Antimatter in the Universe -

constraints from gamma-ray astronomy

Nuclear Antimatter

- high energy gamma-rays from the local and Galactic neighbourhood
- antimatter domain boundaries in the early Universe

Positrons

- e^+e^- annihilation radiation from the Galaxy
- what's next in MeV astronomy ?

Peter von Ballmoos, IRAP Toulouse

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 $n_B \cong n_{\bar{B}} \sim n_\gamma$.

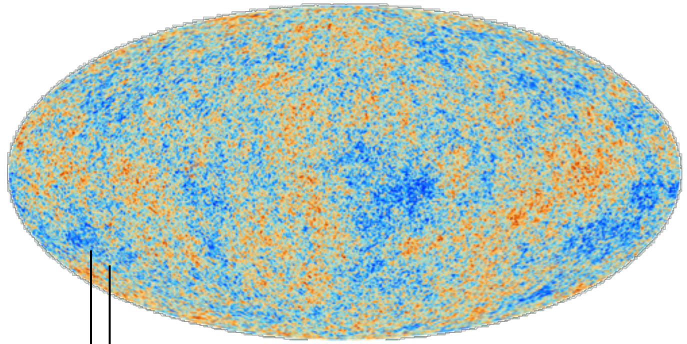
After feeeze-out (T < 1 GeV), the baryon density to photon number density ratio η becomes

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

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

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

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



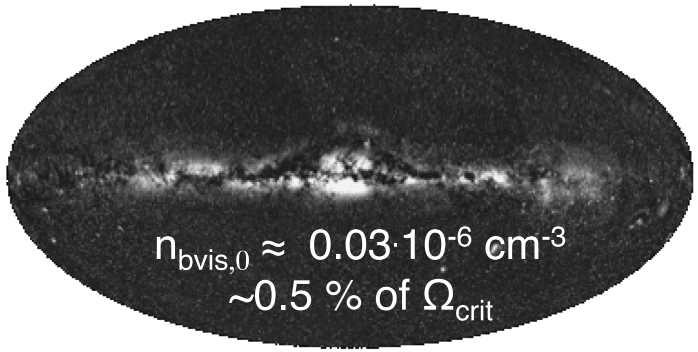
Temperature of CMB

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

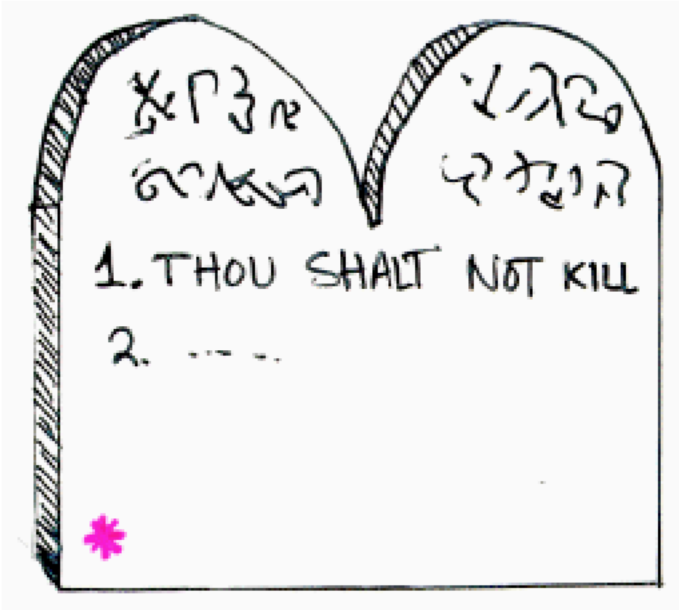
fit of CMB powerspectrum

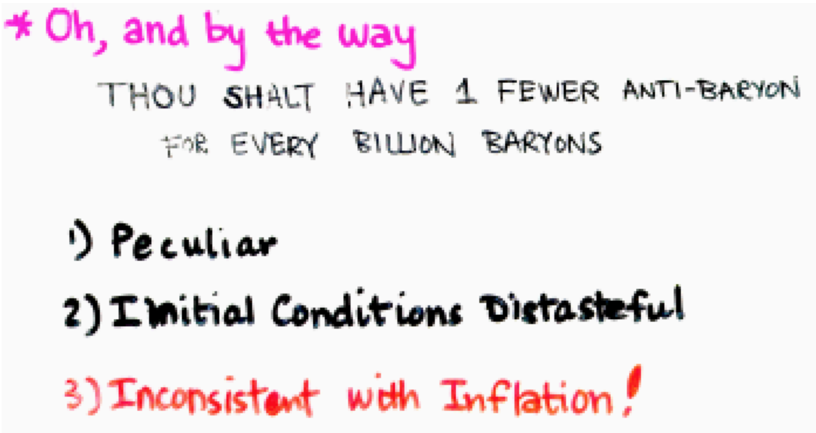
$n_{b,0} \approx 0.25 \cdot 10^{-6}\ \text{cm}^{-3}$

$\sim 4\%$ of Ω_{crit}



Baryon Asymmetry – an initial condition ?





(slide by A. Cohen, 1999)

=> search for antimatter in the Universe

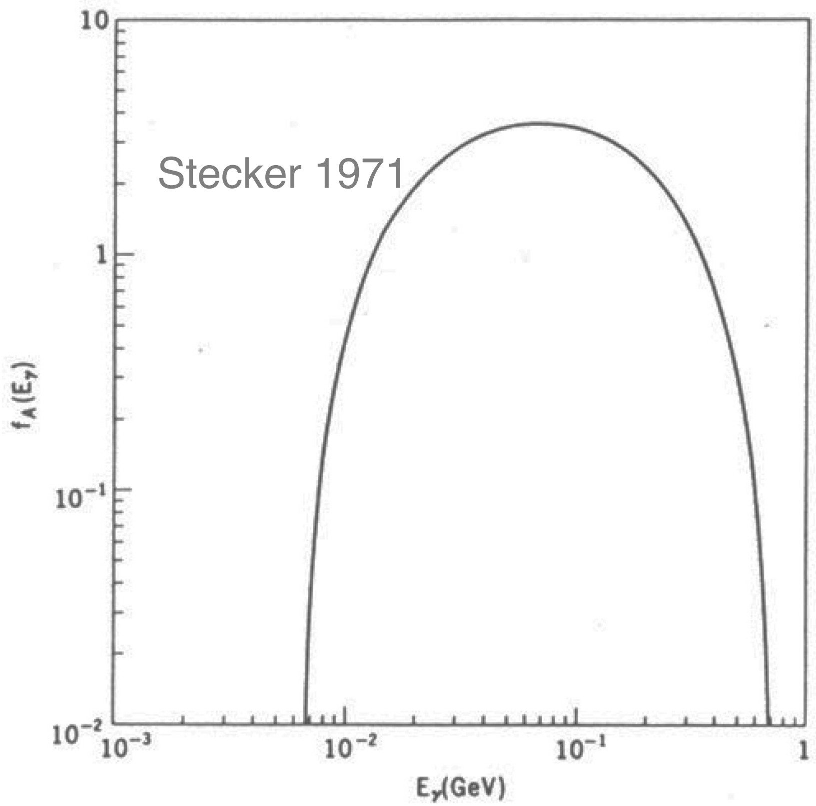
gamma radiation is emitted from the points of contact between regions of matter and antimatter

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 $2m_N c^2 \longrightarrow$ 200 MeV γ's

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



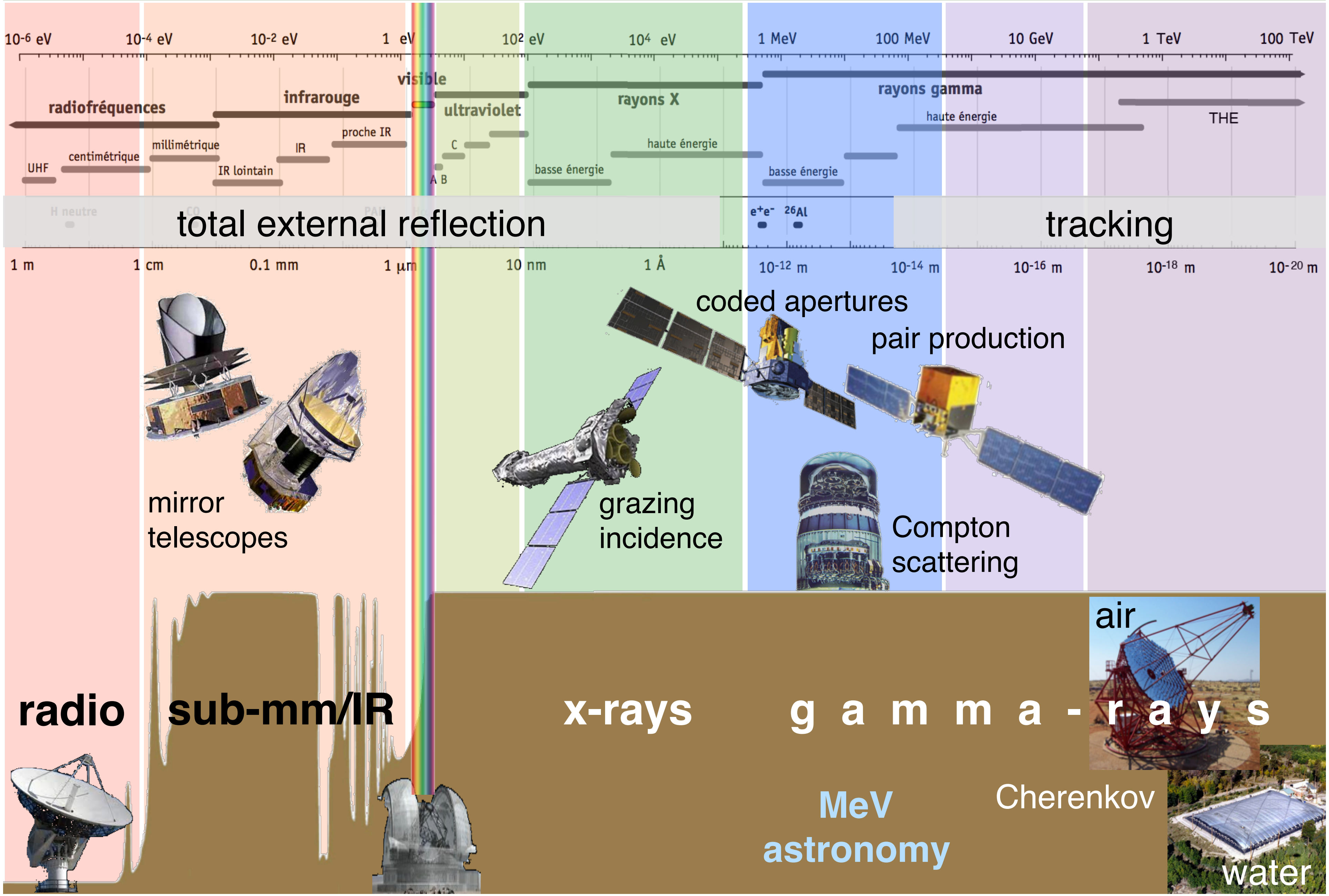
1/2 of $2m_N c^2 \longrightarrow$ ν's

1/6 of $2m_N c^2 \longrightarrow$ 100 MeV e^- / e^+

typical rest-frame spectrum produced by p-$\bar{\text{p}}$ annihilation with $\pi°$ decay

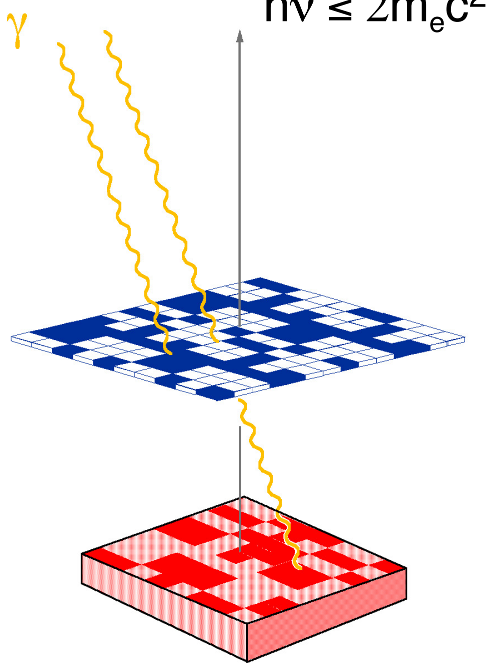
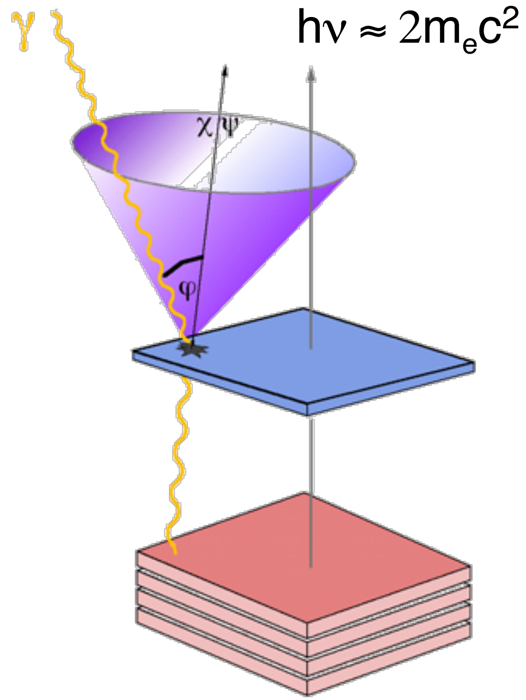
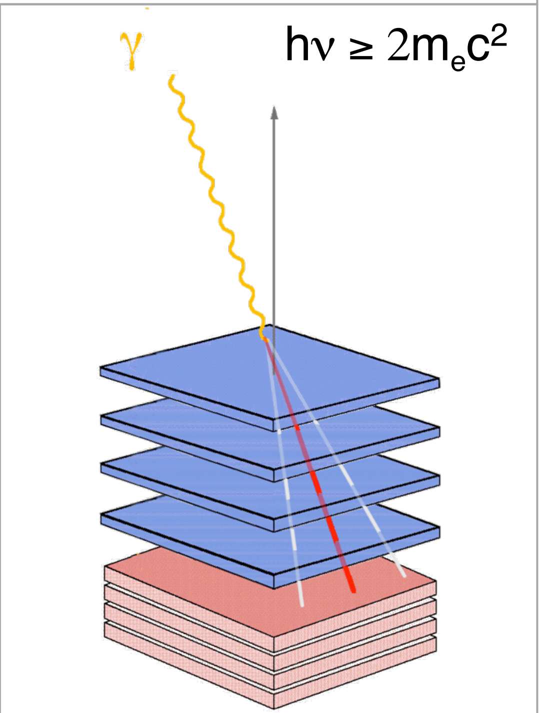
maximum intensity at $m_\pi c^2/2 \sim 70$ MeV

