

# Internship of Bachelor

Laboratoire de Physique Théorique et Hautes Énergies (LPTHE)

**Reproduction of the results of the article “Constraints on the antistar fraction in the Solar system neighborhood”**

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## 1. Theory- anti stars

→ An antimatter section in the universe: not possible because of symetrie

→ Antistars and anti matter clouds as contamination in a Universe dominated by matter: most probable

→ Detection of sources thanks to the emission of gamma rays during the annihilation proton-antiproton (Gamma rays between **70- 938 MeV**) .

$$p + \bar{p} \rightarrow \pi_1^0 + \pi_2^0 + \dots = \gamma + \gamma + \dots$$

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## 2. Article project

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

Simon Dupourqué, Luigi Tibaldo, and Peter von Ballmoos

*Institut de Recherche en Astrophysique et Planétologie (IRAP)*

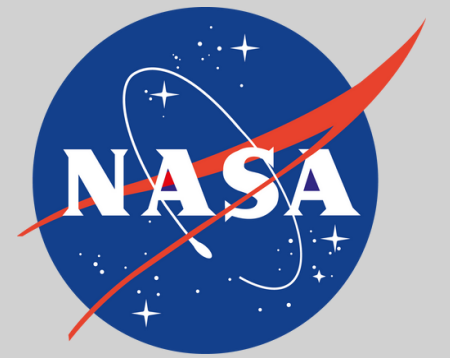
*Université de Toulouse, CNRS, UPS, CNES*

*31400 Toulouse, France*

(Dated: April 22, 2021)

## Code filtrage du 4FGL-DR2

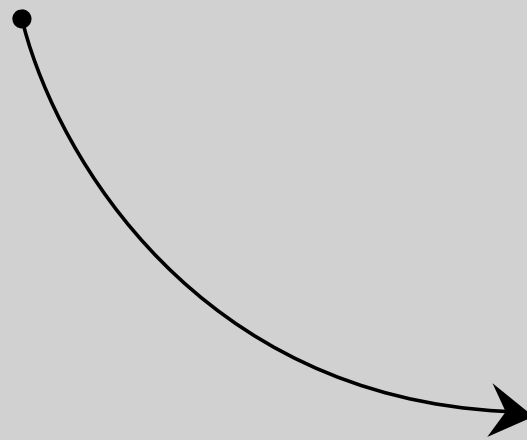
Fermi LAT (Fermi Large Area Telescope)



- Study astrophysical and cosmological phenomenas (pulsars, active galactic nuclei, high-energy sources et matière noire,...)
- Gamma rays detector (20 MeV - 300 GeV)
- Catalogue : 4FGL-DR2 (5787 gamma-ray sources)

Code filtrage du 4FGL-DR2

Objective: Sort the catalog to keep only the potential anti-star candidates



Apply constraints on these gamma-ray sources (Steigman's paper)

## Code filtrage du 4FGL-DR2

Exemples of constraints on the sources :

- Extended sources are excluded → anti-stars are expected to be point sources.
- Already cataloged (known) sources are, of course, excluded (pulsars, galactic centers, etc.).
- Sources with a total Test Statistic (TS), summed over energy bands, lower than 9 are excluded.

Code filtrage du 4FGL-DR2

| Name              | <i>l</i> | <i>b</i> | <i>J</i> (0.1 - 100 GeV)             | Φ (1 - 100 GeV)                  | TS (1 - 100 GeV) |
|-------------------|----------|----------|--------------------------------------|----------------------------------|------------------|
|                   | degrees  | degrees  | erg cm <sup>-2</sup> s <sup>-1</sup> | cm <sup>-2</sup> s <sup>-1</sup> |                  |
| 4FGL J0548.6+1200 | 194.9    | -8.1     | $(4.2 \pm 0.9) \times 10^{-12}$      | $(2.0 \pm 0.6) \times 10^{-10}$  | 8.17001          |
| 4FGL J0948.0-3859 | 268.3    | 11.2     | $(2.5 \pm 0.7) \times 10^{-12}$      | $(1.4 \pm 0.5) \times 10^{-10}$  | 3.17782          |
| 4FGL J1112.0+1021 | 243.8    | 61.2     | $(2.5 \pm 0.5) \times 10^{-12}$      | $(6.0 \pm 2.4) \times 10^{-11}$  | 6.18527          |
| 4FGL J1232.1+5953 | 127.4    | 57.1     | $(1.8 \pm 0.3) \times 10^{-12}$      | $(4.7 \pm 1.8) \times 10^{-11}$  | 3.27565          |
| 4FGL J1348.5-8700 | 303.7    | -24.2    | $(3.0 \pm 0.6) \times 10^{-12}$      | $(9.3 \pm 3.3) \times 10^{-11}$  | 7.04146          |
| 4FGL J1710.8+1135 | 32.2     | 27.5     | $(2.5 \pm 0.6) \times 10^{-12}$      | $(4.8 \pm 2.3) \times 10^{-11}$  | 0.552135         |
| 4FGL J1721.4+2529 | 48.1     | 30.2     | $(3.3 \pm 0.5) \times 10^{-12}$      | $(1.1 \pm 0.3) \times 10^{-10}$  | 8.78427          |
| 4FGL J1756.3+0236 | 28.9     | 13.4     | $(4.4 \pm 1.0) \times 10^{-12}$      | $(1.9 \pm 0.5) \times 10^{-10}$  | 5.02135          |
| 4FGL J1759.0-0107 | 25.9     | 11.1     | $(5.9 \pm 1.3) \times 10^{-12}$      | $(2.5 \pm 0.6) \times 10^{-10}$  | 8.62541          |
| 4FGL J1806.2-1347 | 15.5     | 3.5      | $(9.4 \pm 2.2) \times 10^{-12}$      | $(4.7 \pm 1.0) \times 10^{-10}$  | 7.76874          |
| 4FGL J2029.1-3050 | 12.3     | -33.4    | $(2.6 \pm 0.6) \times 10^{-12}$      | $(1.2 \pm 0.4) \times 10^{-10}$  | 7.99515          |
| 4FGL J2047.5+4356 | 83.9     | 0.3      | $(1.4 \pm 0.4) \times 10^{-11}$      | $(4.5 \pm 1.6) \times 10^{-10}$  | 5.17449          |
| 4FGL J2237.6-5126 | 339.8    | -55.0    | $(2.3 \pm 0.5) \times 10^{-12}$      | $(7.0 \pm 2.4) \times 10^{-11}$  | 0.714205         |
| 4FGL J2330.5-2445 | 35.8     | -71.7    | $(1.6 \pm 0.4) \times 10^{-12}$      | $(8.6 \pm 2.6) \times 10^{-11}$  | 8.69572          |

