Can Primordial Antideuterons be Detected in the Cosmic Radiation?

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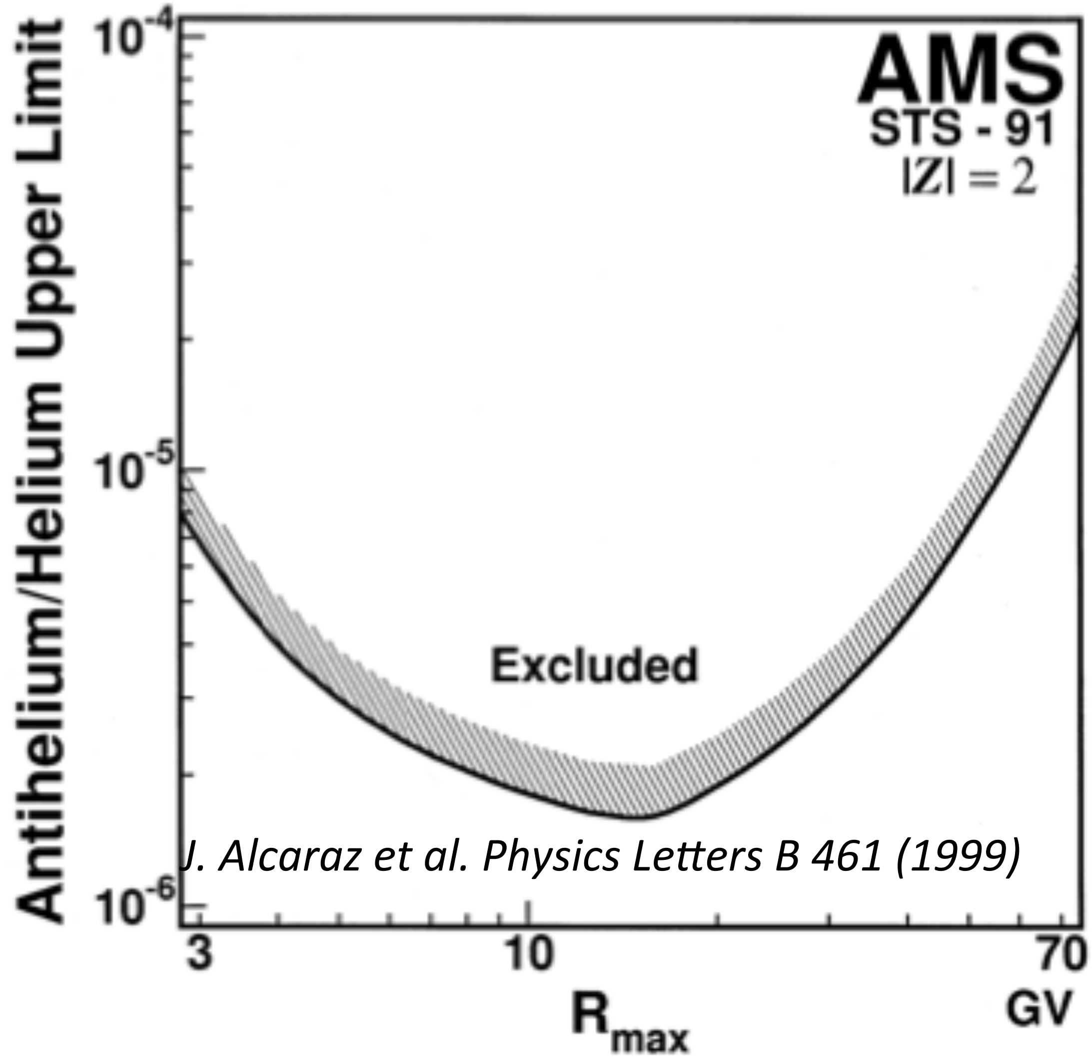
Antideuteron 2014
June 6, 2014
UCLA

In a word…

No

Antihelium Limits



AMS-01 He/He < 1.1 x 10^{-6}

AMS-02 Should reach 10^{-9} (Is this worthwhile?)

Extragalactic Antimatter in cosmic rays

- Are cosmic rays an effective probe of the antibaryon content of the universe?
- Constraints on the Intergalactic Transport of Cosmic Rays, Adams, Freese, Laughlin, Schwadron and GT, ApJ. **491**, 6 (1997).
- Propagation of CRs from other galaxies is highly constrained by magnetic fields, both in the ISM and in the IGM.
- Global magnetic field structure of the universe is uncertain. Here we will explore the optimal case for transport of CRs to our galaxy from long distances.
- For low energy (GeV) cosmic rays the gyroradius << coherence length. In this limit particles tend to follow field lines and magnetic field geometry dominates the path followed by extragalactic CRs.

