Antimatter in Space

Did we find antimatter in the Universe ?

Is there evidence for baryonic antimatter stars, lumps or domains ?

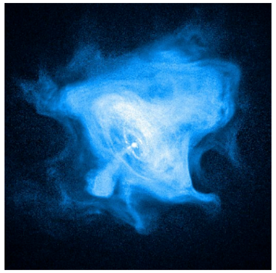
Do we see $\overline{p}$ or e^+ from dark matter annihilation or decay ?

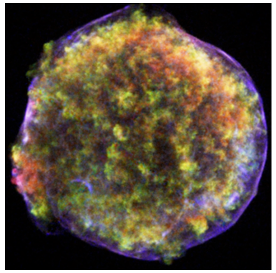
Peter von Ballmoos, IRAP Toulouse

antimatter is produced

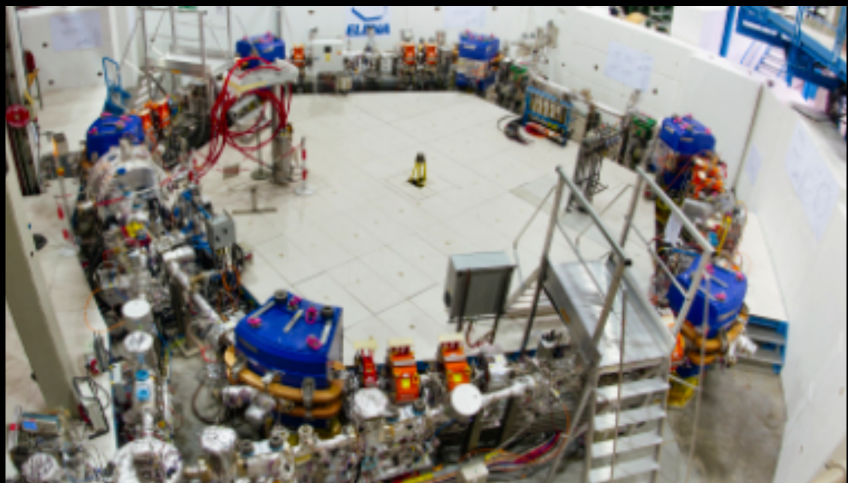
… sicut in caelo, et in terra








accelerators
targets
decelerators



Antimatter in Space

Did we find antimatter in the Universe ? yes, lots !

Is there evidence for baryonic antimatter stars, lumps or domains ?

Do we see $\bar{p}$ or e^+ from dark matter annihilation or decay ?

many high energy processes in astrophysics create e^+ or $\bar{p}$

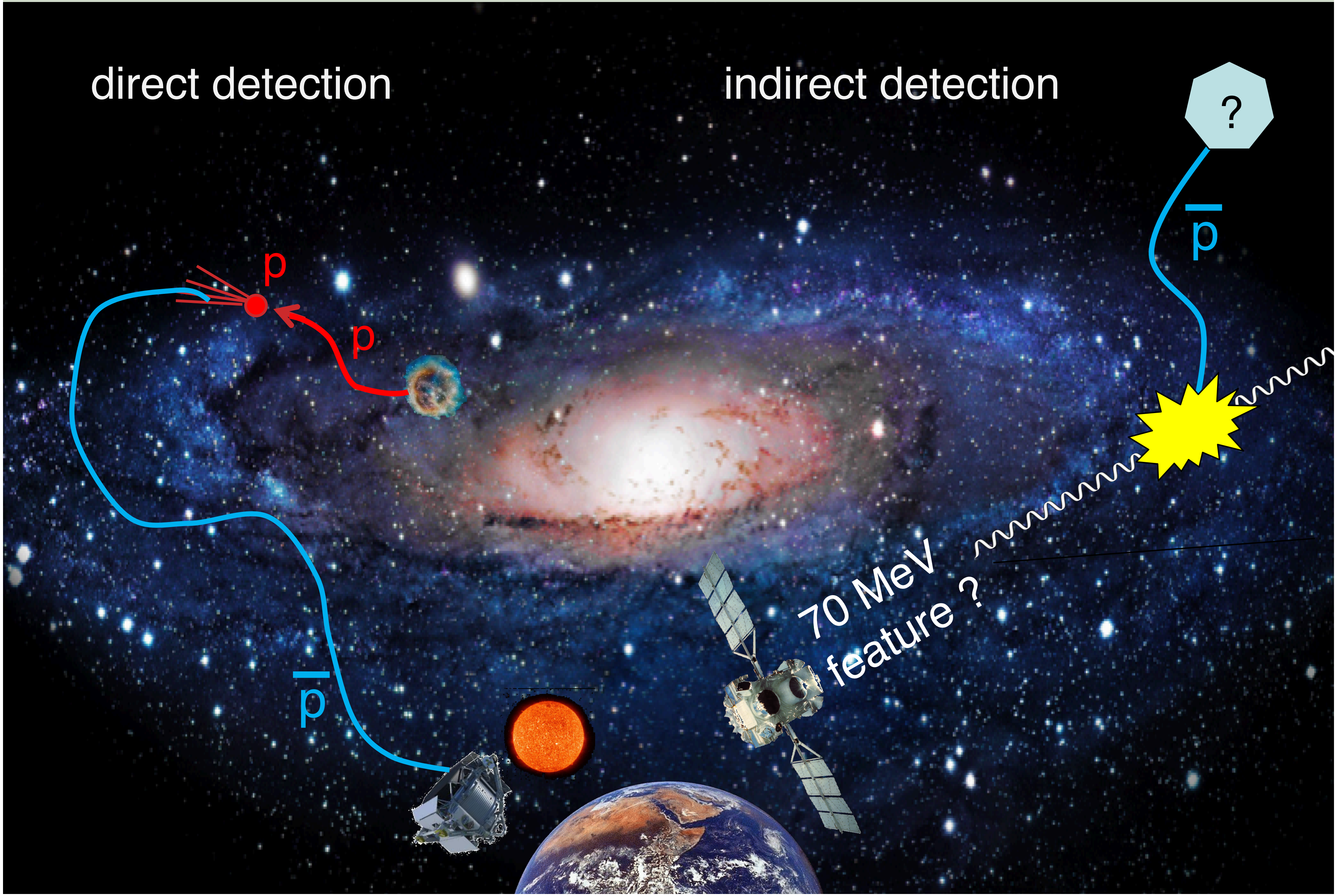
so is there space for primordial antimatter or exotic physics ?
the difficulty is in modelling the production, transport (and annihilation) of the "secondary" antiparticles

this is a short review of observational evidence for both

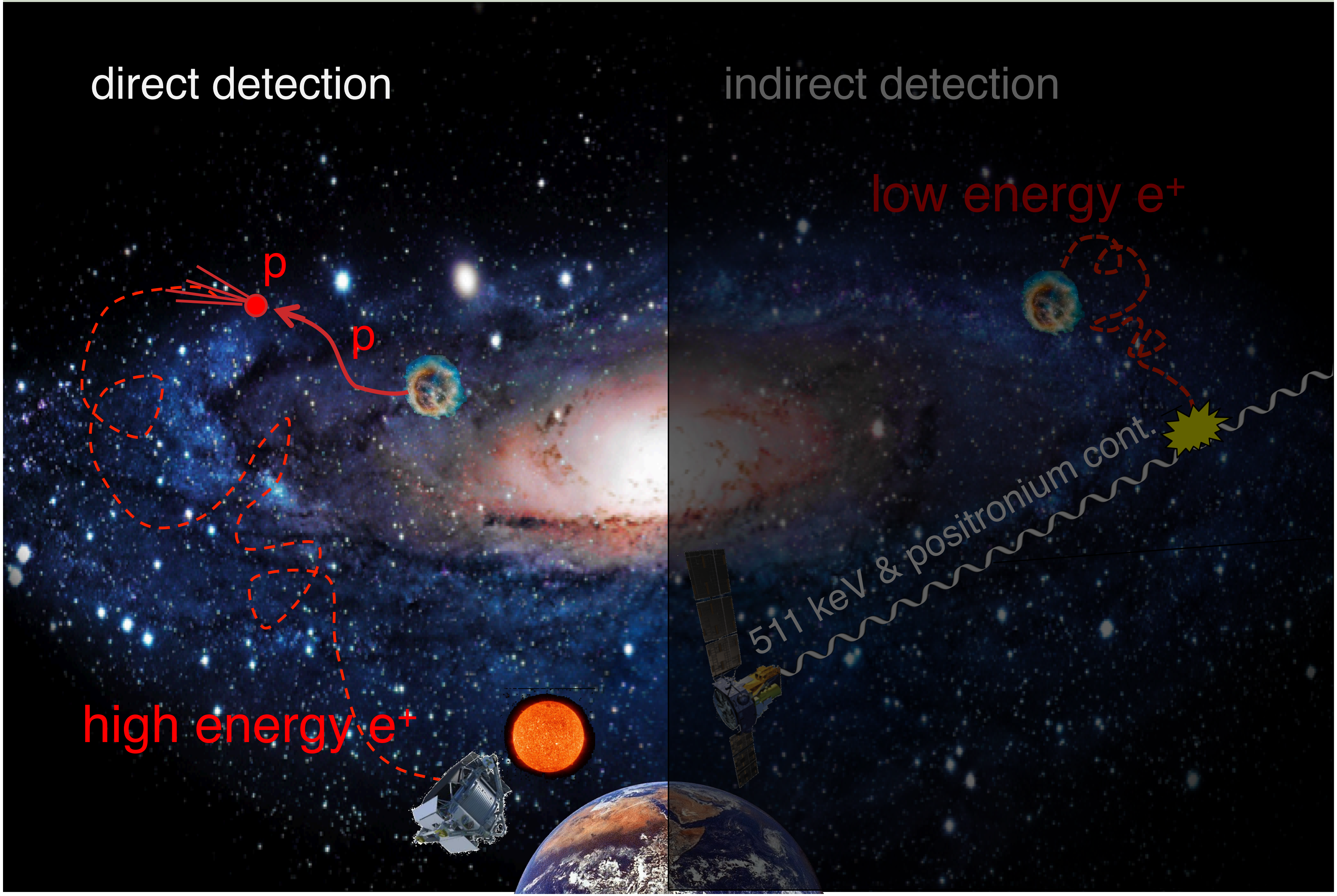
baryonic antimatter and positrons in the Universe

Peter von Ballmoos, IRAP Toulouse

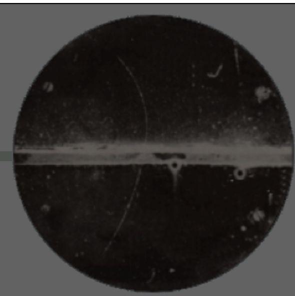
baryonic antimatter



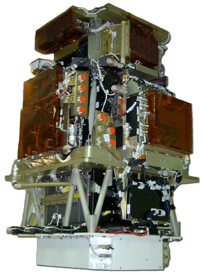
Positrons in Space



Positrons in Space



direct detection



Pamela

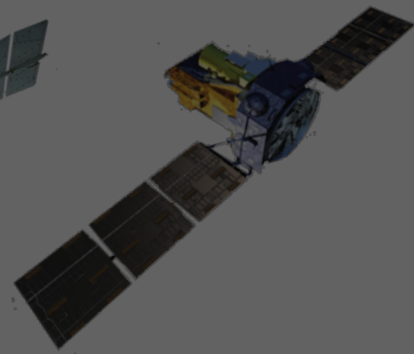
AMS-02

$E_{e^+} > 1$ GeV

- e^+ fraction
- "PAMELA anomaly"
- scenarios for the e^+ anomaly

indirect detection

Compton-GRO



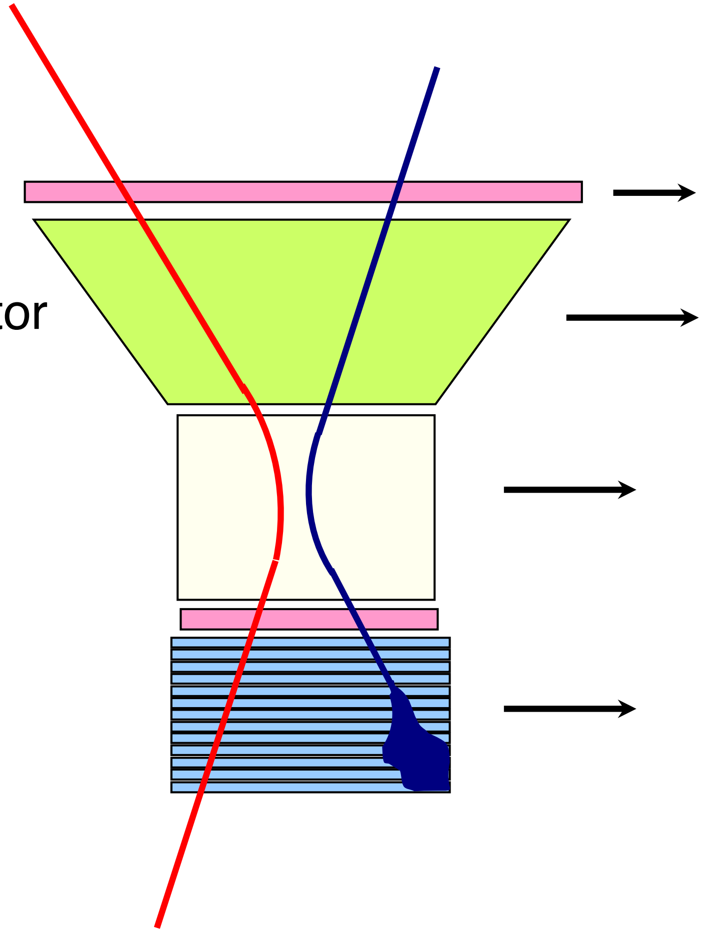
INTEGRAL

$E_{e^+} < 1$ MeV

- legend of the "great annihilator"
- todays annihilation sky
- e^+ sources, transport, annihilation

direct positron detection : the typical e^+ and e^- instrument

need of a magnet spectrometer for e^+ and e^- separation



Time of Flight (ToF) → direction & charge

Transition Radiation Detector (TRD) or Gas Cherenkov → e / hadron discrimination

Magnet Spectrometer → rigidity / charge sign

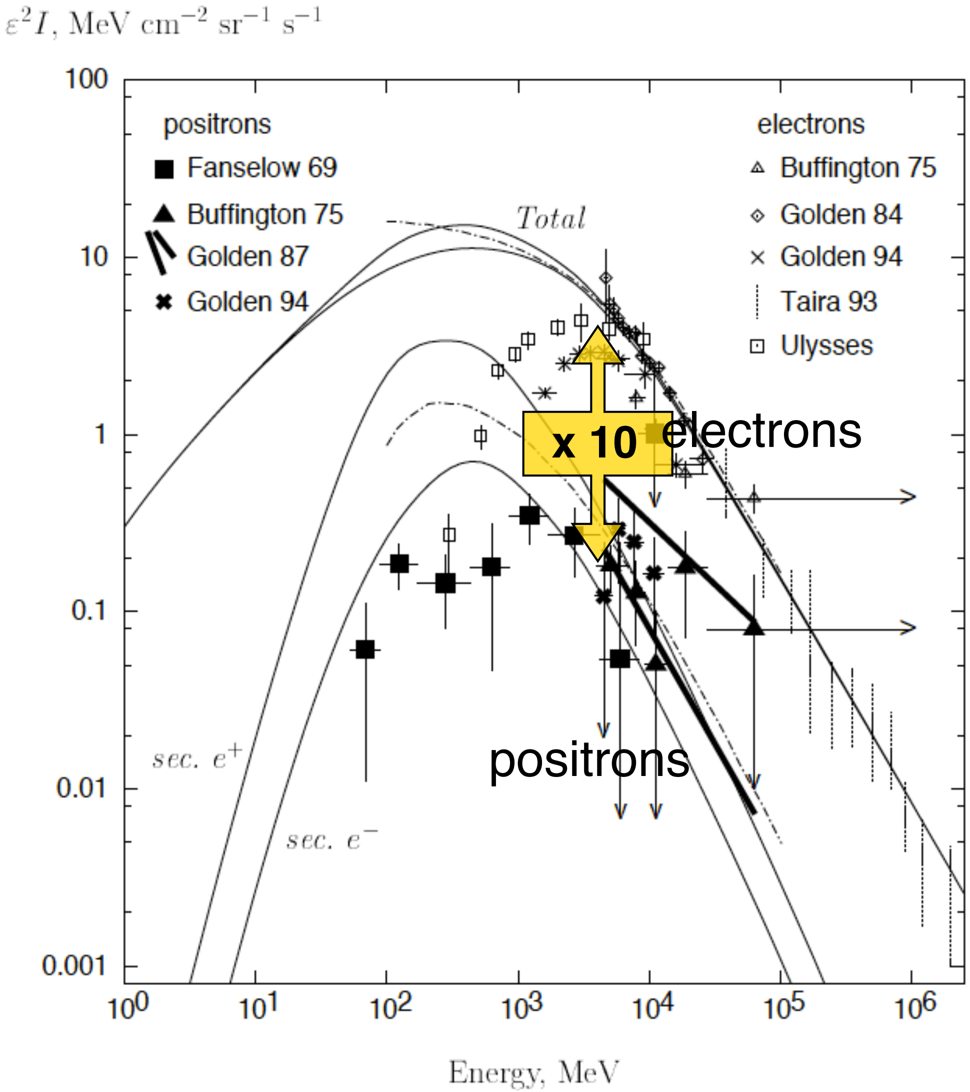
EM Calorimeter → energy & shower shape

need for efficient proton rejection :
the flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of $>10^4$

adapted from M. Schubnell U. Michigan

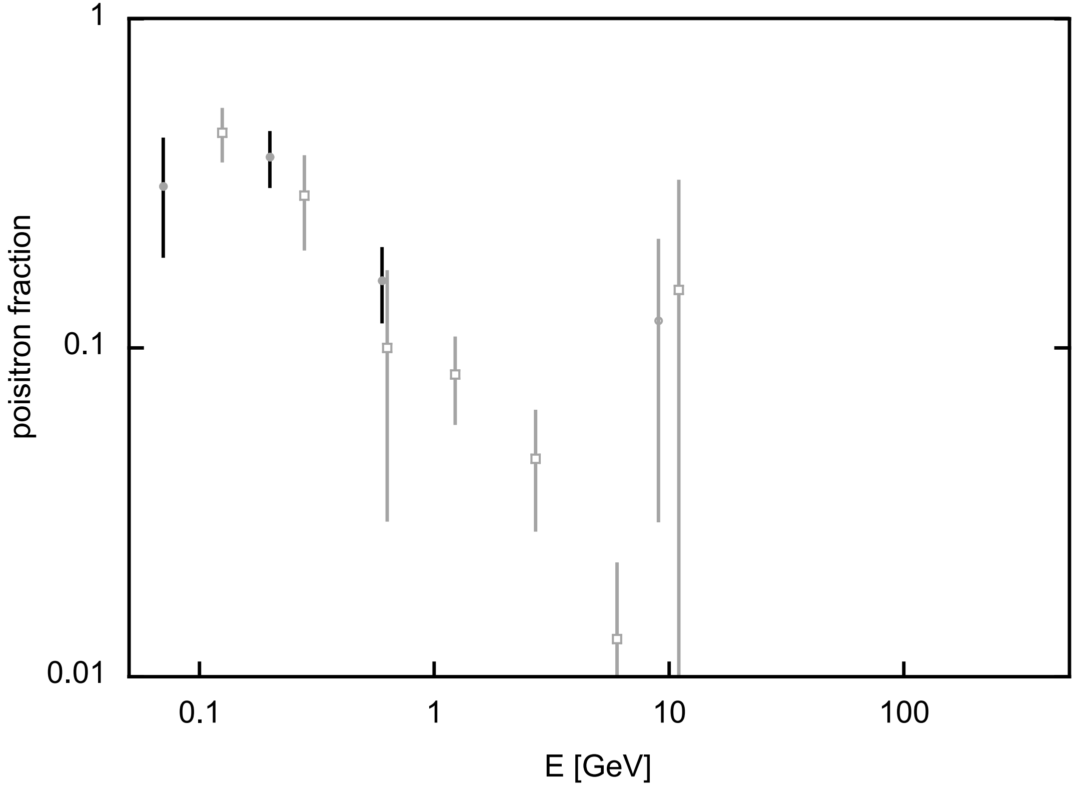
direct positron detection : the e⁺ fraction

High energy positrons (E_{e^+} > 1 GeV) are observed in cosmic rays

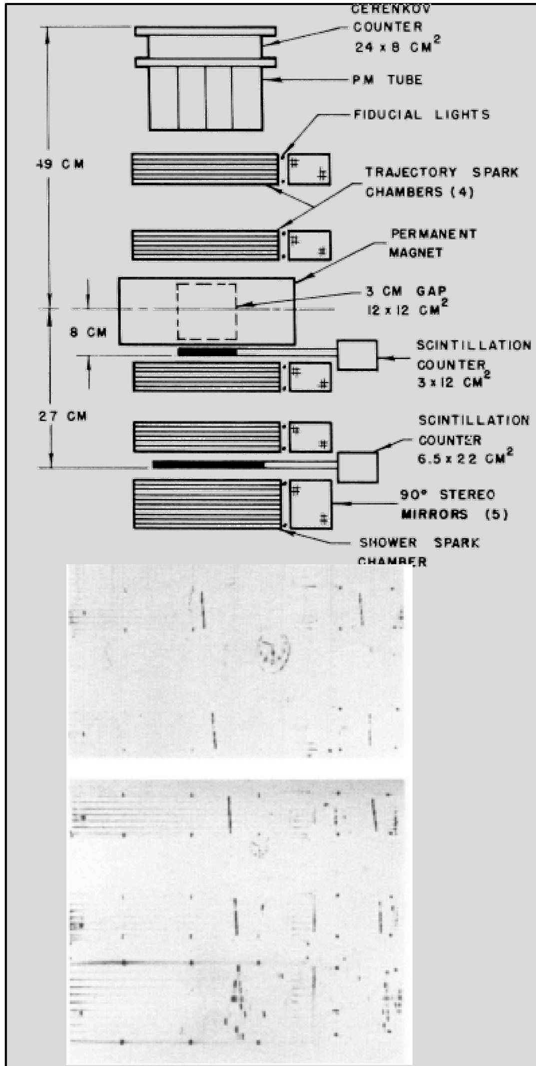


expected at this level from decays following p+p collisions, but ...

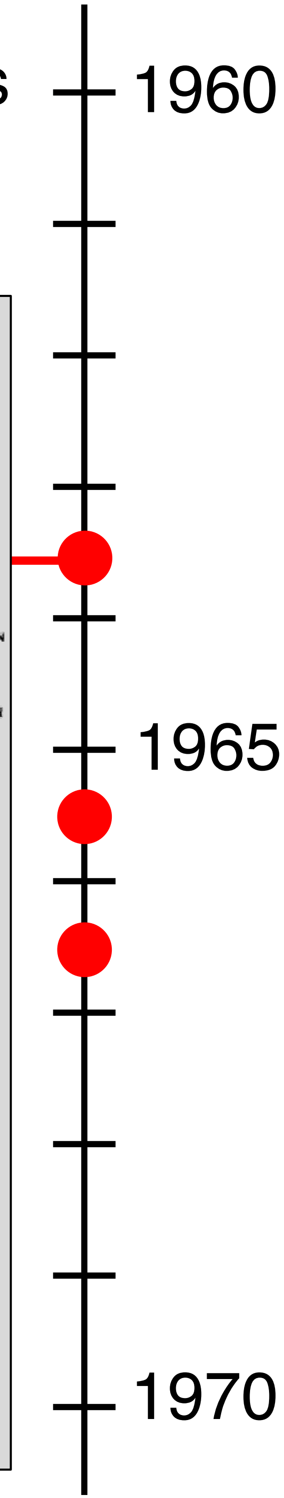
Positron fraction $\frac{e^+}{e^- + e^+}$: early balloon experiments



De Shong (1964)
Fanselow (1969)
Agrinier (1969)



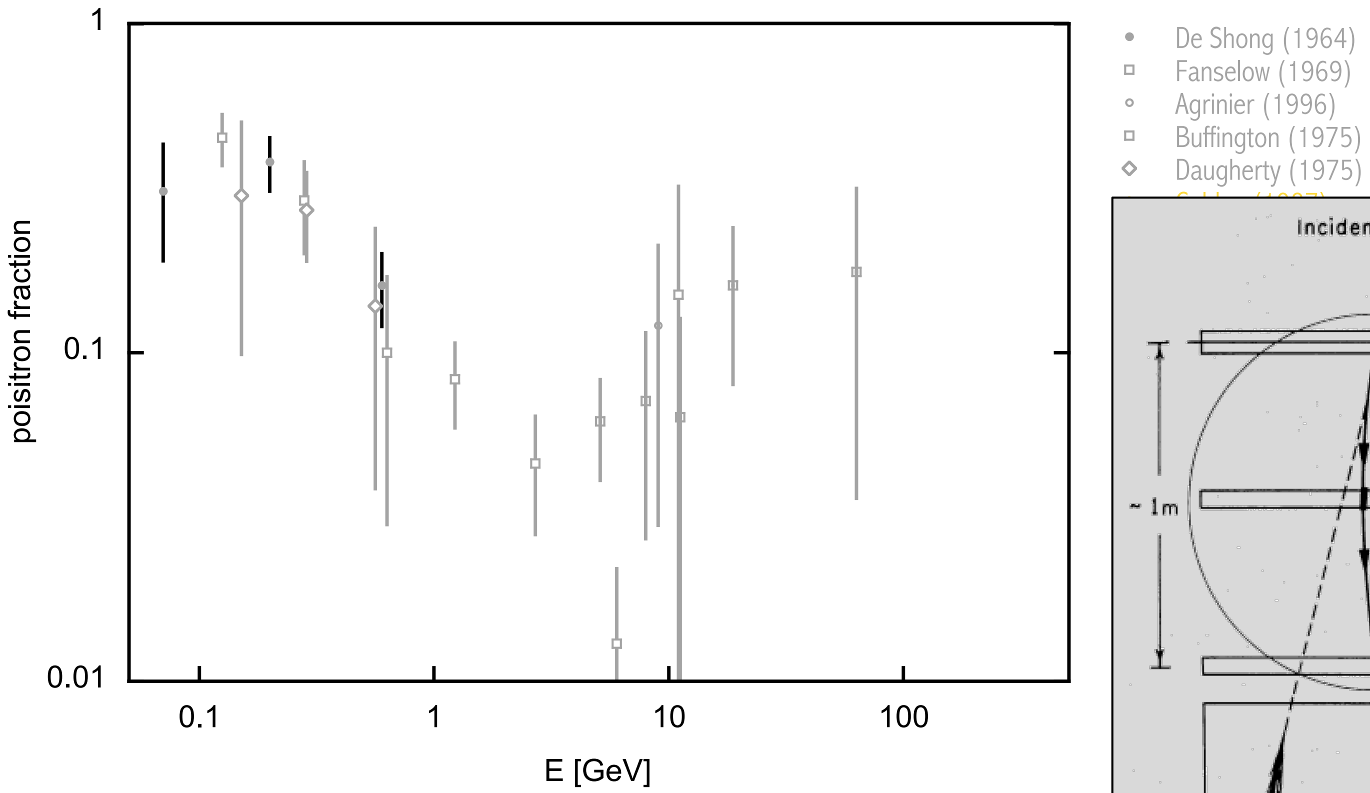
De Shong, Hildeband, Meyer, Phys. Rev. Let. 12 (1964)

