SPECTRAL ANALYSIS OF THE GALACTIC POSITRON ANNIHILATION EMISSION

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- Introduction
- SPI/INTEGRAL data analysis
- Models of the annihilation spectrum
- Fit of the phase fractions
- Fate of positrons in the bulge
- Discussion on the origin of positrons

- # Introduction

Production of e^+ in the Galaxy

- 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 $\pi^+ \rightarrow \mu^+ \rightarrow e^+$	-> $E_{e+} \sim 10\text{-}100$ MeV
- e^+e^- pair production	-> accretion disks & jets $\gamma + \gamma \rightarrow e^+ + e^-$	-> $E_{e+} \leq 1$ MeV
	-> pulsar magnetosphere $\gamma + \gamma \rightarrow e^+ + e^-$	-> $E_{e+} \sim 1\text{-}1000$ GeV
- exotic processes	-> e.g. dark matter, … $dm + dm \rightarrow e^+ + e^-$	-> $E_{e+} \sim ?$ MeV

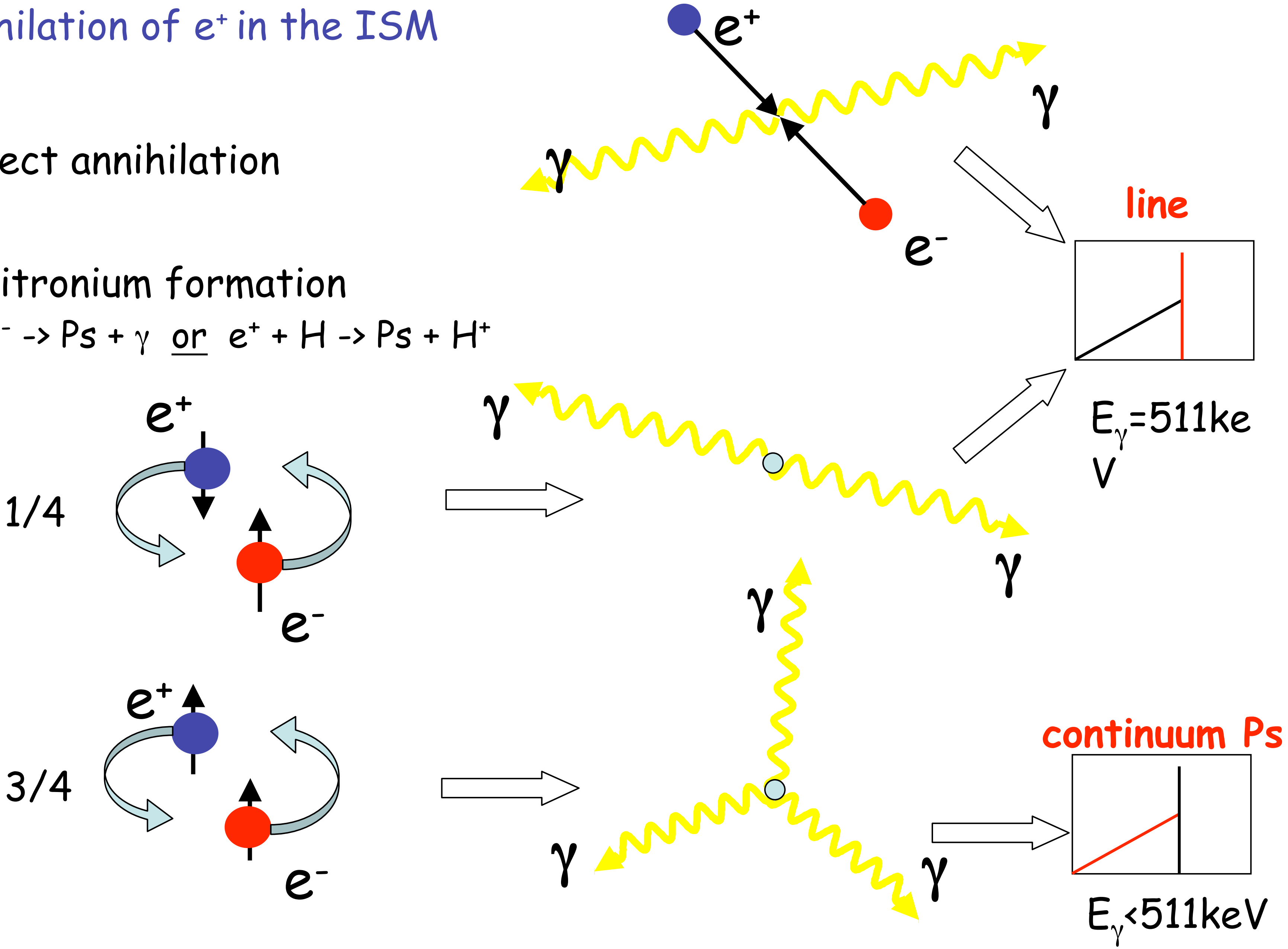
Origin of galactic e^+ is yet unknown

Annihilation of e^+ in the ISM

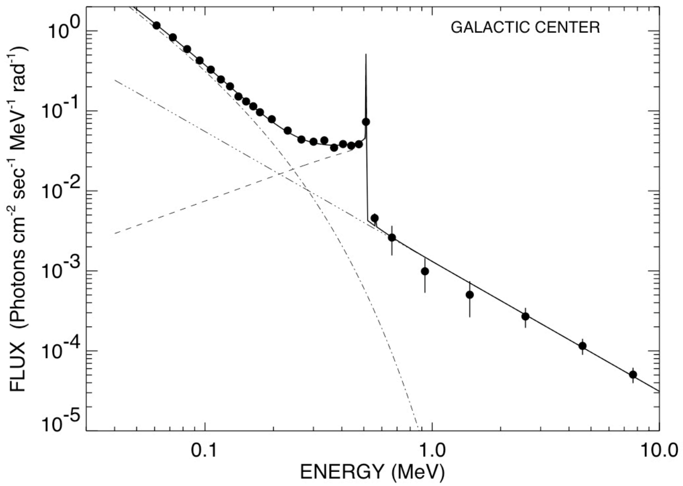
- Direct annihilation

- Positronium formation

$e^+ + e^- \rightarrow Ps + \gamma$ <u>or</u> $e^+ + H \rightarrow Ps + H^+$



History of observations



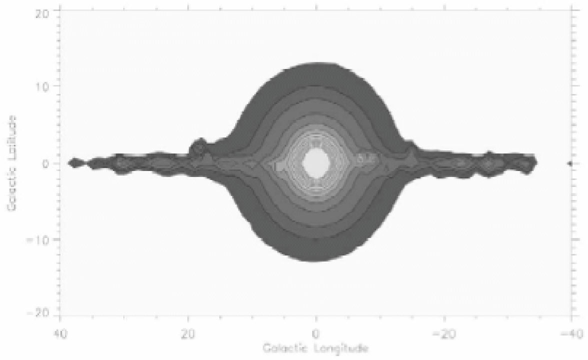
Kinzer et al., 2001

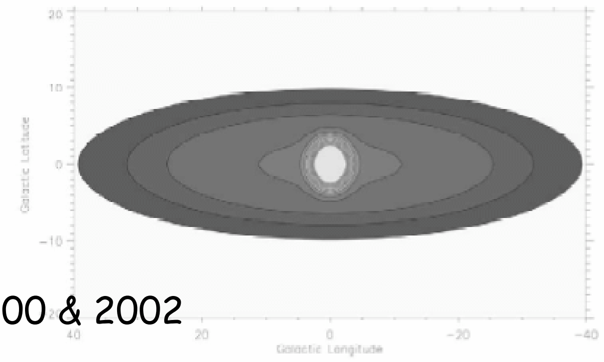
- 1970-1974 balloon borne NaI spectrometer (Rice)
- 1977-1989 balloon borne Ge spectrometers
  -> correlation between measured flux and FOV (Albernhe et al., 1981)
- 1979-1980 HEAO3 -> variability (Riegler et al., 1981)
  -> revisited by Mahoney et al., 1994
- 1981-1985 SMM
- 1991-1997 OSSE -> First maps
- 1995-1997 TGRS

GC flux ~ 10^{-3} γ s^{-1} cm^{-2}

f_{Ps} = (93 ± 4)%

Bulge to disk flux ratio: B/D ~ 0.2-3.3





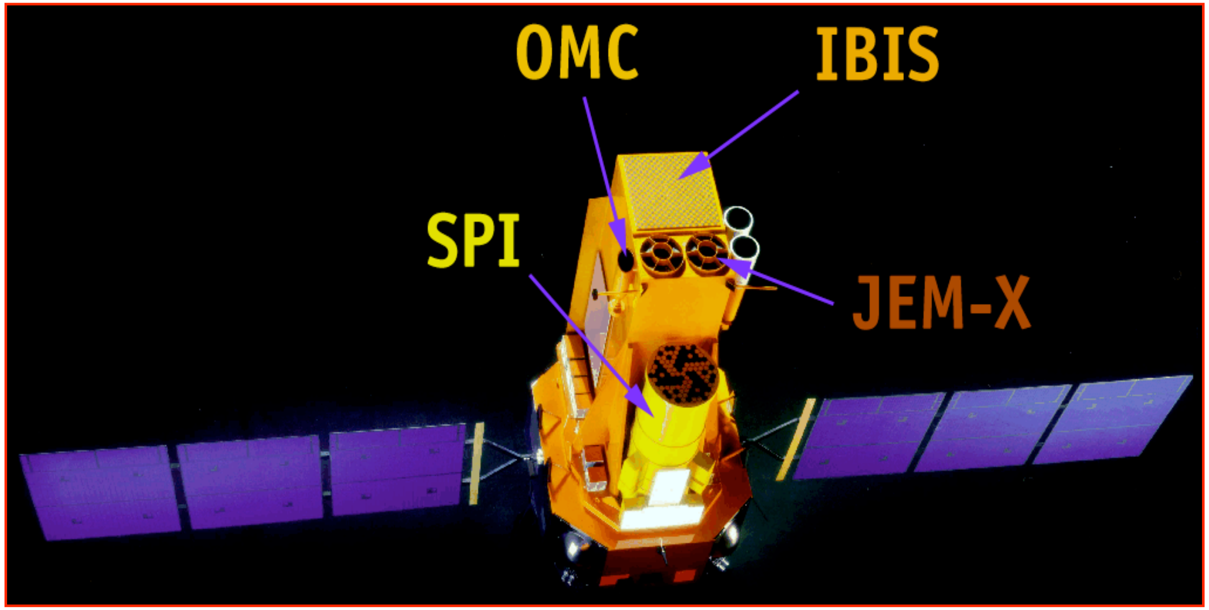
Milne et al., 2000 & 2002

- SPI data analysis

Observation with SPI/INTEGRAL

INTEGRAL

ESA's INTErnational Gamma-Ray Astrophysics Laboratory



Launch : 17 october 2002

Mission duration : 2008 (+?)

Orbit : 72 h, excentric

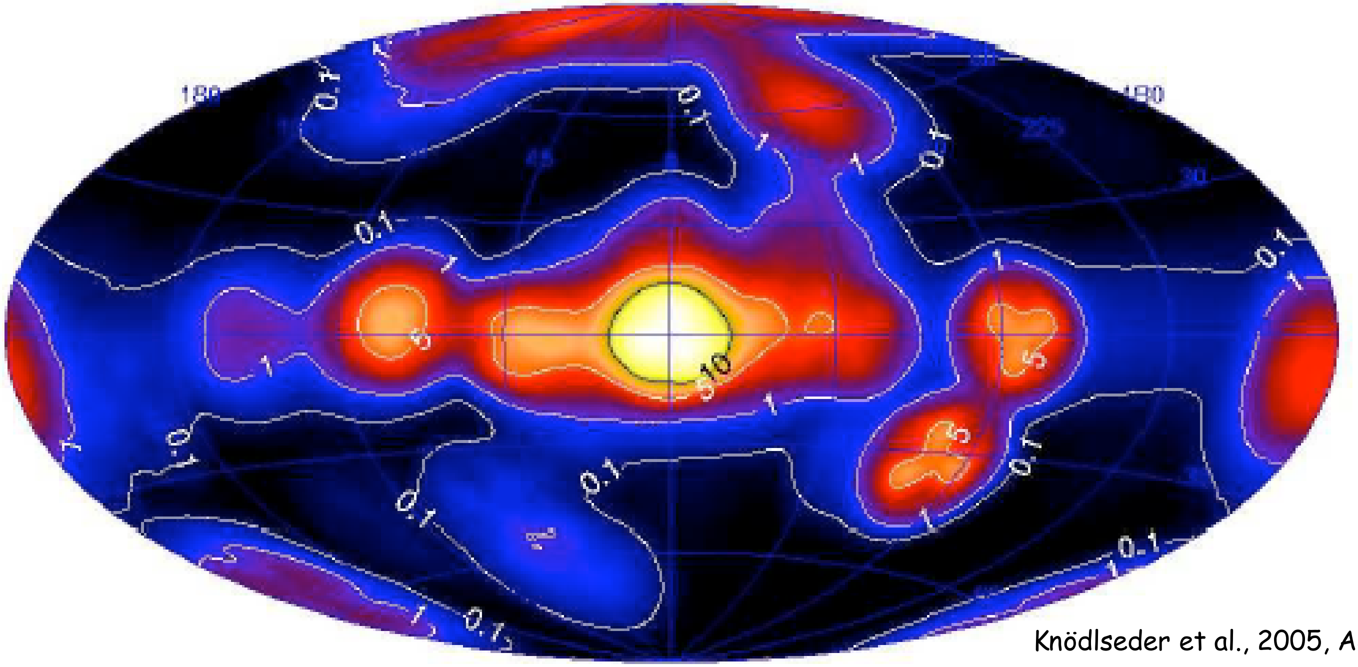
IBIS : Imager on Board the Integral Satellite	15 - 10000 keV, 12', R ≈ 12
SPI : SPectrometer onboard Integral	20 - 8000 keV, 2.5°, R ≈ 500
JEM-X : Joint European Monitor for X-rays	3 - 35 keV, 3', R ≈ 10
OMC : Optical Monitoring Camera	550 nm (V band), 6"

• SPI data analysis

Imaging the annihilation emission => spatial distribution of the sources
Spectroscopy => $f_{Ps} = N_{Ps}/N_{ann}$ and line shape => in which medium e^+ annihilate

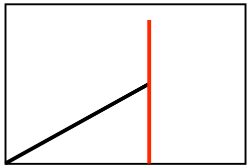
- December 10, 2004 public INTEGRAL data release
- Total exposure time : 15.3 Ms after filtering (flares, end of orbits…)
- Relatively uniform exposure for $|l|<50^\circ$ and $|b|<15^\circ$.

