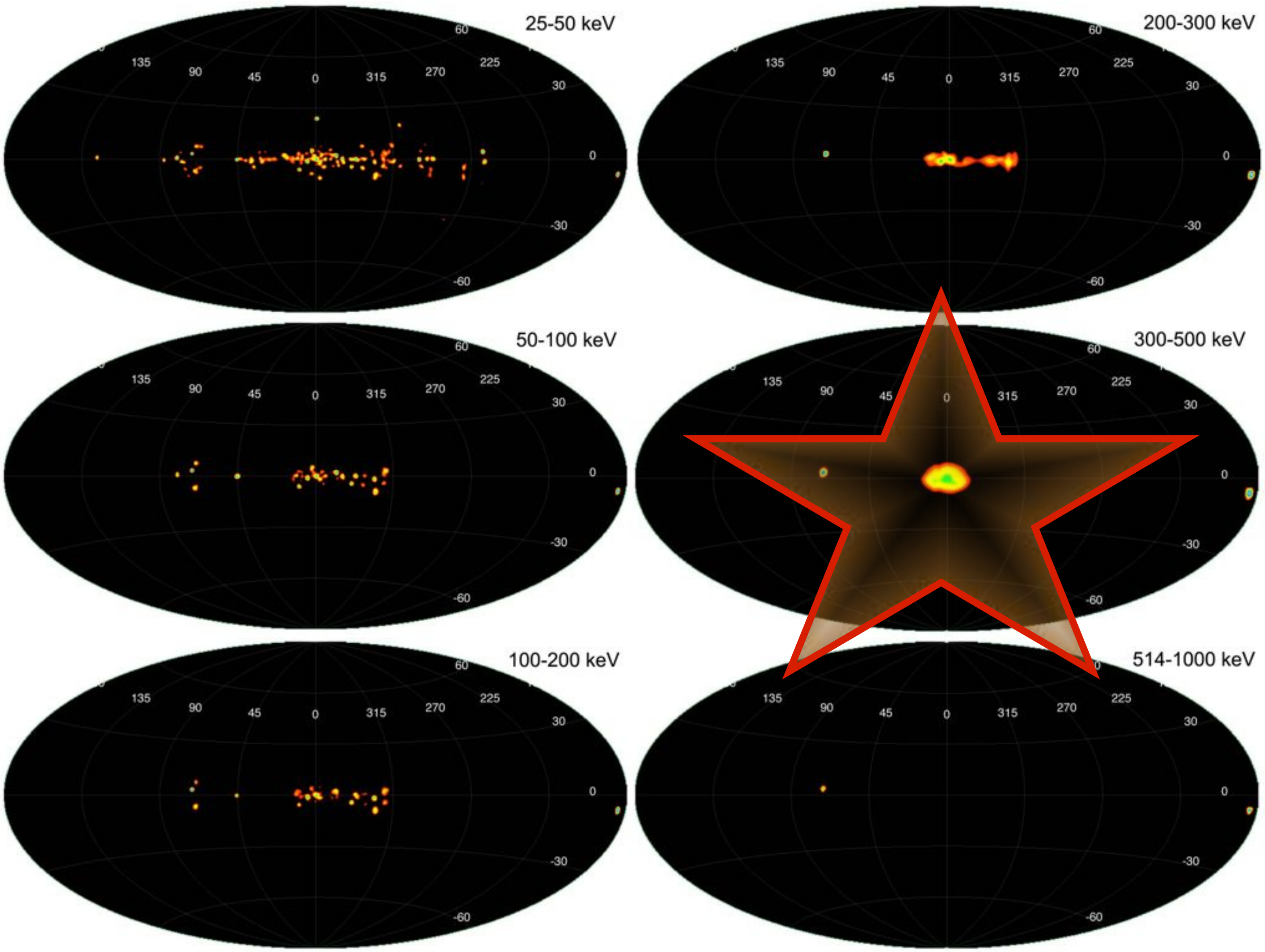
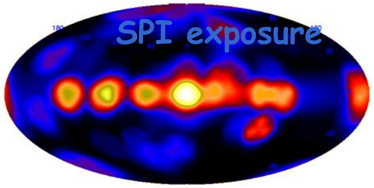
The High-Energy Sky (hard-X to HE γ-rays)

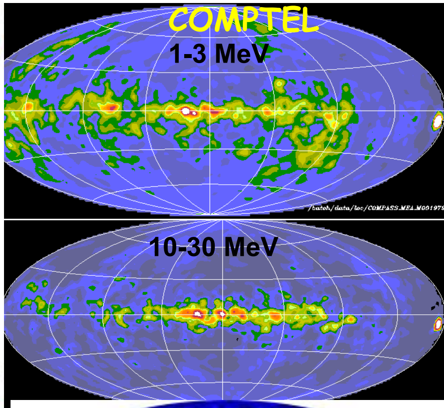


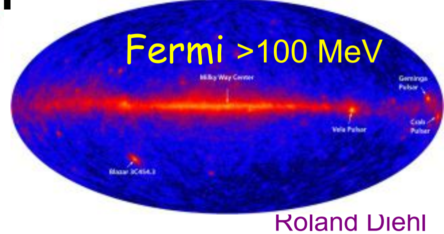
☆ **Annihilation Emission is Different!**

obs = 750 days, SPI/MREM

Knödlseder et al.





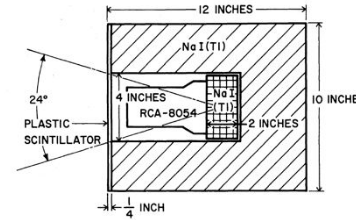


Observations
of
Galactic Positron Annihilation

Contents

The First Gamma-Ray Line Detected: Positron Annihilation!

Balloon Experiments of Rice Gamma-Ray Group:



☆ This is a Celestial 0.5 MeV Line

-> Positron Annihilation in Interstellar Space!

☞ *Johnson, Harnden & Haymes (1972, 1973); Haymes et al. (1975)*

120 W. N. JOHNSON AND R. C. HAYMES Vol. 184

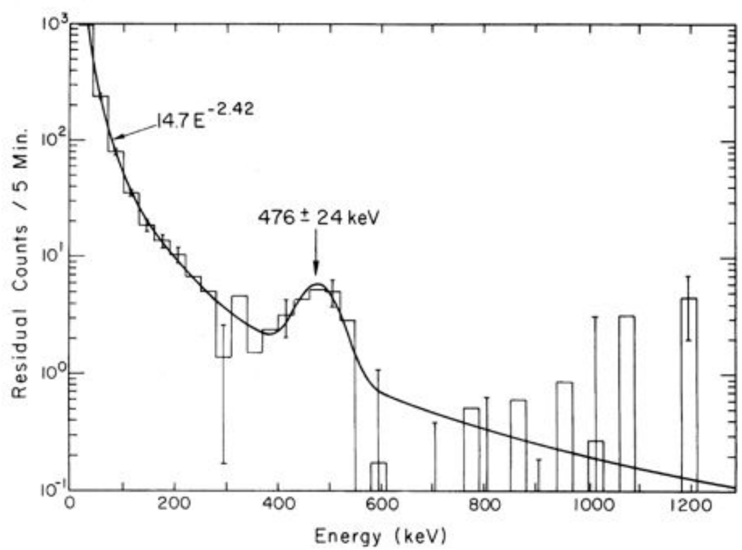


FIG. 15.—A histogram representation of the measured flux from the galactic-center region, as determined by a weighted average of the 1970 and 1971 observations. The pulse-height channels have been combined into consecutive 30 keV energy intervals. Also shown is the best-fit power-law continuum with the best Gaussian photopeak superimposed at energy of 476 keV. The displayed error bars represent $\pm 1\ \sigma$.

Haymes et al. (1975)

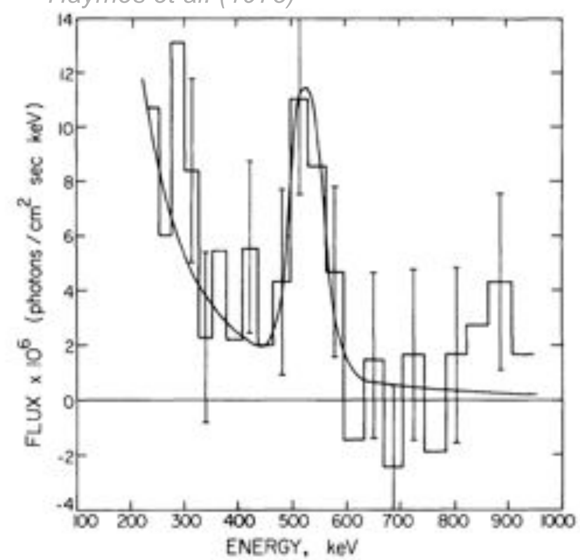


FIG. 6.—Measured differential energy spectrum of the galactic center region, for energies below 1.0 MeV. The solid curve is the best-fit power law. Bins plotted are each 0.5 FWHM wide in energy. The spectral line at 0.5 MeV is at the 3.5 σ confidence level. Other spectral lines may also exist in this low energy portion of the spectrum.

"Certainty": High-Resolution Detection

- ☆ **Bell/Sandia Balloon Experiment with Ge Detector**
  - ☞ *Leventhal, MacCallum, Stang (1978)*

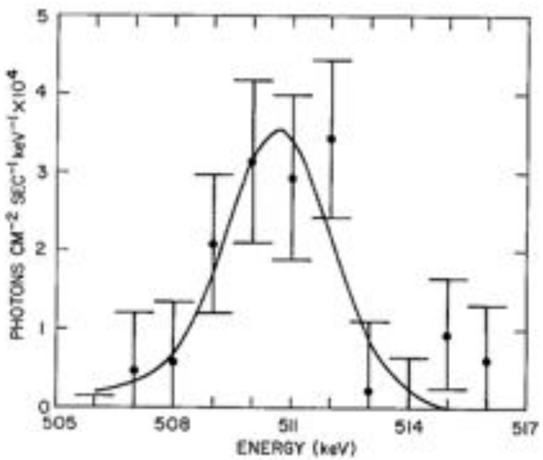


FIG. 2b.—An expanded version of Fig. 2a in the vicinity of 511 keV. The line center was found at 510.7 ± 0.5 keV with a width limited by system resolution at ≲3.2 keV. The line flux was found to be $(1.22 \pm 0.22) \times 10^{-3}$ photons cm^{-2}s^{-1} at the top of the atmosphere.

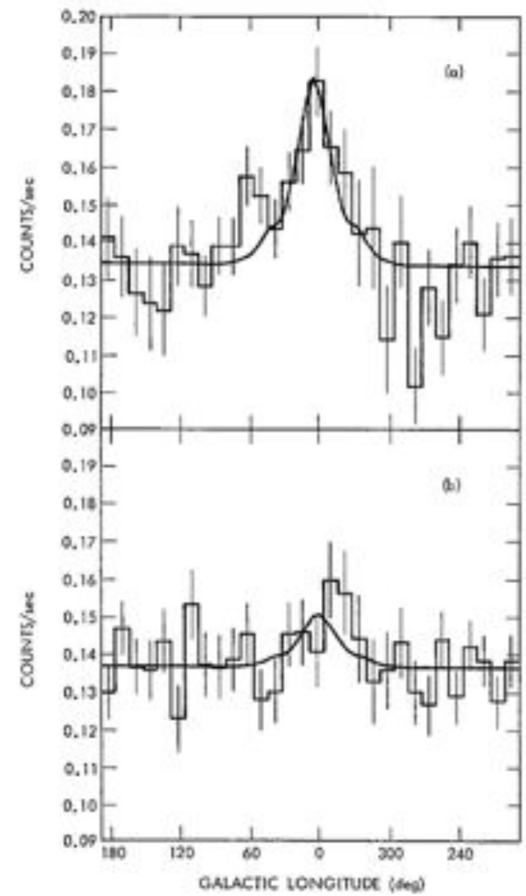
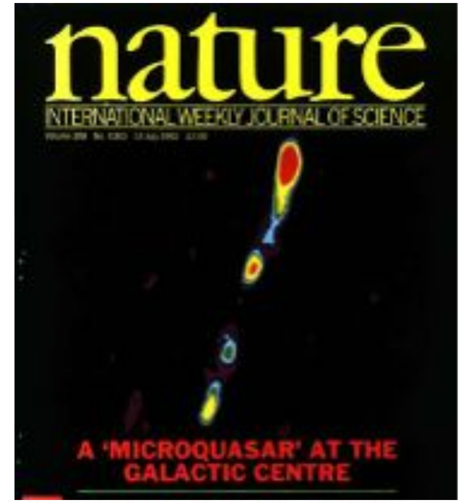


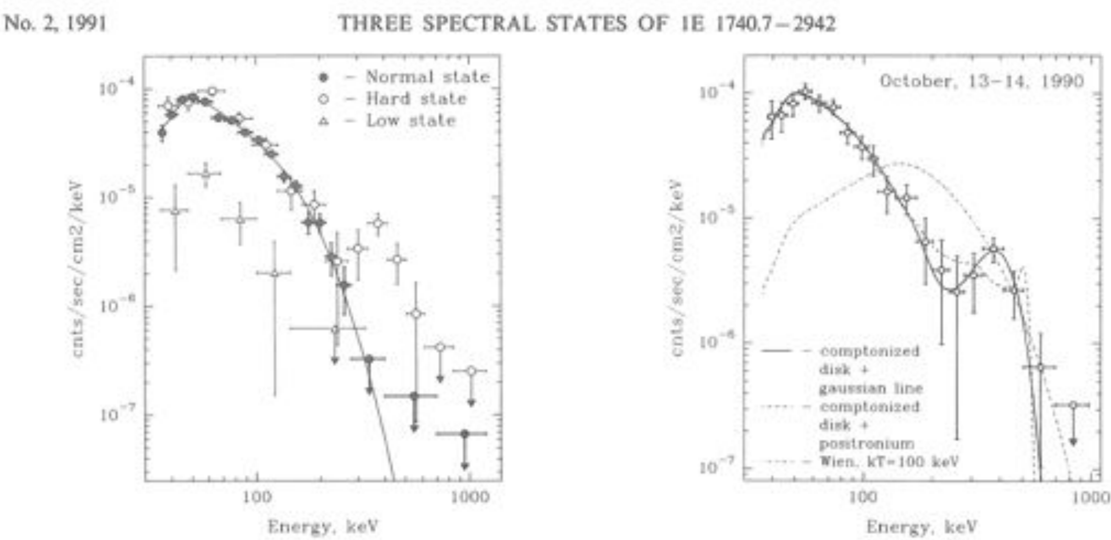
FIG. 1.—Net instrumental and astronomical 511 keV line flux as a function of galactic longitude for the (a) 1979 fall galactic plane scan and (b) all 1980 spring scans. An on-line bandpass of 8.54 keV was used for the 1979 fall data, and 13.42 keV for the 1980 spring data. The solid lines show the best-fitting background level, source intensity, and source galactic longitude for a point source.

- ☆ **HEAO-C Satellite Ge Experiment**
  - ☞ Detections in 1979, 1980 at Different Intensities
  - ☞ *Riegler et al. 1981*
- ☆ **Time-Variable Annihilation Source in GC !**

The "Great Annihilator"

- ☆ **1E1740.7-2942: A Peculiar Source**
  - ☞ Radio Source with ~pc Scale Jets & High Variability
  - ☞ Donor Star not Seen (MC?)
    - » *Cray, Cram, Ekers; Mirabel (1991)*
    - » *Leventhal et al., SciAm 1991*
- ☆ **γ-ray Variability as Seen with SIGMA:**
    - » *Bouchet et al. (1991)*
    - » *Sunyaev et al. (1991)*
  - ☞ Different Spectral States?





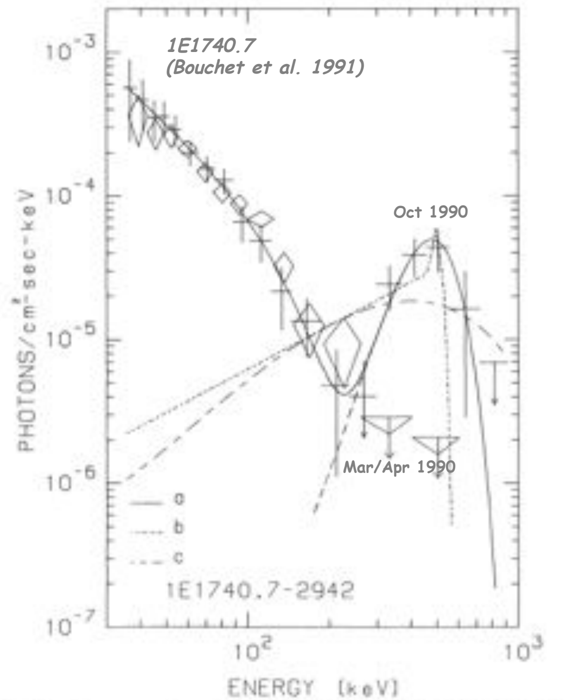
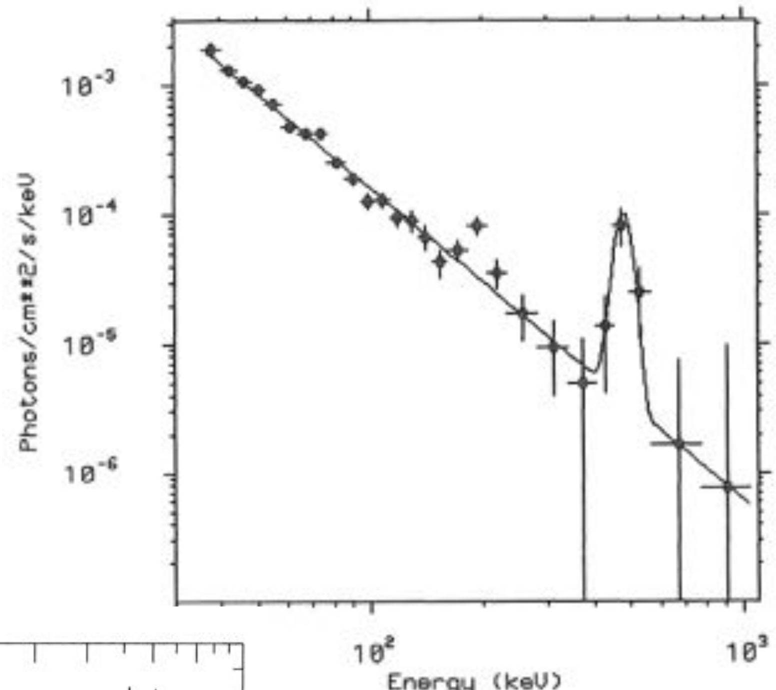


Fig. 1.—Energy spectrum of 1E 1740.7−2942 as obtained by SIGMA on 1990 October 13 (*crosses*); the spectrum derived from 1990 March/April (*diamonds*) is shown for comparison. Line a (*solid*) represents the best fit for the Comptonization law plus the Gaussian line. Line b (*short-dashed*) represents the positronium part of the Comptonized disk plus positronium model. Line c (*long-dashed*) represents the high-temperature part of the two-temperature Comptonization disk model.

