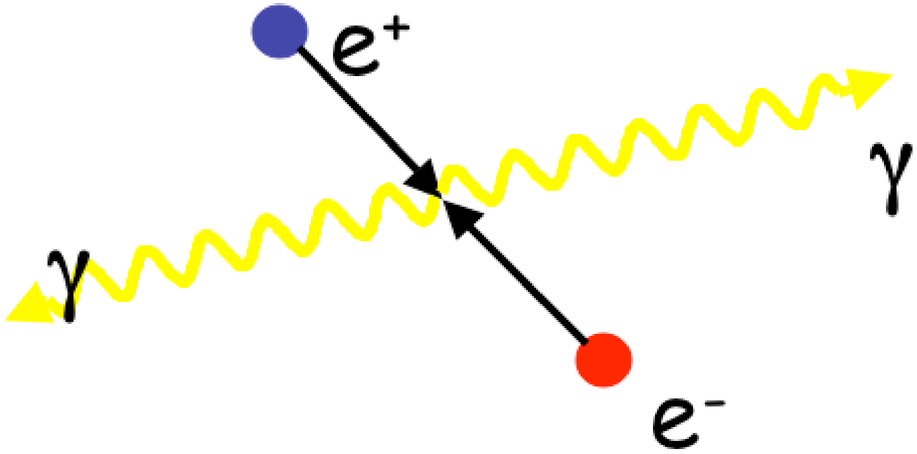
THE 511 keV AS SEEN BY INTEGRAL

LOW-ENERGY POSITRONS IN OUR GALAXY



- Introduction
- SPI/INTEGRAL observations
- Possible sources of positrons
- Propagation of low energy positrons
- Conclusions

Production of e^+ in the Galaxy

- β^+ isotopes	-> SNe, novae … $Xp \to Xn + e^+ + \nu_e$	-> $E_{e+} \sim 1$ MeV
- π^+ decay	-> CR interactions with ISM $p + p \to p + n + \pi^+$ and $\pi^+ \to \mu^+ \to e^+$	-> $E_{e+} \sim 10\text{-}100$ MeV
- e^+e^- pair production	-> accretion disks & jets $\gamma + \gamma \to e^+ + e^-$	-> $E_{e+} \leq 1$ MeV
	-> pulsar magnetosphere $\gamma + \gamma \to e^+ + e^-$	-> $E_{e+} \sim 1\text{-}1000$ GeV
- exotic processes	-> e.g. dark matter, … $dm + dm \to e^+ + e^-$	-> $E_{e+} \sim ?$ MeV

