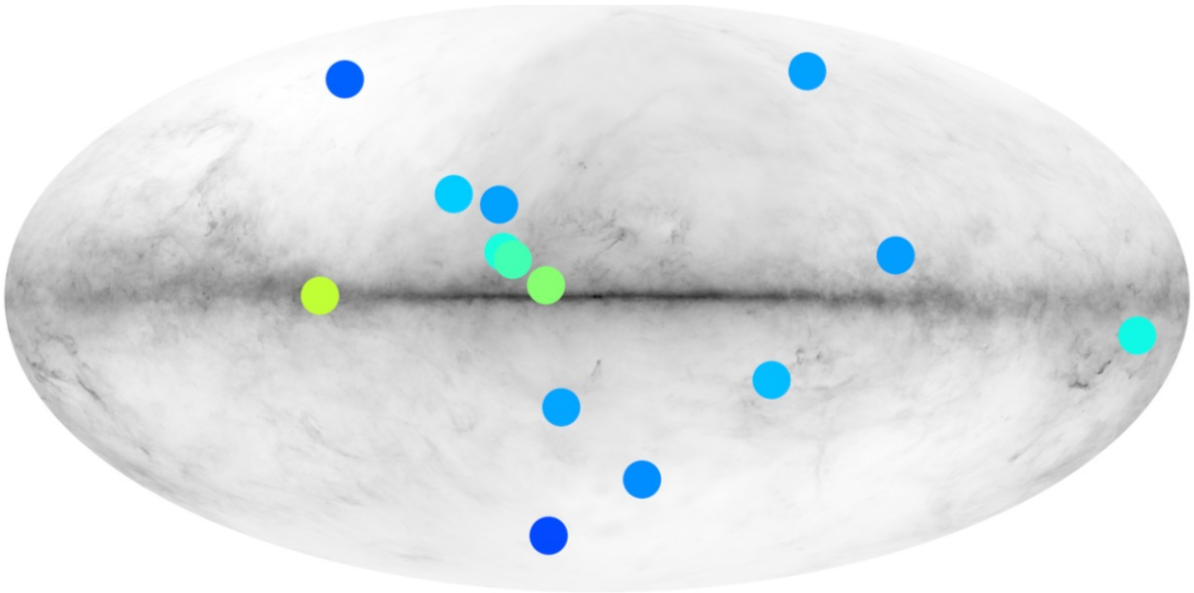
Search for matter-antimatter annihilation features in the Universe

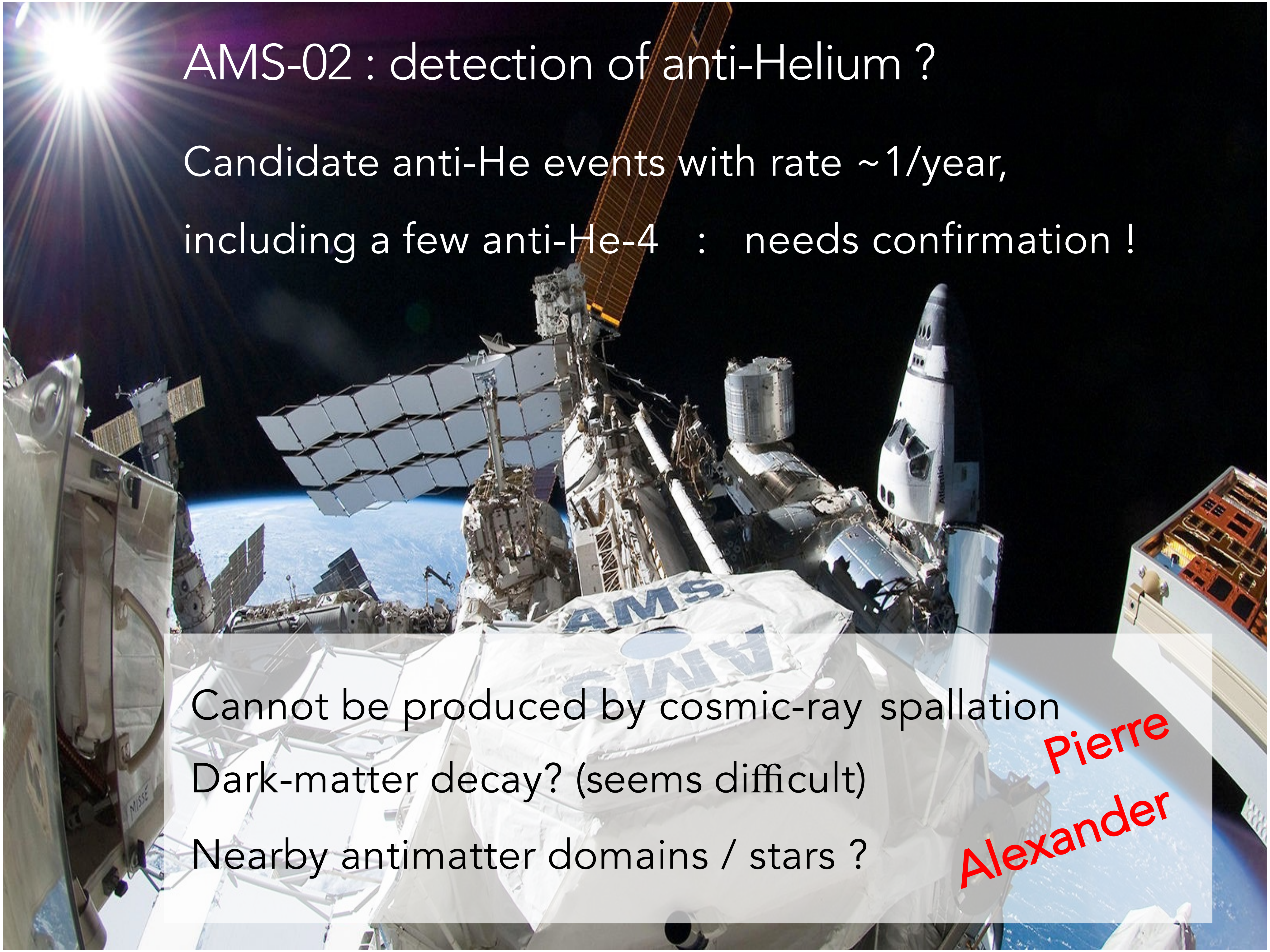


Peter von Ballmoos, IRAP Toulouse

AMS-02 : detection of anti-Helium ?

Candidate anti-He events with rate ~1/year,

including a few anti-He-4 : needs confirmation !



Cannot be produced by cosmic-ray spallation

Dark-matter decay? (seems difficult)

Nearby antimatter domains / stars ?

Pierre Alexander

A nearby antimatter domain?

The discovery of a single anti-helium nucleus in the cosmic-ray flux would definitely point toward the existence of stars and even of entire galaxies made of anti-matter

Salati et al. Nucl. Phys. B 70 1–3 1999

Anticlouds or antistars

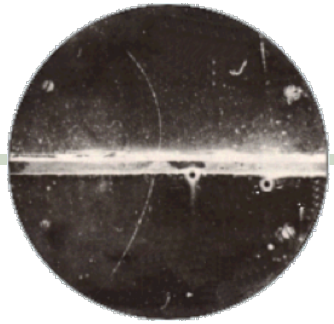
Challenge #1: how do they form? (e.g. Affleck-Dine mechanism)

Challenge #2: how do they manage to survive?

Antistars in galactic halos accrete matter slowly enough to survive!

Challenge #3: how are the antinuclei accelerated?

