Spectral analysis of the 511 keV Line

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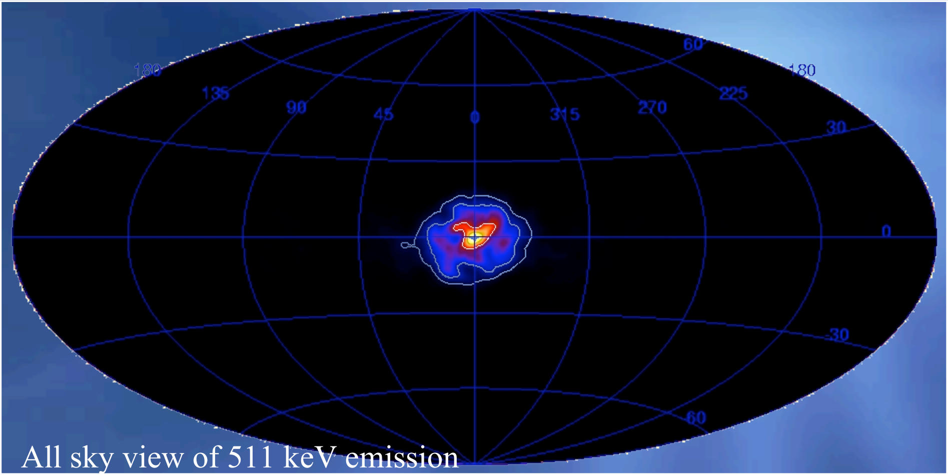
(C.E.S.R)

From P. Jean et al. A&A, in press (astro-ph/0509298)

I. *Introduction*
II. *Annihilation spectrum*
    1. *Independent model*
    2. *Astrophysical model*
III. *Positrons in the Galactic bulge*
IV. *Conclusion*

Introduction:

The view of INTEGRAL-SPI



All sky view of 511 keV emission

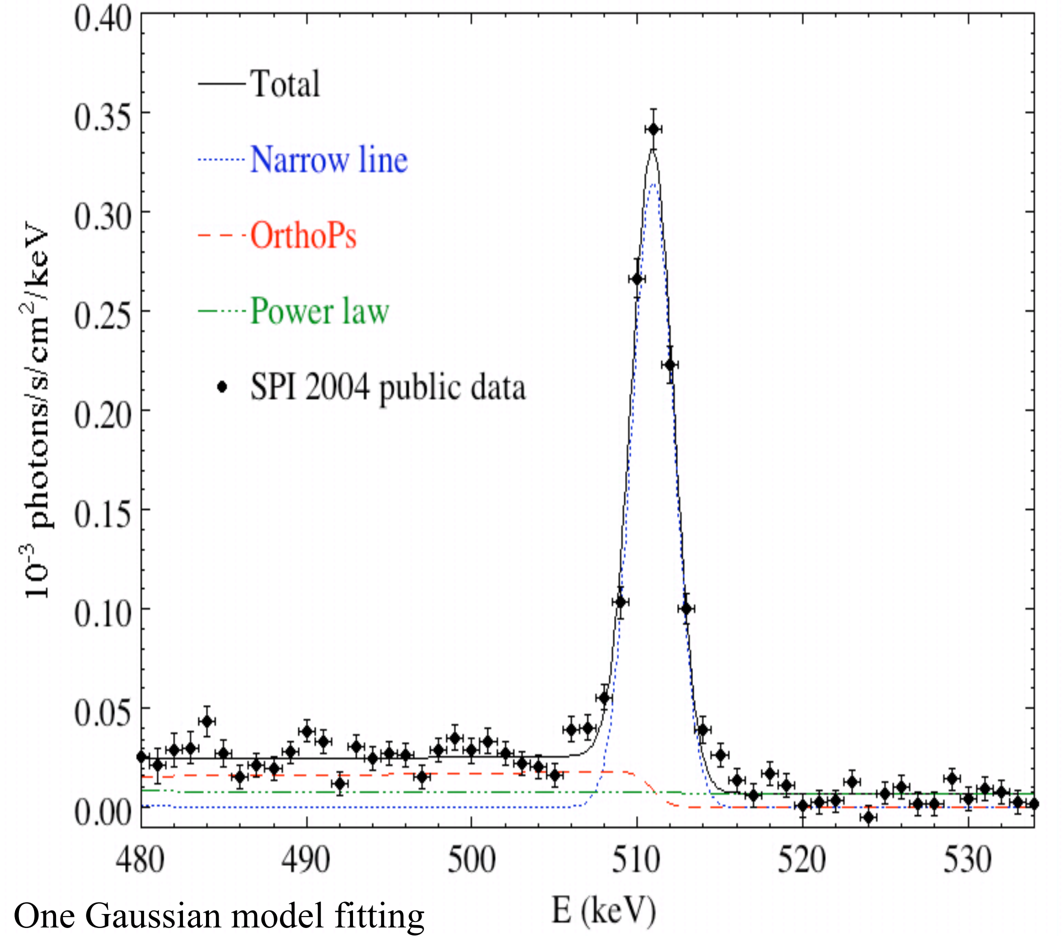
Knödlseder et al, A&A 2005

Morphological analysis by model fitting :

- Bulge : 2D Gaussian shaped emission : ~8°x7° FWHM
  Flux = (1.09 ± 0.04) 10^{-3} γ/s/cm^{-2}
  Positron production rate: 1.5×10^{43} e^+/s
- Galactic disk : emission detected (~3-4σ)
  Flux ~ 4-6 10^{-4} γ/s/cm^{-2}
  Positron production rate: 0.3×10^{43} e^+/s
  can be attributed to e^+ produced by ^{26}Al & ^{44}Ti