situating the relevant gamma-ray astromomy



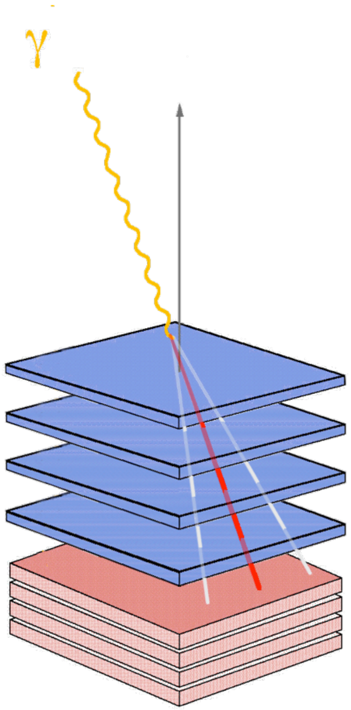
Instrument concepts in gamma-ray astronomy

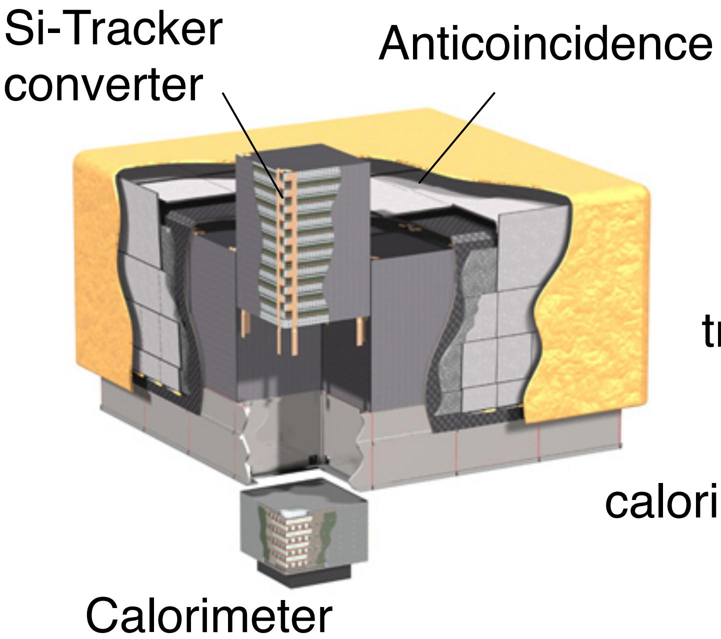
adapt to the interaction processes in the transition region $\mathbf{m_e c^2 < h\nu < m_e c^2}$

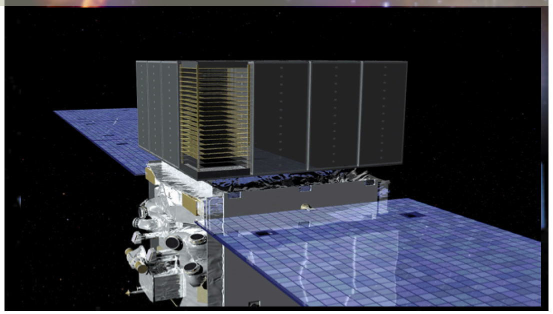
	geometric optics absorption	**quantum optics** incoherent scattering	pair-conversion / tracking
detector aperture	$h\nu \leq 2m_e c^2$ 	$h\nu \approx 2m_e c^2$ 	$h\nu \geq 2m_e c^2$ 
	ex. coded masks "on-off" collimators	ex. Compton telescopes	ex. silicon trackers spark chambers

pair-conversion telescope

FERMI / LAT



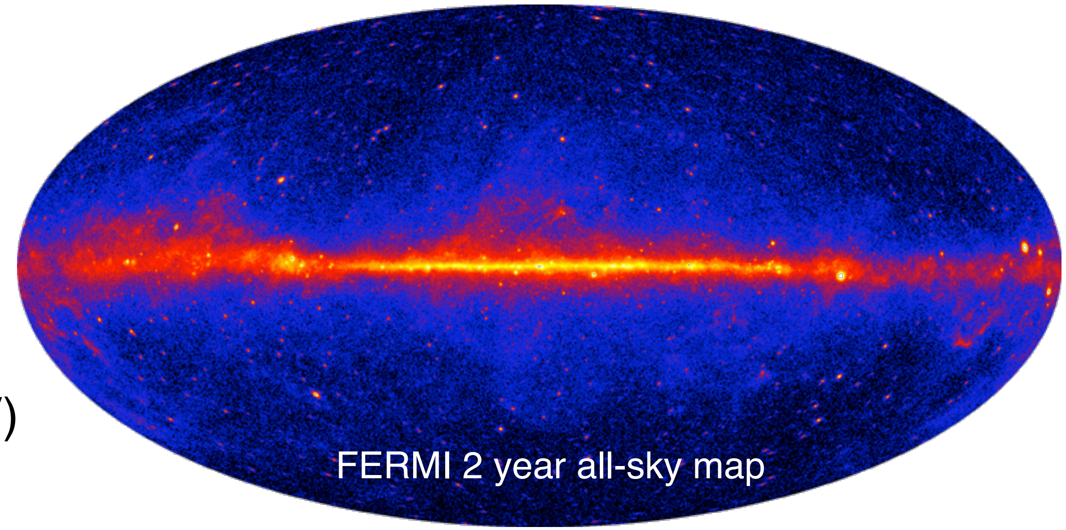




tracker	Si, 80 m^2 single sided
	W foil interleaved
	4 x 4 x 18 xy planes
calorimeter	1536 CsI crystals
	8.6 R.L, hodoscopic
mass	2789 kg

performance

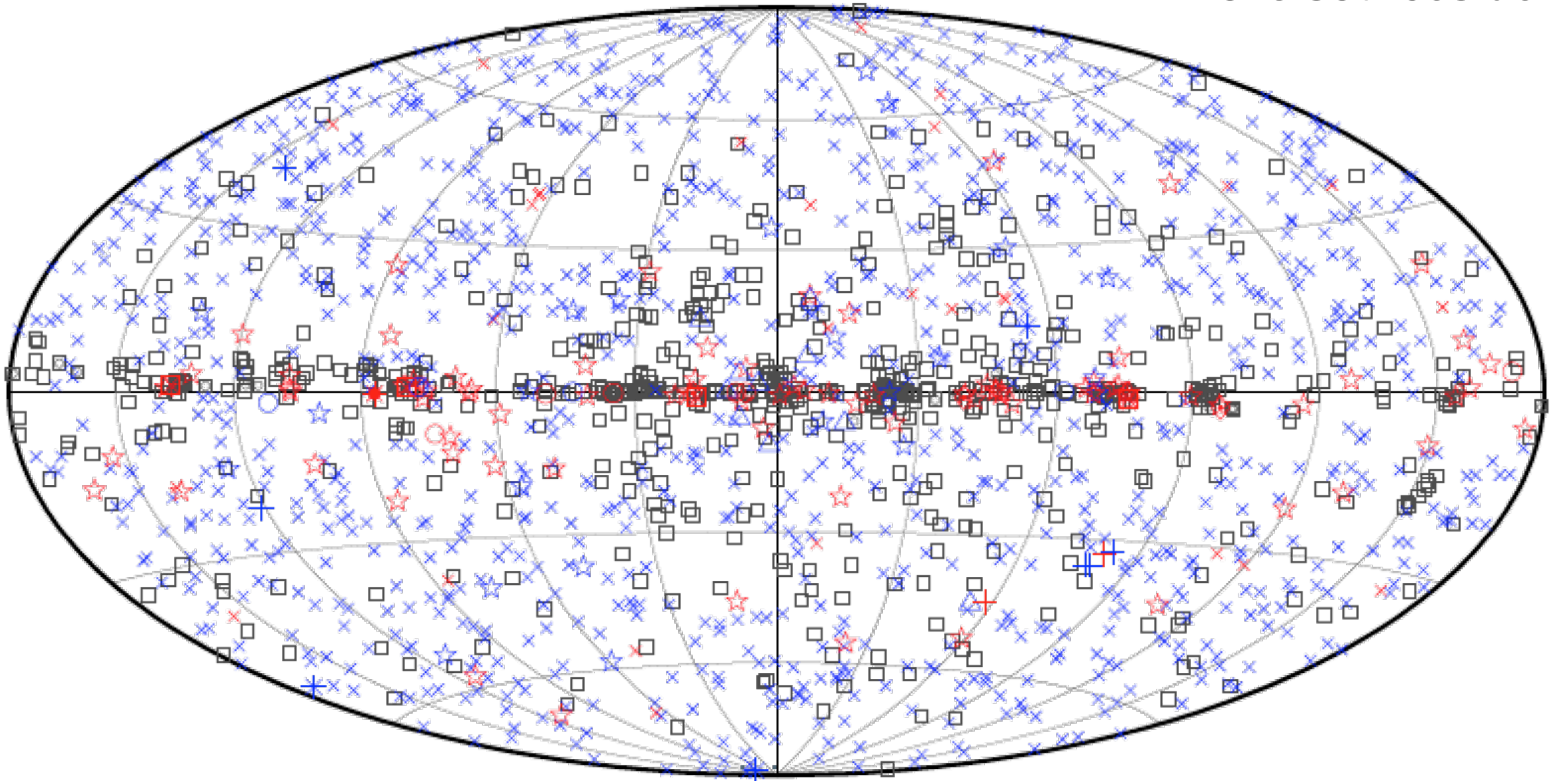
Energy	0.1– 300 GeV
Field of view	2.4 steradian
angular res.	3° - 0.04°
Eff. area	7000 cm^2 (1GeV)
E/ΔE :	6 - 18% (1σ)



FERMI LAT Second Source Catalog - 2FGL (0.1-100 GeV)

Abdo et al. 2012, ApJS.199

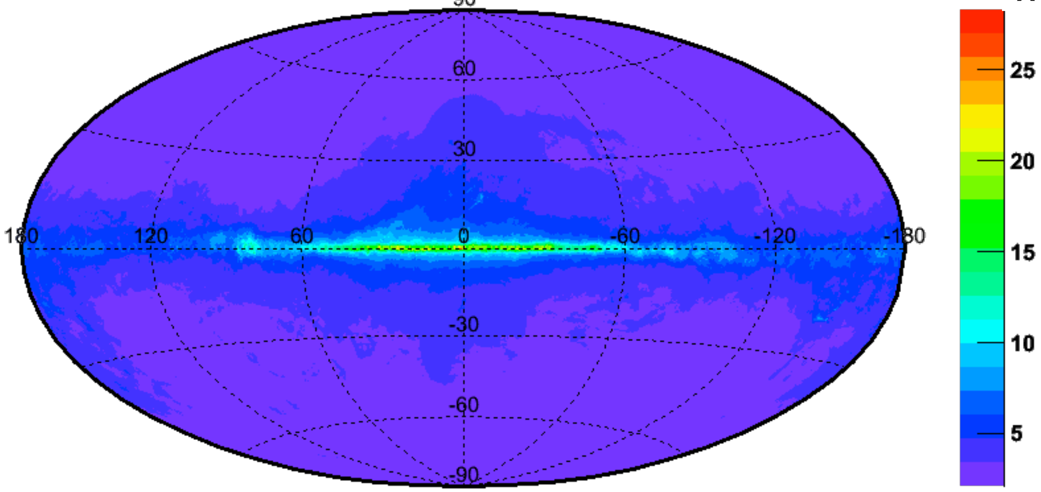
- 1873 sources detected



- □ No association
- × AGN
- ✳ Starburst Gal
- + Galaxy
- ⊡ Possible association with SNR or PWN
- ☆ Pulsar
- ◇ PWN
- ○ SNR
- △ Globular cluster
- ⊠ HMB
- ✷ Nova

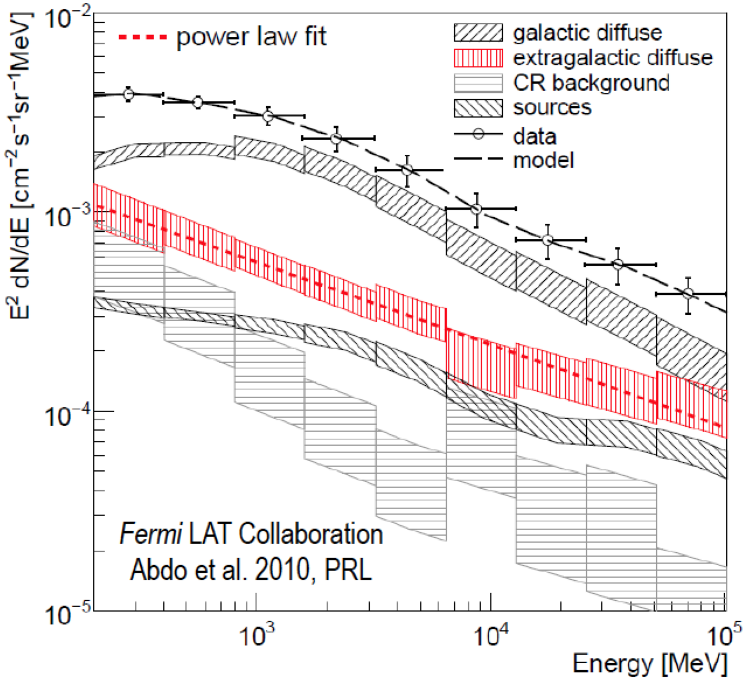
- 127 firmly identified
- 1170 associated
- 576 w/o plausible counterpart

FERMI : point sources sensitivity and diffuse background



3-year differential sensitivity for an isolated point source

minimum flux above 100 MeV to obtain a 5σ detection in 3 years (assuming a power law spectrum α=-2)



the components of the diffuse high-energy spectrum and the Isotropic Diffuse Gamma-Ray Emission

gamma rays (100 MeV) do not provide a unique signature for AM annihilation.

