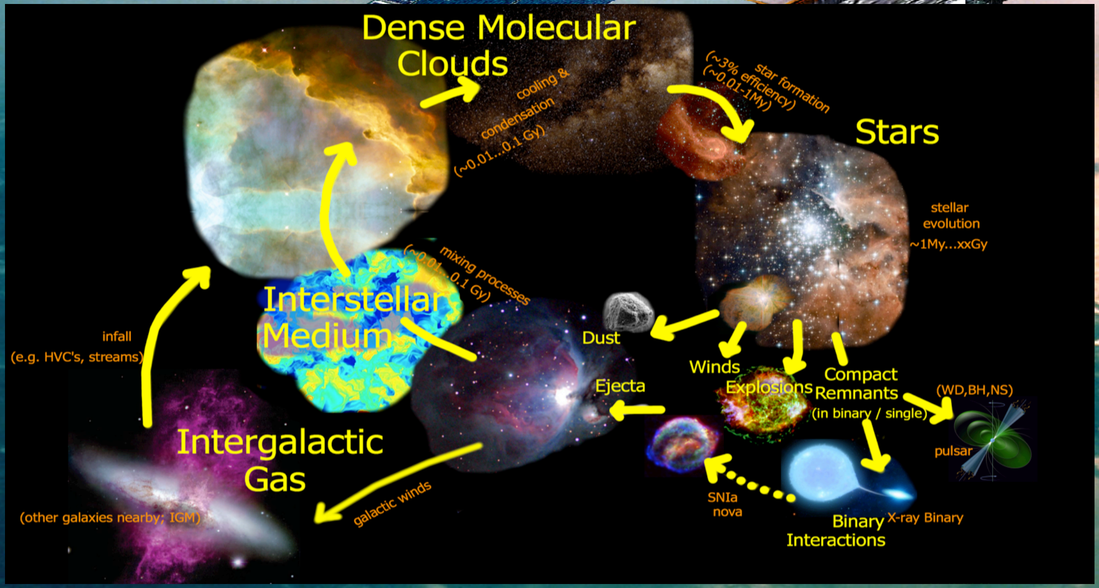
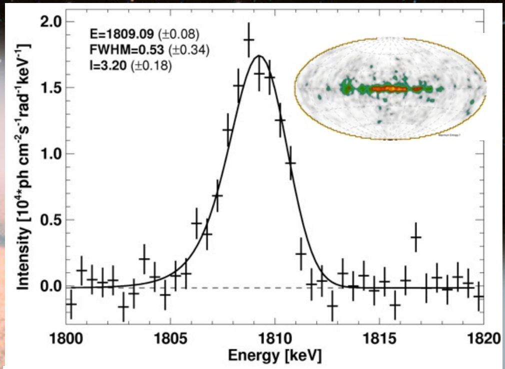
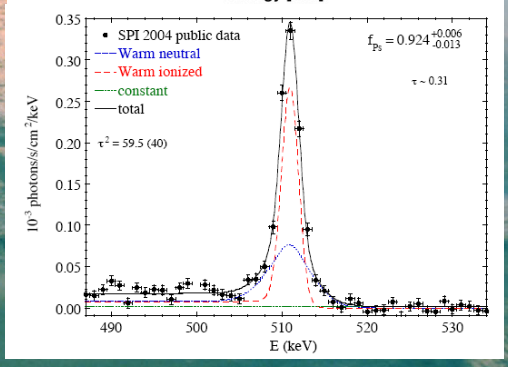
