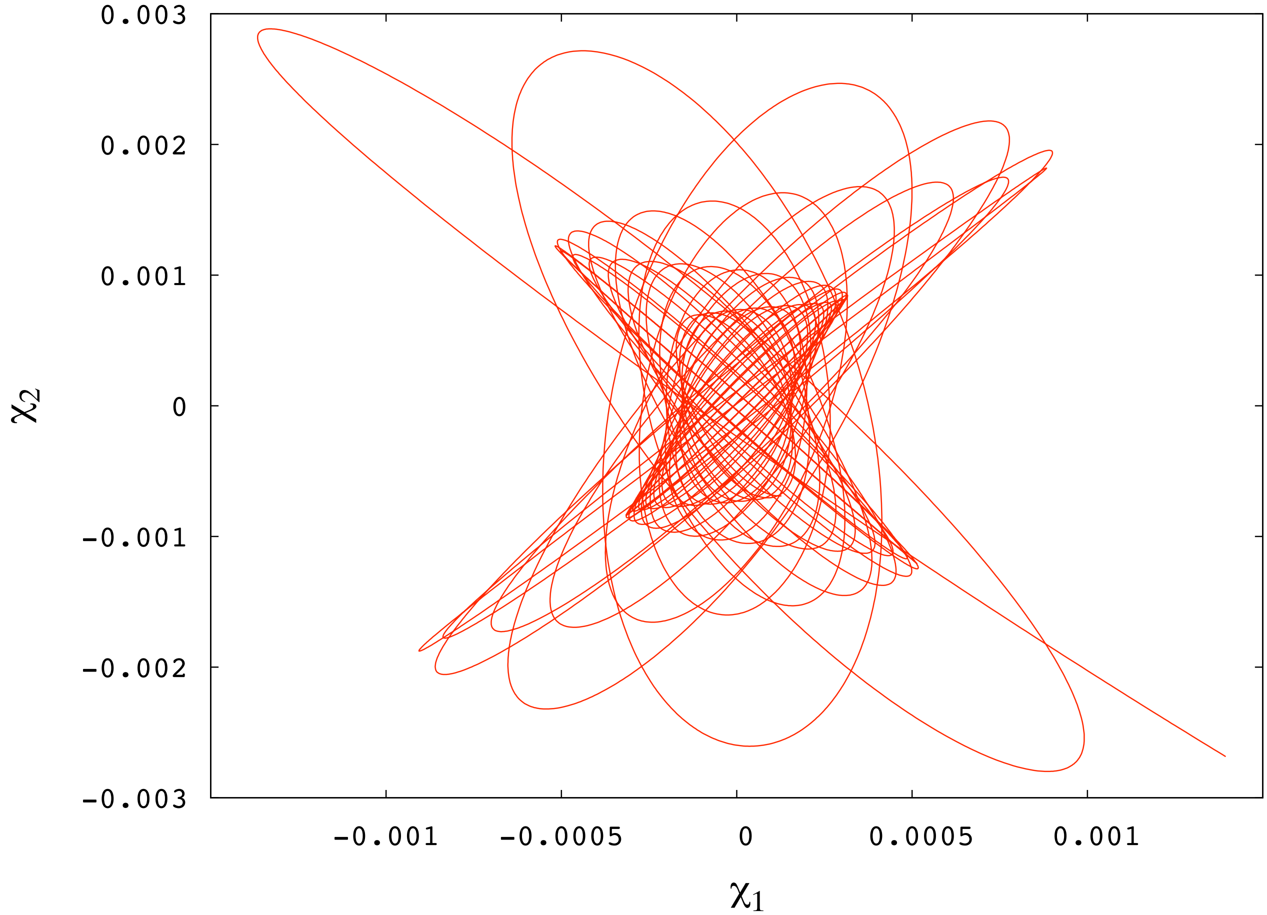
where C_M, γ, and M_0 are constant parameters. A modification of this distribution by a power factor, M^ν, or, which is the same, by a log term in the exponent, $\exp(\kappa \ln M)$ leads to the same log-normal form of the distribution with some change of the parameter values.



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



3 dimensional picture of $U(\chi)$, showing B-nonconservation.



