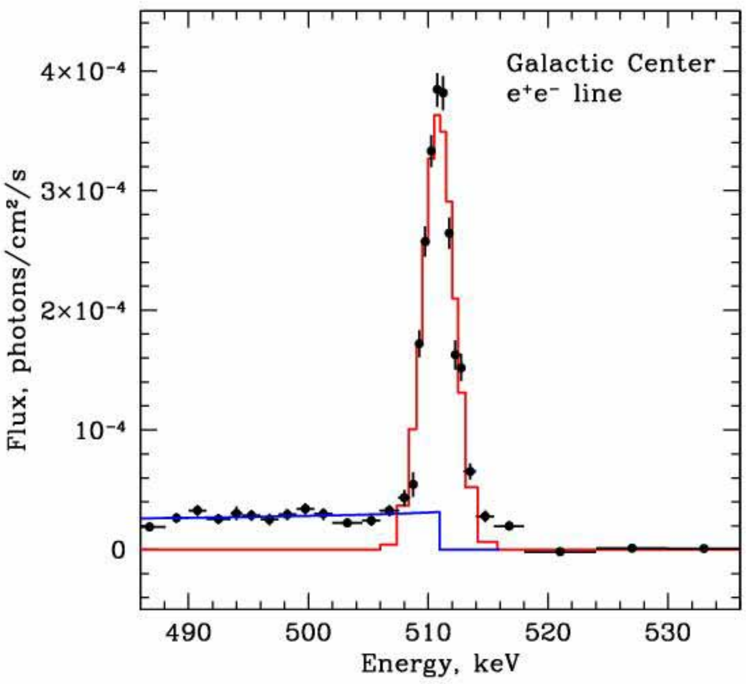
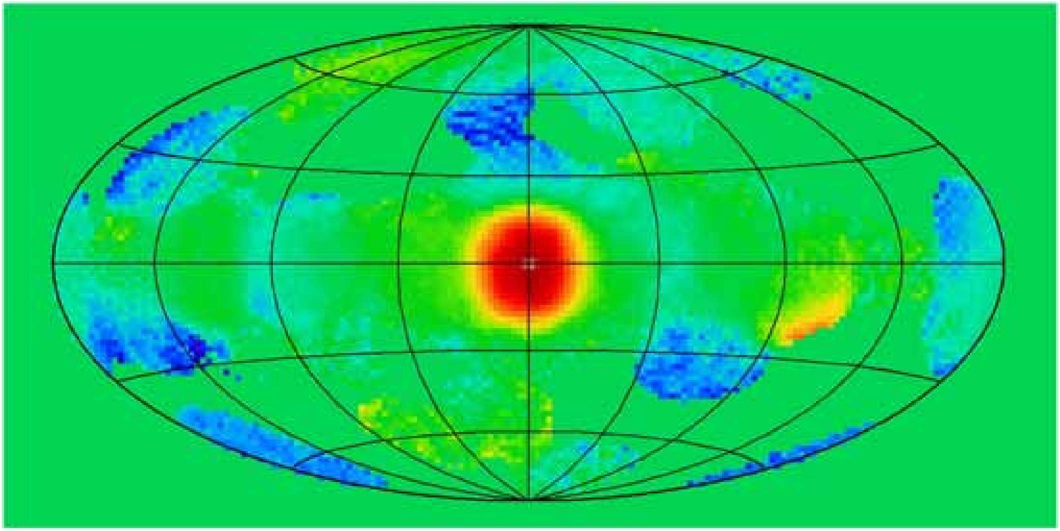
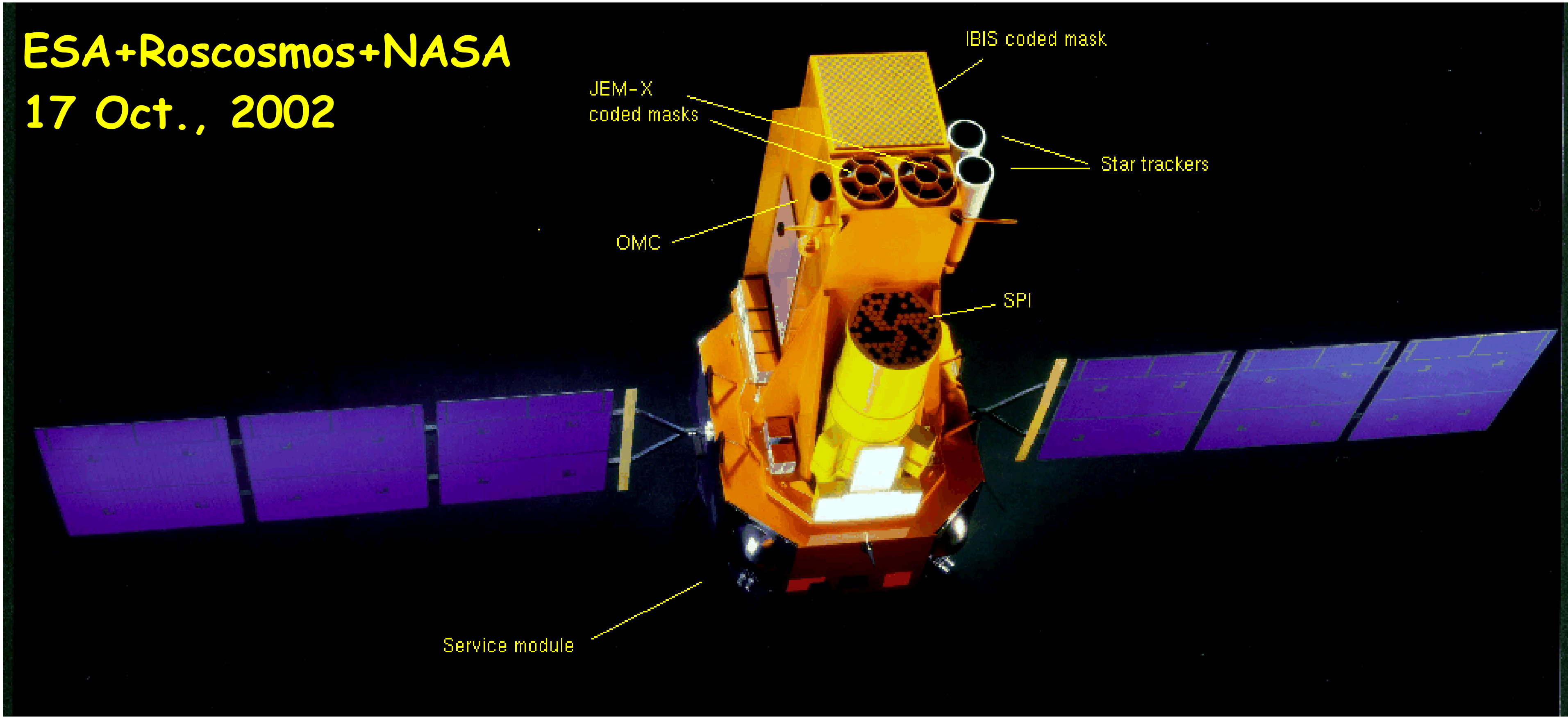
Electron-positron annihilation emission from the Galaxy

E.Churazov, R.Sunyaev, S.Sazonov, M.Revnivtsev, D.Varshalovich

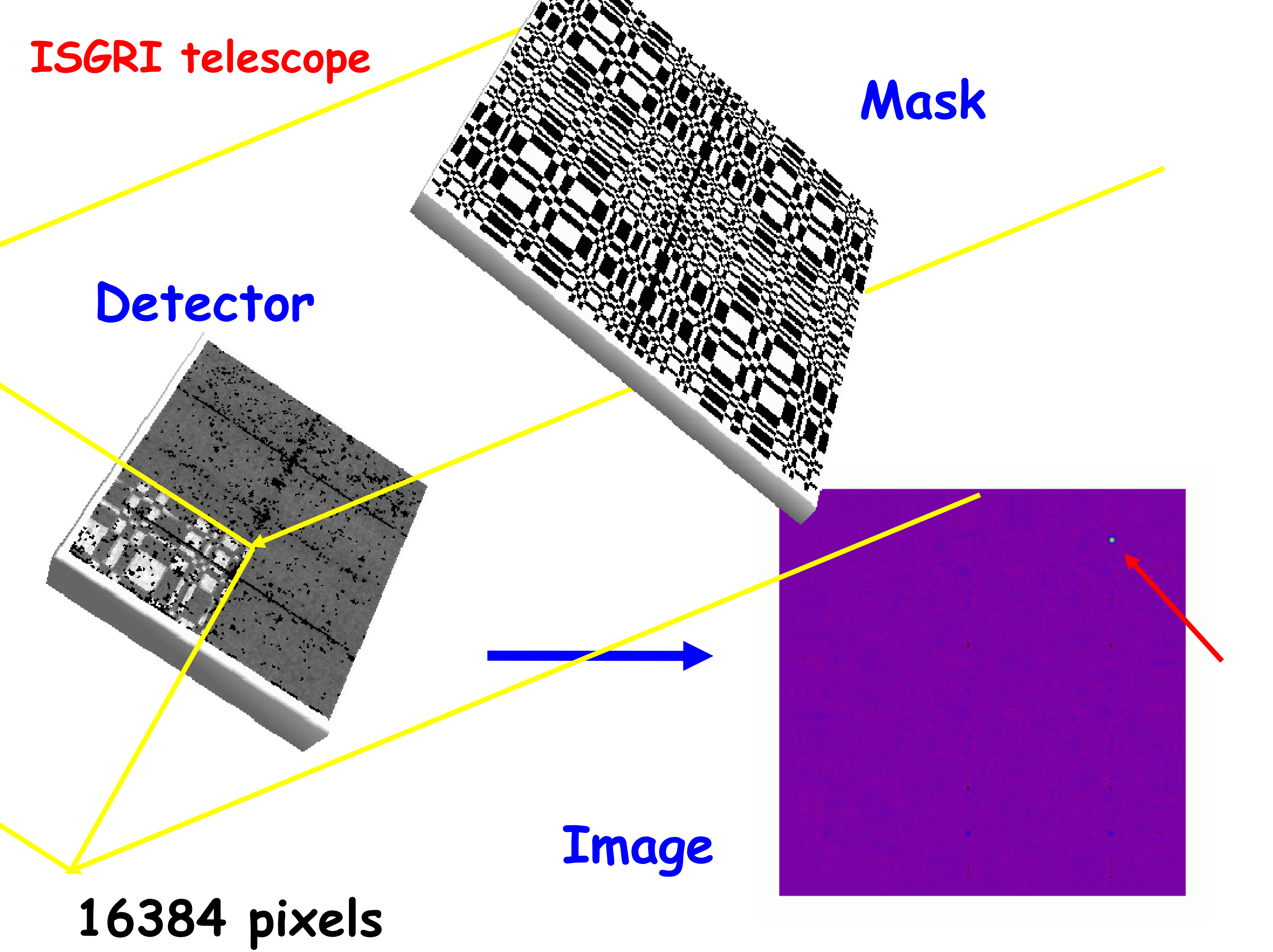




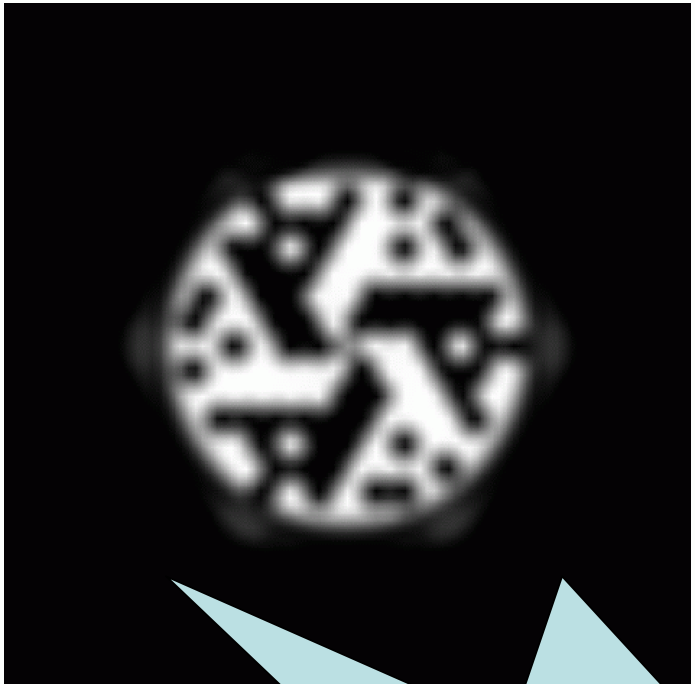
INTEGRAL Observatory

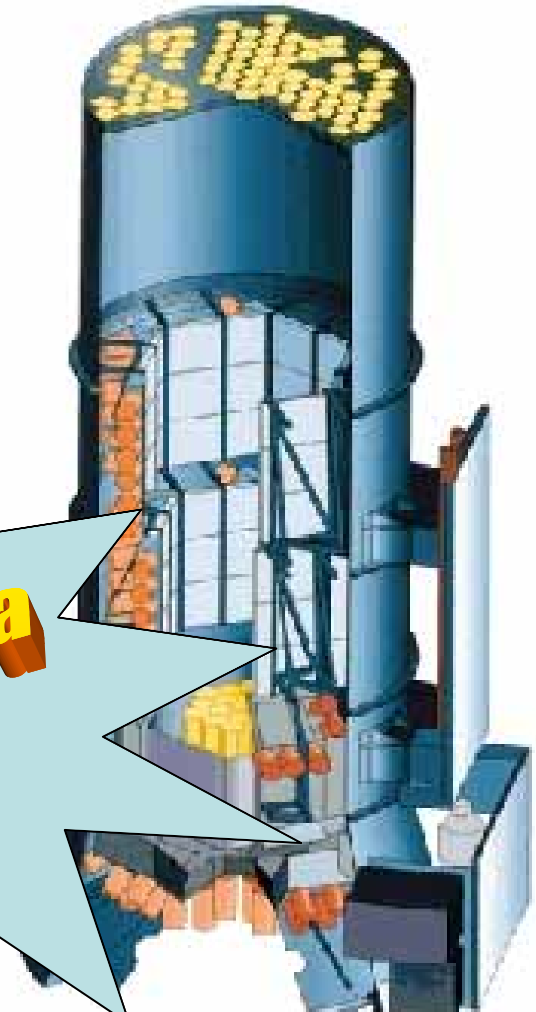


Energy range : 20 keV – 8 MeV
Angular resolution: 10'-1°
Energy resolution: E/ΔE~600 @ 1 MeV