*List containing the 14 candidates from the review*

Stage L3 - LPTHE

|           | Name              | <b>l (longitude)</b> | <b>b (latitude)</b> | <b>J (0.1 - 100 GeV)</b> | <b>Flux (1 - 100 GeV)</b> | <b>TS (1 - 100 GeV)</b> |
|-----------|-------------------|----------------------|---------------------|--------------------------|---------------------------|-------------------------|
| <b>0</b>  | 4FGL J0548.6+1200 | 194.9                | -8.1                | 4.2e-12                  | 2.0e-10                   | 8.17001                 |
| <b>1</b>  | 4FGL J0948.0-3859 | 268.3                | 11.2                | 2.5e-12                  | 1.4e-10                   | 3.17782                 |
| <b>2</b>  | 4FGL J1112.0+1021 | 243.8                | 61.2                | 2.5e-12                  | 6.0e-11                   | 6.18527                 |
| <b>3</b>  | 4FGL J1232.1+5953 | 127.4                | 57.1                | 1.8e-12                  | 4.7e-11                   | 3.27565                 |
| <b>4</b>  | 4FGL J1348.5-8700 | 303.7                | -24.2               | 3.0e-12                  | 9.3e-11                   | 7.04146                 |
| <b>5</b>  | 4FGL J1710.8+1135 | 32.2                 | 27.5                | 2.5e-12                  | 4.8e-11                   | 0.55213                 |
| <b>6</b>  | 4FGL J1721.4+2529 | 48.1                 | 30.2                | 3.3e-12                  | 1.1e-10                   | 8.78427                 |
| <b>7</b>  | 4FGL J1756.3+0236 | 28.9                 | 13.4                | 4.4e-12                  | 1.9e-10                   | 5.02135                 |
| <b>8</b>  | 4FGL J1759.0-0107 | 25.9                 | 11.1                | 5.9e-12                  | 2.5e-10                   | 8.62541                 |
| <b>9</b>  | 4FGL J1806.2-1347 | 15.5                 | 3.5                 | 9.4e-12                  | 4.7e-10                   | 7.76874                 |
| <b>10</b> | 4FGL J2029.1-3050 | 12.3                 | -33.4               | 2.6e-12                  | 1.2e-10                   | 7.99515                 |
| <b>11</b> | 4FGL J2047.5+4356 | 83.9                 | 0.3                 | 1.4e-11                  | 4.5e-10                   | 5.17449                 |
| <b>12</b> | 4FGL J2237.6-5126 | 339.8                | -55.0               | 2.3e-12                  | 7.0e-11                   | 0.71421                 |
| <b>13</b> | 4FGL J2330.5-2445 | 35.8                 | -71.7               | 1.6e-12                  | 8.6e-11                   | 8.69572                 |

*List containing the 14 candidates from the review*  
*With our code (Sorting of catalog)*