=> upper limits to the annihilation rate

a "matter trail" from the solar system to the Galaxy

solar system

micro-meteorites and solar wind particles are continuously bombarding the earth without causing annihilation radiation. Aproximating the a solar wind flux with $nv \approx 2 \cdot 10^8 (d / 1\mathrm{AU})^{-2}\ cm^{-2}\ s^{-1}$, one can roughly estimat the annihilation radiation from an anti-planet :

$$F_\gamma(100 MeV) \approx 10^8 (r/d)^2\ ph\ cm^{-2}\ s^{-1}$$

r,d : radius, distance of anti-planet

example : Jupiter ($r= 7 \cdot 10^7$ m, $d=7 \cdot 10^{11}$m) : $F_\gamma \approx 1$ ph cm^{-2} s^{-1}
FERMI features ~10^{-8} ph cm^{-2} s^{-1} sensitivites

stars

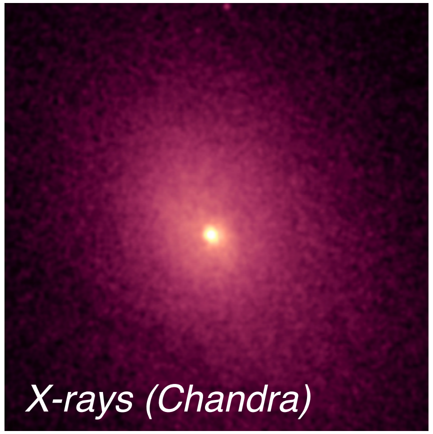
Bondi Hoyle accretion of galactic gas onto an anti-star would produce detectable 100 MeV fluxes (FERMI) out to at least 100 pc, corresponding to ~ 100'000 stars => antimatter fraction $f_{AM} \leq 10^{-5}$

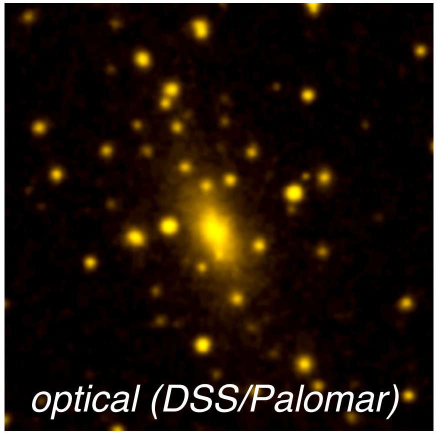
galactic gas

the observed diffuse galactic gamma ray flux (well exlained by CR interaction) limits the antimatter fraction $f_{AM} \leq 10^{-15}$!

the argument can obviously be extended as long as a sufficiently dense matter trail extends out to the next bigger structure ...

hot intracluster gas - constraints from HE gamma-rays





galaxy cluster Abell 2029

In galaxy clusters the majority of the baryons are in the hot intracluster gas.
=> we detect the X-rays produced through thermal bremsstrahlung

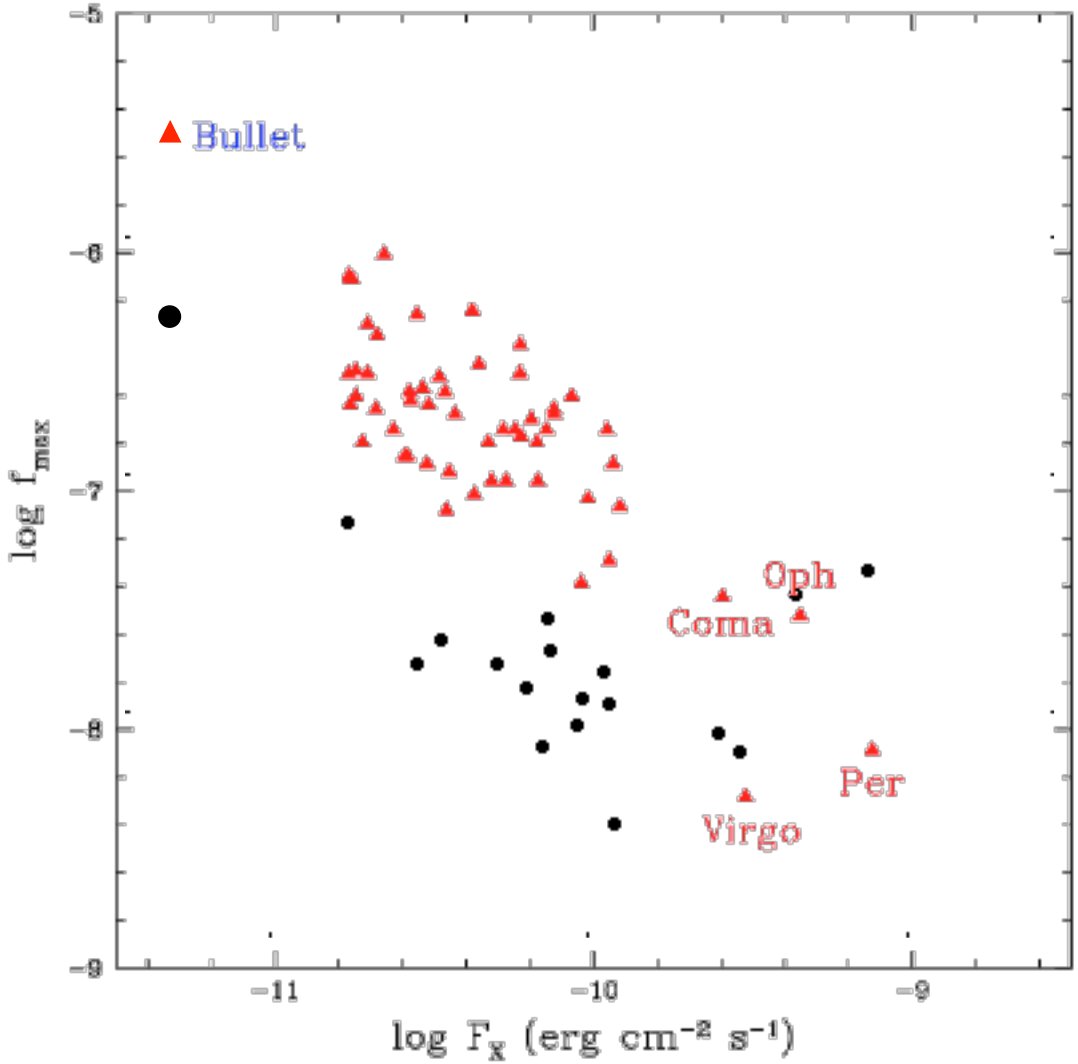
For antibaryons mixed with baryons at a ratio $f = n_{\overline{B}} / n_B$

=> high energy **γ-rays from p$\overline{\text{p}}$ annihilation** $F_\gamma \propto \frac{f}{\sqrt{T_{Gas}}} \int \frac{n_B^2 dV}{4\pi R^2}$

occuring in the same
two-body collisions that produce x-rays $F_X \propto \sqrt{T_{Gas}} \int \frac{n_B^2 dV}{4\pi R^2}$

see e.g. Steigman 1976

hot intracluster gas - constraints from HE gamma-rays



$$f \leq const \cdot T_{Gas} \frac{F_\gamma}{F_x}$$

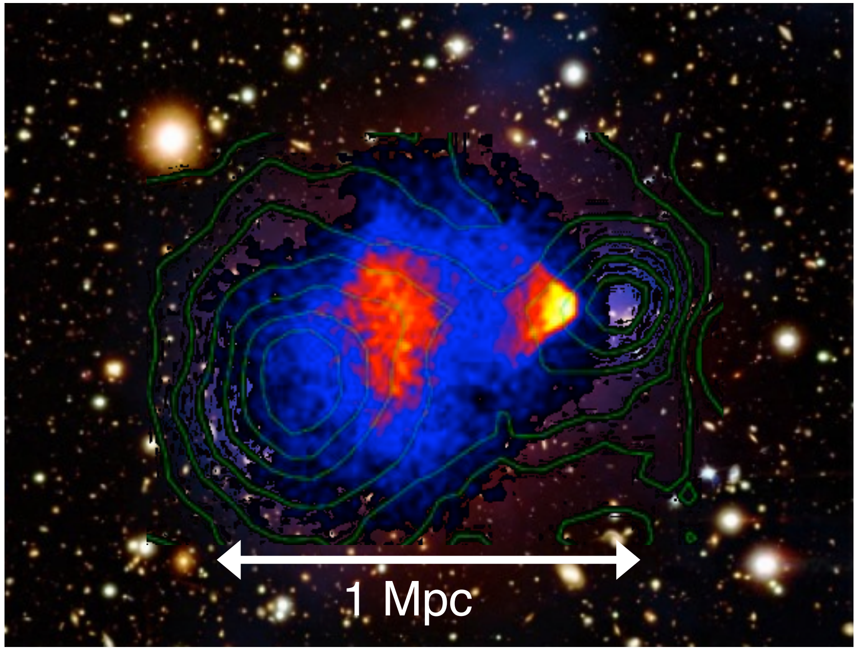
GeV γ-ray flux upper limits :

EGRET ▲
Reimer et al, 2003

FERMI ●
Ackerman et al, 2010
extrapolated down to 100 MeV

adapted from
Steigman 2008

Bullet Cluster



Bullet Cluster (dist 1.14 Gpc)
X-ray : Chandra
optical : Magellan and HST
lensing : Magellan / ESO

colliding clusters of galaxies (relative speed ≈ 4700 km/s)

Fermi !

$$f \leq const \cdot T_{Gas} \frac{F_\gamma}{F_x} = const \cdot 14keV \frac{5.3 \cdot 10^{-9}\, ph\ cm^{-2} s^{-1}}{4.7 \cdot 10^{-12}\, erg\ cm^{-2} s^{-1}} \cong 5 \cdot 10^{-7}$$

dynamical state of the system => clusters were initially separated by ~ 20 Mpc

=> matter/antimatter domains ≥ tens of Mpc

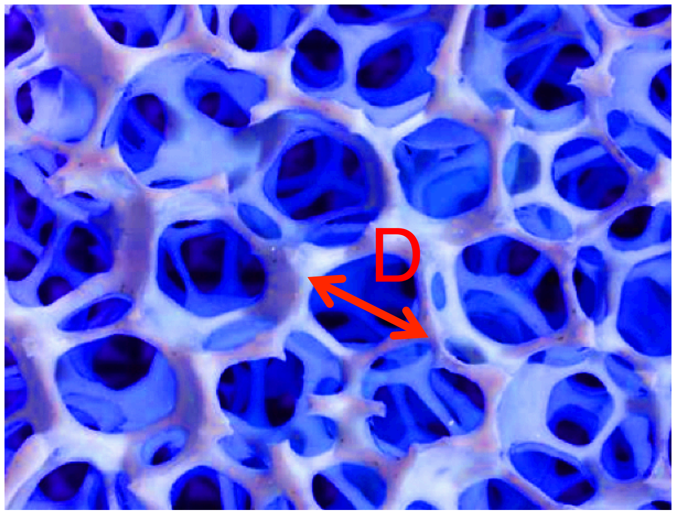
antimatter domains and the diffuse gamma-ray background

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.

