INTEGRAL Observations of the Galactic 511 keV Emission and MeV Gamma-ray Astrophysics

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On behalf of the INTEGRAL/SPI Science Team

Rironkon Seminar, 12/26/05

MeV Gamma-ray Astrophysics

- *Nucleosynthesis*

  -e.g. ^{26}Al (1.809MeV), ^{60}Fe (1.172,1.333MeV), ^{44}Ti(1.156MeV from CasA&Vela)

- *Supernovae*

  - e.g. ^{56}Co-->^{56}Fe ($t_{1/2}$ = 79 d, E =0.847, 1.238 MeV)

- *Neutron Star Binaries*

  -e.g. Neutron-Proton recombination line at 2.223 MeV (Bildsten, Salpeter & Wasserman 1993)

- *Cosmic Ray Interactions*

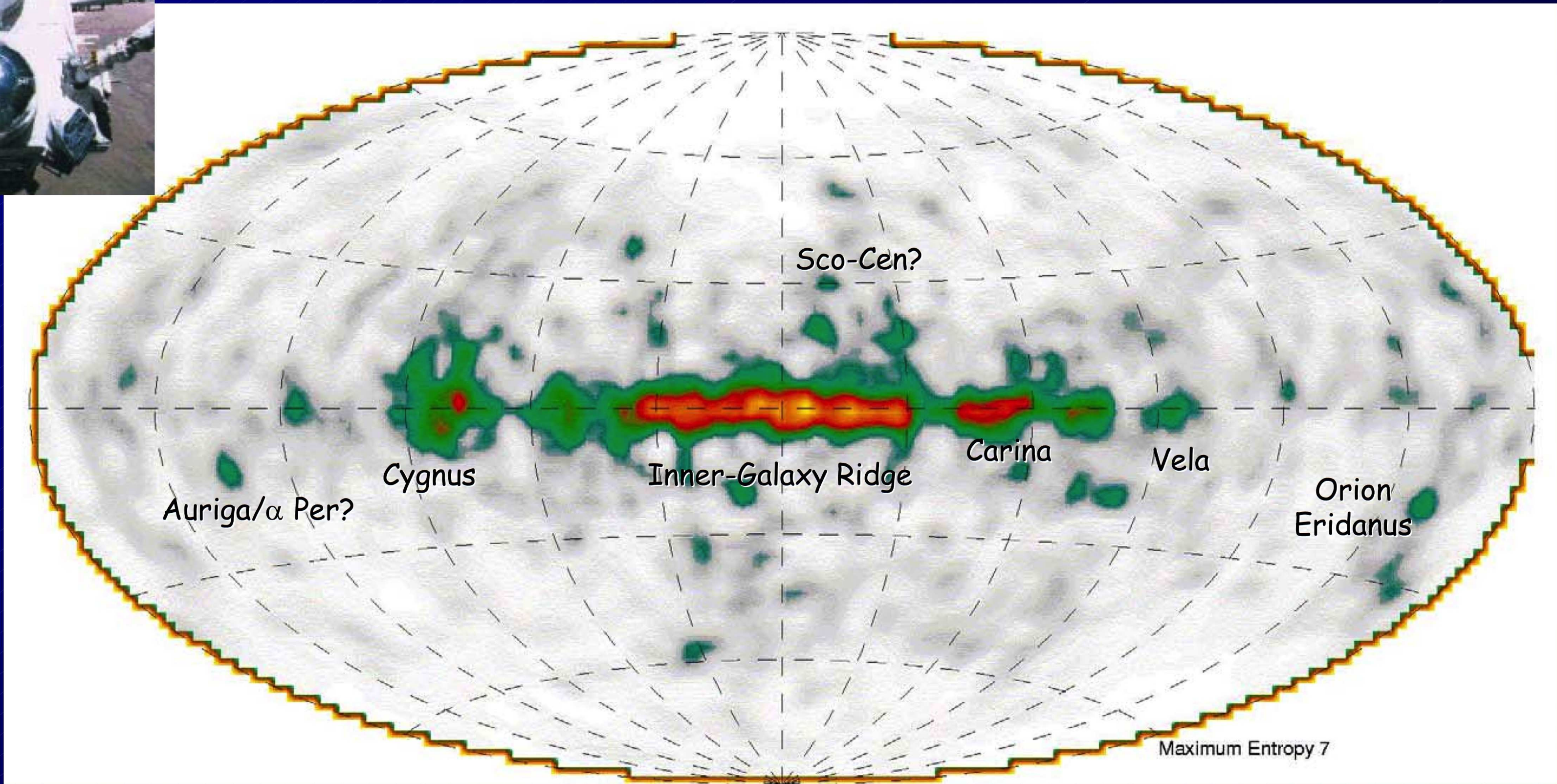
  -e.g ^{12}C excitation line (4.439 MeV), and ^{16}O excitation line (6.129 MeV)

- *Gamma-Ray Bursts/Hypernovae*
- *Black Holes*
- *Pulsars*
- *Solar Flares*
- *AGNs*
- *Cosmic Gamma-ray Background, etc.*

PROBLEM:

Small S/N ~ less than 1%

^{26}Al Sky Map

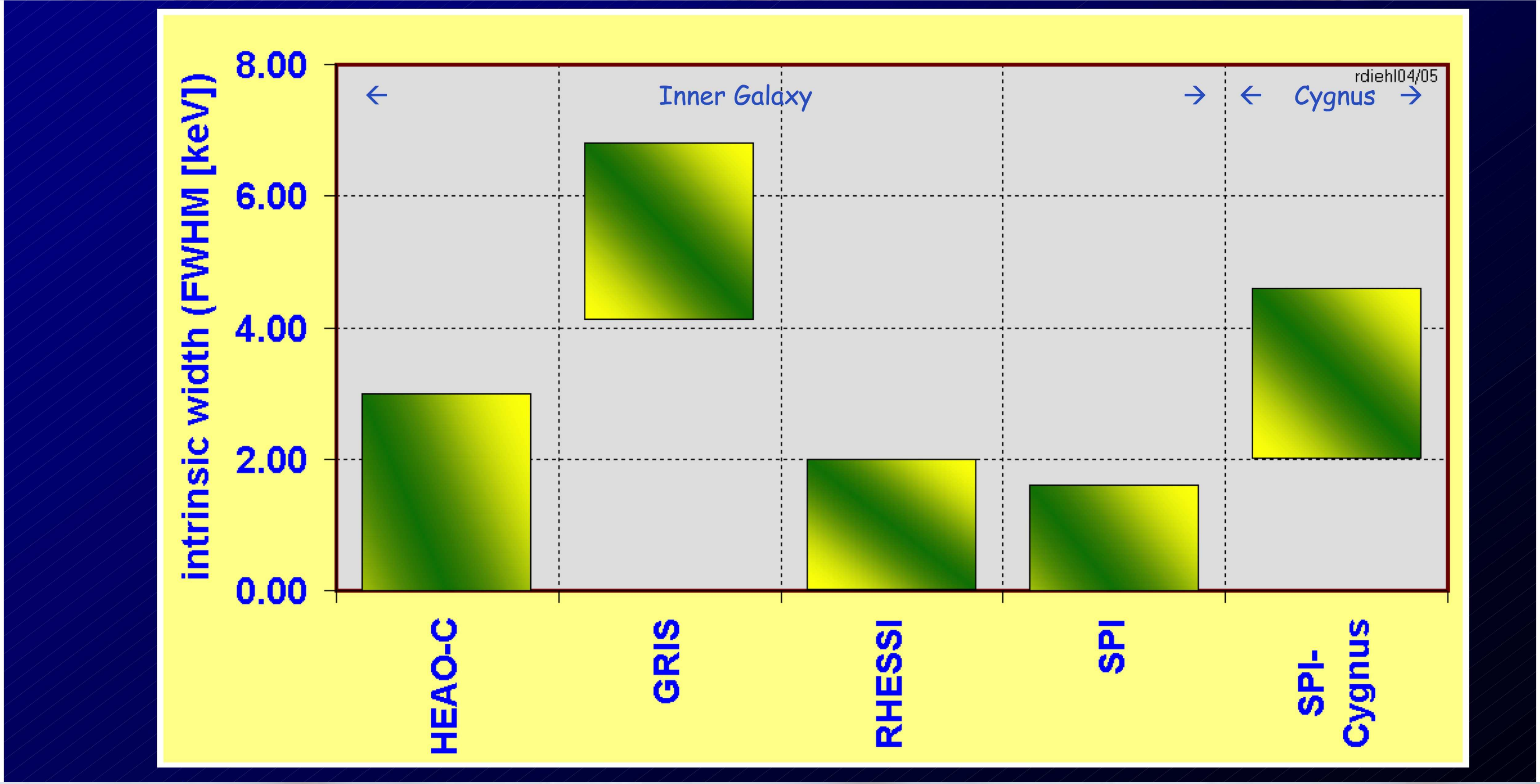


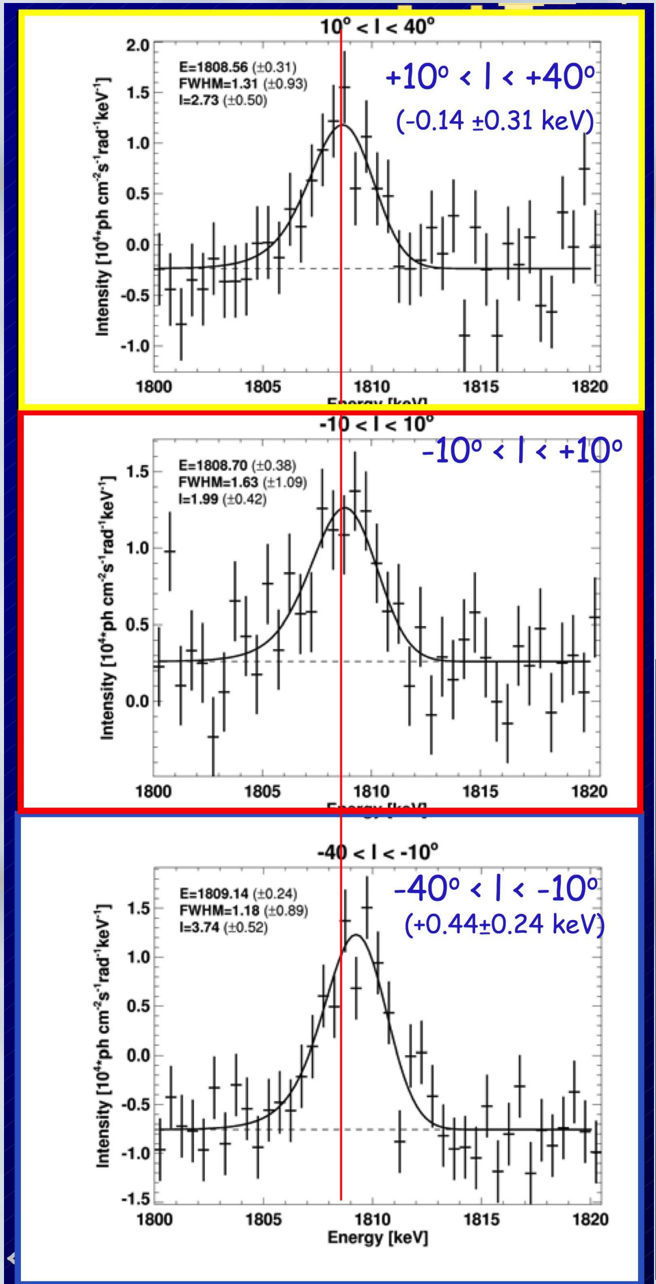
Complete CGRO Mission
(Plüschke et al. 2001)