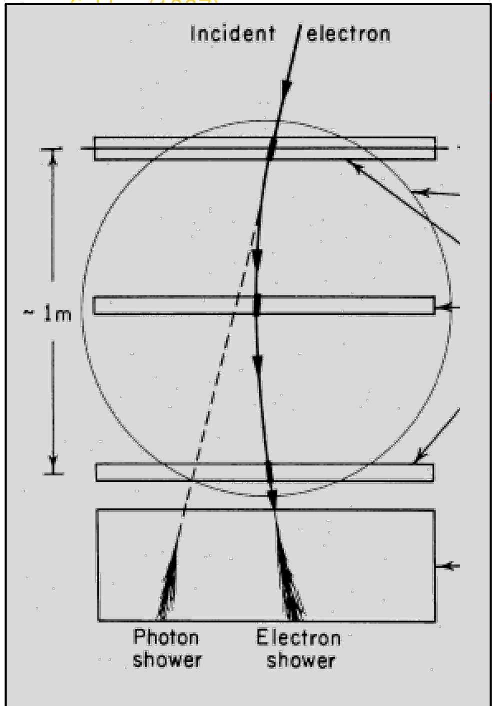


positron fraction ≈ 0.1

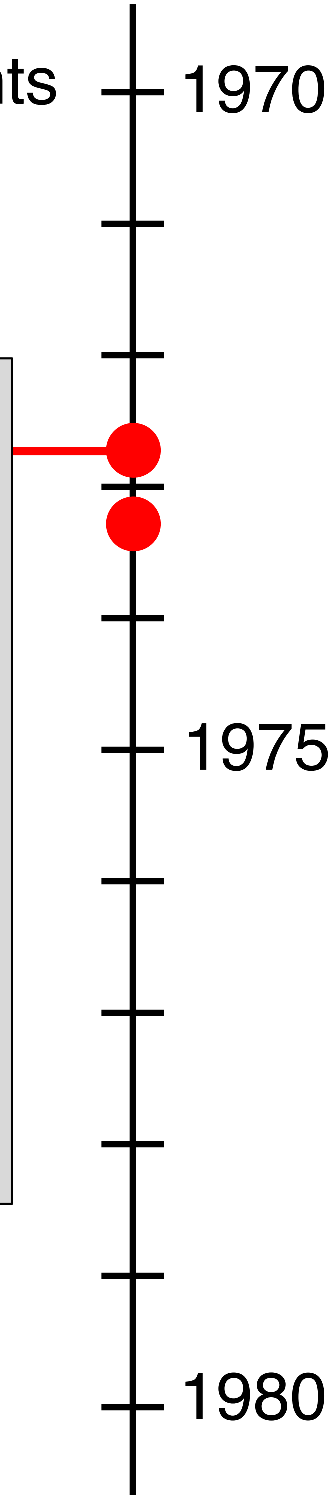
consistent with expectations assuming production in interstellar space by cosmic rays encountering 4 g/cm² of material

Positron fraction $\frac{e^+}{e^- + e^+}$: early balloon experiments



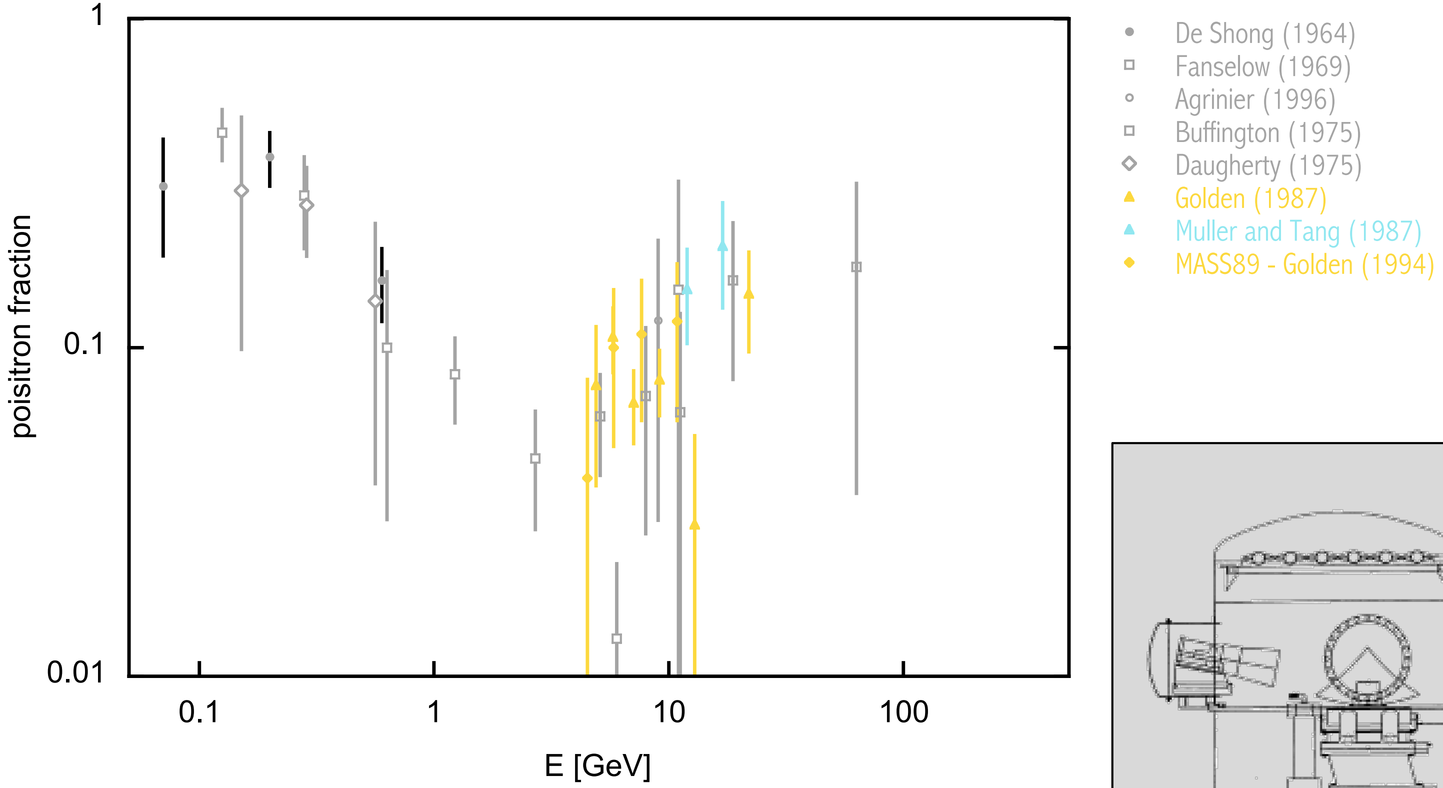


Buffington, Orth, Smoot, 1974

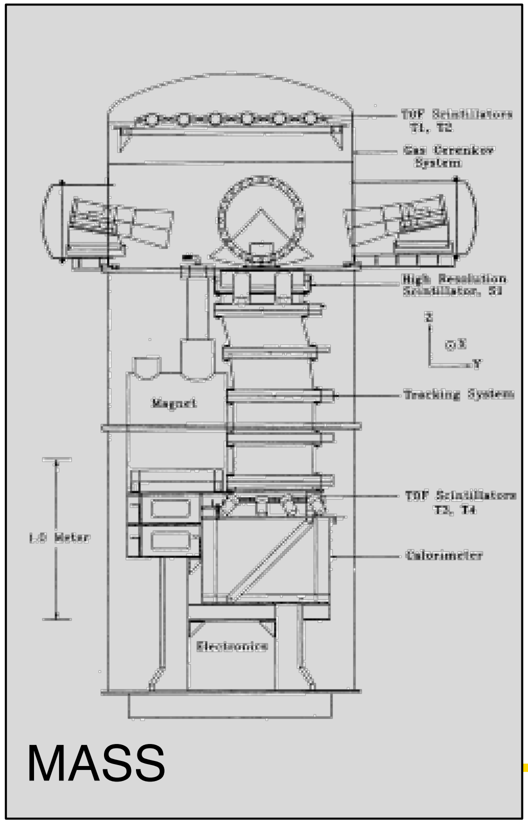


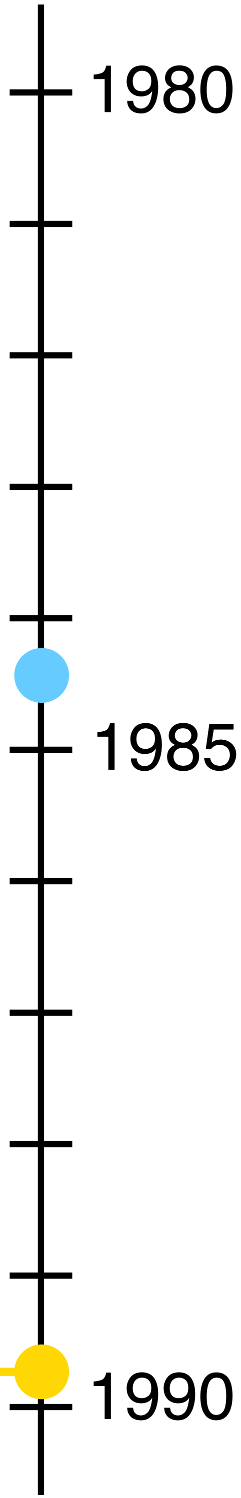
challenges :
- proton contamination
- low statistics (small A_{eff}, short flights)
- atmospheric positrons
- inter-comparisons (at low E) difficult because of
  - cutoff rigidity
  - solar modulation/activity

Positron fraction $\frac{e^+}{e^- + e^+}$: an increase > 10 GeV ?

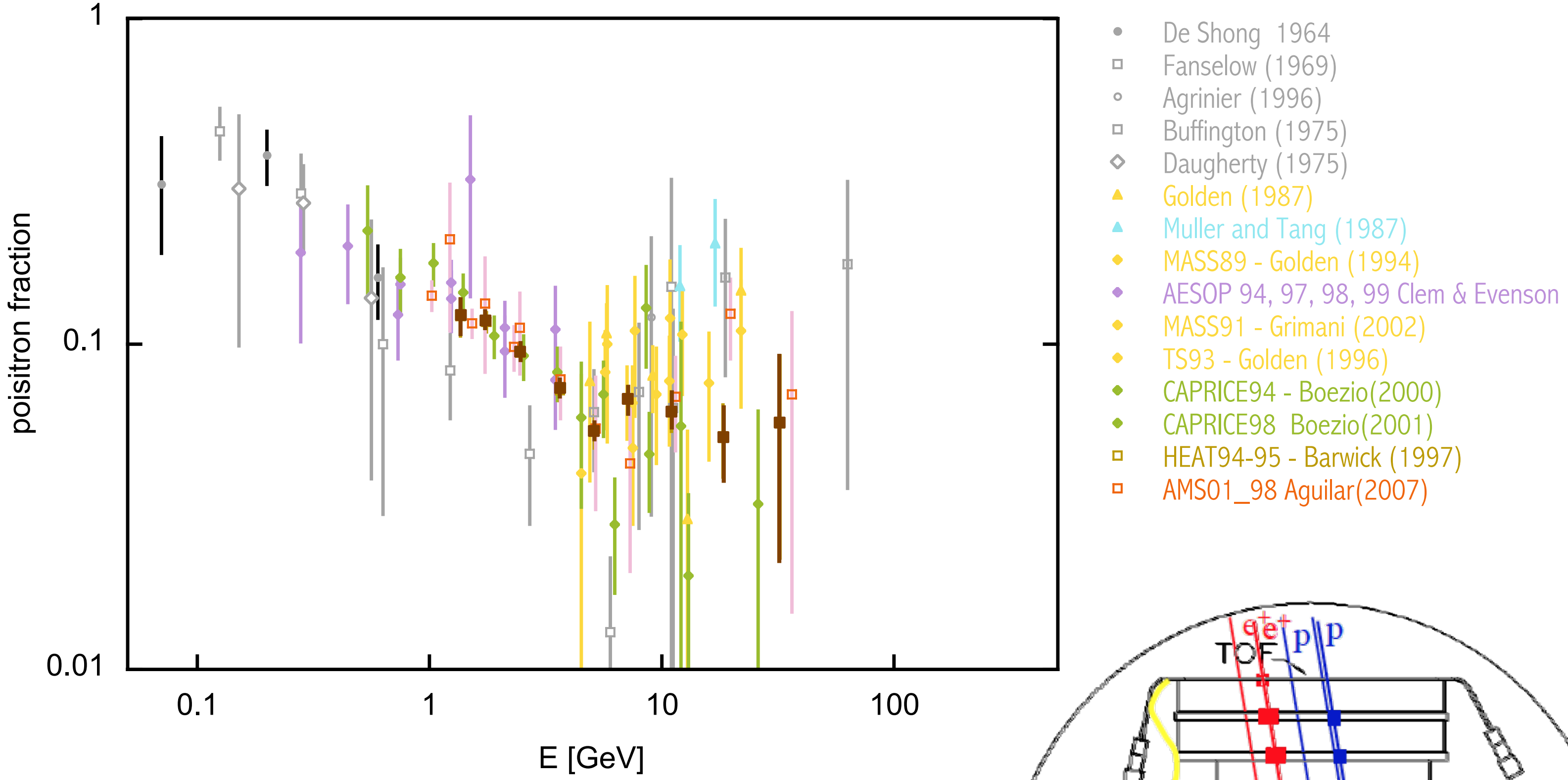


Müller and Tang (1987) : "This increase appears to suggest that either a **primary component of positrons becomes significant above 10 GeV** or that the spectrum of primary negatrons decreases above 10 GeV more sharply than that of secondary positrons."

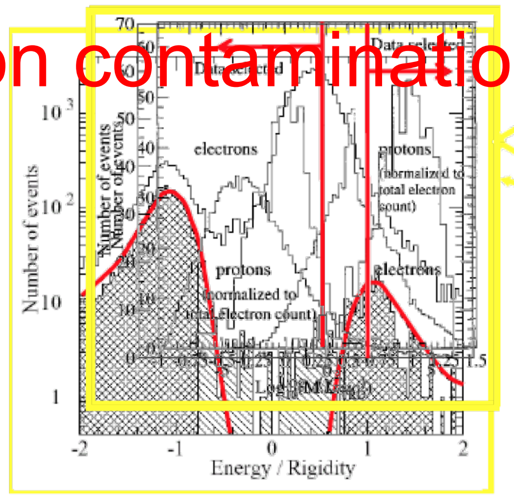


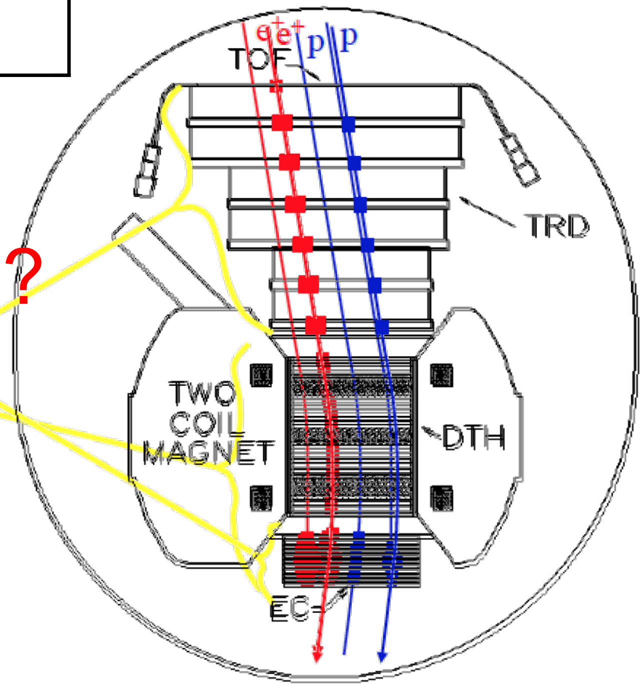


Positron fraction $\frac{e^{+}}{e^{-}+e^{+}}$: an increase > 10 GeV ?

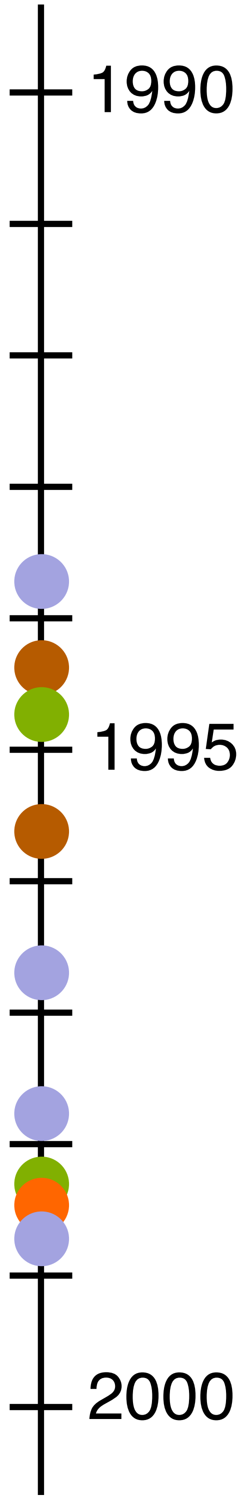


proton contamination ?

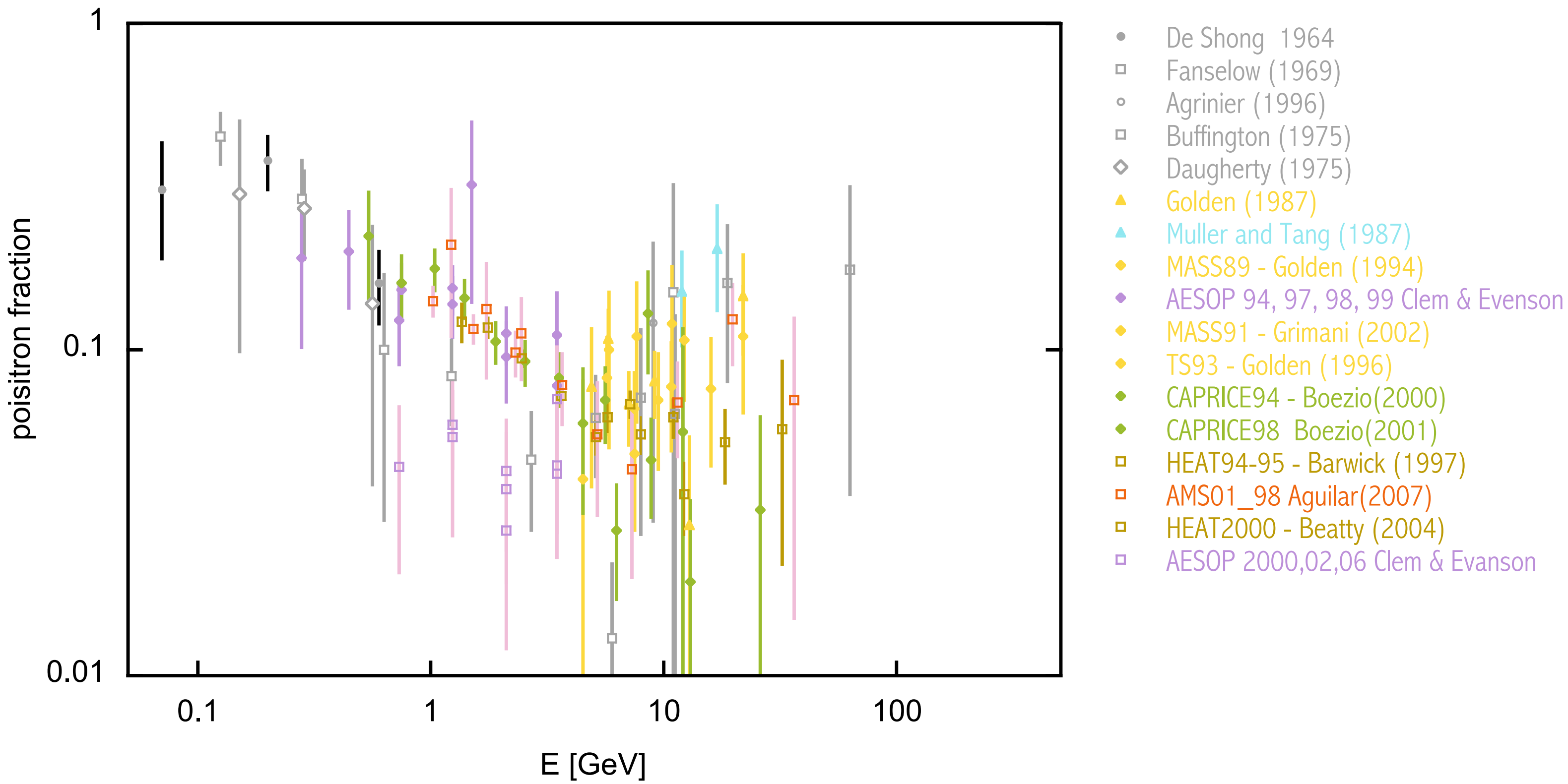


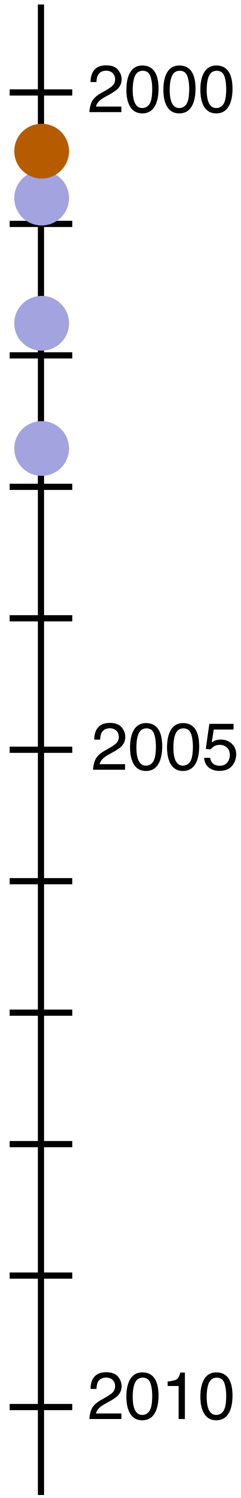


HEAT
particle ID !
(redundancy)



Positron fraction $\frac{e^+}{e^- + e^+}$: an increase > 10 GeV ?

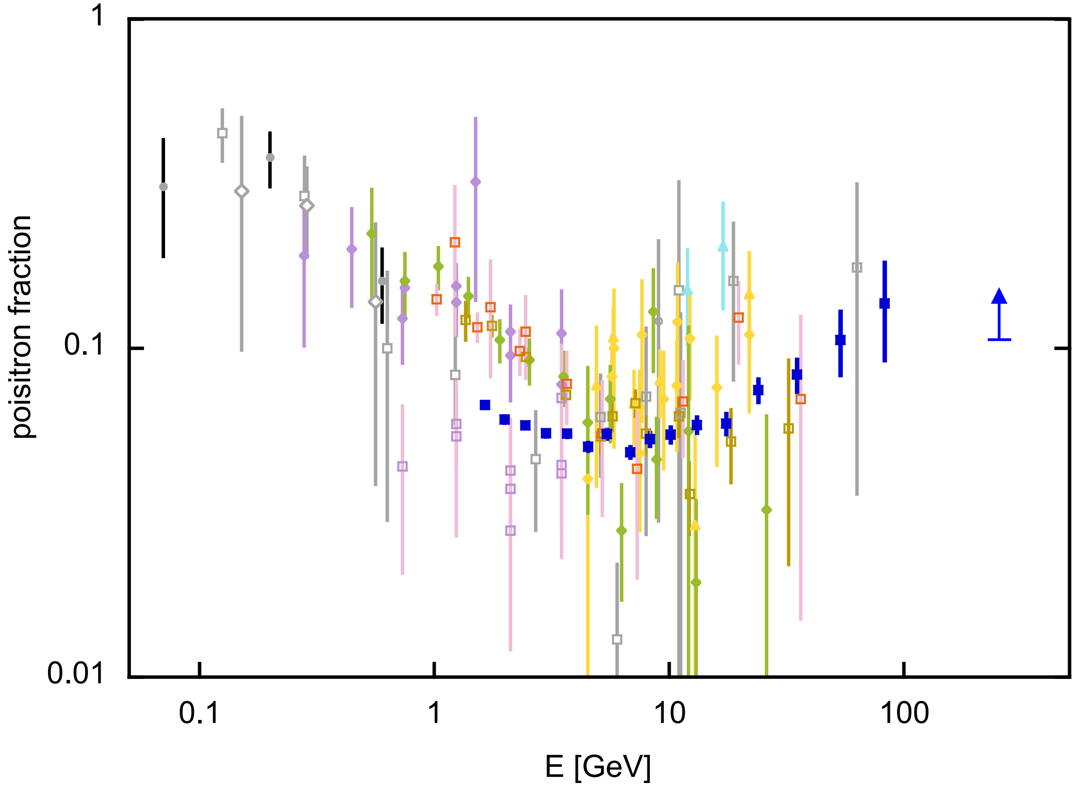


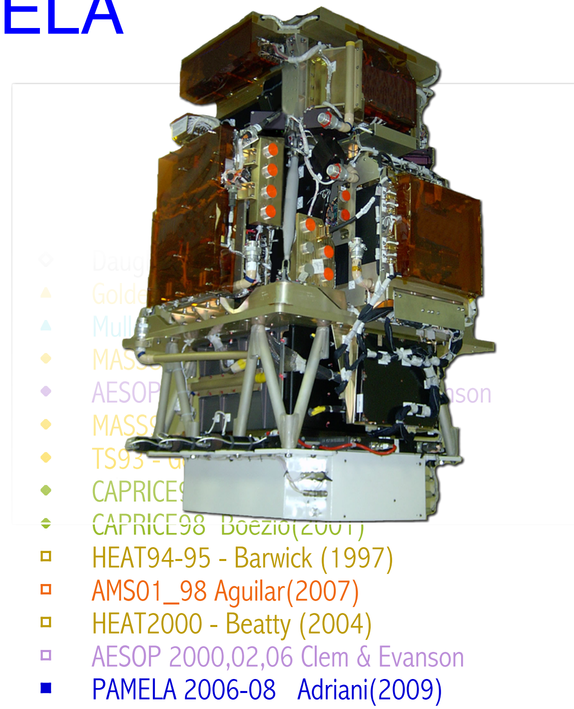


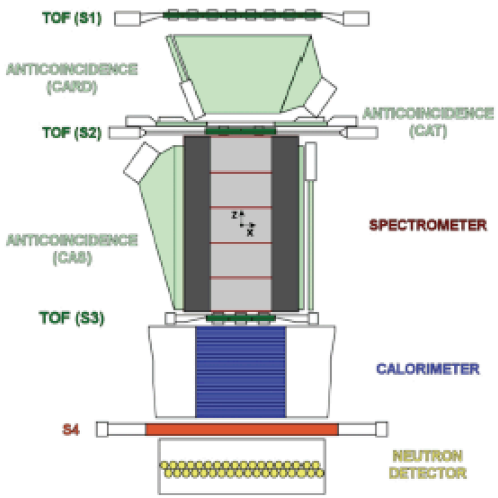
MASS (Golden 1996) : ... measurements do not show any compelling evidence for an increase in this ratio with energy, and our results are consistent with a constant fraction of 0.078 ± 0.016 over the entire energy region."

