THE 511 keV EMISSION OF POSITRON ANNIHILATION IN THE MILKY WAY

NP, Boehm, Bykov, Diehl, Ferrière, Guessoum, Jean, Knoedlseder,
Marcowith, Moskalenko, Strong, Weidenspointner

Reviews of Modern Physics, 2011 (arXiv: 1009.4620)

POSITRON HISTORY

1928 (**Dirac**): Prediction of “anti-electron”

1932 (**Anderson**): Discovery of “positron” from cosmic rays

1934 (**Klemperer and Chadwick**): Annihilation gamma-ray line at 511 keV

1934 (**P. Joliot and I. Curie**): Production in β^+-decay

1934 (**Mohorovicic**): Prediction of ***positronium***

1951 (**Deutch**): Production of positronium

1956 (**Ginzburg**): p-p collisions in cosmic rays produce e^+

1964 (**Shong et al.**): Discovery of positrons in cosmic rays

1969 (**Stecker**): In ISM, most e^+ should form positronium

Annihilation of positrons with electrons

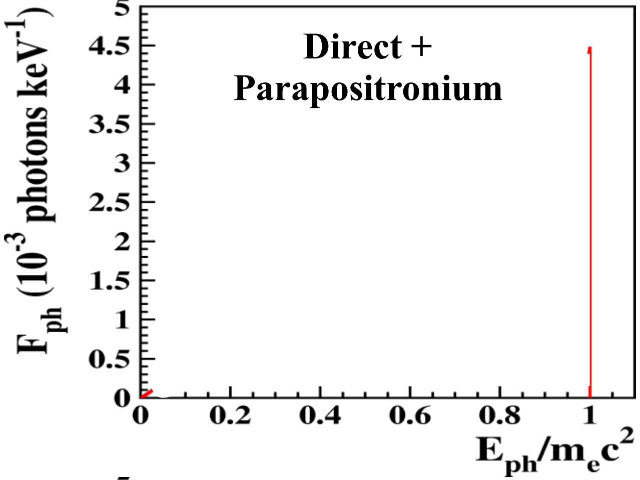
Either **directly** (2 γ of E = 511 keV each),
or, after formation of **Positronium (Ps)**, with probability **f**

Probability
:1/4

$^1S_0$

S=0
(singlet)

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

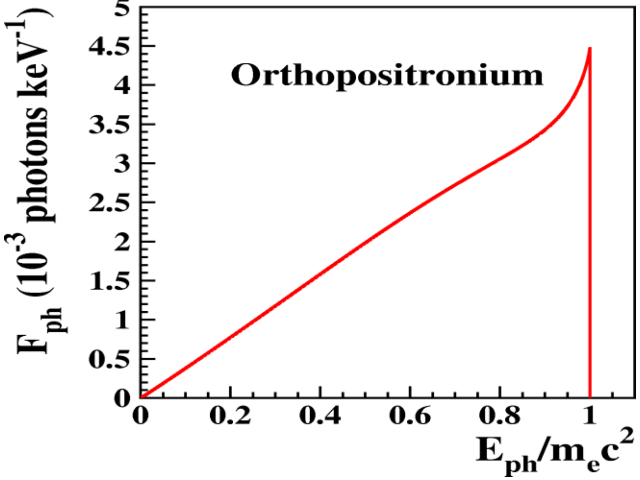


Probability
:3/4

$^3S_1$

S=1
(triplet)

$\tau = 1.4\ 10^{-7}$ s ⇒ 3 γ of E ≤ 511 keV



$$\left.\begin{array}{l} F_{2\gamma} = \underset{\text{direct}}{2(1-f)} + \underset{\text{paraPs}}{1/4\ \ 2\ f} \\[2em] F_{3\gamma} = \underset{\text{orthoPs}}{\frac{3}{4}\ \ 3\ f} \end{array}\right\} \quad f = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})}$$

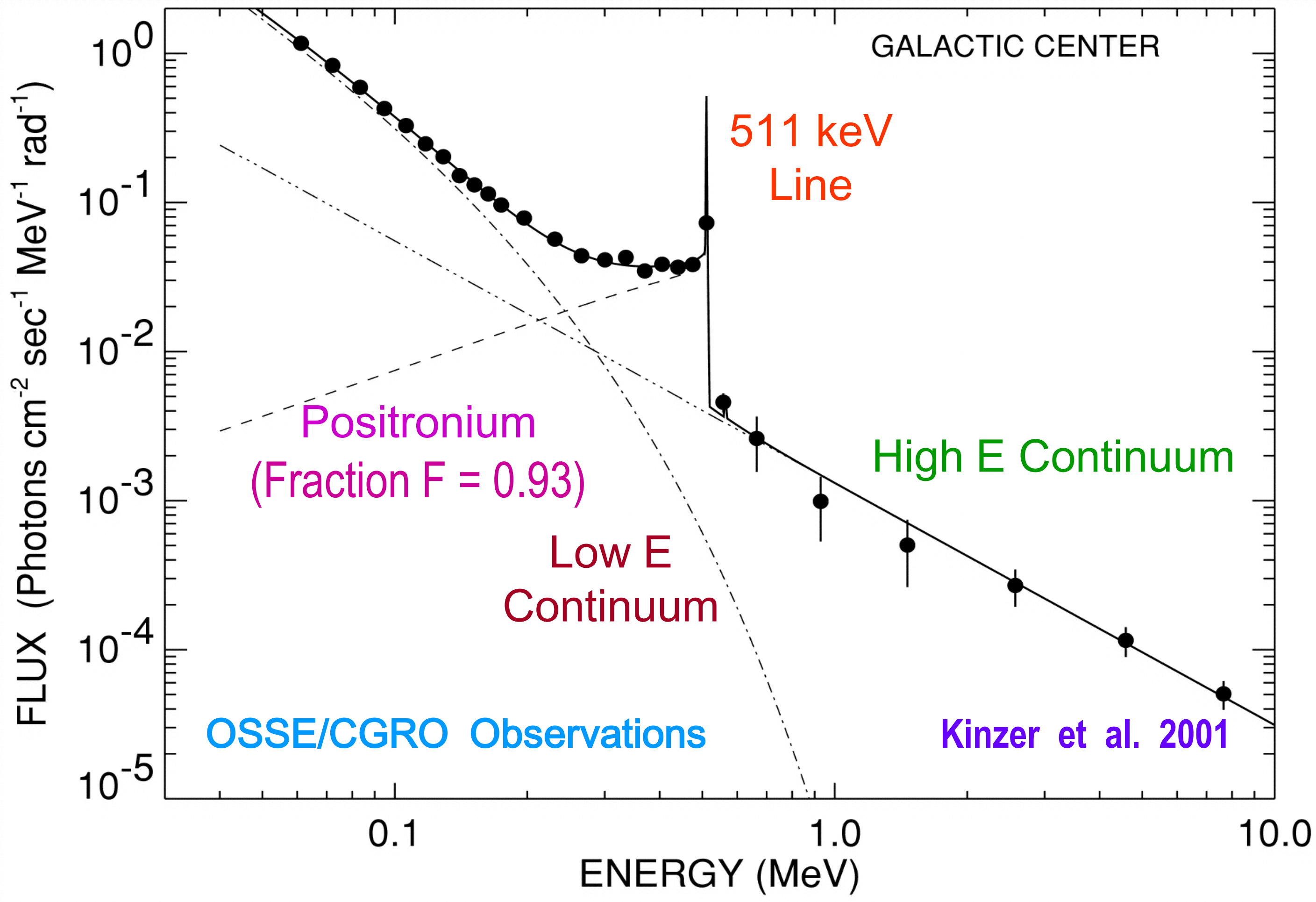
Positronium fraction

Positron annihilation radiation from the Galactic center region

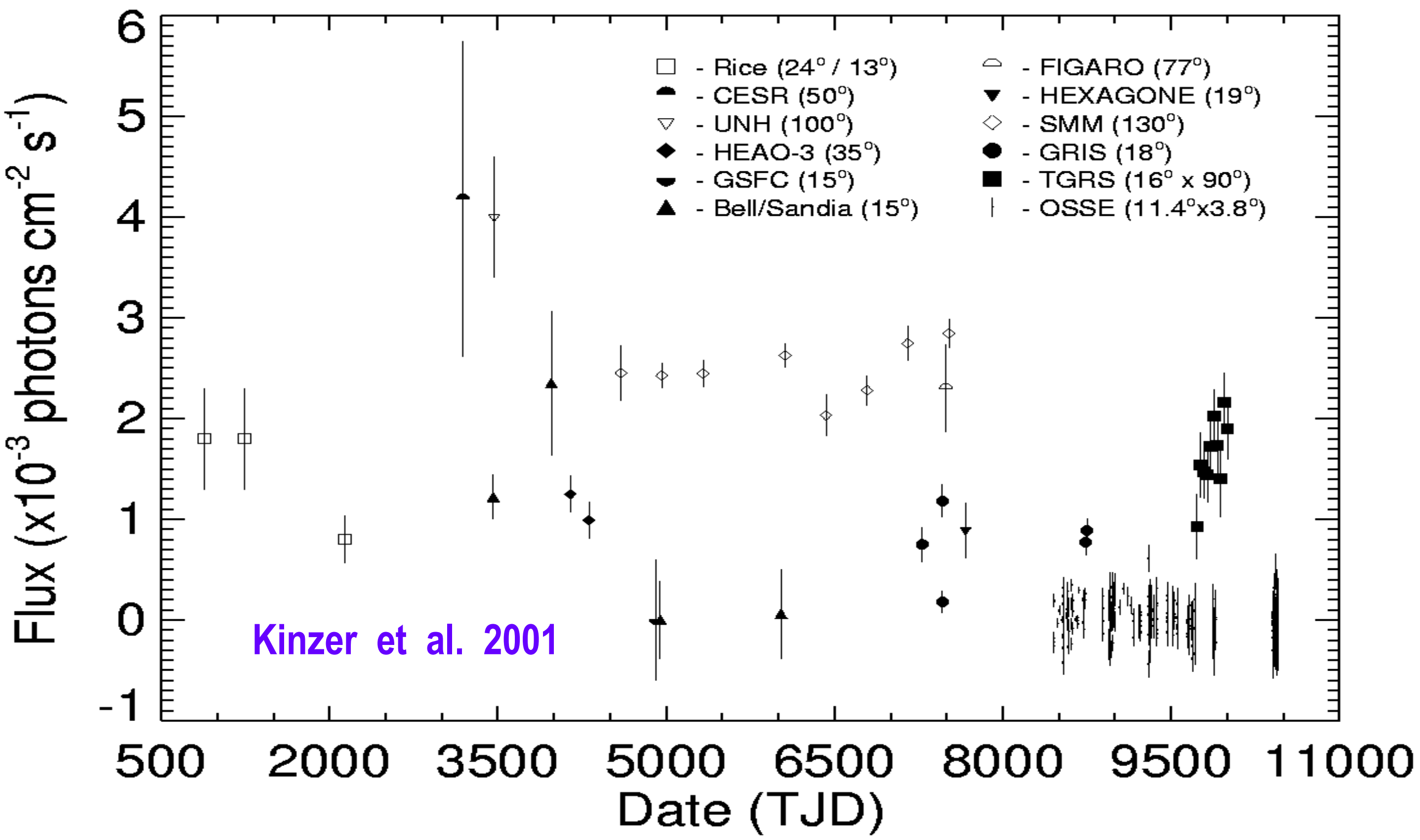
First (and brightest) γ-ray line detected outside the solar system
(**Johnson et al. 1972**, *Rice U*. Na detector : **Leventhal et al. 1978** *Bell-Sandia* Ge detector)

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

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



511 keV emission measurements in the Galactic Center direction



Kinzer et al. 2001

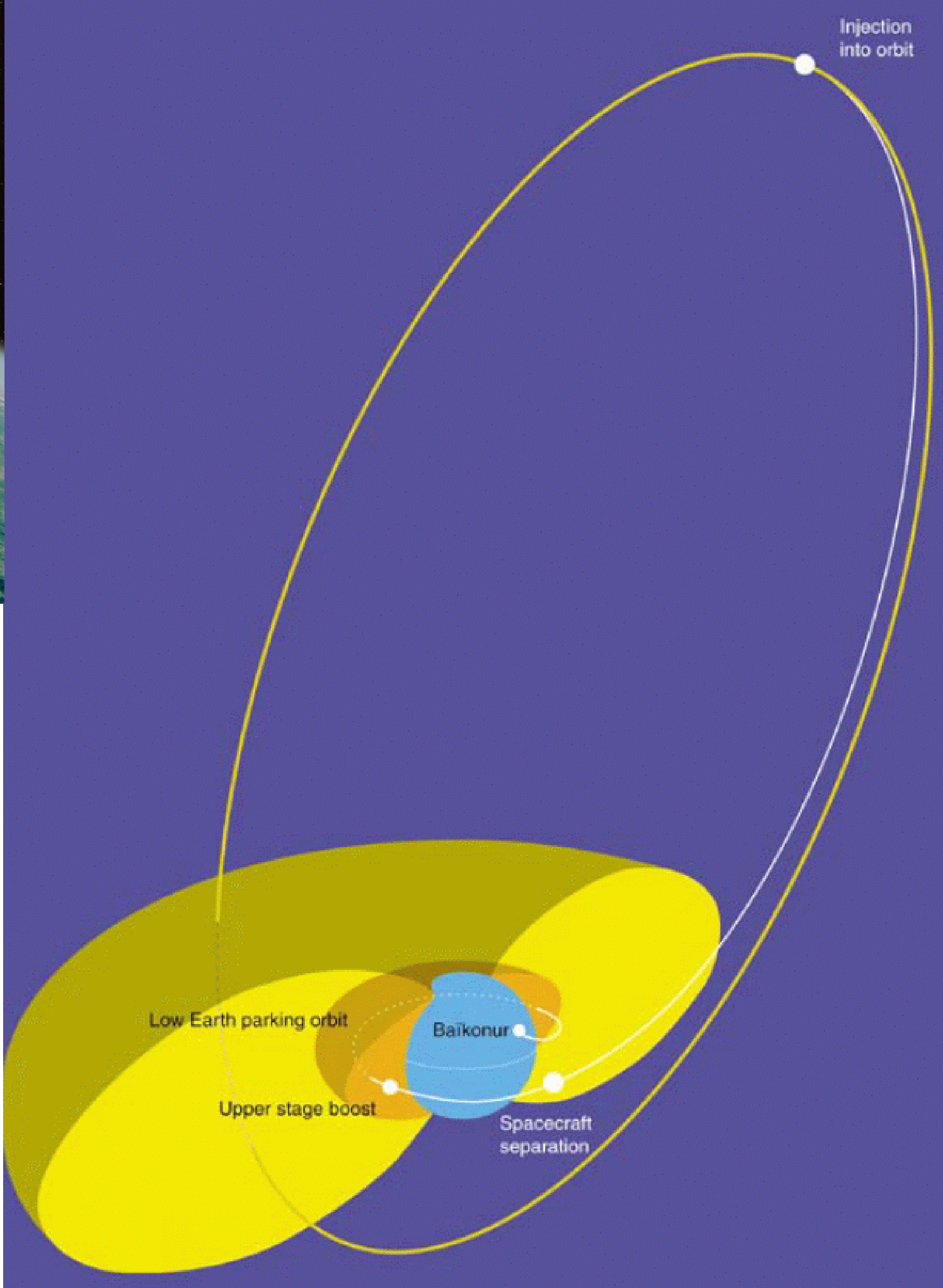
Early reports (80ies) for flux variability not confirmed by OSSE/CGRO

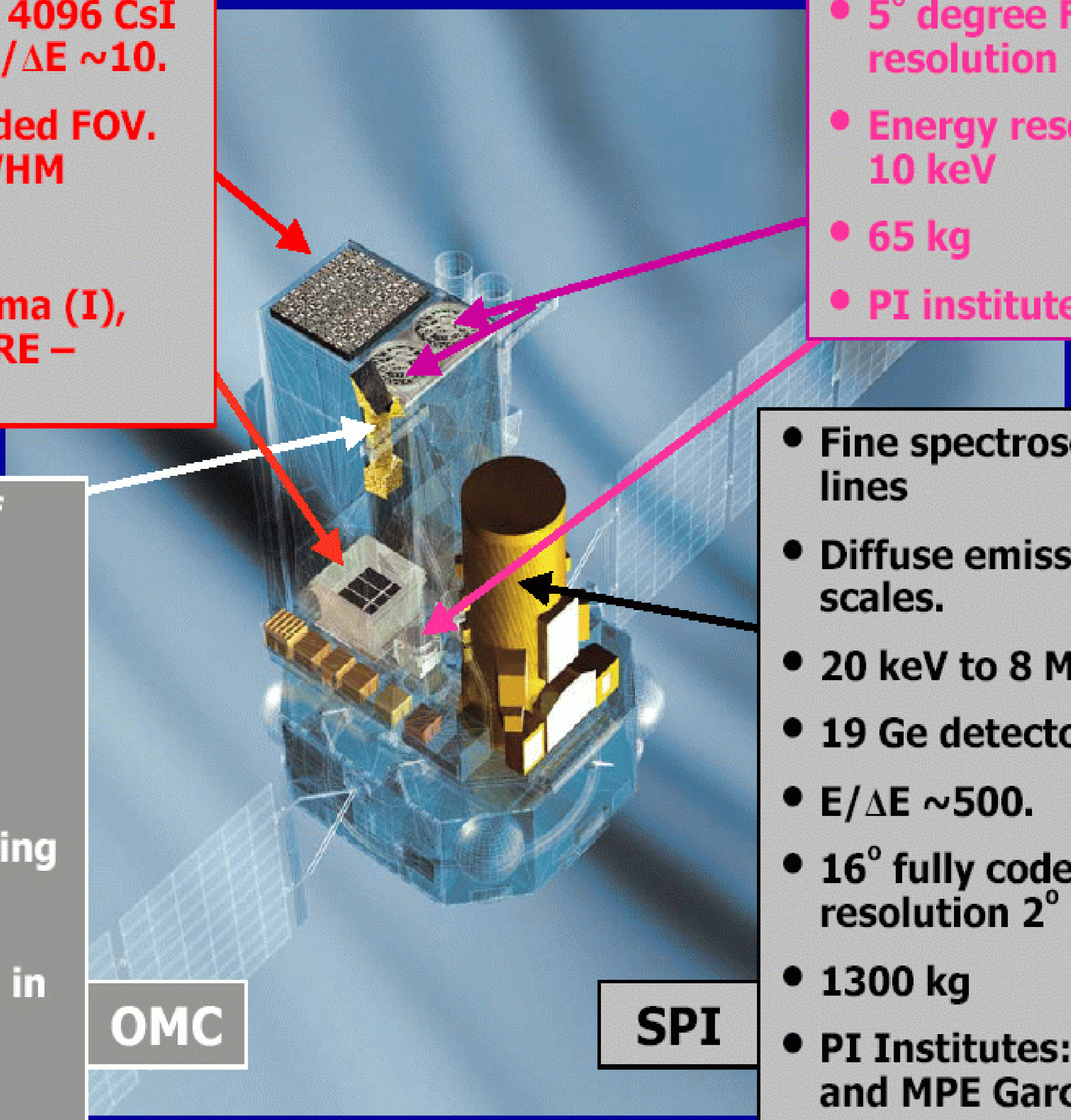
Flux correlated with instrument field of view ⇒diffuse emission

INTEGRAL (ESA)

Launched October 2002

Largest part of INTEGRAL’s orbit is found outside Earth’s magnetic (Van Allen) belts, which are full of cosmic ray particles and are sources of background noise for gamma-ray detectors.





