GAMMA-RAY LINE ASTRONOMY

N. Prantzos
Institut d'Astrophysique de Paris

COSMIC RADIOACTIVITIES AND GAMMA-RAY LINE ASTRONOMY

- 1954 : **W. Baade** : Supernovae powered by decay of ^{254}Cf ($\tau_{1/2}$ = 70 days)
- 1963 : **T. Pankey Jr.** : Supernovae powered by decay of ^{56}Co ($\tau_{1//2}$= 77 days)
- 1964 : **F. Hoyle + W. Fowler** : ^{56}Fe is produced as ^{56}Fe (stable)
- 1968 : **J. Bodansky + D. Clayton + W. Fowler** : ^{56}Fe is produced as ^{56}Ni (unstable)
- 1969 : **D. Clayton +S. Colgate + J. Fishman** : Gamma-rays from ^{56}Co in SN detectable
- 1982 : **D. Clayton** : Evaluation of yields of major radionuclides for gamma-ray line astronomy, assuming that Supernovae make the solar abundances of the daughter stable isotopes. ALL CORRECT !

  But : ^{26}Al missed ! (because ^{26}Mg is produced as such)
- 1977 : **D. Arnett, R. Ramaty** : ^{26}Al from SN explosions may also be detectable

- 1970's: **Balloons** : Discovery of 511 keV line towards Galactic Center
- 1984 : **HEAO-3 (NASA)** : Discovery of ^{26}Al towards Galactic Center
- 1987 : **SMM + Balloons** : Discovery of ^{56}Co in SN1987A
- 1990s : **GRO (NASA)** : Discovery of ^{57}Co (SN1987A), mapping of ^{26}Al (Galaxy), ^{44}Ti (Cas-A), 511 keV (Bulge+Disk ?)

2000s : **INTEGRAL(ESA)** : ^{60}Fe (Galaxy), Mapping of 511 keV (Bulge+Disk)

Difficulties of gamma-ray astronomy

Very weak fluxes of gamma photons ⇒ Very long exposures required

Impossibility (?) to focus gamma photons ⇒ Low angular resolution

Detectors in space traversed by cosmic rays ⇒ high background noise

Advantages of gamma-ray astronomy

Gamma photons very penetrating ⇒ access to places unreachable in other wawelengths

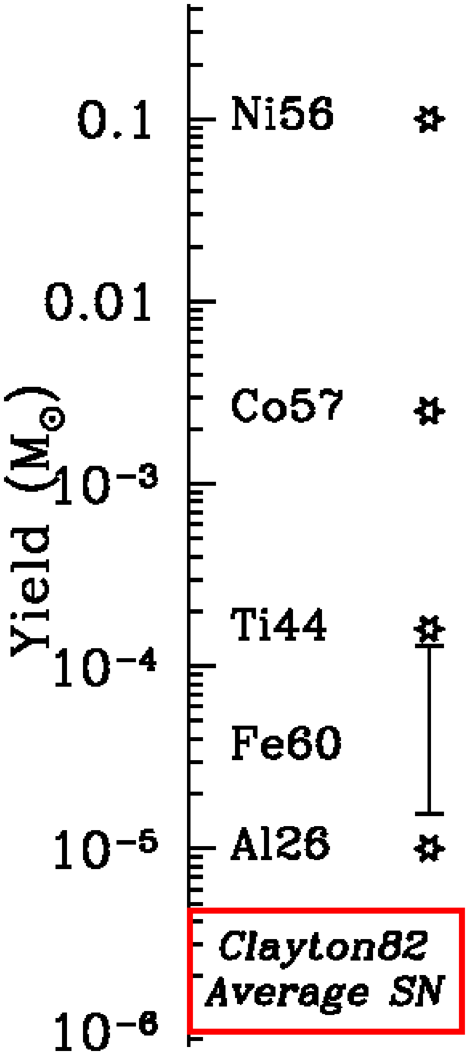
Nuclear gamma-ray lines ⇒ signature of specific atomic nuclei
Best diagnostics of nucleosynthesis and nuclear astrophysics

ASTROPHYSICALLY IMPORTANT γ-RAY LINE EMITTERS

Decay Chain	**Lifetime [y]**	**γ-ray Energy [keV]** (branching ratio [%])	**Site** (detections)	**Process Type**
$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li}$	0.21	478 (100)	Novae	explosive H burning
$^{56}\mathrm{Ni} \longrightarrow {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Fe}$	0.31	847 (100), 1238 (68) 2598 (17), 1771 (15) and 511 from e^{+}	SNe (SN1987A, SN1991T)	NSE burning
$^{57}\mathrm{Co} \longrightarrow {}^{57}\mathrm{Fe}$	1.1	122 (86), 136 (11)	SNe (SN1987A	NSE burning
$^{22}\mathrm{Na} \longrightarrow {}^{22}\mathrm{Ne}$	3.8	1275 (100) and 511 from e^{+}	Novae	explos. H burning
$^{44}\mathrm{Ti} \longrightarrow {}^{44}\mathrm{Sc} \longrightarrow {}^{44}\mathrm{Ca}$	89	68 (95), 78 (96) 1156 (100) and 511 from e^{+}	SNe (Cas A)	NSE α freeze-out
$^{26}\mathrm{Al} \longrightarrow {}^{26}\mathrm{Mg}$	$1.04\ 10^{6}$	1809 (100) and 511 from e^{+}	ccSNe, WR Novae, AGB (Galaxy) (Cygnus;Sco-Cen; Orion; Vela)	H burning (ν-proc.)
$^{60}\mathrm{Fe} \longrightarrow {}^{60}\mathrm{Co} \longrightarrow {}^{60}\mathrm{Ni}$	$3.8\ 10^{6}$	1173 (100), 1332 (100) 59 (2)	SNe (Galaxy)	He,C shell burning
$e^{+} \longrightarrow \mathrm{Ps},.. \longrightarrow \gamma\gamma(\gamma)$	$\sim 10^{7}$	$2{\cdot}511$ ($\sim$100), cont <510	radioactivities Pulsars, μQSOs, ... (Galactic bulge; disk)	β^{+} decay rel. plasma

$\tau_{\mathrm{SOURCE}} >> \tau_{\mathrm{RAD}}$ **ONE POINT SOURCE**	$\tau_{\mathrm{SOURCE}} \sim \tau_{\mathrm{RAD}}$ **SEVERAL POINT SOURCES**	$\tau_{\mathrm{SOURCE}} << \tau_{\mathrm{RAD}}$ **DIFFUSE EMISSION**

Yields of major radioactivities from massive stars



Ni56 → Co56 → **Fe56**

Co57 → **Fe57**

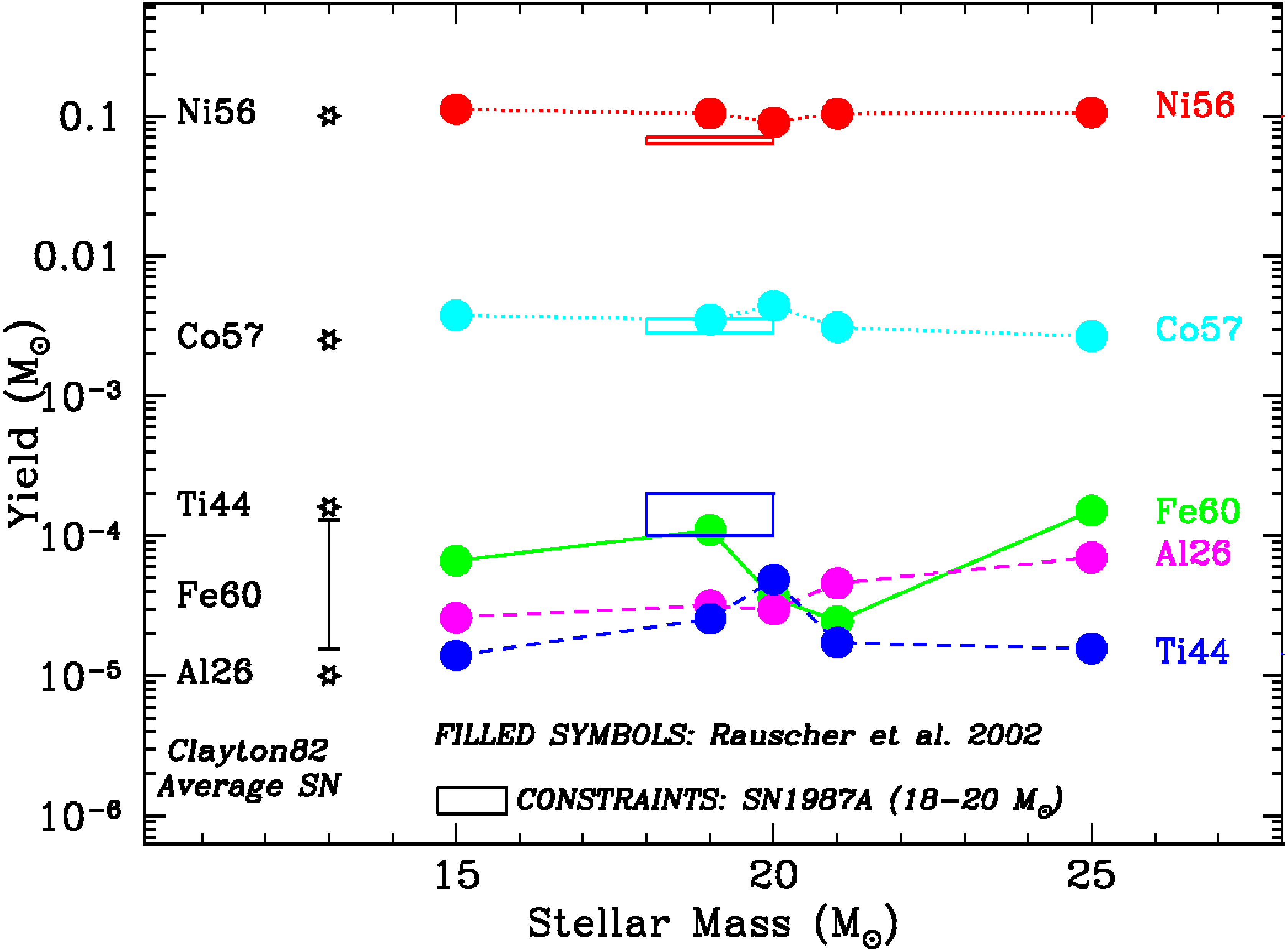
Ti44 → Sc44 → **Ca44**

Fe60 → Co60 → **Ni60**

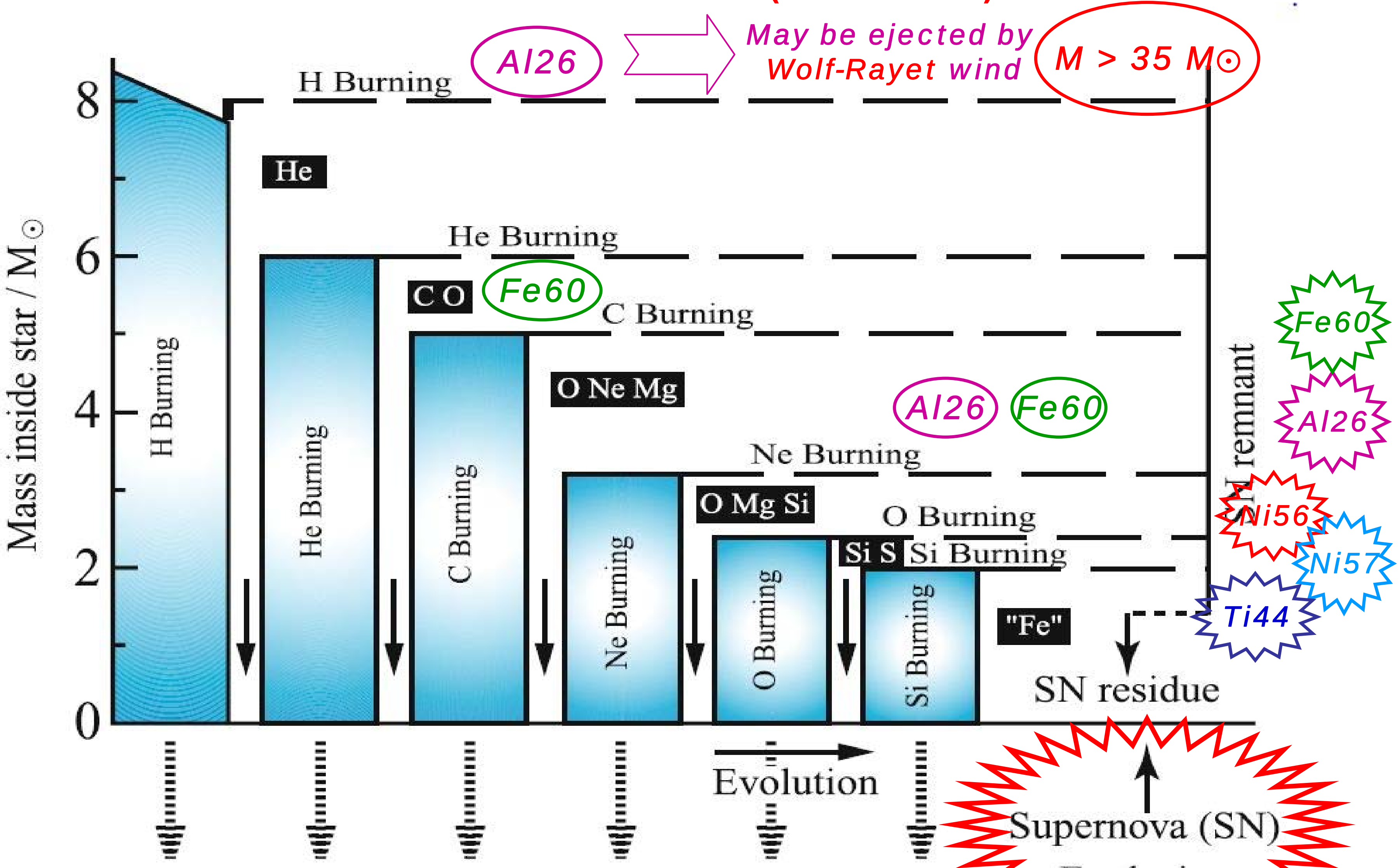
Al26 → **Mg26**

Assuming that the corresponding stable nuclei are produced at their Solar system abundances

Yields of major radioactivities from massive stars



Massive star evolution (schematic)



T_C (K)	$6x10^7$	$2\ x10^8$	$9\ x10^8$	$1.7\ x10^9$	$2.3\ x10^9$	$4\ x10^9$
ρ_C (g.cm^{-3})	5	700	$2\ x10^5$	$4\ x10^6$	10^7	$3\ x10^7$
Time scale	$7\ 10^6$ years	$5\ x10^5$ years	600 years	0.5 years	6 months	1 day

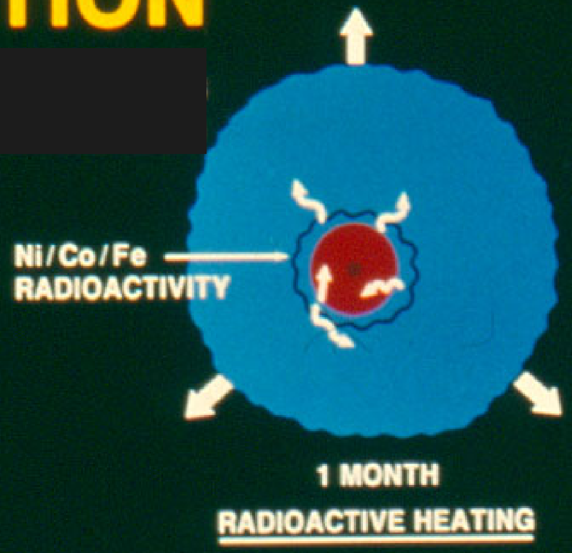
TYPE II SUPERNOVA ENVELOPE EVOLUTION

Radioactivity from the decay chain

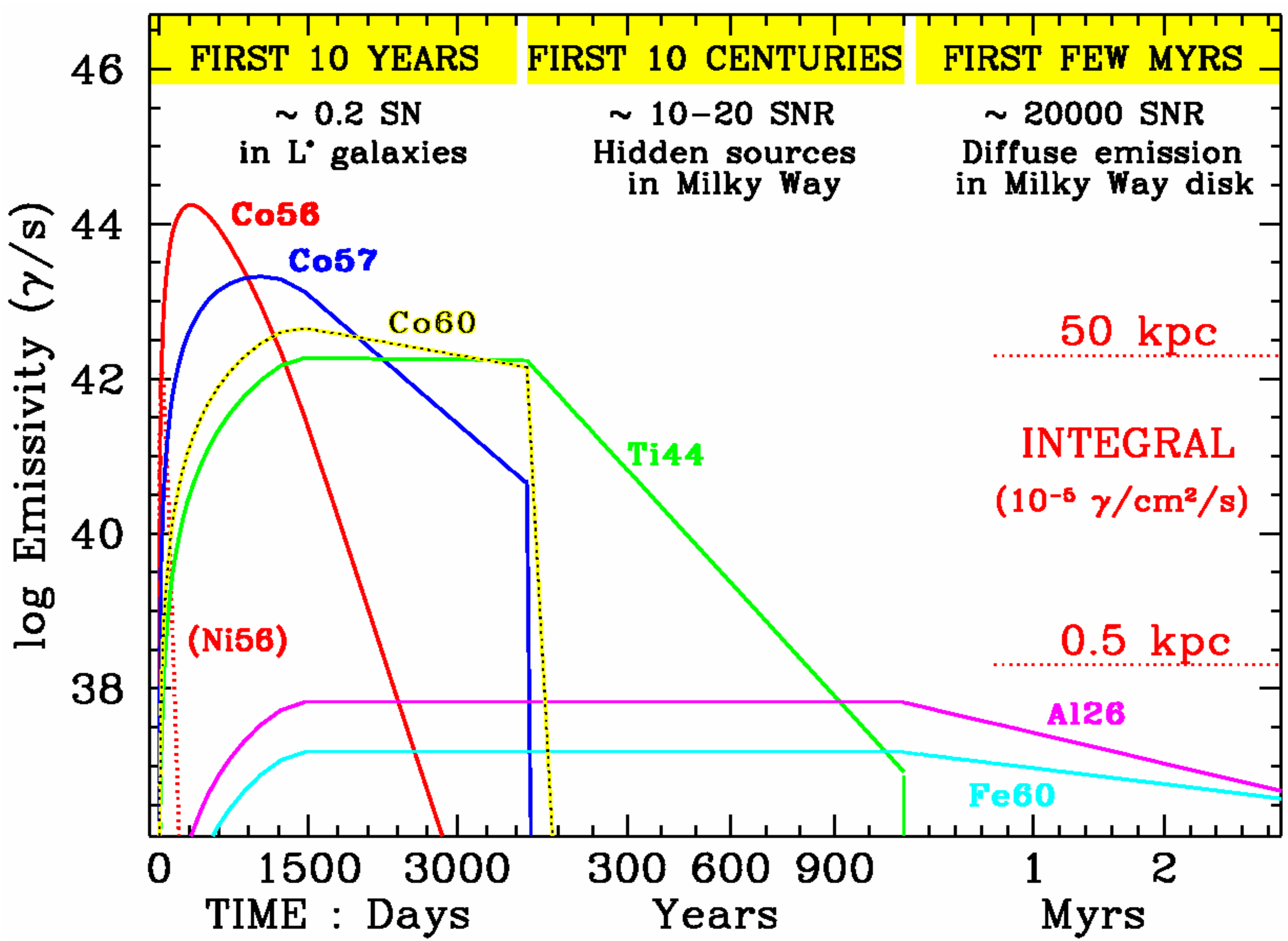
Nickel-56 ⇒ Cobalt-56 ⇒ Iron-56

(7 days) (77 days)