HEAT (Beatty 2004) : "... a primary contribution to the positron intensity above a few GeV can still not be ruled out."

Positron fraction $\frac{e^+}{e^- + e^+}$: + PAMELA



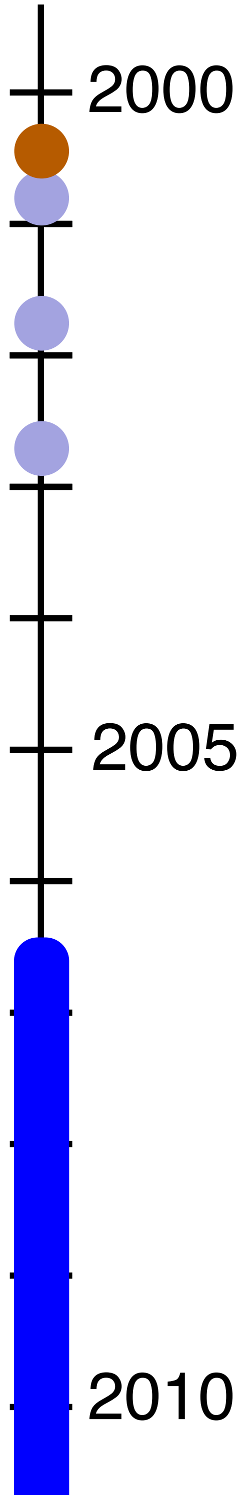




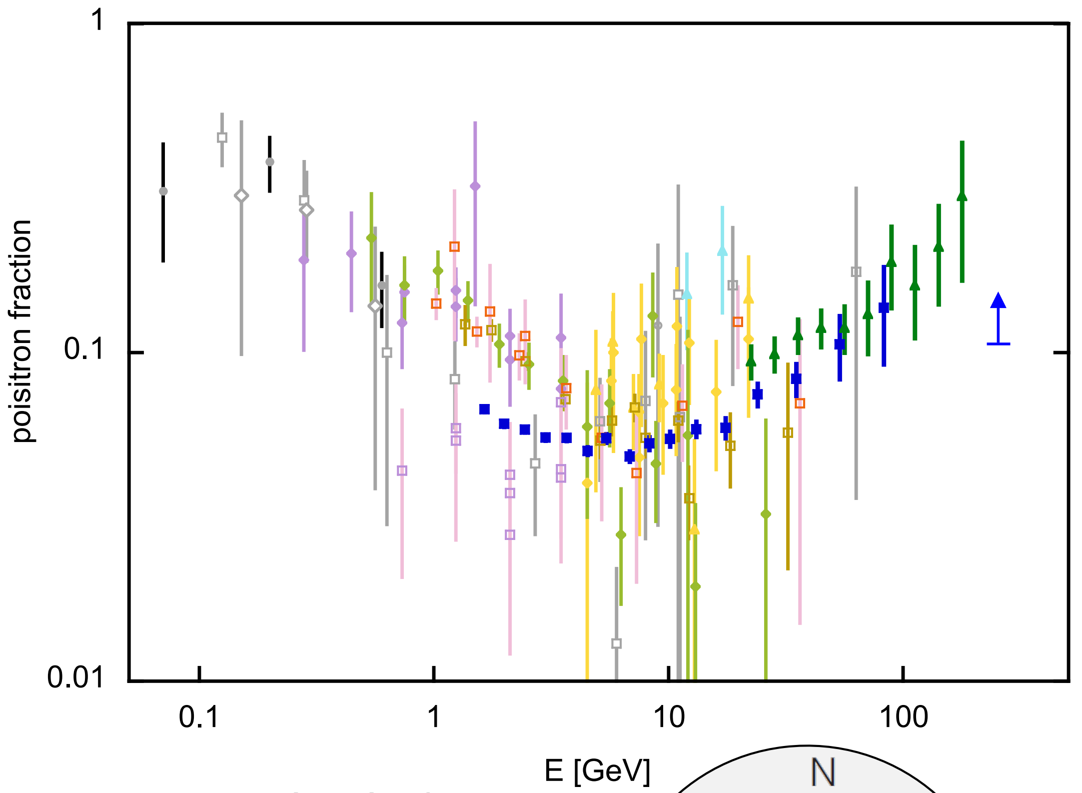
$1.6 \cdot 10^5$ e-and e+ detected
151672 e-and 9,430 e+ identified

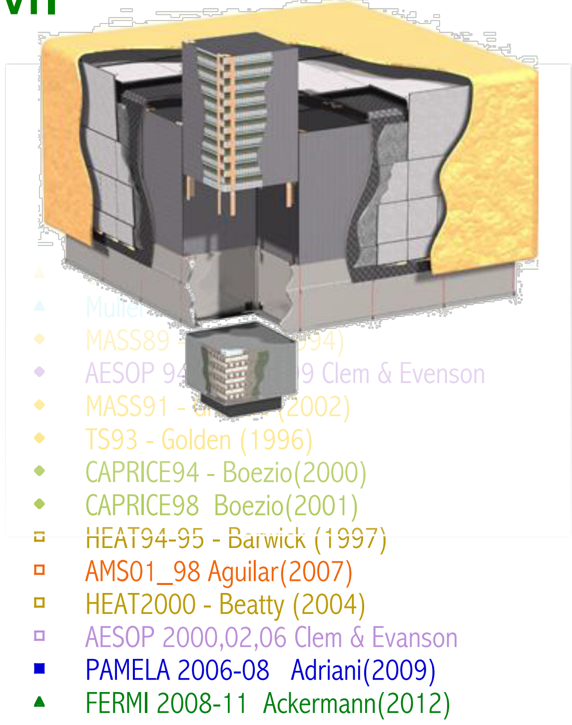
=> flood of articles attributing the e+ excess to the decay or annihilation of DM

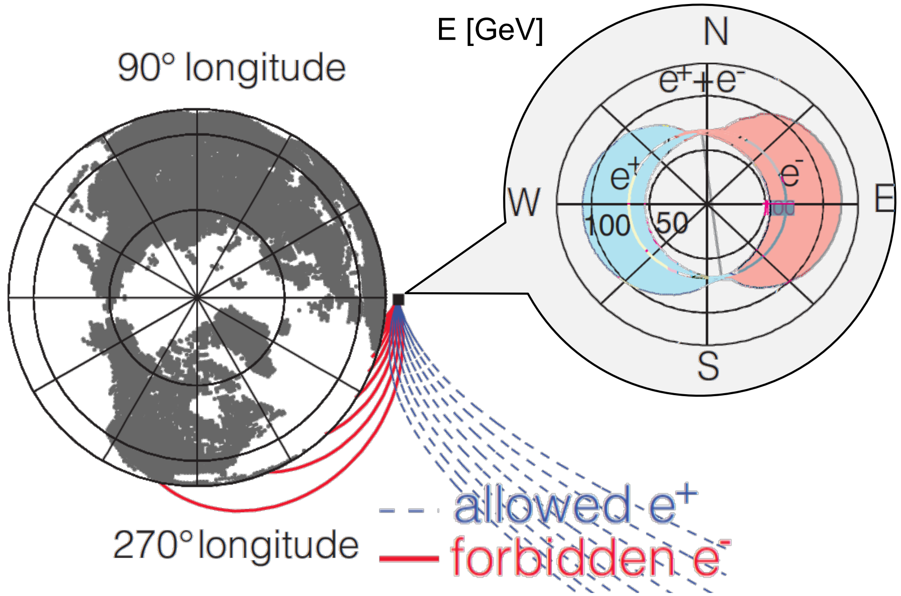
=> excess of papers denying the need for an explanation in terms of DM



Positron fraction $\frac{e^+}{e^- + e^+}$: + FERMI

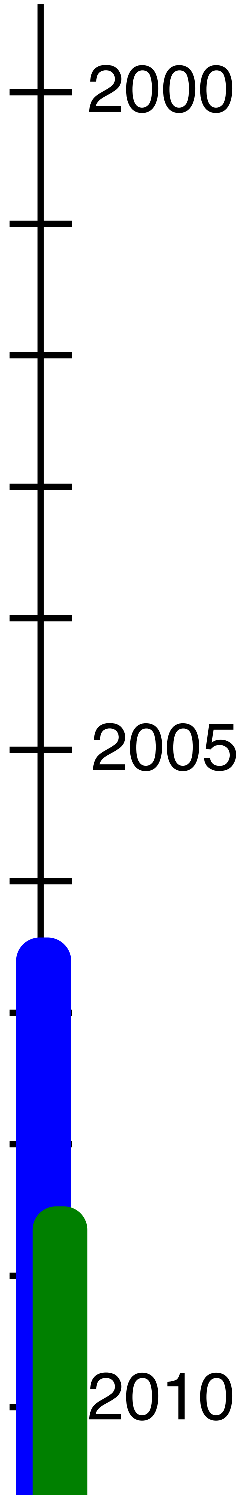




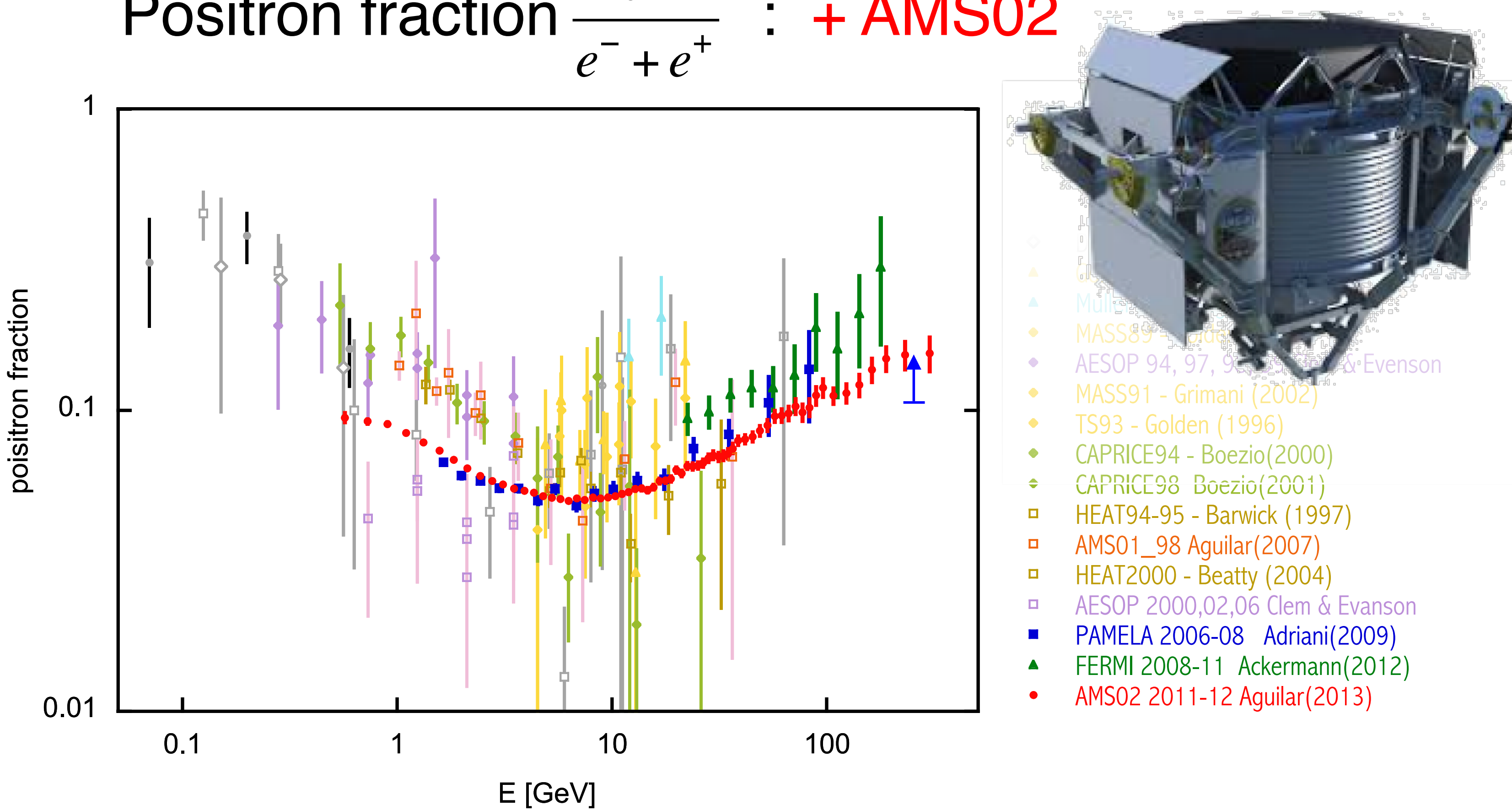


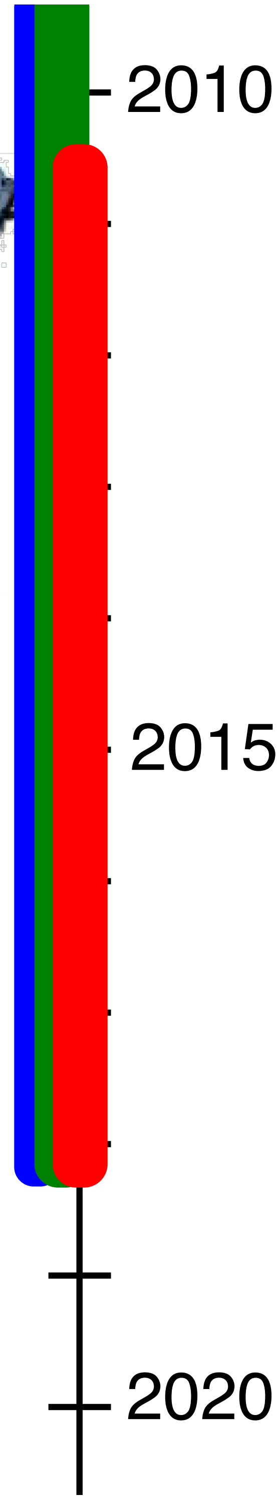
confirmation of the "PAMELA excess"

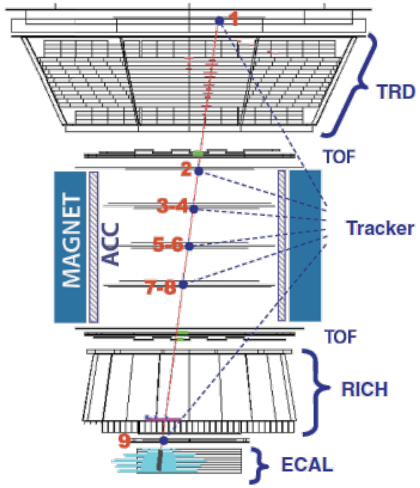
(FERMI LAT is a γ-ray telescope without a magnet on-board … it identifies e^+/e^- using the earth B !)



Positron fraction $\frac{e^+}{e^- + e^+}$: + AMS02



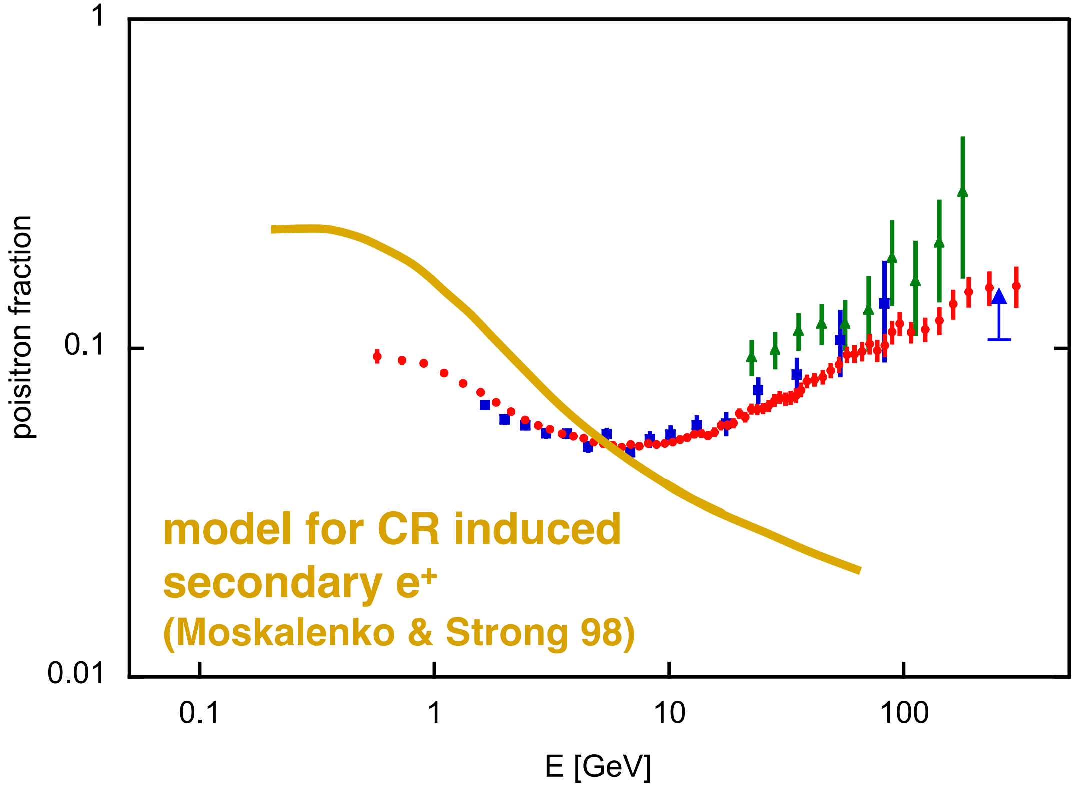




$6.8 \cdot 10^6$ positrons and electrons detected

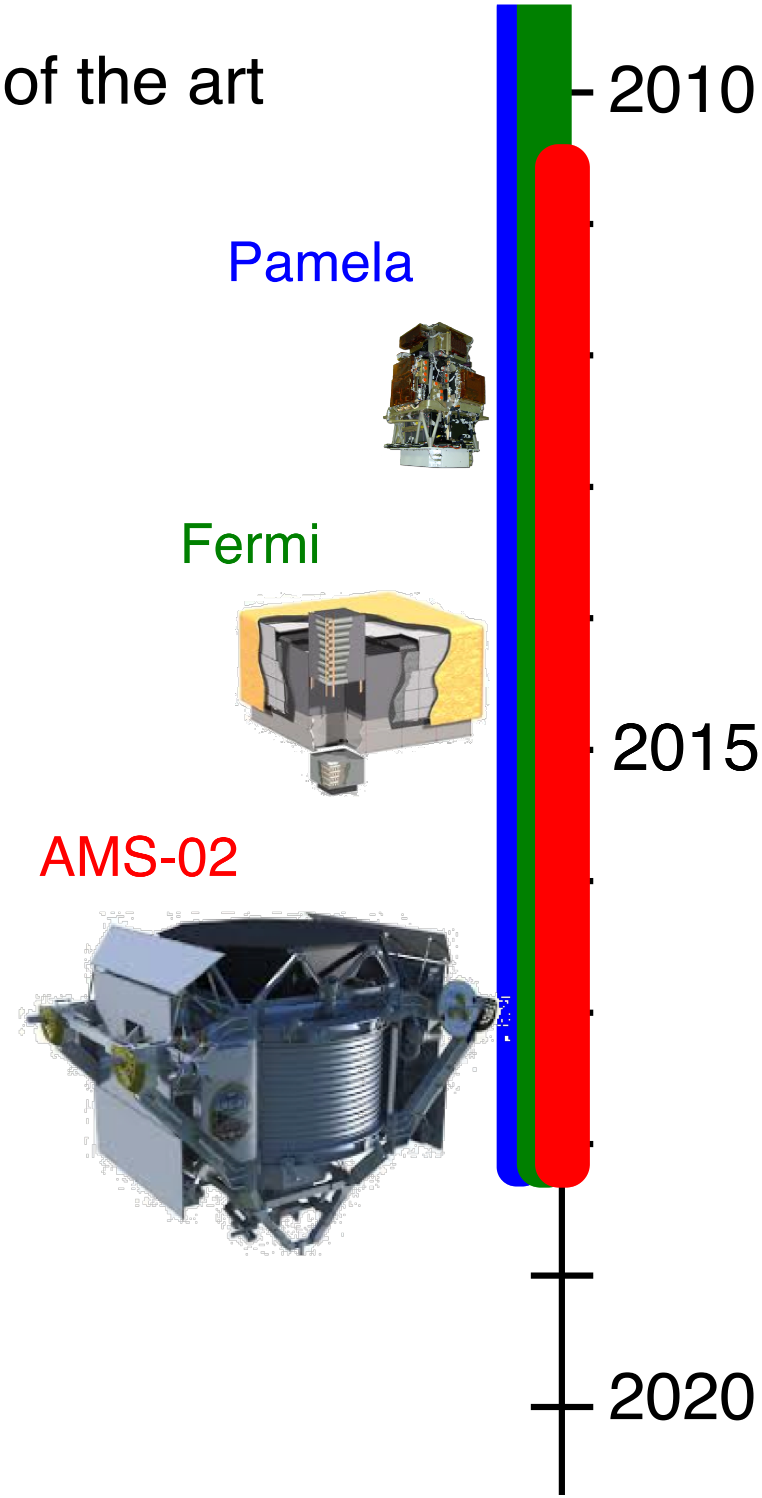
Aguilar 2013 : "... positron fraction spectrum shows no fine structure, and the positron to electron ratio shows no observable anisotropy. Together, these features show the existence of new physical phenomena."

Positron fraction $\frac{e^+}{e^- + e^+}$: the state of the art



"anomaly" ?
with respect to what ?

=> models for CR induced
secondary positrons

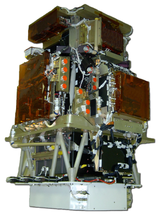


the positron to electron ratio shows no observable anisotropy

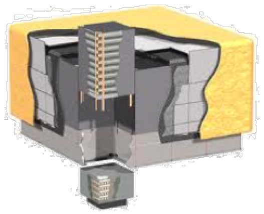
anisotropy expected from a local source

If the excess has a particle physics origin, it should be isotropic

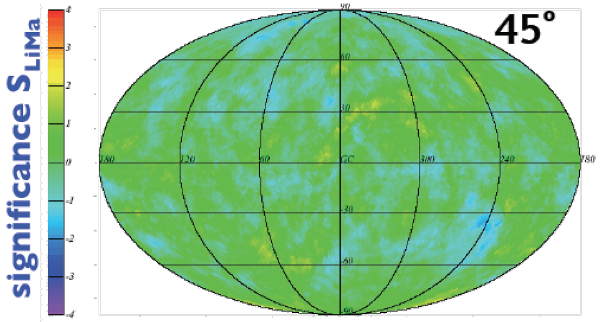
Pamela

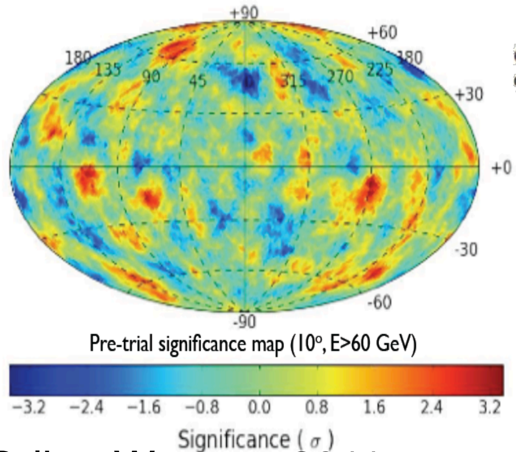


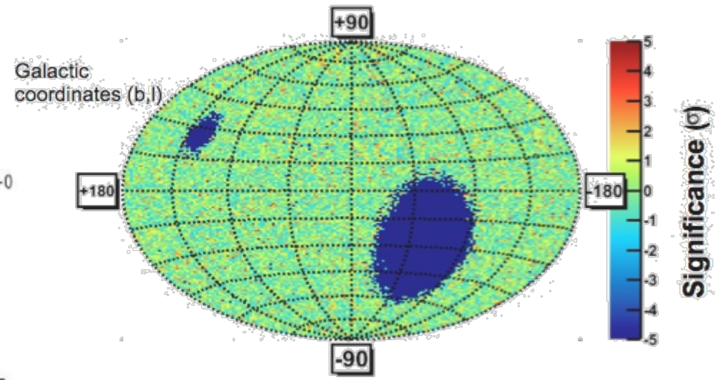
Fermi



AMS-02







Giaccari, 2012

Drlica-Wagner, 2011

AMS collaboration,
ICRC 7/2013

no significant anisotropy found in either data !