Other Sources with Transient Annihilation Lines

- ☆ **Nova Musca**
  - ☞ X-ray Transient with Flare on 8Jan1991
  - ☞ 0.5 MeV Line Seen in 13 hr Observation on 20 Jan with SIGMA
    - » *Goldwurm et al. 1992*



- ☆ **1H 1822-371 Transient South of GPlane**
  - ☞ HEAO-A4 NaI/CsI Phoswich in CsI Shield
  - ☞ Search for 511 keV Emission Reveals New Source in One of Three Epochs Only
    - » *Briggs et al. 1995*

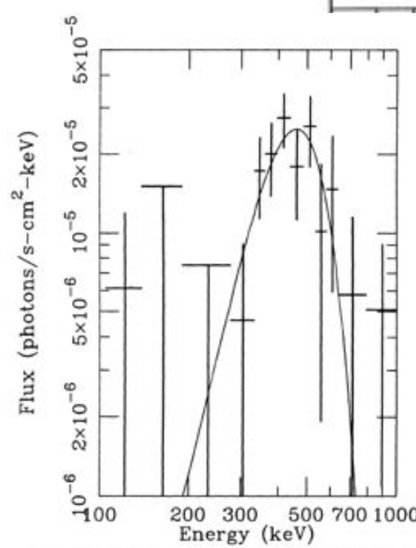
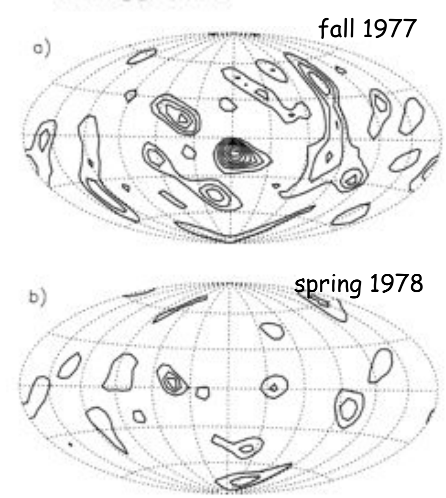


FIG. 5.—The spectrum of the source detected in 1977 September from the *HEAO* A-4 Medium Energy Detectors. The feature in the 300–700 keV range is best fitted with a broad Gaussian with a FWHM of 249 ± 51 keV centered on 461 ± 22 keV. The flux of this broad Gaussian is $(6.6 \pm 1.2) \times 10^{-3}$ photons $(cm^2\ s\ keV)^{-1}$.



Positron Annihilation Line in Solar Flares

Chupp et al. 1973; 1975

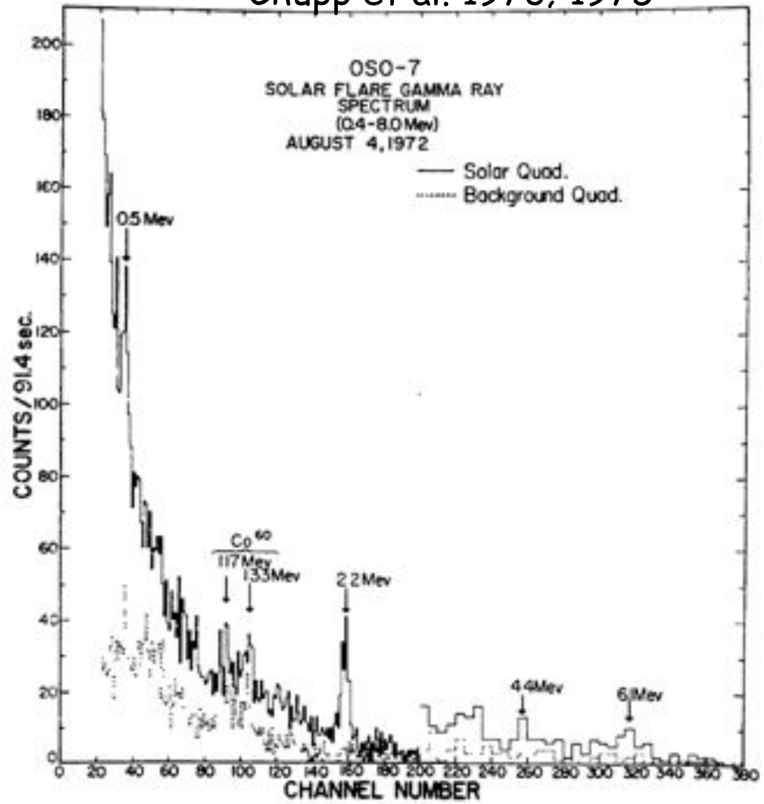
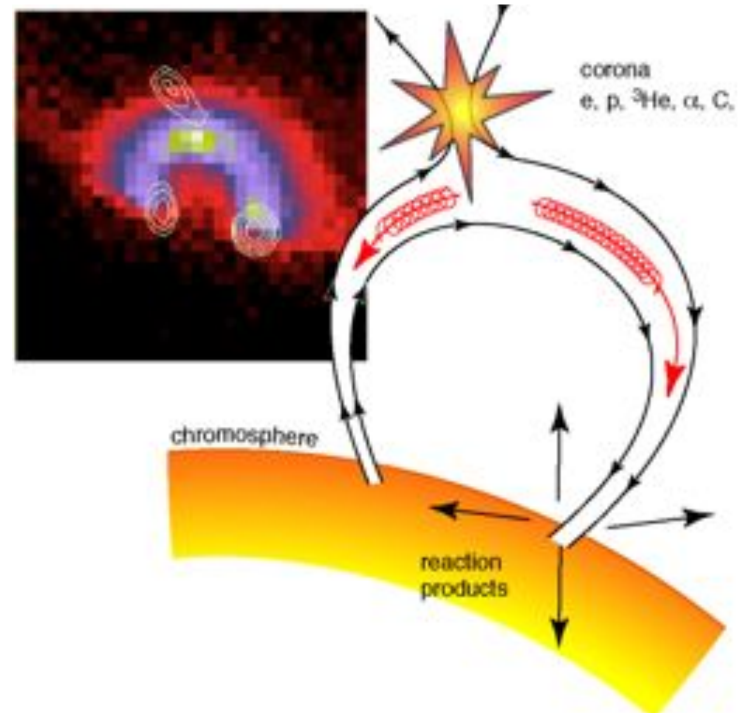
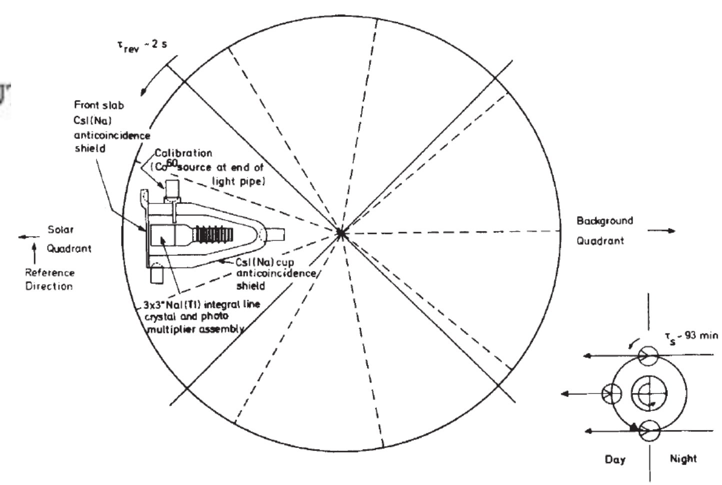


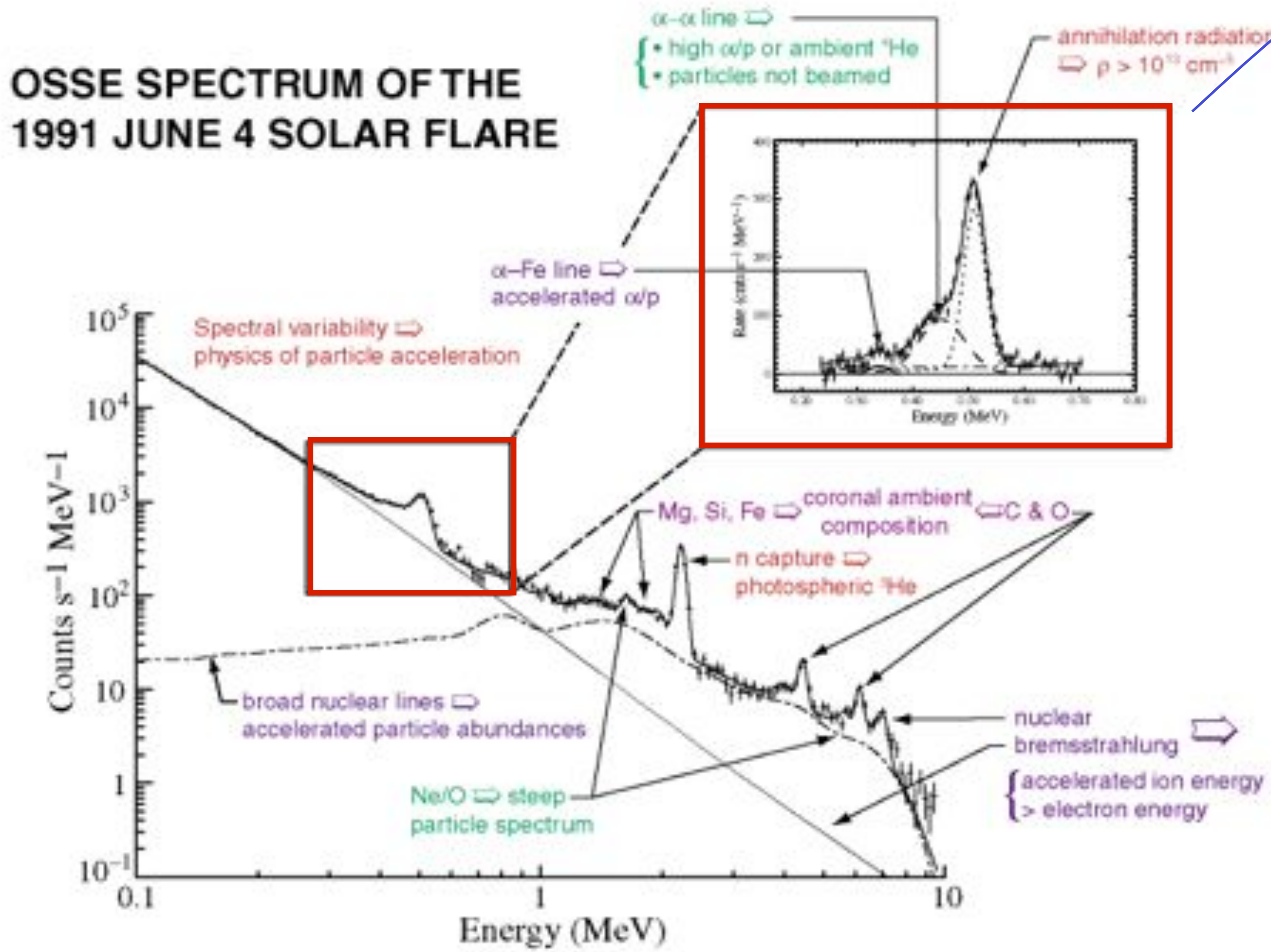
Fig. 4. Complete gamma-ray spectrum – 1972, August 4; 0624–0633 U





- ☆ **Detected with NaI Detector on OSO-7 Satellite**
- ☆ **Evidence of Ion Acceleration in Solar Flares**

Physics from Solar-Flare Gamma-Ray Spectra



RHESSI Line Shapes for Different Conditions

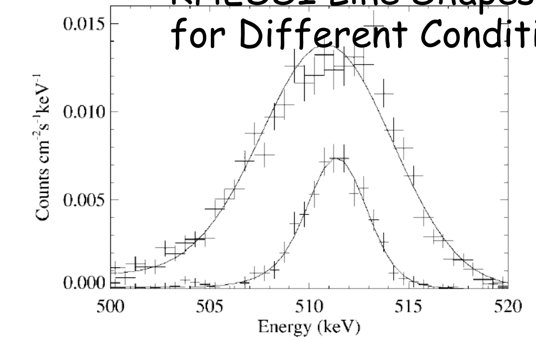
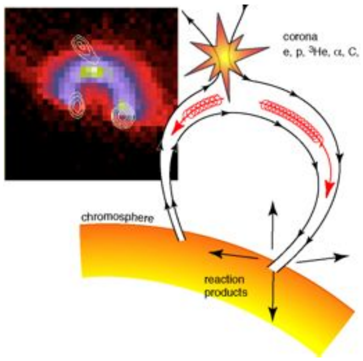
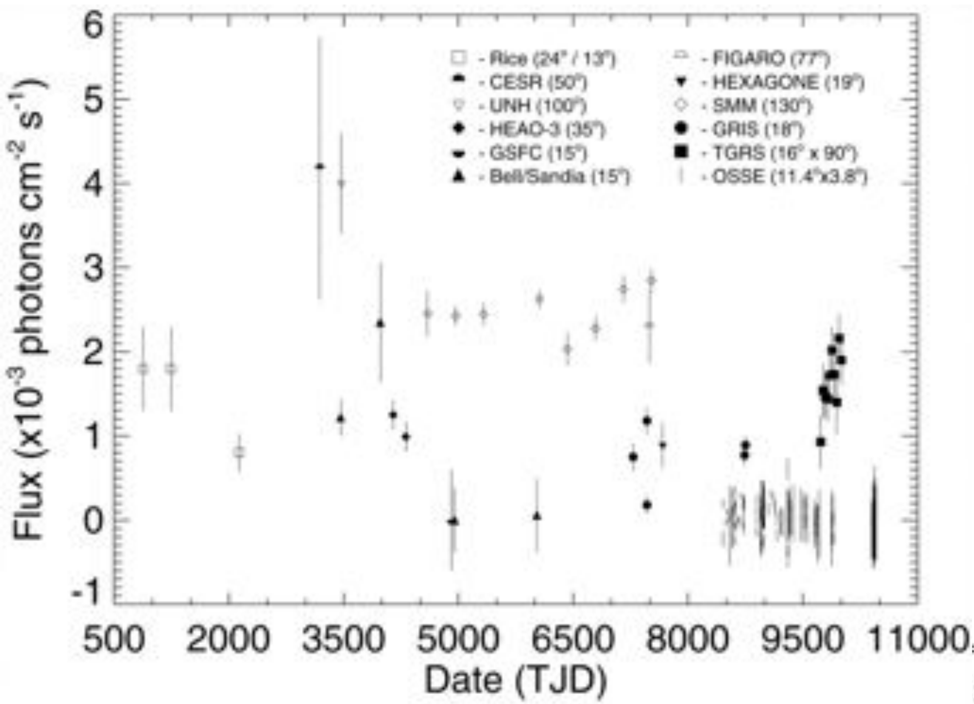


FIG. 3.—Count spectra of the solar 511 keV annihilation line (instrumentally broadened) derived by subtracting bremsstrahlung and nuclear contributions during the October 28 flare when the solar line was broad (11:06–11:16 UT) and narrow (11:18–11:30 UT). The solid curve is the best-fitting model that includes a Gaussian line and positronium continuum.



Roland Diehl

The 80*ies*: A Decade of "Chasing the Annihilator"



- ☆ Diversity of Balloon & Satellite Expriments
- ☆ Controversial (but non-contemporaneous Intensities

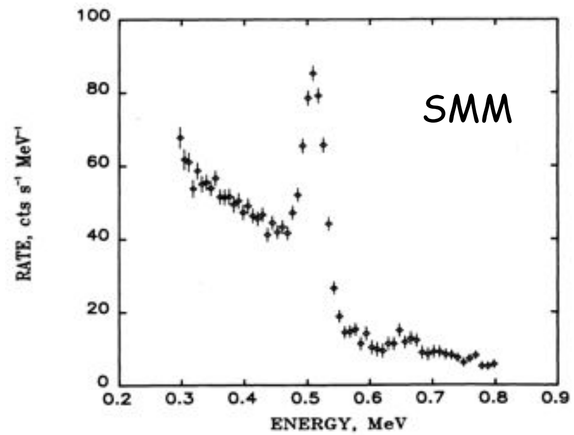
Date	511 keV Line Flux[a] (10^{-4} photons cm^{-2} s^{-1})	Name	FOV[b] (FWHM)	References
		Galactic Center Observations ($l = 0°$; $b = 0°$ unless otherwise specified)		
1977.86.........	12.2 ± 2.2	Bell-Sandia	15°	Leventhal et al. 1978
1979.29.........	23.5 ± 7.1	Bell-Sandia	15°	Leventhal et al. 1980
1981.89.........	0.0 ± 6.0	GSFC	15°	Paciesas et al. 1982
1981.89.........	0.0 ± 3.8	Bell-Sandia	15°	Leventhal et al. 1982
1984.89.........	0.6 ± 4.4	Bell-Sandia	15°	Leventhal et al. 1986
1988.33.........	7.5 ± 1.7	GRIS	18°	Gehrels et al. 1991
1988.83.........	11.8 ± 1.6	GRIS	18°	Gehrels et al. 1991
1989.39.........	8.9 ± 2.7	HEXAGONE	18°	Chapuis et al. 1991
1991.5..........	0.9 ± 0.9	OSSE ($b = -3°.0$)	11°.4 × 3°.8	Purcell et al. 1992
1991.5..........	2.2 ± 0.9	OSSE ($b = -1°.5$)	11°.4 × 3°.8	Purcell et al. 1992
1991.5..........	2.7 ± 0.5	OSSE ($b = 0°$)	11°.4 × 3°.8	Purcell et al. 1992
1991.5..........	2.2 ± 1.3	OSSE ($b = 1°.5$)	11°.4 × 3°.8	Purcell et al. 1992
1991.5..........	1.8 ± 0.9	OSSE ($b = 3°.0$)	11°.4 × 3°.8	Purcell et al. 1992
		In-Plane Off-Center Observations ($b = 0°$)		
1988.83.........	1.8 ± 1.1	GRIS ($l = -25°$)	18°	Gehrels et al.1991
1991.5..........	0.9 ± 0.6	OSSE ($l = -21°$)	11°.4 × 3°.8	Purcell et al. 1992
1991.5..........	0.7 ± 0.6	OSSE ($l = 25°$)	11°.4 × 3°.8	Purcell et al. 1992

[a] The listed fluxes were derived assuming emision from a point source.
[b] Long axis of OSSE detectors in Galactic plane.

