THE 511 keV EMISSION OF POSITRON ANNIHILATION IN THE MILKY WAY

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Marcowith, Moskalenko, Strong, Weidenspointner

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Annihilation of positrons with electrons

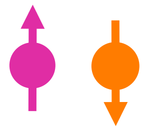
Either **directly** (2 γ of E = 511 keV each),
or, after formation of **Positronium (Ps)**, with probability **f**

Probability:
1/4

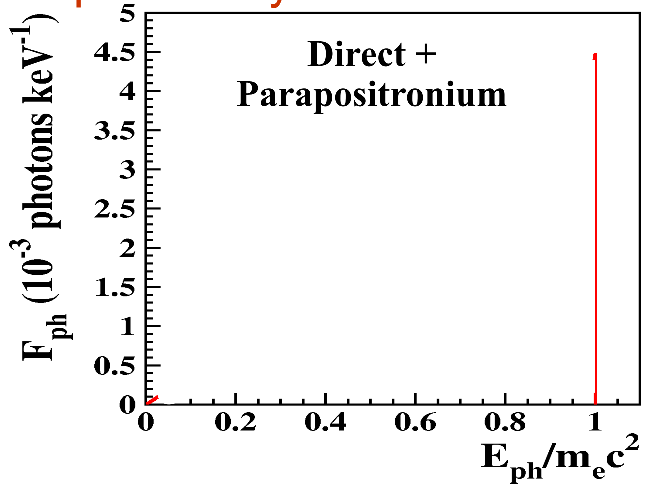
Parapositronium

S=0
(singlet)

$^{1}S_{0}$



$\tau = 1.25\ 10^{-10}$ s $\rightarrow$ **2 γ** of E = 511 keV

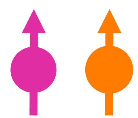


Probability:
3/4

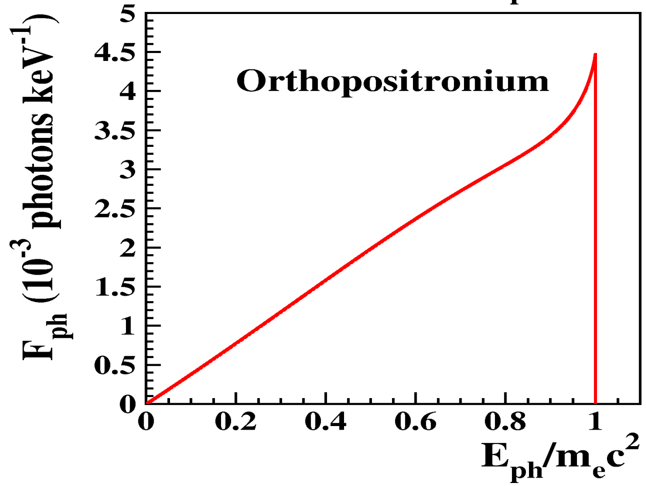
Orthopositronium

S=1
(triplet)

$^{3}S_{1}$



$\tau = 1.4\ 10^{-7}$ s $\longrightarrow$ **3 γ** of $E \leq 511$ keV



$F_{2\gamma} = 2(1-f) + 1/4\ \ 2f$
(direct) (paraPs)

$F_{3\gamma} = 3/4\ \ 3f$
(orthoPs)

$$f = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})}$$

Positronium fraction

Positron annihilation radiation from the Galactic center region

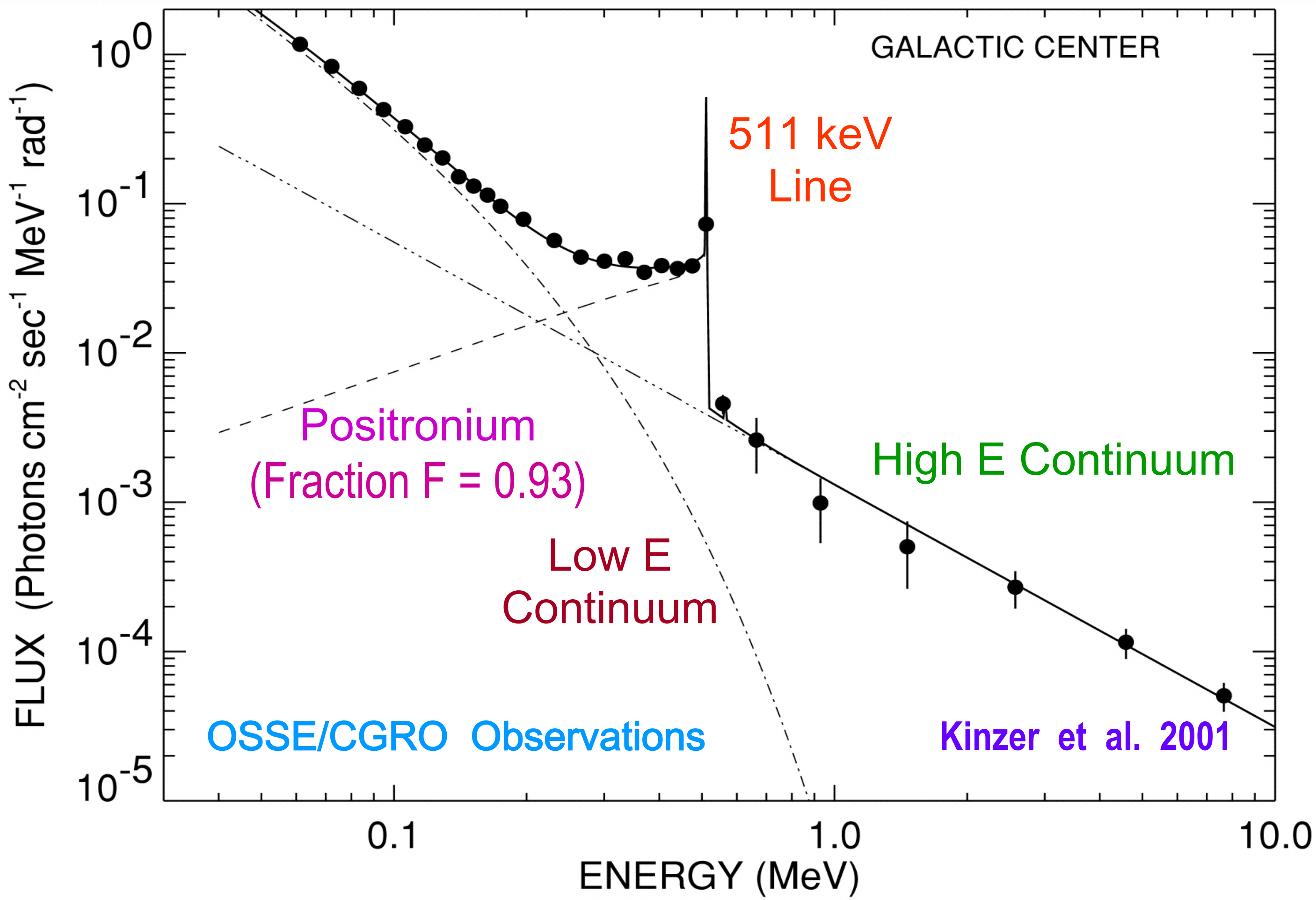
First (and brightest) γ-ray line detected from outside the solar system

(**Johnson et al. 1972**, *Rice U*. Na detector : **Leventhal et al. 1978** *Bell-Sandia* Ge detector)

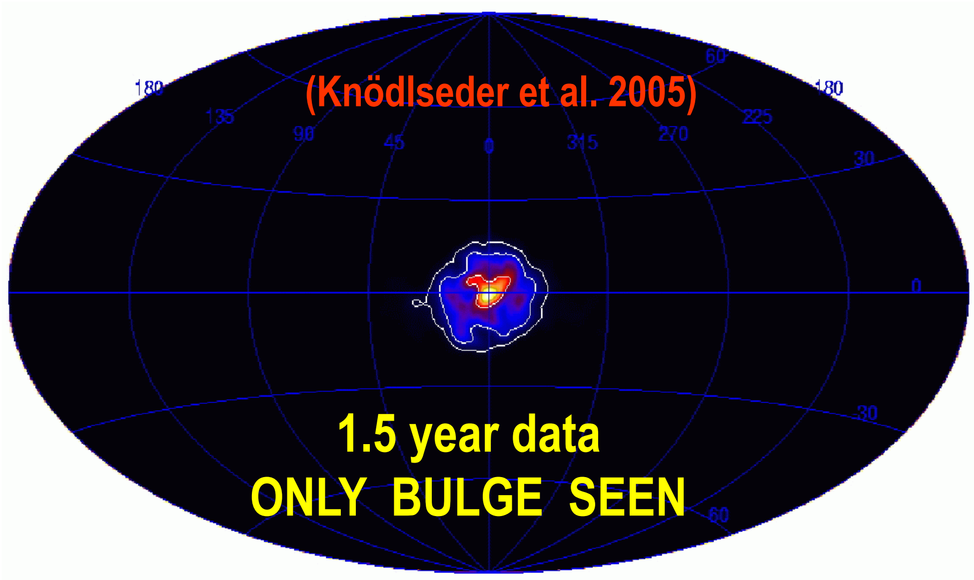
Flux (~10^{-3} cm^{-2} s^{-1}) + Distance (8 kpc~27000 l.y.)⟹ Luminosity ~10^{37} erg/s (a few 10^3 $L_{\odot}$)

