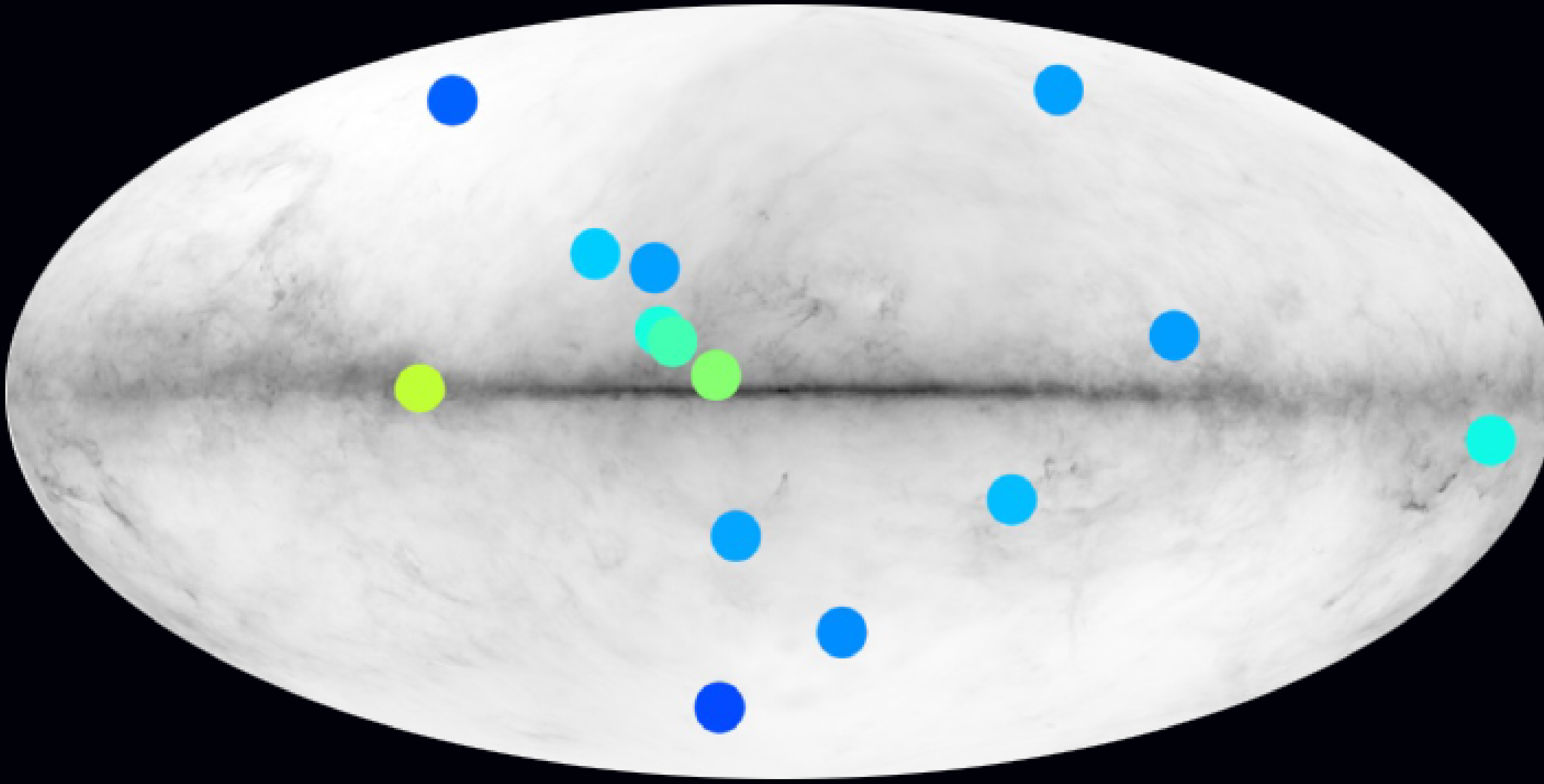
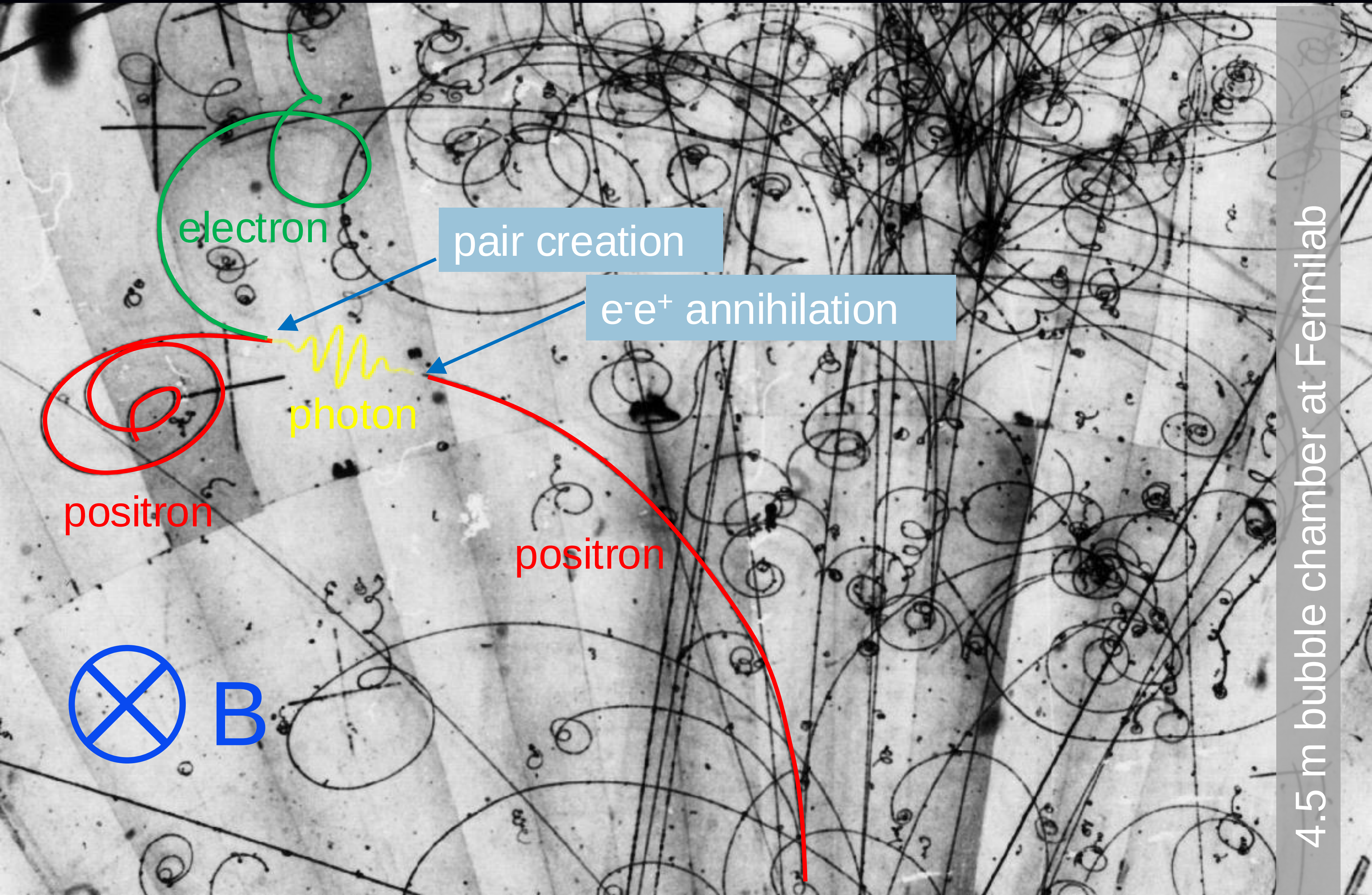
What (really) Antimatters in Gamma-Ray Astronomy



Peter von Ballmoos, IRAP Toulouse

What's the matter with antimatter ?



1000'000'000
baryons

1000'000'000
antibaryons

so why is there something
rather than nothing ?

Baryon Asymmetry

In the Big Bang
equal quantites of matter
and antimatter
are created

In case of perfect symmetry between particles and antiparticles,
(almost) all this matter and antimatter should have annihilated.

We're here to affirm that this did not happen.

Estimating the magnitude of the Baryon Asymmetry

In the hot primordial Universe ($kT >> m_n c^2$), fermions and radiation were in equilibrium; the number densities of baryons, antibarions and photons was $n_B \cong n_{\bar{B}} \sim n_\gamma$

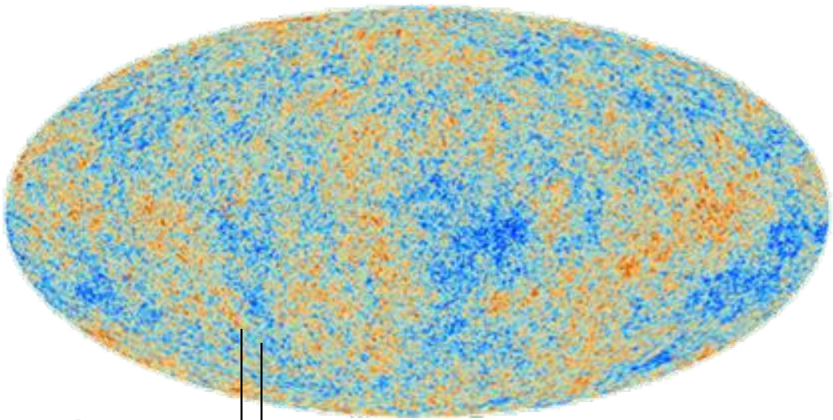
After feeeze-out (T < 1 GeV), the **baryon density to photon number density** ratio η becomes

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

the cosmic expansion lets this ratio invariant ($n_B \sim T^3$, $n_\gamma \sim T^3$) and since $n_{\bar{B}} \cong 0$

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma}$$

$$\approx \frac{0.25 \times 10^{-6}}{412} \approx 6 \times 10^{-10}$$



Temperature of CMB

$n_{\gamma,0} \approx 410\ cm^{-3}$

fit of CMB powerspectrum

$n_{b,0} \approx\ 0.25 \cdot 10^{-6}\ cm^{-3}$

~ 4% of Ω_{crit}

1000'000'001
baryons

1000'000'000
antibaryons

B a r y o n A s y m m e t r y

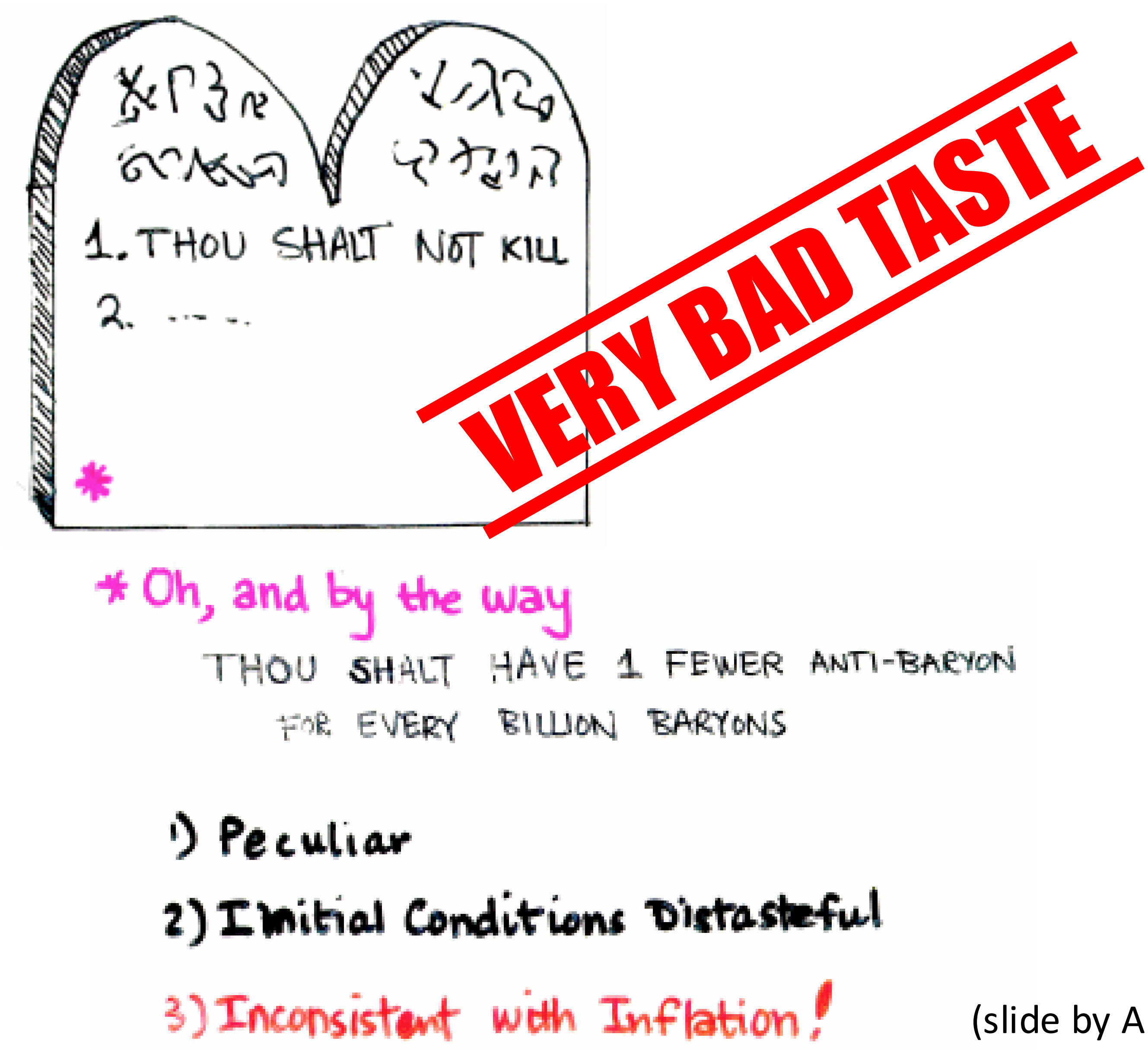
Baryon Asymmetry – option "locally asymmetric Universe"

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

... well, mostly

excluded by Cohen, De Rujula, Glashow, ApJ, 495, 539–549 (1998)

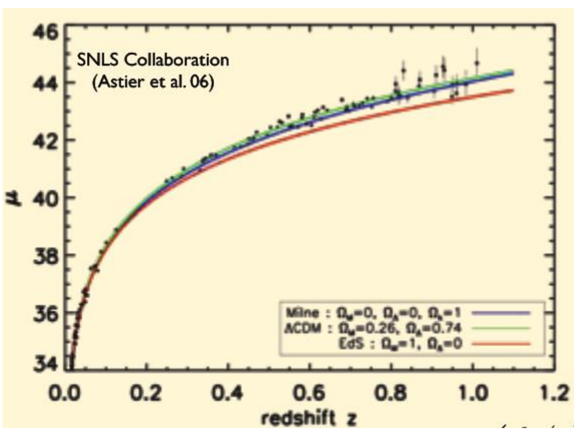
Baryon Asymmetry – option "initial condition"



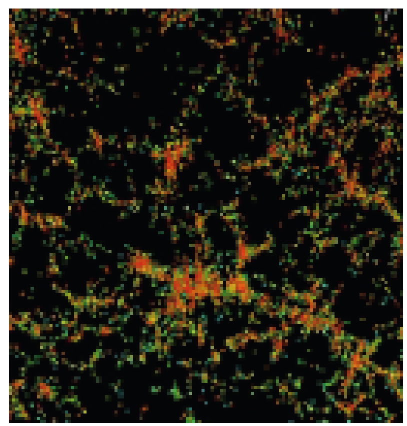
(slide by A. Cohen, 1999)