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

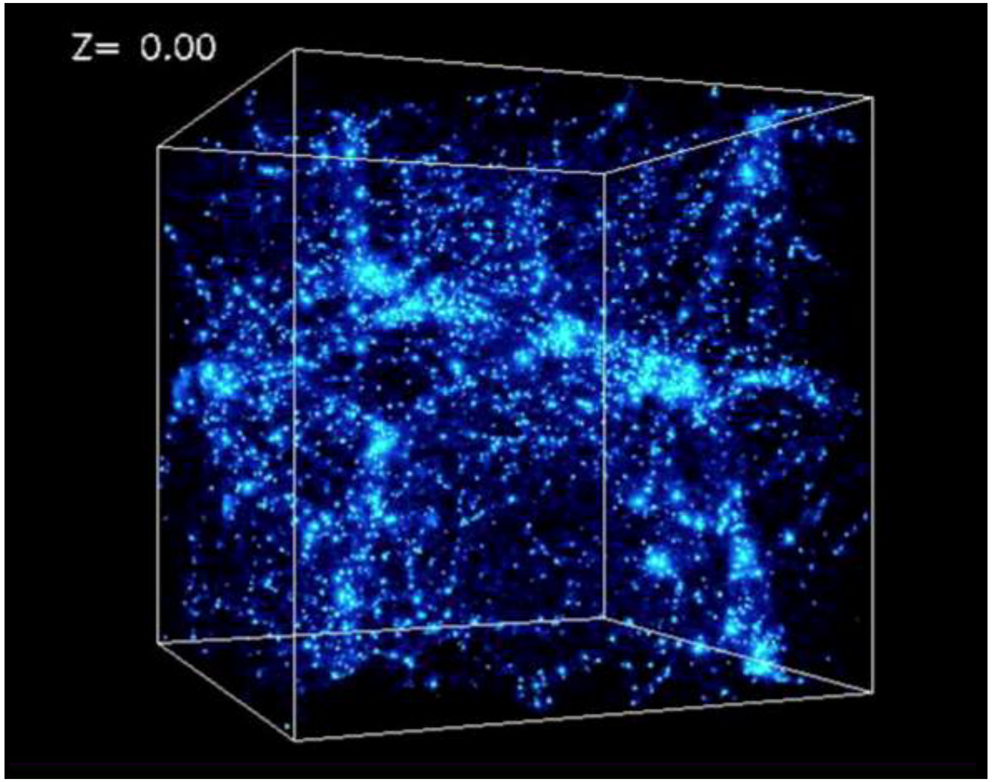
=> redshifted gamma-ray "bump" above ~ 1 MeV



what domain-size D (> 20 Mpc)
is compatible with
the observed MeV gamma-ray sky ?

antimatter domains and the diffuse gamma-ray background

Cohen, De Rújula, and Glashow (CDG,1998) propose to
combine **gamma-ray constraints** with the fact that **CMB is highly uniform**



antimatter domains and the diffuse gamma-ray background

Cohen, De Rújula, and Glashow (CDG,1998) propose to combine **gamma-ray constraints** with the fact that **CMB is highly uniform**

$t=3.8 \cdot 10^5$ y **recombination**

z≈1100 **n and $\bar{n}$ must have been uniform**

=> annihilation at domain boundaries is inavoidable

=> drop in pressure in the annihilation region

=> matter and antimatter flow into this region

=> annihilation due to flow of n and n into combustion zone

t=3 Gy **Structure formation**

z ≈ 20 **n and $\bar{n}$ separate**

=> further annihilation uncertain (-> ignaored)

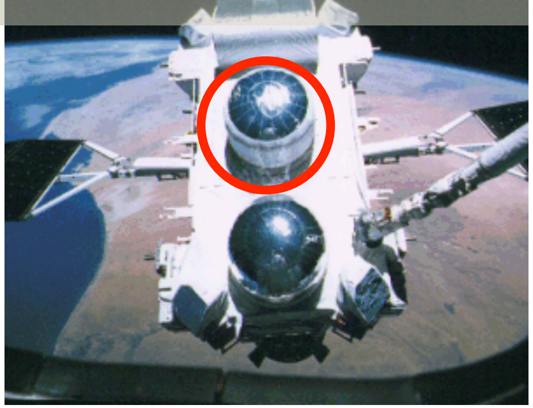
=> the spectrum of photons continues to evolve dur to the expansion of the universe as well as subsequent scattering

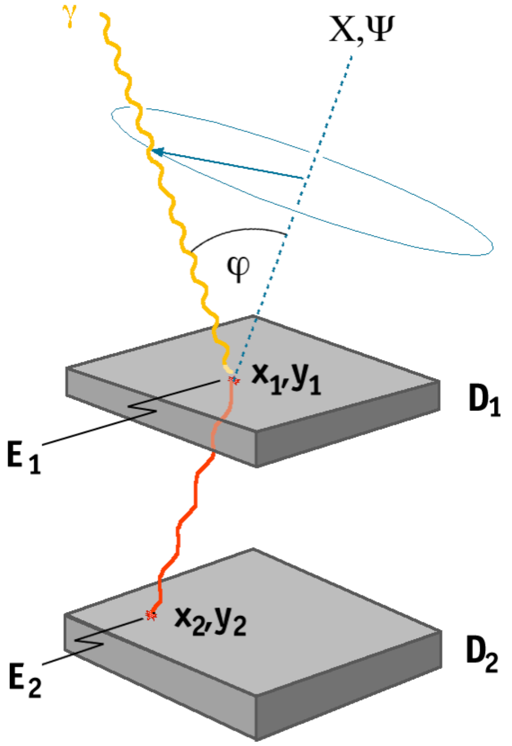
t=13.8 Gy **today**

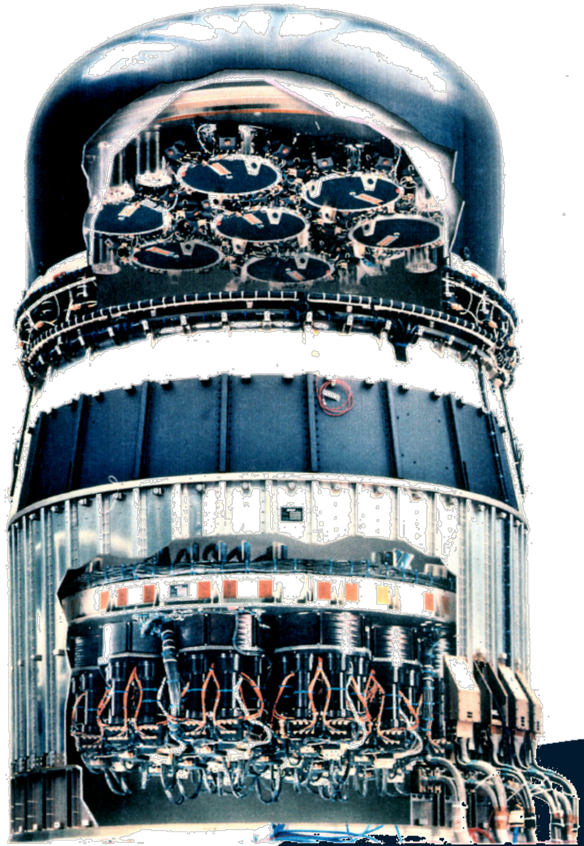
z=0 => calculated γ-ray spectrum shifted from 100 MeV -> 1 MeV

Compton Telescopes

GRO/COMPTEL



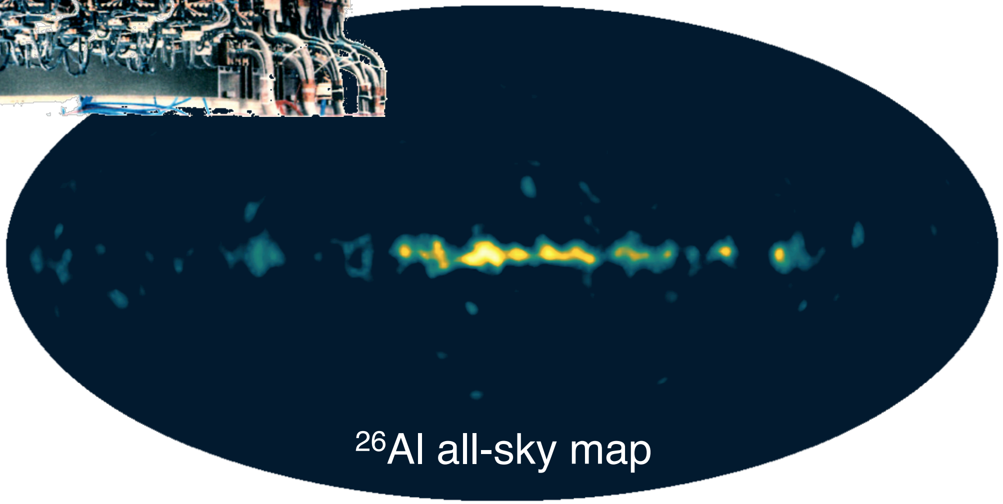




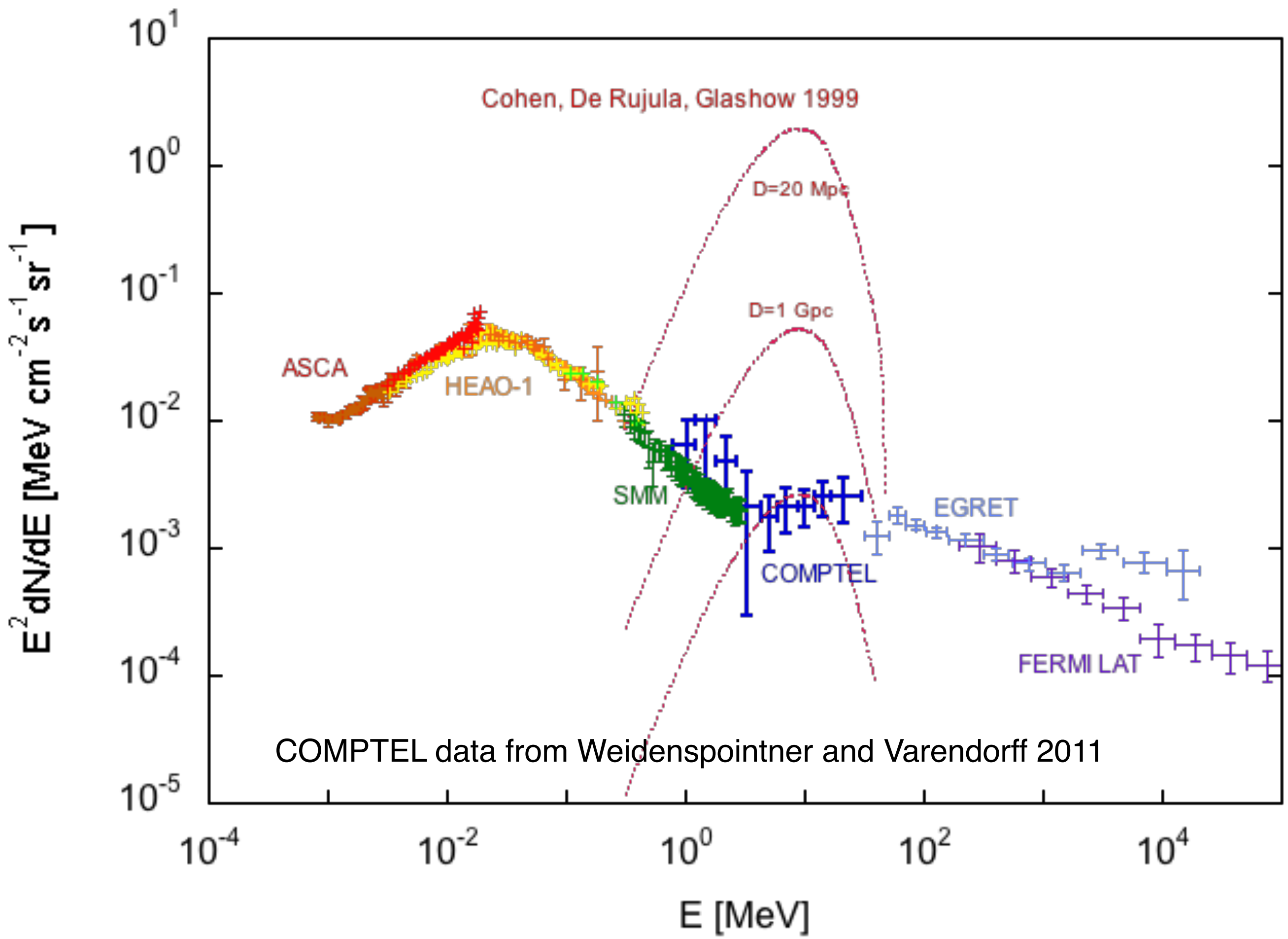
D1	NE 213A, A=4188 cm^2
D2	NaI(Tl) A=8620 cm^2
	both Anger cameras
	TOF, anticoincidence
Mass	1460 kg

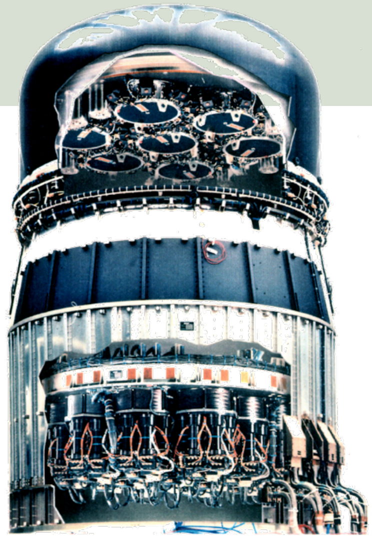
performance

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)