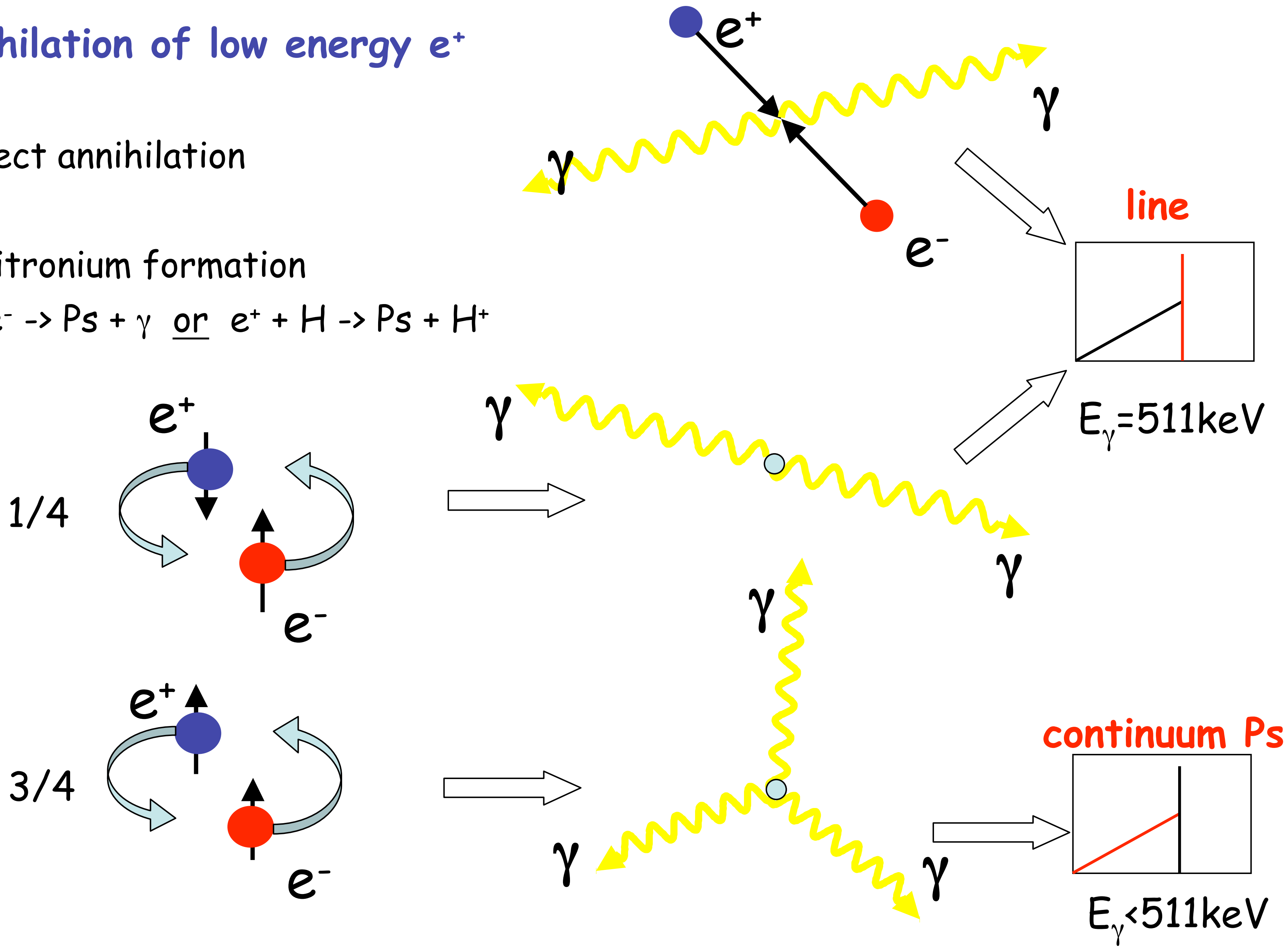
Origin of galactic e^+ is yet unknown

Annihilation of low energy e^+

- Direct annihilation

- Positronium formation

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



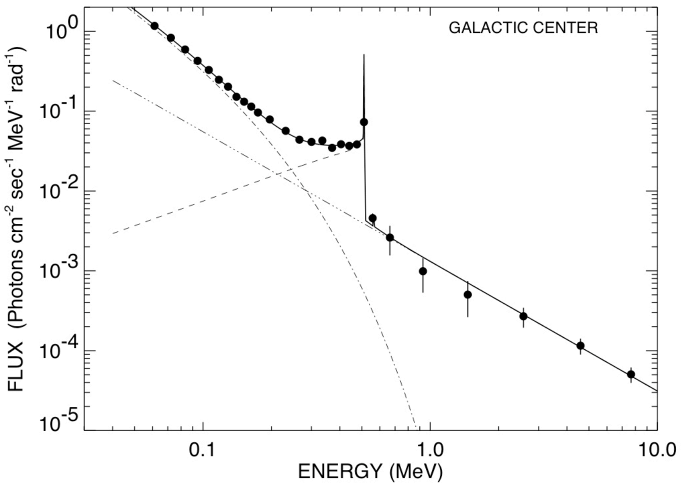
History of observations prior to INTEGRAL

- 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
- 1981-1985	SMM
- 1991-1997	OSSE -> First maps
- 1995-1997	TGRS

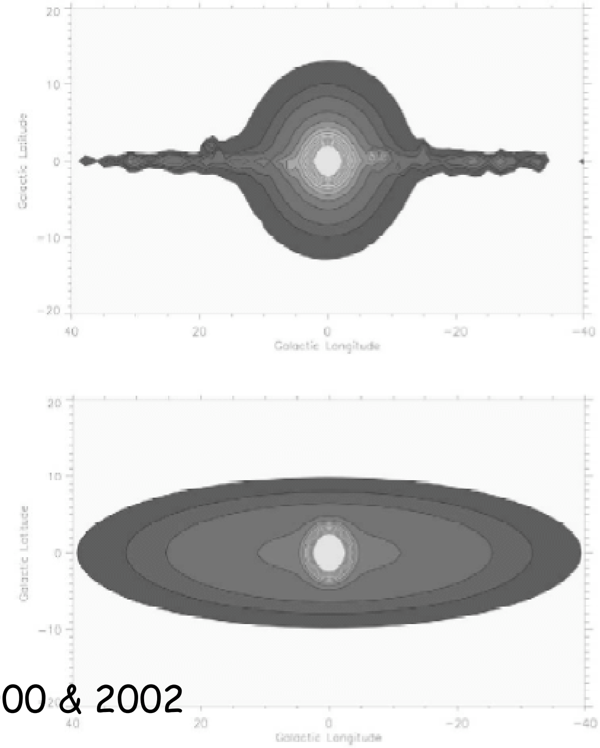
GC flux ~ $10^{-3}\ \gamma\ s^{-1}\ cm^{-2}$