IBIS

- Accurate point source imaging and location.
- Broad lines and continuum.
- 15 keV – 10 MeV
- 16384 CdTe (ISGRI), 4096 CsI (PICsIT) detectors. E/ΔE ~10.
- 9°x 9°degree fully coded FOV. Angular resol 12′ FWHM
- 630 kg
- PI Institutes: IAS Roma (I), CEA-Saclay (F), ITESRE – Bologna (I)

JEM-X

- Source identification and monitoring in X-rays
- 3 –35 keV X-ray monitoring
- Microstrip Xe gas detectors
- 5° degree FOV with 3′ spatial resolution
- Energy resolution of 15% at 10 keV
- 65 kg
- PI institute: DSRI (Dk)

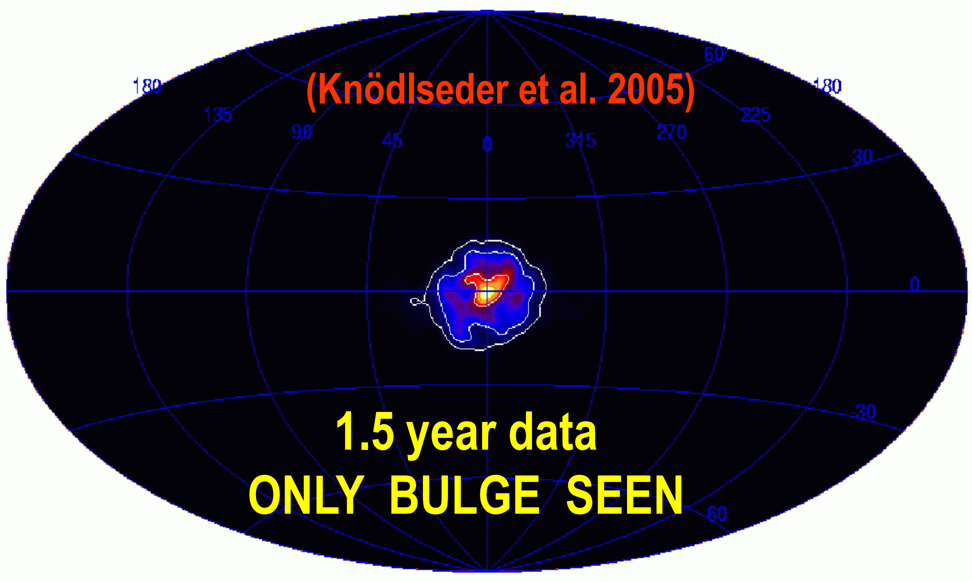
OMC

- Optical monitoring of high-energy sources
- 500 – 600 nm wavelength range
- CCD (2048 x 1024 pixels)
- 5° x 5° FOV, 20″ imaging
- 17 kg
- Sensitivity: 18.2 mag in 1000 s
- PI Institute: INTA/LAEFF (Esp)

SPI

- Fine spectroscopy of narrow lines
- Diffuse emission on > deg scales.
- 20 keV to 8 MeV
- 19 Ge detectors @ 90 K,
- E/ΔE ~500.
- 16° fully coded FOV. Angular resolution 2° FWHM
- 1300 kg
- PI Institutes: CESR Toulouse (F) and MPE Garching (D)

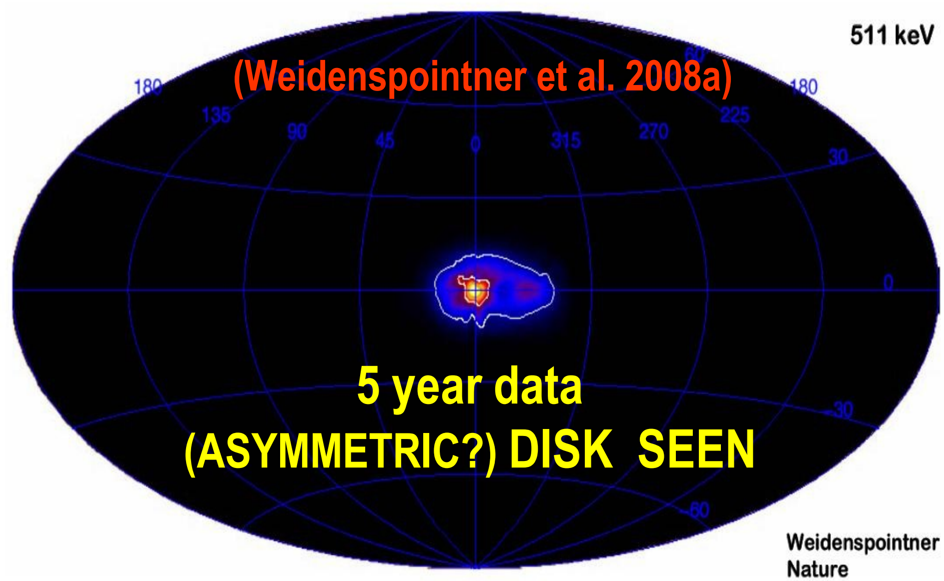
SPI/INTEGRAL all-sky distribution of the 511 keV line of e^{-} - e^{+} annihilation



(Knödlseder et al. 2005)

1.5 year data

ONLY BULGE SEEN



(Weidenspointner et al. 2008a)

5 year data

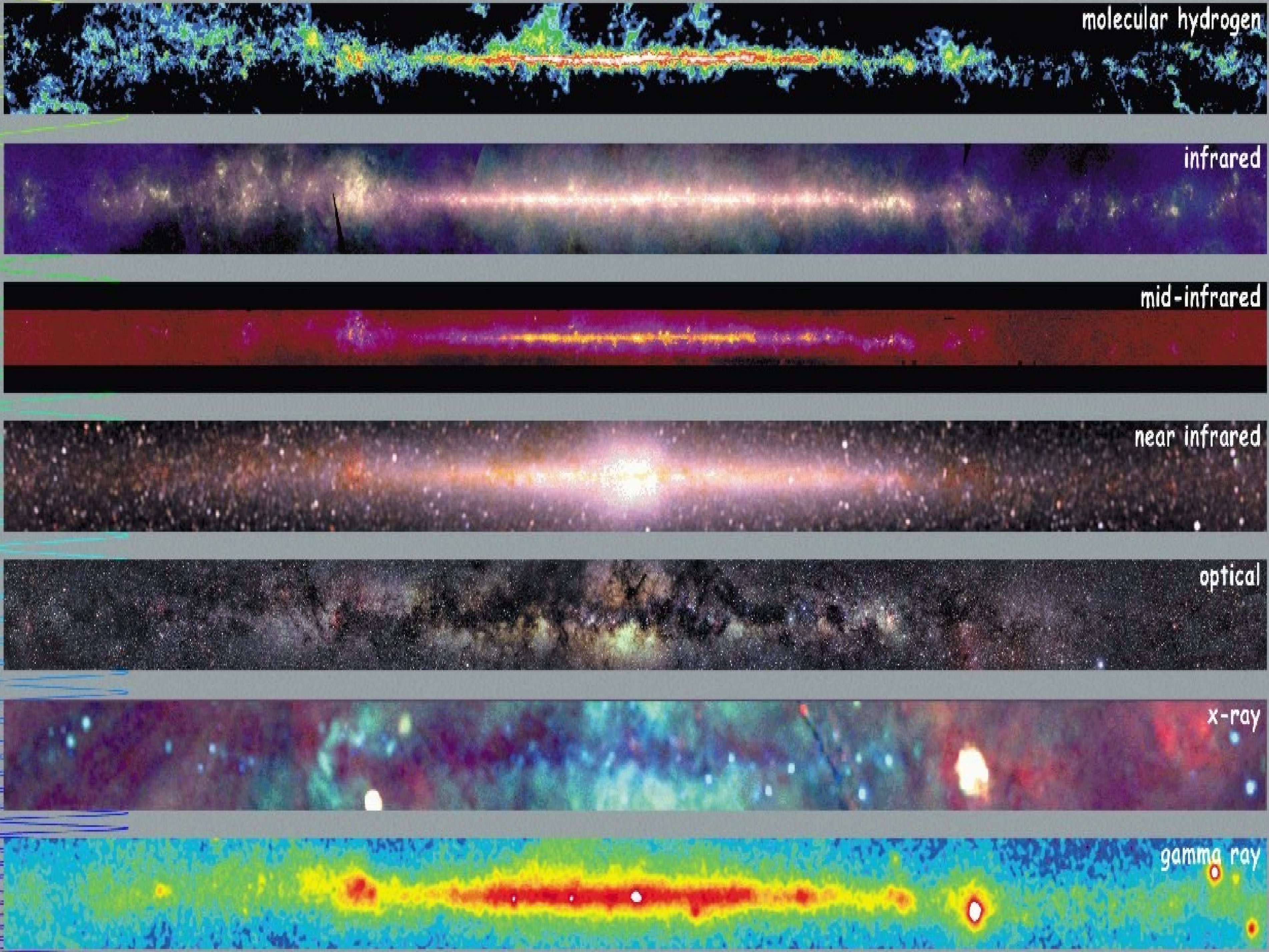
(ASYMMETRIC?) DISK SEEN

Weidenspointner Nature

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

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


molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray

Requirements from the positron source(s)

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

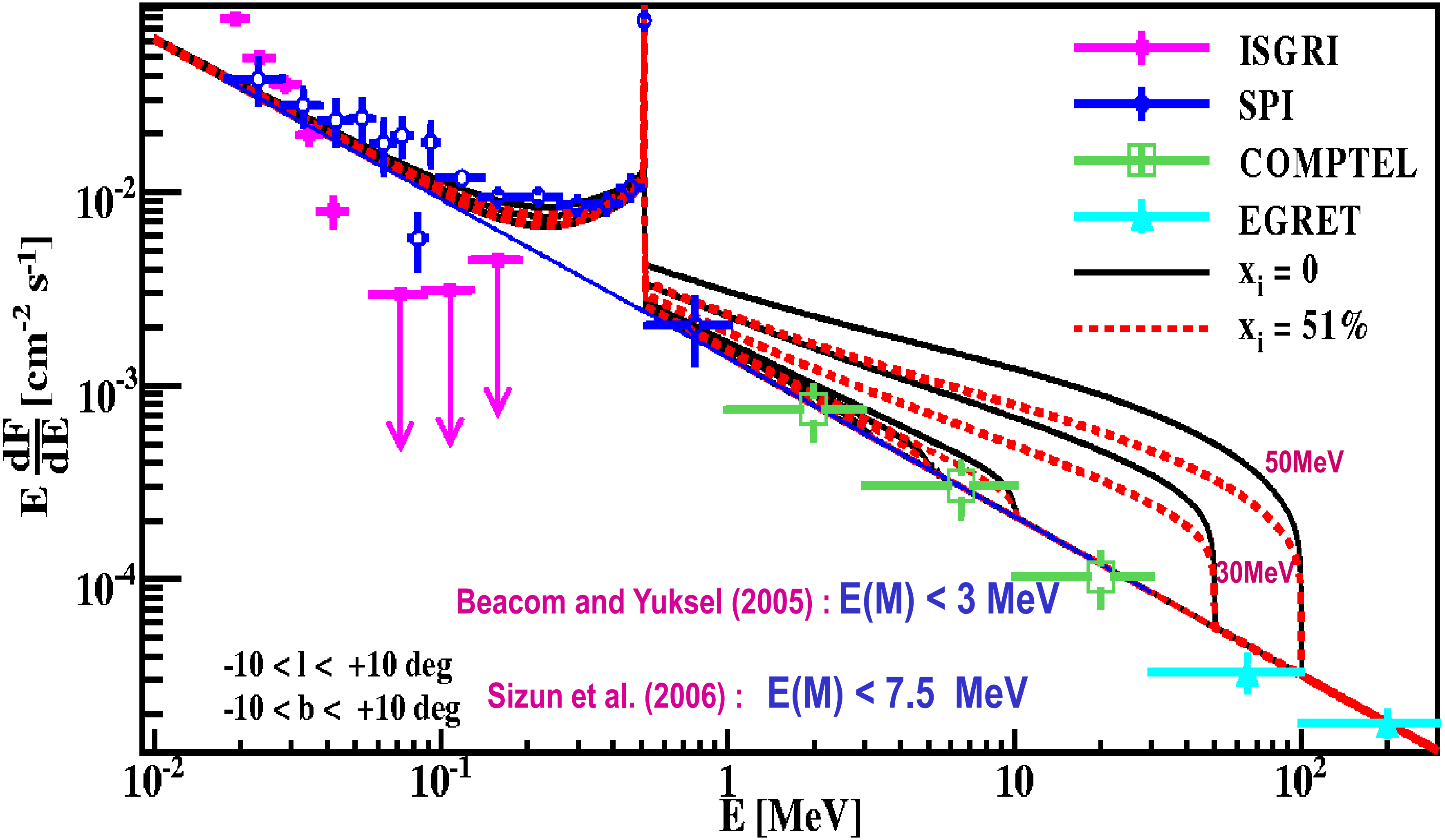
~1.2 10^{43} e^+ s^{-1} (Bulge)
~0.8 10^{43} e^+ s^{-1} (Disk)

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



Beacom and Yuksel (2005) : E(M) < 3 MeV

Sizun et al. (2006) : E(M) < 7.5 MeV

IF Dark Matter : mass much smaller than “canonical” (GeV) values

POSITRON SOURCES

I. Stellar Nucleosynthesis of radioactive nuclei

Astrophysical positron producing radioactivities

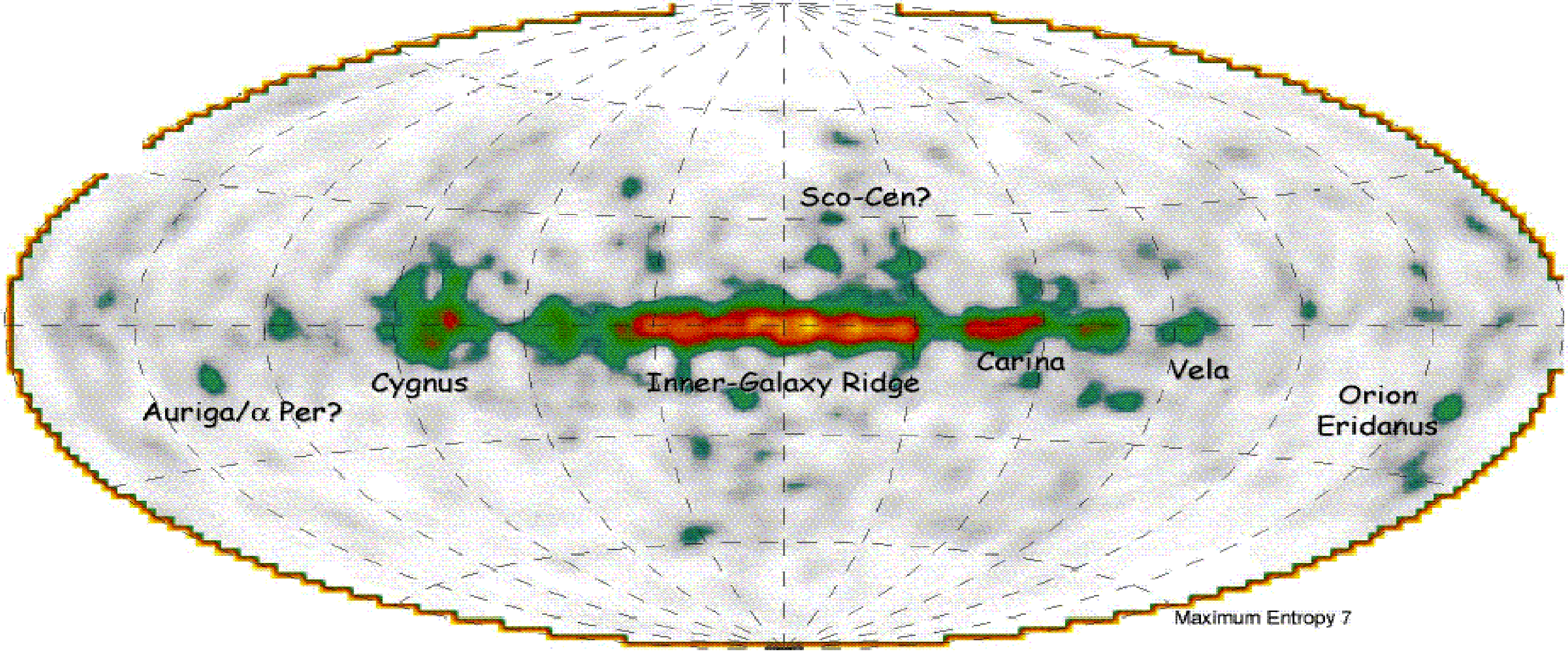
Nuclide	Decay chain	Decay mode and e^+ BR^a	Lifetime	Associated γ-ray lines Energy in keV (BR^a)	Endpoint e^+ energy (keV)	[redacted]	Sources
^{56}Ni	$^{56}\text{Ni} \longrightarrow {}^{56}\text{Co}^*$	EC^b	6.073 d	158(0.99), 812(0.86)		[redacted]	SNIa
	$^{56}\text{Co} \longrightarrow {}^{56}\text{Fe}^*$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

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

SN RATES IN MILKY WAY			SNIa		Core collapse SN	
	Stellar mass^a 10^{10} $M_\odot$	Spectral type	Specific rate^b SNuM	Rate century^{-1}	Specific rate^b SNuM	Rate century^{-1}
Bulge	1.4	E0	0.044	0.062	-	-
Nuclear Bulge	0.15	Sbc/d-Irr^c	0.17-0.77	0.025-0.115	0.86-2.24	0.13-0.33
Thin disk	2.3	Sbc	0.17	0.4	0.86	2
Thick disk	0.5	E0	0.044	0.022	-	
Total bulge	1.5			0.087-0.18		0.13-0.33
Total disk	2.8			0.42		2
Total Milky Way	4.3			0.5-0.6		2.13-2.33

[redacted]

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



Complete CGRO Mission
(Plüschke et al. 2001)

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

Emission hot-spots in directions tangent to **spiral arms** suggest **massive stars** at the origin of ^{26}Al

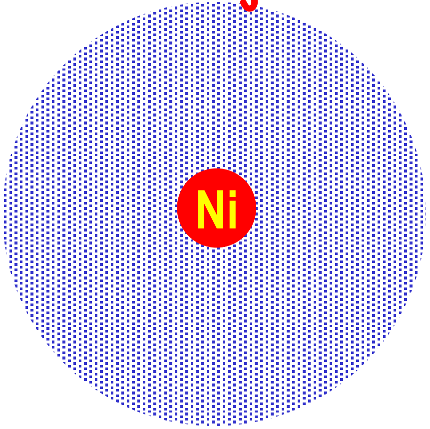
Each ^{26}Al decay releases 0.82 e^+ : **0.4 10^{43} e^+/s** produced (= **0.5 SPI disk**)

Decay of Ti44, produced in CC-SN : all positrons escape **(τ ~ 80 yr)**

Estimated e^+ production Rate **~ 3 10^{42} s^{-1}** ; **OK FOR 0.5 DISK, NOT FOR BULGE**