Cosmic diffuse X- and Gamma-Ray Background

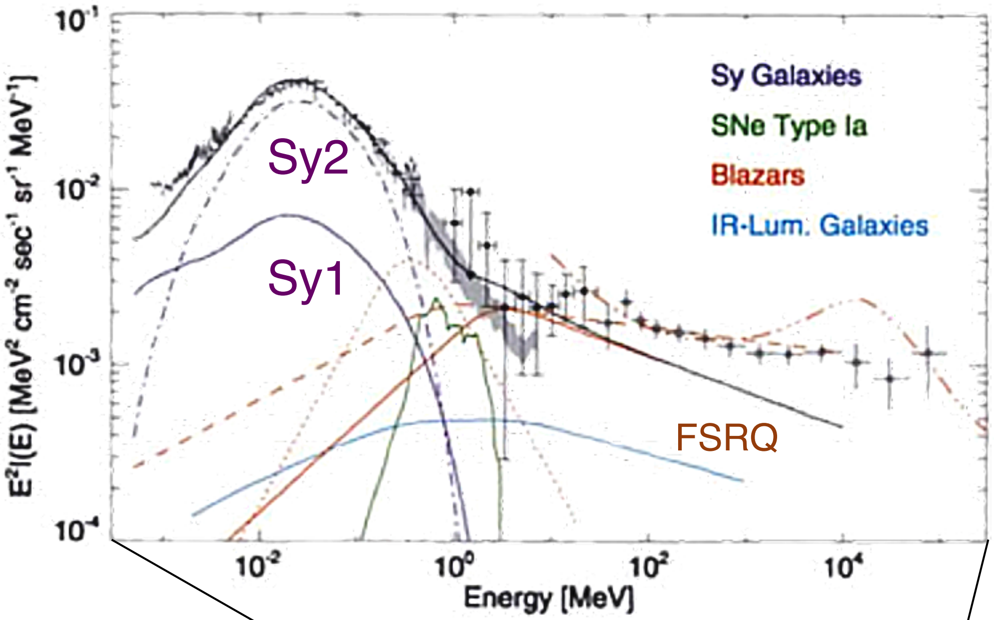


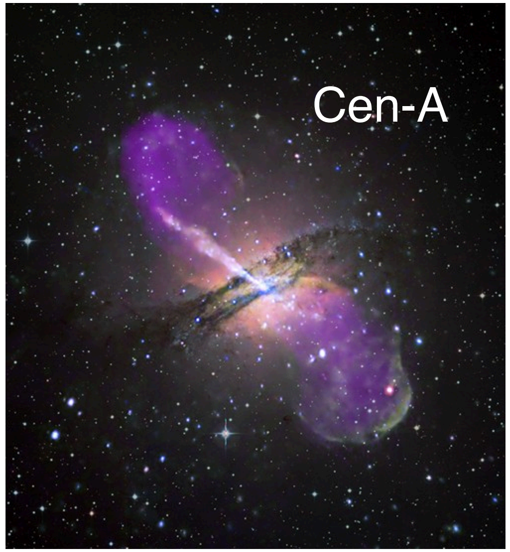


COMPTEL

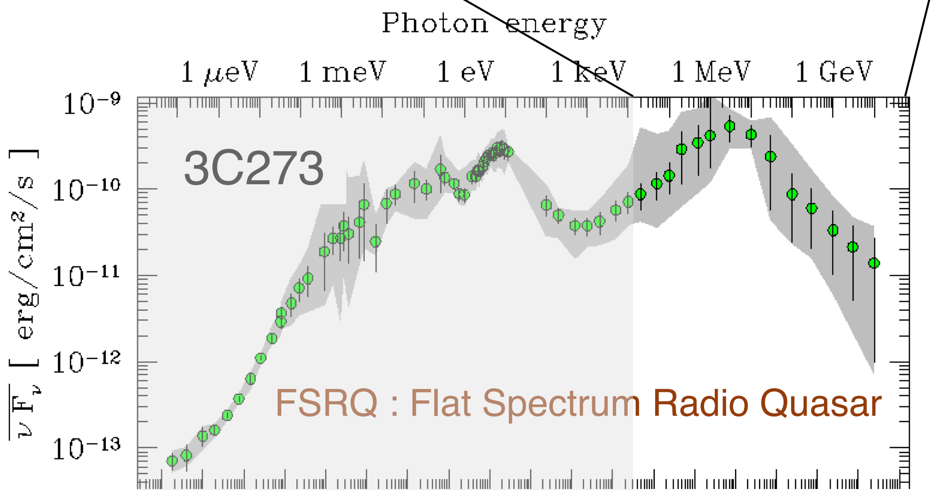
- no MeV bump
- transition from a softer to a harder component at ~ 5 MeV
- no deviation from isotropy within statistics

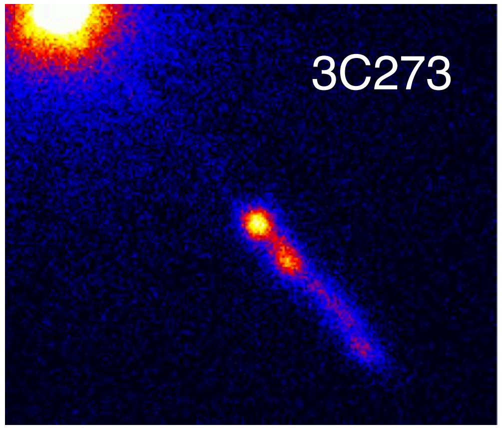
MeV background explained as unresolved AGN's



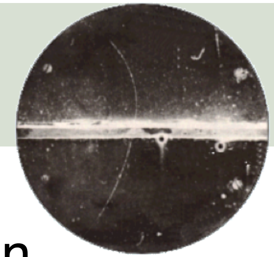


superposition of spectra from various classes of unresolved point sources
=> no need for antimatter domains with sizes D ≈ the observable Universe



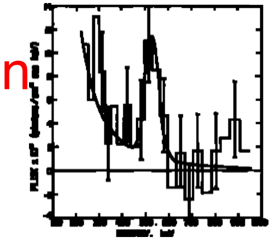


detecting galactic positrons

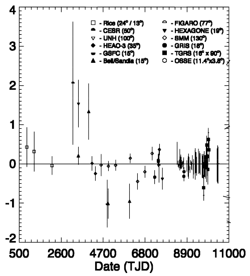


1970-1974 **Rice balloon** : detection of galactic e^-e^+ radiation

1977-1989 **balloon borne Ge spectrometers** : confirmation
correlation between measured flux and FOV

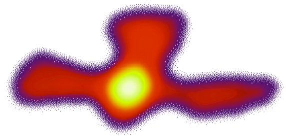


1979-1980 **balloons & (HEAO3)** : variability
the "Great Annihilator"

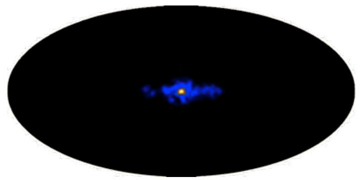


1981-1985 **SMM** : no variability

1991-1997 **GRO/OSSE** : first maps of GC region
"Great Annihilator" contested

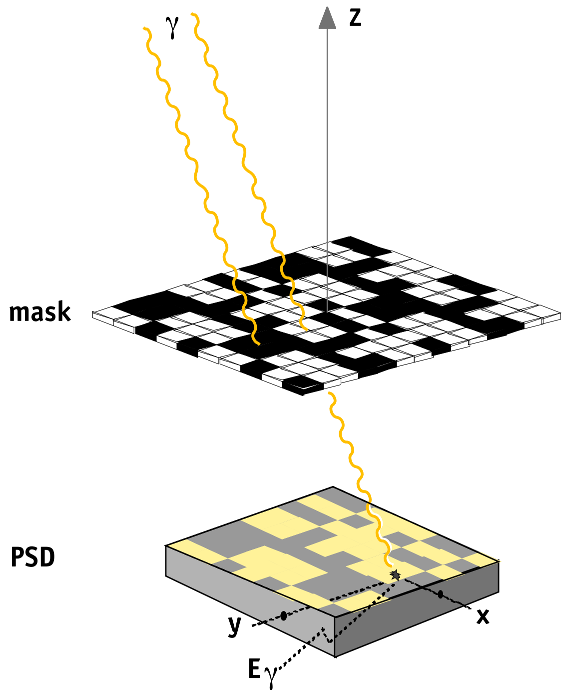


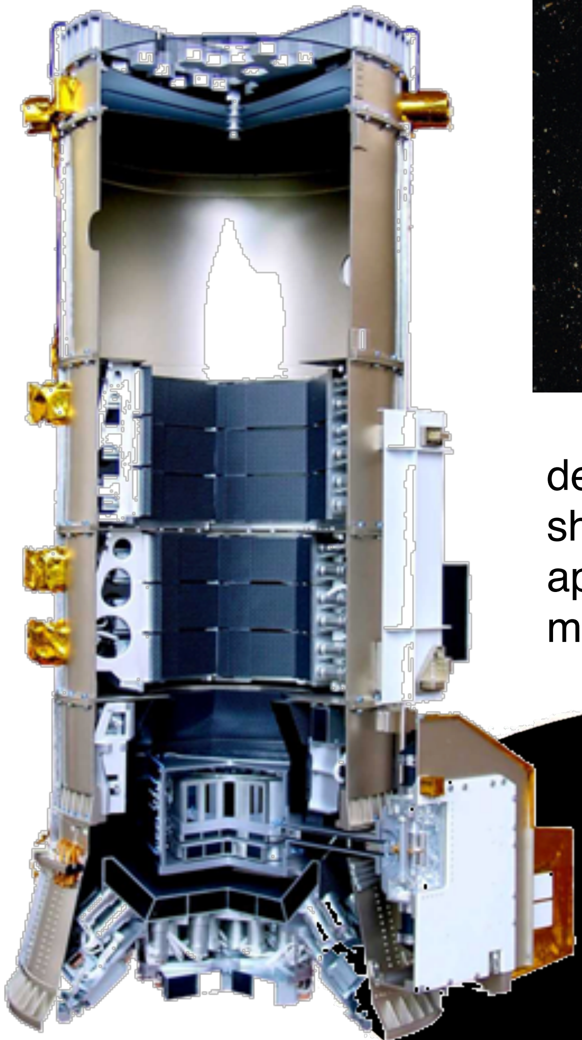
2002 - ... **INTEGRAL**

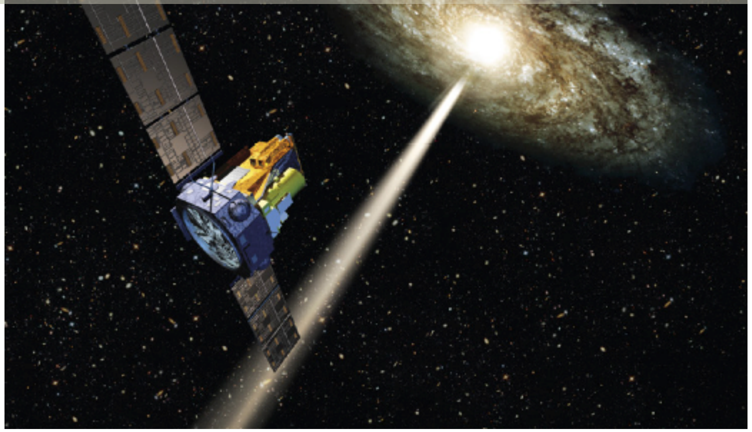


coded mask imaging

INTEGRAL/SPI







detectors	19 cryogenic Ge detectors
shield	600 kg BGO
aperture	W coded mask (30 mm)
mass	1230 kg

performance

Energy : 20 keV - 8 MeV

Field of viev: 16° (33°)

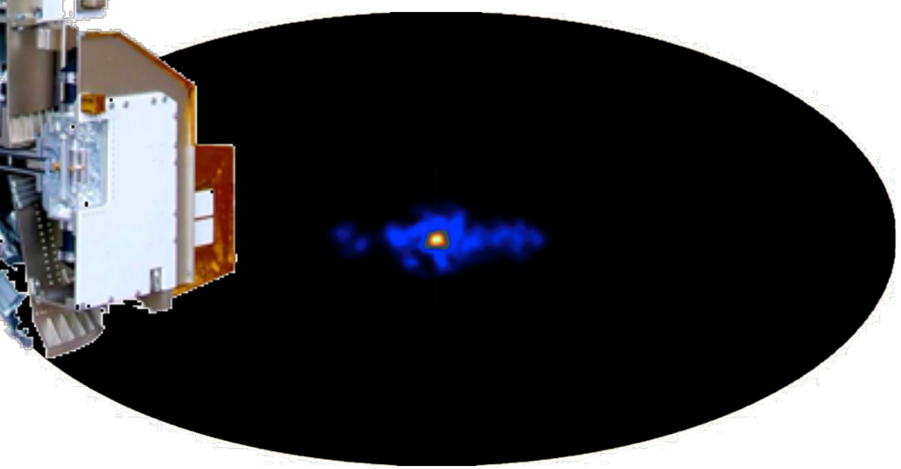
Angular resolution : 2°

$E/\Delta E \approx 500$

Principal objectives

nucleosynthesis and e^+e^- emission

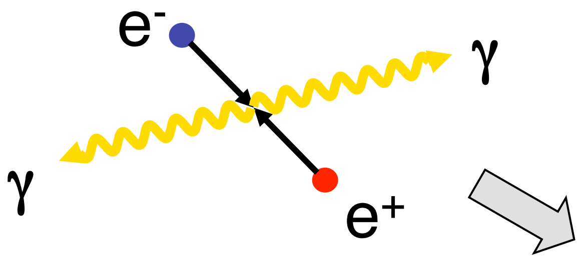
compact galactic/extragalactic objects

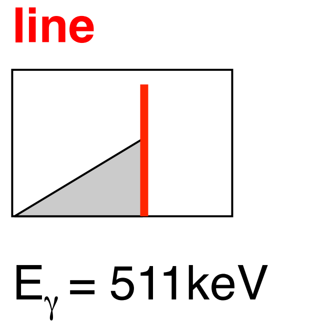


e+e- annihilation map (Skinner et al 2011)

annihilation of e^+ in the ISM

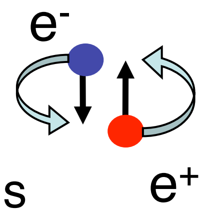
Direct annihilation



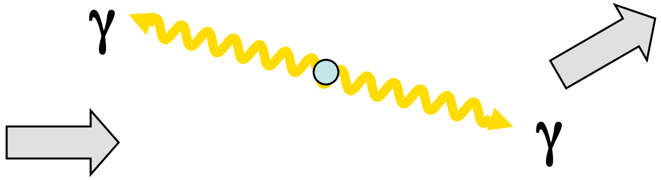


Positronium formation
$e^+ + e^- \rightarrow Ps + \gamma$ or
$e^+ + H \rightarrow Ps + H^+$