f_{Ps} = (93 ± 4)%

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



Kinzer et al., 2001

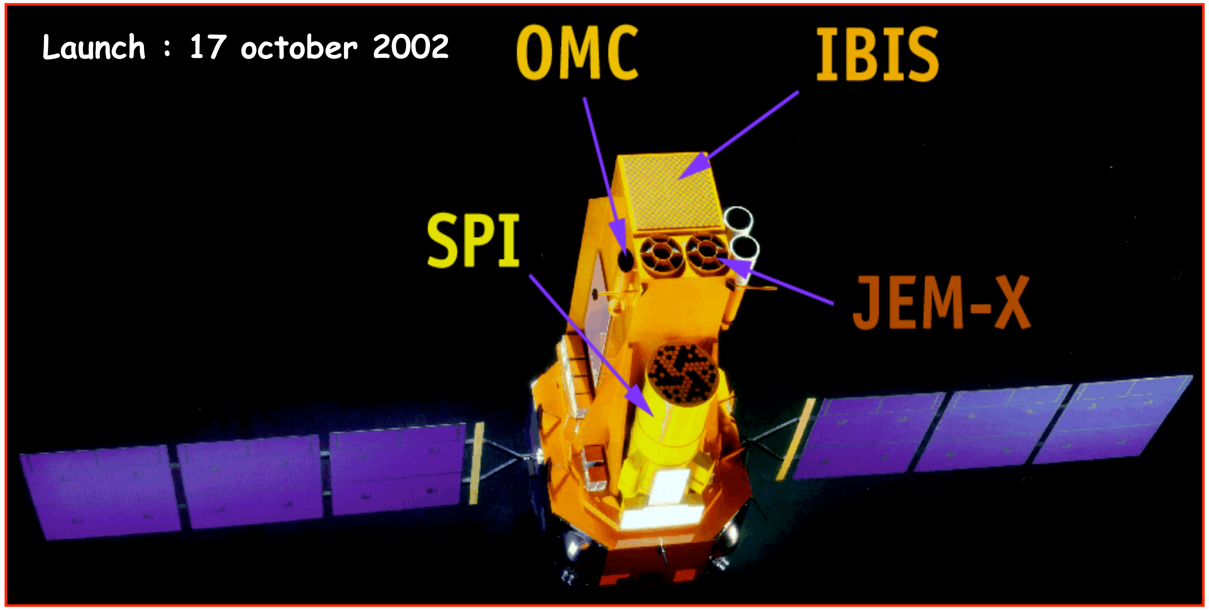


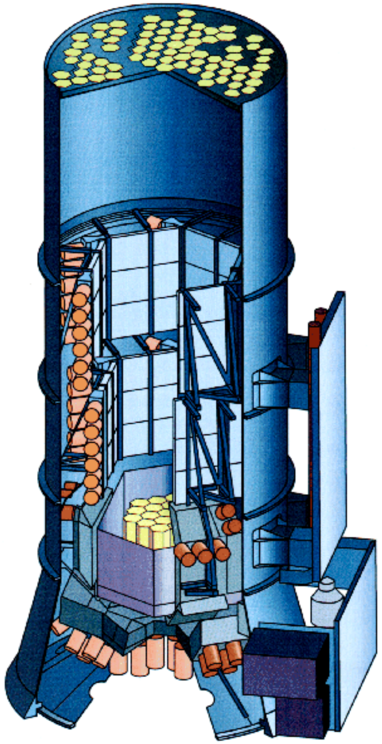
Milne et al., 2000 & 2002

Observation with SPI/INTEGRAL

INTEGRAL

ESA's INTErnational Gamma-Ray Astrophysics Laboratory





19 germanium detectors

Energy range : 20 keV - 8 MeV

$\Delta E \approx 2$ keV at 1 MeV

Field of view ≈ 20°

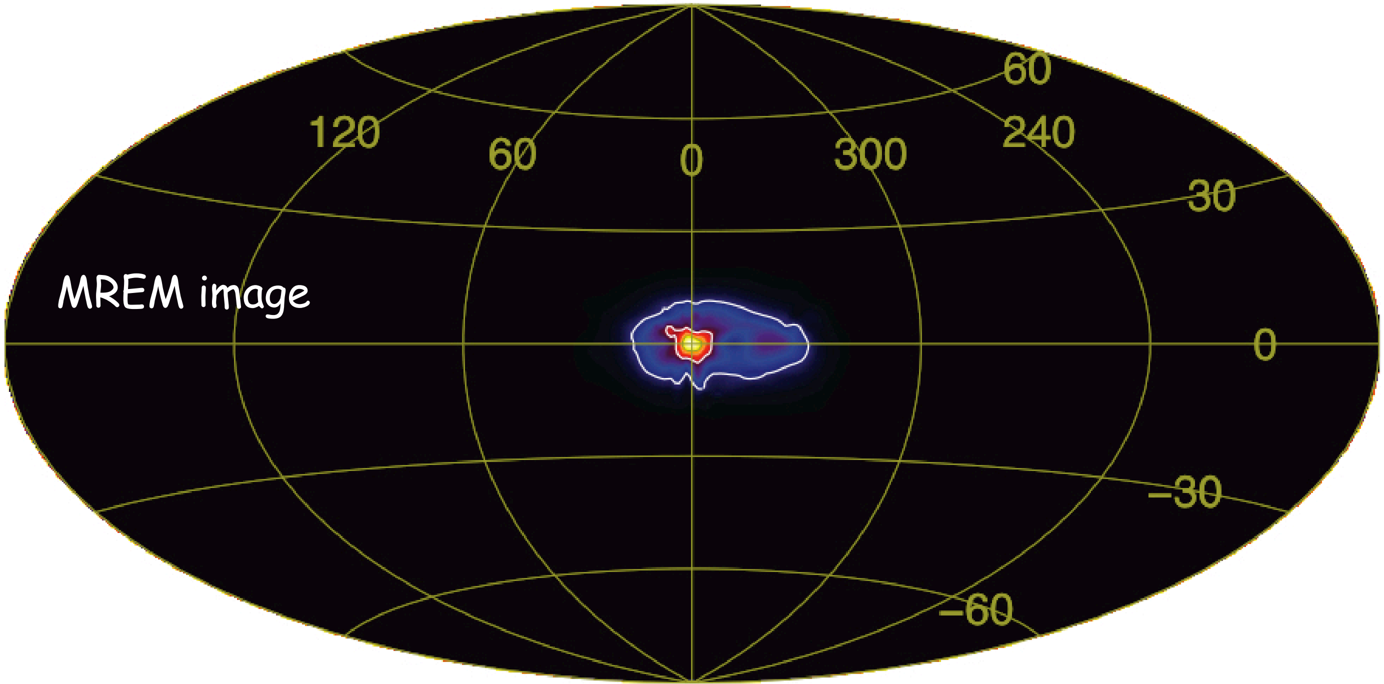
Angular resolution ≈2°

Scientific objectives of SPI : nucleosynthesis, diffuse emissions, origin of positrons

- Imaging the annihilation emission => spatial distribution of the sources
- Spectroscopy ($f_{Ps} = N_{Ps}/N_{ann}$ and line shape) => conditions of ISM where e^+ annihilate

Observation with SPI/INTEGRAL

Imaging: the all-sky distribution of the 511 keV line emission



Weidenspointer et al., 2008

Morphological analysis by model fitting :

- Bulge : 2 Gaussians : 3° & 11° FWHM, Flux ~ 10^{-3} γ/s/cm^2
- Galactic disk : Asymmetric, F(l<0°) = 1.7 × F(l>0°), Flux ~ 7 × 10^{-4} γ/s/cm^2

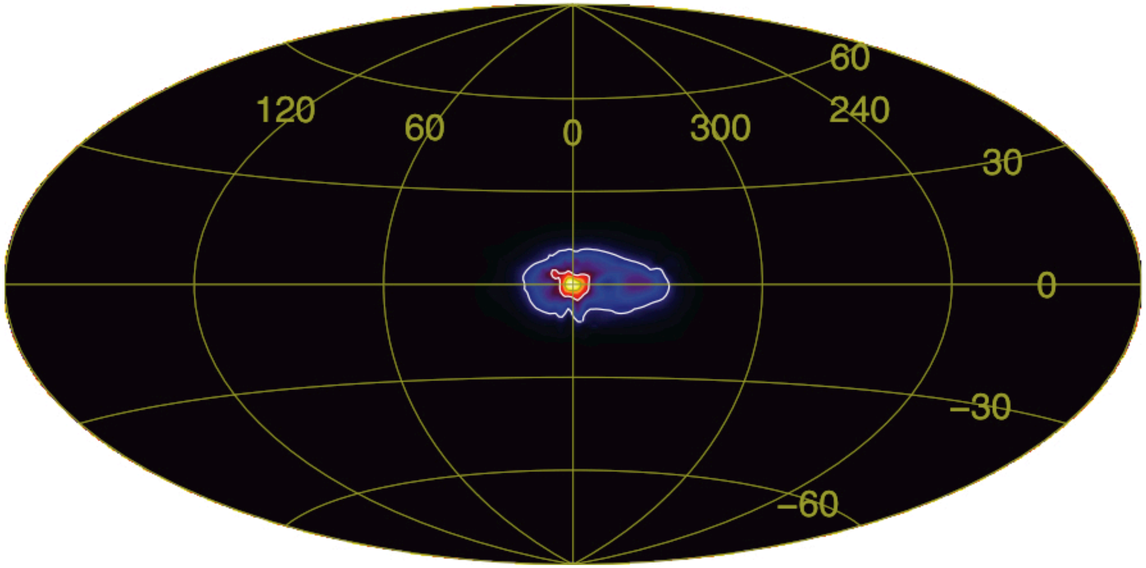
-> no point sources

-> B/D flux ratio ~ 0.8-2.9 : old star population favored if e^+ annihilate close to their sources