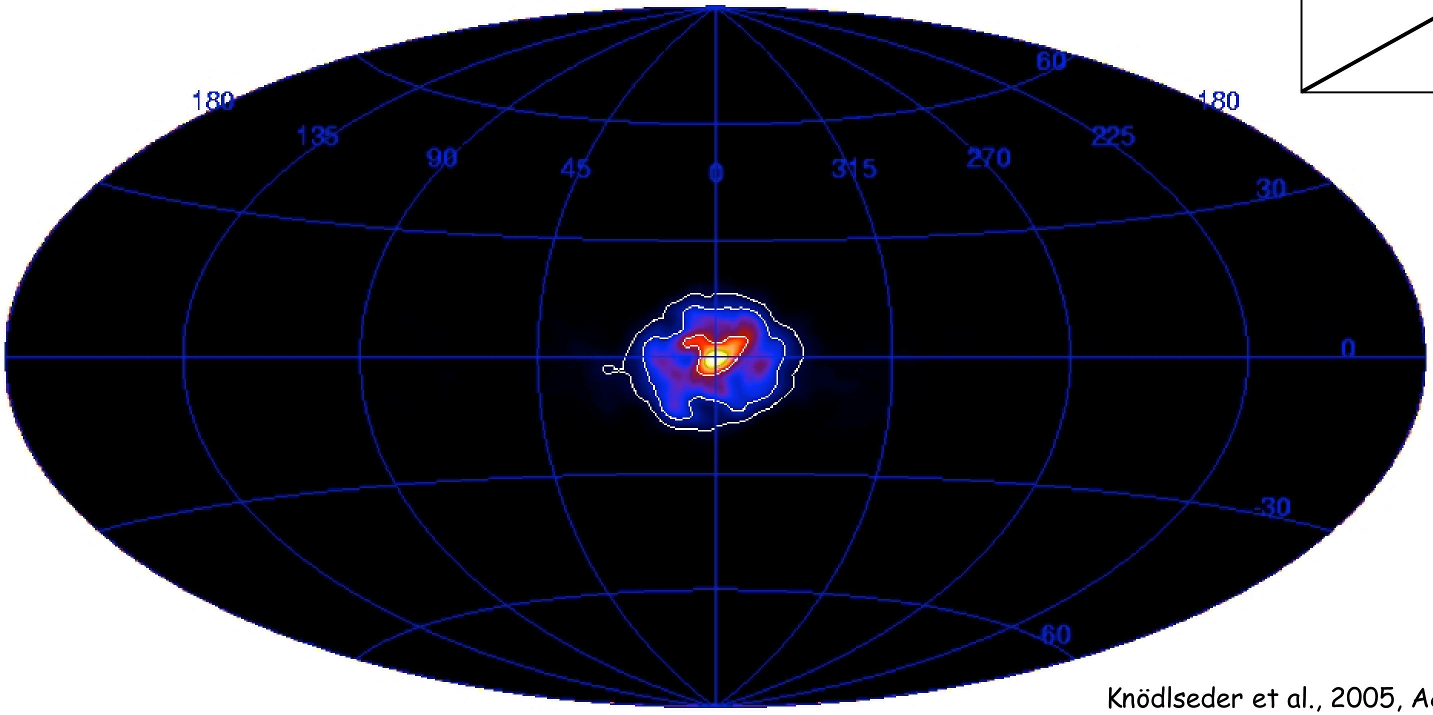
Exposure map



Knödlseder et al., 2005, A&A in press

The all-sky distribution of the 511 keV line emission





Knödlseder et al., 2005, *A&A in press*

Morphological analysis by model fitting :

- Bulge : 2D Gaussian shaped emission : ~8°x7° FWHM

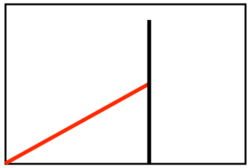
  Flux = $(1.09 \pm 0.04)\ 10^{-3}\ \gamma/s/cm^{-2}$

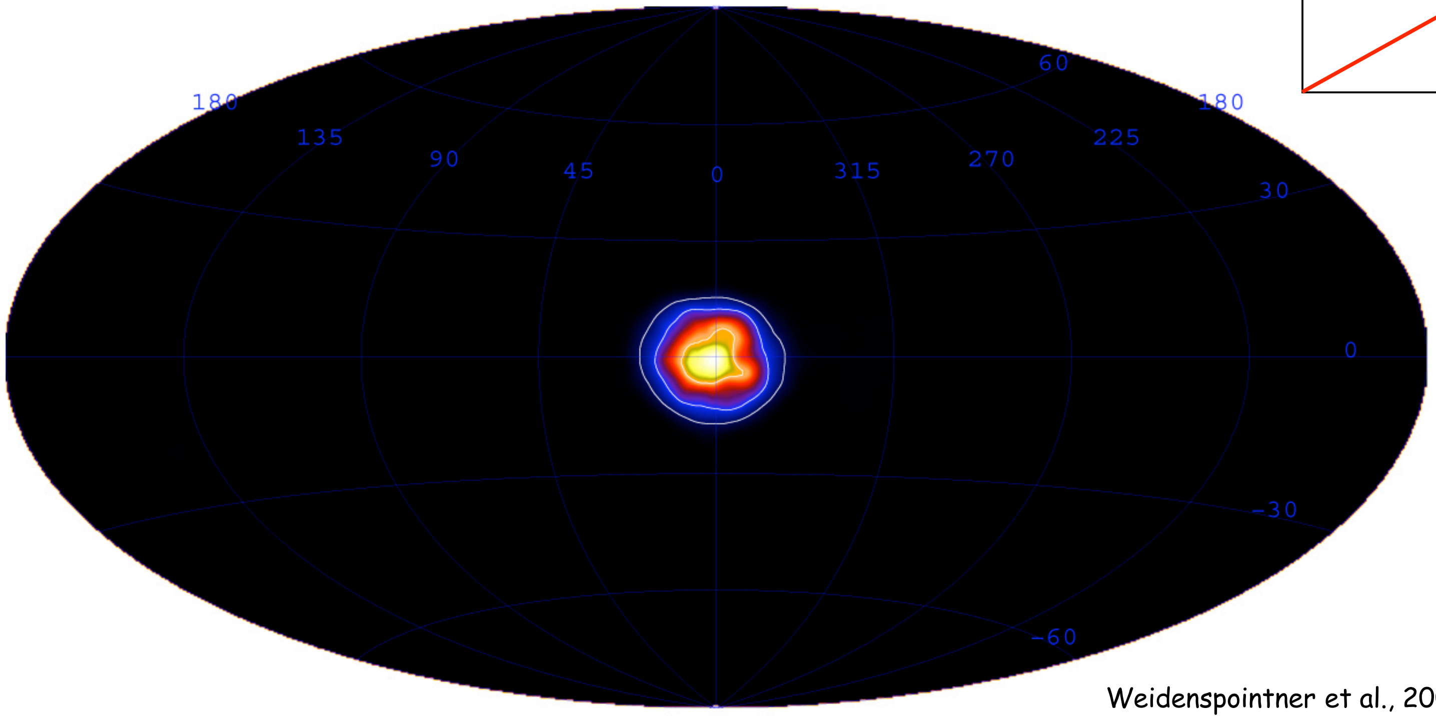
- Galactic disk : emission detected (~3-4σ)

  Flux ~ 4-6 $10^{-4}\ \gamma/s/cm^{-2}$

  can be attributed to e^+ produced by ^{26}Al & ^{44}Ti

The all-sky distribution of the OrthoPs continuum emission





Weidenspointner et al., 2005, submitted.

Intervals : 410-430, 447-465 and 490-500 keV

Morphological analysis by model fitting :

- emission detected at ~10σ.
- 2D Gaussian shape : ~8° FWHM compatible with the 511 keV distribution