2. Projet sur l'article

Code filtrage du 4FGL-DR4

| Name              | <i>l</i> | <i>b</i> | <i>J</i> (0.1 - 100 GeV)             | Φ (1 - 100 GeV)                  | TS (1 - 100 GeV) |
|-------------------|----------|----------|--------------------------------------|----------------------------------|------------------|
|                   | degrees  | degrees  | erg cm <sup>-2</sup> s <sup>-1</sup> | cm <sup>-2</sup> s <sup>-1</sup> |                  |
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| 4FGL J0948.0-3859 | 268.3    | 11.2     | $(2.5 \pm 0.7) \times 10^{-12}$      | $(1.4 \pm 0.5) \times 10^{-10}$  | 3.17782          |
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| 4FGL J1348.5-8700 | 303.7    | -24.2    | $(3.0 \pm 0.6) \times 10^{-12}$      | $(9.3 \pm 3.3) \times 10^{-11}$  | 7.04146          |
| 4FGL J1710.8+1135 | 32.2     | 27.5     | $(2.5 \pm 0.6) \times 10^{-12}$      | $(4.8 \pm 2.3) \times 10^{-11}$  | 0.552135         |
| 4FGL J1721.4+2529 | 48.1     | 30.2     | $(3.3 \pm 0.5) \times 10^{-12}$      | $(1.1 \pm 0.3) \times 10^{-10}$  | 8.78427          |
| 4FGL J1756.3+0236 | 28.9     | 13.4     | $(4.4 \pm 1.0) \times 10^{-12}$      | $(1.9 \pm 0.5) \times 10^{-10}$  | 5.02135          |
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| 4FGL J1806.2-1347 | 15.5     | 3.5      | $(9.4 \pm 2.2) \times 10^{-12}$      | $(4.7 \pm 1.0) \times 10^{-10}$  | 7.76874          |
| 4FGL J2029.1-3050 | 12.3     | -33.4    | $(2.6 \pm 0.6) \times 10^{-12}$      | $(1.2 \pm 0.4) \times 10^{-10}$  | 7.99515          |
| 4FGL J2047.5+4356 | 83.9     | 0.3      | $(1.4 \pm 0.4) \times 10^{-11}$      | $(4.5 \pm 1.6) \times 10^{-10}$  | 5.17449          |
| 4FGL J2237.6-5126 | 339.8    | -55.0    | $(2.3 \pm 0.5) \times 10^{-12}$      | $(7.0 \pm 2.4) \times 10^{-11}$  | 0.714205         |
| 4FGL J2330.5-2445 | 35.8     | -71.7    | $(1.6 \pm 0.4) \times 10^{-12}$      | $(8.6 \pm 2.6) \times 10^{-11}$  | 8.69572          |