“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 friction, $H \gg m$. 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.

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 disappeared after χ decay.

"Separate universes" with $k = 0$ but different equations of state: radiation and mixture of matter and radiation. Initial

$$\delta\rho = 0$$

rises and tends to a large constant value. After χ decay, density contrast tends to zero, for large bubble size when the pressure contrast is not essential.

Equal (zero) curvature case

$$\rho_r = \frac{3m_{Pl}^2}{32\pi(t+t_r)^2}, \quad \rho_m = \frac{m_{Pl}^2}{6\pi(t+t_m)^2}$$

Initially at $t = 0$: $\rho_r = \rho_m$, i.e.

$$t_m = 4t_r/3$$

At large t the density contrast becomes of the order of unity:

$$\frac{\delta\rho}{\rho_r} = \frac{\rho_m - \rho_r}{\rho_r} = \frac{7}{9}$$

After χ decay:

$$\rho_m \to \rho_r = \frac{3m_{Pl}^2}{32\pi(t+t_d)^2}$$

and for large t the density contrast tends to zero (???):

$$\frac{\delta\rho}{\rho} \sim \frac{t_d - t_r}{t}$$

2. Second period of $\delta\rho$ generation after the QCD phase transition at T $\sim$ 100 MeV when quarks made non-relativistic 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.

$$r_B = \frac{\delta\rho}{\rho} = \frac{\beta n_\gamma m_p}{(\pi^2/30) g_* T^4} \approx 0.07\beta\, \frac{m_p}{T}.$$

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 anti-atmosphere if β slowly decreases.

Mass spectrum, log-normal:

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

C, γ, and M_1 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.

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.

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

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

Mass density at onset of MD stage:

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

EVOLUTION IN THE EARLY UNIVERSE

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.

What anti-objects could survive against early annihilation?

Jeans wave length at the onset of MD:

$$\lambda_J = c_s \left(\frac{\pi M_{Pl}^2}{\rho}\right)^{1/2} \approx 10t \left(\frac{T}{m_N}\right)^{1/2}$$

with speed of sound $c_s \approx (T/m_N)^{1/2}$.
Initial value of the Jeans mass:

$$M_J \approx 135 \left(\frac{T}{m_N}\right)^{3/2} M_{Pl}^2 t \approx 100 \frac{M_\odot}{\beta^{1/2}}$$

M_J slowly, as $1/\sqrt{T}$ increases?
λ_j rises with time?

WRONG! **Because in MD object** $T \sim 1/a^2$ **and** $M_J \sim 1/a^{3/2}$.

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:

$$t_{diff} \approx 2 \cdot 10^{11}\,\text{sec}\left(\frac{M_B}{M_\odot}\right)\left(\frac{\text{sec}}{R_B}\right)\left(\frac{\sigma_{e\gamma}}{\sigma_{Th}}\right)$$

Thermal energy stored inside B-ball

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

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:

$$l_p = \frac{1}{(\sigma n)} \sim \frac{m_p^2}{\alpha^2 T^3} = 0.1\, cm \left(\frac{MeV}{T}\right)^3$$

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

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

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.

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.

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, $l_c \equiv l_B$.

$$l_p = \frac{1}{\sigma_{tot} n_{\bar{p}}} = 10^{24}\, cm \left(\frac{cm^{-3}}{n_{\bar{p}}}\right) \left(\frac{barn}{\sigma_{tot}}\right)$$

Compact 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 $l^p_{free} > l_c$:

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

Total number of annihilations:
$\dot{N}_p = 4\pi l_c^3 \dot{n}_p/3.$
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

$$\tau = 10^{15}\ sec\ \left(\frac{10^{-15} cm^3/s}{\sigma_{ann} v}\right)\left(\frac{cm^{-3}}{n_p}\right),$$

if supply of protons from galactic gas is sufficient.

They could survive in the halo.

