Constraints on the antistar fraction in the Solar system neighborhood from the 10-years *Fermi* Large Area Telescope gamma-ray source catalog

Simon Dupourqué

supervised by
Luigi Tibaldo &
Peter Von Ballmoos

IRAP, Toulouse

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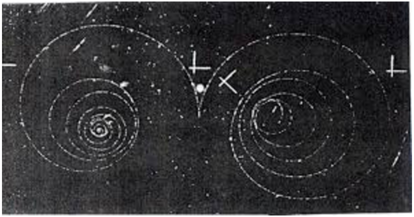
Summary

Introduction

Matter-antimatter asymmetry

(Almost) symmetric physical processes $\nRightarrow$ local asymmetric universe



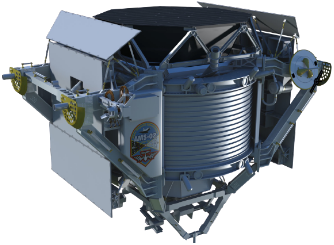
Why so ? big question in physics/astrophysics/cosmology

The observable universe is assumed to be free of antimatter domains [a]

[a] Cohen, A. G. *et al.* A Matter-Antimatter Universe? *The Astrophysical Journal* **495,** 539–549 (Mar. 1998).

AMS-02 $\overline{He}$ events

- AMS-02 has announced the tentative detection of 6 $\overline{{}^3He}$ and 2 $\overline{{}^4He}$
- Possible origins discussed in Poulin *et al.* 2019 [b]
  - Challenging to explain in term of known physics (especially $\overline{{}^4He}$)
  - If confirmed implies the existence of nearby antimatter domains
  - Antistars are favored

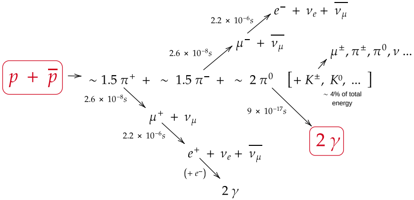


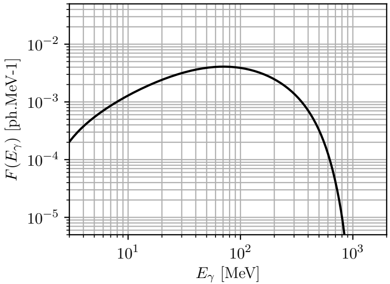
"The detection of a single anti-helium [...] would be a smoking gun [...] for the existence of anti-stars and of anti-galaxies" [c]

[b] Poulin, V. *et al.* Where do the AMS-02 antihelium events come from? *Physical Review D* **99,** 023016 (Jan. 2019)

[c] Chardonnet, P. *et al.* Antimatter cosmic rays. *New Astron.* **4,** 275–282 (1999)

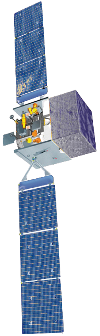
π_0 decay as an antimatter tracer

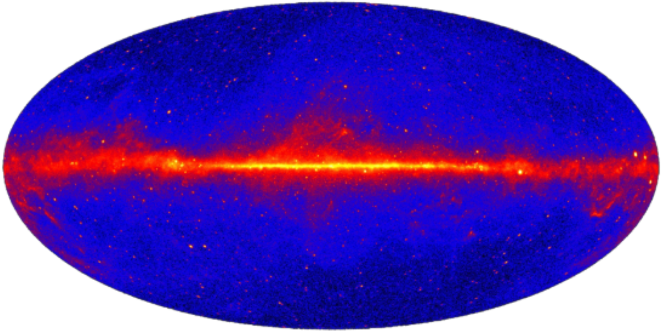




- Annihilation at matter-antimatter region boundaries
- Production of γ-ray with baryonic matter annihilation
- Characteristic spectrum with peak at ~ 70 MeV with a cutoff at proton mass