Morphological analysis

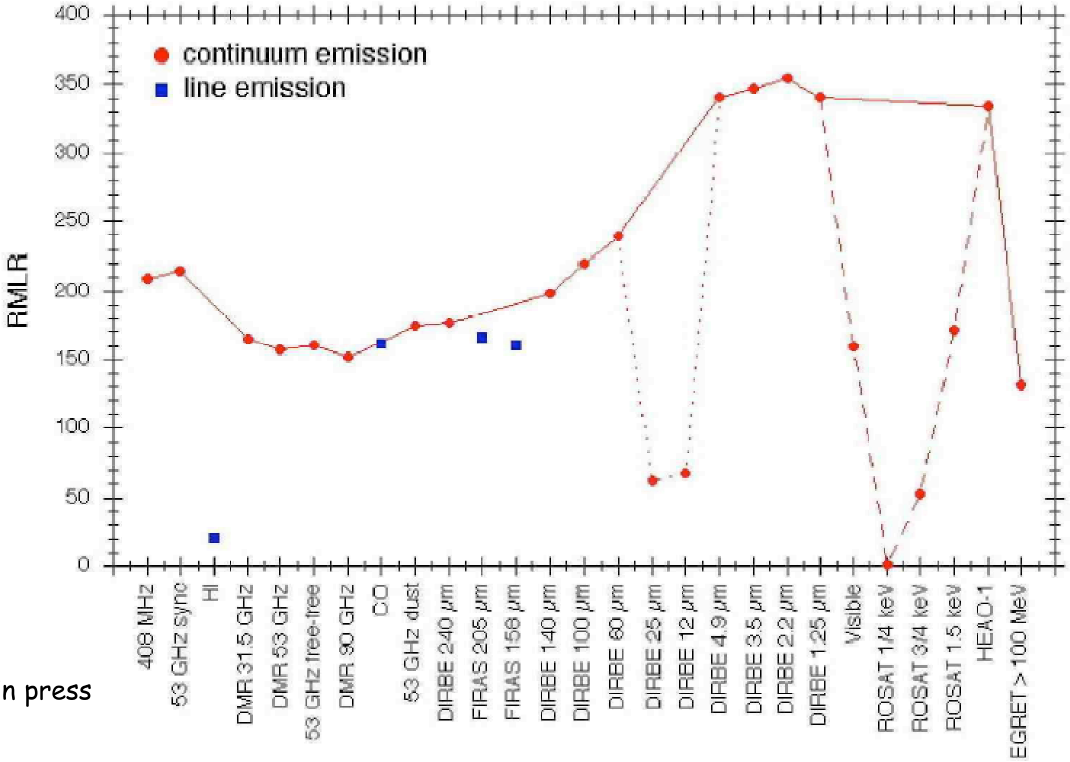
- Bulge to disk flux ratio

  B/D ~ 1-3

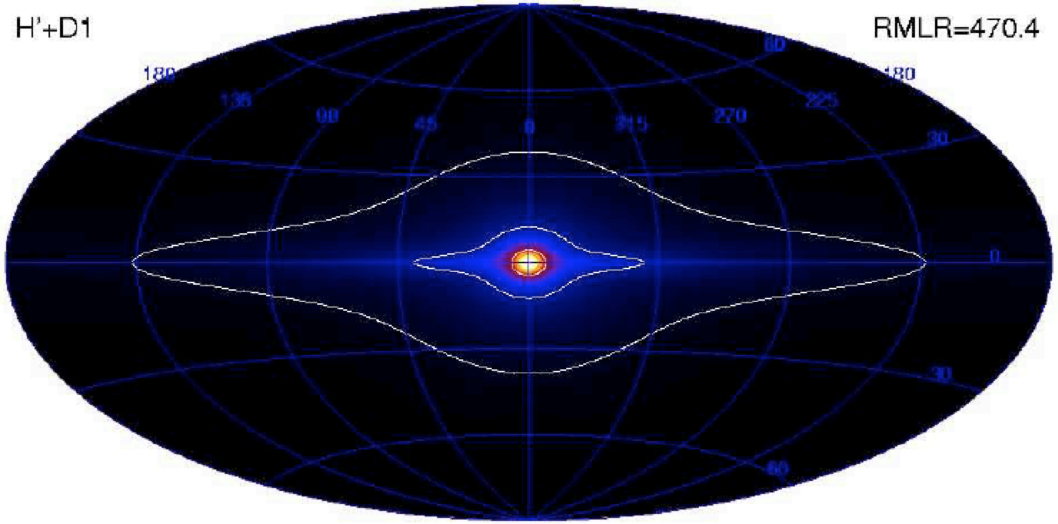
- Bulge to disk luminosity ratio

  B/D ~ 3-9

- Correlation with tracers
  & galactic distributions



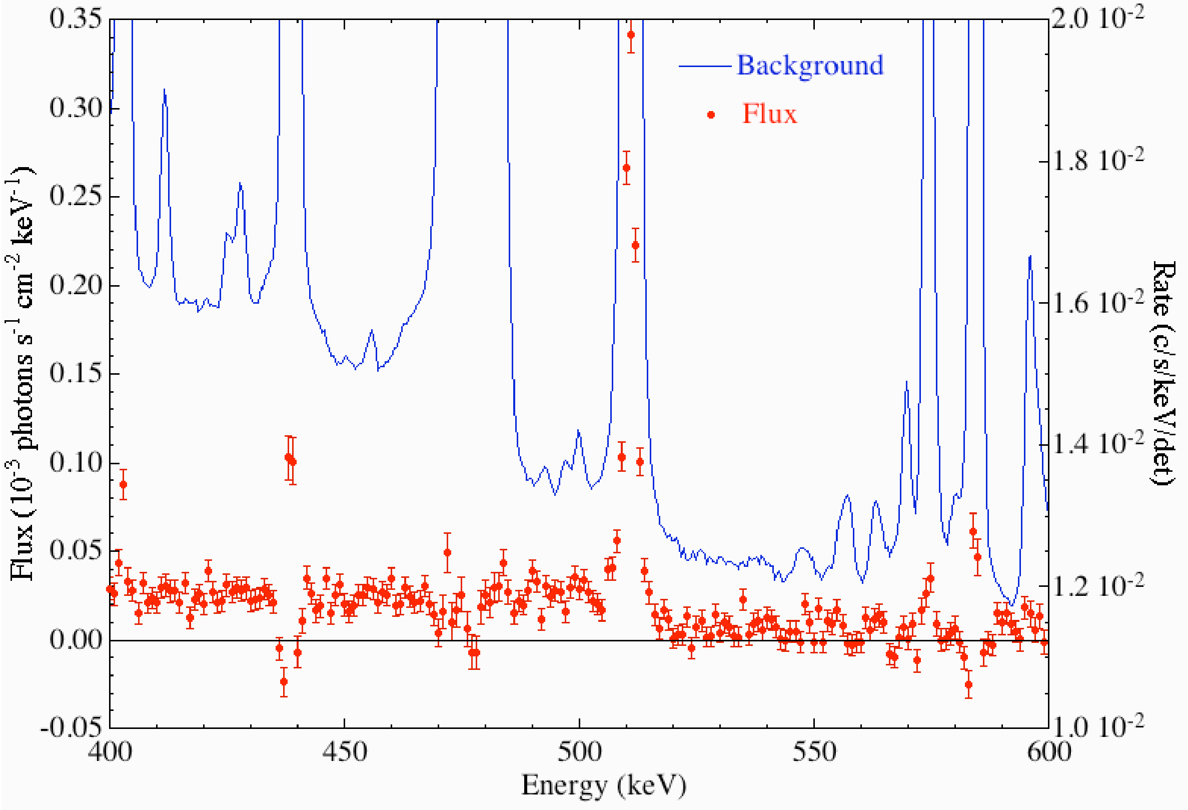
Knödlseder et al., 2005, A&A in press



old stellar population favored

Spectral analysis of the annihilation emission

- Spectrum extracted by model fitting assuming a 8°x7° Gaussian distribution



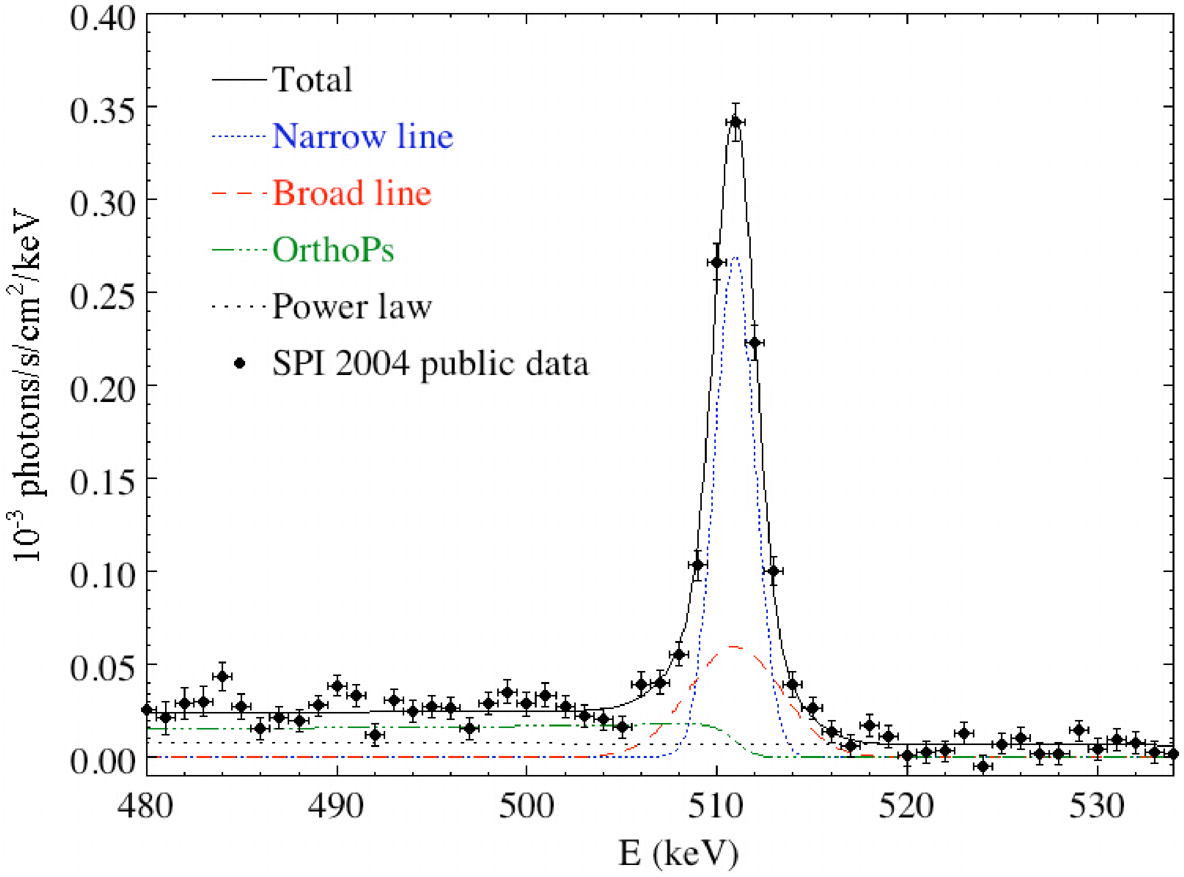
- Exclusion of energy bands with strong instrumental background lines.
- Flux and spectral characteristics obtained by fitting analytical models (Gaussians, orthoPs continuum…) to the cleaned spectrum

Best spectral model

$$S_l(E) = I_n \times G(E,\Gamma_n) + I_b \times G(E,\Gamma_b) + I_{3\gamma} \times O(E) + A_c \left(\frac{E}{511}\right)^s$$

Param.	Measured values
I_n	$(0.72 \pm 0.12 \pm 0.02)\ 10^{-3}\ s^{-1}\ cm^{-2}$
Γ_n	$1.32 \pm 0.35 \pm 0.02$ keV
I_b	$(0.35 \pm 0.11 \pm 0.02)\ 10^{-3}\ s^{-1}\ cm^{-2}$
Γ_b	$5.36 \pm 1.22 \pm 0.06$ keV
$I_{3\gamma}$	$(4.23 \pm 0.32 \pm 0.03)\ 10^{-3}\ s^{-1}\ cm^{-2}$
A_c	$(7.17 \pm 0.80 \pm 0.06)\ 10^{-6}\ s^{-1}\ cm^{-2}\ keV^{-1}$

Jean et al., 2005, A&A in press



$\chi^2 \sim 171.3$ (d.o.f. 148)

Broad line (3.2σ)
~1/3 of the 511 keV flux
=> detection of Ps
formed in-flight

Total 511 keV flux :
$(1.07 \pm 0.03)\ 10^{-3}\ \gamma/s/cm^{-2}$

Ps fraction : 96.7±2.2 %

- Models of the annihilation spectrum

In which ISM phase positrons annihilate?

The method consist in :

1 - modelling the e^+e^- spectrum in each phase (Guessoum, Jean & Gillard 2005).

we neglect Doppler shifts due to :

- Galactic rotation in the GC region (< 0.02 keV)
- turbulence of the ISM ($v_{turb.} < v_{therm.}$)

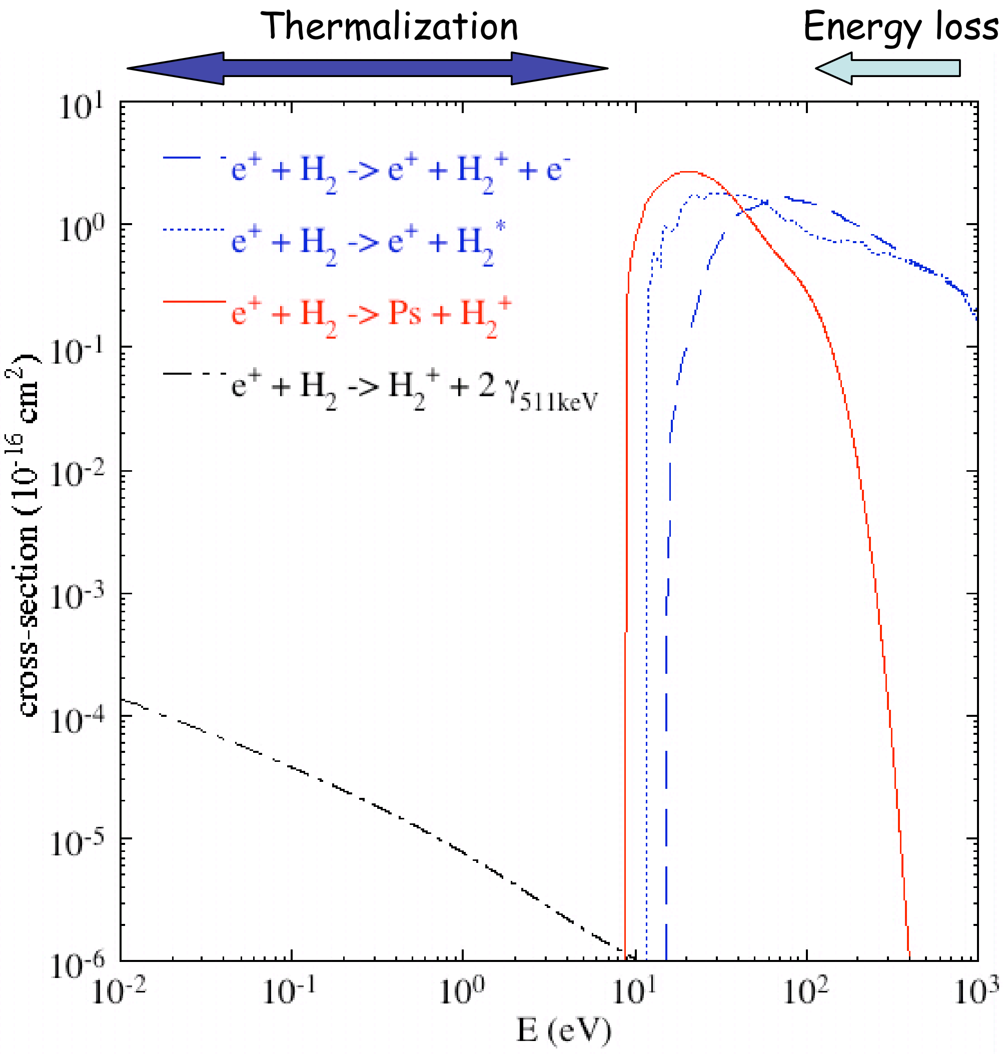
The ISM is characterized by 5 phases

Phase	T (K)	Ion. Frac.	Local density (cm^{-3})
Molecular	10	0.	1000
Cold	80	0.	40
Warm Neutral	8000	0.	0.4
Warm Ionized	8000	1.	0.2
Hot	10^6	1.	0.003

2 - fit a combination of modelled spectra

$$S_{ISM}(E) = I_{e^+e^-} \times \sum_{i=1}^{5} f_i \times S_i(E, x_{gr}) + A_c \left(\frac{E}{511}\right)^s$$