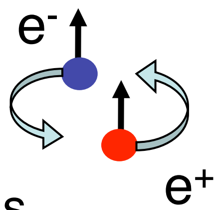
ParaPs 1/4



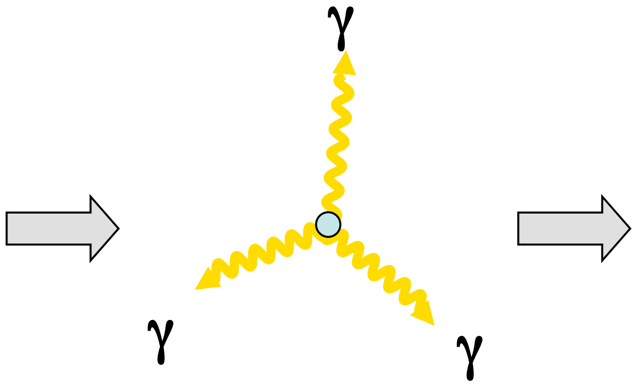
singlet, lt :1.3×10^{-10} s

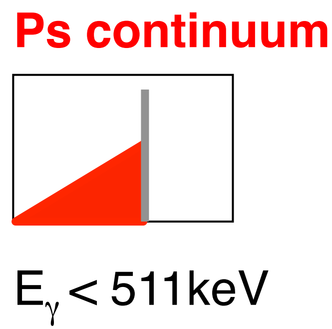


OrthoPs 3/4

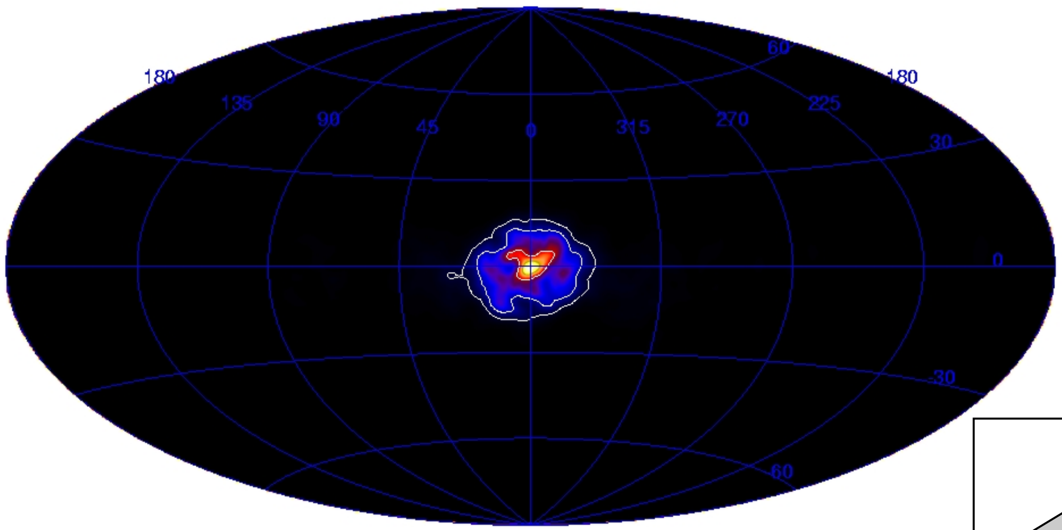


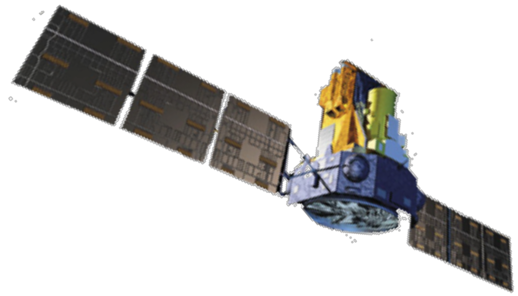
triplet, lt : 1.4×10^{-7} s

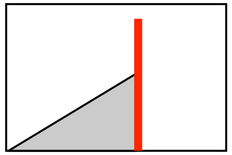




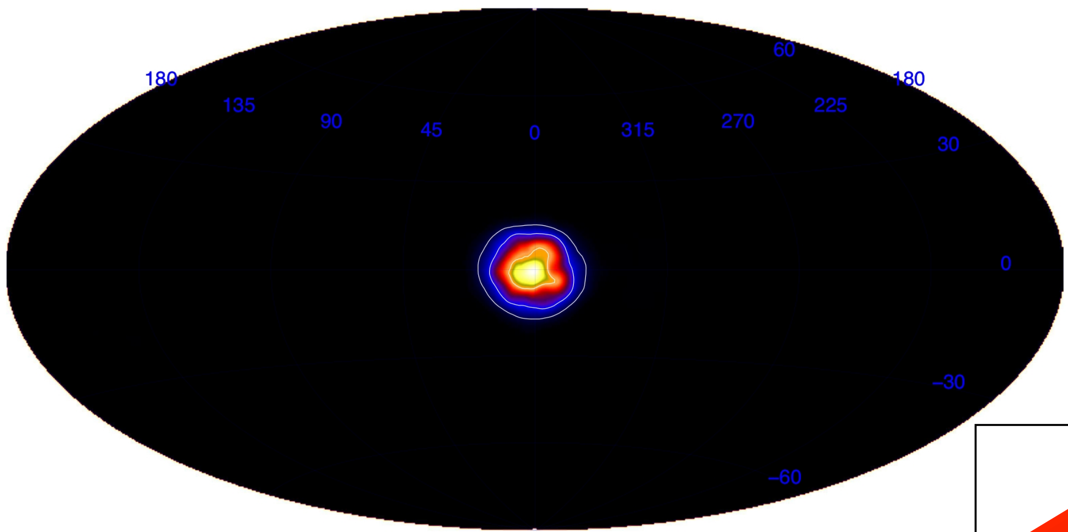
Imaging : 511 keV line and Ps continuum emission



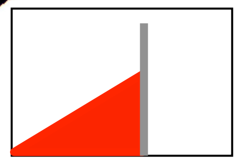




Knödlseder et al. (2005)



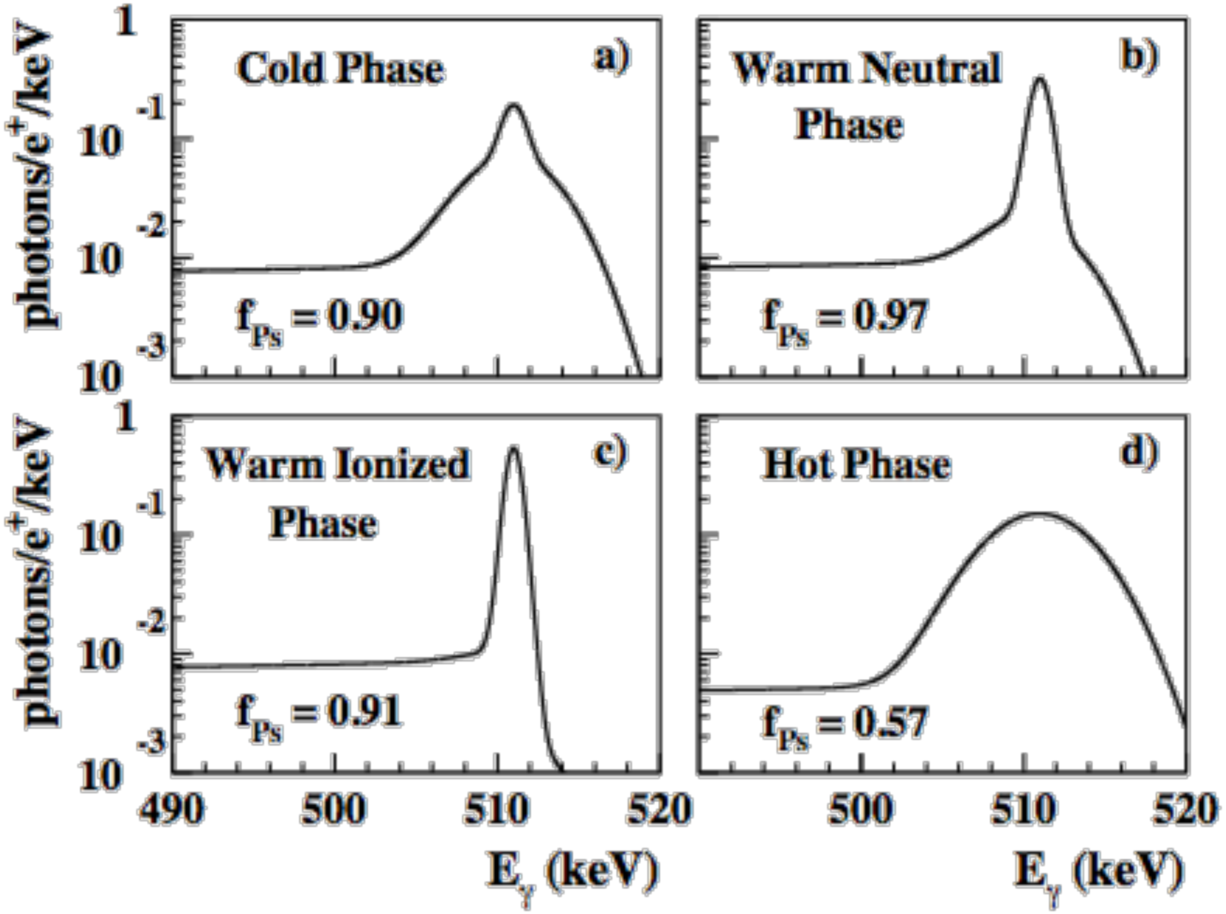
410–430, 447−465, and 490–500 keV



Weidenspointner et al. (2006)

line shape depends on annihilation medium

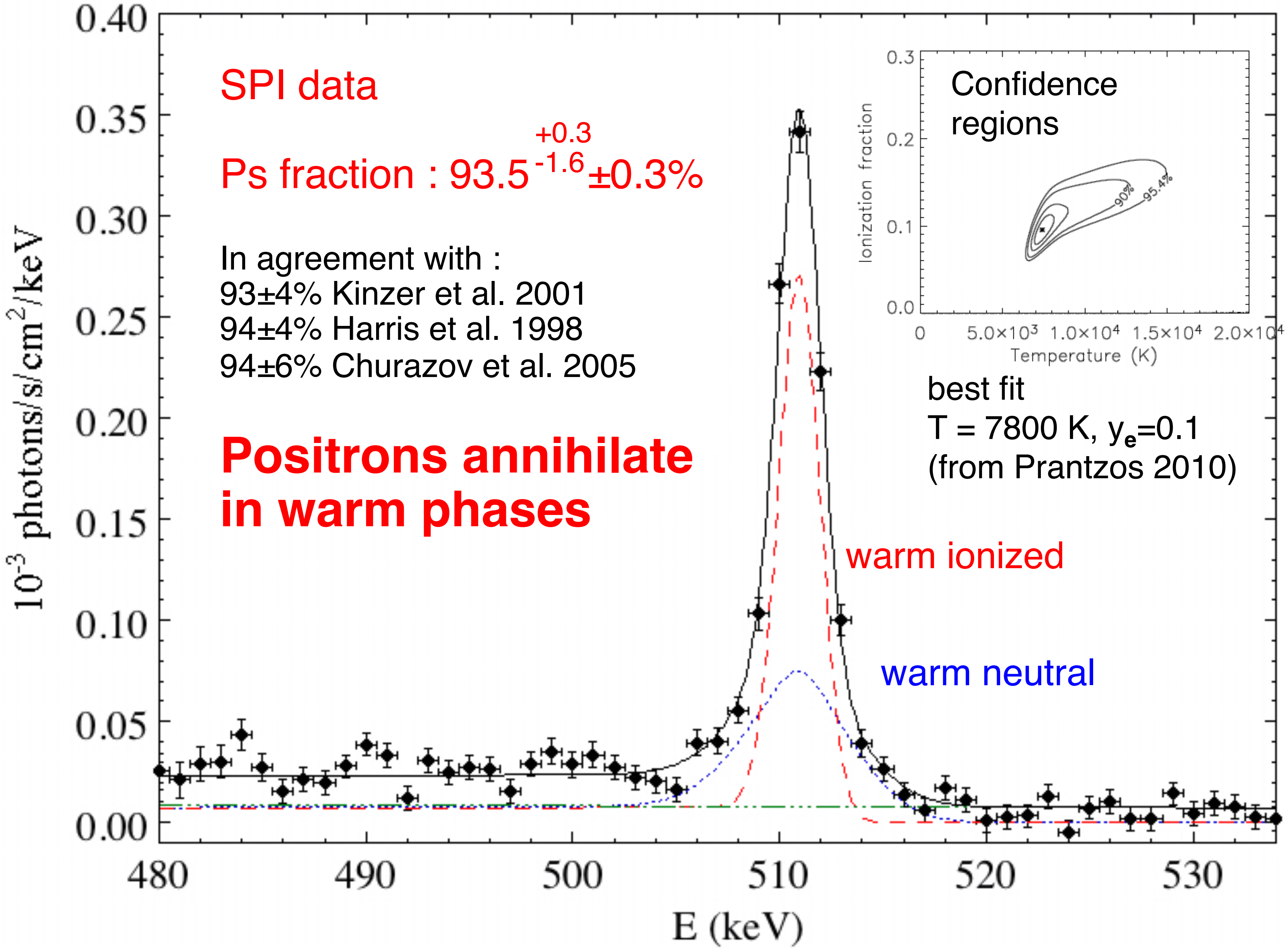
temperature and ionization fraction



V.Tatischeff (2008)