Scenarios for the e+ "anomaly"

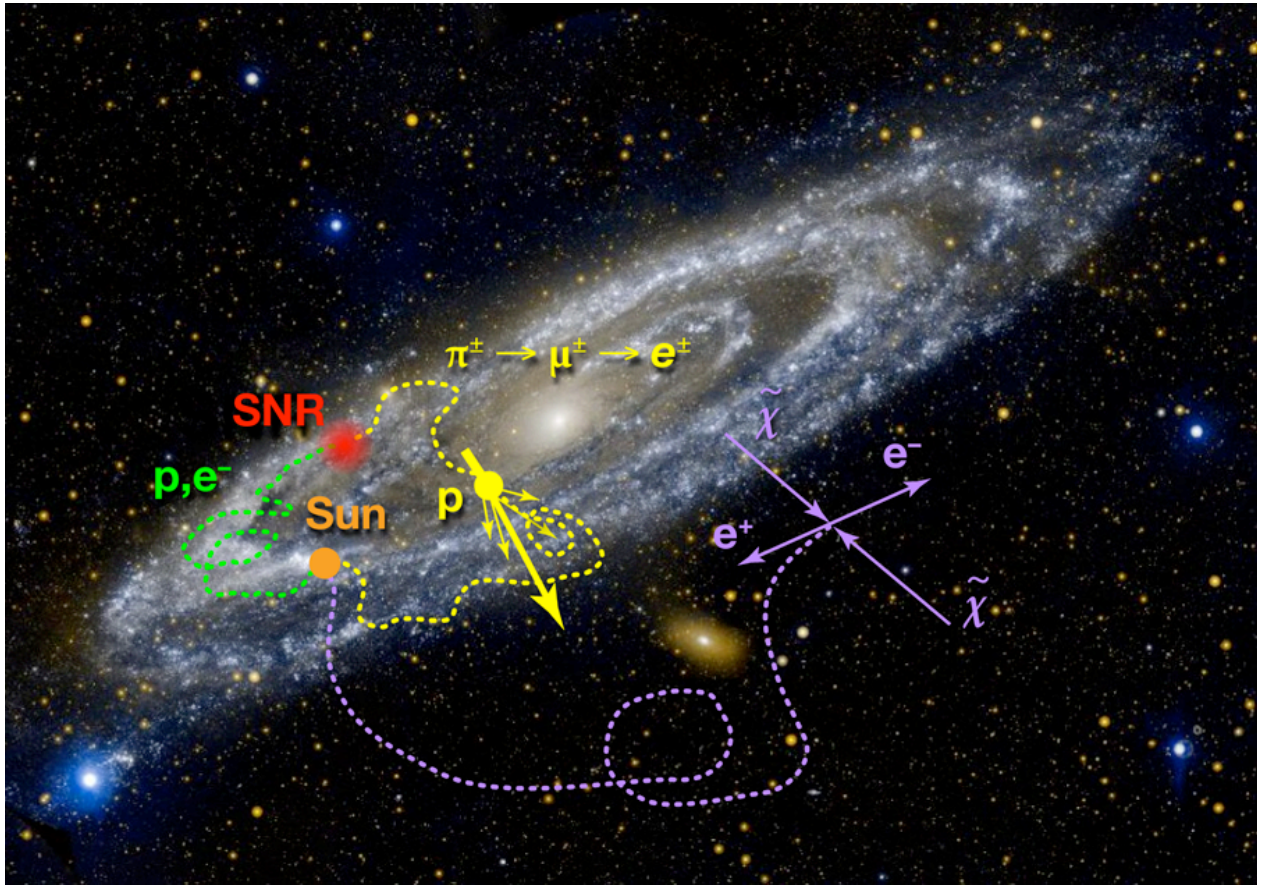


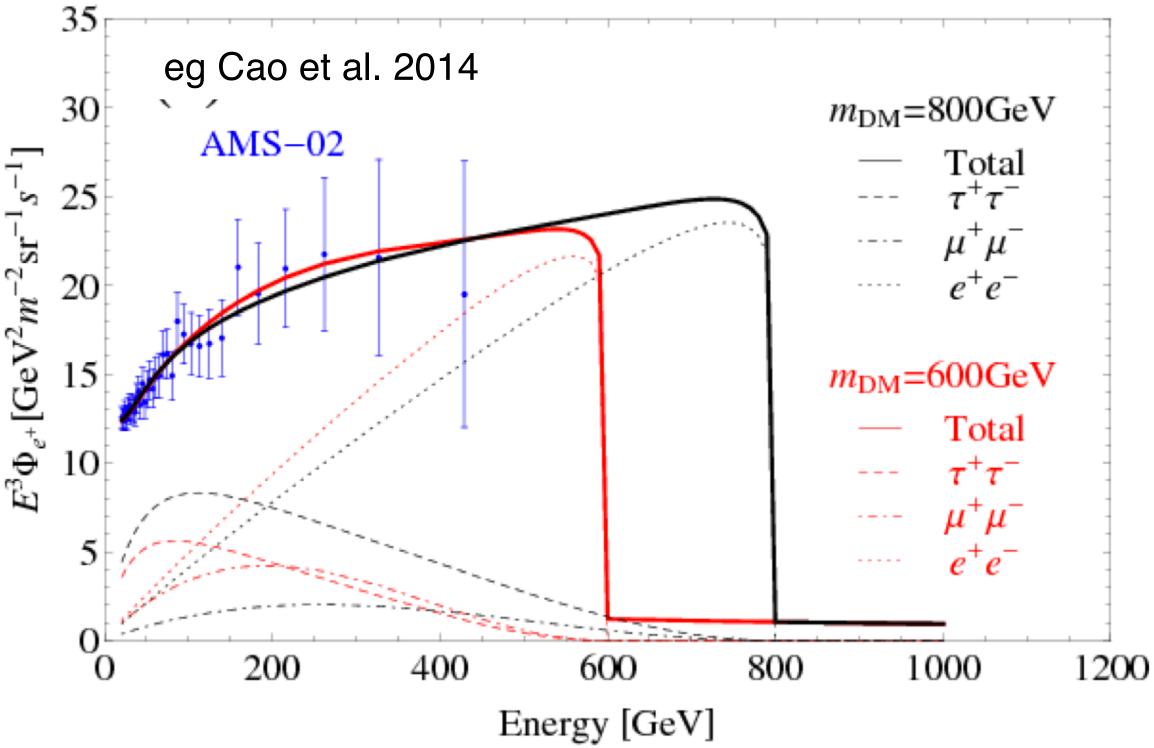
illustration by Coutu 2013

- γ-rays converting into e-e+ pairs in the vicinity of the magnetic poles of pulsars
- decay of radioisotopes within a cosmic accelerator (supernova remnant)
- dark matter particles annihilating in the galactic halo ...

- or a revisited model for the production/propagation of secondary e^+ ...

dark matter scenario for the e+ "anomaly" (one of many*)

DM particles annihilating in the galactic halo ..

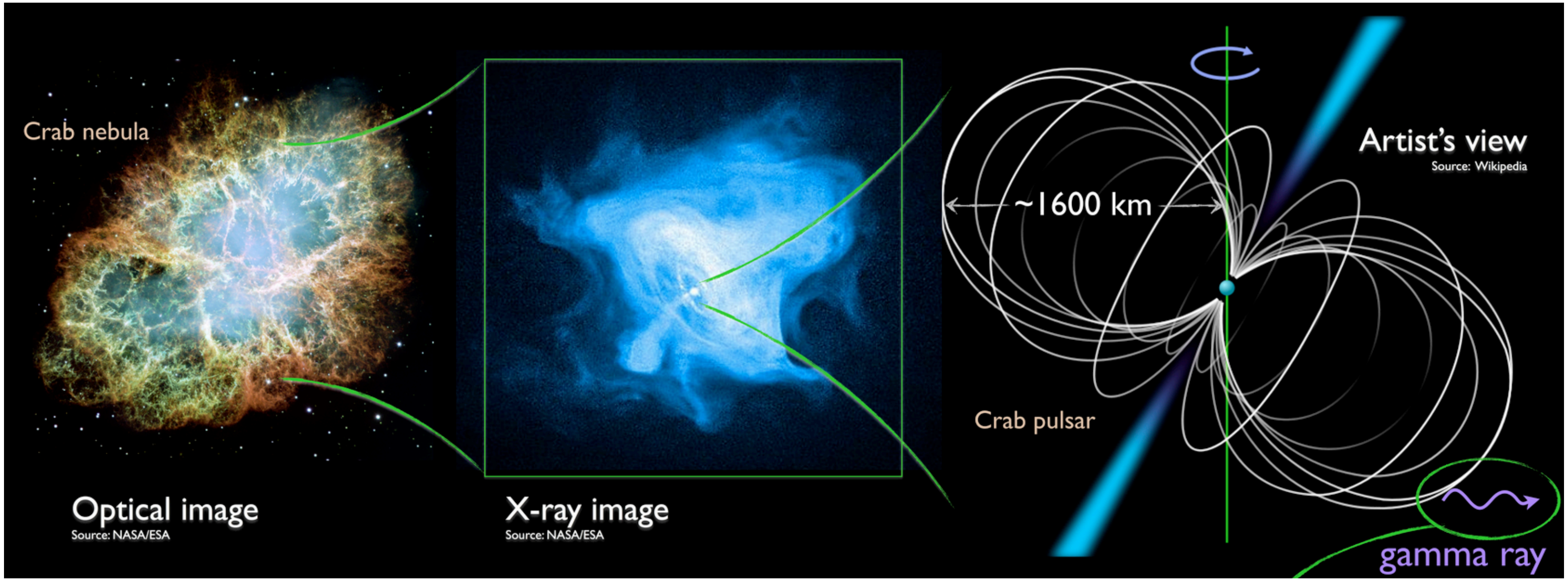


AMS-02 positron flux (Aguilar et al 2014) and prediction from dark matter annihilation with best fit of annihilation cross section and fractions of lepton final states.

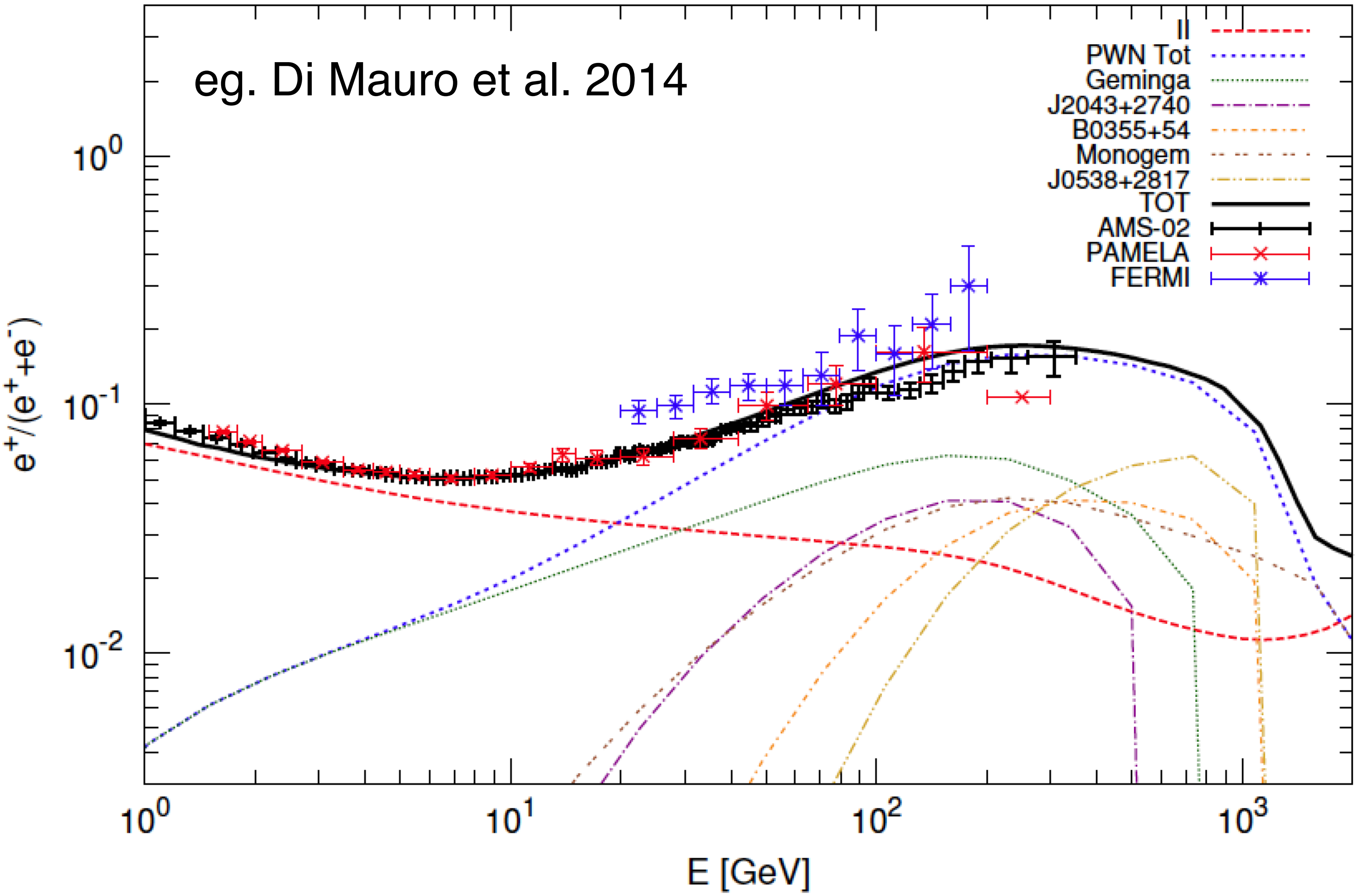
* 560 out of 1164 citations of the *Adriani et al (2009)* Nature paper on the Pamela excess contain ‘dark’ in the title;
761/1164 mention it in the abstract

"standart" astrophysical scenarios for the e+ "anomaly"

endpoints of stellar evolution
- pulsars
- supernova remnants

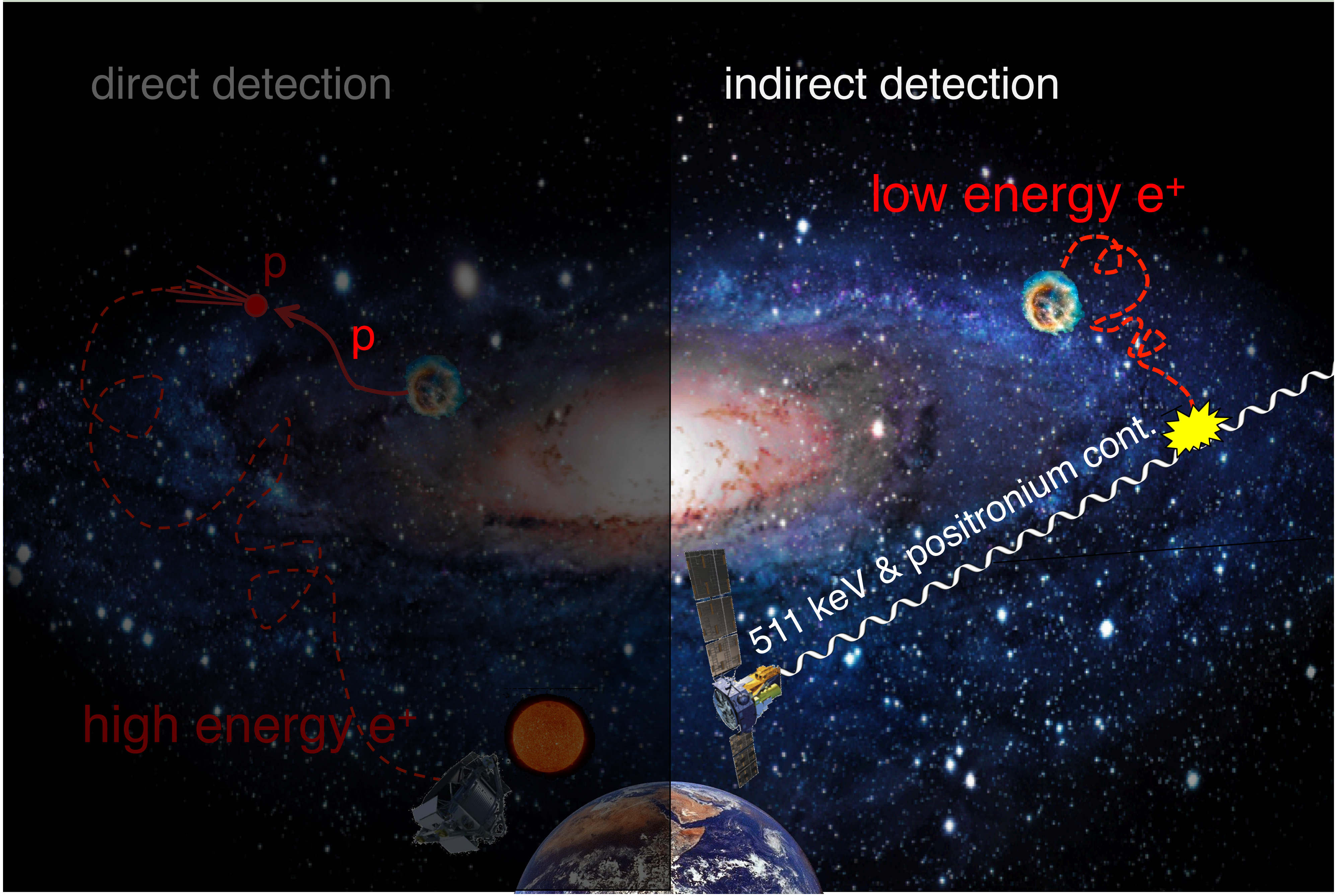


Pulsar scenario for the e+ "anomaly"



pulsar contribution is supplied by the 5 “most-powerful” pulsars in the ATNF catalog

positrons

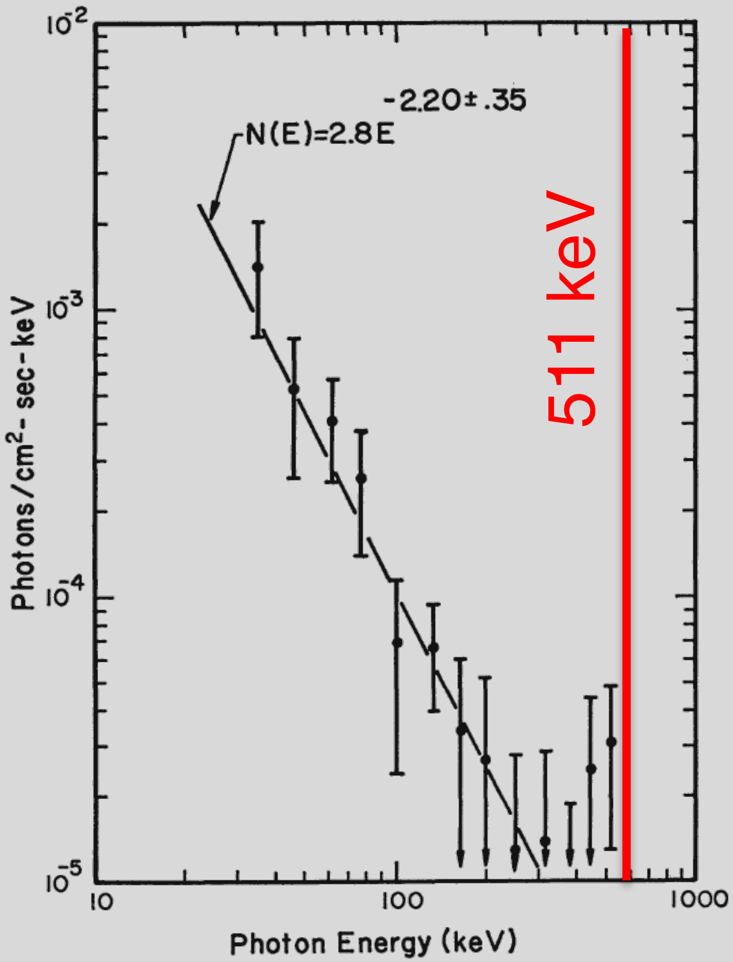

direct detection
indirect detection
low energy e+
p
p
511 keV & positronium cont.
high energy e+

1960

the early years : balloon astronomy

1965

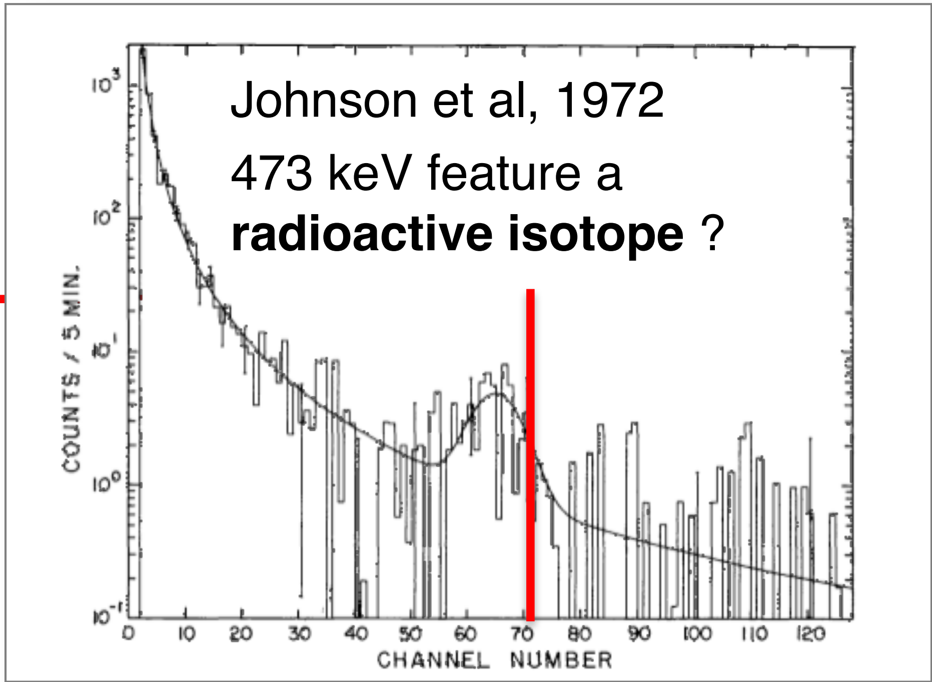
1970



Observation of Hard Radiation from the Region of the Galactic Center
Haymes, Ellis, Fishman, Glenn, Kurfess, ApJ. 157, 1969

the galactic e^+ are already in the data …

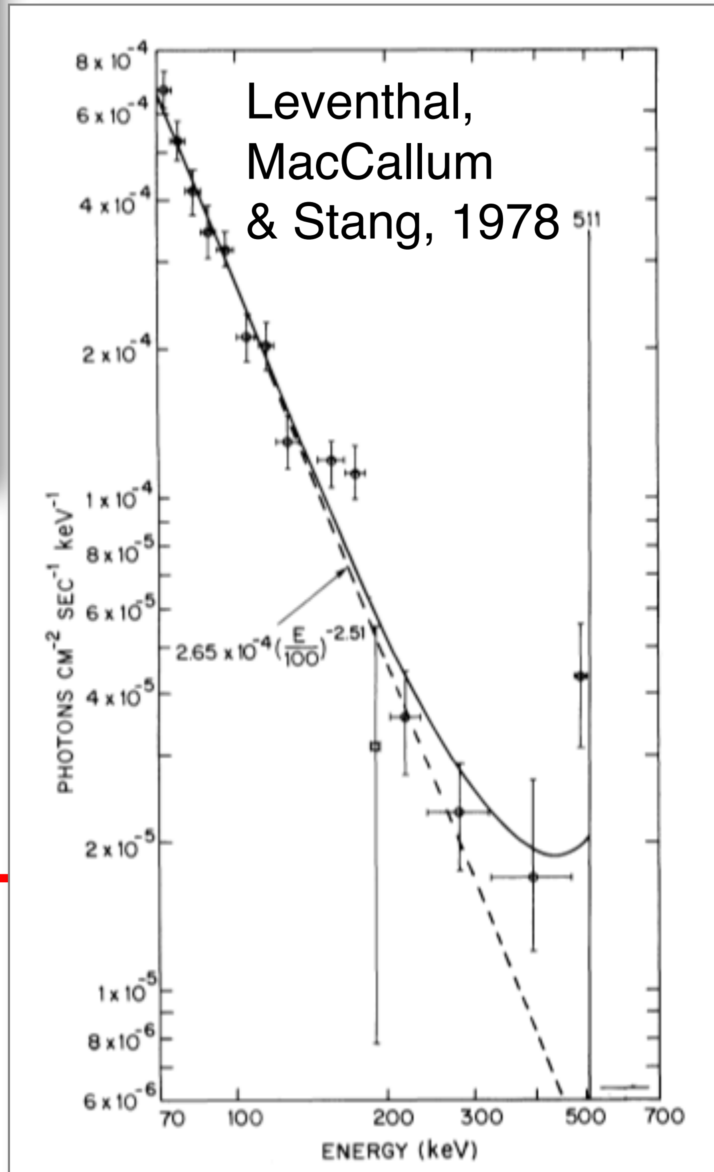
1970



Johnson et al, 1972

473 keV feature a **radioactive isotope** ?

