INTEGRAL/SPI and ^{26}Al in the Galaxy

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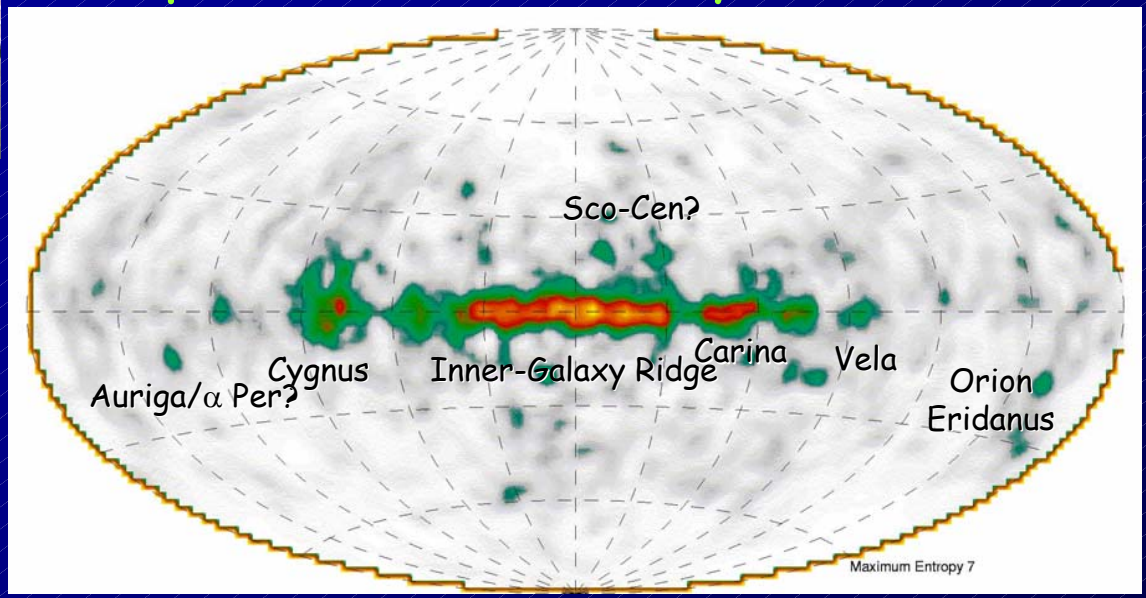
with

H. Halloin, A.W. Strong, J. Knödlseder, K. Kretschmer, W. Wang, et al…

- ^{26}Al Astrophysics Issues Reminder
- INTEGRAL/SPI ^{26}Al Data & Analysis Aspects
- SPI ^{26}Al Line Spectroscopy (Large-Scale)

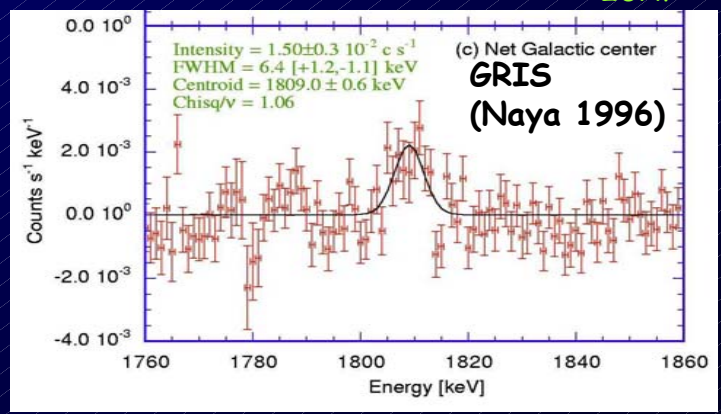
Measurements of the Sky at 1809 keV: ^{26}Al

Maps Recent Nucleosynthesis in the Galaxy (τ_{26Al}~1My)



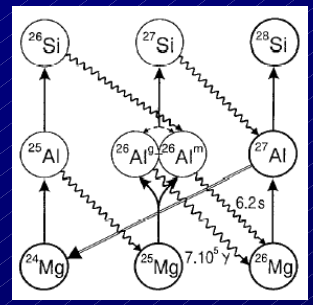
9 Years of Data (CGRO Mission)
(Plüschke et al. 2001)

Line Shape Reflects Kinematics (τ_{26Al}~1My)



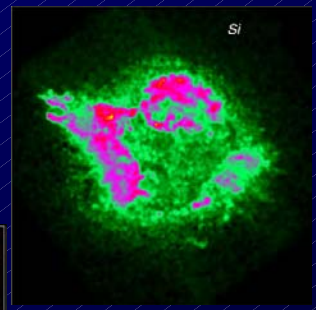
Candidate Sources of ^{26}Al

- p-rich Environment -> H Burning
- Seed Nuclei (Ne-Na group or Mg)
- Ejection of Nuclear Ashes (Wind, Explosion)



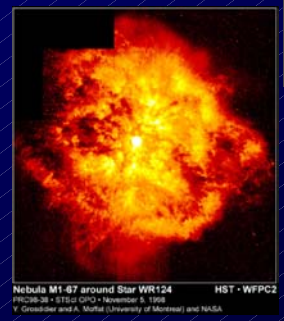
Core-Collapse Supernovae

- Explosive Burning in O-Ne Shell, Triggered by SN Shock Wave
- Ejection of Pre-SN ^{26}Al and Explosive-Burning ^{26}Al



Massive Stars in their Wolf-Rayet Phase

- Core H-Burning -> ^{26}Al Production During ~10^{5}y MS Phase
- WR Phase Mixing & Stellar Wind -> Ejection into ISM

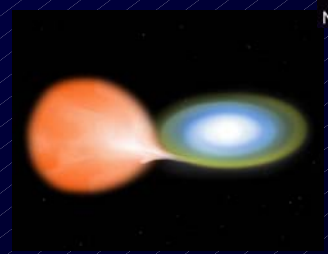


AGB Stars (M>4M$_{\odot}$)

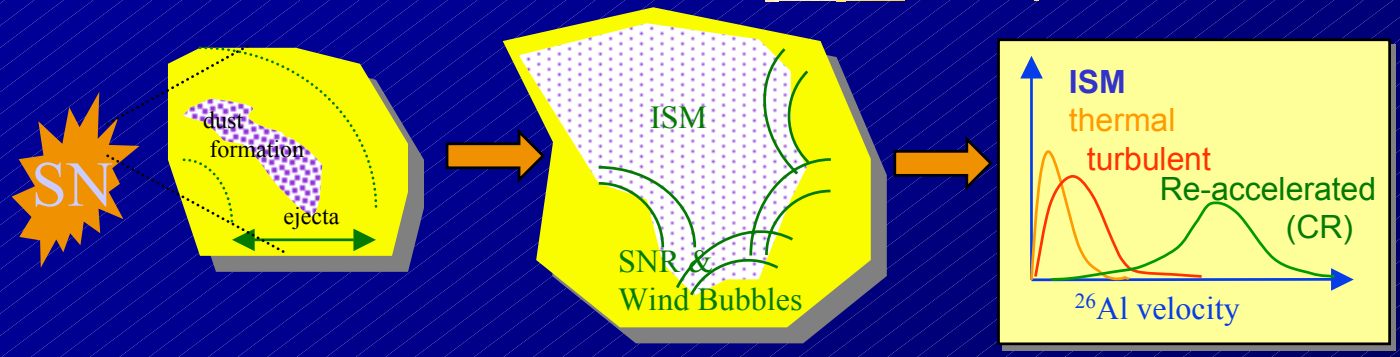
- H Shell Burning, Fresh Seed Nuclei from He Pockets
- Ejection Through Thermal Pulses, >> ^{26}Al Decay Time

