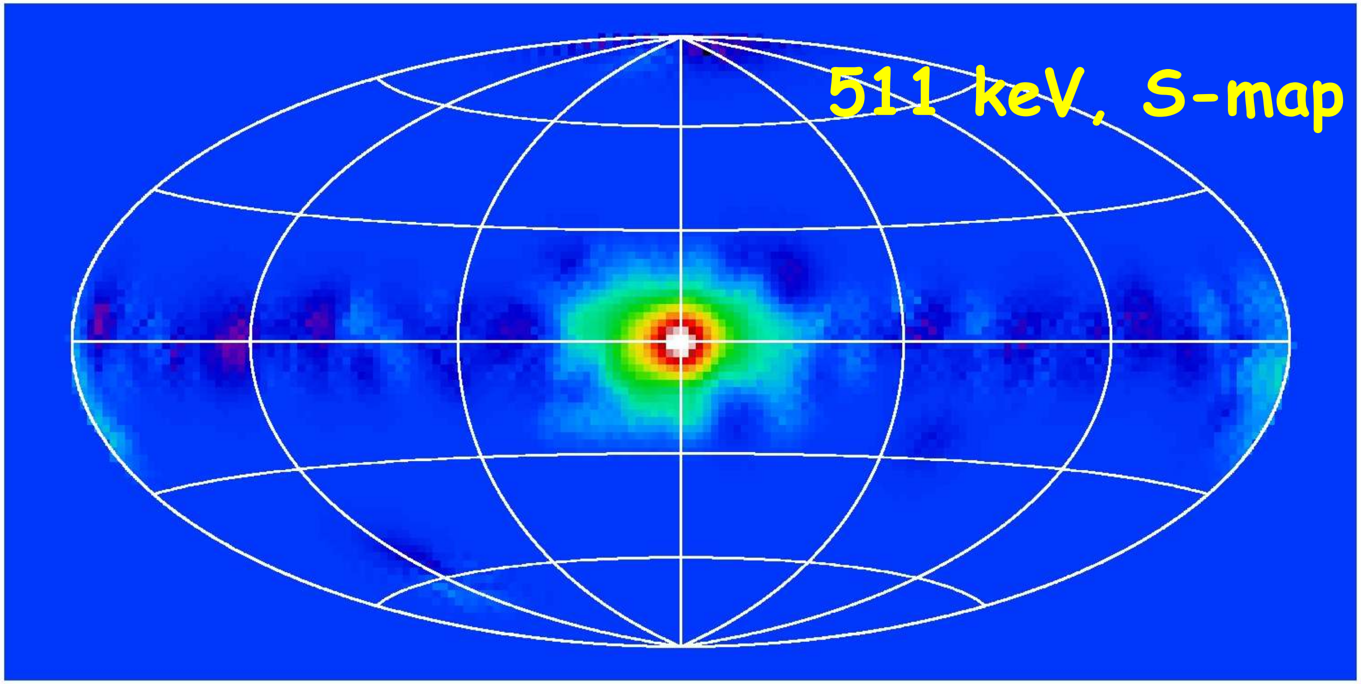
Annihilation of positrons in the Galaxy

S. Sazonov & E. Churazov
(MPA, Garching and IKI, Moscow)
and INTEGRAL team



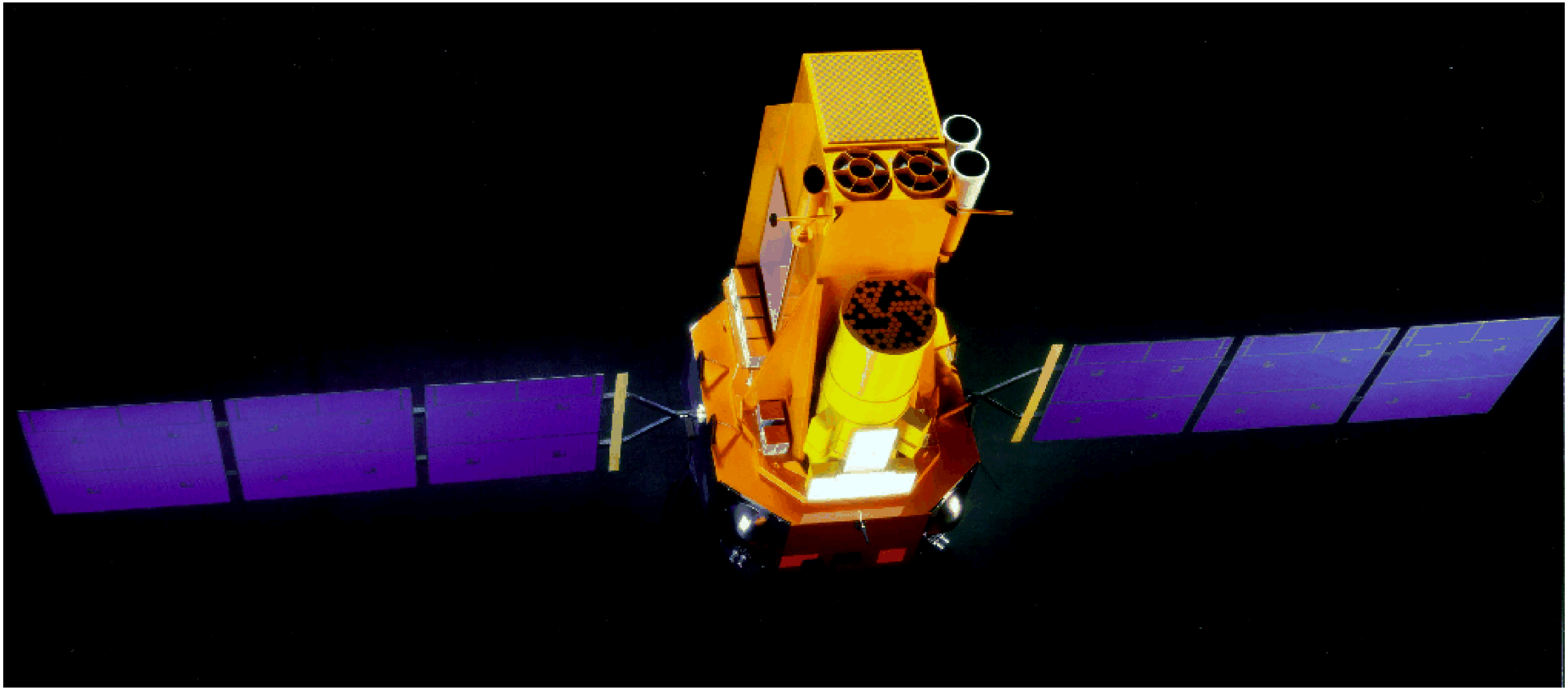
$e^+ e^-$ line @ 511 keV from the Galactic Center region

- Discovered in 1972 as a ~ 476 keV feature (Rice U, NaI detector)
  Johnson, Harden & Haymes, 1972; Johnson & Haymes, 1973
- Identified with a narrow 511 keV line in 1978 (Bell-Sandia, Ge detector)
  Leventhal, MacCallum & Stang, 1978
- Observed by SMM, OSSE, TGRS ...

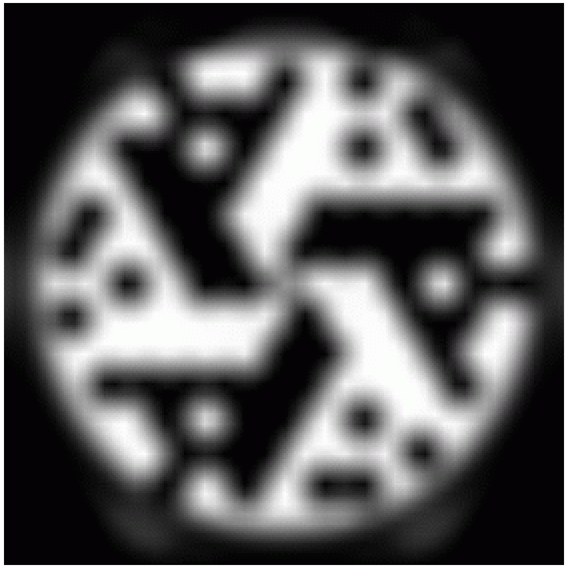
- The brightest γ-line in the Galaxy (~10^{-3} phot/cm^2/s)

- Many possible channels for positron production:
  - Nucleosynthesis (SNe, Novae, WR, AGB): e.g. Ni56, Ti44, Al26
  - Cosmic rays interaction with ISM ($\pi^+ \rightarrow e^+$)
  - Black holes and pulsars (pair production)
  - (Light) Dark matter decay and annihilation