Detecting Cosmic Animatter



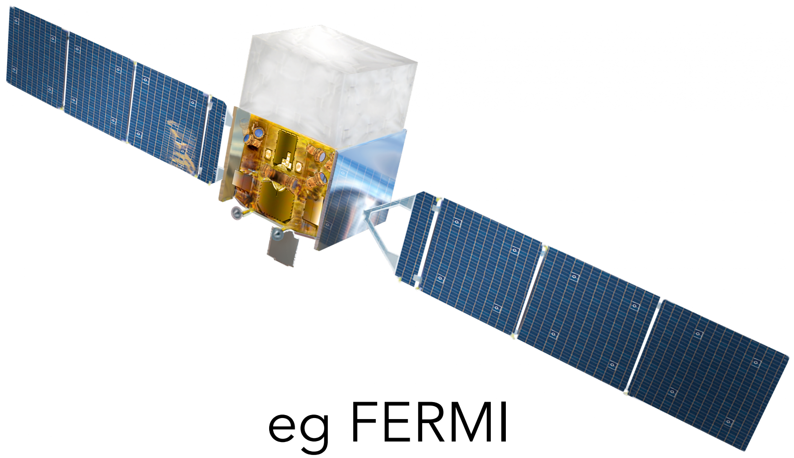
direct detection

- positrons, baryons
- as a cosmic ray component
- magnetic spectrometers

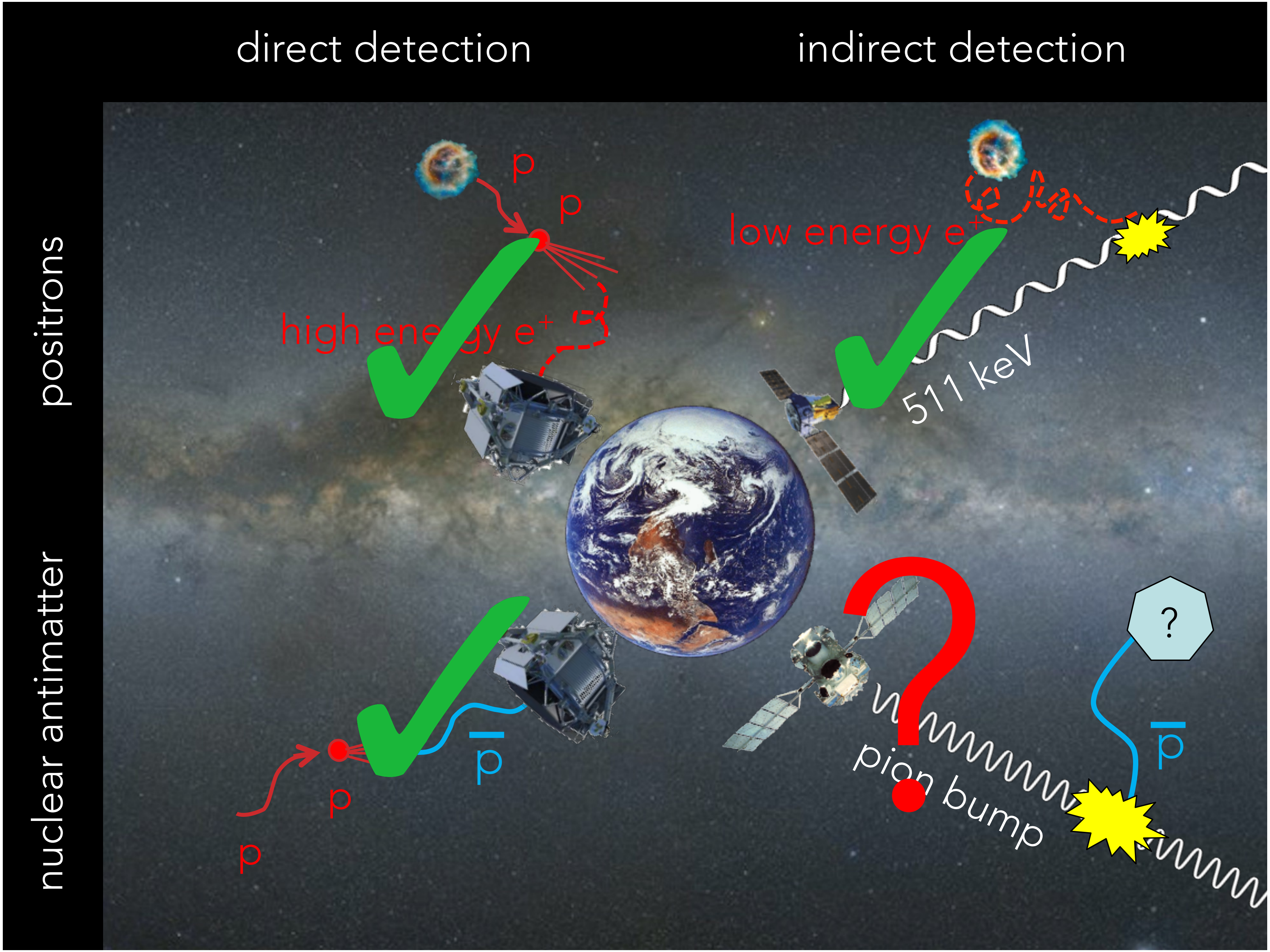
eg AMS-02

indirect observation

- positrons, (baryons)
- through annihilation signatures
- gamma-ray telescopes



eg FERMI


direct detection
indirect detection
positrons
nuclear antimatter
p
p
high energy e+
low energy e+
511 keV
p
p
p̄
pion bump
?
p̄

gamma rays from nucleon-antinucleon annihilation

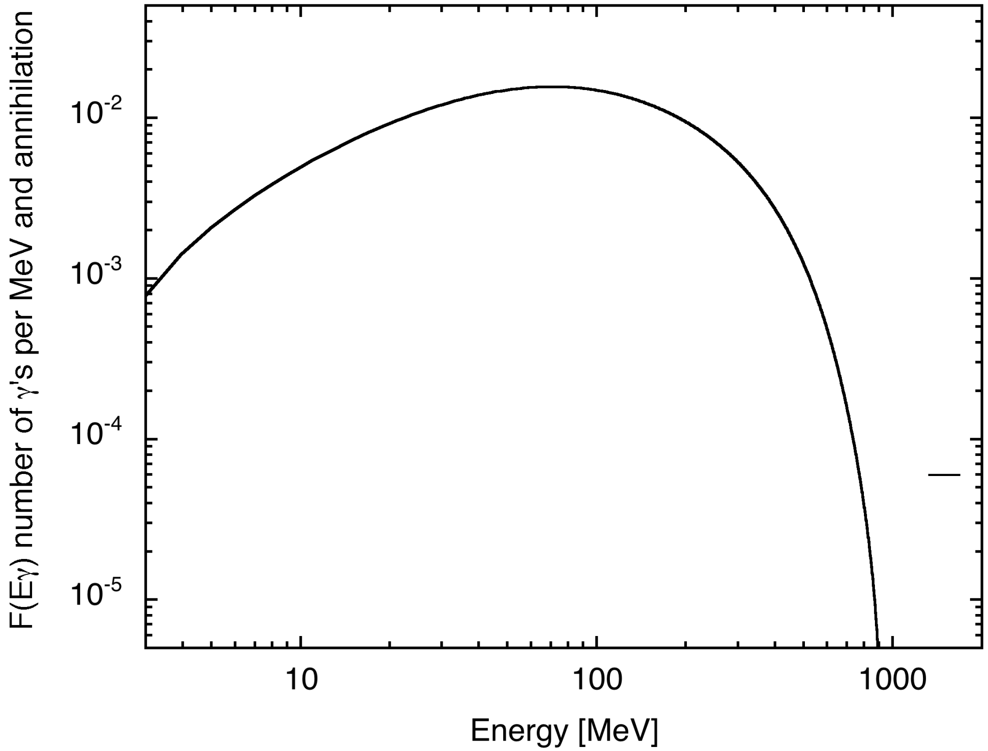
$$N - \bar{N} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \end{cases}$$

$\gamma + \gamma$ 1/3 of $2m_Nc^2$ ⟶ 200 MeV γ's

$$\hookrightarrow \pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_\mu) + \nu_\mu(\bar{\nu}_\mu)$$

1/2 of $2m_Nc^2$ ⟶ ν's

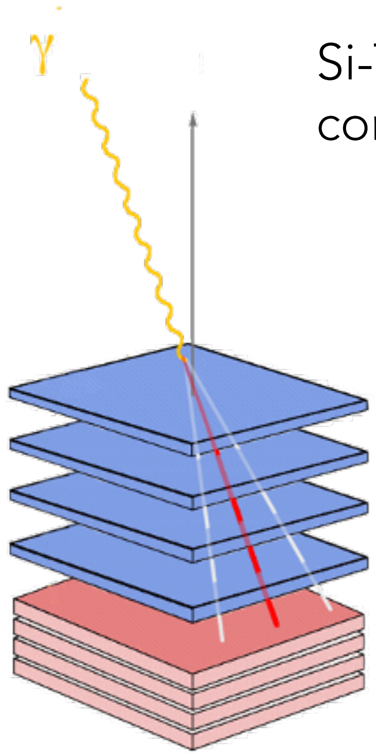
1/6 of $2m_Nc^2$ ⟶ e^-, e^+ (100 MeV)