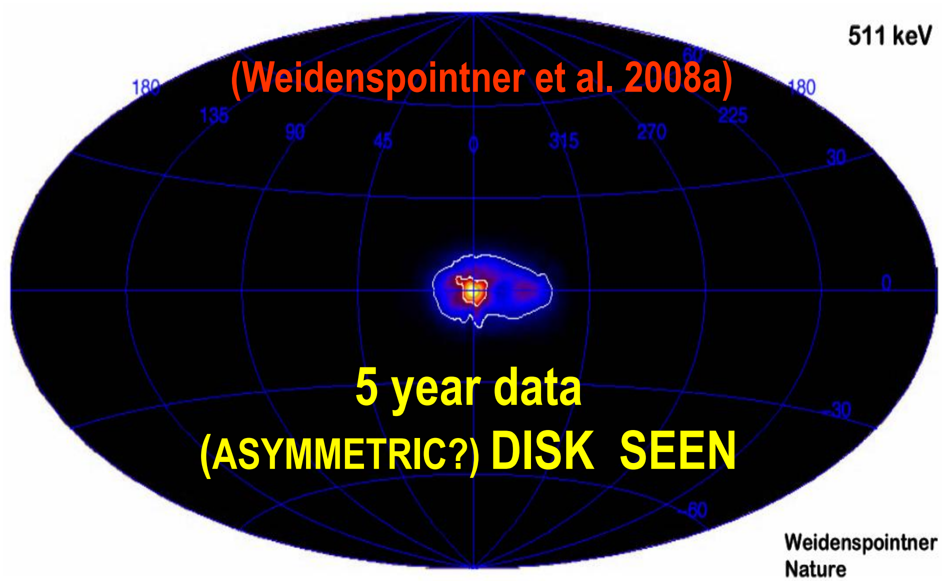
Positron annihilation rate : ~2 10^{43} s^{-1}

If activity maintained for 10^{10} years : 3 $M_{\odot}$ of positrons annihilated



SPI / INTEGRAL all-sky distribution of the 511 keV line of $e^- - e^+$ annihilation

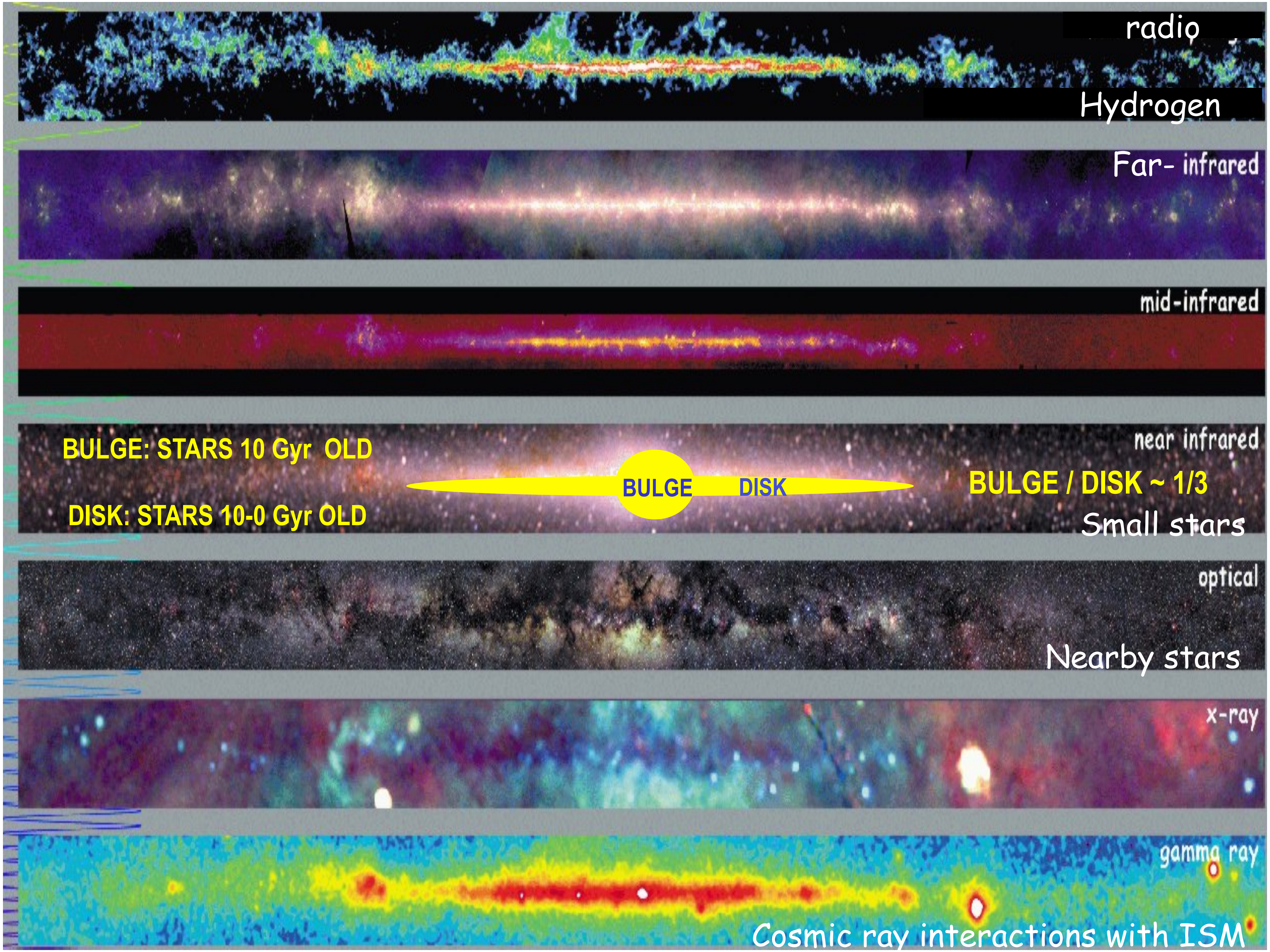




Weidenspointner et al. (2008b) :

	F_{511} $(10^{-4}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	L_{511} $(10^{42}\ \mathrm{s}^{-1})$	$\dot{N}_{e+}$ $(10^{42}\ \mathrm{s}^{-1})$
Bulge + thick disk			
Narrow bulge	$2.7^{+0.9}_{-0.4}$	$2.3^{+0.8}_{-0.7}$	$4.1^{+1.5}_{-1.2}$
Broad bulge	$4.8^{+0.7}_{-0.4}$	$4.1^{+0.6}_{-0.4}$	$7.4^{+1.0}_{-0.8}$
Thick disk	$9.4^{+1.8}_{-1.4}$	$4.5^{+0.8}_{-0.7}$	$8.1^{+1.5}_{-1.4}$
Total	17.1	10.9	19.6
Bulge/Disk	0.8	1.4	1.4

High Bulge/Disk emission ratio: No equivalent in any other wavelength !



radio
Hydrogen
Far- infrared
mid-infrared
near infrared
BULGE: STARS 10 Gyr OLD
DISK: STARS 10-0 Gyr OLD
BULGE
DISK
BULGE / DISK ~ 1/3
Small stars
optical
Nearby stars
x-ray
gamma ray
Cosmic ray interactions with ISM

Requirements from the positron source(s)

1) Total production Rate *(Steady state)* **: ~2. 10^{43} e^+ s^{-1}**

~1.2 10^{43} e^+ s^{-1} (Bulge)

~0.8 10^{43} e^+ s^{-1} (Disk)

2) Morphology: Bulge/Disk ~1.4

(assuming that positrons annihilate close to their sources)

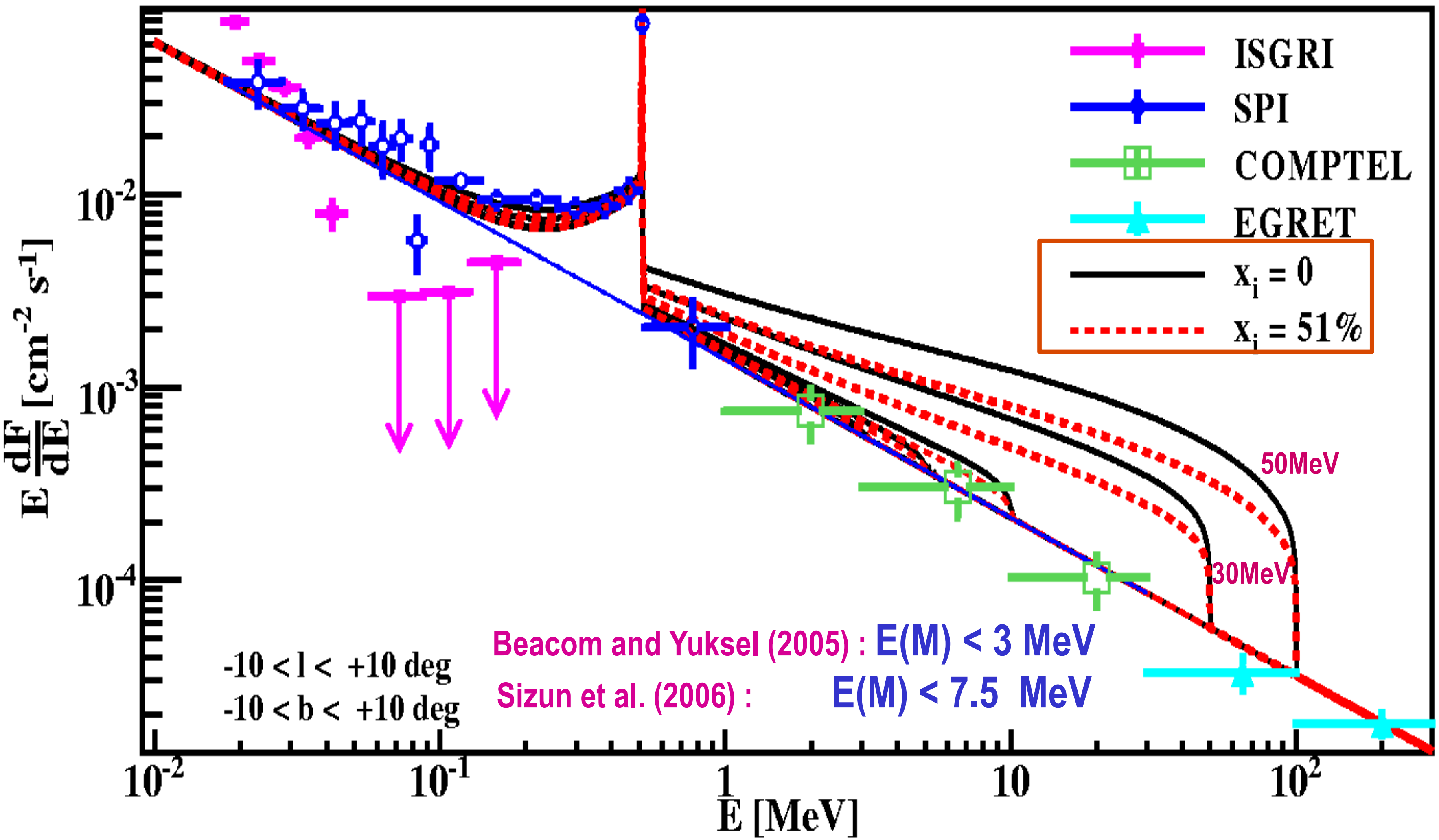
3) Positron injection energy < a few MeV