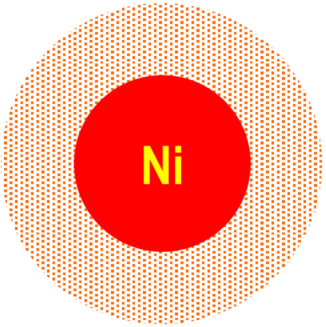
Positron sources : Medium-lived radioactivity from SN

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



Core collapse SN
(Massive stars)

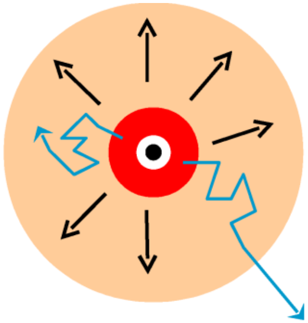
$M_{Ni56} \sim 0.07\ M_\odot$ $M_{Envelope} \sim 10\ M_\odot$



Thermonuclear SN
(White dwarfs)

$M_{Ni56} \sim 0.7\ M_\odot$ $M_{Envelope} \sim 0.7\ M_\odot$

Thermonuclear SN (SNIa): release **more e^+** which **escape easier** (*in principle*) from the expanding envelope than in the case of SNII



Number of positrons produced per SNIa:

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

Frequency of SNIa in MW :

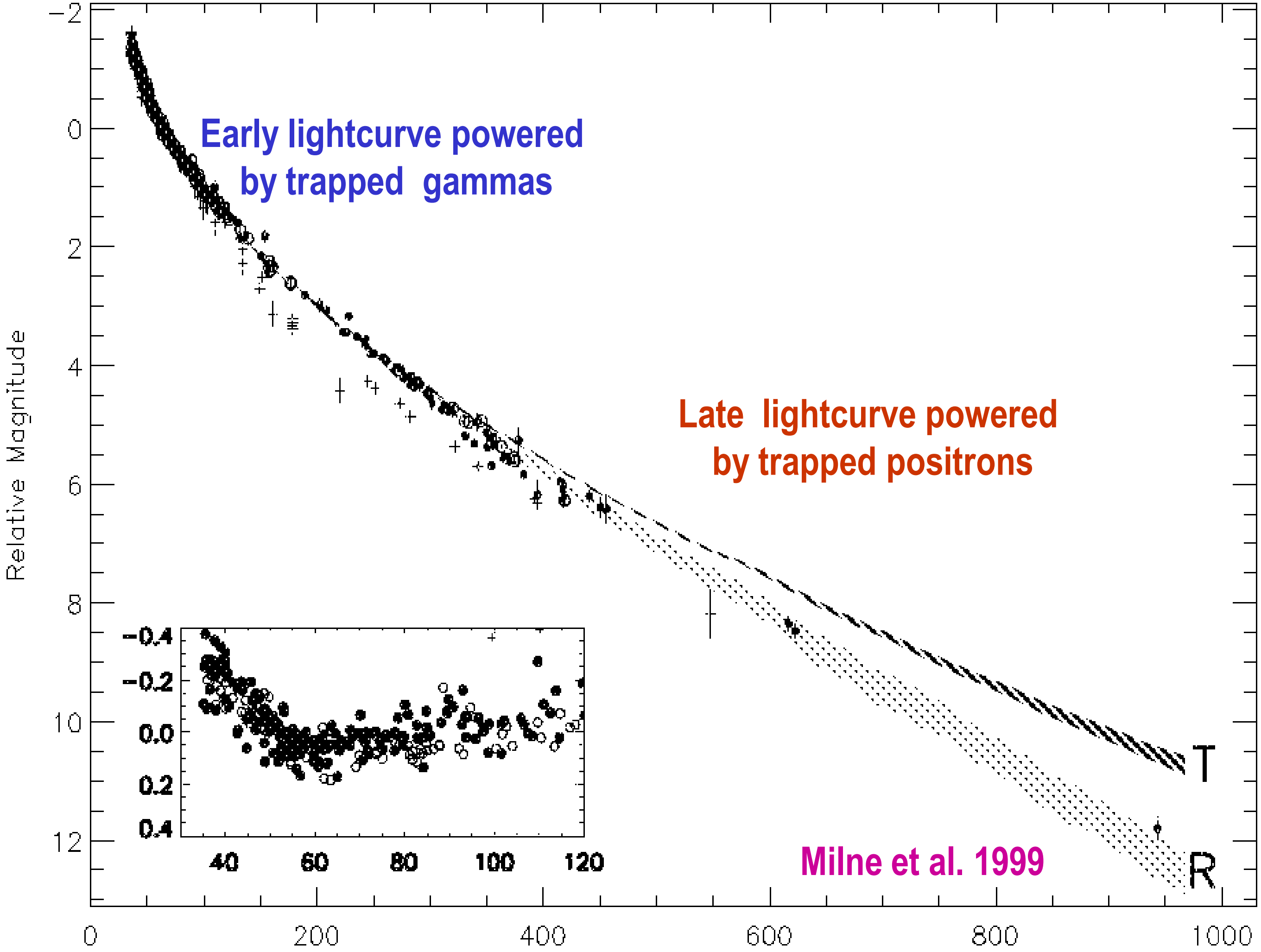
$f \sim 0.5\ /100\ \mathrm{yr} \sim 1.6\ 10^{-10}\ \mathrm{s}^{-1}$

Rate of positrons released by MW SNIa:

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

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



Early lightcurve powered by trapped gammas

Late lightcurve powered by trapped positrons

Milne et al. 1999

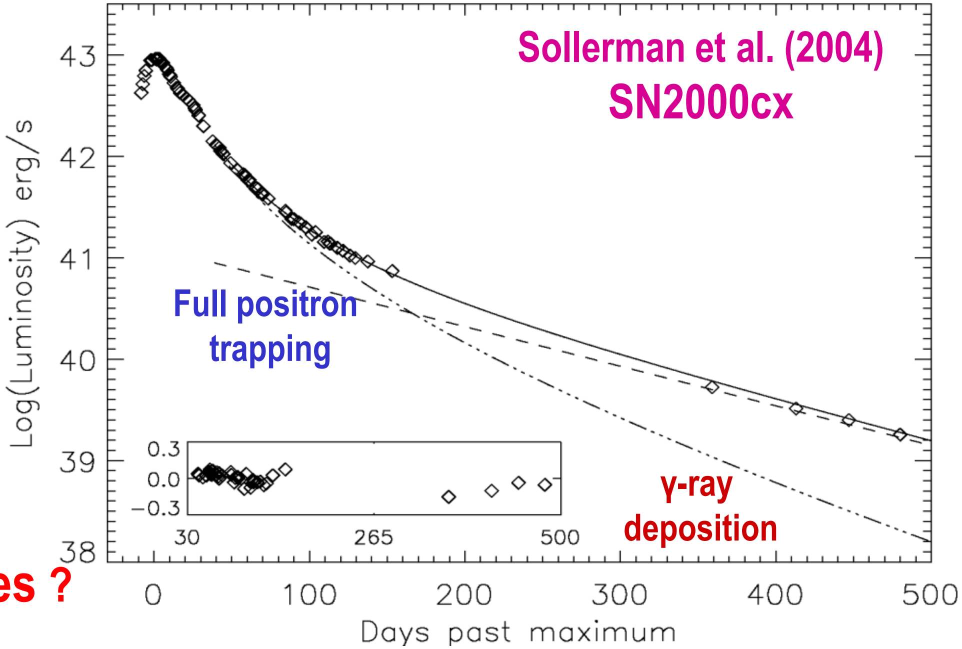
Observations of late lightcurves of SNIa in late 1990ies:

$N \sim 8\ 10^{52}\ e^+$ (escape fraction $f \sim 0.03$)

If f=4% of e^+ escape SNIa, 2 10^{43} e^+/s are ejected in ISM

Observations of late L_{BOL} (*including* NIR) analyzed with 1D models suggest f=0%

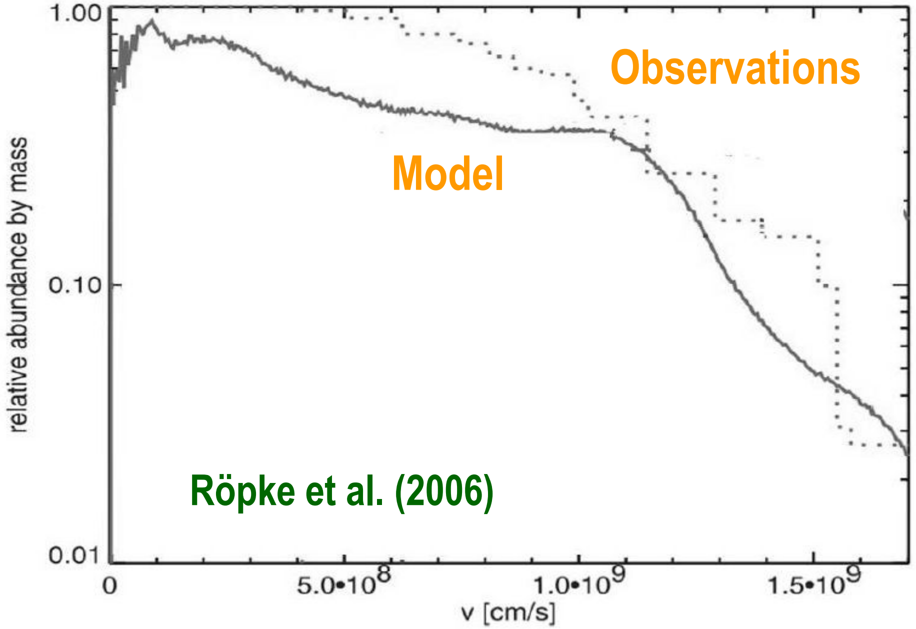
Observations, supported by 3D models, find substantial Ni-56 at high velocities (=outer layers) and early times


Sollerman et al. (2004)
SN2000cx

Full positron trapping

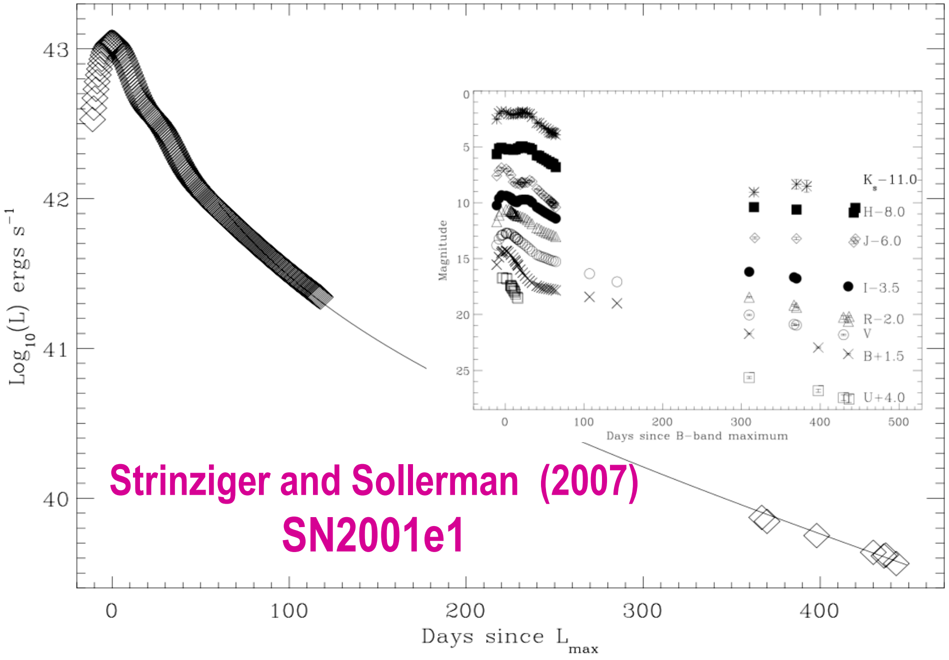
γ-ray deposition

Could f=4% e^+ from Ni56 leak out at *early* times ?


Observations

Model

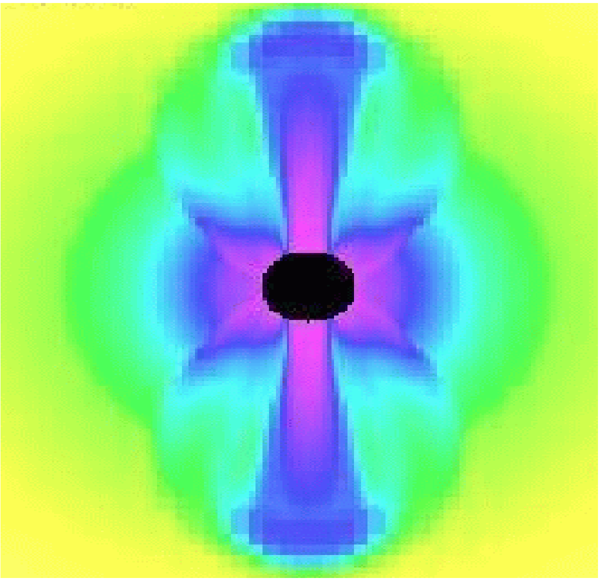
Röpke et al. (2006)


Strinziger and Sollerman (2007)
SN2001e1

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)

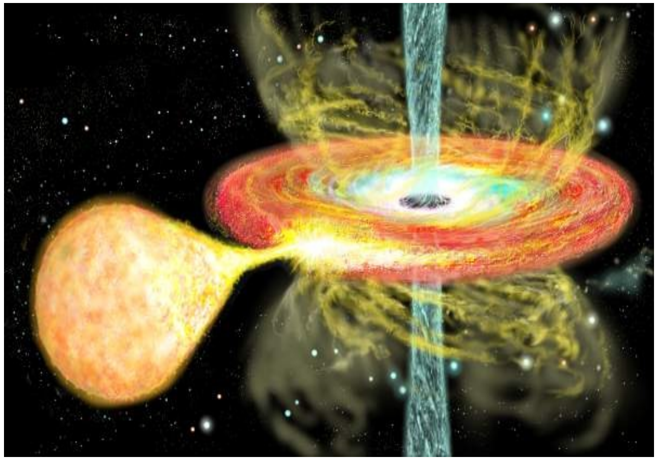
Novae models (**Hernanz et al. 2002**)
^{13}N: abundant BUT too short-lived (e^+ trapped)
^{22}Na: long-lived BUT not enough (factor 40)

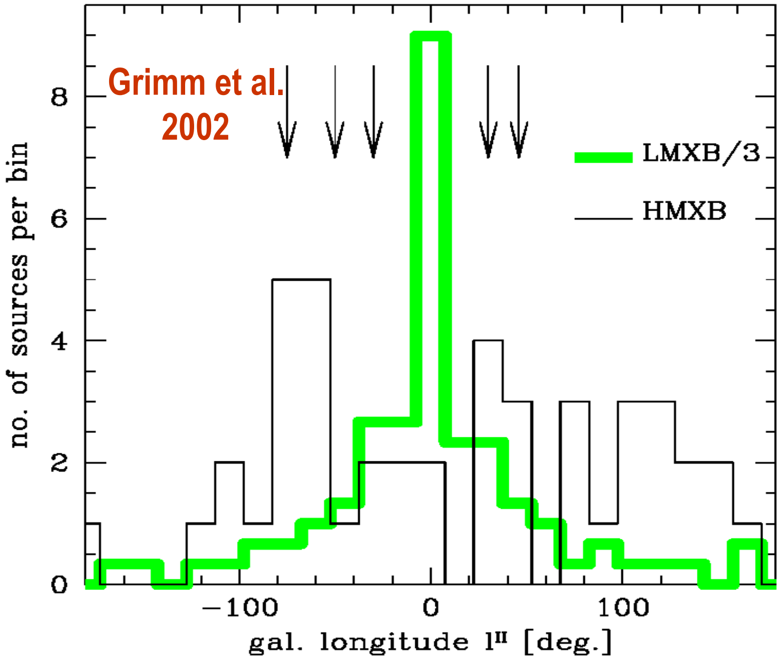
POSITRON SOURCES

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

Pair production of positrons, ejected by Outflows/Jets in Low Mass X-ray Binaries (LMXB) ?

(NP 2004)





Grimm et al. 2002

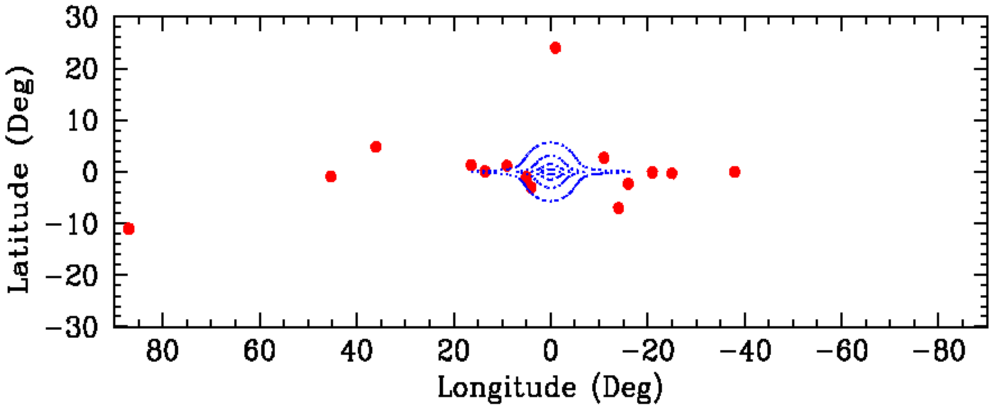
LMXBs strongly concentrated in low galactic longitude **(Grimm et al. 2002)**

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

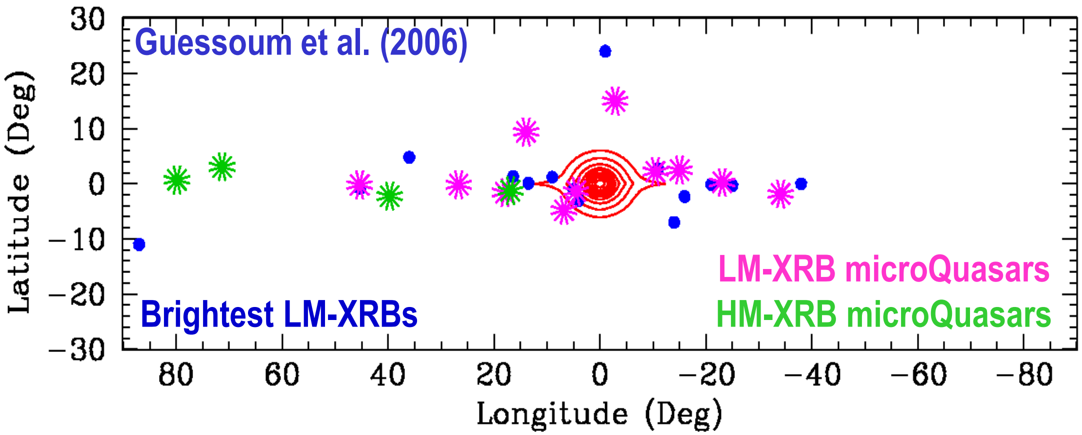


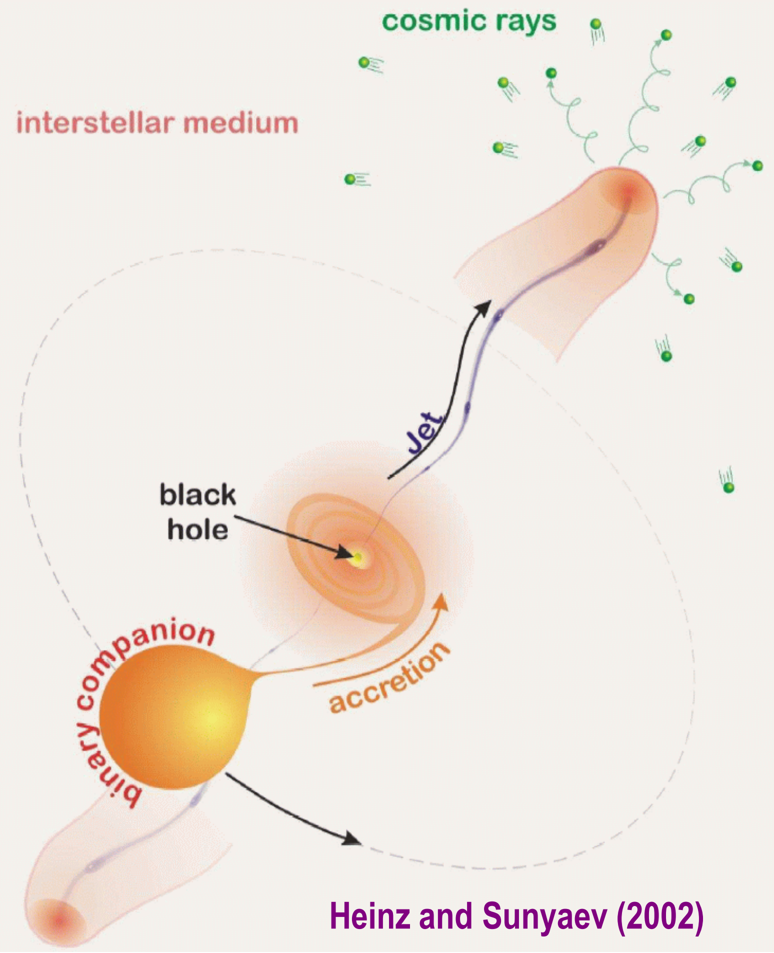
However, 80% of total LMXB X-ray emissivity comes from a dozen or so bright sources, **not clustered in the bulge…**

If $L_{e+} \propto L_X$, morphology is not OK

Jets in Microquasars ?