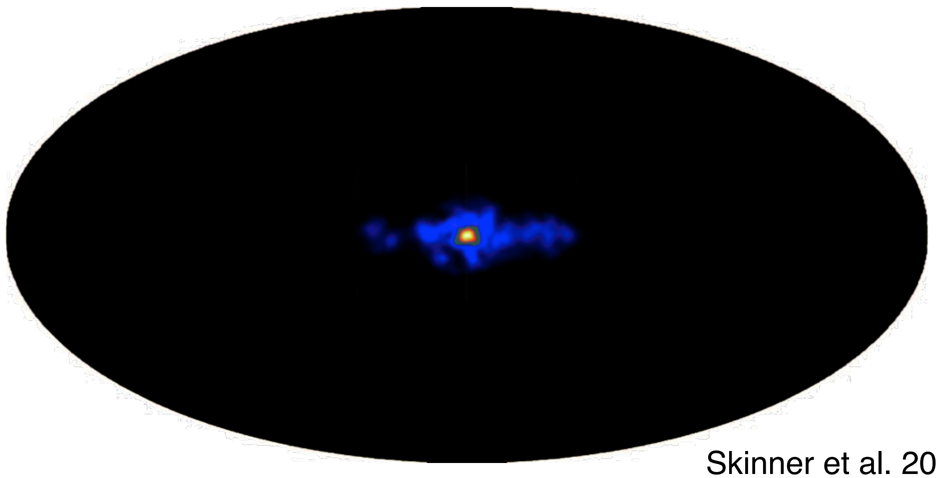
Spectroscopy : Fit of the phase fractions

Jean et al., 2005



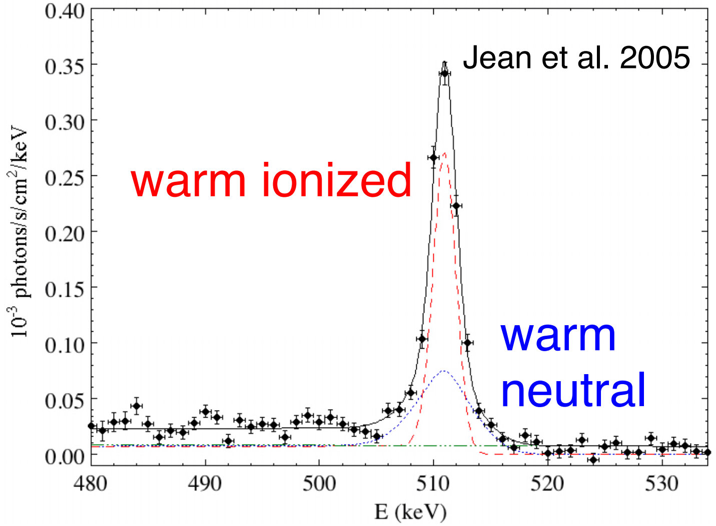
What we know (in a nutshell)

morphology



Skinner et al. 2011

spectroscopy



- **total flux ~ 2 · 10^{-3} γ/s/cm^{-2}**
- **narrow bulge** / wide bulge / disk -
- **bulge / disk = 1-3**
- **slight asymmetry**

- **no point sources,**
- **no fountain,**
- **no other source regions**

- **Positronium fraction : 93.5 %**
- **annihilate in warm phases**

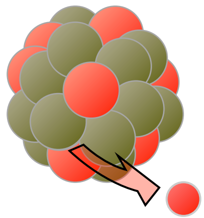
How to produce 2×10^{43} e^+/s in our Galaxy

Annihilation rates : (source at GC)	$(1.5 \pm 0.1) \times 10^{43}\ s^{-1}$ in the bulge $(0.3 \pm 0.2) \times 10^{43}\ s^{-1}$ in the disk	
β^+ isotopes	SNe, novae … $X\text{-}p \rightarrow X\text{-}n + e^+ + \nu_e$	$E_{e+} \sim 1$ MeV
π^+ decay	CR interactions with ISM $p + p \rightarrow p + n + \pi^+$ and $\pi^+ \rightarrow \mu^+ \text{->} e^+$	$E_{e+} \sim 10\text{-}100$ MeV
e^+e^- pair production	accretion disks & jets $\gamma + \gamma \rightarrow e^+ + e^-$ pulsar magnetosphere $\gamma + \gamma \rightarrow e^+ + e^-$	$E_{e+} \leq 1$ MeV $E_{e+} \sim 1\text{-}1000$ GeV
exotic processes	e.g. dark matter, … $dm + dm \rightarrow e^+ + e^-$	$E_{e+} \sim$? MeV

origin of galactic e^+ is still unknown

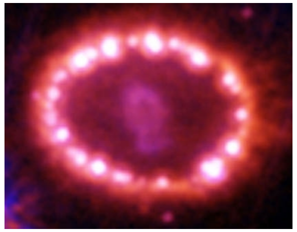
the origin of the galactic e^+ : two grand families

Cosmic Explosions
radioactive decays



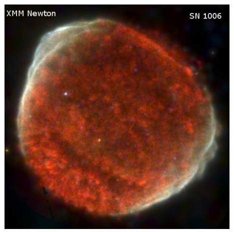
gravitationnal collaps

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



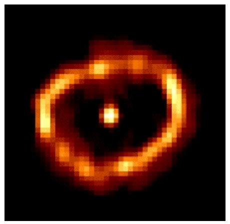
thermonuclear exlosions

SN de type Ia

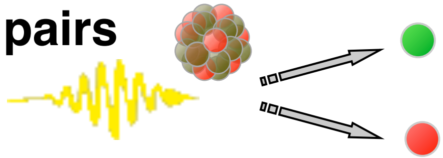


Thermonuclear runaways

Novae
X-ray bursters

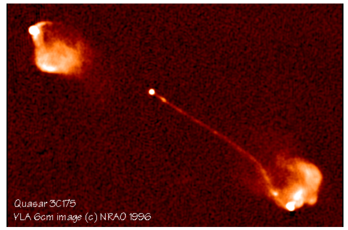


Cosmic accelerators
production of e^-e^+ pairs



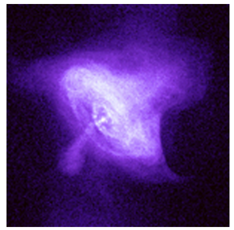
Accretion on compact objects

Binaries
Micro-quasars



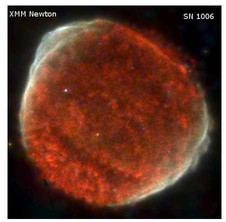
Rotating neutron stars

Pulsars
Magnetars



Explosions and shocks

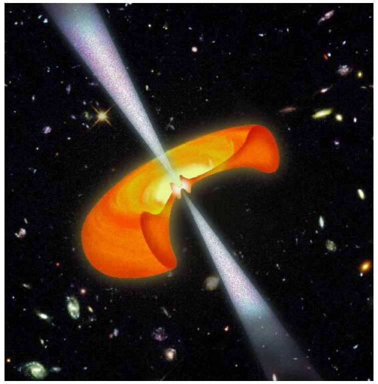
gamma-ray bursts
supernova remnants
Interaction CR/ISM



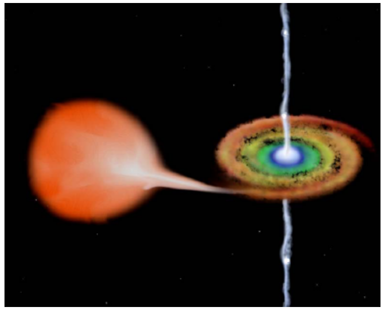
+ "light" dark matter ...

The source of galactic positrons

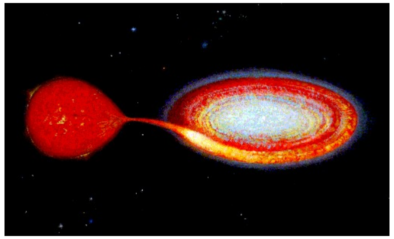
revealed by the slight asymmetry in the e^+e^- distribution ?



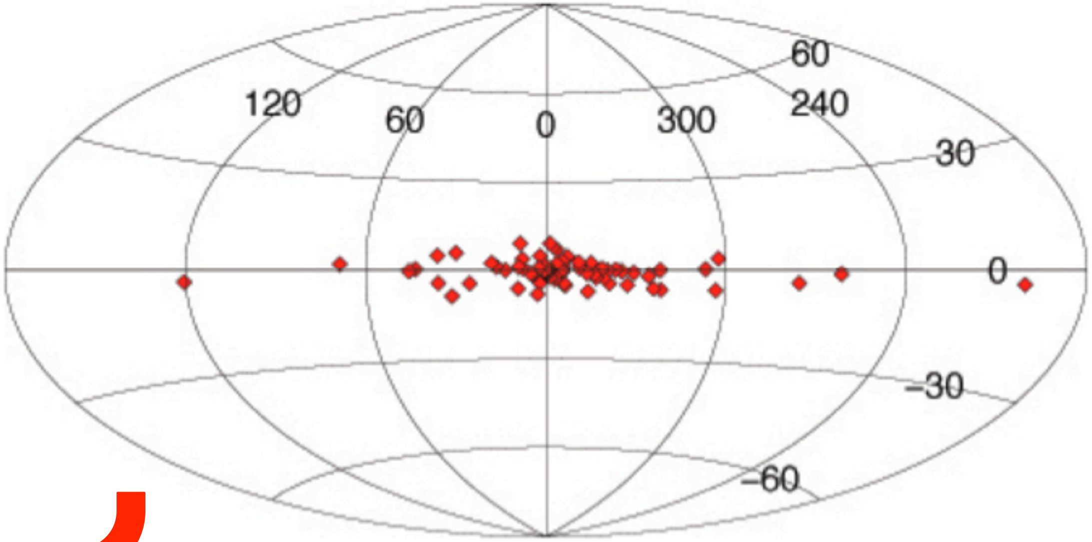
GRB/Hypernovae



XRB
μQSO



SN Ia, novae



Weidenspointner et al. (2008)

likely e^+ origin : Type 1a 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	(7-20) x 10^{-6}	(1-4) x 10^{-3}