Positrons in Molecular medium
(T~10 K)

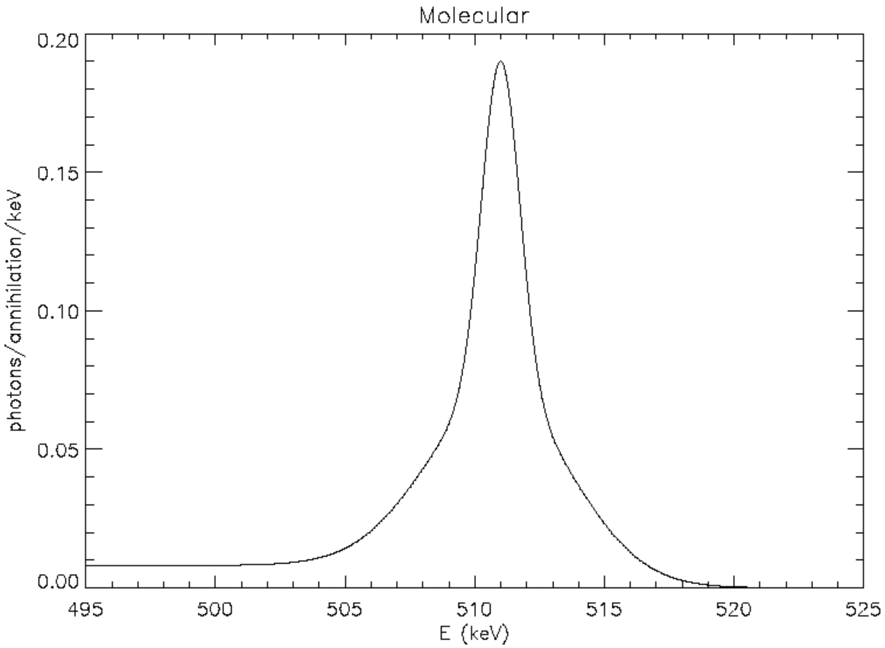


Fraction of Ps in flight : ~89%

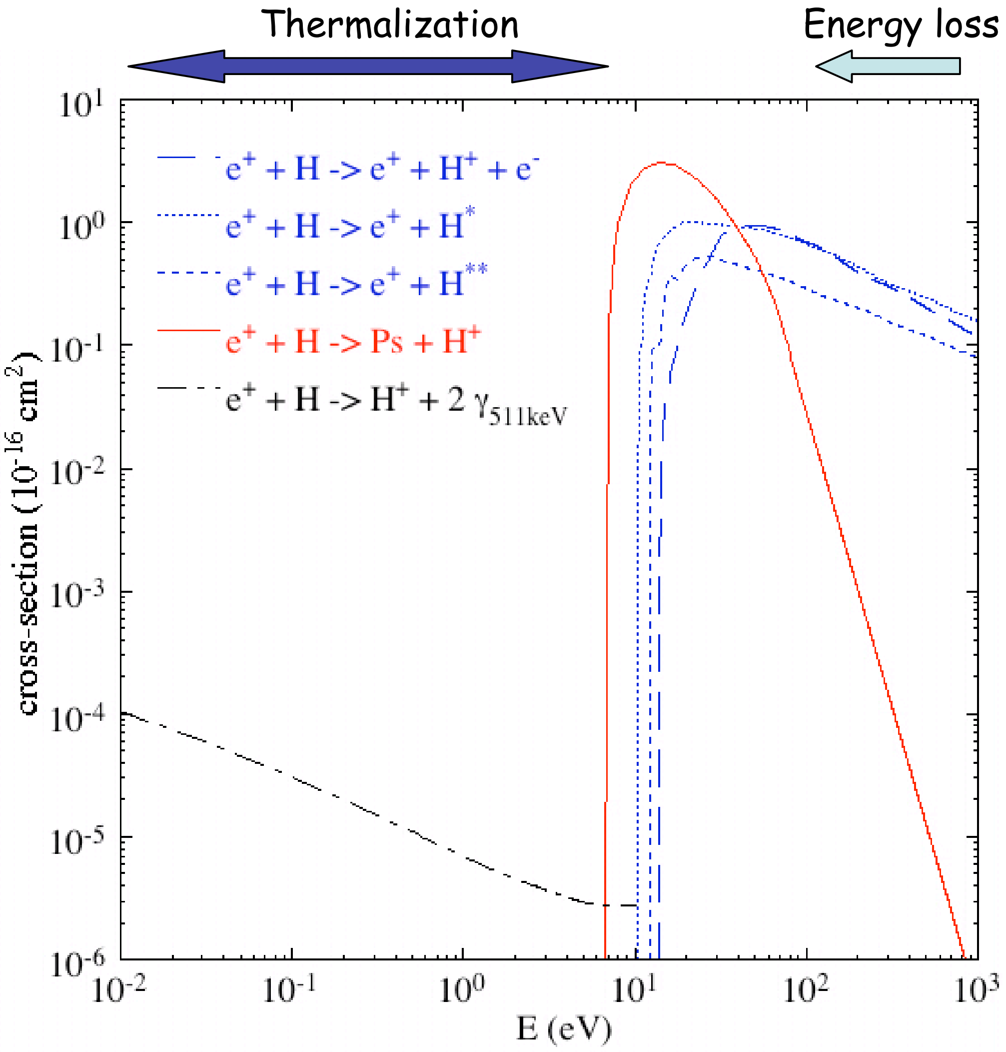
Γ_{Ps} = 6.4 keV

Γ_{DA} = 1.7 keV

Fraction of Ps : ~89%



Positrons in Cold medium
(T~80 K)

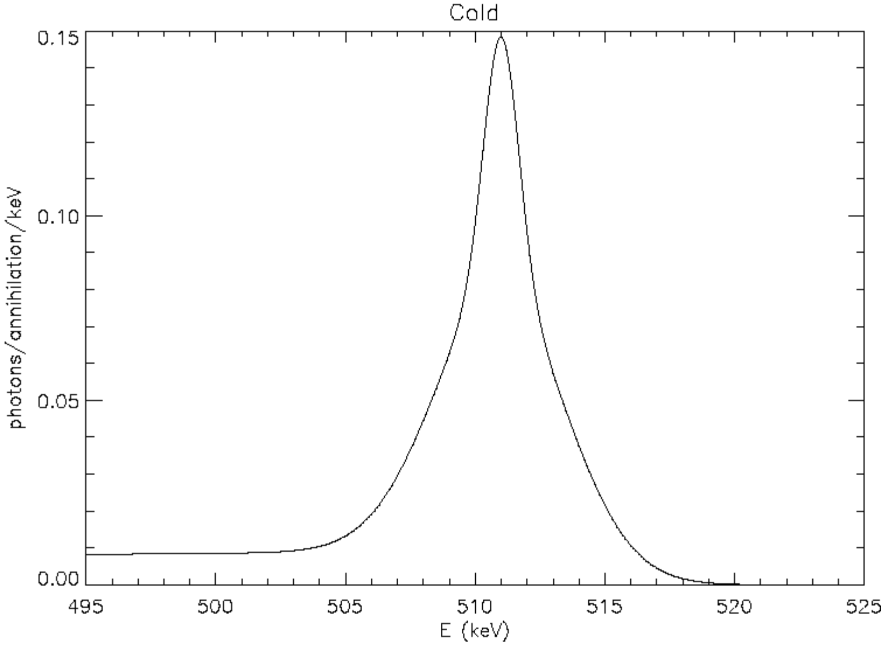


Fraction of Ps in flight : ~94%

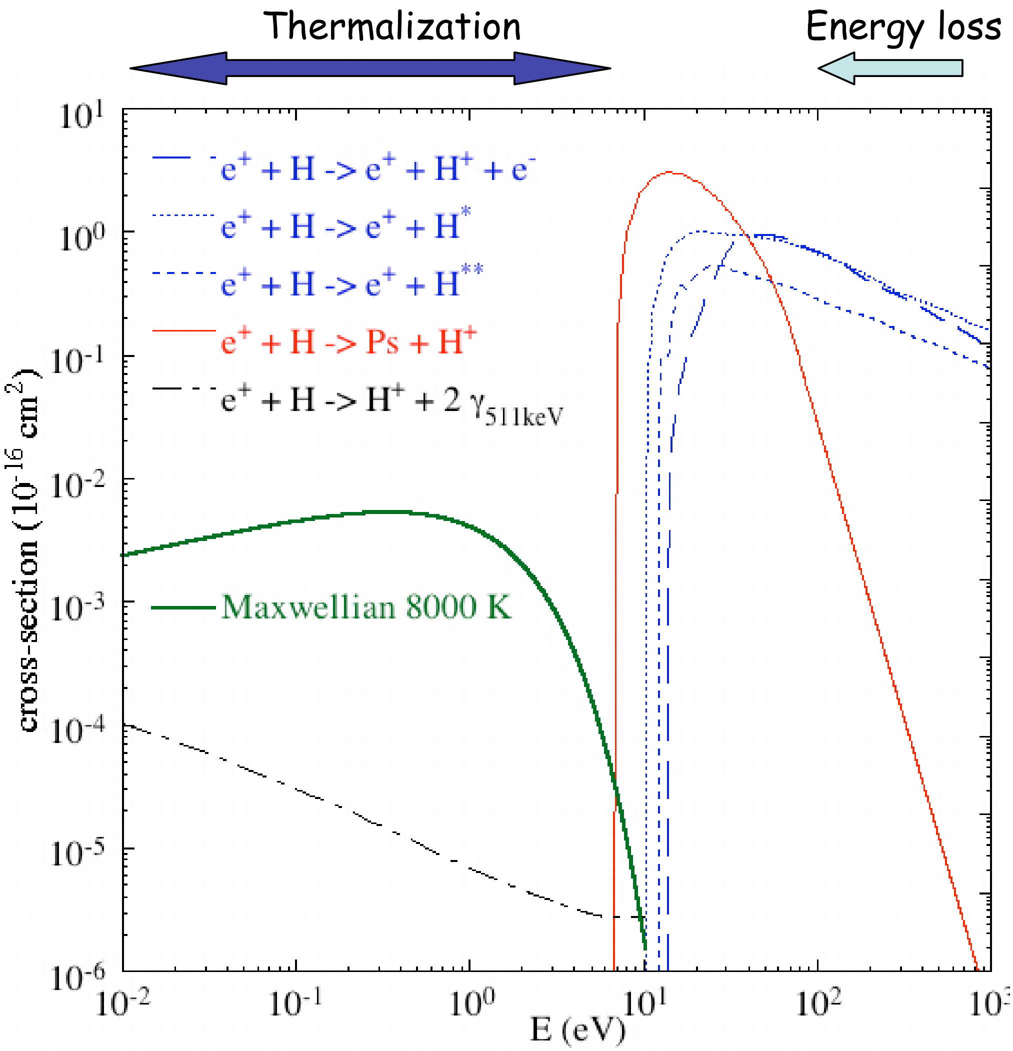
Γ_{Ps} ~ 5.8 keV

Γ_{DA} = 1.56 keV

Fraction of Ps : ~94%



Positrons in Warm neutral medium (T~8000 K)