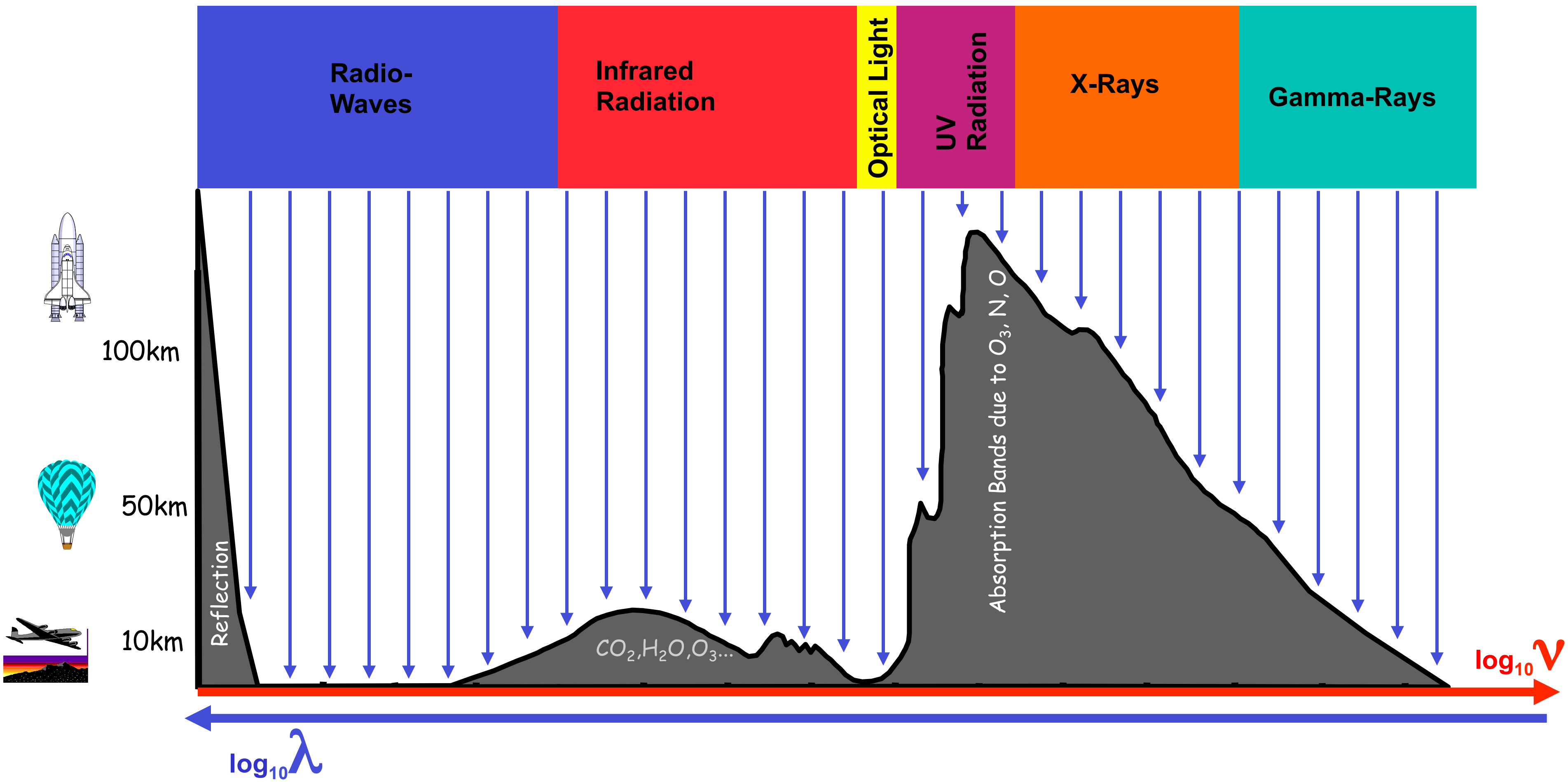
Ge Detectors in Space: Studying Cosmic Nucleosynthesis with INTEGRAL