Baryon Asymmetry – option "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

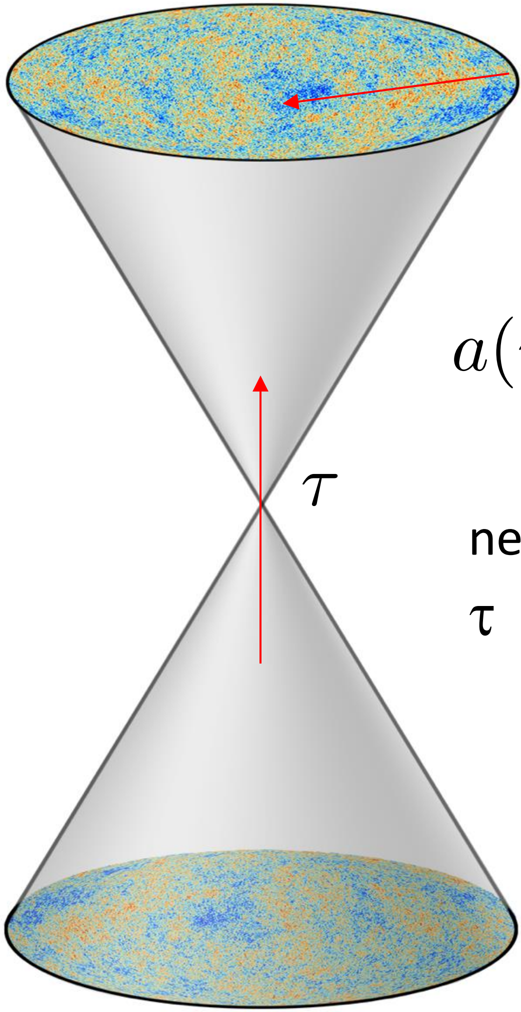


stucture formation

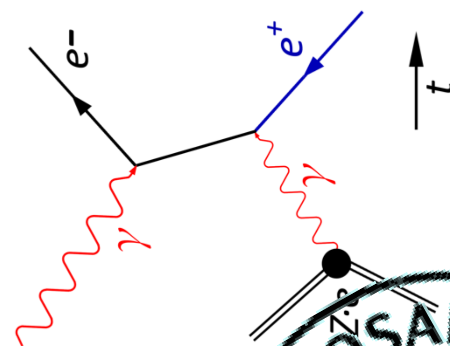
2023/09 : The ALPHA-g experiment at CERN is consistent with antihydrogen falling down

proposed by Benoit-Levy A. and Chardin G. , A&A 537, A78 (2012)
excluded by Anderson, E.K., et al . Nature 621, 716–722 (2023)

Baryon Asymmetry – option "CPT Symmetric Universe"



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

proposed by Boyle L., Finn K. and Turok N., PRL 121, 251391 (2018)

Baryon Asymmetry – option "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 $_{(T >> 1\ MeV)}$ → B≠0 $_{(T \sim 3}$

by a majority of the physics community

Violation of C and CP

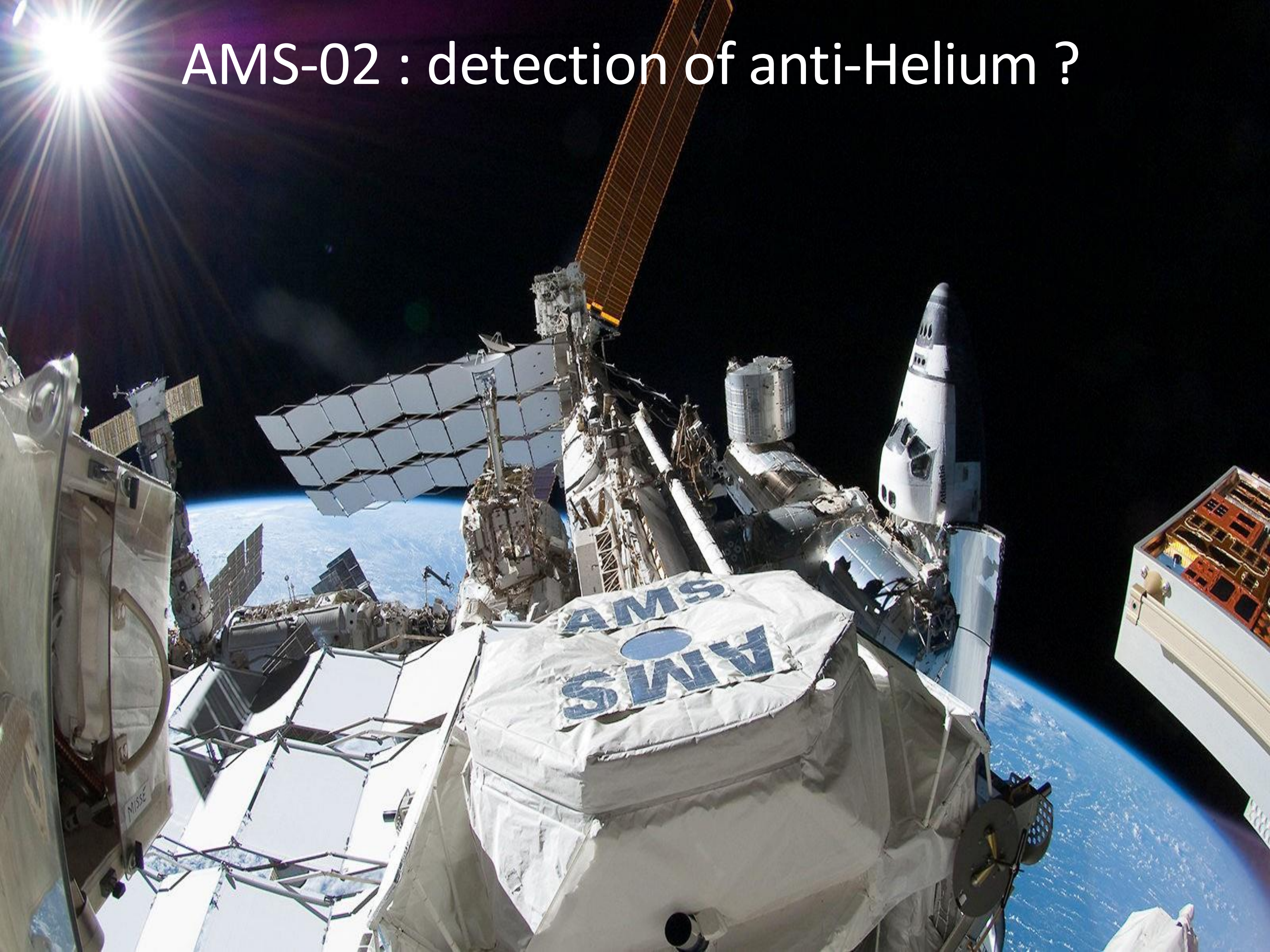
K_L° physics (~ 10^{-3} effect)

Departure from thermal equilibrium

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

proposed by Sakharov, J Exp Theor Physics Letters. 5: 24–27 (1967)

AMS-02 : detection of anti-Helium ?



Anti-^{4}He detection by AMS-02 ?

from S. Ting, CERN Colloquium of May 24 2018,

Latest Results from the AMS Experiment on the International Space Station
https://indico.cern.ch/event/592392

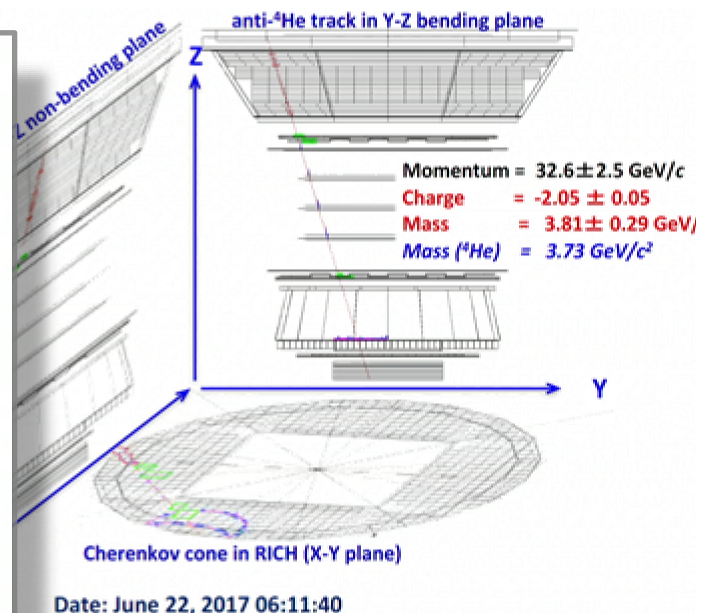
Observations on $^4\overline{He}$

1. We have two $^4\overline{He}$ events with a background probability of 3×10^{-3}.

2. Continuing to take data through 2024 the background probability for $^4\overline{He}$ would be $2x10^{-7}$, i.e., greater than 5-sigma significance.

3. The $^3He/^4He$ ratio is 10-20% yet $^3\overline{He}/^4\overline{He}$ ratio is 300%. More data will resolve this mystery.

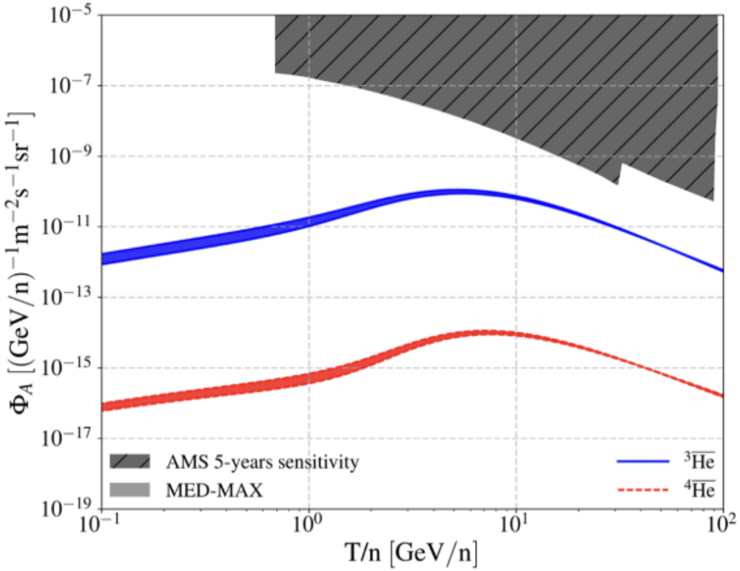
75



~ one candidate anti-He event per year, still needs confirmation !

Possible origin of the AMS anti-He events

cosmic-ray secondaries

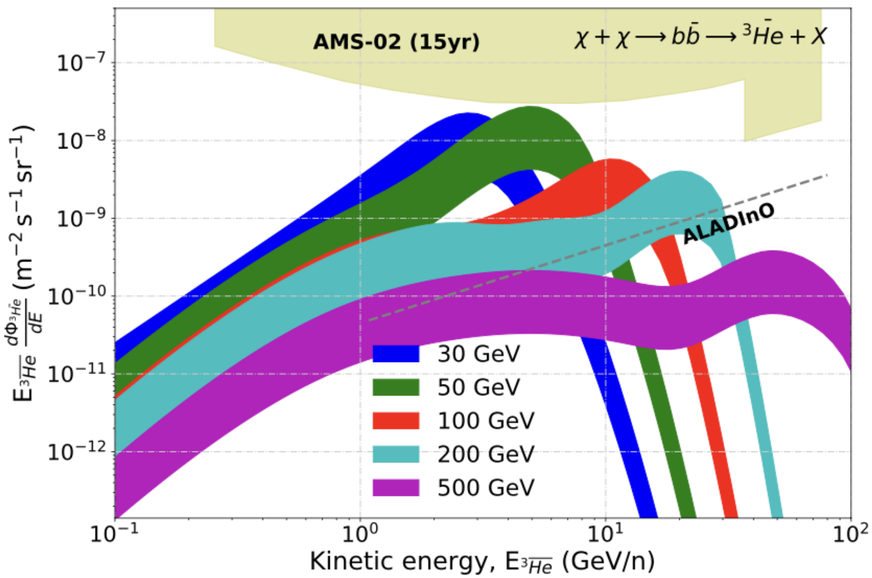


predicted secondary flux of anti-^{3}He and anti-^{4}He

AMS measurement is ~ 6 orders of magnitude above anti-4He "secondary" prediction

Poulin, Salati et al, Phys. Rev. D 99, 023016 (2019)

DM annihilation



upper limits for the anti-^{3}He spectrum from WIMP annihilation

annihilation of WIMPs in simple 2- or 4-body final states cannot produce any appreciable flux of 4He

De La Torre Luque et al, JCAP10, 0172024)

Possible origin of the AMS anti-He events

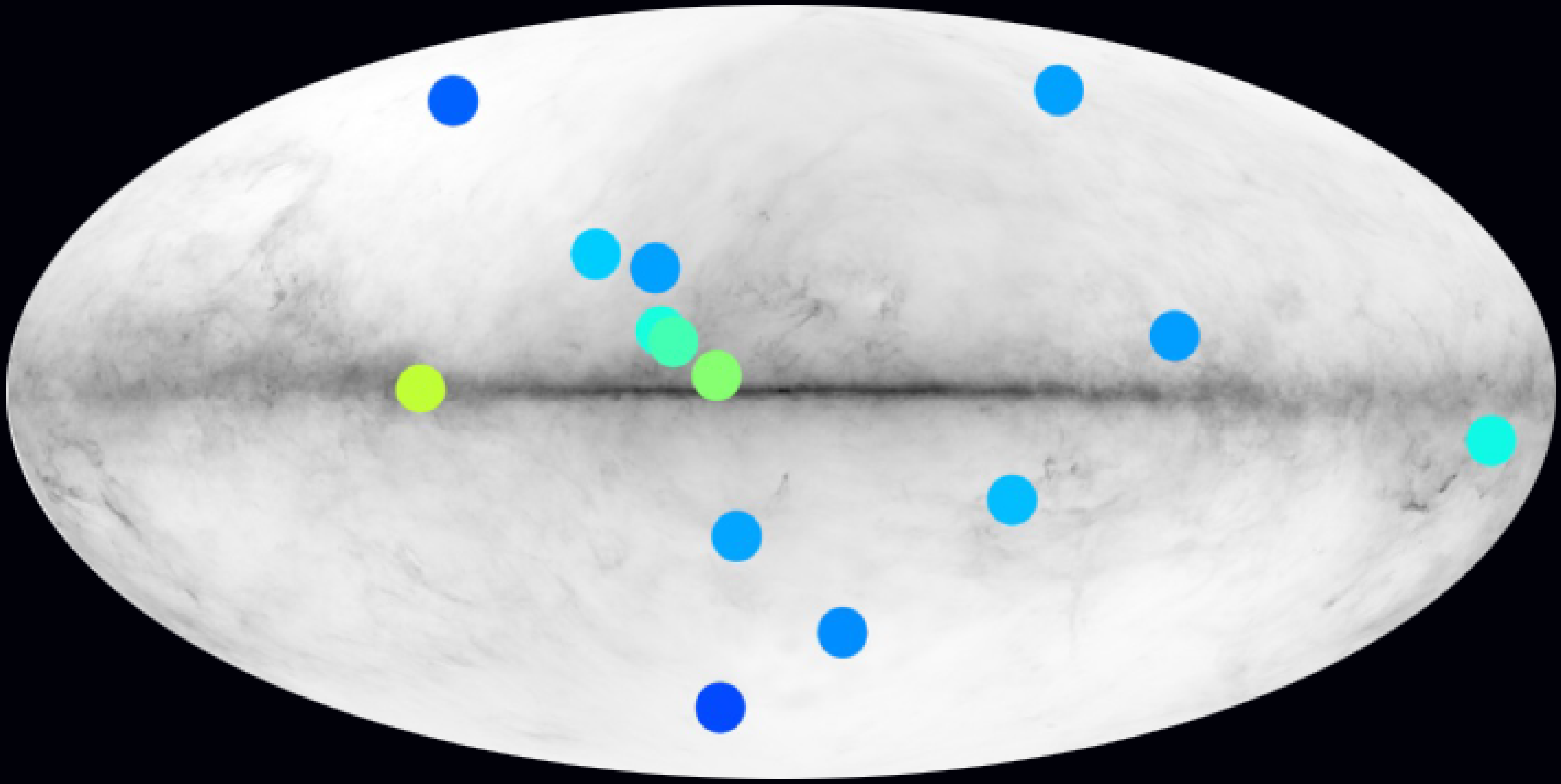
what if the AMS anti-helium atoms were just cosmic antimatter ?