ISGRI telescope
Mask
Detector
Image
16384 pixels

SPI





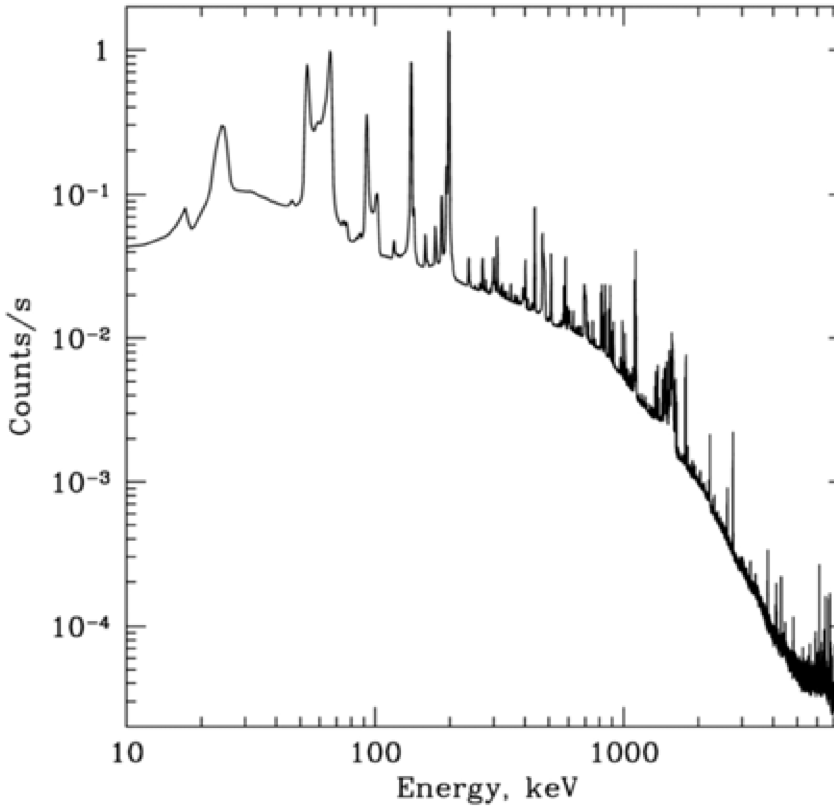
17

19 pixel camera

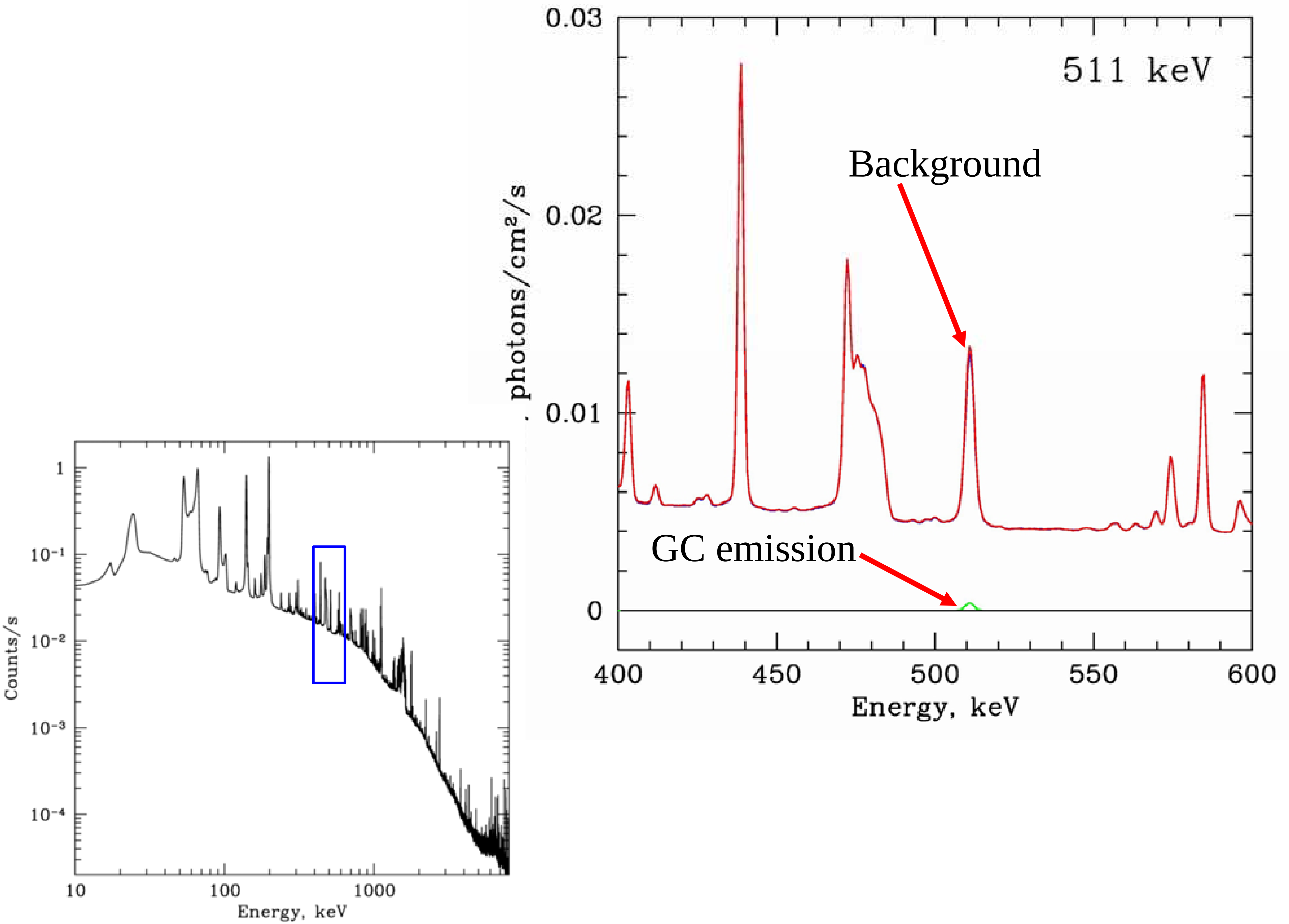
No lens

SPI

Ge, 85°



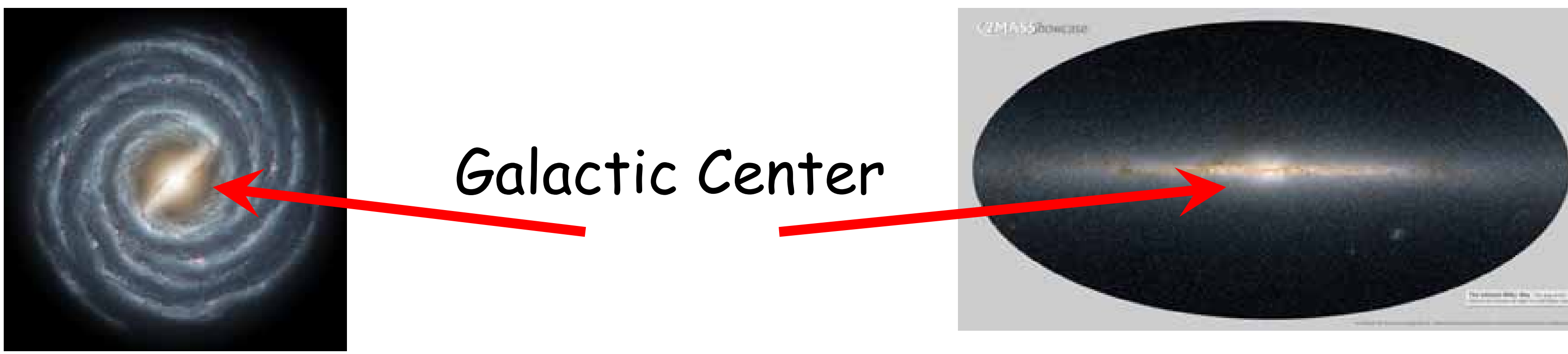
Energy resolution ~2 keV @ 511 keV



Counts/s
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10
100
1000
Energy, keV
photons/cm²/s
0.03
0.02
0.01
0
400
450
500
550
600
Energy, keV
511 keV
Background
GC emission

e^+e^- Line @ 511 keV from Galactic Center region

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



Spatial distribution is uncertain
Spectral properties are uncertain
Origin of positrons is uncertain

(Many) Potential sources of positrons:

astrophysics

Nucleosynthesis:

Massive stars (SN II, WR: e.g. ^{26}Al) ◄

Low mass stars (SNIa - ^{56}Co, Novae - ^{13}N)

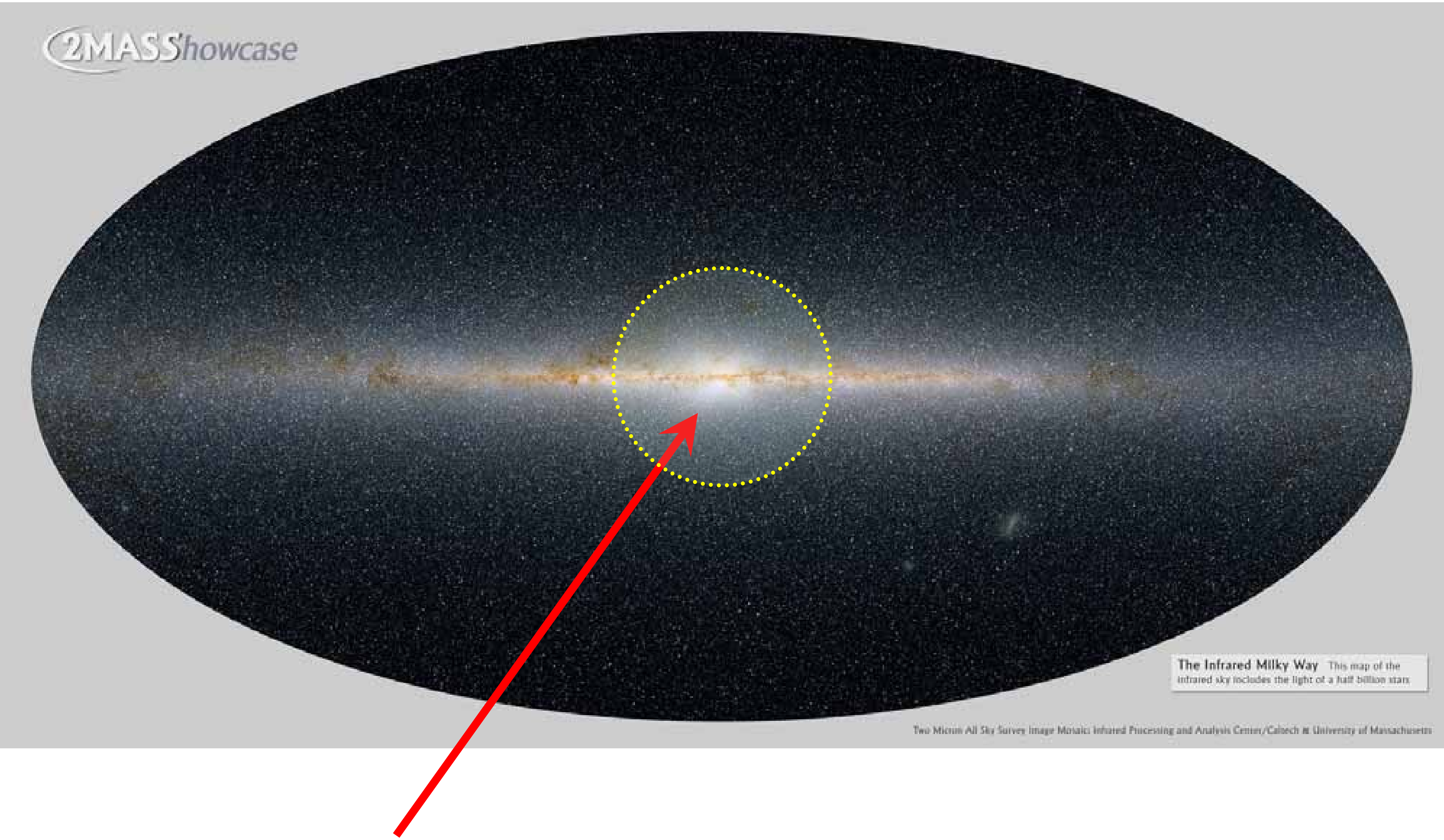
Cosmic ray protons interactions with ISM (π^+)

Microquasars (jets), pulsars

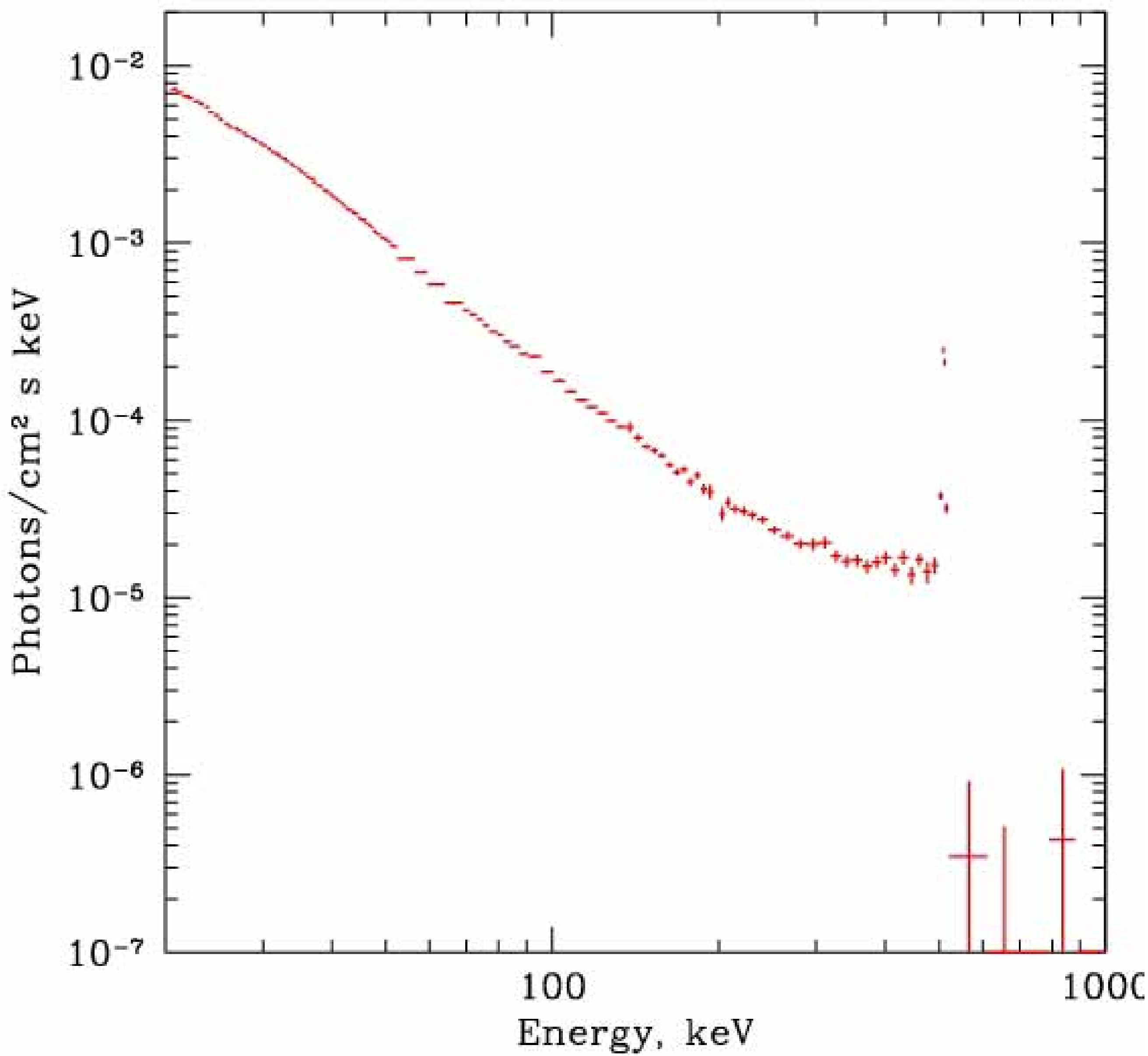
Supermassive black hole Sgr A*

(Light) Dark matter annihilation ◄

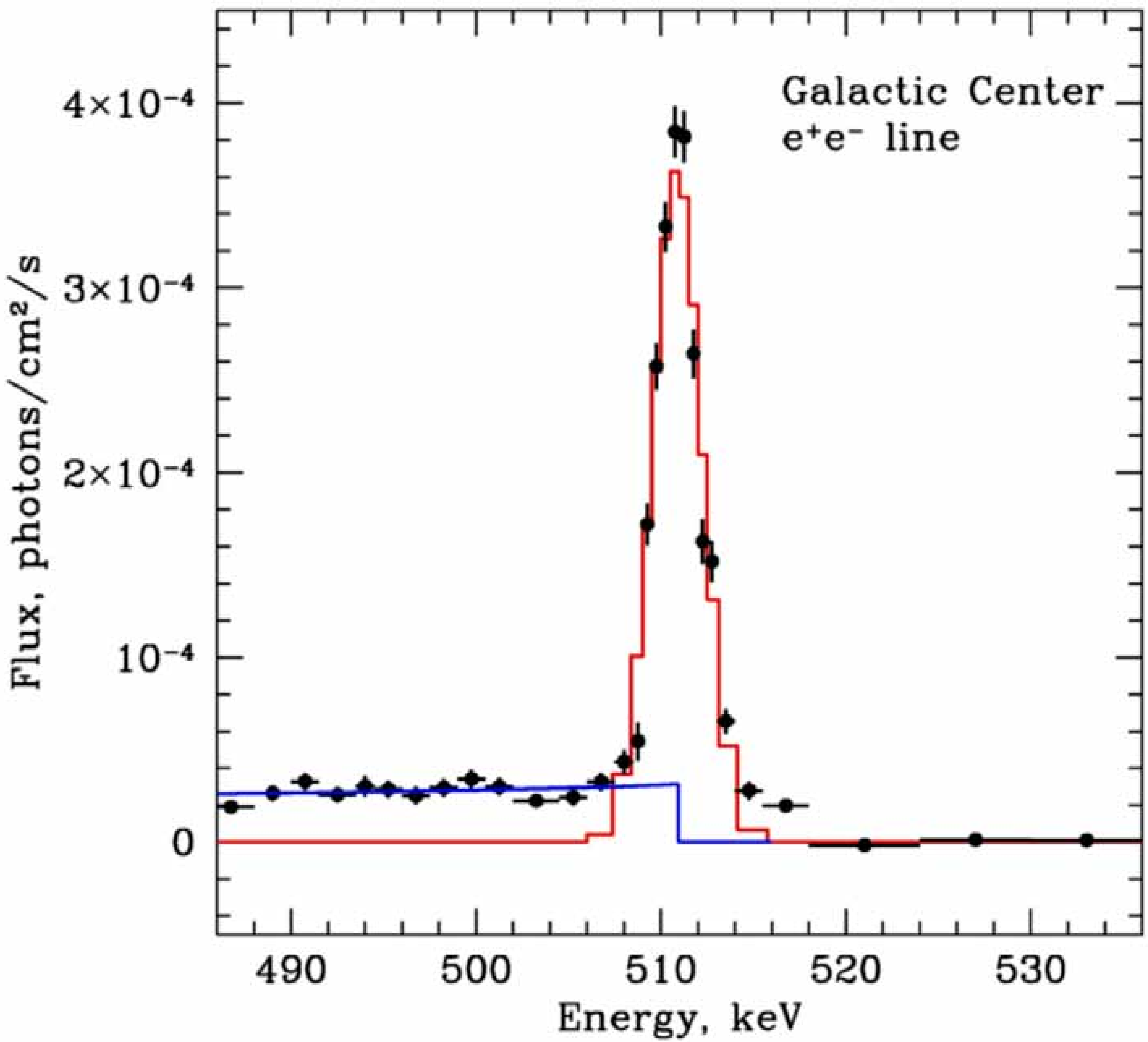
This school



Galactic Center



Photons/cm² s keV
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
100
1000
Energy, keV