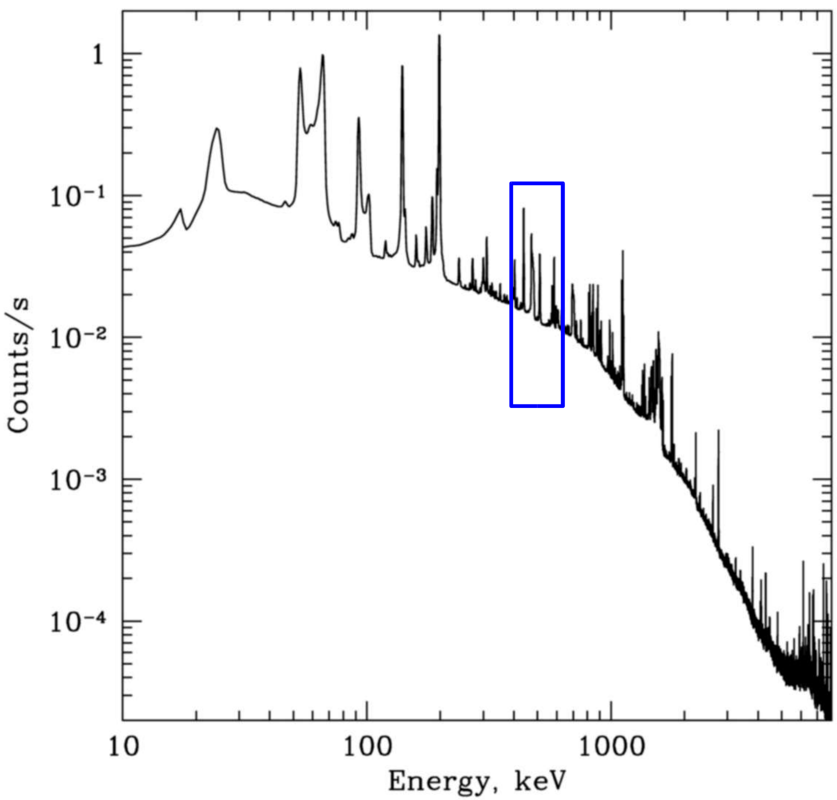
ESA's INTEGRAL gamma-ray observatory

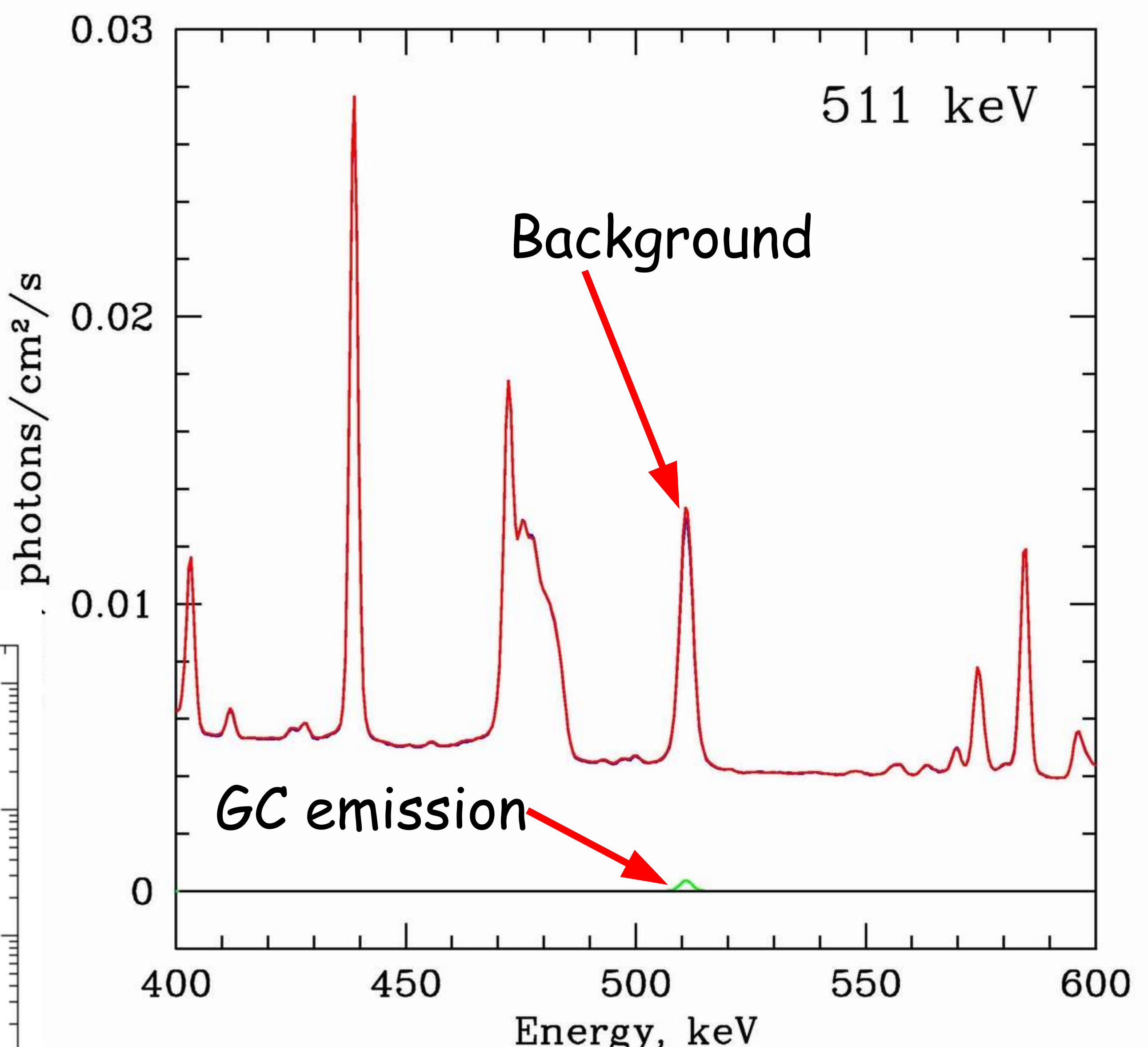


SPI
coded mask
Germanium
spectrometer

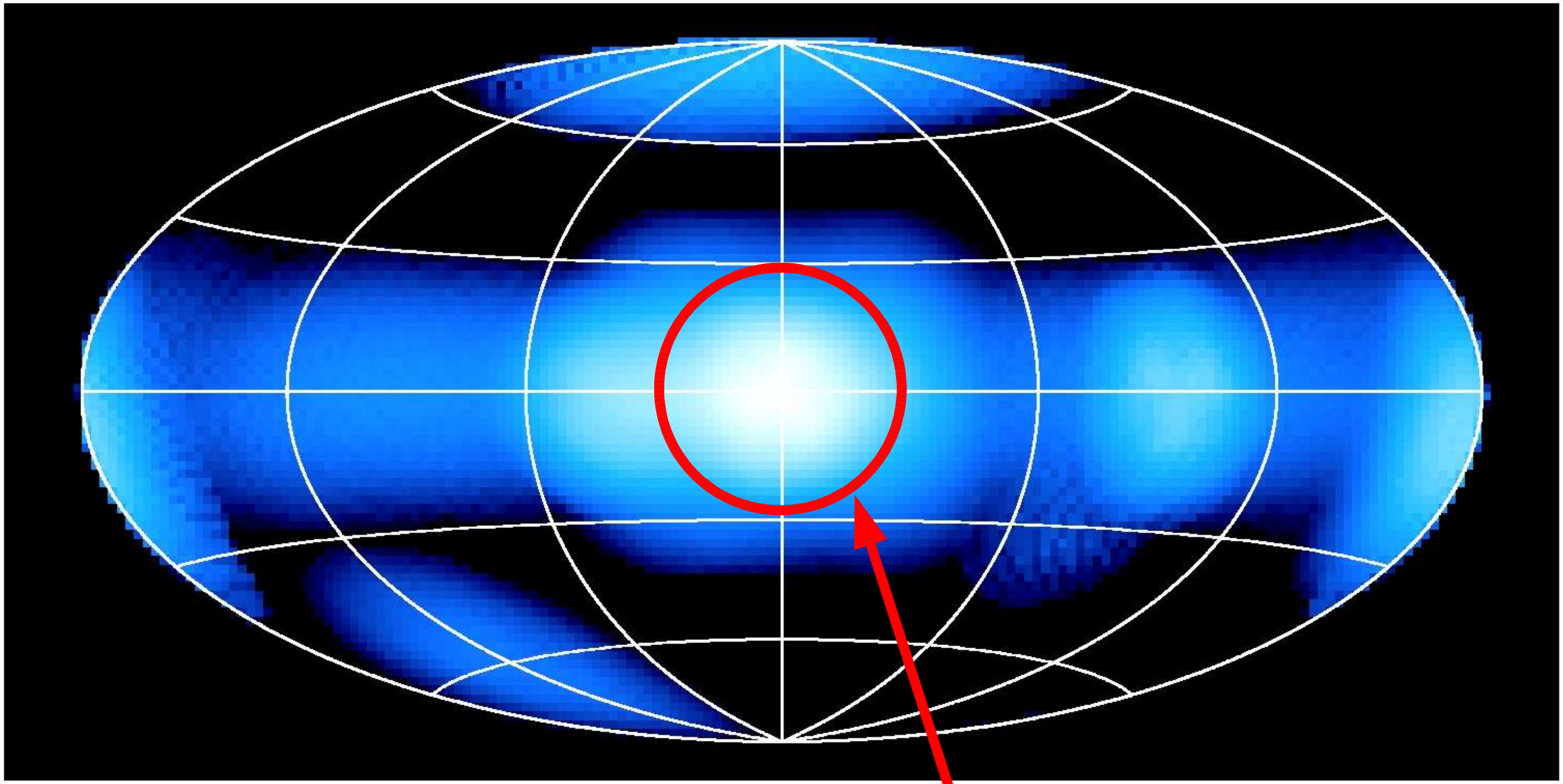


Usual problem:
instrument background completely dominates the signal

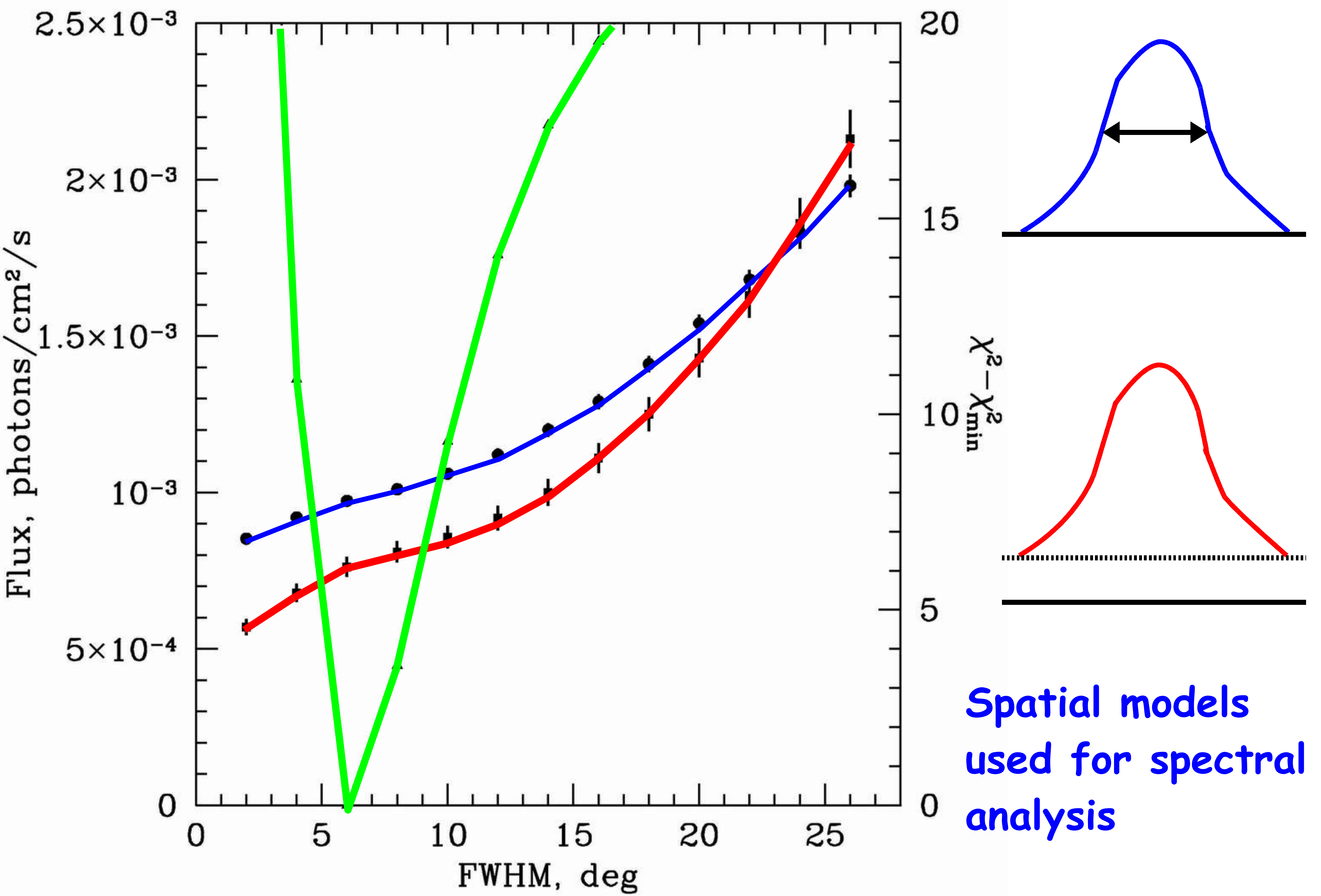




Exposure map

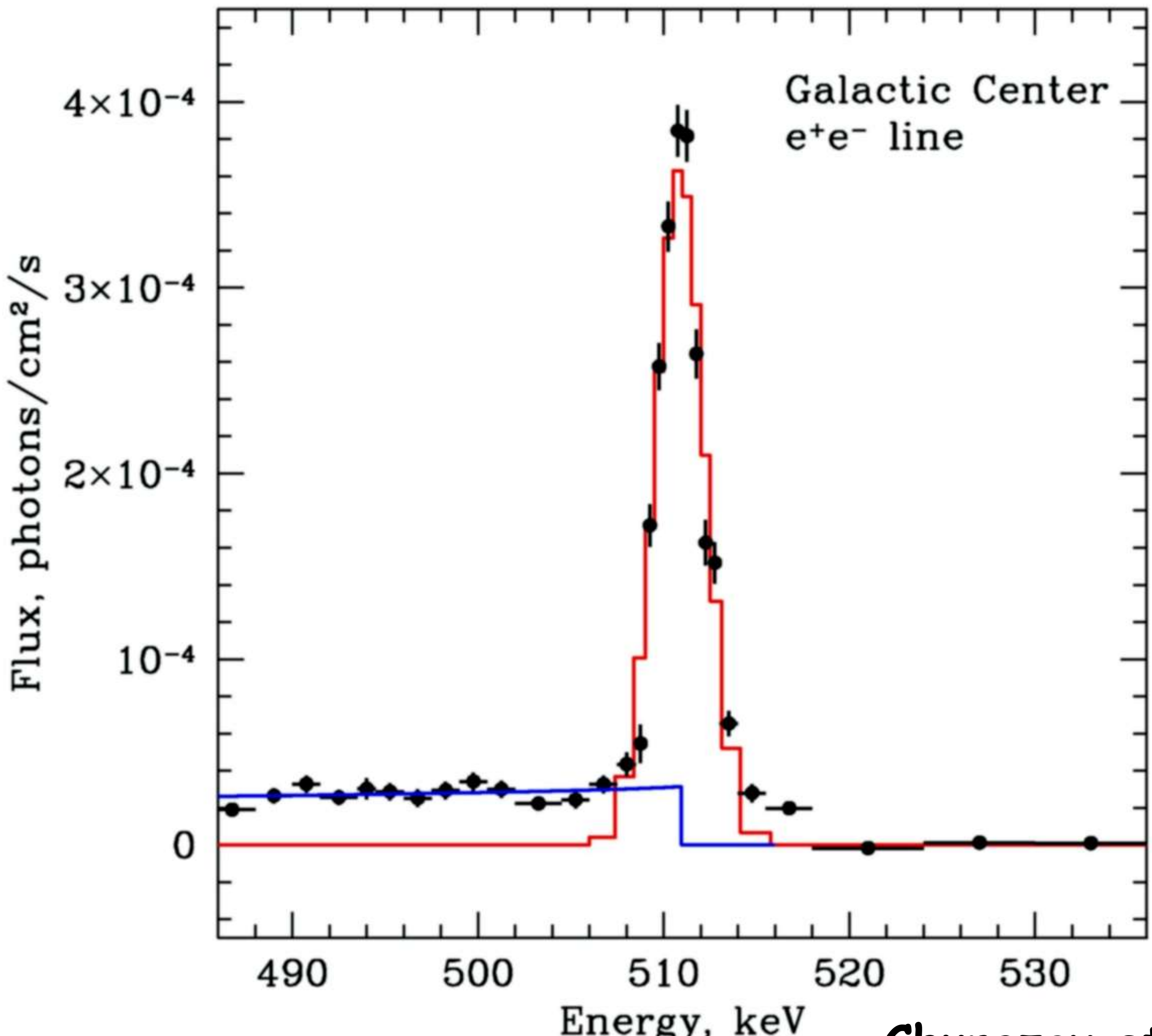


~4 Msec



Spatial models used for spectral analysis

Spectrum measured with INTEGRAL/SPI and best-fit model