^{26}Al Line Width

- *Inner-Galaxy Line is Probably "Narrow" (~1 keV)*
- *Cygnus Region (young stars, WR-dominated) ?*

Courtesy of R. Diehl

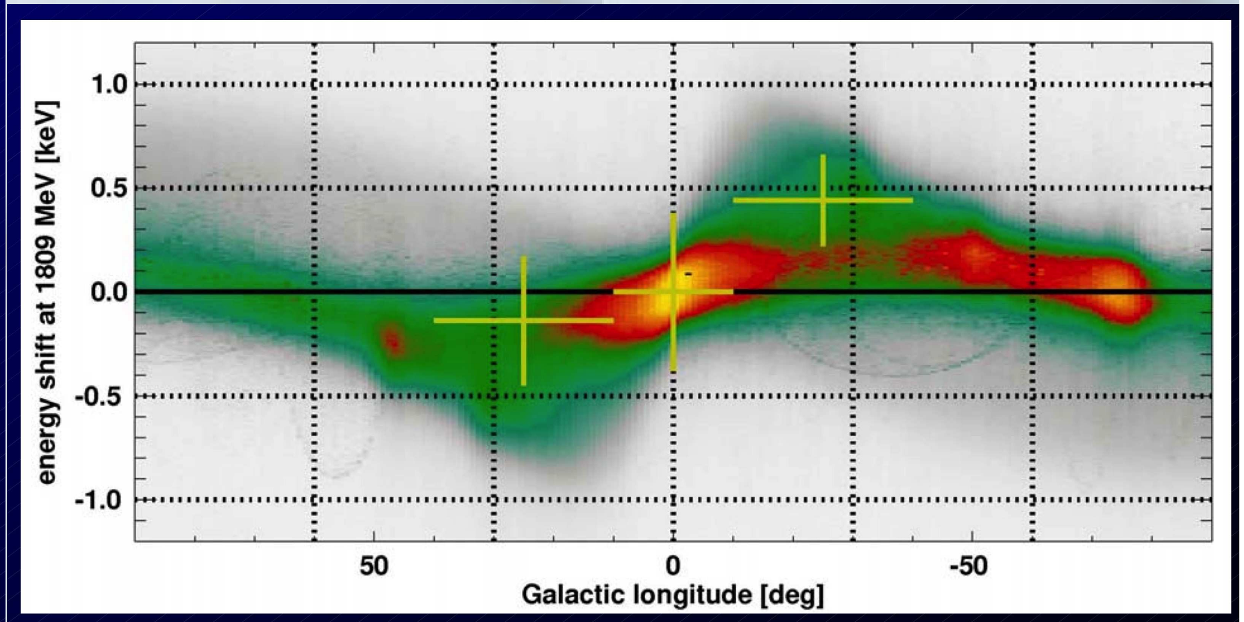




Galactic Rotation

- Doppler Shift of the Centroid
- The Sources are not Localized
- Steady-State Mass of ^{26}Al = 2.8 ($\pm$0.8) Mo

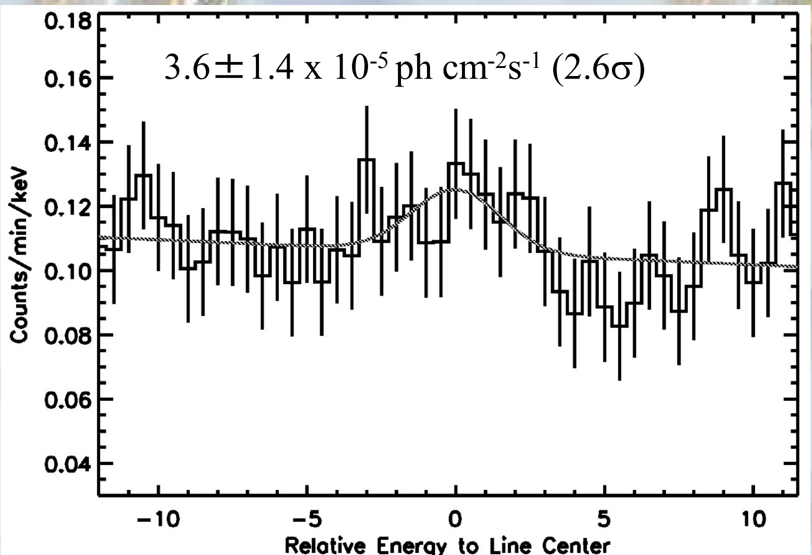
Courtesy of R. Diehl

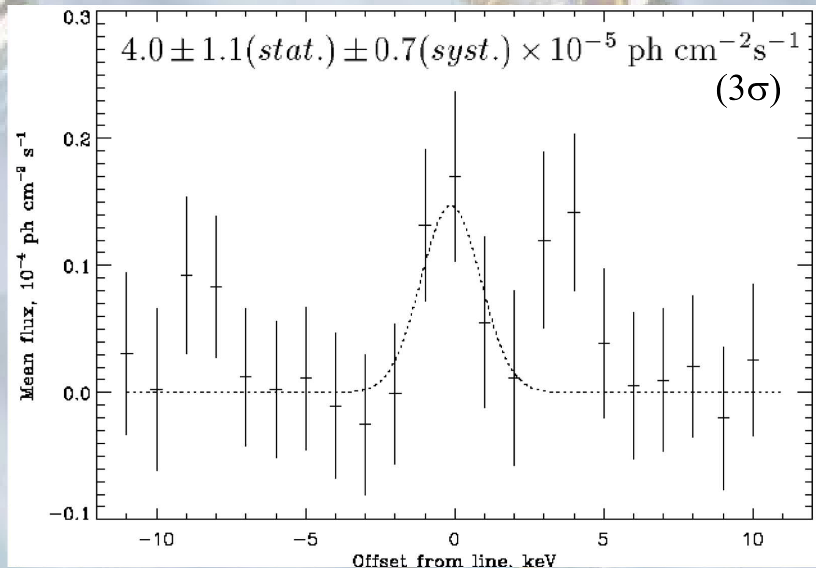


^{60}Fe

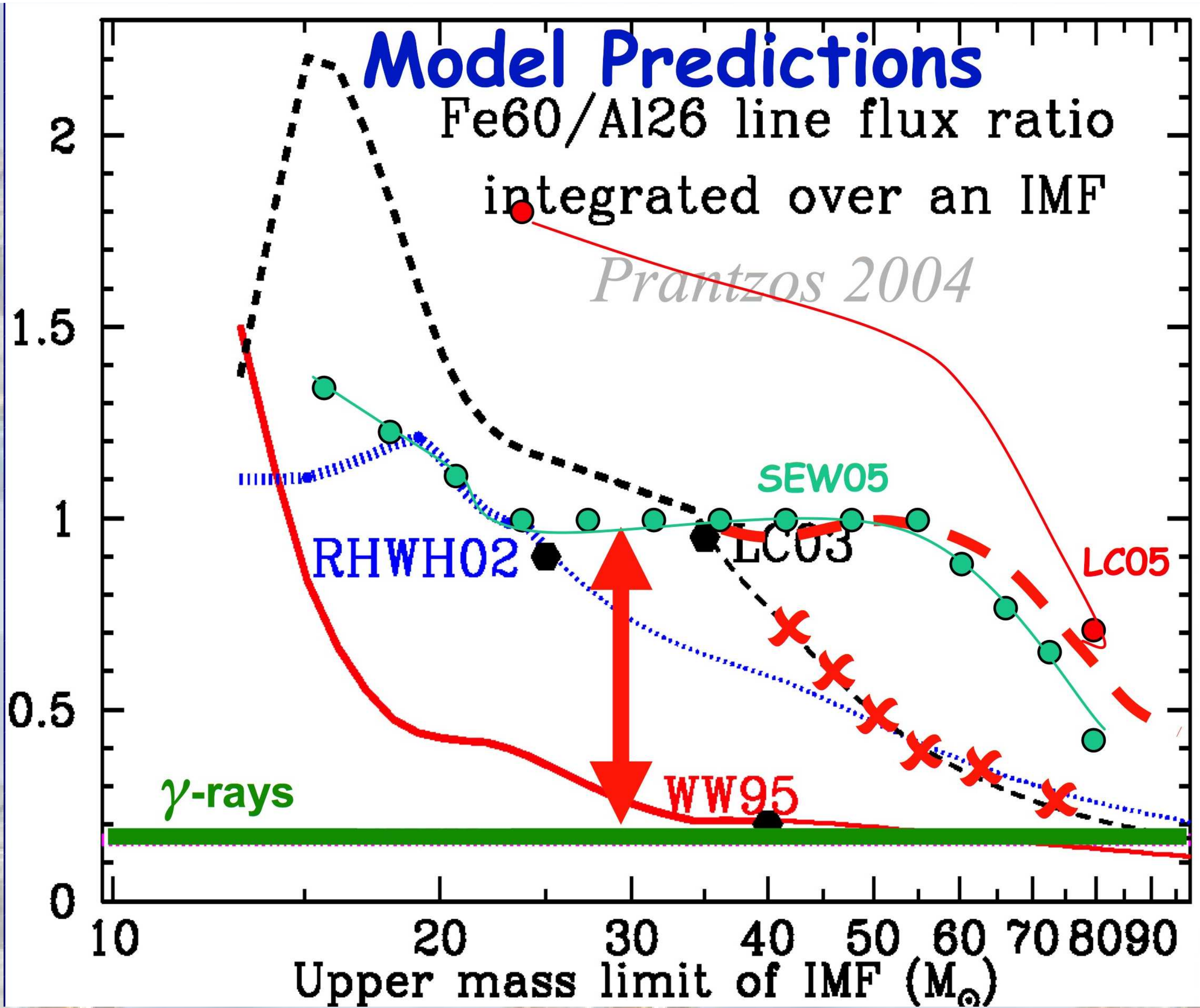
-Marginal (3-4σ) detections of the 1.172 and 1.333 MeV lines