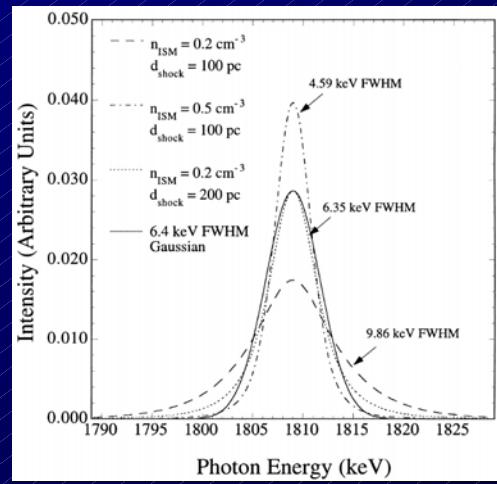
Novae

- H Accretion onto White Dwarf
- Explosive H Burning with Seed Nuclei Admixture

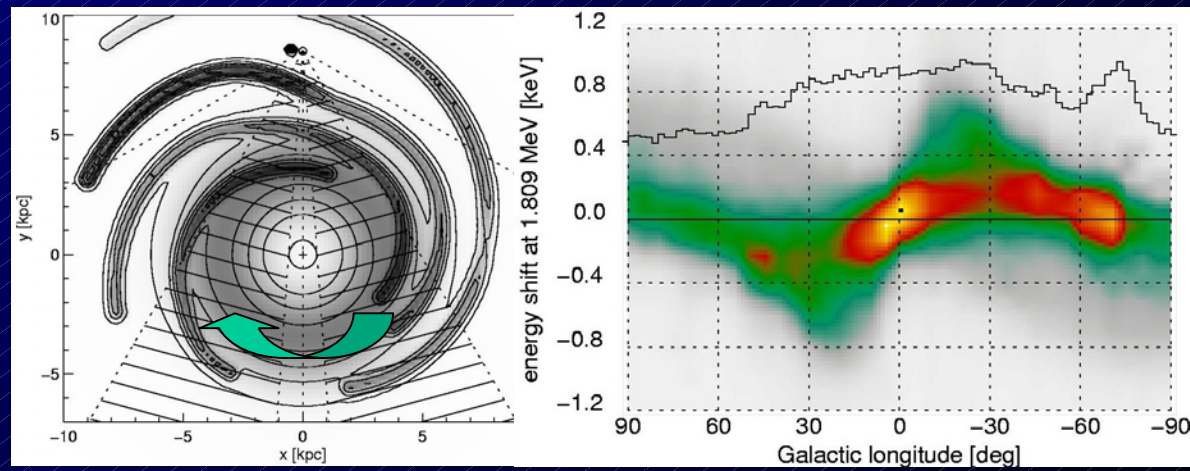


^{26}Al Line Shape Astrophysics





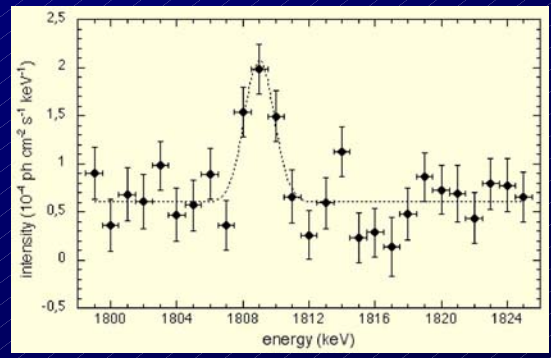
- Ejection and Slowing-Down of ^{26}Al from Sources
  - ^{26}Al Ejected into Hot Cavities (WR Winds, …)
    -> ISM Turbulence <-> Line Width
  - ^{26}Al Condensed on Dust, Re-accelerated -> High-Velocity Tail?
    - *Chen et al. 1997; Sturner & Naya 1999*
- Galactic Rotation
  - ^{26}Al Sources in Spiral Arms, Along Line-of-Sight
    -> ^{26}Al Source Location Along LoS
    - *Gehrels et al. 1996; Kretschmer et al. 2003*

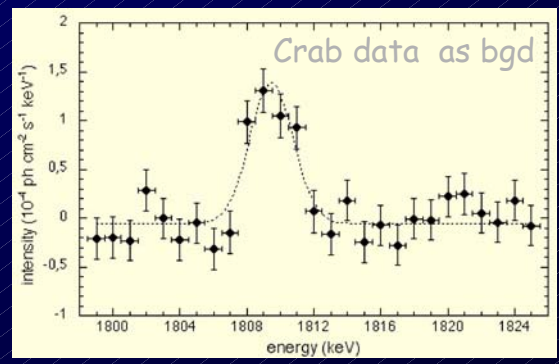


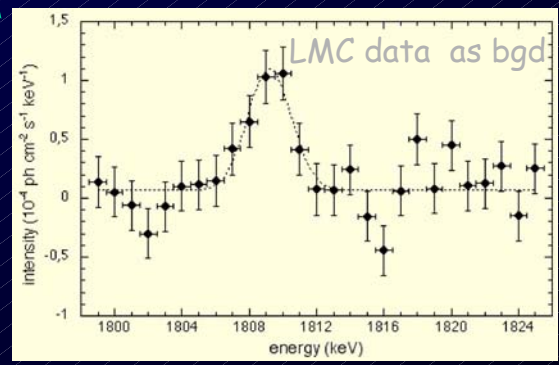
Spectroscopy by Imaging Analysis

Diehl et al., A&A 411 (2003)

- ☆ Adopt Sky Intensity Distribution from a Model
  - ☞ Use Tracers (e.g. Dust Emission 240 mm), COMPTEL's Map, Exponential-Disks
  - ☞ Rather Insensitive to Map Detail
- ☆ Adjust Background and Skymap Intensity per Energy Bin
  - ☞ Fix Relative Count Ratios of 19 Detectors, Adjust/Fit Bgd Level per Pointing (MPE)
  - ☞ Model Time History of Line Background from Activation Tracer (adjust per Orbit) (CESR)



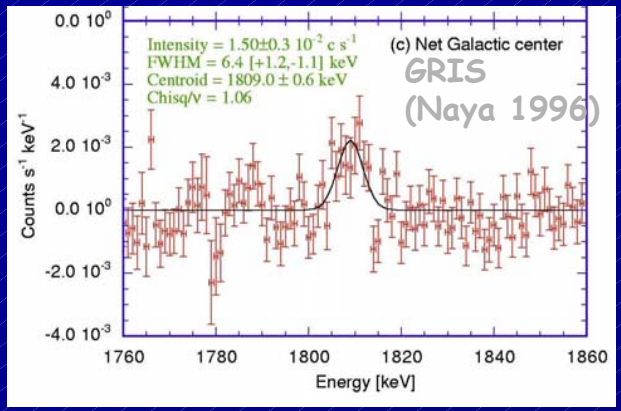


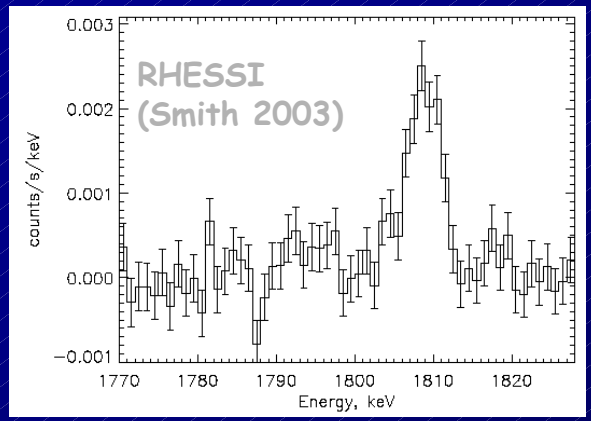


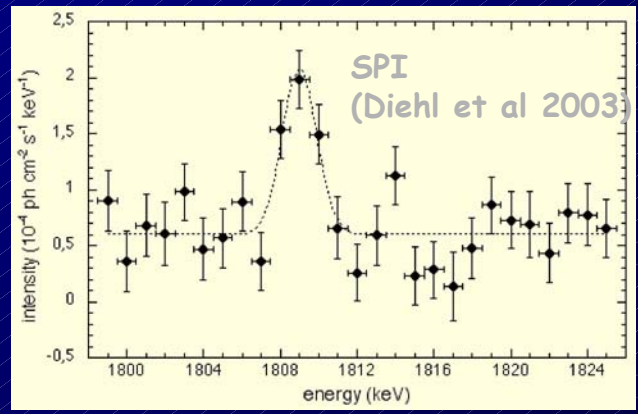
- **Results** (GCDE-1 0.8 Ms)
  - ☆ Detection of ^{26}Al (0.8Ms GCDE-1) (~6σ)
  - ☆ Consistency:
    - ☞ Flux 4 ±1 10^{-4} ph cm^{-2} s^{-1} rad^{-1}
    - ☞

	FWHM [keV]	I [10^{-4} ph cm^{-2} s^{-1}]
uncertainty	0.7	1.4
fit value Fig. 6	2.1	3.3
fit value Fig. 7	3.1	3.3
fit value Fig. 8	3.1	4.7

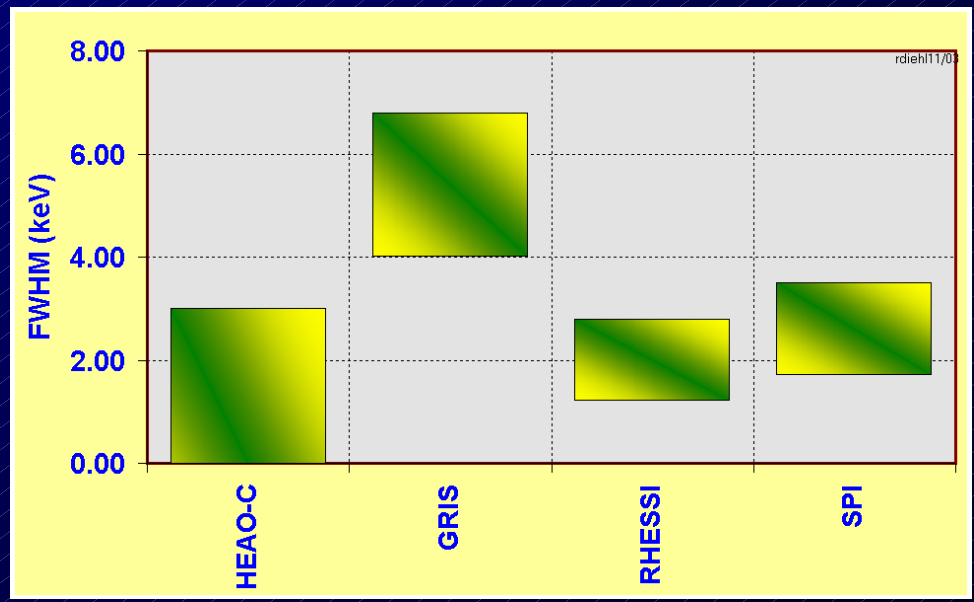
^{26}Al Line Width: Velocity of ^{26}Al in ISM