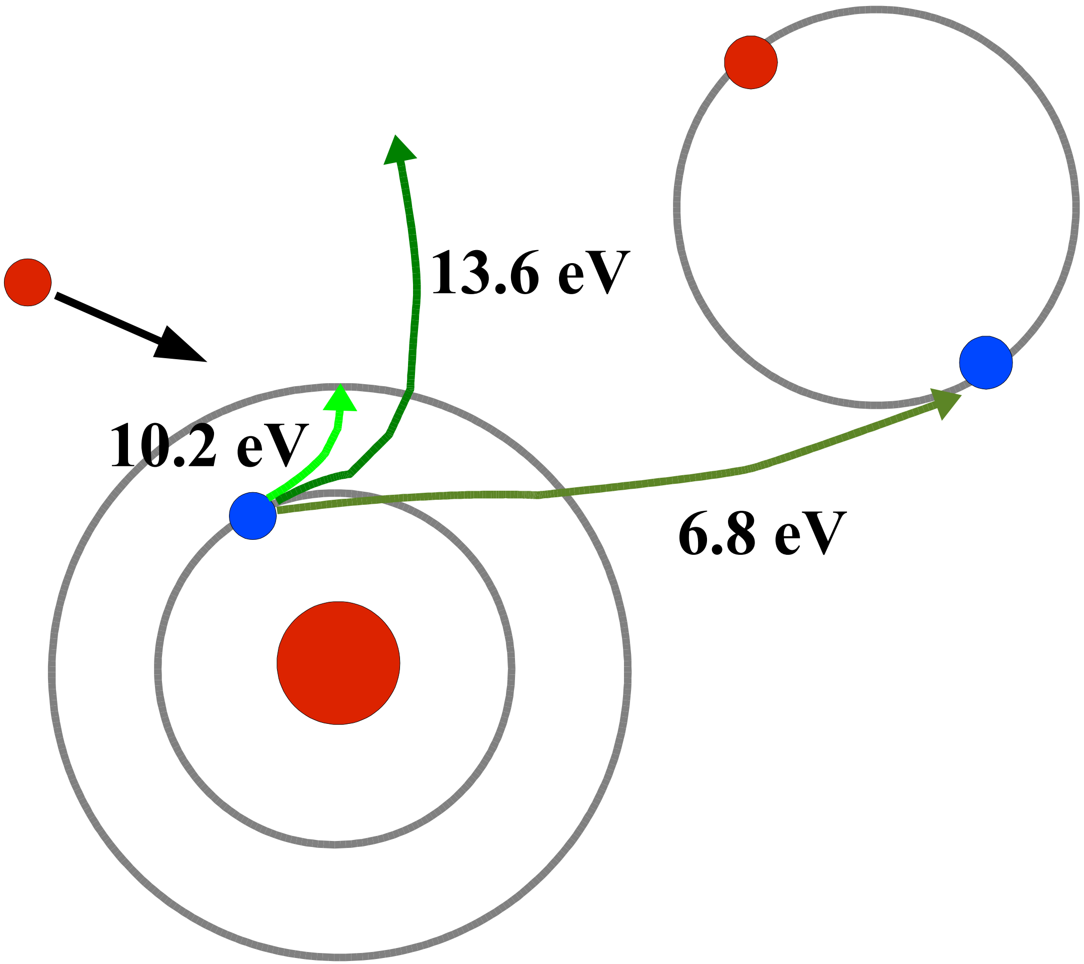
Churazov et al. 2005

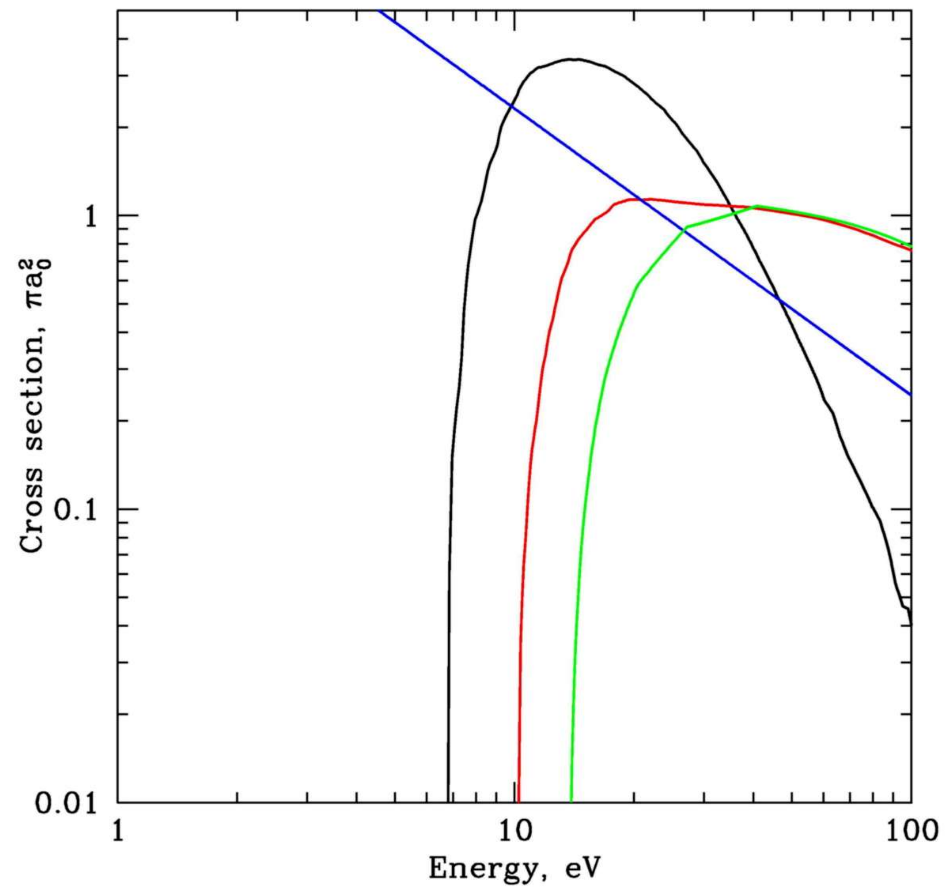
Processes in hydrogen plasma (dust free)

- Positrons born hot – at least few hundred keV
- Deceleration of positrons:
  Ionization, Excitation, Coulomb losses
- Direct annihilation $\sigma \mathrm{v} \sim \sigma_T c$
  Bound electrons, free electrons => 2 photons
- Radiative recombination (if ionized)
- Charge exchange (if neutral, E>6.8 eV) $\sigma \sim \pi r_0^2$
  Positronium formation => 2 or 3 photons