RHESSI (Smith 2004) *INTEGRAL/SPI (Harris et al. 2005)*



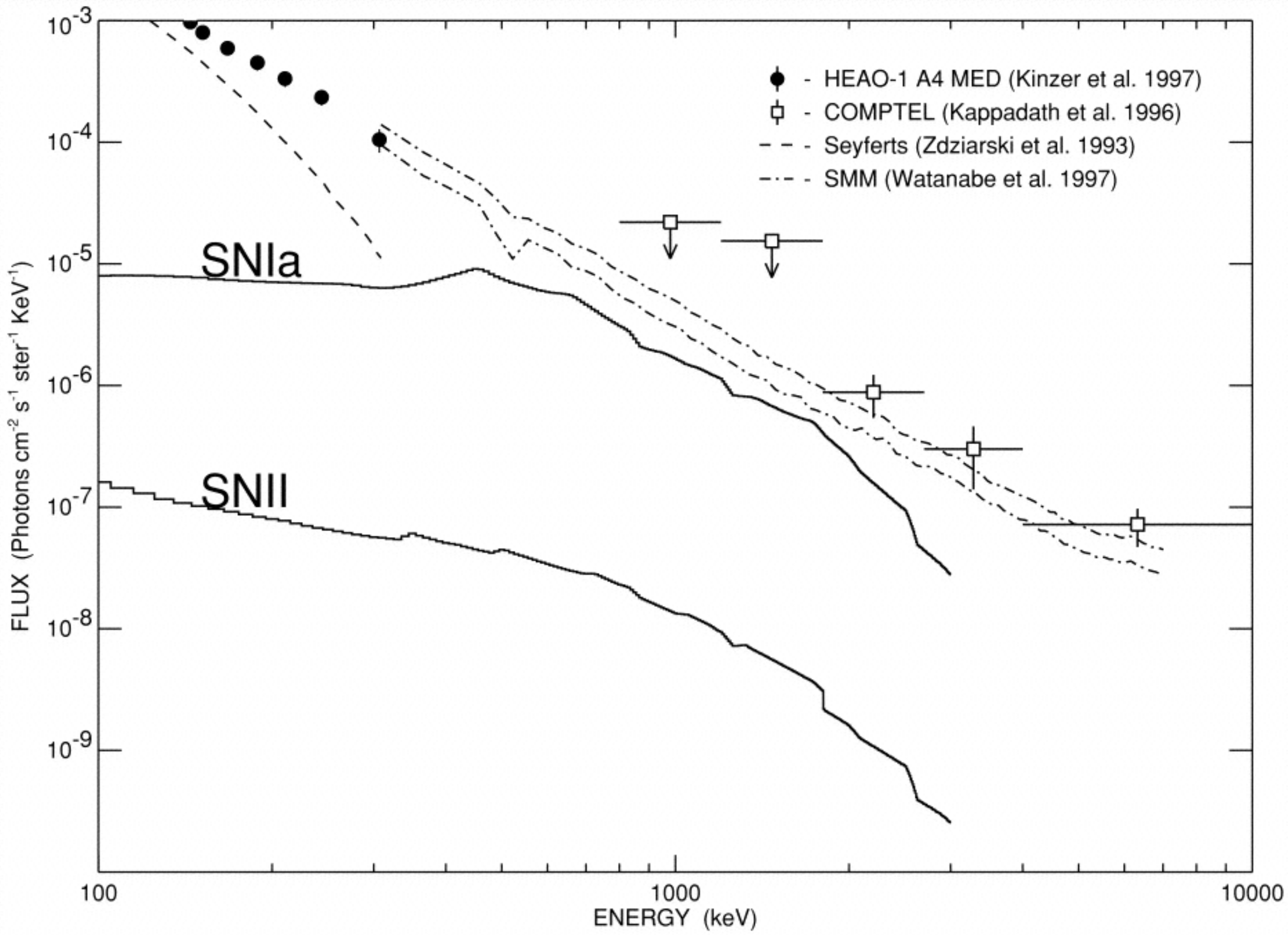


- the $^{60}Fe/^{26}Al$ ratio ~ 0.11 ± 0.03 *[INTEGRAL/SPI(Harris et al. 2005)]*



Some other source of ^{26}Al besides explosive nucleosynthesis in core-collapse SNe are required!

Cosmic Gamma-ray Background



(Watanabe et al. 1999)

-SNIa can not make this contribution? (Zhang et al. 2004)

-Is Dark Matter responsible? (Ahn et al. 2005)

-A future mission (e.g. ACT) could answer.

-the decay chain $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

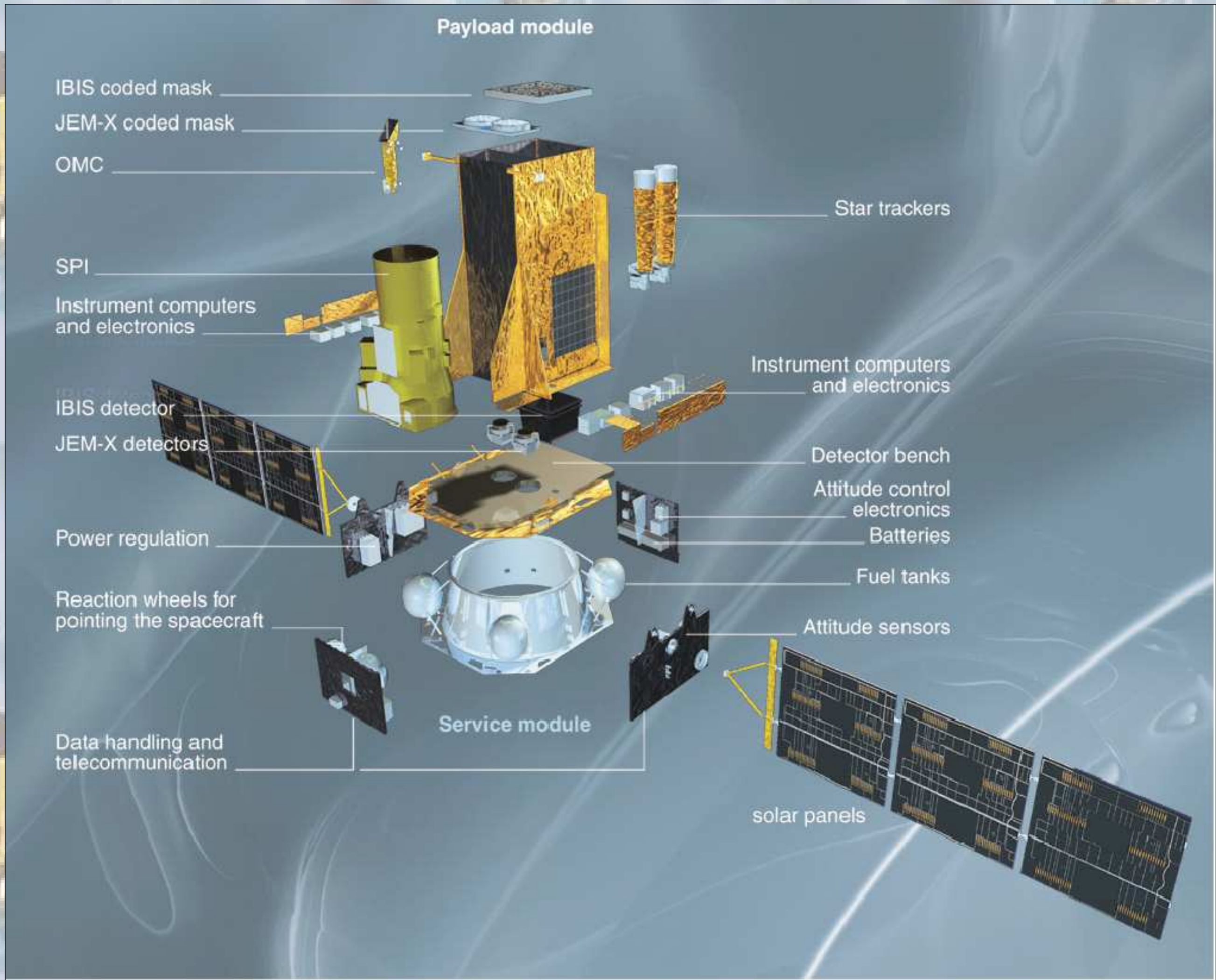
INTEGRAL Mission Description

- European Space Agency (ESA) mission
  - Launched 17 Oct., 2002
- Mission Science
  - Gamma-ray astronomy in 15 keV - 10 MeV range
  - Supporting x-ray and optical monitoring
- Payload
  - Main Instruments
    - SPI: germanium spectrometer
    - IBIS: CdTe + CsI imager
  - Monitor Instruments
    - JEM-X: x-ray monitor
    - OMC: optical monitor

Mission Description (cont.)

- *Follow-on to Compton Gamma-Ray Observatory (CGRO).*
- *New technologies result in significant improvements in performance over CGRO.*
  - *Germanium detectors $\Rightarrow$ ~ 50 x better energy resolution*
  - *CdTe detectors $\Rightarrow$ ~ 15 x better angular resolution*
- *Forms complementary set with SWIFT (gamma-ray bursts) and GLAST (high-energy gamma-rays).*

INTEGRAL Spacecraft



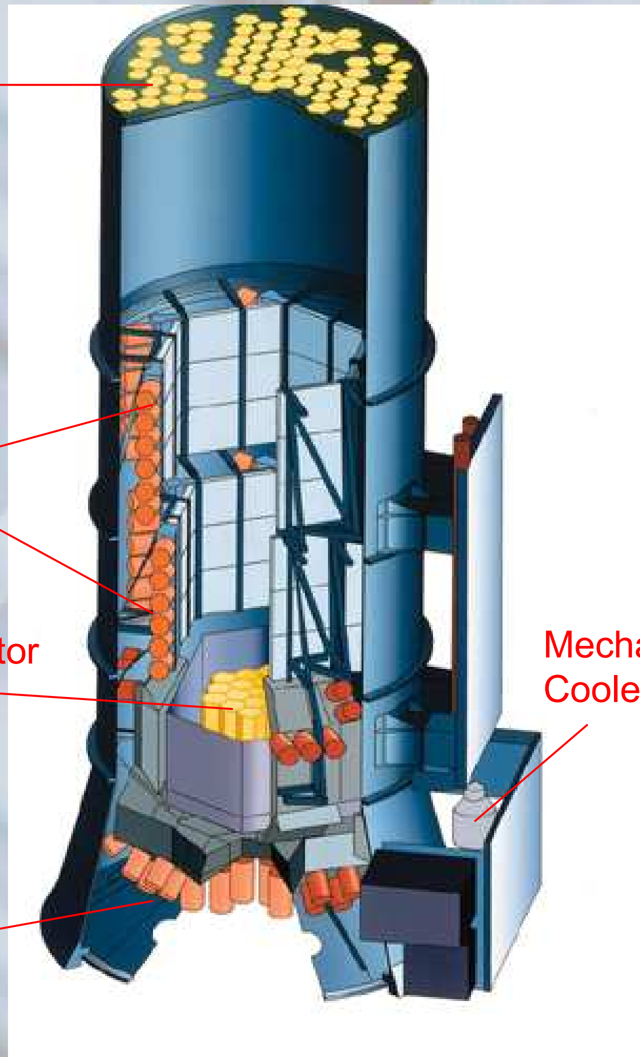
Detectors

	Energy Range	Energy Resolution	Field of View	Angular Resolution	Detector Area
SPI (SPectrometer on INTEGRAL	18 keV - 8 MeV	2.2keV @1.3MeV	16 deg fully coded	2.5 deg FWHM	500 cm^2 (19 hexagonal Ge detectors)
IBIS (Imager on Board the Integral Satellite)	15 keV - 10 MeV	8% @100keV 10% @1MeV	8.3 x 8.0 deg fully coded	12 arcmin FWHM	2600 cm^2(4x4x2 mm CdTe pixels) ISGRI, 3000 cm^2 (9x9x30 mm CsI pixels)PICsIT
JEM-X (Joint European X-ray Monitor)	3-35keV	1.3keV @10keV	4.8deg fully coded	3 arcmin	500 cm^2 (2 imaging microstrip gas chambers (90% Xenon + 10% Methane)