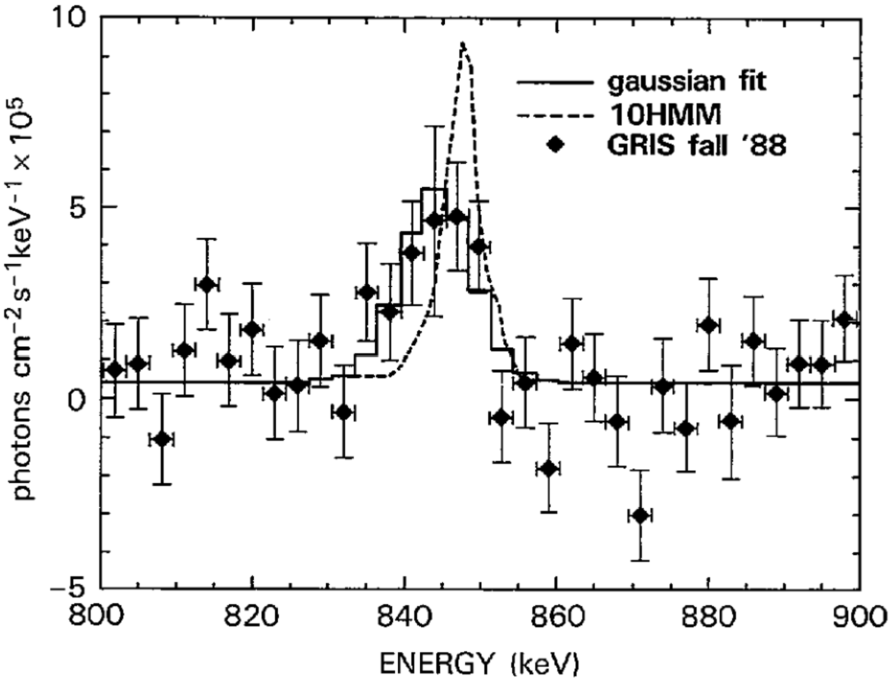
powers the optical lightcurves of supernovae

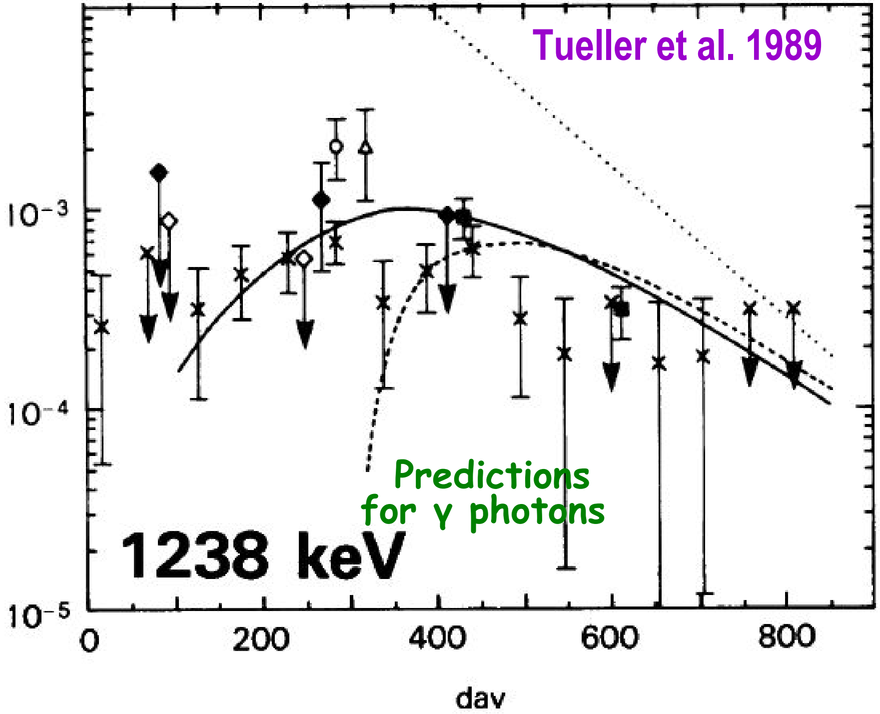


Radioactivities in supernovae and supernova remnants



847 keV line of Co56 from SN1987A (18 M⊙ star in LMC, at 50 kpc)





Tueller et al. 1989

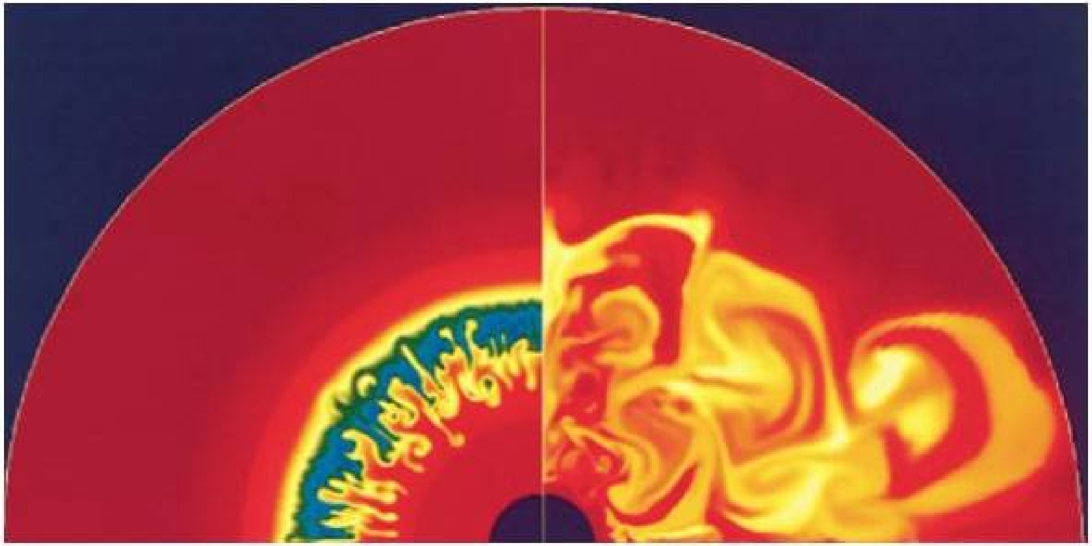
Predictions for γ photons

Confirmation of explosive nucleosynthesis (stable Fe-56 is produced as unstable Ni-56)

Line seen 6 months earlier than expected !

Confirmation that radioactivity powers the late lightcurves of supernovae

Hydrodynamic instabilities mix the SN interior, bringing heavy atomic nuclei from the core near the surface.



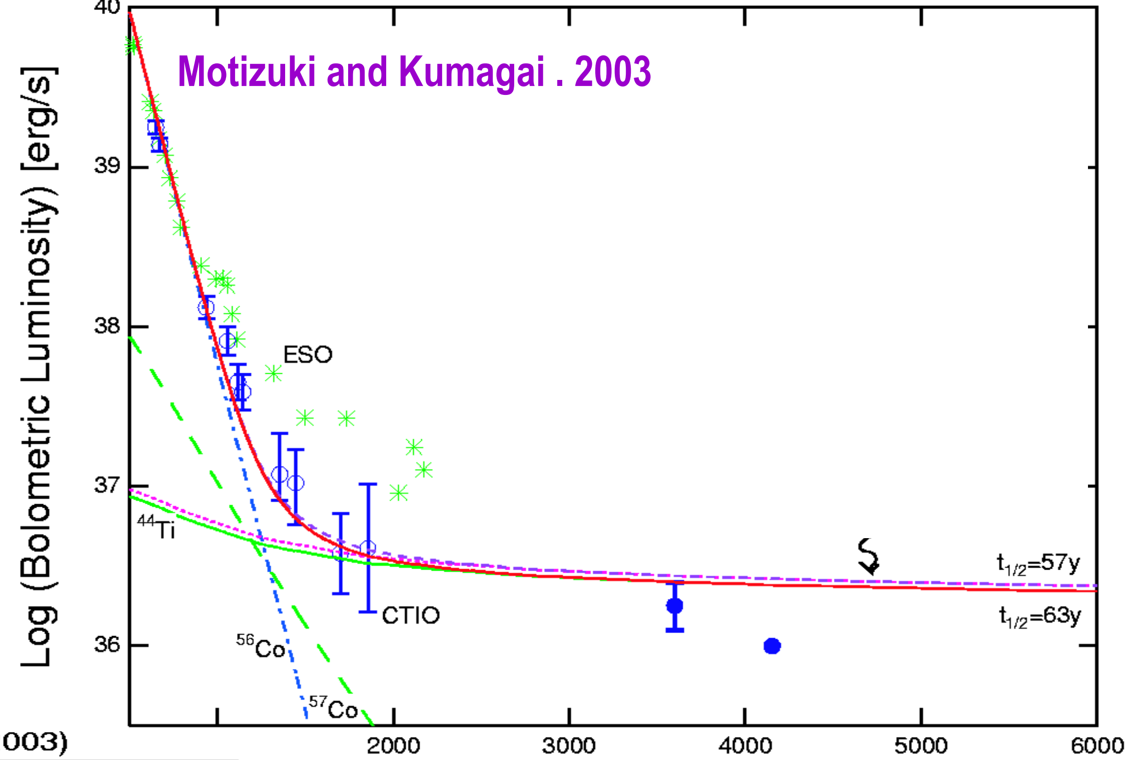
SN1987A

From early lightcurve:

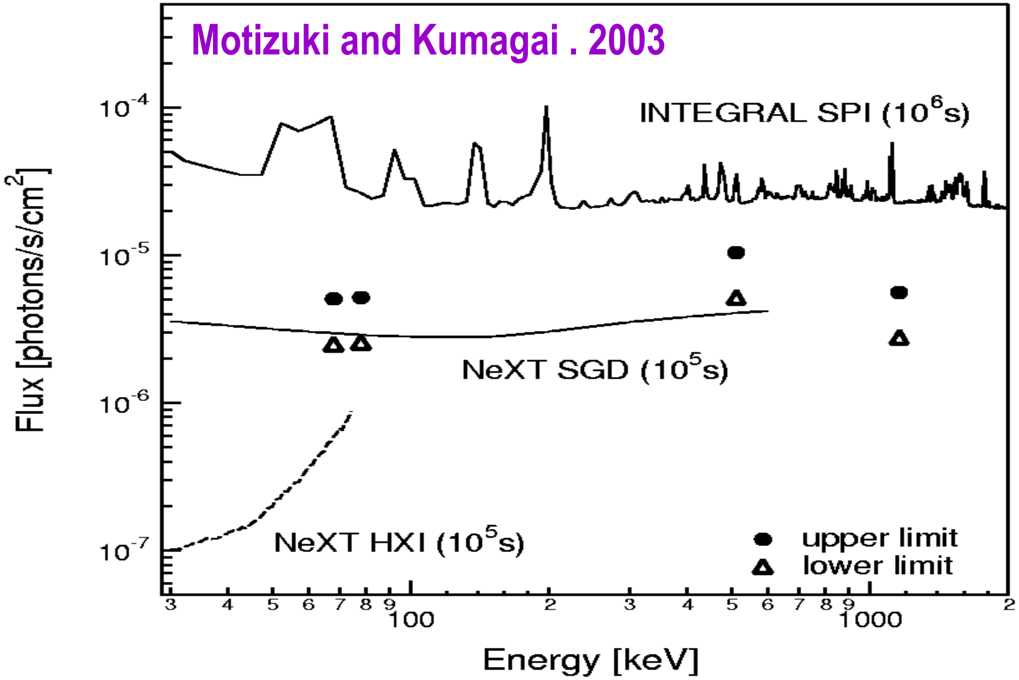
0.07 $M_\odot$ of Ni-56

From late lightcurve:

1-2 10^{-4} $M_\odot$ of Ti-44



Flux Prediction for Day 6000 (2003)



Ti-44 γ-ray lines

too week to be seen

by SPI/INTEGRAL

Ti-44 in Cas A

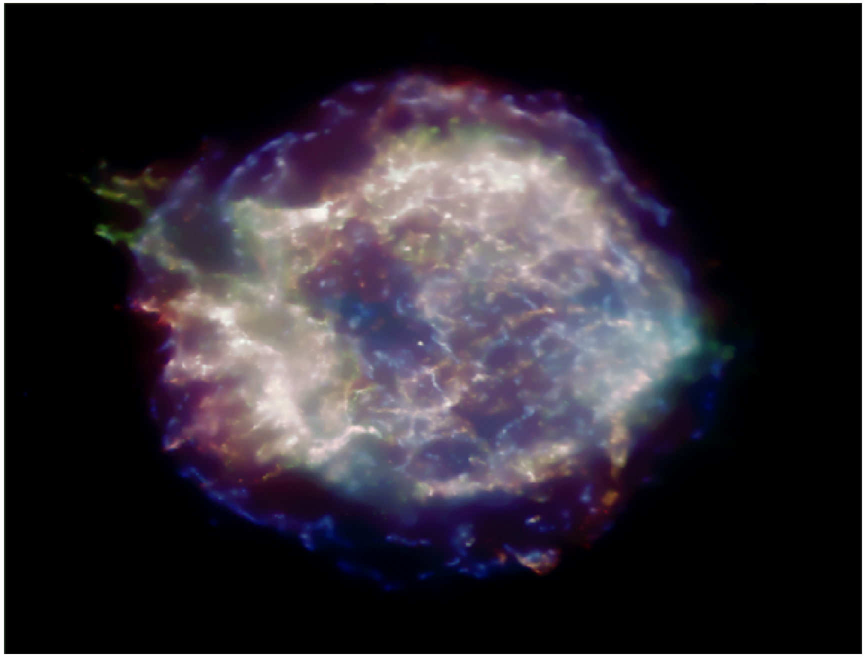
(d≈3 kpc, age≈320 yr)

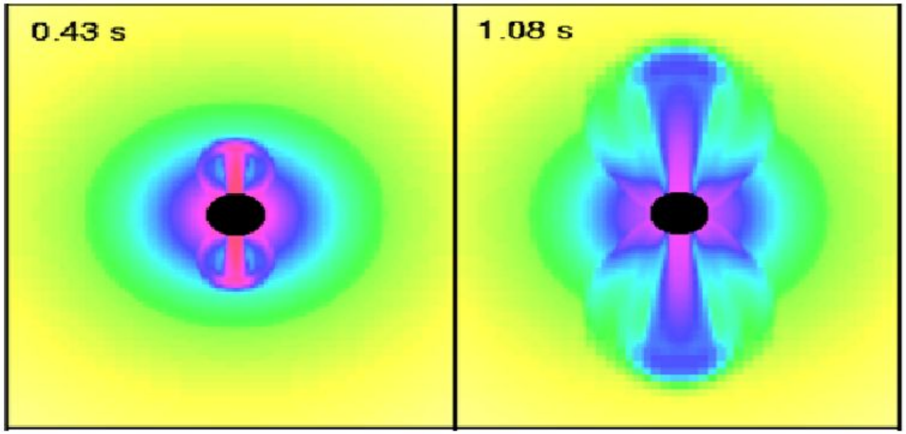
From observations: **1-2 10^{-4} $M_\odot$** of Ti-44

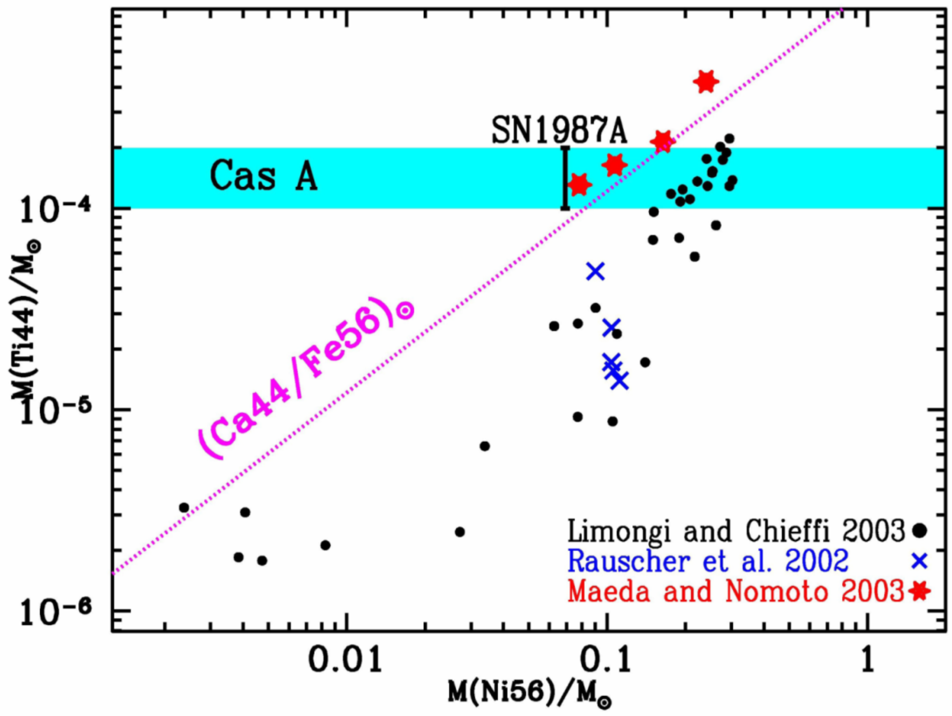
COMPTEL: 1.156 MeV (*Iyudin et al. 1994*)
Beppo-Sax: 68 + 78 keV (*Vink et al. 2002*)
IBIS-ISGRI: 68+78 keV (*Renaud et al. 2006*)

1) Spherical and energetic explosion,producing solar Ca44/Fe56 or ~0.2 $M_\odot$ of Ni56.
Bright explosion! Why was not then observed 3 centuries ago?

2) SN1987A-like explosion(~0.07 $M_\odot$ of Ni56)
What mechanism makes so large Ti44/Ni56 ratios?
Asymmetric explosions ?