(sub-class of XRBs, permanent jets in low/hard state)





Galactic population estimated to ~100

IF composed of $e^- e^+$ pairs,

microquasar jets

can provide up to **$\sim 10^{43}$ e^+/s**

Galaxy-wide

(Guessoum, Jean and NP 2006)

BUT: Particle content UNKNOWN

($p - e^-$ or $\mathbf{e^- - e^+}$?)

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)*

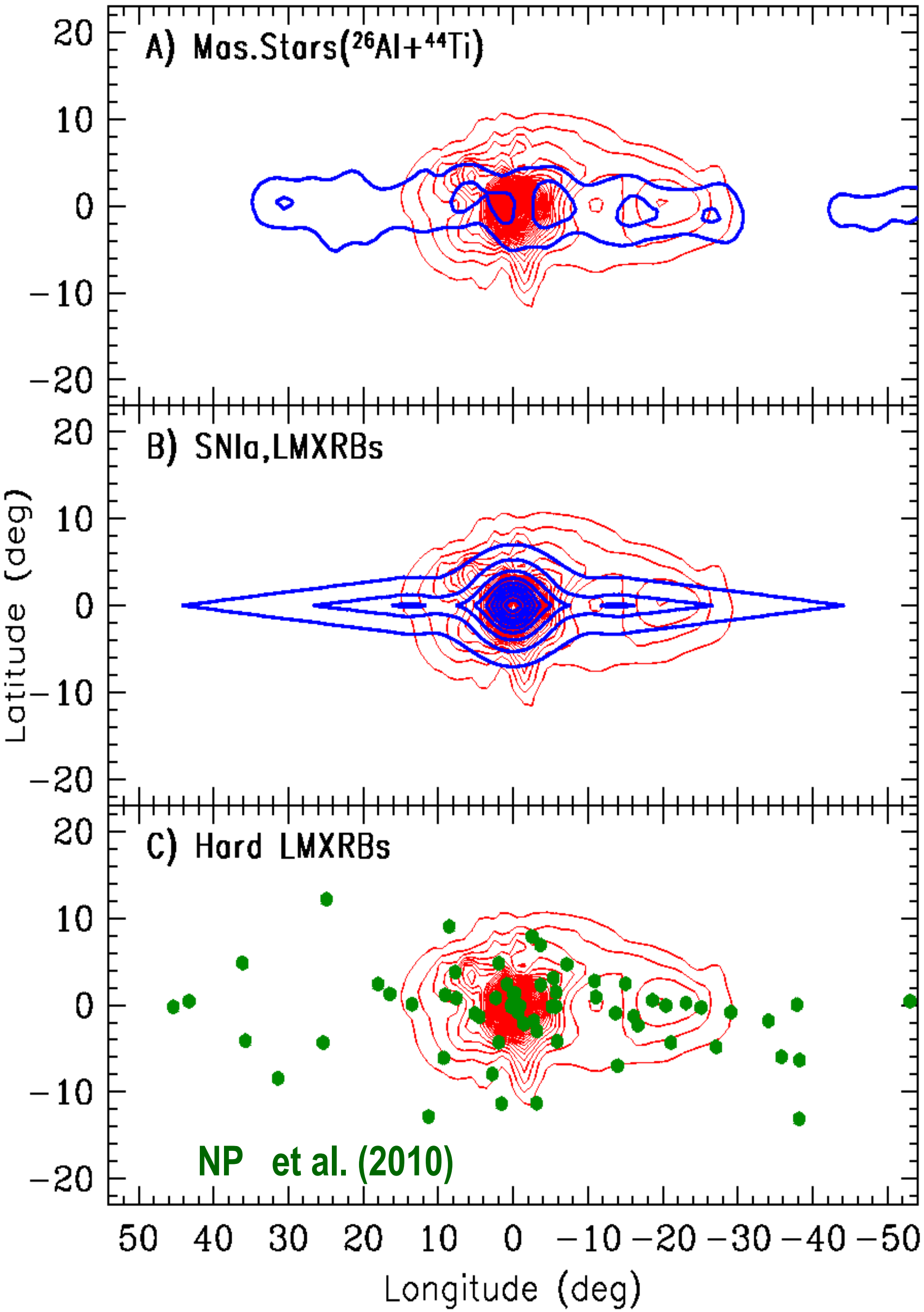
2) Heavy (GeV-TeV) DM particles ?

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



NP et al. (2010)

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**

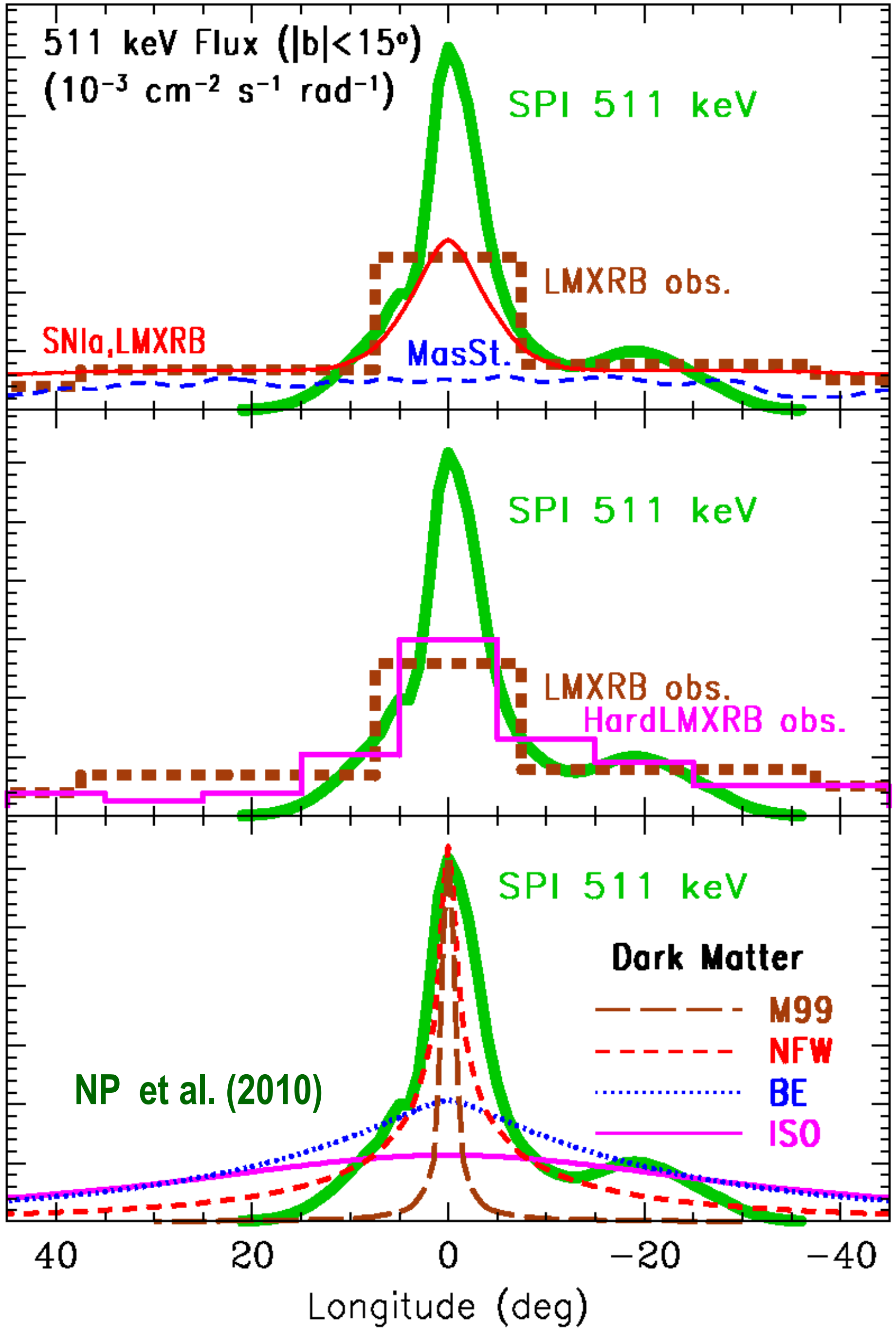
Bottom panel:

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

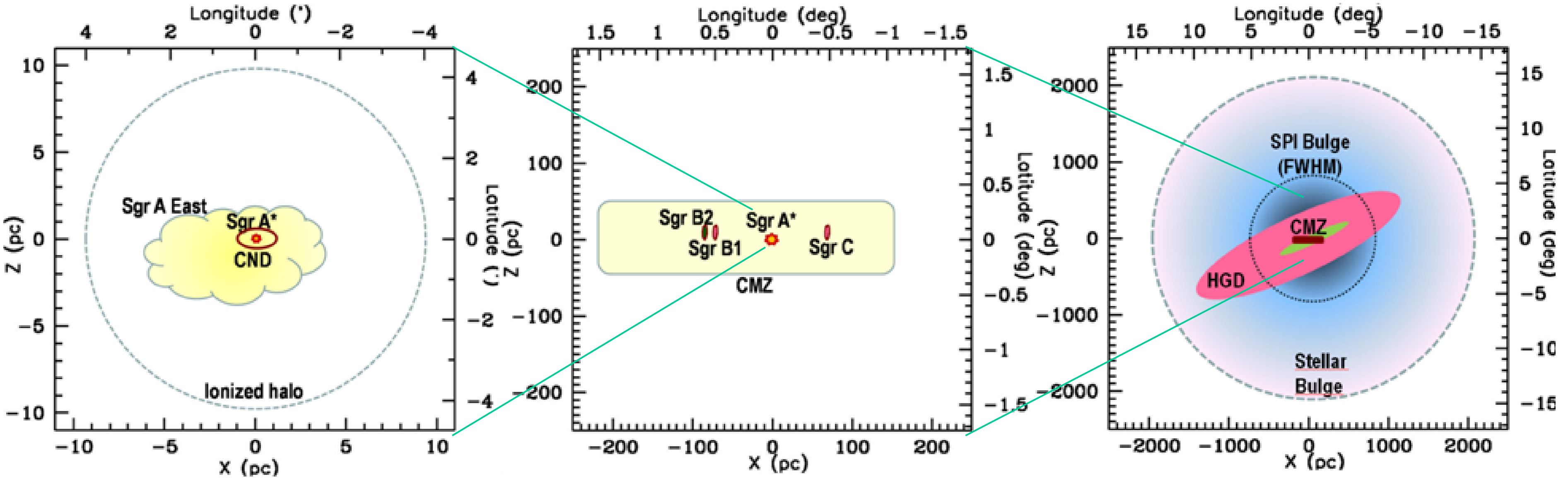
(asymmetric?)

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



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

Accretion of gas from one (or many) disrupted star(s) up to 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 inflight annihilation (*Cheng et al. 2010*)

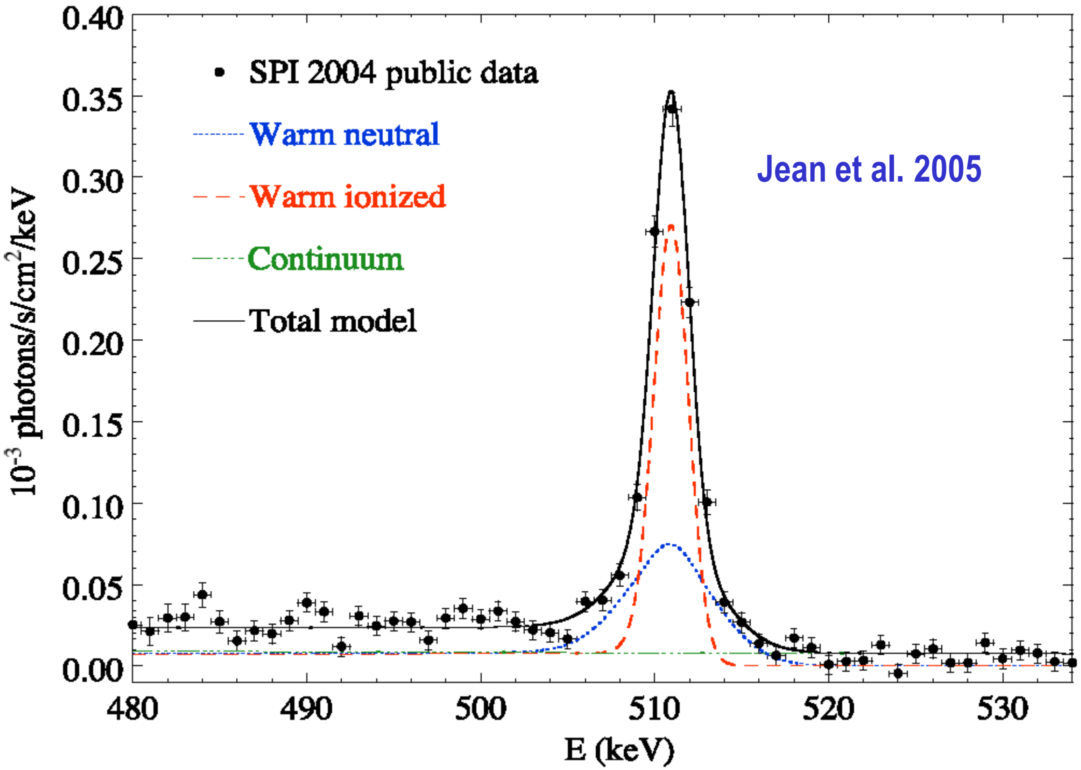
Model requires higher activity in the past since Sgr A* is ~inactive now
NO MORE STEADY STATE ASSUMPTION

Candidate positron sources in the Galaxy

NP et al. (2010)

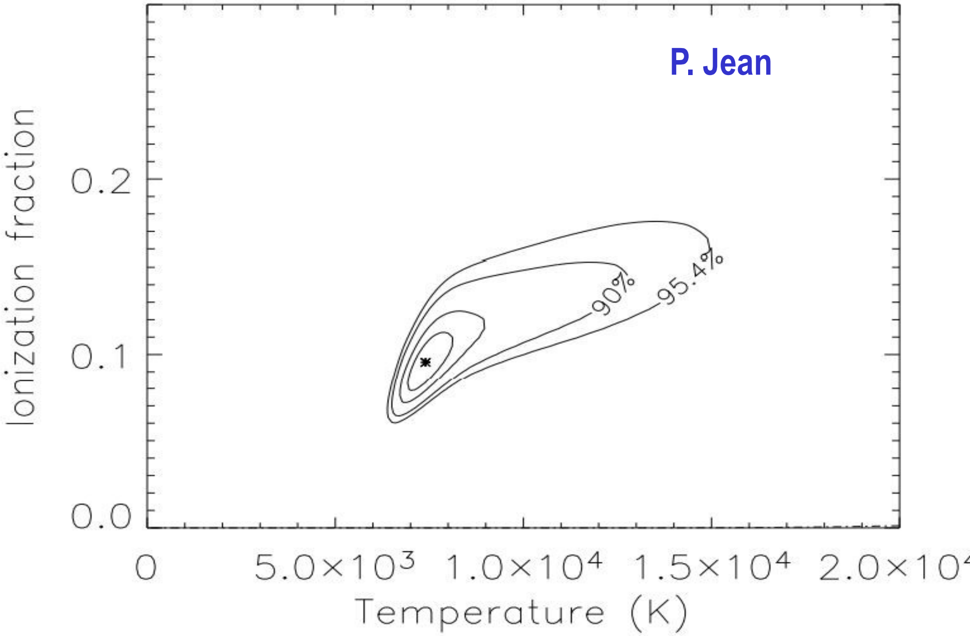
Source	Process	E(e$^+$)^a (MeV)	e$^+$ rate^b $\dot{N}_{e+}$ (10^{43} s^{-1})	Bulge/Disk^c B/D	Comments
Massive stars: ^{26}Al	β^+-decay	~1	0.4	<0.2	$\dot{N}, B/D$: Observationally inferred
Supernovae: ^{44}Ti	β^+-decay	~1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+-decay	[redacted]	[redacted]	[redacted]	Assuming $f_{e+,esc}$=0.04
~~Novae~~	~~β^+-decay~~	~~~1~~	~~*0.02*~~	~~<0.5~~	Insufficent e$^+$ production
~~Hypernovae/GRB: ^{56}Ni~~	~~β^+-decay~~	~~~1~~	~~?~~	~~<0.2~~	Improbable in inner MW
~~Cosmic rays~~	~~p-p~~	~~~30~~	~~0.1~~	~~<0.2~~	Too high e$^+$ energy
LMXRBs	$\gamma-\gamma$	[redacted]	[redacted]	[redacted]	Assuming L_{e+} ~0.01 $L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	[redacted]	[redacted]	[redacted]	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	[redacted]		Too high e$^+$ energy, unless B >0.4 mG
	$\gamma-\gamma$	1	[redacted]		Requires e$^+$ diffusion to ~1 kpc
Dark matter	Annihilation	1 (?)	[redacted]		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	[redacted]		Only cuspy DM profiles allowed
	~~Decay~~	~~1~~	~~?~~		Ruled out for all DM profiles
Observational constraints		<7	2	>1.4	