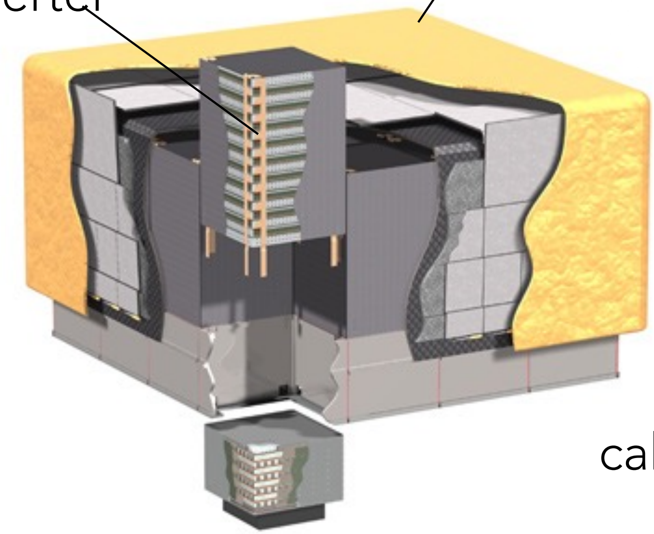


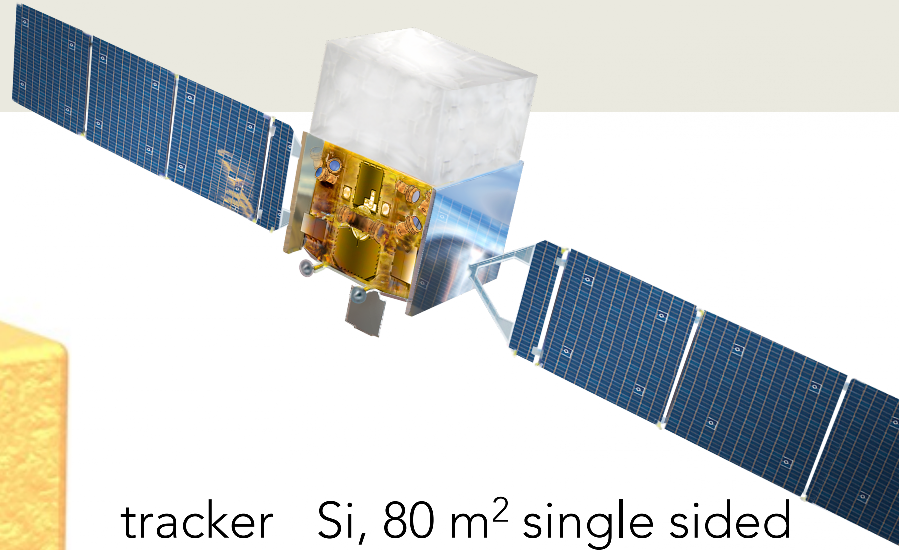
typical rest-frame spectrum produced by p-p annihilation with π° decay

maximum intensity at $m_\pi c^2/2$ ~ 70 MeV

FERMI/ LAT





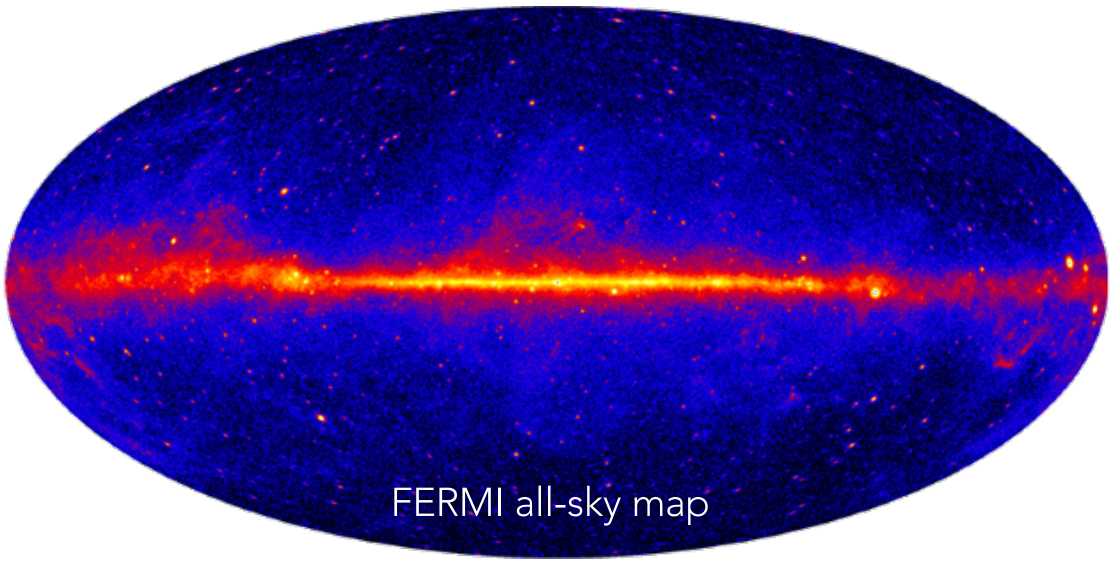


tracker	Si, 80 m^2 single sided
	W foil interleaved
	4 x 4 x 18 xy planes
calorimeter	1536 CsI crystals
	8.6 R.L, hodoscopic
mass	2789 kg

pair-conversion telescope

performance

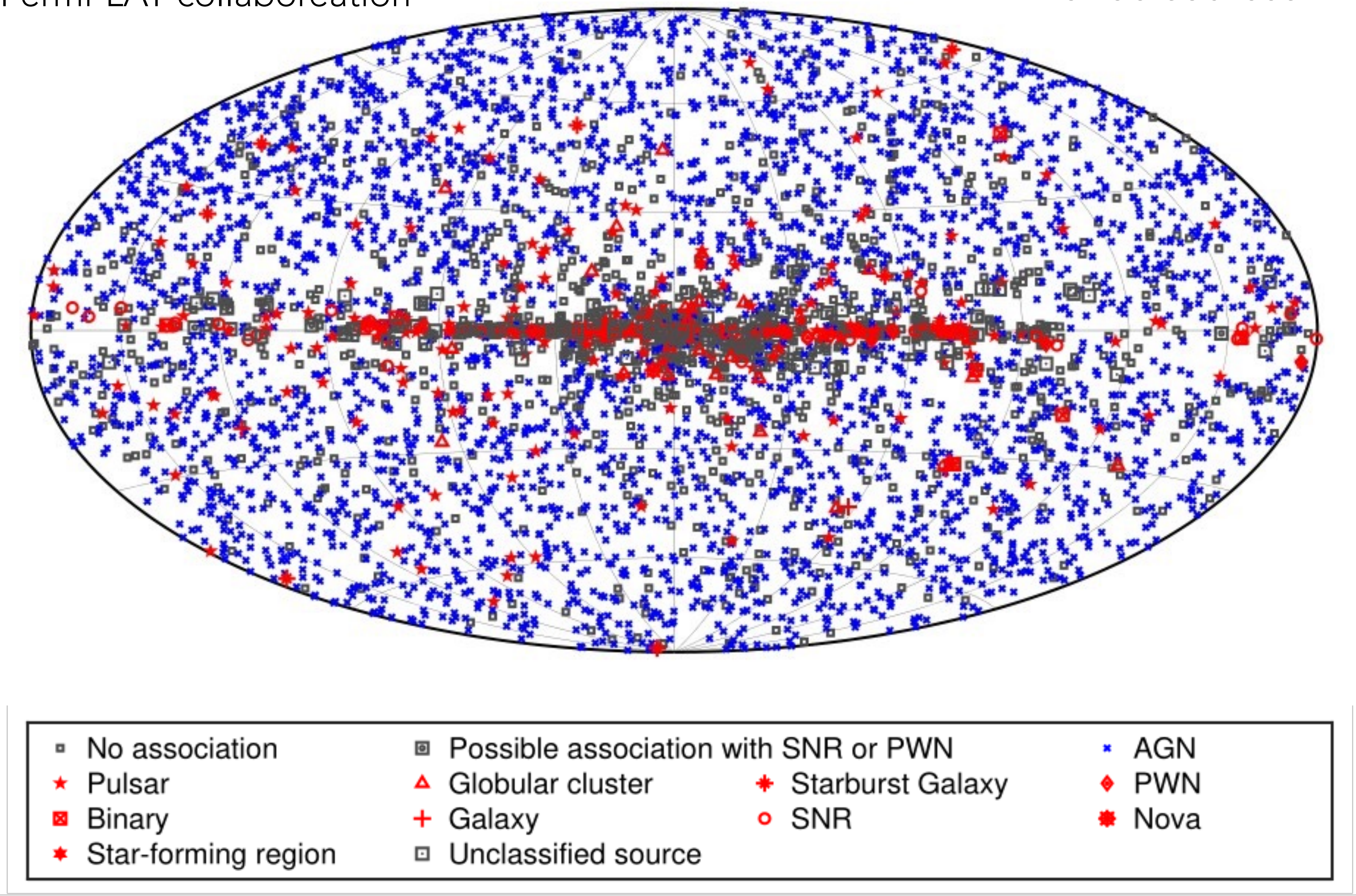
Energy	0.1– 300 GeV
Field of view	2.4 steradian
angular res.	3° - 0.04°
Eff. area	7000 cm^2 (1GeV)
E/ΔE :	6 - 18% (1σ)



FERMI LAT 10-year Source Catalog (50 MeV - 1 TeV)