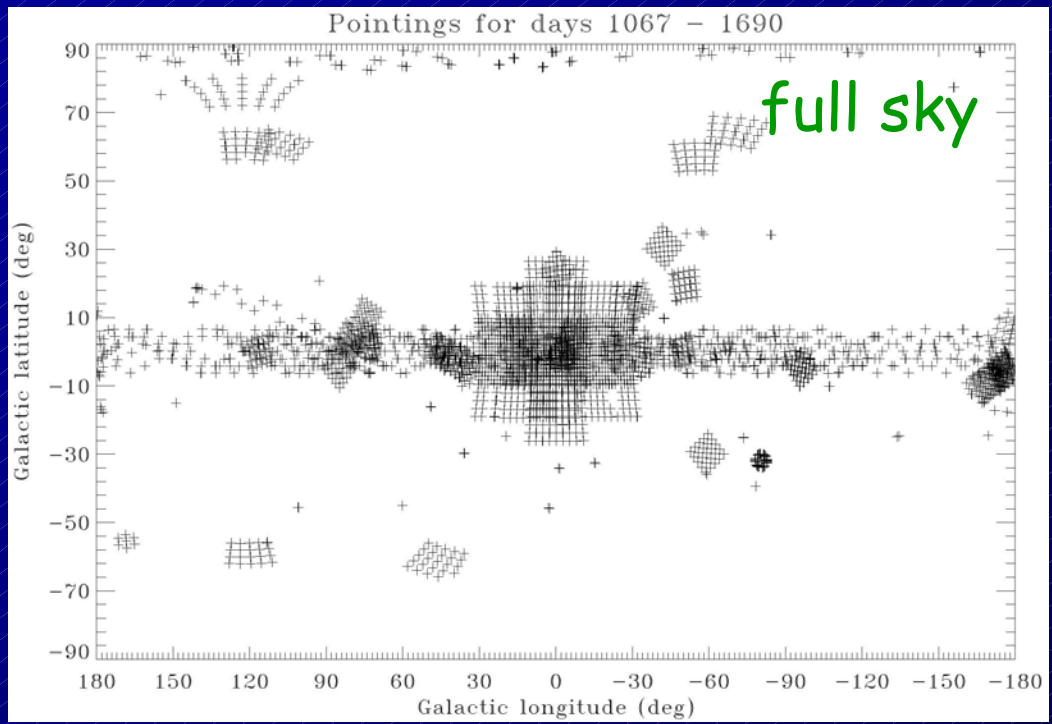
- ☆ Broad Line was Difficult to Understand
  - ☞ ^{26}Al on Dust?
  - ☞ Huge ISM Cavities?
  - ☞ *Chen et al. 1997*
- ☆ Issue Dissappeared?



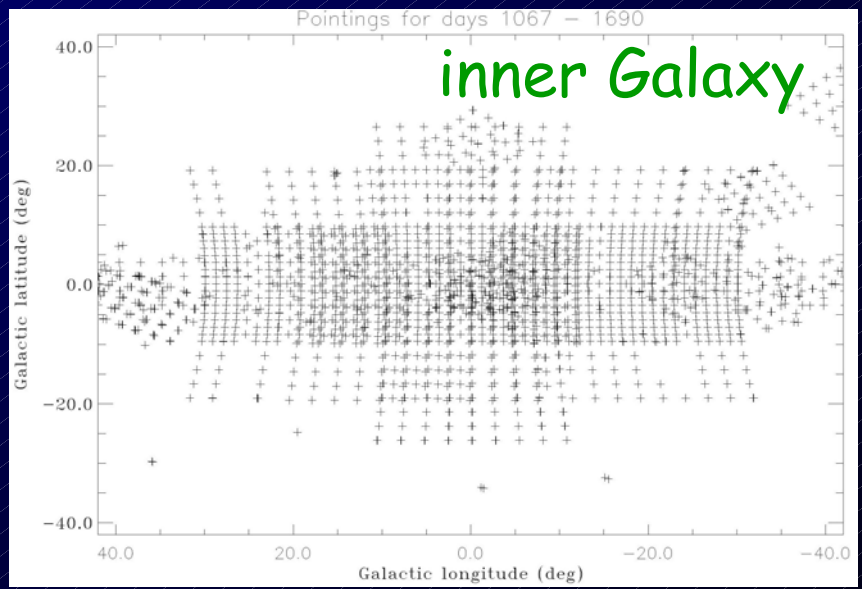
The INTEGRAL ^{26}Al Sky Survey

Core Program, GPS, Specific Targets

- ☆ "Dither Patterns" Scattered over the Sky

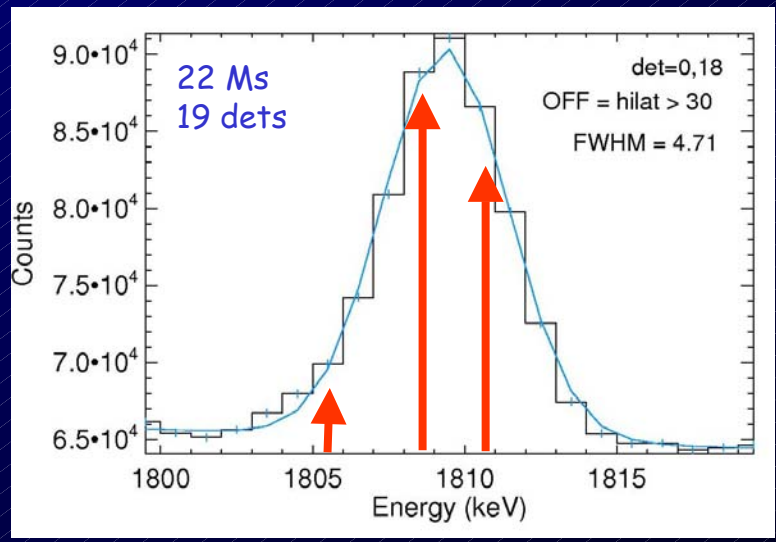


- Status late 2004:
- Rev 15-225
  - ISWT Data (CP, PI)
  - Public Data
  - Data with PI Permission for ^{26}Al Study
  - 13 Msec total

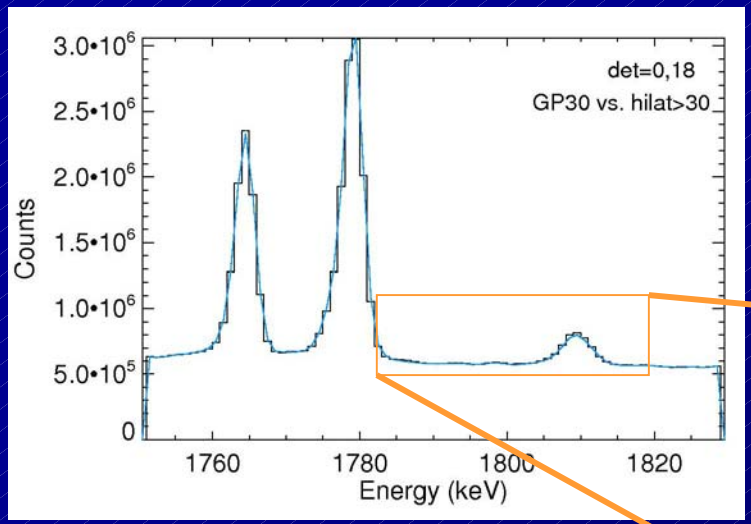


Ge Detector Spectra from SPI

- ☆ Spectral Background Feature at ~1810 keV:
  - ☞ Complex of Instrumental Lines
    - 1808.63 keV ^{26}Mg, $^{26/27}$Na (^{27}Al (p,α)+ n capture activation) — 52.3±0.7%
    - 1810.77 keV ^{56}Co, ^{56}Mn — 38.8±0.5%
    - 1805.5x keV? (degradation / origin tbd) — 8.9±1%
  - ☞ Variable Activation
    - Radioactivity Build-Up
    - CR Flux Variations (Belts, Sun)
  - ☞ Expected ^{26}Al Signal: ~2-4%
    - 1808.63 keV ^{26}Mg

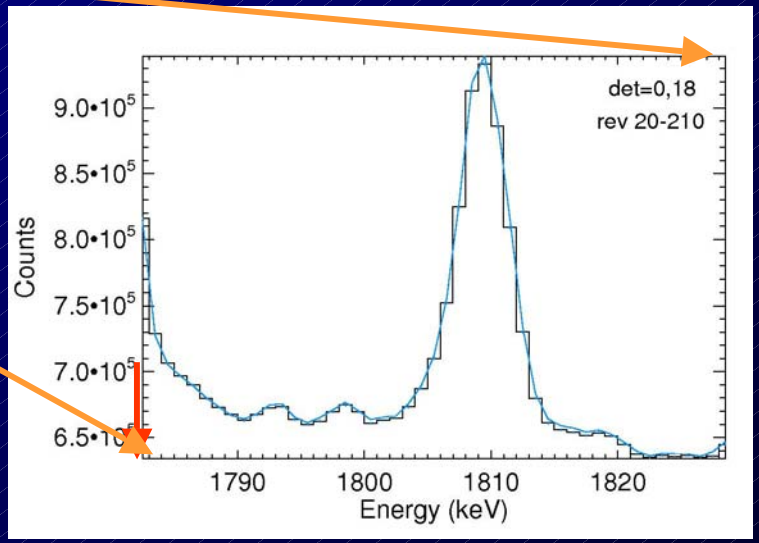


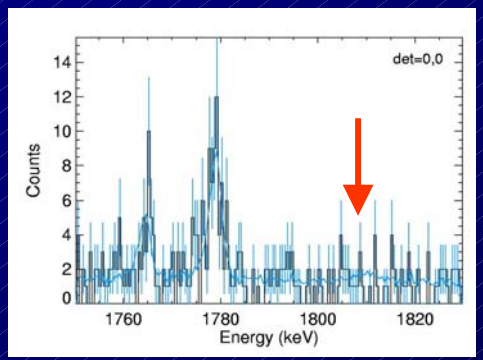
Ge Detector Spectra from SPI



☆ Spectral Features around ~1800 keV:

- ☞ Coontinuum plus Instrumental Lines
  - 1764 keV ^{26}Mg, $^{26/27}$Na (^{27}Al (p,α)+ n capture activation)
  - 1779 keV ^{26}Mg, $^{26/27}$Na (^{27}Al (p,α)+ n capture activation)
  - 1808.63 keV ^{26}Mg, $^{26/27}$Na (^{27}Al (p,α)+ n capture activation)
  - 1810.77 keV ^{56}Co, ^{56}Mn

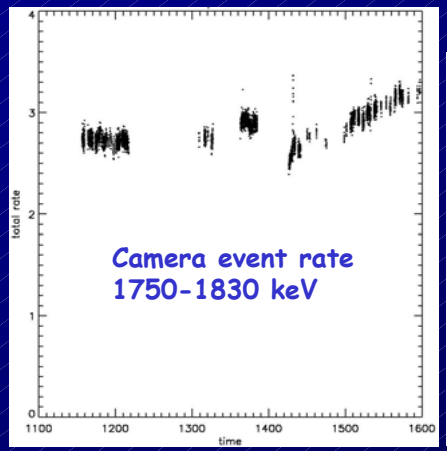


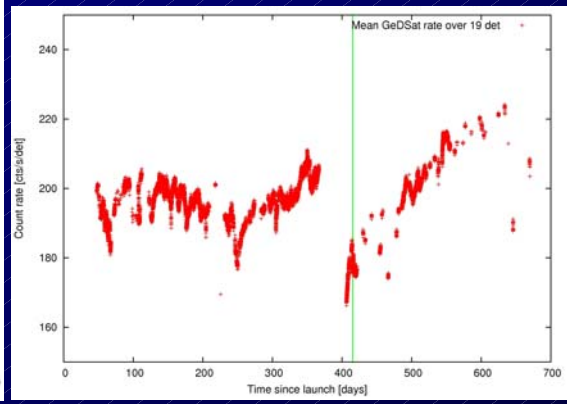


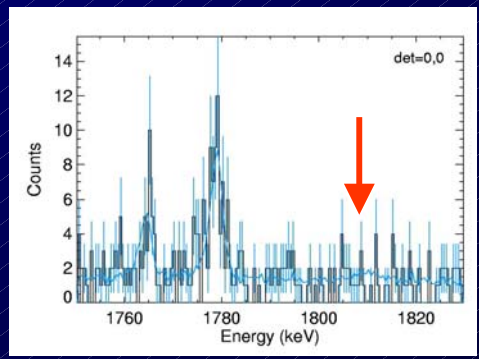
- ☞ Variable Activation of Continuum & Lines
  - Radioactivity Build-Up
  - CR Flux Variations (Belts, Sun)
- ☞ Expected ^{26}Al Signal: ~2-4%
- ☞ Low Statistics per Measured Spectrum (1/2h)
  - > 120000 spectra in SE Survey analysis

☆ Analysis Challenges

- ☞ Understand Background
  - ON/OFF Re-Normalizations
  - Complete Activation History
  - Line Identifications
- ☞ Model / Fit Background Properly
- ☞ Account for Low-Number Statistics
  - > 10000 Spectra / Msec







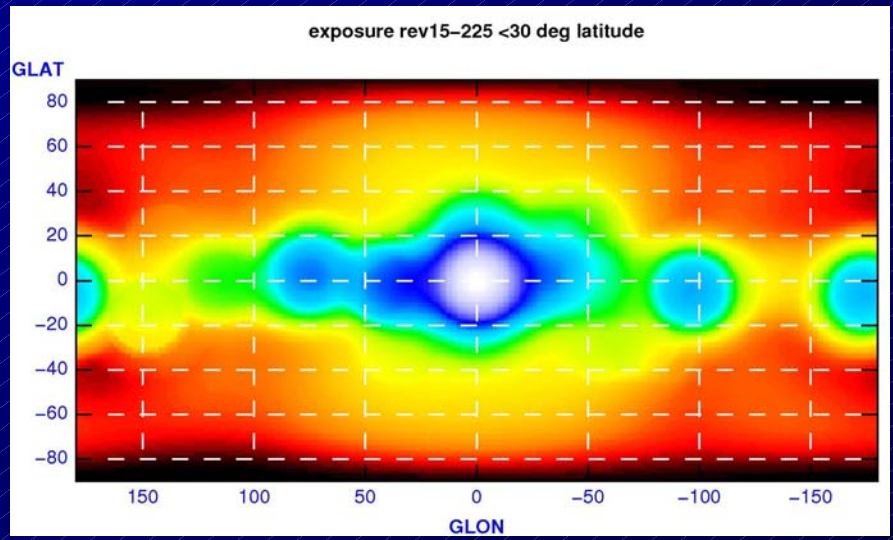
☆ Analysis Methods

- ☞ Imaging Spectroscopy with SPI
  - **ON/OFF Spectra Sanity Checks**
  - **Fitting Model Skymaps per Energy Bin -> First-Order Spectra**
  - **Iterative Deconvolutions -> High-Resolution Spectra**

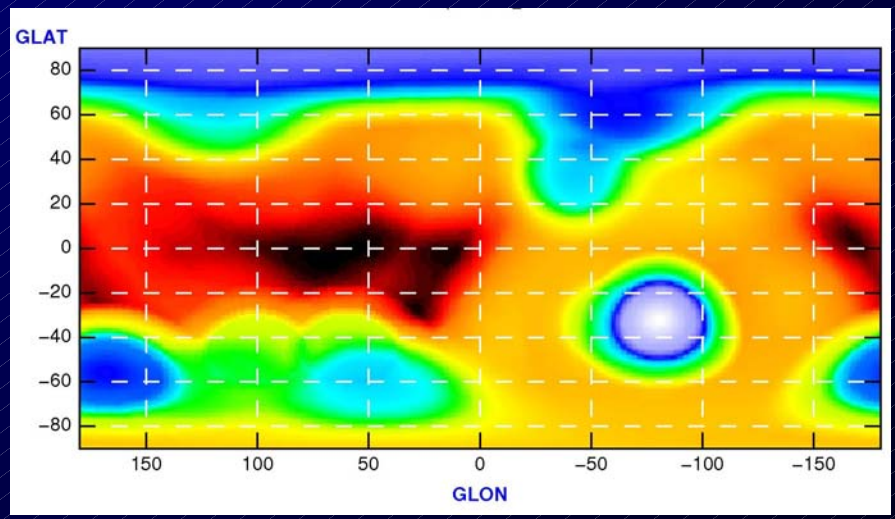
Current Dataset (Largescale ^{26}Al Study)

- Rev 15-225 (...19 Aug 2004)
  - ISWT Data (CP, PI)
  - Public Data
  - Data with PI Permission for ^{26}Al Study
  - 13 Msec total

☆ All pointings below 30deg

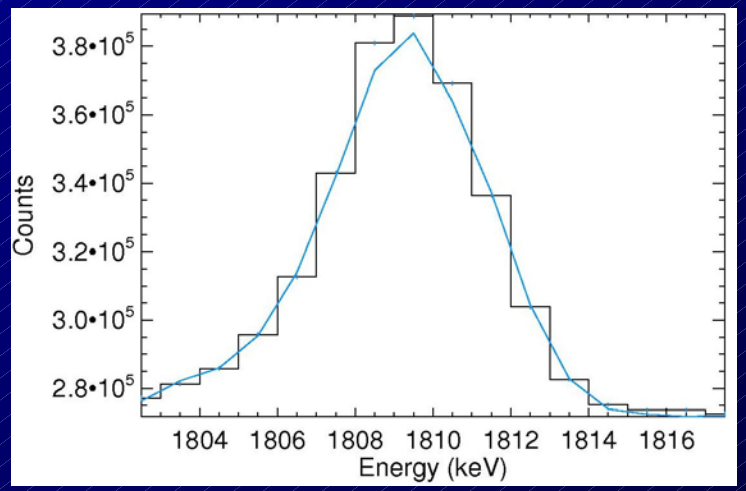


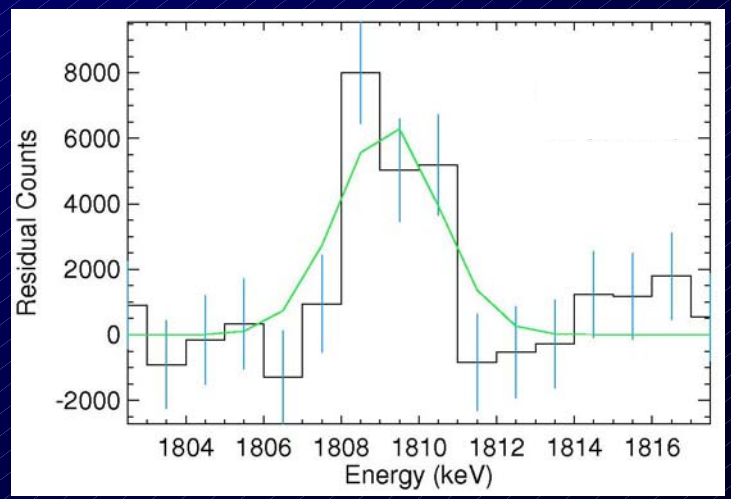
☆ All pointings above 30 deg



Results: Simple/Straightforward ON/OFF

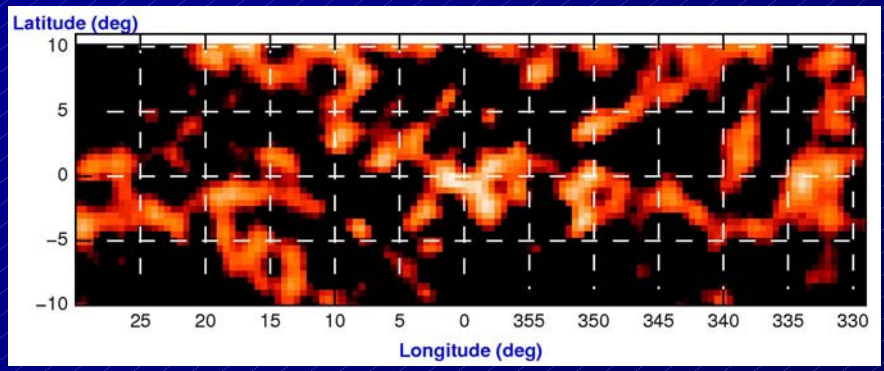
- ☆ Separate Database:
  - ☞ ON= pointing latitudes <30° (11.08 Ms)
  - ☞ OFF= pointing latitudes >30° (2.1 Ms)
- ☆ Subtract & Inspect
  - ☞ 13σ Residual Signal
  - ☞ Width ~ "instrumental"
    Width < background feature at 1810 keV
  - ☞ Intensity ~as Expected
    - 21000 counts; expect 25000
      from I~3 10^{-4} ph cm^{-2} s^{-1} rad^{-1}
      for this exposure (at GC 3.31 Ms) and A_{eff}~25 cm^2