List containing the 14 candidates from the review

Stage L3 - LPTHE

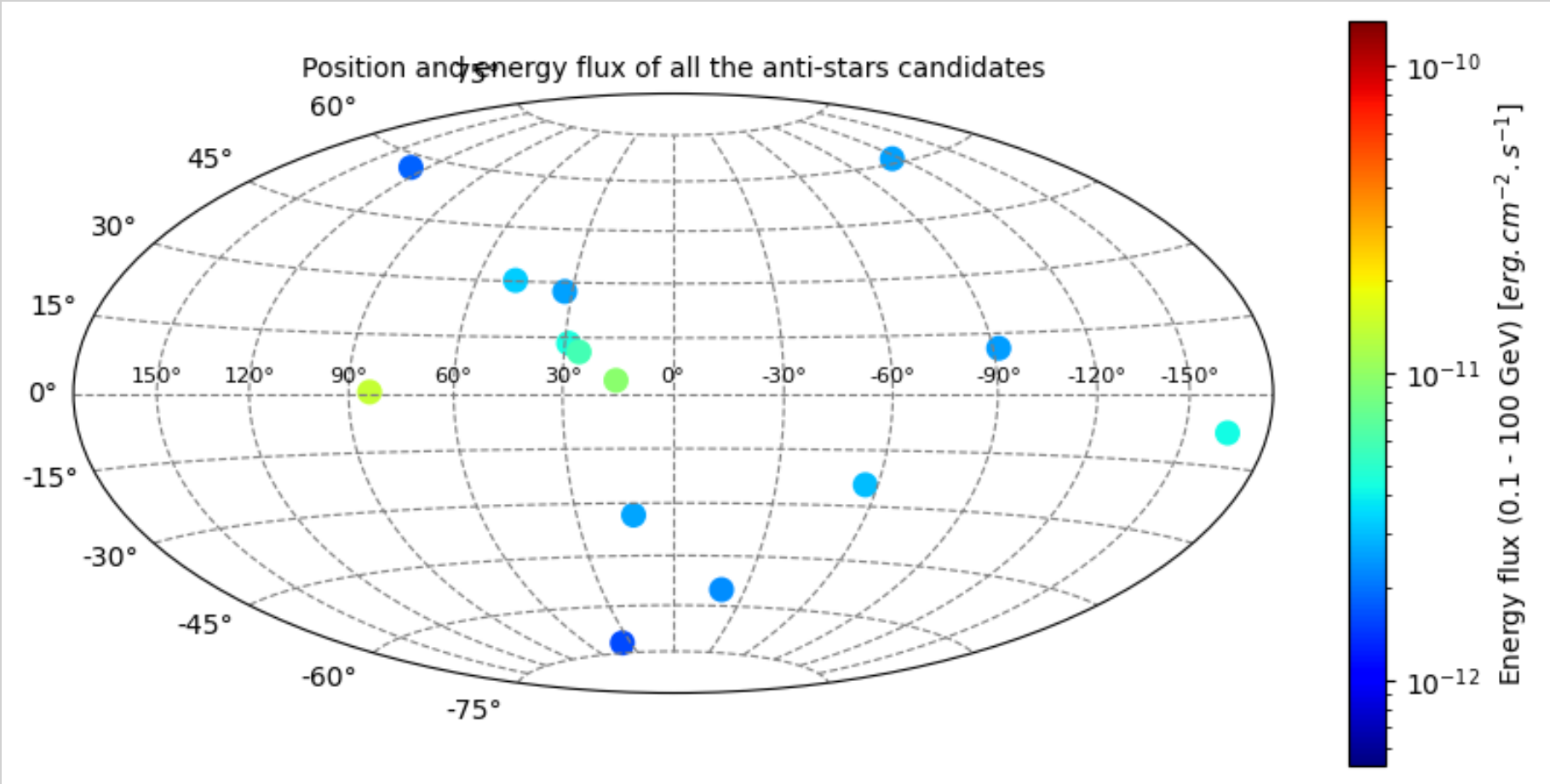
+31 nouveaux candidats

|    | Name              | <i>l</i> (longitude) | <i>b</i> (latitude) | <i>J</i> (0.1 - 100 GeV) | Flux (1 - 100 GeV) | TS (1 - 100 GeV) |
|----|-------------------|----------------------|---------------------|--------------------------|--------------------|------------------|
| 0  | 4FGL J0548.6+1200 | 194.9                | -8.1                | 4.2e-12                  | 2.0e-10            | 8.17001          |
| 1  | 4FGL J0948.0-3859 | 268.3                | 11.2                | 2.5e-12                  | 1.4e-10            | 3.17782          |
| 2  | 4FGL J1112.0+1021 | 243.8                | 61.2                | 2.5e-12                  | 6.0e-11            | 6.18527          |
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| 4  | 4FGL J1348.5-8700 | 303.7                | -24.2               | 3.0e-12                  | 9.3e-11            | 7.04146          |