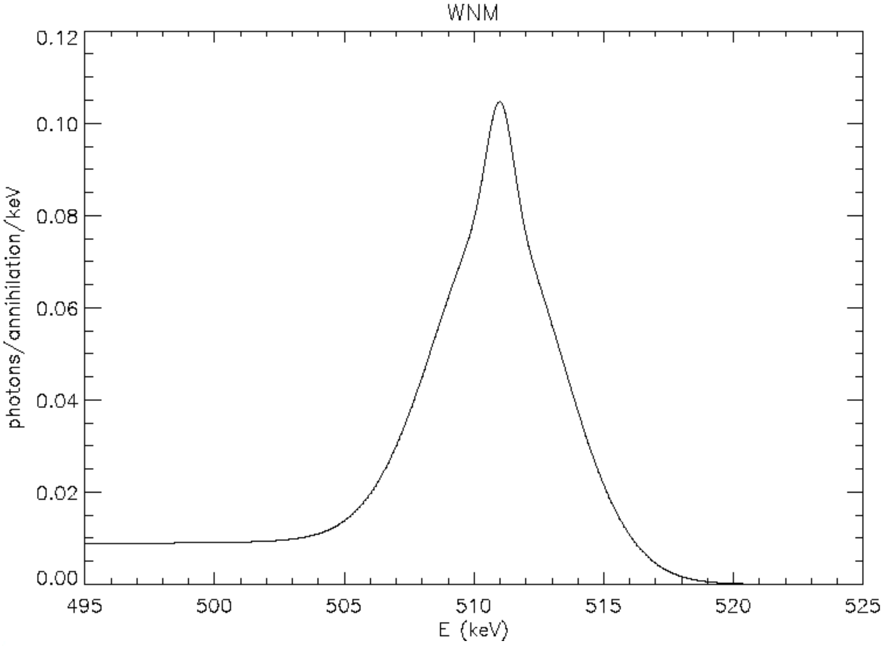


Fraction of Ps in flight : ~94%

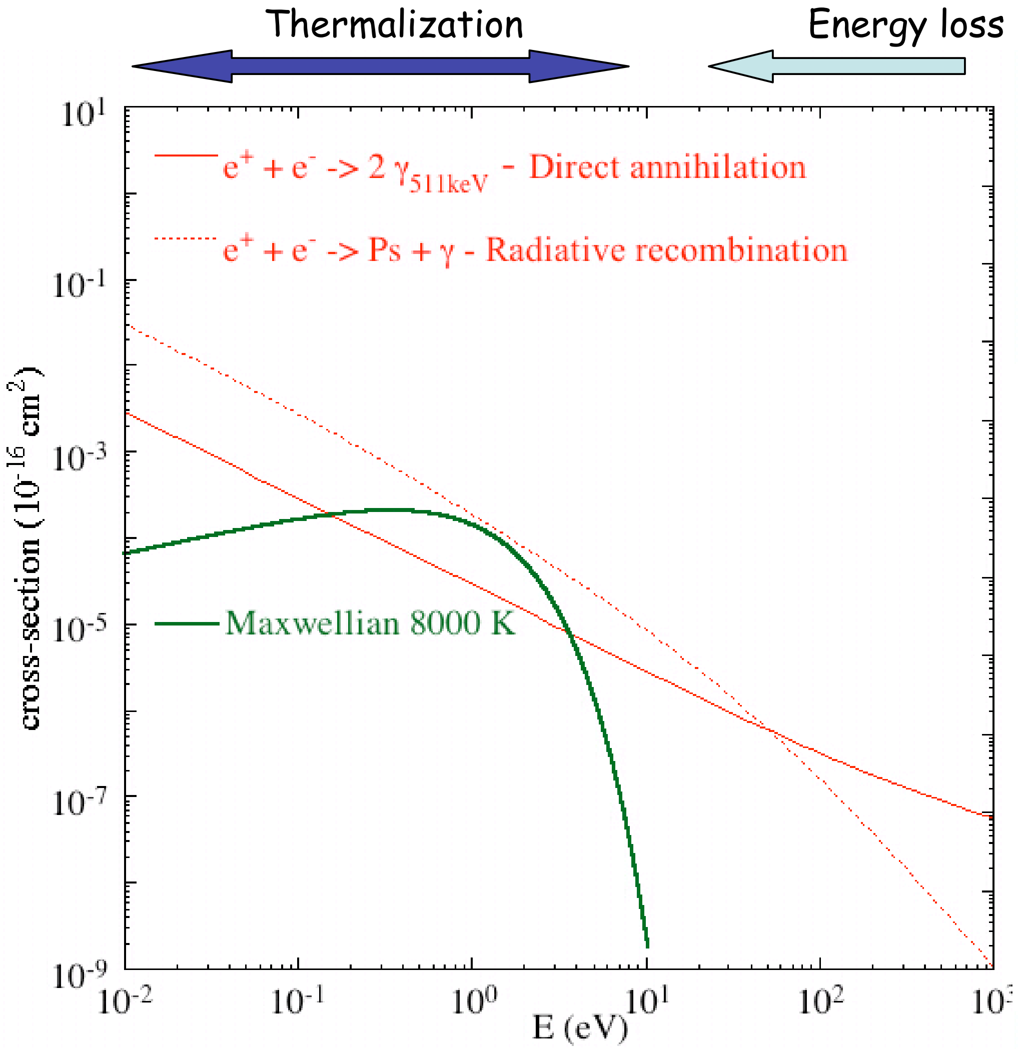
Γ_{Ps} ~ 5.8 keV

Γ_{CE} = 1.16 keV

Fraction of Ps : ~100%



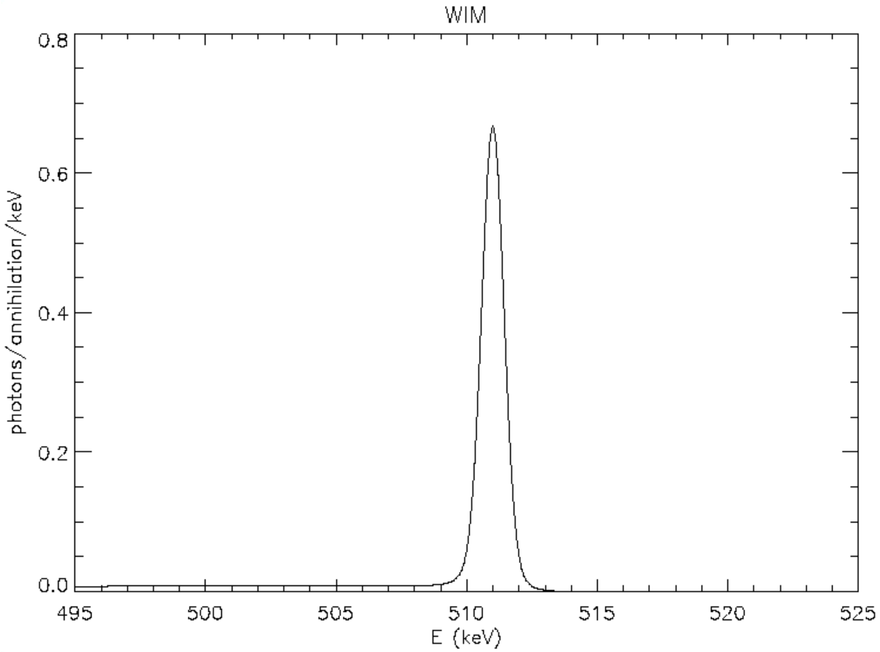
Positrons in Warm ionized medium (T~8000 K)



Fraction of Ps in flight : ~0%

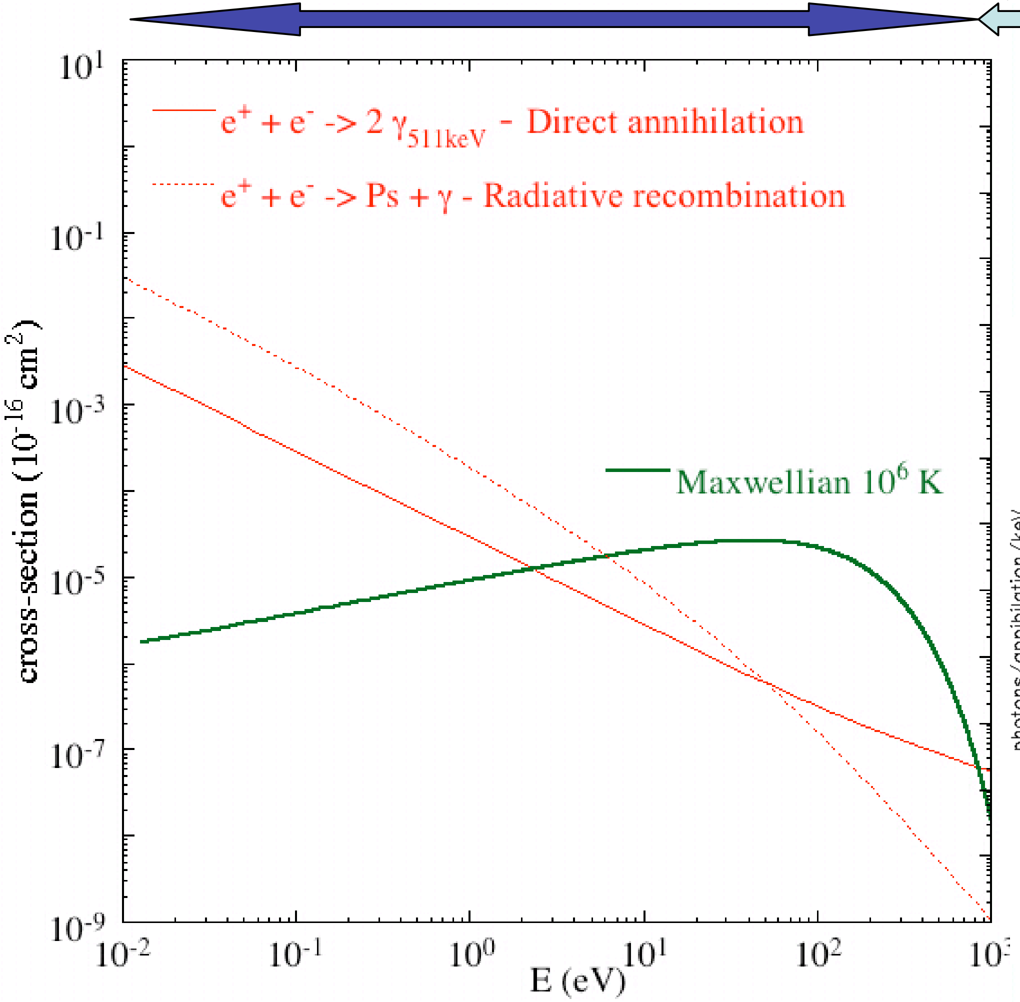
$\Gamma_{DA} = \Gamma_{RR} = 0.98$ keV

Fraction of Ps : ~87%



Positrons in Hot medium
(T~10^6 K)

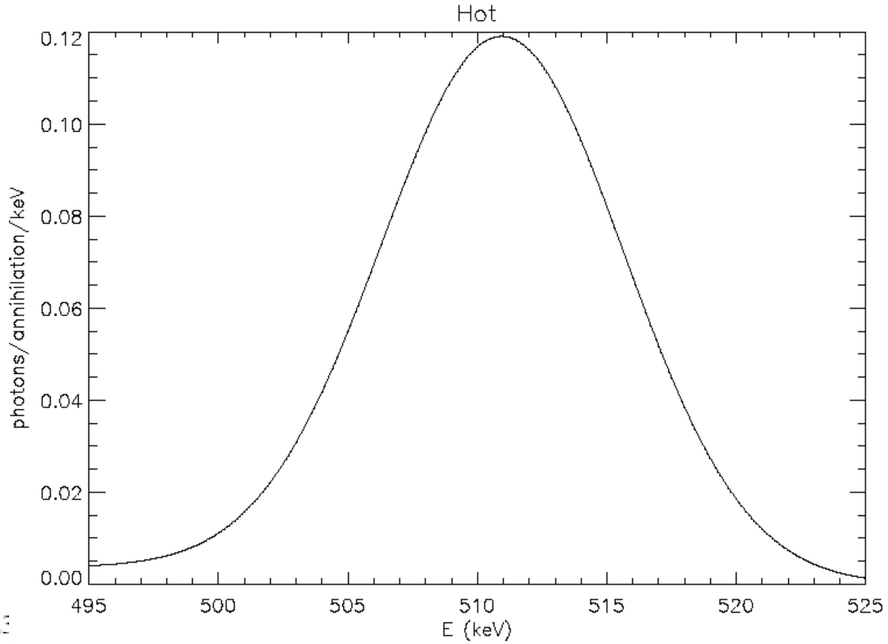
Thermalization Energy loss



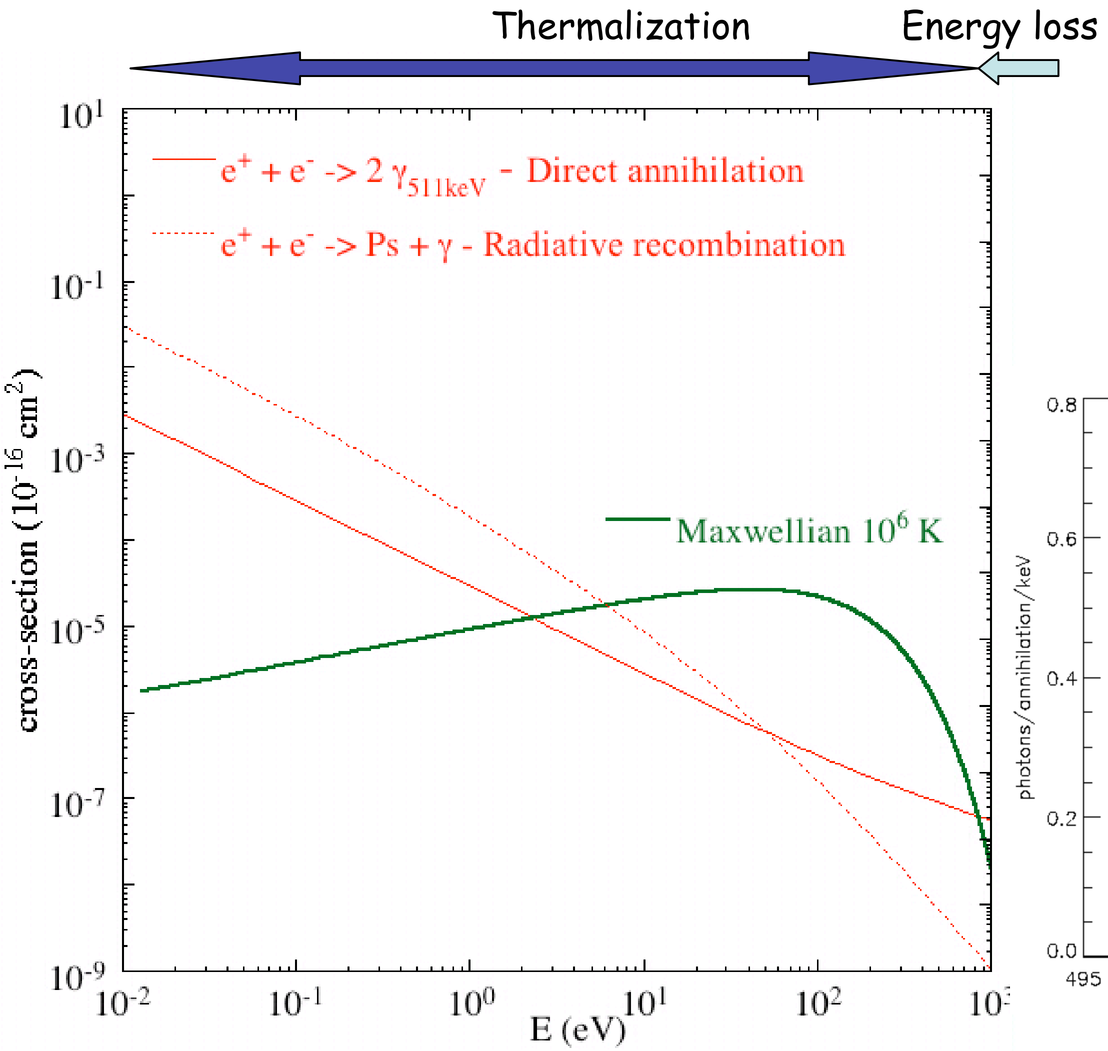
Fraction of Ps in flight : ~0%

$\Gamma_{DA} = \Gamma_{RR}$ = 11 keV

Fraction of Ps : ~42%



Positrons in Hot medium with interstellar grains ($T \sim 10^6$ K)