1975



Leventhal, MacCallum & Stang, 1978

balloone borne Ge detectors solve the puzzle :

a **narrow annihilation line** at 510.7±0.3 keV and an orthopositronium continuum

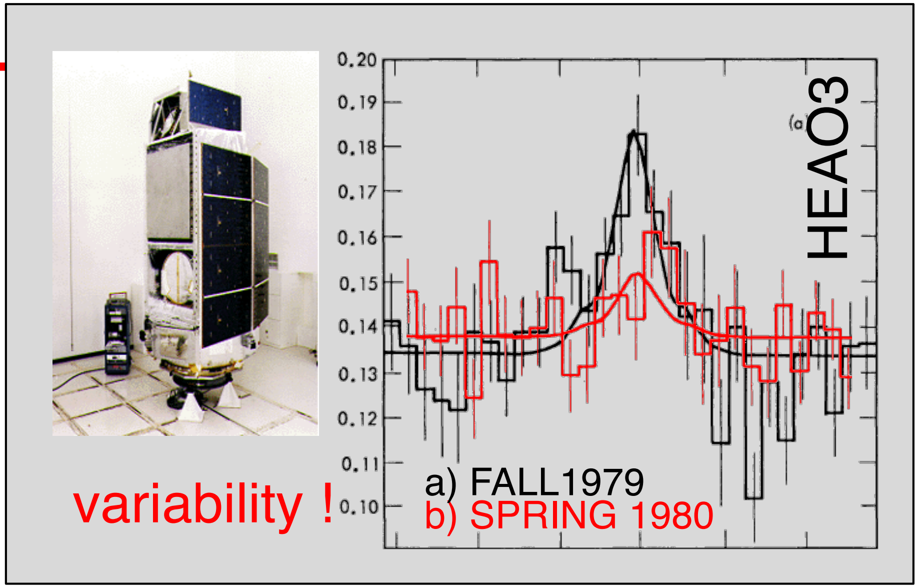
1980

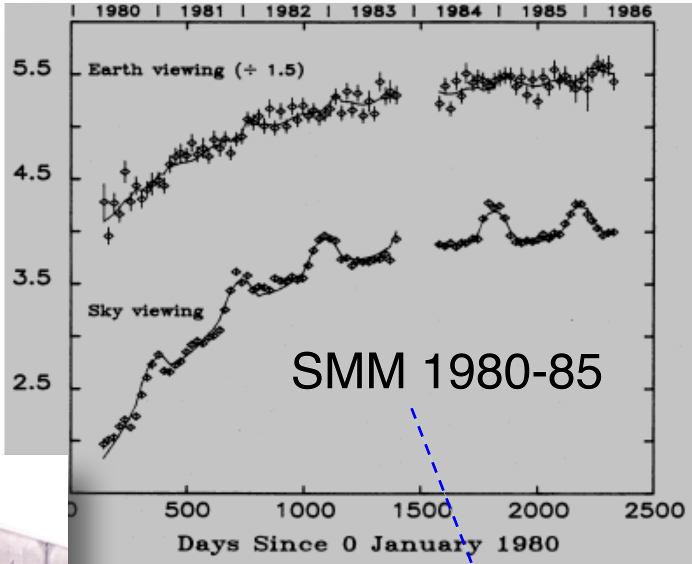
variability ?

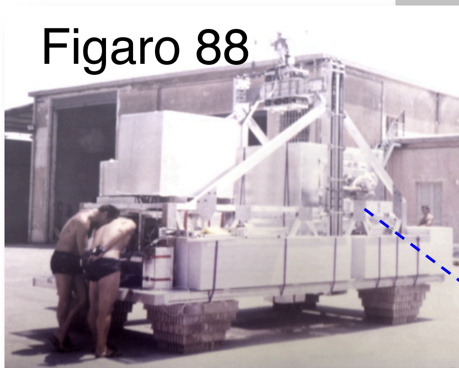
1980

1985

1990







SMM 1980-1989

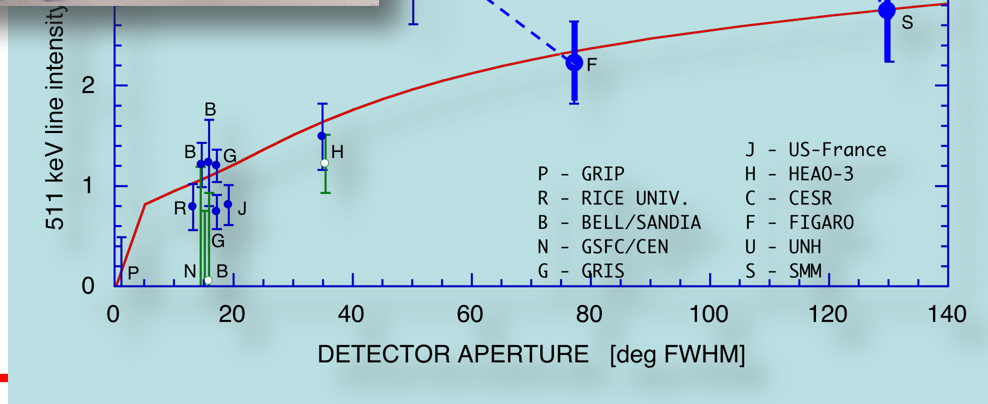
no variability needed

$Flux_{511}$ ~ FOV

=> 2 component model

diffuse disk+compact GC

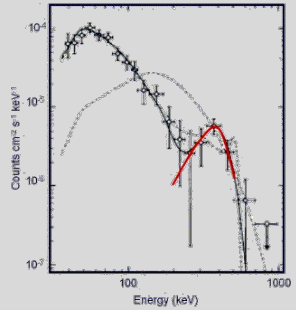
Lingenfelter & Ramaty, 1989
Share et al.,1988 & 1990
von Ballmoos, 1991



1990

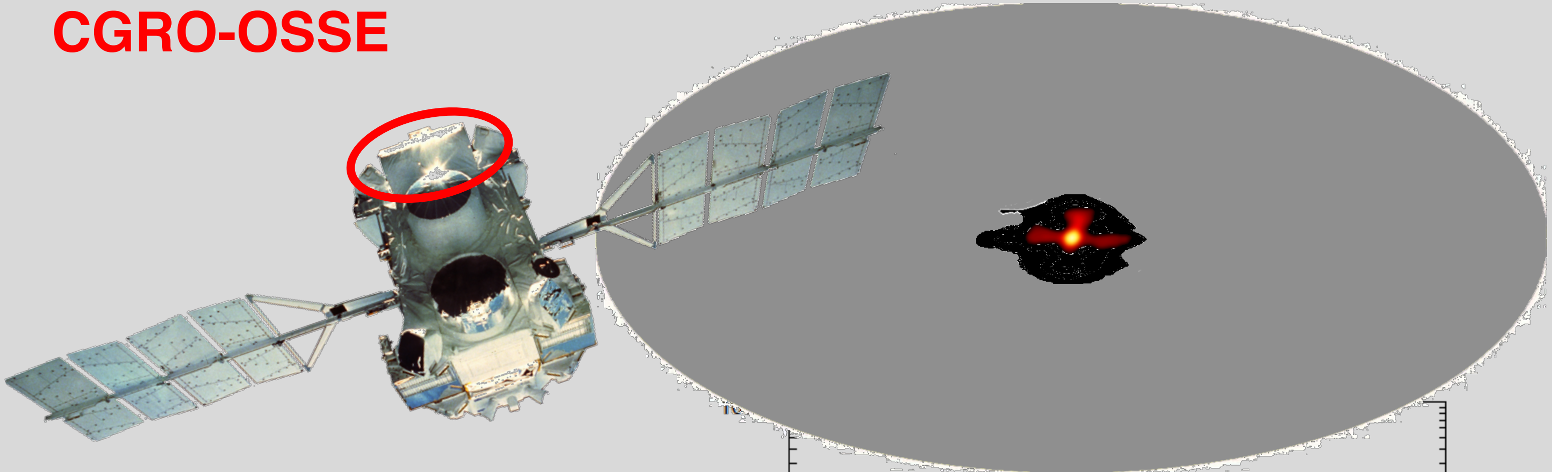
the great annihilator is back !

SIGMA observes an outbreak of the
galactic center source 1E 1740.7-2942
broad, redshifted annihilation line



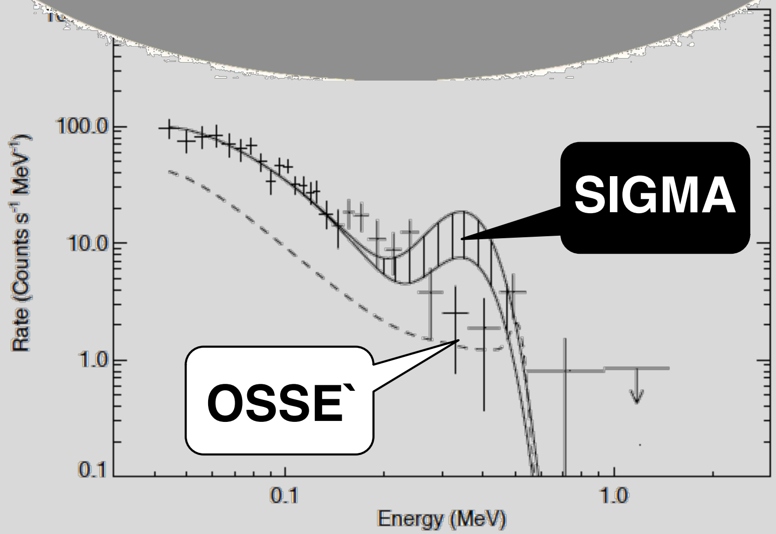
CGRO-OSSE

1995

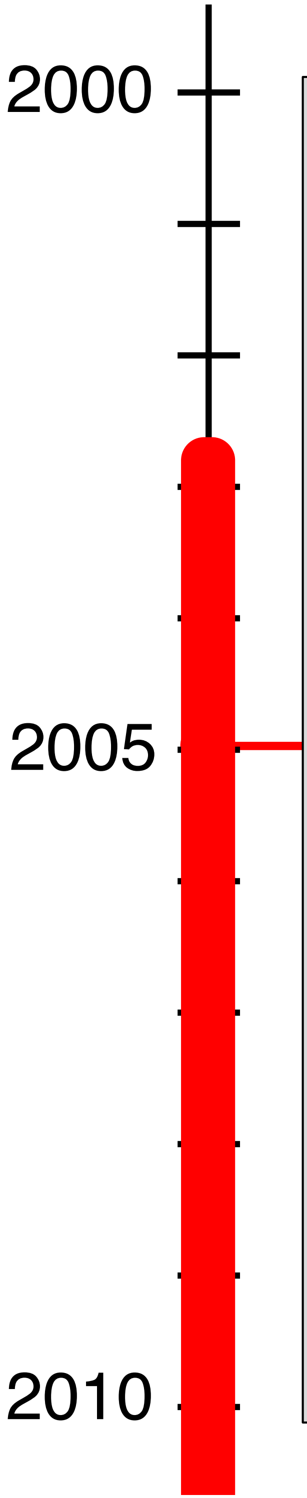


no variability

=> no need for
a "great annihilator"
Purcell et al 1997



2000



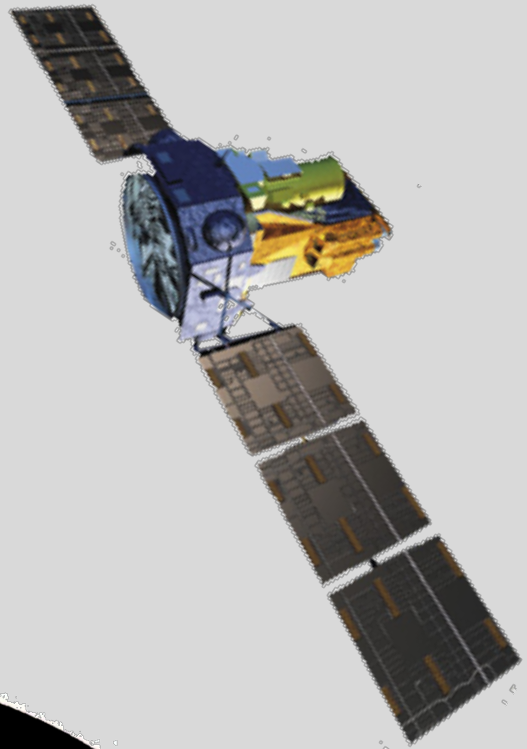
INTEGRAL SPI

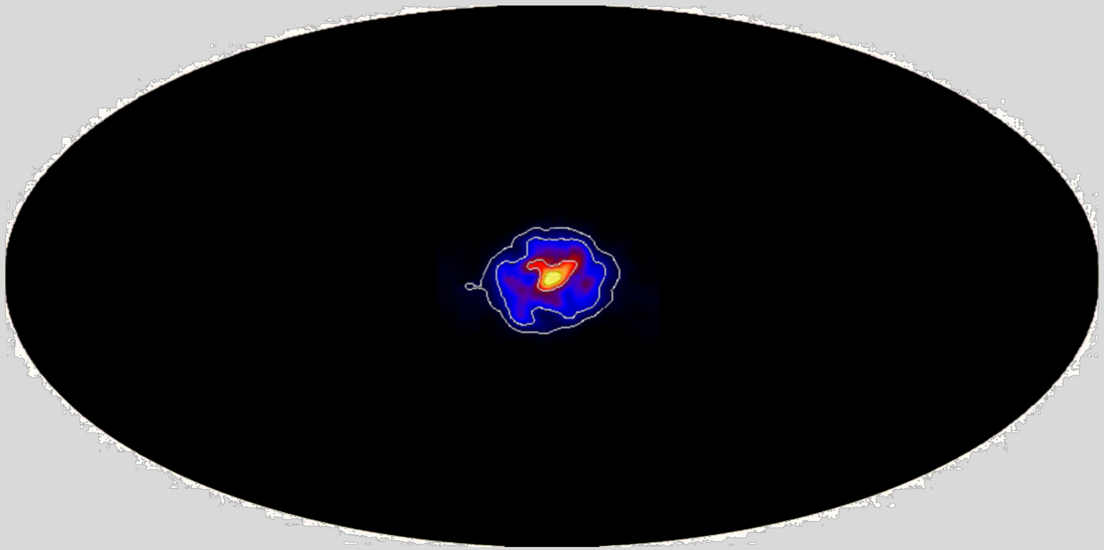
the first 511 keV all-sky map

first year of INTEGRAL data,

Bulge : 2D Gaussian ~ 8° x 7° FWHM
Bulge/Disk = 1-3

no point sources
no fountain
no other sources





Knödlseder et al. 2005

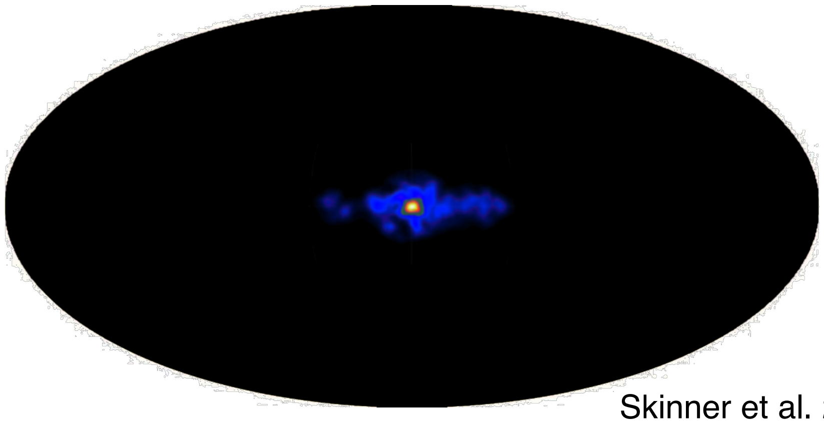
2010

2015

2020

status (in a nutshell) : total flux ~ 2 · 10^{-3} γ/s/cm^{-2}

morphology



Skinner et al. 201

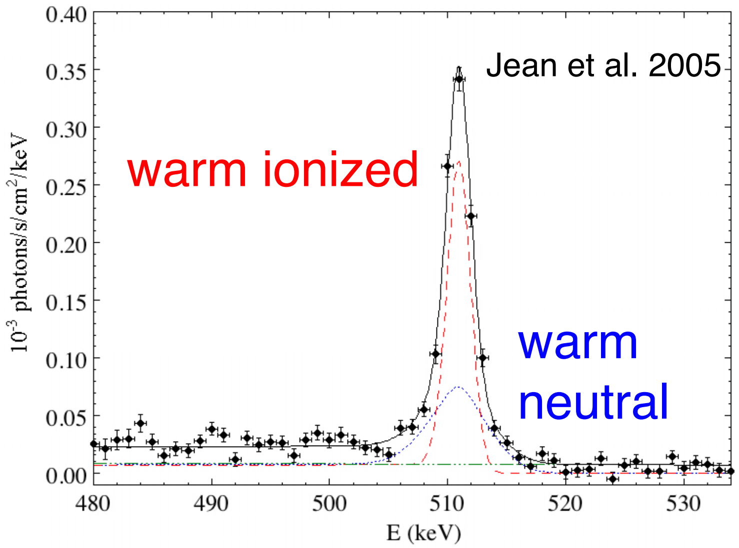
narrow bulge, wide bulge, disk

bulge / disk = 1-3

slight asymmetry

no point sources,
no fountain,
no other source regions

spectroscopy



positrons annihilate in warm phases

=> we need to explain
2·10^{43} annihilations s^{-1}
at the Galactic Center

… there are **too many** cadidate sources !

Galactic Supernovae *(Ramaty & Lingenfelter, 1979)*

Galactic Supernovae + escape from the disk *(Higden et al., 2007)*

Hypernovae/GRB explosions in the galaxy *(Lingenfelter &Heuter, 1984; Bertone et al., 2006)*

Novae *(Clayton & Hoyle, 1974; Jose, Coc & Hernanz, 2003)*

LMXBs *(Prantzos, 2004)*

HMXBs / Micro-Quasars *(Guessoum et al, 2006)*

Wolf-Rayet stars *(Dearbourne & Blake, 1985)*

Red Giants *(Norgaard, 1980)*

Pulsars *(Sturrock, 1971)*

Millisecond pulsars *(Wang, 2005; 2006)*

Cosmic Ray interactions with matter *(Ramaty, 1970)*

Light (MeV) dark matter *(Boehm et al., 2004)*

'Heavy' 500 GeV DM + de-excitation from an excited state *(Finkbeiner & Weiner, 2007)*

Sgr A* *(Titarchuk & Chardonnet, 2006; Totani, 2007)*

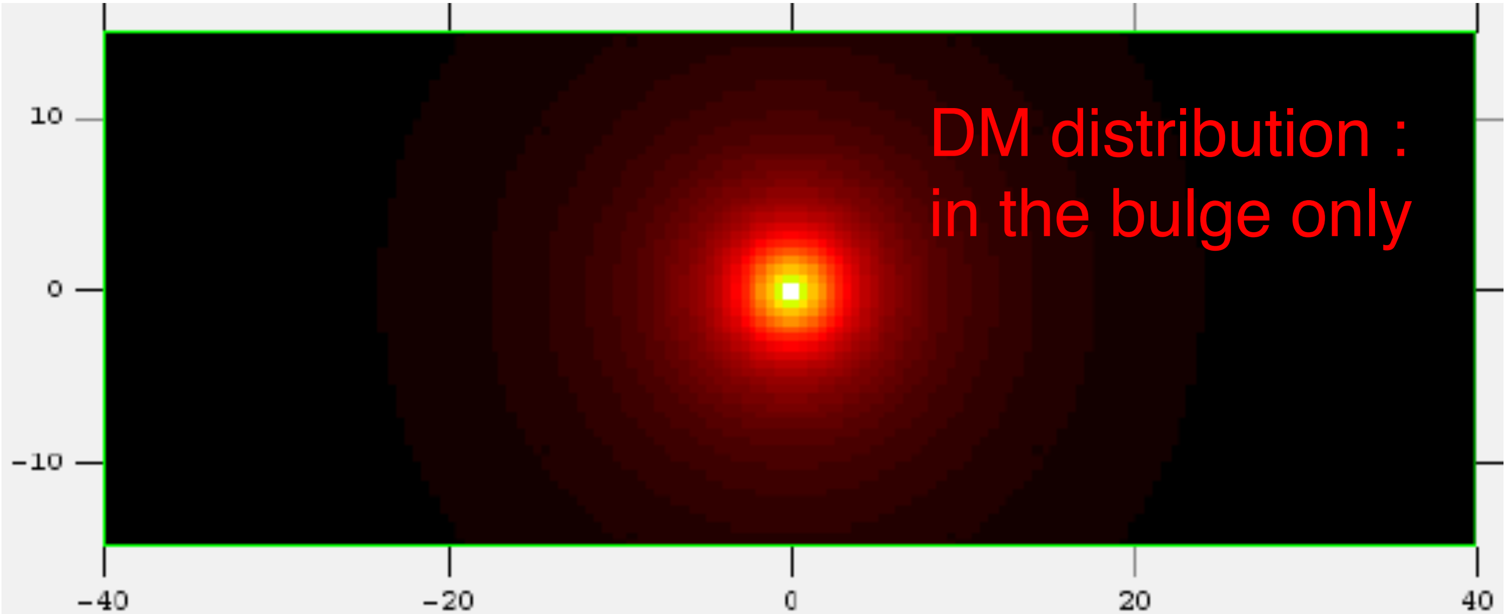
not to speak of strangelets, Q balls, relic particles, decaying, axinos, primordial black holes, superconducting cosmic string, dark energy stars, and moduli, decays, sterile neutrinos, mirror matter, moduli, millicharged fermions, unstable branons ….thunderstorms, bananas (40K), yourself …

e^+ origin : "light" dark matter (Boehm et al., 2003)

neutralinos : $\chi + \chi \rightarrow e^+ + e^-$

"Fayet" particle : $f + f \rightarrow e^+ + e^-$

$m_f \sim 10 - 100$ MeV => low energy e^+ & no HE γ

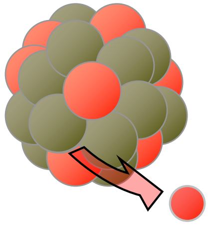


$m_\chi \sim 0.1 - 1$ TeV => $\chi + \chi$ would produce not only e^+ but also other particles emitting HE γ