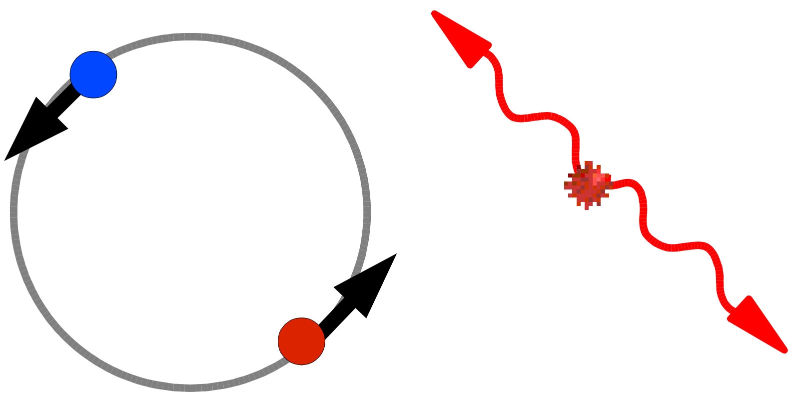
Bussard, Ramaty & Drachman 1979

Positron interactions with a neutral H atom

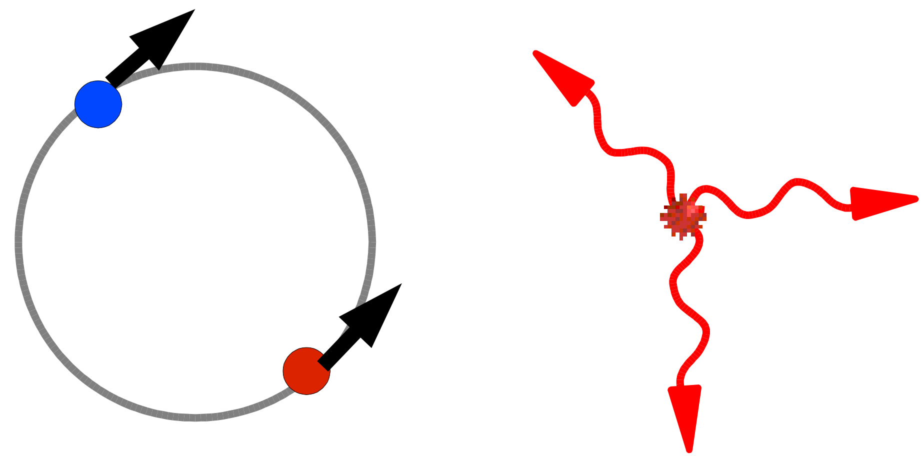




$$\text{CE} + \text{RR} = \begin{cases} \text{Para-positronium}, & \frac{1}{4} & 2\gamma \\ \text{Ortho-positronium}, & \frac{3}{4} & 3\gamma \end{cases}$$



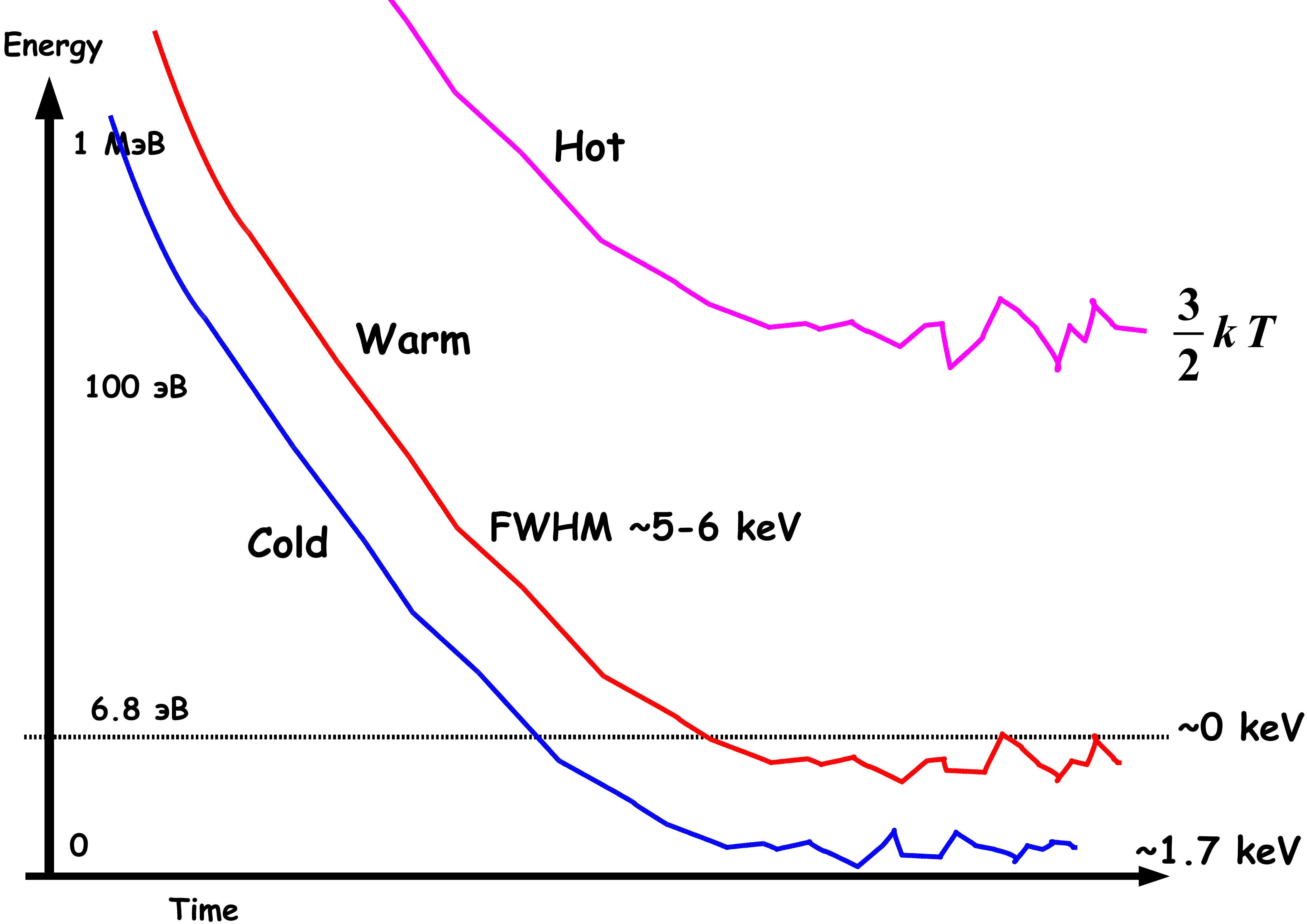
10^{-10} s

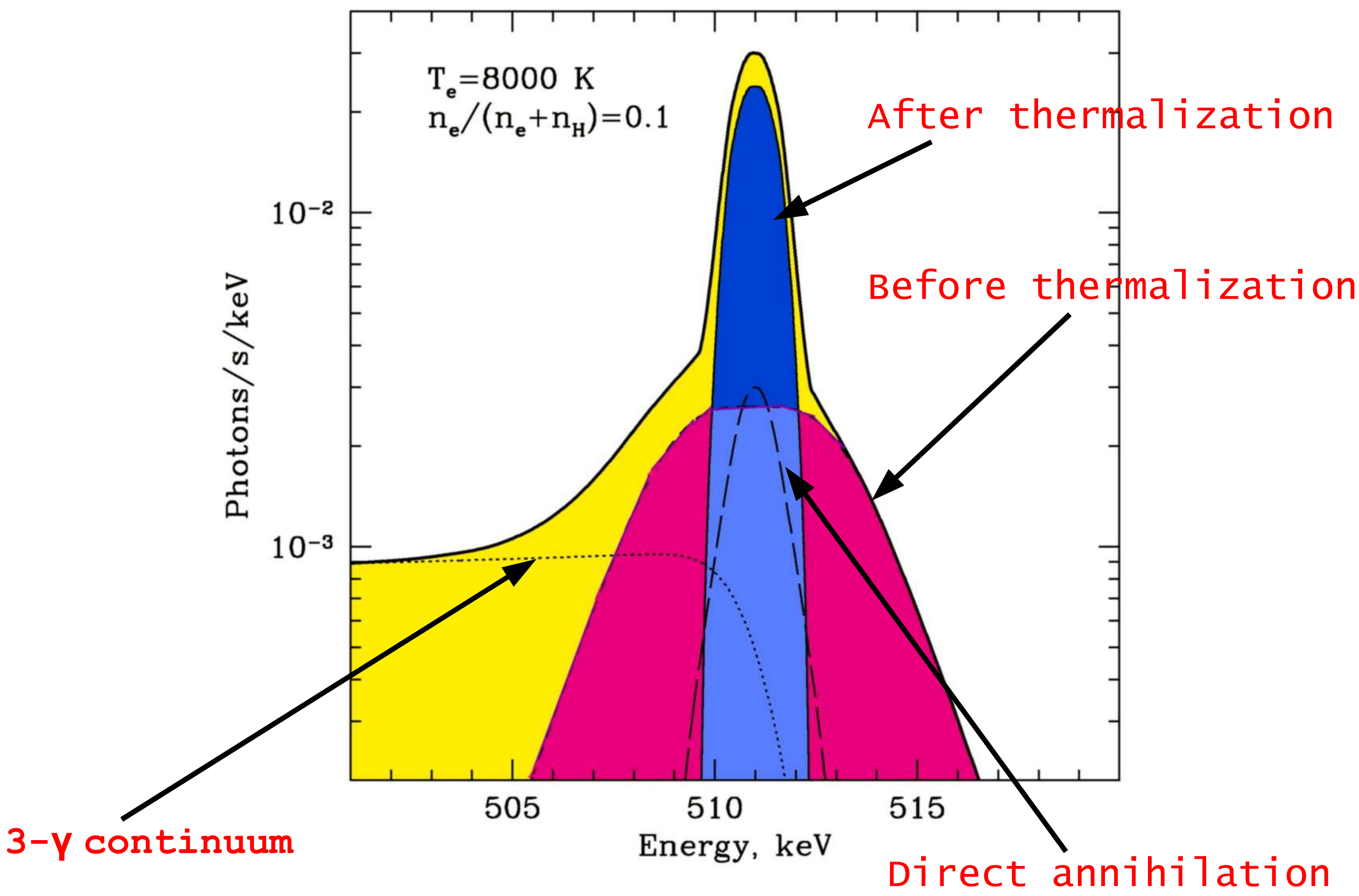


10^{-7} s

$$\frac{F_{3\gamma}}{F_{2\gamma}} = \frac{\frac{3}{4} \times 3}{\frac{1}{4} \times 2} = 4.5$$

$$\text{Deviations from 4.5} \rightarrow \frac{\text{Direct annihilation}}{\text{CE+RR}}$$


Energy
1 МэВ
100 эВ
6.8 эВ
0
Time
Hot
Warm
Cold
FWHM ~5-6 keV
$\frac{3}{2} k T$
~0 keV
~1.7 keV



T_e=8000 K
$n_e/(n_e+n_H)$=0.1
After thermalization
Before thermalization
Photons/s/keV
10^{-2}
10^{-3}
505
510
515
Energy, keV
3-γ continuum
Direct annihilation

$$E = 510.988\,\mathrm{keV} \Rightarrow \frac{E}{m_e c^2} = 0.99998 \pm 7 \times 10^{-5}$$

Bulk velocity < 20-40 km/s (Earth motion!)