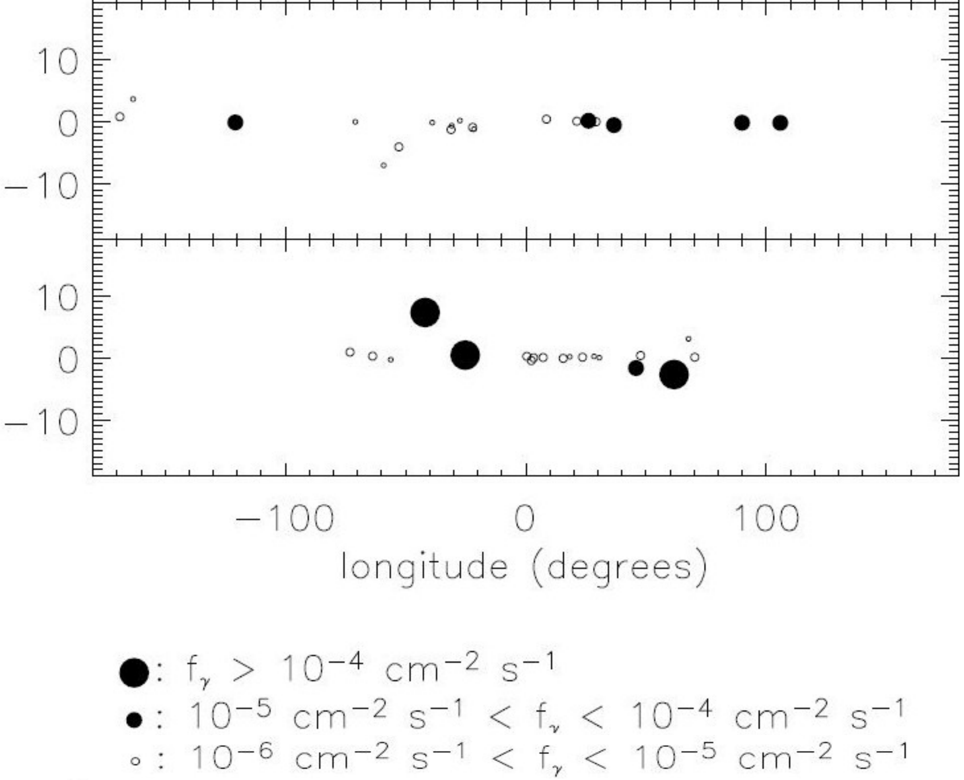






Assuming that :
-CCSN produce ~10^{-4} $M_{\odot}$ of Ti-44
-CCSN rate in Milky Way is ~3/century

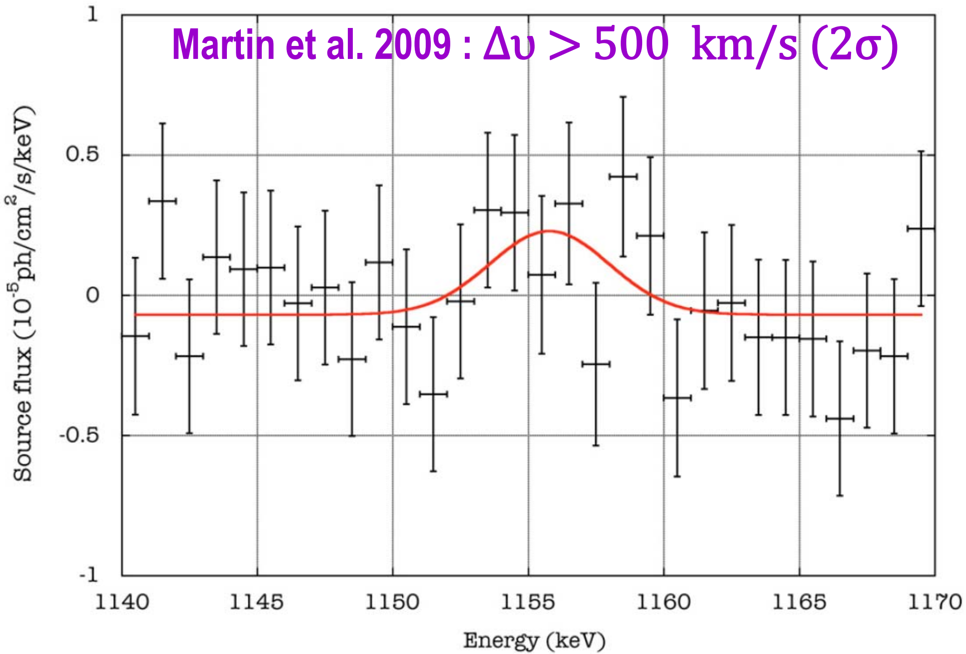
One would expect **a few SN remnants** to be detected in Ti-44 lines
(The et al. 2006)

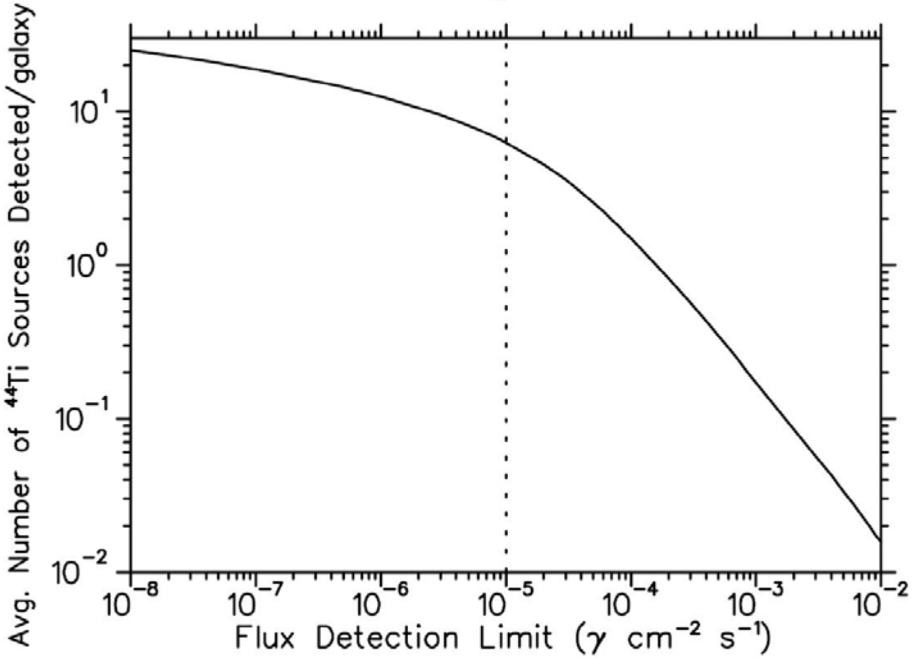


Only Cas A is seen…

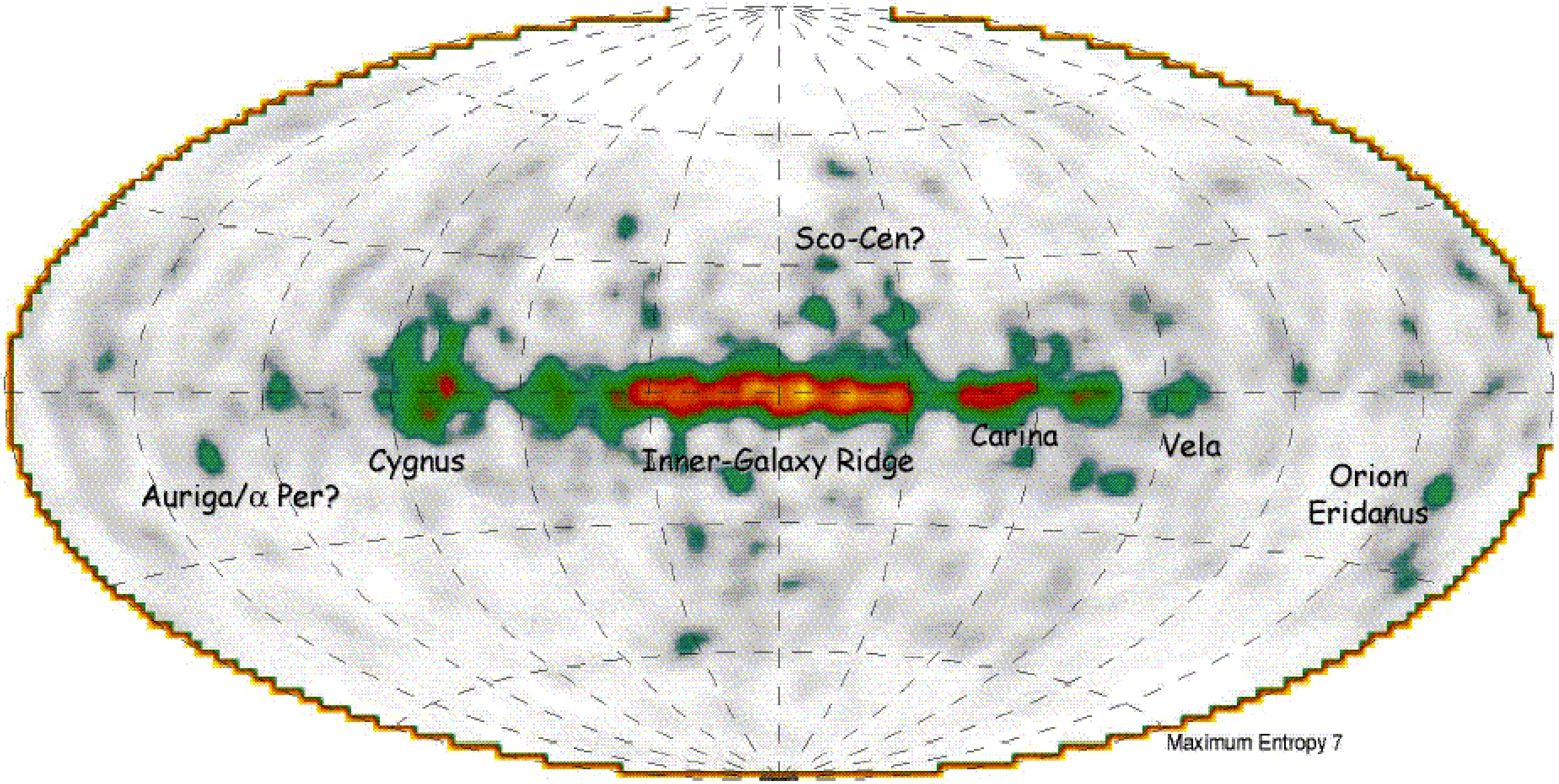
Is Ca-44 produced mostly in **rare**, **prolific,** SN **?**

Or are the lines too broad ?


Martin et al. 2009 : $\Delta\upsilon > 500$ km/s (2σ)



COMPTEL legacy: 1.8 MeV map of Galactic Al-26 ($\tau \approx 1$ Myr)



Complete CGRO Mission
(Plüschke et al. 2001)

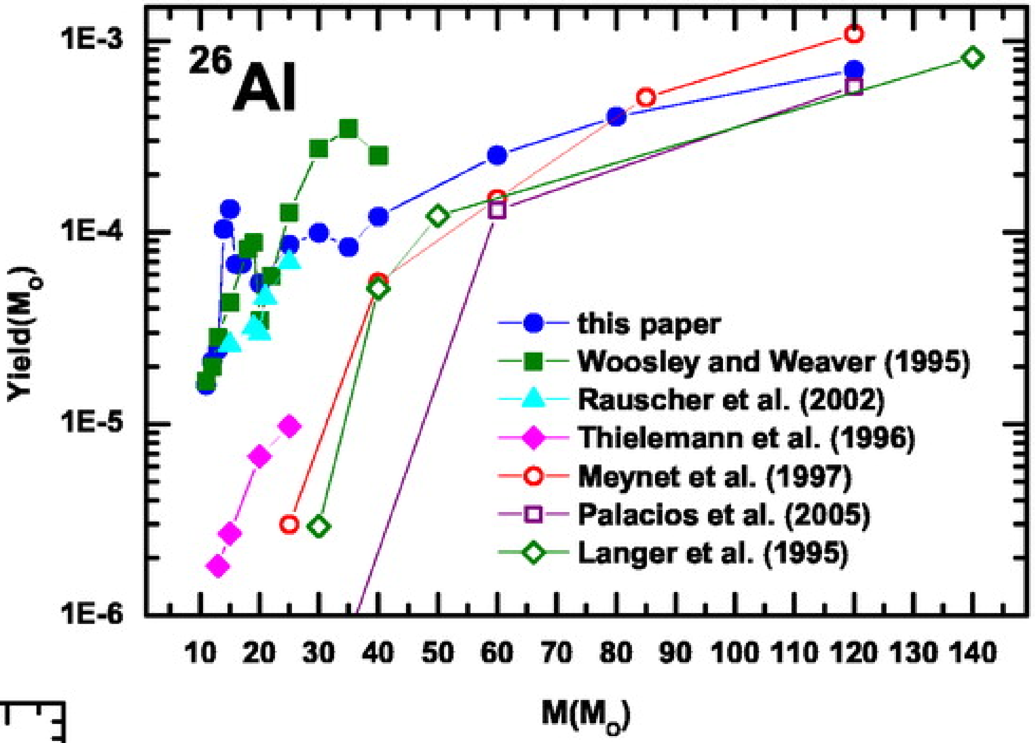
Total flux: $\approx 3\ 10^{-4}$ cm^{-2} s^{-1} $\Rightarrow$ $\approx$ **2.5 $M_\odot$ of Al-26 (per Myr)**

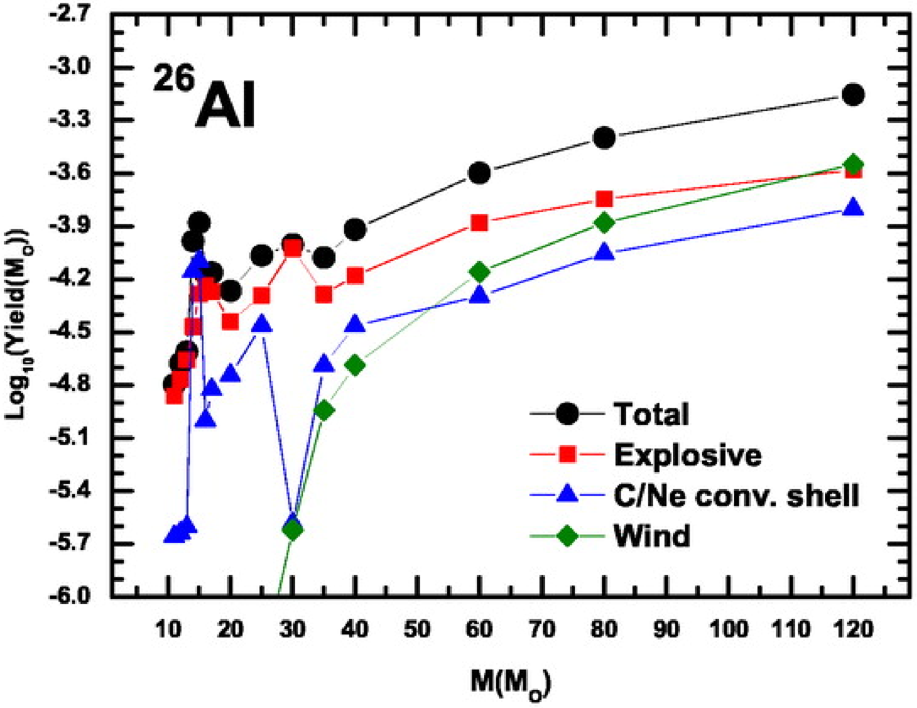
1.8 MeV emission "hot-spots" in the directions tangent to the spiral arms suggest that **massive stars** are at the origin of Al26

Al-26 production in massive stars

is affected by several factors

First study across the whole mass range
of massive stars of solar metallicity
with **mass loss**
(*but no rotation, no ν-nucleosynthesis*)
by Chieffi and Limongi (2006)



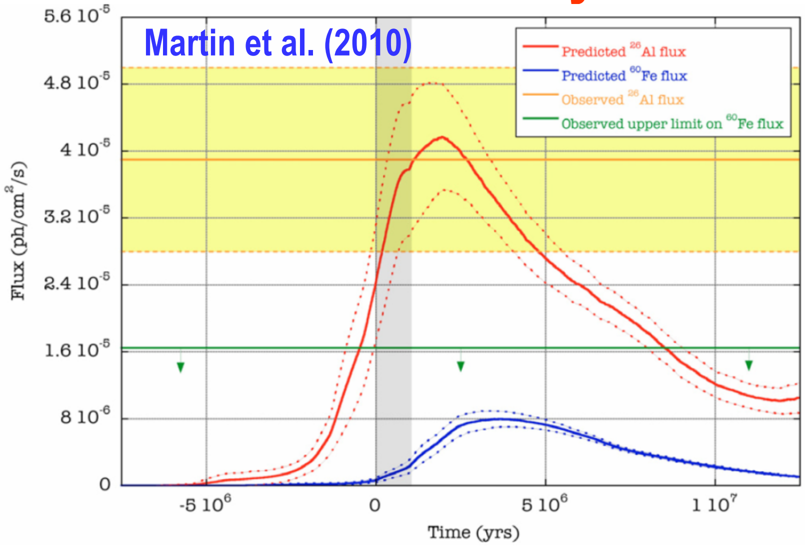


It showed that explosive production
always dominates
hydrostatic production
(ejected by the winds)

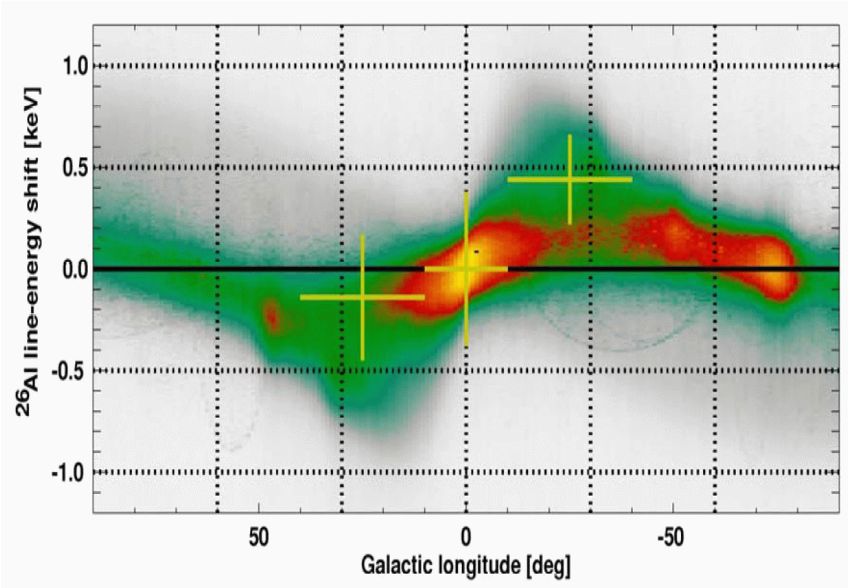
But what about rotation,
especially at Z>Z⊙ ?