IBIS

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

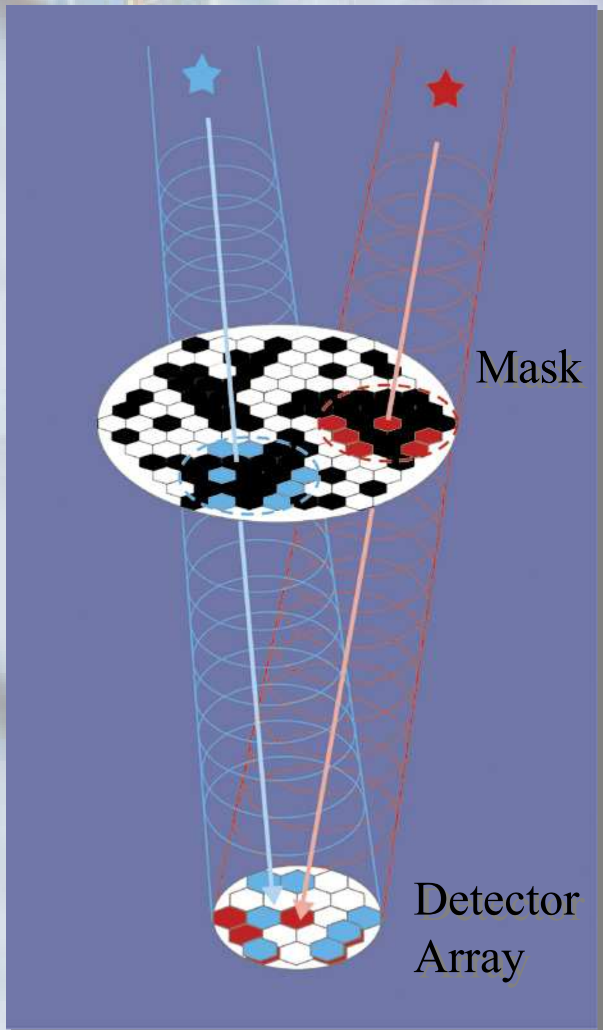
SPI

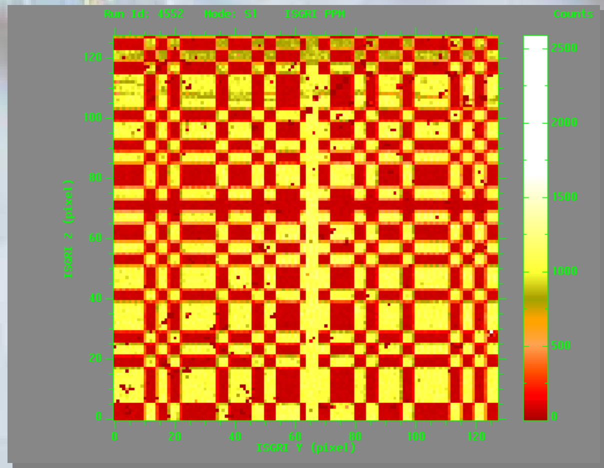


JEM-X

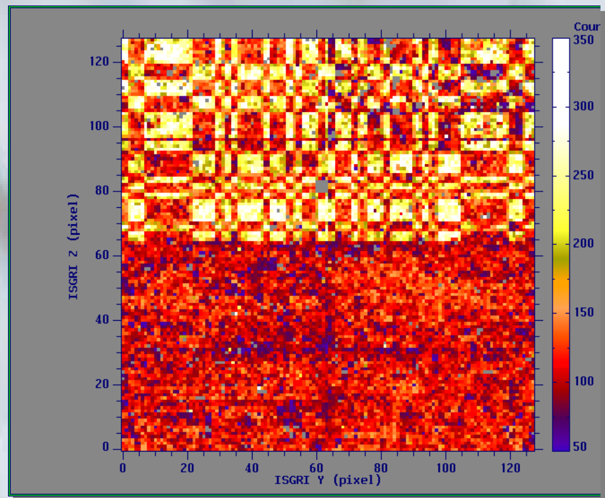
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Coded Aperture Imaging (SPI, IBIS and JEM-X)





IBIS fully-coded Crab shadowgram



IBIS off-axis Crab shadowgram

Some Highlights

•**Discoveries of various new sources**

HMXB:IGR J16318-4848, IGR J16320-4751, IGR J17391-3021, **Seyfert**: IGR J18027-1455
LMXB:IGR J16358-4726, IGR J16418-4532, IGR J17464-3213, **Neutron star:** IGR J17597-2201
γ-ray Sources: IGR J00291+5934,IGR J06074+2205,IGR J07597-3842,IGR J11305-6256,
IGR J16167-4957,IGR J16479-4514, IGR J16558-5203,IGR J17252-3616,
IGR J18325-0756,IGR J18450-0435,IGR J18483-0311,IGR J21247+5058

•**A faint persistent source within 1' of Sgr A*** (Bélanger et al., 2005, astro-ph/0508128)

•**Identification of the Galactic TeV (H.E.S.S.) sources: IGRJ18135-1751 & AX J1838.0-065**
(Ubertini et al., ApJ 629, L109, 2005; Malizia et al., ApJ 630, L157, 2005)

•**Fast X-ray transients of just a few hours duration: XTE J1739-302**
(Sguera et al., astro-ph/0508018; Smith et al., astro-ph/0510658)

•**ms pulsar IGR J00291+5934: the fastest known accreting X-ray pulsar (1.67ms, P_{orb}= 2.46h)** (e.g. Falanga et al., A&A 436, 647, 2005)

•**Anomalous X-ray Pulsar 4U 0142+614** (den Hartog et al., 2004,ATel #293)

•**Gamma-RayBursts or X-ray flashes**
(e.g. GCN #3059, 3323, 3348, 3430, 3446, 3472, 3552, 3607, 4002, 4007, 4192).

511 keV Emission

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Possible Positron Sources

- Massive stars (e.g. Wolf-Rayet)
  - *Positrons created by nucleosynthesis in stellar interior, convected to surface and transported into interstellar medium (ISM) by stellar wind.*
- Hypernovae
  - *Asymmetric explosion of a massive (> 30 M_{sun}) star. Positrons can be efficiently transported outward by strong jets and escape into low optical depth regions where they subsequently annihilate.*
- Black Holes (BH)
  - *Pair plasmas believed to exist in BH jets.*
  - *Could either be aggregate emission from many BHs in Galactic Center region or from a single massive BH at Galactic Center.*
- Type Ia Supernovae
  - *Beta-decay of radioactive nuclei created in SN explosion and transported into ISM)in expanding shell.*

Possible Positron Sources

- *Dark Matter*
  - *There has been recent speculation on the possible existence of light ($mc^2 < 100$ MeV) dark matter particles which would decay or annihilate primarily through the formation of electrons and positrons.*

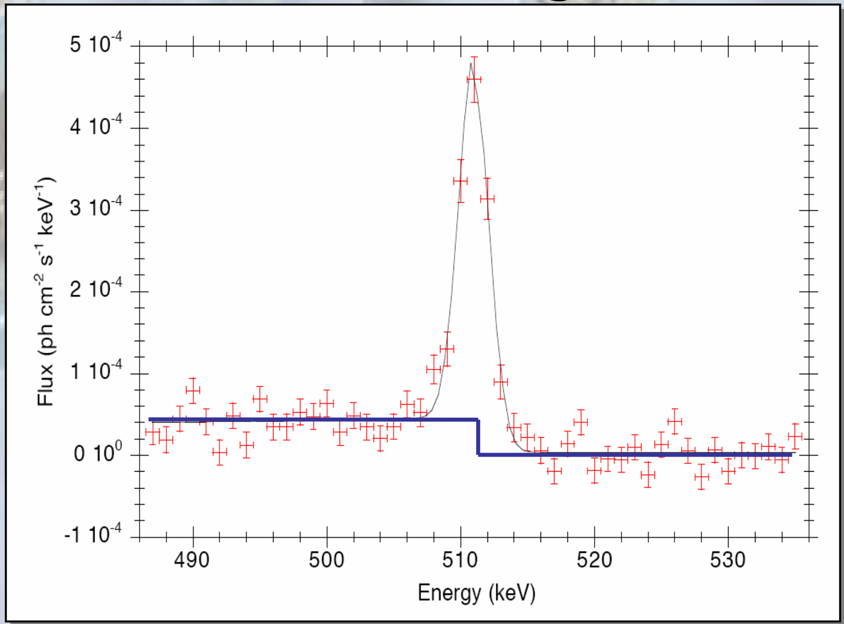
- *Superconducting Strings*
  - *Positron production proportional to Galactic magnetic field.*

511 keV Spectroscopy

- *Measured line energy consistent with rest energy, mc^2 = 511.00 keV.*

- *Narrow line width (2.3 keV) consistent with annihilation in warm interstellar clouds.*