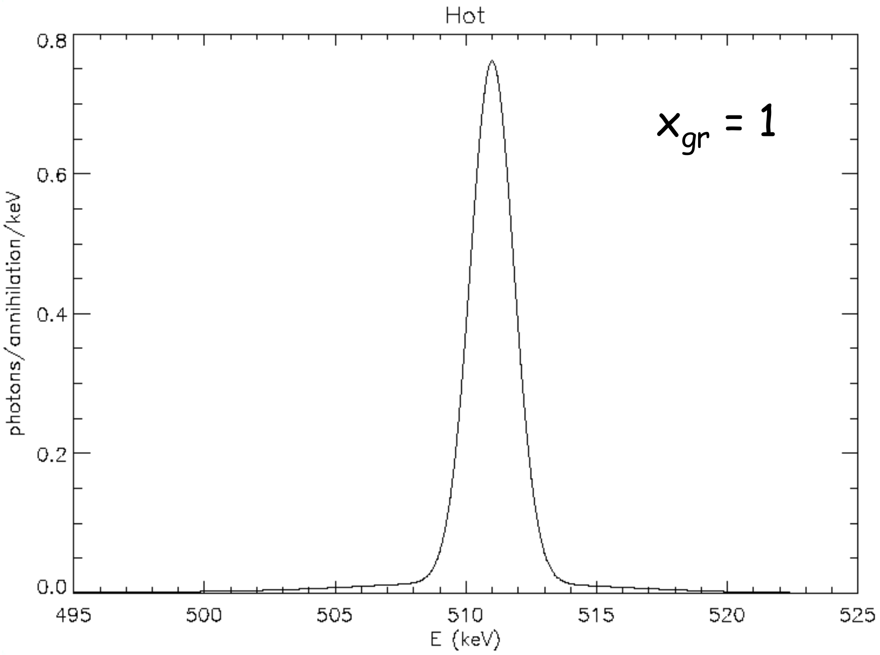
Fraction of Ps in flight : ~0%

$\Gamma_{DA} = \Gamma_{RR} = 11$ keV

$\Gamma_{DAgrain} \sim 2$ keV

$\Gamma_{Psgrain} \sim 1.4$ keV

Fraction of Ps : ~18%

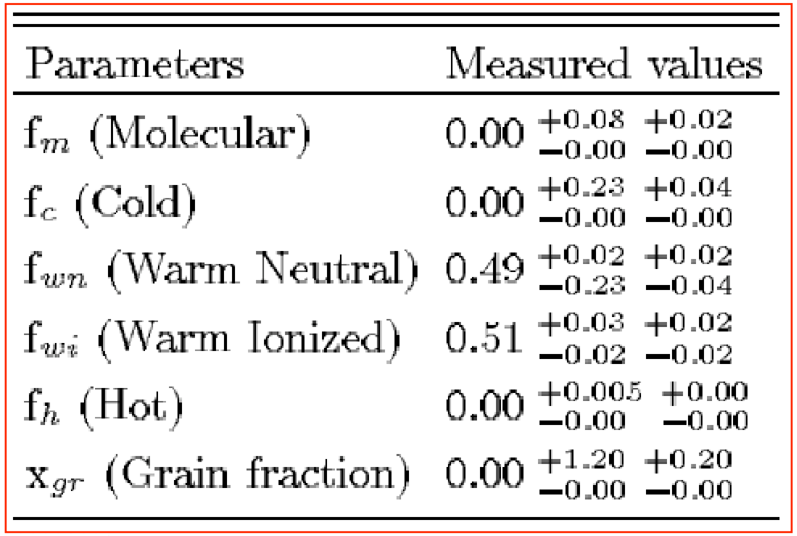


$x_{gr} = 1$ standard abundance of grains (Krugel 2003)

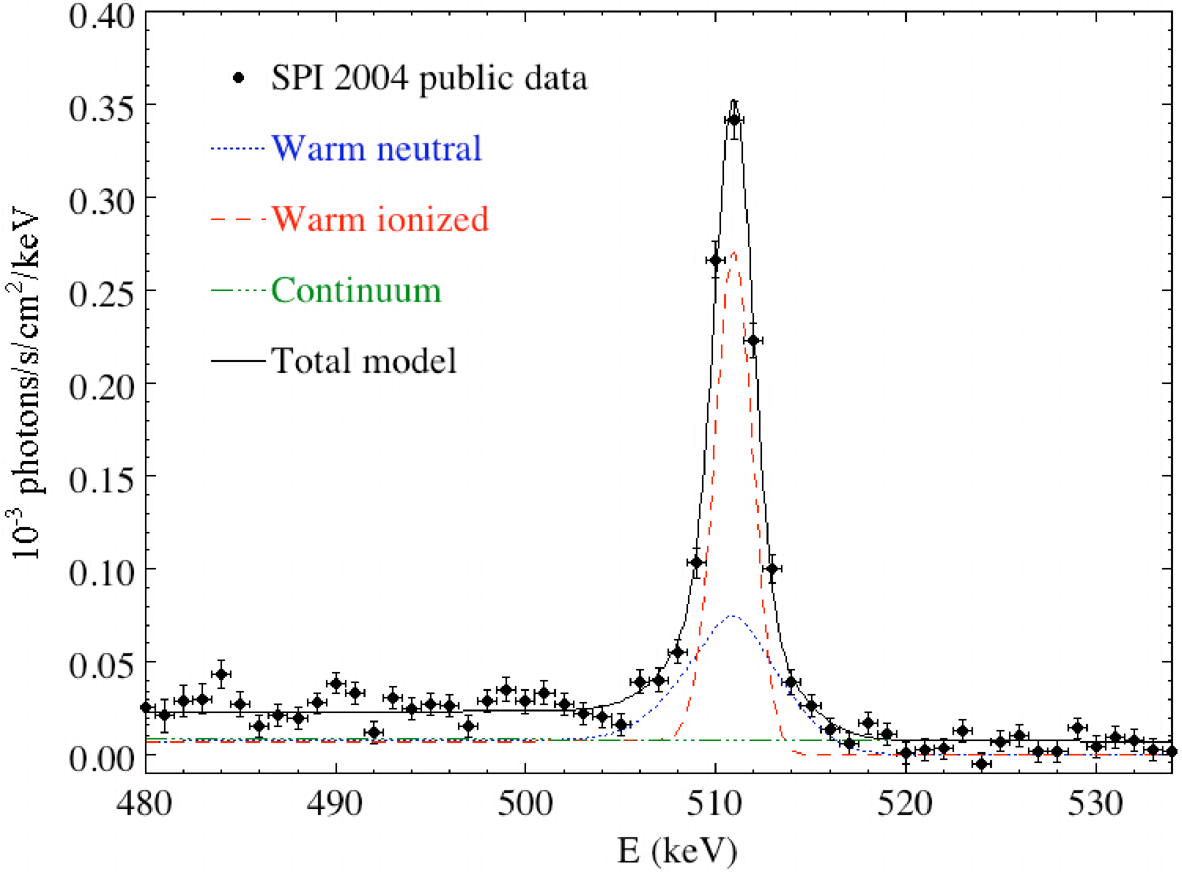
- Fit of the phase fractions

$$S_{ISM}(E) = I_{e^+e^-} \times \sum_{i=1}^{5} f_i \times S_i(E, x_{gr}) + A_c \left(\frac{E}{511}\right)^s$$

f_i : contribution of phase i



Parameters	Measured values
f_m (Molecular)	$0.00\,^{+0.08}_{-0.00}\,^{+0.02}_{-0.00}$
f_c (Cold)	$0.00\,^{+0.23}_{-0.00}\,^{+0.04}_{-0.00}$
f_{wn} (Warm Neutral)	$0.49\,^{+0.02}_{-0.23}\,^{+0.02}_{-0.04}$
f_{wi} (Warm Ionized)	$0.51\,^{+0.03}_{-0.02}\,^{+0.02}_{-0.02}$
f_h (Hot)	$0.00\,^{+0.005}_{-0.00}\,^{+0.00}_{-0.00}$
x_{gr} (Grain fraction)	$0.00\,^{+1.20}_{-0.00}\,^{+0.20}_{-0.00}$



Jean et al., 2005, A&A in press

χ^2 ~ 176.4 (d.o.f. 148)

Ps fraction : $93.5^{+0.3}_{-1.6} \pm 0.3\%$

In agreement with :
93±4% Kinzer et al. 2001
94±4% Harris et al. 1998
94±6% Churazov et al. 2005

Positrons annihilate in warm phases

- Fate of positrons in the bulge

Gas content in the Bulge

-> using estimations of H_2, HI & HII gas masses & distributions in the emitting galactic bulge region ($r \leq 600$ pc)

-> assuming HI: 50% in Cold & 50% in WNM
HII: 90% in WIM & 10% in hot (Ferriere 1998)

Phase	n (cm^{-3})	Filling Factor	Half-size (pc)	Phase fraction
Molecular	3600	0.04%	3-30	<8%
Cold	146	0.2%	~5	<23%
Warm Neutral	1.46	18%	0.1-50	~49%
Warm Ionized	0.77	10%	10-100	~51%
Hot	0.009	72%	50-100	<0.5%

-> **If** e^+ are uniformly distributed and annihilate without propagating
then the phase fractions = filling factors => $\mathbf{f_{hot} \sim 70\%}$
but observations yield $\mathbf{f_{hot} < 0.5\%}$ => no sources in hot phase ?
=> e^+ escape the hot phase ?

Propagation of e^+ in the bulge

-> if $E > E_{ql}(n,B)$ => e^+ in resonance with Alven waves => quasi-linear diffusion (D_{ql})

-> if $E < E_{ql}(n,B)$ => diffusion regime uncertain !!!
collisional regime provides an upper-limit => D_{coll}