Proton flux into an anti-cloud:

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

Total number of $\bar{\mathrm{p}}$ in the cloud:

$N_{\bar{p}} = 4\pi l_c^3 n_{\bar{p}}/3.$

Flux is sufficient to destroy the anti-cloud in 10^{17} sec if:

$$\left(\frac{n_{\bar{p}}}{cm^3}\right) \left(\frac{l_c}{pc}\right) < 3 \cdot 10^4$$

The luminosity for volume annihilation:

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

Flux on the Earth at d=10 kpc: $10^{-7}\gamma/\mathrm{s}/\mathrm{cm}^2$ or $10^{-5}\mathrm{Mev}/\,\mathrm{s}/\mathrm{cm}^2$, to be compared with cosmic background $10^{-3}/\mathrm{MeV}/\mathrm{s}/\mathrm{cm}^2$.

Compact stellar type objects, $l_s \gg l_{free}$, surface annihilation - all that hits the surface annihilate.

Gamma-radiation from $\bar{\mathrm{p}}\mathrm{p} \to$ pions and $\pi^0 \longrightarrow 2\gamma$ ($E_\pi \sim 500$ MeV) and from e^+e^--annihilation originating from $\pi^\pm$-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%.

Luminocity is so small because annihilation takes place in a small shell on the surface.

Stellar wind:

$$\dot{M} = 10^{12} W \, g/sec$$

where $W = \dot{M}/\dot{M}_\odot$.
If all "windy" particles annihilate, the luminosity per star:

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

Density of galactic antiprotons.

The total number of antiparticles from stellar wind is determined by:

$$\dot{N} = -\sigma_{ann} v \, n_p n_{\bar{p}} V_{gal} + S$$

where $S = W \epsilon (N_s/10^{12}) \, 10^{48}/sec$, N_s is the number of stars in the galaxy, ϵ is the fraction of antistars. Hence:

$$n_{\bar{p}} = \left(\frac{3 \cdot 10^{-5}}{cm^3}\right) \epsilon W \left(\frac{N_s}{10^{12}}\right) \left(\frac{barn}{\sigma_{ann} v}\right)$$

Number density of antinuclei is bounded by the density of "unexplained" $\bar{\text{p}}$ 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 $\bar{\mathrm{p}}$ 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 (???):

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

Annihilation pressure pushes the stars apart. Collision time $\sim$ 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.

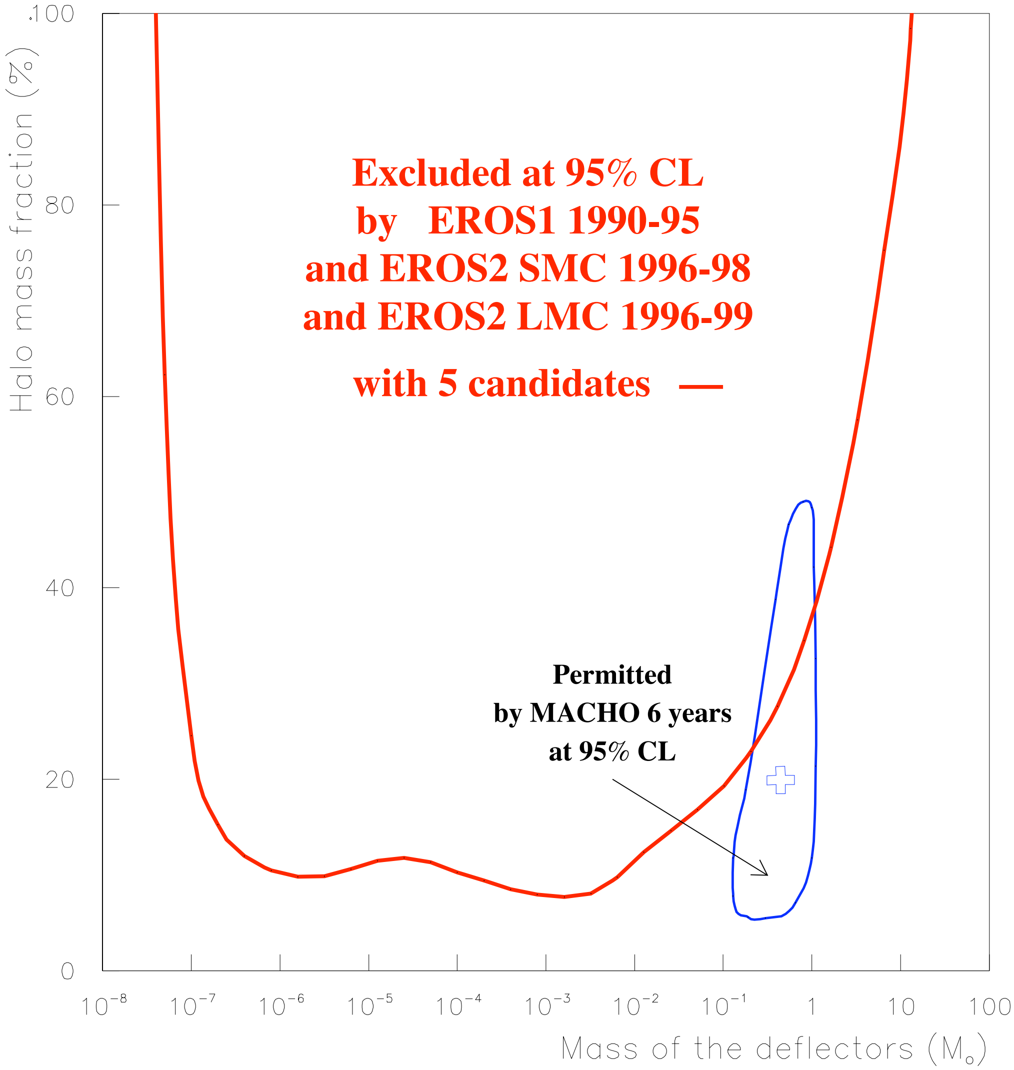
Photon polarization: e.g. e^+ are predominantly “right handed”, the same is transferred to bremsstrahlung. Antineutron decays create left-handed e^-.