"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, 1999

"the detection of **a single Z < - 2 nucleus** would imply the existence of anti-stars !" Coppi 2004

"the detection of **one anti-helium nucleus** would be a striking evidence for the existence of anti-stars in our Galaxy" Casadei 2006

but **how can we identify anti-stars ?**



Constraints on the Antistar Fraction in the Solar System neighborhood from the 10- year Fermi-LAT gamma-ray source catalog

LUIGI TIBALDO, SIMON DUPOURQUÉ, PETER VON BALLMOOS

Dupourqué et al. Phys. Rev. D 103, 083016 2021

irap

gamma rays from nucleon-antinucleon annihilation

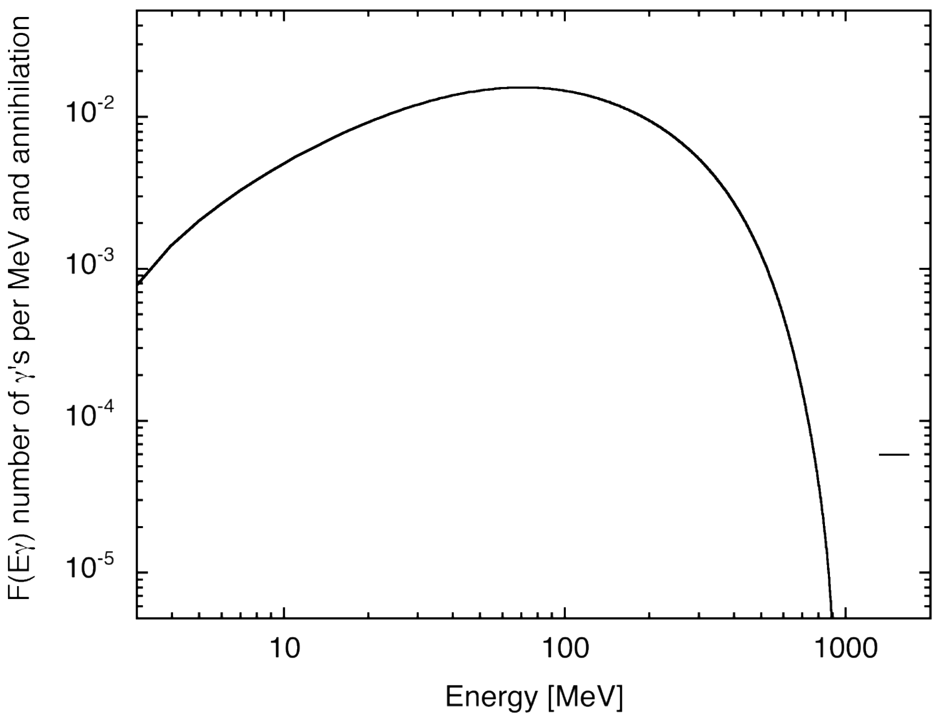
$$N - \bar{N} ® \begin{cases} p^0 ® g + g \\ p^{\pm} ® m^{\pm} + n_m(\bar{n}_m) \end{cases}$$

1/3 of $2m_Nc^2$ ® 200 MeV γ's

$$\hookrightarrow p^{\pm} ® e^{\pm} + n_e(\bar{n}_m) + n_m(\bar{n}_m)$$

1/2 of $2m_Nc^2$ ® ν's

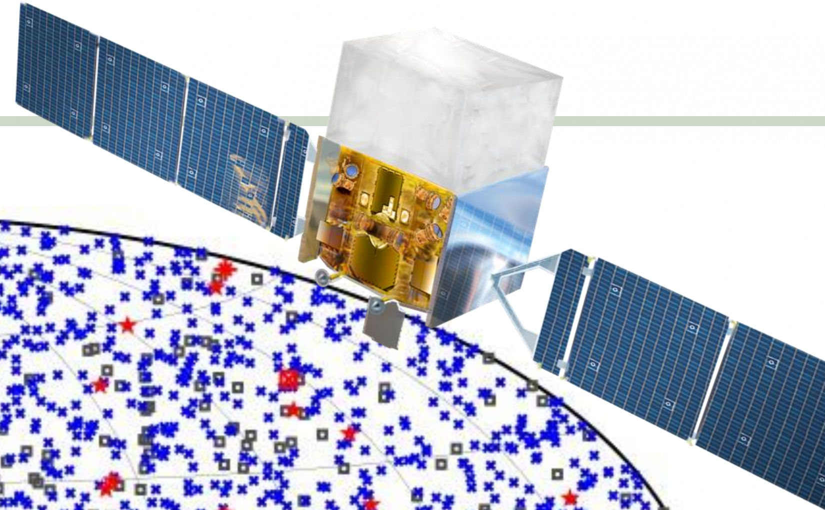
1/6 of $2m_Nc^2$ ® e^-, e^+ (100 MeV)



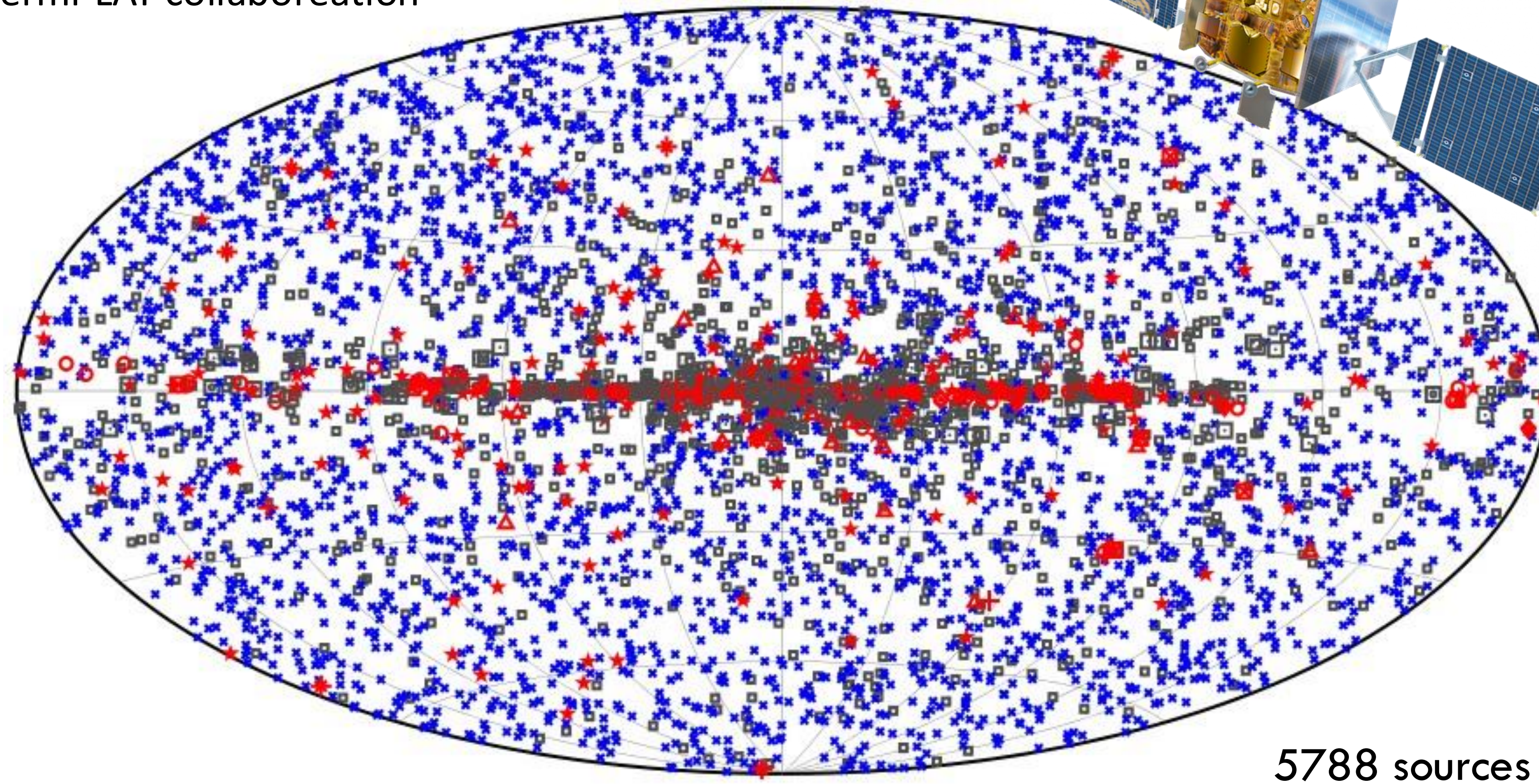
typical rest-frame spectrum produced by p-p annihilation with π° decay

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

FERMI LAT 10-year Source Catalog



Fermi-LAT collaboreation



5788 sources

Antistar candidates : selection criteria, selected candidates

Exclusion criteria

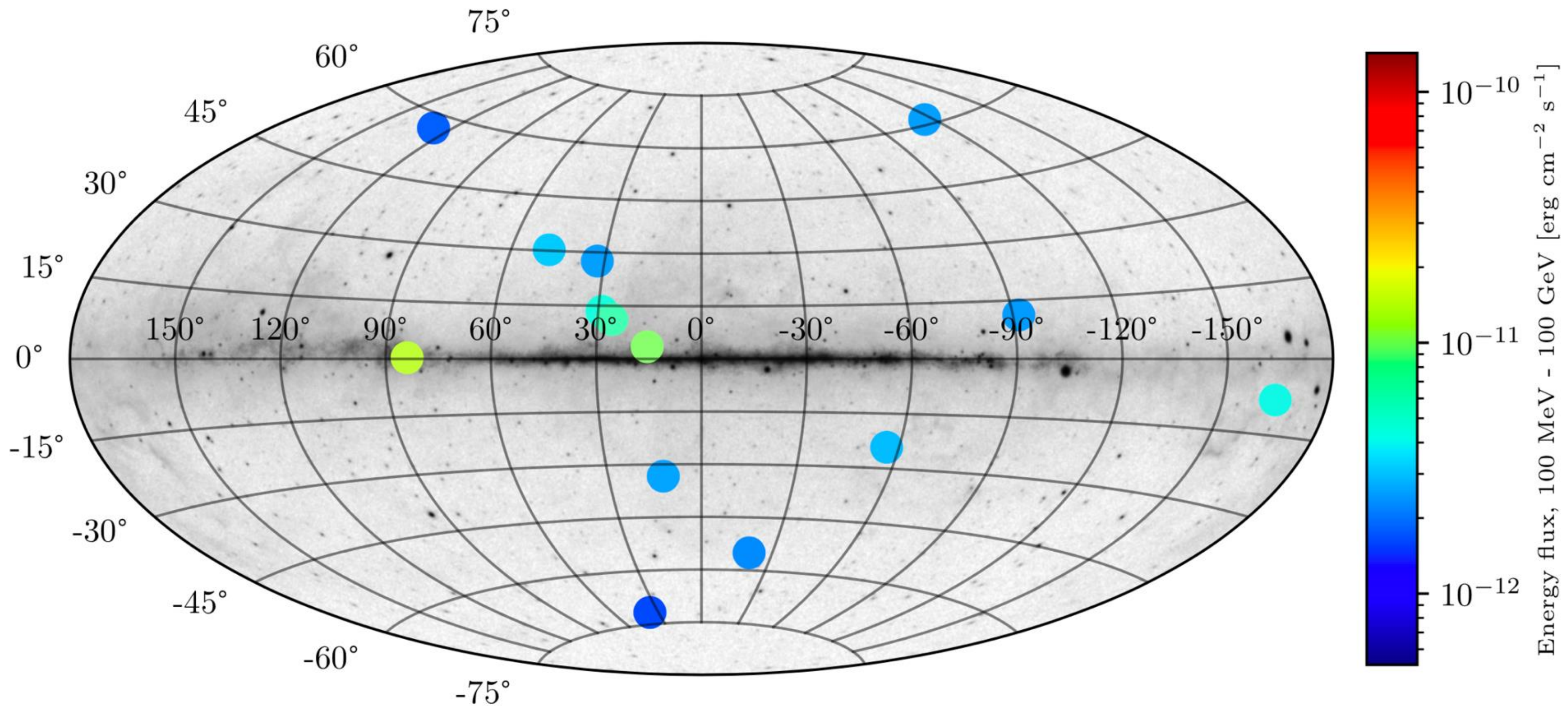
1. Extended sources
2. Not associated
3. Significance $> 3\sigma$ for $E > 1$ GeV
4. Flagged sources

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

=> estimate upper limits on antistar fraction/density in our Galaxy

Antistar candidates : what are they ?