Fermi-LAT collaboreation

5788 sources



Antistar candidates : selection criteria, selected candidates

Exclusion criteria

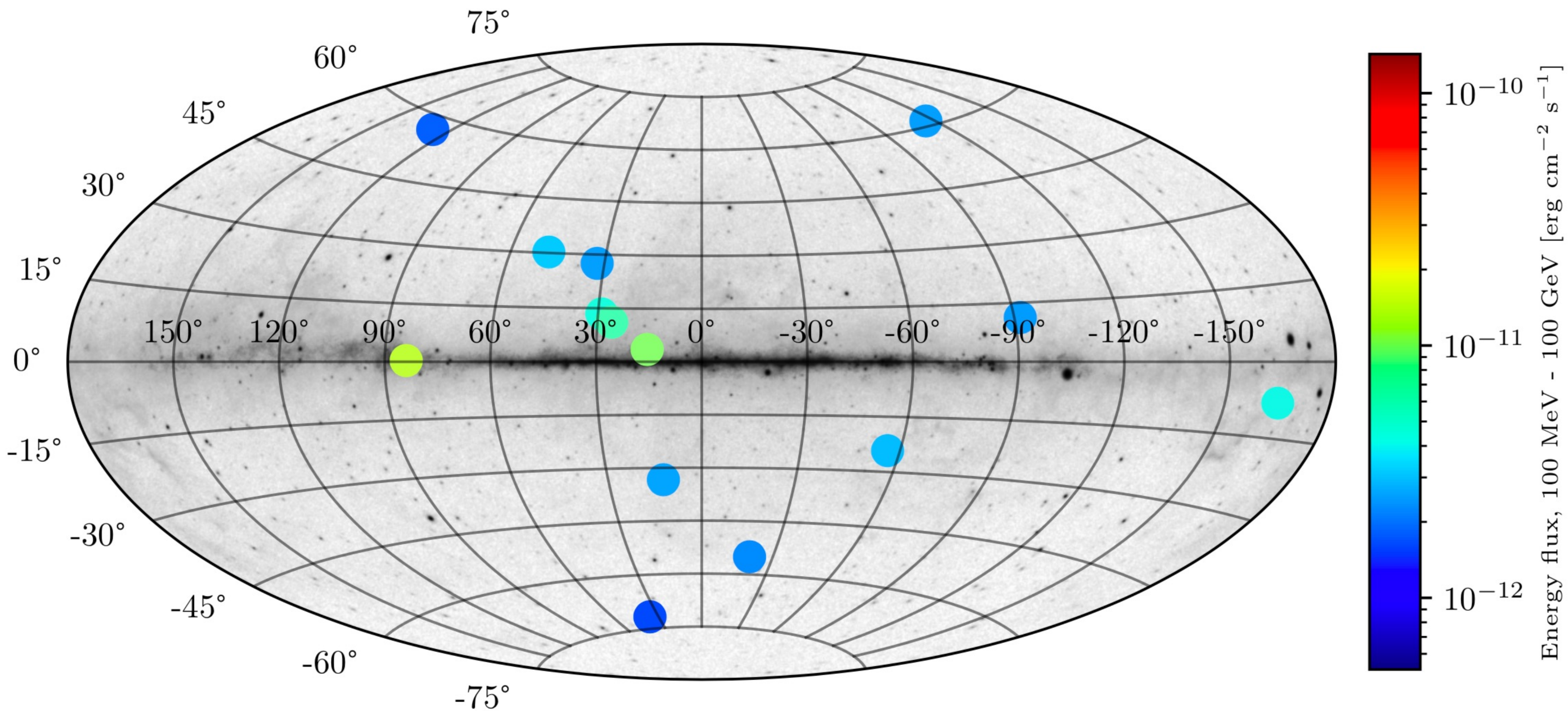
1. Extended sources
2. Not associated
3. Significance $> 3\sigma$ for $E > 1$ GeV
4. Flagged sources

14 candidates
for 5788 sources

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	$(1.6 \pm 0.4) \times 10^{-12}$

=> upper limits on antistar fraction/density

Antistar candidates : what are they ?



Properties

- no clear pattern on the sky
- weak sources close to the detection threshold

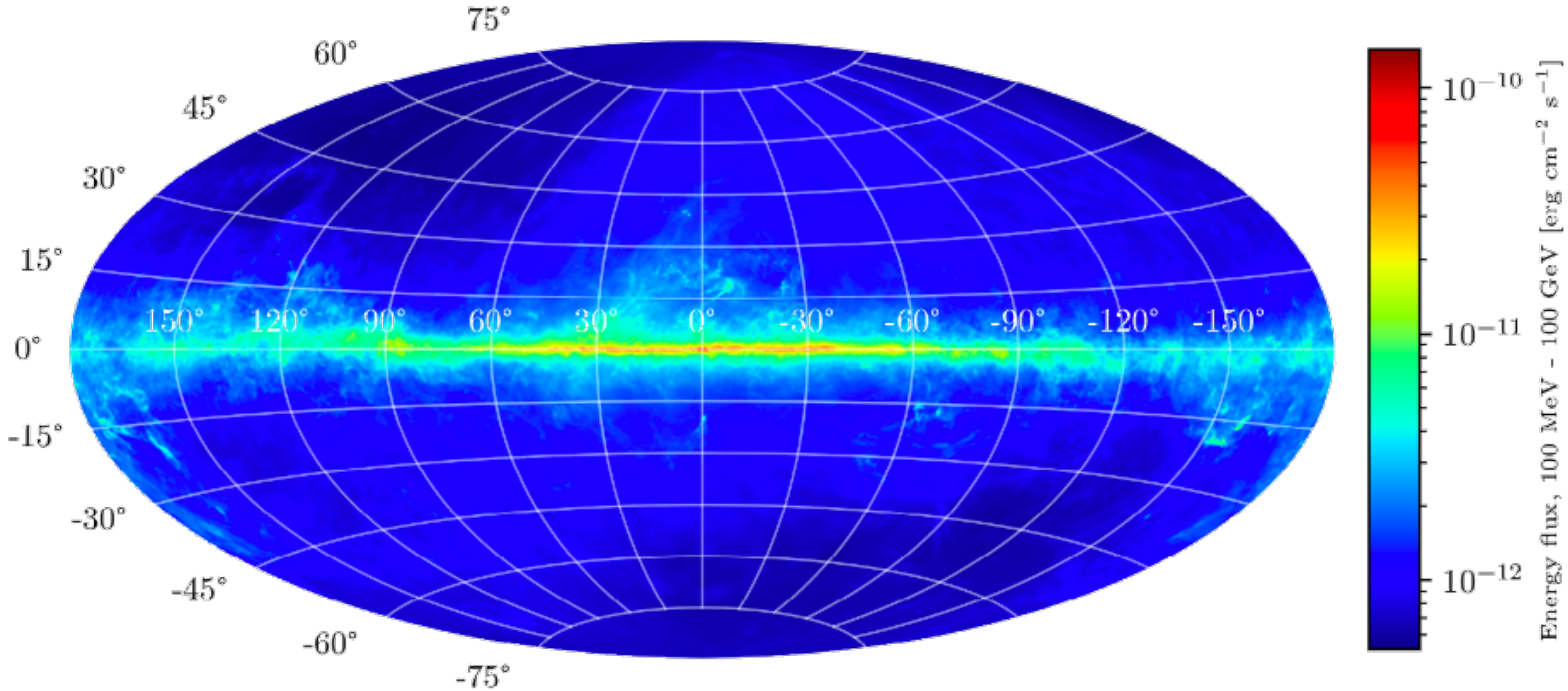
Alternatives explanations

- unknown pulsars
- AGNs
- defect of interstellar emission model

FERMI / LAT sensitivity to antistars

Input

- instrument response functions
- background model
- matter-antimatter annihilation spectrum

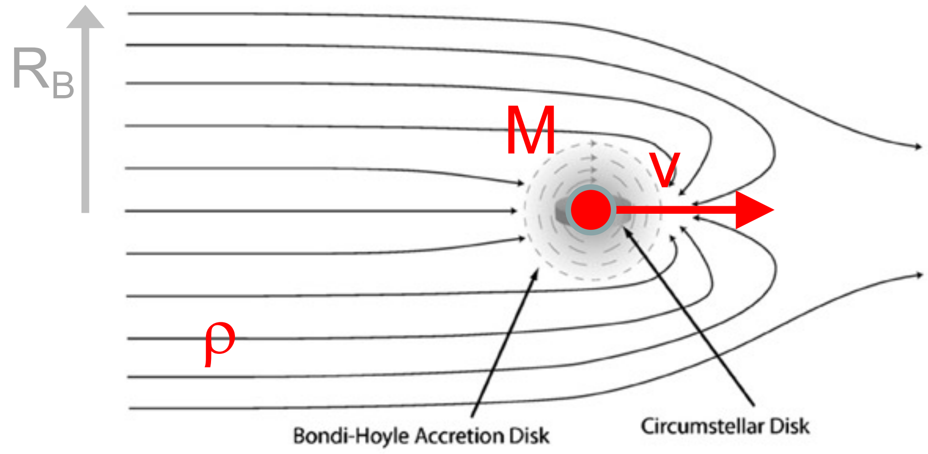


minimum antistar flux detectable by FERMI/LAT

Antistar luminosity

Bondi-Hoyle accretion

proton-antiproton annihilation



matter density — antistar mass — antistar speed w.r.t. surrounding matter — Sound speed