Fermi-LAT & 4FGL-DR2





- γ-ray telescope : 20 MeV - 2 TeV
- Catalog : 10 years of data, 5788 sources

Observational constraints for antimatter

Selection criteria & selected candidates

Exclusion criteria

1. Extended sources
2. Not associated
3. Significance $> 3\sigma$ for $E > 1$ GeV
4. Flagged sources

14 candidates for 5788 sources

$\hookrightarrow$ upper limits

Name	l degrees	b degrees	J (0.1 - 100 GeV) (erg cm^{-2} s^{-1})
4FGL J0548.6+1200	194.9	-8.1	$(4.2 \pm 0.9) \times 10^{-12}$
4FGL J0948.0-3859	268.3	11.2	$(2.5 \pm 0.7) \times 10^{-12}$
4FGL J1112.0+1021	243.8	61.2	$(2.5 \pm 0.5) \times 10^{-12}$
4FGL J1232.1+5953	127.4	57.1	$(1.8 \pm 0.3) \times 10^{-12}$
4FGL J1348.5-8700	303.7	-24.2	$(3.0 \pm 0.6) \times 10^{-12}$
4FGL J1710.8+1135	32.2	27.5	$(2.5 \pm 0.6) \times 10^{-12}$
4FGL J1721.4+2529	48.1	30.2	$(3.3 \pm 0.5) \times 10^{-12}$
4FGL J1756.3+0236	28.9	13.4	$(4.4 \pm 1.0) \times 10^{-12}$
4FGL J1759.0-0107	25.9	11.1	$(5.9 \pm 1.3) \times 10^{-12}$
4FGL J1806.2-1347	15.5	3.5	$(9.4 \pm 2.2) \times 10^{-12}$
4FGL J2029.1-3050	12.3	-33.4	$(2.6 \pm 0.6) \times 10^{-12}$
4FGL J2047.5+4356	83.9	0.3	$(1.4 \pm 0.4) \times 10^{-11}$
4FGL J2237.6-5126	339.8	-55.0	$(2.3 \pm 0.5) \times 10^{-12}$
4FGL J2330.5-2445	35.8	-71.7	$(1.6 \pm 0.4) \times 10^{-12}$

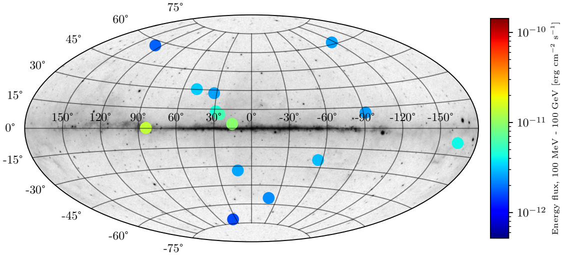
What are they ?

Properties

- No clear pattern on the sky
- Weak sources close to the detection threshold

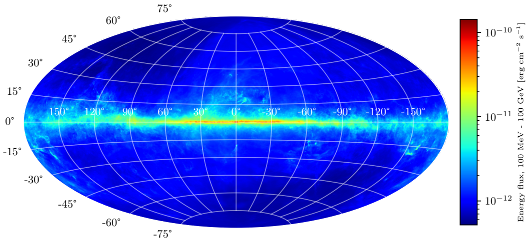
Alternative explanations

- Unknown pulsar, AGN
- Defect of interstellar emission model



Proving or disproving the antistar nature requires significant multiwavelength work

Sensitivity skymap of the LAT



Semi-analytical formula for the significance:

- Instrument response functions
- Background model
- Spectrum of the source

$\hookrightarrow$ Minimum flux for the detection of an antistar source

Estimating the antistar fraction

Luminosity derivation

- Bondy-Hoyle accretion model
- $p - \overline{p}$ annihilation

Luminosity L_γ

ISM density
Antistar Mass
Antistar speer w.r.t ISM
ISM sound Speed

$$L_\gamma \simeq 8.45 \times 10^{35} \left(\frac{\rho}{m_p \text{ cm}^{-3}}\right) \left(\frac{M}{M_0}\right)^2 \left(\frac{\sqrt{v^2 + c^2}}{10 \text{ km s}^{-1}}\right)^{-3}$$

Density ρ [d] and galactic rotation curve [e] from models, $c \simeq 1$ km s^{-1}

[d] Shibata, T. *et al.* A Possible Approach to Three dimensional Cosmic-ray Propagation in the Galaxy. IV. Electrons and Electron induced γ-rays. *The Astrophysical Journal* **727,** 38 (Jan. 2011)

[e] Reid, M. J. *et al.* Trigonometric Parallaxes of High-mass Star-forming Regions: Our View of the Milky Way. *The Astrophysical Journal* **885,** 131 (Nov. 2019)

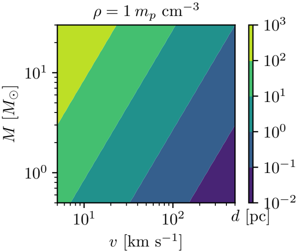
Parametrized fraction $f_{\bar{*}}$

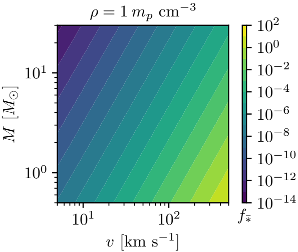
Method by Steigman[f]

1. Brightest candidate $\Leftrightarrow$ closest antistar
2. Hypothesis on mass and speed $\rightarrow$ distance
3. At most 1 antistar in the defined volume