Galactic Center
e⁺e⁻ line
Flux, photons/cm²/s
4×10⁻⁴
3×10⁻⁴
2×10⁻⁴
10⁻⁴
0
490
500
510
520
530
Energy, keV

$$\frac{E}{m_e c^2} = 1.00002 \pm 7\,10^{-5}$$

$$(\pm 3.5\,10^{-5})$$

Velocity < 30 km/s

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

Spread of velocities < 800 km/s =>
Positrons are cold

Total flux ~
10^{-3} phot/cm^2/s = 10^{43} β^+/s = 10^{37} erg/s

Processes in hydrogen plasma (dust free)

- Positrons born hot - at least few hundred keV
- Direct annihilation $\sigma v \approx \pi \sigma_T c$

  Bound electrons, free electrons => 2 photons
- Deceleration of positrons:

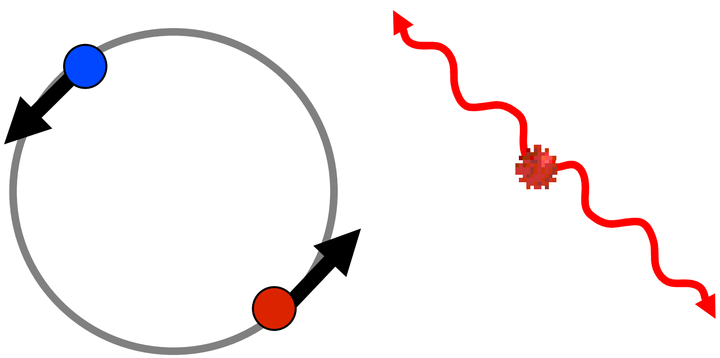
  Ionization, Excitation, Coulomb losses
- Radiative recombination (if ionized, T - low)
- Charge exchange (if neutral, E>6.8 eV)

  Positronium formation => 2 or 3 photons

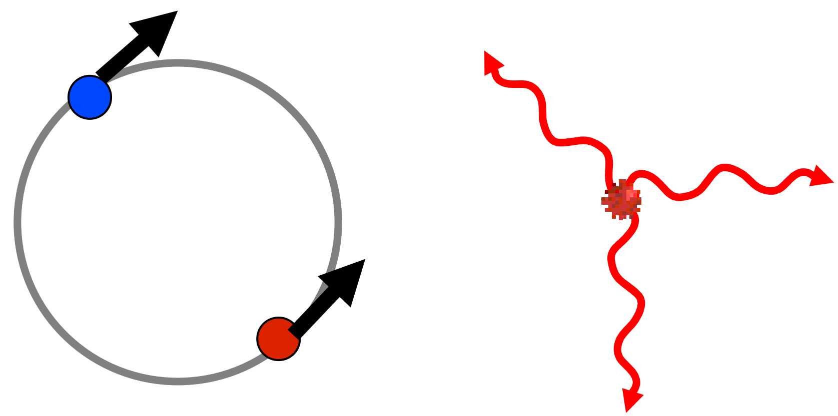
Bussard, Ramaty & Drachman 1979

$$\mathbf{DA} = 2\gamma$$

$$\mathbf{CE+RR} = \begin{cases} \textit{Para-positronium} & 0.25 & 2\gamma \\ \textit{Ortho-positronium} & 0.75 & 3\gamma \end{cases}$$



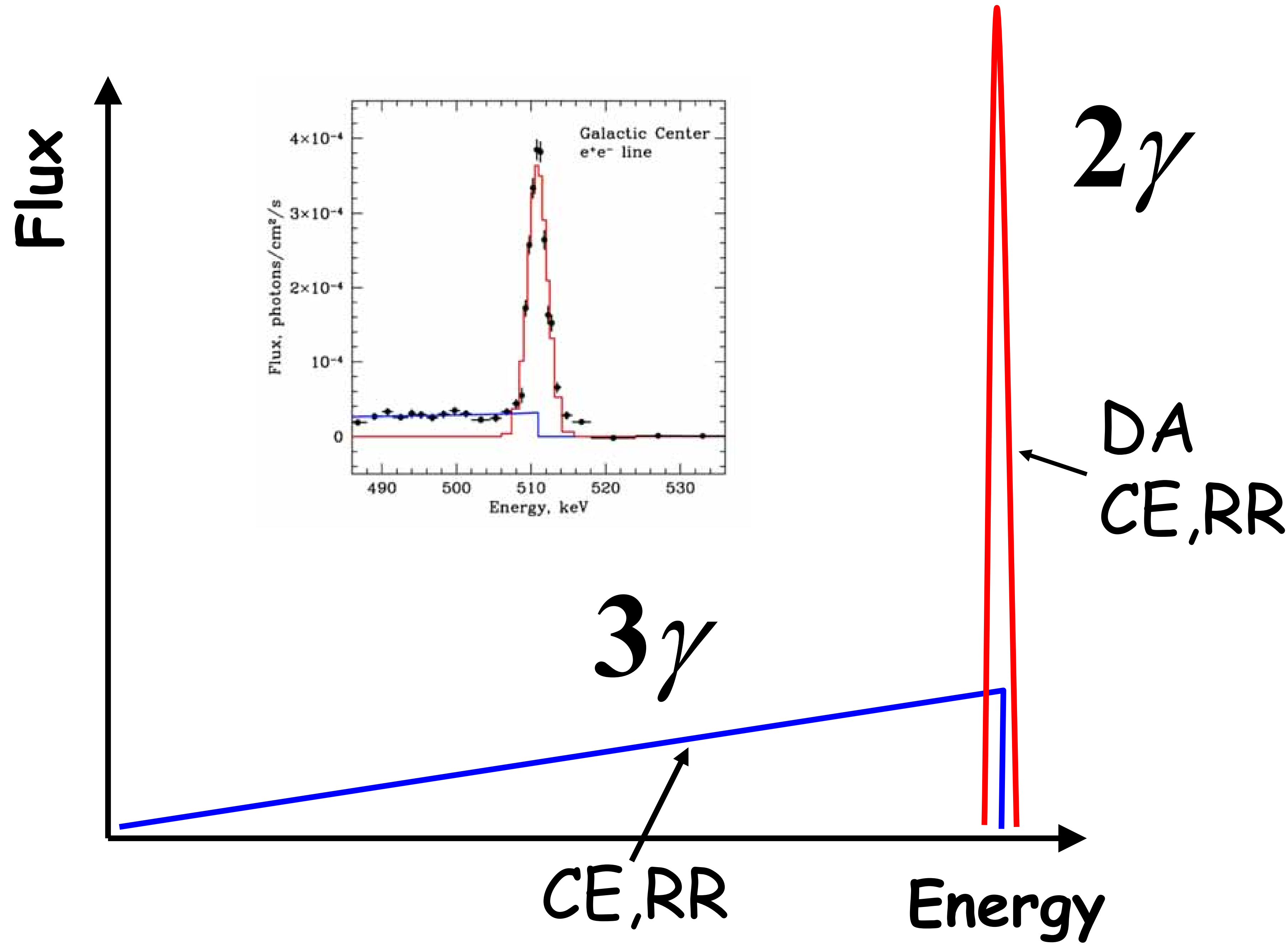
$10^{-10}\,s$ line



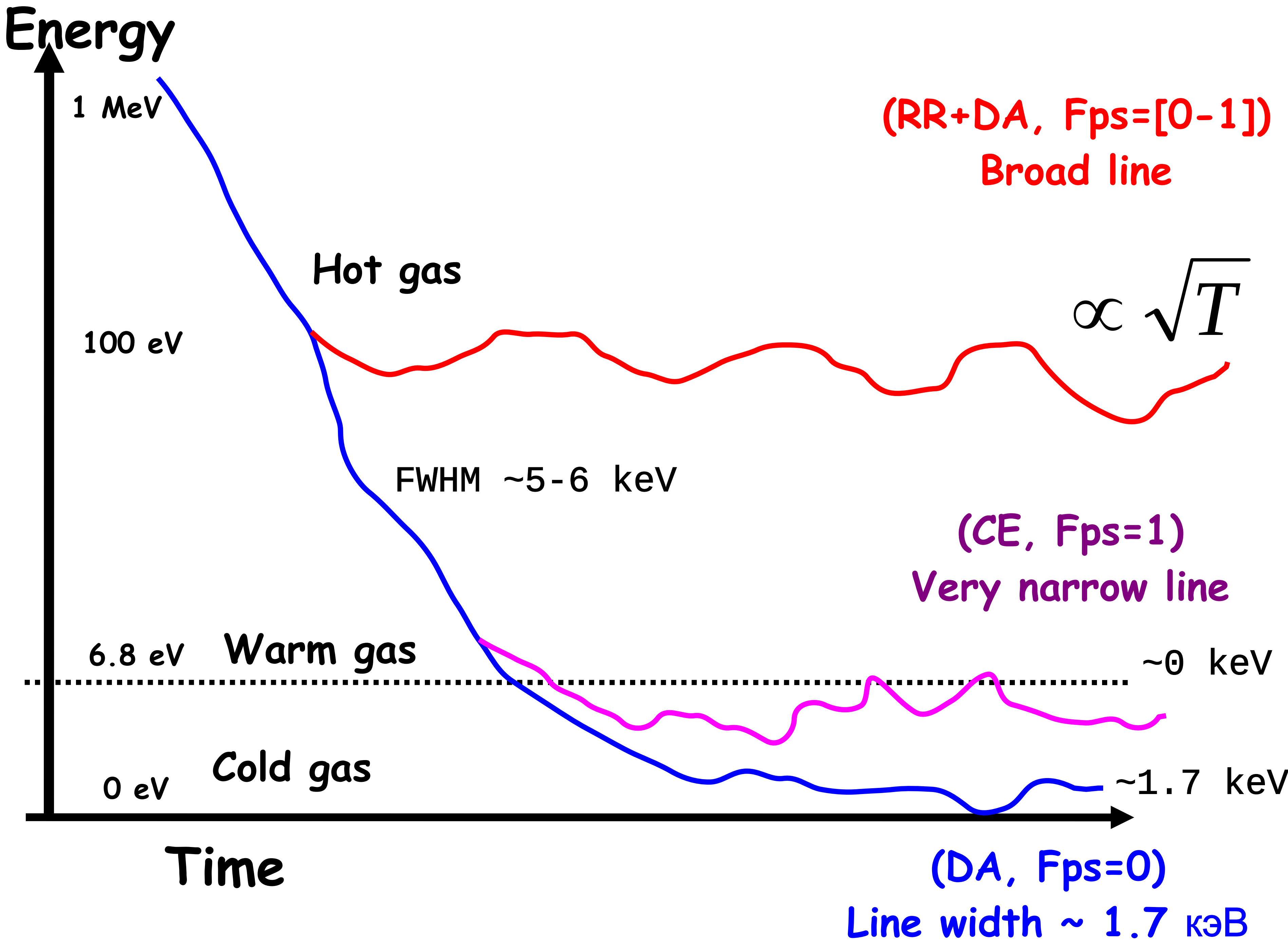
$10^{-7}\,s$ continuum

$$\frac{F_{3\gamma}}{F_{2\gamma}} = \frac{0.75\times 3}{0.25\times 2} = 4.5$$

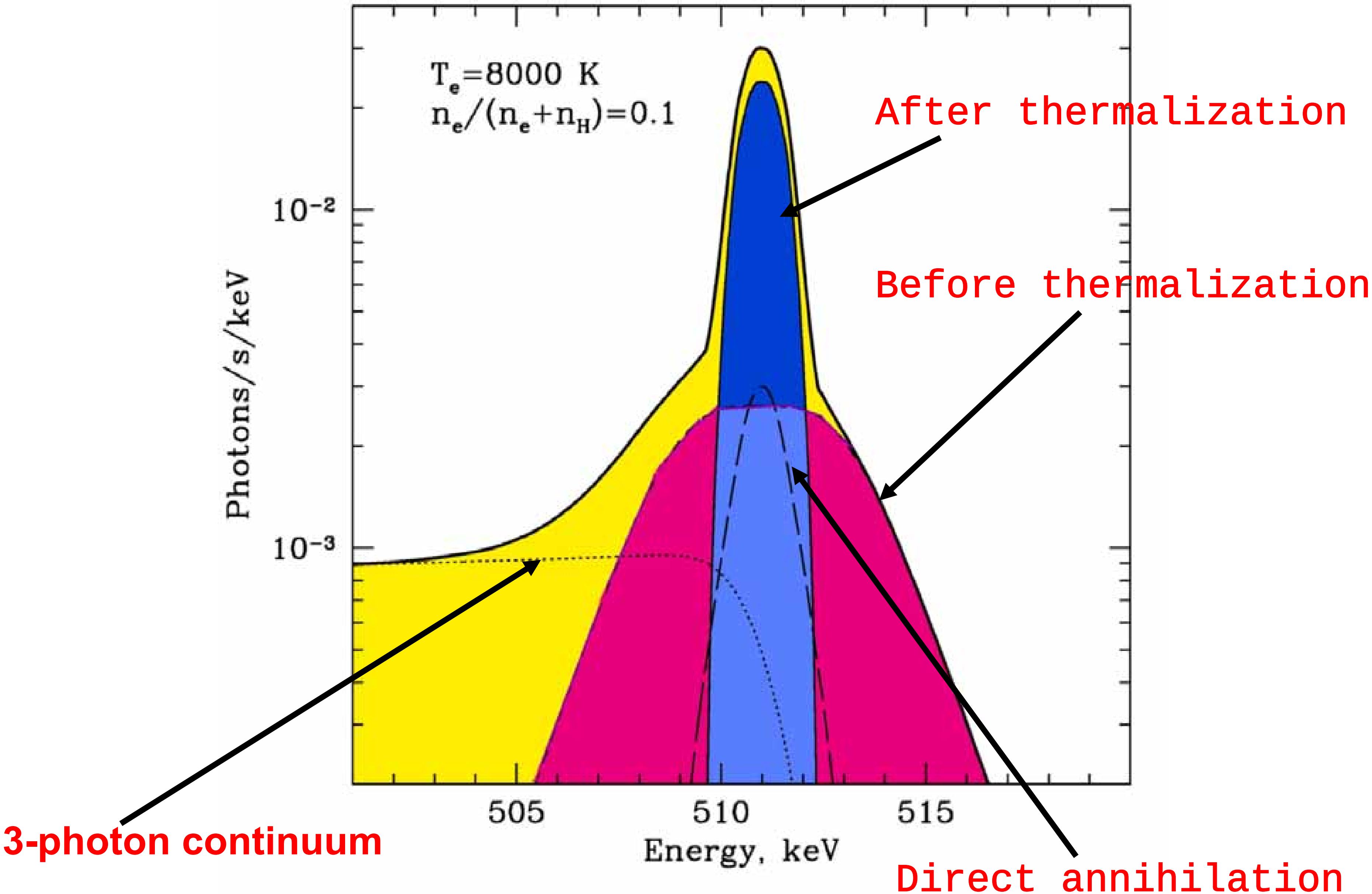
$$\frac{\mathbf{DA}}{\mathbf{CE+RR}}$$



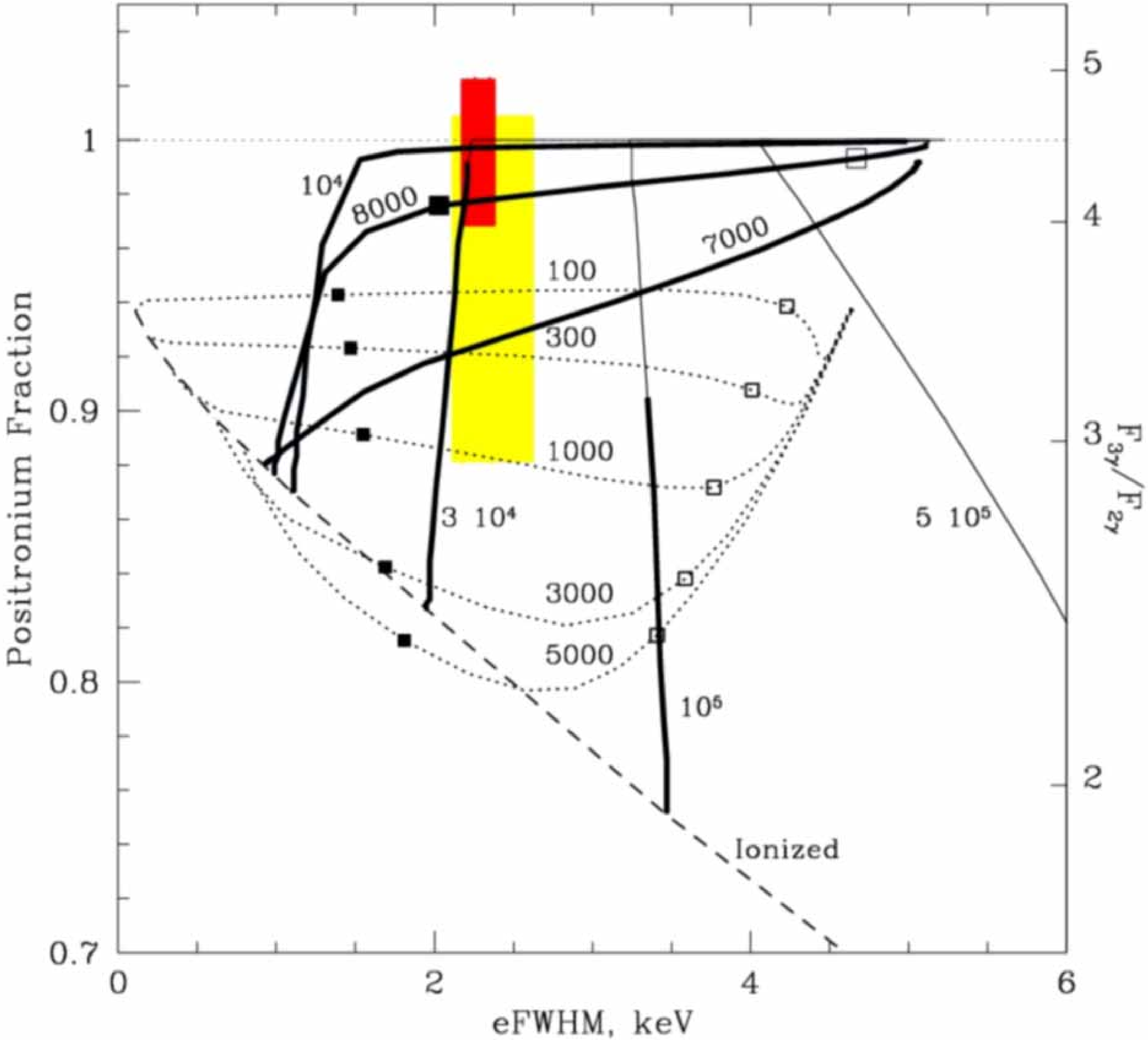
Flux
Galactic Center
e⁺e⁻ line
Flux, photons/cm²/s
4×10⁻⁴
3×10⁻⁴
2×10⁻⁴
10⁻⁴
0
490
500
510
520
530
Energy, keV
2γ
DA
CE,RR
3γ
CE,RR
Energy