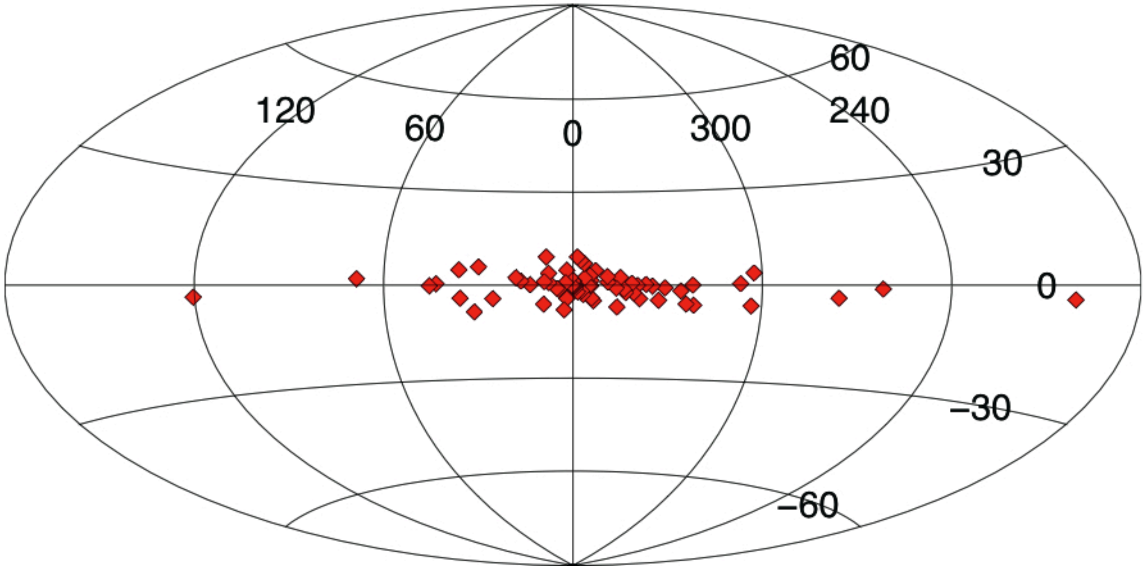
-> Similar asymmetry in the spatial distribution of LMXBs emitting at high energy