(constraint from observed GC spectrum in MeV region)

Spectrum in the > MeV region: constrains the energy of *released* e+

(or the mass of their parent dark matter particles)

because they may annihilate in-flight

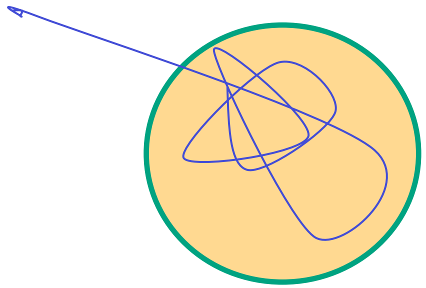


IF Dark Matter : particle mass much smaller than "canonical" (GeV) values

POSITRON SOURCES : I. Stellar Nucleosynthesis of radioactive nuclei

Produced in hot and dense inner stellar regions through (mostly explosive) nucleosynthesis

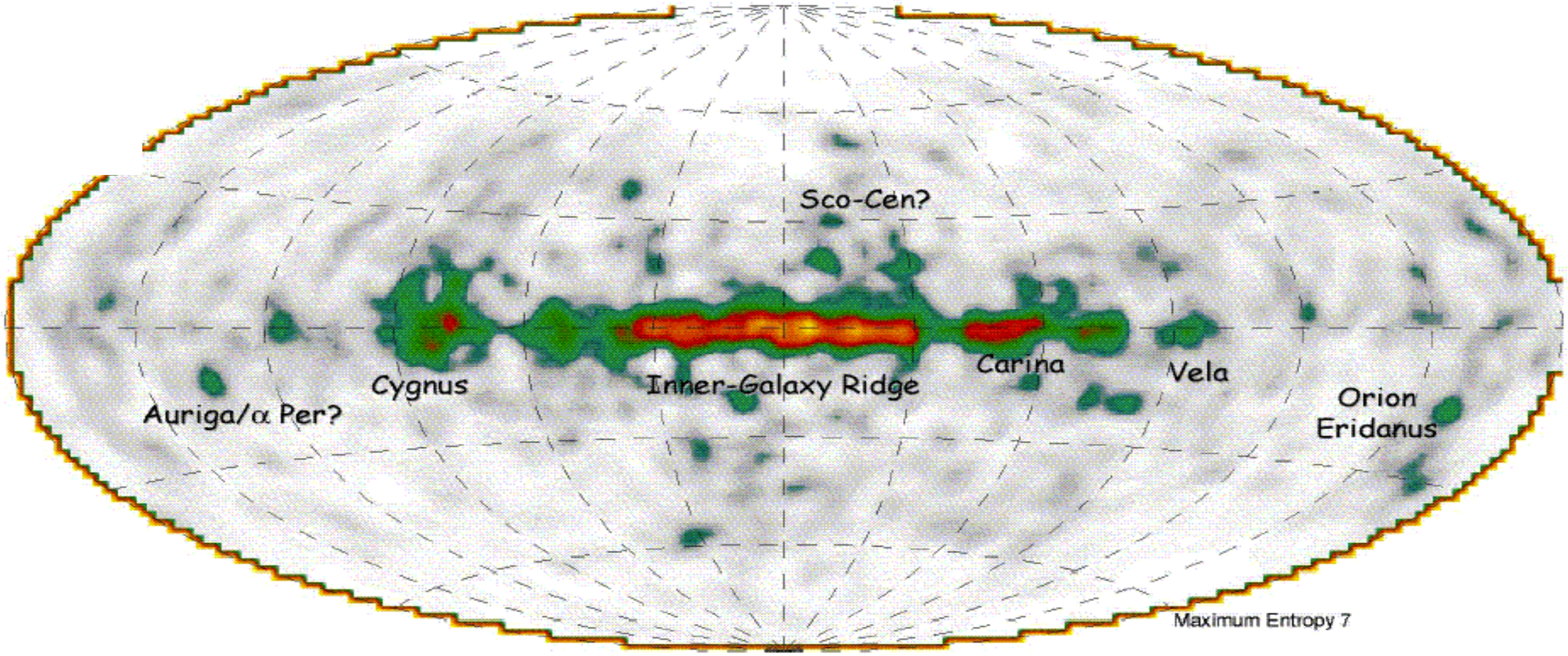
They must be produced in *large amounts* and *decay slowly enough* to allow for the positrons of their decay to escape from the dense region (otherwise the annihilation photons will be trapped and remain undetectable)



Nuclide	Decay chain	Decay mode and e^+ BR[a]	Lifetime	Associated γ-ray lines Energy in keV (BR[a])	Endpoint e^+ energy (keV)	Mean e^+ energy (keV)	Sources
^{56}Ni	$^{56}Ni \longrightarrow {}^{56}Co^*$	EC[b]	6.073 d	158(0.99), 812(0.86)			**Supernovae from white dwarfs (SNIa)**
	$^{56}Co \longrightarrow {}^{56}Fe^*$	e^+ (0.19)	77.2 d	2598(0.17), 1771(0.15)	1458.9	610	
^{22}Na	$^{22}Na \longrightarrow {}^{22}Ne^*$	e^+ (0.90)	2.61 y	1275(1)	1820.2	215.9	**Novae**
^{44}Ti	$^{44}Ti \longrightarrow {}^{44}Sc^*$	EC[b]	59.0 y	68(0.94), 78(0.96)			**Supernovae from massive stars**
	$^{44}Sc \longrightarrow {}^{44}Ca^*$	e^+ (0.94)	3.97 h	1157(1)	1474.2	632.	
^{26}Al	$^{26}Al \longrightarrow {}^{26}Mg^*$	e^+ (0.82)	$7.4\ 10^5$ y	1809(1)	1117.35	543.3	

(a) BR:Branching Ratio (in parenthesis); (b) EC: Electron capture

COMPTEL / CGRO legacy: 1.8 MeV map of Galactic ^{26}Al (long lived : $\tau \approx 1$ Myr)



Total flux: **≈ 4 10^{-4} cm^{-2} s^{-1} ⇒ ≈ 2.8 $M_\odot$ of ^{26}Al per Myr**

Each ^{26}Al decay releases 0.82 e^+ : **0.4 10^{43} e^+/s** produced (= **0.5 SPI disk**)

Decay of **Ti44 (**progenitor of stable Ca44**),** produced in CC-SN :

Estimated e^+ production Rate **~ 0.3 10^{43} s^{-1}**

Al26 + Ti44 : OK FOR DISK, NOT FOR BULGE

Major radioactivity in SN : $^{56}Ni \xrightarrow[8.8\ days]{} {}^{56}Co \xrightarrow[113\ days]{0.2\ e+} {}^{56}Fe$

Thermonuclear SN (SNIa): White dwarfs In accreting or merging binaries

They produce $M_{Ni56} \sim 0.7\ M_{\odot}$

Number of positrons produced per SNIa:

$$N = 0.19\ M_{Ni56}\ M_{\odot}\ N_A / 56 \sim 3\ 10^{54}$$

Frequency of SNIa in MW :

$$f \sim 0.5 / 100\ yr \sim 1.6\ 10^{-10}\ s^{-1}$$

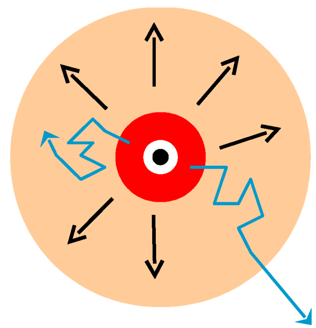
Rate of positrons released by MW SNIa:

$$R = f\ N \sim 4.5\ 10^{44}\ s^{-1}$$

OK if just `4% of them escape and annihilate in the ISM !

What fraction of the e^+ produced by the short-lived Co56 manage to escape the SNIa ejecta?