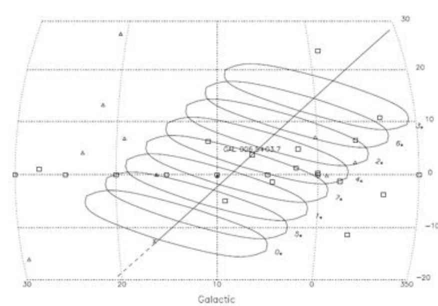
- ☆ Point Source only, or also Diffuse Emission??

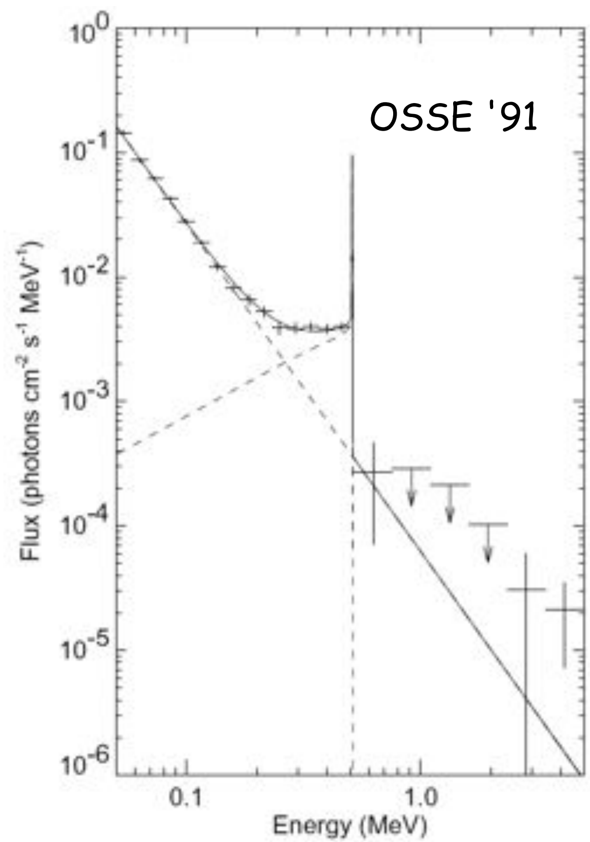
The Case for Galactic-Diffuse 511 keV Emission

- ☆ **Predictions from Diffuse Nucleosynthesis and Cosmic-Ray Sources**
  - ☞ Ramaty et al. 1968...1994...
- ☆ **SMM** (~130 deg Field-of-View) **Detection of Diffuse 511 keV Emission**
  - ☞ Share et al. 1988



- ☆ **OSSE Scanning of Galactic Plane**
  - ☞ Purcell, Kinzer, et al. 1993ff





The End of "Line Variability"

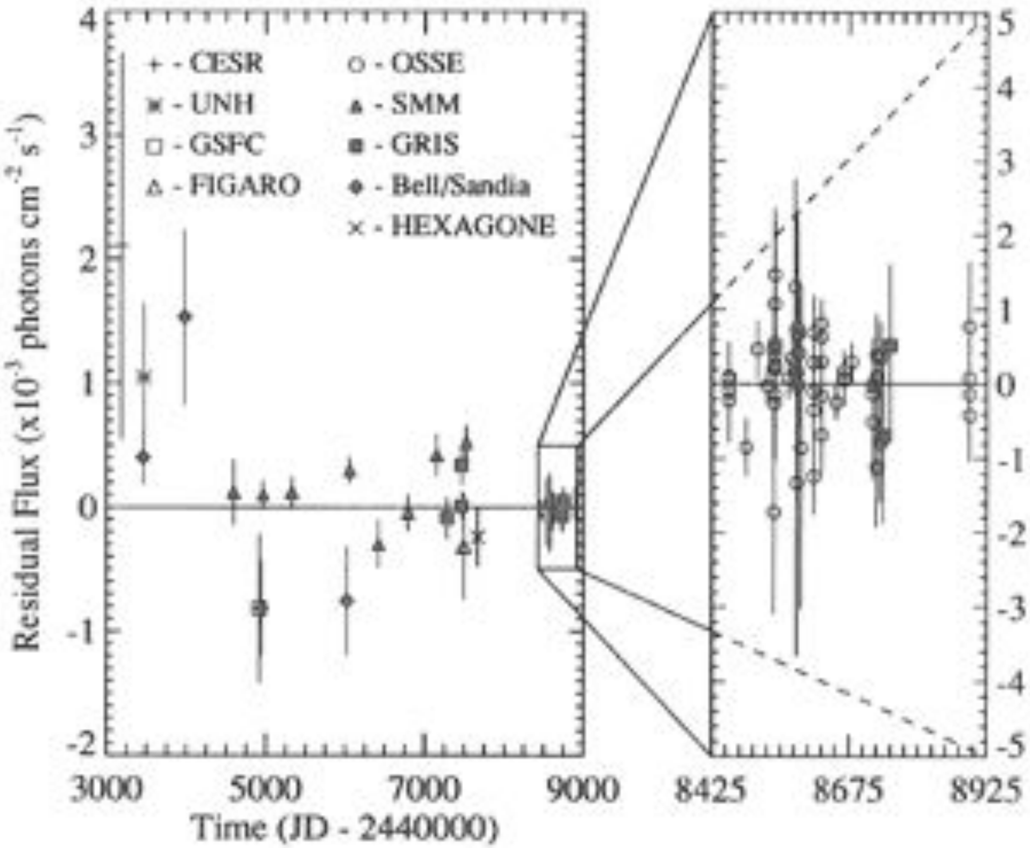
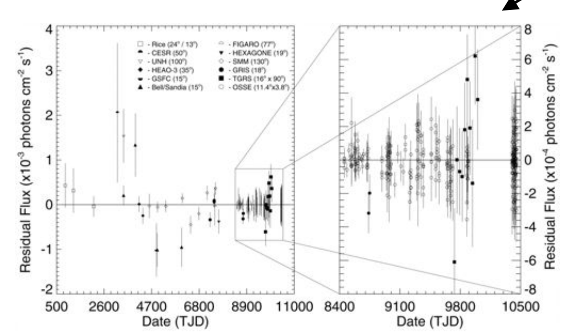


FIG. 3.—Historical summary of the 511 keV line flux from the Galactic center region as observed by various balloon and satellite instruments, including the recent OSSE results.. Note that the uncertainties displayed represent statistical uncertainties only. The diffuse contribution from the OSSE best-fit two-component model has been subtracted from the reported flux for each observation. References: *SMM*—(Share et al. 1990); GRIS—(Gehrels et al. 1991); Bell/Sandia—(Leventhal et al. 1978, 1980, 1982, 1986, 1993); FIGARO—(Neil et al. 1990); HEXAGONE—(Chapuis et al. 1991); CESR—(Albernhe et al. 1981); UNH—(Gardner et al. 1982); GSFC—(Paciesas et al. 1982).

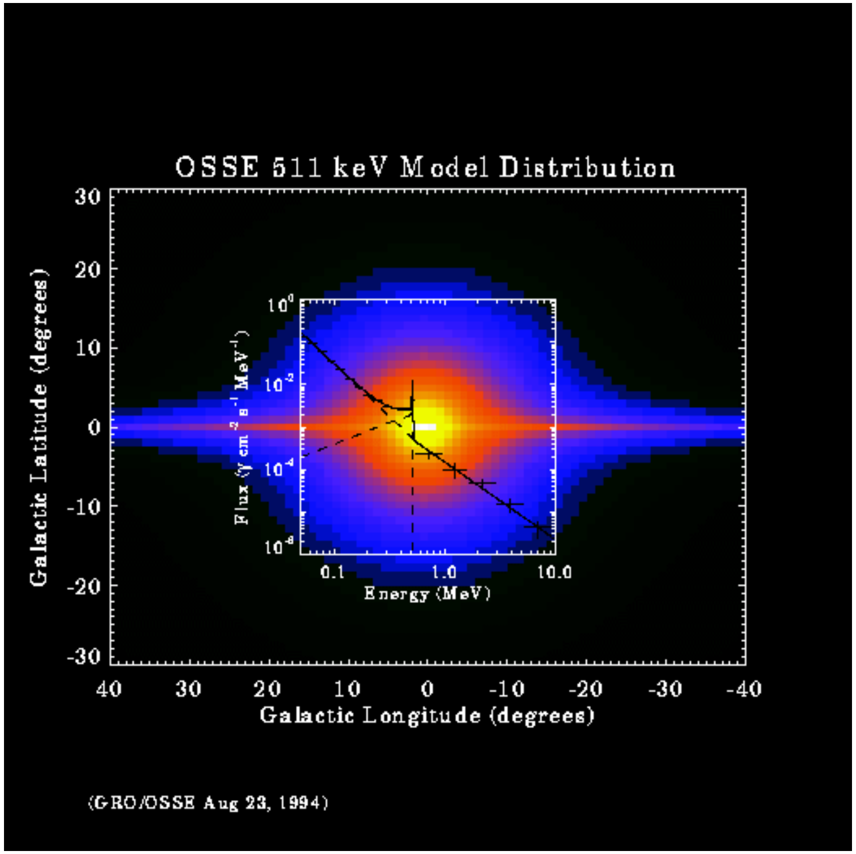
- ☆ **After Subtraction of Diffuse-Model Emission, No Other Emission Remains on ~yrs Time Scale**

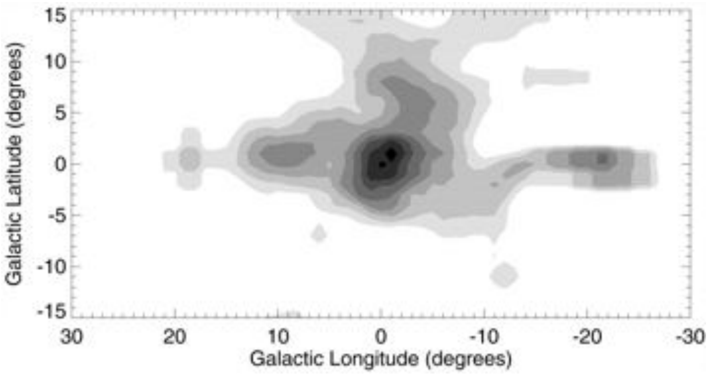
☞ *Purcell et al. 1993; 1997*

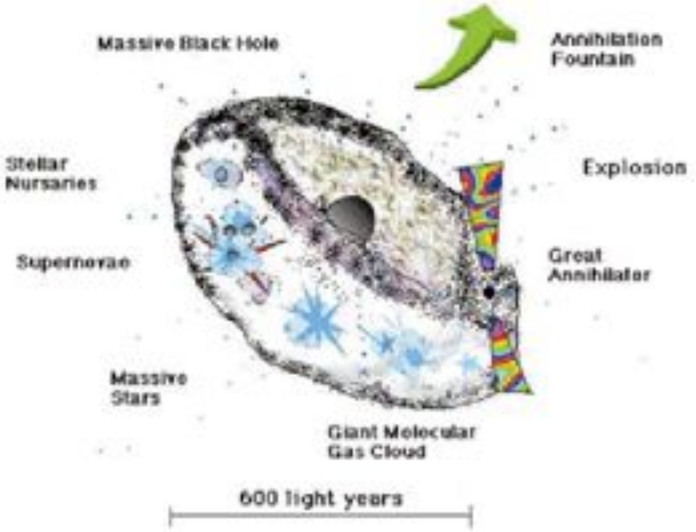


Measurements of Galactic e⁺ Annihilation

- “Imaging” with OSSE



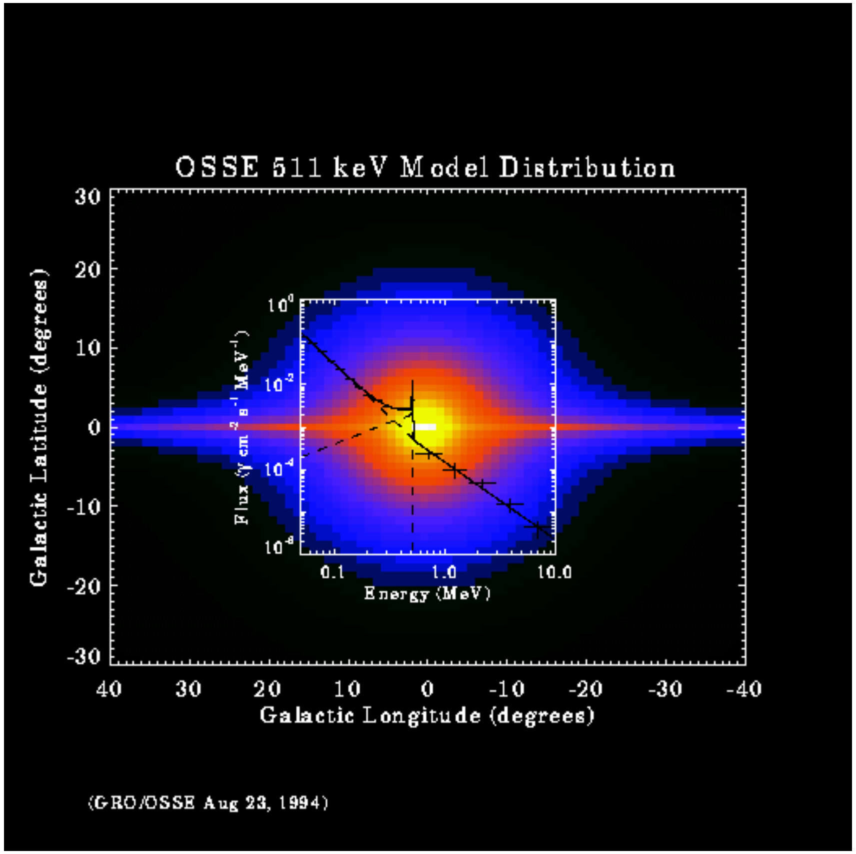




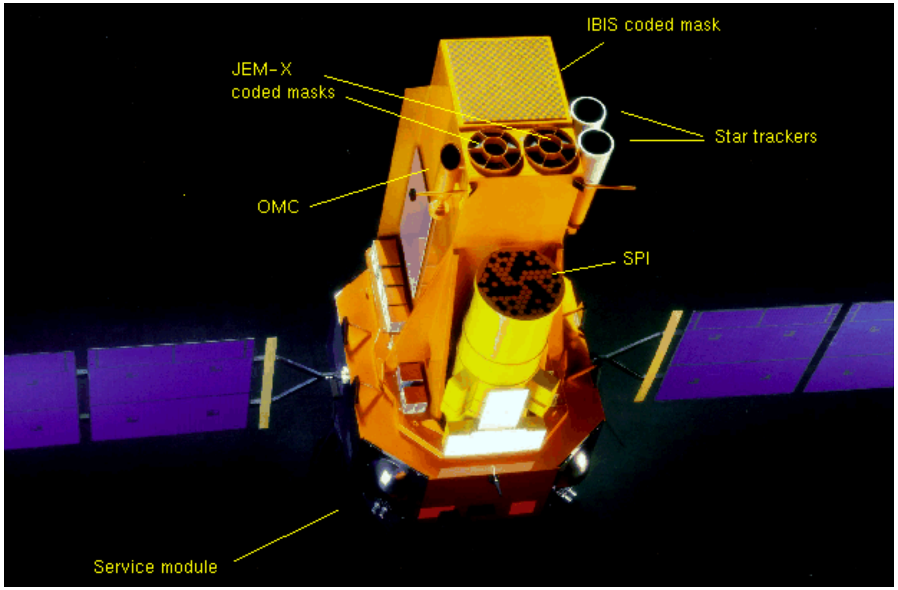
- ☆ Extended Diffuse Emission
- ☆ An Extension towards the Norther Galaxy
  - ☞ ("positive-latitude enhancement PLE"; "annihilation fountain")

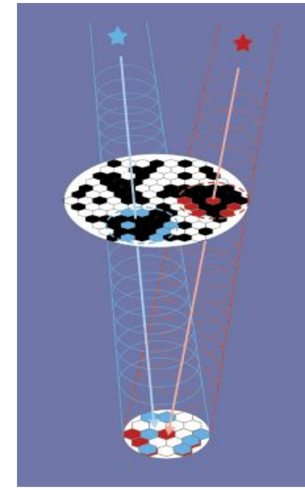
Positron Annihilation in the Galaxy – pre-INTEGRAL

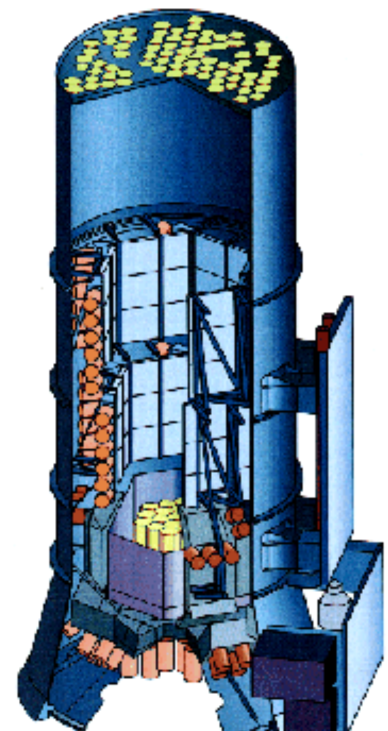
- ☆ **Steady Diffuse Annihilation Emission from Inner Galaxy**
- ☆ **Possibly a Special Contribution from SMBH**
- ☆ **Possibly Transients with 511 keV Line Flares**