Studies of 1.8 MeV emission of Al-26 in the Galaxy

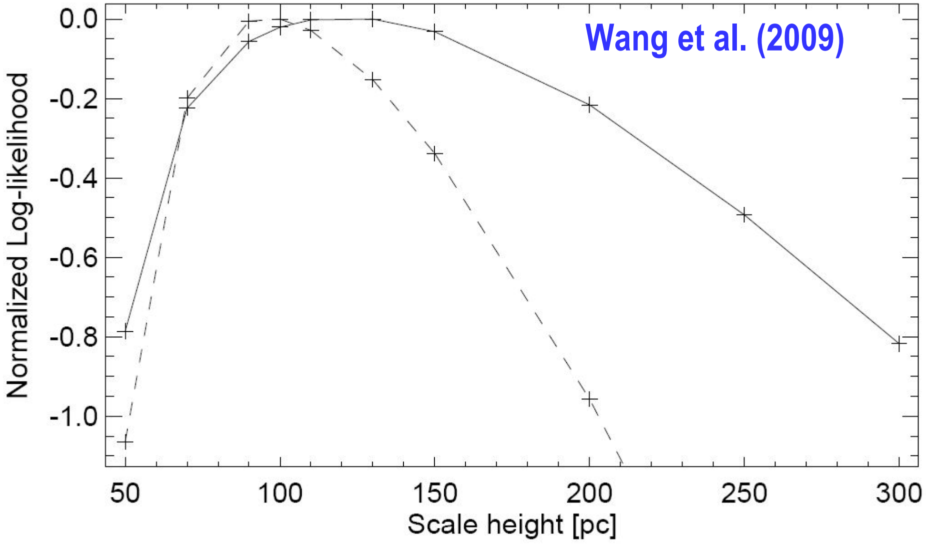
1) History and properties of stellar associations
and star forming regions,
(e.g. Carina, Cygnus, Orion)
through population synthesis models
and multiwavelength observations



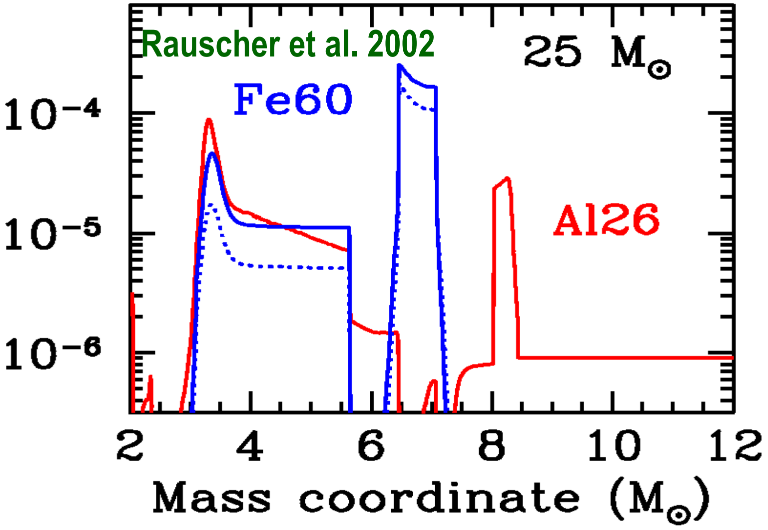
2) Large scale motions of Al-26 in Galaxy
through broadening/shift
of 1.8 MeV line
across the Galactic plane



3) Large scale motions of Al-26 in Galaxy
through extension of emission
of 1.8 MeV line
perpendicularly to the Galactic plane
(hints for galactic chimneys/fountains)



Al26 (τ ≈ 1 Myr) and Fe60 (τ≈ 3 Myr) from SNII : parallel lives…



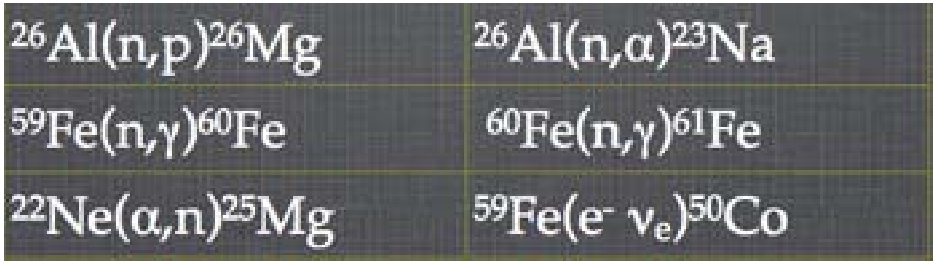
Al26 produced by: $^{25}Mg(p,\gamma)^{26}Al$

- Hydrostatic H-burning in H layer
- Hydrostatic Ne-burning in Ne layer
- Explosive Ne-burning in Ne layer
- Neutrino-process in C-Ne layers

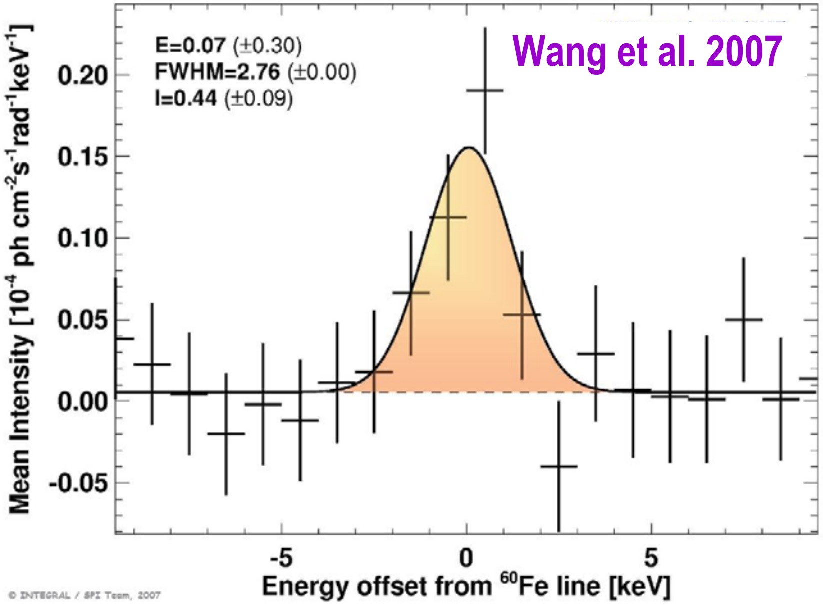
Fe60 produced by: $^{58}Fe(n,\gamma)^{59}Fe(n,\gamma)^{60}Fe$

- Hydrostatic s-process in He layer
- Hydrostatic Ne-burning in Ne layer
- Explosive Ne-burning in Ne layer
- Explosive He-burning in He layer

Important uncertainties still affecting key nuclear reaction rates :



$^{26}Al(n,p)^{26}Mg$	$^{26}Al(n,\alpha)^{23}Na$
$^{59}Fe(n,\gamma)^{60}Fe$	$^{60}Fe(n,\gamma)^{61}Fe$
$^{22}Ne(\alpha,n)^{25}Mg$	$^{59}Fe(e^- \nu_e)^{50}Co$



Fe60 is seen in the Galaxy by RHESSI and SPI/INTEGRAL,with

flux ratio (Fe60/Al26) ~0.15

In broad agreement with theoretical expectations

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

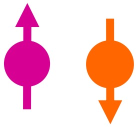
Either **directly** (2 γ of E = 511 keV each),
or, after formation of **Positronium (Ps),** with probability **f**

Probability:
1/4

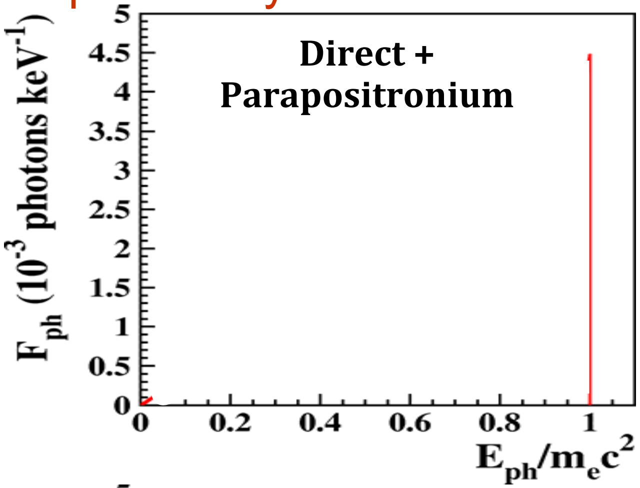
Parapositronium

S=0
(singlet)

$^1S_0$



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

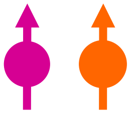


Probability:
3/4

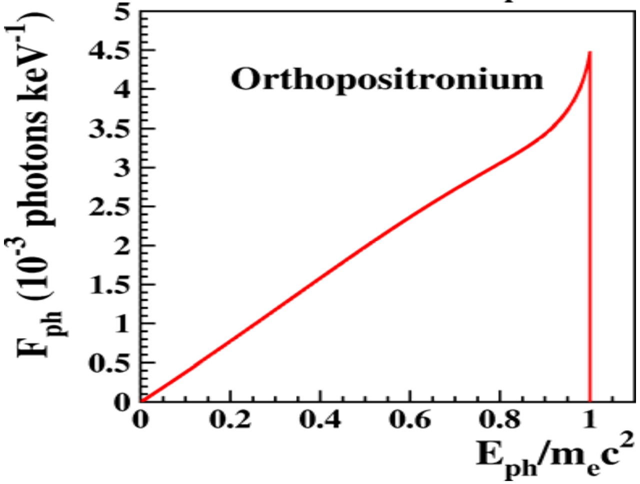
Orthopositronium

S=1
(triplet)

$^3S_1$



$\tau = 1.4\ 10^{-7}$ s → $3\ \gamma$ of $E \leq 511$ keV



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

Positronium fraction

Positron annihilation radiation from the Galactic center region

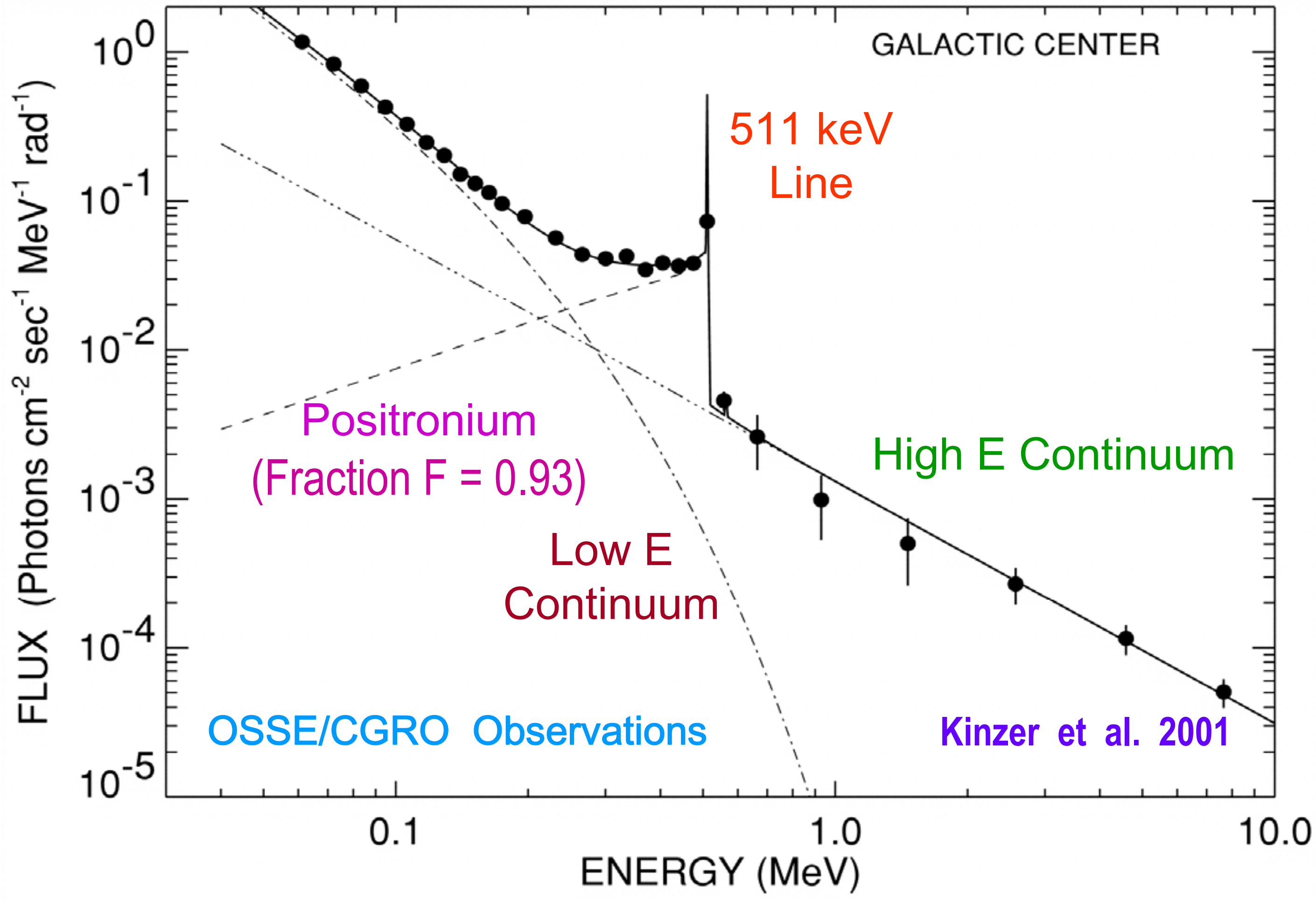
First (and brightest) γ-ray line detected from outside the solar system

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

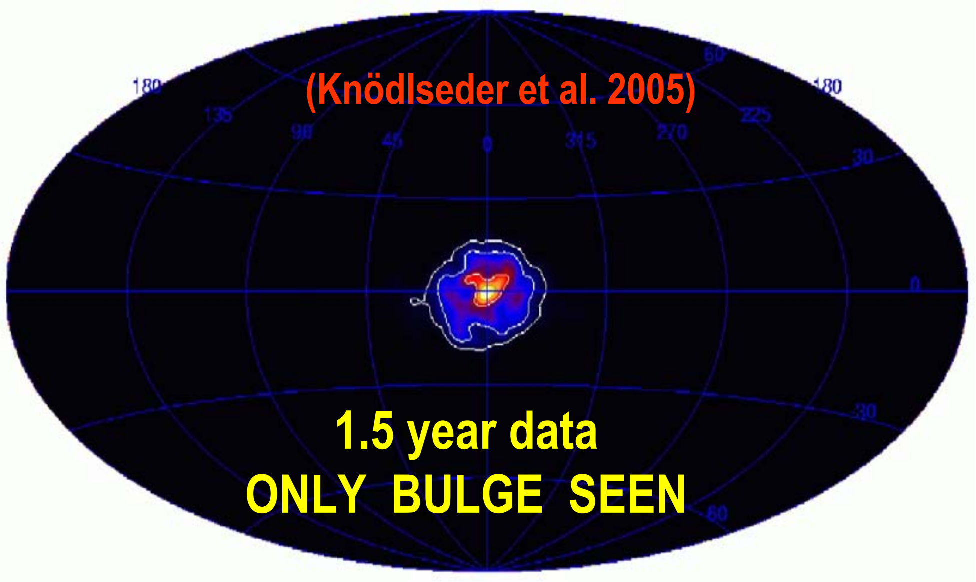
Flux (~10^{-3} cm^{-2} s^{-1}) + Distance (8 kpc~27000 l.y.)$\Rightarrow$ Luminosity ~10^{37} erg/s (a few 10^{3} $L_{\odot}$)

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

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

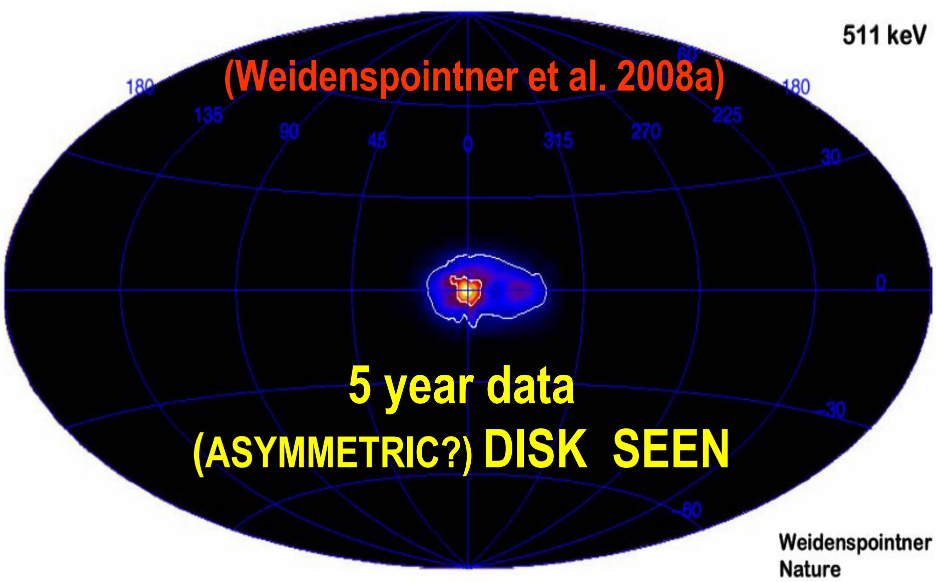


SPI / INTEGRAL all-sky distribution of the 511 keV line of e^- - e^+ annihilation



(Knödlseder et al. 2005)

1.5 year data
ONLY BULGE SEEN



(Weidenspointner et al. 2008a)

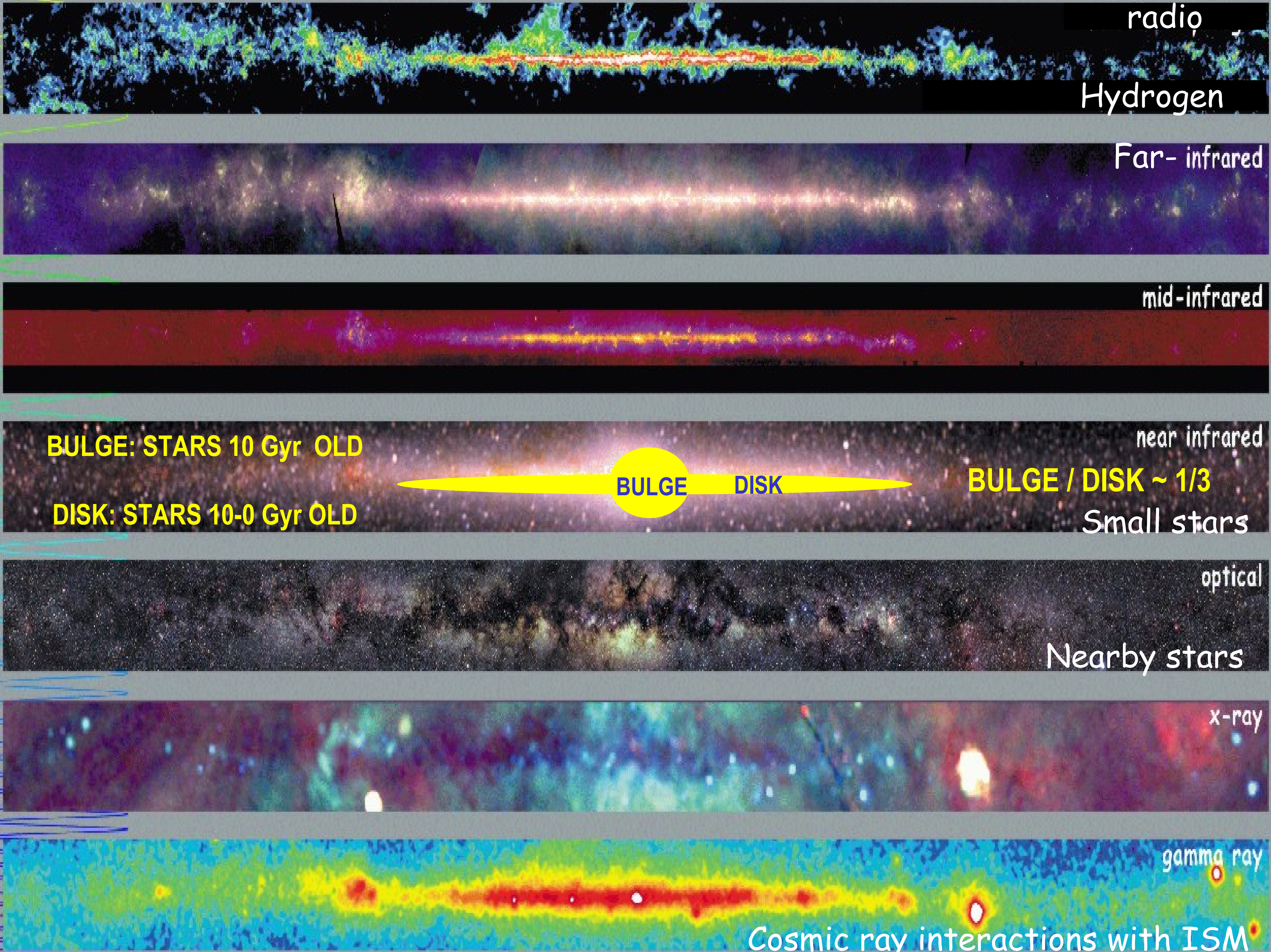
5 year data
(ASYMMETRIC?) DISK SEEN

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
Bulge/Disk	0.8	1.4	1.4

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



BULGE: STARS 10 Gyr OLD

DISK: STARS 10-0 Gyr OLD

BULGE / DISK ~ 1/3

Small stars

Nearby stars

Cosmic ray interactions with ISM

Requirements from the positron source(s)