Physics of 511 keV line profile



The line and continuum shape
provide information
on the physical conditions
in the annihilation region
(T ~8 000 K,
Warm neutral and ionized
phases of ISM)

But very little on the propagation
of the positrons, from their sources
to the annihilation region…

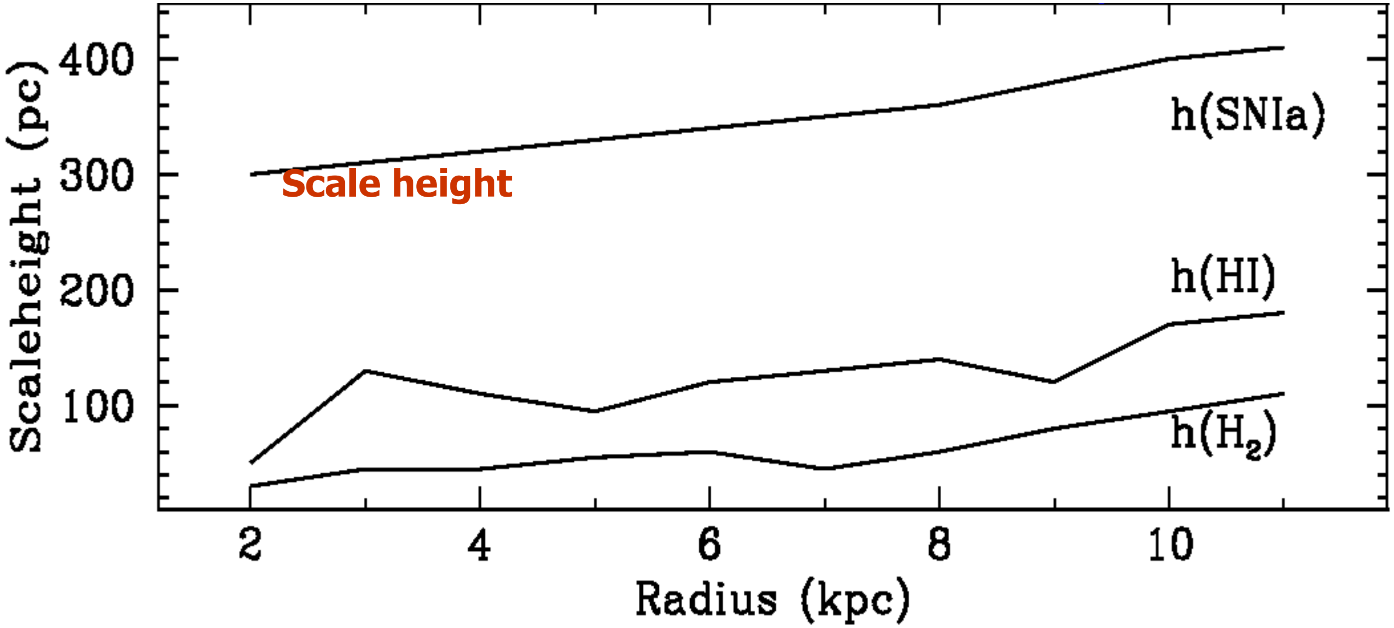


Implicit assumption :

Positrons annihilate close to their sources

Gamma-ray morphology reflects source morphology

Not necessarily true



Most of SNIa positrons released outside the gaseous disk, in low density medium

Positron propagation and annihilation in the interstellar medium

Positrons are born hot (> a few hundred keV in any case)

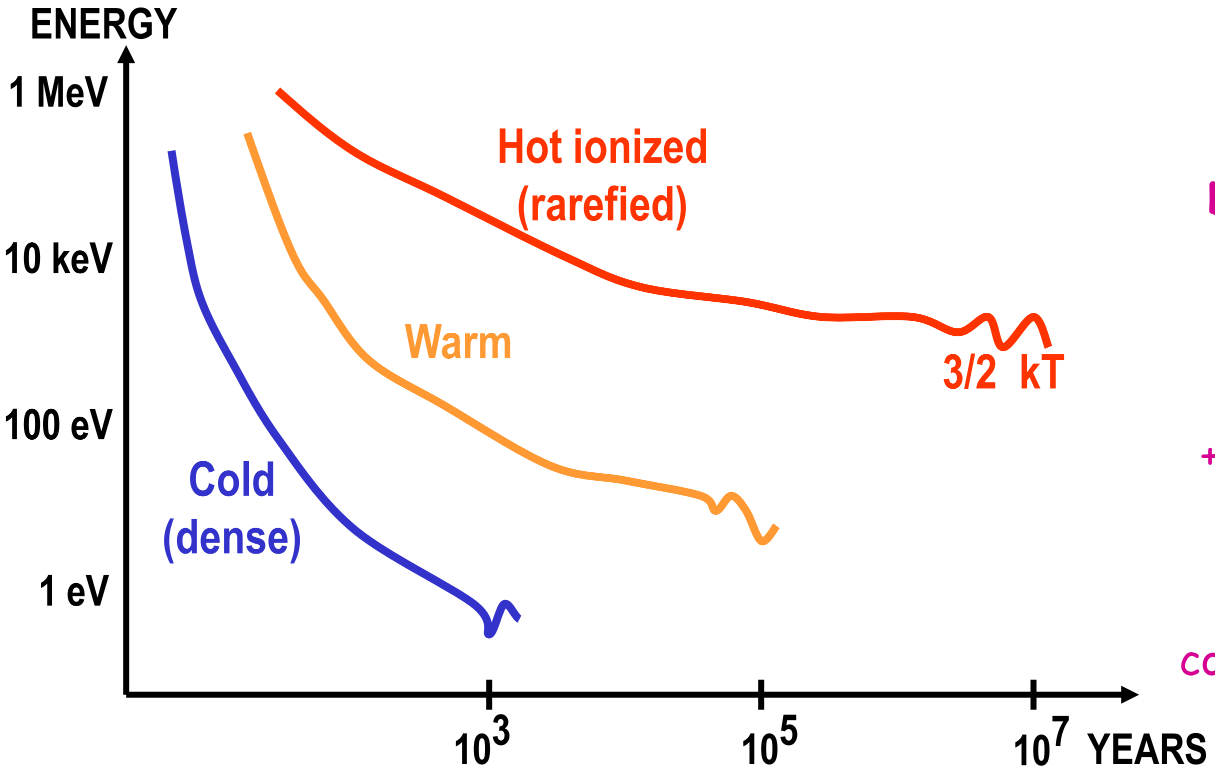
They decelerate (ionization, excitation, Coulomb losses)

They annihilate directly (on bound and free electrons)

Or, **after formation of Positronium**

(Radiative recombination, in ionized medium)

(Charge exchange, in neutral medium and E > 6.8 eV)



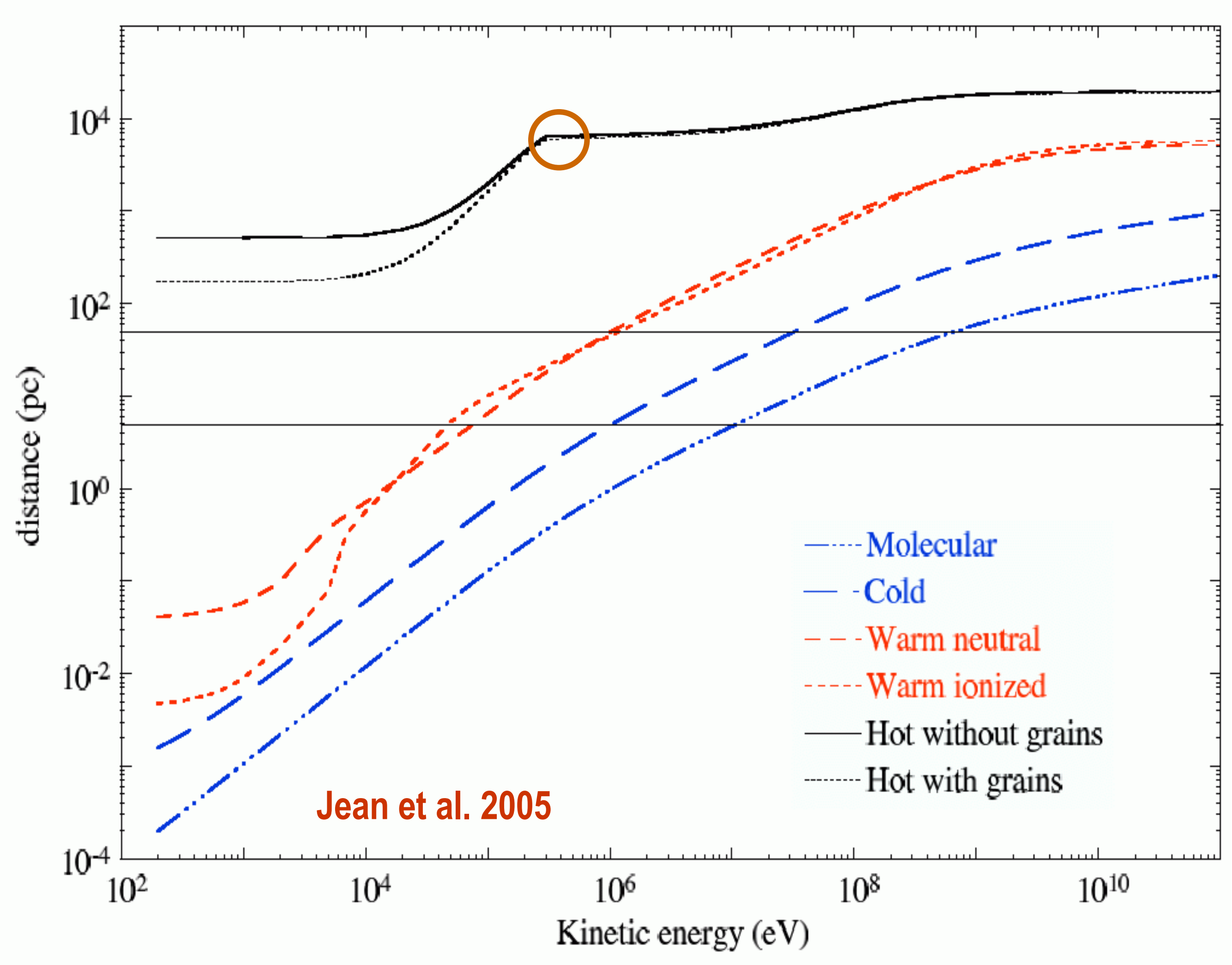
Critical parameters:

Densities and filling factors
of the various phases
of the ISM
(Bussard et al. 1979)

+ the presence of **dust grains**
(Zurek 1983)

+ intensity and
configuration of **magnetic field**

Distance travelled by positrons before annihilating

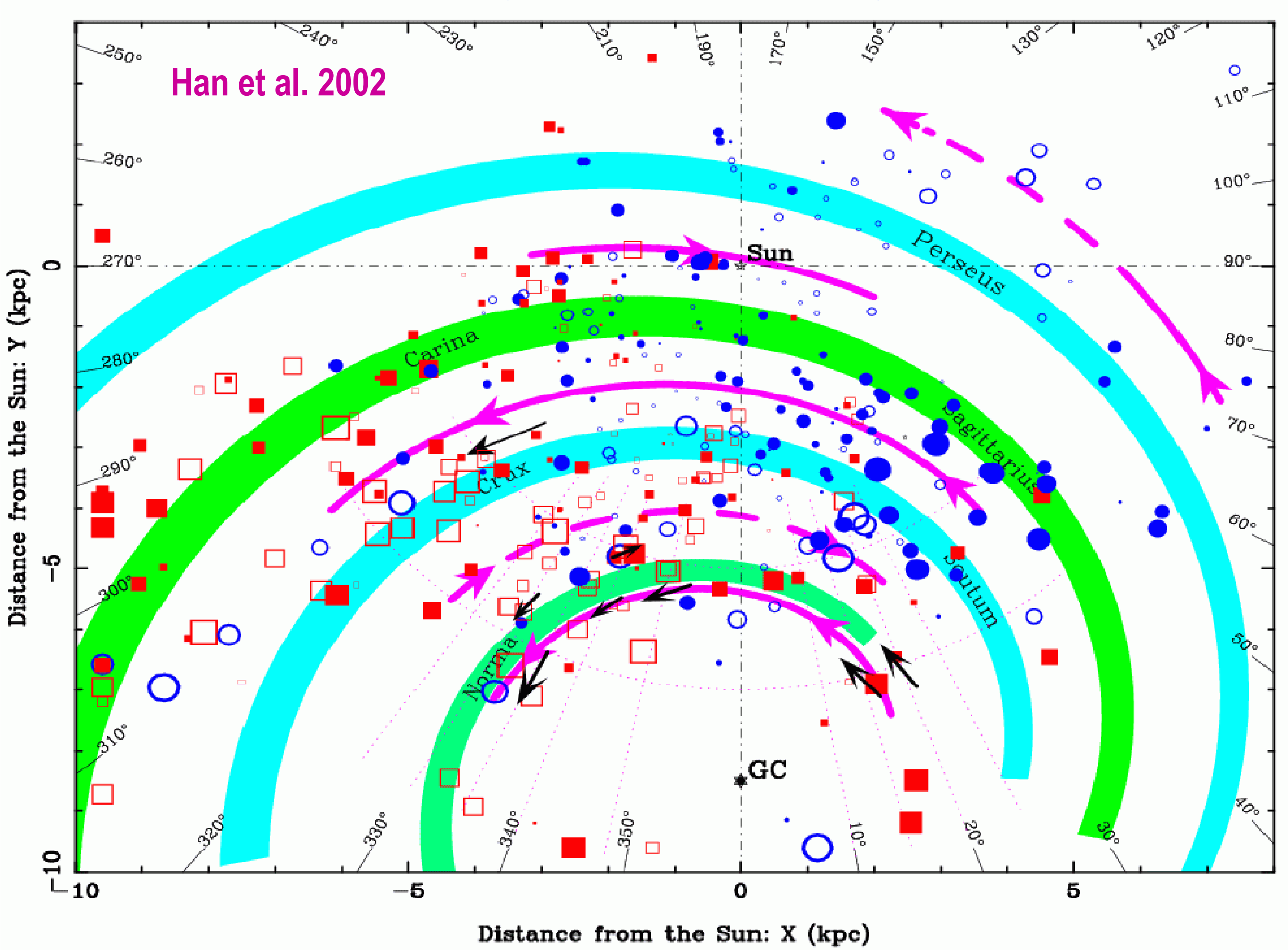


Positrons released in a hot
and low density medium
can travel far away from their sources
(many kpc) in a calm, unmagnetized plasma

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

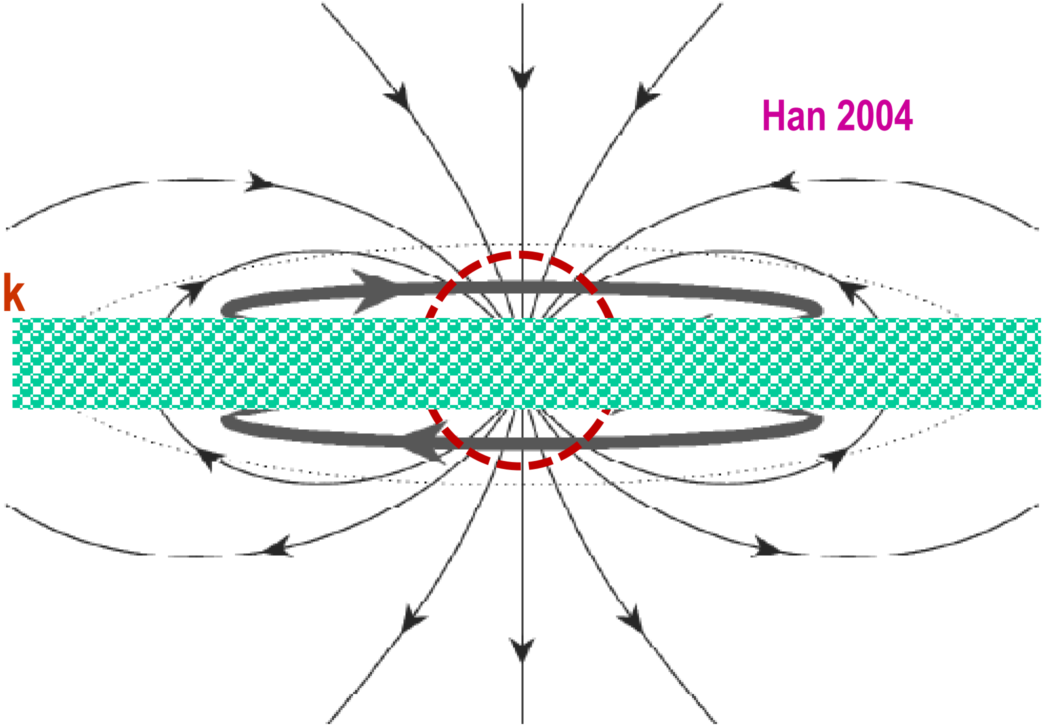
The Galactic Magnetic field

Irregular (turbulent) field dominant in the disk (a few μG,
but there is also a substantial **regular (toroidal)** component (1-2 μG),
with intensity inverted between spiral arms



But, the magnetic field configuration away from the disk is unknown

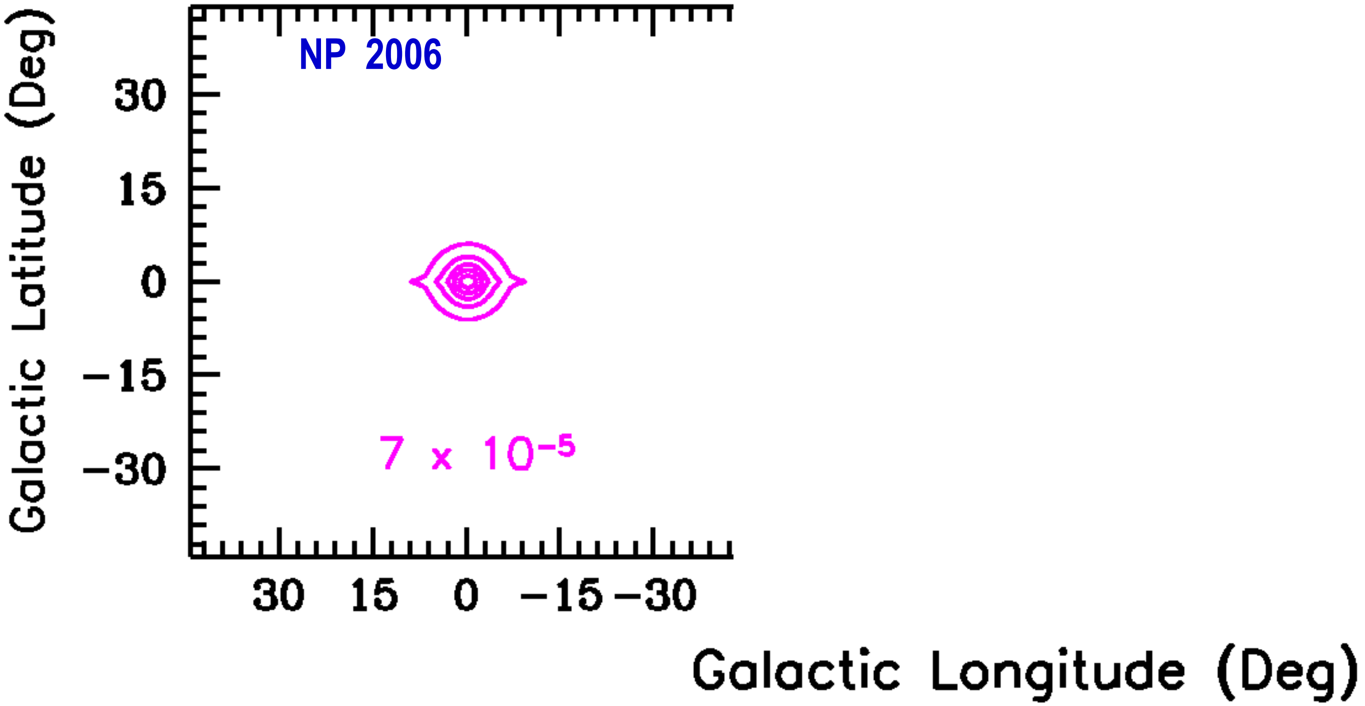
IF the galactic magnetic field has
a poloidal component (*Han 2004*)
a (difficult to estimate) fraction
of disk positrons should escape the disk
and be chaneled
(through the low density halo)
to the bulge, where they are better
confined (because of its stronger
magnetic field)
and they finally annihilate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


Han 2004

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

Possible to explain full 511 keV emission with radioactivities alone (Co56 from SNIa and Al26+Ti44 from CCSN)

Enhanced Bulge (*from transfer of 50% disk SNIa positrons*)
+ Thick disk *(remaining 50% of disk SNIa positrons away from their sources*)
+ Thin disk (*positrons from Al26 and Ti44 close to their sources: spiral arms)*



Summary

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

Its spatial morphology cannot be explained by
conventional astrophysical sources,
Unless positrons produced in the disk annihilate away from it
or positrons produced in the Galactic center diffuse in the bulge

Possible astrophysical scenarios:
-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 is the key issue !