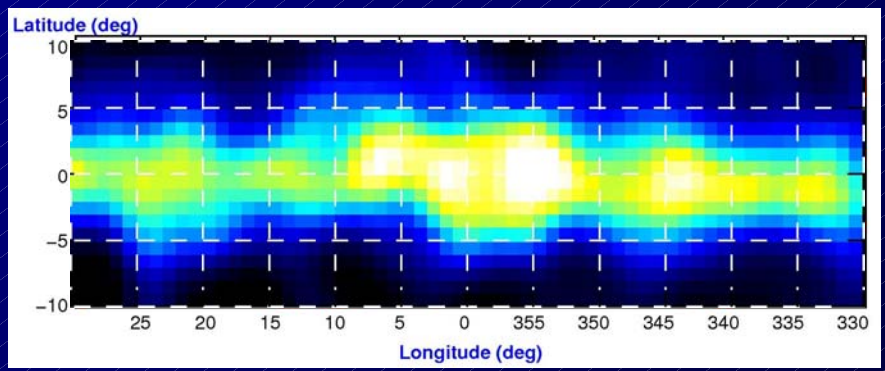




Value	Name	Error
1809.21	Centroid	0.11
1.30	Width	0.00
21024	Counts	1630
12.90	sigma of detection	

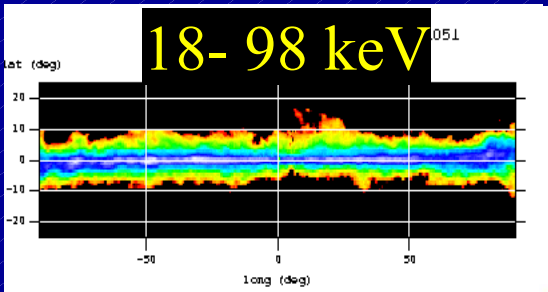
Imaging Attempts: SPI vs. COMPTEL

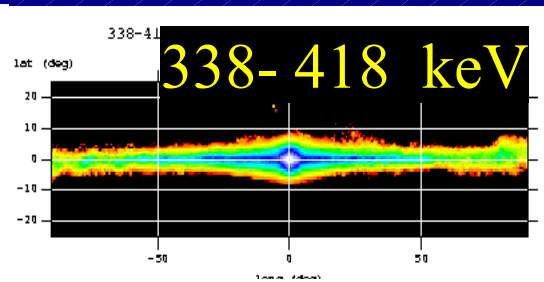
- "Unbiased" Imaging
  - Spiskymax = Maximum Entropy Method
  - Pixelized Sky; Background from Model Fitting
  - 

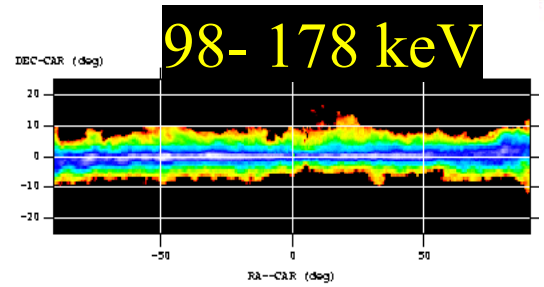
  - ~15σ total ^{26}Al signal (~3.3Ms@GC)
  - cmp: COMPTEL ME
  - 

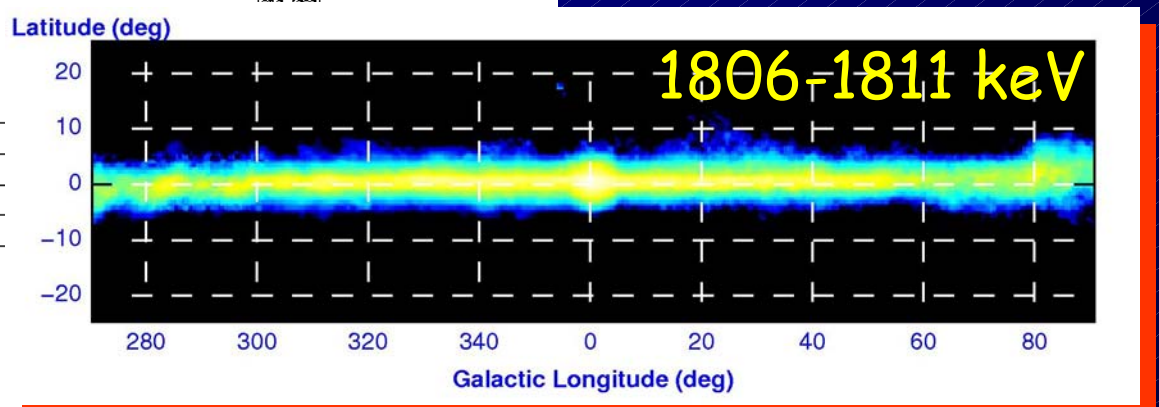
  - >50σ total ^{26}Al signal (~10Ms@GC)
  - *Signal Still Well Below Imaging Threshold!*
    - *COMPTEL GC exposure ~5 INTEGRAL Mission years*

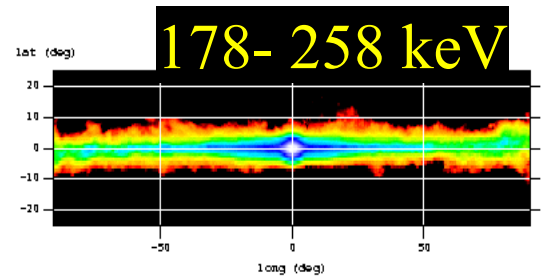
Imaging by Model Fits with "pixon" Components
(CO, HI, Gaussians)

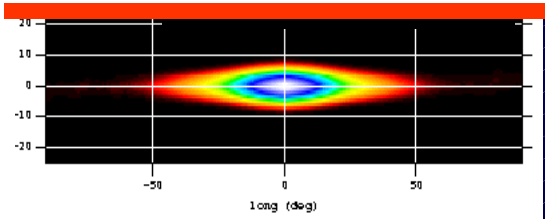


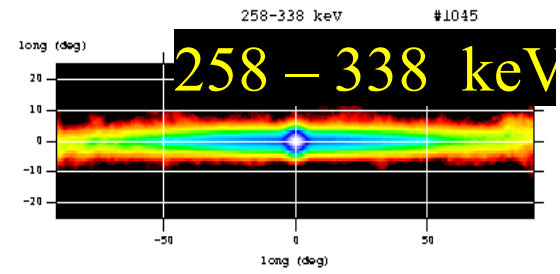


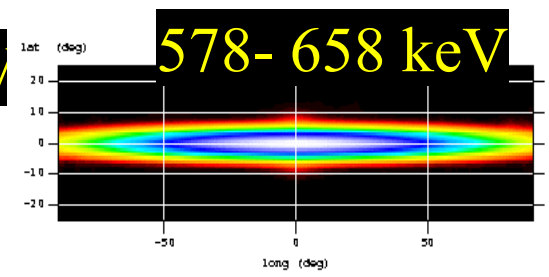


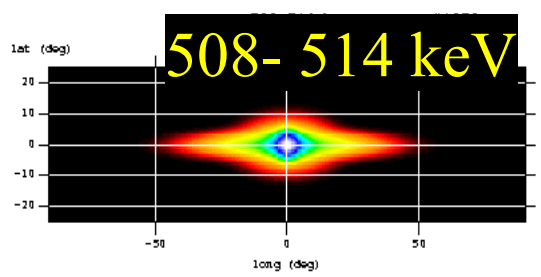










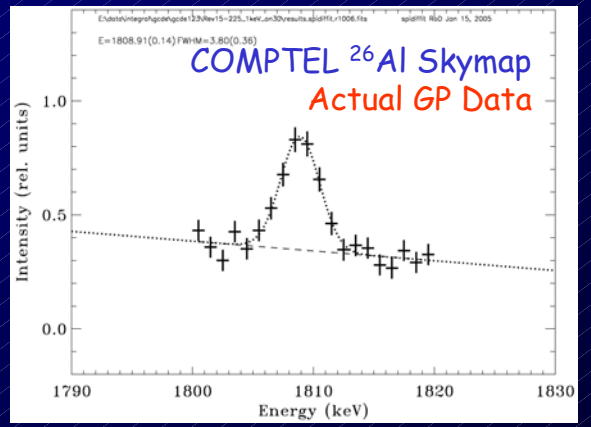


Imaging Spectroscopy: Validation of Sky Signal

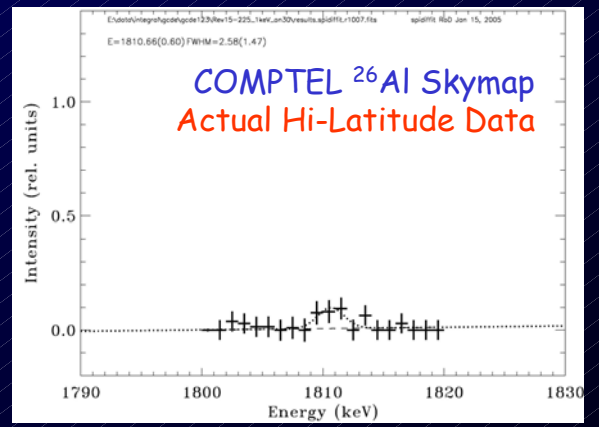
Method: Sky Model (&Bgd) Fitting per Energy Bin -> Spectrum