INTEGRAL's Ge γ-Spectrometer in Space





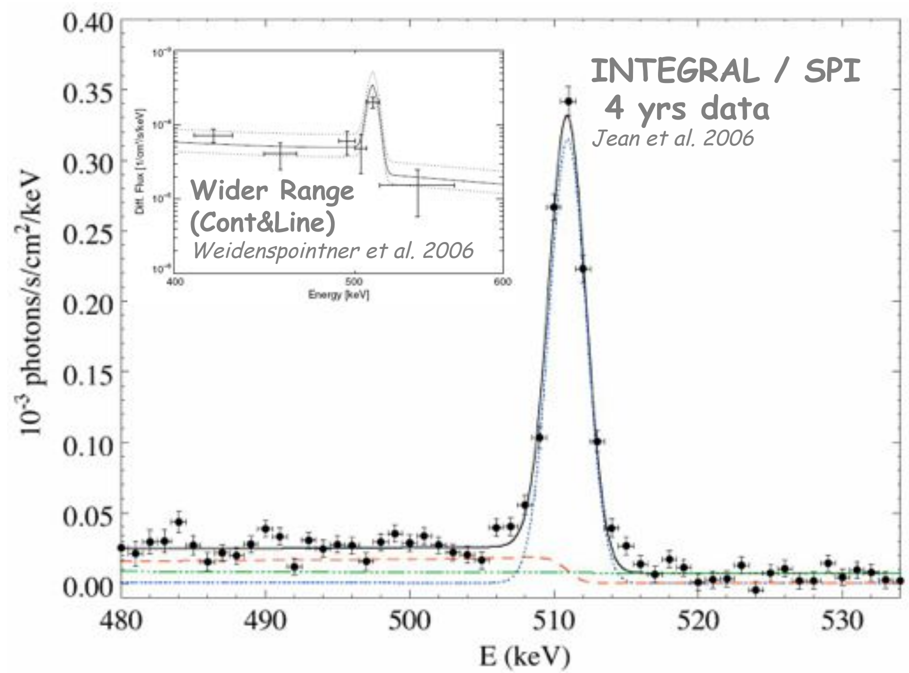


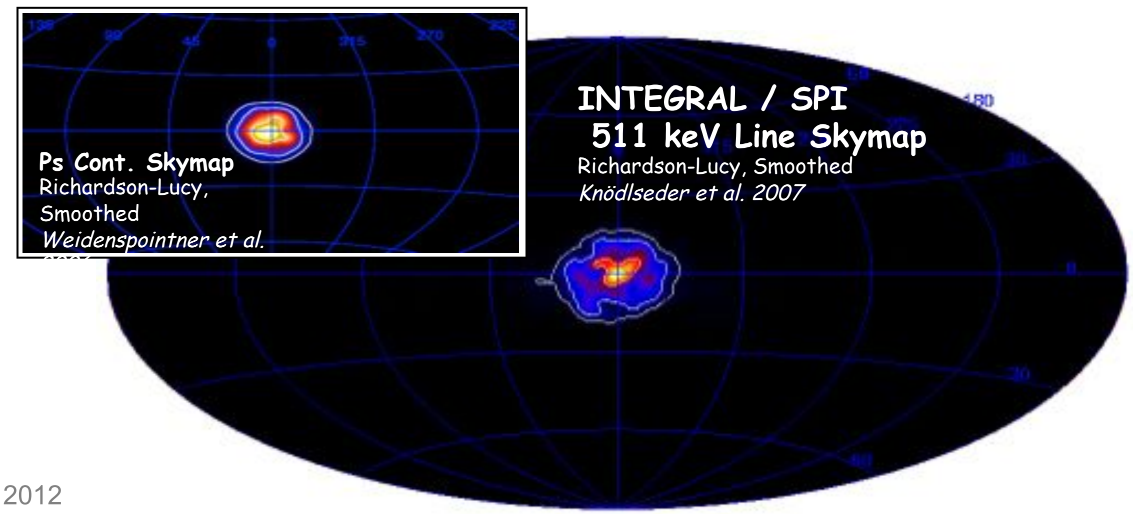
SPI: Coded-Mask Telescope 15-8000 keV
Energy Resolution ~2.2 keV @ 662 keV
Spatial Precision 2.6° / ~2 arcmin
Field-of-View 16x16°

Observing Annihilation of Positrons in the Galaxy

INTEGRAL / SPI:

- Extended Emission (~8-10°) at
  1.01 (±0.02) 10^{-3} ph cm^{-2} s^{-1}
- Ps Continuum:
  4.3 (±0.3) 10^{-3} ph cm^{-2} s^{-1}
  f_{Ps} 0.967 ±0.022
- Corresponds to ~ 2 10^{43} e^{+} s^{-1}
- Line Slightly Broadened

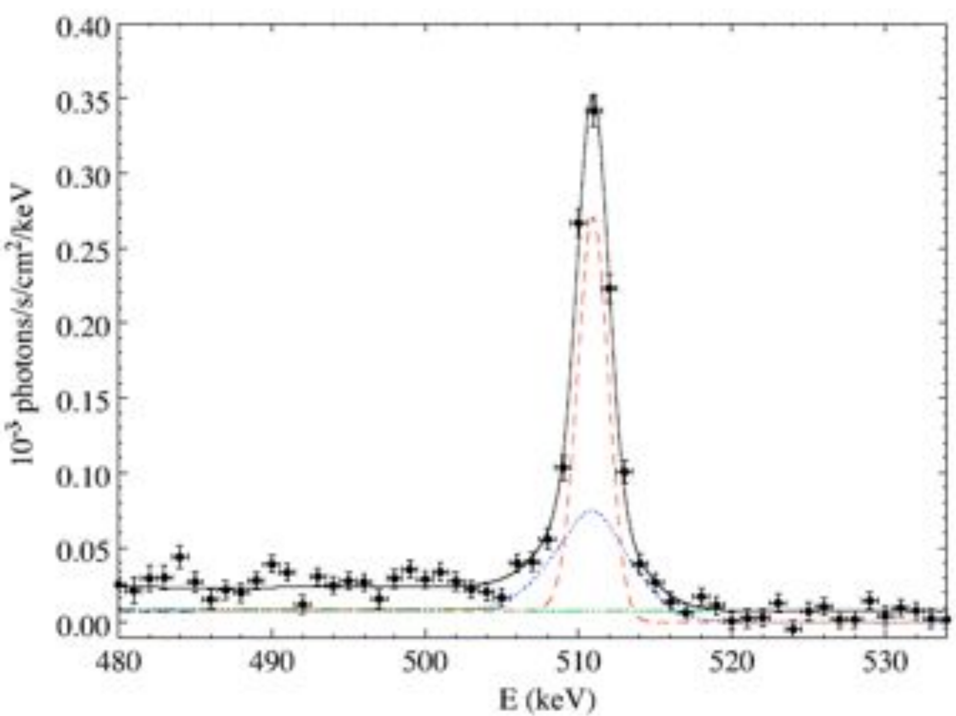


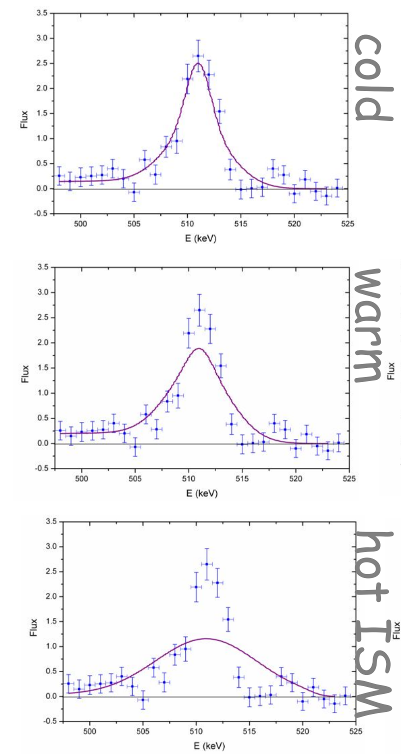


Annihilation Conditions and the Line Width

☆ Annihilation Environments:

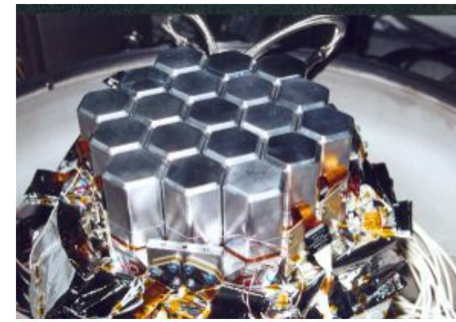
- In-Flight -> broad line
- Hot ISM -> broad line
- Warm&Cold ISM -> narrow line
- On Dust Grains -> narrow line





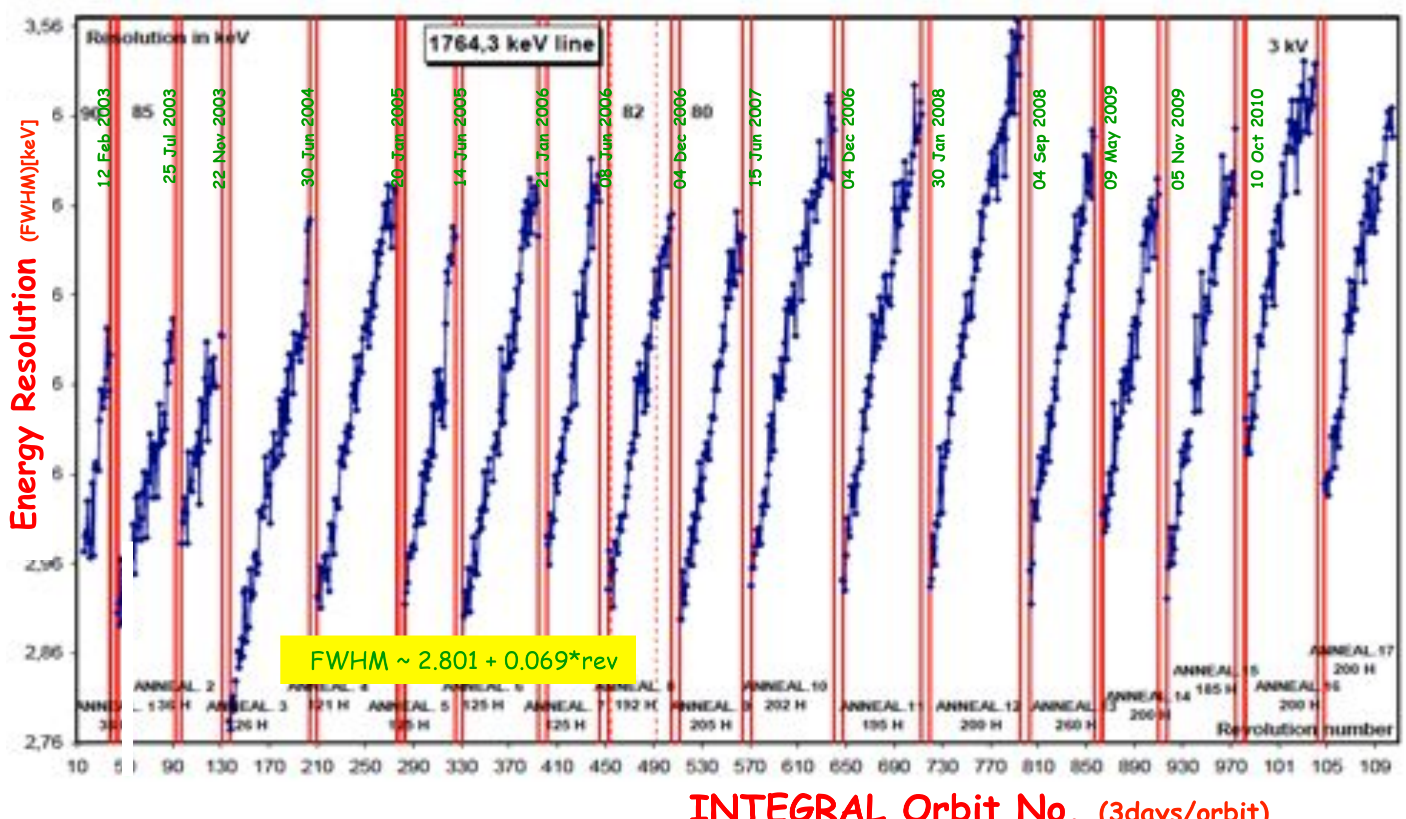
High-Resolution Gamma-Ray Spectroscopy in Space: SPI on INTEGRAL

- **Cosmic-Ray Irradiation -> Degradation of Charge Collection**
  - ☆ ~2% per Orbit, ~20% in 6 Months (@1 MeV)
- **Annealing**
  - ☞ ~100-200 hrs at 105°C, few hrs at 90K



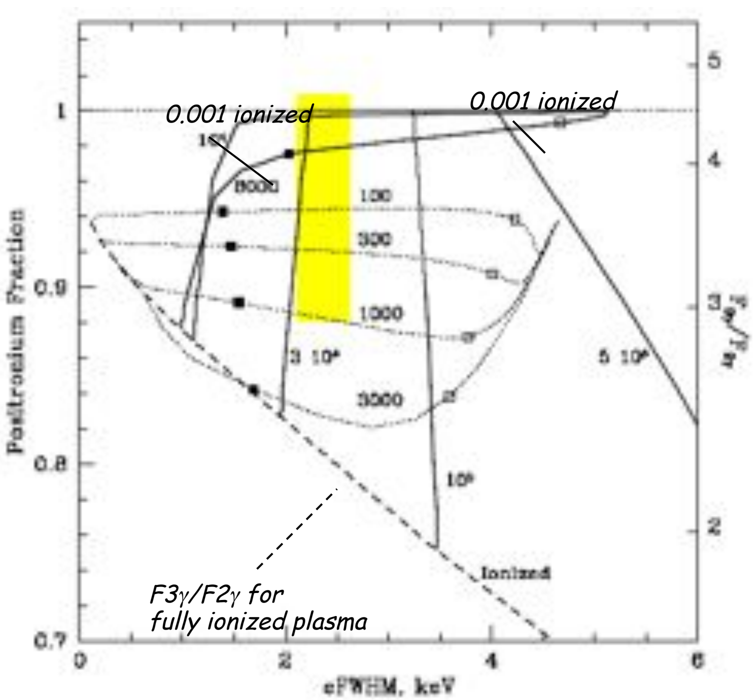
✓18 Annealings Successfully Completed (Jan 2012)

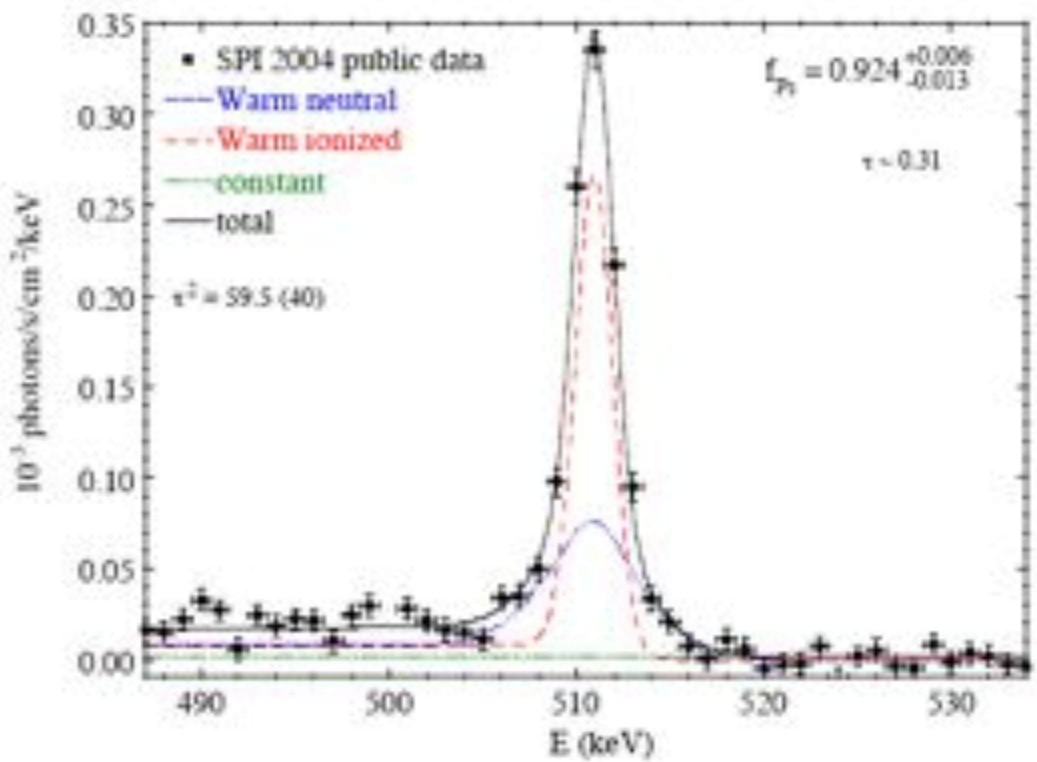
✓15 of 19 Detectors Operational with Fine Resolution



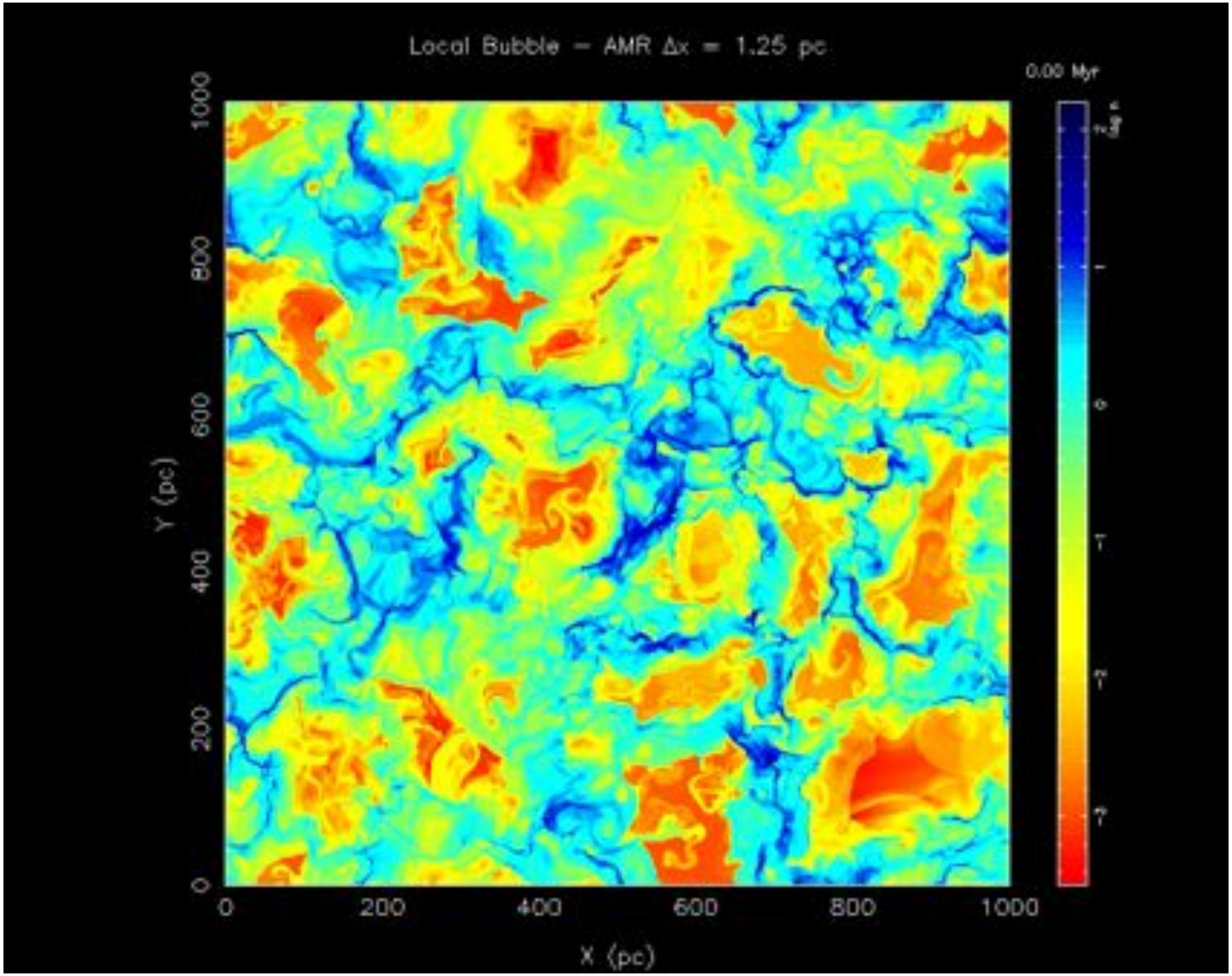
Annihilation Conditions: Which ISM Phase?