Annihilation spectra:

Independent model



One Gaussian model fitting

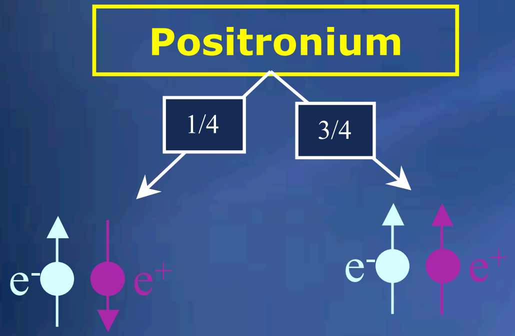
Jean et al. A&A in press

Param.	Measured values
$I_{2\gamma}$	$(1.01 \pm 0.02) \times 10^{-3}\ s^{-1}\ cm^{-2}$
$\Gamma_{2\gamma}$	2.2 ± 0.1 keV
$I_{3\gamma}$	$(4.3 \pm 0.3) \times 10^{-3}\ s^{-1}\ cm^{-2}$
A_c	$(7.5 \pm 0.8) \times 10^{-6}\ s^{-1}\ cm^{-2}\ keV^{-1}$

Ps fraction : 98.4±2.0 %

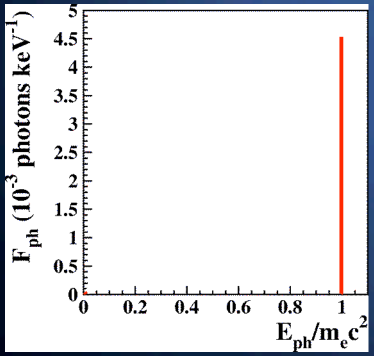
Positronium

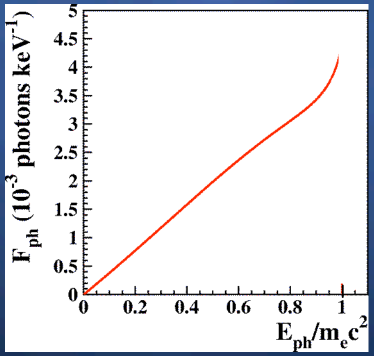
Unstable bounded state between a positron and an electron



Parapositronium
2 γ de ~511 keV

Orthopositronium
3 γ < 511 keV



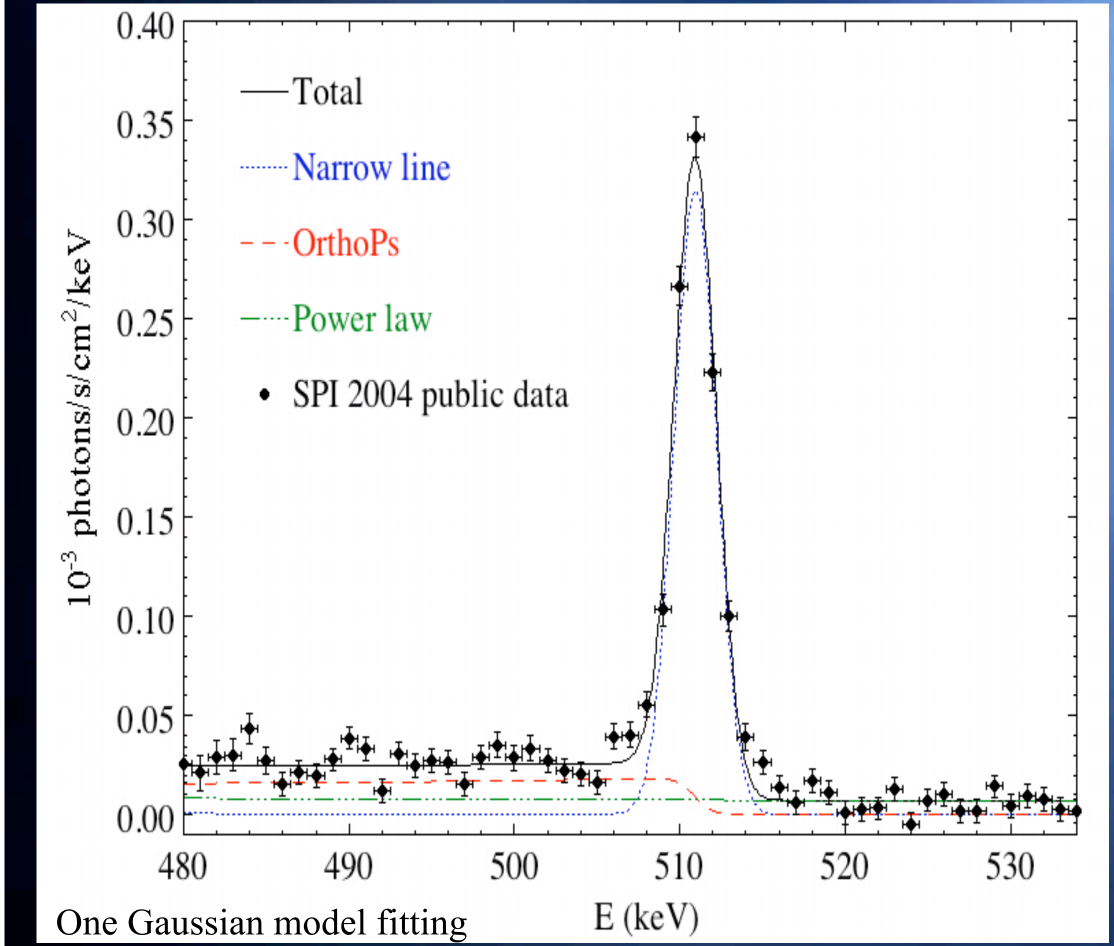


Orthopositronium: $\tau = 1{,}4.10^{-7}$ s
Spectrum : Continuum

Parapositronium: $\tau = 1{,}25.10^{-7}$ s
Spectrum : 511 keV Line

Annihilation spectra:

Independent model



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Jean et al. A&A in press

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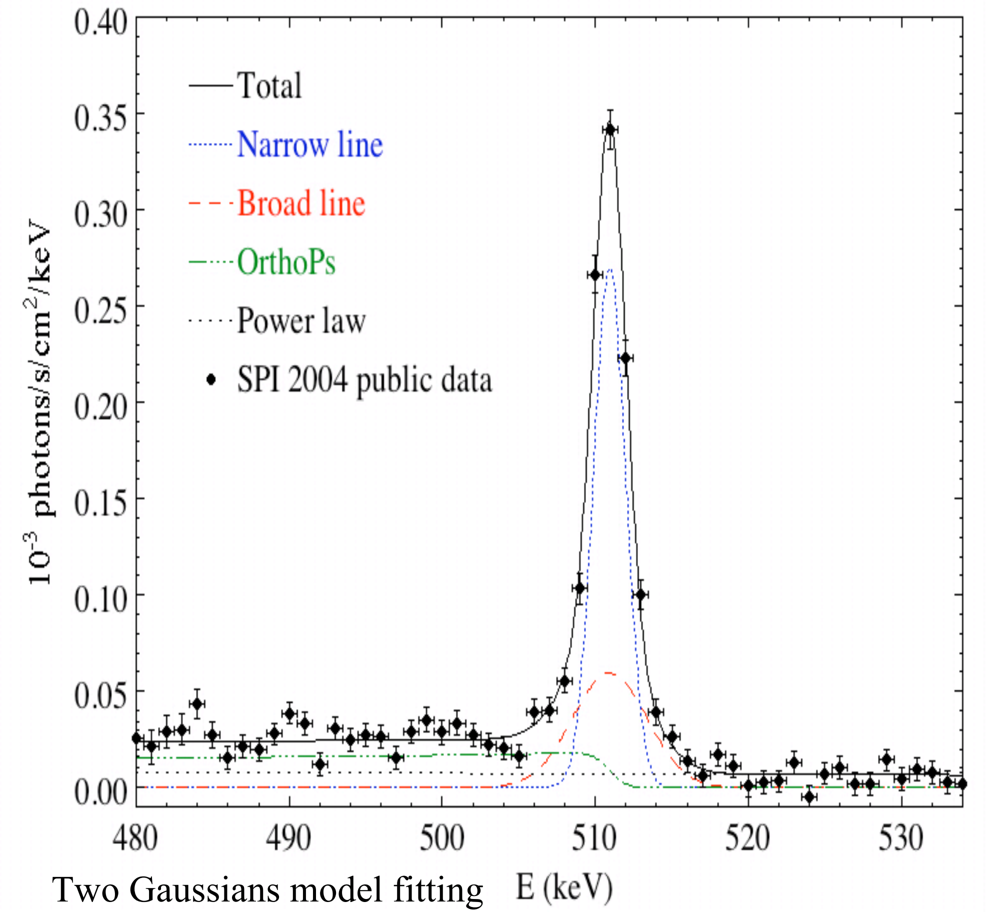
Annihilation spectra:

Independent model



Two Gaussians model fitting

Jean et al. A&A in press

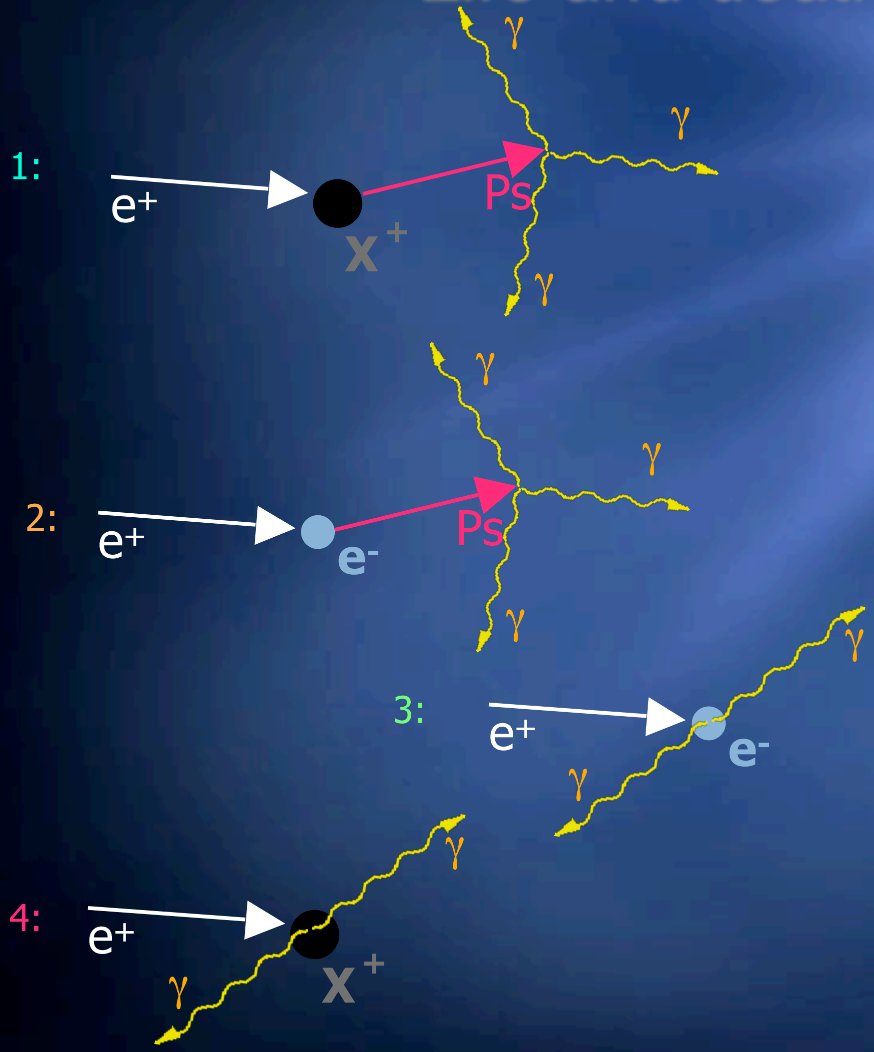
Param.	Measured values
I_n	$(0.72 \pm 0.12 \pm 0.02)\ 10^{-3}\ s^{-1}\ cm^{-2}$
Γ_n	$1.32 \pm 0.35 \pm 0.02$ keV
I_b	$(0.35 \pm 0.11 \pm 0.02)\ 10^{-3}\ s^{-1}\ cm^{-2}$
Γ_b	$5.36 \pm 1.22 \pm 0.06$ keV
$I_{3\gamma}$	$(4.23 \pm 0.32 \pm 0.03)\ 10^{-3}\ s^{-1}\ cm^{-2}$
A_c	$(7.17 \pm 0.80 \pm 0.06)\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