Perform Identical Analysis on "OFF" Reference Dataset

- Key Aspects:
  - Identical Sky and Background Models
  - Different Measurement without ^{26}Al Counts
    - Choose High-Latitude Reference (all pointings b>30°)
    - Match to Pointing/Exposure Scheme of Real Dataset

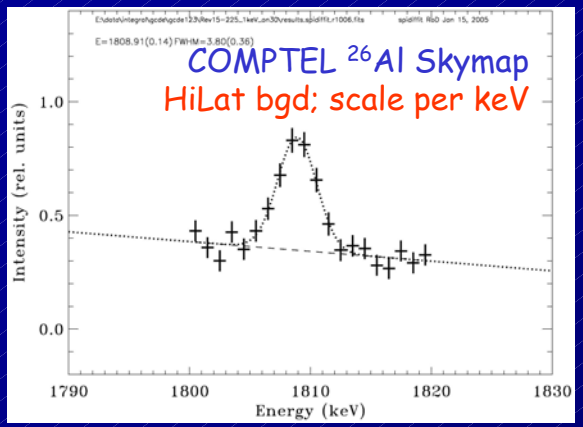


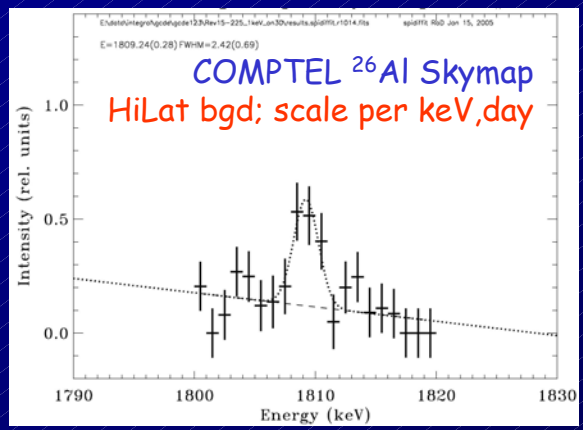
- Expectations:
  - "DC-Level"/Offset: Reflects Background Model Accuracy
    - Continuum Part Dominates Count Spectrum
    - Poor Bgd Fit Increases Apparent Sky Correlation of Data
  - Spectral Feature:
    - If Instrumental-Background Feature:
      - Spectral Features ~Similar for Both Cases
      - Spectral Feature Mirrors Instrumental Feature (Width, I_{line}/I_{cont})
    - If Celestial Signature:
      - Spectral Feature ~Absent for OFF Data
      - Spectral Feature Differs from Instrumental Feature (Width, I_{line}/I_{cont})

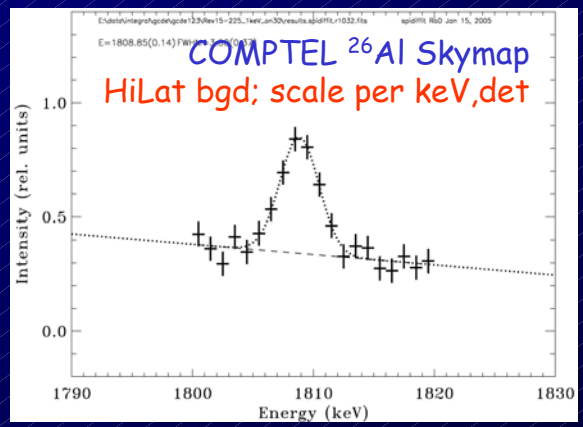


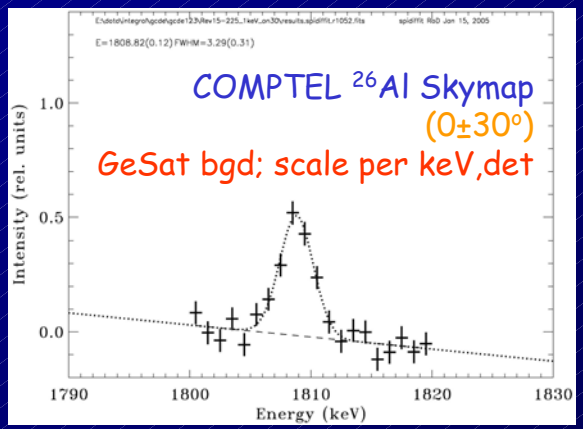
Imaging Spectroscopy: Sky Signal Systematics

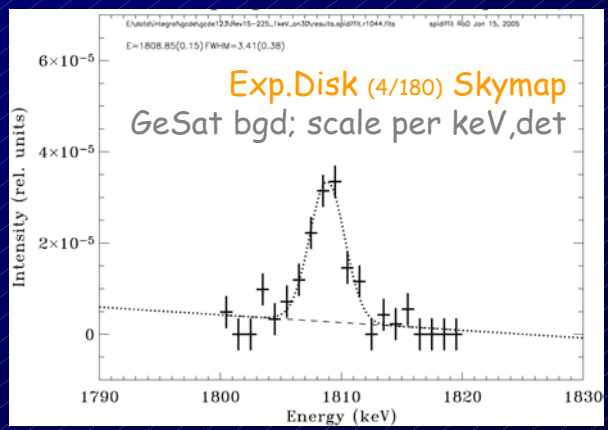
Variations of Input Models: Background, Sky

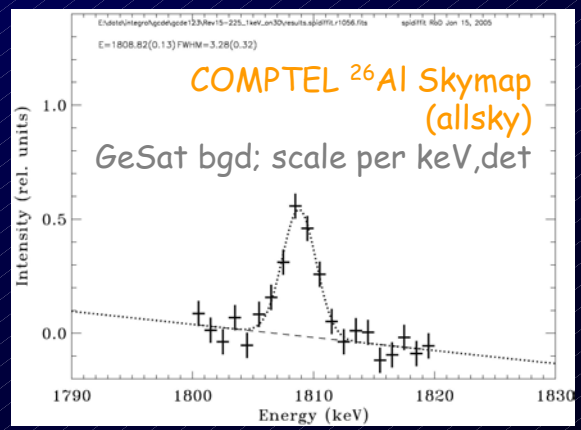












- Need to Use Reliable Background Time Variability Model; Sky Model ~Uncritical
- Width~Stable

^{26}Al Line Shape Studies

Goals

- Line Centroid Accuracy
  - Doppler Shifts from Galactic Rotation & ISM Kinematics
- Line Width Accuracy
  - Average ISM Turbulence in ^{26}Al Source Regions