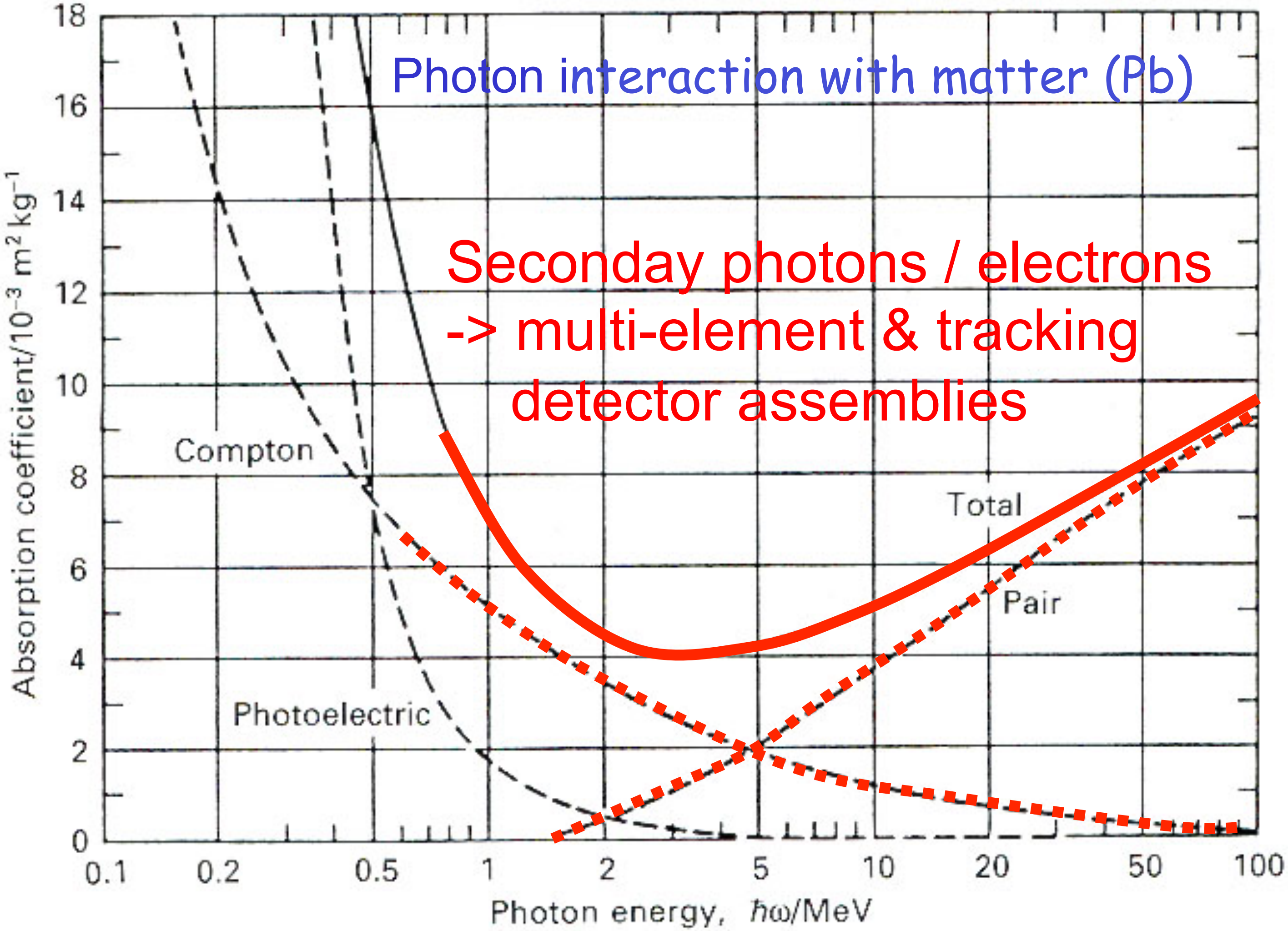




Astronomical Observations throughout the electromagnetic spectrum



Gamma-Ray Astronomical Telescopes:
Interaction of HE photons with matter



-> Secondary Particles … -> e.m. cascade

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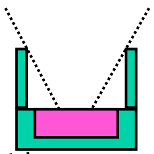
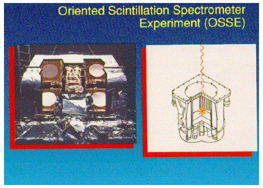
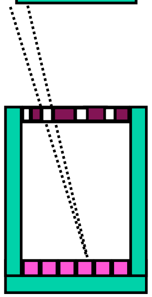
Gamma-Ray Astronomy Instruments