$$\mathrm{FWHM} = 2.47 \pm 0.11\,\mathrm{keV}$$

Differential velocity < 800 km/s

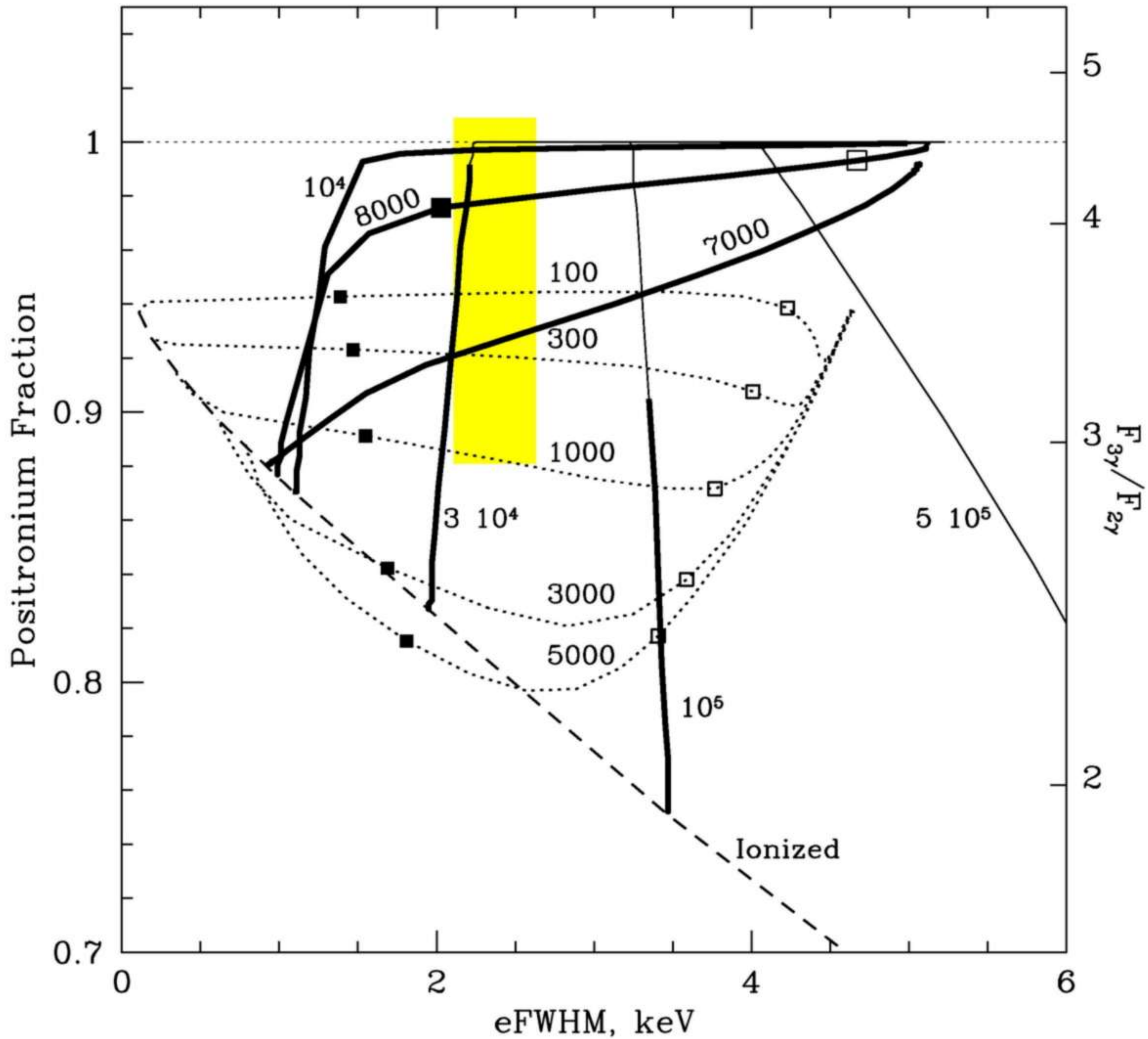
$$F_{PS} = 0.94 \pm 0.06 \Rightarrow \textbf{Positronium dominates}$$

Churazov et al. 2005

Parameters of GC positron annihilation spectrum

Instrument	Line energy (keV)	FWHM[a] (keV)	Positronium fraction	References
GRIS	–	2.5±0.4	–	Leventhal et al. 1993
HEAO-3	510.92 ± 0.23	1.6±1.35	–	Mahoney et al. 1994
HEXAGONE	511.53 ± 0.34	2.73±0.75	–	Durouchoux et al. 1993
OSSE	–	–	0.93±0.04	Kinzer et al. (2001)
TGRS	510.98 ± 0.1	1.81±0.54	0.94±0.04	Harris et al. (1998)
SPI/INTEGRAL	511.06 ± 0.18	2.95±0.5	–	Jean et al. (2003)
SPI/INTEGRAL	510.954 ± 0.075	2.37±0.25	0.94±0.06	this work

Churazov et al. 2005



Standard ISM phases

Phase	T_e K	n, cm^{-3}	χ	T_s, years	T_a, years
Cold	80	30	0	10^3	10^4
WN	8000	0.3	0.1	10^5	7×10^4
WI	8000	0.3	0.5	10^5	7×10^4
Hot	8×10^5	0.003	1	10^7	3×10^8

$\mathrm{FWHM} + F_{PS} \Rightarrow$

WN – OK

Cold+WN+WI – OK

Hot < 10 %

Total rate and Supernovae

$$\textbf{Flux:} (0.7 \div 1.5) \times 10^{-3} \,\text{phot/s/cm}^2 \Rightarrow$$

$$(1 \div 2) \times 10^{43} \,\text{annihilations/s}$$

$$\text{Luminosity: a few } 10^{37} \,\text{erg/s}$$

$$^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe} \quad \tau = 6.1\text{d, } 78.8\text{ d} \quad 18\% \,\beta^+$$

$$^{44}\text{Ti} \rightarrow {}^{44}\text{Sc} \rightarrow {}^{44}\text{Ca} \quad \tau = 62\text{ yr, } 4\text{ yr} \quad 95\% \,\beta^+$$

$$^{26}\text{Al} \rightarrow {}^{26}\text{Mg} \quad \tau = 7.2 \times 10^5\text{ yr} \quad 82\% \,\beta^+$$

Clayton et al., 70's

Supernovae

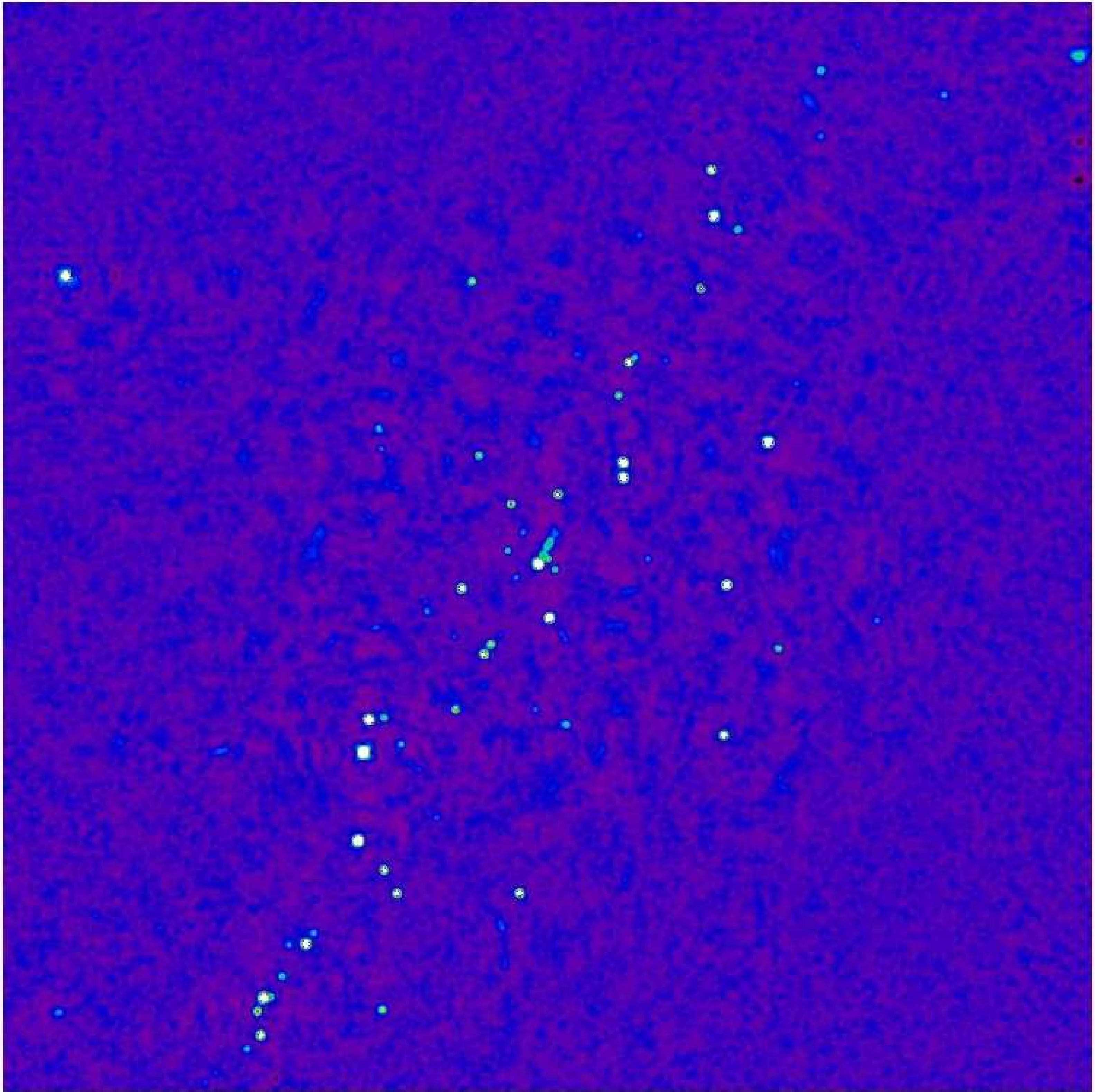
Table 2: **TABLE 2.** Galactic positron production rates from SNe. Italicized values denote prefered values from a range.

SN Type (1)	SN Rate[a] (2)	Isotope (3)	Isotopic Yield ($M_\odot$) (4)	Delayed Ann. Frac. (5)	Positron Yield [per SN][b] (6)	Positron Yield [per s][c] (7)
Ia	0.4±0.1					
		^{56}Ni	*0.5*(0.2-0.8)	0.001-0.11	*8*(1-20)[d]	*1.0*(0.8-1.3)
		^{44}Ti	(*0.2*-12) x 10^{-4}	0.99	0.04-3.8	*0.01*-0.49
		^{26}Al	10^{-6}	1.00	4 x 10^{-3}	4 x 10^{-4}
Ib	$0.3^{+0.5}_{-0.1}$					
		^{56}Ni	0.18±0.10	0.0	0.00	0.00
		^{44}Ti	(*6*-22) x 10^{-5}	0.85-*0.99*	0.1-0.4	*0.01*-0.29
		^{26}Al	*0.8*(0.3-20) x 10^{-4}	1.00	0.01-0.91	*0.03*(0.00-0.23)
II	$3.1^{+0.7}_{-1.9}$					
		^{56}Ni	0.08-0.28	0.0	0.00	0.00
		^{44}Ti	(*3*-22) x 10^{-5}	0.34-*0.99*	0.03-0.62	*0.21*(0.01-0.79)
		^{26}Al	*0.8*(0.3-20) x 10^{-4}	1.00	0.01-0.91	*0.30*(0.00-1.11)