Observation with SPI/INTEGRAL

Imaging: the all-sky distribution of the 511 keV line emission



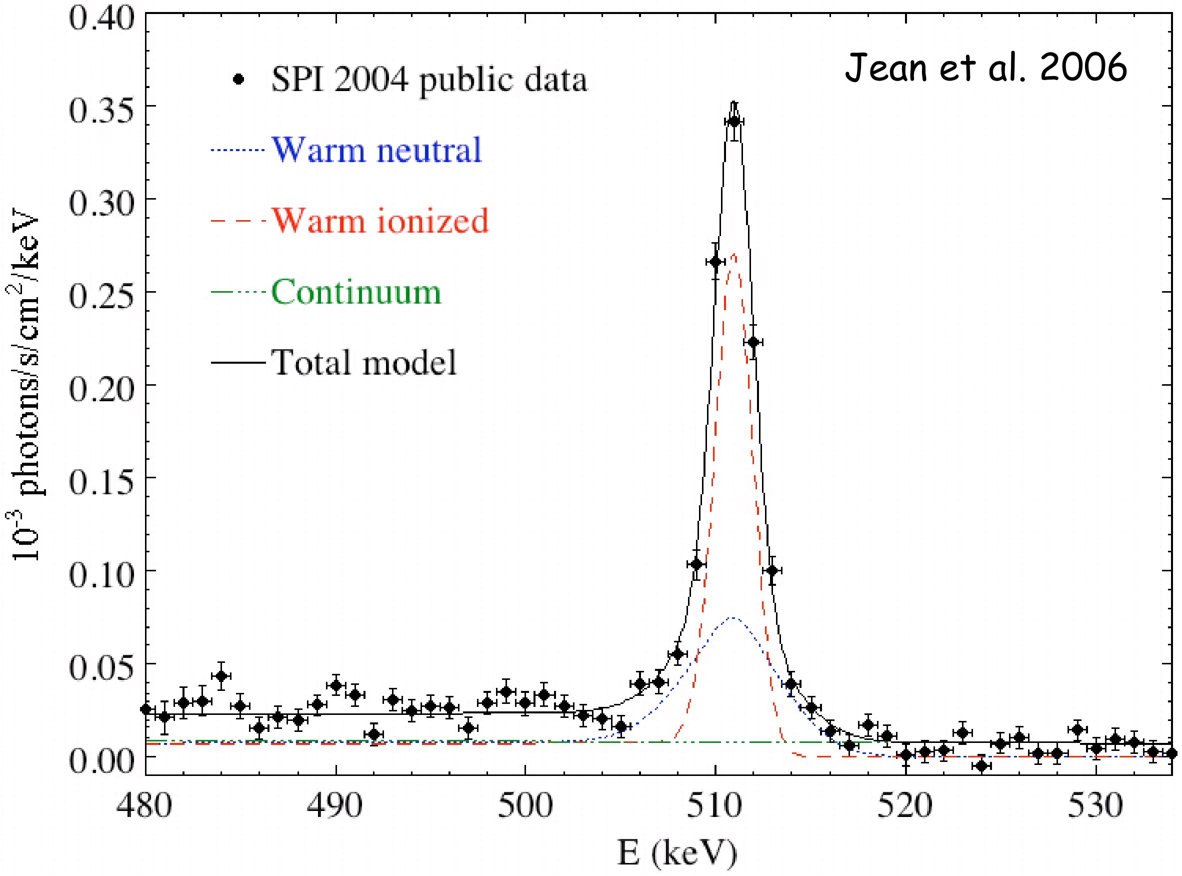
A MREM image of the 511 keV emission



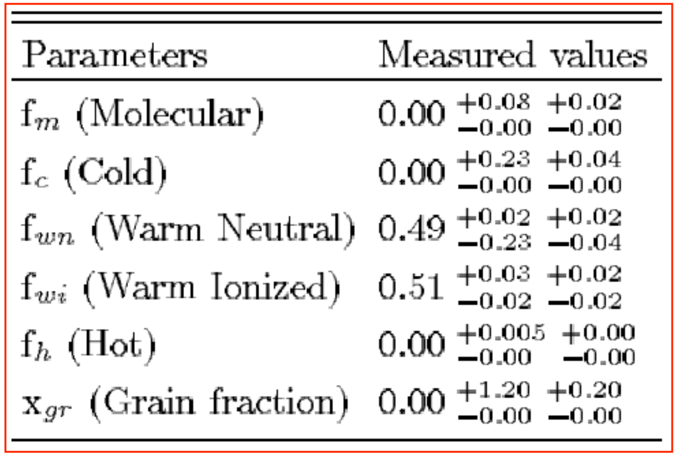
Hard LMXBs in the 3rd IBIS catalogue (Bird et al. 2007)

Observation with SPI/INTEGRAL

Spectral analysis: fit the phase fractions in the bulge



f_i : contribution of phase i



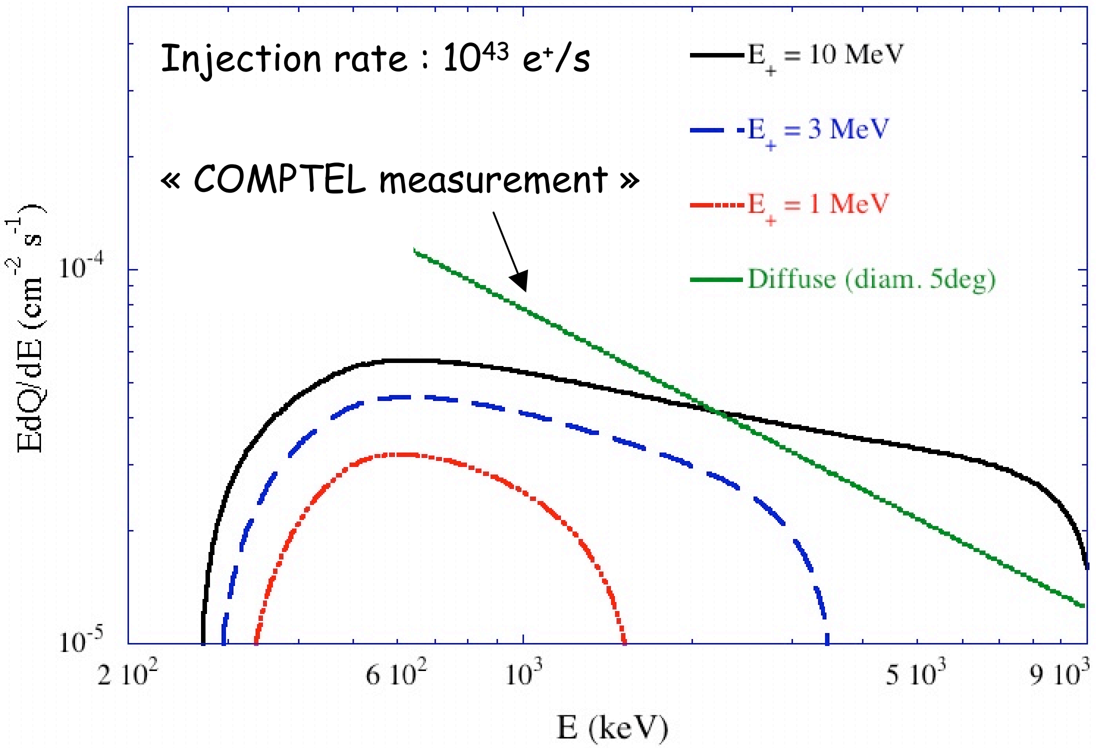
Parameters	Measured values
f_m (Molecular)	$0.00^{+0.08}_{-0.00}\ ^{+0.02}_{-0.00}$
f_c (Cold)	$0.00^{+0.23}_{-0.00}\ ^{+0.04}_{-0.00}$
f_{wn} (Warm Neutral)	$0.49^{+0.02}_{-0.23}\ ^{+0.02}_{-0.04}$
f_{wi} (Warm Ionized)	$0.51^{+0.03}_{-0.02}\ ^{+0.02}_{-0.02}$
f_h (Hot)	$0.00^{+0.005}_{-0.00}\ ^{+0.00}_{-0.00}$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

Ps fraction : (97±2) %

Positrons annihilate at energies < 10 eV, in warm phases (Jean et al. 2006) or in a warm slightly ionized phase (Churazov et al. 2005).

Observation with SPI/INTEGRAL

Spectral analysis: annihilation in flight of relativistic positrons



If positrons are produced in a **steady state** in the *GC* then their initial kinetic energy should be < 8 MeV else the intensity of the inflight annihilation emission would be detected at high energy (Aharonian & Atoyan 1981, Beacom & Yuksel 2006, Sizun et al. 2007)

Possible sources of positrons

Observational facts

- Annihilation rates: $(1.1 - 3.0) \times 10^{43}\ s^{-1}$ in the bulge
  $(0.8 - 0.5) \times 10^{43}\ s^{-1}$ in the disk
- Morphology: B/D ~ 1.4 - 6 (luminosity ratio)
  Possible asymmetry of the emission from the disk
- Spectral analysis: Initial kinetic energy of e^+ (steady state) < 8 MeV
  Positrons annihilate in warm phases