- ☆ **Warm Ionized ISM is Dominating Annihilation Environment**
- ☆ **No ISM Grain “Narrowing” Needed**
  - ☞ *Jean et al. 2005, 2006*
    - – **Fitting Different Phases with their Characteristic Spectral Shapes**
  - ☞ *Churazov et al. 2004*
    - – **Determining the best-matching Temperature and Ionization Fraction**





The Dynamic Interstellar Medium



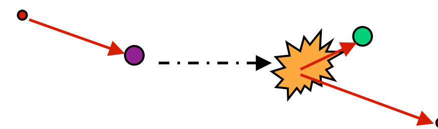
☆ **Positrons propagate in a Dynamic, Evolving Multi-Phase Medium**

☞ *D. Breitschwerdt & Miguel Avillez 2003*

cmp gadget sim Springel

Positron Production Processes

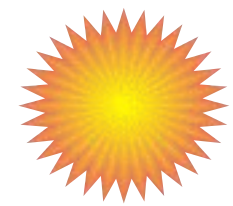
✓ Cosmic-Ray Nuclear Reactions



- ☆ e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$
- ☆ Pion Production in HE Collisions $p + p \rightarrow \pi^+ + X$

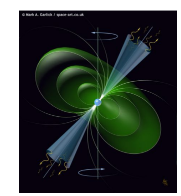
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (\tau = 2{,}6 \cdot 10^{-8}\ s)$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\tau = 2{,}2 \cdot 10^{-6}\ s)$$

✓ Hot-Plasma Pair Production



- ☆ 'kT>MeV'-Plasma $\gamma + \gamma \rightarrow e^+ + e^-$
  - ☞ Accretion Columns & Disks
  - ☞ Jet Bases

✓ E.M.-Cascade Pair Production

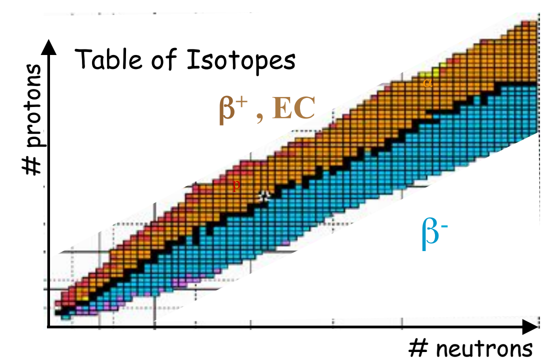


- ☆ Strong Magnetic Fields $\gamma + B \rightarrow e^+ + e^-$
  - ☞ Pulsars
  - ☞ Jets

✓ Nucleosynthesis

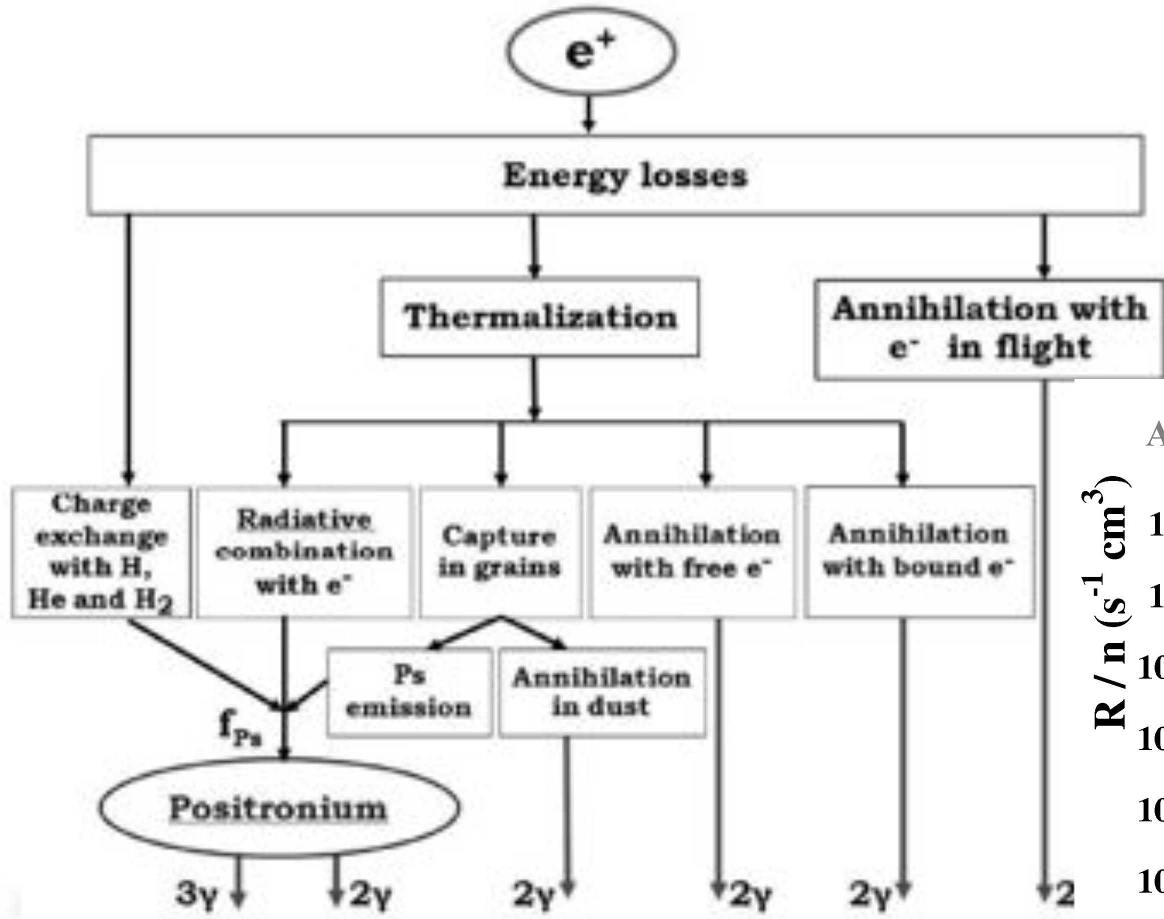
- ☆ e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$, $^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{18}F(\beta^+)$

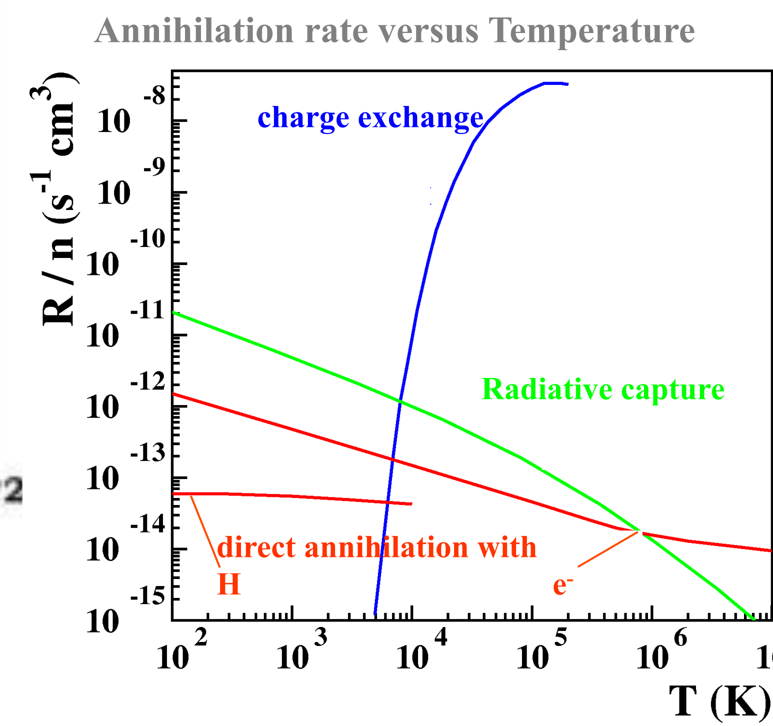
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$$



Annihilation and Ambient-Gas Conditions

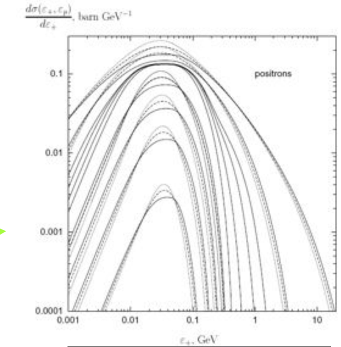
- ☆ Variety of Channels to 'Capture' an e^-
- ☆ Dominating: Charge Exchange with H Atoms





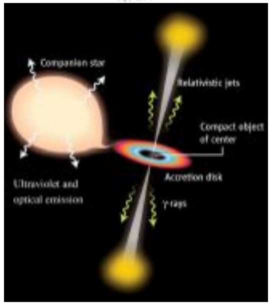
The Sources of Positrons: Which E_{e+}?

- **Pion Production**
  - ☆ Sources: Cosmic Rays & ISM
  - ☆ **Positron Energies: <E>~30 MeV**



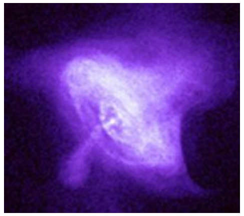
- **Pairs from Hot Plasma**
  - ☆ Sources: Accreting Binaries
  - ☆ **Positron Energies: ~MeV**

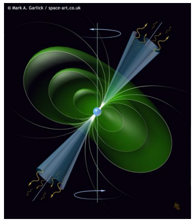
    T>100 keV (E_{thr}=1.02 MeV)



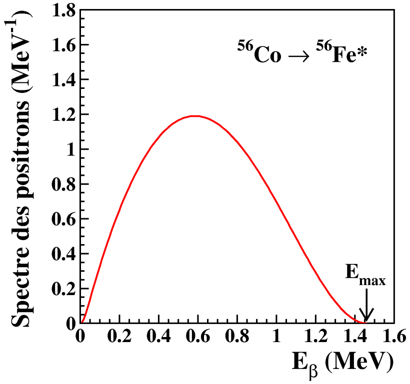
- **Pairs from Strong Magnetic Fields**
  - ☆ Sources: Pulsars, Magnetars
  - ☆ **Positron Energies: ~MeV…GeV**

    (E_{thr}=1.02 MeV) ($B>10^{12}$G)



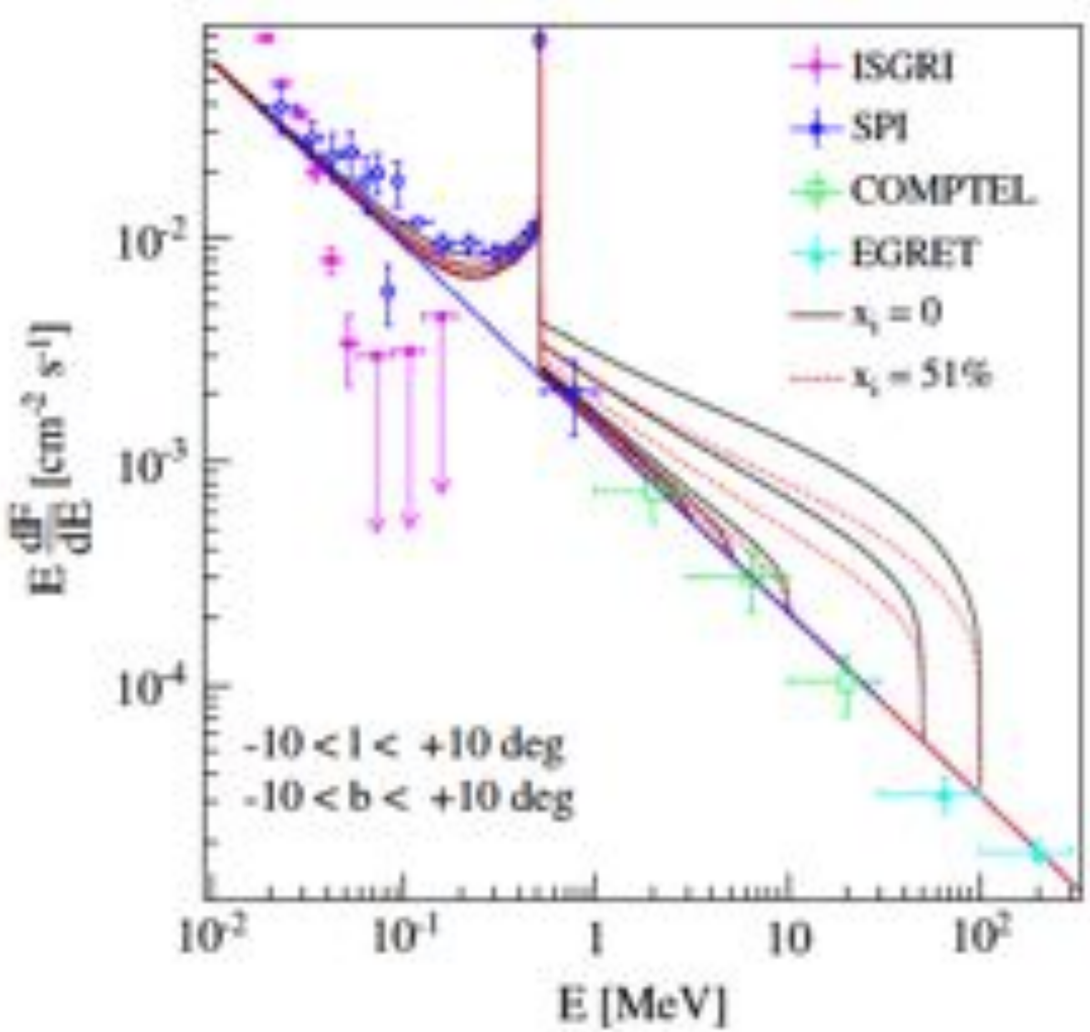


- **Radioactive Nuclei**
  - ☆ Sources: Supernovae, Novae, Cosmic Rays & ISM
  - ☆ **Positron Energies: ~MeV**

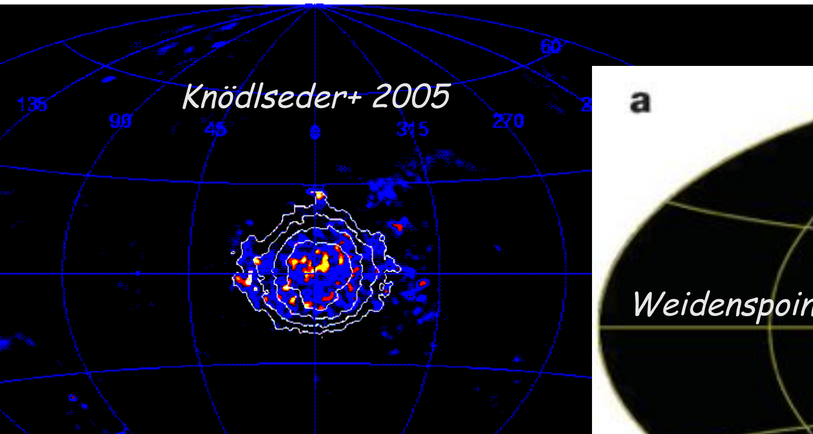


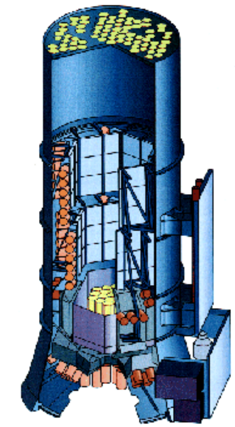
Observing Positrons at Relativistic Energies

- ☆ **No clear signal at MeV and above (below plausible predictions for slowing-down and in-flight annihilation)**