Energy
1 MeV
100 eV
6.8 eV
0 eV
Time
(RR+DA, Fps=[0-1])
Broad line
$\propto \sqrt{T}$
Hot gas
FWHM ~5-6 keV
(CE, Fps=1)
Very narrow line
Warm gas
~0 keV
Cold gas
~1.7 keV
(DA, Fps=0)
Line width ~ 1.7 кэВ



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



Positronium Fraction
eFWHM, keV
$F_{3\gamma}/F_{2\gamma}$
0.7
0.8
0.9
1
0
2
4
6
2
3
4
5
10^4
8000
7000
100
300
1000
3000
5000
$3\ 10^4$
10^5
$5\ 10^5$
Ionized

Fraction of positrons forming positronium

F_{PS}=98±0.04%

F_{PS} + FWHM ➔

Annihilation in plasma with T~ 8000-10000 K
And ionization degree ~ few %

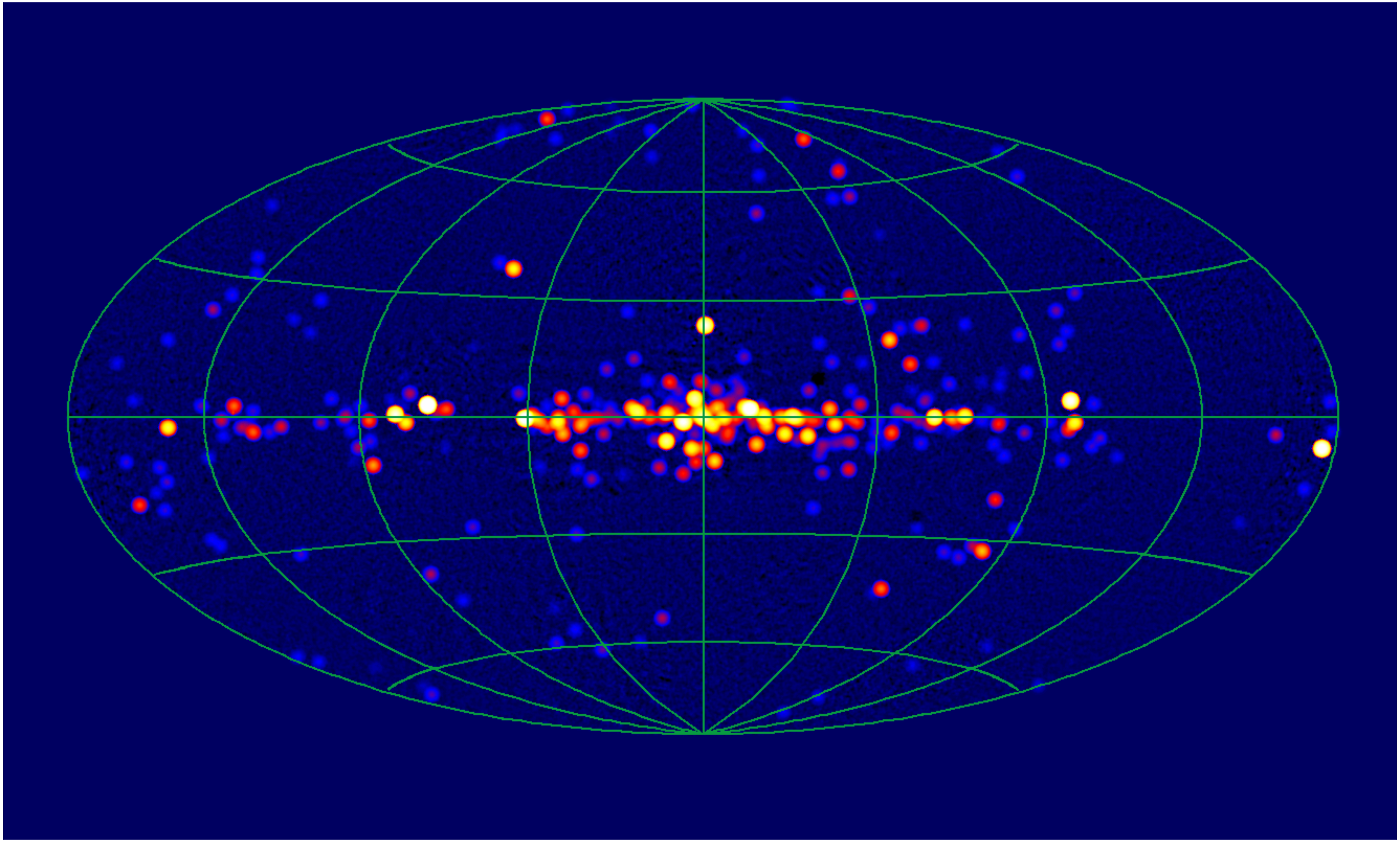
Upper limit on the hot medium ~ few %

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	$3\,10^8$

Transport of positrons through ISM

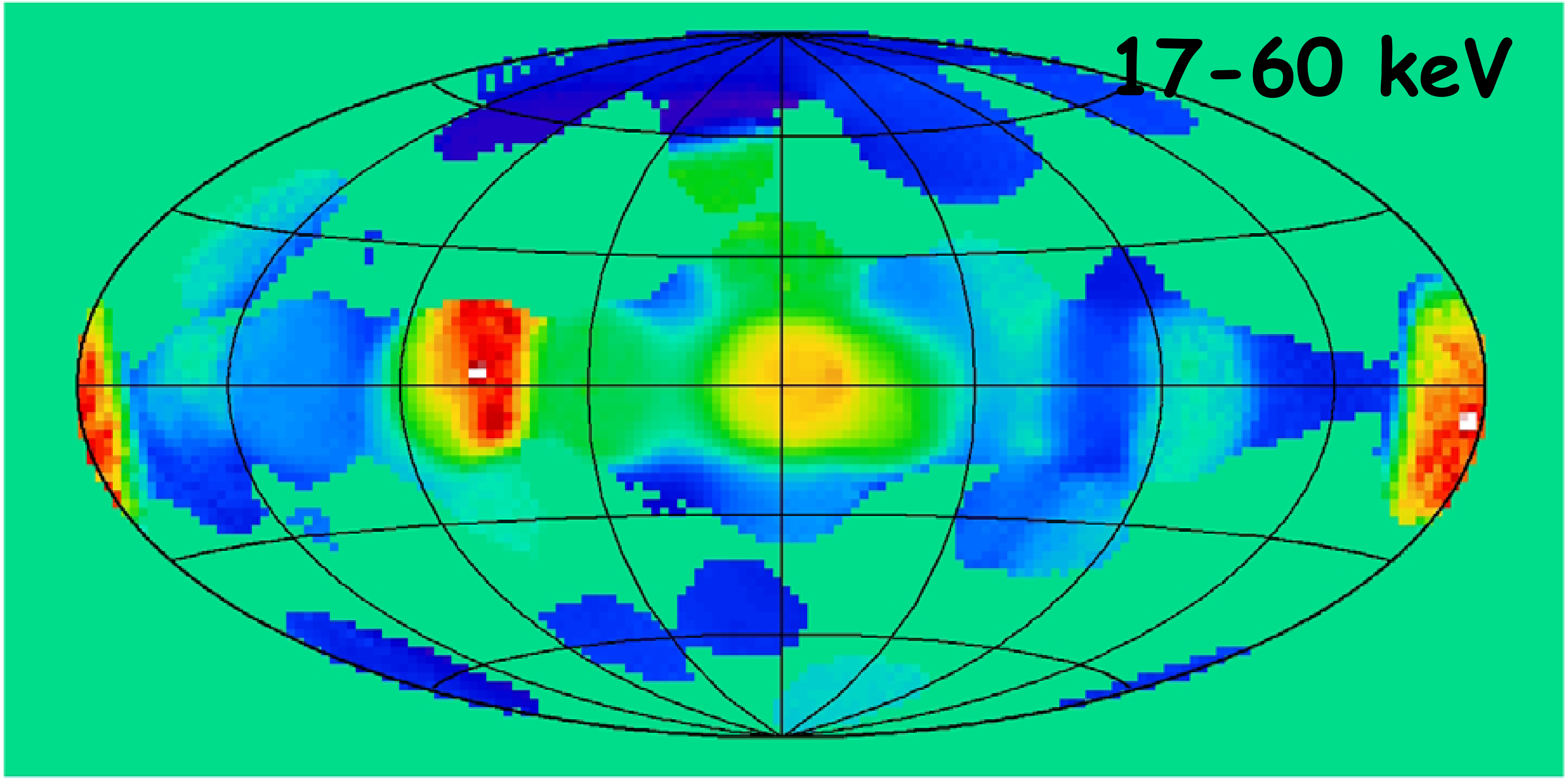
- **Free migration between phases?**
- **Positrons locked to phase?**
- **Life time of hot phase?**

INTEGRAL ALL-SKY SURVEY (17-60 keV)