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

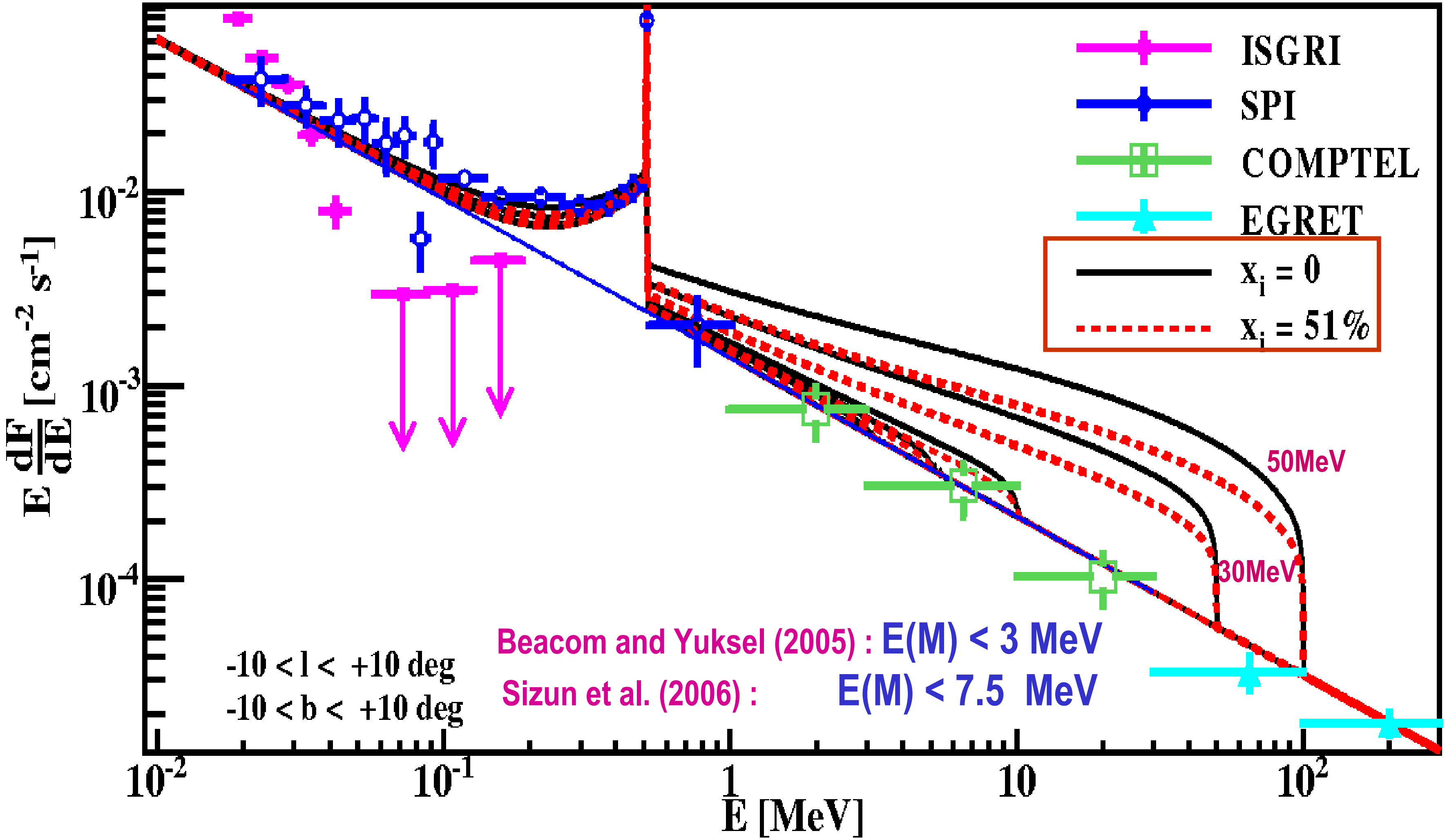
~1.2 10^{43} e^{+} s^{-1} (Bulge)
~0.8 10^{43} e^{+} s^{-1} (Disk)

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

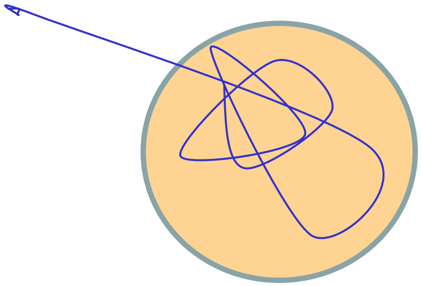


Beacom and Yuksel (2005) : E(M) < 3 MeV

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

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

POSITRON SOURCES : I. Stellar Nucleosynthesis of radioactive nuclei

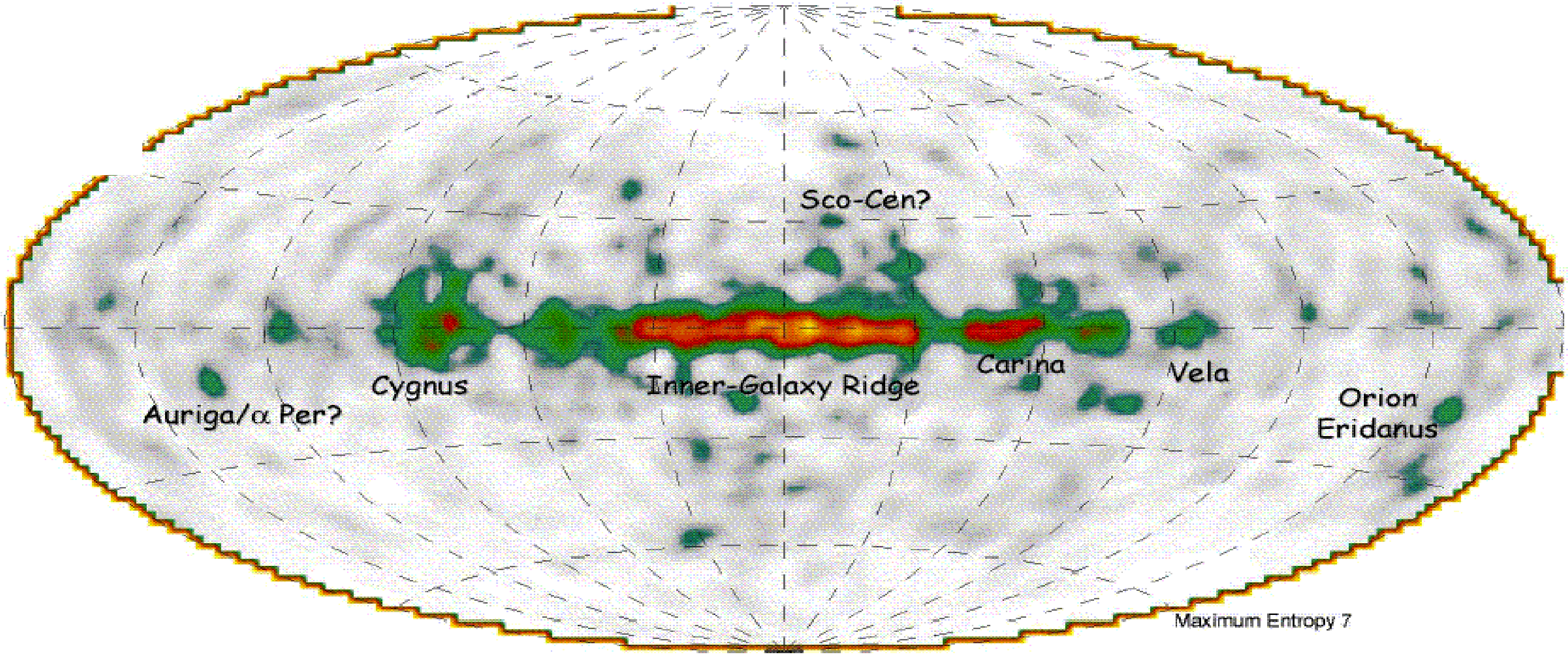


Produced in hot and dense inner stellar regions
through (mostly explosive) nucleosynthesis
They must be produced in *large amounts* and
decay slowly enough to allow for the positrons of their decay
to escape from the dense region (otherwise the annihilation photons
will be trapped and remain undetectable)

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	$^{56}\mathrm{Ni} \longrightarrow {}^{56}\mathrm{Co}^*$	EC^b	6.073 d	158(0.99), 812(0.86)			**Supernovae from white dwarfs (SNIa)**
	$^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Fe}^*$	e^+ (0.19)	77.2 d	2598(0.17), 1771(0.15)	1458.9	610	
^{22}Na	$^{22}\mathrm{Na} \longrightarrow {}^{22}\mathrm{Ne}^*$	e^+ (0.90)	2.61 y	1275(1)	1820.2	215.9	**Novae**
^{44}Ti	$^{44}\mathrm{Ti} \longrightarrow {}^{44}\mathrm{Sc}^*$	EC^b	59.0 y	68(0.94), 78(0.96)			**Supernovae from massive stars (CCSN)**
	$^{44}\mathrm{Sc} \longrightarrow {}^{44}\mathrm{Ca}^*$	e^+ (0.94)	3.97 h	1157(1)	1474.2	632.	
^{26}Al	$^{26}\mathrm{Al} \longrightarrow {}^{26}\mathrm{Mg}^*$	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)



Complete CGRO Mission
(Plüschke et al. 2001)

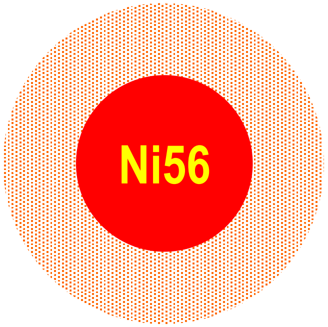
Total flux: $\approx$ **4 10^{-4} cm^{-2} s^{-1}** $\Rightarrow$ **$\approx$ 2.8 $M_\odot$ of ^{26}Al per Myr**

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 : $^{56}\mathrm{Ni} \xrightarrow[8.8\ \mathit{days}]{} {}^{56}\mathrm{Co} \xrightarrow[113\ \mathit{days}]{0.2\ e+} {}^{56}\mathrm{Fe}$



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

Frequency of SNIa in MW :
$f \sim 0.5 / 100\ \mathrm{yr} \sim 1.6\ 10^{-10}\ \mathrm{s}^{-1}$

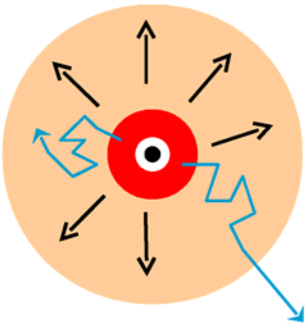
Rate of positrons released by MW SNIa:

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

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

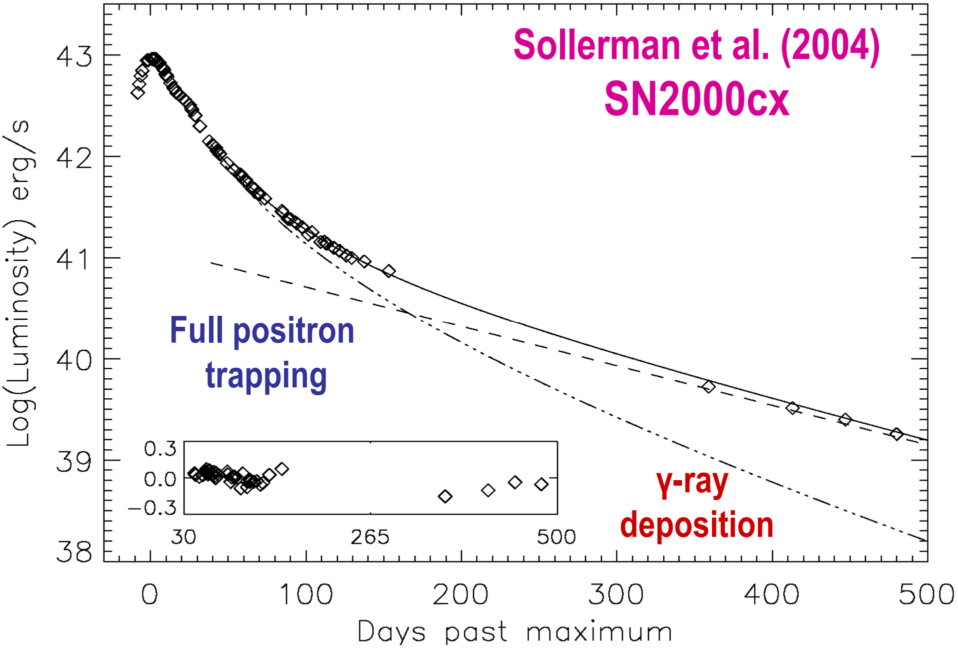
What fraction of the e^+ produced
by the short-lived Co56 manage to
escape the SNIa ejecta?

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



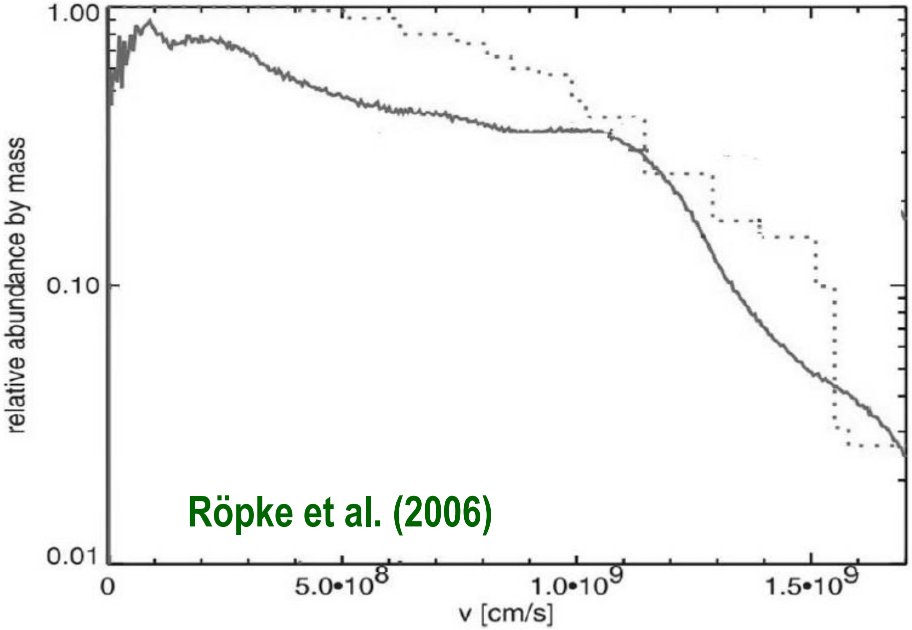
What fraction of positrons from Co-56 decay escapes SNIa ?

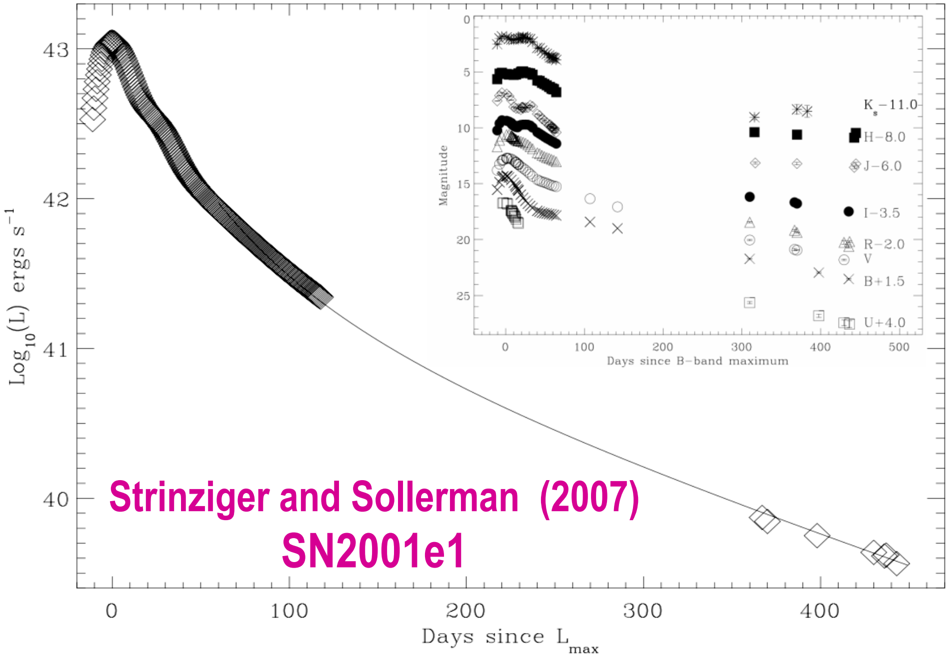
Observations of late L_{BOL} (*including* NIR) analyzed with *stratified* 1D models suggest f=0%



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

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





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

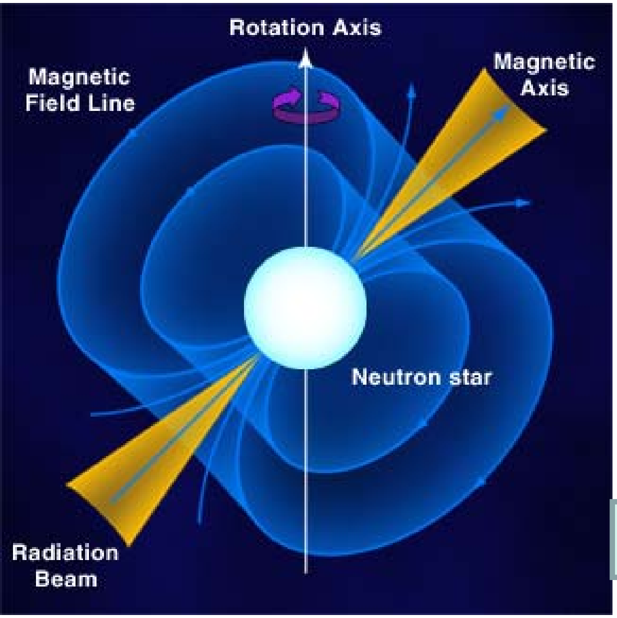
only ~ 10^{42} e^+ s^{-1} of ~30 - 40 MeV are produced, mainly in the disk

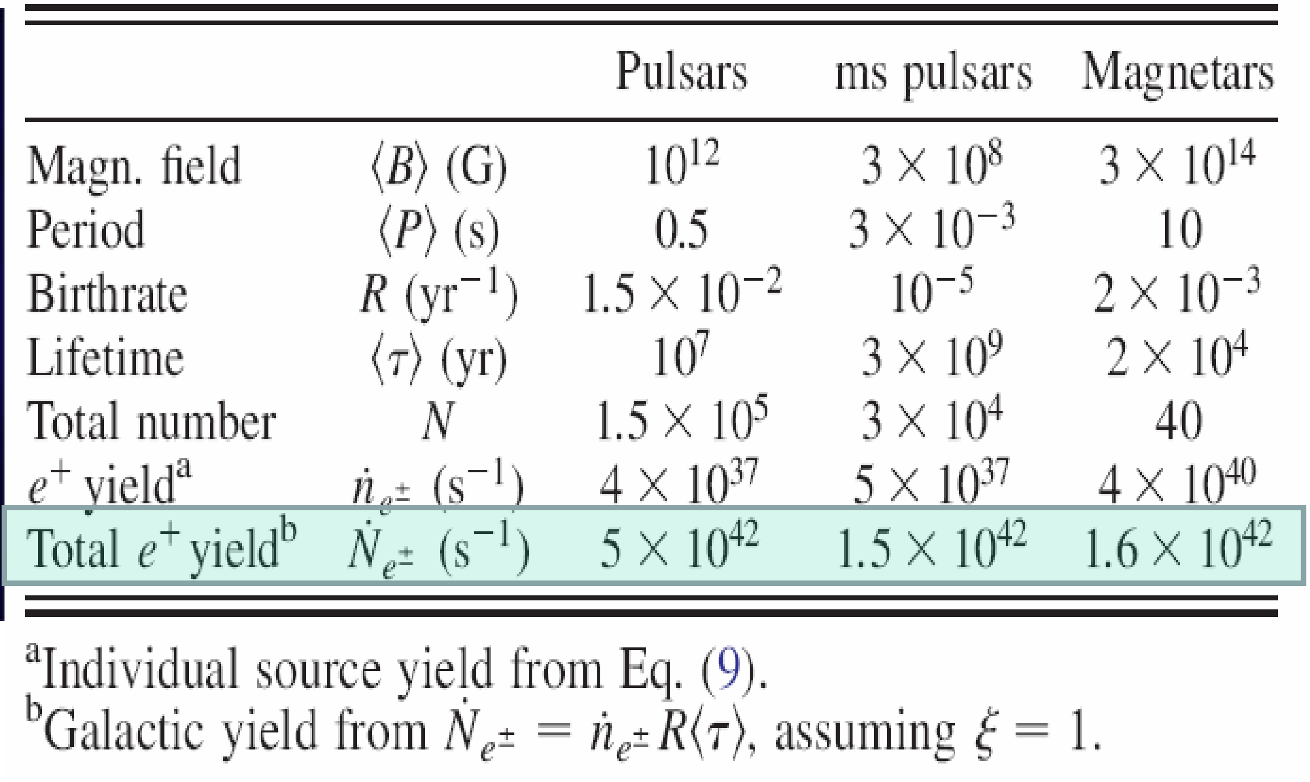
b) Photon - photon interactions $\gamma\gamma \rightarrow e^- e^+$

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).