| 5  | 4FGL J1710.8+1135 | 32.2                 | 27.5                | 2.5e-12                  | 4.8e-11            | 0.55213          |
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| 9  | 4FGL J1806.2-1347 | 15.5                 | 3.5                 | 9.4e-12                  | 4.7e-10            | 7.76874          |
| 10 | 4FGL J2029.1-3050 | 12.3                 | -33.4               | 2.6e-12                  | 1.2e-10            | 7.99515          |
| 11 | 4FGL J2047.5+4356 | 83.9                 | 0.3                 | 1.4e-11                  | 4.5e-10            | 5.17449          |
| 12 | 4FGL J2237.6-5126 | 339.8                | -55.0               | 2.3e-12                  | 7.0e-11            | 0.71421          |
| 13 | 4FGL J2330.5-2445 | 35.8                 | -71.7               | 1.6e-12                  | 8.6e-11            | 8.69572          |

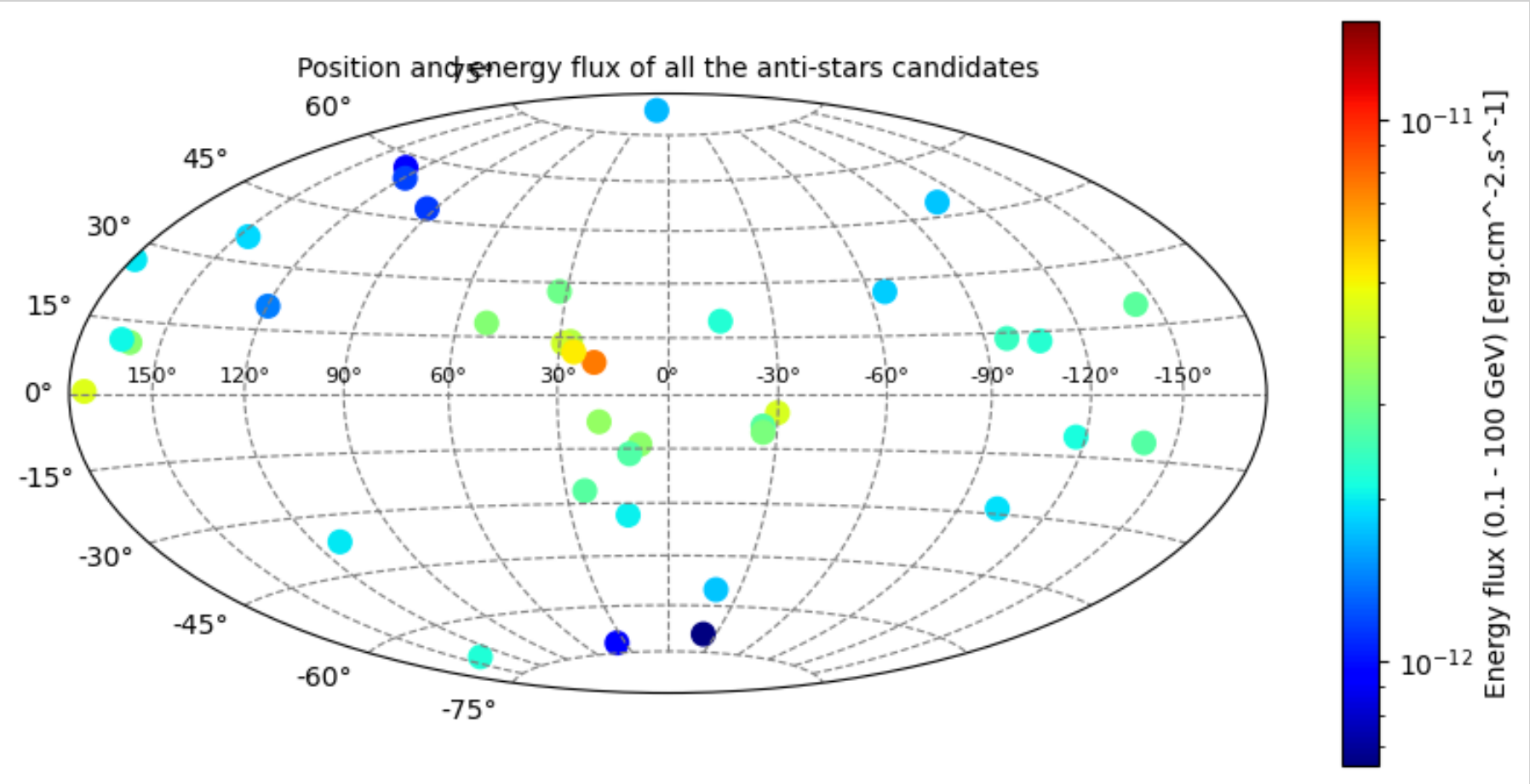
List containing the 14 candidates from the review  
With our code (Sorting of catalog)