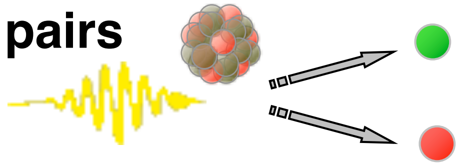
=> not observed with COMPTEL, EGRET

The origin of the galactic e^+ : two grand families

Cosmic Explosions
radioactive decays

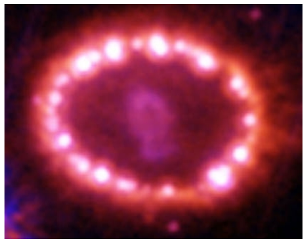


Cosmic accelerators
production of e^-e^+ pairs



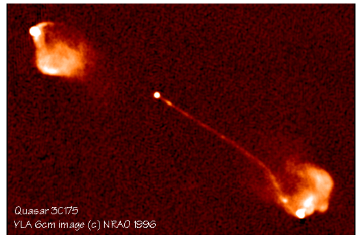
gravitationnal collaps

SN type II (Core-collapse)
gamma-ray burst



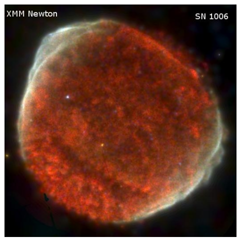
Accretion on compact objects

Binaries
Micro-quasars



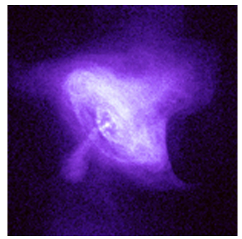
thermonuclear exlosions

SN de type Ia



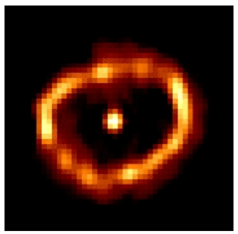
Rotating neutron stars

Pulsars
Magnetars



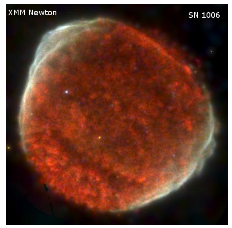
Thermonuclear runaways

Novae
X-ray bursters

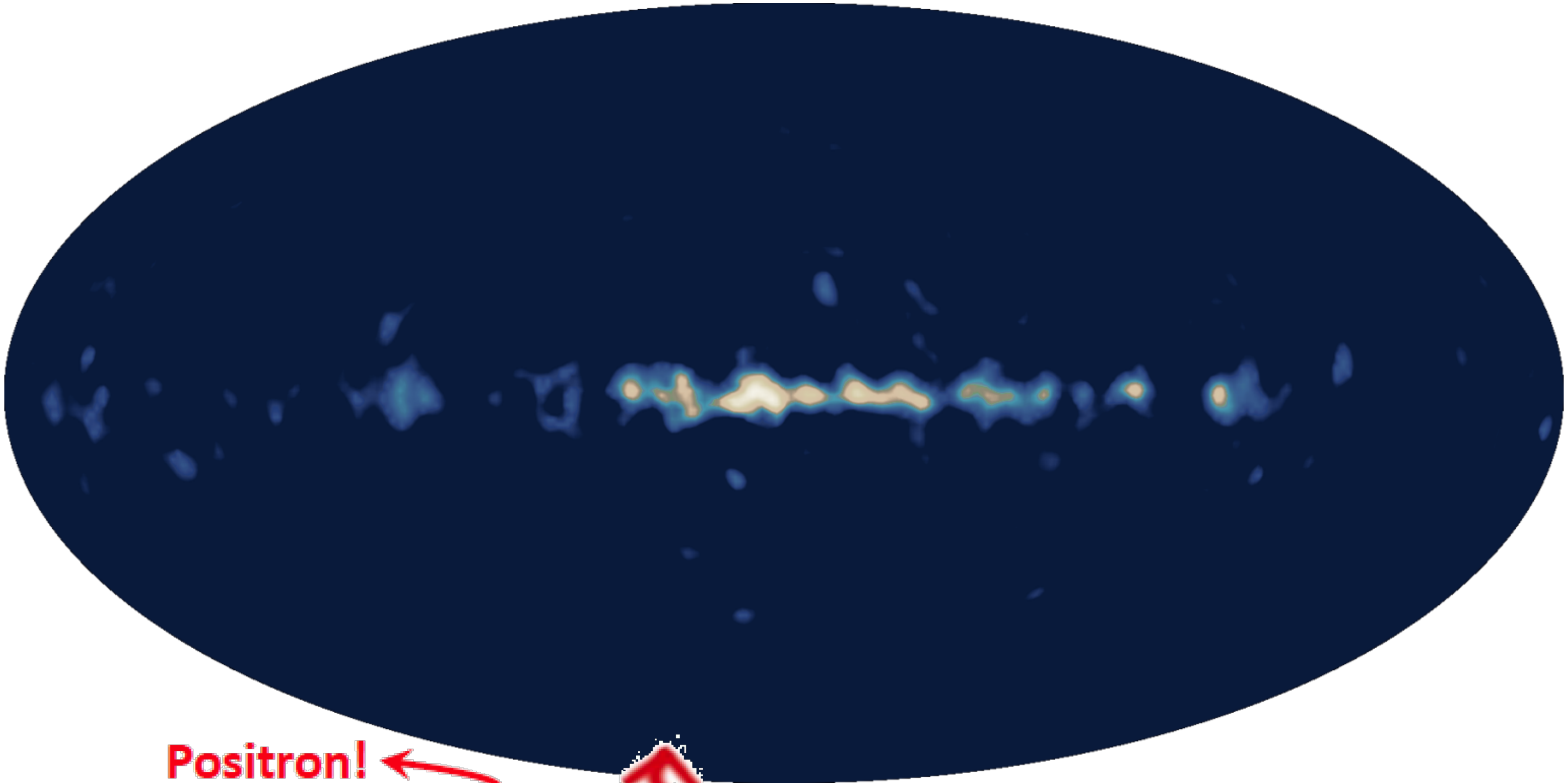


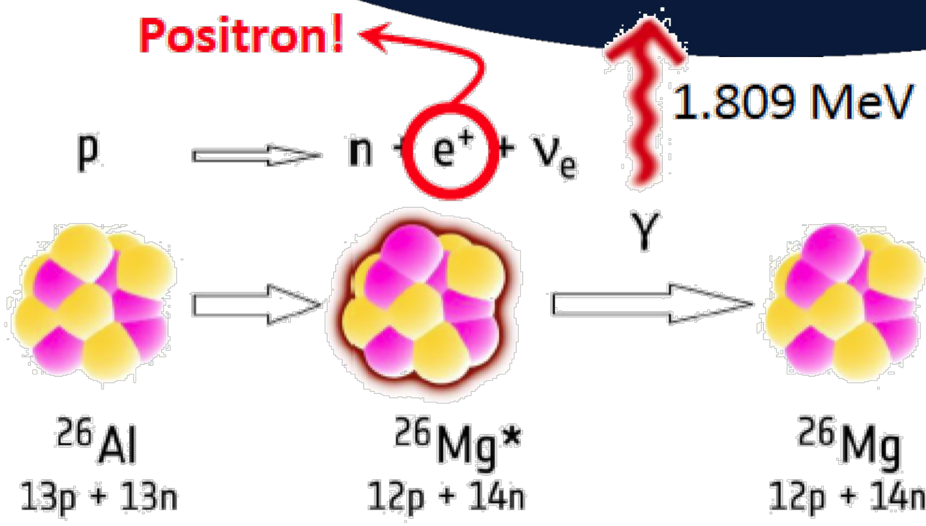
Explosions and shocks

gamma-ray bursts
supernova remnants
Interaction CR/ISM



certain contribution to the e$^+$: ^{26}Al from type II supernovae

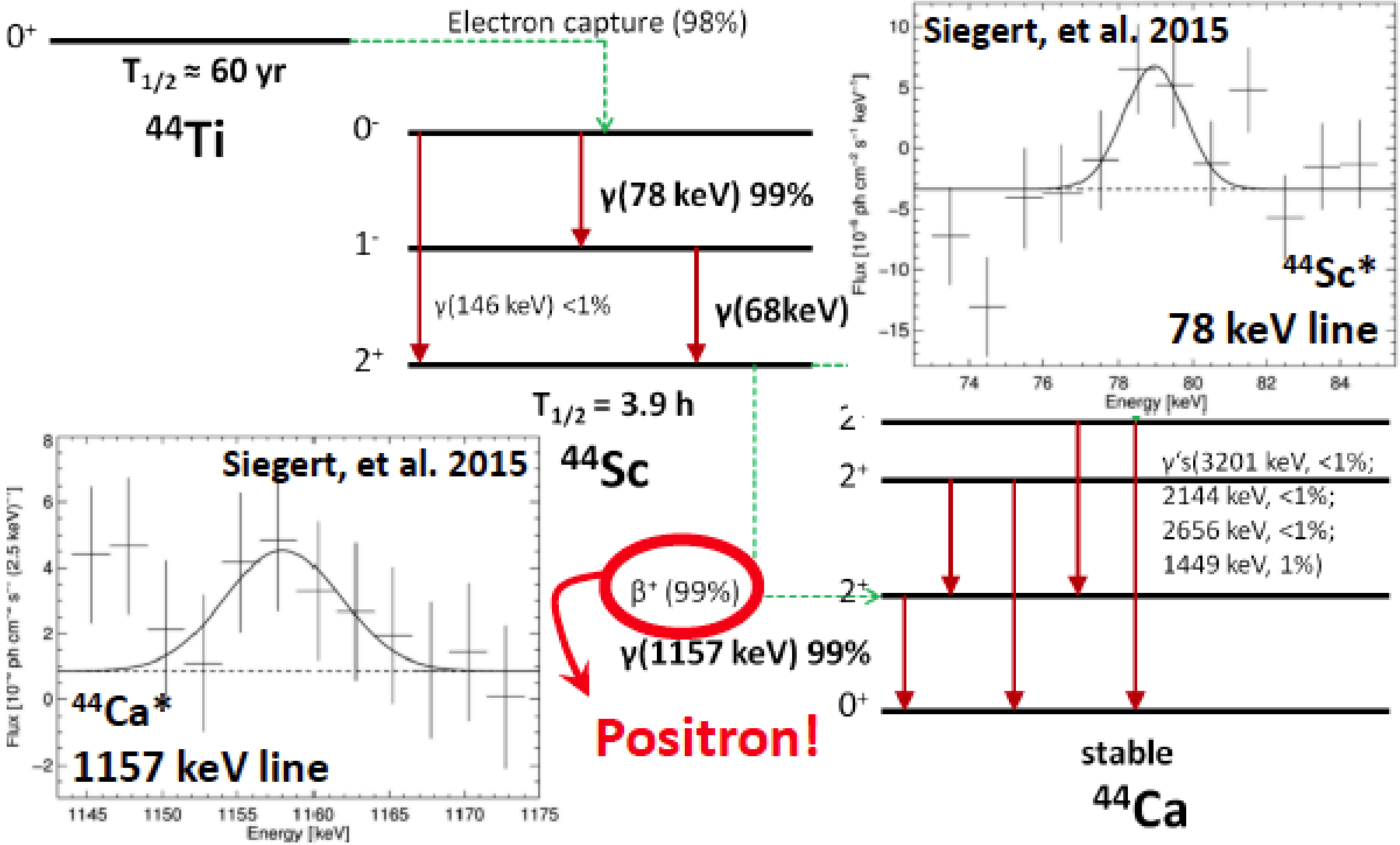




The observed 2-3 Mo ^{26}Al in the Galaxy correspond to a production rate of

$N_{e+,26} \approx 4 \cdot 10^{42}\ e^+\ s^{-1}$

possible e^+ origin : ^{44}Ti from type II supernovae



$$\dot{M}_{44} = \left(\frac{^{44}Ca}{^{56}Fe}\right)_{\odot} (R_{SNIa} Y_{56}^{SNIa} + R_{CCSN} Y_{56}^{CCSN}) \Rightarrow 3 \cdot 10^{42}\ e^+\ s^{-1}$$

likely e^+ origin : Type Ia supernovae

Positron production processes

- $^{57}Ni \rightarrow {}^{57}Co$ (τ = 52 hr, 40%)
- $^{56}Co \rightarrow {}^{56}Fe$ (τ = 111 d, 19%)
- $^{44}Sc \rightarrow {}^{44}Ca$ (τ = 5.4 hr (87 yr), 99%)

Yields	Ch	Sub-Ch
^{57}Ni	0.01 - 0.03	0.01 - 0.03
^{56}Co	0.4 - 1.1	0.3 - 0.9
^{44}Sc	$(7\text{-}20) \times 10^{-6}$	$(1\text{-}4) \times 10^{-3}$

Woosley 1997; Woosley & Weaver 1994

Galactic Rate : $R_{e+} \propto f \times \nu_{SNIa} \times M_{56}$

=> how much heat -> envelope

=> how much e+ escape ?

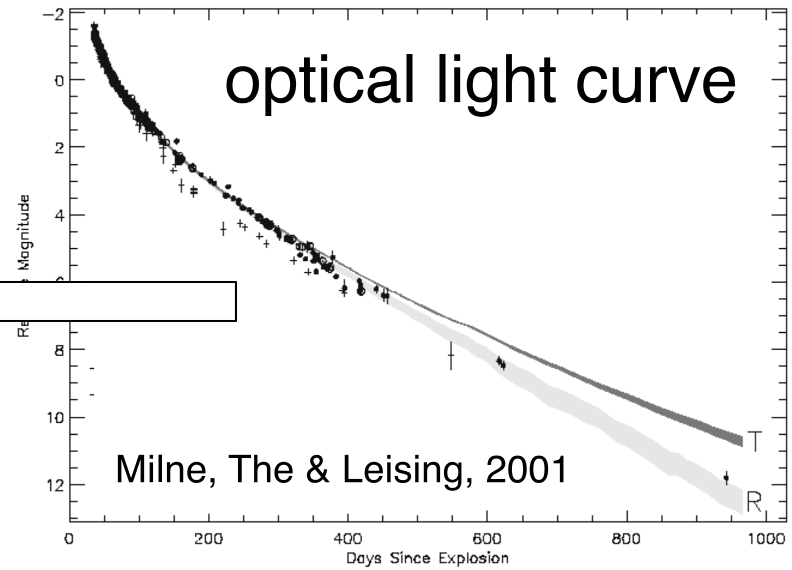
-> f < 15% (Chan & Lingenfelter, 1993)

$M_{56} \sim 0.6\ M_*$ & $\nu_{SNIa} \sim 0.003\ yr^{-1}$

=> **$R_{e+} < 3.7\ 10^{43}\ s^{-1}$**.

-> f ~ 5% (Milne, The & Leising, 2001)

=> **$R_{e+} \sim 1.2\ 10^{43}\ s^{-1}$**



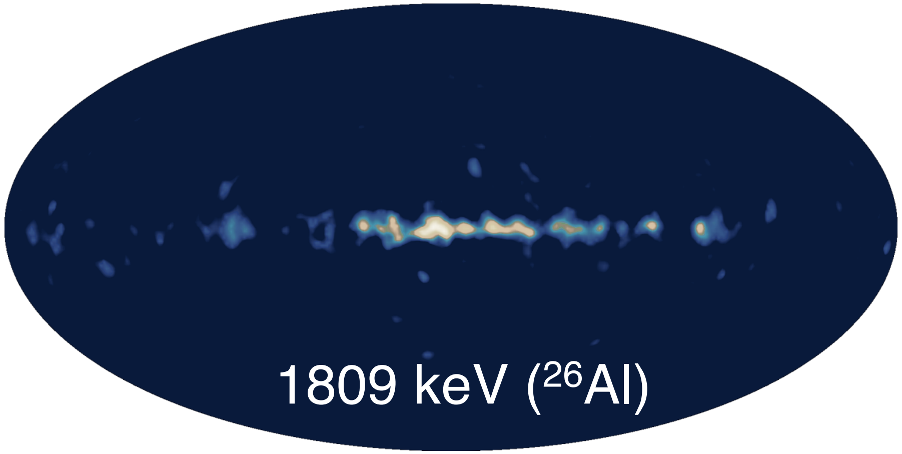
-> f ~ 4% (Prantzos et al, 2011)

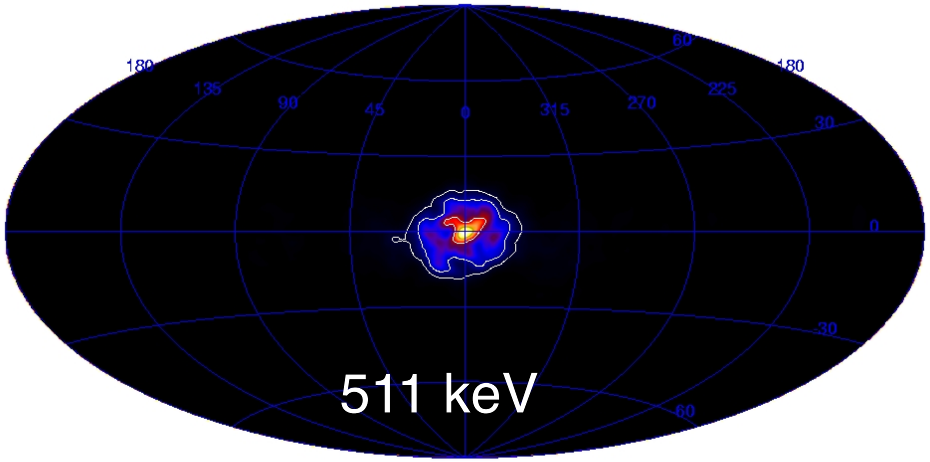
$M_{56} \sim 0.7\ M_*$ & $\nu_{SNIa} \sim 0.006\text{-}0.007\ yr^{-1}$

=> **$R_{e+} \sim 2\ 10^{43}\ s^{-1}$**

Although SNeIa belong to the old population their $(B/D)_{SNeIa} < 1$

e^+ origin : disk and bulge





^{26}Al produced in SNII/Ib & WR

$^{26}Al \to {}^{26}Mg + \beta^+ + \gamma$ (85%)

$F_{1.8} \Rightarrow M_{26} \sim 2\text{-}3\ M_*$ $\Rightarrow R_{e+} \sim 4 \times 10^{42}\ s^{-1}$

^{44}Ti produced in SNs

$^{44}Ti \to {}^{44}Sc \to {}^{44}Ca + \beta$ (99%)

$M_{44} \sim (3 \pm 1) \times 10^{-6}\ M_\odot\ yr^{-1}$ (chem. evol.)

$\Rightarrow R_{e+} \sim 3 \times 10^{42}\ s^{-1}$

(Morphology & esc. fraction unknown)

Obs. disk flux $(4\text{-}8) \times 10^{-4}$ ph $cm^{-2}\ s^{-1}$

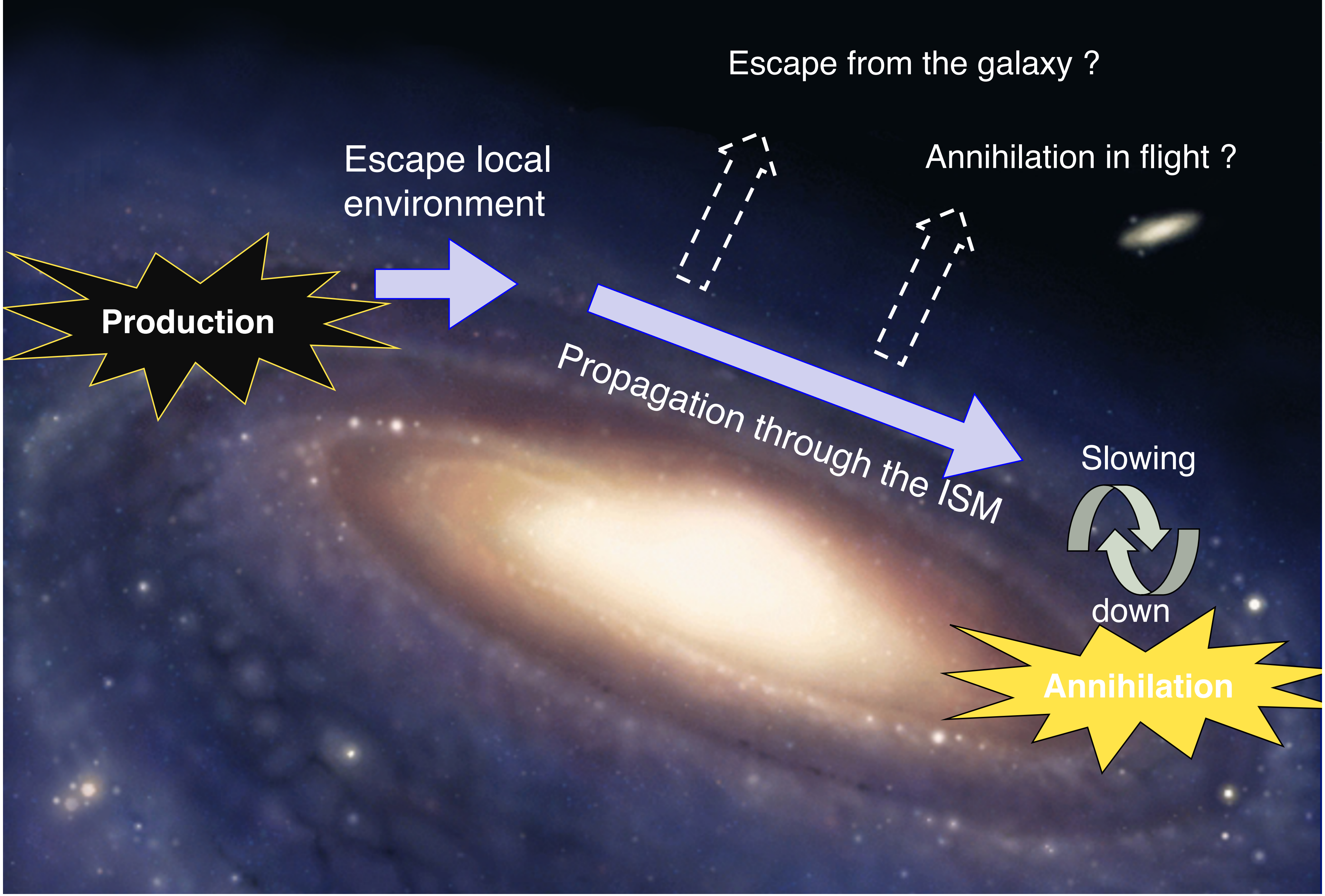
60-100% explained by ^{26}Al

Rest (if any) is easily explained by ^{44}Ti

but what about the bulge ?

need of a pure bulge positron source ?

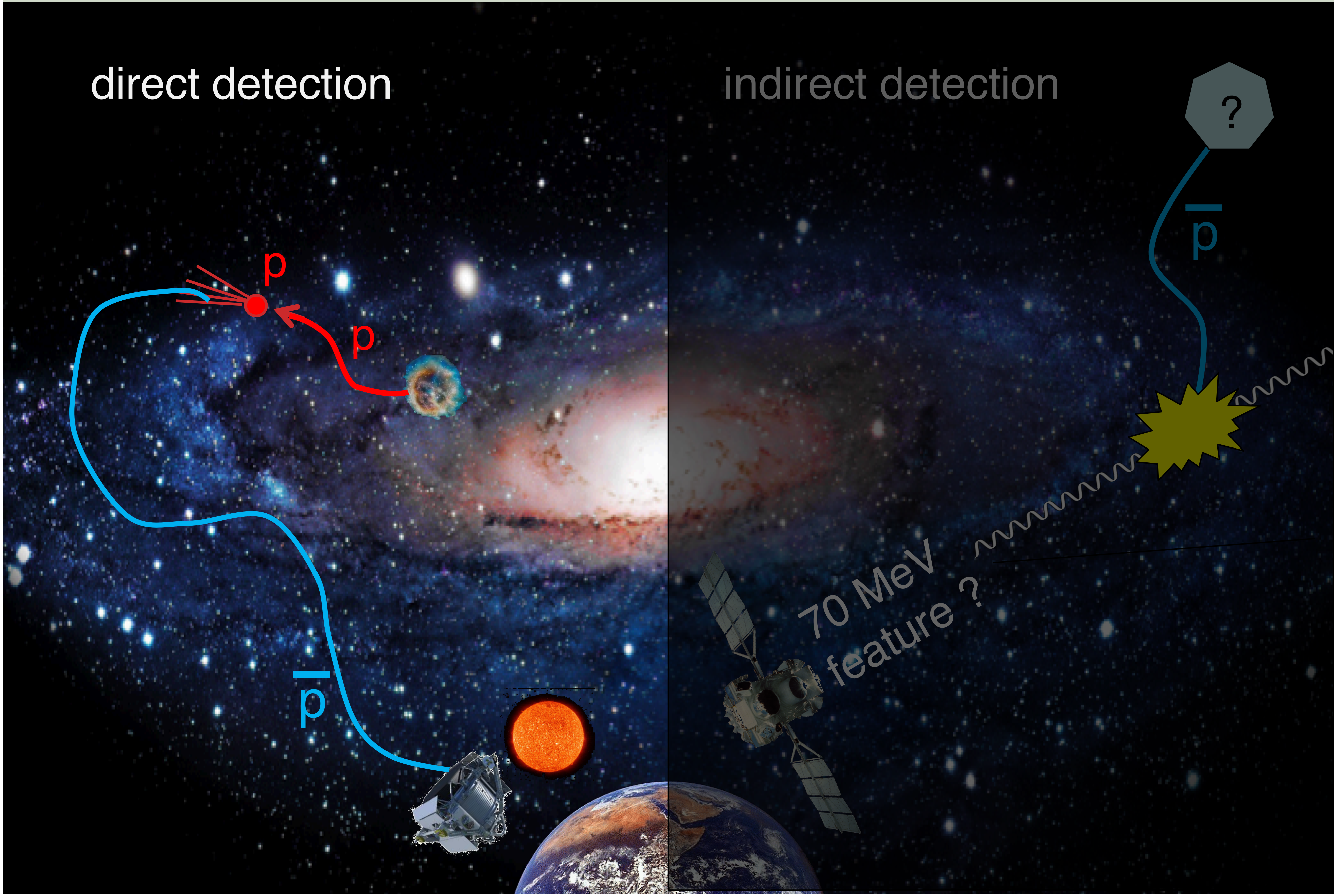
We are ***NOT*** observing e^+ sources !



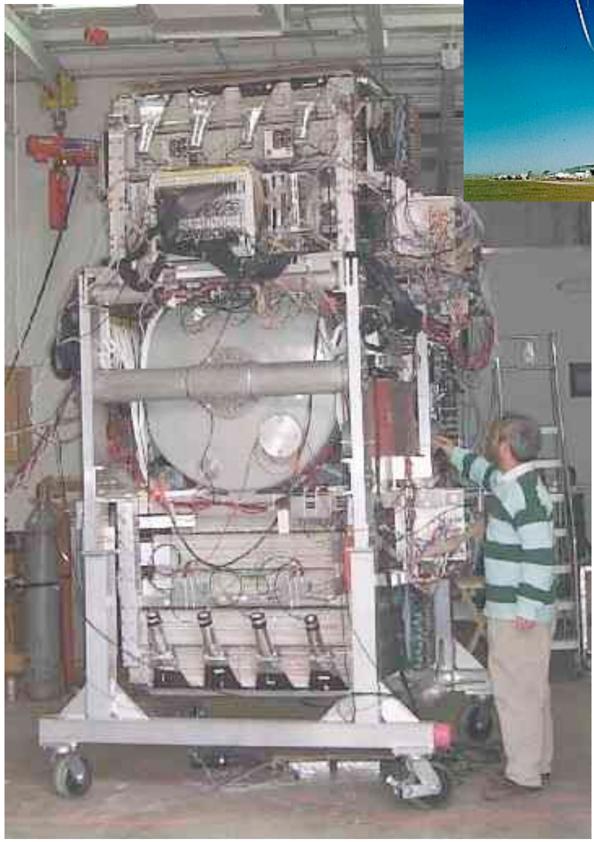
Candidate sources and Constraints (Prantzos et al 2011)

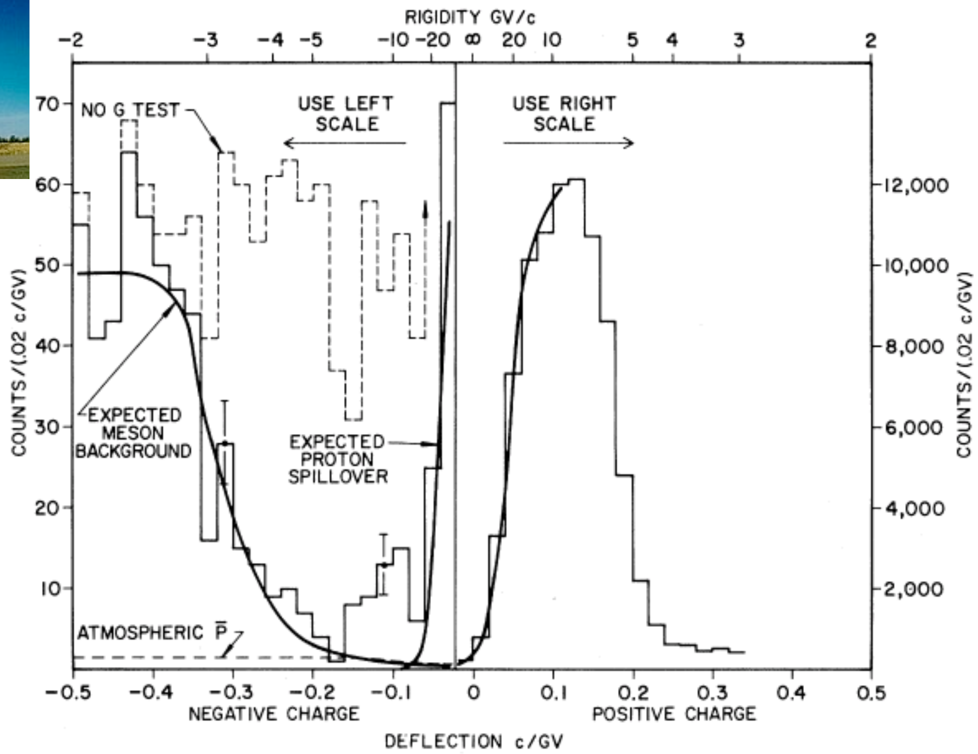
Source	Process	$E(e^+)^a$ (MeV)	e^+ rate^b $\dot{N}_{e+}$ (10^{43} s^{-1})	Bulge/Disk^c B/D	Comments
Massive stars: ^{26}Al	β^+-decay	~1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{44}Ti	β^+-decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	~1	*2*	<0.5	Assuming $f_{e+,esc}$=0.04
Novae	β^+-decay	~1	*0.02*	<0.5	Insufficent e^+ production
Hypernovae/GRB: ^{56}Ni	β^+-decay	~1	?	<0.2	Improbable in inner MW
Cosmic rays	p-p	~30	0.1	<0.2	Too high e^+ energy
LMXRBs	$\gamma-\gamma$	~1	*2*	<0.5	Assuming L_{e+} ~0.01 $L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	~ 1	*1*	<0.5	e^+ load of jets uncertain
Pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.5*	<0.2	Too high e^+ energy
ms pulsars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.15*	<0.5	Too high e^+ energy
Magnetars	$\gamma-\gamma$ / $\gamma-\gamma_B$	>30	*0.16*	<0.2	Too high e^+ energy
Central black hole	p-p	High	?		Too high e^+ energy, unless B >0.4 mG
	$\gamma-\gamma$	1	?		Requires e^+ diffusion to ~1 kpc
Dark matter	Annihilation	1 (?)	?		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	?		Only cuspy DM profiles allowed
	Decay	1	?		Ruled out for all DM profiles
Observational constraints		<7	2	>1.4	

baryonic antimatter



Evidence for the Existence of Cosmic-Ray Antiprotons (Golden 1979)