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.


Excluded at 95% CL
by EROS1 1990-95
and EROS2 SMC 1996-98
and EROS2 LMC 1996-99
with 5 candidates
Permitted
by MACHO 6 years
at 95% CL
Halo mass fraction (%)
Mass of the deflectors (M_o)
100
80
60
40
20
0
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100

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:

$$\mathbf{N_{\bar{S}}/N_S \le 10^{-6}W^{-1}},$$

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:

$$N_{\bar{S}}/N_S = (\bar{H}e/He) \leq 10^{-6},$$

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 $^4\bar{\mathrm{He}}$ 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 $\bar{\nu}$ in the first burst from anti-SN explosion.

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

THE END

Next slides: models of "normal" explanations of the positron line.

0.511 MeV line from Galactic bulge:

$\Phi_{511\,\mathrm{keV}} \approx 1.0 \cdot 10^{-3}\ \mathrm{photons\ cm^{-2}\,s^{-1}}$

Implies about $3{\cdot}10^{43}$ annihilations per second inside the central kiloparsec.

Suggested mechanisms of explanation of 0.511 MeV line:

1. Ia supernovae.
2. Low mass X-ray binary systems.
3. Energetic $e^{\pm}$ and γ created by accretion on the super–massive black hole at the Galactic Center.
4. Positron production in accretion to super–massive central black hole and to surrounding primordial black holes with mass about 10^{17} g.

5. Annihilating light dark matter particles.

6. Decaying unstable relics e.g. sterile neutrinos.

7. MeV right-handed neutrino interacting with baryonic matter.

8. Strangelets.

9. Positrons originating from primordial antimatter.

10. Decays of milli–charged particles.

11. Evaporation of 10^{16} g PBH.

Evaporating BH with mass centered near 10^{17} g

Smaller masses lead to an exessive e.m. radiation at high energy, while larger masses result in an excess of lower energy photons.