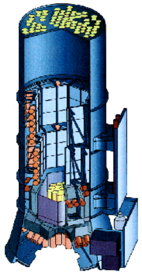
Photon Counters and Telescopes



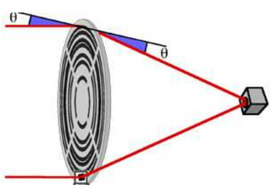


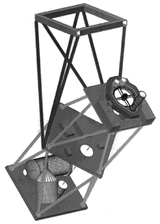
- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield



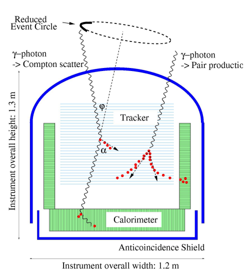


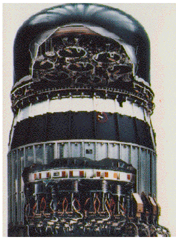
- **Coded Mask Telescopes**
  (Shadowing Mask & Detector Array)
  (e.g. SIGMA, INTEGRAL)
  Spatial Resolution Defined by Mask & Detector Elements Sizes





- **Focussing Telescopes**
  (Laue Lens & Detector Array)
  (CLAIRE, MAX)
  Spatial Resolution Defined by Lens Diffraction & Distance



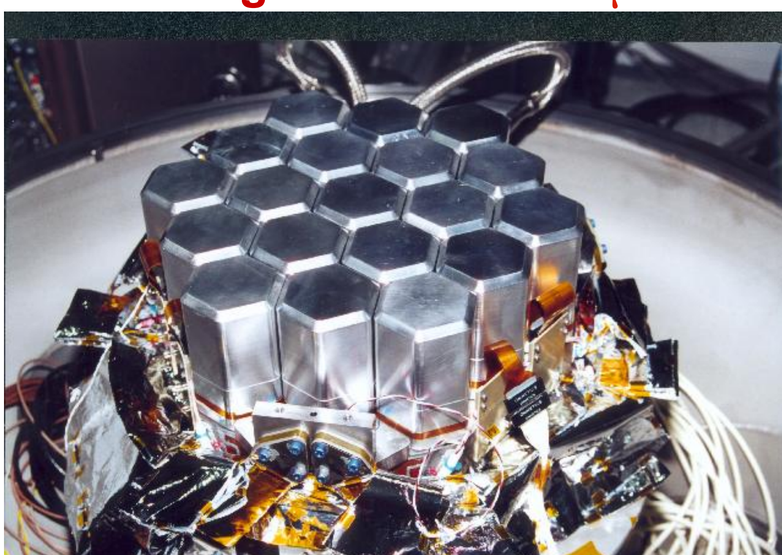


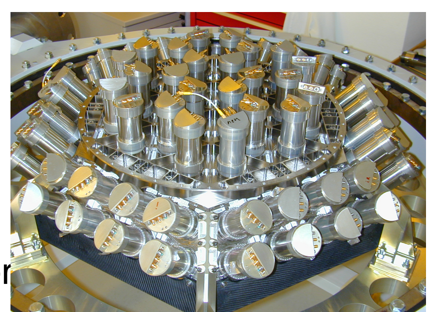
- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, LXeGRiT, MEGA, ACS)
  Spatial Resolution Defined by Detectors' Spatial Resolution