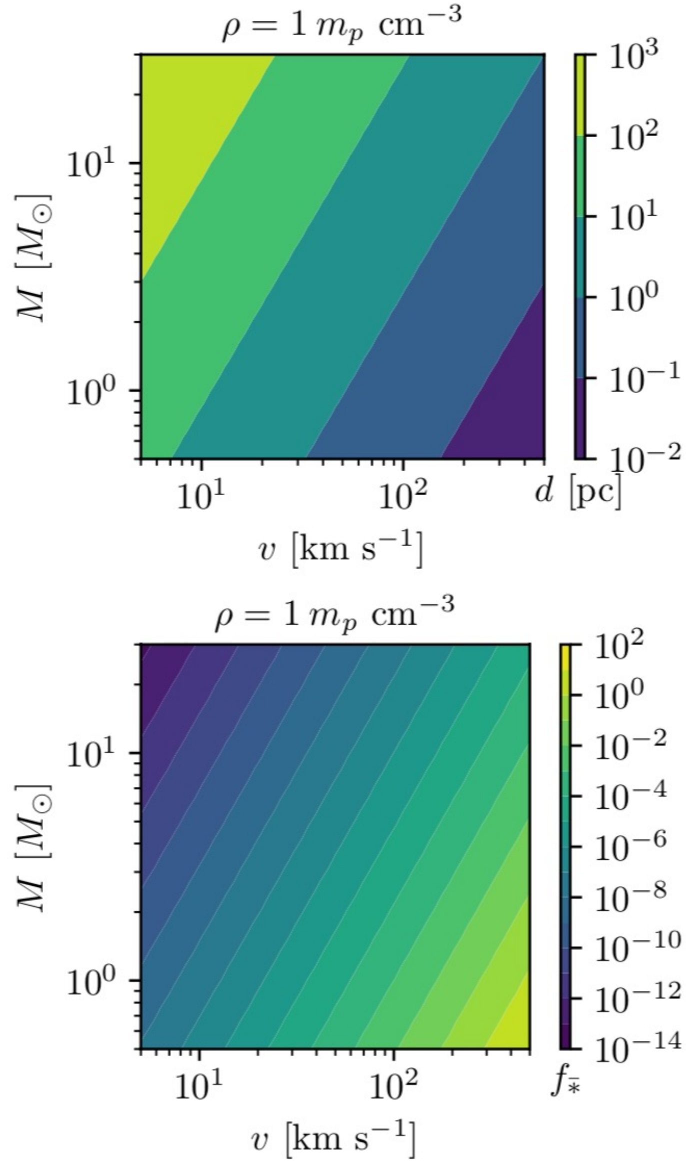
$$L_\gamma = 8.45 \times 10^{35} \left(\frac{\rho}{m_p\,\mathrm{cm}^{-3}}\right)\left(\frac{M}{M_\odot}\right)^2 \left(\frac{\sqrt{v^2+c^2}}{10\,\mathrm{km\,s^{-1}}}\right)^{-3}\ \mathrm{ph\,s^{-1}}$$

ρ and galactic rotation curve obtained from models, $c \simeq 1$ km s^{-1}

1) Parametric method (Steigmann 1976)

Antistars have the same position, mass, velocity distribution as normal stars

- brightest candidate = closest antistar
- hypothesis on mass and speed → distance
- at most one antistar in the defined volume

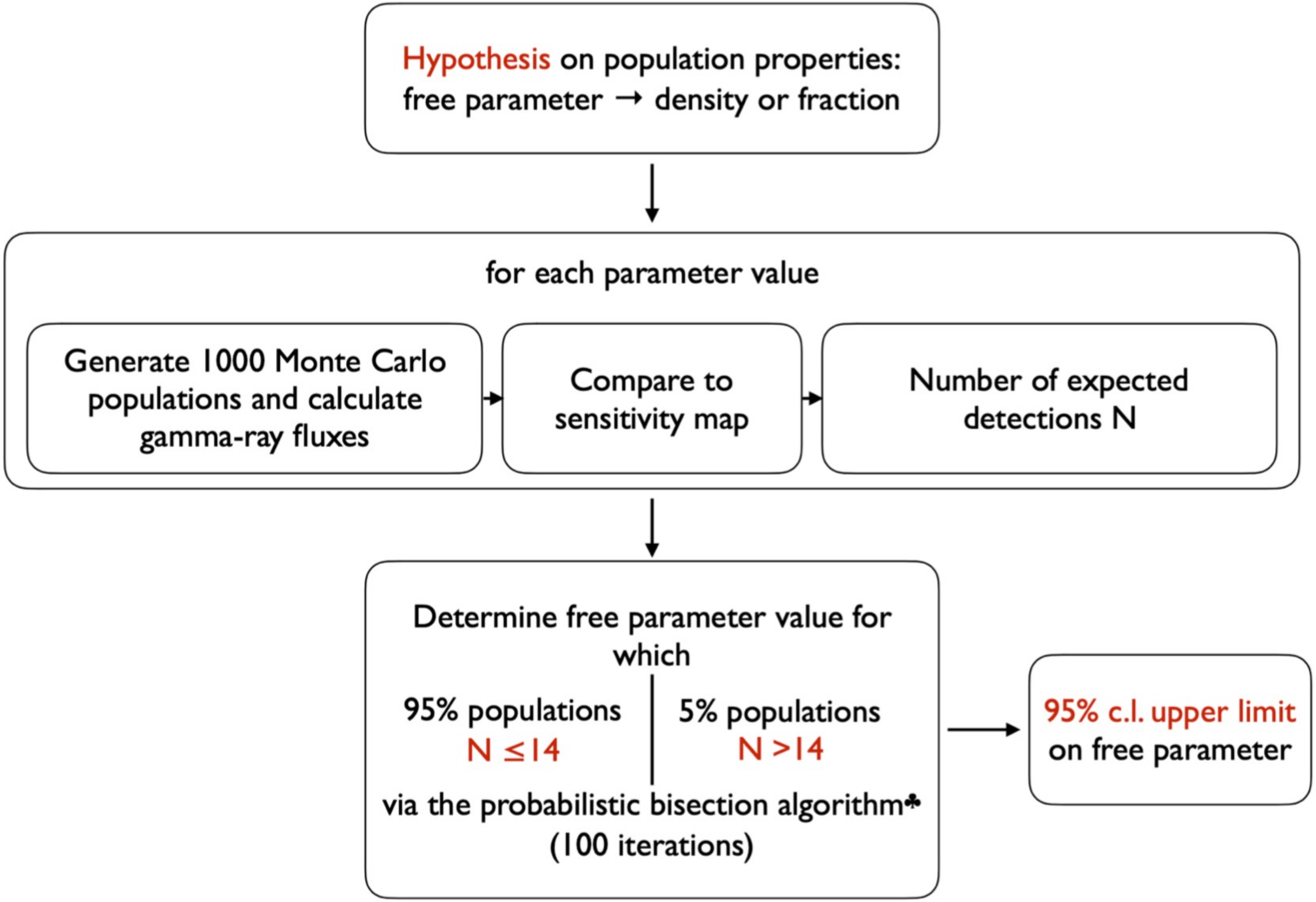


Limitations

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

Steigman, G. Observational Tests of Antimatter Cosmologies
Annual Review of.Astronomy and Astrophysics.14,.339.–37.2