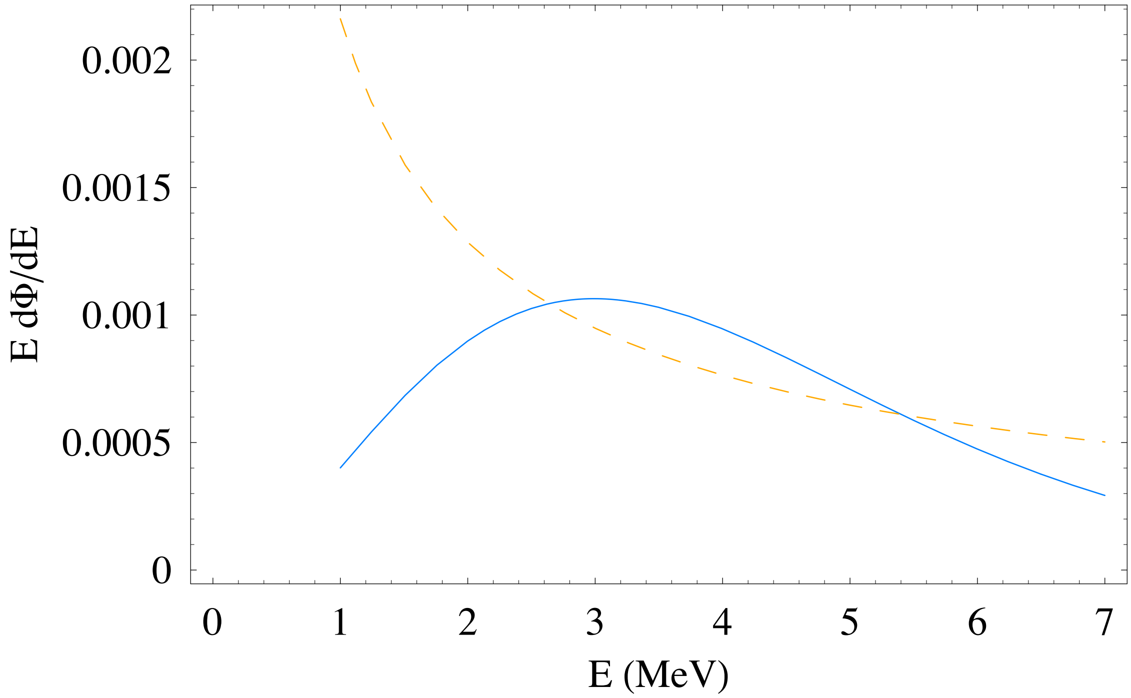


Figure 1: **Gamma ray spectra from primordial BHs with mass $M = 10^{16}$ g (blue solid curve) and of the diffuse background (red dashed curve) in γ cm^{-2} s^{-1} as a function of energy E in MeV. The number of BHs is normalized by the condition that they produce the observed positron flux.**