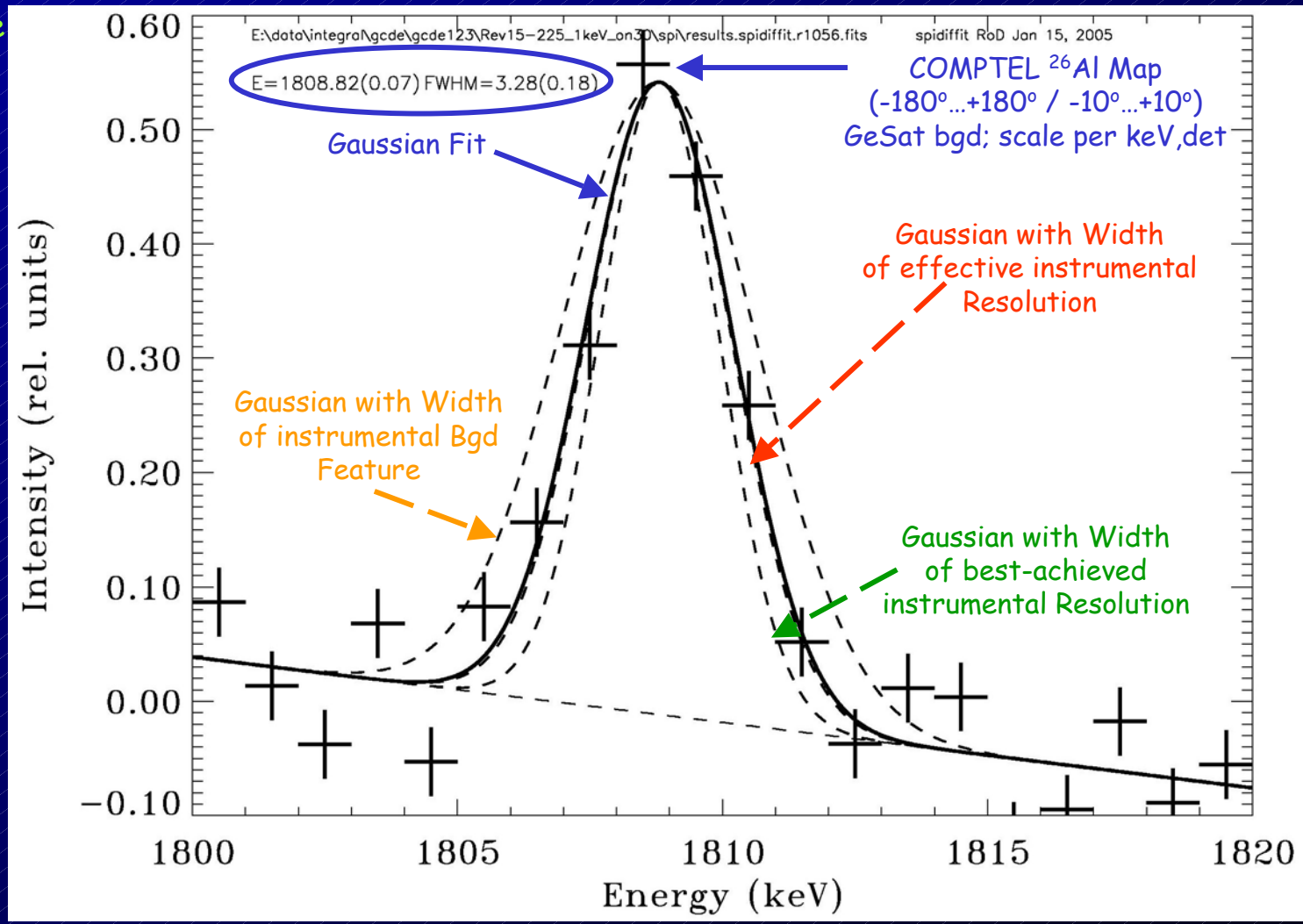
Challenges

- Absolute Energy Calibration
- Relative Adjustment of Ge Detectors
- Ge Detector Degradation from Energetic-Particle Bombardement (with Annealings)

Imaging Spectroscopy: ^{26}Al Line Shape (1)

- Standard Processed Data
  - "ISDC" Energy Calibration, Livetime Correction, Detector Failure Handling
  - No "Corrections" for Degradation & Annealings
- Standard Response
  - No Time Variability

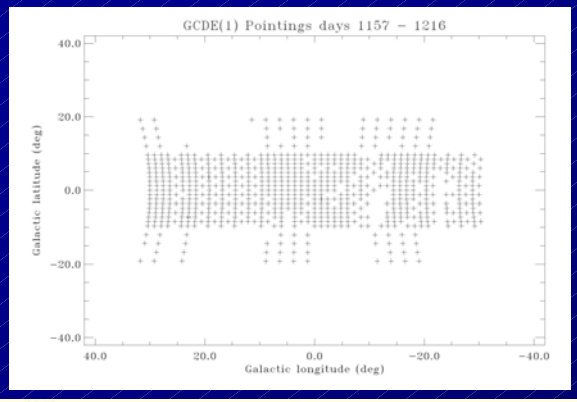
The Galactic ^{26}Al Line is not significantly broadened

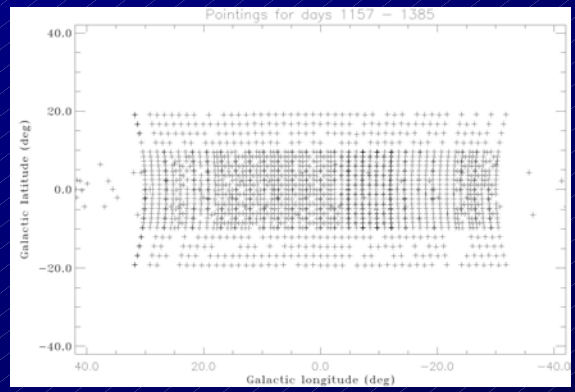


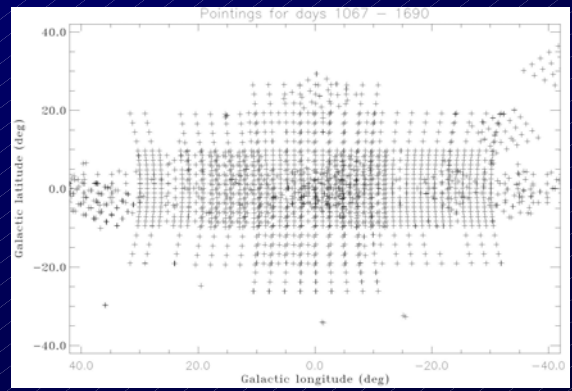
SPI's Inner Galaxy Survey

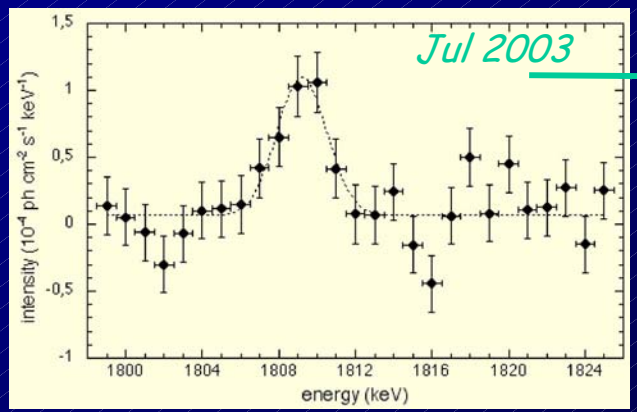
INTEGRAL Core Program: "GCDE"

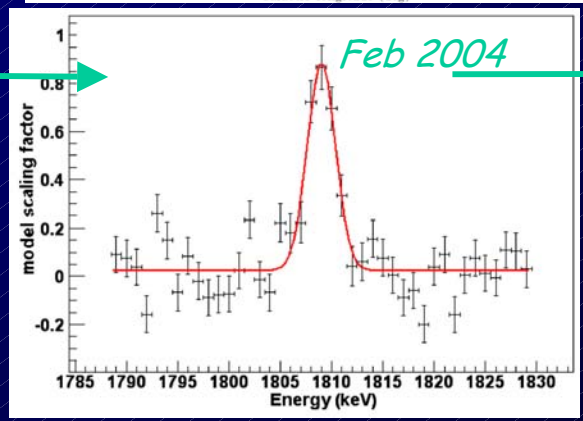
- Inner-Galaxy Observing Times:
  - GCDE1: ~1 Msec
  - GCDE1+2: ~3.6 Msec
  - Rev15-225 ~11 Msec