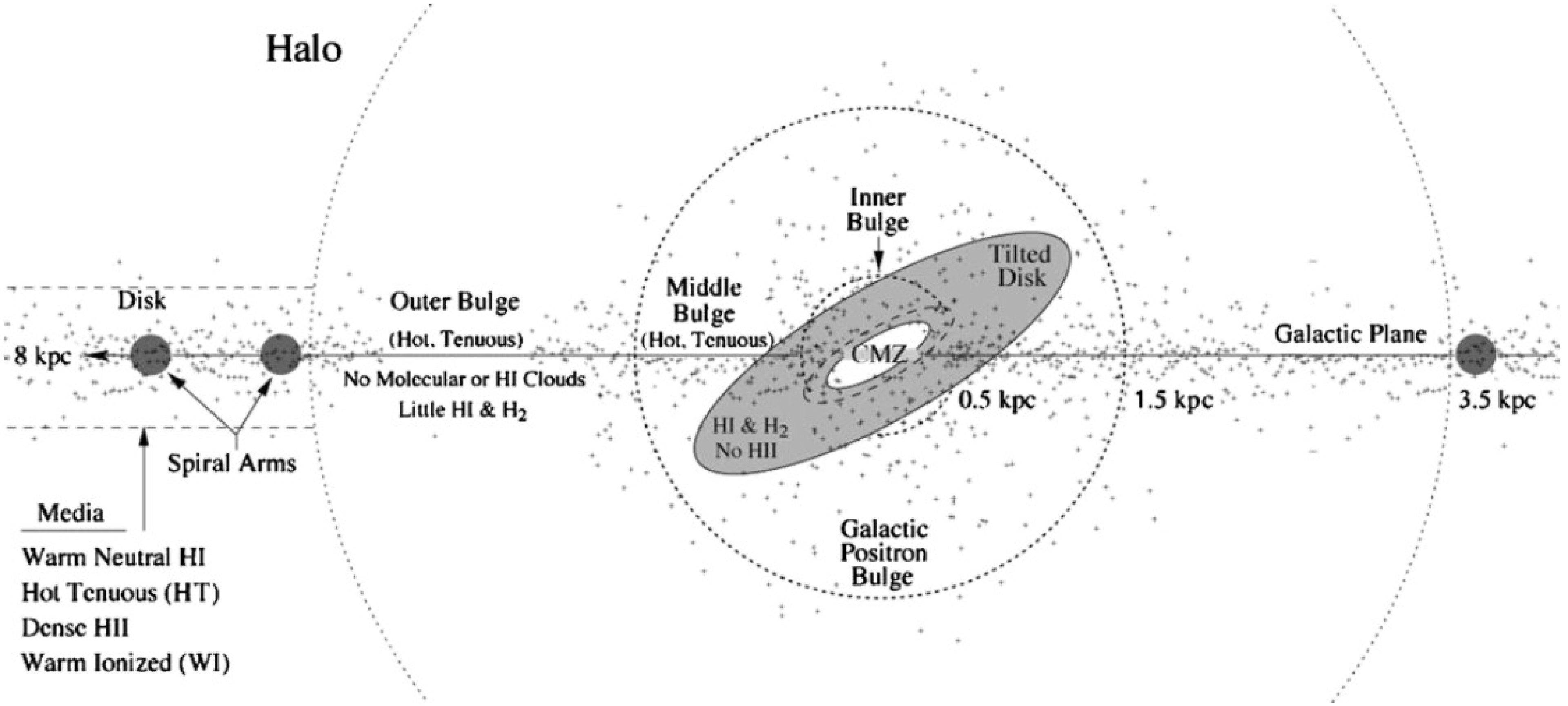
Particle physics solutions ???
(annihilating dark matter particles,
tangle of superconducting cosmic strings…)

The future of studies of Galactic 511 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 ?
- 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?

- **(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?

- **(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*)

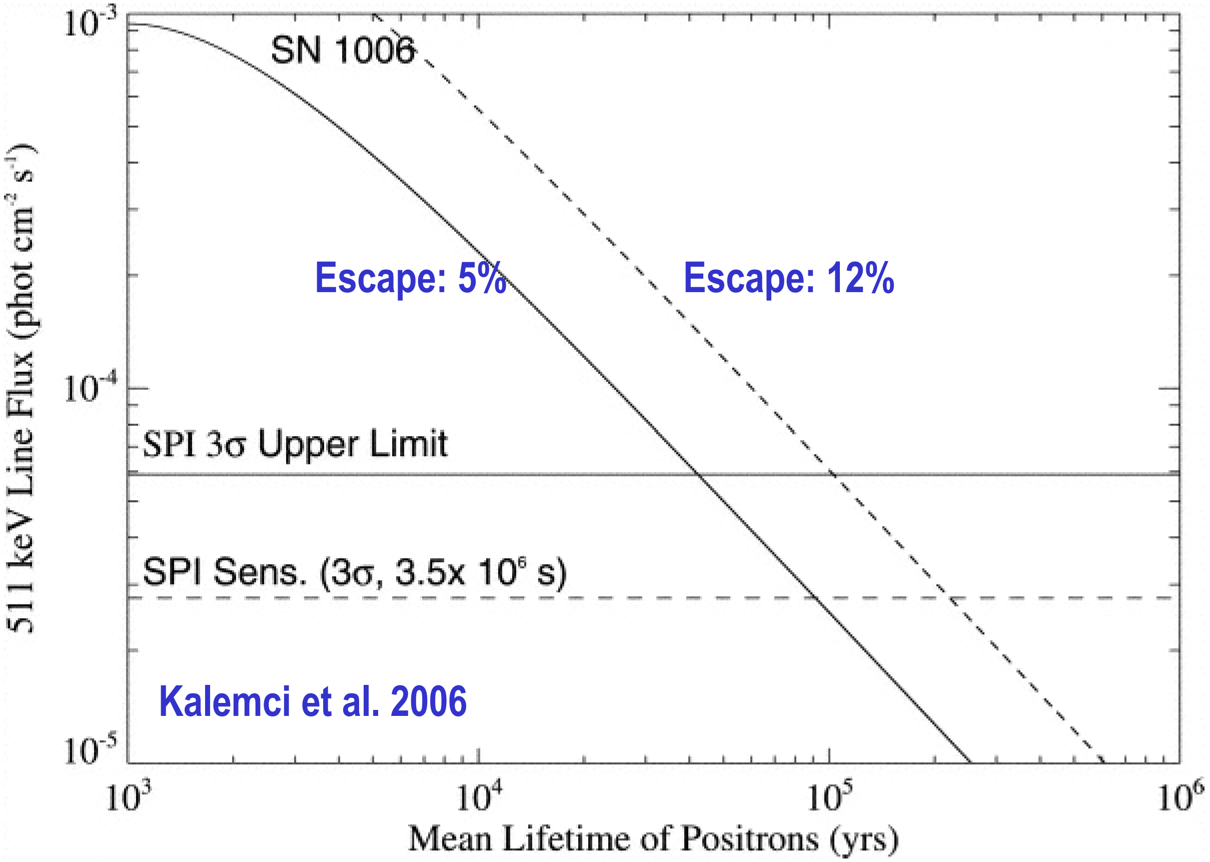
Fate of radioactivity positrons of SNIa

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

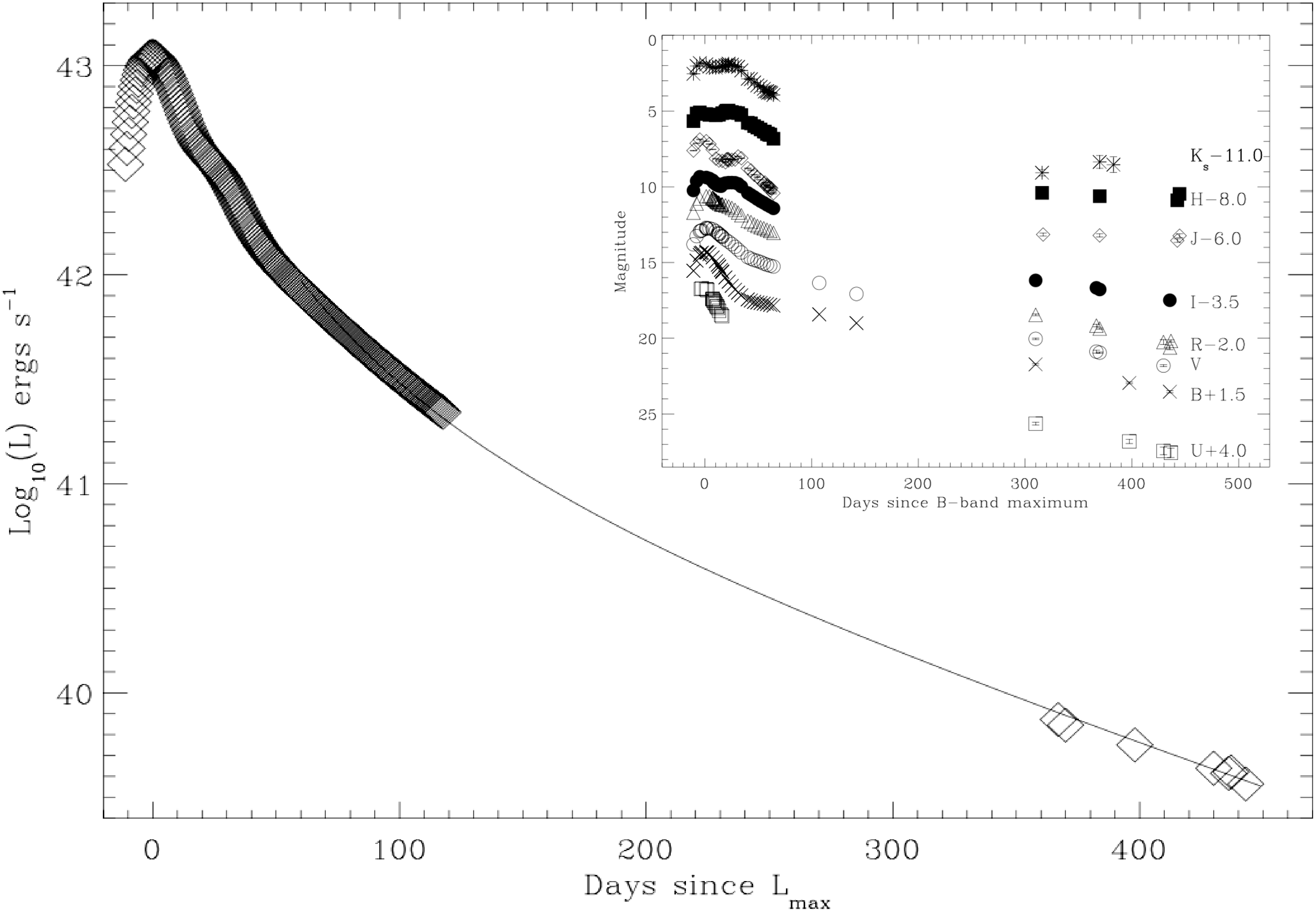
2) Local annihilation of all positrons + escape of 511 keV photons : no e^+ escape, local 511-emission seen

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

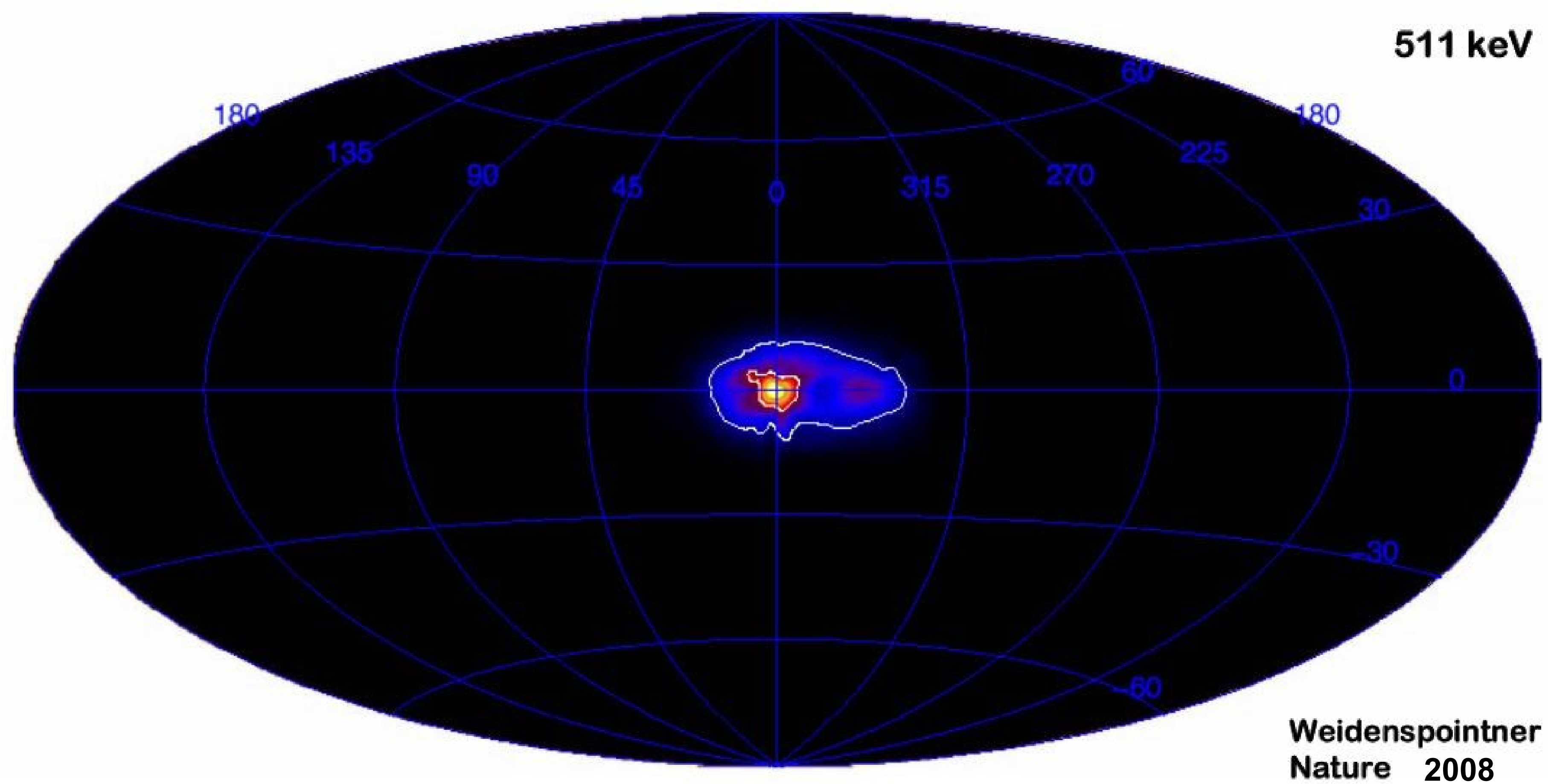
No detection of
511 keV emission
from SN1006
with SPI