It depends on unknown intensity and configuration of the supernova magnetic field



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It depends on unknown intensity and configuration of the supernova magnetic field

The optical display of SNIa is powered by radioactivity of Co-56 on a ~yr timescale

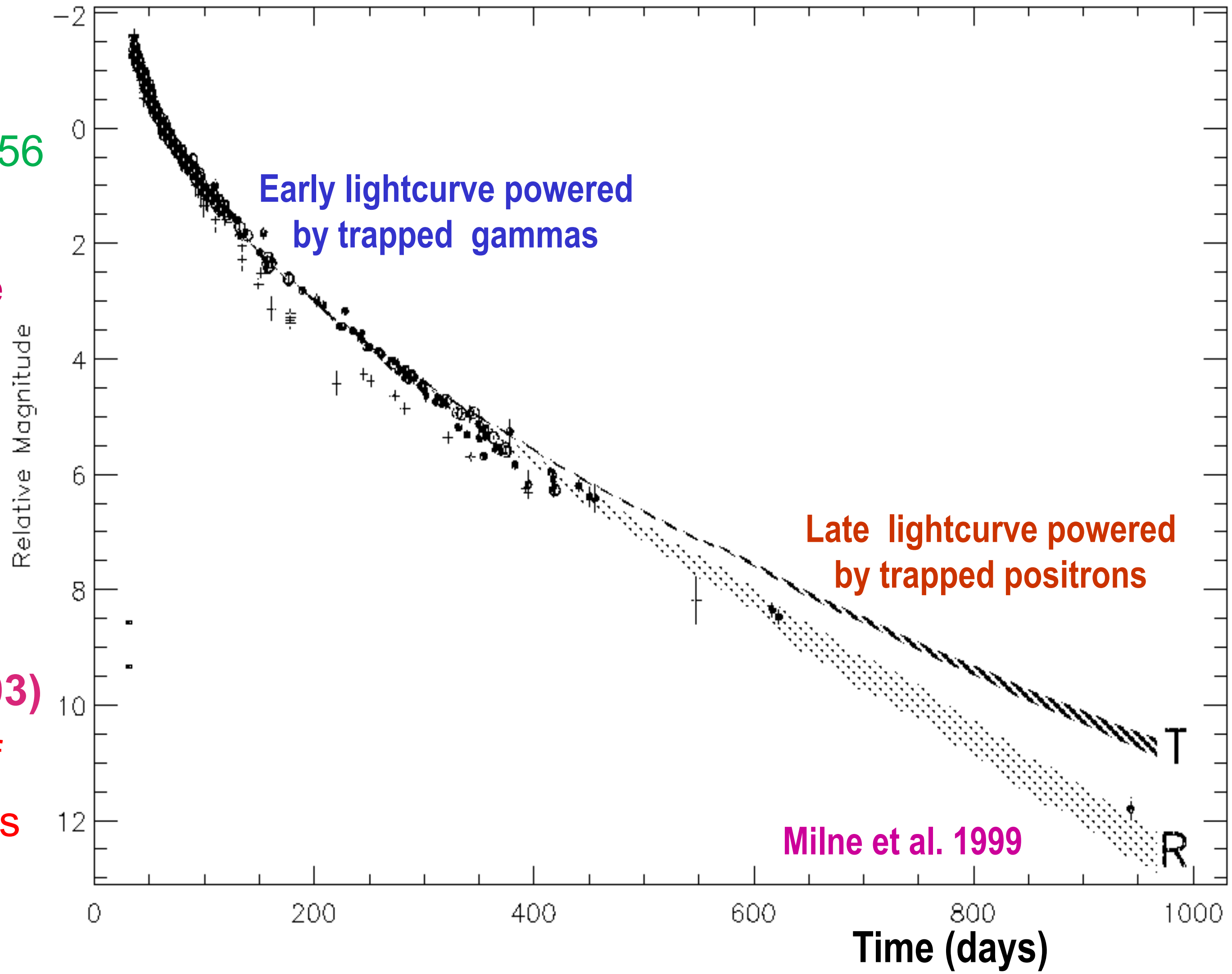
Observations of late optical lightcurves of SNIa in late 1990ies suggested :

$N \sim 8\ 10^{52}\ e^+$

(escape fraction f ~ 0.03)

But observations of bolometric lightcurves in 2000s suggest

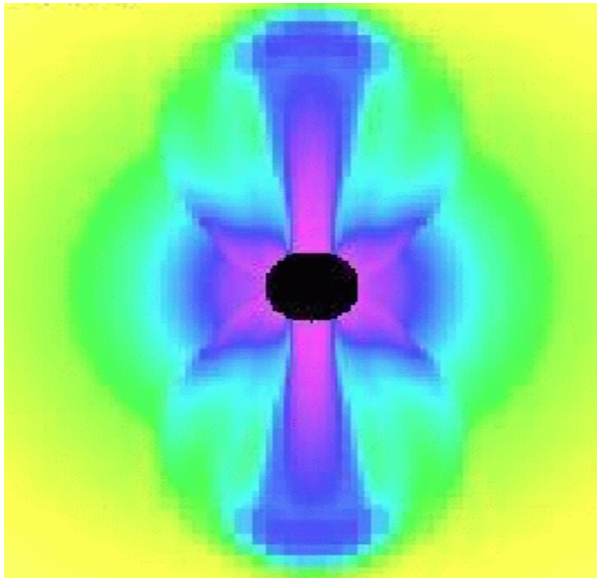
f ~ 0



Besides, the expected SNIa Bulge/Disk ratio is < 1

Other sources of positrons from nucleosynthesis?

Hypernova(e)/Gamma Ray Burst in Galactic Center ?
(Rudaz and Stecker 1988, Nomoto et al. 2001, Cassé et al. 2003, Parizot et al. 2005)



Hypernova/GRB models suggest/require large amounts of Ni56 (0.5 $M_\odot$) and easier escape of e^+ along the rotation axis *(if one forgets about magnetic fields !)*

But: more massive stars/HN explosions expected in the disk, particularly in the molecular ring…

Also, HN improbable in high metallicity regions, like the GC…
(Stanek et al. 2005, Woosley and Heger 2005)

Novae ?

Nova distribution in M31 peaked in bulge ***(Ciardulo et al. 1987)***

Positron production through
^{13}N(14 min), ^{18}F(2.6 hr), ^{22}Na(3.75 yr)

Novae models (***Hernanz et al. 2002***)
^{13}N: abundant BUT too short-lived (e^+ trapped)
^{22}Na: long-lived BUT not enough (factor 40)

POSITRON SOURCES : 2. High Energy processes in (or induced by) compact objects

a) Inelastic p – p collisions of cosmic rays hitting the interstellar medium

$$p + p \rightarrow \pi + X \qquad \pi^+ \rightarrow \mu^+ \nu_\mu \qquad \mu^+ \rightarrow e^+ \nu_\mu \nu_e$$

But : rate of pp collisions is known from associated γ-ray emission

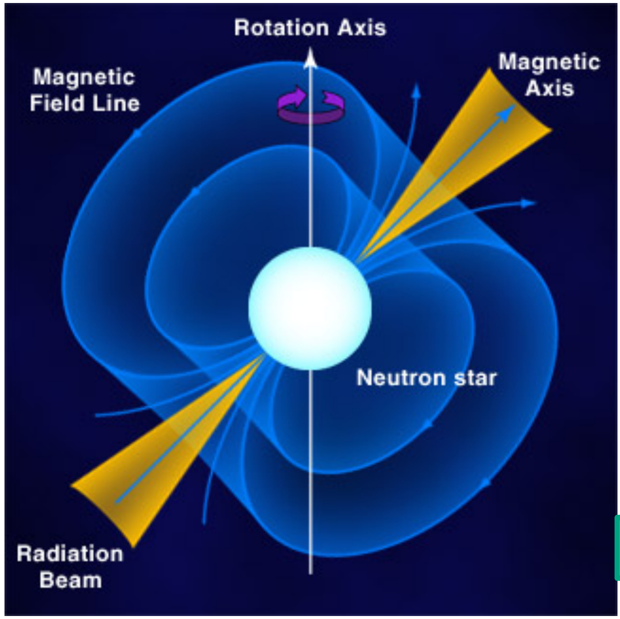
only $\sim 10^{42}$ e^+ s^{-1} of ~30 - 40 MeV are produced, mainly in the disk

b) Photon - photon interactions $\gamma\gamma \rightarrow e^- e^+$

c) Photon – magnetic field interactions ($B > 10^{12}$ G) $\gamma + B \rightarrow e^- e^+$

Positron production in isolated neutron stars

through pair creation in the intense magnetic field of the compact object



		Pulsars	ms pulsars	Magnetars
Magn. field	$\langle B \rangle$ (G)	10^{12}	3×10^{8}	3×10^{14}
Period	$\langle P \rangle$ (s)	0.5	3×10^{-3}	10
Birthrate	R (yr^{-1})	1.5×10^{-2}	10^{-5}	2×10^{-3}
Lifetime	$\langle \tau \rangle$ (yr)	10^{7}	3×10^{9}	2×10^{4}
Total number	N	1.5×10^{5}	3×10^{4}	40
e^+ yield[a]	$\dot{n}_{e^\pm}$ (s^{-1})	4×10^{37}	5×10^{37}	4×10^{40}
Total e^+ yield[b]	$\dot{N}_{e^\pm}$ (s^{-1})	5×10^{42}	1.5×10^{42}	1.6×10^{42}

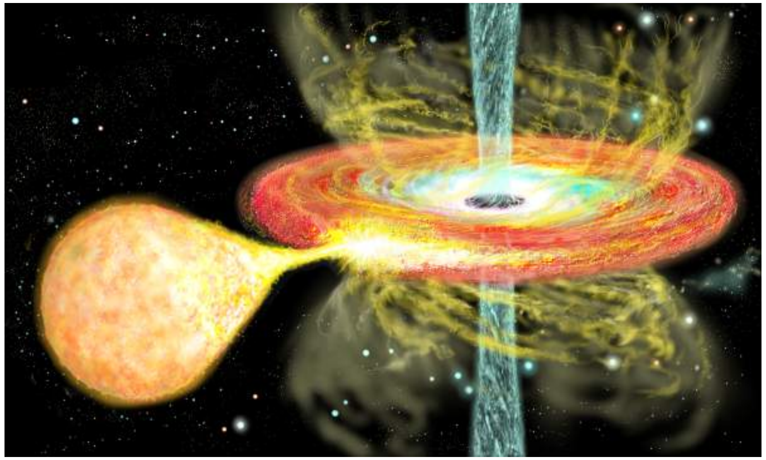
[a]Individual source yield from Eq. (9).
[b]Galactic yield from $\dot{N}_{e^\pm} = \dot{n}_{e^\pm} R \langle \tau \rangle$, assuming $\xi = 1$.