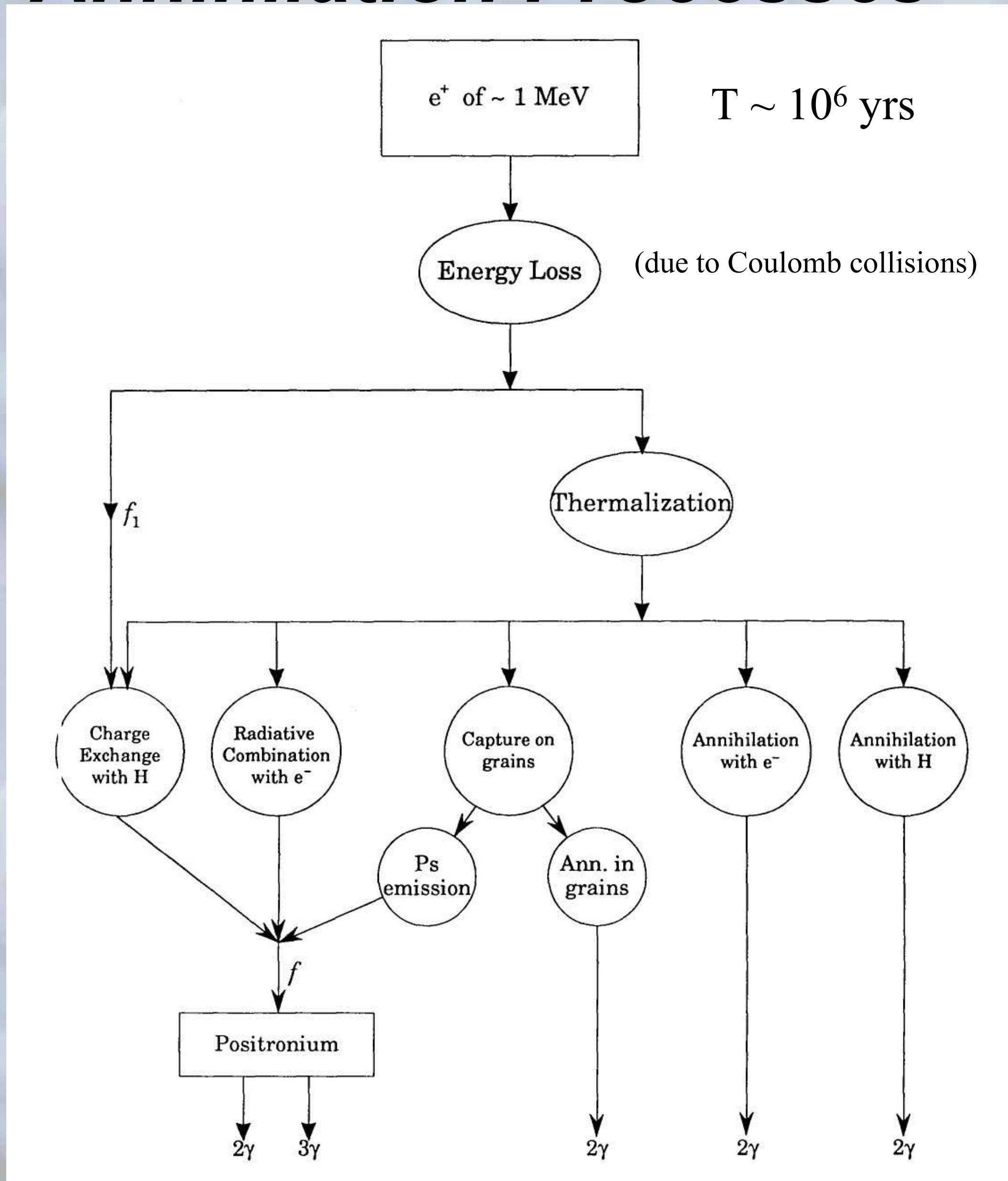
- *Step in continuum from positronium (ps). Ortho-positronium is formed 3/4 of the time and undergoes 3-photon decay.*



511 keV Line Flux (10^{-3} cm^{-2} s^{-1})	1.35 ± 0.11
Line Energy (keV)	511.14 ± 0.08
FWHM (keV)	2.34 ± 0.24
Positronium Continuum Flux (10^{-3} cm^{-2} s^{-1})	4.7 - 10.2
Ps fraction	> 0.88

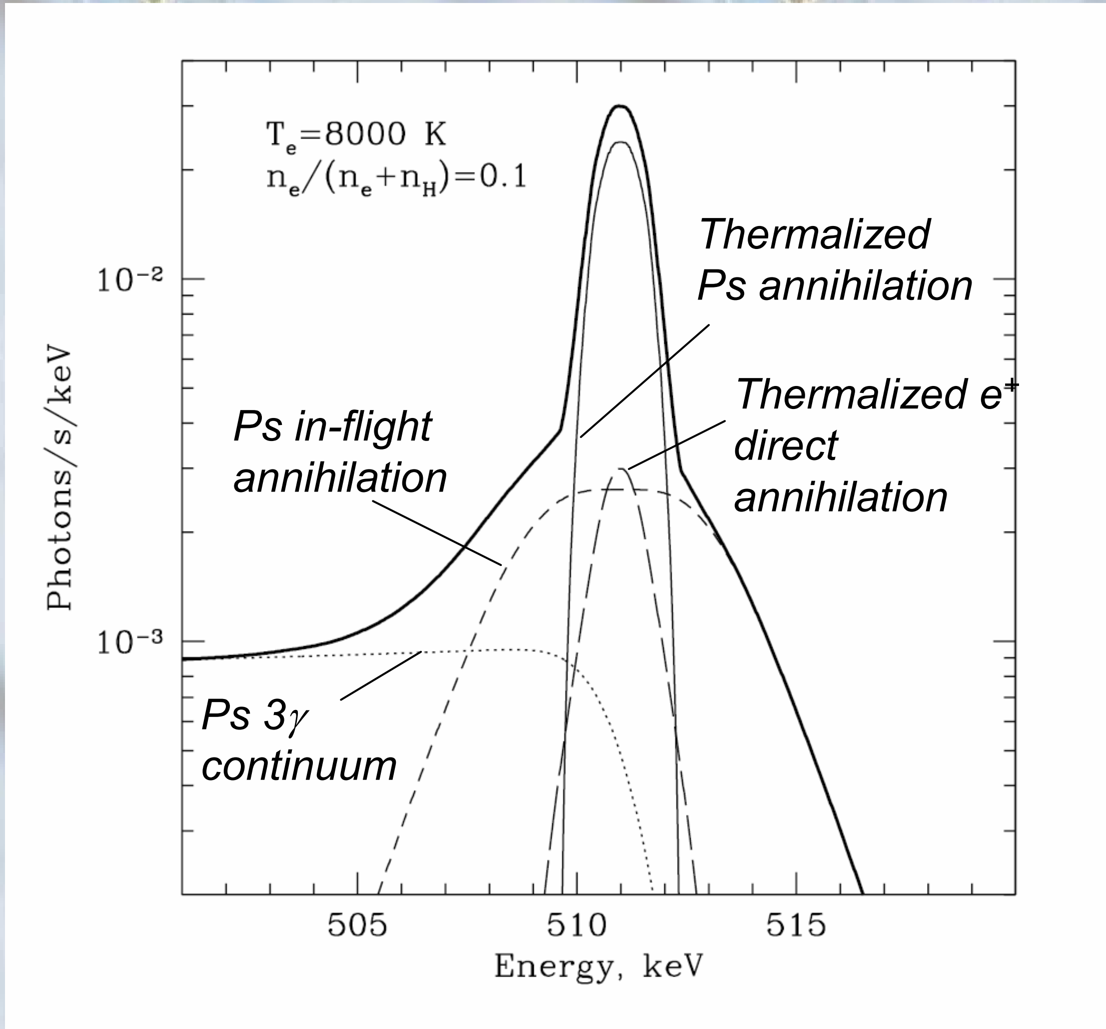
Annihilation Processes

Guessoum et al.(1991)



511 keV Line Profile
(Churazov et al., 2005)

- *Positrons probably migrate far from source and annihilate somewhere in ISM.*
- *511 keV line profile and positronium fraction are diagnostic of annihilation region.*
- *Annihilation probably takes place in warm ($T \sim 10^4$ K) partially ionized region of ISM.*

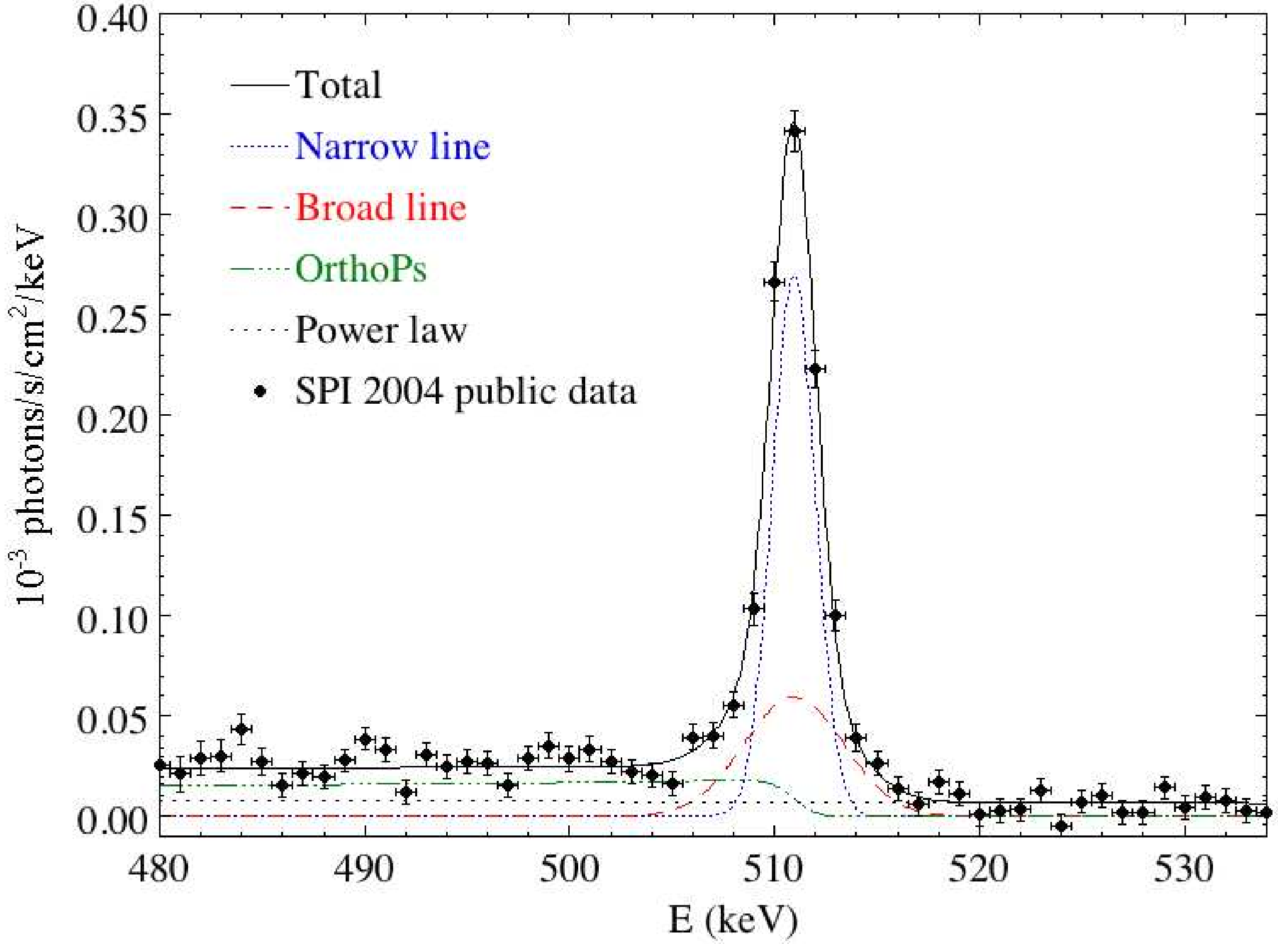


Courtesy of P. Jean

Best spectral model

$$S_l(E) = I_n \times G(E,\Gamma_n) + I_b \times G(E,\Gamma_b) + I_{3\gamma} \times O(E) + A_c \left(\frac{E}{511}\right)^s$$