Total 511 keV flux :
$(1.07\pm0.03)\ 10^{-3}\ \gamma/s/cm^{-2}$

Ps fraction : 96.7±2.2 %

Annihilation spectra:

Life and death of the positron



Energy loss

e^+ loss this energy by Columbian interaction:

- ☆ Ionization, excitation of atoms & molecules
- ☆ Interaction with free electrons
- ☆ IC, Bremss, Sync, Scattering on P-Waves

Positronium in flight by charge exchange with H, H_2 or He

Thermalized positron

1: Charge exchange:

$$e^+ + H \rightarrow Ps + H^+$$
$$e^+ + H_2 \rightarrow Ps + H_2^+$$
$$e^+ + He \rightarrow Ps + He^+$$

2: Radiative combination:

$$e^+ + e^- \rightarrow Ps$$

3: Direct annihilation with free electrons:

$$e^+ + e^- \rightarrow 2\gamma$$

4: Direct annihilation with bounded electrons:

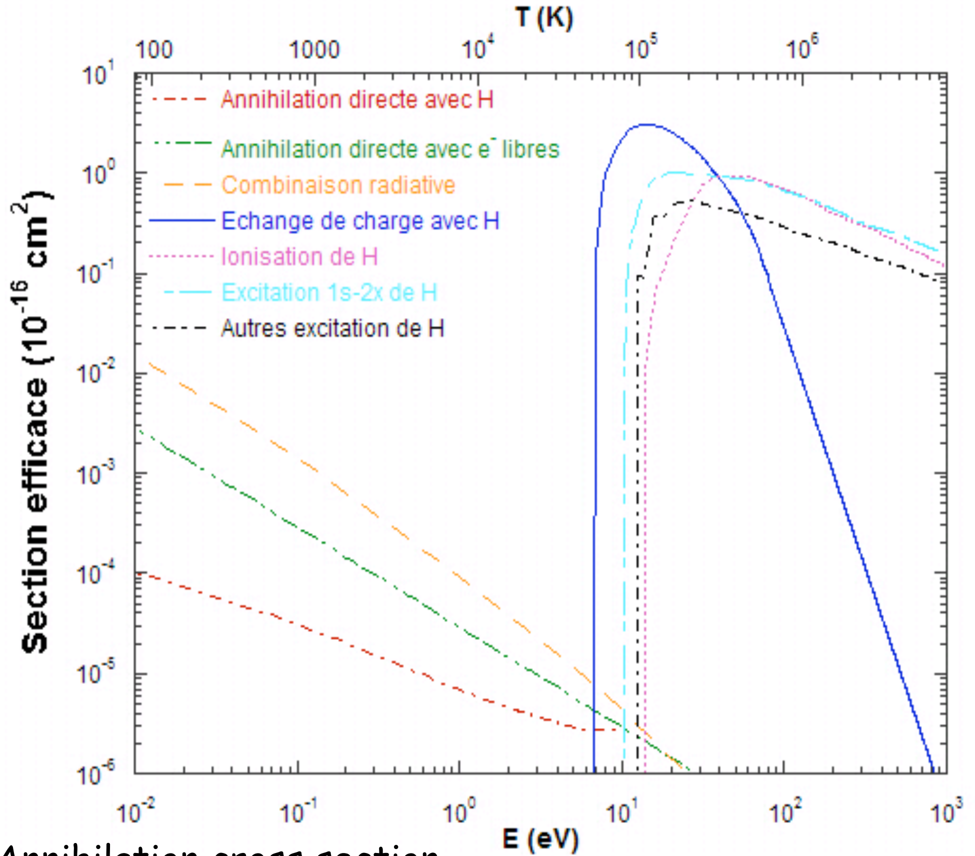
$$e^+ + H \rightarrow 2\gamma + H^+$$
$$e^+ + H_2 \rightarrow 2\gamma + H_2^+$$
$$e^+ + He \rightarrow 2\gamma + He^+$$