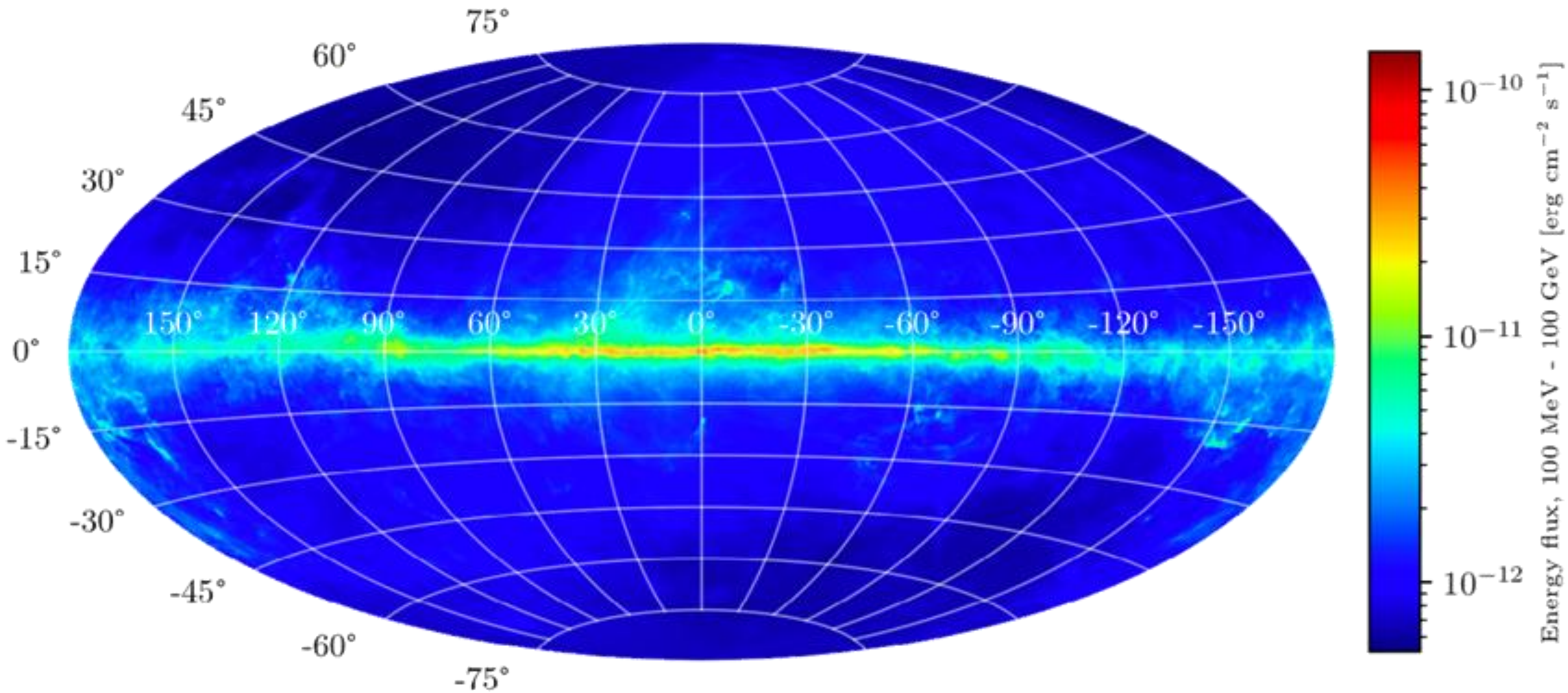
Properties

- 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



minimum antistar flux detectable by FERMI/LAT

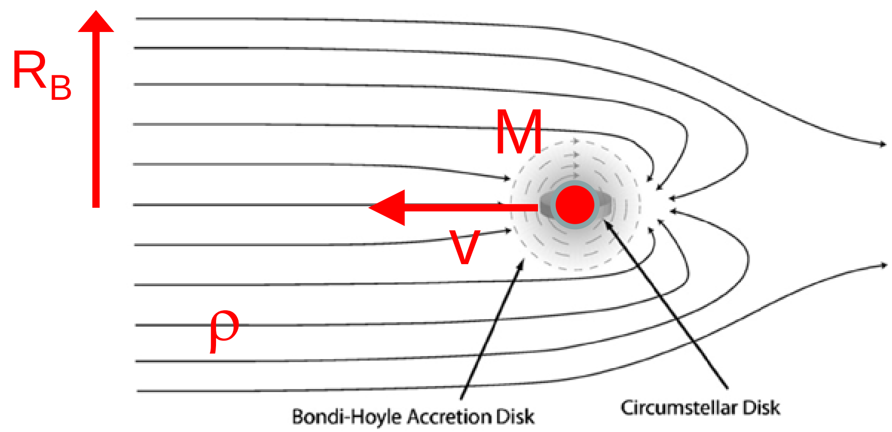
Input

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

Antistar luminosity

Bondi-Hoyle accretion

proton-antiproton annihilation



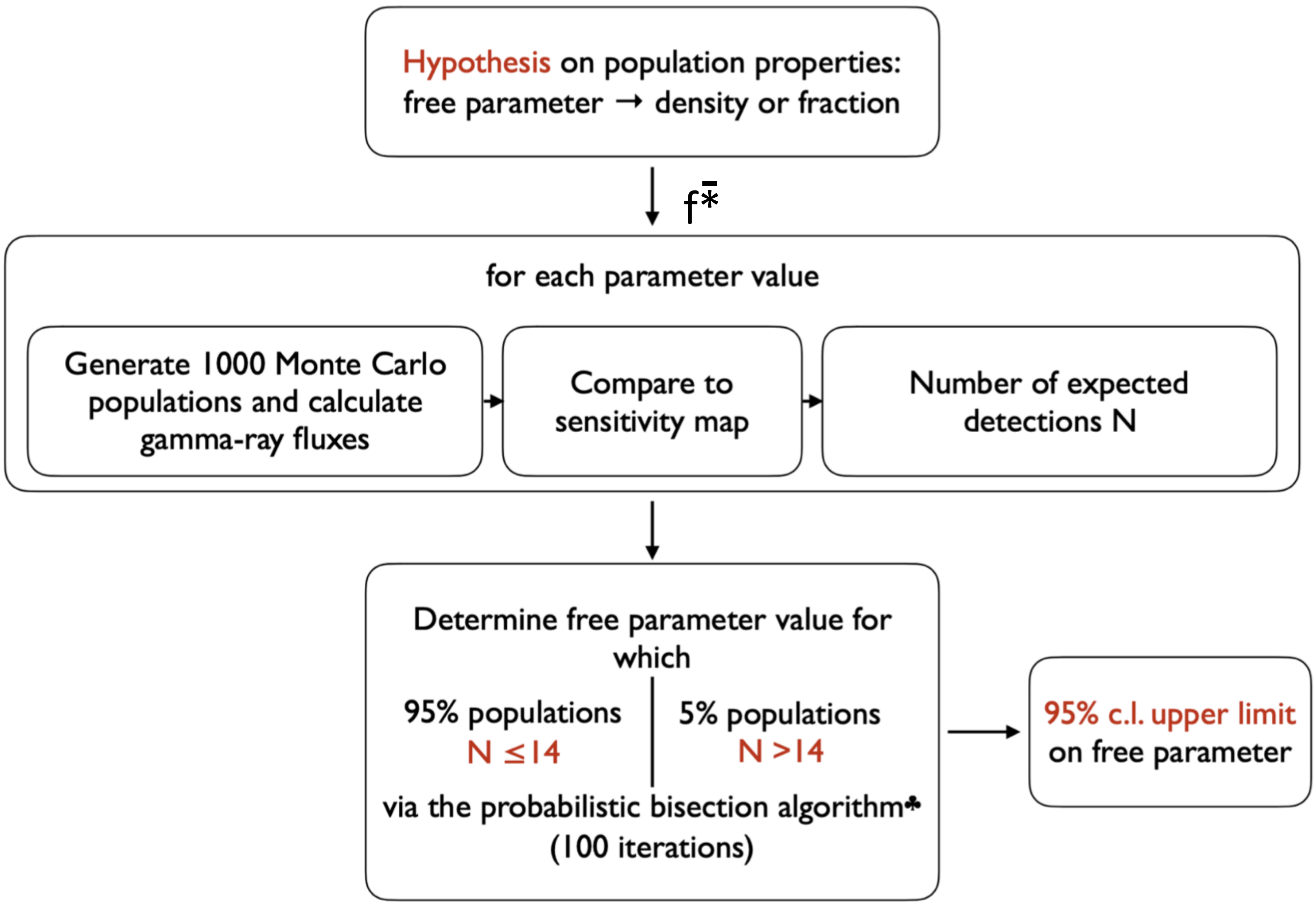
matter density — antistar mass — antistar speed w.r.t. surrounding matter — Sound speed

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

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

Antistar fraction - Monte Carlo method

for a given antistar fraction $f^{\bar{*}}$ (only free parameter),
using the `galaxya` stellar population synthesis code
we estimate the number of antistars that should be detected (estimator $N^{\bar{*}}$)



Hypothesis I : star-like distribution

Same spatial, mass, and velocity distribution as stars

- no physical justification

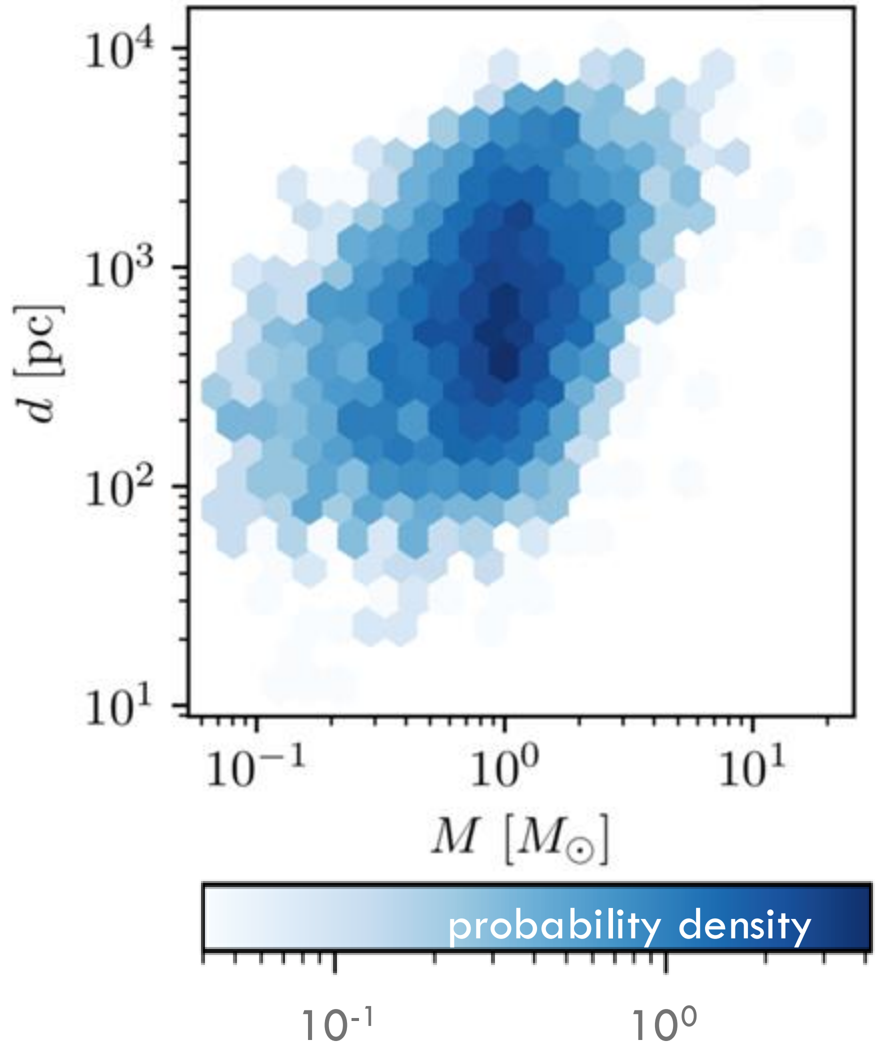
- compare with earlier results

`galaxya` stellar population synt 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

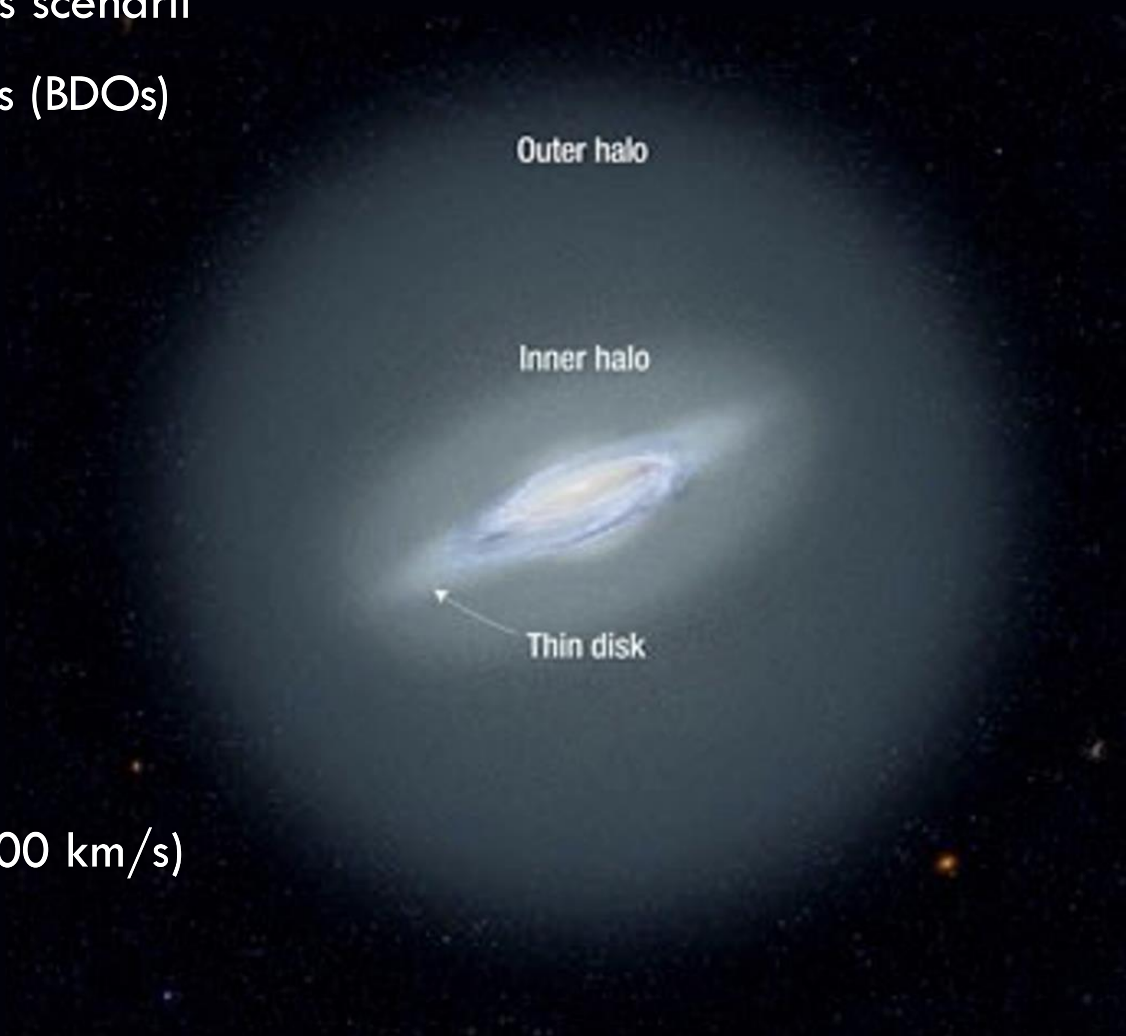
Expected in some baryogengesis scenarii

Subclass of baryo-dense objects (BDOs)

aka MACHOs studied

as dark-matter candidates

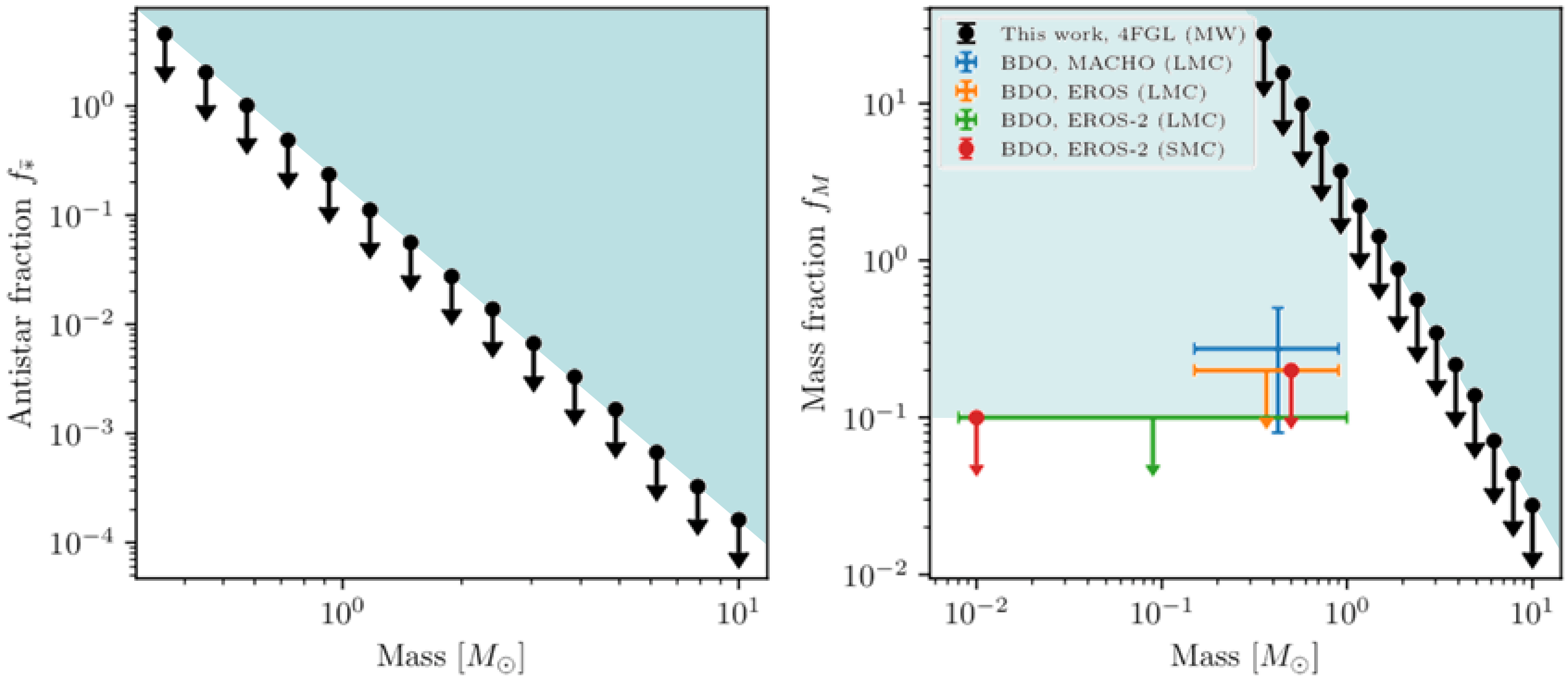
Milky Way halo structure



Properties

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

Hypthesis II: primordial antistars



Derive limits as a function of 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

summary

AMS-02 $^4\overline{He}$ detections point to the existence of nearby antistars

14 antistar candidates in the Fermi 4FGL-DR2 Catalog

Limits on antistar fraction using a novel Monte Carlo approach :