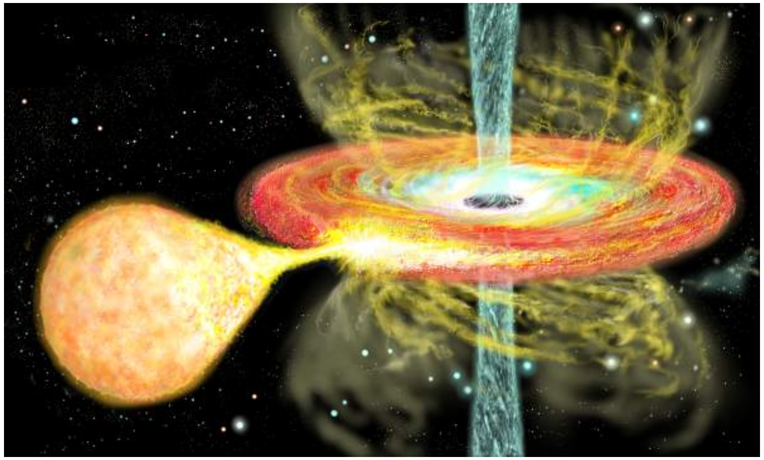
[b] Galactic yield from $\dot{N}_{e^\pm} = \dot{n}_{e^\pm} R \langle \tau \rangle$, assuming $\xi = 1$.

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

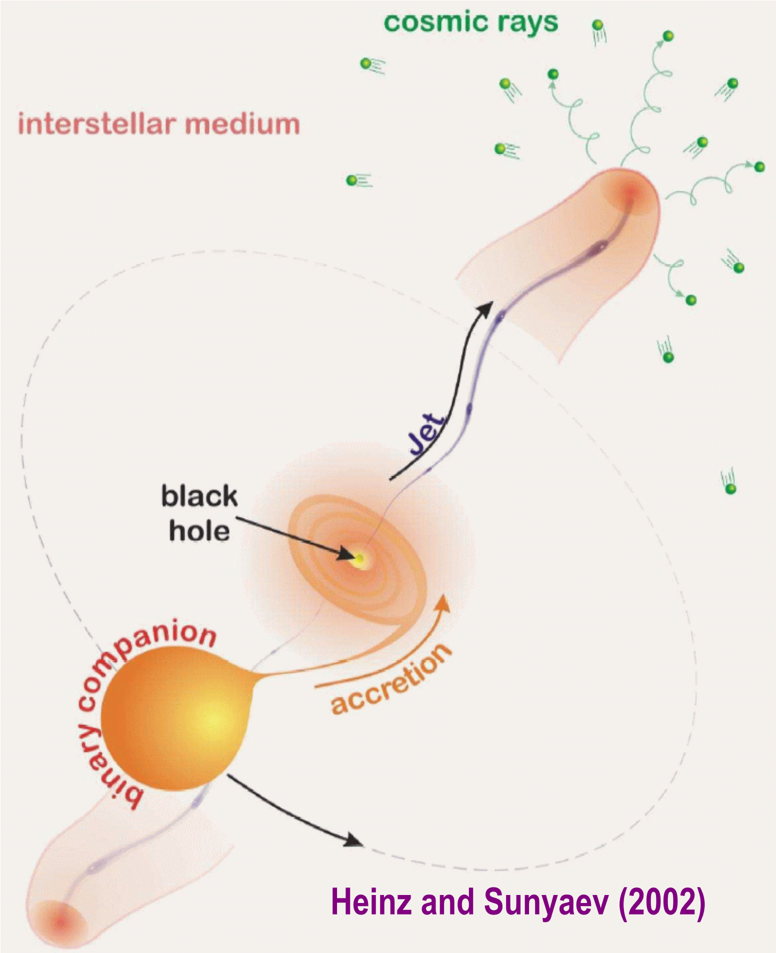
Total positron rate OK for disk, not for bulge

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



Heinz and Sunyaev (2002)

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 ?

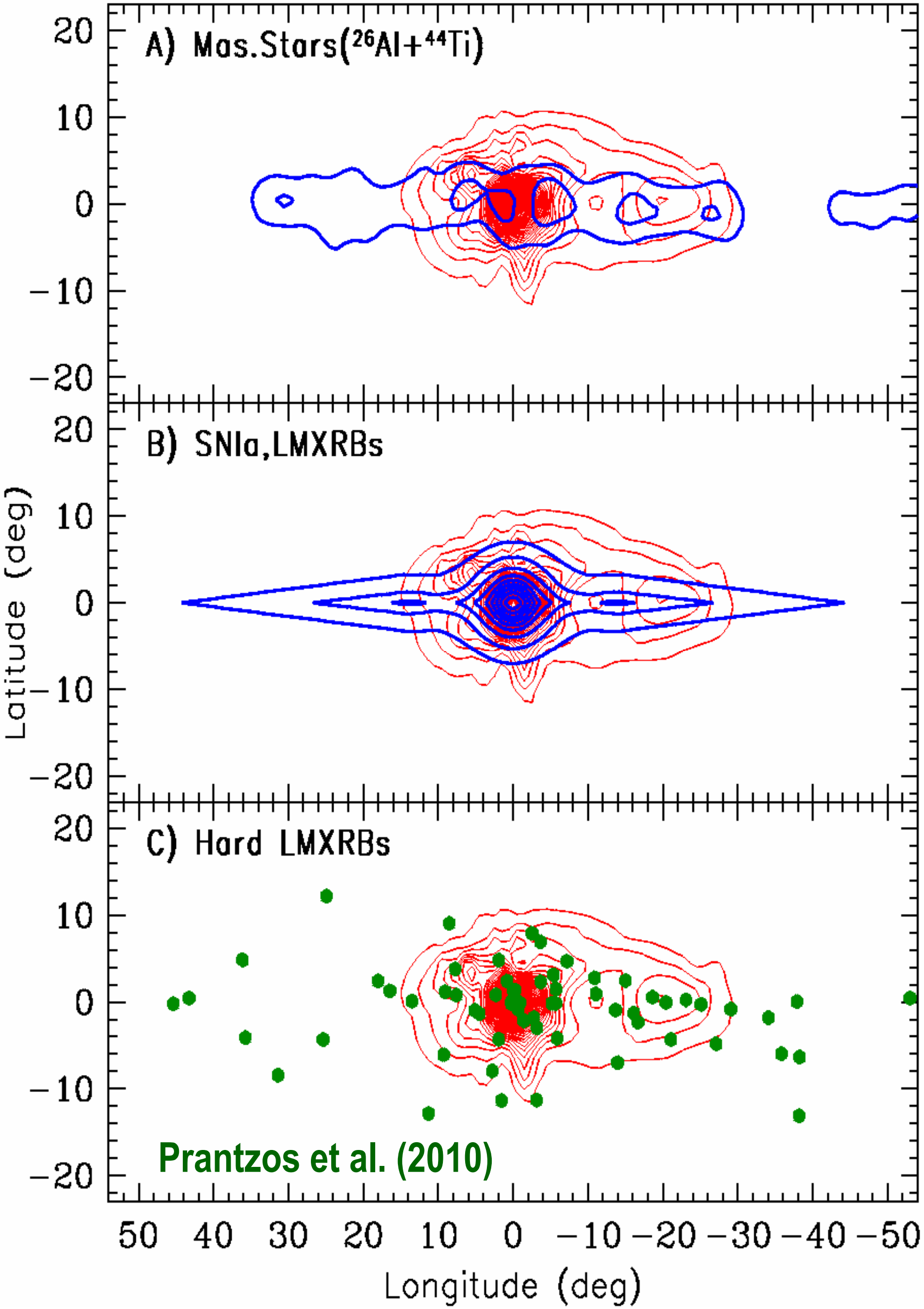
De-exciting (provided they possess ~MeV energy levels)
(*Finkbeiner and Weiner 2007, Pospelov and Ritz 2007*)

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



Prantzos et al. (2010)

In all panels:
***Red isocontours*: 511 keV observations**
(from Weidenspointner et al. 2008a)

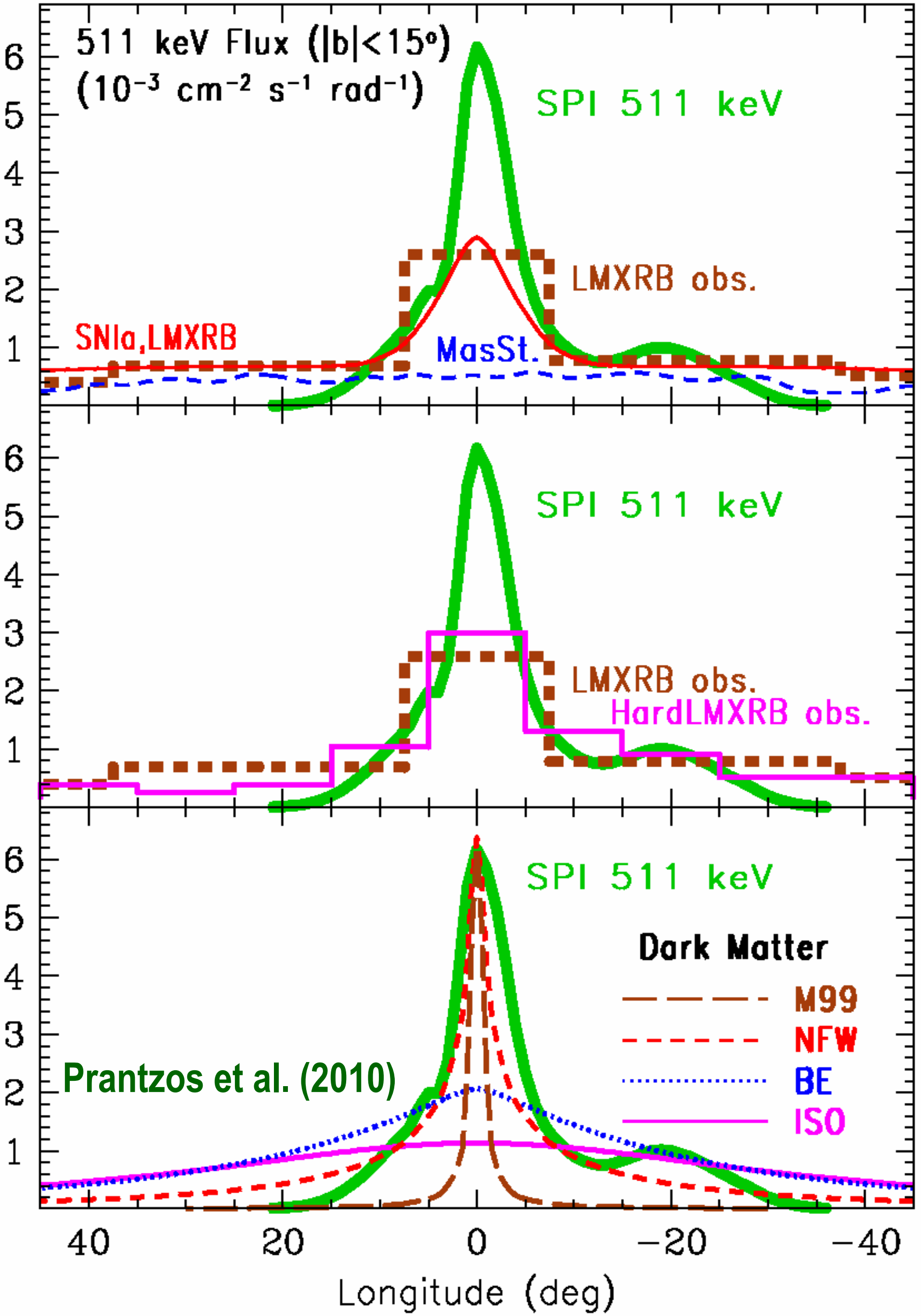
Top panel:
***Blue isocontours*: 1.8 MeV (Al26) observations**
(= Massive stars)

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

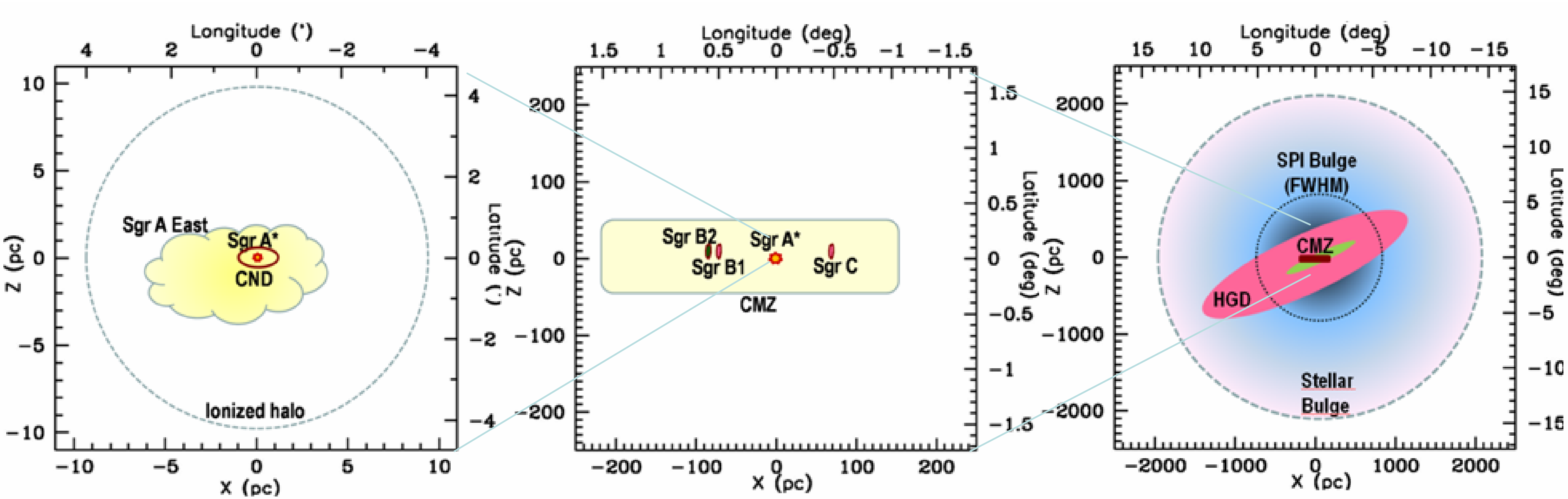
Only some specific distributions
(M99, NFW)
of *annihilating*
Dark Matter particles
are as peaked as
the observed 511 keV one
They are apparently ruled out
by observations of dwarf galaxies



Prantzos et al. (2010)

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

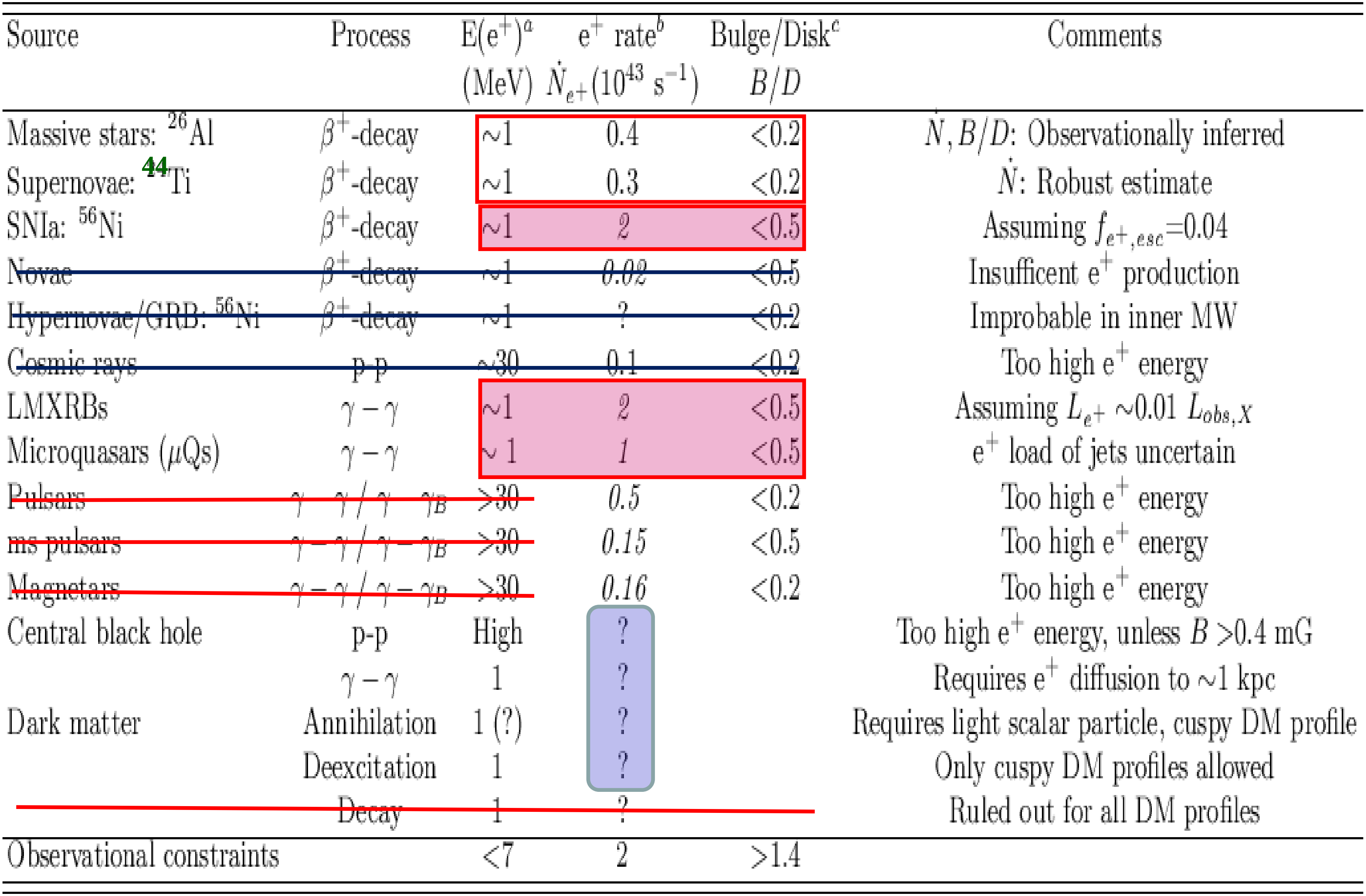
Accretion of gas from one (or many) disrupted star(s) 10^5 - 10^7 yr ago onto the SMBH

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



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	~1	*2*	<0.5	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	$\gamma-\gamma$	~1	*2*	<0.5	Assuming L_{e^+} ~0.01 $L_{obs,X}$
Microquasars (μQs)	$\gamma-\gamma$	~ 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 ~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	

Prantzos et al. (2010)