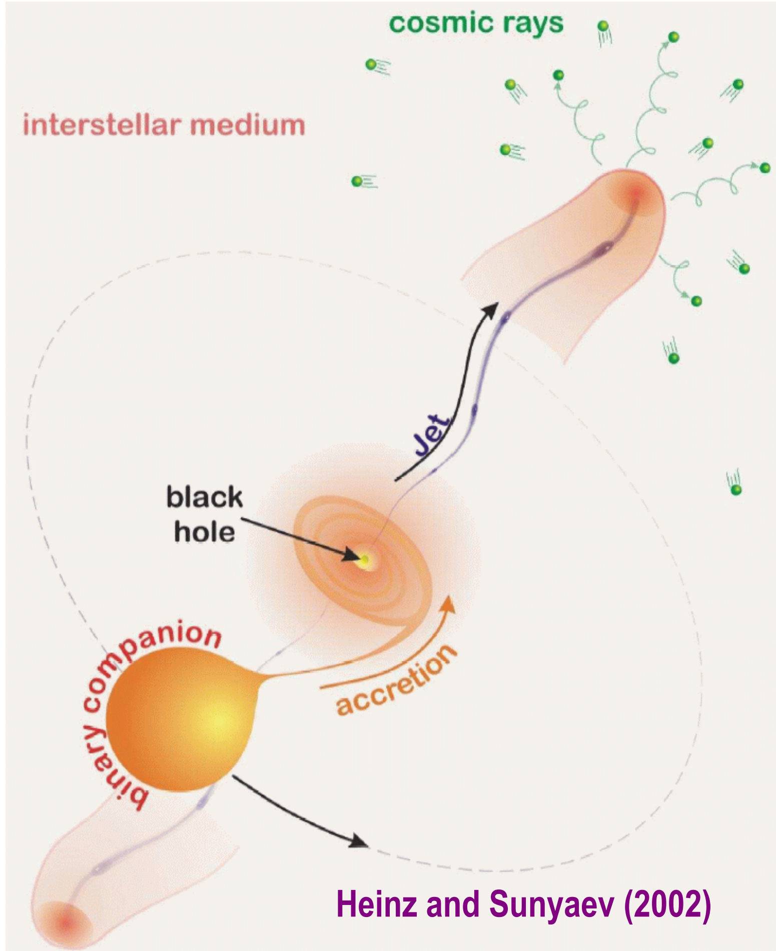
Pulsars: young objects, concentrated in disk, not in bulge

Total positron rate OK for disk, not for bulge

Positrons expected to be produced at high (TeV-GeV) energies, not in MeV range

Pair production of positrons, ejected by Outflows/Jets in Low Mass X-ray Binaries (LMXB) and microquasars ?
(Heinz and Sunyaev 2002, NP2004, Guessoum et al. 2006)





Total X-emissivity of Galactic LMXBs: 2 10^{39} erg/s
(2 10^{38} erg/s for HMXB, Grimm et al. 2002)
Energy required for 10^{43} e^{+}/s: 1.6 10^{37} erg/s
OK, IF about 1% of X-ray radiated energy is used for e^{+} formation

BUT: Particle content UNKNOWN ($p - e^{-}$ or e^{-} - e^{+} ?)

Injection energy of positrons UNKNOWN

Other sources of galactic positrons ?   Dark matter ?

1) Light (MeV) DM particles ?

1a) Annihilating (*Boehm et al. 2004, Gunion et al. 2006, Ascasibar et al. 2005)*

1b) Decaying *(Hooper and Wang 2004, Piccioto and Pospelov 2005, Pospelov et a. 2008)*

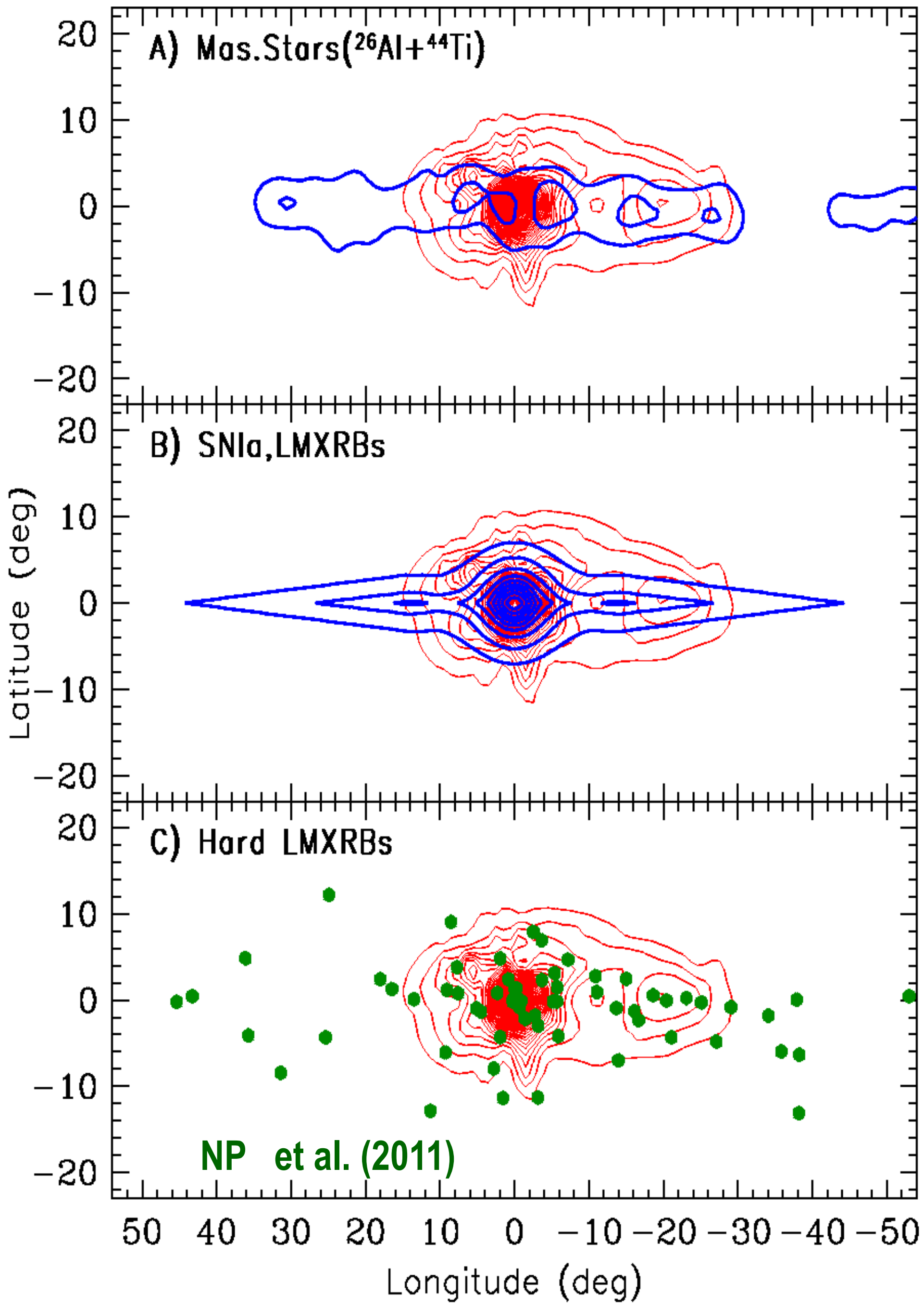
2) Heavy (GeV-TeV) DM particles ?

De-exciting (provided they possess ~MeV energy levels)
(*Finkbeiner and Weiner 2007, Pospelov and Ritz 2007*)

In Milky Way: velocity dispersion ~100 km/s ⇒
Kinetic energy of a 500 GeV DM particle ~1 MeV

Case 1a produces more peaked profiles than Case 2 and even more peaked than Case 1b

However: density profiles of DM in inner Galaxy and signal intensity virtually unknown



In all panels:

***Red isocontours*: 511 keV observations**

(from Weidenspointner et al. 2008a)

Top panel:

***Blue isocontours*: 1.8 MeV (Al26) observations**

(= Massive stars)

Middle panel:

***Blue isocontours*: Expected SNIa**

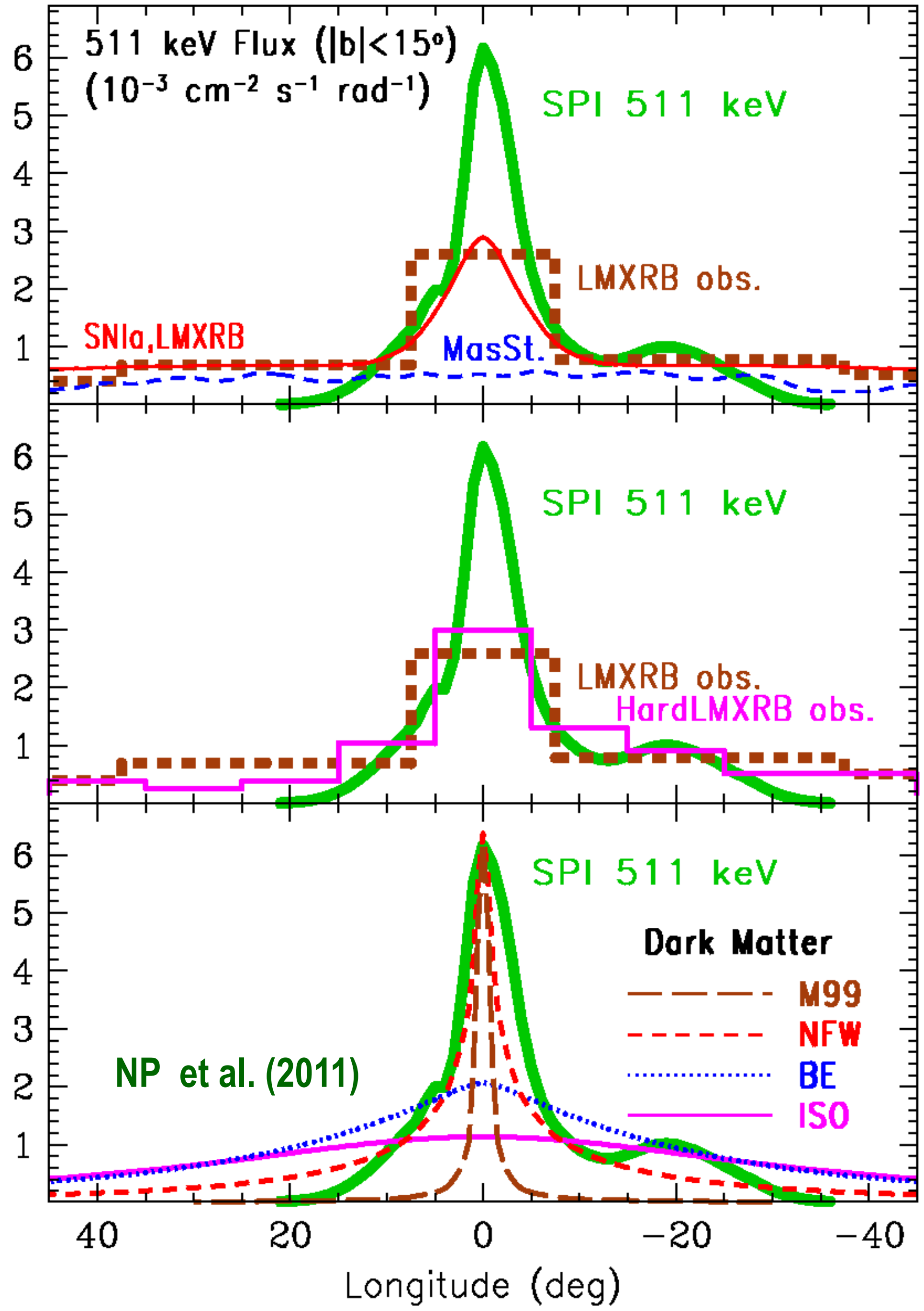
Bottom panel:

***Green Dots:* Observed Hard LMXRBs**

(asymmetric?)

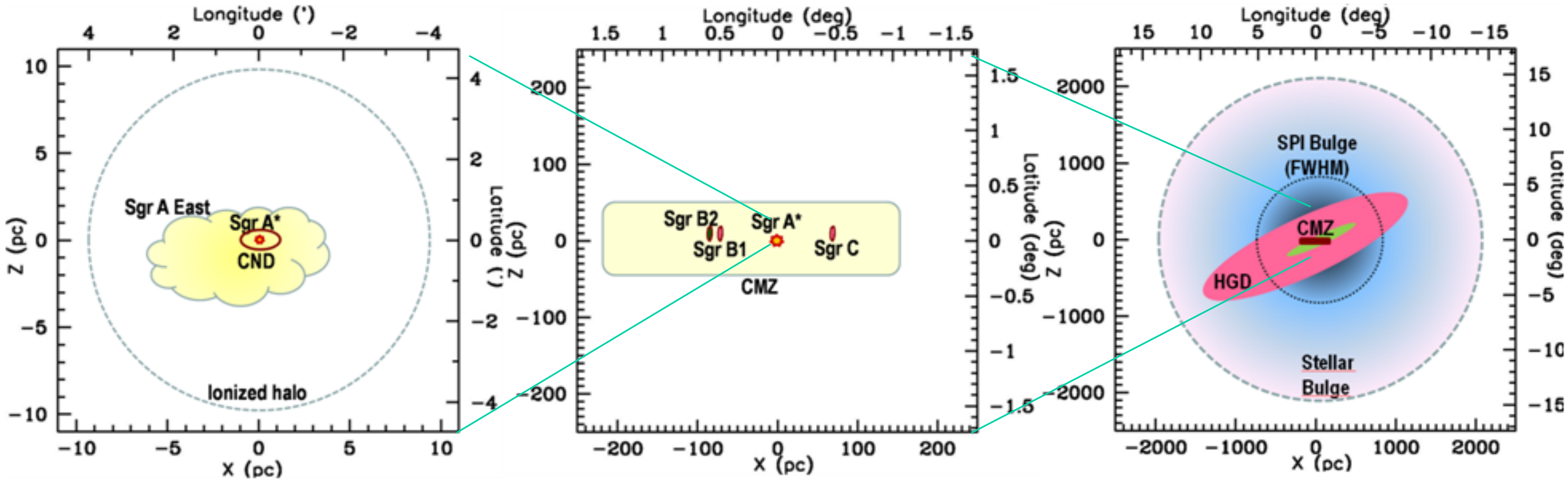
No observed or expected distribution
of known astrophysical sources
is as peaked as
the observed 511 keV one

Only some specific distributions
(M99, NFW)
of *annihilating*
Dark Matter particles
are as peaked as
the observed 511 keV one
They are apparently ruled out
by observations of dwarf galaxies



The Supermassive Black Hole in the Galactic Center

Mass: $4\ 10^6\ M_\odot$ Bolometric luminosity: ~ 10^{36} erg/s



Model requires higher activity in the past since Sgr A* is ~inactive now

NO MORE STEADY STATE ASSUMPTION

Higher regular accretion activity in the past, interrupted ~300 yr ago (Totani 2006)

e+ produced by pair production in inner accretion disk of SMBH

Accretion of gas from one (or many) disrupted star(s) 10^5 - 10^7 yr ago onto the SMBH

and proton acceleration ; secondary e+ produced in p-p collisions (*Cheng et al. 2006*)

High magnetic field (>0.4 mG) required for e^+ to lose energy before annihilation (*Cheng et al. 2010*)

Positrons must diffuse throughout the bulge, escaping the Central Molecular Zone (CMZ)

Candidate positron sources in the Galaxy

NP 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	$\sim$1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{44}Ti	β^+-decay	$\sim$1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	$\sim$1	*2*	<0.5	Assuming $f_{e+,esc}$=0.04
~~Novae~~	~~β^+-decay~~	~~$\sim$1~~	~~*0.02*~~	~~<0.5~~	Insufficent e^+ production
~~Hypernovae/GRB: ^{56}Ni~~	~~β^+-decay~~	~~$\sim$1~~	~~?~~	~~<0.2~~	Improbable in inner MW
~~Cosmic rays~~	~~p-p~~	~~$\sim$30~~	~~0.1~~	~~<0.2~~	Too high e^+ energy
LMXRBs	$\gamma-\gamma$	$\sim$1	*2*	<0.5	Assuming $L_{e^+} \sim 0.01\ L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	$\sim$ 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 $\sim$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	

Implicit assumption :

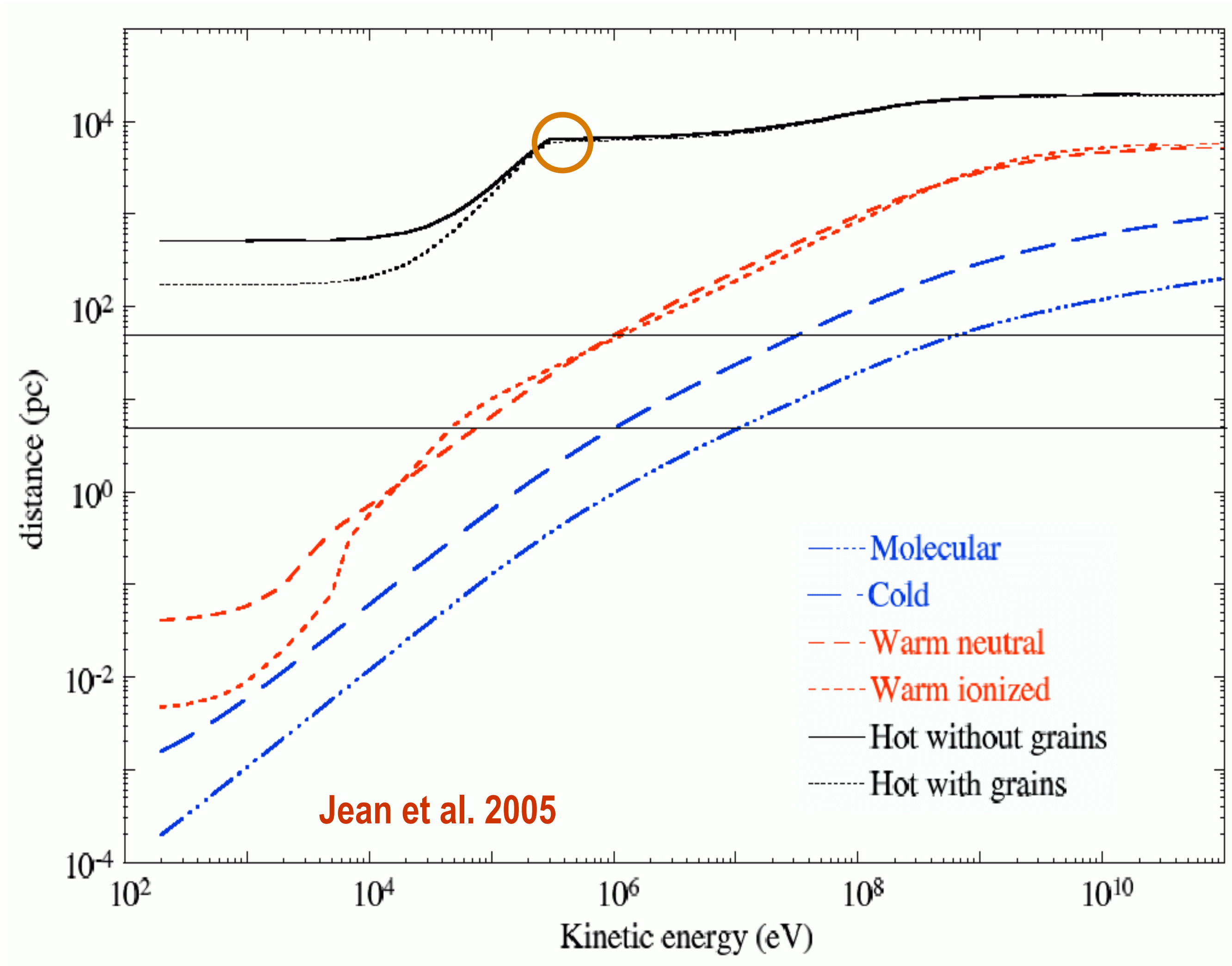
Positrons annihilate close to their sources ⇒