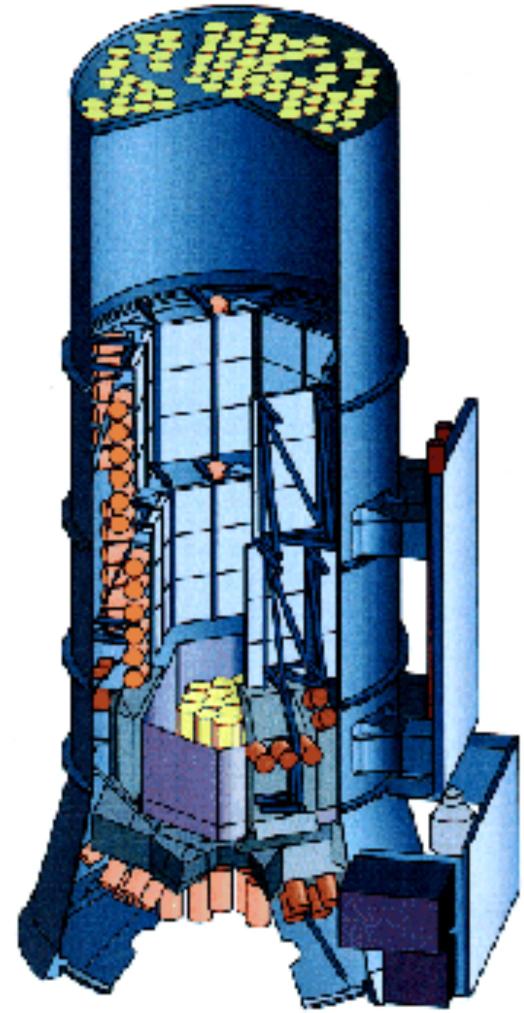
Achieved Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

The INTEGRAL Spectrometer (SPI)

- **Coded-Mask Telescope**
- **19 Ge Detectors** (5.5x5.5x7cm)
- **BGO Anticoincidence Detector & Shield**
- **Stirling Cryocooler**
- **Energy Range 15-8000 keV**
- **Energy Resolution ~2.2 keV @ 662 keV**
- **Angular Resolution ~2 arcmin**
- **Field-of-View 16x16°**
- **Timing Resolution 52 μs**







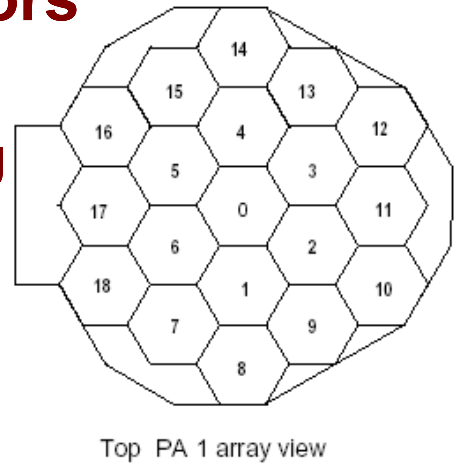
SPI Detectors

- ☆ **n-type**
  - – (holes travel to outer electrode, ie fast)
- ☆ **Hexagonal, co-axial**
  - ☞ 69.42mm high, 32 mm sides (diameter 55 mm)
    → 178 cm^3, 951g
  - ☞ Central bore 6mm diameter, 55mm length
  - ☞ Backside passivated (low leakage currents)
- ☆ **High-purity: Impurity Levels 0.5…1.5 10^{10}**
- ☆ Produced by
  UMICORE (Olen, Belgium)
- ☆ **Encapsulated in Al housing**
  - ☞ Open housing (vacuum)
  - ☞ Outer diameter 60.65 mm; 1134g
- ☆ Manufactured by
  Eurisys Measures
  (Strasbourg, France)
- ☆ **Operational Conditions**
  - ☞ HV 3500…4500 V
  - ☞ T 80…90K