2) Monte Carlo method



Hypothesis I : star-like distribution

Same spatial, mass, and velocity distribution as stars

- no physical justification

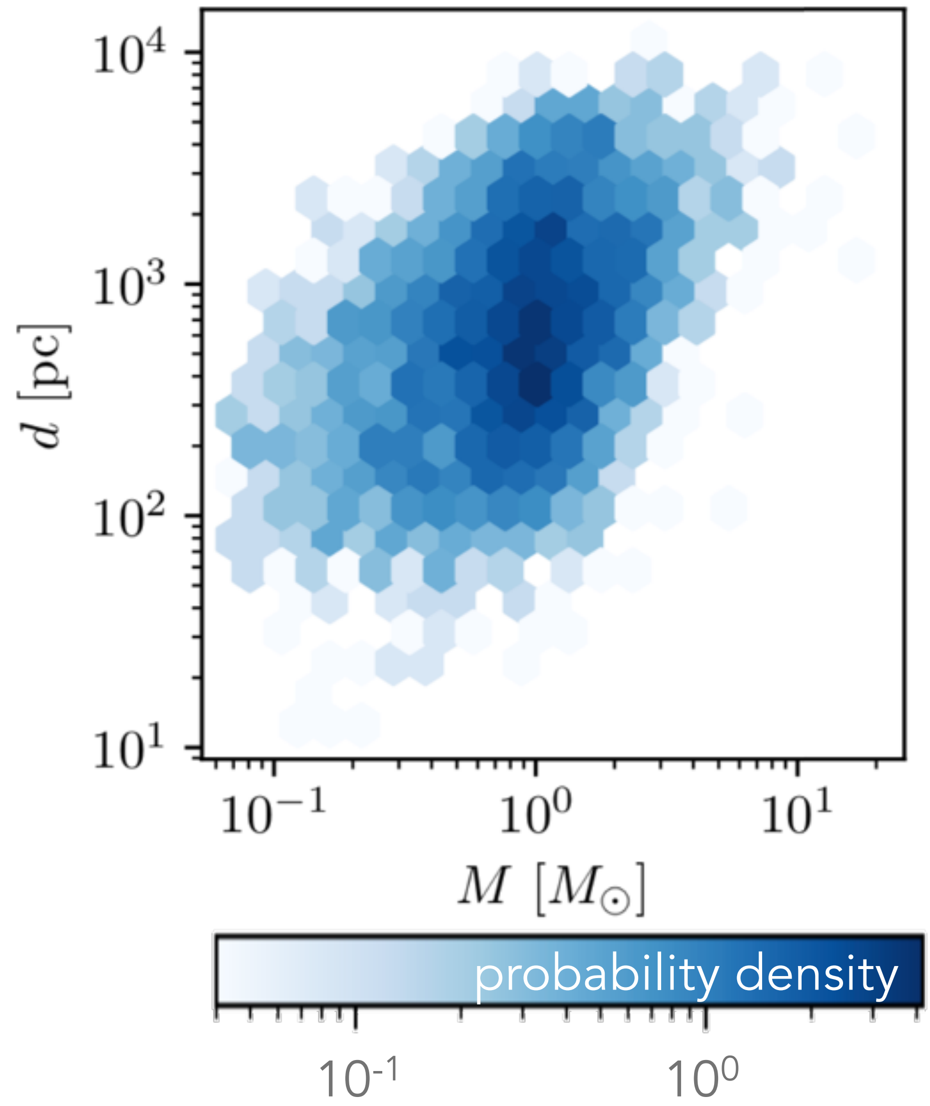
- compare with earlier results

`galaxya` stellar population synthesis code

$f_{\bar{*}} < 2.5 \times 10^{-6}$ (95 % c.l.)

Steigmann 1976 < 10^{-4}

von Ballmoos 2014 < 4×10^{-5}



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

Hypthesis II: primordial antistars

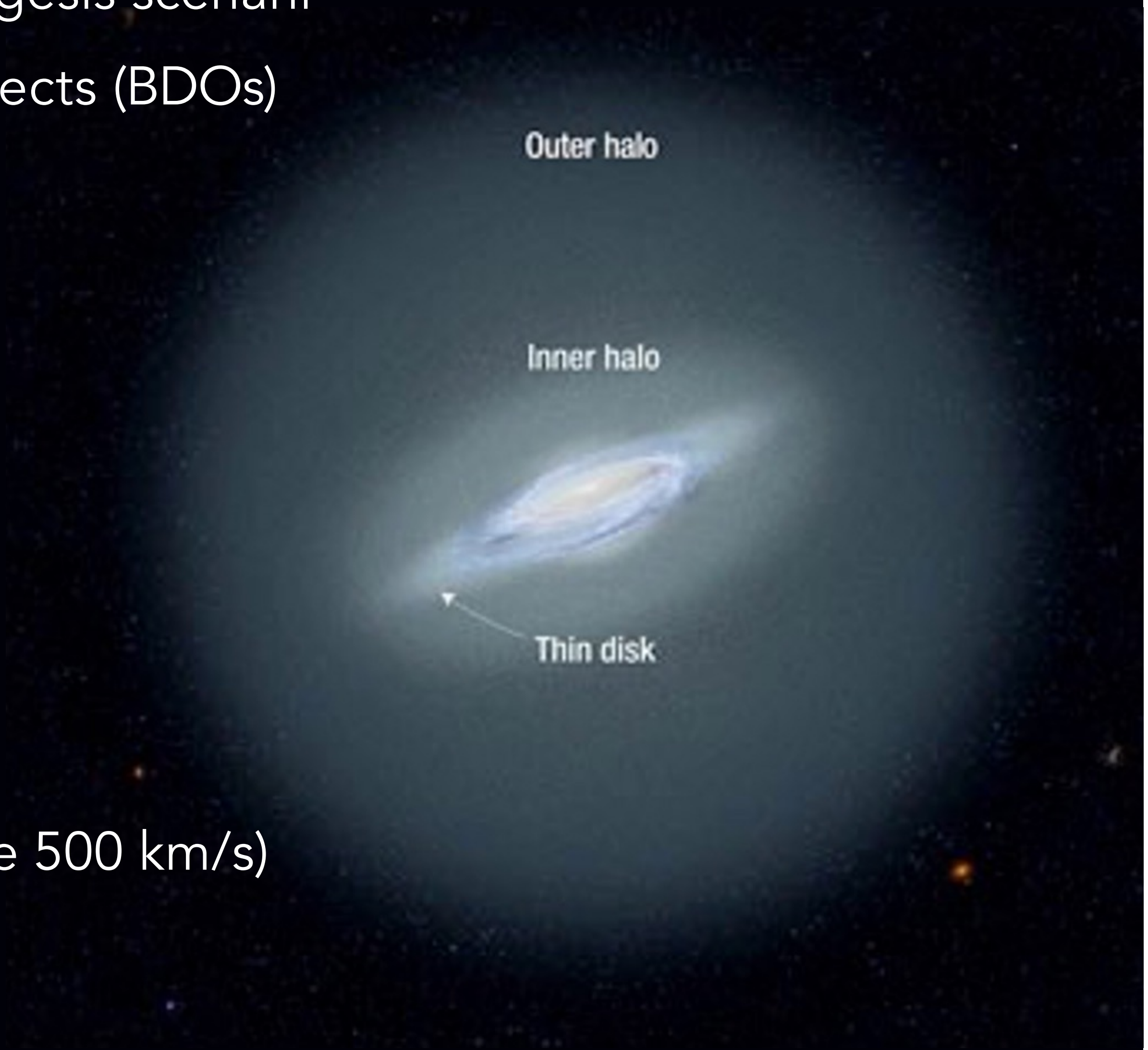
Expected in some baryogengesis scenarii

Subclass of baryo-dense objects (BDOs)