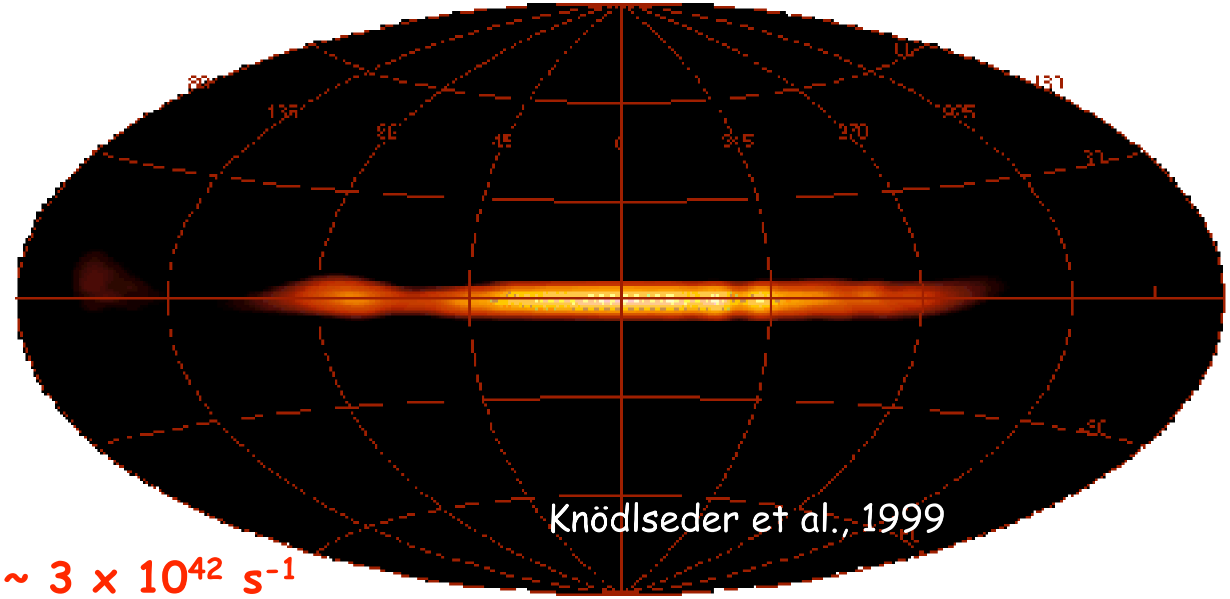
How to produce ~ $2\text{-}3 \times 10^{43}\ e^+/s$?

- β^+ isotopes produced in stars
  -> ^{26}Al : SNII, WR
  -> ^{44}Ti : SNII
  -> ^{56}Co : SNe
  -> ^{22}Na : O-Ne Novae → Not enough e^+ (Hernanz et al. 1999)
- Compact sources
  -> Black-holes
  -> Pulsars → Not enough e^+ (Harding & Ramaty 1987)
- Cosmic-rays
  -> $p + p \rightarrow p + n + \pi^+$ and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ →
- Dark matter →

$\}$ $E_+ > 10$ MeV

Possible sources 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

$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca + \beta^+$ ($T_{1/2} \sim 60$ 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 could explain all or a fraction of the disk emission

Possible sources 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 : $R_{e+} \propto f \times \nu_{SNIa} \times M_{56}$

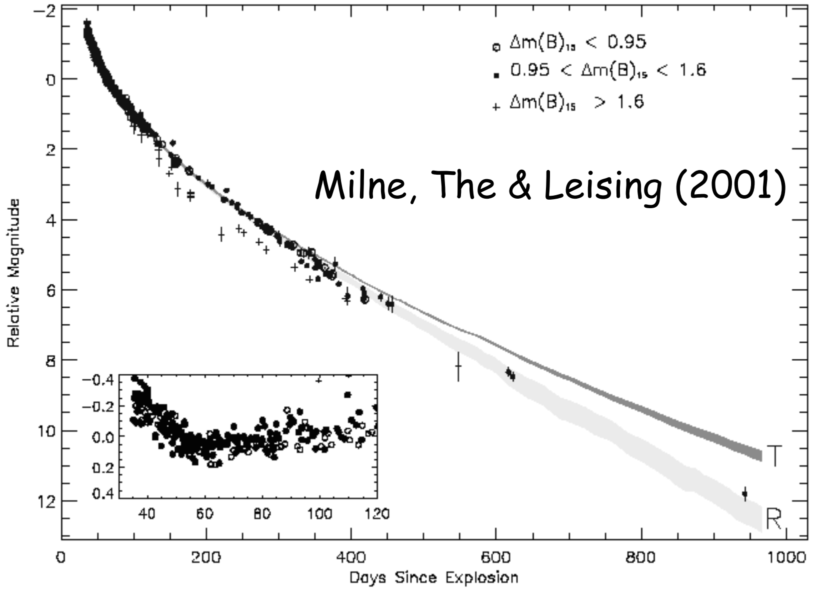
$M_{56} \sim 0.6\ M_{*}$ & $\nu_{SNIa} \sim 0.003\ \mathrm{yr}^{-1}$

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

=> $\mathbf{R_{e+} < 4 \times 10^{43}\ s^{-1}}$.

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

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

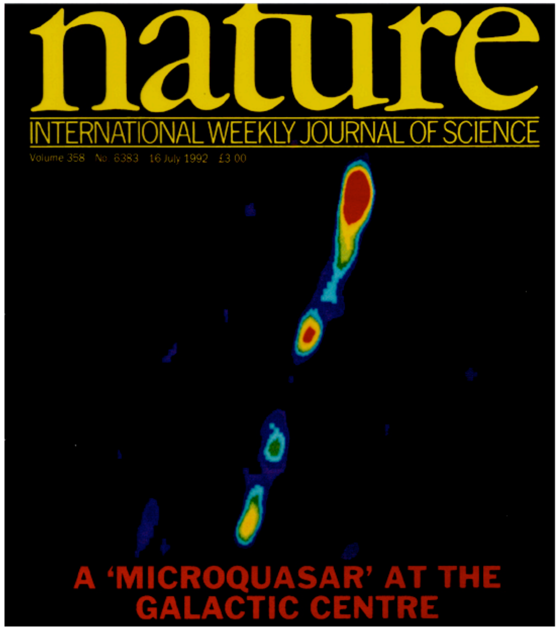


Milne, The & Leising (2001)

- Recent observation of bolometric light curves suggested **f ≈ 0** (Sollerman et al. 2004)
- Although SNeIa belong to the old population their distribution seems to give $(B/D)_{SNeIa} < 1$