Param.	Measured values
I_n	$(0.72 \pm 0.12 \pm 0.02) \times 10^{-3}$ s^{-1} cm^{-2}
Γ_n	$1.32 \pm 0.35 \pm 0.02$ keV
I_b	$(0.35 \pm 0.11 \pm 0.02) \times 10^{-3}$ s^{-1} cm^{-2}
Γ_b	$5.36 \pm 1.22 \pm 0.06$ keV
$I_{3\gamma}$	$(4.23 \pm 0.32 \pm 0.03) \times 10^{-3}$ s^{-1} cm^{-2}
A_c	$(7.17 \pm 0.80 \pm 0.06) \times 10^{-6}$ s^{-1} cm^{-2} keV^{-1}



$\chi^2 \sim 171.3$ (d.o.f. 148)

Broad line detected (3.2σ)
I_b ~1/3 of the 511 keV flux

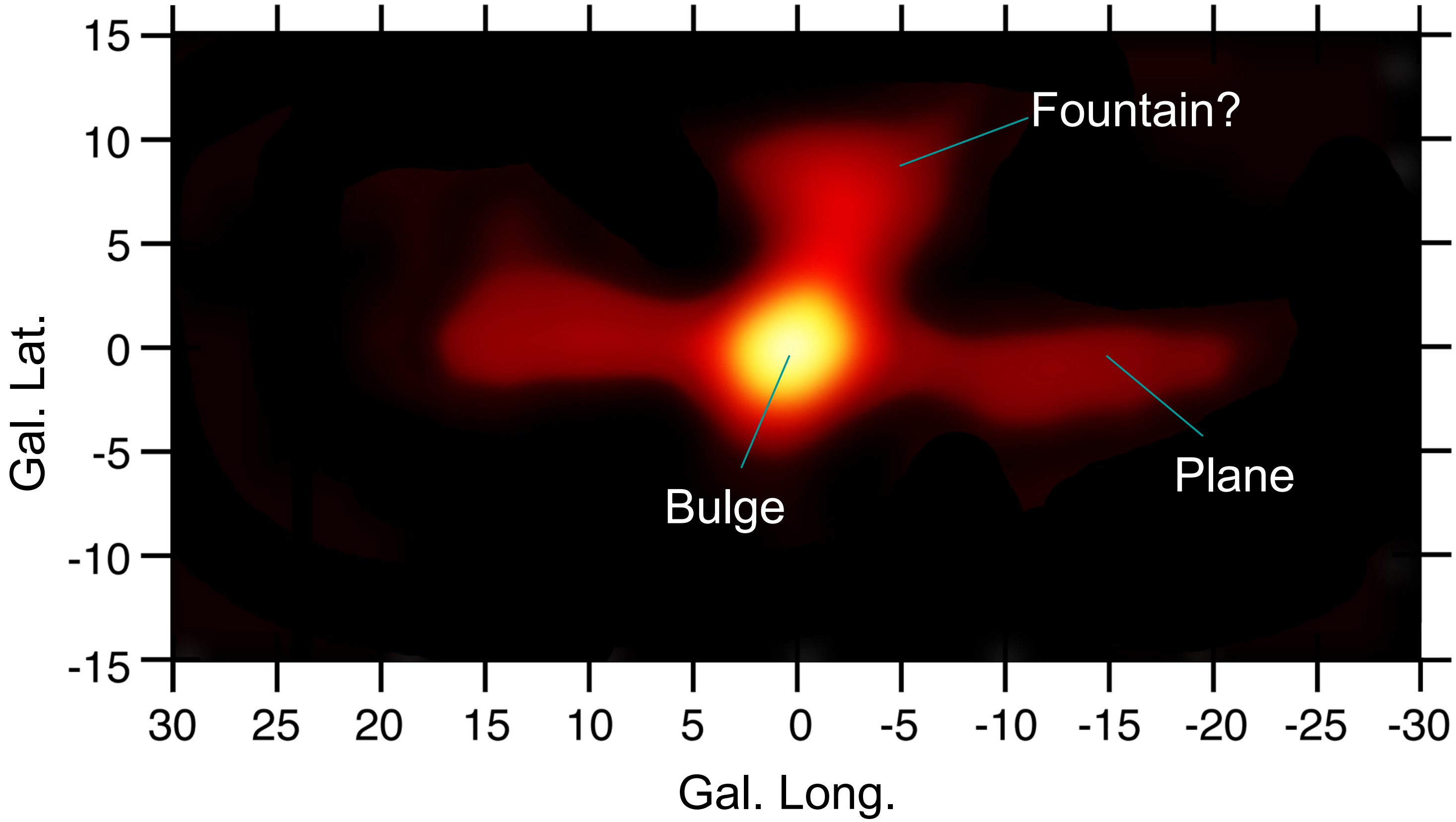
Total 511 keV flux :
$(1.07 \pm 0.03) \times 10^{-3}\ \gamma$ s^{-1} cm^{-2}

Ps fraction : 96.7±2.2 %
(systematic error ~ 0.2%)

Remark :
- s = 1.75 (fixed)
  Kinzer et al., 1999
- line centroïds are fixed

CGRO/OSSE 511 keV Map

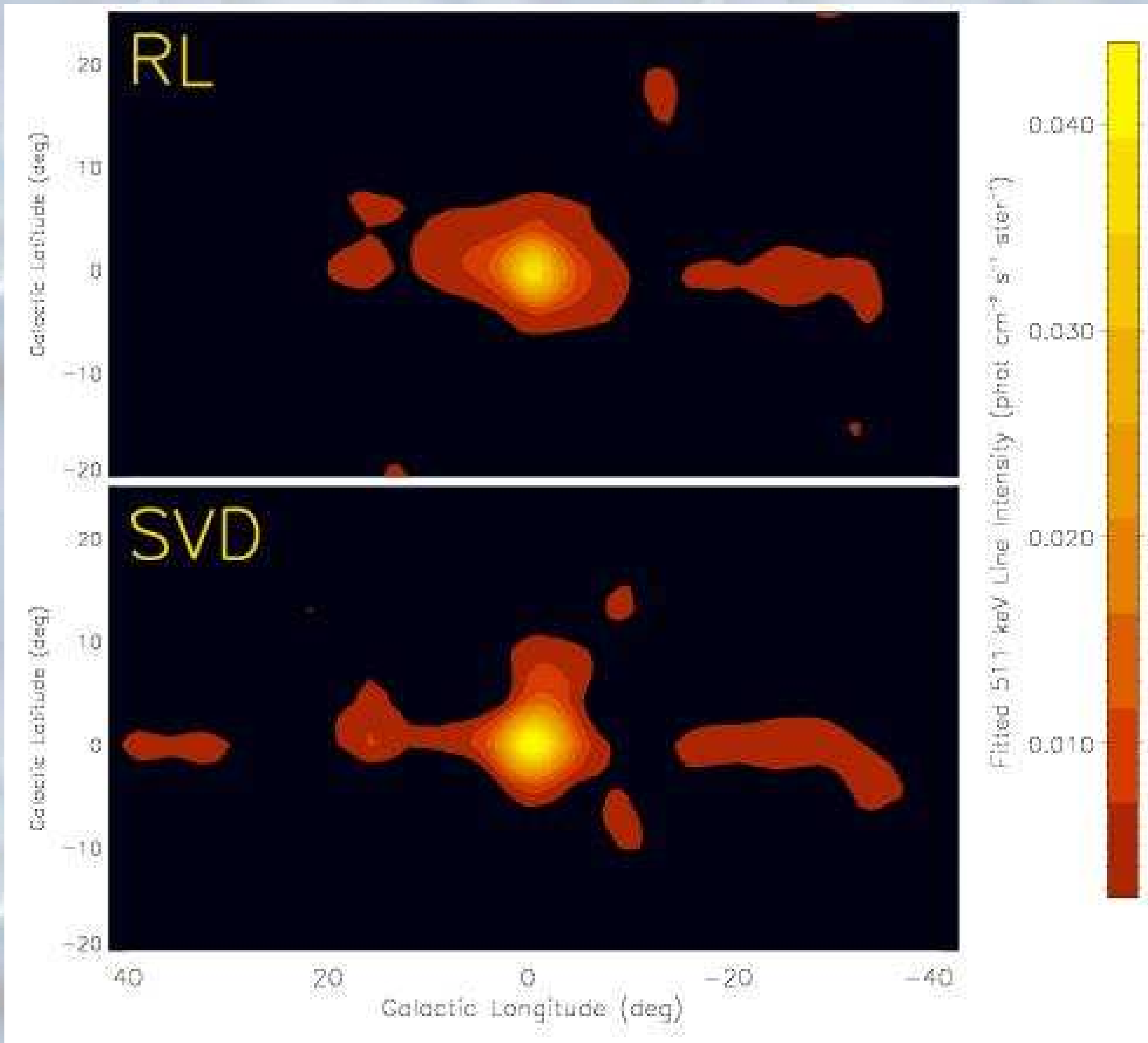
(Purcell et al., ApJ, 1997)