Intergalactic Magnetic Fields

Estimate IG magnetic field from typical galactic field strength $B_{gal} \sim$ 1-3 μG in two ways:

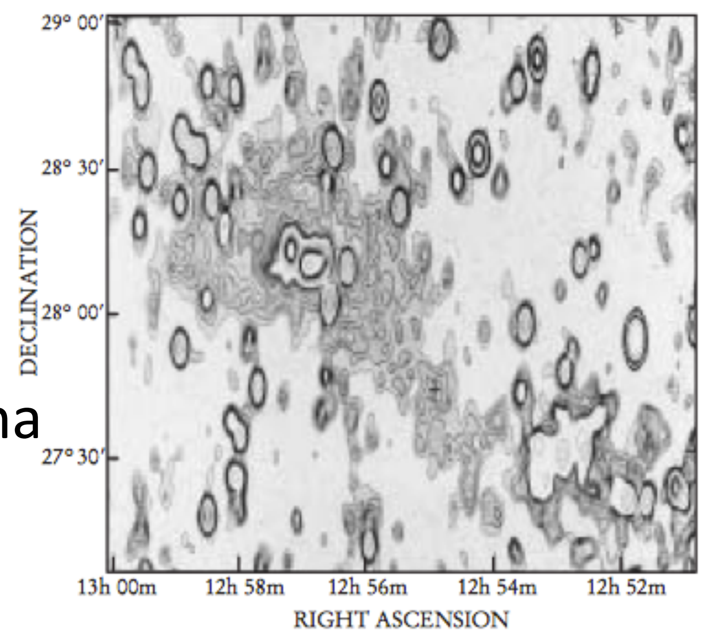
1. Flux freezing: assume galaxy formed from a much larger region. $\Phi = BR^2 =$ constant.

$$B_{IGM} = B_{gal} \left(\frac{\rho_{gal}}{\rho_{IG}} \right)^{-2/3} (1+z)^{-2} \sim 10^{-9} G$$

2. Far from a galaxy, leading order term in magnetc field multipole expansion (dipole ~ r^{-3}) dominates.

$$B_{IGM} = B_{gal} \left(\frac{\rho_{IG}}{\rho_{gal}} \right)^{-2/3} \sim 10^{-12} G$$

- Galactic winds, field diffusion, reconnection, dynamo activity… can only increase B_{IGM}.
- Synchrotron observations outside Coma cluster (Kim et al 1989) B $\gtrsim$ 100 nG.
- 10^{-12}G < B_{IGM} < 10^{-7} G is a fair estimate.



Optimal Intergalactic CR Transport

- For typical (GeV/n) cosmic rays, even tiny (10^{-12} G) intergalactic fields bend particles on scales ~ 1 pc, so coherence length is most important.
- Independent of origin, cosmic B fields will be pulled along by baryonic matter (tied to galaxies). Expansion, tension will straighten fields out $\Rightarrow$ coherence lengths $l \sim 1$ Mpc (typical distance between galaxies).
- In this optimal model, extragalactic CRs propagate from galaxy to galaxy along straight field lines and reach our galaxy after encountering $N = c\langle t\rangle / l \approx 1500$ galaxies.
- Simple diffusion with diffusion length $R_0 = (Dt)^{1/2} = (ctl/3)^{1/2} = 32\ \mathrm{Mpc}\ (l\,/1\mathrm{Mpc})^{1/2}(t\,/10\ \mathrm{Gy})^{1/2}$

Intergalactic Transport

- Diffusion Equation: $$\frac{\partial n}{\partial t} = D\nabla^2 n - \Lambda n \qquad D = \frac{cl}{3}$$
- Similarity Solution:

$$n(r,t) = t^{\frac{1}{2}} e^{-\Lambda t} f(\xi) \quad f(\xi) = f_0[1 - erf(\xi/2)]/\xi \quad \xi \equiv r/R_0$$

- CR flux (from one galaxy): $F = (L_{CR}/4\pi r^2) g(\xi) e^{-\Lambda t}$

$$L_{CR} = \lim_{\xi \to 0} 4\pi r^2 \mathcal{F} = -\lim_{\xi \to 0} 4\pi r^2 D \frac{\partial n}{\partial r} = 4\pi f_0 (lc/3)^{3/2}$$

$$g(\xi) \equiv [1 - erf(\xi/2) + \xi \pi^{-\frac{1}{2}} \exp(\xi^2/4)]$$

where g(ξ) encapsulates departure of CR flux from naïve result $\mathcal{F} = L_{CR}/4\pi r^2$ which applies in the limit of no diffusion ($l \to \infty$).