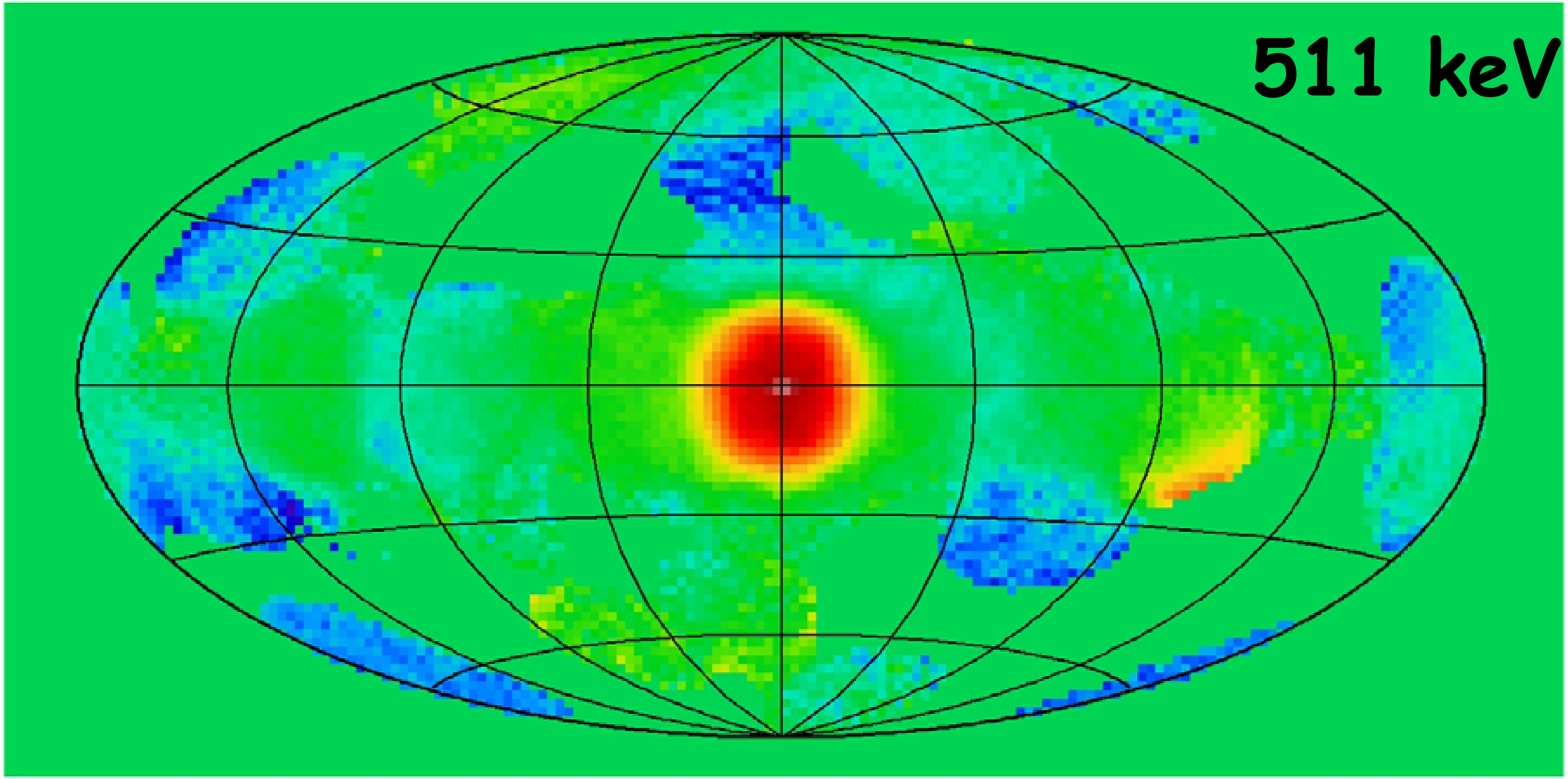


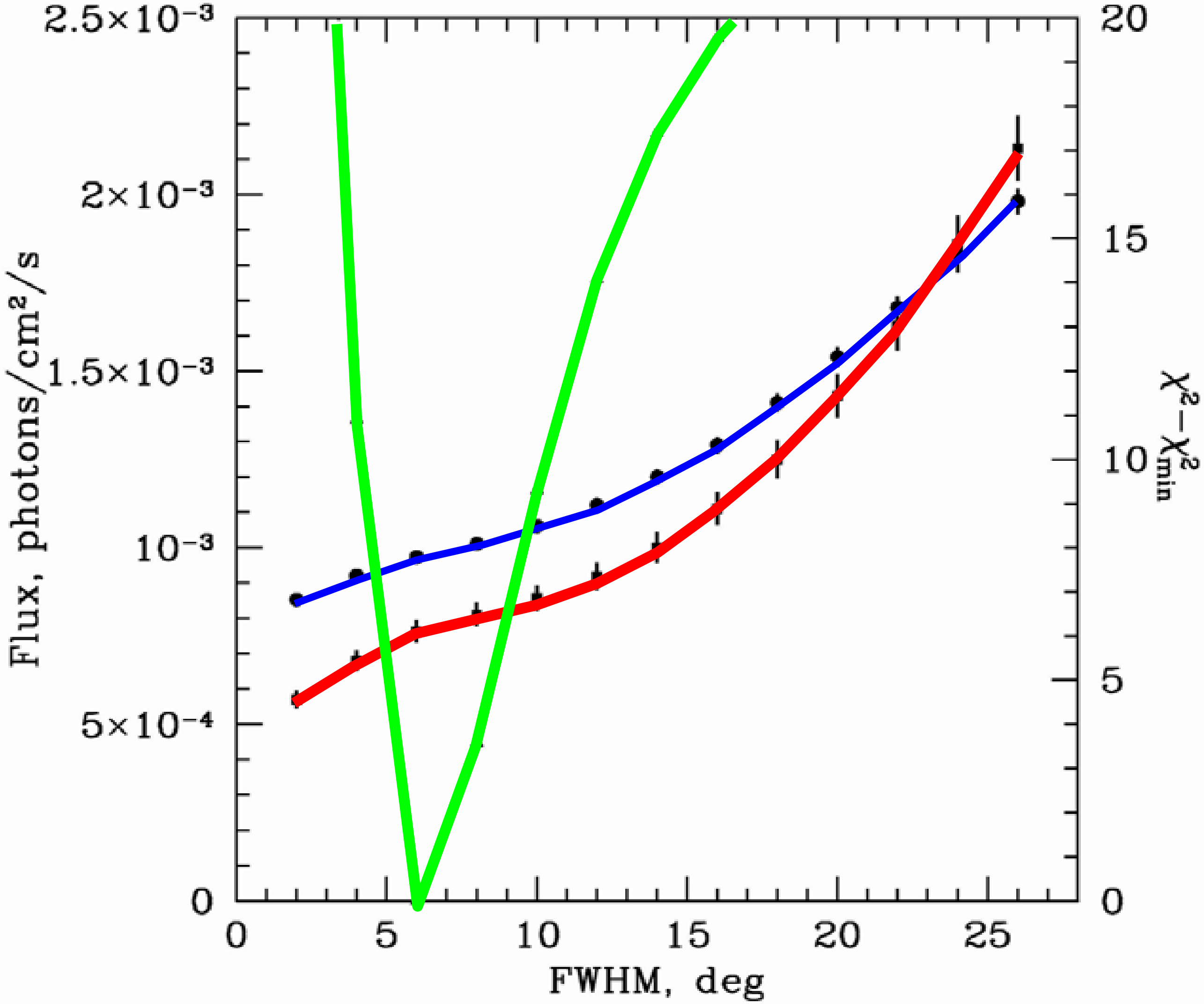
ISGRI/INTEGRAL

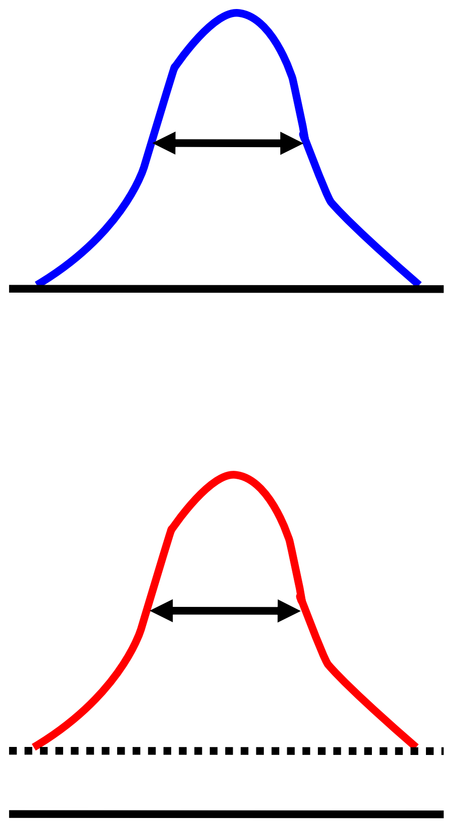
Krivonos et al., 2007



SPI/INTEGRAL


511 keV

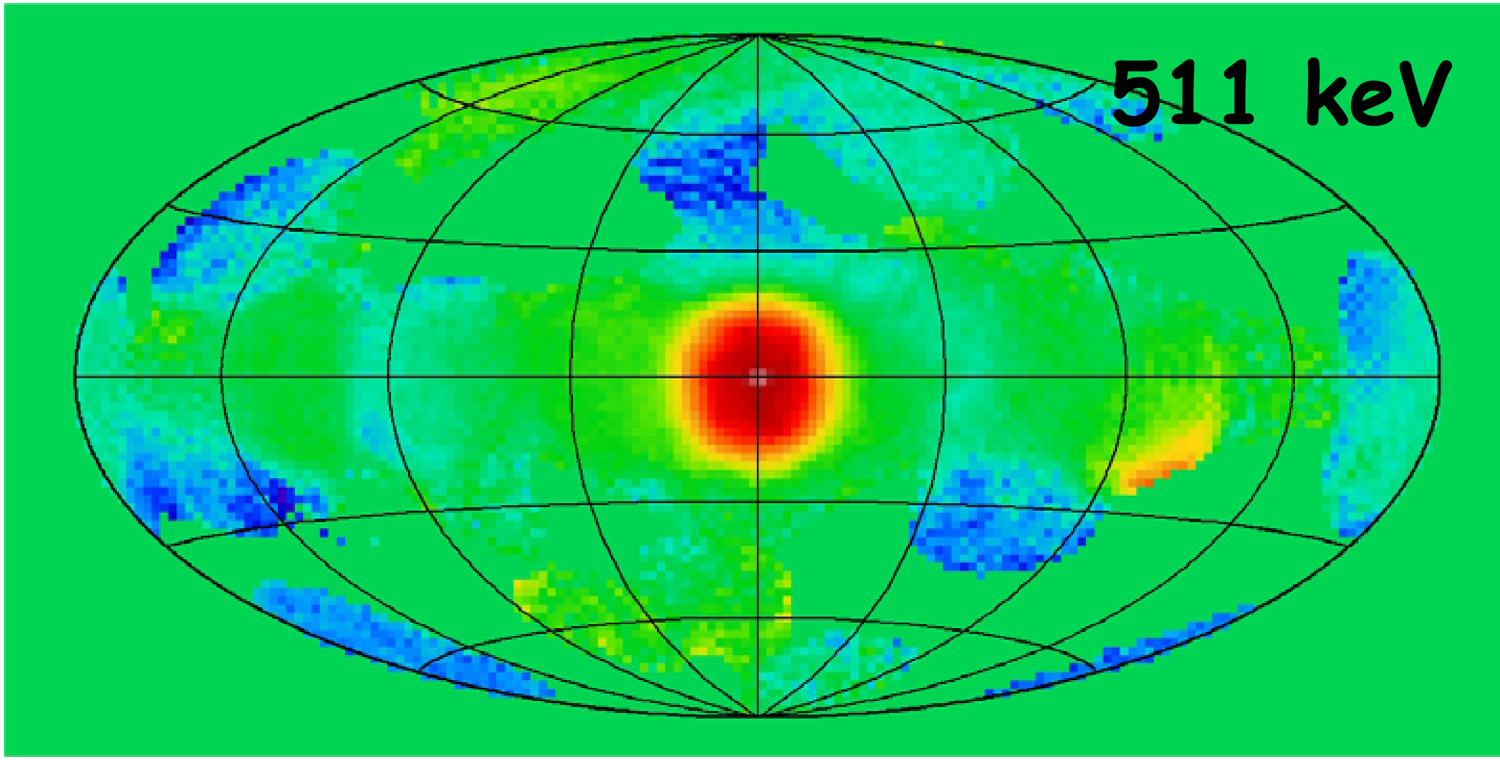




Not a point source!

Size ~ 6°

Flux ~ 10^{-3} ph/s/cm^2



- Total flux ~ 10^{-3} phot/cm^2/s = 10^{43} β^+/s = 10^{37} erg/s
- Total initial luminosity γ10^{37} erg/s
- Not a compact source
- Strong bulge
- "Weak" disk B/D= 3 - 9 [in luminosity 0.3-0.5]

Potential sources of positrons:

astrophysics

Nucleosynthesis:

Massive stars (SN II, WR: e.g. ^{26}Al)

Low mass stars (SNIa – ^{56}Ni, Novae - ^{13}N)

Cosmic ray protons interactions with ISM (π^{+})

Microquasars (jets), pulsars, GRBs

Supermassive black hole Sgr A*

(Light) Dark matter annihilation

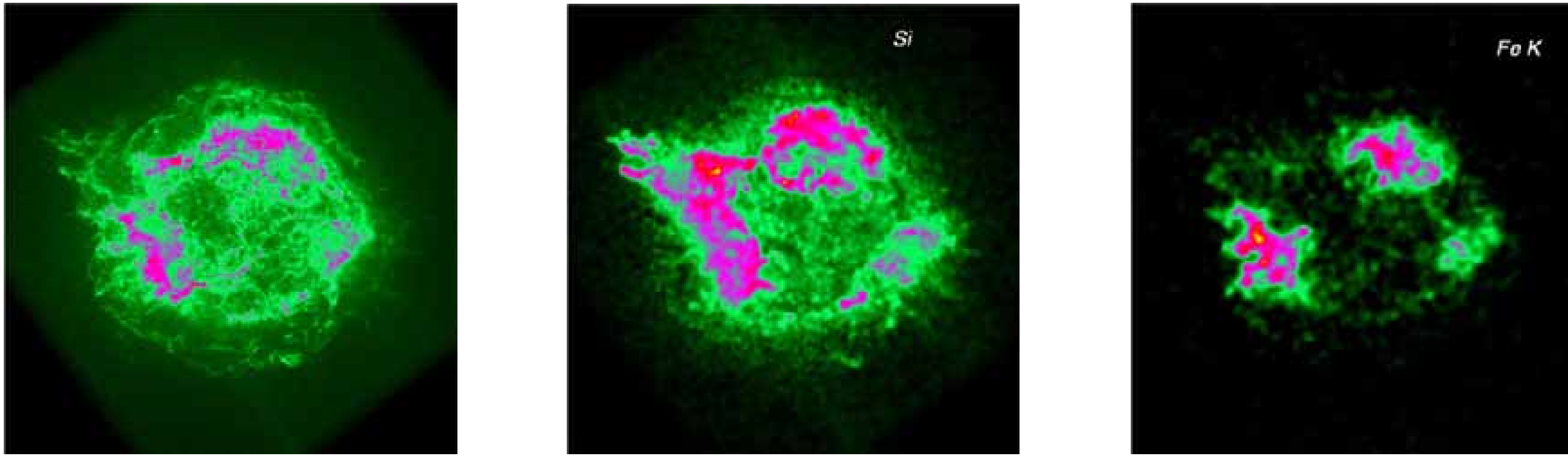
This school

Supernovae

$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$	$\tau = 6.1d, 78.8$ d	$18\% \beta^+$
$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$	$\tau = 62$ y, 4 y	$95\% \beta^+$
$^{26}Al \rightarrow {}^{26}Mg$	$\tau = 7.2\,10^5$ y	$82\% \beta^+$

Clayton et al., 70's

SNII (core collapse of massive stars)

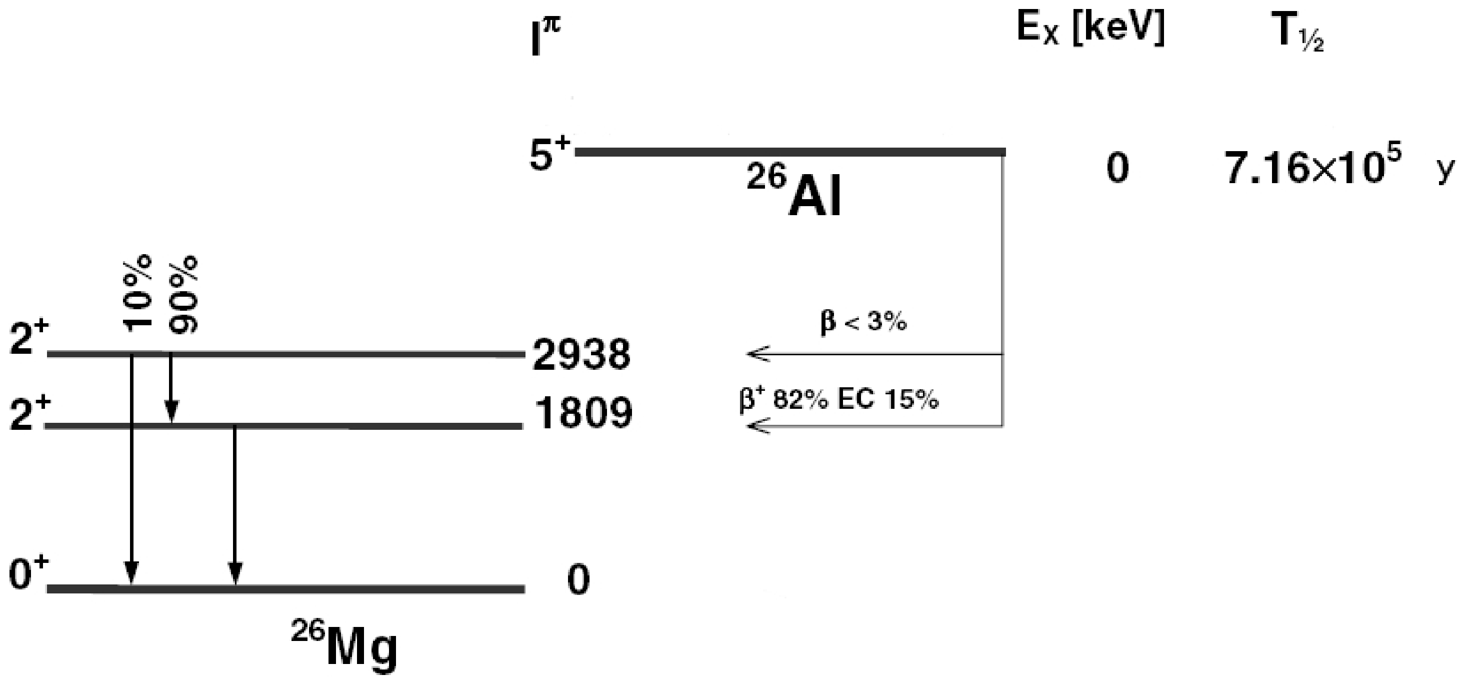


$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, 80 days, $\beta^+ = 19\%$, 0.07 $M_\odot$ ✖