Mapping 511 keV line emission: OSSE/SMM/TGRS

Richardson-Lucy Algorithm

Singular Value Decomposition Algorithm



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Courtesy of P. Milne

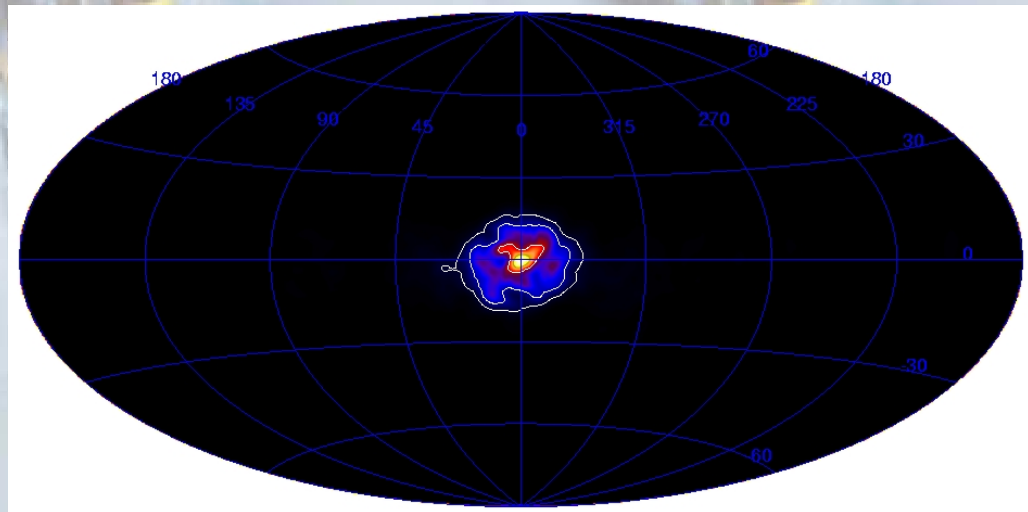
INTEGRAL/SPI vs. CGRO/OSSE

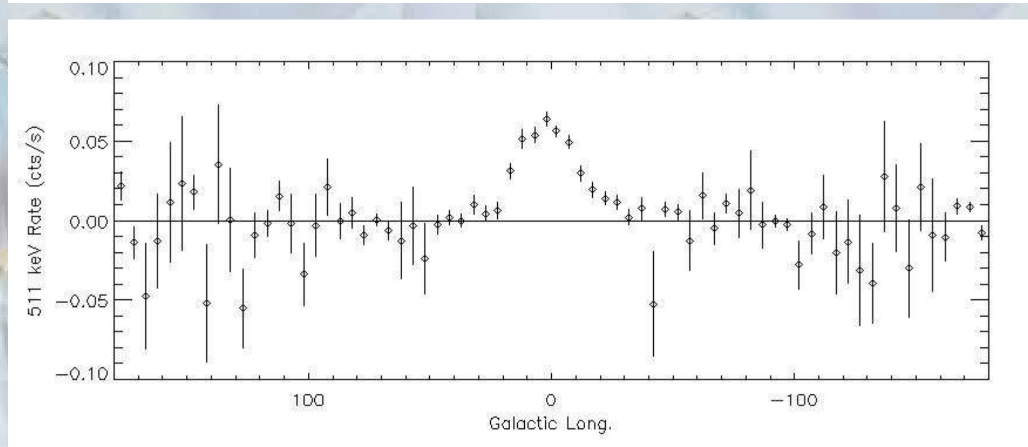
	OSSE	INTEGRAL/SPI
Background	Low-earth orbit. Variable background.	High orbit outside magnetosphere. Stable background.
Imaging	Simple 4° x 11° collimator.	Coded aperture. 3° resolution.
Energy Resolution ($E/\Delta E$ @ 511 keV)	~ 10	~ 250
Narrow Line Sensitivity (511 keV, 10^6 sec)	~ 5 x 10^{-5} cm^{-2} s^{-1}	~ 5 x 10^{-5} cm^{-2} s^{-1}

511 keV Spatial Distribution

- *Bulge distribution*
  - *Data are reasonably well fit by symmetric gaussian with FWHM = 8° ± 1°*
  - *No evidence for OSSE "fountain"*
  - *Ensemble of point sources cannot be ruled out*
- *Concentration of flux at GC suggests older population.*

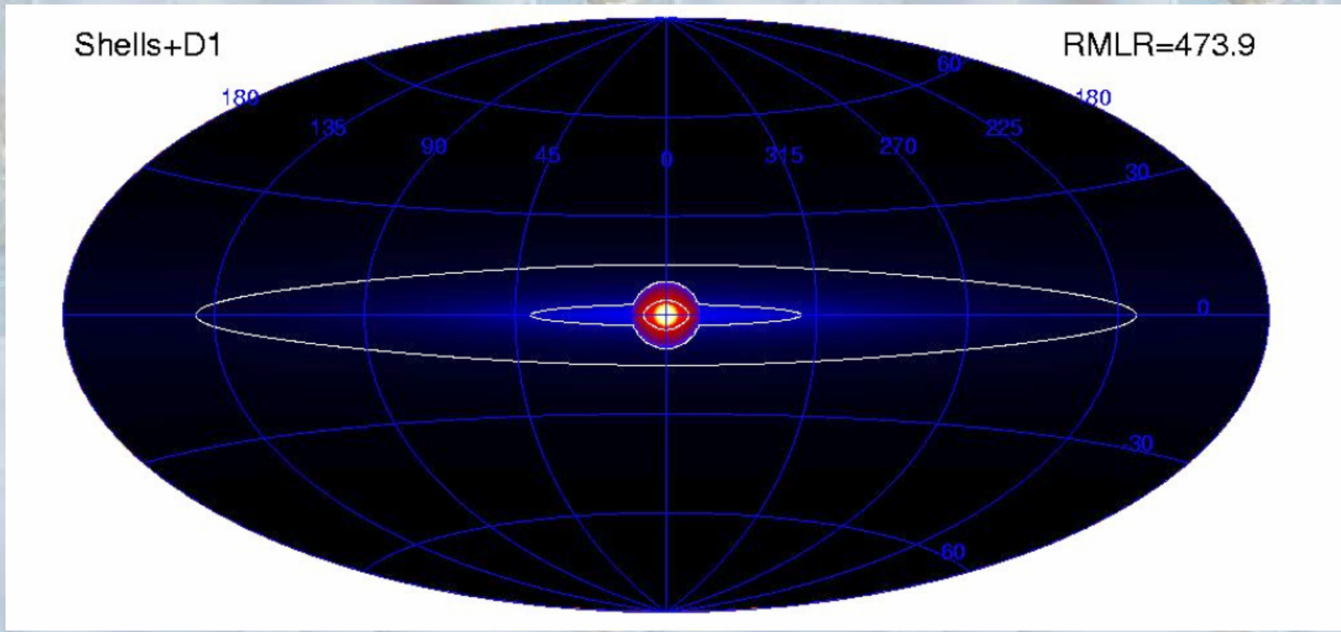
Knodlseder et al., 2005





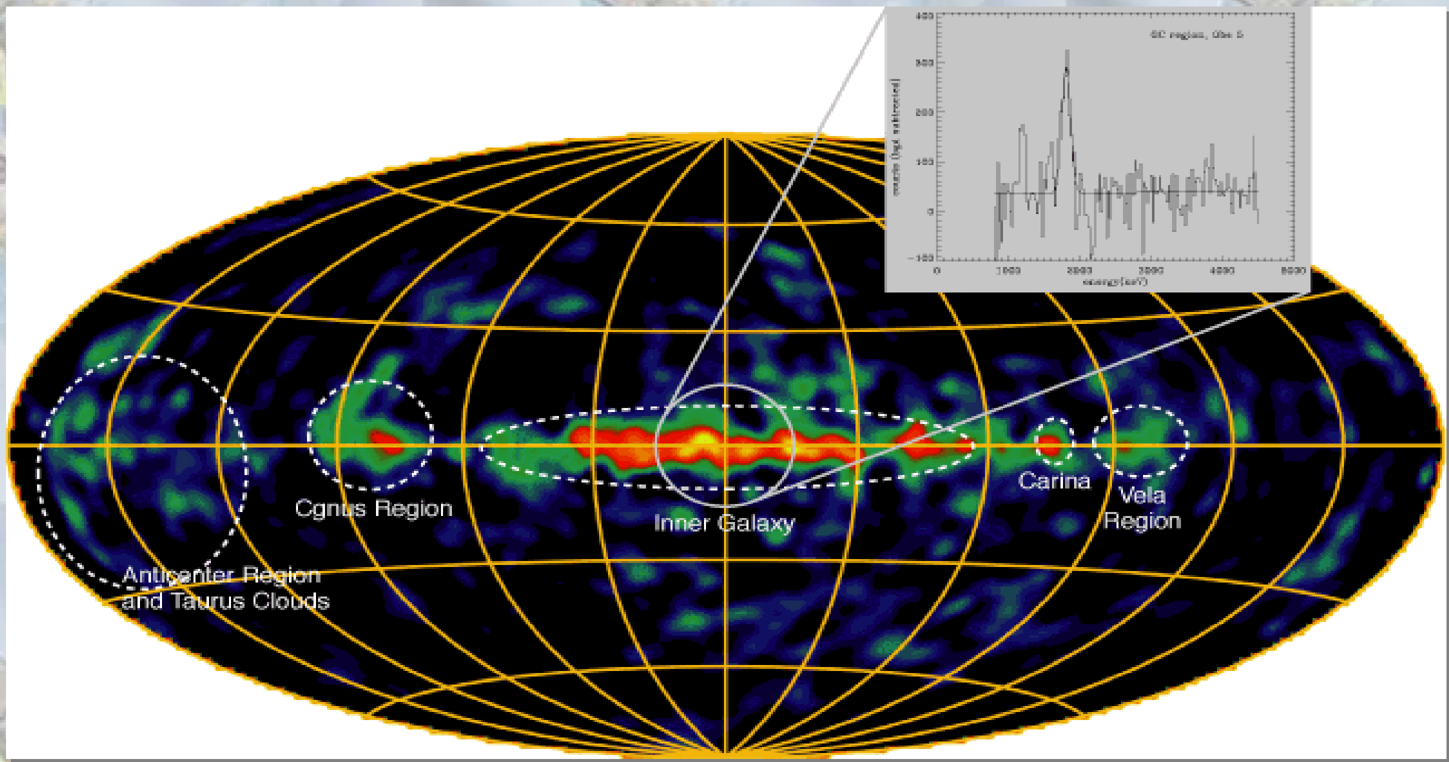
Teegarden, Watanabe et al., 2005

511 keV Bulge + Disk Model



- *INTEGRAL marginally detects 511 keV galactic disk component at 3-4 σ significance.*
  - *F_{511} = (7$\pm$5) x 10^{-4} cm^{-2} s^{-1} (Knodlseder et al., 2005)*
  - *Bulge/disk ratio = 1 - 3*

CGRO/COMPTEL ^{26}AL (1809 keV) Map



- ^{26}*Al in the Galaxy is most likely produced by nucleosynthesis in massive stars.*
  - *$E\gamma$ = 1809 keV*
  - *Half-life = 7.2 x 10^5 yr*