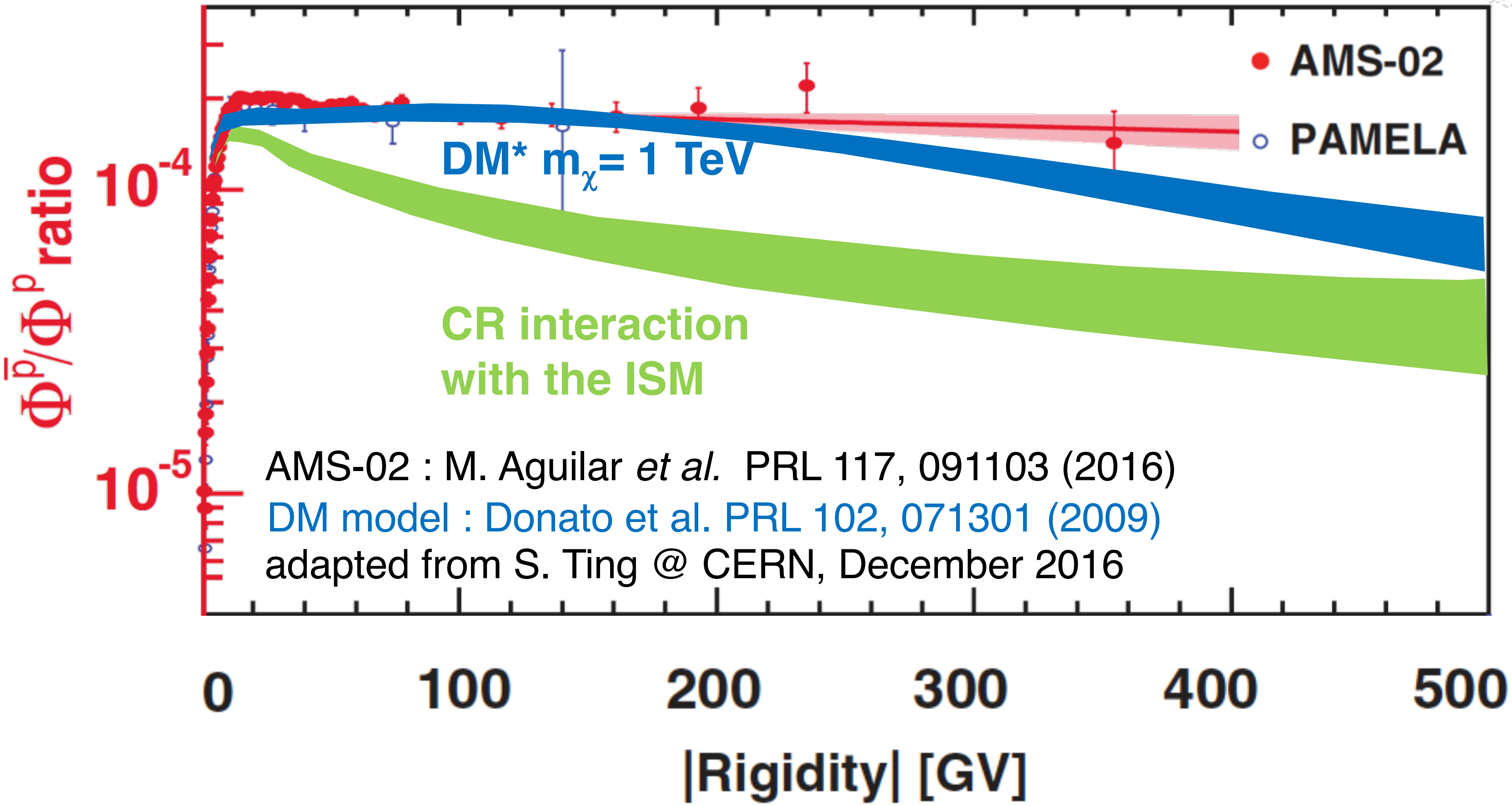




46 antiproton candidates observed (rigidity 5.6 -12.5 GV/*c*)
(18.3 of them expected to be atmospheric /instrumentationbackground)

The $\bar{p}/p$ ratio is $(5.2 \pm 1.5) \times 10^{-4}$

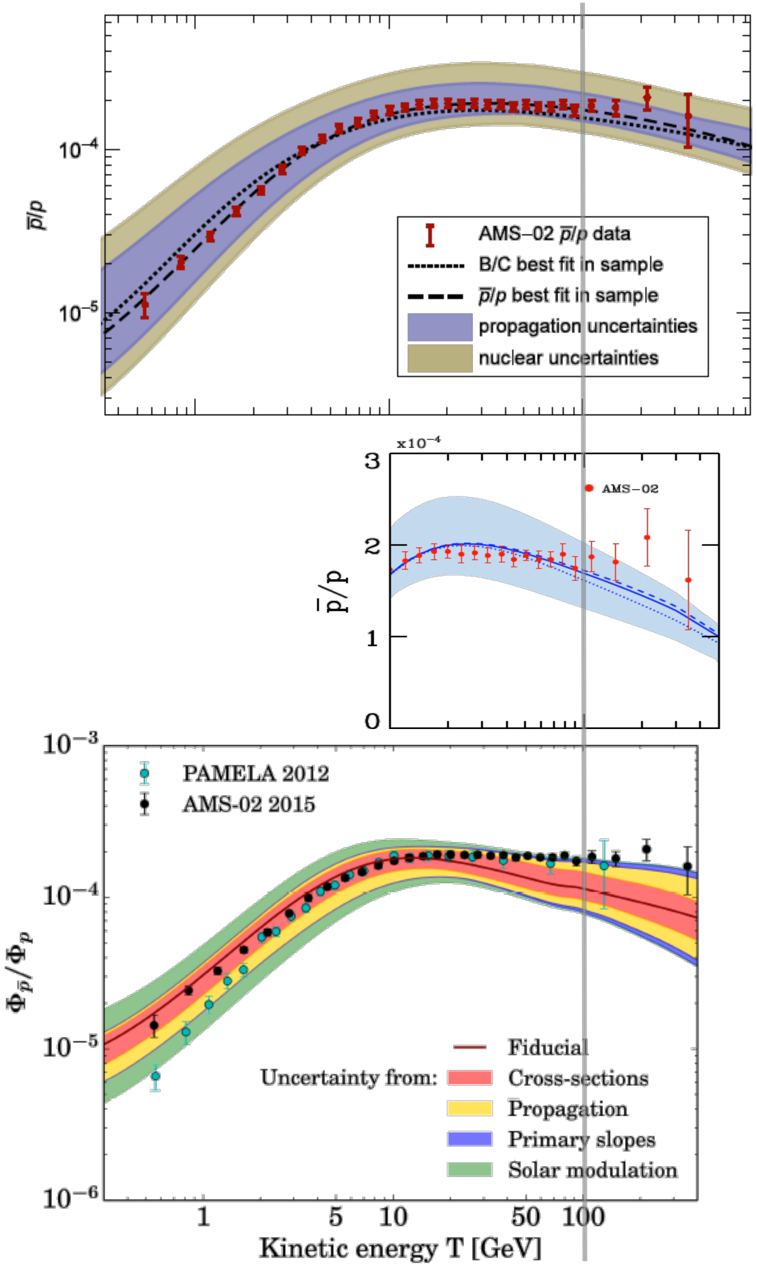
AMS-02 : antiproton/proton ratio



=> presentation by **Zhi-Cheng Tang**

"Antiproton Flux and Antiproton-to-Proton Flux Ratio in Primary Cosmic Rays Measured with the AMS on ISS"

modelling secondary antiproton production



no primary sources of antiprotons like dark matter annihilations are required

R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145

… do not report any signifcant anomaly …

C.Evoli, D.Gaggero and D.Grasso, arXiv: 1504.05175; JCAP 12 (2015) 039

…no real need for primary sources of antiprotons

V.Poulin, M.Cirelli, P.Salati and P.O.Serpico, JCAP09 (2015) 023; [arXiv:1504.04276].

Anti-Helium detection by AMS-02 ?

from S. Ting, December 2016, CERN Colloquium

The First Five Years of the Alpha Magnetic Spectrometer
on the International Space Station https://indico.cern.ch/event/592392

To date we have observed

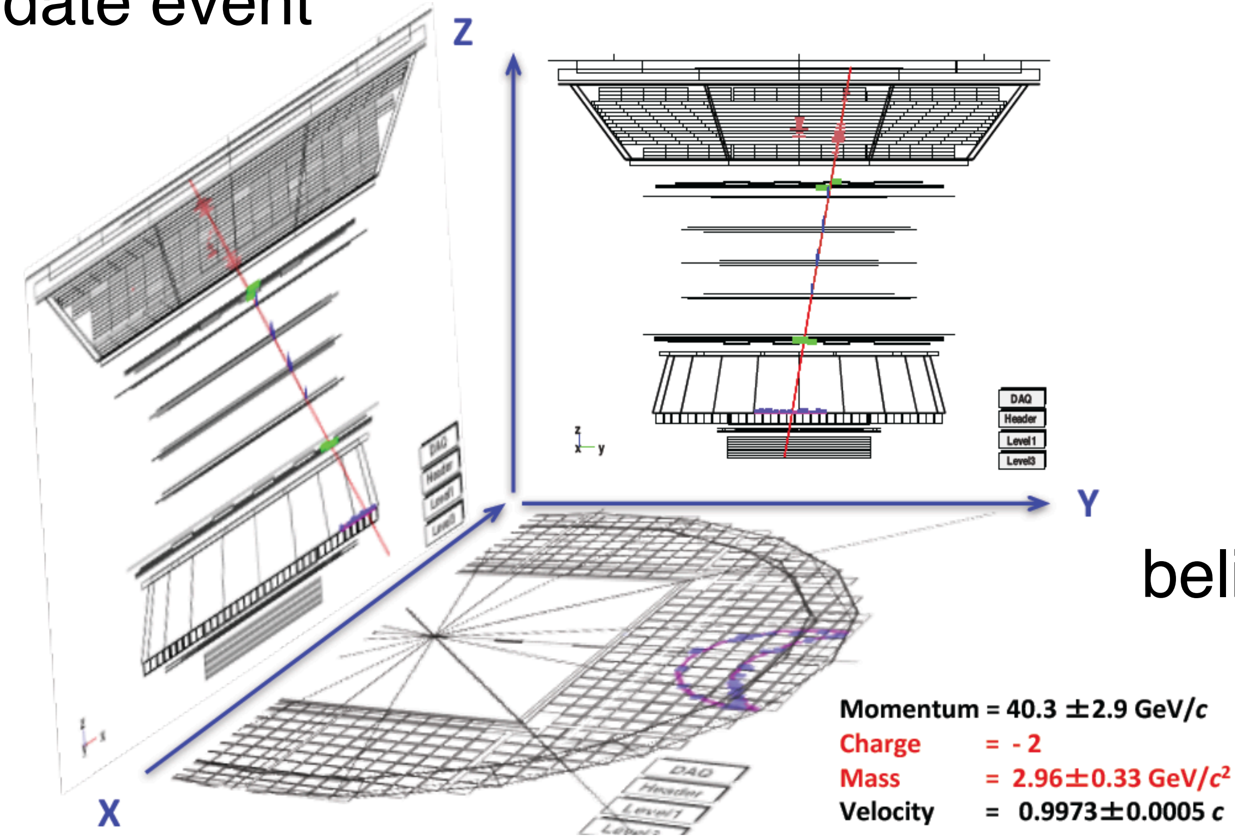
a few events

with Z = -2 and

with mass around ^{3}He.

Anti-Helium detection by AMS-02 ?

candidate event



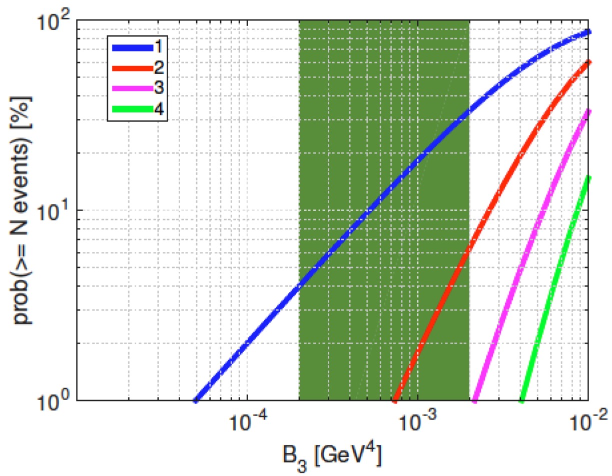
believe it or not ?

signal-to-background ratio of ~ **one event in 10^9**

35 billion simulated helium events: MC study shows low background

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.

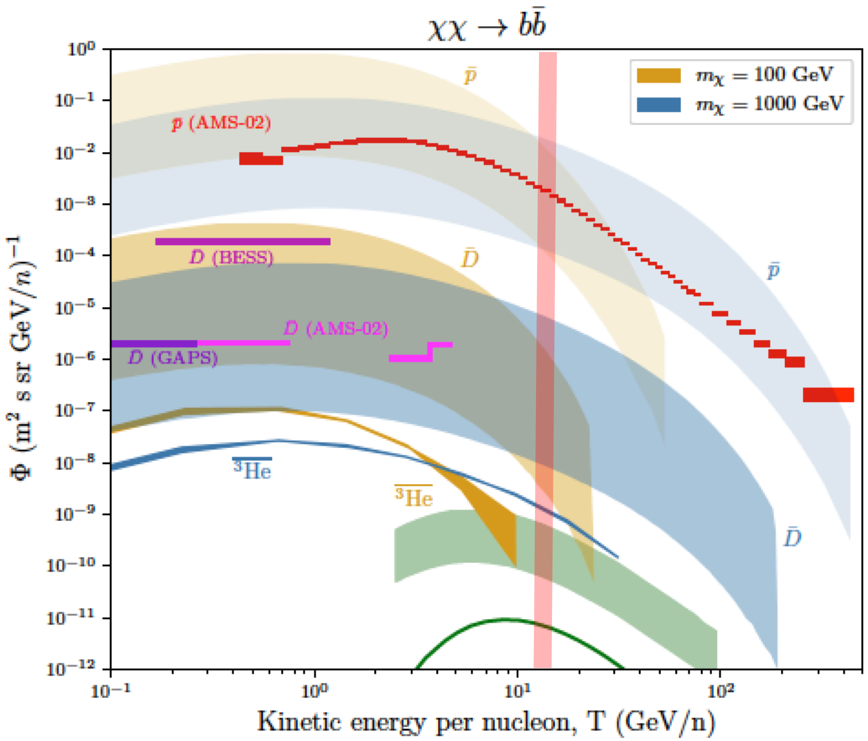
Anti-Helium detection by AMS-02 - how would it be explained ?



secondary origin ? Blum et al 2017
scaling law of nuclear coalescence

resulting cross section is 1-2 orders of magnitude higher than earlier estimates.

Fig : Poisson probability for detecting 1 to 4 ^{3}He events in a 5-yr analysis of AMS02



dark matter annihilation or decay
Coogan and Profumo (2017)

normalize fluxes to obtain one antihelium (11.5 – 13.5 GeV/n) in 5 years, models also fit AMS p flux and D limit

eg. for **mχ** = 100 GeV
=> cross section $\langle\sigma v\rangle = 7.3 \cdot 10^{-26}$ cm^{-3} s^{-1}

Anti-Helium detection by AMS-02 ?

and why not the Holy Grail of baryogenesis ?

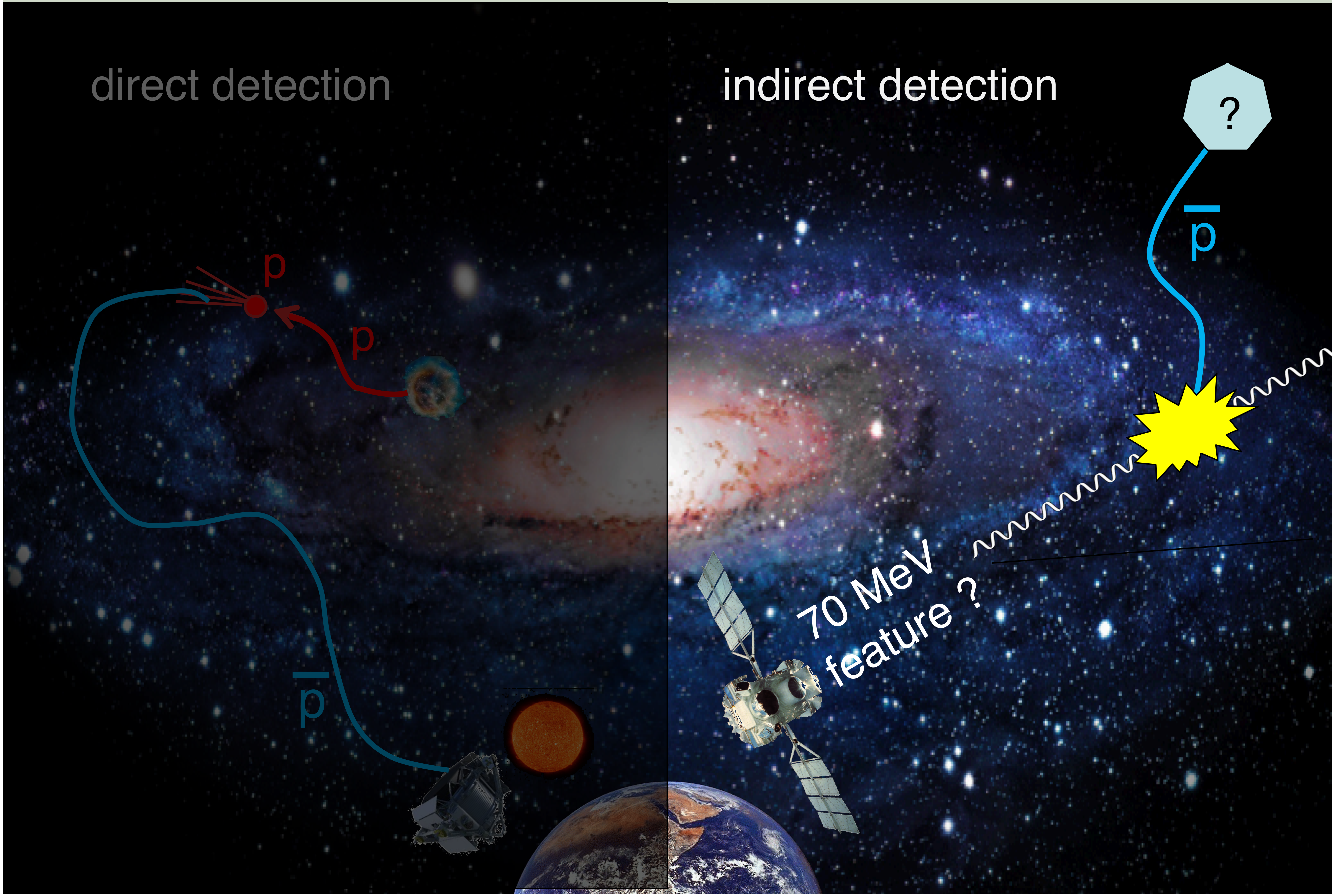
"The discovery of **a single anti-helium* nucleus** in the cosmic ray flux would definitely point toward the existence of stars and even of entire galaxies made of anti-matter"
Salati et al, 1999

"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

* ^{4}He, supposedly …

baryonic antimatter



gamma rays from nucleon-antinucleon annihilation

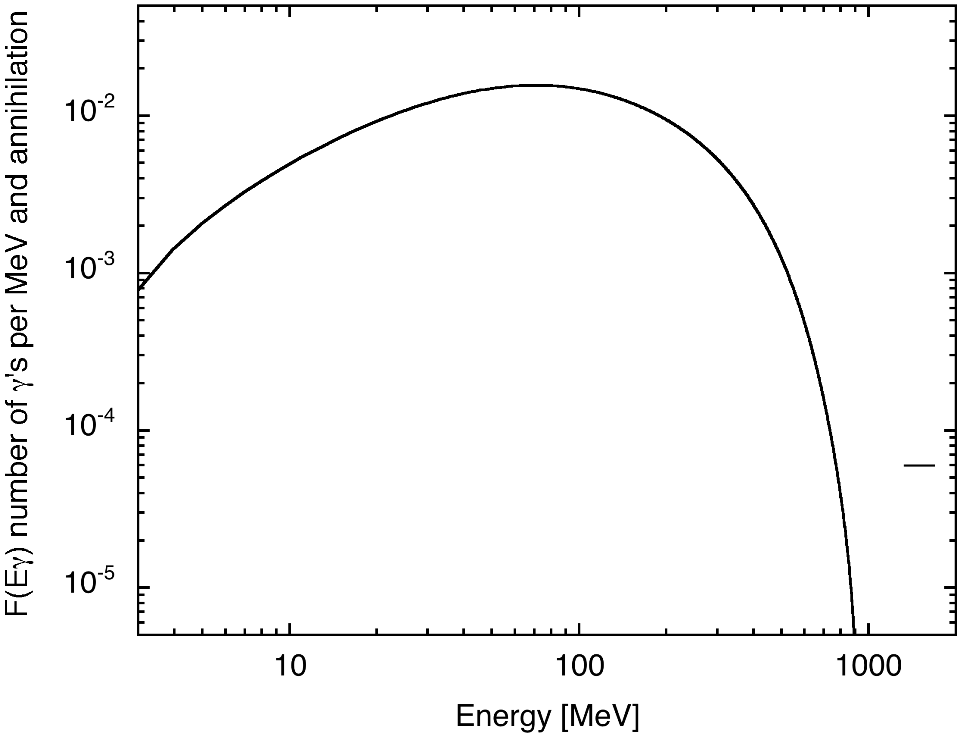
$$N - \bar{N} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \end{cases}$$

1/3 of $2m_Nc^2 \rightarrow$ 200 MeV γ's

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

1/2 of $2m_Nc^2 \rightarrow$ ν's

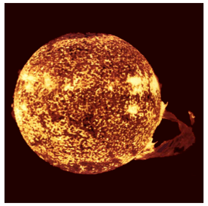
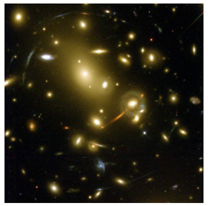
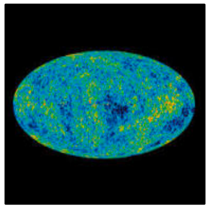
1/6 of $2m_Nc^2 \rightarrow$ e^-, e^+ (100 MeV)



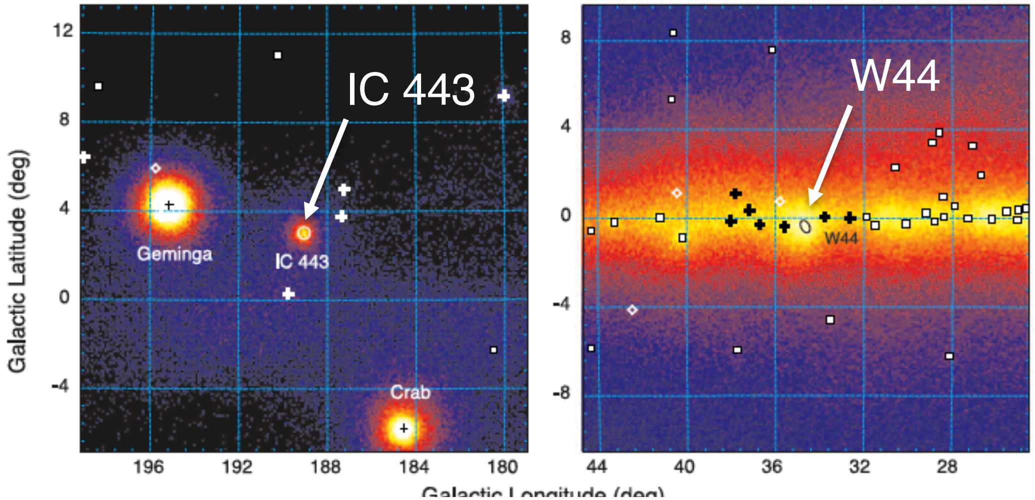
typical rest-frame spectrum produced by p-p annihilation with π° decay

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

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

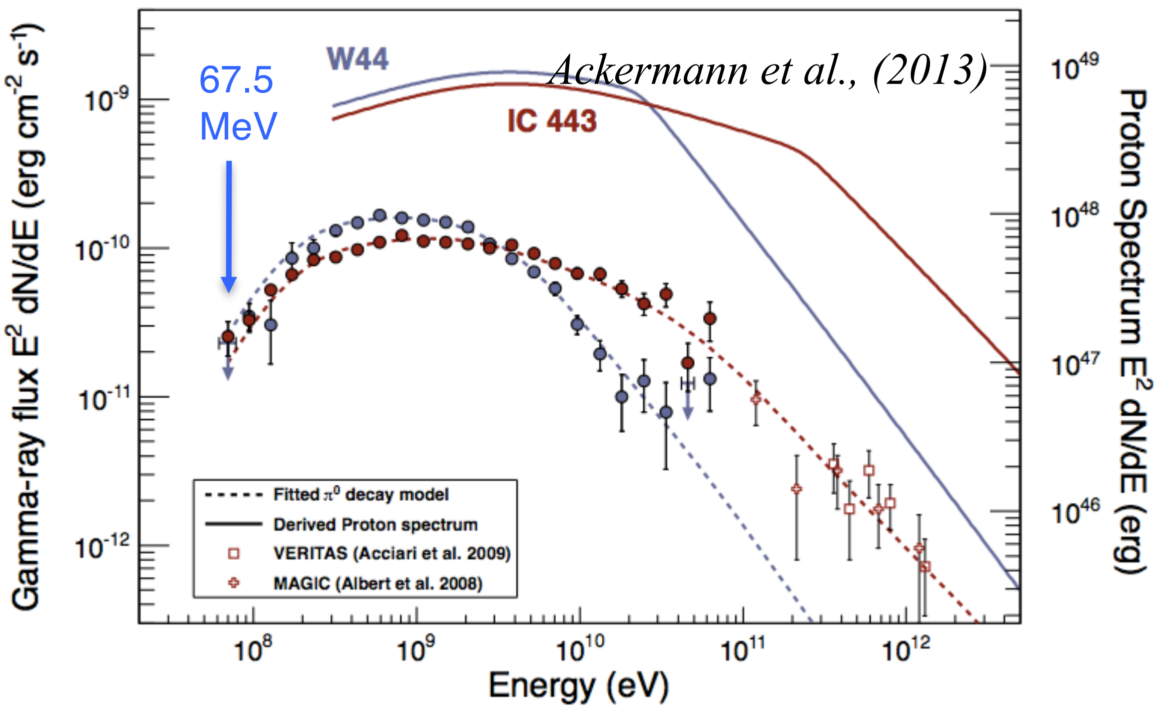
	object	probe	observatory	AM limit
	**asteroids**	solar wind [micro-meteorites cosmic rays]	Fermi	**< 4 km Ø** if in main-belt
	**stars** within 150 pc	galactic gas (Bondi-Hoyle accretion)	Fermi	$\mathbf{f_{AM} \leq 4 \cdot 10^{-5}}$
	**galactic gas**	galactic gas	Fermi	$\mathbf{f_{AM} \leq 10^{-15}}$
	**intracluster gas**	intracluster gas	Fermi	$\mathbf{f_{AM} \leq 10^{-8} - 10^{-6}}$
	**primordial matter region**	primordial matter region	Comptel	**> 1 Gpc**

Gamma-rays from π^0 decay in old supernova remnants



IC 443 Supernova remnant
Age ~ 10000 years
Distance 1.5 kpc

W44 Supernova remnant
Age ~ 10000 years
Distance 2.9 kpc



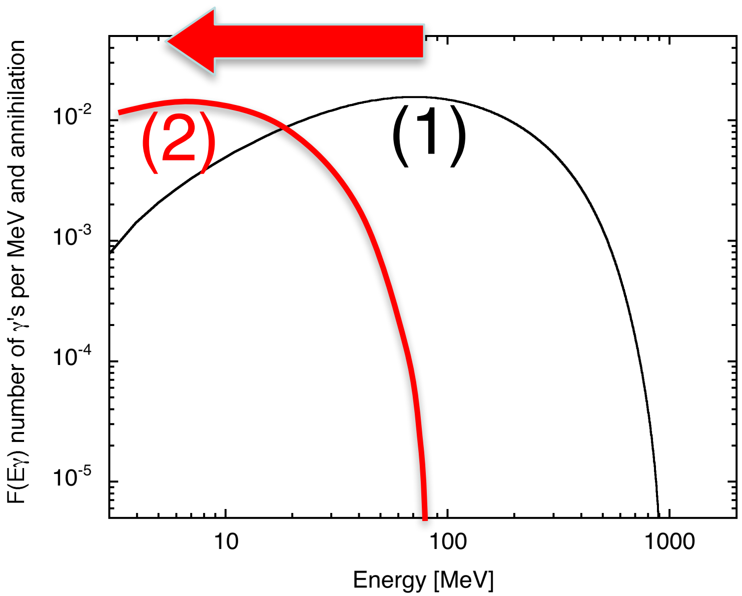
=> direct evidence that cosmic-ray protons are accelerated in SNRs

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.