Woosley 1997; Woosley & Weaver 1994

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

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

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

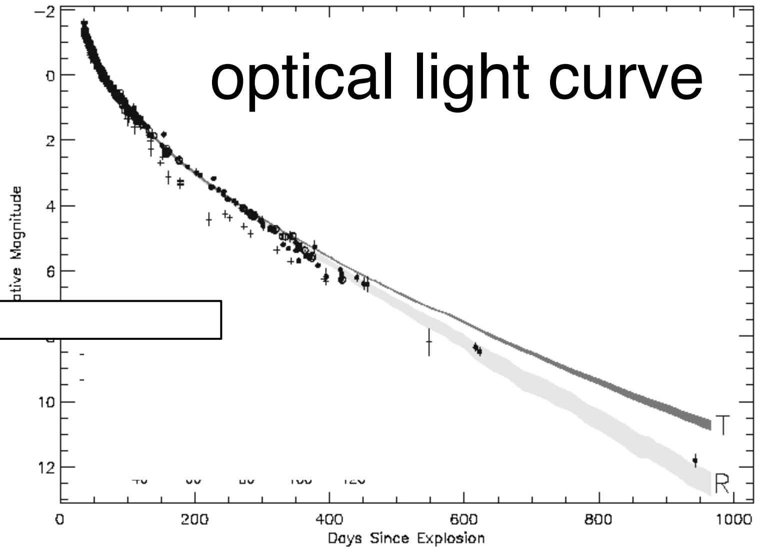
=> **$R_{e+} < 3.7\ 10^{43}\ s^{-1}$.**

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

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

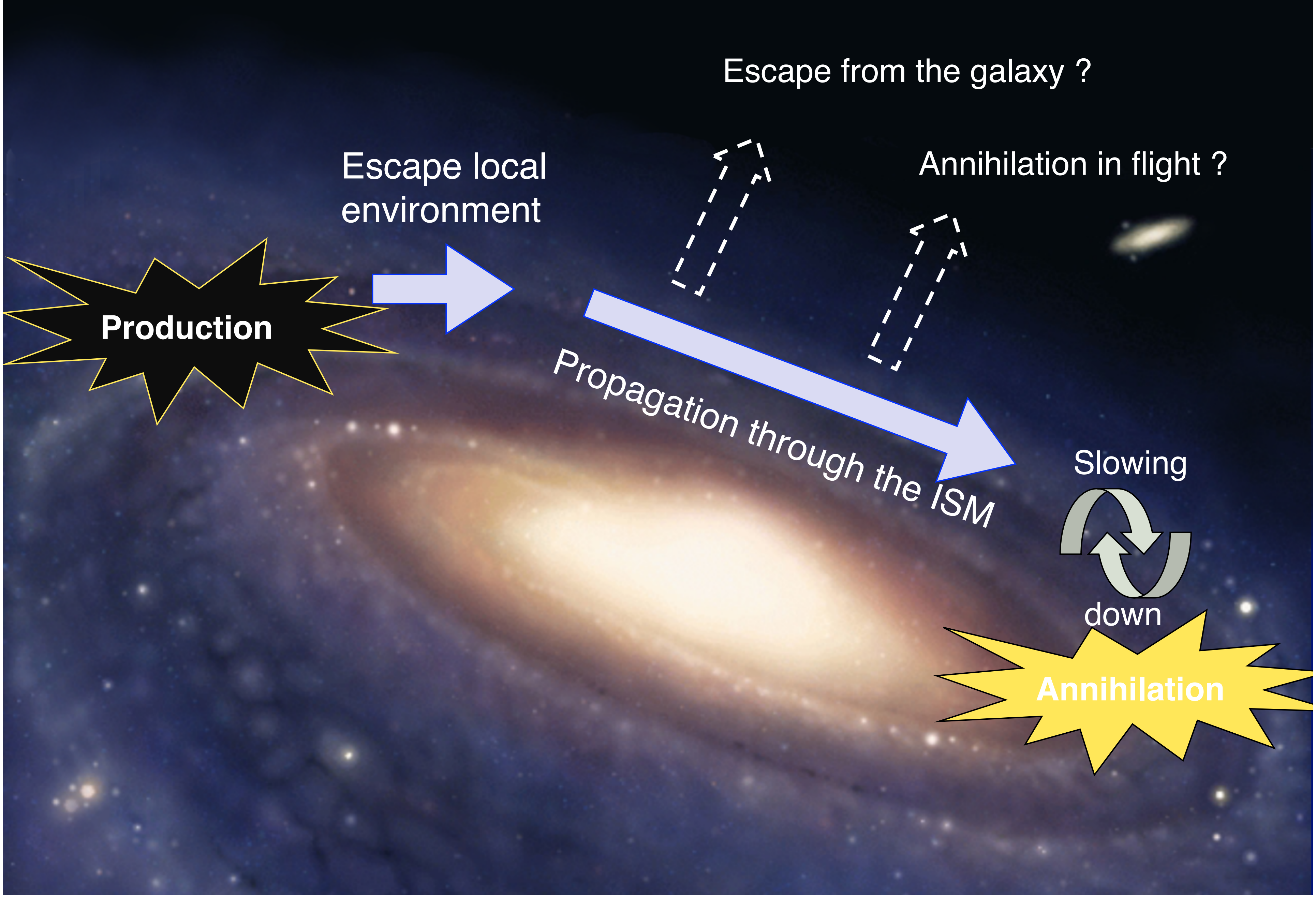
Although SNeIa belong to the old population their distribution seems to give $(B/D)_{SNeIa} < 1$

=> how much heat -> envelope
=> how much e+ escape ?



Milne, The & Leising, 2001

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



Antimatter astronomy ***is*** MeV astronomy

MeV astronomy (100 keV-10 MeV) allows to observe both baryonic and leptonic antimatter in the Universe

➔ test baryon symmetric Univers to cosmological distances

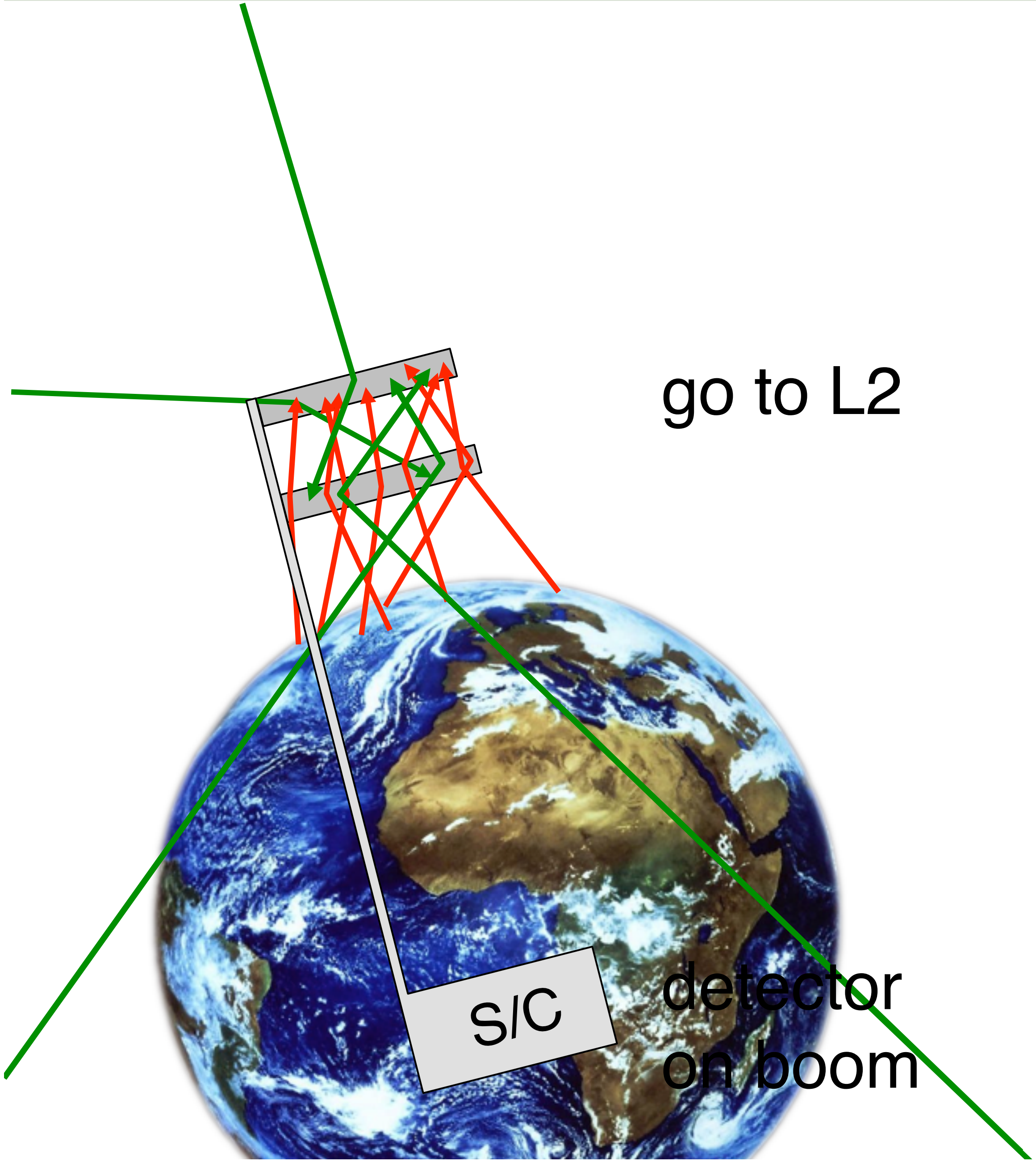
➔ annihilation of the lightest charged leptons that should be at the endpoint of any annihilation process.

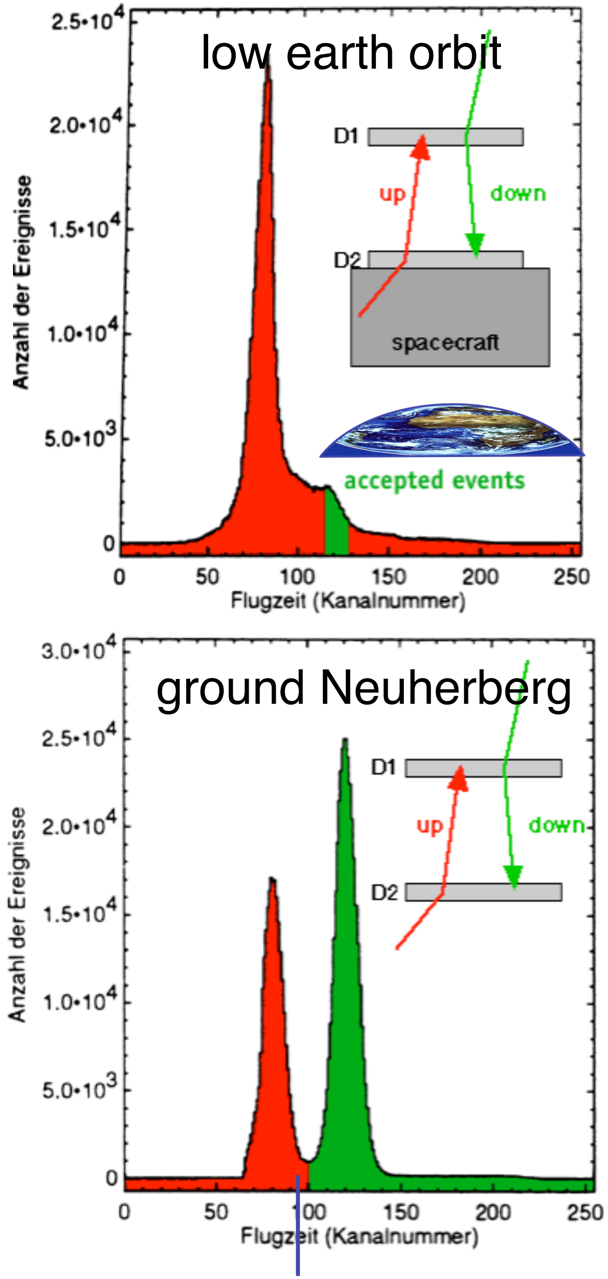
✚ gamma-ray bursts, supernovae, radioactivities, AGN's ...

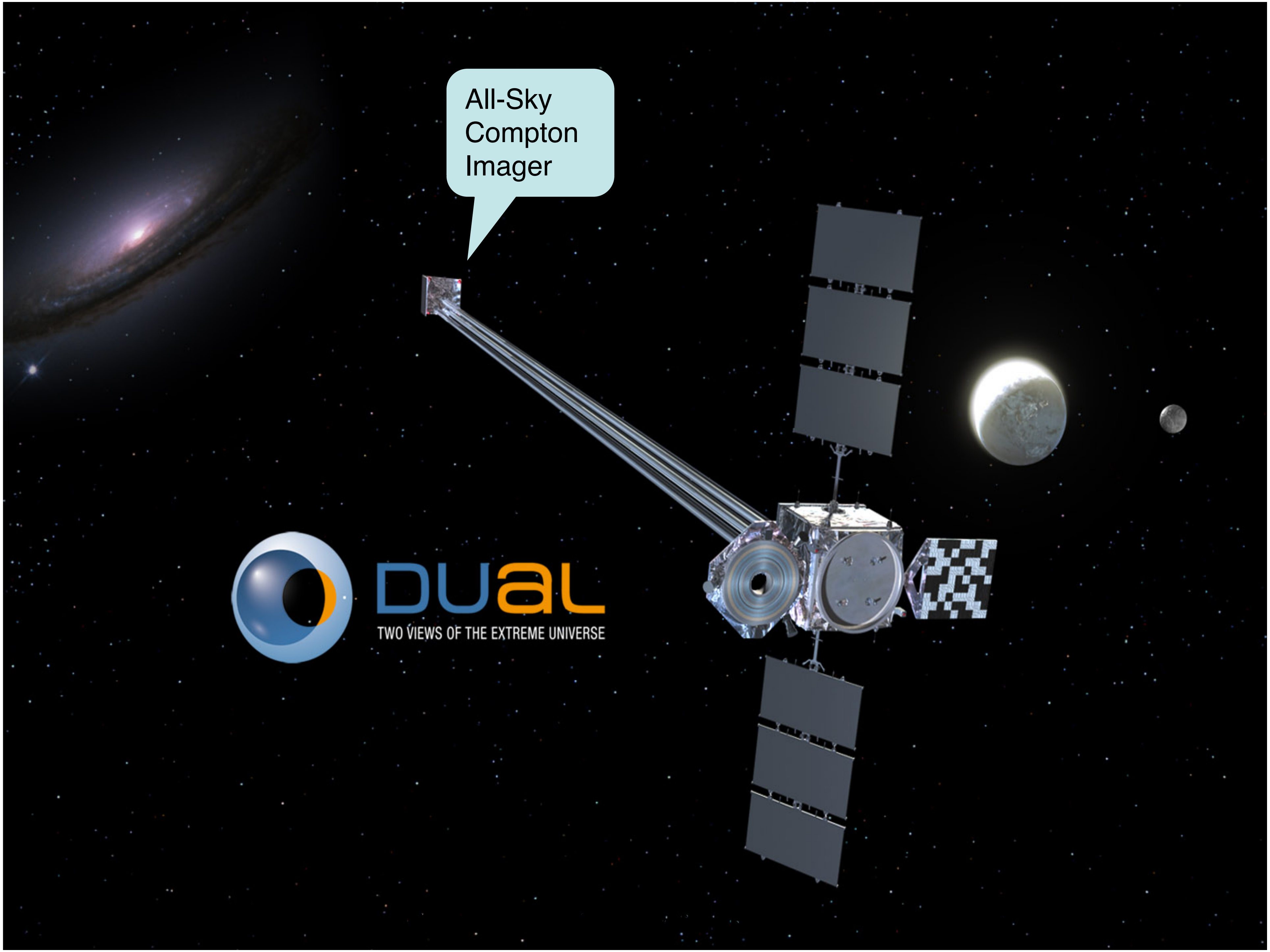
*"A new **dedicated satellite MeV γ-ray detector is required** to clarify the observational situation and to determine the flux and spectrum of γ-rays in this critical energy range. The satellite should be **light-weight and contain only the MeV detector** and no other experiments in order to minimize the mass in which cosmic rays can induce intrinsic MeV photon production. It should be also flown in a region **far from the Earth's radiation belts**, since such radiation induces intrinsic MeV photon production within the satellite and detector."* Stecker, 2002

yet, there is no new gamma-ray mission on the horizon ! why ?

Background reduction : solid angle option






All-Sky Compton Imager
DUAL
TWO VIEWS OF THE EXTREME UNIVERSE

[redacted]

e^+ origin : dark matter

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

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

light dark matter (Boehm et al., 2003)

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

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

distribution in the bulge only