511 keV from ^{26}Al

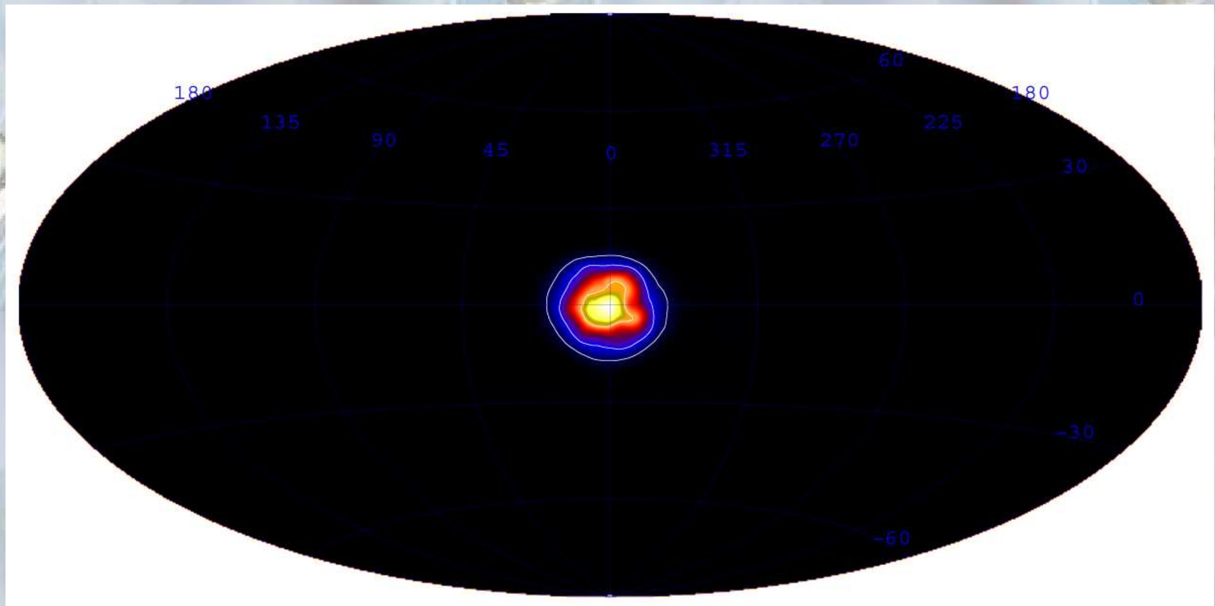
- *511 kev disk component could be accounted for by ^{26}Al decay*
  - *$^{26}Al(\beta^+)^{26}Mg$,*
    - *f_{decay} = 82% (β^+ decay fraction)*
  - *$F_{1809} \approx 7 \times 10^{-4}\ cm^{-2}\ s^{-1}$*
  - *$F_{511} = f_{decay} \times f_{511} \times F_{1809}$*
    $= 3.5 \times 10^{-4}\ cm^{-2}\ s^{-1}$

(f_{511} = no. of 511 keV ph/annihilation ≈ 0.65)

Predicted 511 keV disk component flux from ^{26}Al decay is ~ 50% of observed value but still within error bar.

Positronium Map

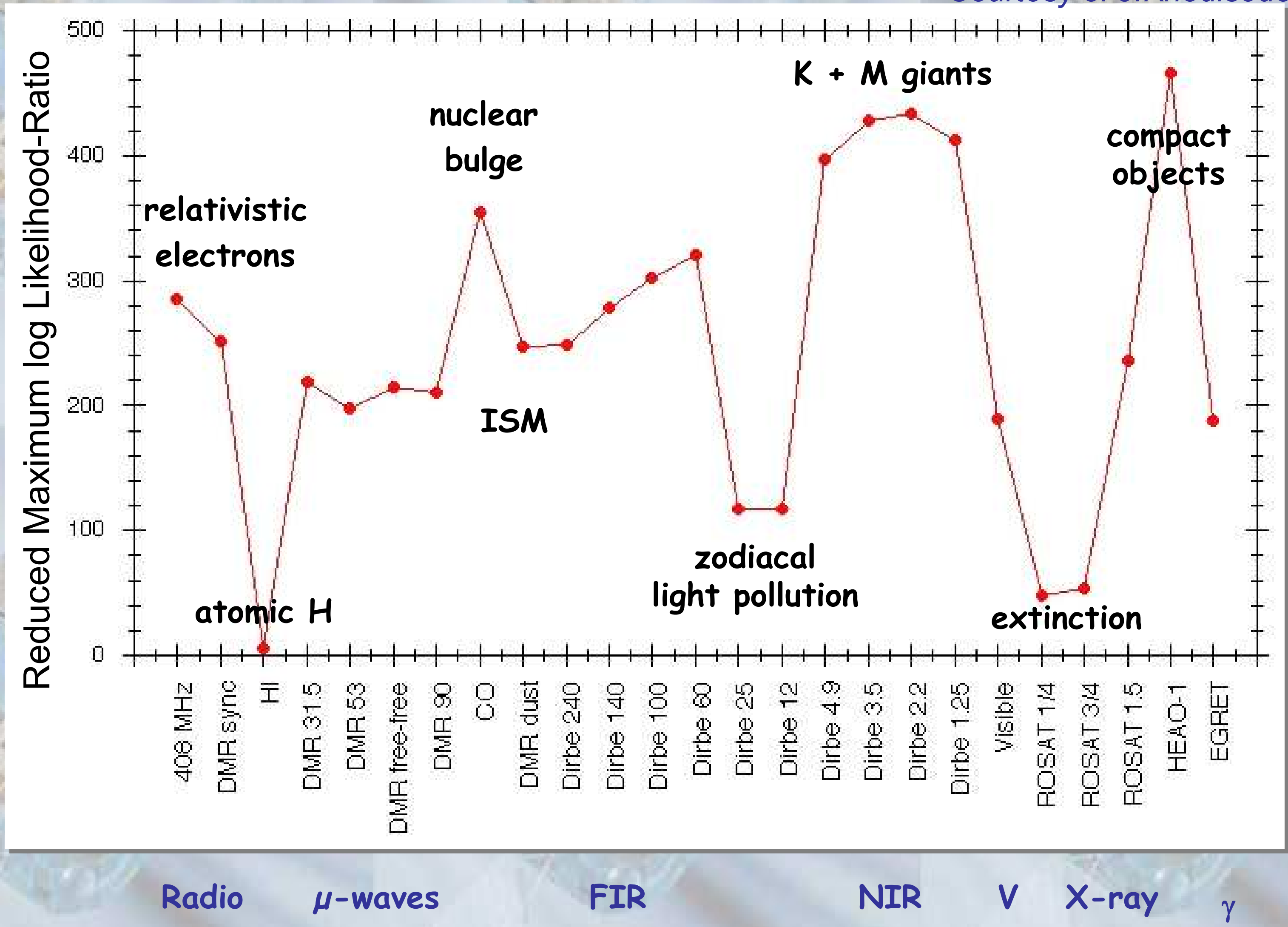
Weidenspointner et al.,2005



- *More difficult measurement due to broader energy range.*
  - *Smaller signal-to-background ratio*
  - *More complex background*
- *Similar morphology to 511 keV narrow line.*
- *Consistent with OSSE results.*

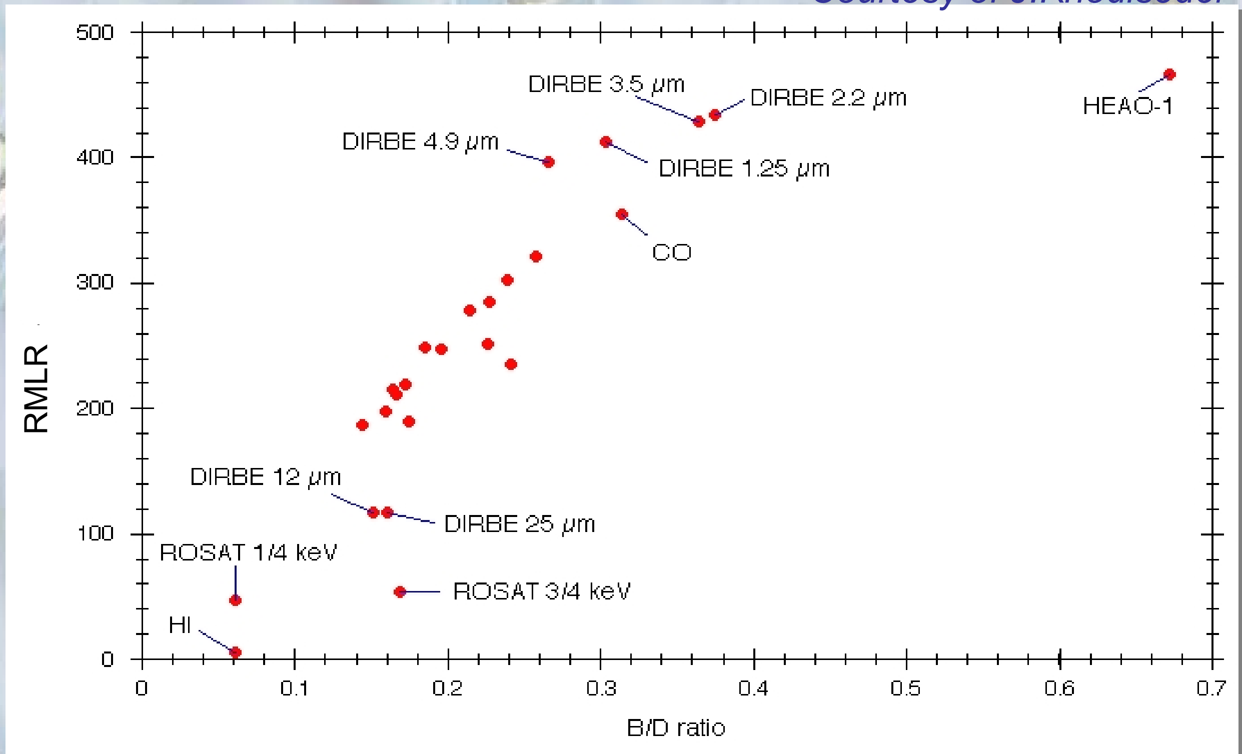
Searching for Tracer of 511 keV Emission

Courtesy of J.Knodlseder



Likelihood vs. Bulge-to-Disk Ratio

Courtesy of J.Knodlseder



- Data favour large B/D ratio
- HEAO-1 traces X-ray binaries
- Low-mass X-ray binaries show a strong concentration towards GC (B/D ~ 1.8)

Origin of positrons

- LMXB ?
- Old stellar population (SN Ia) ?
- Dark Matter ?

LMXB 511 keV Limits

No smoking gun

Knodlseder et al., 2005

Source	l (deg	b (deg)	Distance (kpc)	3 σ Flux Limit (10^{-4} ph cm^{-2} s^{-1})
GX 5-1	5.08°	-1.02°	~ 8?	< 0.7
GRS 1915+105	45.37°	-0.22°	12.5	< 1.0
A 0620-00	209.96°	-6.54°	1.5 - 2.5	< 3.8
Nova Muscae	295.30°	-7.07°	5.5	< 2.0
Cir X-1	322.12°	0.04°	> 8	< 1.1
Cen X-4	332.24°	23.89°	?	< 1.7
GX 349+2	349.10°	2.75°	?	< 0.8
Sco X-1	359.09°	23.78°	0.7	< 1.5

•Also a Comprehensive Line Search (Teegarden & Watanabe 2005) does not find any 511 keV point sources

Conclusions

(511 keV Emission)

- *INTEGRAL/SPI has measured the spatial and spectral profiles of the Galactic 511 keV emission.*
- *Spatial distribution:*
  - *~10° symmetric bulge component in the direction of the Galactic Center.*
  - *Weakly detected disk component, possibly from ^{26}Al decay.*
  - *Positronium spatial distribution similar to narrow line spatial distribution.*
  - *Favors older population, e. g. LMXB or SNIa, or perhaps dark matter origin.*
- *Spectral distribution:*
  - *Narrow line: FWHM ~ 2 keV*
  - *Line energy = electron rest energy within errors*
  - *Positronium step: ps fraction > ~ 0.9*
  - *Indicates that annihilation takes place in warm (~ 10^4 K) partially ionized region of the ISM.*