2. Projet sur l'article

Positions et flux d'énergie

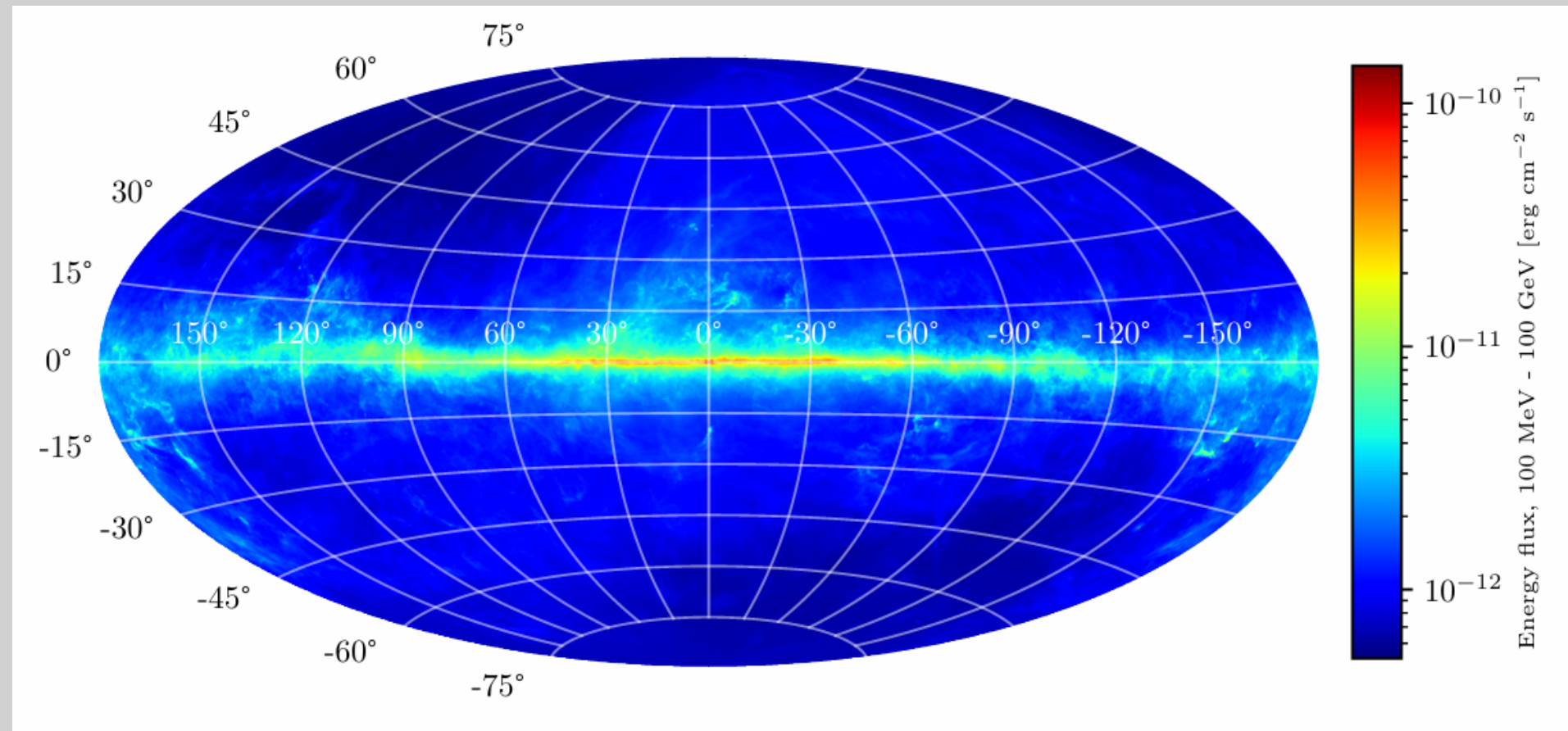


Catalogue 4FGL-DR2



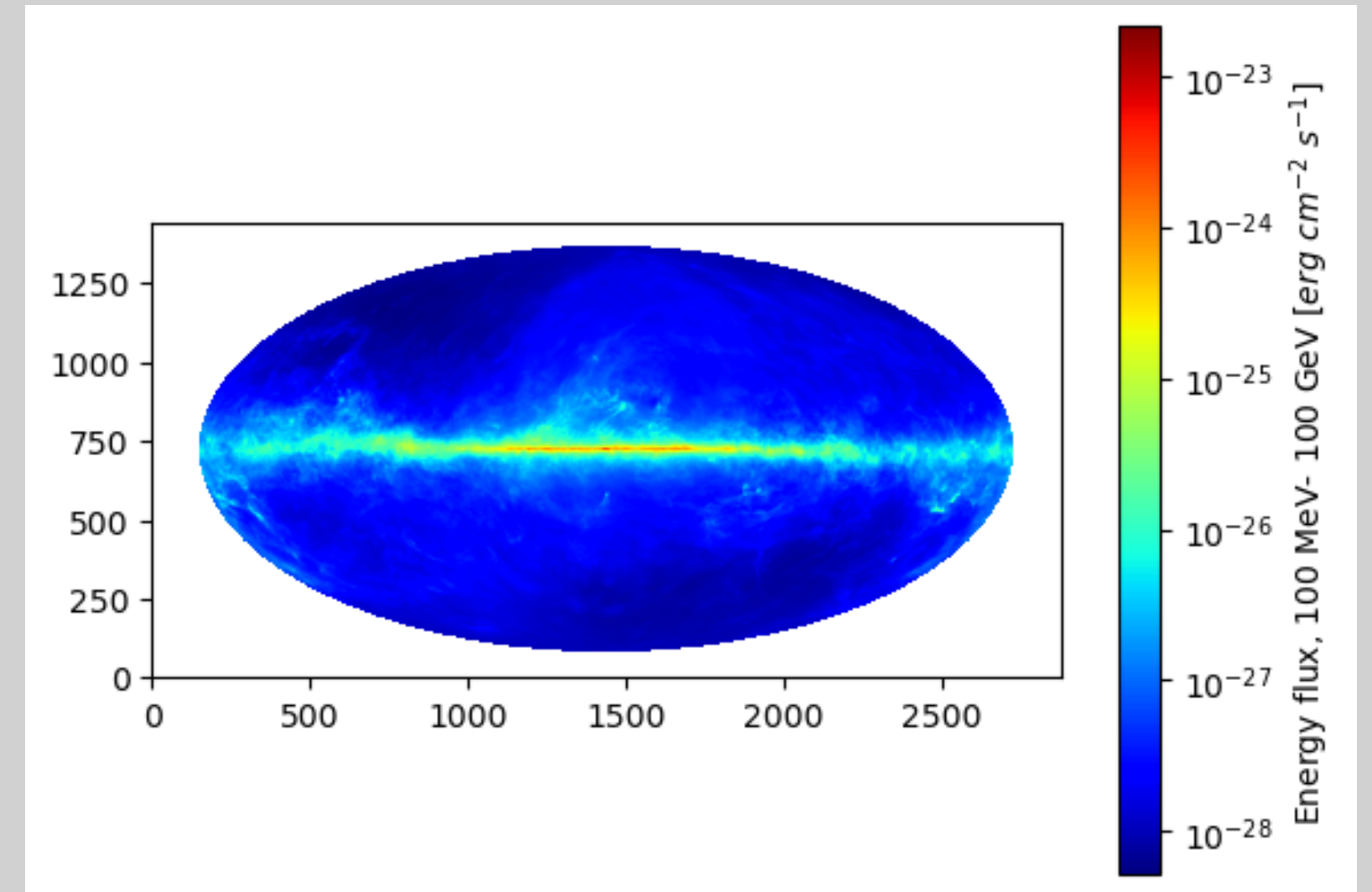
Catalogue 4FGL-DR4

## Sensitivity



*Galactic map of sensibility (article)*

Stage L3 - LPTHE



*Galactic map of sensibility obtained*

2. Projet sur l'article

## Détermination du flux d'anti-étoiles

→ We determine the population of anti-stars by their flux of gamma rays, for this we must first determine the brightness of the anti-stars