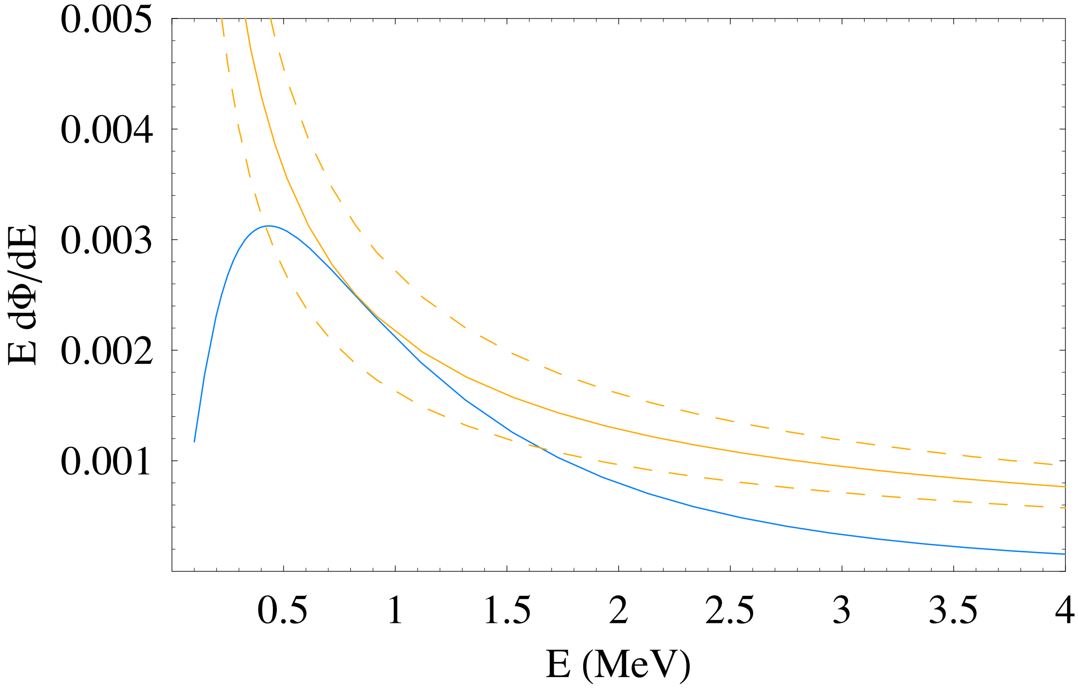


Figure 2: **Gamma ray spectra from primordial BHs (dark–blue solid curve) and of the measured background (light–red solid curve) from the Galactic Bulge in γ cm^{-2} s^{-1} as a function of energy E in MeV. The BHs are assumed to have log–normal mass distribution with the parameters: $\gamma = 1$ and $M_0 = 6 \cdot 10^{16}$ g. The number of BHs is now normalized by the condition that their total mass in the innermost 0.6 kpc is $5 \cdot 10^9$ $M_\odot$. The gamma flux from primordial BHs does not exceed the $\pm 25\%$ uncertainty of the measured gamma ray flux (red dashed lines) and can produce enough positrons to explain the 511 keV line.**

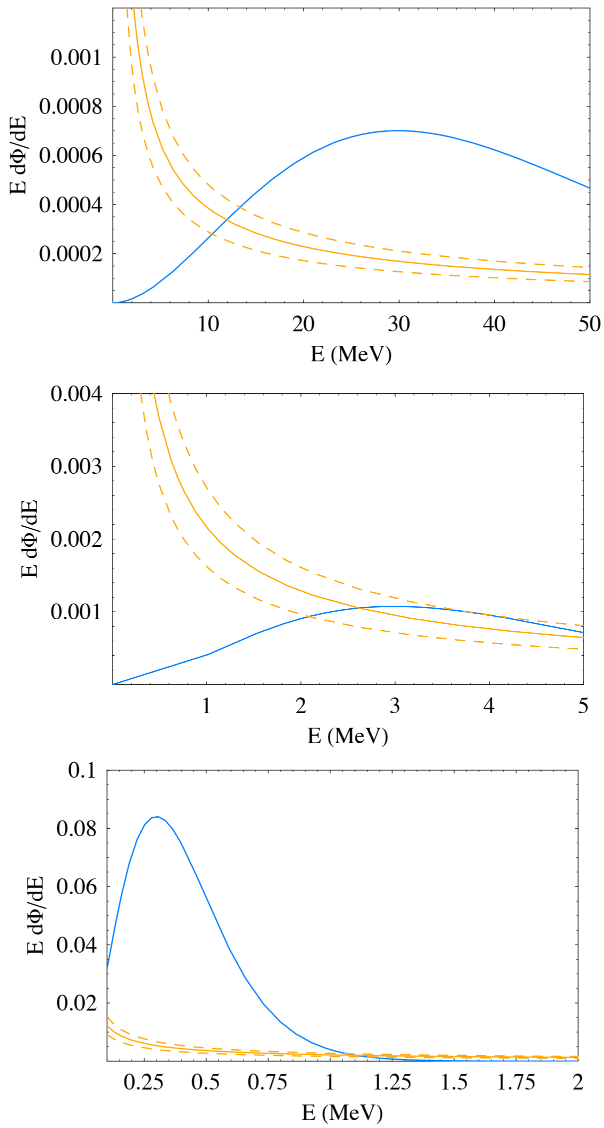


Figure 3: **Gamma ray spectra from primordial BHs (dark–blue solid curve) and of the measured background (light–red solid curve) from the Galactic Bulge in** $\gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ **as a function of energy** E **in MeV. The BHs are assumed to have all the same mass:** $M = 10^{15} g$ **(upper panel),** $M = 10^{16} g$ **(central panel) and** $M = 10^{17} g$ **(lower panel). The number of BHs is normalized by the condition that they produce the right amount of positrons to explain the observed 511 keV line. Red dashed lines are the** $\pm 25\%$ **uncertainty of the measured diffuse gamma flux.**