Positrons are born too early and can not escape

$^{26}Al \rightarrow {}^{26}Mg$, $7\ 10^5$ yr, $\beta^+ = 82\%$, 0.016 $M_\odot$

$^{26}Al \rightarrow {}^{26}Mg$

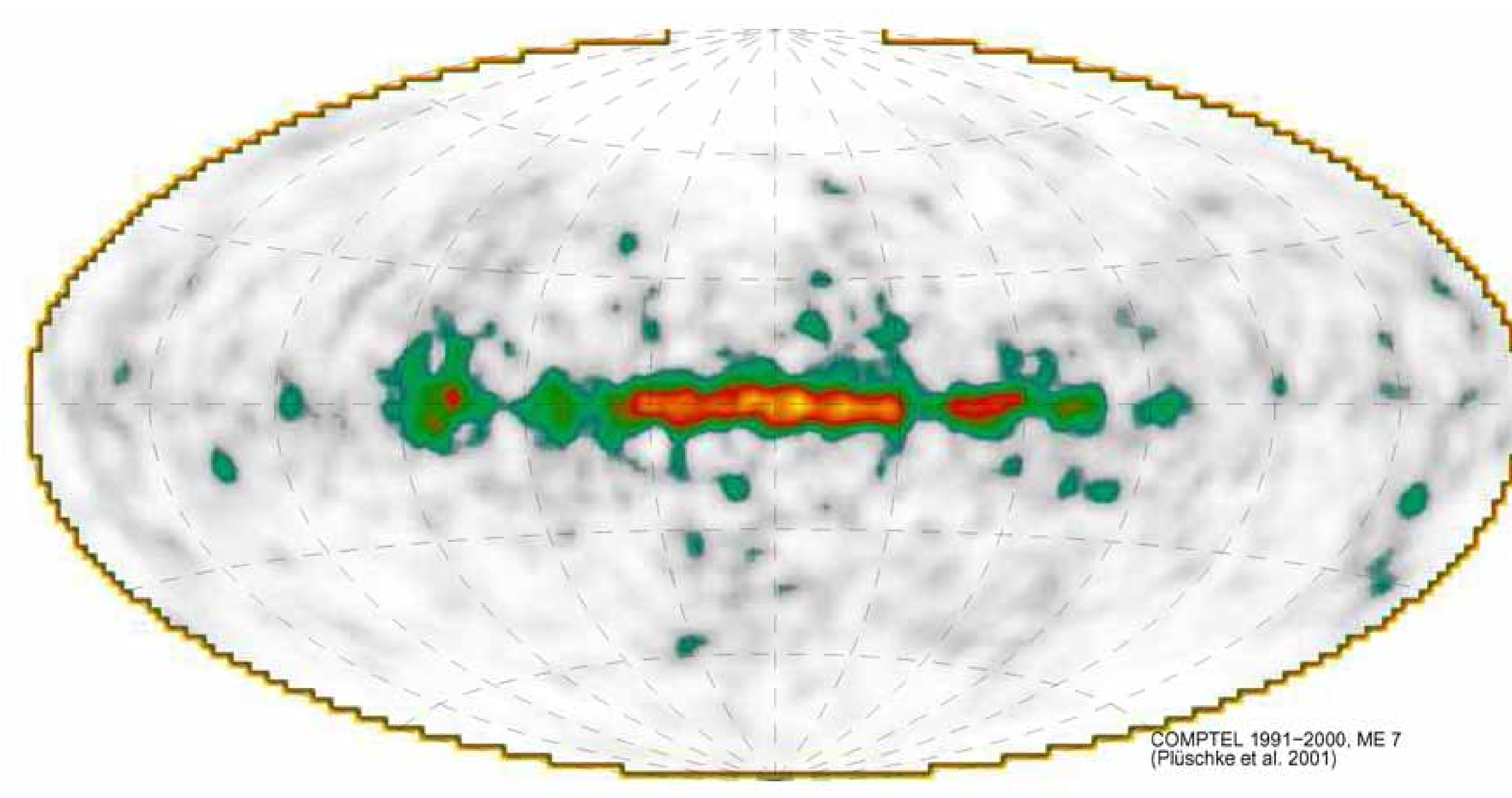


Massive stars:
SNII (core collapse)
WR stars

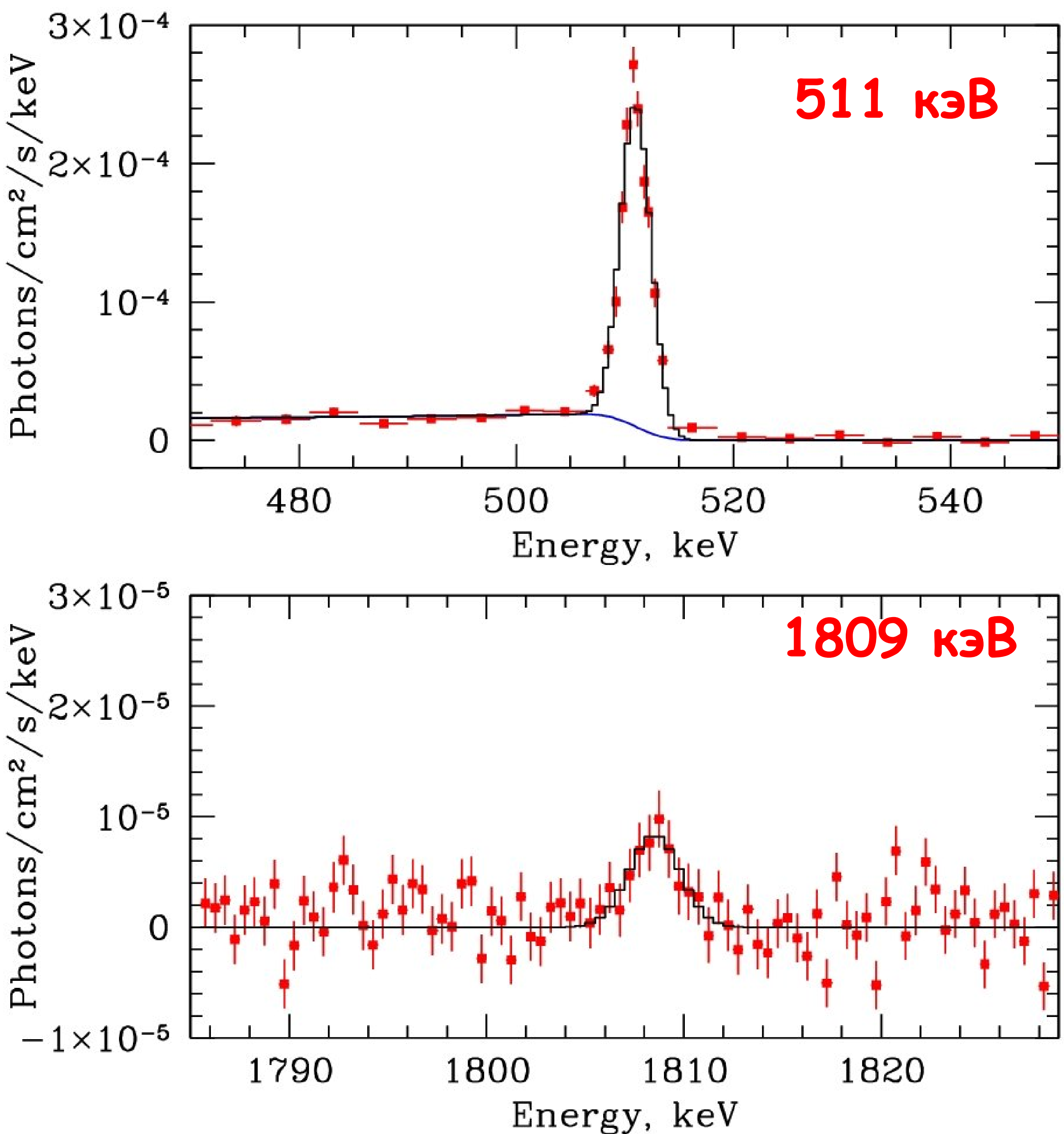
1809 MeV - 99.8% ◀
e^+ - 81.7%

- **Ideal channel for enriching ISM with positrons (long life time)**
- **1809 MeV line is the tracer for this channel**
- **Follows the distribution of massive/young stars in the Galaxy**

^{26}Al map of the Galaxy



Comptel/GRO



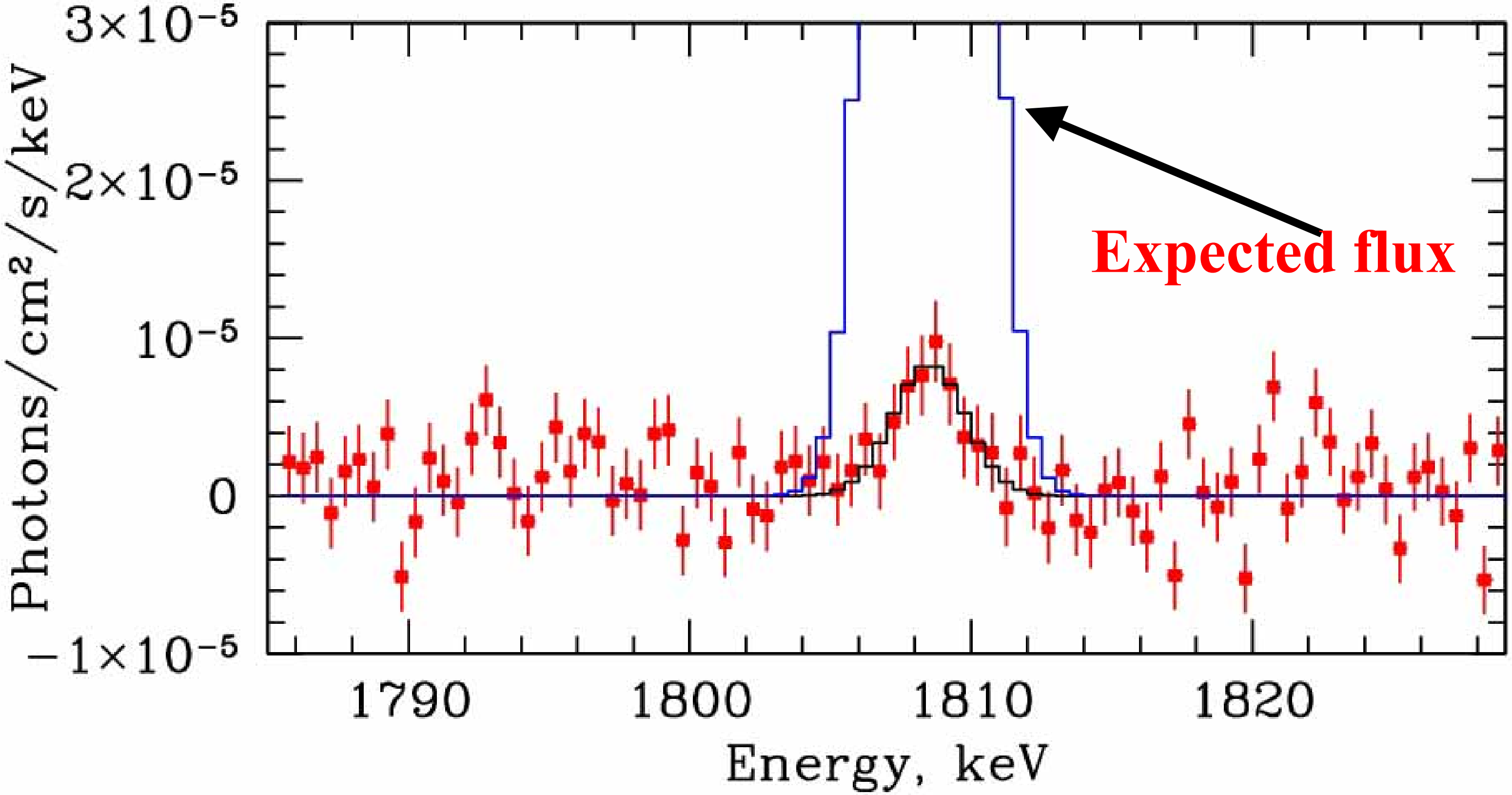
511 кэВ
Photons/cm²/s/keV
3×10⁻⁴
2×10⁻⁴
10⁻⁴
0
480
500
520
540
Energy, keV
1809 кэВ
Photons/cm²/s/keV
3×10⁻⁵
2×10⁻⁵
10⁻⁵
0
−1×10⁻⁵
1790
1800
1810
1820
Energy, keV

Per decay of ^{26}Al :

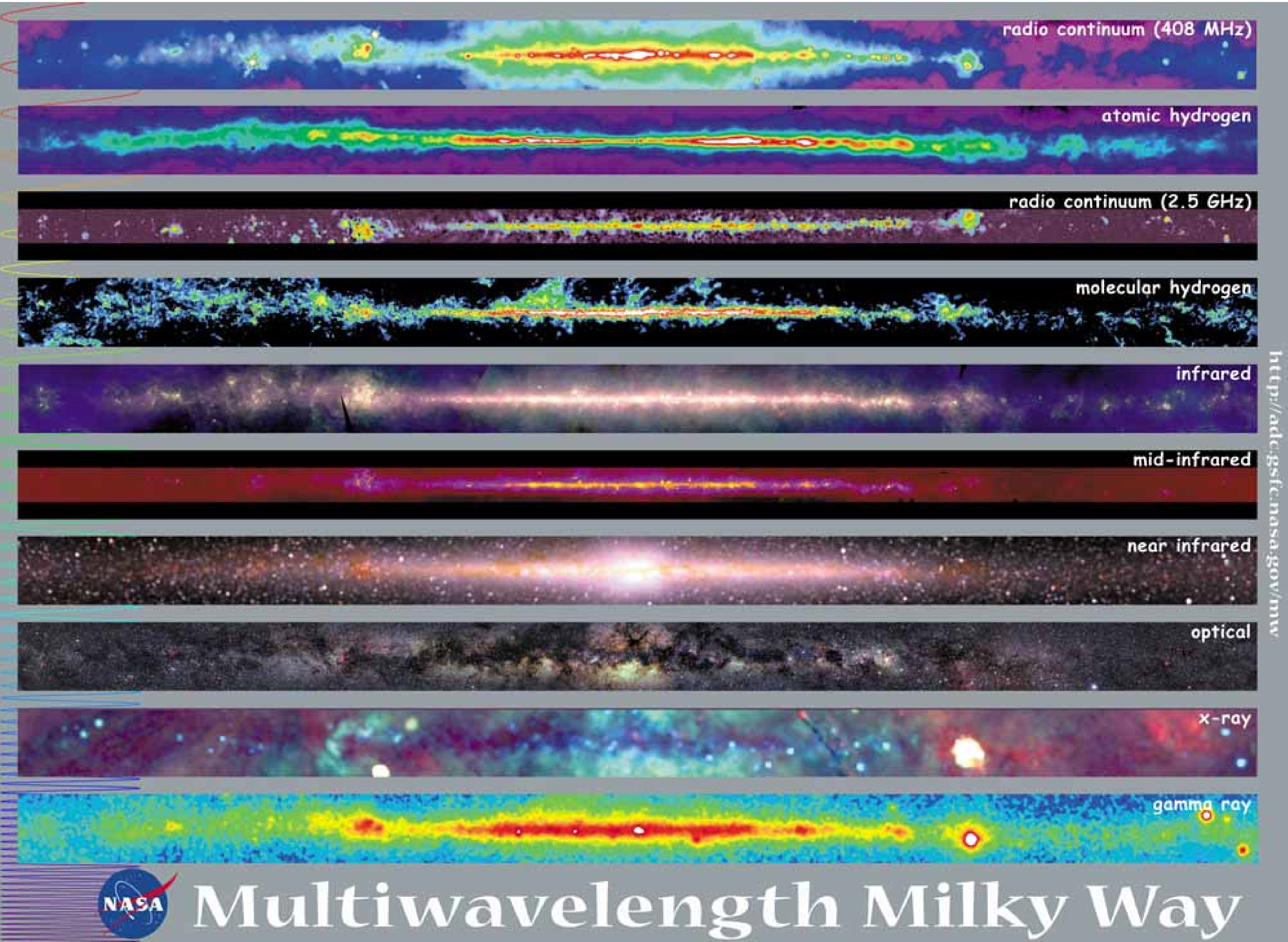
1809 keV

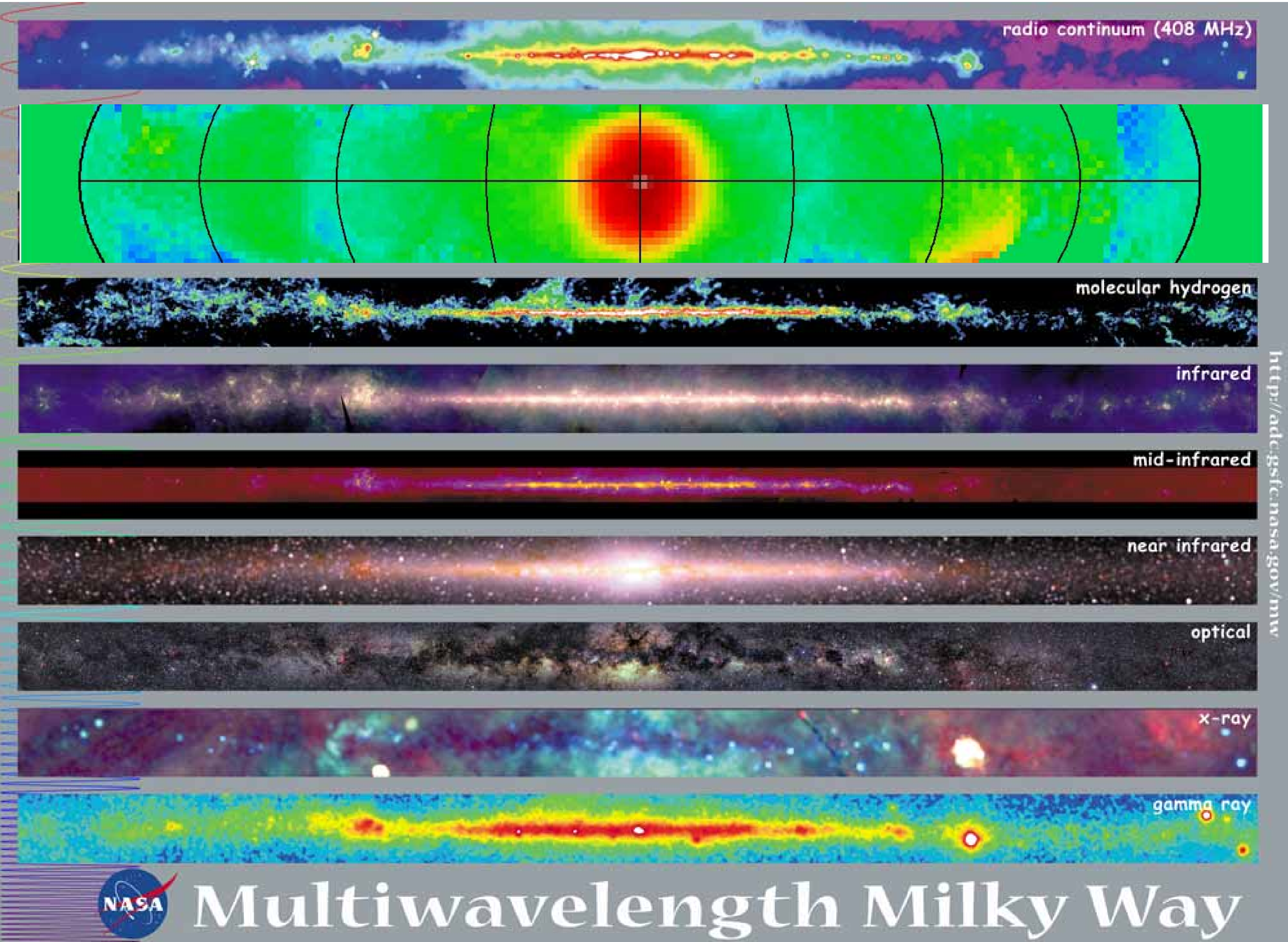
$e^+ \times \frac{1}{4} \times 2 = 0.5 \times 511$ keV

Flux(1809)~2xFlux(511)



Too few ^{26}Al in the bulge => another channel


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way


radio continuum (408 MHz)
molecular hydrogen
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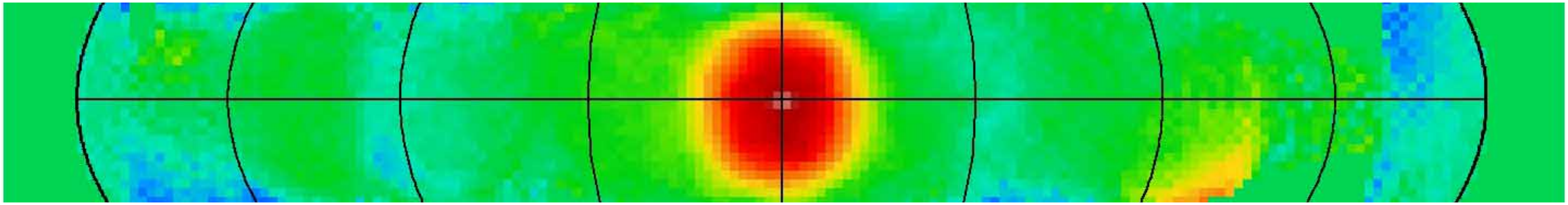
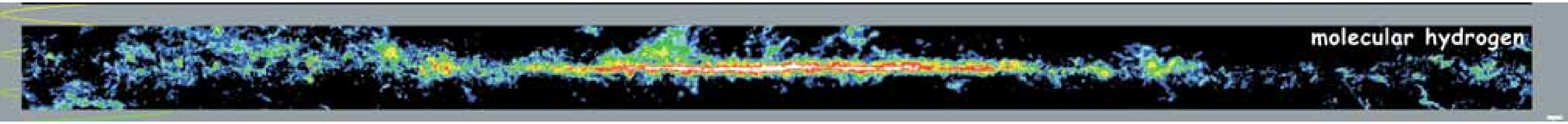
NASA
Multiwavelength Milky Way

Massive stars - are present only in the disk

511кэВ

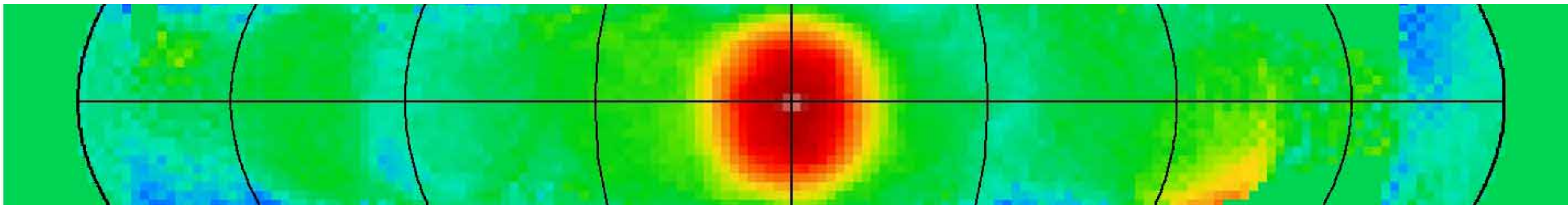


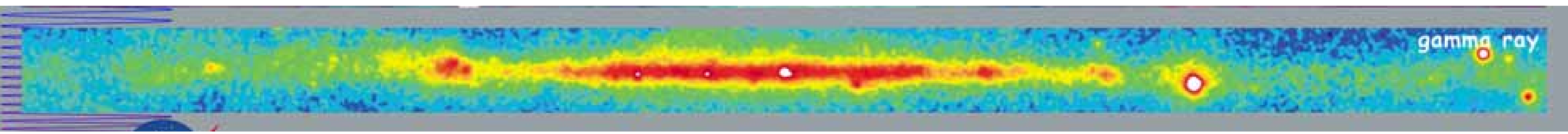


Positrons are not due to massive stars!