Possible sources of positrons

LMXB/Microquasars (Guessoum, Jean & Prantzos, 2006)



nature

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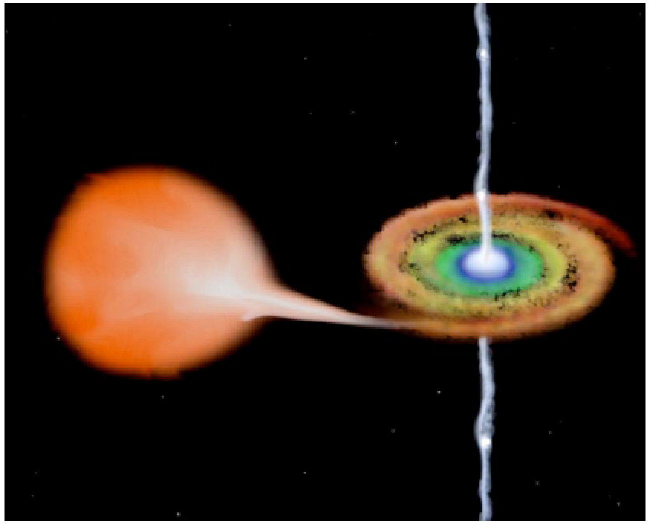
A 'MICROQUASAR' AT THE GALACTIC CENTRE

e^+ produced in the inner regions of accretion disks through $\gamma + \gamma \rightarrow e^+ + e^-$ ($T \sim 10^9$ K). Positrons could be ejected through jets or winds.

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

- Number of microquasars : $N_{\mu Q} \sim 100$ (Paredes 2005)
- $(B/D)_{LMXB} \sim 0.9$ (Grimm et al. 2002)

- $R_{bulge} = N_{\mu Q}(\text{Bulge}) \times R_+$ => $R_{bulge} \sim 5 \times 10^{42}\ e^+/s$
- $R_{disk} = N_{\mu Q}(\text{Disk}) \times R_+$ => $R_{disk} \sim 6 \times 10^{42}\ e^+/s$



LMXBs could explain e^+ from the disk, but :
- Nature of jet (leptonic, hadronic) is not known
- Do e^+ escape the inner regions of the accretion disk?

Bandyopadhyay et al. (2008): ~300-3000 faint LMXBs could explain emission from the bulge

Possible sources of positrons

Sgr A*

Disruption of stars in the vincinity of the supermassive black hole

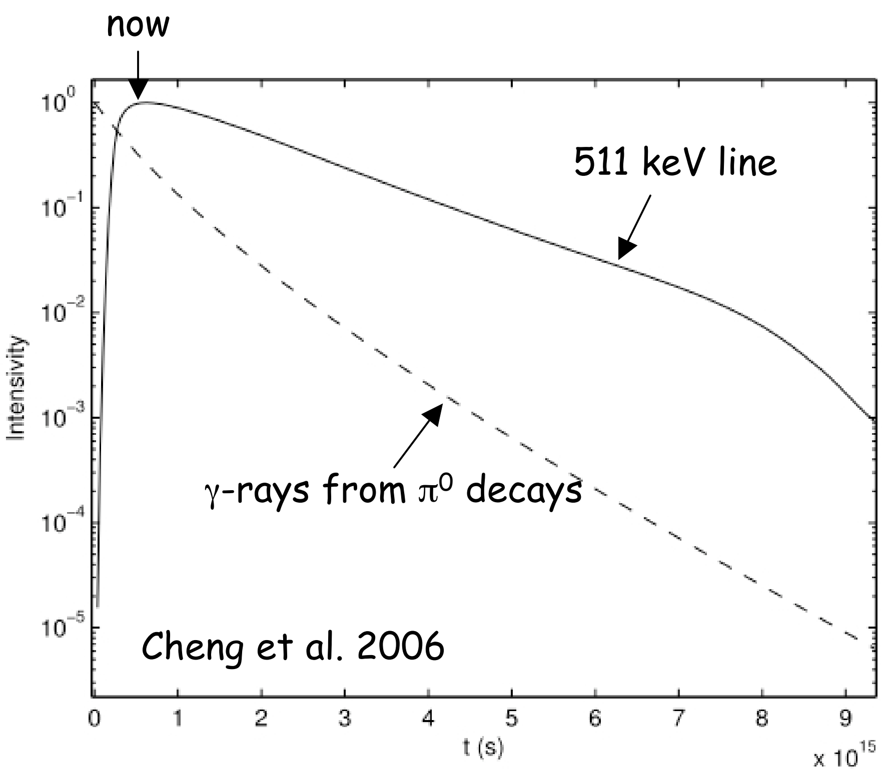
-> a massive star ~10^7 yrs ago (Cheng et al. 2006)

-> stars at a rate of 10^{-5} yr^{-1} (Cheng et al. 2007)

Positrons are produced via the decay of π^+ which are produced in pp collisions

Protons would be accelerated in shocks in the accretion disk.

=> Production of high energy positrons but not in a steady state.



now

511 keV line

γ-rays from π^0 decays

Cheng et al. 2006

Possible sources of positrons

Summary

Sources	Yield	Morph.	Comments
SNIa (^{56}Co)	0-100%	B/D<1	Difficulty for e^+ to escape the ejecta
SNII, WR (^{26}Al)	~15%	D	Could explain a fraction of the disk emission
SNII (^{44}Ti)	~10%	D	Could explain a fraction of the disk emission
LMXBs ($\gamma\gamma$)	0-50%	B/D~1	Could explain the disk emission & its asymmetry
Sgr A* burst (π^+)	0-100%	B	Could explain the bulge emission
Novae (^{22}Na)	~1%	B/D<1	Not enough positrons
Pulsars ($\gamma\gamma_B$)	~0.1%	D	High energy positrons & not enough positrons
Cosmic-rays (π^+)	~5%	D	High energy positrons & not enough positrons
Dark matter ($\chi\chi$)	?%	B	High energy positrons
SNII (^{56}Co)	0%	D	Positrons cannot escape the ejecta

Do the spatial distribution of the annihilation emission trace the spatial distribution of the sources?