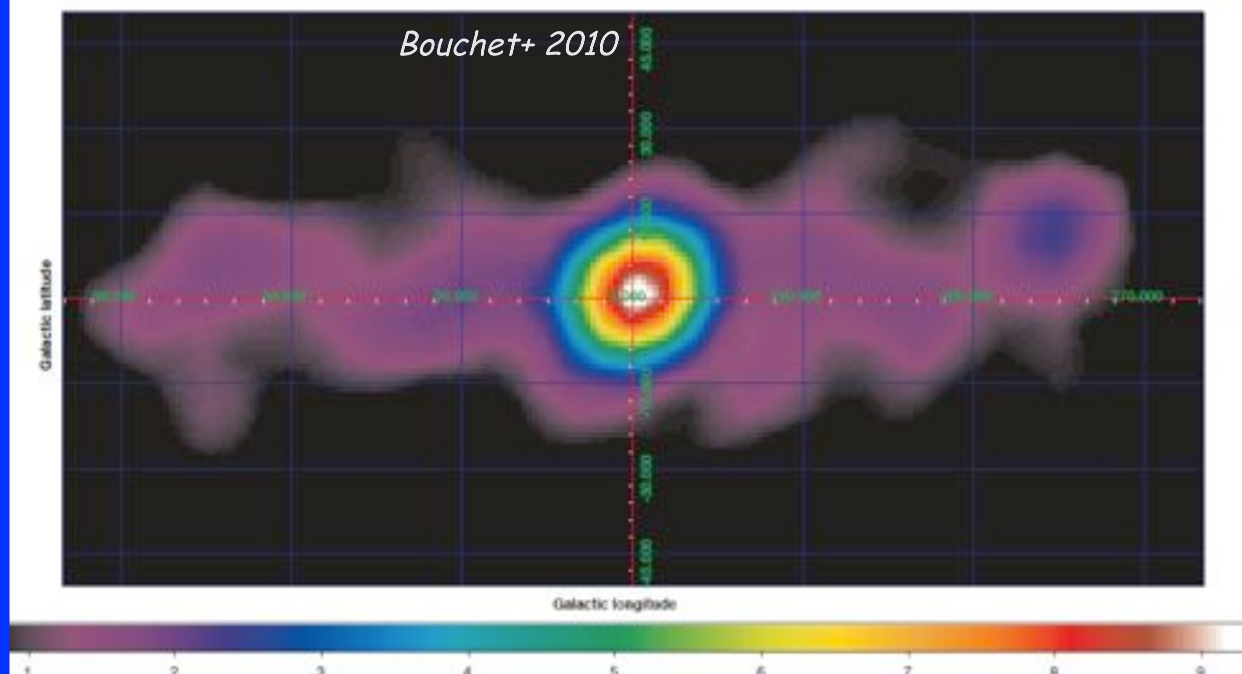


Measuring Galactic Positron Annihilation with SPI



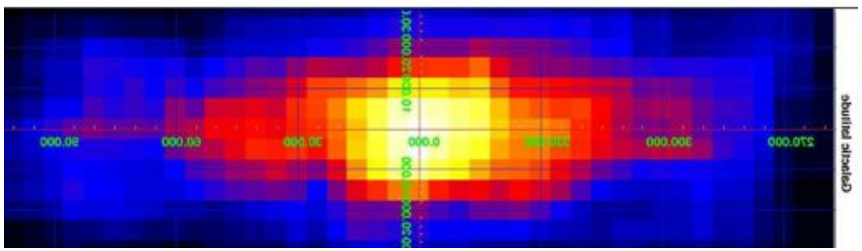


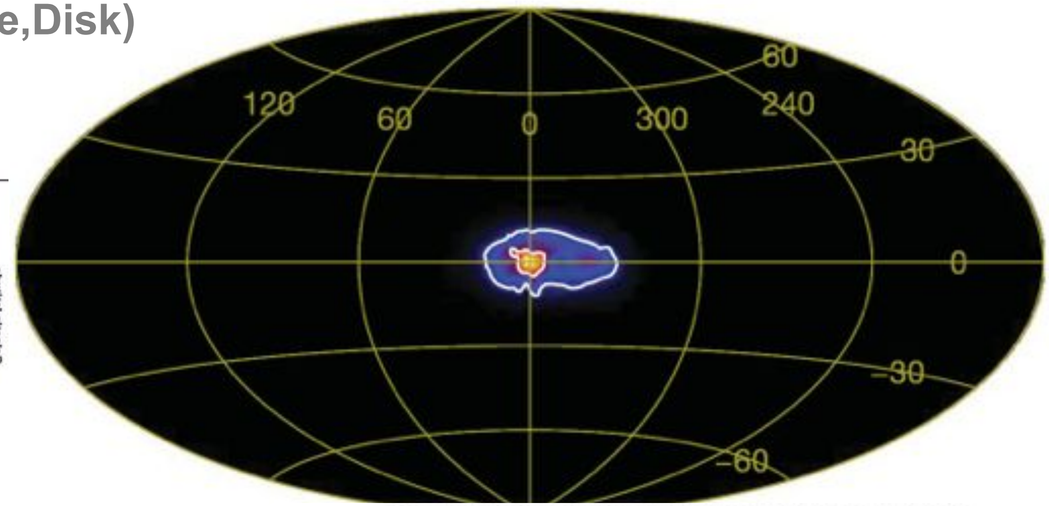
- ☆ **Annihilation γ-rays are dominated by a Bright Inner-Galaxy Component**
- ☆ **The ^{26}Al e+ Produced in the Disk (82%) are a Minor Contribution**
- ☆ **Annihilation γ-ray Emission Presents a Puzzle:**
  - ☞ **e+ Sources ?**
  - ☞ **Propagation !!**
  - ☞ **Annihilation**

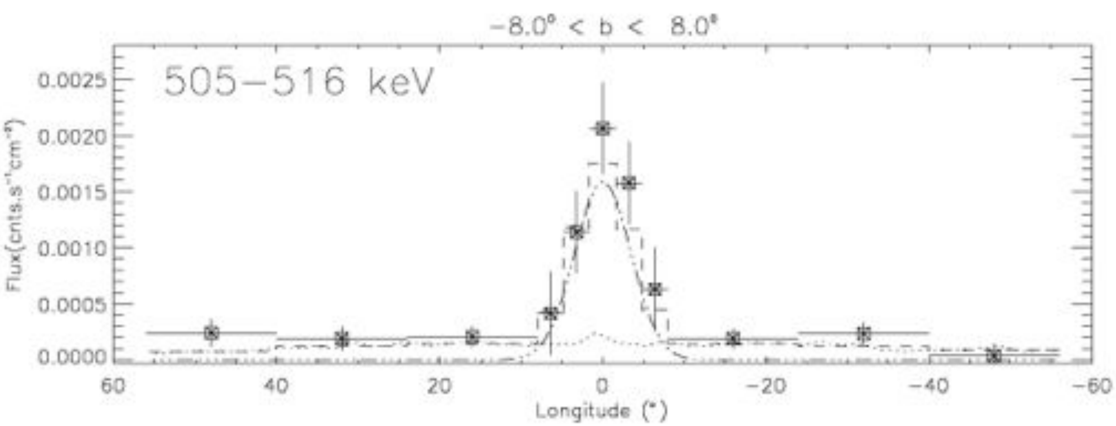


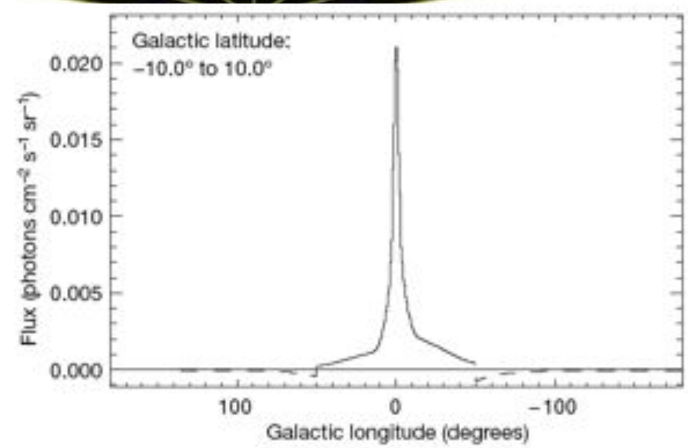
Disk Component: Asymmetric?

- ☆ **Two Different Analysis Methods**
  - ☞ **Iterative 'Pixon'-Model Fitting**
    - » *Bouchet et al. ApJ 2008*
  - ☞ **Plausible e^+ Model Fitting (Bulge,Disk)**
    - » *Weidenspointner et al., Nat 2008*
  - ☞ **(also Different in Bgd Modelling)**







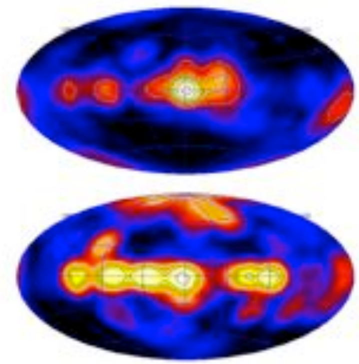


☆ *Note: A Dark-Matter-only Origin of Annihilation Emission would be Symmetric!*

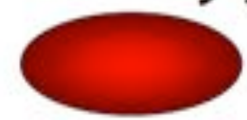
Analysis Issues

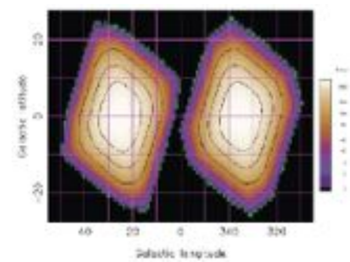
☆ Systematics??

- ☞ Analysis Method?
  - Which Sky Model is Fitted?
  - How is Bgd Defined and Determined?
- ☞ Pointing Pattern?
- ☞ Instrumental Longterm Changes
  - Detector Degradation
  - Background Changes
- ☞ ...

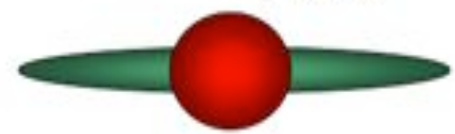


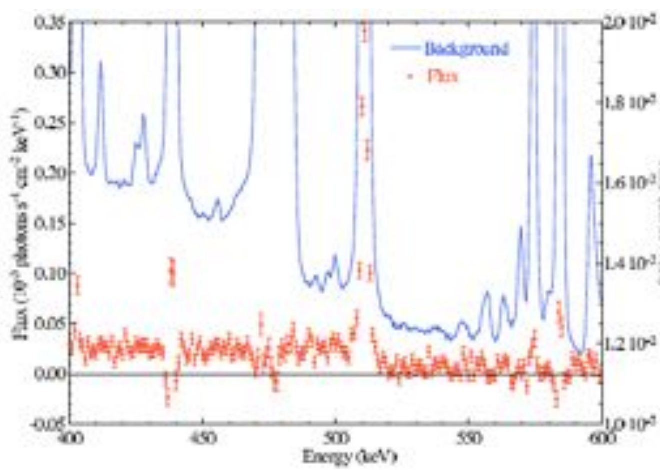
9°x 6°

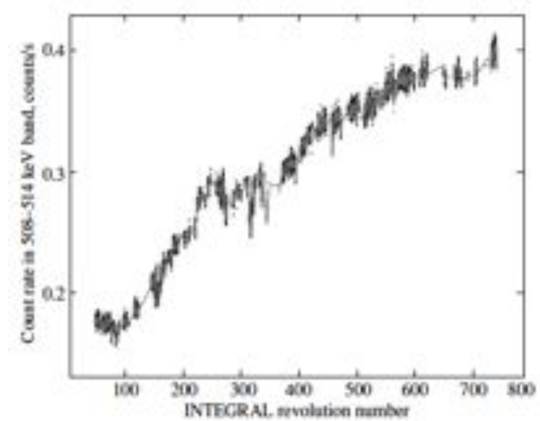




7°x 6°



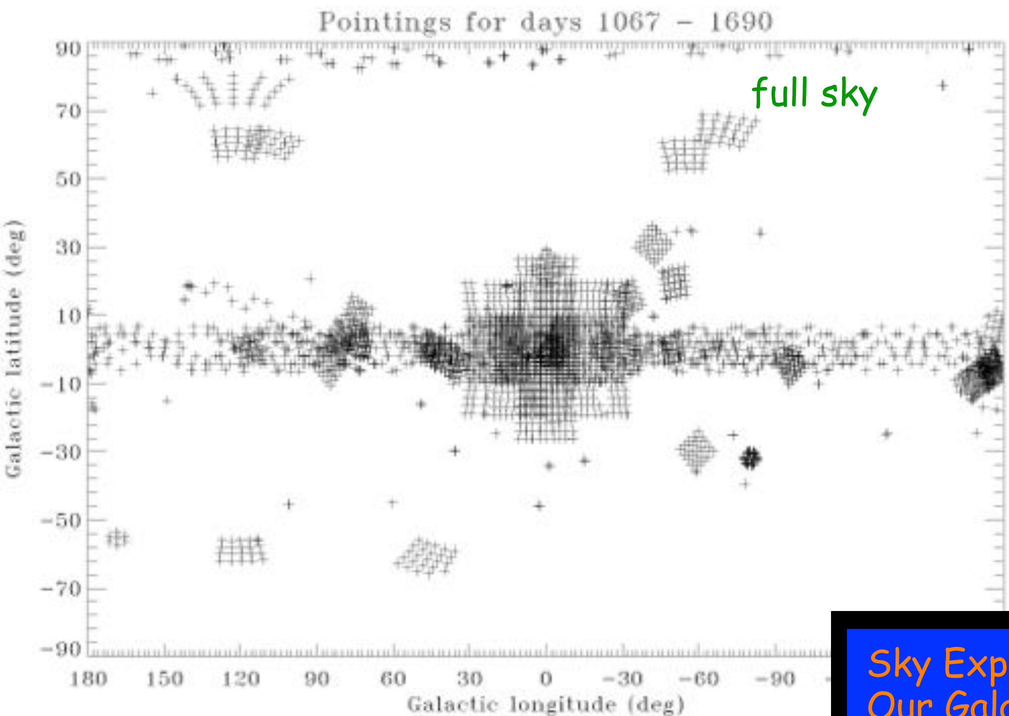


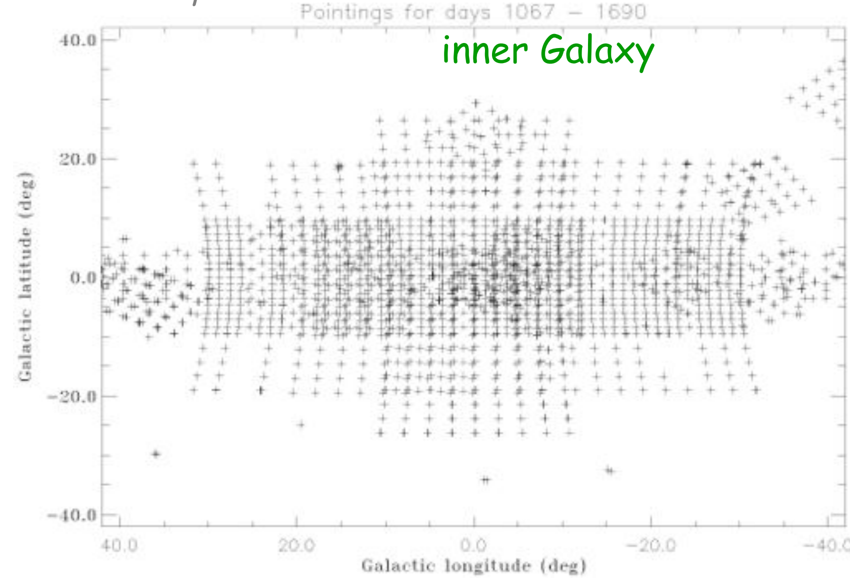


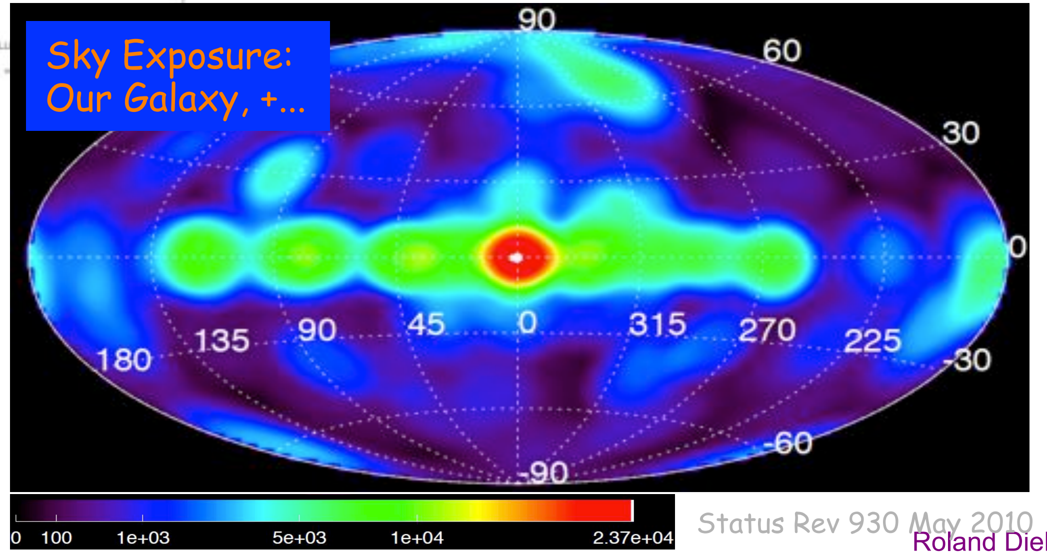
A Sky Survey with INTEGRAL

☆ **“Dither Patterns” Scattered over the Sky**

☞ *Example from late 2004*

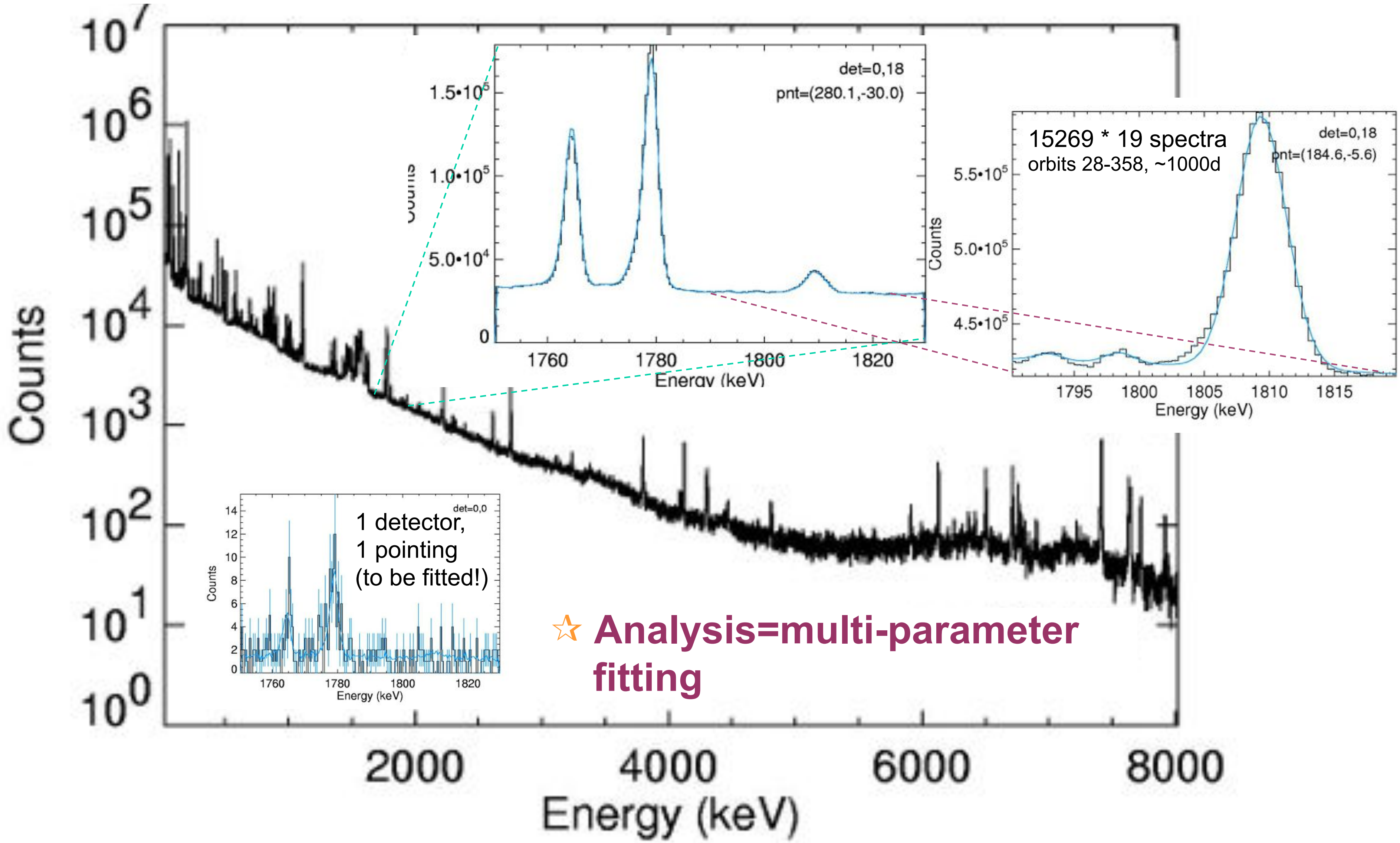






Status Rev 930 May 2010

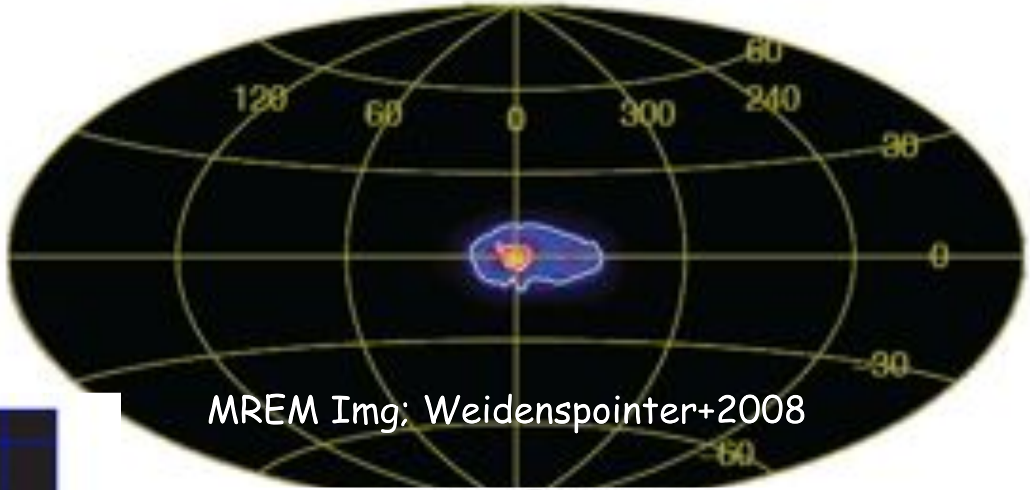
Energy Spectra: Characteristic Examples



☆ **Analysis=multi-parameter fitting**

Morphology in Inner Galaxy

- **Different Approaches**
  - ☞ Imaging Deconvolutions of Different Types
  - ☞ Model Fitting