- Starlike properties : $f_* < 2.5 \times 10^{-6}$ (95% C.L) constraint is 20x stronger than previous results with a more robust method

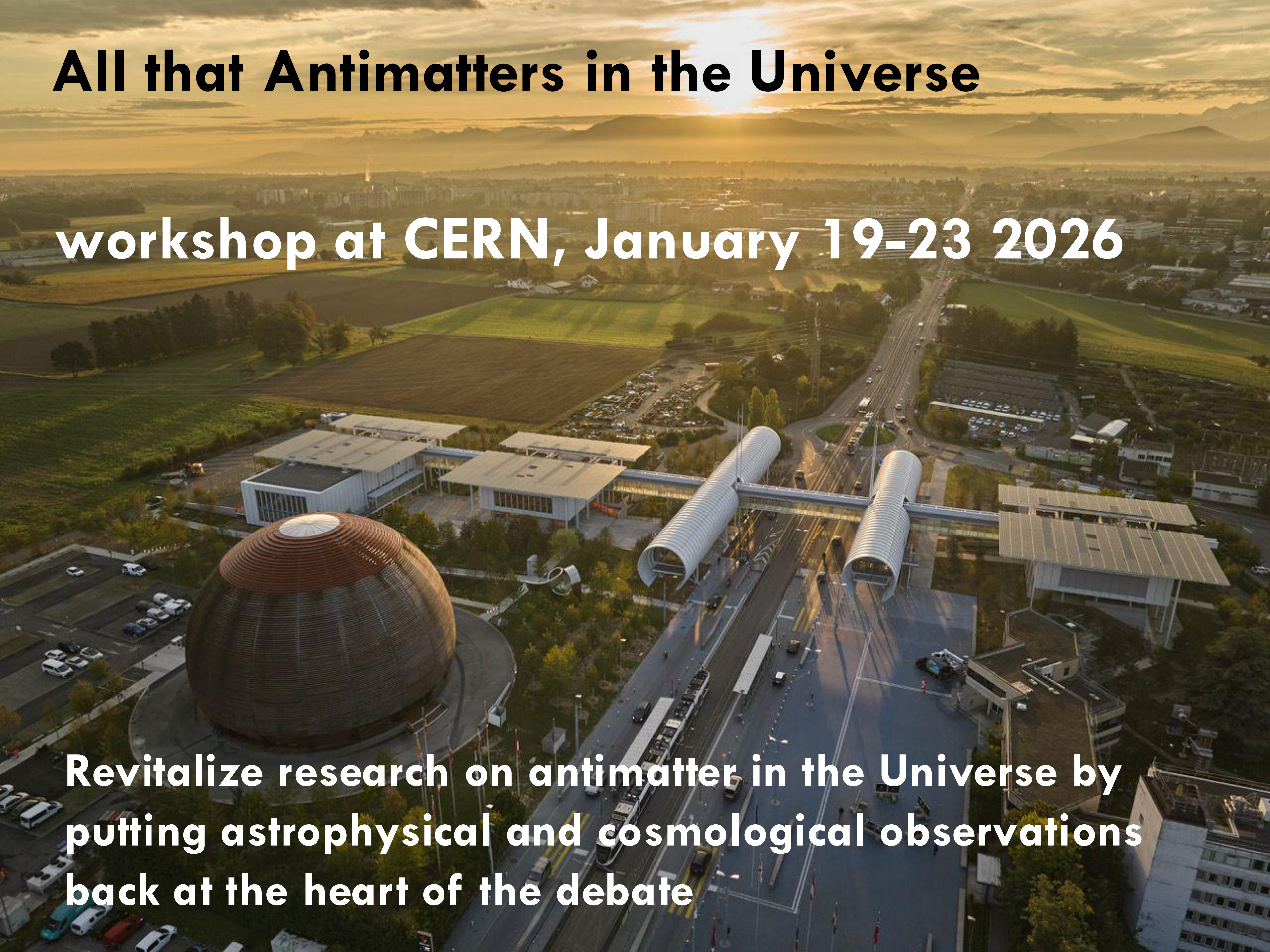
- Primordial antistars: constraints in previously unexplored mass range $2M_\odot - 10M_\odot$,
  Data cannot exclude large number of these objects in the halo

Challenge #1: how do they form ?
Challenge #2: how do they manage to survive ?
Challenge #3: how are the antinuclei accelerated?

conclusions

The **matter-antimatter asymmetry** in the Universe remains **one of the deepest enigmas** in astrophysics, cosmology, and particle physics. While the working hypothesis of a Universe consisting of *matter only* was justified by the data available at the end of the nineties, in the past twenty years there were ground-breaking advances in observational facilities for CR antinuclei (AMS-02 and very soon GAPS), gamma rays (Fermi and soon COSI), and the CMB (Planck). The most recent datasets have hardly been exploited to constrain the matter-antimatter asymmetry. We want to :

Revitalize research on antimatter in the Universe by putting astrophysical and cosmological observations back at the heart of the debate



All that Antimatters in the Universe

workshop at CERN, January 19-23 2026

Revitalize research on antimatter in the Universe by putting astrophysical and cosmological observations back at the heart of the debate

Summary

Antistars get renewed attention due to the possible detection of anti-Helium in CR's.

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

Challenge #1: how do they form ?
Challenge #2: how do they manage to survive ?
Challenge #3: how are the antinuclei accelerated?

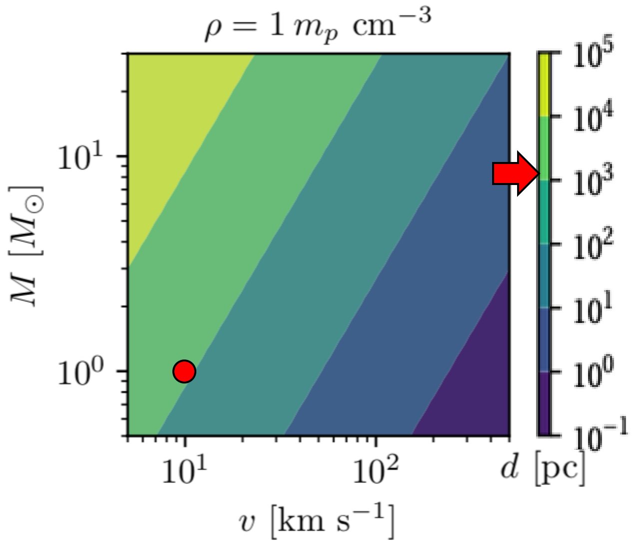
Further improvements by deeper Fermi LAT catalogs, multiwavelength data to rule out antistar nature of candidates, and of course a new telescope optimized in the MeV-GeV energy range (COSI, Astrogam, AMEGO).

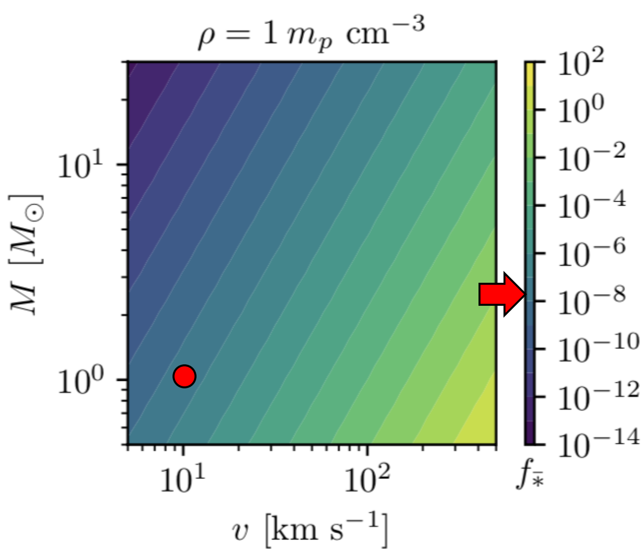
1) Antistar fraction - Parametric method

method of Steigmann (1976) appl. to Fermi data

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



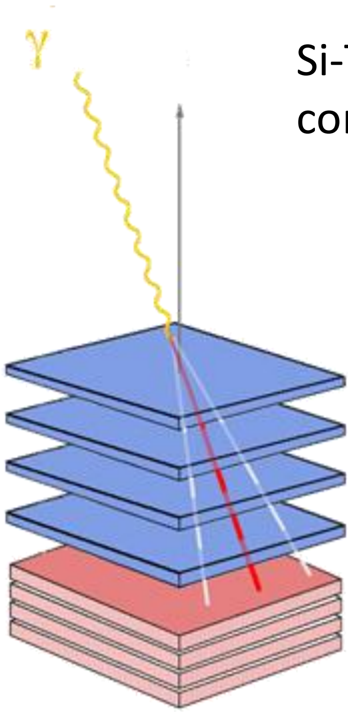


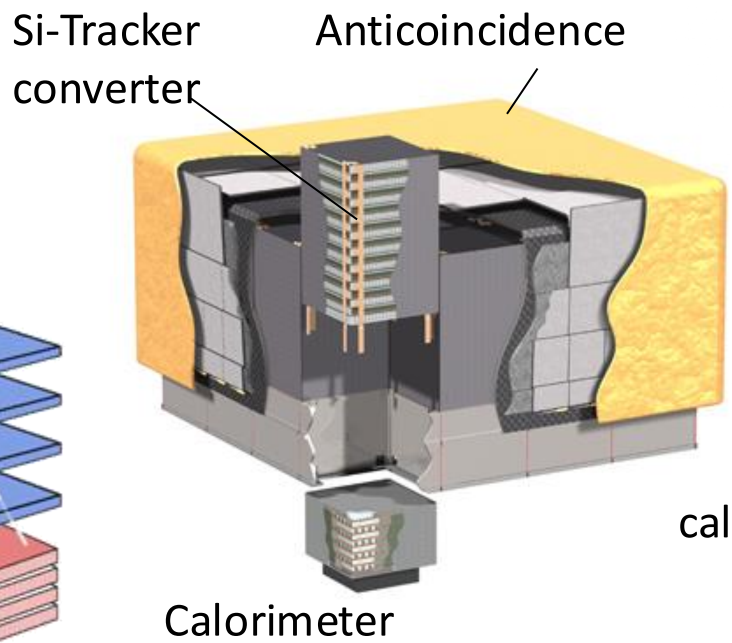
Limitations

- 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

FERMI/ LAT



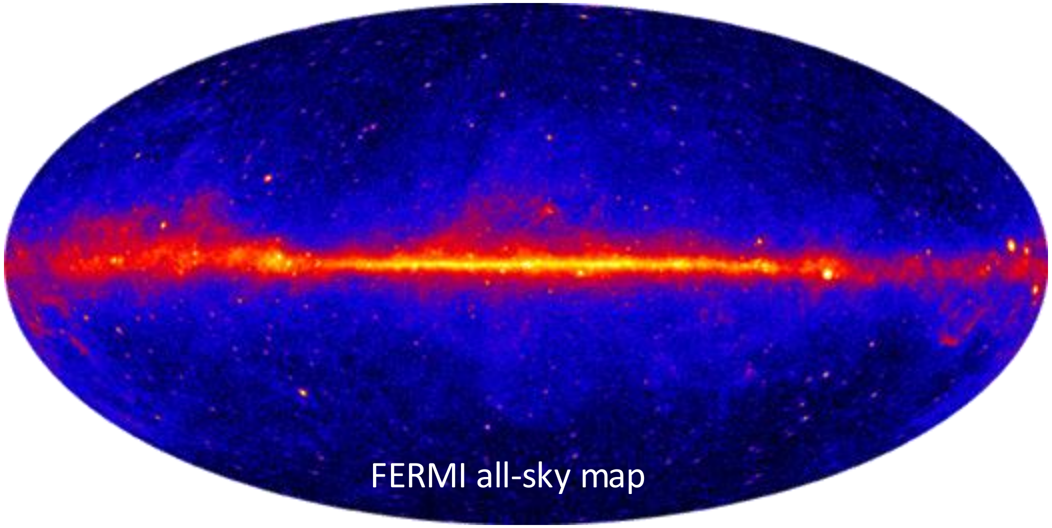


tracker	Si, 80 m^2 single sided
	W foil interleaved
	4 x 4 x 18 xy planes
calorimeter	1536 CsI crystals
	8.6 R.L, hodoscopic
mass	2789 kg

pair-conversion telescope

performance

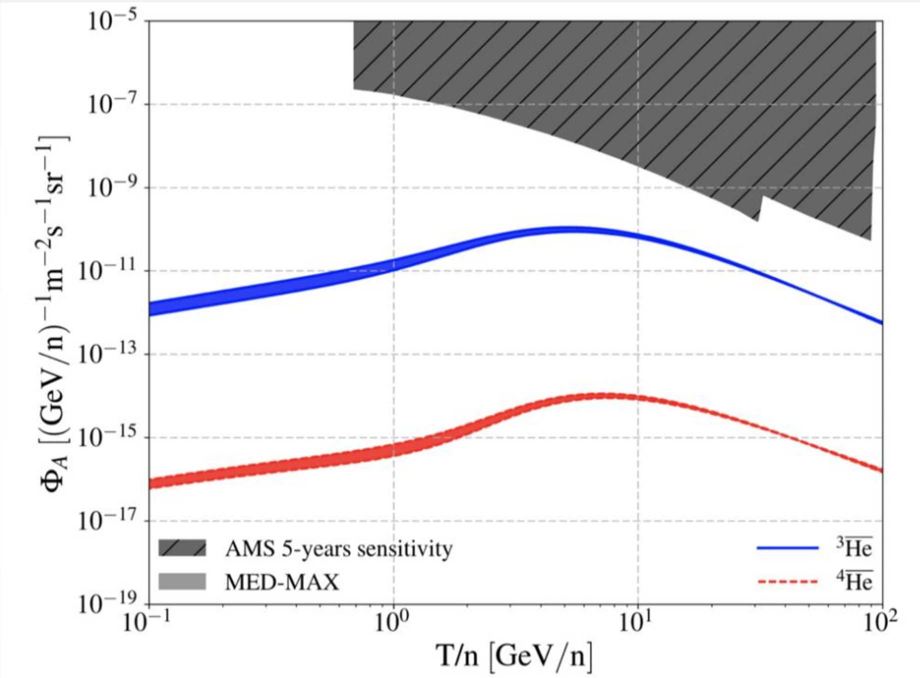
Energy	0.1– 300 GeV
Field of view	2.4 steradian
angular res.	3° - 0.04°
Eff. area	7000 cm^2 (1GeV)
E/ΔE :	6 - 18% (1σ)