aka MACHOs studied

as dark-matter candidates

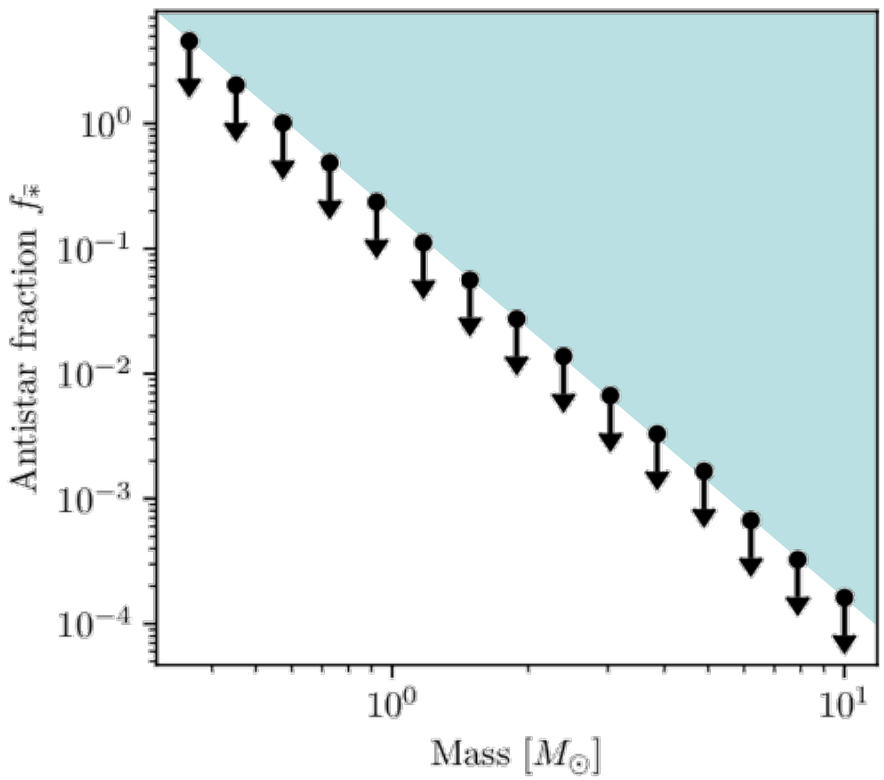
Milky Way halo structure

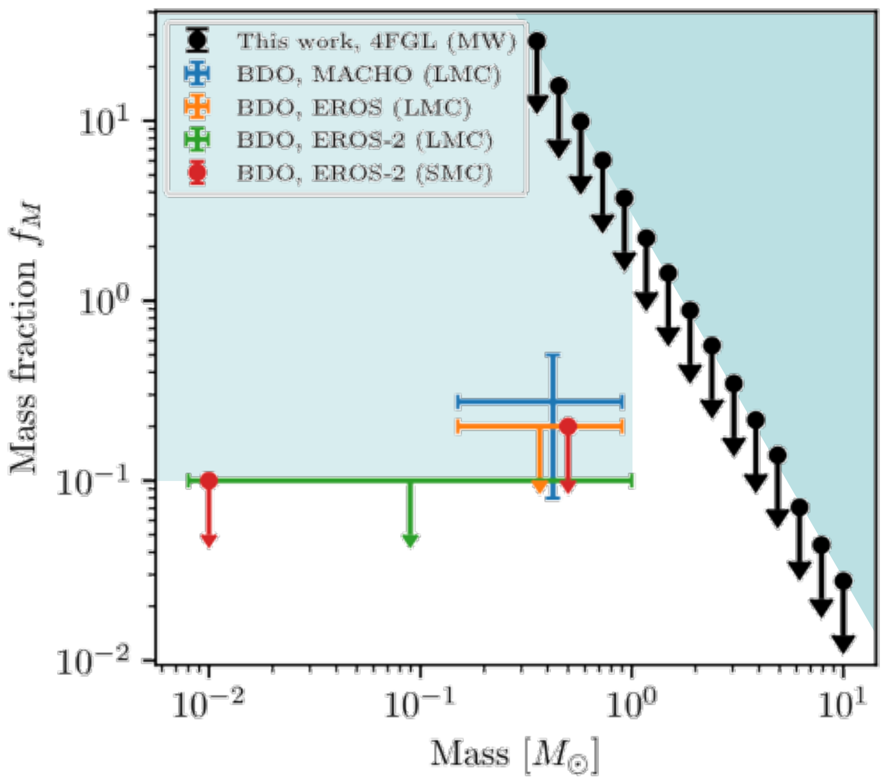


Properties

- uniform spatial distribution
- high velocities (typical value 500 km/s)
- unknown mass

Hypthesis II: primordial antistars





FERMI detection < 60 pc

we can not exclude large numbers in the halo

Mass fraction to compare with microlensing results:
new results in the unexplored mass range > 2 M⊙

What's next?

- deeper Fermi-LAT catalogs: 12-year catalog
- dedicated spectral analysis of source candidates (pion bump)
- multiwavelength data to rule out antistar nature of candidates
    - 4FGL J1721.4+2529 already identified as active galactic nucleus via optical spectroscopy
    - 4FGL J1806.2-1347 has a bright radio counterpart
    - more optical and radio observations on the way

Summary and conclusions

Antistars get renewed attention due to the possible detection of anti-Helium

Upper limits on fraction/density of nearby antistars improved by an order of magnitude

The limits can be further improved by deeper Fermi LAT catalogs and multiwavelength observations …

… or even more with a new telescope optimized in the MeV-GeV energy range (COSI, Astrogam, AMEGO)

the end

well, not quite

one more thing :

Matter - Antimatter Asymmetry

what is ***your*** prefered scenario
for the baryon asymmetry ?

bau

Baryo- or Lepto-genesis

Baryon asymmetry is created from a matter–antimatter symmetric initial state : baryon-generating interactions produce matter and antimatter at different rates. The three necessary "Sakharov conditions" (1967) are:

Baryon Number Violation

obvious : $B=0_{(T >> 1\ \mathrm{MeV})} \rightarrow B\neq 0$

Violation of C and CP

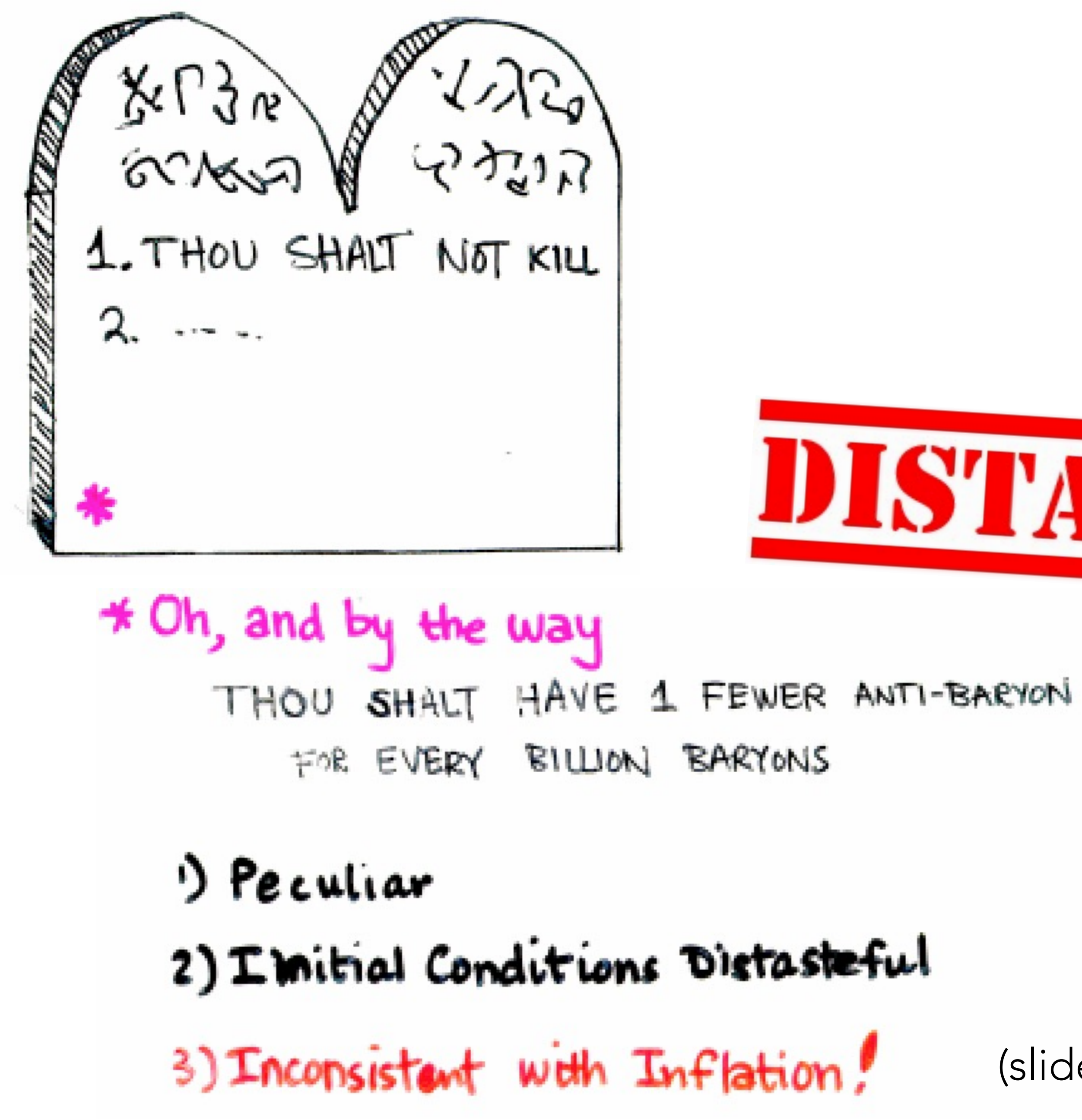
K_L° physics (~ 10^{-3} effect)

by a majority of the physics community

Departure from thermal equilibrium

Universe expands and cools off with time
this is a departure from thermal equilibrium.