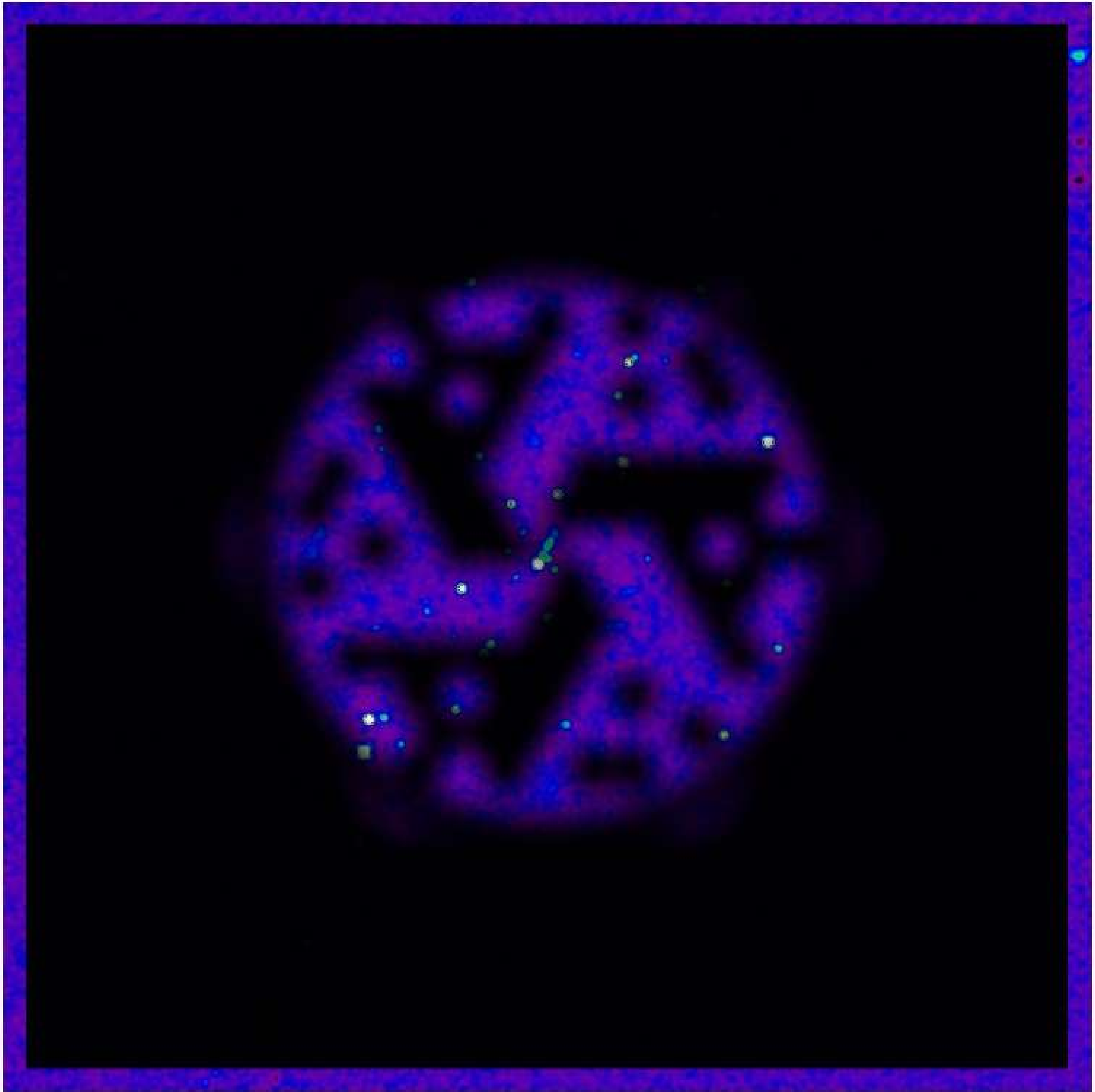
[a] The SN rate is in units of SNe per century.
[b] The yields per SN are in units of 10^{52} positrons SN^{-1}.
[c] The yields per second are in units of 10^{43} positrons s^{-1}.
[d] The SN Ia yield per SN is the from Milne et al. (1999), rather than the product of SN Ia parameters.