Implicit assumption :
Positrons annihilate close to their sources

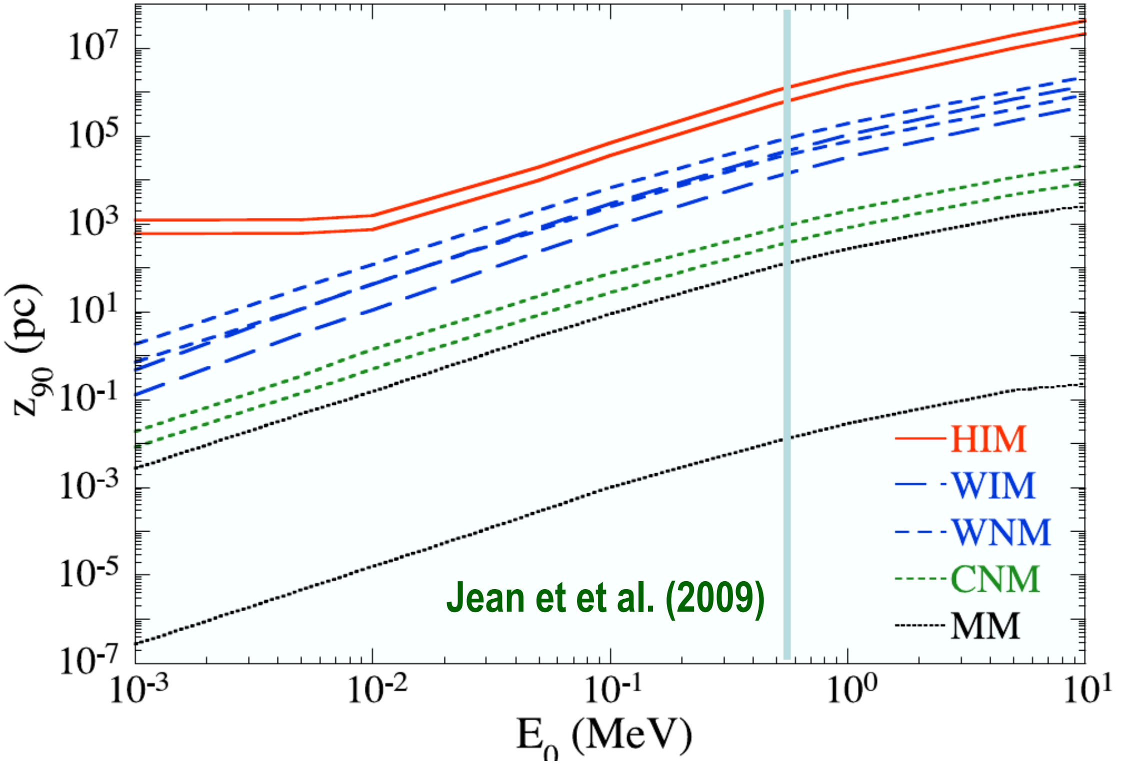
Gamma-ray morphology reflects source morphology

Not necessarily true

Positron propagation in ISM may hold the clue

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)

Positrons propagate in a magnetized, turbulent plasma

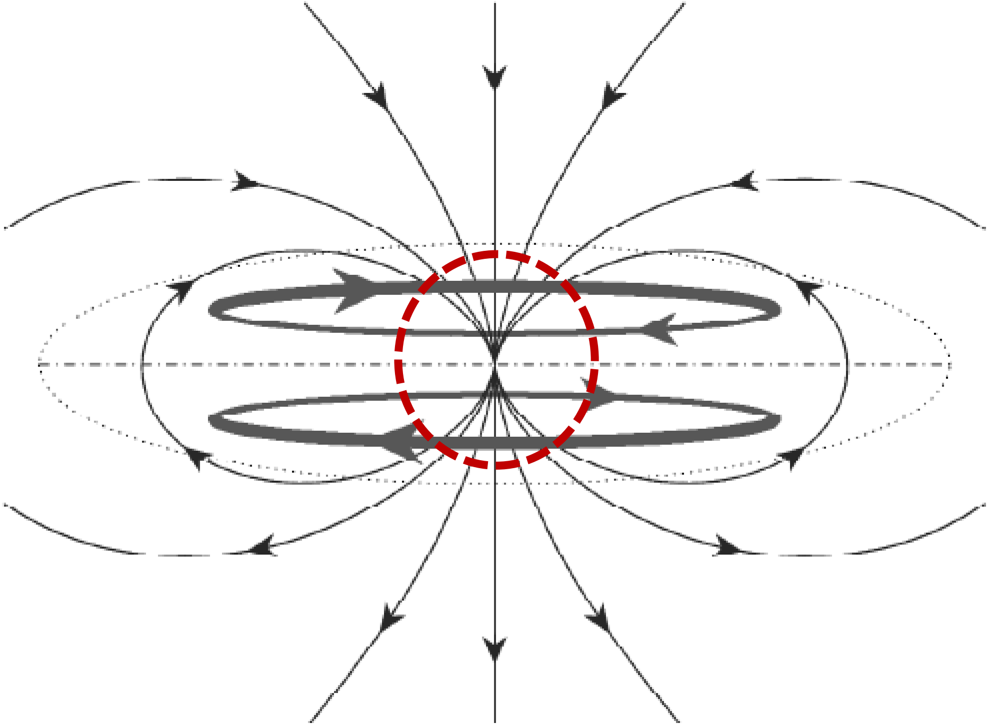


Jean et et al. (2009)

How far can they go from their sources ?

Positrons released in a hot and low density medium
can travel far away from their sources (many kpc)
but **to go where ?**

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
(*Prantzos 2006*)



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

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 appears to be 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?

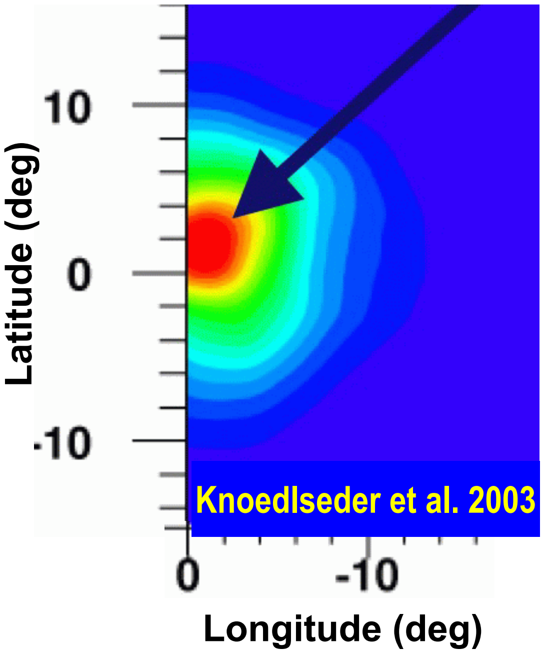
GAMMA-RAY LINE ASTRONOMY

NUCLEOSYNTHESIS AND GAMMA-RAY LINES
NP (2011),
arXiv: 1101.2112

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)*, Vol. 83, pp. 1001-1056

ASTRONOMY WITH RADIOACTIVITIES
Eds. R. Diehl, D. Hartmann, NP (2011)
Springer

The 511 keV line of $e^- - e^+$ annihilation from the inner Galaxy



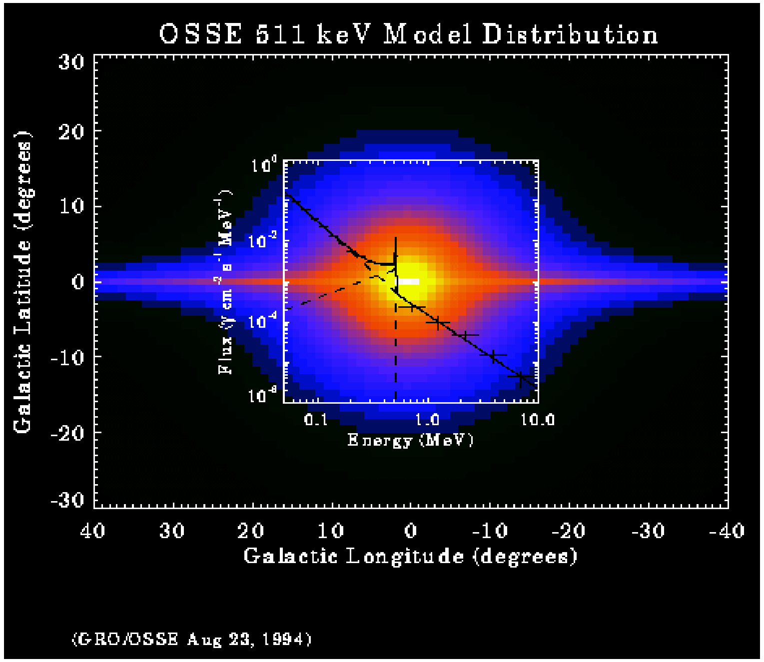
Observed by
SPI / INTEGRAL

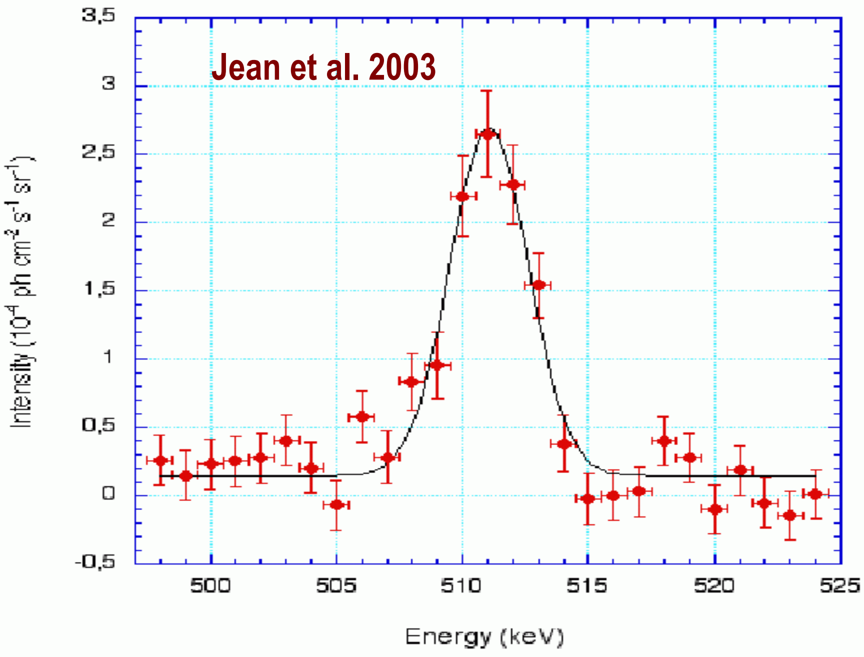
- Only bulge emission seen up to now

-Flux ≈10^{-3} ph/cm^2/s

- Line (relatively) narrow

[talk by P. Jean]





Models of 511 keV sources constrained by:

- **Intensity** (**≈10^{43} e^+ s^{-1}** for steady state)

-**Morphology** (bulge-like, FWHM=9° and bulge/disk ratio > 0.6)

DECAY CHAIN	MEAN LIFE* (yr)	LINE ENERGIES (MeV) (Branching Ratios)	SITE [Detected]	NUCLEAR PROCESS
$^{7}Be \rightarrow {}^{7}Li$	0.21	0.478 (1.)	Novae	Expl.H
$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ e^{+}	0.31	$\underline{0.847}$ (1.) $\underline{1.238}$ (0.685) 2.598 (0.17) 1.771 (0.45)	SN [SN1987A] [SN1991T]	NSE
$^{57}Co \rightarrow {}^{57}Fe$	1.1	$\underline{0.122}$ (0.86) $\underline{0.136}$ (0.11)	SN [SN1987A]	α-NSE
$^{22}Na \rightarrow {}^{22}Ne$	3.8	1.275 (1.)	Novae	Expl.H
$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$ e^{+}	89	$\underline{1.156}$ (1.) 0.068 (1.) 0.078 (0.98)	SN [CasA]	α-NSE
$^{26}Al \rightarrow {}^{26}Mg$ e^{+}	1.1 10^{6}	$\underline{1.809}$ (1.)	WR, AGB Novae SNII [Galaxy] [Vela]	St.H Expl.H St.Ne Expl.Ne ν
$^{60}Fe \rightarrow {}^{60}Co \rightarrow {}^{60}Ni$	2.2 10^{6}	1.322 (1.) 1.173 (1.)	SN	n-NSE

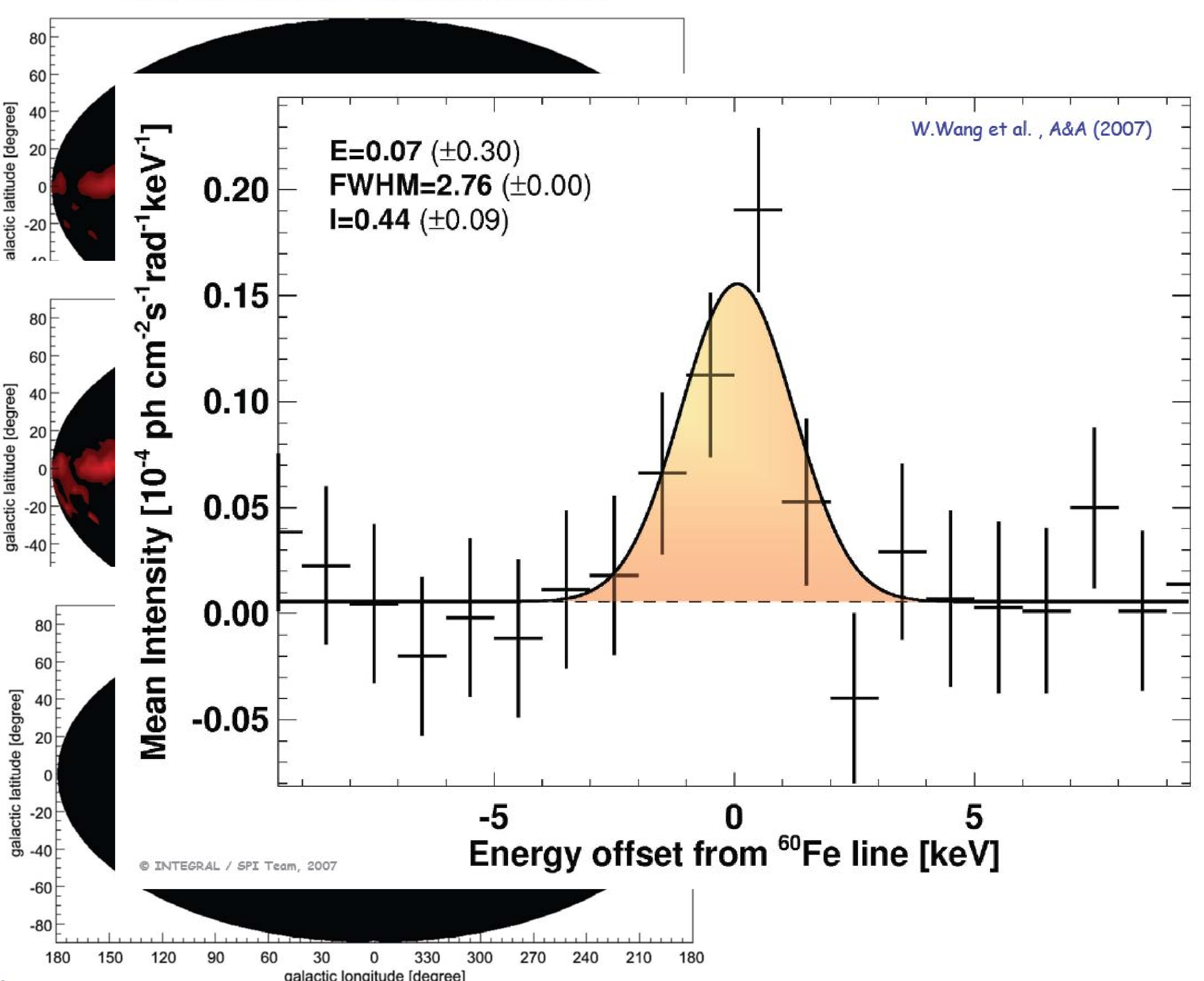
*: Double decay chains: the longest lifetime is given; *Underlined*: lines detected

In *parentheses*: branching ratios; In *brackets*: sites of lines detected

St.(Expl.): Hydrostatic(Explosive) burning; NSE:Nuclear statistical equilibrium

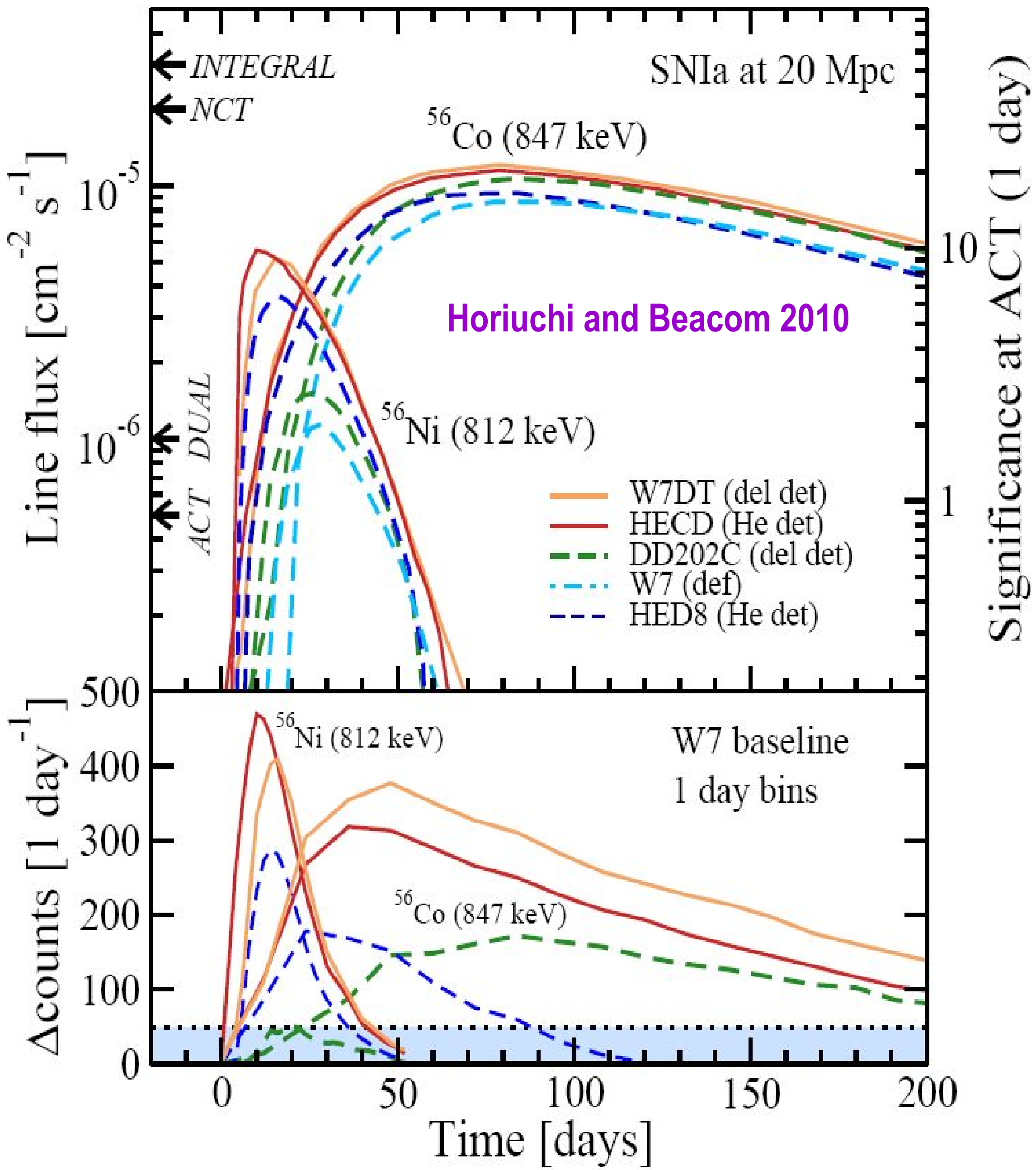
α: α-rich "freeze-out"; n-: normal "freeze-out"; ν: neutrino-process