$$\Phi = \frac{L_{\gamma}}{4\pi d^2}$$

Flux

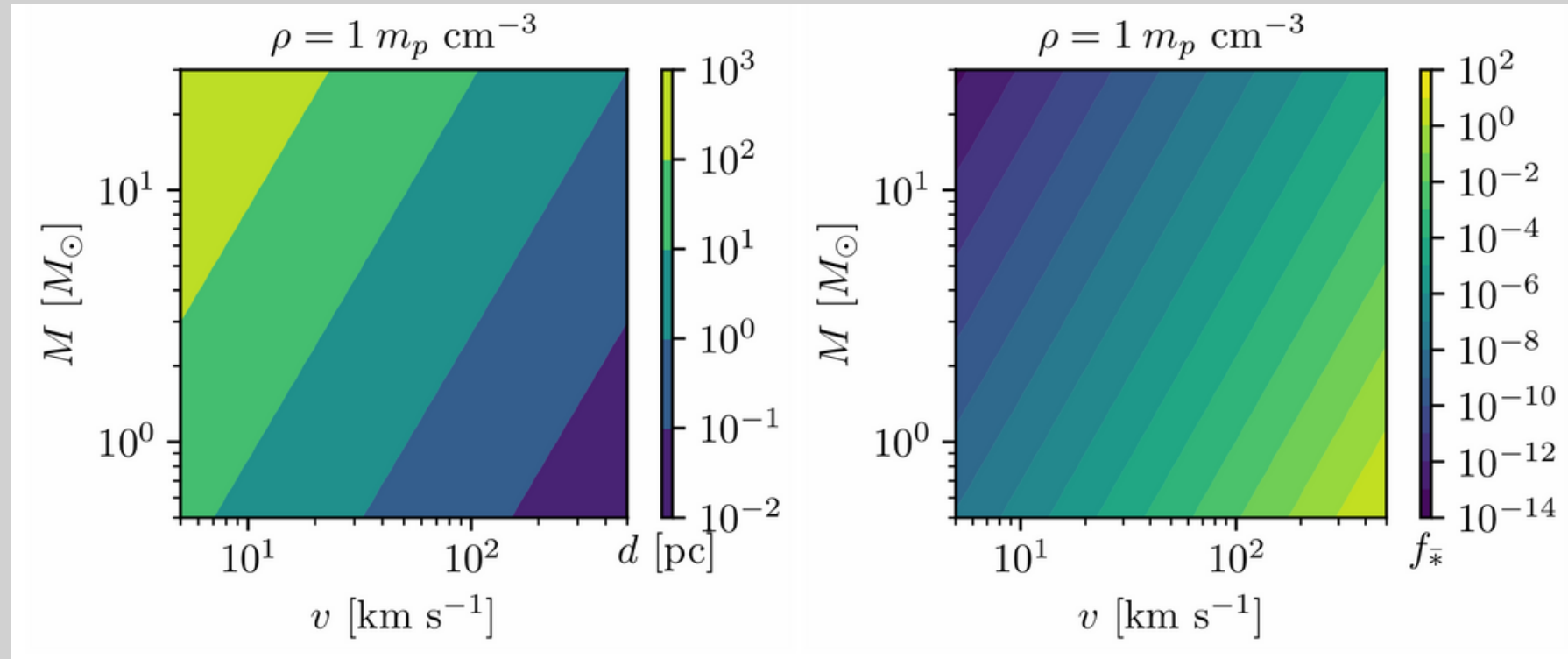
$$L_{\gamma} = 8.45 \cdot 10^{35} \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\rho}{m_p cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km \cdot s^{-1}} \right)^{-3} [ph \cdot s^{-1}]$$

Luminosité

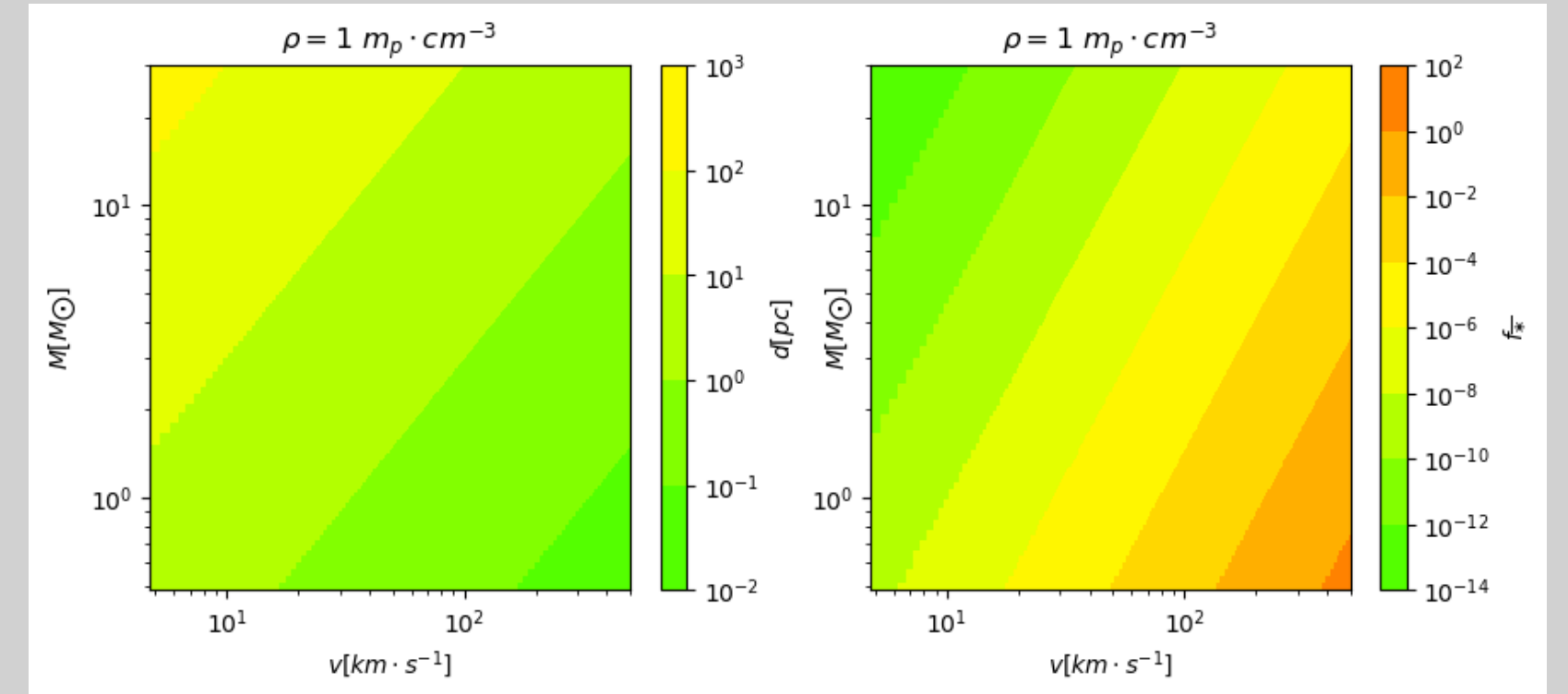
How do we stabilised this equation?