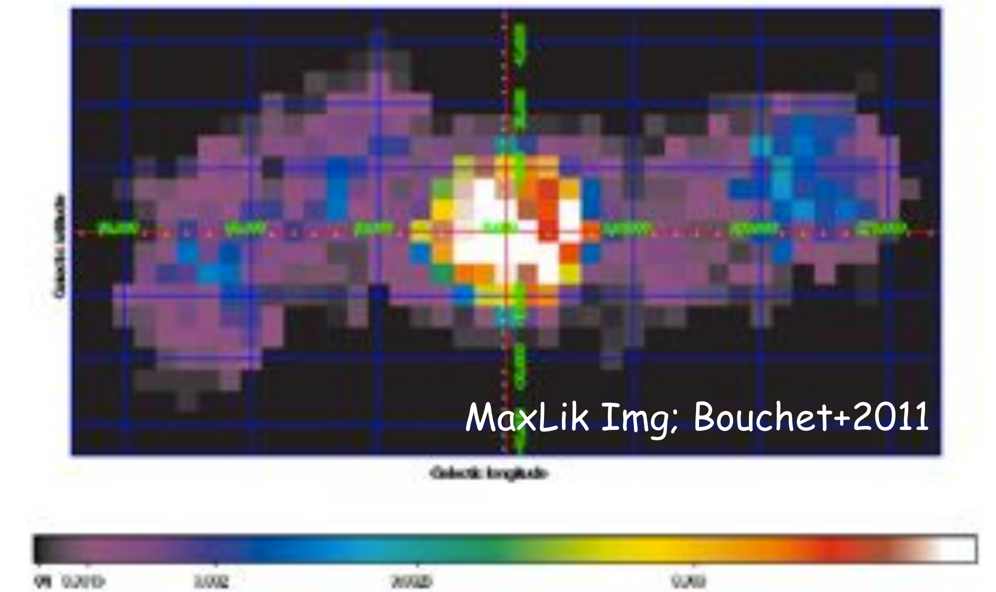
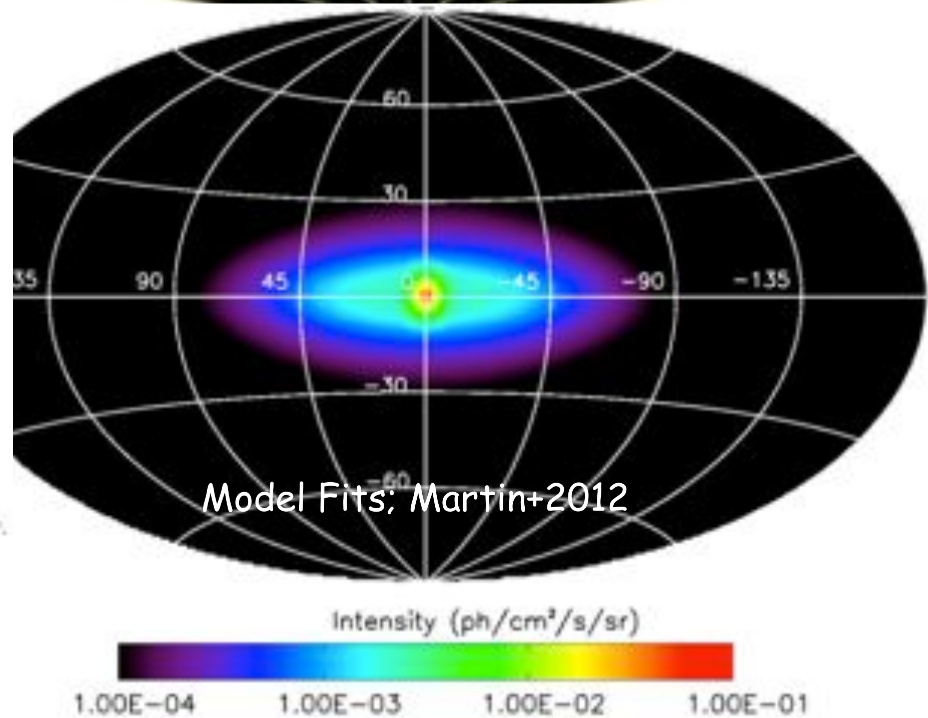
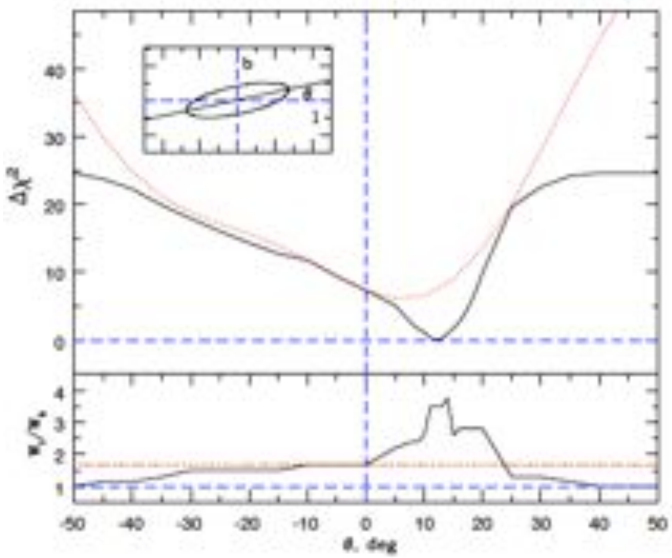


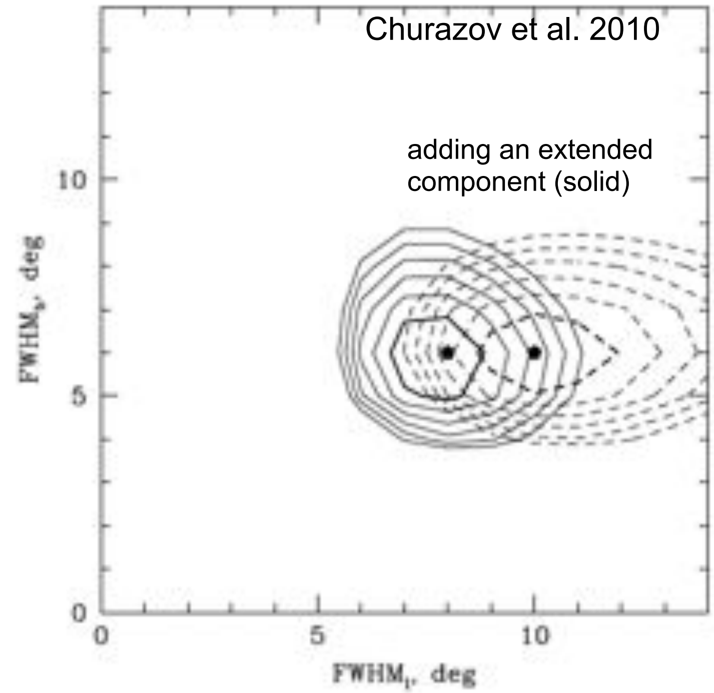
Figure 7. 508.25–513.75 keV INTEGRAL SPI smoothed (top hat of 2 pixels) intensity map in photons cm^{-2} s^{-1}. Pixel size is 5° × 5°.



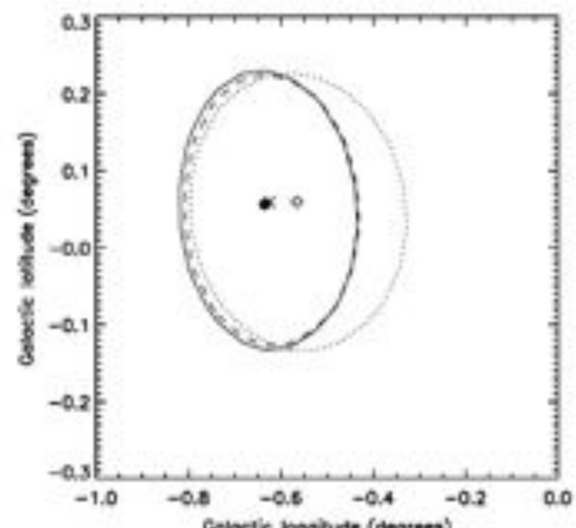
Morphology Investigations

- **Correlated Image Properties**
  - ☞ **Extent in Longitude/Latitude (Gaussians)**
  - ☞ **Tilt with respect to Galactic Plane**



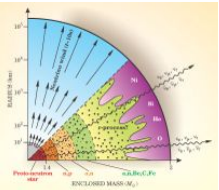


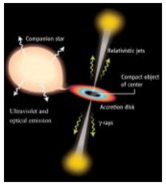
  - ☞ **Bulge Centroid** (Bouchet+2009)

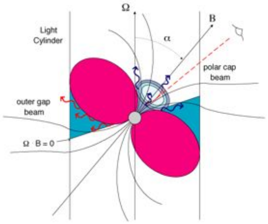


Candidate Positron Sources

- ☆ Nucleosynthesis
- ☆ Accreting Binaries
- ☆ Pulsars
- ☆ SMBH?
- ☆ Dark Matter?







Prantzos et al., RMP 83 (2011)

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	Insufficient 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	γ-γ	~1	2	<0.5	Assuming $L_{e^+} \sim 0.01\ L_{obs,X}$
Microquasars (μQs)	γ-γ	~1	*1*	<0.5	e^+ load of jets uncertain
Pulsars	γ-γ/γ-γ_B	>30	*0.5*	<0.2	Too high e^+ energy
ms pulsars	γ-γ/γ-γ_B	>30	*0.15*	<0.5	Too high e^+ energy
Magnetars	γ-γ/γ-γ_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
	γ-γ	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	

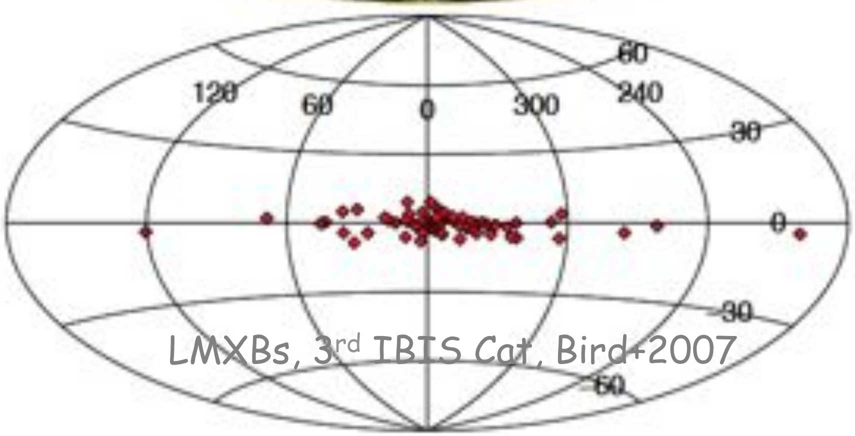
[a]Typical values are given.
[b]e^+ rates: in roman: observationally deduced or reasonable estimates; in italic: speculative (and rather close to upper limits).
[c]Sources are simply classified as belonging to either young ($B/D < 0.2$) or old (< 0.5) stellar populations.

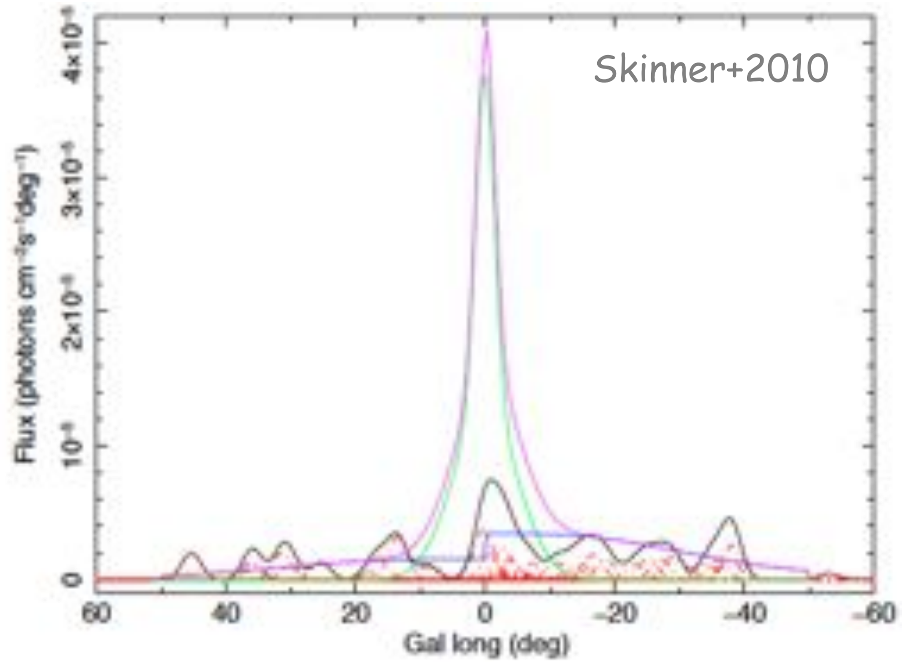
☞ **Only Gamma Rays Can Tell**

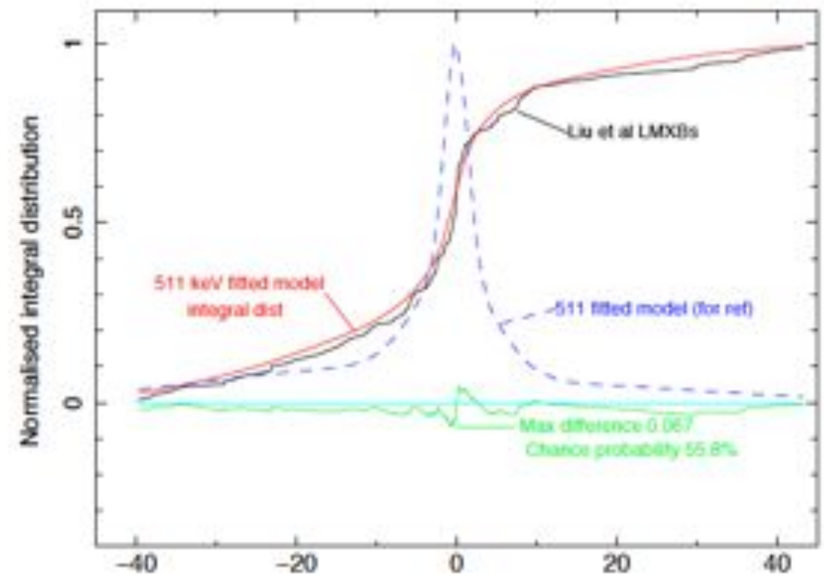
→ **Locations??**

Comparisons of Spatial Distributions: LMXB?