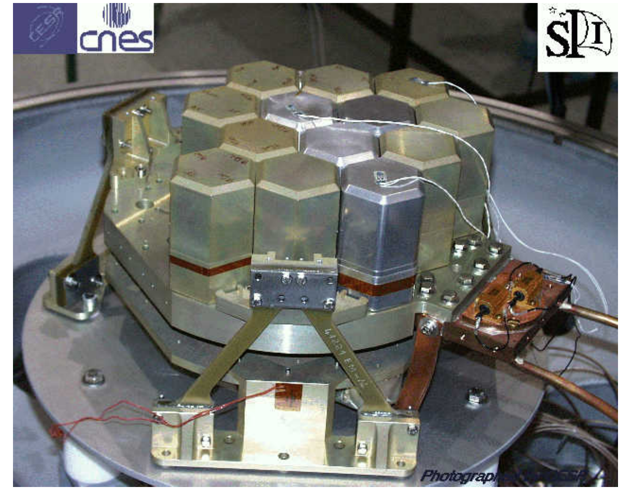
Photographed by CESR

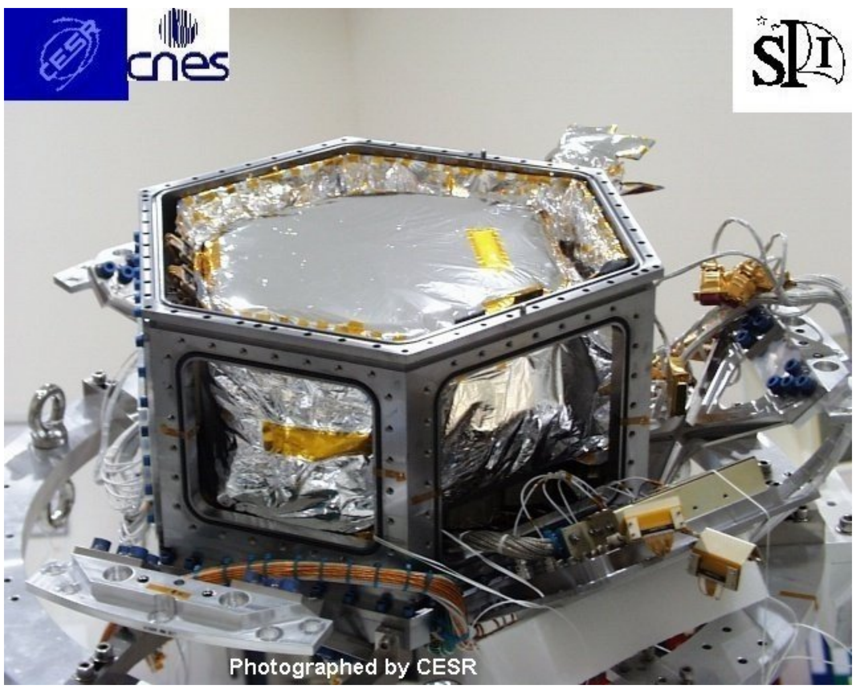
The SPI Detector Set

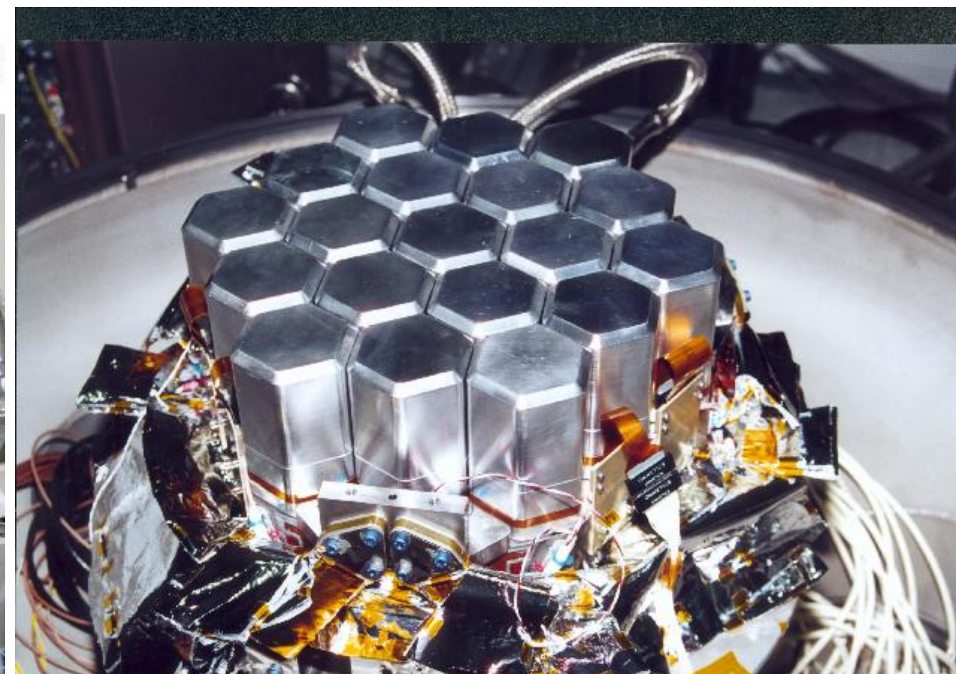
- "Camera" = 19 Detectors
  - ☆ Total area 508 cm²
  - ☆ Total weight of Ge: 18kg
  - ☆ Mounted on Be plate
    - ☞PA1 on Cold Plate
    - ☞PA 2 on 210K plate
    - ☞Signal: 50 mV / 1 MeV