- Steigman
- Bondi-Hoyle-Littleton accretion

## Détermination du flux d'anti-étoiles



*Limit distances and fractions of the anti-stars in relation to certain parameters (graphs extracted from the article)*



*Limit distances and fractions of the anti-stars in relation to certain parameters (our results)*

$$f_* \leq 2.68 \times 10^3 \left( \frac{\Phi_{\max}}{\text{cm}^{-2} \text{ s}^{-1}} \right)^{3/2} \left( \frac{\rho}{\text{m}_p \text{ cm}^{-3}} \right)^{-3/2} \left( \frac{M}{M_\odot} \right)^{-3} \left( \frac{\sqrt{v^2 + c^2}}{10 \text{ km s}^{-1}} \right)^{9/2}$$

# THANK YOU FOR YOUR ATTENTION !

## References:

- Simon Dupourqué, Luigi Tibaldo, Peter von Ballmoos. “Constraints on the antistar fraction in the Solar system neighborhood from the 10-years Fermi Large Area Telescope gamma-ray source catalog”. Physical Review D, 2021, ·10.1103/PhysRevD.103.083016·. ·hal-03172556v3·
- G. Steigman, Observational tests of antimatter cosmologies, Annual Review of Astronomy and Astrophysics 14, 339 (1976).
- Bondi-Hoyle Littleton Accretion - PACS: 95.30.Lz, 97.10.Gz, 98.35.Mp, 98.62.Mw

## Détermination du flux d'anti-étoiles

[Photons/proton]

Variation de la masse de  
l'anti-étoile [Kg/sec]

$$L_{\gamma} = g_{\gamma} \underbrace{\frac{dM}{dt} \frac{1}{m_p}}_{\text{[Protons /sec]}}$$

## Détermination du flux d'anti-étoiles

$$L_\gamma = g_\gamma \frac{dM}{dt} \frac{1}{m_p} \xrightarrow{?} L_\gamma = 8.45.10^{35} \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\rho}{m_p cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km. s^{-1}} \right)^{-3}$$

- $g_\gamma$  compris entre 3,83 - 3,93
- $m_p = 1,67 \times 10^{-27}$
- $\frac{dM}{dt}$  reste à déterminer
- $8.45 \times 10^{35}$  reste à déterminer

## Détermination du flux d'anti-étoiles

$$L_\gamma = g_\gamma \frac{dM}{dt} \frac{1}{m_p} \xrightarrow{?} L_\gamma = 8.45.10^{35} \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\rho}{m_p cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km. s^{-1}} \right)^{-3}$$

Bondi-Hoyle-Littleton accretion :

$$\frac{dM}{dt} = 4\pi G^2 \frac{\rho_\infty}{m_p} M^2 (v_\infty + c_s)^{-\frac{3}{2}} \quad \text{avec} \quad \rho_\infty = m_p \eta_0$$

$$\frac{dM}{dt} = \left[ 4\pi (G M_{sol})^2 m_p (10 km. s^{-1})^{-3} (1. cm^{-3}) \right] \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\eta_0}{cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km. s^{-1}} \right)^{-3}$$
$$= 3.74.10^{11} g. s^{-1}$$

## Détermination du flux d'anti-étoiles

$$L_{\gamma} = g_{\gamma} \frac{dM}{dt} \frac{1}{m_p} \longrightarrow L_{\gamma} = 8.45.10^{35} \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\rho}{m_p cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km. s^{-1}} \right)^{-3}$$

On retrouve bien :

$$L_{\gamma} = 8.45.10^{35} \left( \frac{M}{M_{sol}} \right)^2 \left( \frac{\rho}{m_p cm^{-3}} \right) \left( \frac{\sqrt{v^2 + c_s^2}}{10 km. s^{-1}} \right)^{-3}$$