☆ **Annihilation Emission Distribution versus Locations of X-Ray Binaries**







☆ **No Point Sources seen individually**

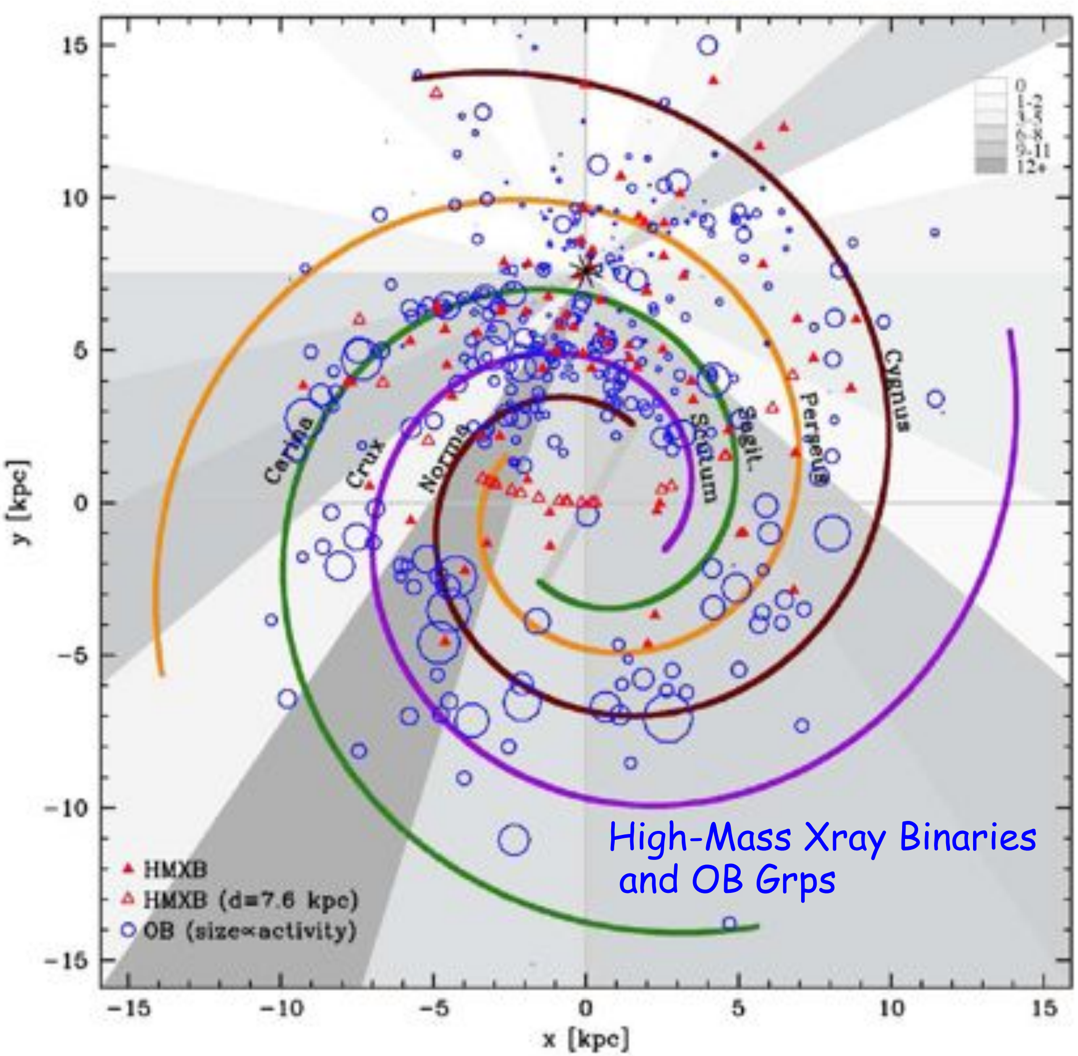
☞ **2σ limit 1.6...4 10^{-4} ph cm^{-2} s^{-1} (IBIS)**

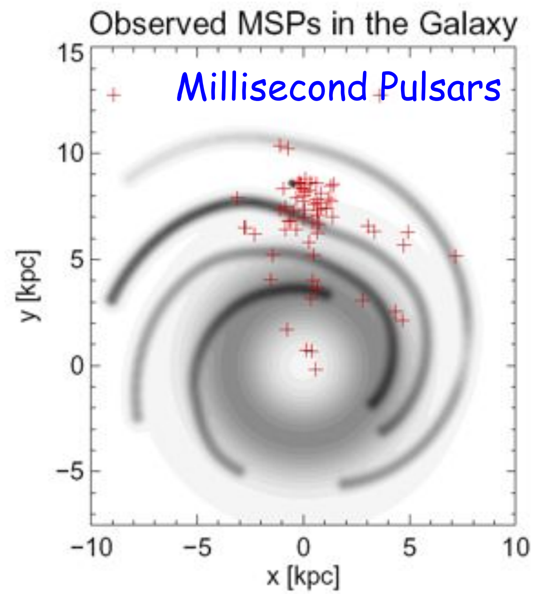
Candidate Sources

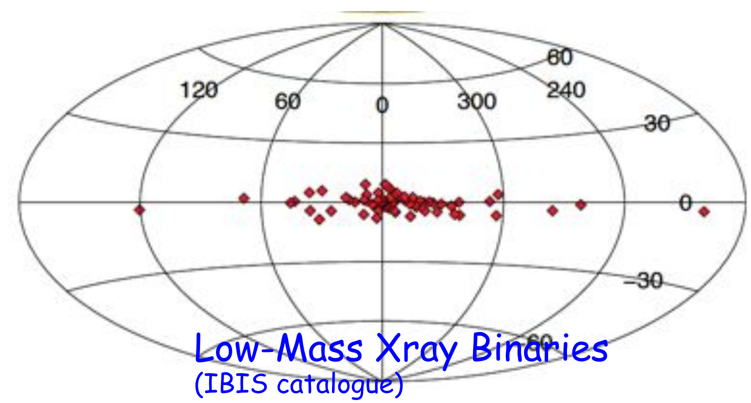
- **Observational Selection Biases:**

e.g. LMXBs: Matter from Companion Star Accretes onto Compact Star → X-Rays

– **LMXBs, HMXBs, Micro-Quasars, Millisecond-Pulsars, X-ray Bursters**





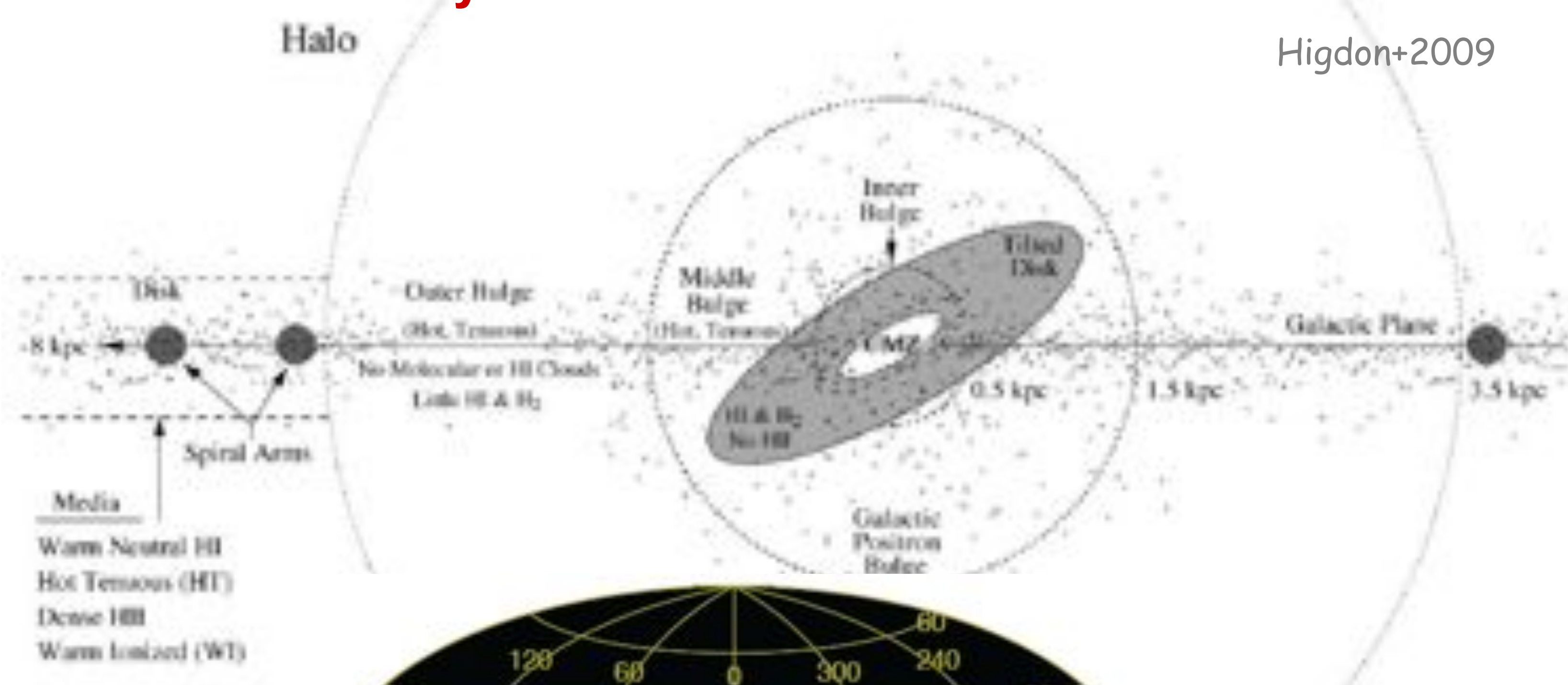


Comparisons of Spatial Distributions: Nucleosynthesis?

☆ **Model Positron Transport and Sources & Galactic Structure →**

☞ **Radioactivities only!**

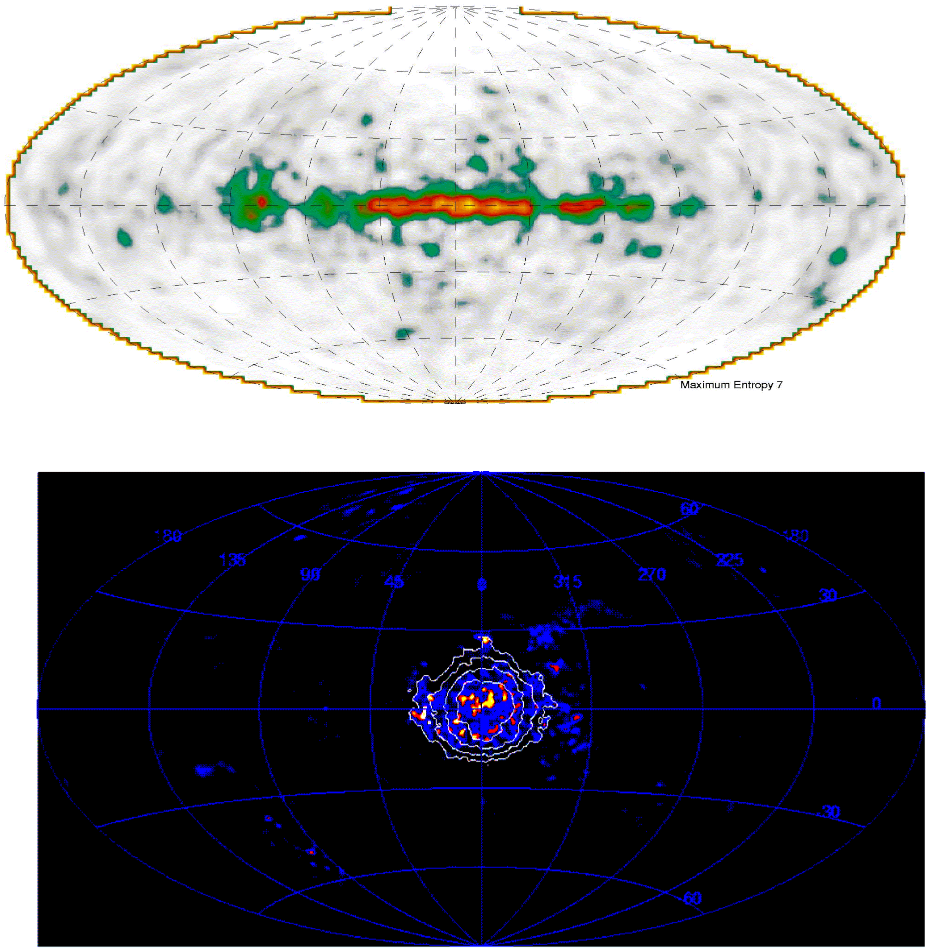
Thus we have shown (Table 7) that, when positron propagation is considered, the positrons from the β^+-decay chains of the radioactive nuclei, ^{56}Ni, ^{44}Ti, and ^{26}Al, produced in Galactic supernovae, can fully account for all of the features of the diffuse Galactic 511 keV annihilation radiation observed by SPI/INTEGRAL. *We*

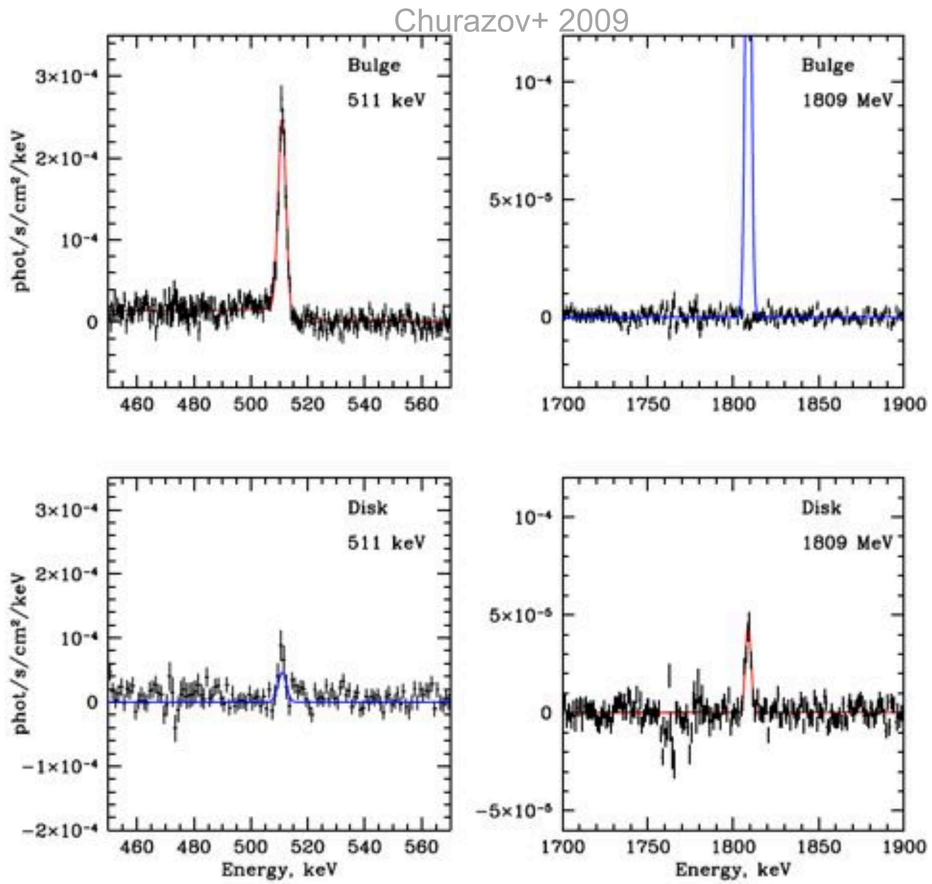


Higdon+2009

MREM; Weidenspointer+2008

^{26}Al and Positron Annihilation

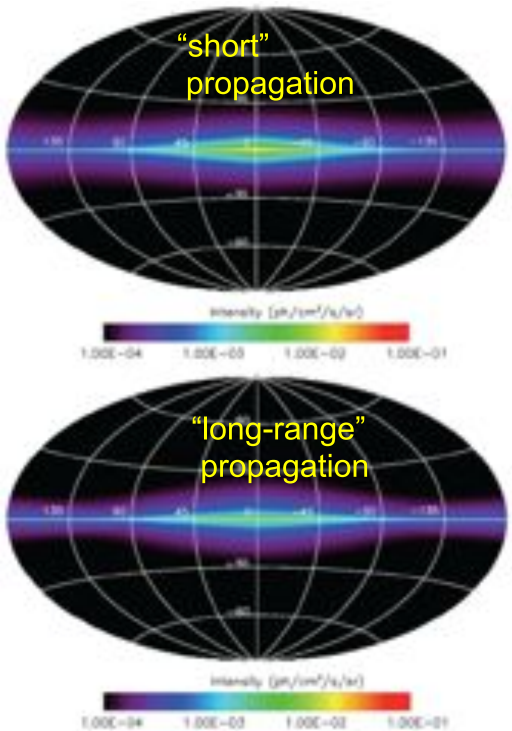




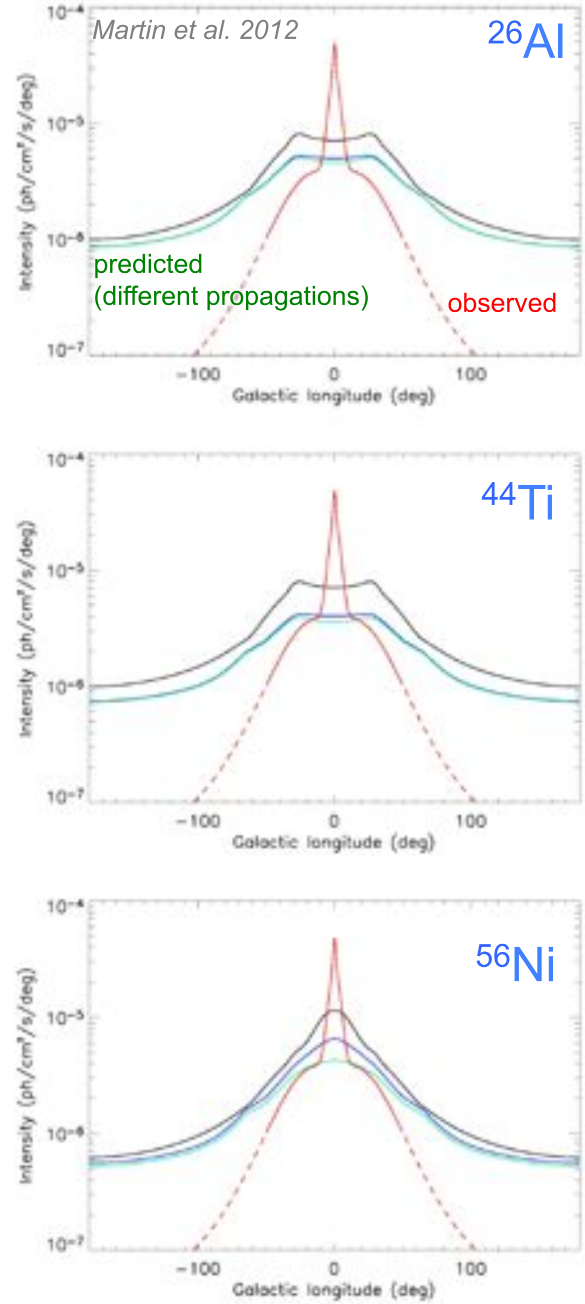
- ☆ ^{26}Al e+ are only a minor contribution in the bulge, but ~all in disk
- ☆ Annihilation Emission Not/Indirectly Related to Nucleosynthesis

Morphology of Positron Annihilation Emission

- **Nucleosynthesis Explains the Disk Emission**



- **Another Source Needed for the Bulge**



Galactic Positron Annihilation: Summary

- ☆ Annihilation γ-Rays are a New Astronomical Domain / Window
- ☆ Galactic-Disk Emission: More-than-enough Sources, probably Nucleosynthesis; Bulge Emission: a Puzzle
- ☆ Positron Transport and Annihilation Environment Diagnostics → Cosmic-Ray and ISM Astrophysics
- ☆ Spatial Profile of Annihilation Emission → Discriminate Candidate Sources
  - ☞ Disk versus Bulge Sources
  - ☞ Galaxy Survey
  - ☞ Deep Exposures are Needed to Constrain Contributions of Specific Source Types (Individual, Groups)
  - ☞ SPI++, and Next-Generation Instruments