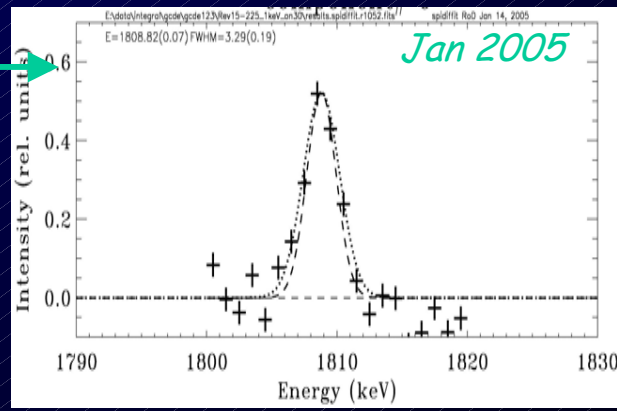






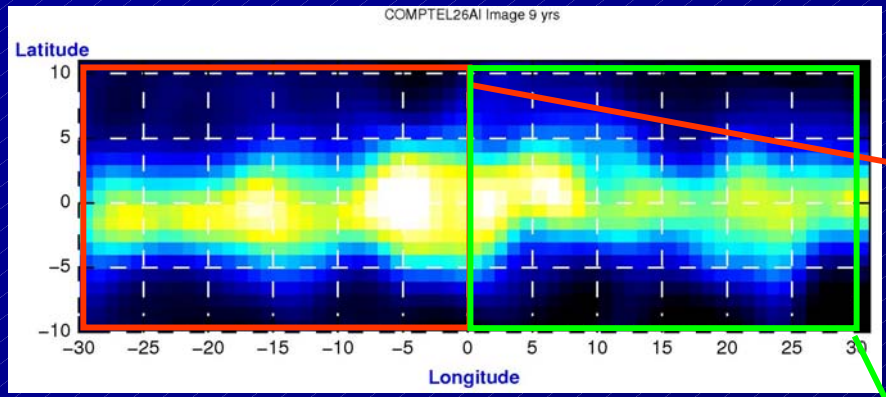


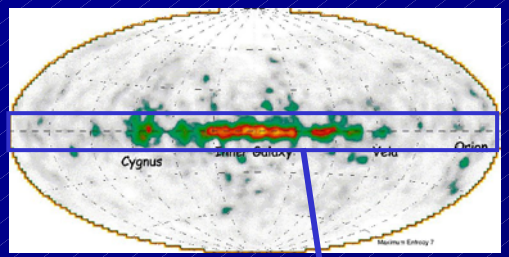


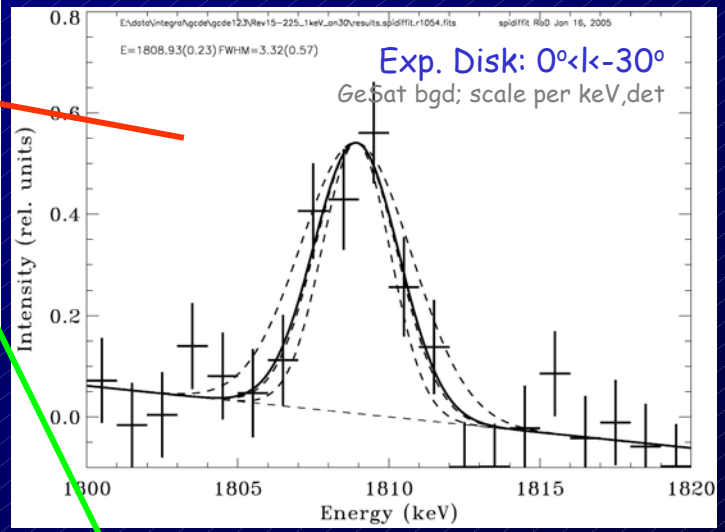


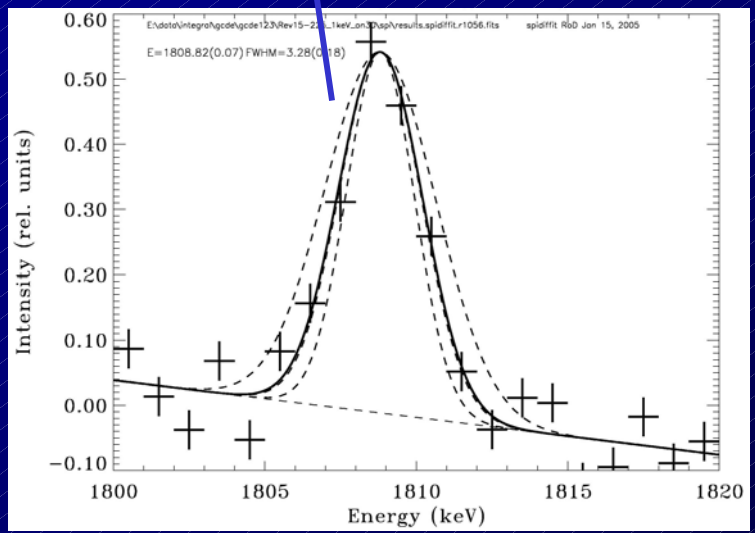
- *Detailed Assessment in Progress (Bgd Model, Systematics Checks…)*

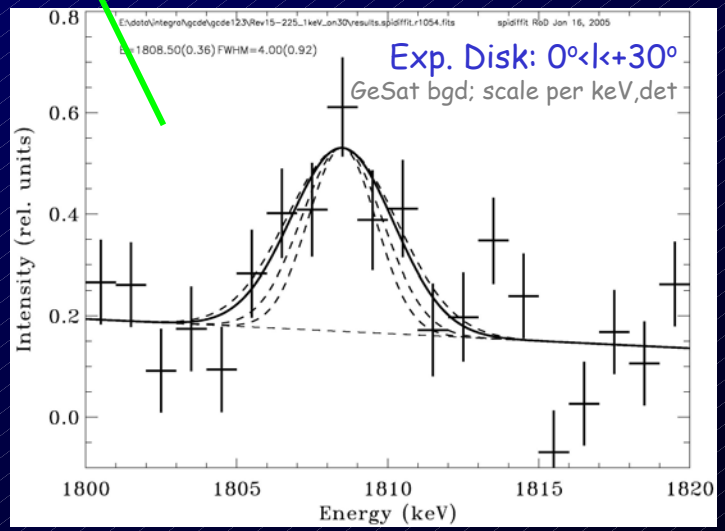
Imaging Spectroscopy: Line Shape Variations in the Galaxy?







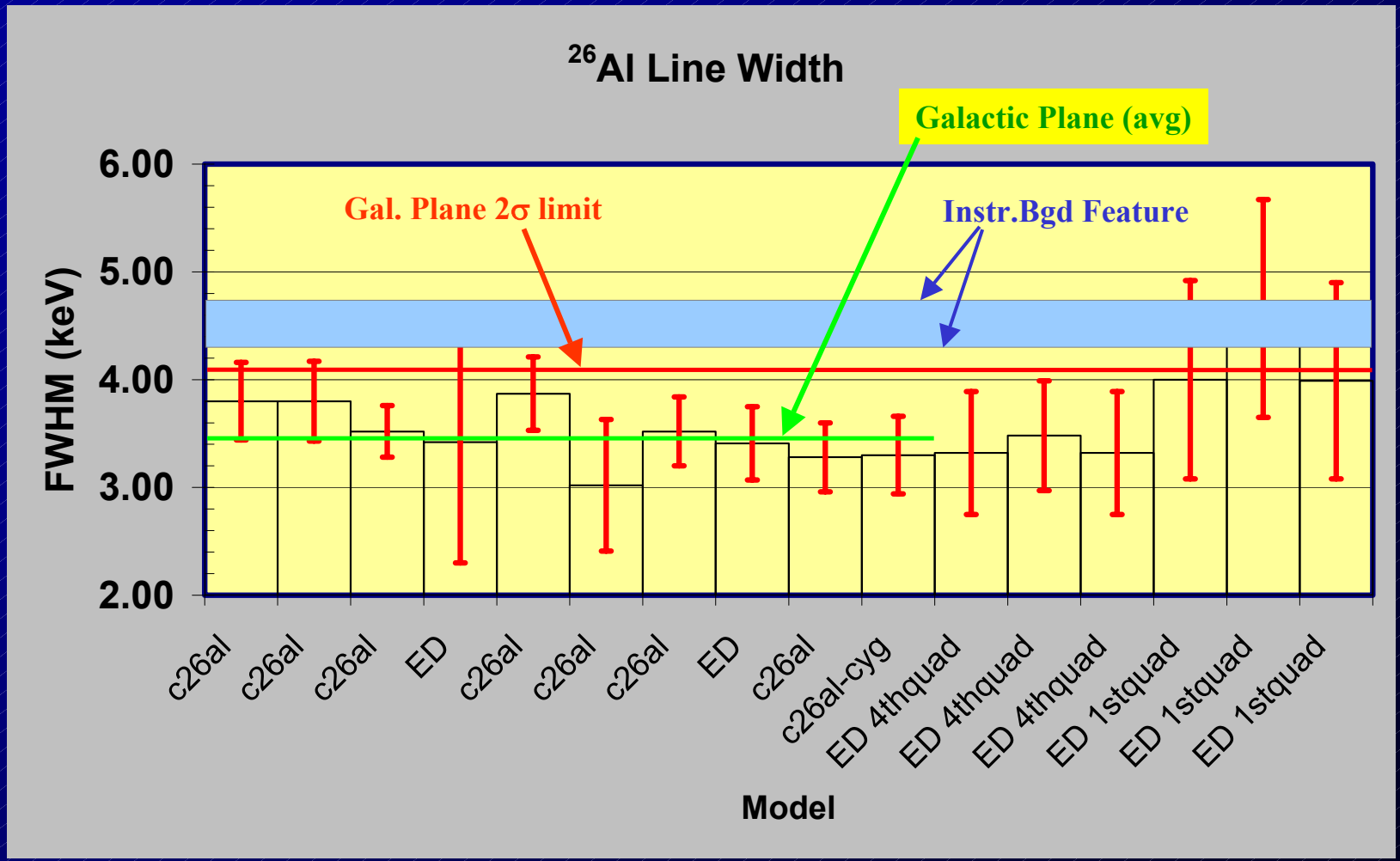




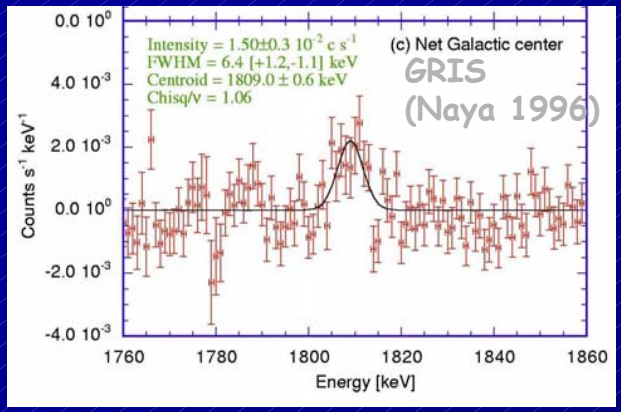
- Need Statistics & High-Resolution
- Data Processing & Analysis (Degradation!)

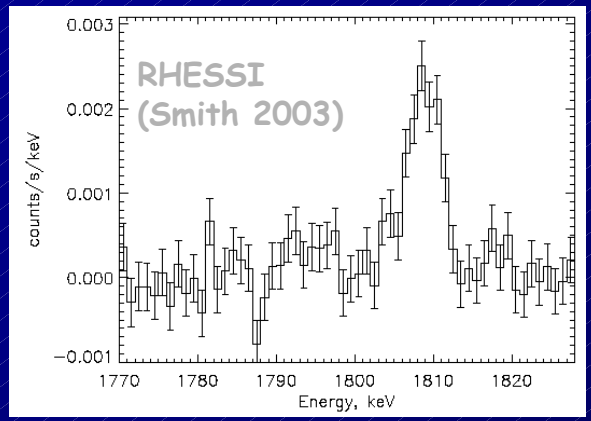
^{26}Al Line Width Details

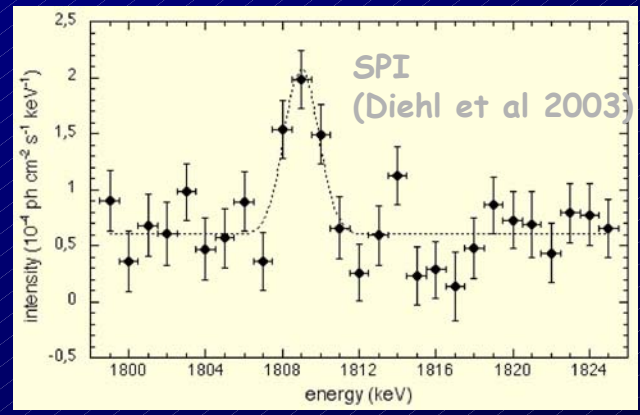
- Compare Width for Different Sky Models & Par's:



^{26}Al Line Width: Summary







- ☆ Broad Line was Difficult to Understand, Seems not Confirmed
- ☆ Cygnus Region May Show ISM Turbulence