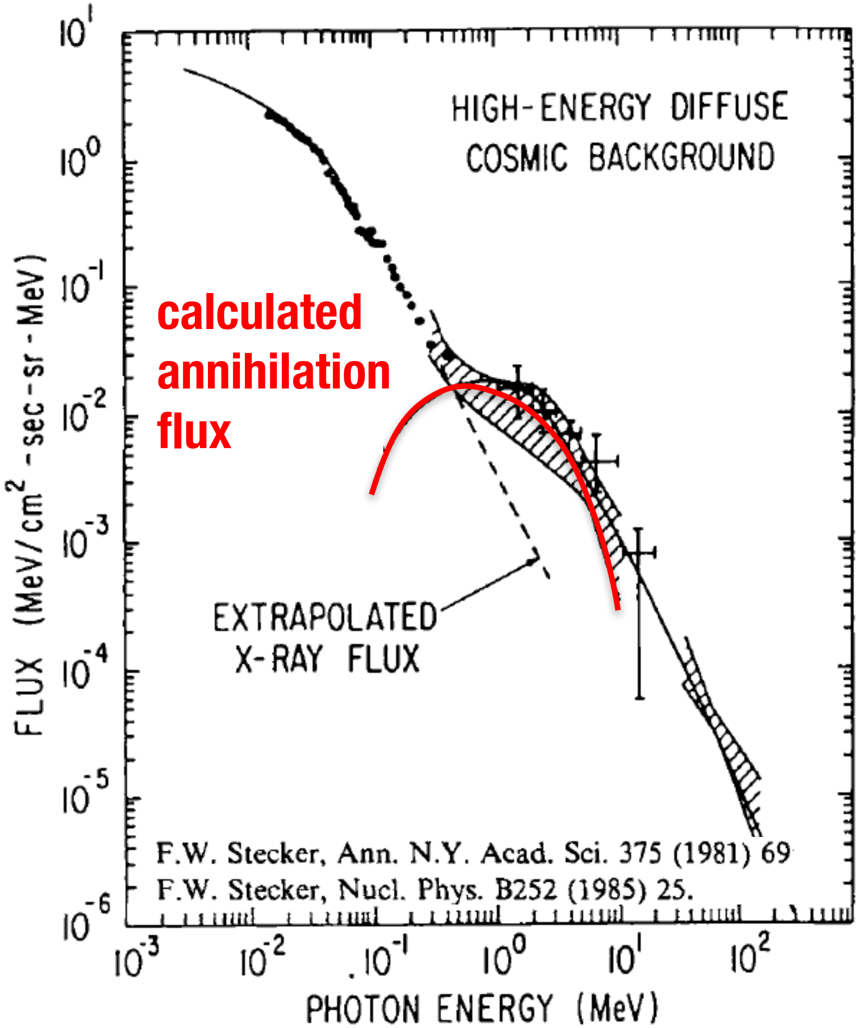
$$y\frac{\partial I}{\partial y}+\epsilon\frac{\partial I}{\partial \epsilon}=2I+\frac{y^2\Omega\nu}{[1+\Omega(y-1)]^{1/2}}\left[A(\epsilon)I-\int_\epsilon^{b(\epsilon)}d\epsilon' B(\epsilon|\epsilon')I(\epsilon',y)-\xi^2\Omega n_c y^3 v(T(y))\frac{\sigma_A(T(y))}{\pi r_e^2}G_A(\epsilon)\right]\cdots$$



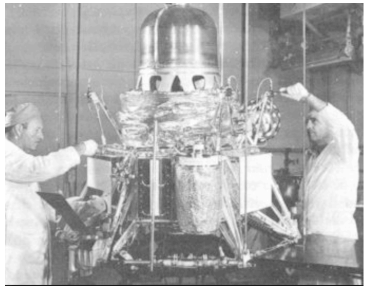
(1) typical rest-frame spectrum produced by p-$\bar{p}$ annihilation with π° decay

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

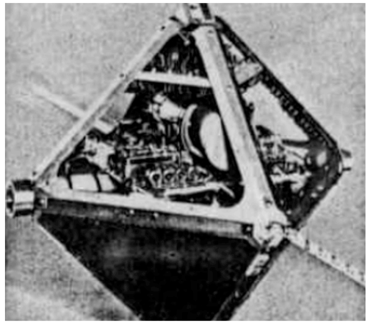
a "Pion bump" in the Cosmic Gamma-Ray Background ?



early observation of the CGB



Ranger 3 1964
Metzger et al.

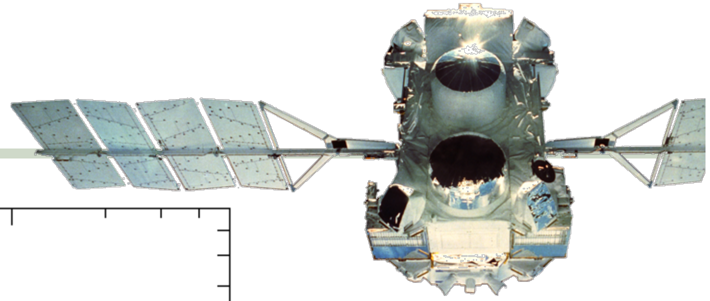


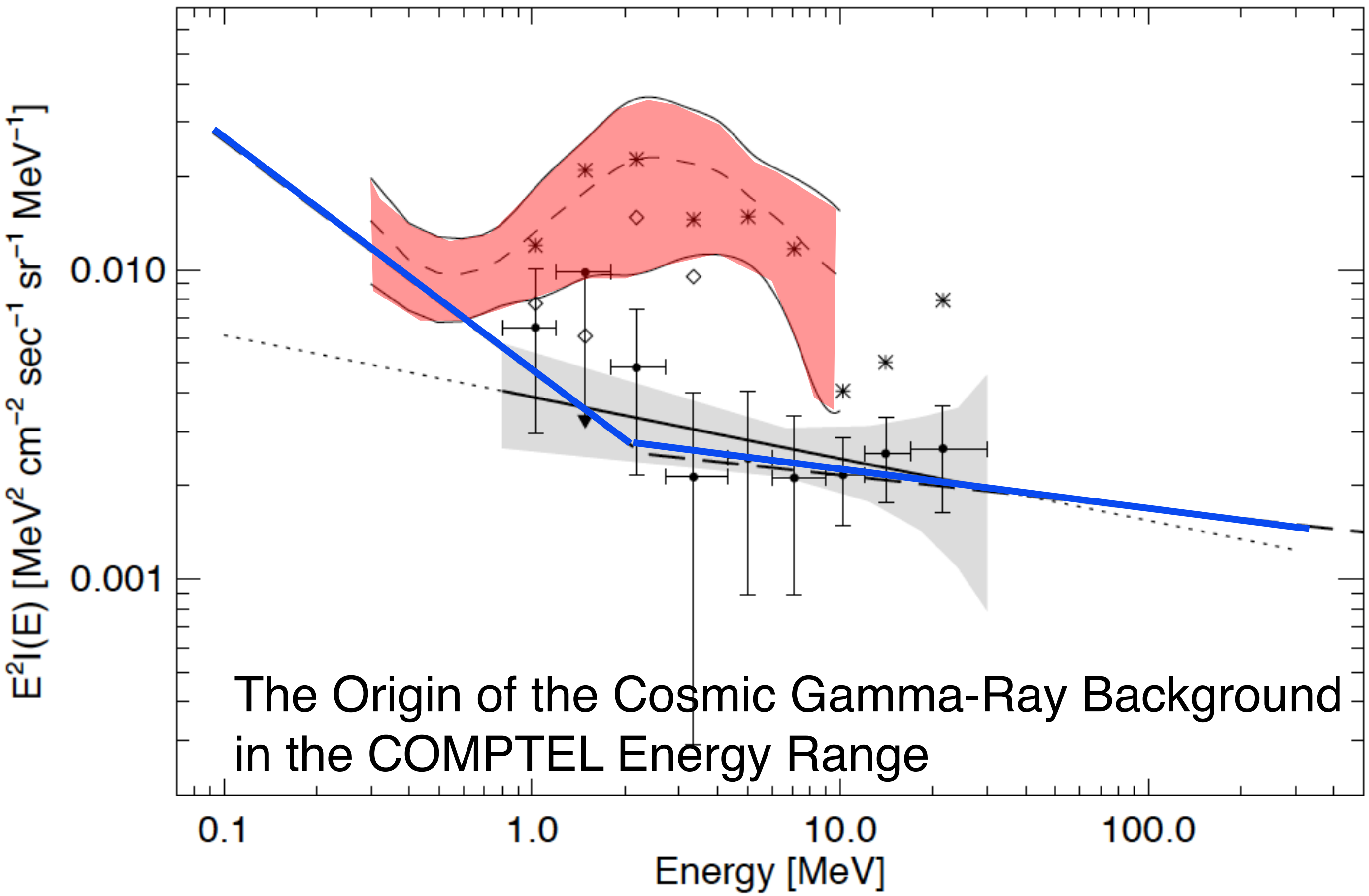
ERS-18, 1970
Vette et al.

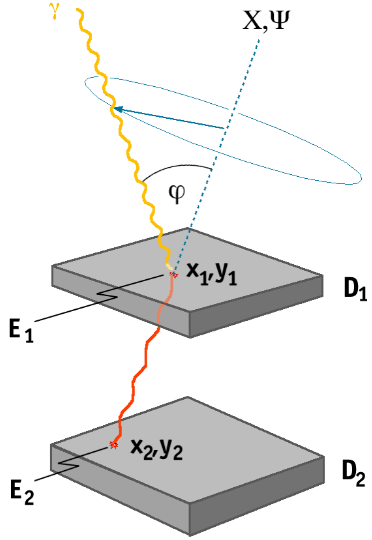
Apollo 15, 1973
Trombka et al.

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

Georg Weidenspointner's thesis 1999



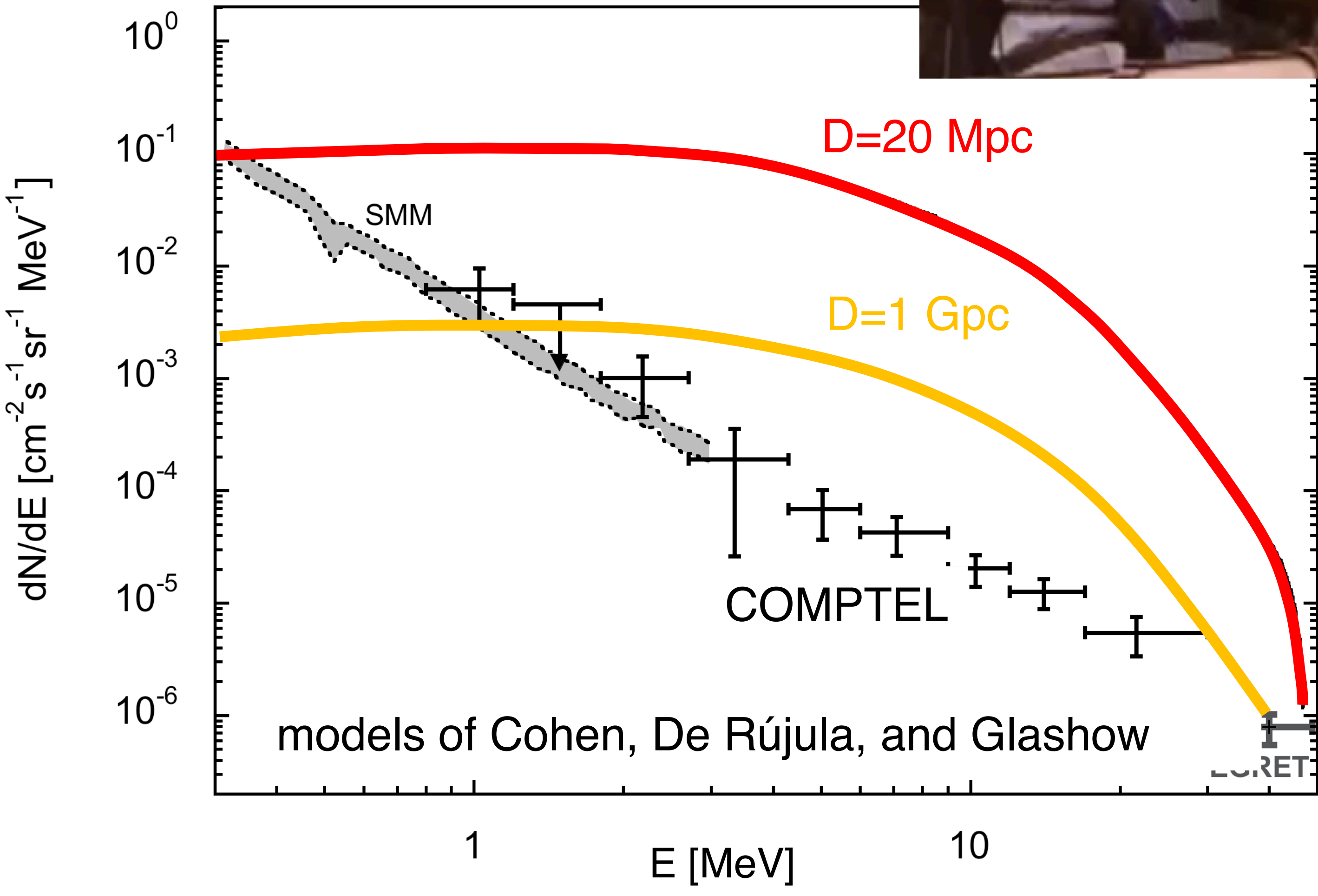


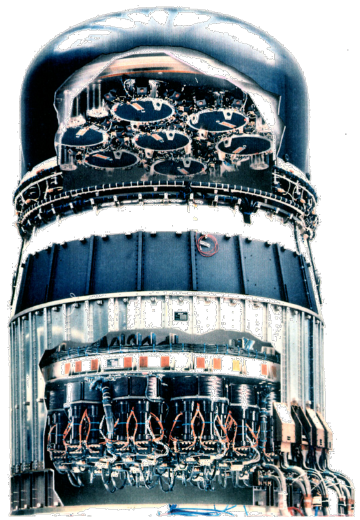


COMPTEL data (Weidenspointner and Varendorff 2001**)**
- no pion bump
- transition from a softer to a harder component at ~ 5 MeV
- no deviation from isotropy within statistics

Cosmic diffuse X- and Gamma-

Cohen, De Rújula, and Glashow (1998) to
with the fact that **CMB is highly uniform.**
At recombination $\bar{n}$ and n must have be
=> annihilation at domain boundaries is





COMPTEL

hiding away antimatter in compact objects

should the AMS-02 observation of anti-helium be confirmed,

we will need to go back and check the gamma-ray sky, as well as carefully searching scars on the CMB

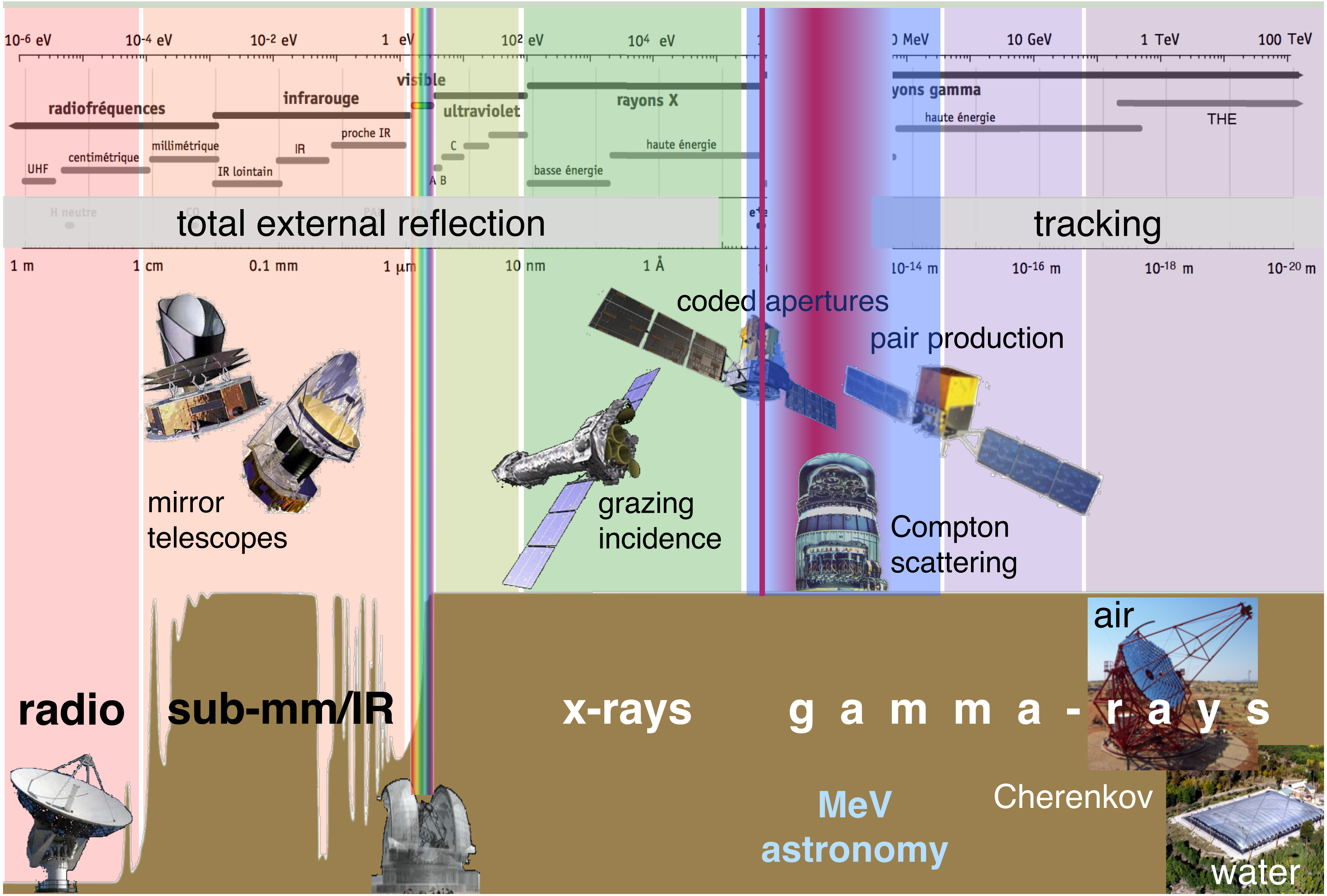
- lumps of antimatter in matter dominated universe ?

- antimatter globular clusters ?

- compact antimatter objects ?
  stars, neutron stars, BH are ideal hideways

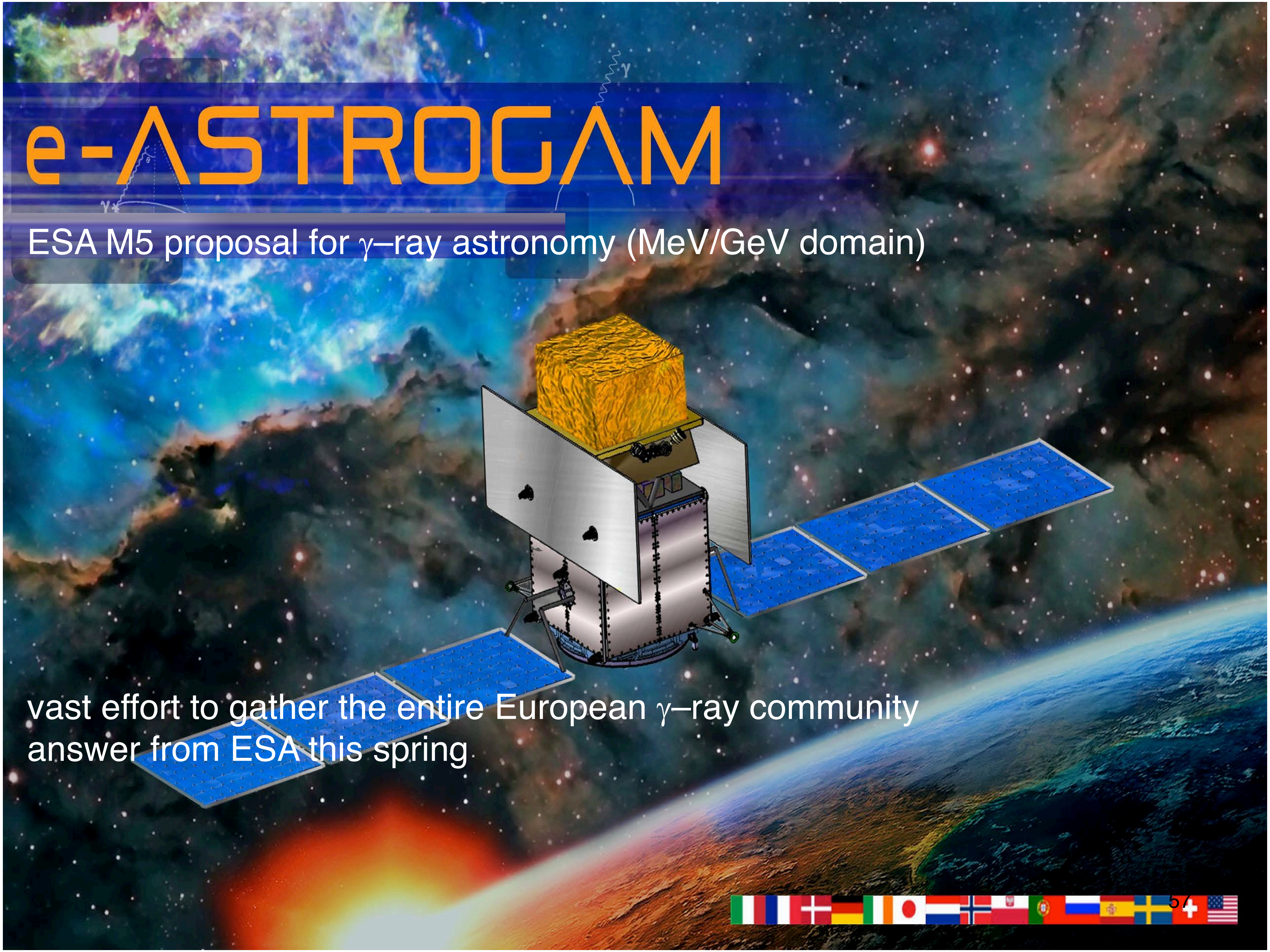
we then probably would have to find a kind of *symmetry breaking* in the stellar evolution of antimatter vs matter …

MeV astronomy is Antimatter astronomy



e-ASTROGAM

ESA M5 proposal for γ–ray astronomy (MeV/GeV domain)



vast effort to gather the entire European γ–ray community
answer from ESA this spring