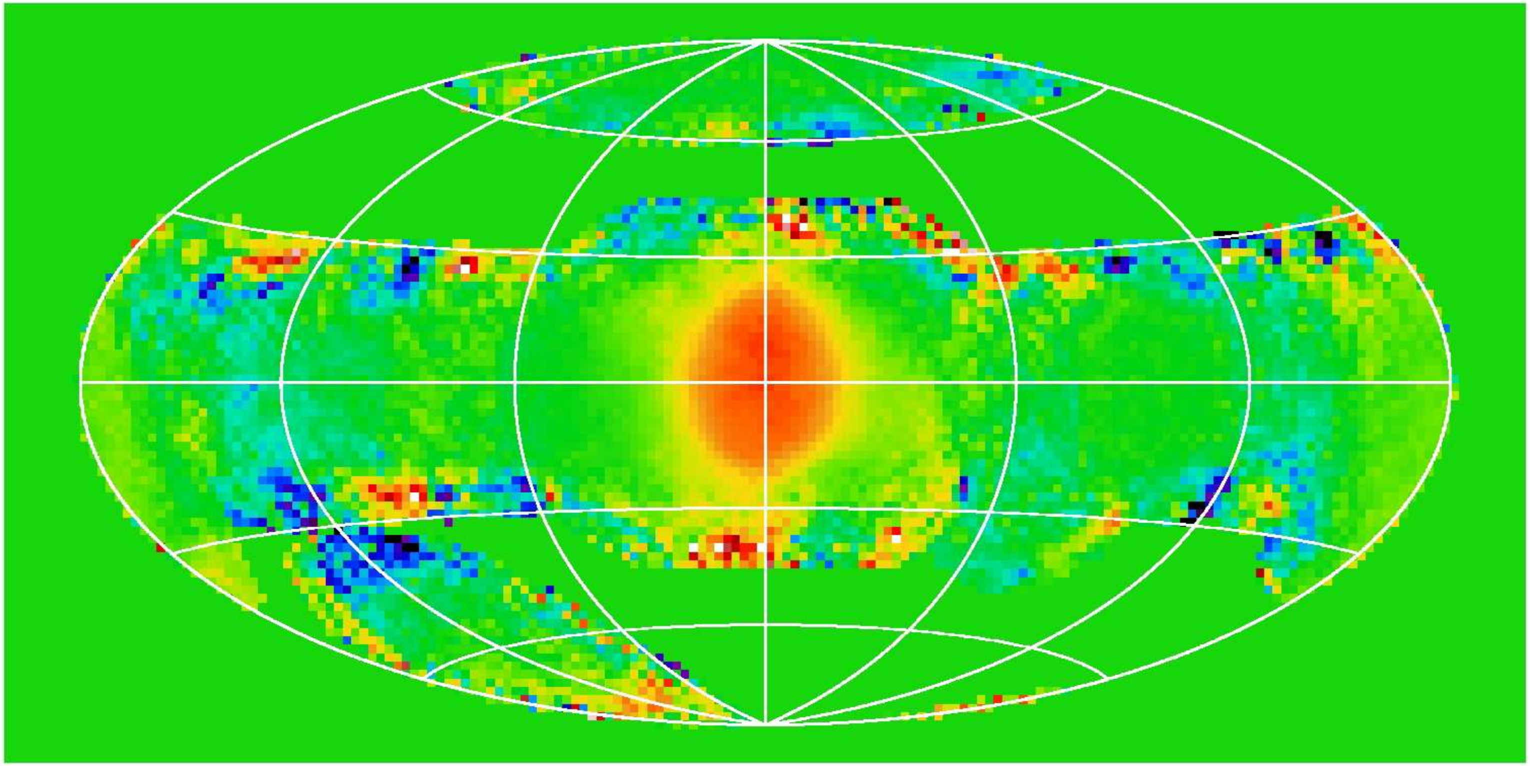
Milne, Leising, The 1999

IBIS/ ISGRI

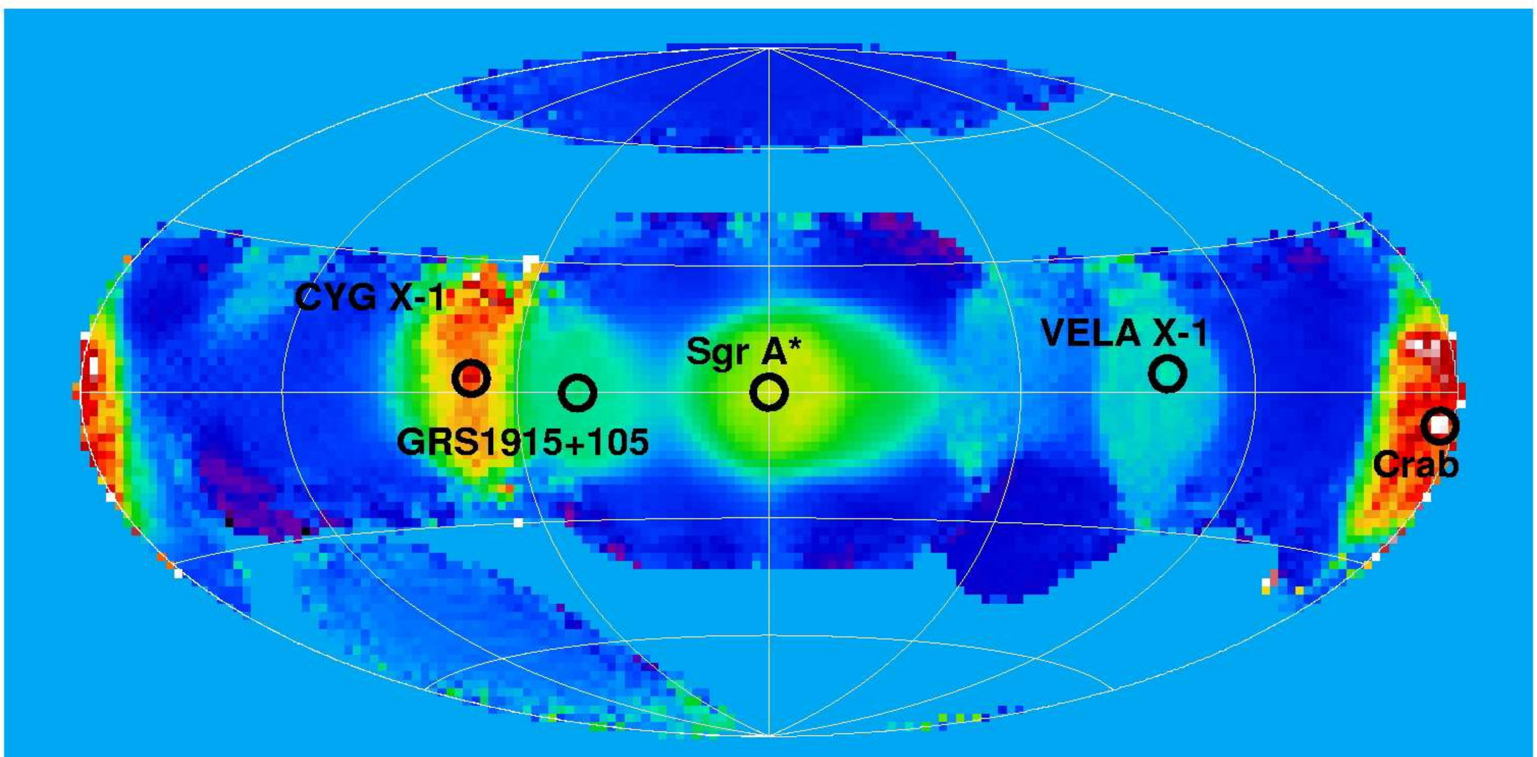


SPI



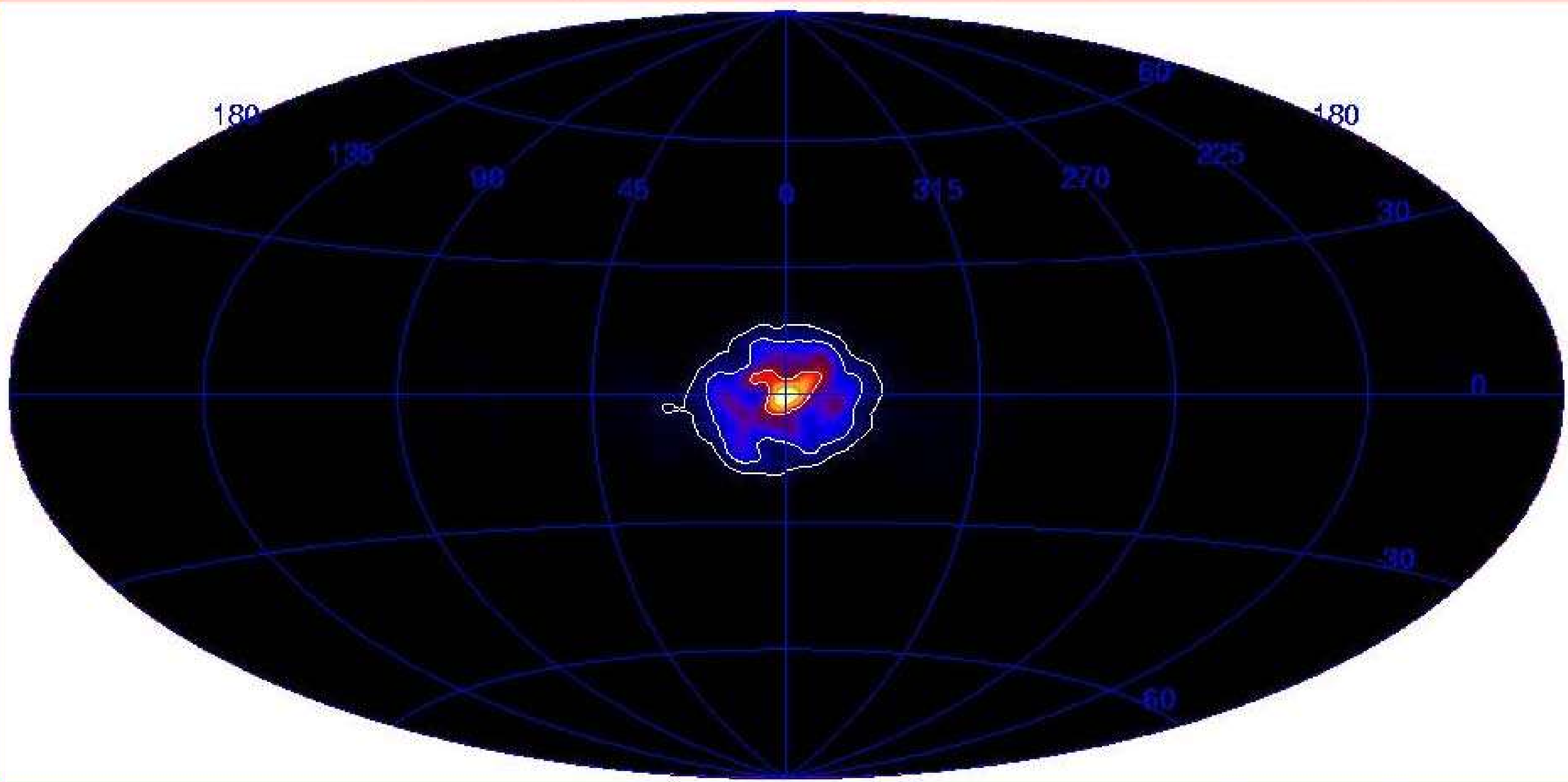


511 keV



50 keV

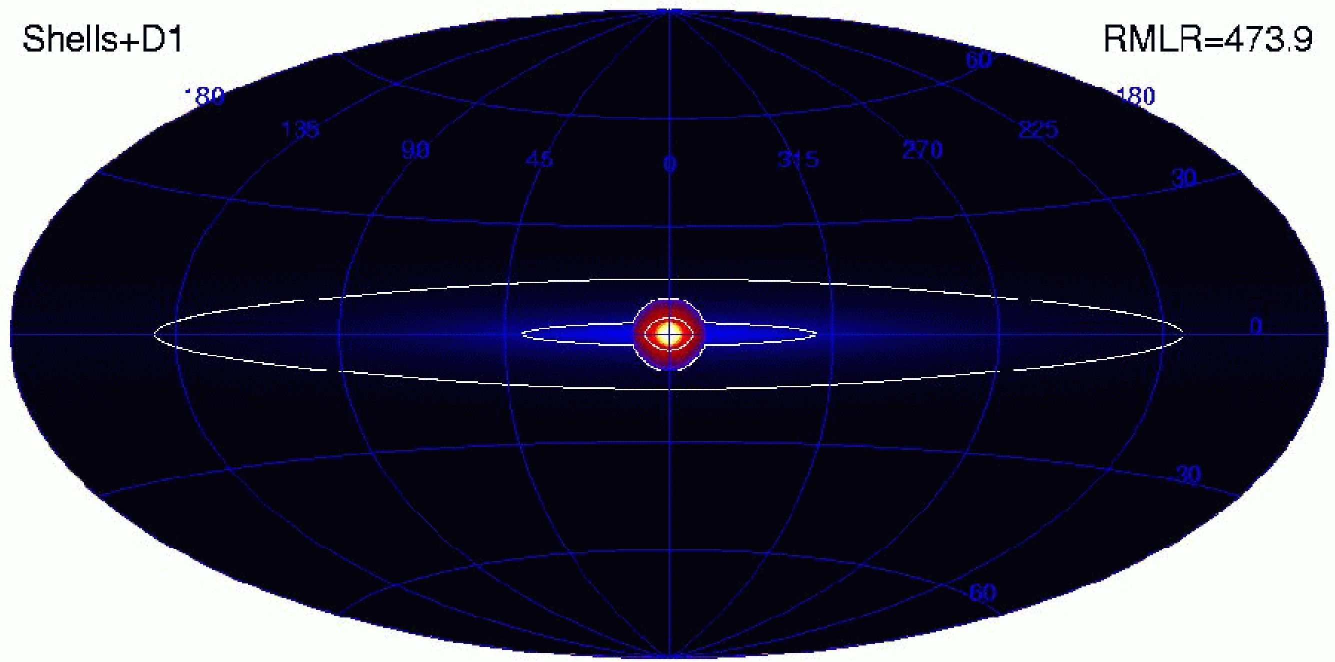
An all-sky image of 511 keV emission

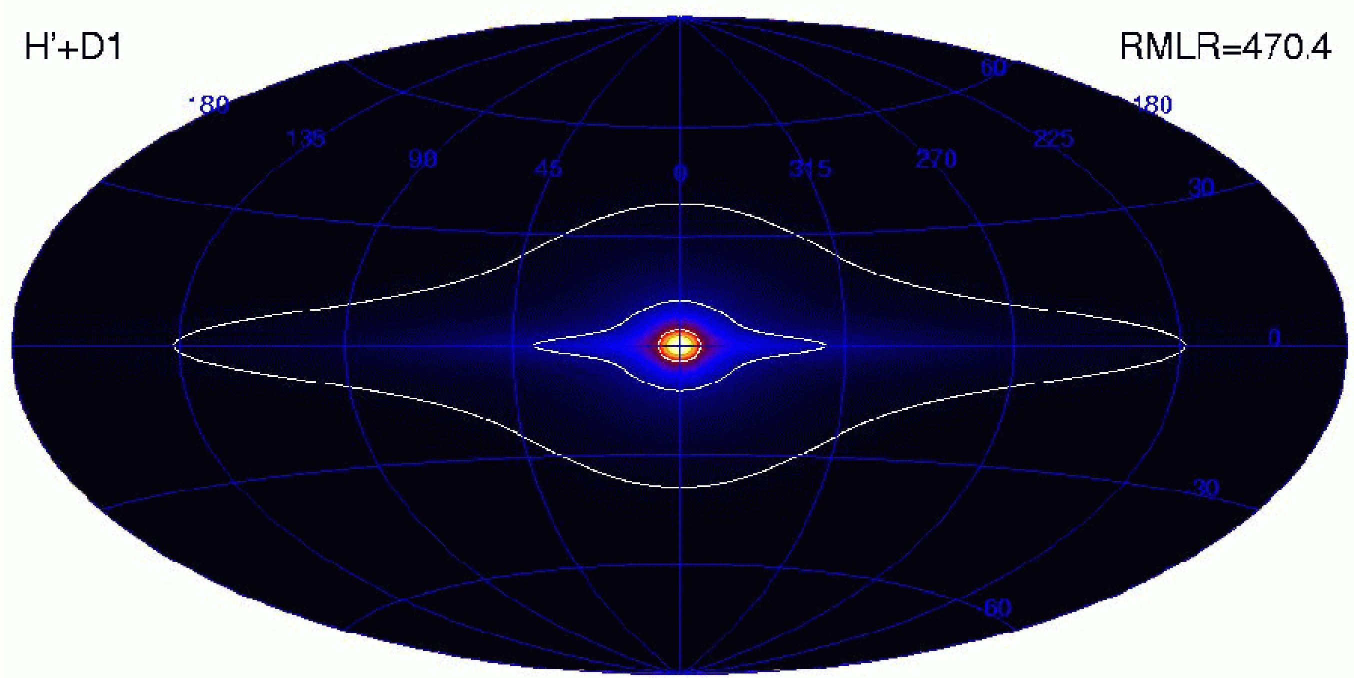


- Iteration 17 of accelerated Richardson-Lucy algorithm
- 5° x 5° boxcar smoothing
- Integrated 511 keV flux : 1.4×10^{-3} ph cm^{-2} s^{-1}

Knoedlseder et al. 2005

511 keV imaging





Knoedlseder et al. 2005

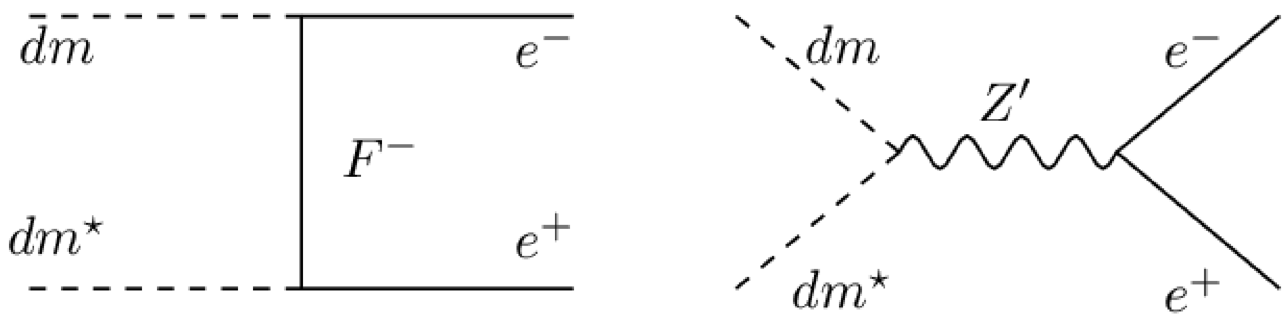
Results of 511 keV imaging

- Emission concentrated to the bulge
- Not a point source at Sgr A* or a few discrete sources
- Bulge/disk (luminosity) ratio ~3-9 (model dependent)
- Size of the central bulge 6-10 degrees
- Disk emission (if any) can be explained by decay of ^{26}Al (young stellar population)

Knoedlseder et al. 2005

MeV dark matter: has it been detected?