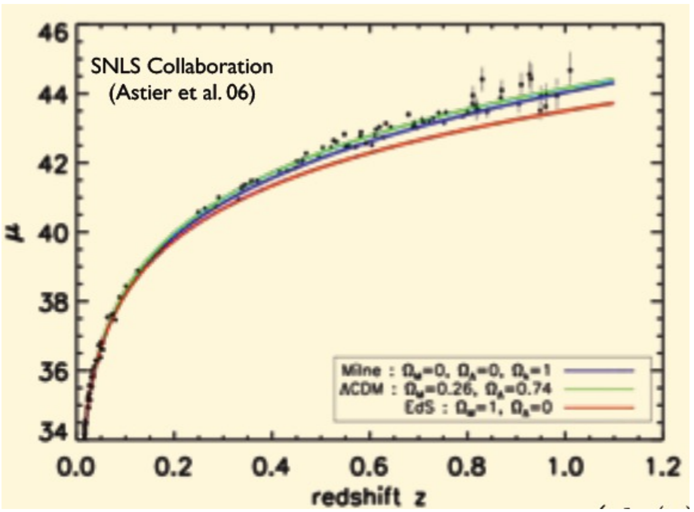
Baryon Asymmetry – an initial condition



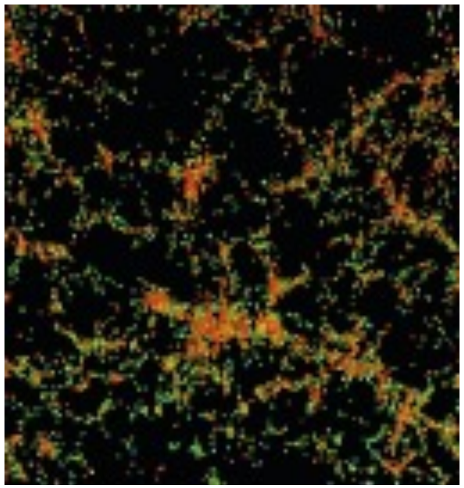
(slide by A. Cohen, 1999)

Dirac-Milne Universe

– Matter-antimatter symmetric universe
– Matter and antimatter repel each other
– Linear expansion factor, $a(t) \sim t$ (Milne)
– Solves horizon problem (no inflation)
– No need for dark matter/energy
– Cosmological tests :



SN1a

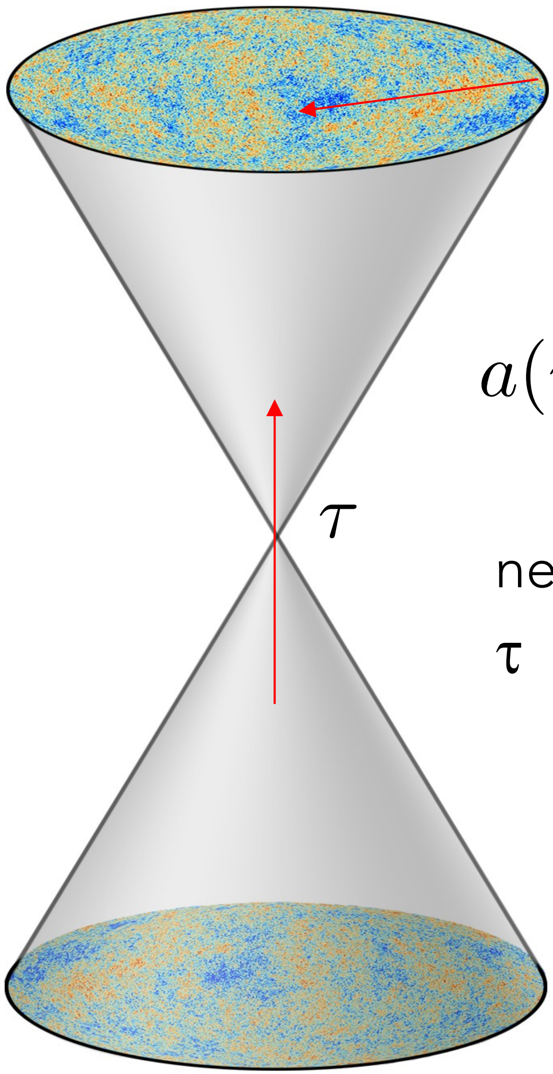


stucture formation

.....

A. Benoit-Levy and G. Chardin, Astron. Astroph. (2012)

CPT Symmetric Universe



$a(\tau)$

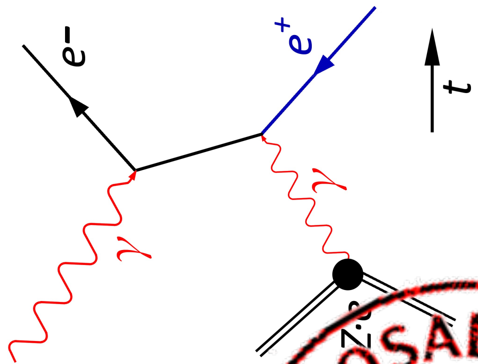
$a(\tau) \propto \tau$

τ

new isometry

$\tau \rightarrow -\tau$

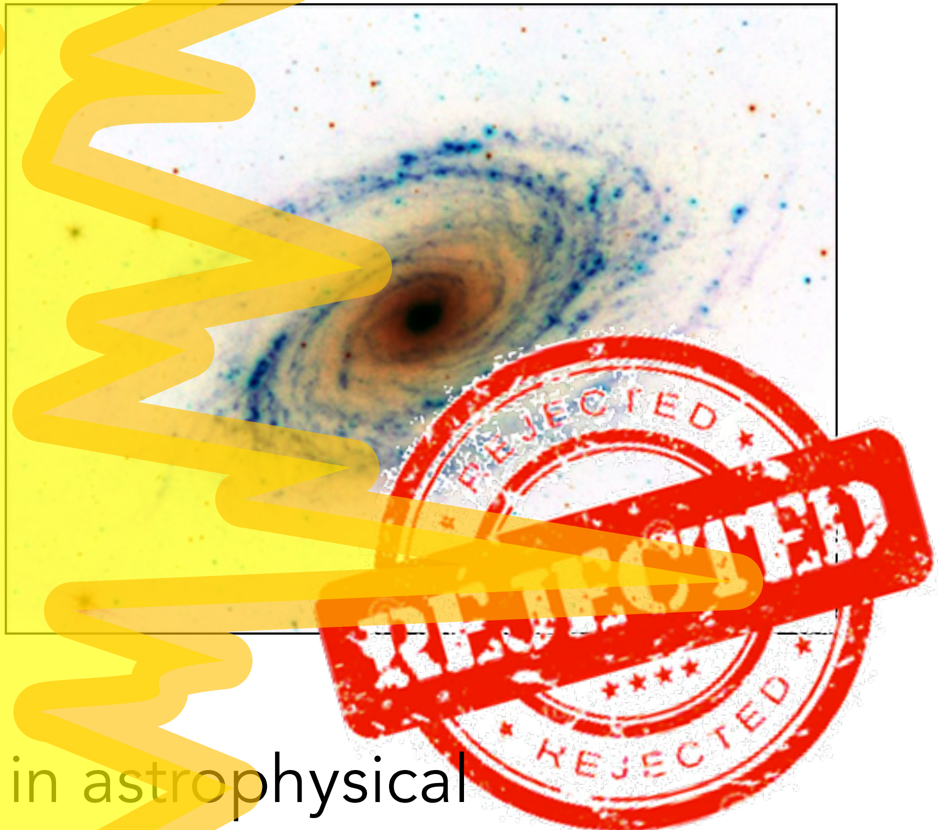
our Universe as the mirror image of an antimatter universe extending backwards in time before the Big Bang. In analogy to the creation of a e^-e^+ pair



preserves CPT symmetry of the Universe - “Antiuniverse” pair

Latham Boyle, Kieran Finn and Neil Turok, PRL 121, 251391 (2018)

astrophysical antimatter

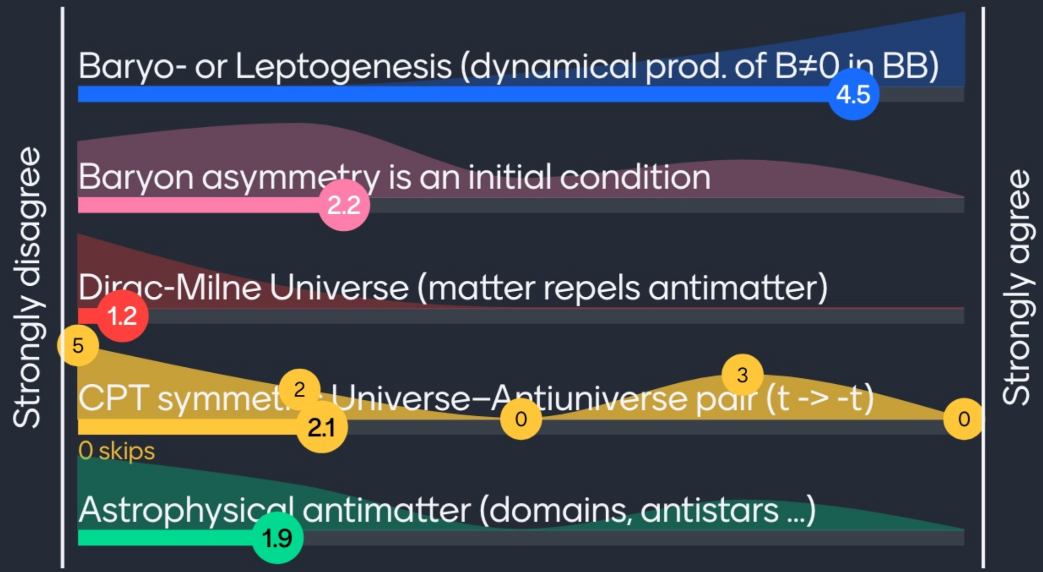


primordial antimatter survived in astrophysical objects - stars, clouds, galaxies, domains … made from antiquarks and positrons, rather than quarks and electrons.

…. well, mostly

my prefered scenario for the baryon asymmetry is ...

Mentimeter



10

physicists "to-do" list : rank in oder of priority

Mentimeter

9