Gamma-ray morphology reflects source morphology

Not necessarily true

Positron propagation and annihilation in the interstellar medium

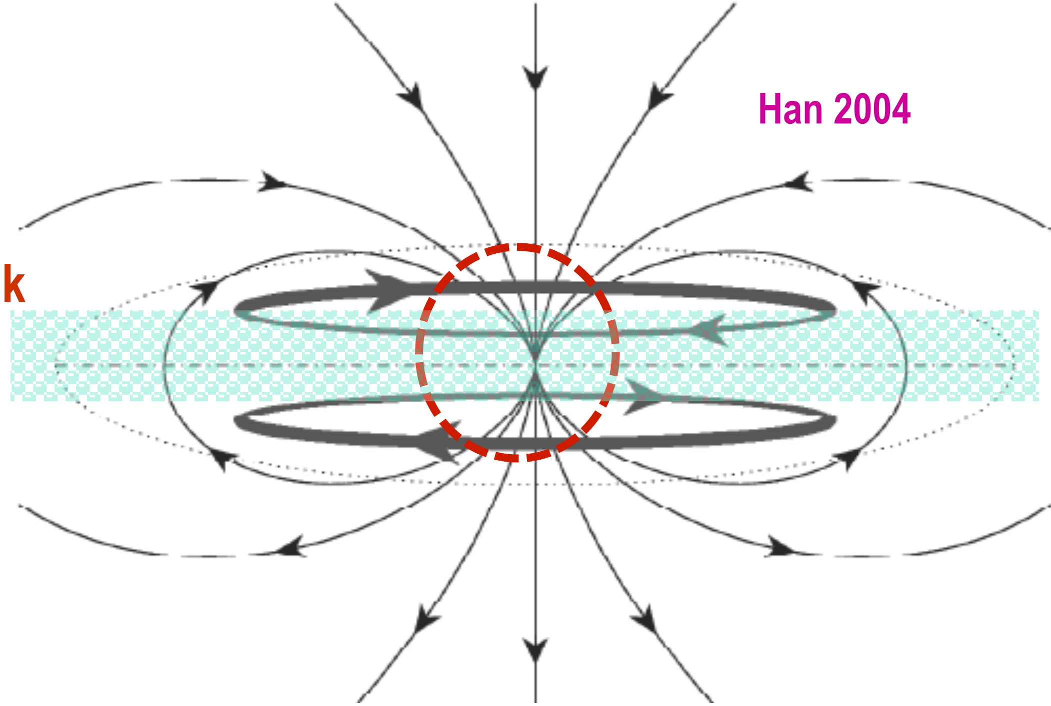
Distance travelled by positrons before annihilating



Positrons released in a hot
and low density medium
can travel far away from their sources
(many kpc) in a calm, unmagnetized plasma

BUT, propagation of low energy positrons
in the **turbulent, magnetized** ISM
is very poorly understood

IF the galactic magnetic field has
a poloidal component (*Han 2004*)
a (difficult to estimate) fraction
of disk positrons should escape the disk
and be chaneled
(through the low density halo)
to the bulge, where they are better
confined (because of its stronger
magnetic field)
and they finally annihilate
(*NP 2006*)



However, radio-observations of
magn. field configuration
in external spirals
suggest rather an X-shaped filed
(*Heesen et al. 2009*)

Recent simulations suggest rather low
e+ transfer fractions
(Posters: Alexis, Martin)

Summary

The origin of the oldest known and brightest
extra-solar gamma-ray line remains unknown at present

conventional astrophysical sources,

or positrons produced in the Galactic center diffuse in the bulge

-A specific bulge (=old)? population (LMXRBs, microquasars, ms pulsars?)
- Transfer of disk positrons to the bulge through magnetic field ?
- Diffusion of positrons from central black hole to the bulge ?

Positron propagation appears to be the key issue !

(annihilating dark matter particles,
tangle of superconducting cosmic strings…)

(i) Observations of 511 keV emission:

- how far do the spheroid and disk extend ?
- are there yet undetected regions of low surface brightness?
- is the disk emission asymmetric indeed?
- how do the 1.8 MeV and 511 keV disk emissions compare to each other?

keV emission

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- ## (ii) Physics of e+ sources
- what is the e+ escaping fraction in SNIa ?
- what is the SNIa rate in the inner (star forming) and in the outer (inactive) bulge?
- what are the e+ yields, activity timescales, and spatial distribution in the bulge of LMXRBs or microquasars?
- how can the past level of activity of the central supermassive black hole be reliably inferred?

keV emission

(i) Observations of 511 keV emission

- what is the true spatial distribution of the emission?
- how far do the spheroid and disk extend ?
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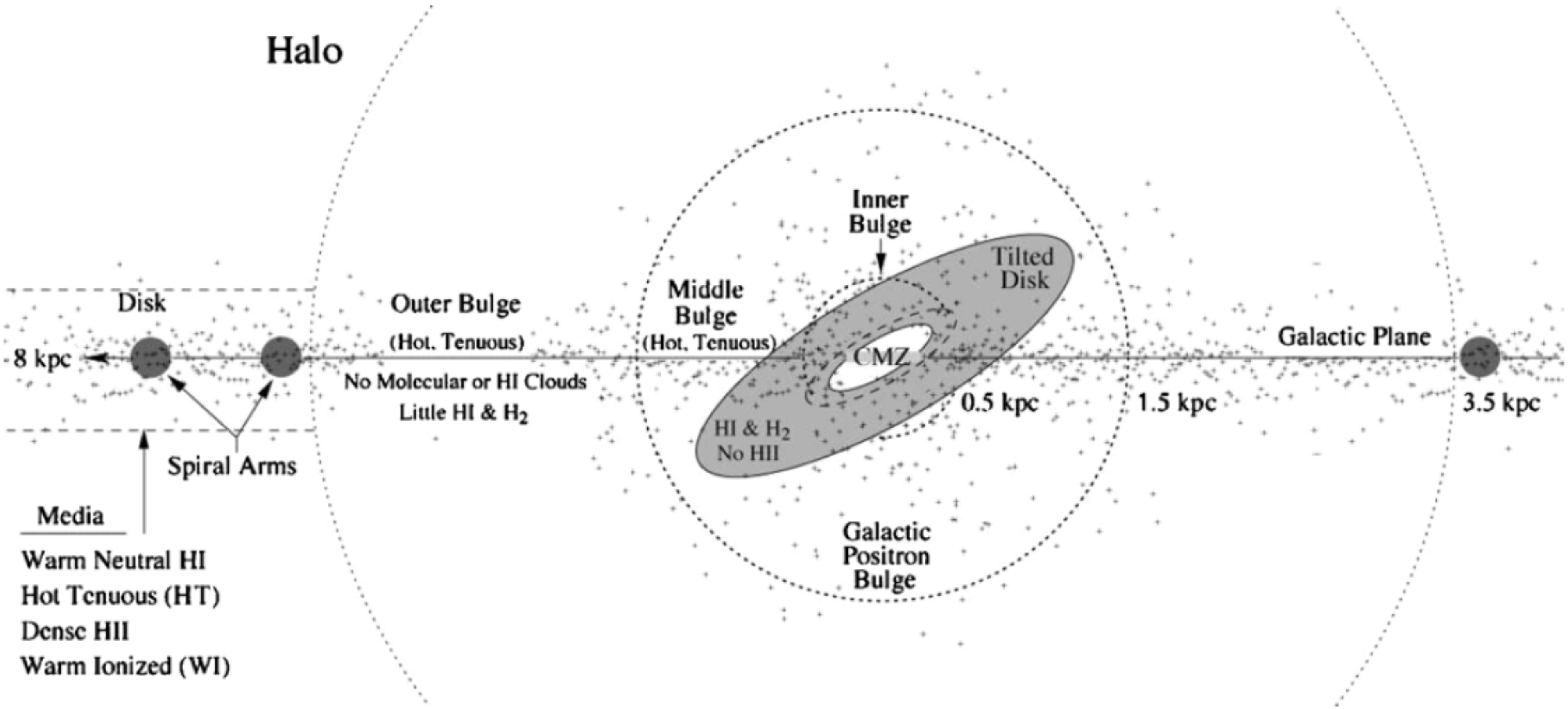
- ## (iii) Positron propagation
- what is the large scale configuration of the Galactic magnetic field?
- what are the properties of interstellar plasma turbulence and how do they affect the positron transport?
- what are the dominant propagation modes of positrons and what is the role of re-acceleration?