DM annihilation



For 511 keV line, light (1-100 MeV) DM particles needed
Heavier DM particles (GeV-TeV range) favored by theorists

SPI observations imply that our DM halo profile is cuspy
Slope ~ 1, consistent with N-body simulations/observations
DM decay requires an even steeper profile – unlikely

Ascasibar et al. 2005

Conclusions from INTEGRAL/SPI observations

- Precise line parameters ($v<30$ km/s, Δv <800 km/s)
- Annihilation medium: Warm slightly ionized medium – OK

  Neither pure Cold nor Hot (<8%)
- ~10^{43} positrons/s, L~10^{37} erg/s => L_i~γ 10^{37} erg/s
- Flux confined to bulge, disk is weak
- Either >7 discrete positron sources, or truly diffuse
- DM scenario is viable, as well as others (SN Ia, LMXB...)

What next with INTEGRAL/SPI?

- Improved constraints on morphology (bulge, disk ...)
- Improved parameters of annihilation spectrum
- Spectro-Imaging
- Tighter upper limits/detections for individual Galactic sources and nearby galaxies

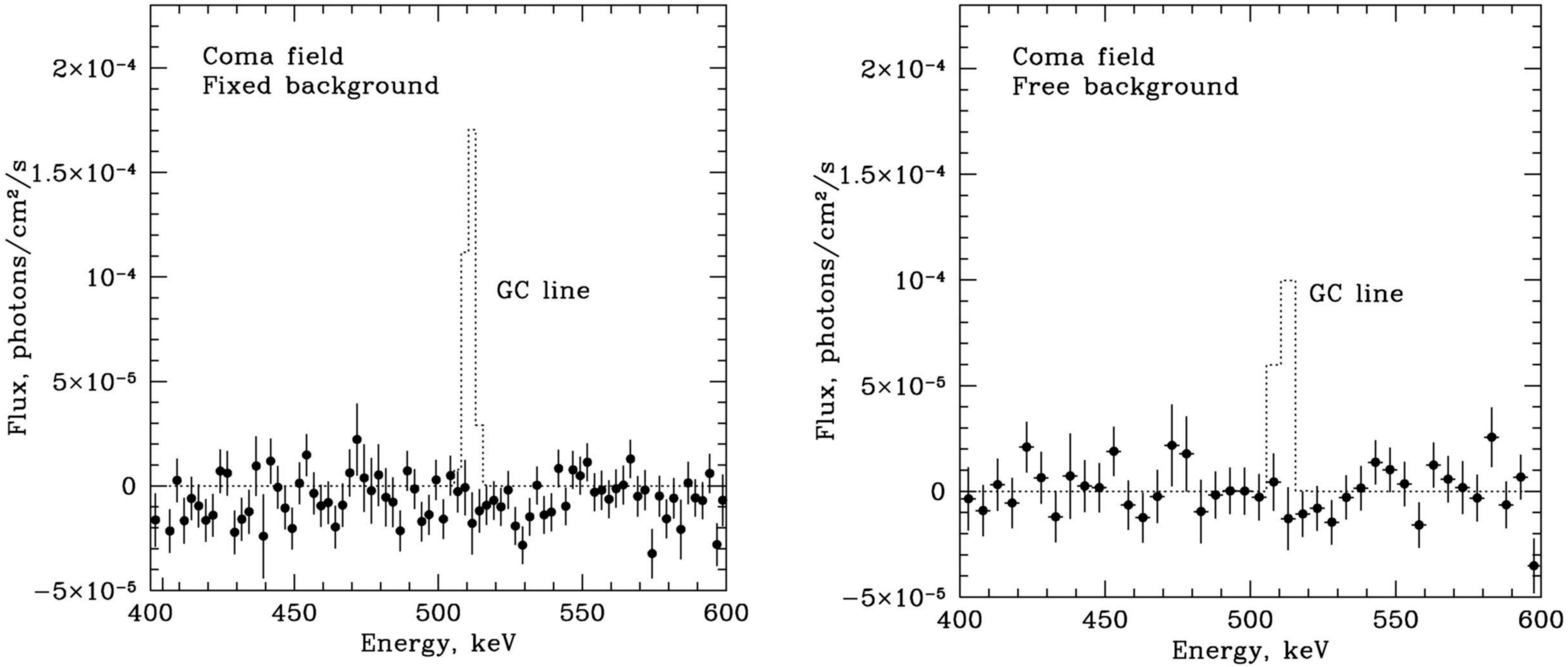
This will further narrow possibilities for positron sources and annihilation media

Future progress (after INTEGRAL) may be connected with:

- Significantly reduced background (e.g. by flying in near-Earth orbit). Currently B/S~50 at best for SPI

- A focusing gamma-ray telescope – ideal for studying annihilation emission from individual sources

Verifying the background subtraction procedure



Fixed background:

Energy	510.988	±	0.035	keV
FWHM	2.47	±	0.11	keV

Free background:

Energy	510.954	±	0.075	keV
FWHM	2.37	±	0.25	keV

$$m_e c^2 = 510.999\,\mathrm{keV}$$

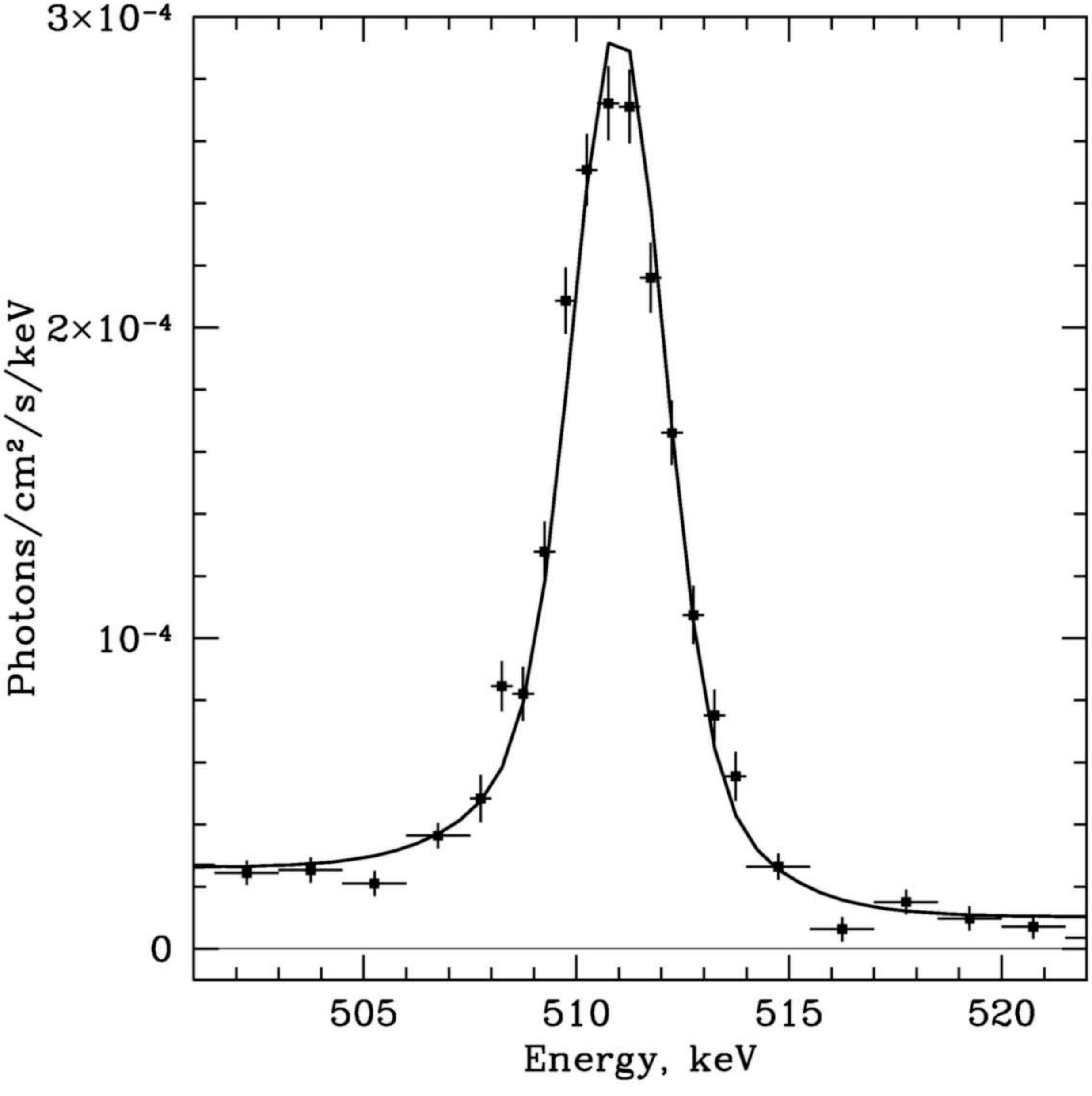
Bulk velocity < 20-40 km/s (Earth motion!)

Differential velocity < 500-1000 km/s

$F_{PS} = \mathbf{0.94 \pm 0.06} \Rightarrow$ **Positronium dominates**

$\mathbf{FWHM} + F_{PS} \Rightarrow$

Single phase: 8000 K, 10% HII
Or multi-phase, excluding hot phase



3×10⁻⁴
2×10⁻⁴
10⁻⁴
0
505
510
515
520
Energy, keV
Photons/cm²/s/keV

$$\text{Flux: } 10^{-3}\ \text{phot/s/cm}^2 \Rightarrow 2\times 10^{43}\ \text{annihilations/s}$$

$$E = 510.988\ \text{keV} \Rightarrow \frac{E}{m_e c^2} = 0.99998 \pm 7\times 10^{-5}$$

Bulk velocity < 20-40 km/s (Earth motion!)

$$\text{FWHM} = 2.47 \pm 0.11\ \text{keV}$$

Differential velocity < 800 km/s

$$F_{PS} = 0.94 \pm 0.06 \Rightarrow \text{Positronium dominates}$$

$$\text{FWHM} + F_{PS} \Rightarrow$$

Single phase: 8000 K, 10% HII
Or multi-phase, excluding hot phase

Parameters of GC positron annihilation spectrum

Instrument	Line energy (keV)	FWHM[a] (keV)	Positronium fraction	References
GRIS	–	2.5±0.4	–	Leventhal et al. 1993
HEAO-3	510.92 ± 0.23	1.6±1.35	–	Mahoney et al. 1994
HEXAGONE	511.53 ± 0.34	2.73±0.75	–	Durouchoux et al. 1993
OSSE	–	–	0.93±0.04	Kinzer et al. (2001)
TGRS	510.98 ± 0.1	1.81±0.54	0.94±0.04	Harris et al. (1998)
SPI/INTEGRAL	511.06 ± 0.18	2.95±0.5	–	Jean et al. (2003)
SPI/INTEGRAL	510.954 ± 0.075	2.37±0.25	0.94±0.06	this work

Energy 510.988 ± 0.035 keV

FWHM 2.47 ± 0.11 keV