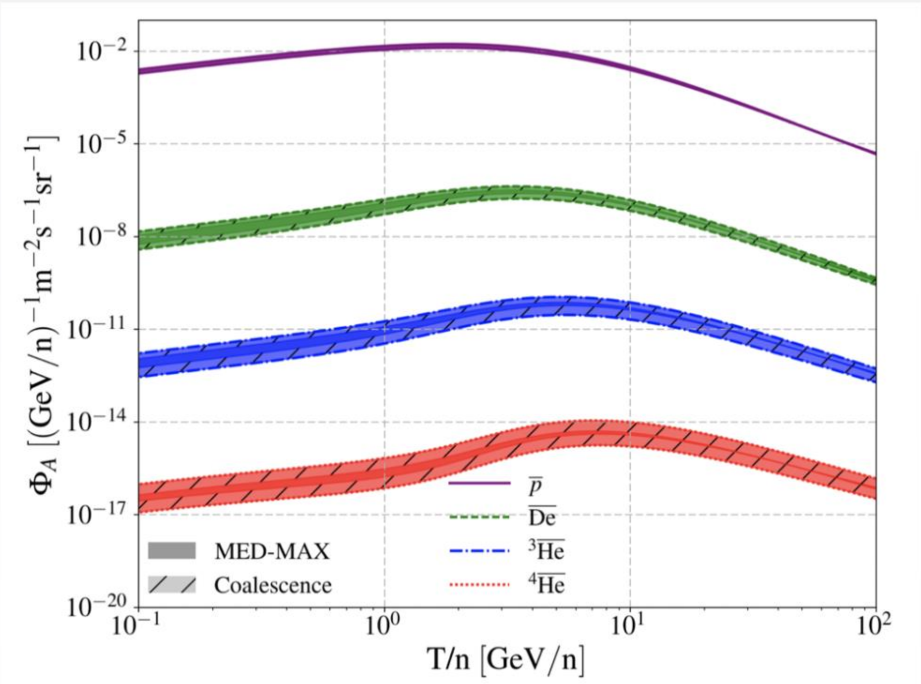


FERMI all-sky map

Secondaries cannot explain $^{4}\overline{He}$

- The coalescence scenario predicts a hierarchy in the flux of anti-nuclei $\phi_{A+1} \approx 10^{-3}\text{-}10^{-4}\phi_A$
- AMS measurement is ~ 6 orders of magnitude above $^{4}\overline{He}$ "secondary" prediction
- Where is the anti-De???

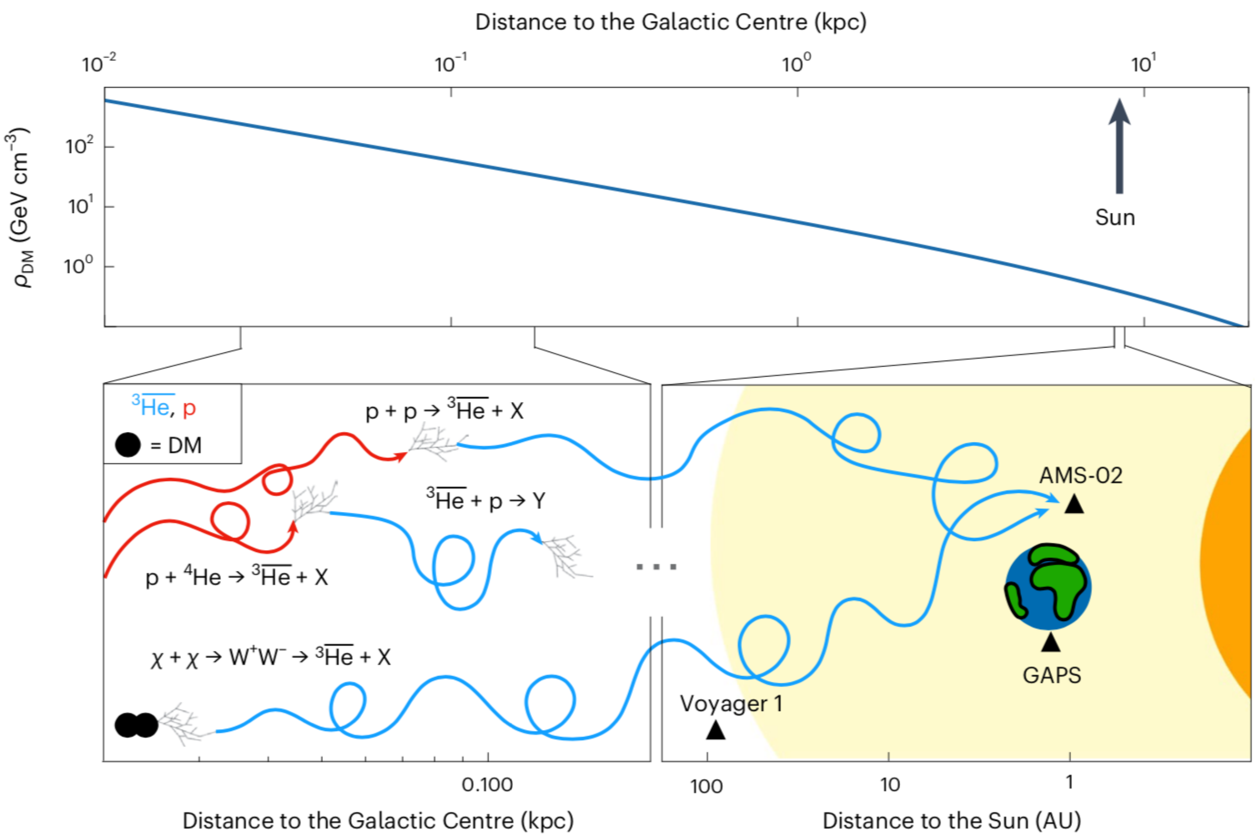




VP, Salati++ PRD99 (2019)

Anti-Helium detection by AMS-02 - how would it be explained ?

ALICE/LHC measurement of the inelastic interaction cross section of $^3\overline{He}$ with matter as input to GALPRPOP calculations of the propagation of $^3\overline{He}$ through the Galaxy
- $^3\overline{He}$ from dark-matter (profile below) annihilation => 50% transparency
- $^3\overline{He}$ from CR interactions within the ISM => 25% to 90% transparency (energy dep.)

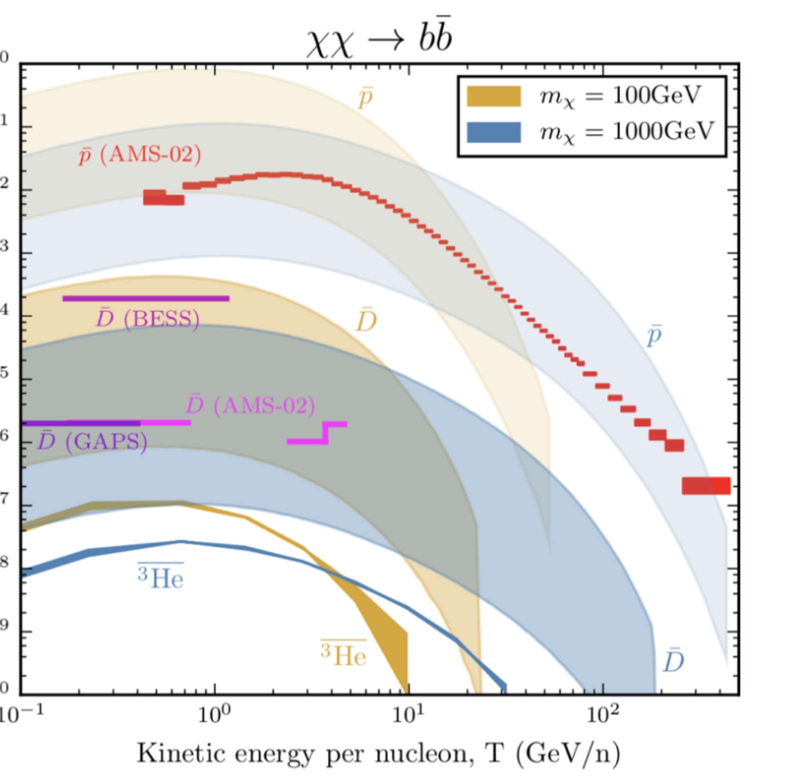


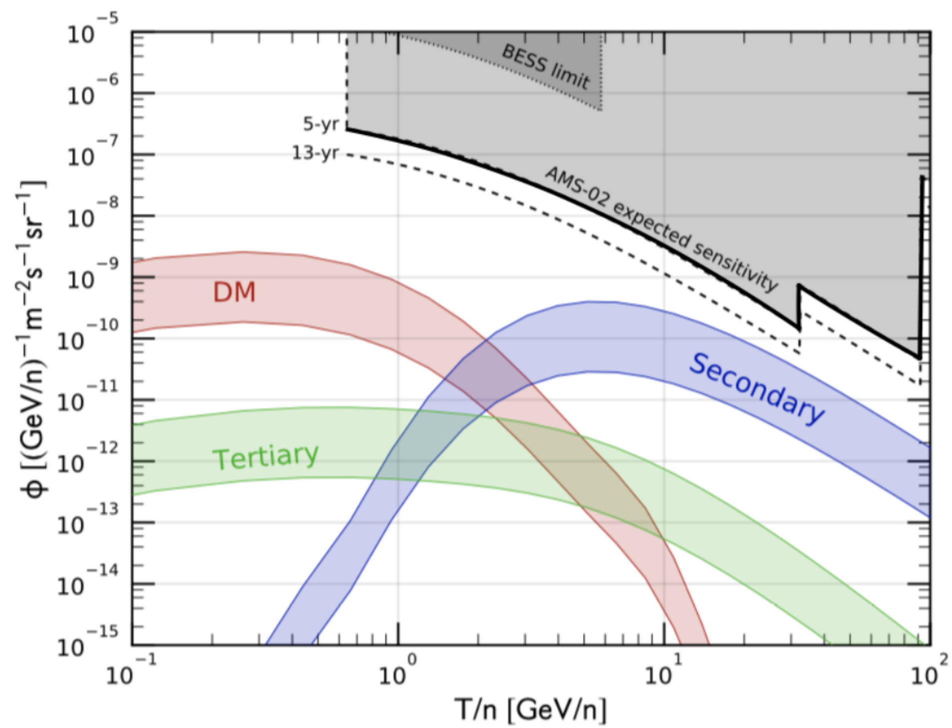
Measurement of anti-3He nuclei absorption in matter and impact on their propagation in the Galaxy

Nature Physics | Volume 19 | January 2023 | 61–71

Anti-^{4}He detection by AMS-02 ?

Dark Matter is at odds with AMS-02 events





Coogan&Profumo, PRD96 (2017)

Korsmeier++ 1711.08465

he Dark Matter flux peaks at low kinetic energy compared to the background.

MS should see associated $\overline{\text{De}}$ and $\bar{p}$: Most of the parameter space is ruled out by $\bar{p}$.

ark Matter models cannot produce $^4\overline{\text{He}}$ via coalescence.

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

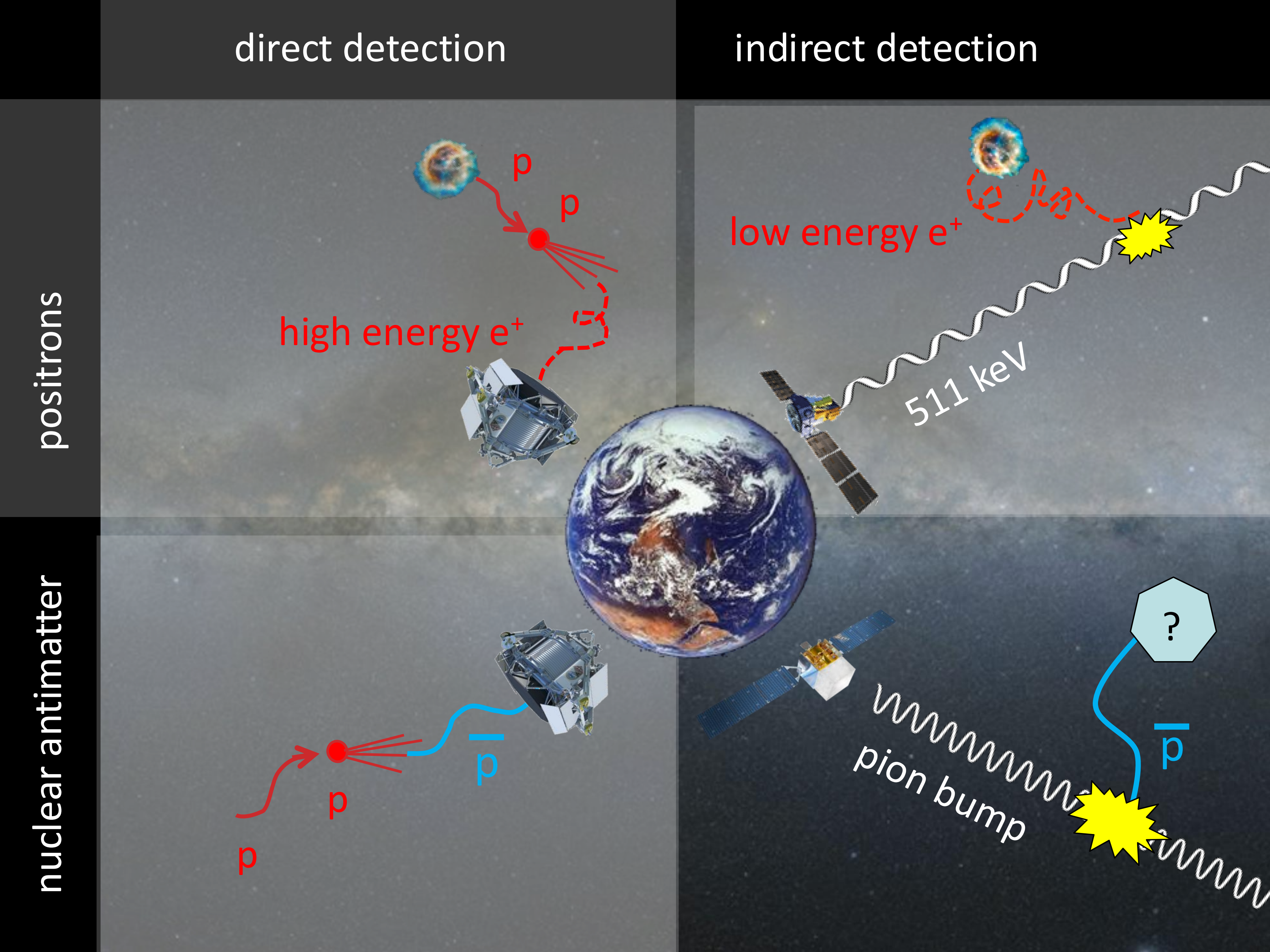
Anticlouds or antistars

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

Challenge #2: how do they manage to survive?

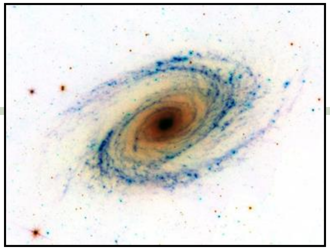
Antistars in galactic halos accrete matter slowly enough to survive!

Challenge #3: how are the antinuclei accelerated?