All-sky image in the 511 keV annihilation line after five years

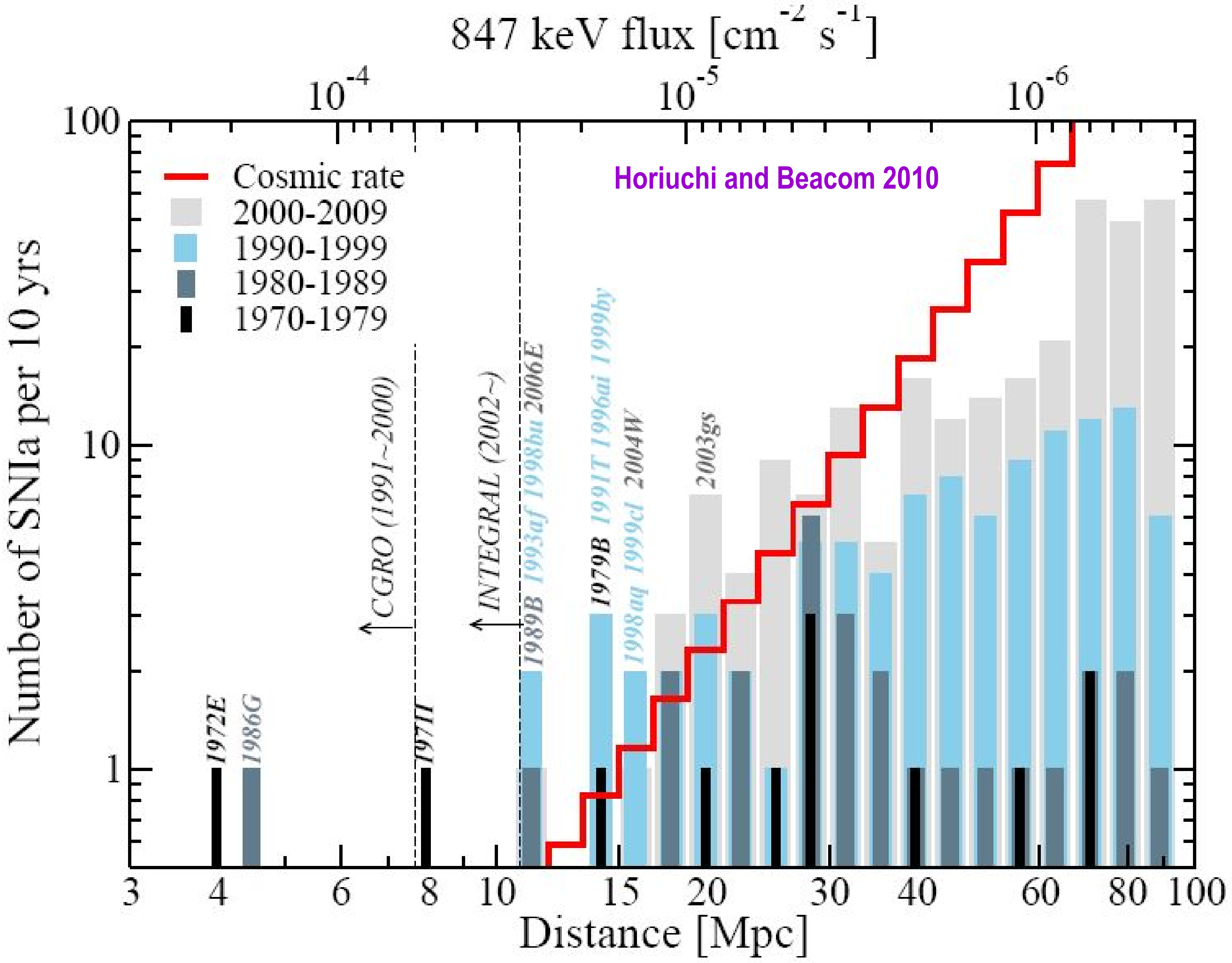


W.Wang et al. , A&A (2007)

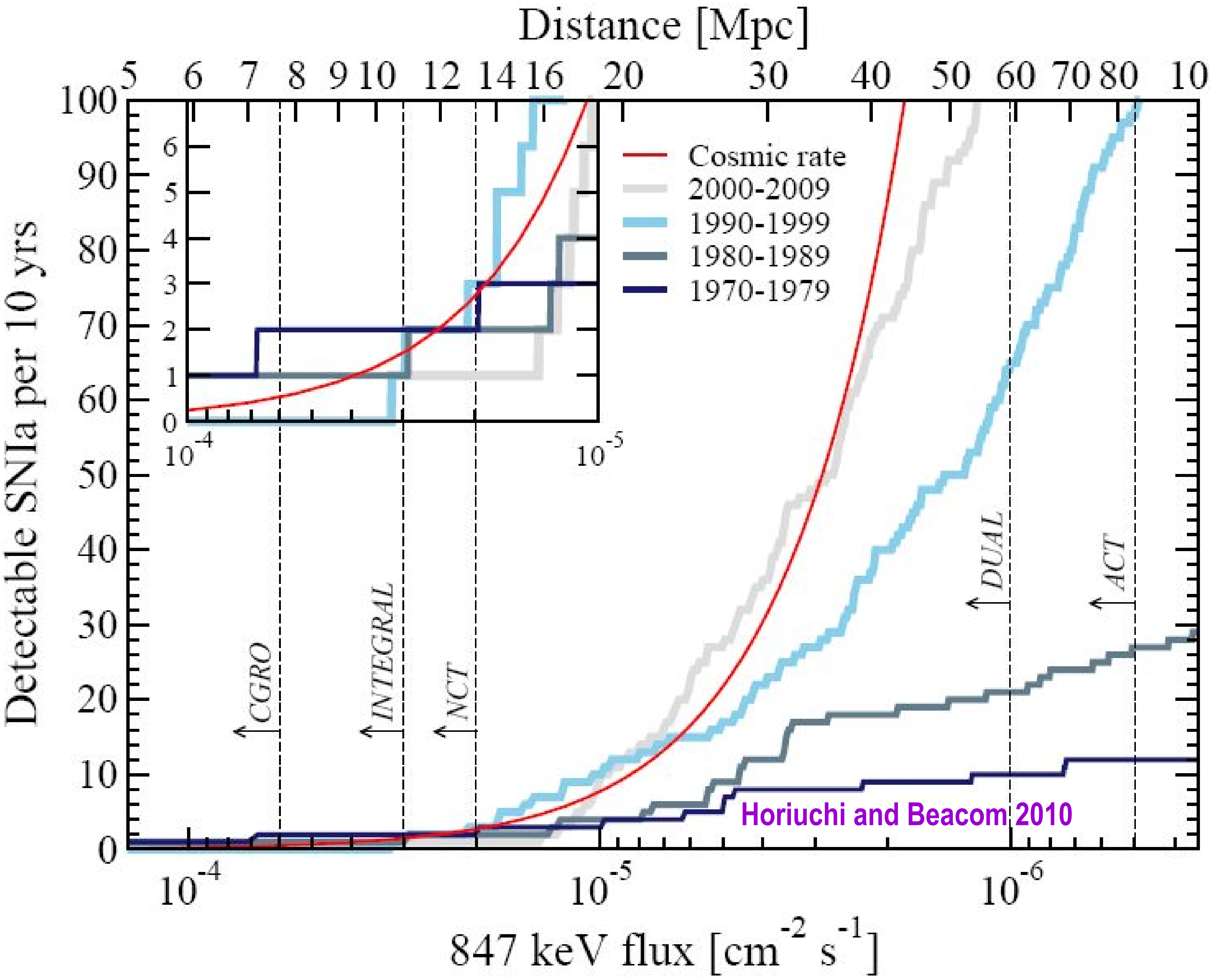
© INTEGRAL / SPI Team, 2007



Horiuchi and Beacom 2010



Horiuchi and Beacom 2010



Horiuchi and Beacom 2010

PRODUCTION MECHANISMS OF ASTROPHYSICAL GAMMA-RAY LINES

1. NUCLEAR DE-EXCITATION

Nuclei excited by :

- Inelastic Scattering : $^{16}\mathrm{O}(p,p')^{16}\mathrm{O}^*$ + 6.129 MeV
- Spallation Reactions : $^{16}\mathrm{O}(p,pa)^{12}\mathrm{C}^*$ + 4.438 MeV
- Radioactive Decay : $^{26}\mathrm{Al}(\beta^+)^{26}\mathrm{Mg}^*$ + 1.809 MeV
- Radiative Capture : $p\,(n,\gamma)\,D$ + 2.223 MeV

2. ELECTRON – POSITRON ANNIHILATION

e^+ produced by :

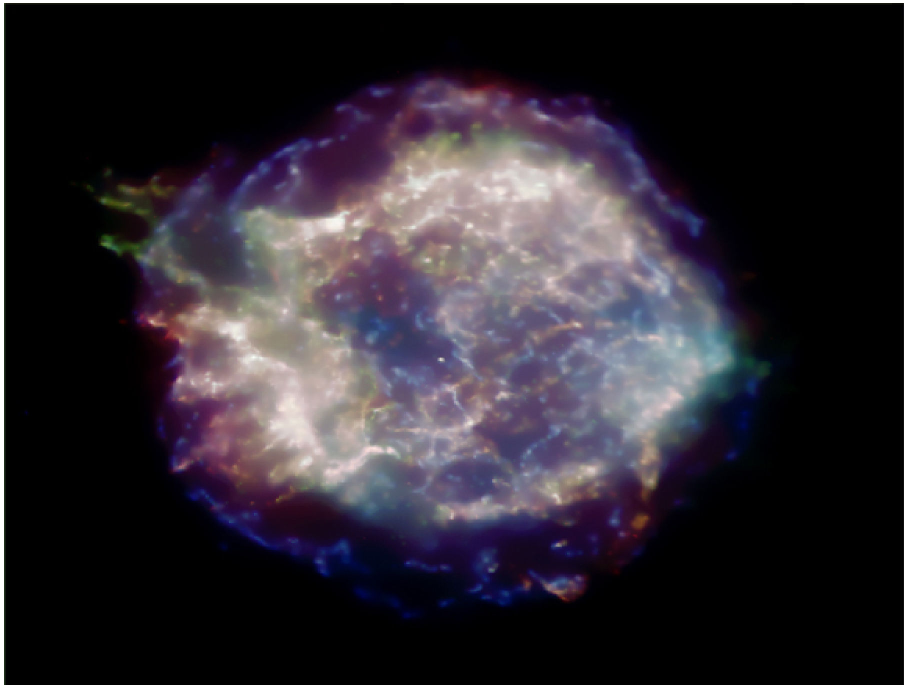
- β^+ decay of radionuclei
- π^+ decay (π^+ produced in high energy interactions: p + p)
- pairs (e^- - e^+) in high energy interactions ($\gamma+\gamma$, $\gamma+e^-$, γ+N etc.

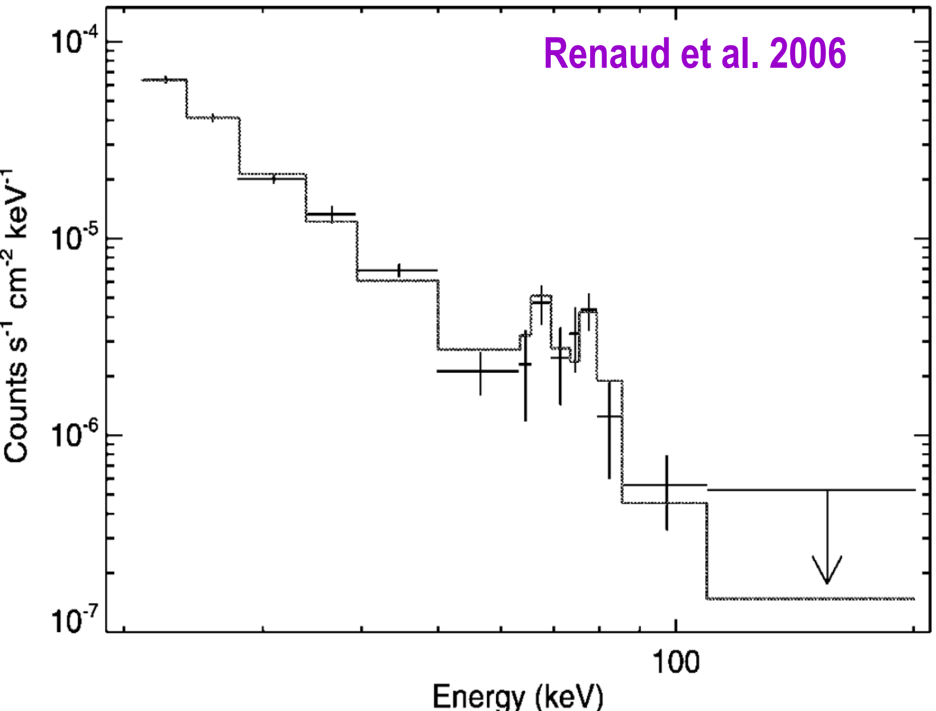
Ti-44 in Cas A

(d≈3 kpc, age≈320 yr)

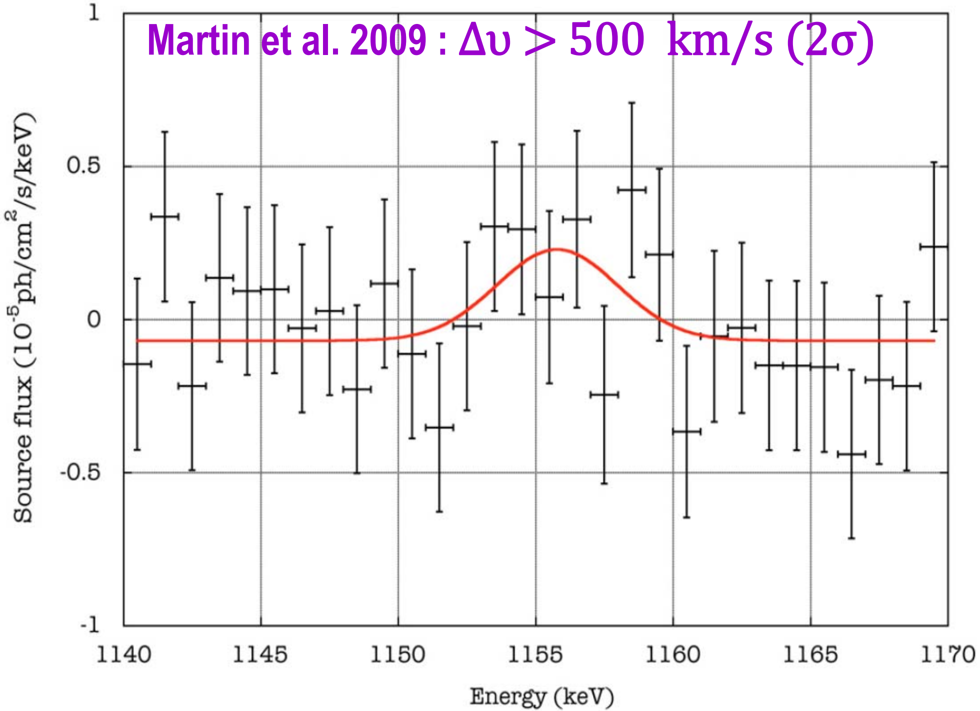
From observations: **1-2 10^{-4} $M_\odot$** of Ti-44

COMPTEL: 1.156 MeV (*Iyudin et al. 1994)*
Beppo-Sax: 68 + 78 keV (*Vink et al. 2002*)
IBIS-ISGRI: 68+78 keV (*Renaud et al. 2006*

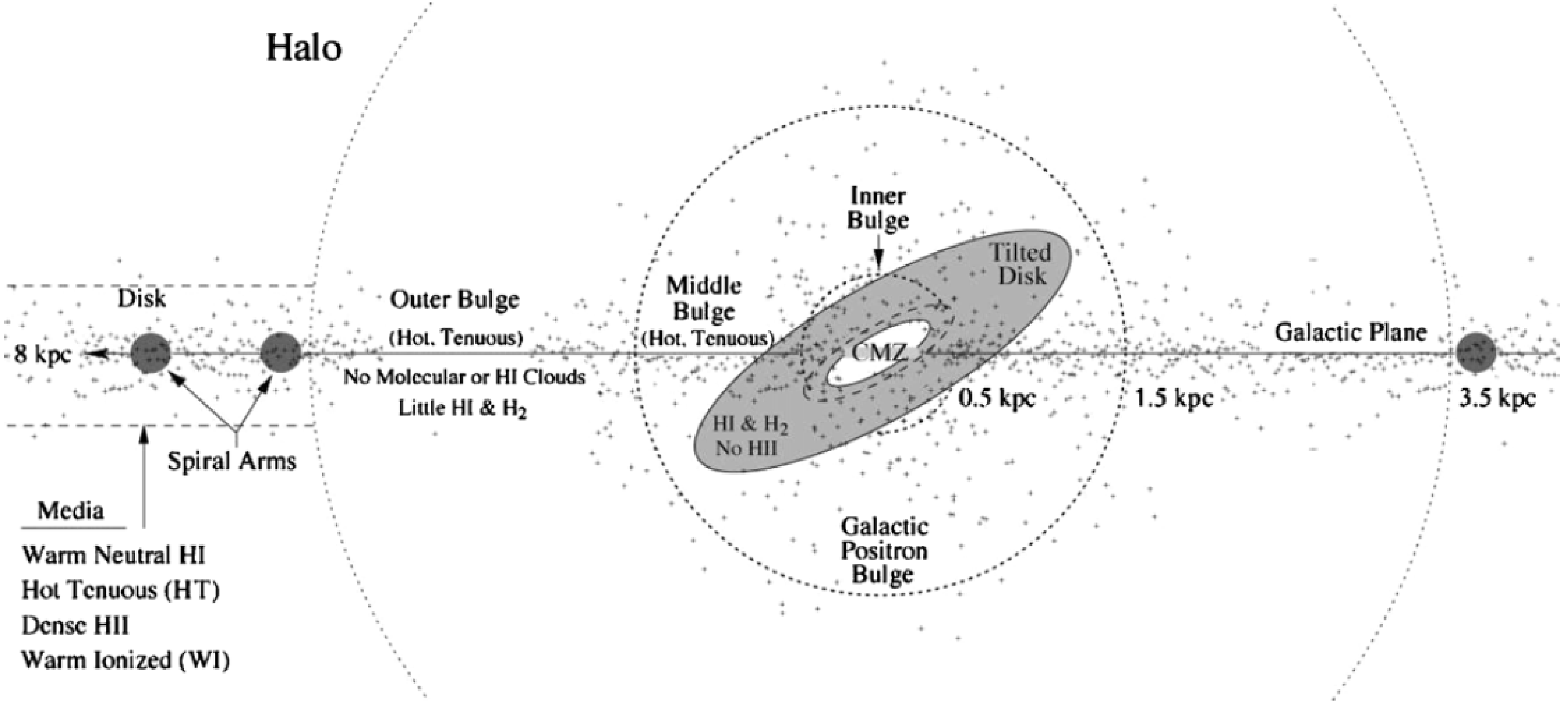




Renaud et al. 2006



Martin et al. 2009 : $\Delta\upsilon > 500$ km/s (2σ)



Transfer of positrons produced by SNIa from the “outer bulge” (?) (hot, tenuous) to the inner one
(*Higdon et al. 2009*)