5: Annihilation on dust grains

Annihilation spectra:

Life and death of the positron

	T (K)	elements
MM	80	H_2, He
CM	100	HI, He
WNM	8000	HI, He
WIM	8000	HII, e^-, He
HM	10^6	HII, e^-, He^{++}

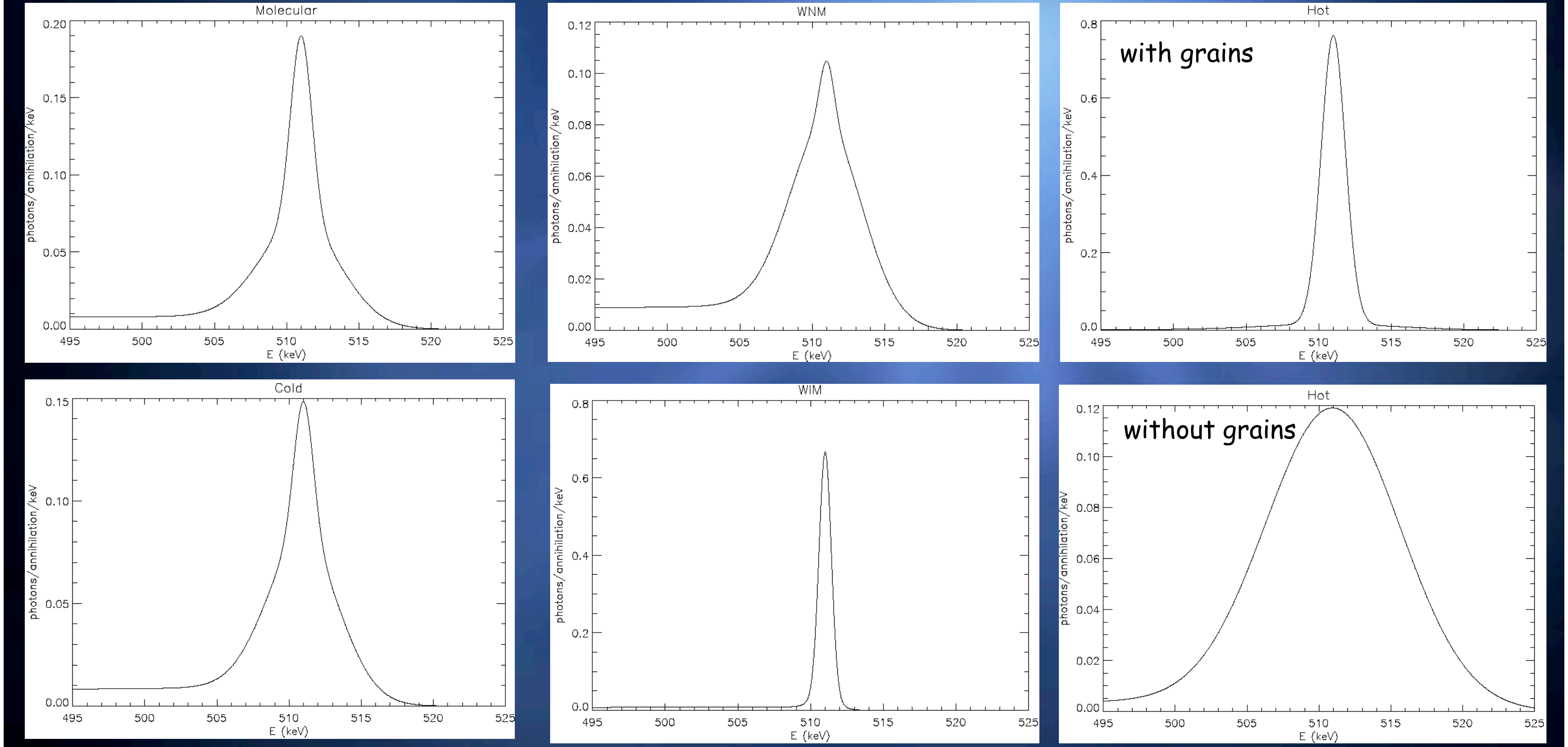


Annihilation cross section

Guessoum, Jean & Gillard, A&A 2005

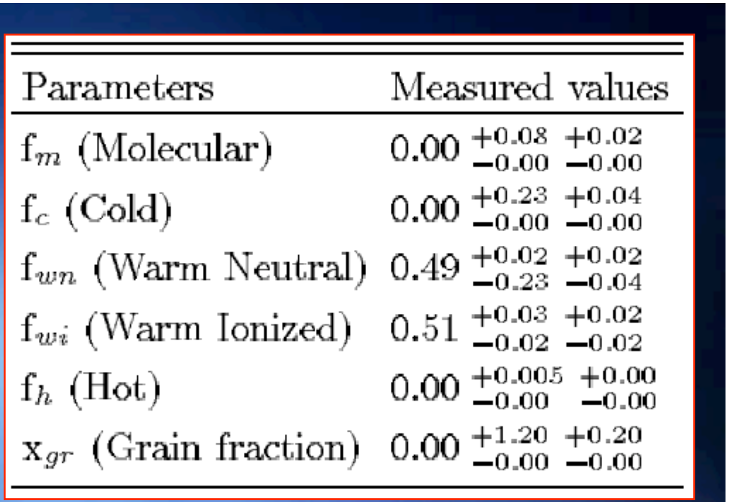
Annihilation spectra:

Astrophysical model



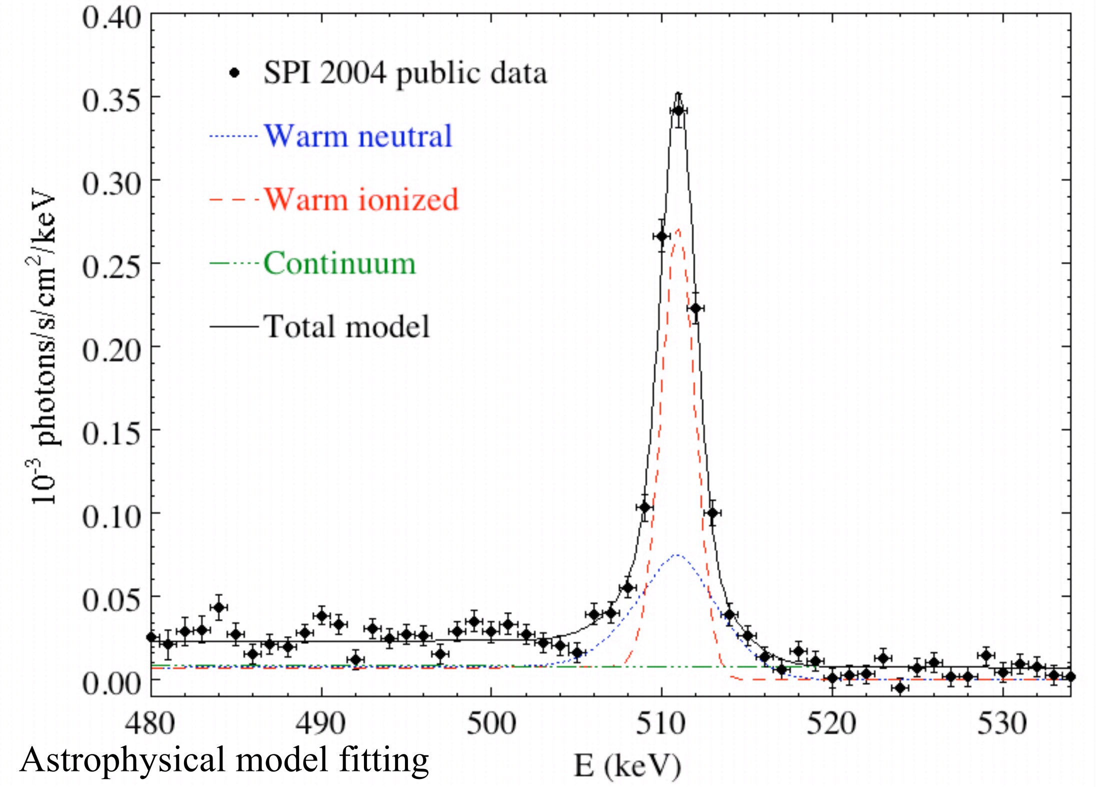
Theoretical annihilation spectra in each phase of the ISM
(Guessoum, Jean & Gillard, A&A 2005)

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



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)	$0.00\,^{+1.20}_{-0.00}\,^{+0.20}_{-0.00}$

f_i : contribution of phase i
S_i: Spectrum of phase i, convolved with response of SPI



Astrophysical model fitting

Jean et al. A&A in press

Ps fraction : 93.5 ±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 of the ISM

Positron in the Galactic Bulge

Diffusion of positron ?

n [cm^{-3}]	ϕ_v [%]	f_i [%]	half-size [pc]	E_{ql} [keV]	d_{max} [pc]	R < 600 pc
$10^3 - 10^7$	< 1	**< 8**	3 -30	10^{-3}	1.	Molecular medium
~ 10^2	< 1	**< 23**	~ 5	0.03	4.8	Cold neutral medium
~ 6.5	~ 20	**~ 49**	0.1 - 50	2.9	47.9	Warm neutral medium
~ 6.5	~ 10	**~ 51**	10 - 100	5.5	44.0	Warm ionized medium
~ 0.01	> 70	**< 0.5**	50 - 100	270	5600	Hot medium

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

Positron in the Galactic Bulge

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

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

-> $d_i \sim \surd\,(6D_i\tau)$
-> $d_{max} = d_{ql} + d_{coll}$

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

=> 1 MeV positrons escape the hot phase

Conclusion

-Results of the spectral analysis :

-> 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

-> low energy positrons E ≤ ~MeV

-Future work :

-> Spectral analysis of the 511 keV emitted by two bulge regions.

-> Spectral analysis of the galactic plane e+e- annihilation emission.