Cosmic Rays: $N+p \rightarrow \pi^{+} \rightarrow e^{+}$

511кэВ





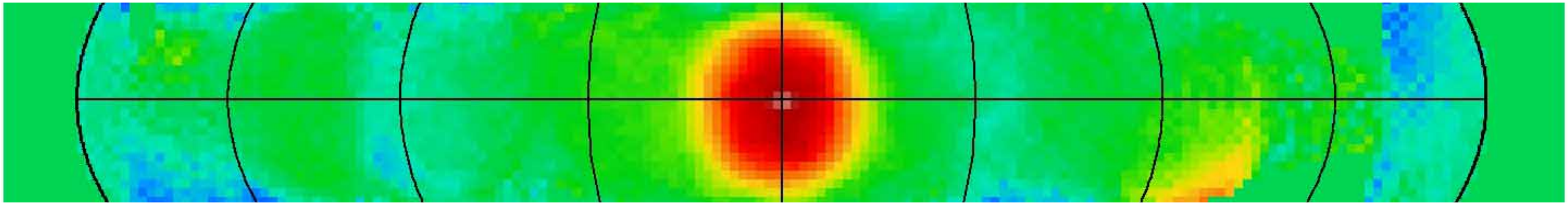
>100 MeV

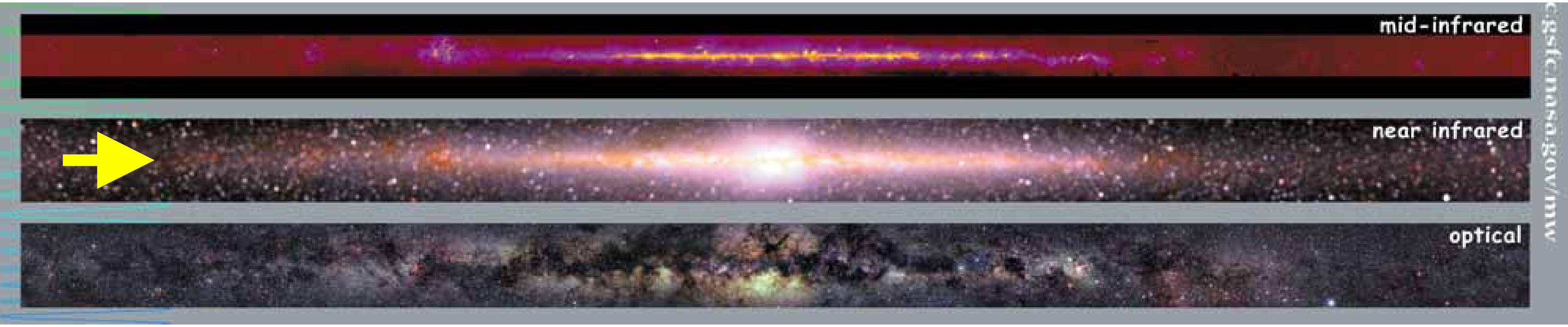
Whole Galaxy ~ 2.5 10^{42} phot/s (~100 MeV) : $2x\pi^{0}$
π^{+} ~ 10^{42} e^{+}/s, but we need 10^{43} e^{+}/s

Positrons are not due to Cosmic Rays!

Low mass (old) stars - Disk + Bulge

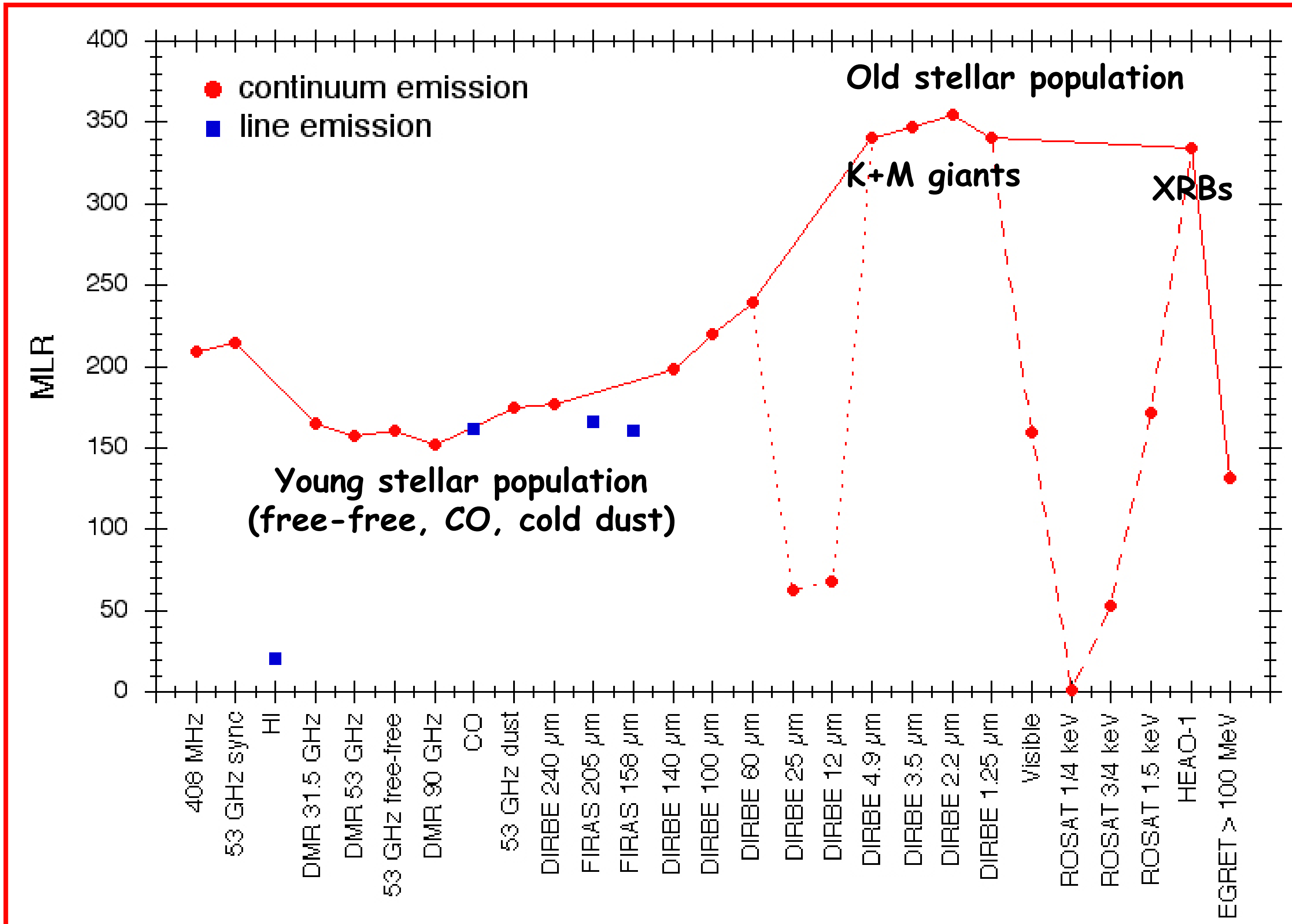
511кэВ





The best match among obvious tracers

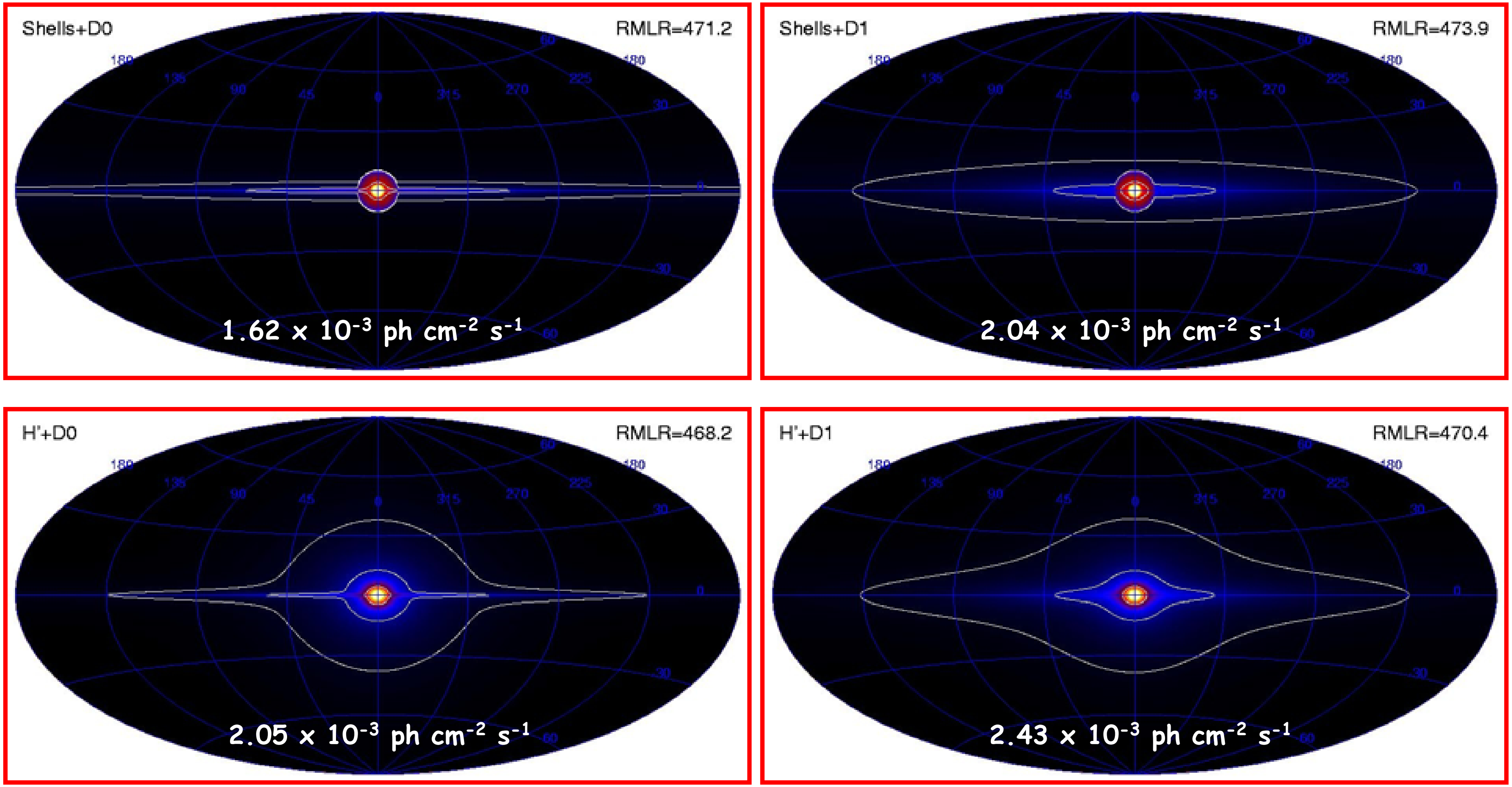
Comparison with tracer maps



Radio μ-waves FIR NIR V X-ray γ

Knoedlsered et al.

Bulge/Halo + Disk models



SPI flux (imaging) $(1.6\text{-}2.4) \times 10^{-3}$ ph cm^{-2} s^{-1}

Knoedlsered et al.

Flux ratios for different components

	Bulge	Halo	Disk
Flux (10^{-3} ph cm^{-2} s^{-1})	1.05 ± 0.07	1.6 ± 0.5	0.7 ± 0.5
L_{511} (10^{43} ph s^{-1})	0.90 ± 0.06	1.2 ± 0.3	0.2 ± 0.1
L_p (10^{43} s^{-1})*	1.50 ± 0.10	2.0 ± 0.5	0.3 ± 0.2

* assuming f_p = 0.93

The 511 keV line emission is bulge dominated :

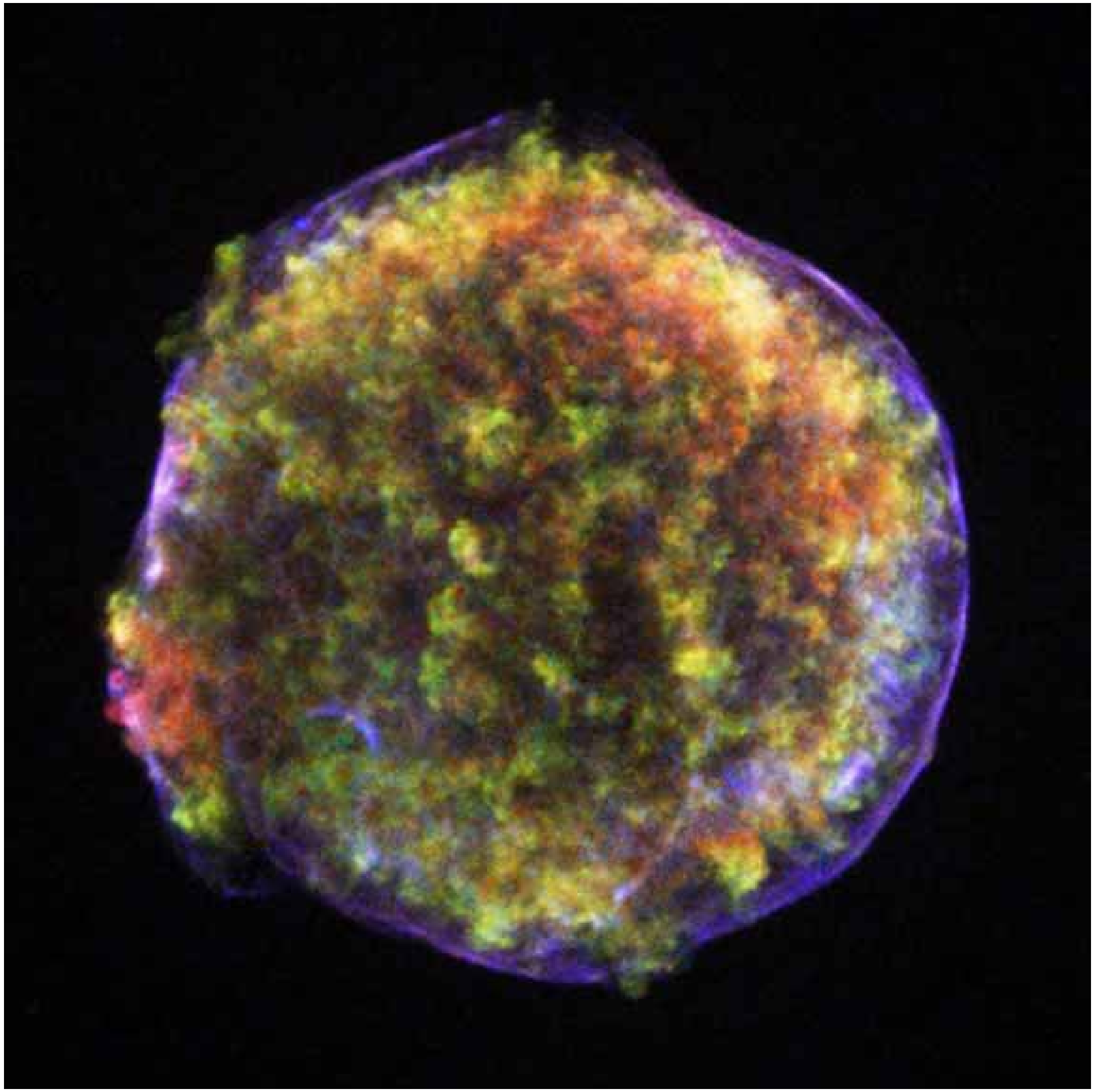
B/D flux ratio : 1 - 3

B/D luminosity ratio : 3 - 9

B/D=0.5 is expected!

Knoedlsered et al.