- Total flux of CRs impinging on our galaxy

$$\mathcal{F}_T = L_{CR} n_{gal} R_0 e^{-\Lambda t} \int_0^\infty g(\xi) d\xi = 4\pi^{-\frac{1}{2}} L_{CR} n_{gal} R_0 e^{-\Lambda t}$$

Galactic Accessibility

- Rate of absorption of extragalactic CRs by our galaxy (disk radius R_D): $L_X = 2\pi R_D^2 x \mathcal{F}_T$, where x is the fractional galactic accessibility.
- CR fraction after each galactic visit: $f_1 = (1-x) + x\tau_{int}/(\tau_{int}+\tau_{esc}) \equiv 1-\alpha x$, $\alpha = \tau_{esc}/(\tau_{int}+\tau_{esc})$.
- Once inside a galaxy CRs remain for a time τ_{esc}, and are destroyed with a time scale τ_{int}. For low energy (<10 GeV) CRs $\tau_{int} \approx \tau_{esc} \approx 10^7$ y ($\alpha = 0.5$).
- Accessibility problem: To survive diffusion, x must be small. If so, CRs have little chance of entering our own galaxy. After N galaxies the remaining fraction $f_N = f_1^N = (1-\alpha x)^N \rightarrow e^{-\alpha N x} \equiv e^{-\Lambda t}$, $\Lambda = \alpha x c/2l$.
- Destruction Function (fraction of total CR flux that can enter our galaxy) $F_D(x) = x(1-\alpha x)^N$ (highly peaked) with maximum $F_{D,max} = \rightarrow (e\alpha N)^{-1} \approx 5 \times 10^{-4}$ for $x_0 = 1/750$ (unlikely).
- Ahlen, Price, Salamon and GT ApJ, 1982 calculate $x \approx 0.1$ for modulation of extragalactic CR by a galactic wind within a dynamical halo model. In this case $F_D \leq 10^{-35}$!

Extragalactic Cosmic Rays?

- Fractional abundance of extragalactic cosmic rays within our galaxy:

  $\chi = L_X/(L_X + L_{CR}) \approx L_X/L_{CR} = 8\pi^{1/2}(R_D{}^2 R_0 n_{gal}) x e^{-\alpha N x}$

  $\approx 0.1[l(\mathrm{Mpc})]^{1/2} F_D \leq 5\times10^{-5}$ (likely much lower).
- Assume that antimatter CRs originate from galaxies of antimatter at some distant scale > a.
- Within our galaxy, the fraction of CRs originating at distances > a to the total number of galactic cosmic rays is

$$\mathcal{R}(a) = \frac{\int_{\xi_a}^{\infty} g(\xi)\,d\xi}{\int_0^{\infty} g(\xi)\,d\xi} = e^{-\frac{\xi_a^2}{4}} - \frac{\pi^{1/2}}{4}\xi_a\left[1 - erf\left(\frac{\xi_a}{2}\right)\right] \rightarrow \frac{e^{-\frac{\xi_a^2}{4}}}{2}$$

  For large a, where $\xi_r = a/R_{0.}$
- $\mathcal{R}$(a) behaves like a Gaussian $\Rightarrow$ volume of the universe producing CRs accessible to our galaxy has a radius of ~$2R_0 \approx 64$ Mpc.

Extragalactic Antimatter in Cosmic Rays?

- Total fractional abundance of antimatter *within* our galaxy $\mathcal{A} = \chi\mathcal{R}f_A$ where f_A is the fraction of anti-galaxies ($f_A = ½$ for a baryon symmetric universe).

  $\mathcal{A} = 0.025\, l^{½} x \exp[-(750x + 244a^2)/l]$

  with l(Mpc), a(1000 Mpc), $f_A = ½$.
- If we maximize $\mathcal{A}$ with respect to x we obtain $\mathcal{A} = 3\times10^{-111}$! (much smaller for x = 0.1)
- $\mathcal{A}$ has Gaussian sensitivity to a and exponential sensitivity to galactic accessibility x.