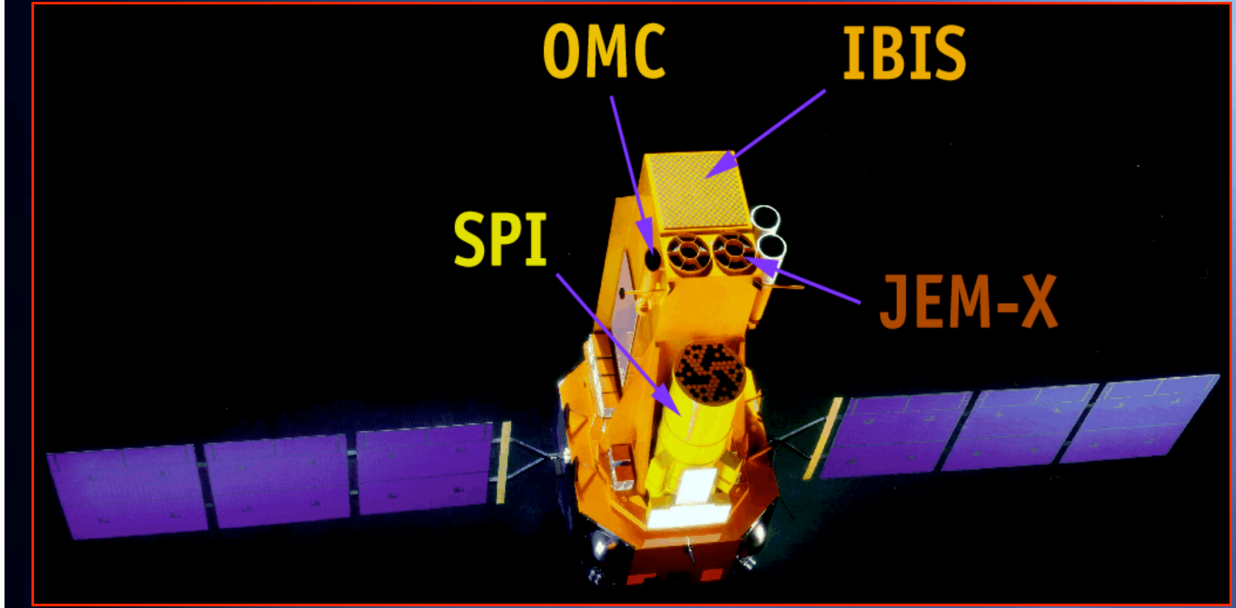
-> Gas content in the galactic bulge (Gillard et al. in prep.)

-> What is the diffusion regime of low energy positrons

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"

• Origin of positrons

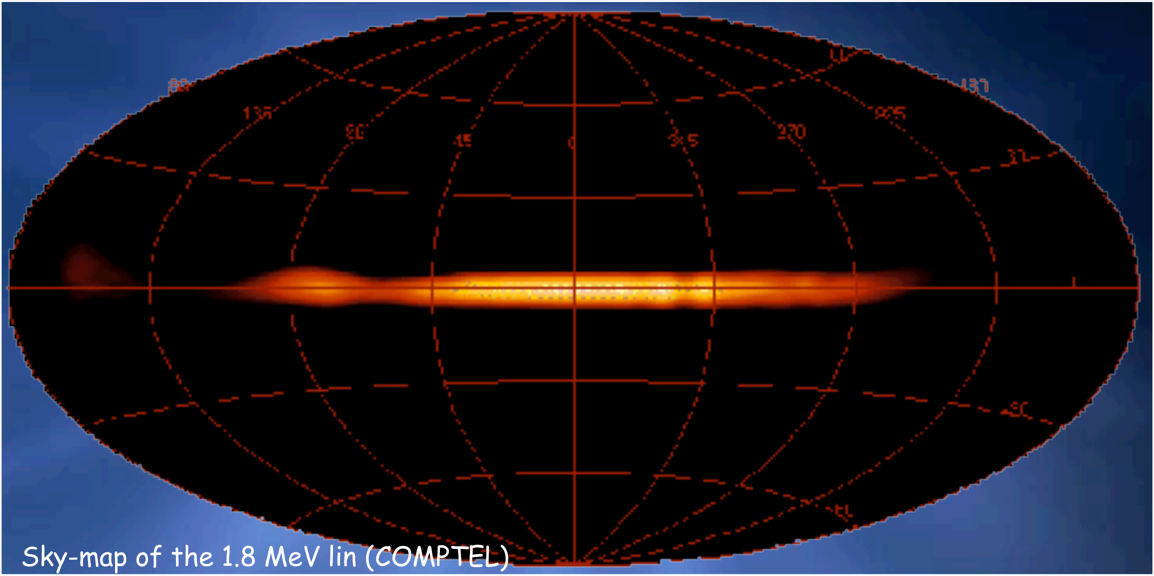
Observationnal facts

- Annihilation rates: (1.5±0.1) × 10^{43} s^{-1} in the bulge
  (0.3±0.2) × 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 lin (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 $\Rightarrow M_{44} \sim (3\pm1)\ 10^{-6}\ M_*$ (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

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

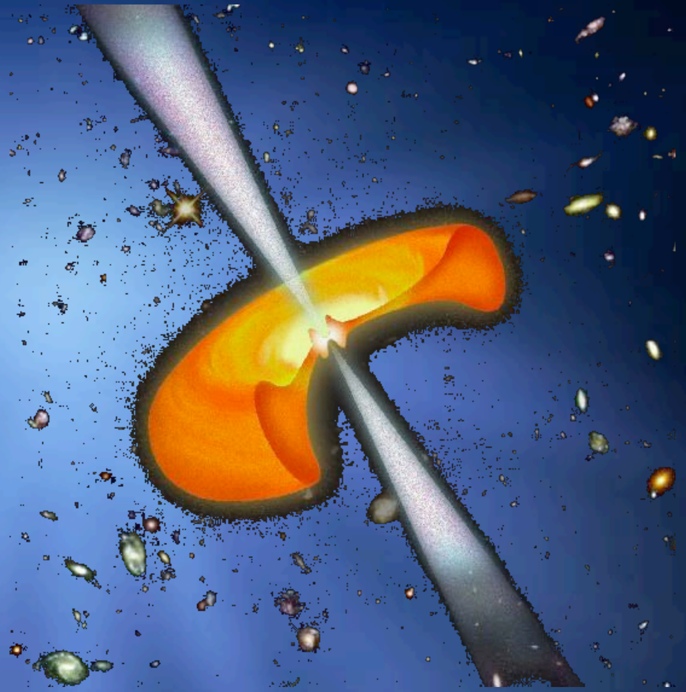
$M_{56} \sim 0.6\ M_*$ & $\nu_{SNIa} \sim 0.003\ yr^{-1}$