SNIa (thermonuclear explosion of WD)



Mass ~1.4 $M_{\odot}$

Ni mass ~0.5 $M_{\odot}$

$^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

80 days, β^{+} = 19%

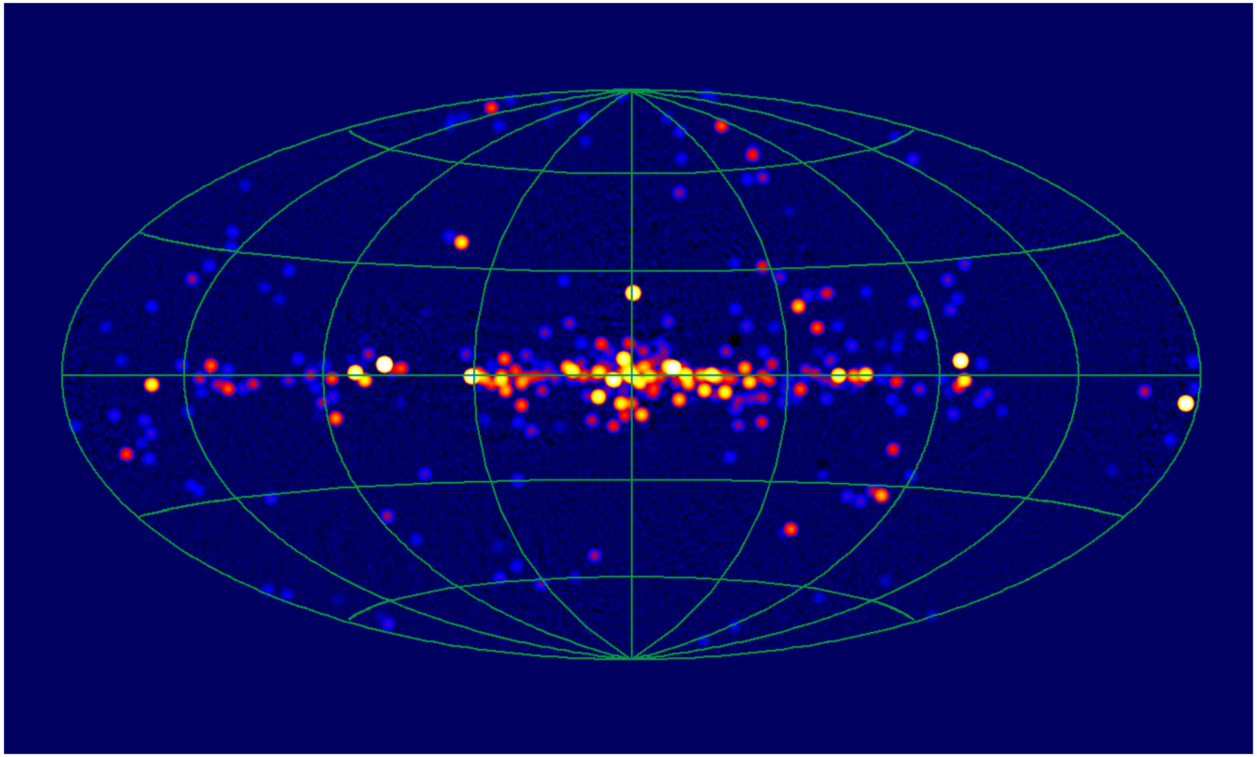
Escape fraction~ few%

Enough positrons, but..

Low mass binaries + pulsars

$$\gamma + \gamma \rightarrow e^+ + e^-$$ (jets?)

Bulge/disk ratio?



Potential sources of positrons:

astrophysics

Nucleosynthesis:

~~Massive stars (SN II, WR: e.g. ^{26}Al)~~

Low mass stars (SNIa - ^{56}Co, Novae - ^{13}N) ◄

(B/D ratio problem!)

~~Cosmic ray protons interactions with ISM (π^{+})~~

Microquasars (jets), pulsars ??????

Supermassive black hole Sgr A* ?????

(Light) Dark matter annihilation ◄

Dark matter and positrons in the GC

Density $\rho_{DM} \propto r^{-0.5} - r^{-1.5}$

Central zone → $\rho^{2}{}_{DM}$

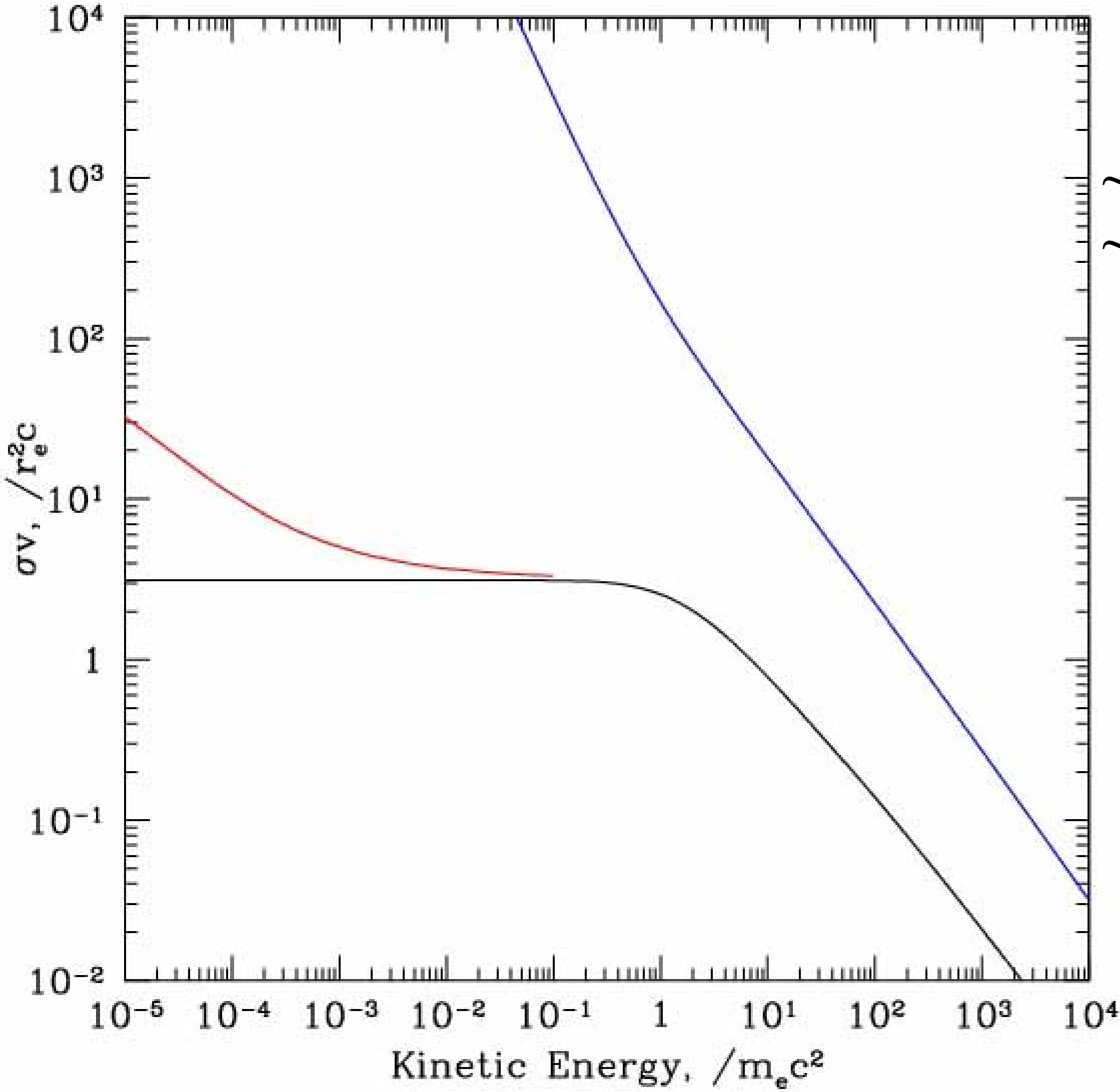
Immediately solves Bulge/Disk problem!

Boehm, Silk, Hooper, Ascasibar, Beacom, Pospelov ….

$$\rho_{DM} \propto r^{-1}$$

M_{DM}<100 MeV (constraints on gamma-rays)
If initial energy of positrons is high => difficult to hide
Cross section depends on velocity (cosmology)

Direct annihilation of relativistic positrons



~ 10 % for E ~ 10 MeV

~ 1.4 % for E ~ 1 MeV

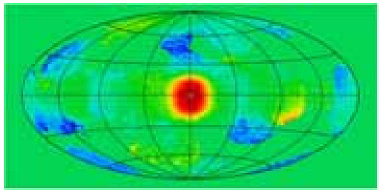
Broad line

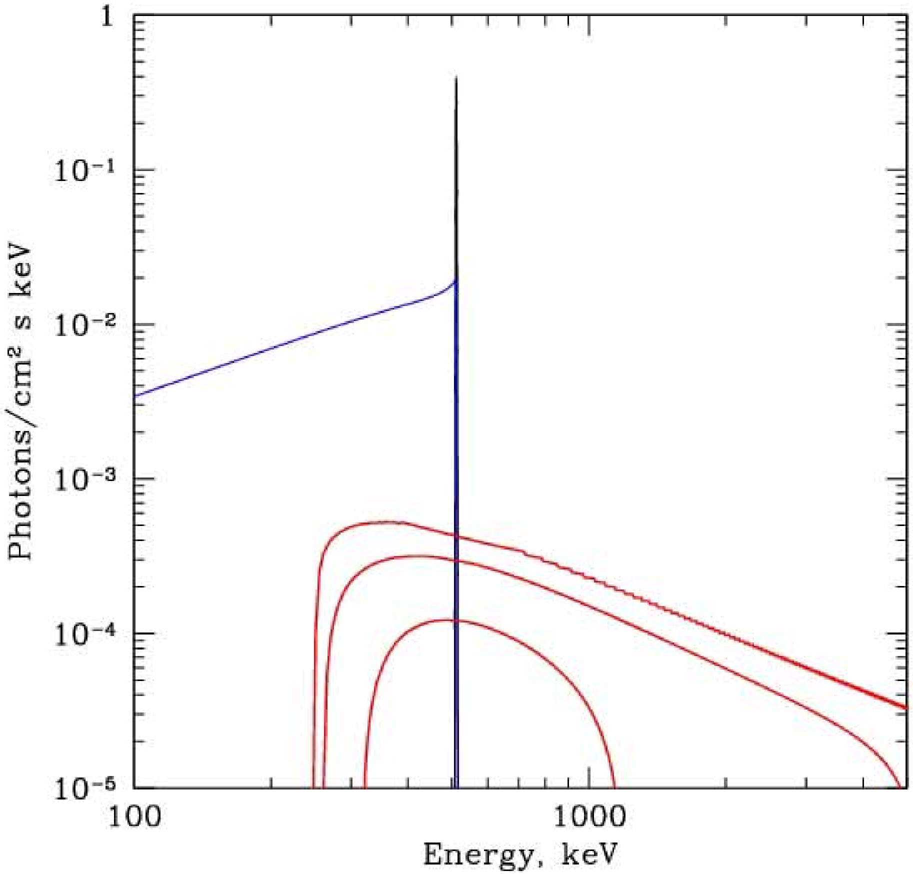
Limits from observations:

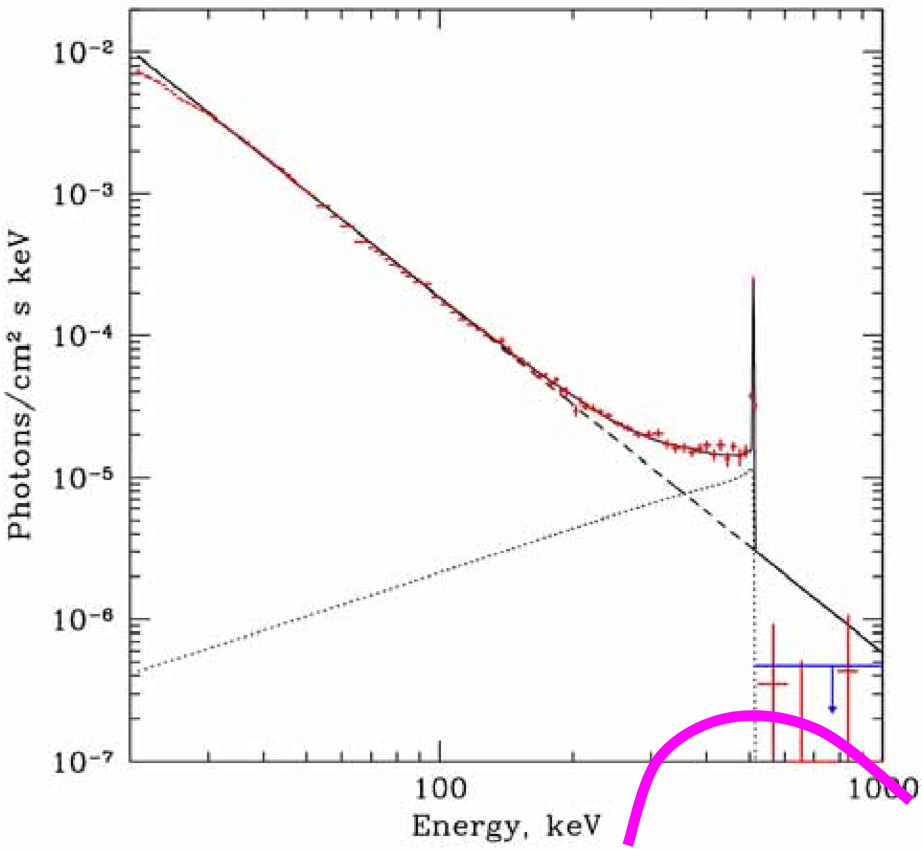
E < 3 МэВ

(Beacom & Yuksel)

(too optimistic)

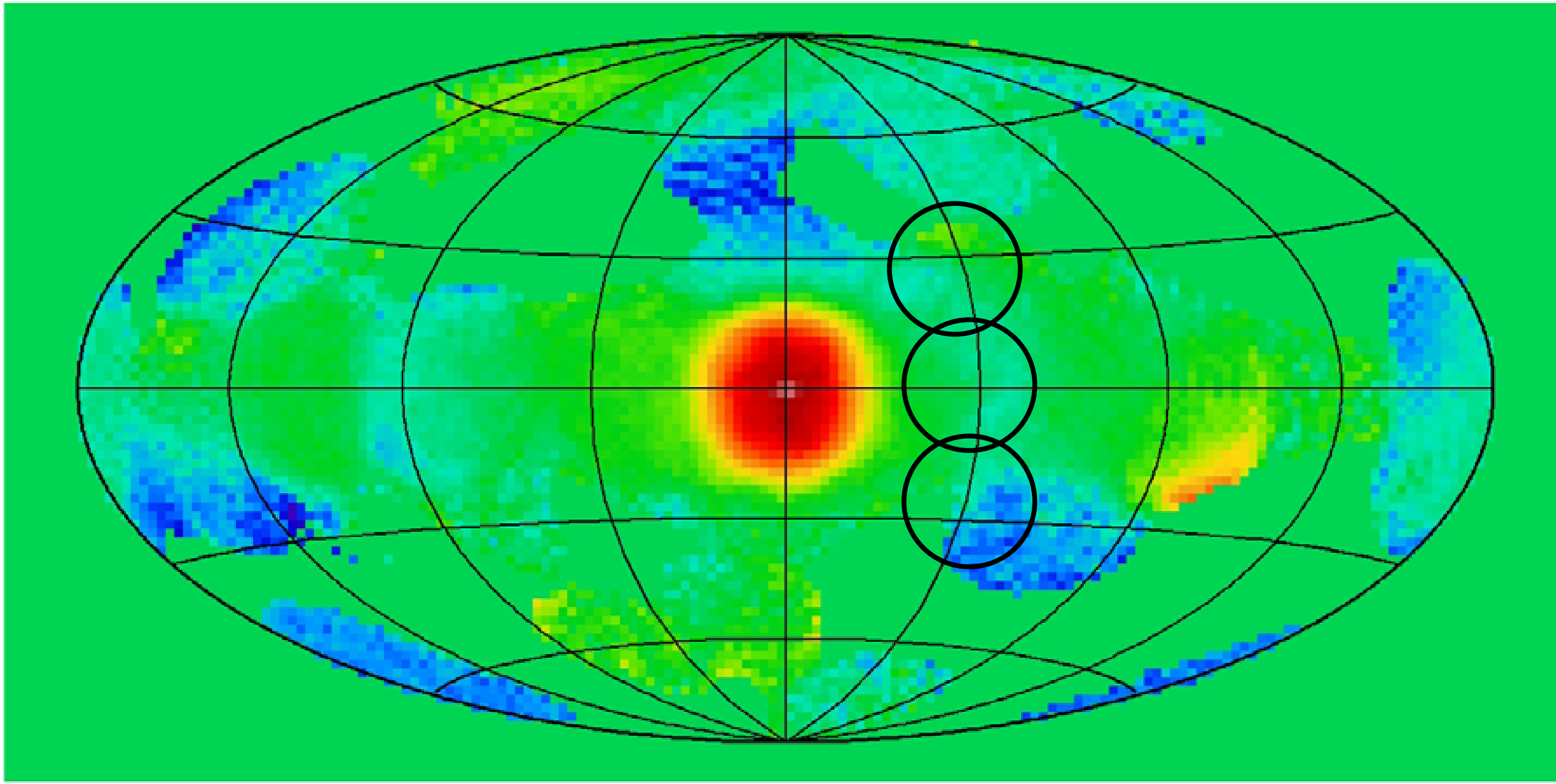






E < 30 MeV now

E < X MeV (by the end of 2007)



4 Msec (2007)

Conclusions

Two most popular explanations:

A. SNIa +/- Low mass systems

but Bulge/Disk ratio!

B. Light dark matter annihilation

"The most famous use of the positron in fiction was Isaac Asimov's use in his robots' positronic brains." (Wikipedia)

2007 = slicing the disk of the Galaxy (B/D)