And so do Strinziger and Sollerman (2007), for SN2001e1



An asymmetric disk detected in 511 keV after 4 years of data

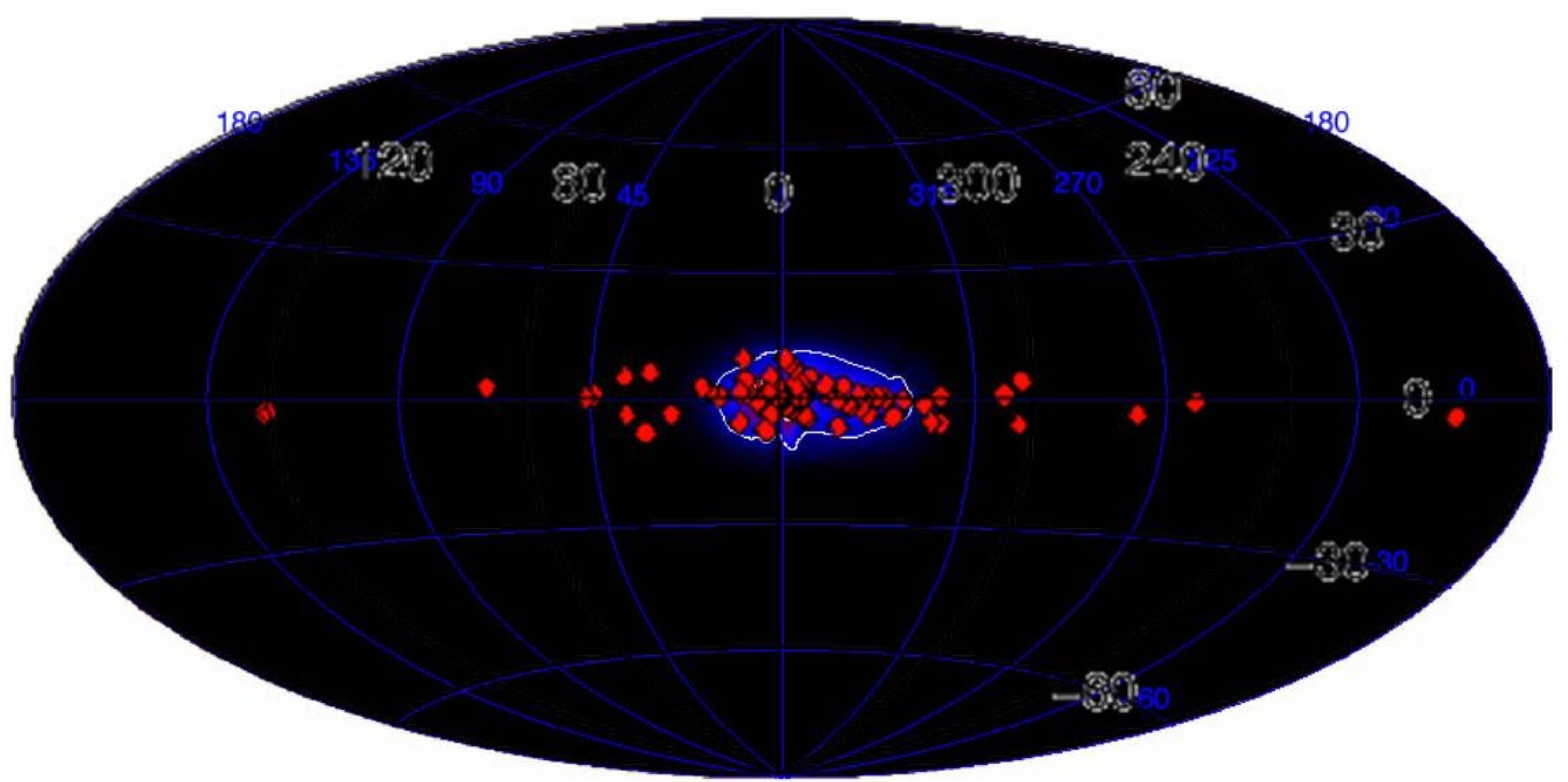


Weidenspointner
Nature 2008

But: Bouchet et al. (2008) see no disk and no asymmetry…

Similar asymmetry detected in disk distribution of Hard-state Low Mass XRBs

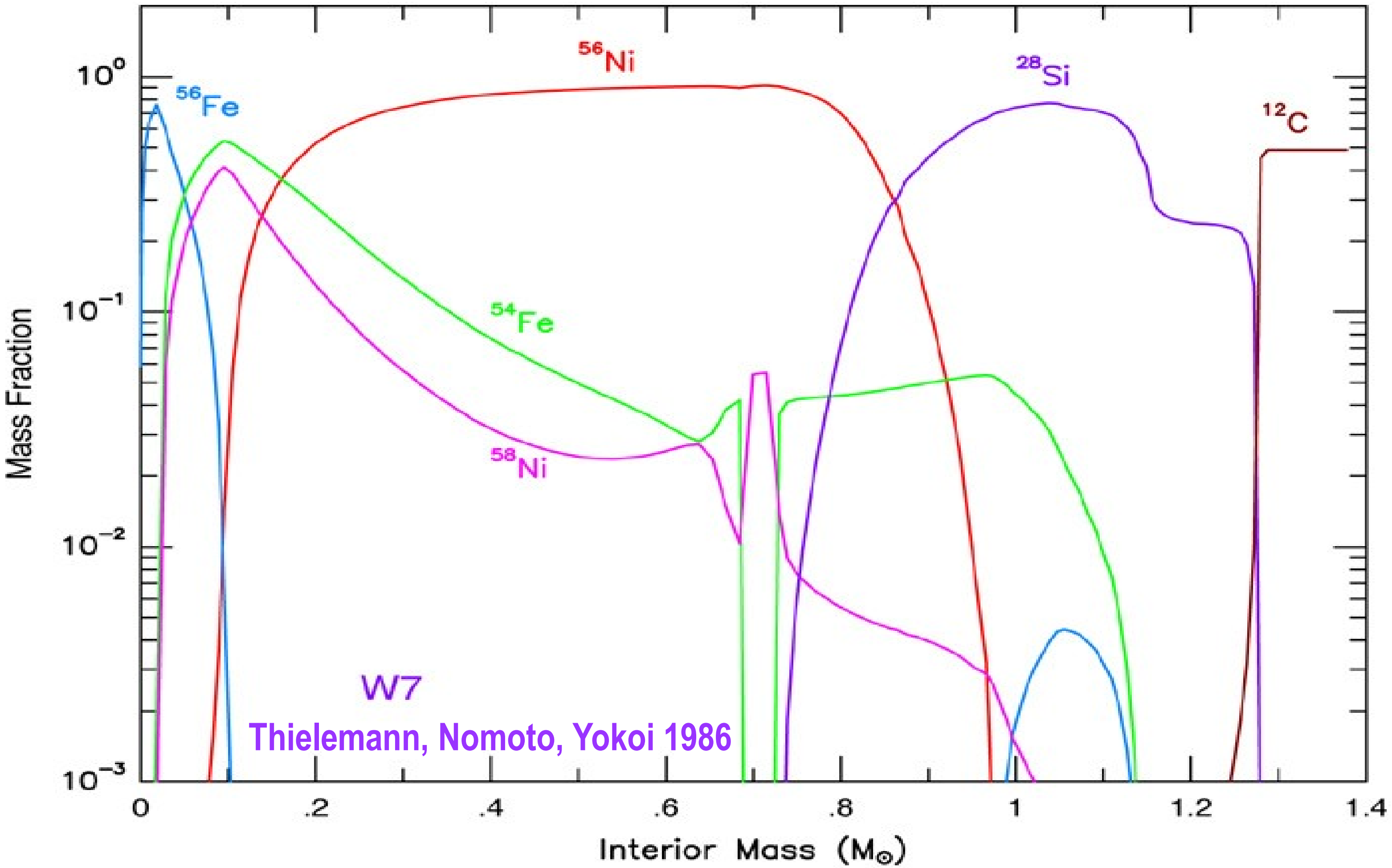
511 keV: Weidenspointner et al., 2008



20-100 keV LMXBs: Bird et al., 2007 Catalog

But: distribution of LMXRBs able to account for <40% of bulge 511 keV emission

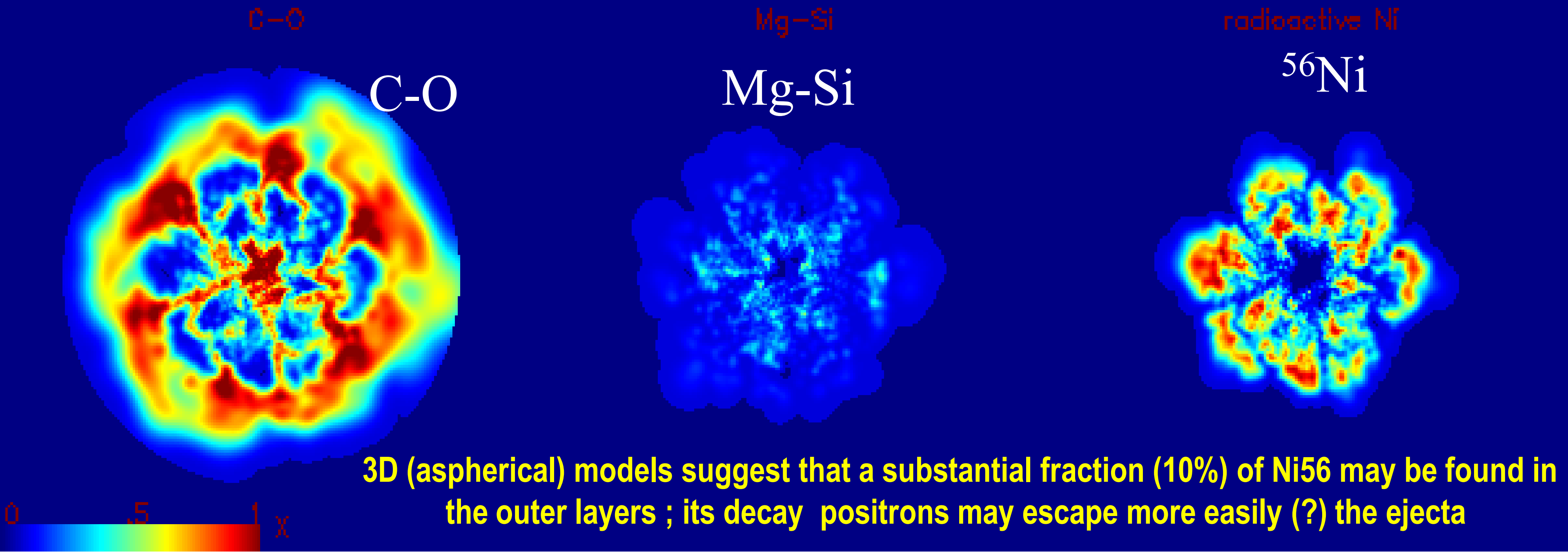
W7: a very successful parameterized SNIa model



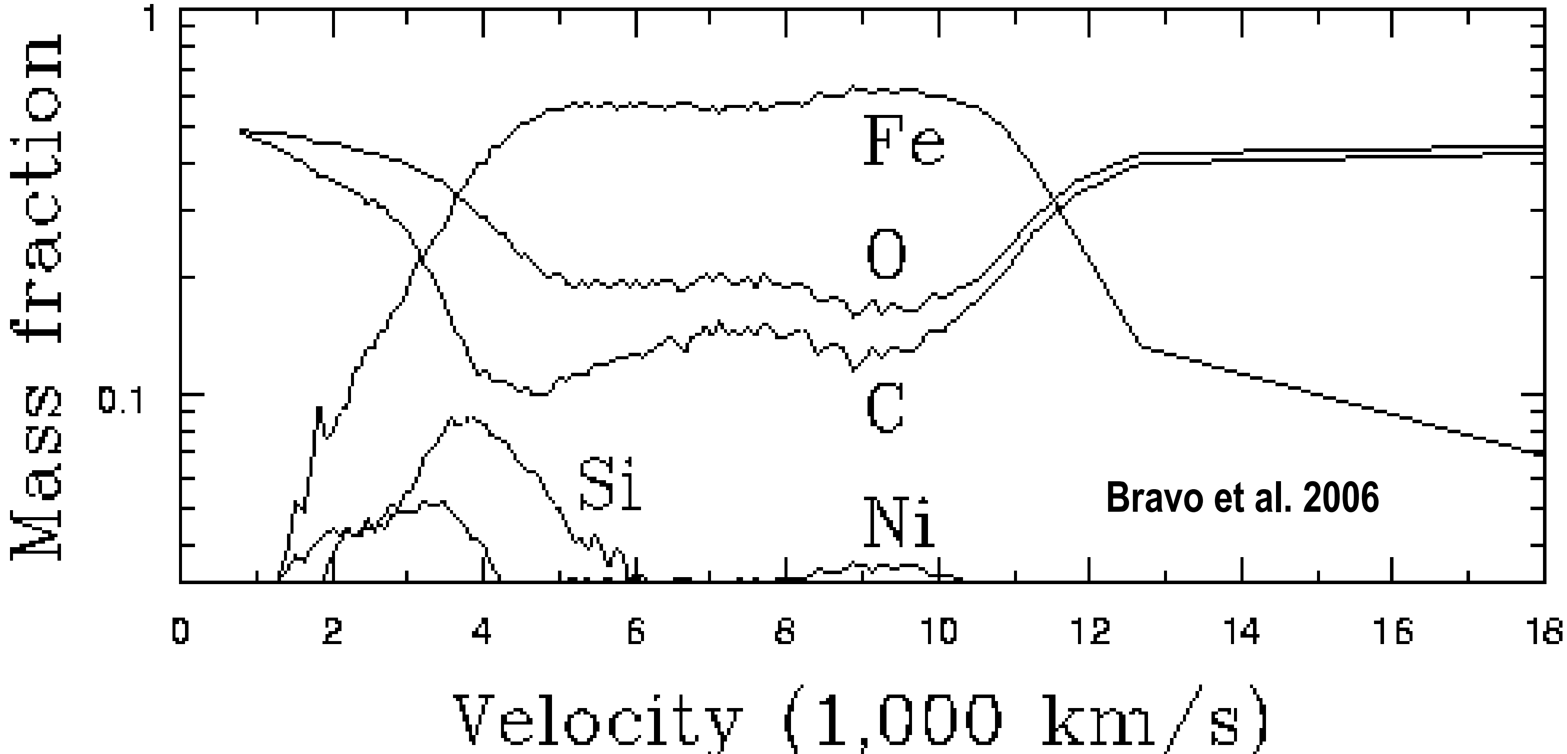
Thielemann, Nomoto, Yokoi 1986

Ideally: the flame should **start slowly** and pre-expand the star,
to avoid too much e^- captures and production of Fe54, Ni58 (for nucleosynthesis)

Then move at densities 10^7-10^8 g/cm^3, to produce ≈**0.7 M⊙ of Ni56**
in intermediate layers (for the optical light curve)
and ≈0.2 M⊙ of Si, S, Ar, Ca (for the early spectra)



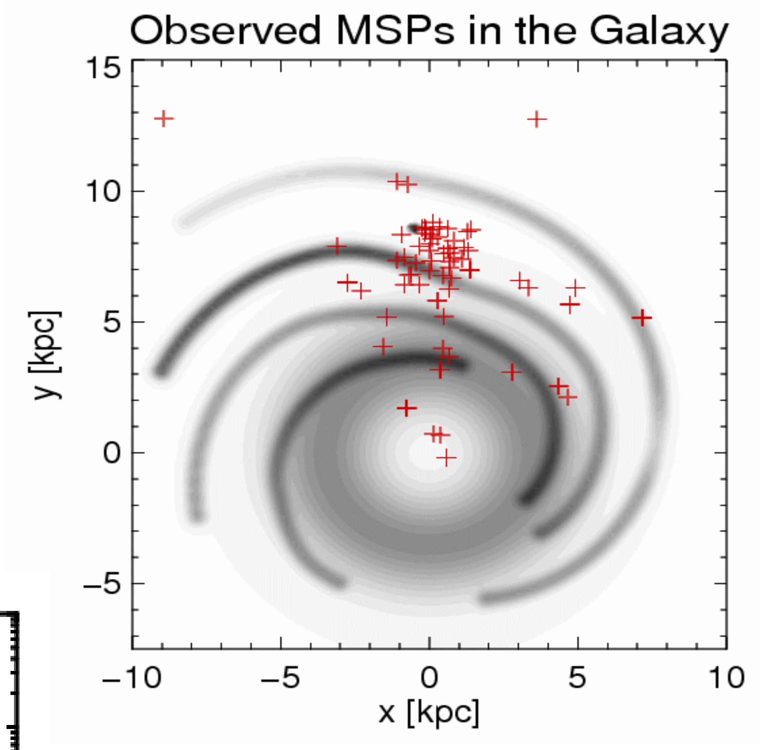
3D (aspherical) models suggest that a substantial fraction (10%) of Ni56 may be found in the outer layers ; its decay positrons may escape more easily (?) the ejecta

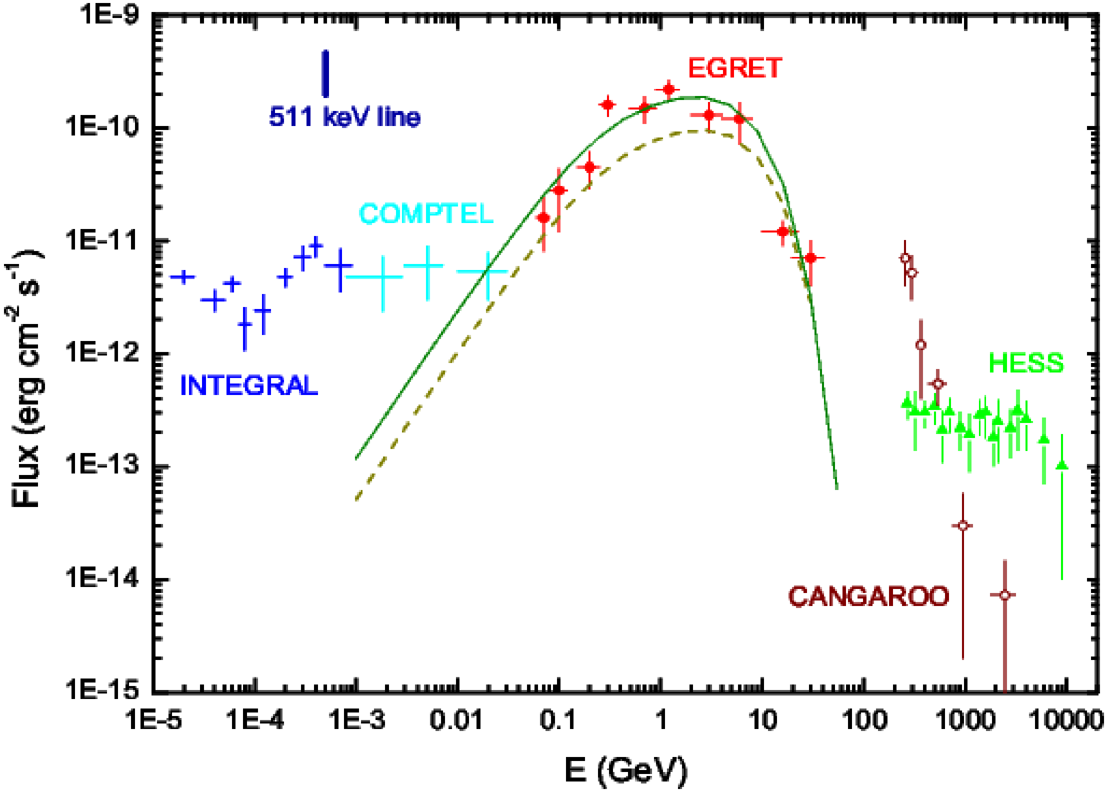


Bravo et al. 2006

Millisecond pulsars ?