Propagation of low energy positrons in the ISM

- Jean et al. (2006): point out uncertainties about the propagation of positrons in ISM and found difficulty for a single positron source to fill the bulge

- Prantzos (2006): suggested that SNIa positrons from the disk might be transported toward the bulge where they annihilate (see also Higdon et al., 2009)

- Jean, Gillard, Marcowith & Ferrière, in prep.: study the propagation of $E<10$ MeV positrons
  - Positrons do not scatter with MHD waves in neutral media
  - Positrons would scatter with MHD waves in WIM & hot when $E>E_{min} \sim 0.01\text{-}1$MeV
  - Positrons that do not scatter with MHD waves, propagate along the turbulent magnetic field lines (collisional transport)

- Low energy e^+ could propagate far from their creation sites: d_{max}(1MeV)~20 kpc/n_H

- The spatial distribution of the 511 keV emission should trace the magnetic field lines

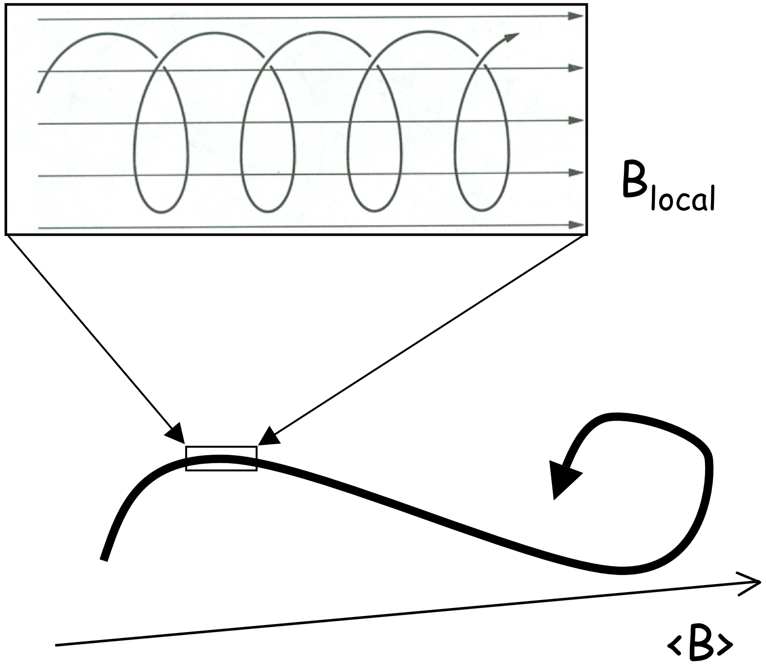
- Positrons escape the hot ionized medium before annihilating.
=> Filling factors of CNM & MM being low, e^+ annihilate mostly in warm phases

Propagation of low energy positrons in the ISM

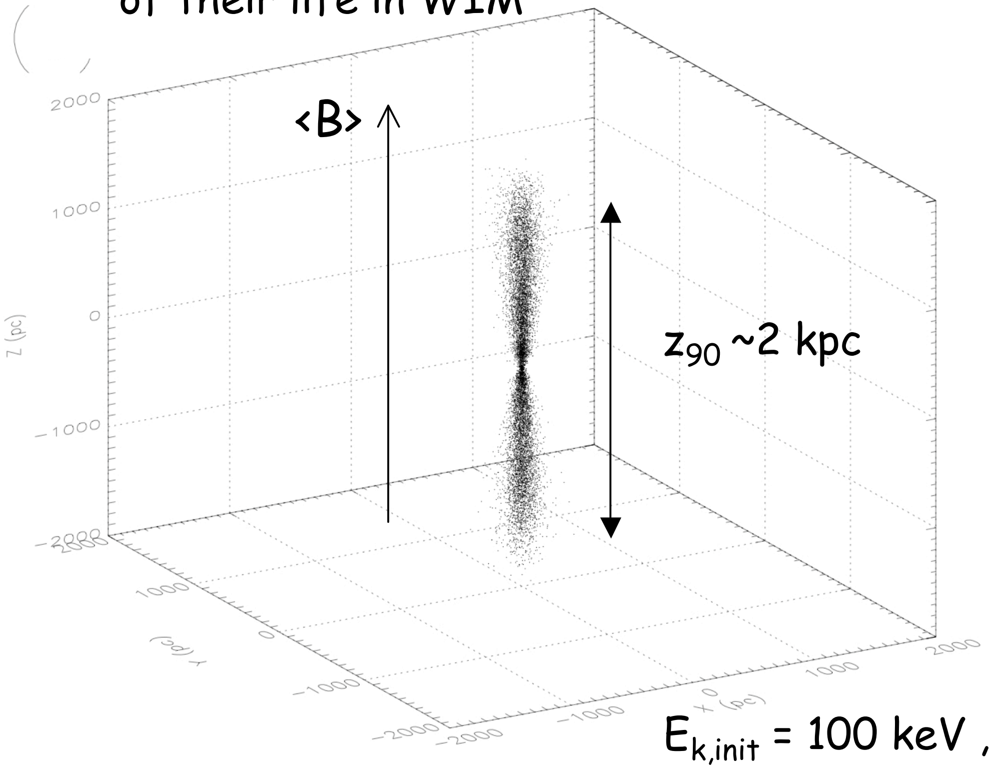
- **Collisional transport**

-> propagation along turbulent magnetic field lines with a ballistic motion

-> pitch-angle slightly scattered in collisions with gas particles



Spatial distribution of e^+ at the end of their life in WIM



$E_{k,init}$ = 100 keV ,
$\Delta B/\langle B\rangle$ = 1,
λ_{max} = 10 pc

Conclusions

- Observations
  - Asymmetry of the disk emission (has to be confirmed, observations in progress)
  - Positrons annihilate in the warm phases

- Most popular solutions to explain the 511 keV emission
  - In the galactic disk: ^{26}Al & ^{44}Ti from massive stars, LMXBs
  - Origin of positrons in the bulge: Sgr A* ? Hidden LMXBs ?
  - Disk & bulge: ^{56}Co from SN Ia & propagation (Prantzos 2006, Higdon et al. 2009)

- How low energy positrons propagate in the ISM?
  - Low energy positrons propagate along magnetic field lines
  - Need for simulations of the transport at Galactic scale (Galprop like modeling)
  - Search for the 511 keV line from e^+ emitted by ^{26}Al in the Cygnus region