Gamma Ray Limits

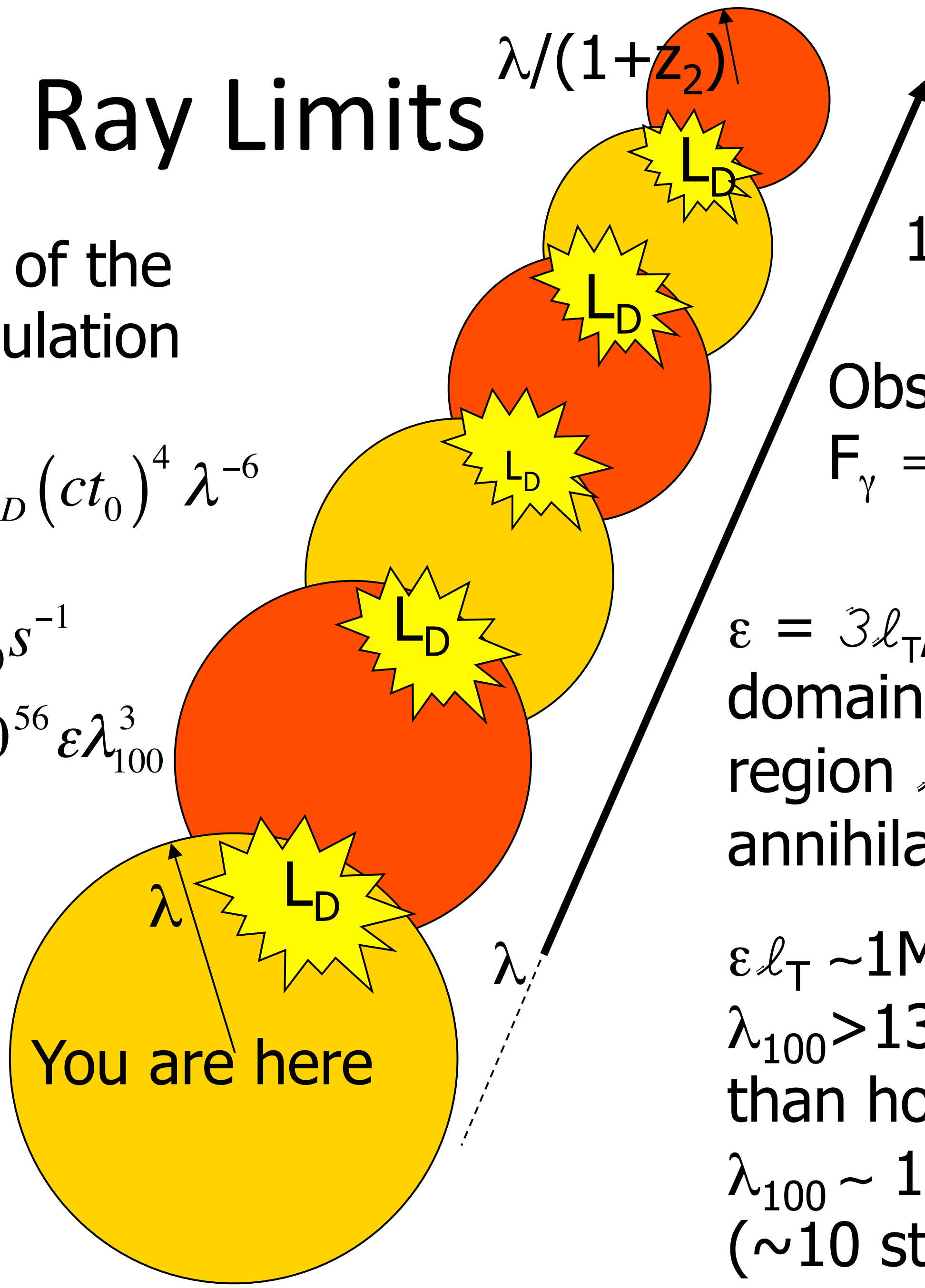
A crude "back of the envelope" calculation

$$F_\gamma = L_D \int_\lambda^{ct_0} n\,dr = L_D \left(ct_0\right)^4 \lambda^{-6}$$

$$\dot{N}_N = 5\times 10^{55}\varepsilon\lambda_{100}^3 s^{-1}$$

$$L_D = g\dot{N}_N = 2\times 10^{56}\varepsilon\lambda_{100}^3$$

ε = fraction of domain that annihilates in t_0



Horizon ct_0

$1+z_2 = (ct_0/\lambda)^2$

Observations of $F_\gamma \Rightarrow \lambda_{100}{}^3 \geq 10^{14}\,\varepsilon$

$\varepsilon = 3\ell_T/\lambda$ spherical domains w/outer region ℓ_T available for annihilation.

$\varepsilon\ell_T \sim 1$Mpc, $\lambda_{100} > 1320$! (larger than horizon).

$\lambda_{100} \sim 1$, $\ell_T \sim 10^{12}$ cm! (~10 stellar radii)

Primordial Antimatter? Not!

- More detailed calculation involving diffuse γ-ray flux (Cohen, DeRujula, Glashow, ApJ, **495**, 539 (1998) "we have ruled out a B = 0 universe with domains smaller than a size comparable to that of the visible universe."
- Under the most optimistic assumptions, cosmic rays cannot diffuse over cosmological distances in the age of the universe.
- Cosmic rays are an ineffective tool to observe a universal baryon symmetry!
- No conceivable increase in experimental sensitivity could increase the distance to which antimatter domains can be detected.
- Antideuterium in cosmic rays can be used to probe for dark matter annihilation but not for cosmological sources.