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

Search for annihilation features

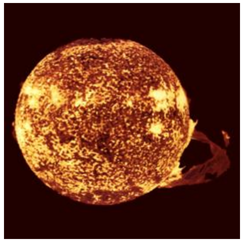



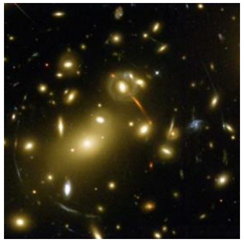
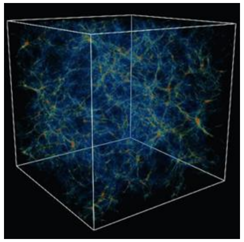
probe the presence of antimatter through ordinary matter with the resulting annihilation gamma-rays providing indirect evidence.

e^+e^- annihilation provides a clear feature, but as most common and easily produced form of antimatter, e^+ are too ubiquitous => $\bar{p}$

on what scale ?





how much baryonic antimatter do gamma-ray observations allow ?

- what antimatter fraction is compatible with the data ?
- are there structures or anisotropies ?

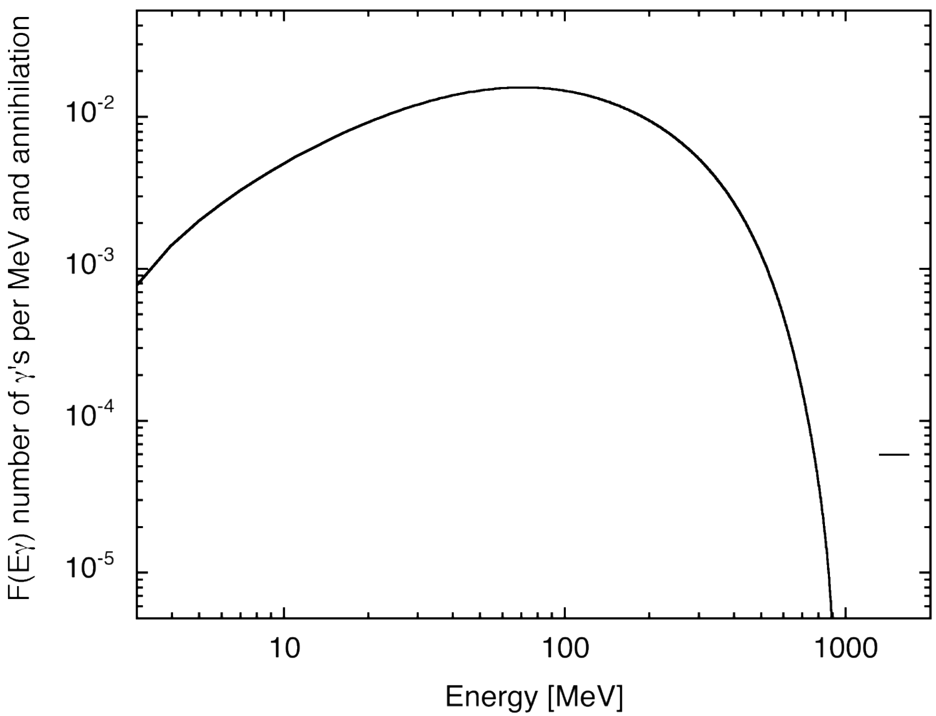
gamma rays from nucleon-antinucleon annihilation

$$N - \bar{N} \text{®} \begin{cases} p^0 \text{®} \; g+g & \text{1/3 of } 2m_Nc^2 \quad \text{20® MeV } \gamma\text{'s} \\ p^{\pm} \text{®} \; m^{\pm} + n_m(\bar{n}_m) \end{cases}$$

$$\hookrightarrow p^{\pm} \text{®} \; e^{\pm} + n_e(\bar{n}_m) + n_m(\bar{n}_m)$$

1/2 of $2m_Nc^2$ ® ν's

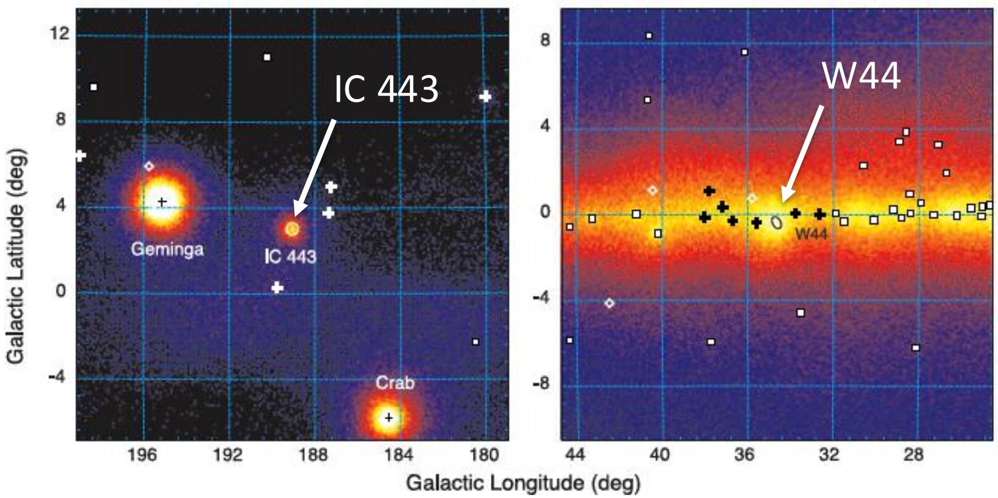
1/6 of $2m_Nc^2$ ® e^-, e^+ (100 MeV)



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

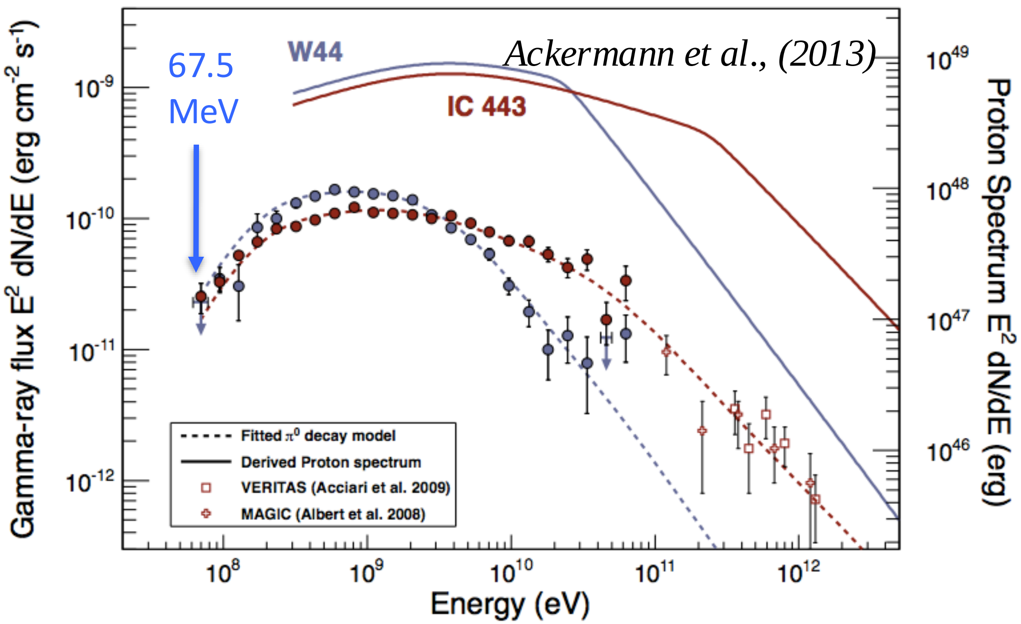
maximum intensity at $m_\pi c^2/2 \sim 70$ MeV

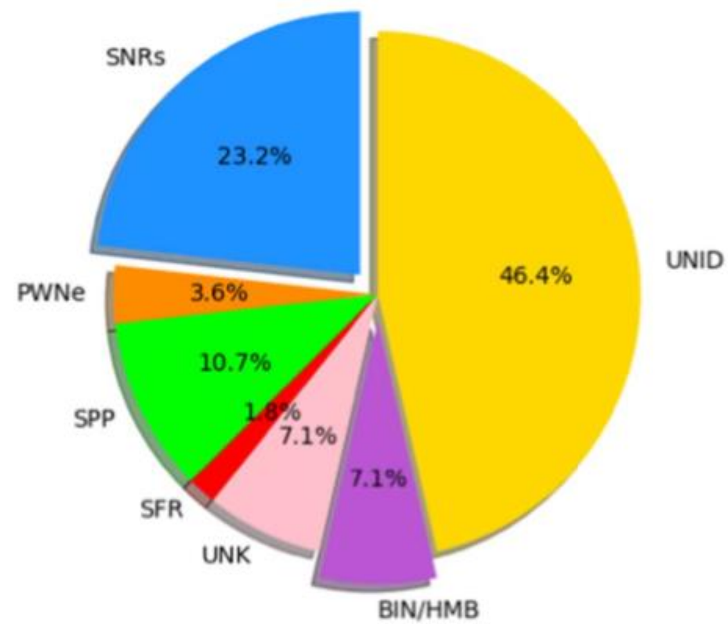
Gamma-rays from π^0 decay **in FERMI sources**



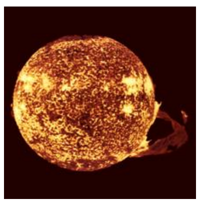
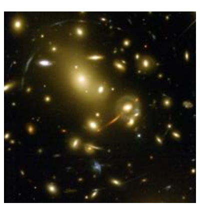
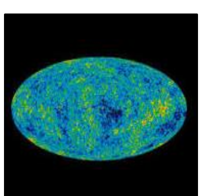
… + W49B, W51C + 9 other SNRs

Abdollahi et al 2022 find 56 FERMI sources with π^0 bumps :
- 13 supernova remnants SNRs
- 2 pulsar wind nebulae
- 6 SPP (SNR/PWNe)
- 1 star-forming region
- 4 binary/HM binary
- 30 unknown & unidentified





"matter trail" from the solar system to clusters of galaxies

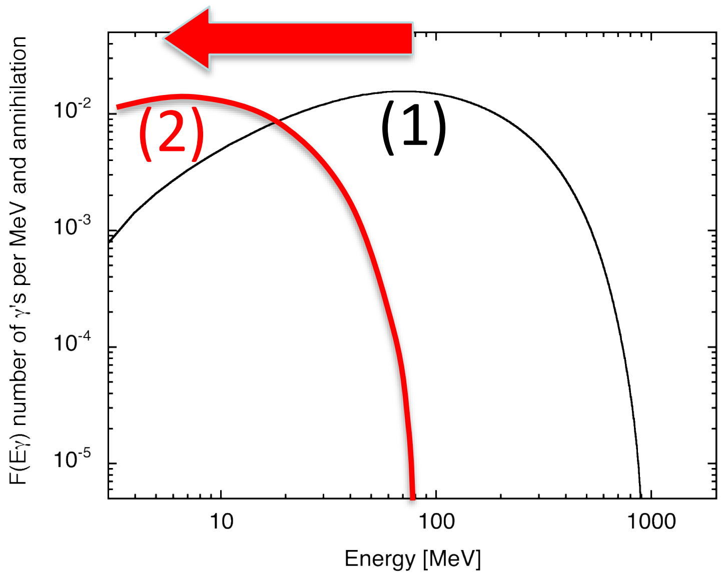
	object	probe	observatory	AM limit
	asteroids	solar wind [micro-meteorites cosmic rays]	Fermi	< 4 km Ø if in main-belt
	disk stars	galactic gas (Bondi-Hoyle accretion)	Fermi	$f_{AM} \leq 2.5 \cdot 10^{-6}$ Halo stars see below
	galactic gas	galactic gas	Fermi	$f_{AM} \leq 10^{-15}$
	intracluster gas	intracluster gas	Fermi	$f_{AM} \leq 10^{-8} - 10^{-6}$
	primordial matter region	primordial matter region	Comptel	> 1 Gpc

antimatter at high redshifts

Annihilation radiation from the boundaries of matter-antimatter regions, emitted in the early Universe before - and/or - after recombination.

Stecker et al. (1971) solved the cosmological photon transport equation accounting for pair production and Compton scattering at high z.

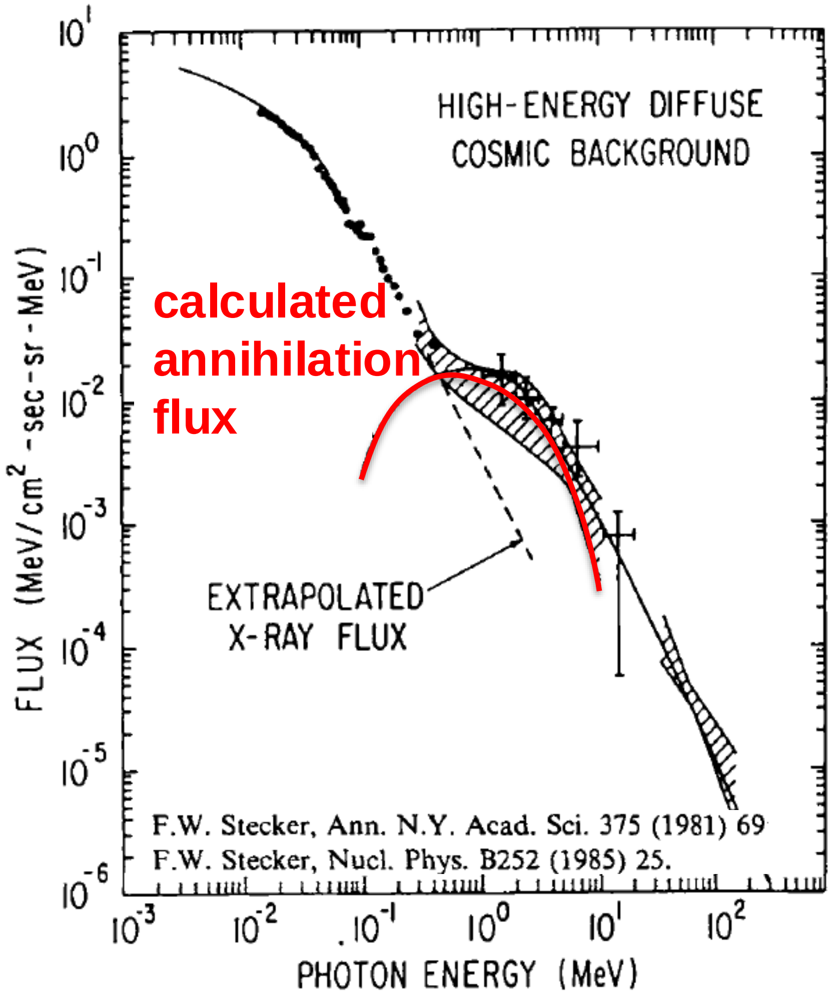
$$y\frac{\partial I}{\partial y}+\epsilon\frac{\partial I}{\partial \epsilon}=2I+\frac{y^2\Omega\nu}{[1+\Omega(y-1)]^{1/2}}\left[A(\epsilon)I-\int_{\epsilon}^{b(\epsilon)}d\epsilon' B(\epsilon|\epsilon')I(\epsilon',y)-\xi^2\Omega n_c y^3 v(T(y))\frac{\sigma_A(T(y))}{\pi r_e^2}G_A(\epsilon)\right]\ \cdots$$



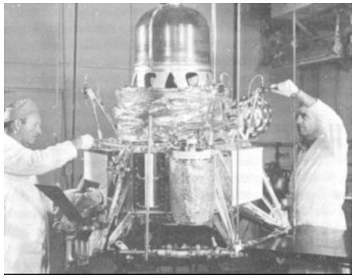
(1) typical rest-frame spectrum produced by p-p̄ annihilation with π° decay

(2) redshifted/scattered p-p feature => 1-10 MeV range (early Universe)

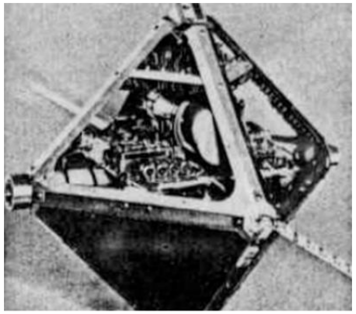
a "Pion bump" in the Cosmic Gamma-Ray Background ?



early observation of the CGB



Ranger 3 1964
Metzger et al.