Transfer of positrons produced by SNIa from the "outer bulge" (?) (hot, tenuous) to the inner one

(*Higdon et al. 2009*)

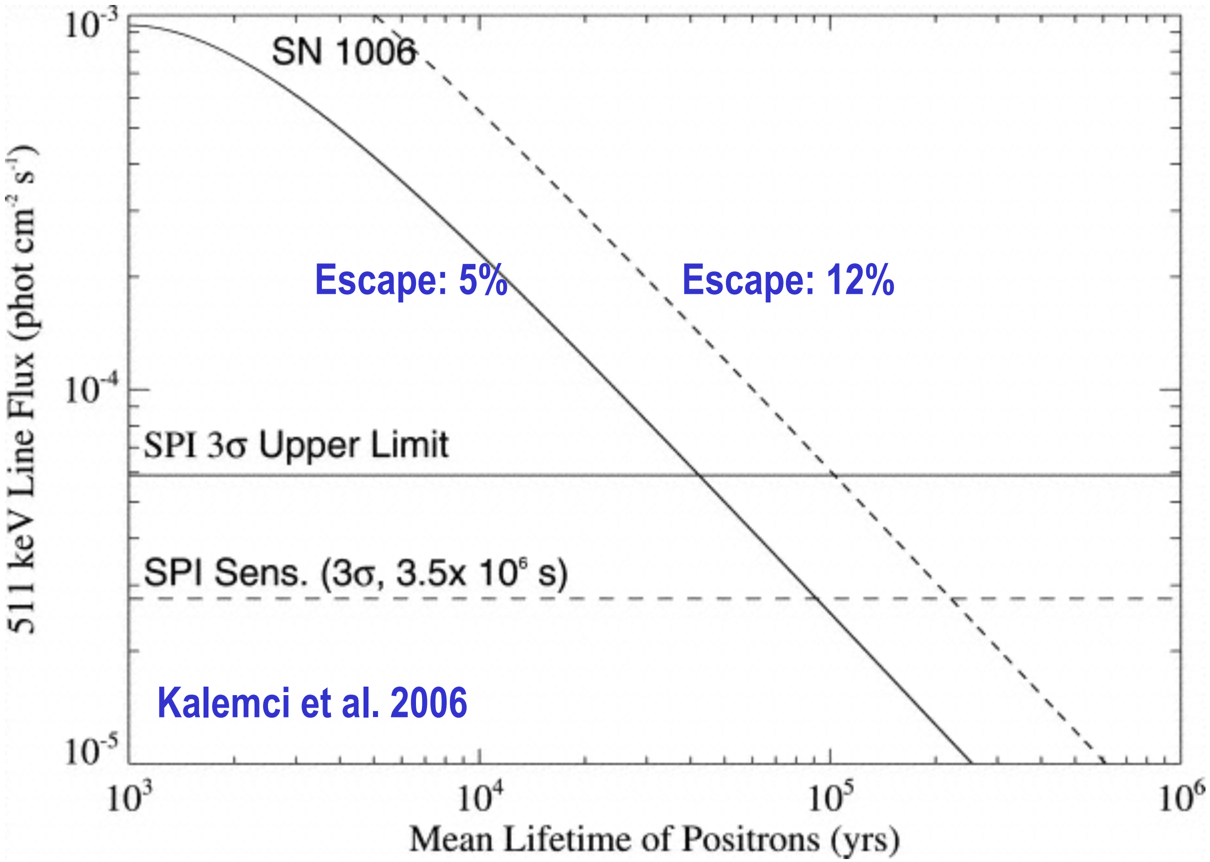
Fate of radioactivity positrons of SNIa

1) Local annihilation of all positrons + downscattering of 511 keV photons : no e^+ escape, no 511-emission seen

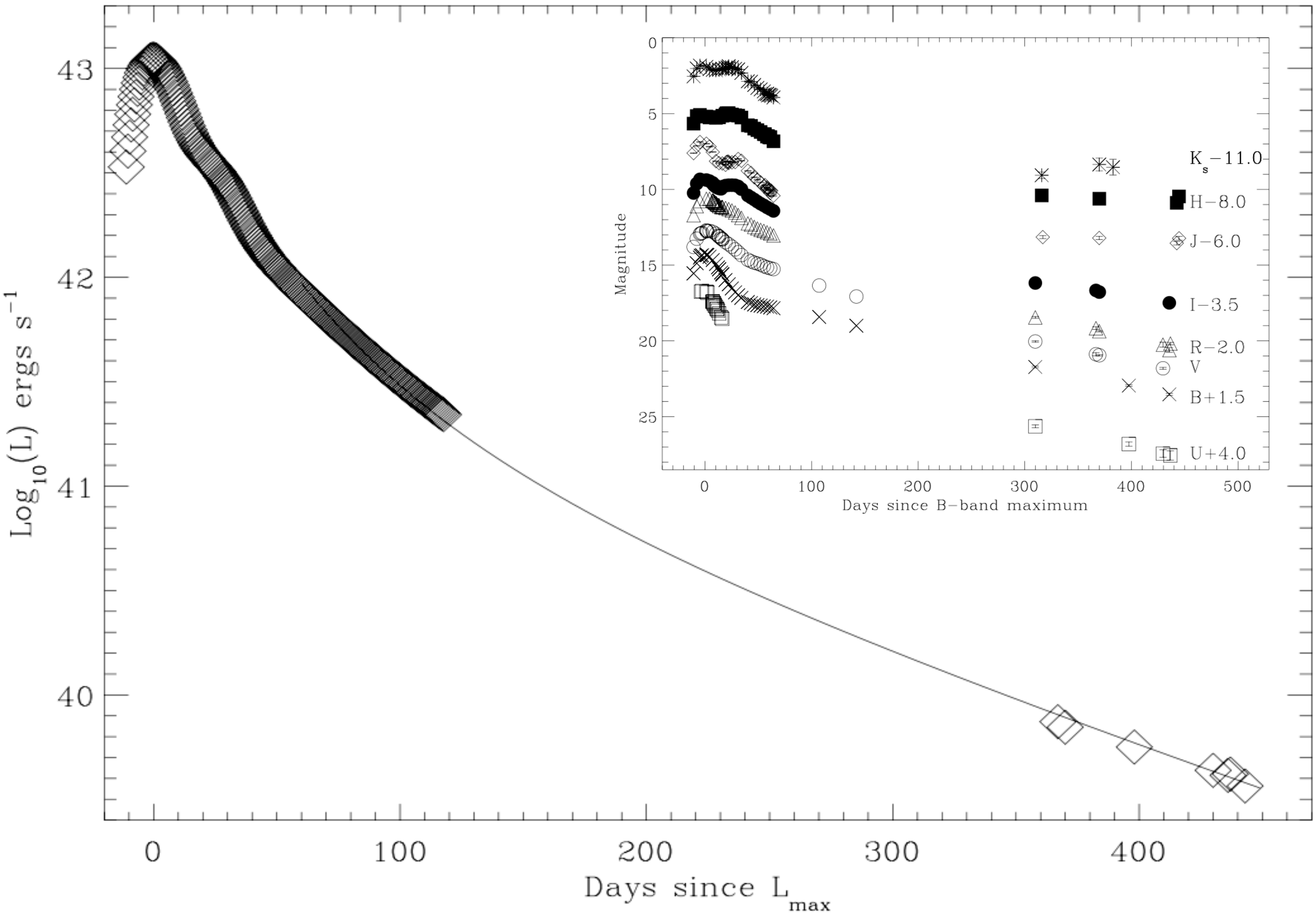
2) Local annihilation of all positrons + escape of 511 keV photons : no e^+ escape, local 511-emission seen

3) Some positrons escape local annihilation and annihilate… somewhere in the ISM

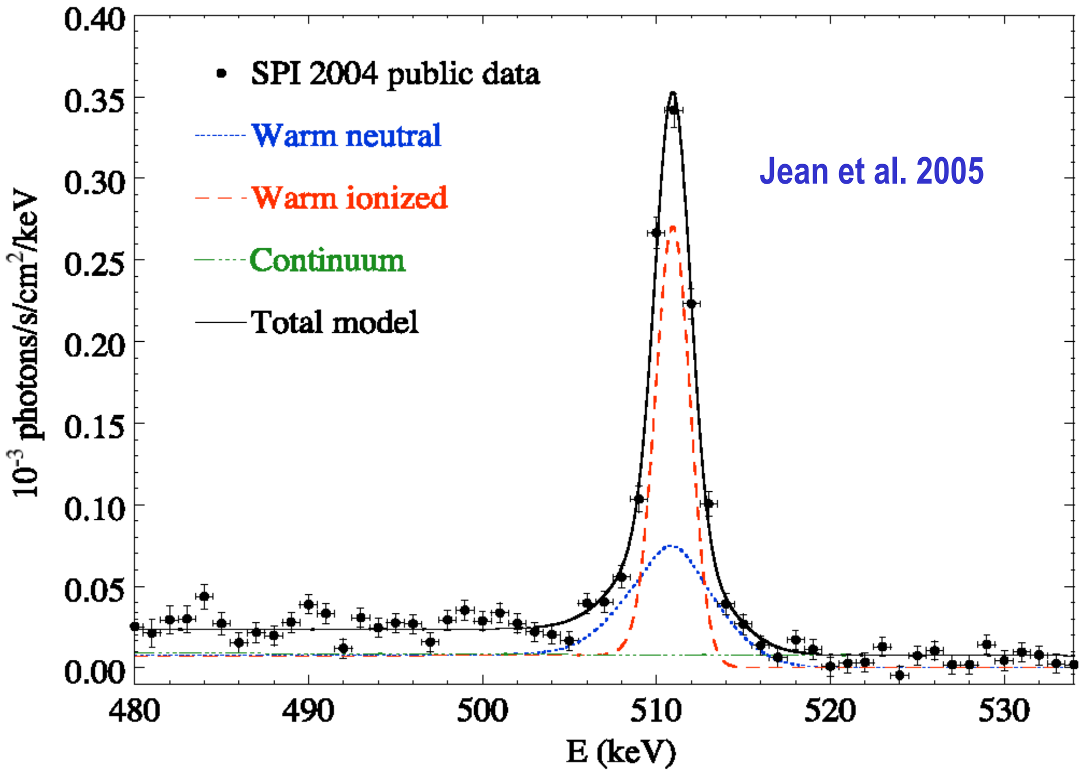
No detection of 511 keV emission from SN1006 with SPI



And so do Strinziger and Sollerman (2007), for SN2001el



Physics of 511 keV line profile



The line and continuum shape provide information

Warm neutral and ionized phases of ISM)

propagation of the positrons, from their sources to the annihilation region…