(Wang 2006)





~6000 ms pulsars needed to explain EGRET data in GC

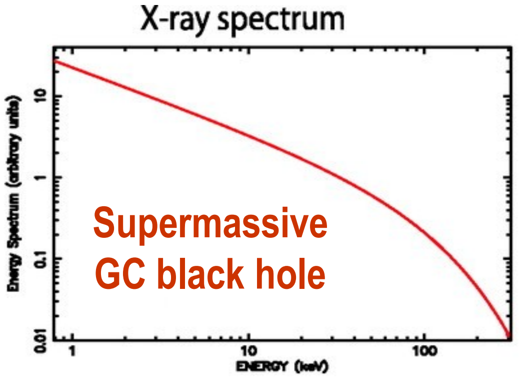
as well as
$5\ 10^{42}$ e+ s^{-1}

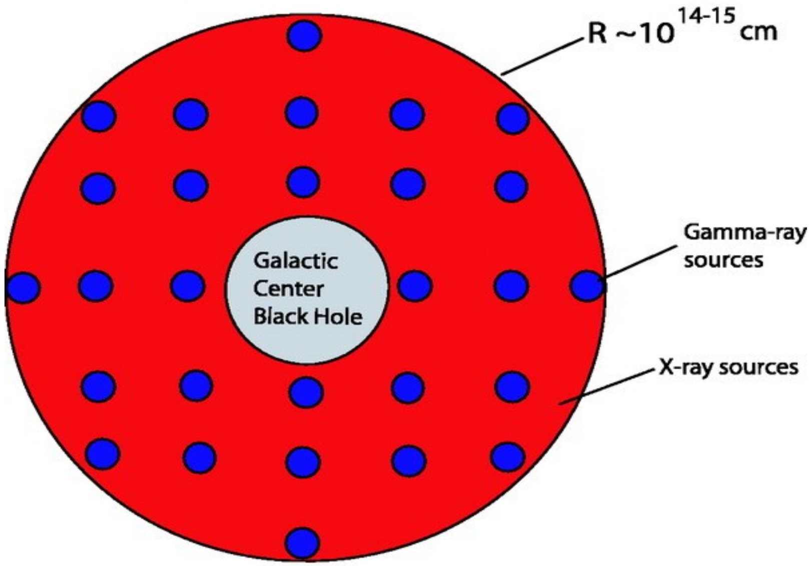
e+ production from X – γ ray interactions in the GC region

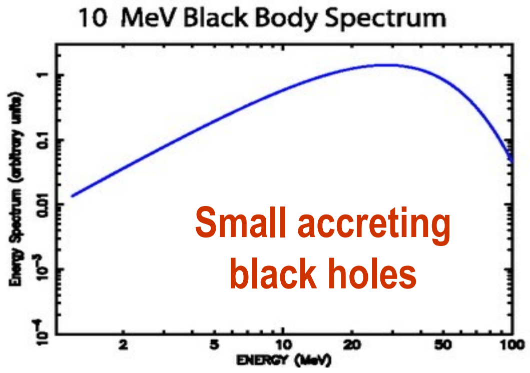
(Titarchuk and Chardonnet 2006)

X-rays from the GC
Supermassive Black Hole

γ-rays from dozens of small (10^{17} g)
accreting black holes in a region
the size of the Solar system

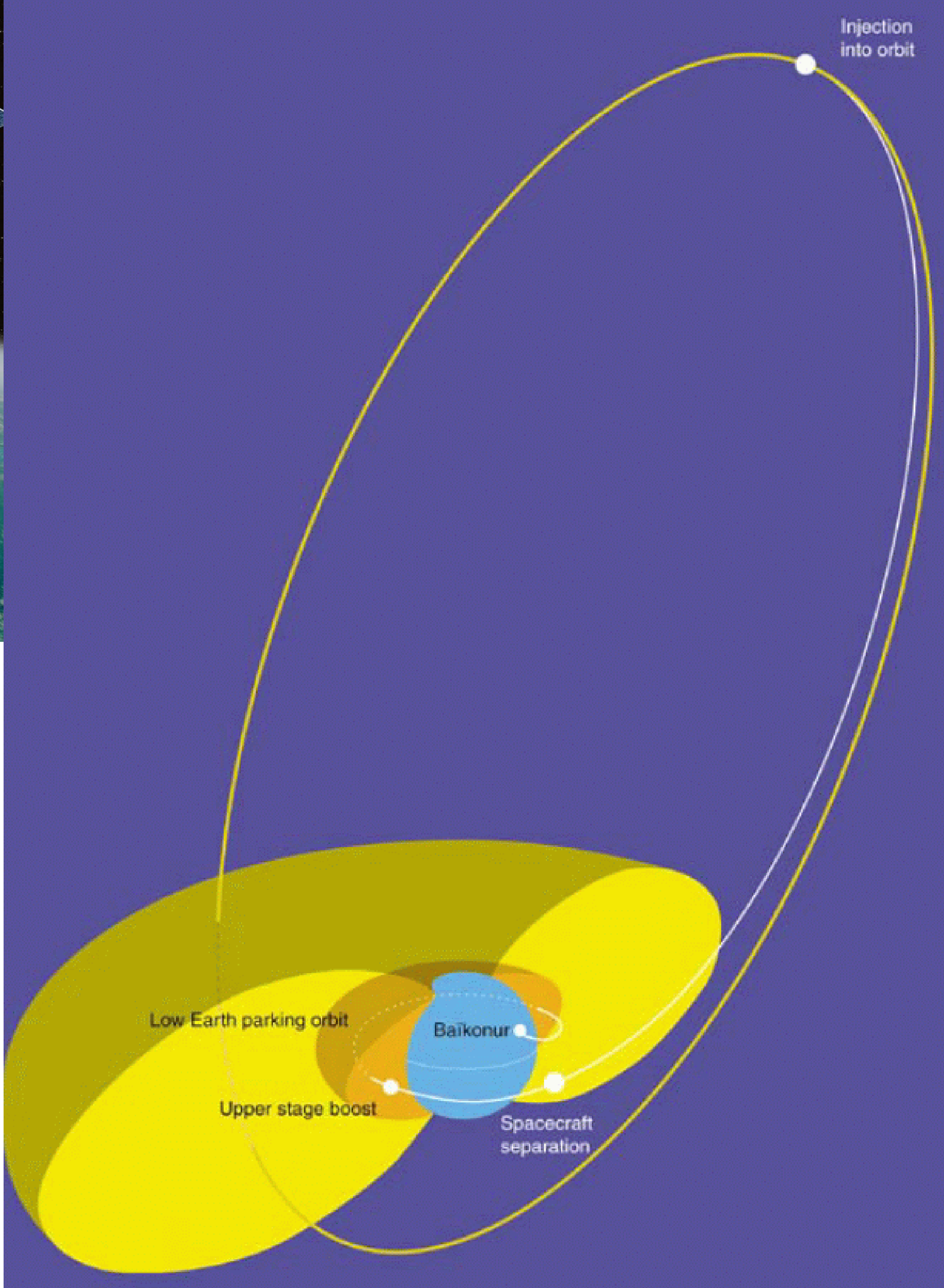




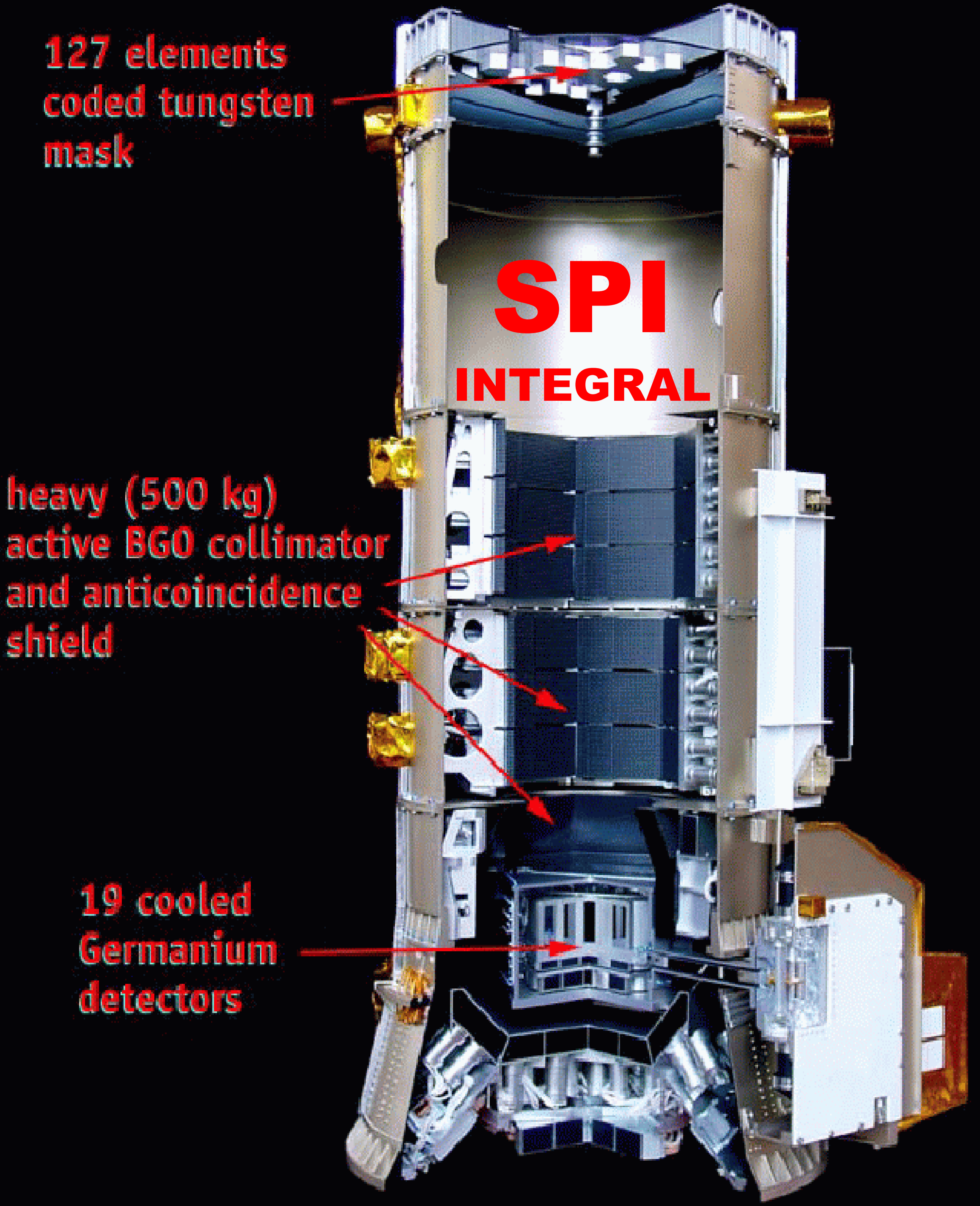


INTEGRAL was launched
on October 22, 2002

Large part of INTEGRAL's orbit
is found outside Earth's magnetic
(Van Allen) belts, which are full
of cosmic ray particles
and are sources of background noise
for gamma-ray detectors.



Instrument design



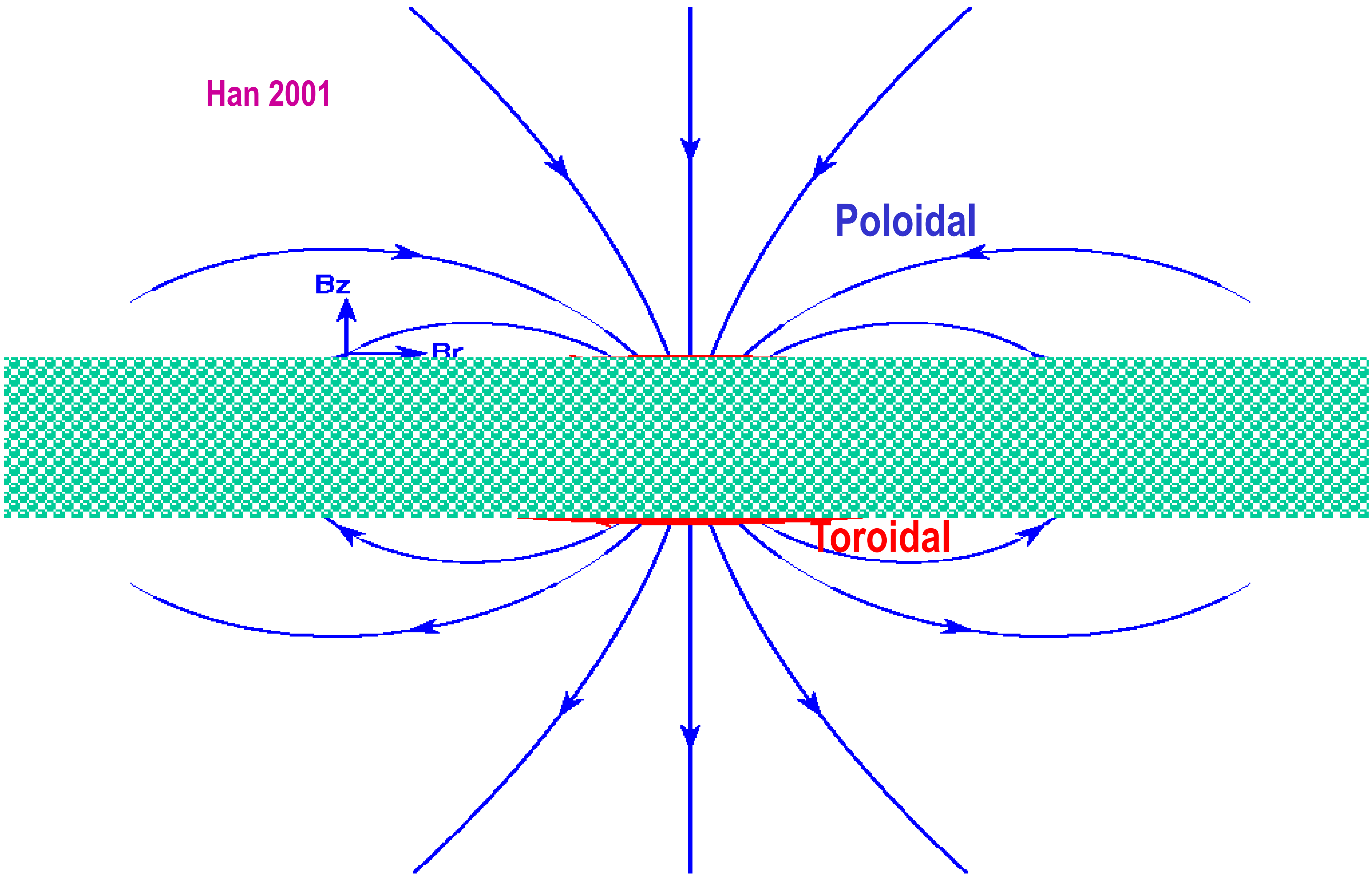
- 19 cooled high purity Germanium detectors
- active cryogenic system (85 K)
- active collimator and anticoincidence shield made of 91 BGO crystals
- 127 elements coded tungsten mask

- 20 keV - 8 MeV
- FOV ≈ 15 / 33 degrees (fully / partially)
- $\Delta E \approx 2.2 - 2.5$ keV @ 1 MeV
- $\Delta\alpha \approx 2.5$ degrees

SPI

Source	Process $E(e^{+}) <$ a few MeV	Morphology Bulge/Disk > 3	Intensity $2\ 10^{43}\ s^{-1}$	Comments
Al26 decay	Radioactivity	Disk	~Observed 511 keV disk	
SNIa	Radioactivity	B/D<1	$2\ 10^{43}\ s^{-1}$ IF 5% of e+ escape	Needs e+ transport from disk to bulge
Novae	Radioactivity	?? Up to B/D~1 if M31-like	$<2\ 10^{41}\ s^{-1}$	
GC Hypernova	Radioactivity	Outer disk	Unknown	
Ti44 decay	Radioactivity	Disk	$3\ 10^{42}\ s^{-1}$	
Cosmic rays	p – p interactions	Disk	$3\ 10^{41}\ s^{-1}$	
LM-XRBs	Pair production	B/D~1 IF strongest sources neglected	OK if 1% of obs. X converted to e+	Needs e+ transport ???
Microquasars	Pair production	Bulge-like clustering but insufficient data	Up to $10^{43}\ s^{-1}$	Needs e+ transport ???
Pulsars	e+ accelerated to high energy	Disk	$10^{40}\ s^{-1}$	
ms pulsars	e+ accelerated to high energy	Obs. In local disk; in Bulge, 6000 needed	$5\ 10^{42}\ s^{-1}$ to explain EGRET obs. in GC	Descendents of LM-XRBs
GC SM Black Hole	p – p (*Cheng et al.*) Pair prod. (*Totani*)	Point source for SPI	Unknown	Needs e+ transport from GC to bulge

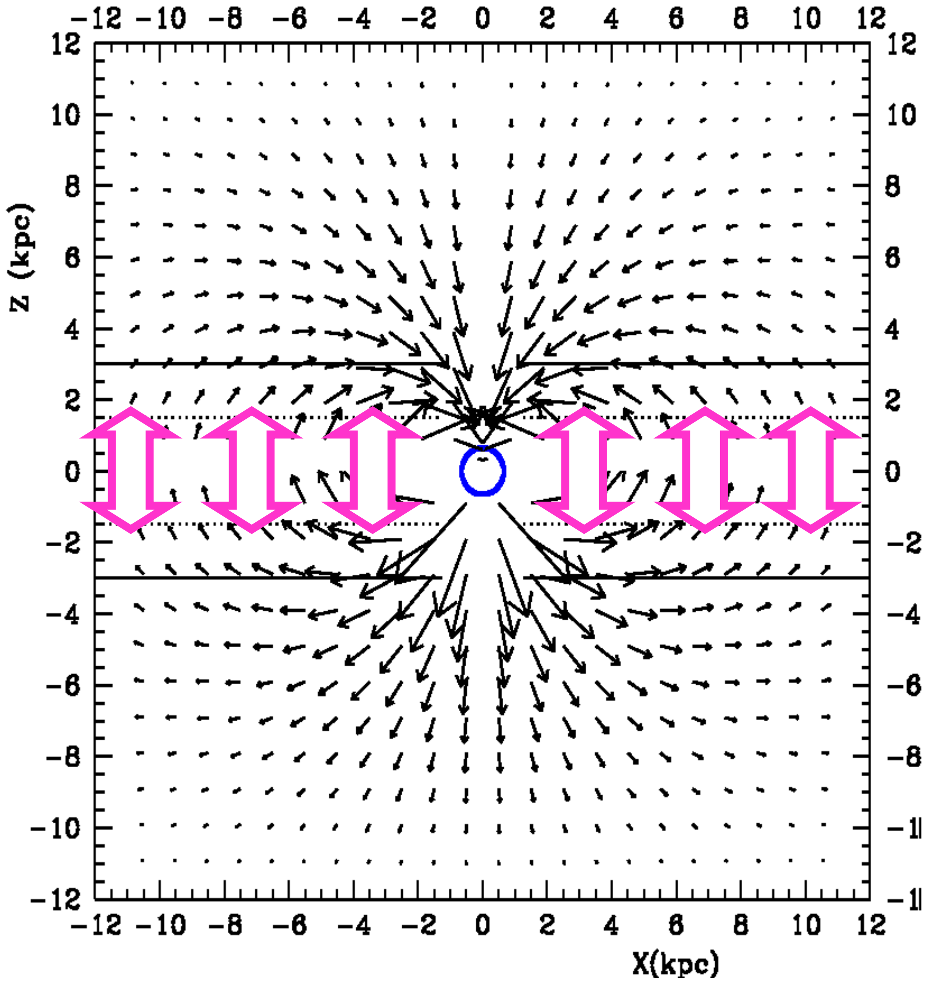
The Galactic Magnetic field



Han 2001

Irregular component (dominant in the disk) ~a few μG at R=8 kpc

Regular component {
Poloidal $\propto 1/r^3$ and ~0.1 μG at R=8 kpc
Toroidal $\propto 1/r$ and ~1-2 μG at R=8 kpc



$$B_X = -3\mu_G \, sin\theta \, cos\theta \, cos\phi \, / \, r^3$$

$$B_Y = -3\mu_G \, sin\theta \, cos\theta \, sin\phi \, / \, r^3$$

$$B_Z = \mu_G \, (1 - 3 \, sin^2\theta) \, / r^3$$

Prantzos (2006)
A (difficult to estimate) fraction
of disk positrons
should escape the disk

(τ_{Annhil} ~ several Myr,
distance ~ several kpc)

Those positrons could be channeled
by the poloidal magnetic field
- *if* it is a dipole -
towards the bulge, where
they are better confined
(because of the stronger
magnetic field of the bulge)
and they finally annihilate

The "magnetic mirror effect"
does not deflect them
back to the disk,
because they enter the poloidal field
with a strong velocity component
parallel to it
(continuity of magnetic field lines from
disk (toroidal) to halo (poloidal) field)