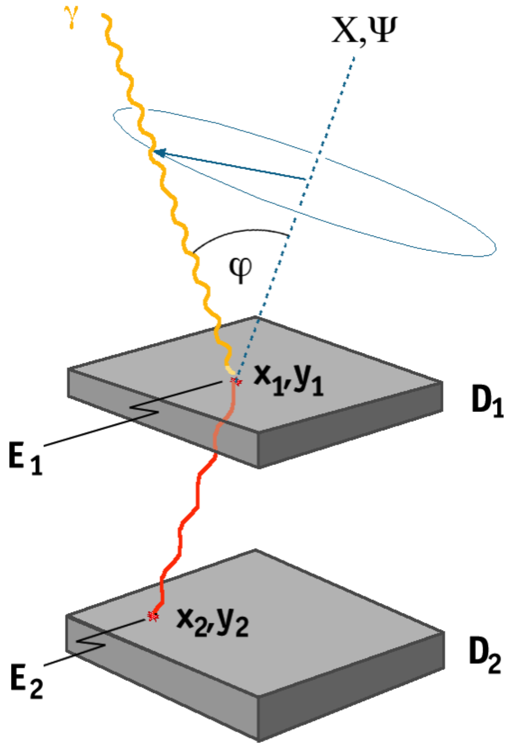
ERS-18, 1970
Vette et al.

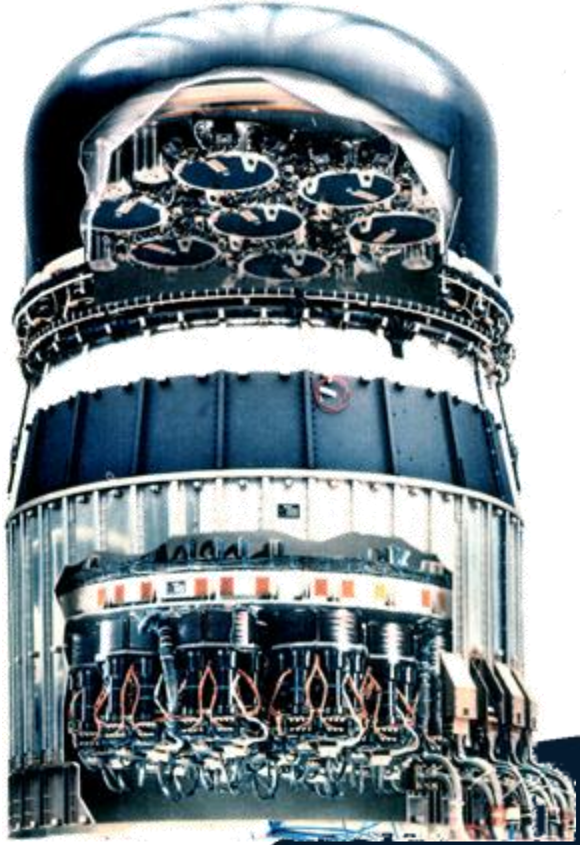
Apollo 15, 1973
Trombka et al.

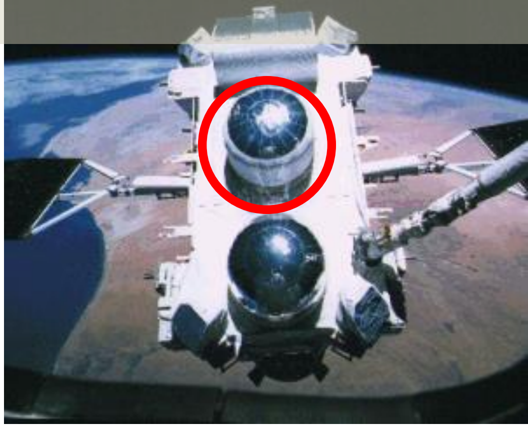
Stecker's solution to a cosmological photon transport equation
taking into account γ-ray production, absorbtion, scattering and redshift

Compton Telescopes

GRO/COMPTEL



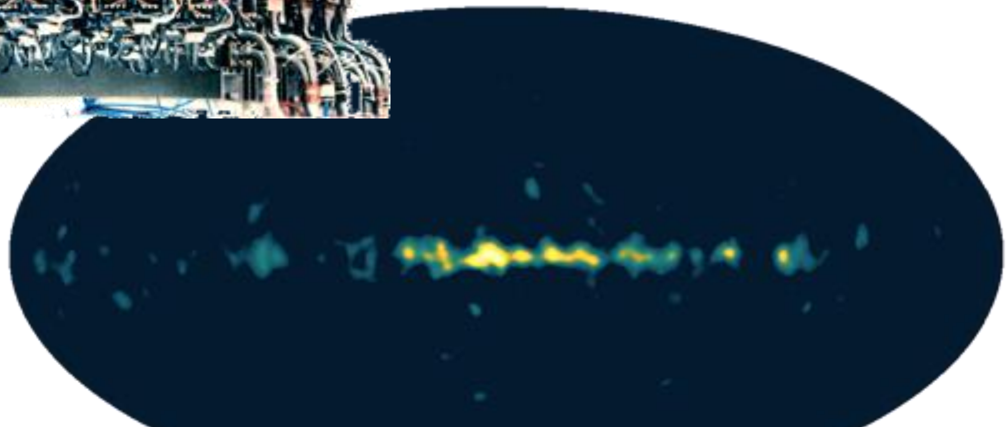




D1	NE 213A, A=4188 cm^2
D2	NaI(Tl) A=8620 cm^2
	both Anger cameras
	TOF, anticoincidence
Mass	1460 kg

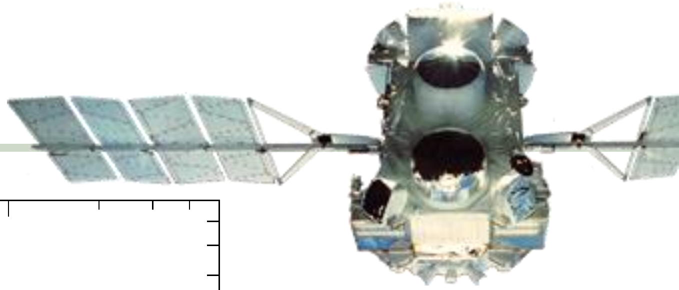
performance

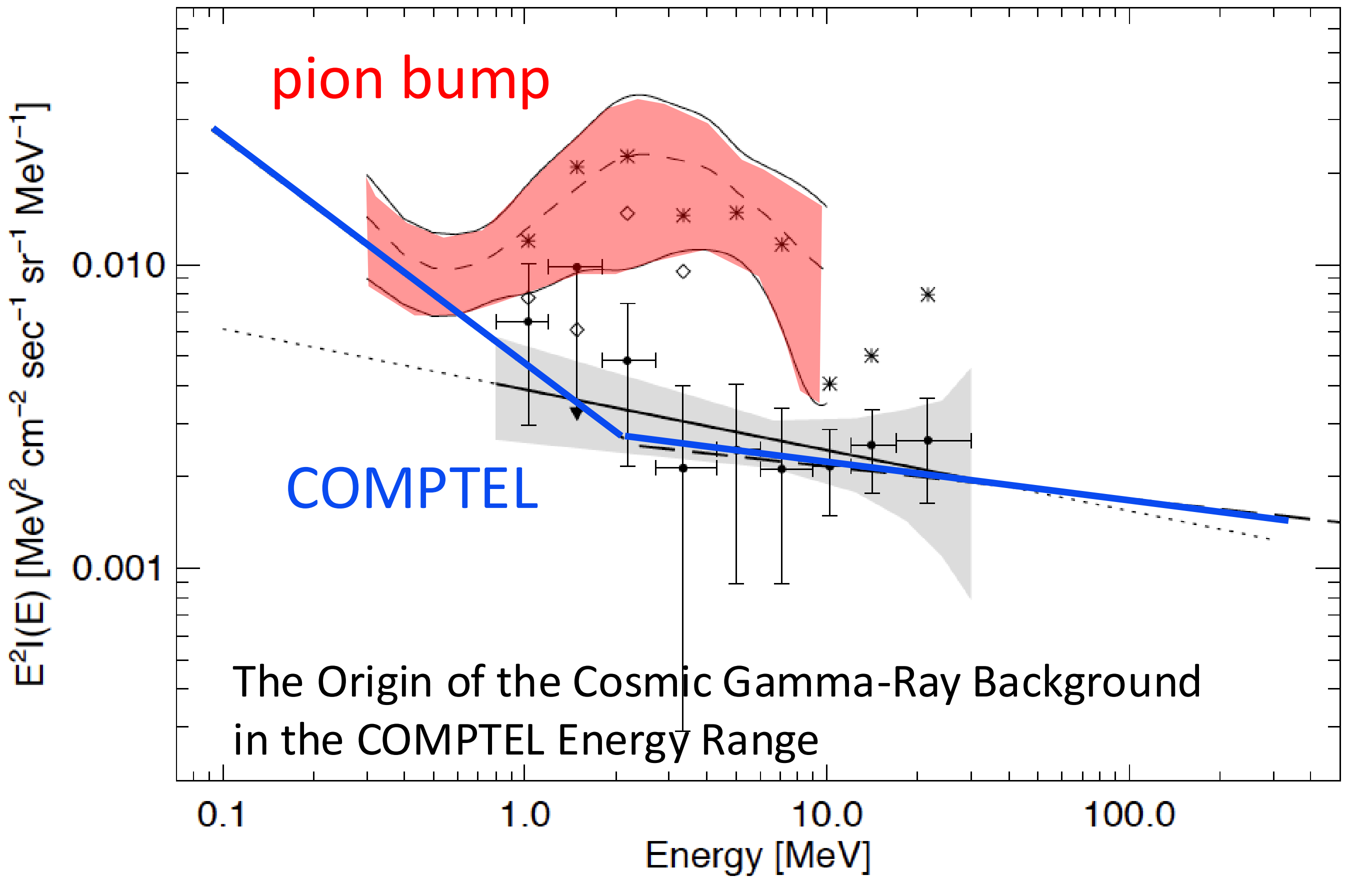
Energy	1 – 30 MeV
Field of view	1 steradian
angular res.	1.7° - 4.4 °
Eff. area	5-30 cm^2
E/ΔE :	5 - 8% (FWHM)

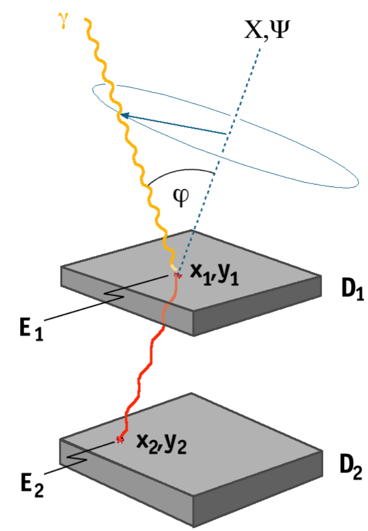


^{26}Al all-sky map

Georg Weidenspointner's thesis 1999





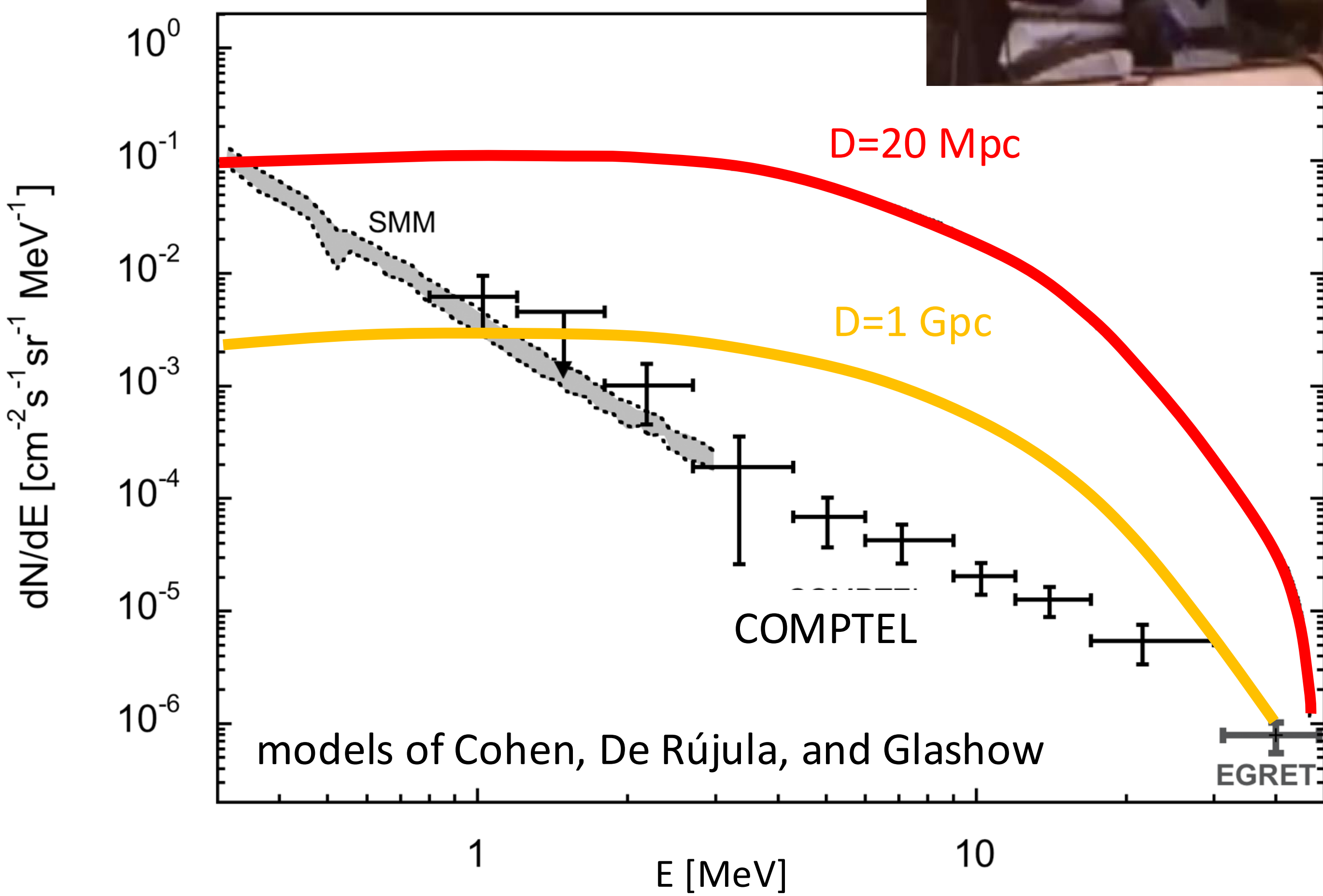


COMPTEL data (Weidenspointner and Varendorff 2001)

- no pion bump
- transition from a softer to a harder component at ~ 5 MeV
- no deviation from isotropy within statistics

Cosmic diffuse X- and Gamma-Ray

Cohen, De Rújula, and Glashow (1998) combin
with the fact that CMB is highly uniform.
At recombination n and n must have been unif
=> annihilation at domain boundaries is inavoi



COMPTEL