-> f is uncertain (< 5%, Milne, The & Leising, 2001)

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

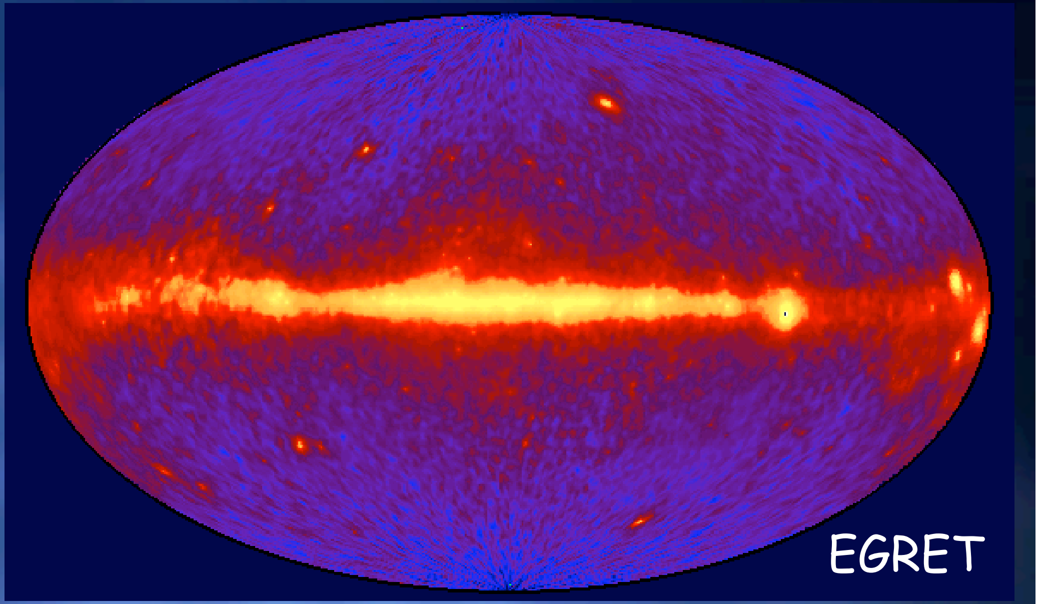
Thermonuclear runaway in the enveloppe of an accreting WD in a binary system.

$^{22}Na \to {}^{22}Ne + \beta^+$ - 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 $R_{e+} \sim R_{\pi+} \sim R_{\pi 0} \sim R_{\gamma>100MeV}$

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

Pulsars

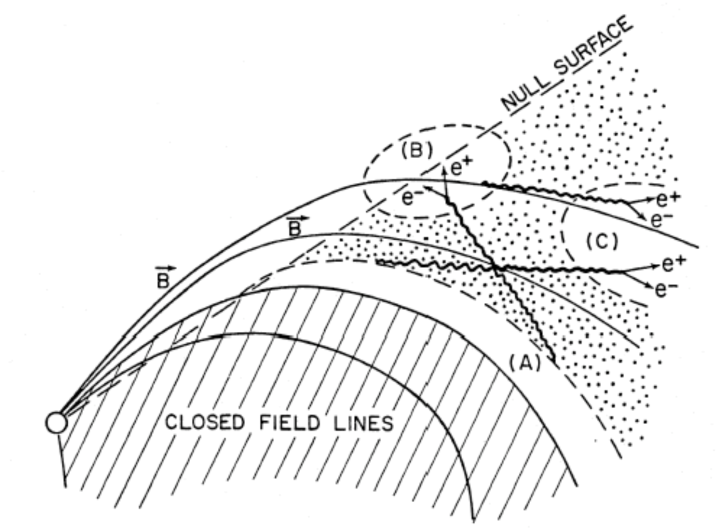
- Harding & Ramaty, 1987

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

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

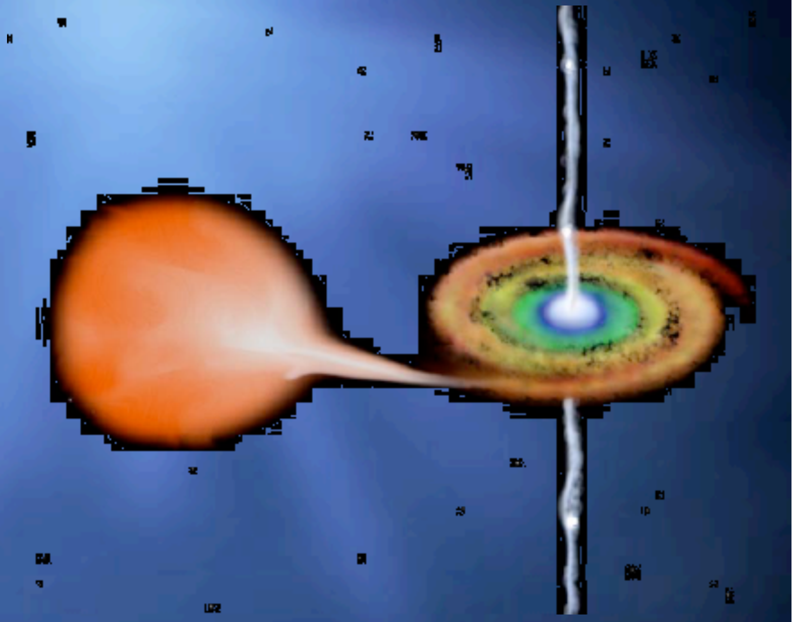
e^+e^- in jets through $\gamma + \gamma \rightarrow e^+ + e^-$

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

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

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

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



Guessoum, Jean & Prantzos, in prep.

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