Limitations

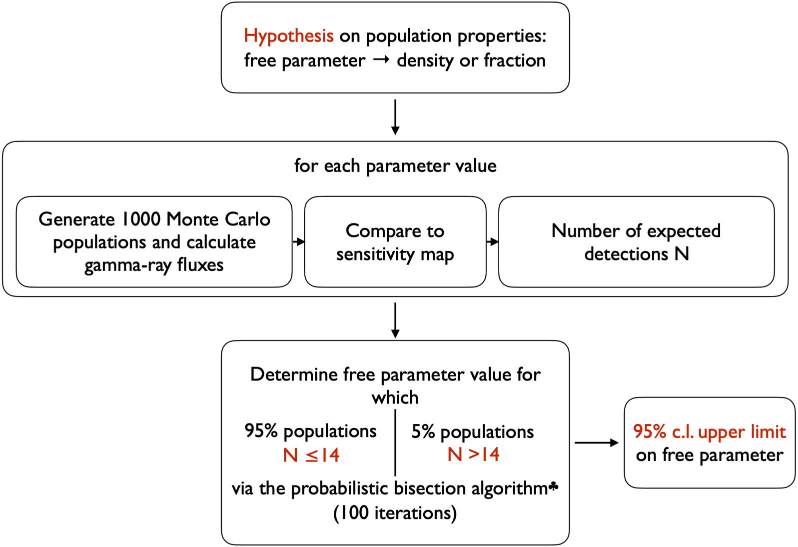
- Arbitrary choices of parameters
- Only one candidate considered
- No well defined statistical meaning





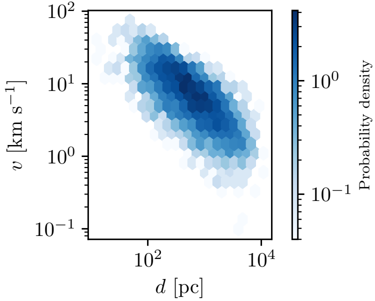
[f] Steigman, G. Observational Tests of Antimatter Cosmologies. *Annual Review of Astronomy and Astrophysics* **14,** 339–372 (1976)

Monte Carlo method



Hypothesis I : starlike distribution

- Antistars have the same position, mass, velocity distribution as normal stars
  - No physical motivation
  - Comparison with earlier results
- Galactic stellar population synthesis using galaxia[g] code
- $f_{\bar{*}} < 2.5 \times 10^{-6}$ (95% C.L)
  - Steigman 1976 $< 10^{-4}$
  - von Ballmoos 2014 $< 4 \times 10^{-5}$



Most likely LAT detection
$1M_\odot$, 10 km/s, 500 pc

[g] Sharma, S. *et al.* Galaxia: a code to generate a synthetic survey of the Milky Way. *The Astrophysical Journal* **730,** 3. ISSN: 1538-4357 (Feb. 2011)

Hypothesis II : primordial antistars

Antistars created in the early universe ?

- Naturally emerge in some baryogenesis scenarii[h]
- Subclass of hypothetical baryon dense objects (BDO), aka MACHOs, also studied as dark matter candidates

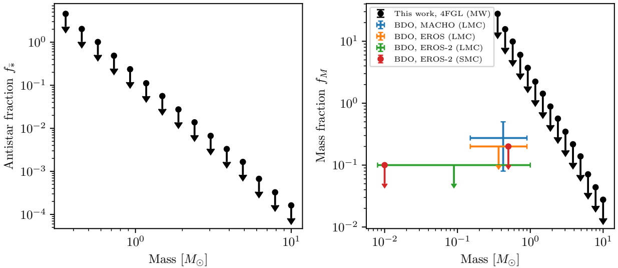
Properties

- Uniform distribution (most of the close ones are in the halo, not in the galactic disk)
- High velocities, typical value of 500 km s^{-1}
- Unknown mass distribution, set to uniform prior

[h] Blinnikov, S. I. *et al.* Antimatter and antistars in the Universe and in the Galaxy. *Phys. Rev. D* **92,** 023516 (2 July 2015).

Results : primordial antistars

- Derive limits as a function of mass (all antistars have the same mass) between 0.3 $M_\odot$ and 10 $M_\odot$
- Converted into mass fraction (w.r.t to DM) to compare with microlensing results : new constraints in previously unexplored mass range ($M > 2M_\odot$)
- Only detectable by the LAT within $\simeq$ 60 pc from the Sun $\rightarrow$ results do not exclude a large number of these objects in the halo



Conclusion

Final remarks

- AMS-02 $\overline{He}$ detections point to the existence of nearby antistars
- 14 antistar candidates in 4FGL-DR2
- Set limits on antistar fraction using novel Monte Carlo approach
  - Starlike properties : $f_{\bar{*}} < 2.5 \times 10^{-6}$ (95% C.L) constraint 20x stronger than previously published results with a more robust methodology
  - Primordial antistars: constraints in previously unexplored mass range $2M_{\odot} - 10M_{\odot}$, data cannot exclude large number of these objects in the halo

Thank you for your attention !