-> $d_i \sim \sqrt{(6 D_i \tau)}$

-> $d_{max} = d_{ql} + d_{coll}$

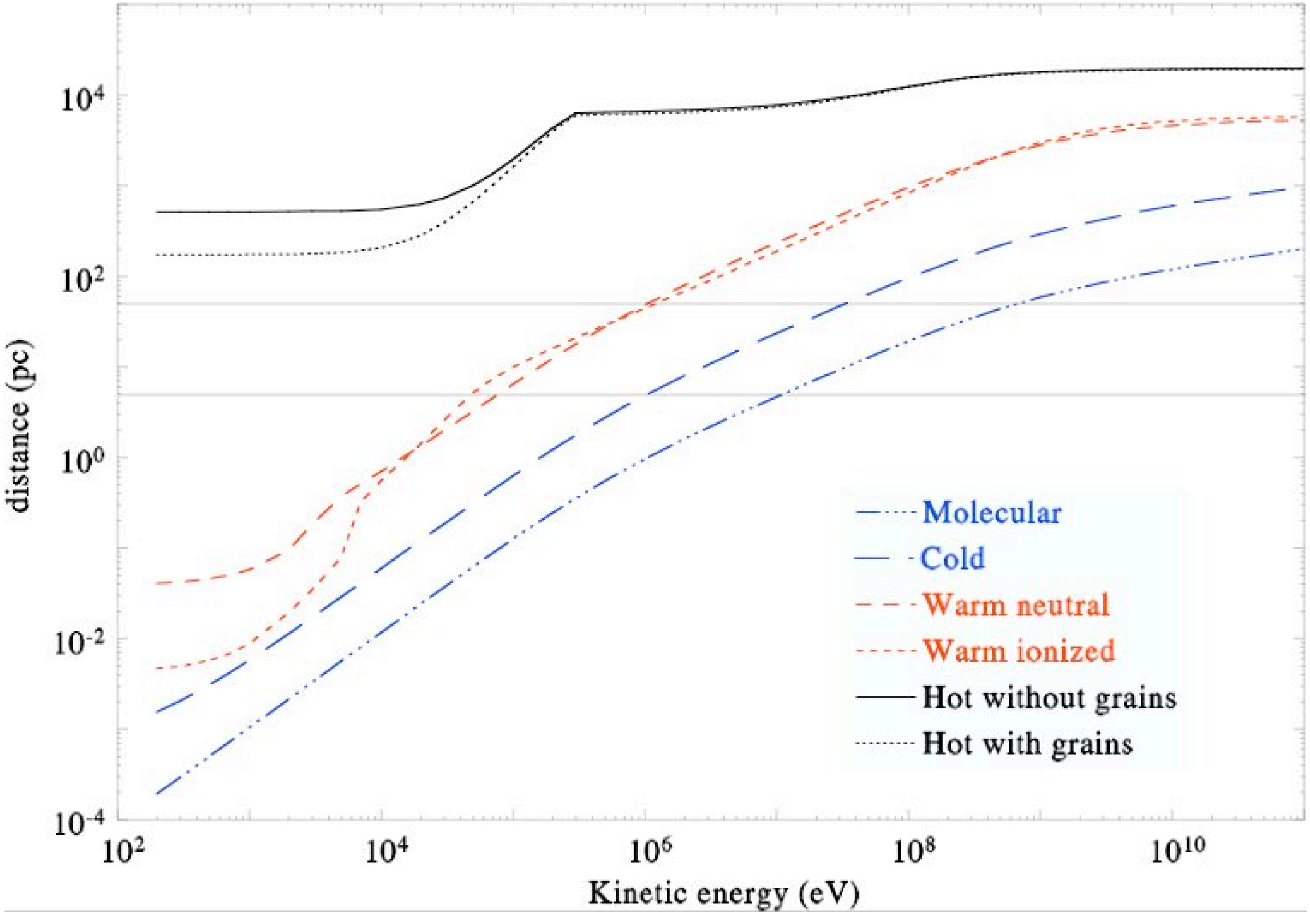
For 1 MeV positrons & $B_{bulge} \sim 10\ \mu G$ (Sofue et al. 1987, LaRosa et al. 2005)

Phase	n (cm^{-3})	Half-size (pc)	E_{ql} (keV)	d_{ql} (pc)	d_{max} (pc)
Molecular	3600	3-30	10^{-3}	1.0	1.0
Cold	146	~5	0.03	4.8	4.8
Warm Neutral	1.46	0.1-50	2.9	47.8	47.9
Warm Ionized	0.77	10-100	5.5	43.9	44.0
Hot	0.009	50-100	270	264	5600

=> 1 MeV positrons escape the hot phase

Initial kinetic energy of e^+

d_{max} vs E_{init}



-> positrons escape (and do not annihilate in) the hot phase

-> high energy positrons ($E \geq 100$ MeV) would escape the bulge => $E < 100$ MeV

-> positrons with ~10 MeV would escape warm media & annihilate in cold gas or in molecular clouds => $E < 10$MeV

• Origin of positrons

Observationnal facts

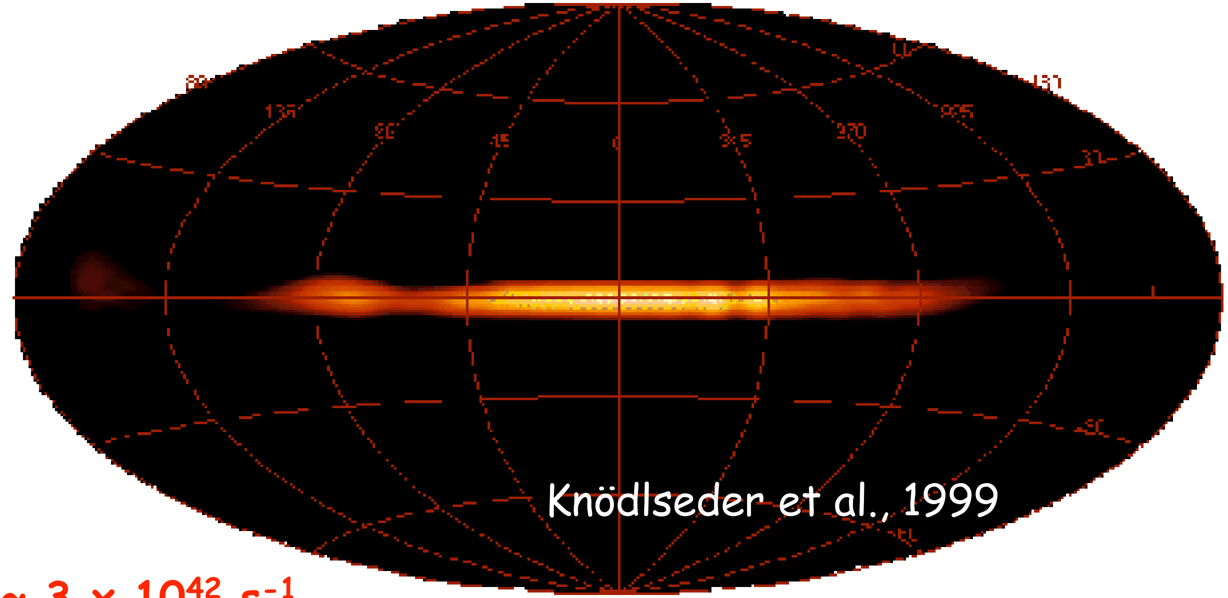
- Annihilation rates: $(1.5 \pm 0.1) \times 10^{43}$ s^{-1} in the bulge
  $(0.3 \pm 0.2) \times 10^{43}$ s^{-1} in the disk
- Bulge to disk luminosity ratio: B/D ~ 3-9
- Energy of e^+ in the bulge: $E < 10$ MeV

How to produce ~ 2×10^{43} e^+/s ?

- β^+ isotopes produced in stars (Colgate, 1970; Clayton, 1973)
  -> ^{56}Co : SNe
  -> ^{26}Al : SNII, WR
  -> ^{44}Ti : SNII
  -> ^{22}Na : O-Ne Novae
- Cosmic-ray -> $p + p \rightarrow p + n + \pi^+$ and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- Compact sources -> Pulsars (Sturrock, 1971; Ramaty, 1978)
  -> Black-holes (Lingenfelter & Ramaty, 1982; Rees, 1982)
- Dark matter

• Origin of positrons

Sky-map of the 1.8 MeV line (COMPTEL)



Knödlseder et al., 1999

Decay of ^{26}Al

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

$^{26}Al \rightarrow {}^{26}Mg + \beta^{+} + \gamma_{1.8MeV}$

$T_{1/2} \sim 0.7$ Myr

-> Contribution of ^{26}Al :

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

Decay of ^{44}Ti

^{44}Ti produced in SNs

$^{44}Ti \rightarrow\ \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca + \beta^{+}$ ($T_{1/2} \sim 60$ yr)

-> Contribution of ^{44}Ti (Milne et al., 2002)

Solar abundance of ^{44}Ca $\Rightarrow M_{44} \sim (3 \pm 1)\ 10^{-6}\ M_{*}$ (Timmes et al., 1996)

$\Rightarrow R_{e+} \sim 2 \times 10^{42}\ s^{-1}$

^{26}Al & ^{44}Ti can explain the disk emission

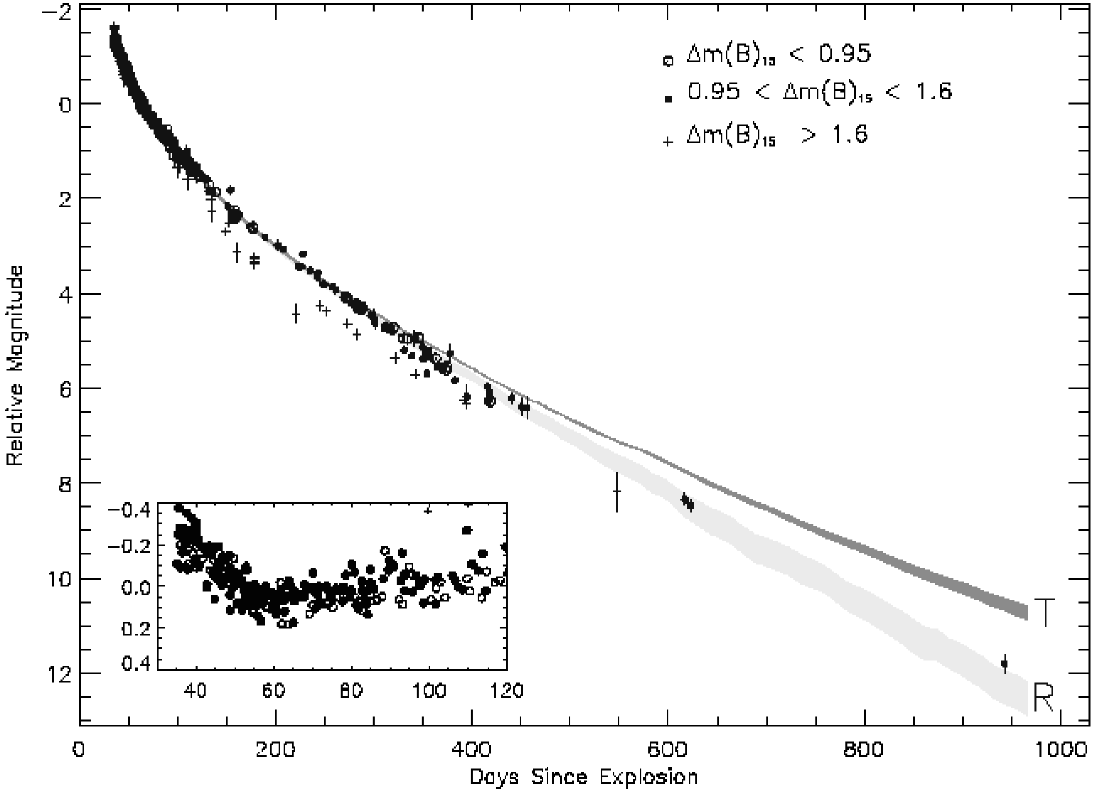
• Origin of positrons

Supernovae

- SNII -> e^+ from ^{56}Co do not escape the ejecta (Chan & Lingenfelter, 1993)

- SNIa -> a fraction **f** of e^+ from ^{56}Co escape the ejecta

Milne, The & Leising, 2001



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)

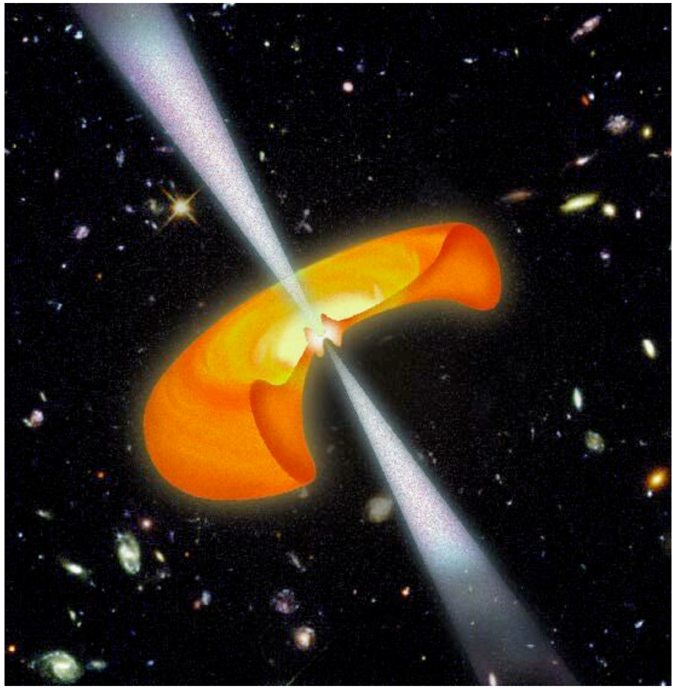
=> **$R_{e+} < 3.7\ 10^{43}\ s^{-1}$.**

-> 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 $(B/D)_{SNeIa} < 1$

- Origin of positrons



SNIc/GRB/Hypernovae

asymetric explosion of a WR star

-> e^+ from ^{56}Co released in the ISM :

=> $N_{e+} \sim 2 \times 10^{54}$ (Cassé et al., 2003)

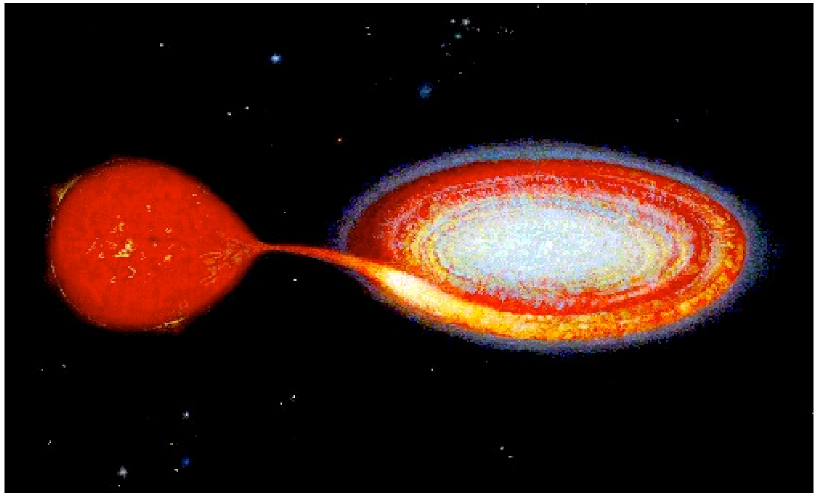
=> Need 0.2 event per millenium in the bulge

-> e^+ produced in the jet :

=> $N_{e+} \sim 10^{56}$ (Parizot et al., 2004)

However massive stars are located mostly in the disk
& a single hypernova cannot fill the bulge

Classical novae



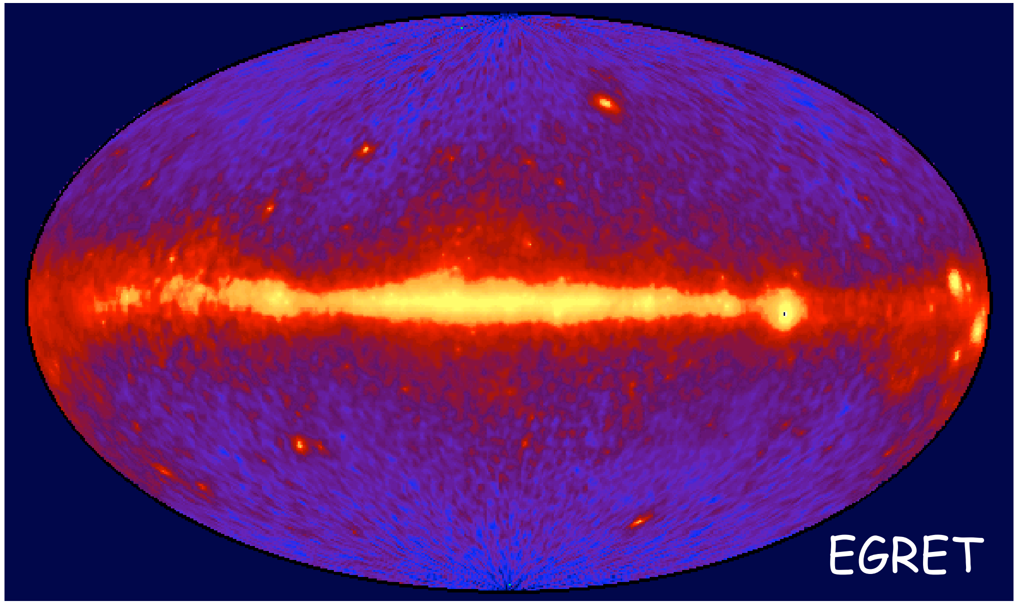
Thermonuclear runaway in the enveloppe of an accreting WD in a binary system.

^{22}Na -> ^{22}Ne + β^+ - in ONe novae only

-> José, Coc & Hernanz, 2003 :
$M_{22} \sim 6 \times 10^{-9} M_*$ & $\nu_{ONe} \sim 10\ yr^{-1}$.

=> $R_{e+} \sim 10^{41}\ s^{-1}$

- Origin of positrons



Cosmic-ray

$p + p \rightarrow p + n + \pi^+$

$\pi^+ \rightarrow \mu^+ \rightarrow e^+$

E > 10 MeV

Contribution of π^+ in the central region assuming $R_{e+} \sim R_{\pi+} \sim R_{\pi 0} \sim R_{\gamma>100\mathrm{MeV}}$

$F_{511\mathrm{keV},\pi+} \sim (2-1.5 f_{Ps}) \times F_{>100\mathrm{MeV}}$ **$\sim 6 \times 10^{-5}\ \gamma\ s^{-1}\ cm^{-2}$**

Pulsars

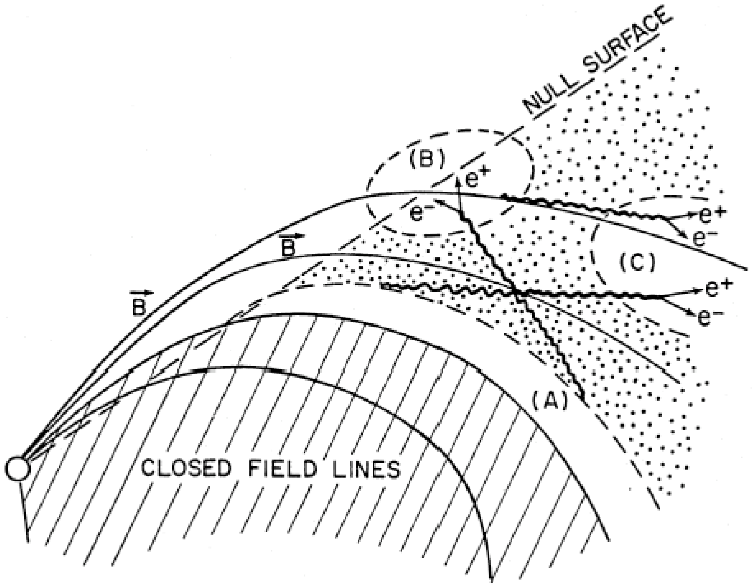
- Harding & Ramaty, 1987

$R_{e+} \propto B \times P^{-1.7}\ s^{-1}\ \mathrm{pulsar}^{-1}$.

e.g. $R_{e+} \sim 10^{36}\ s^{-1}$ for the Crab

E > 10 MeV

Total galactic pulsars => **$R_{e+} \sim 10^{40}\ s^{-1}$**



Cheng, Ho & Ruderman, 1986

- Origin of positrons

LMXB/BH/Microquasar

e^+e^- in jets through $\gamma + \gamma \to e^+ + e^-$

- Positron yield from a jet not clearly known :
  - -> $R_+ \sim 10^{41}\ s^{-1}$ with a large uncertainty
  - -> $E \leq 1$ MeV

- Number of microquasars : $N_{\mu Q} \sim 100$ (Paredes 2005)

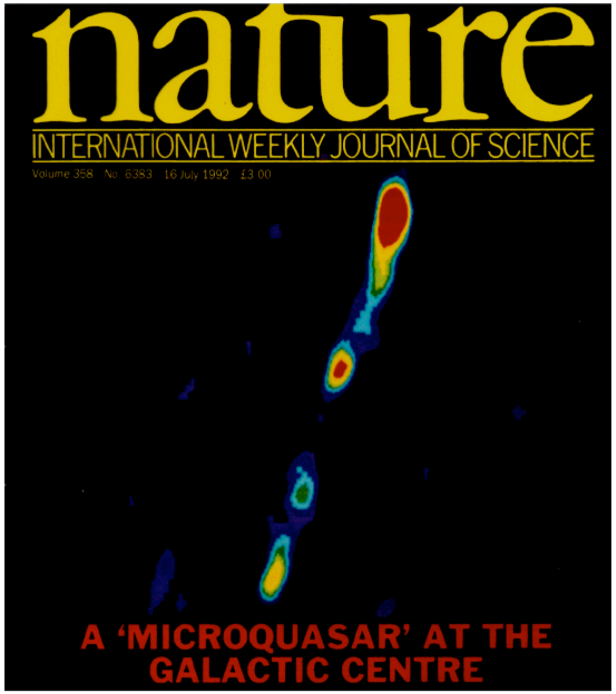
- $(B/D)_{LMXB} \sim 0.9$ (Grimm et al. 2002)

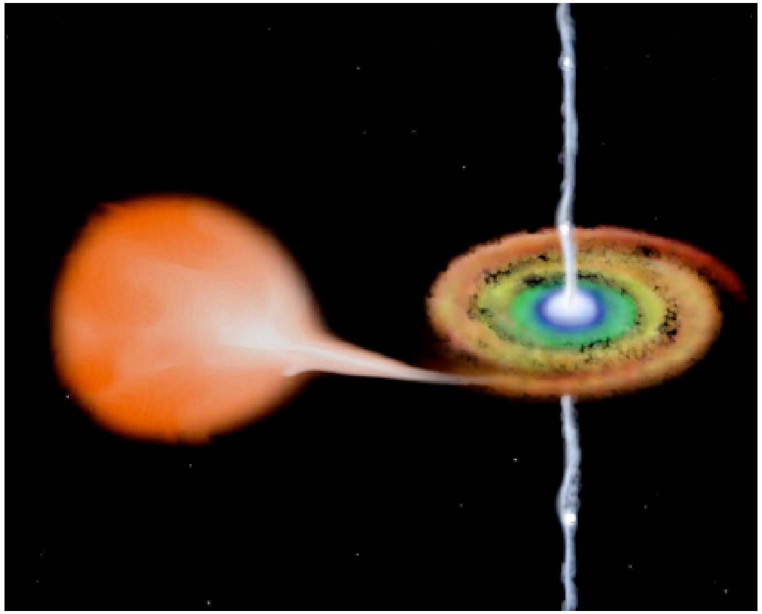
- $R_{bulge} = N_{\mu Q}(\text{Bulge}) \times R_+$ => $R_{bulge} \sim 5 \times 10^{42}\ e^+/s$

- $R_{disk} = N_{\mu Q}(\text{Disk}) \times R_+$ => $R_{disk} \sim 6 \times 10^{42}\ e^+/s$

Remark: constraint on the yield of e+ from microquasars, if microquasars are the source of bulge positrons => $R_+ < 4 \times 10^{41}\ s^{-1}$

Guessoum, Jean & Prantzos, in prep.





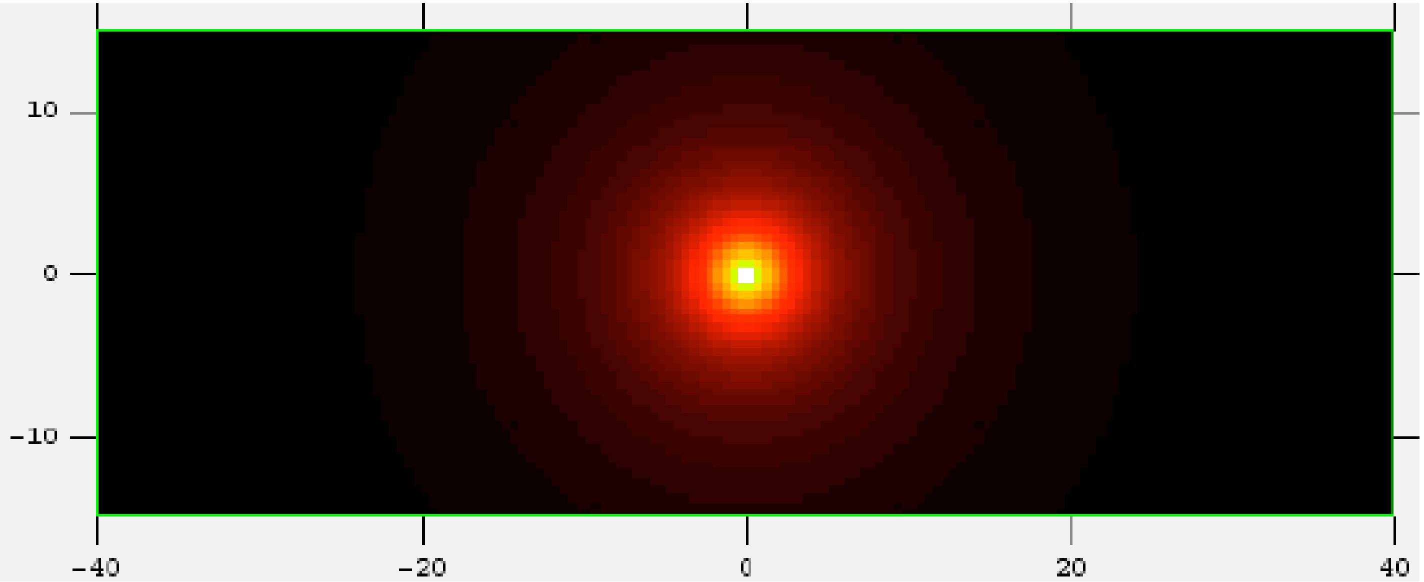
- Origin of positrons

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

Ascasibar & Boehm, 2004
private communication



• Conclusions

- Results of the morphological analysis
  - -> B/D => old stellar population favored (SNIa, novae, LMXB, DM)
  - -> galactic disk emission can be explained by ^{26}Al & ^{44}Ti

- Results of the spectral analysis :
  - -> detection of the emission from annihilation of Ps formed in flight.
  - -> annihilation emission seems to come mostly from warm media
    - => we cannot exclude a fraction (<23%) coming from cold phase
    - => we can exclude an hot phase component (<0.5%).
    - => we do not need interstellar grains to explain the line shape.

- Comparison with gas content and with our knowledge about propagation of e^+:
  - -> positron escape the hot phase
  - -> measured phase fractions in agreement with the filling factors of the gas
  - -> low energy positrons $E \leq \sim$MeV
  - -> diffuse sources : a single source of e^+ cannot fill the bulge

- Questions :
  - -> Do e^+ produced in the galactic disk (by SNIa, novae, LMXB) escape in the halo?
  - -> Are galactic disk e^+ transported toward the bulge (Prantzos, in prep) ?
  - -> What is the diffusion regime of low energy positrons (Marcowith et al., in prep.)?