Top PA 1 array view







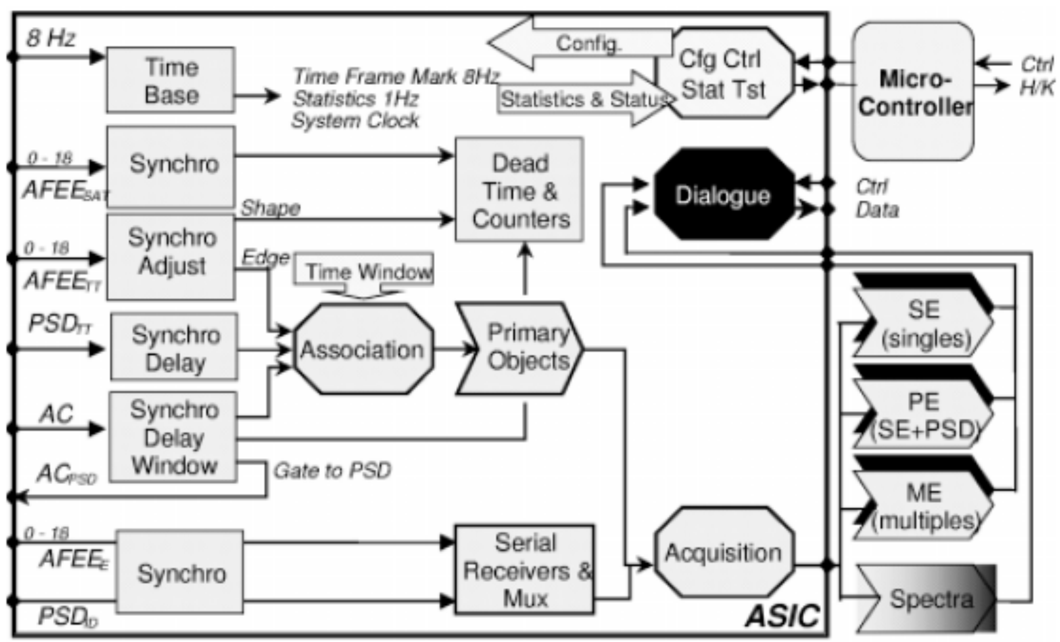
SPI Detector Electronics

Analogue Electronics:

- ✫ Cold-Plate Pre-Amplifier 1 (80K)
  210K Plate Pre-Amplifier-2 with FET; AFEE at ambient ~300K
- ✫ Signal 50 mV / 1 MeV energy deposit
- ✫ Signal time resolution (processing time) 26 μs
- ✫ Saturation clipping at 14 MeV
- ✫ Saturated-event electronics dead time 100 μs
- ✫ PSD circuitry

Digital Electronics:

- ✫ DFEE
  - ☞ Radiation-hardened CMOS ASIC (TEMIC/Atmel)
  - ☞ 8 Hz clock
  - ☞ 50 ns event timing
  - ☞ FIFO event buffering
  - ☞ 725 ns ACS veto pulse



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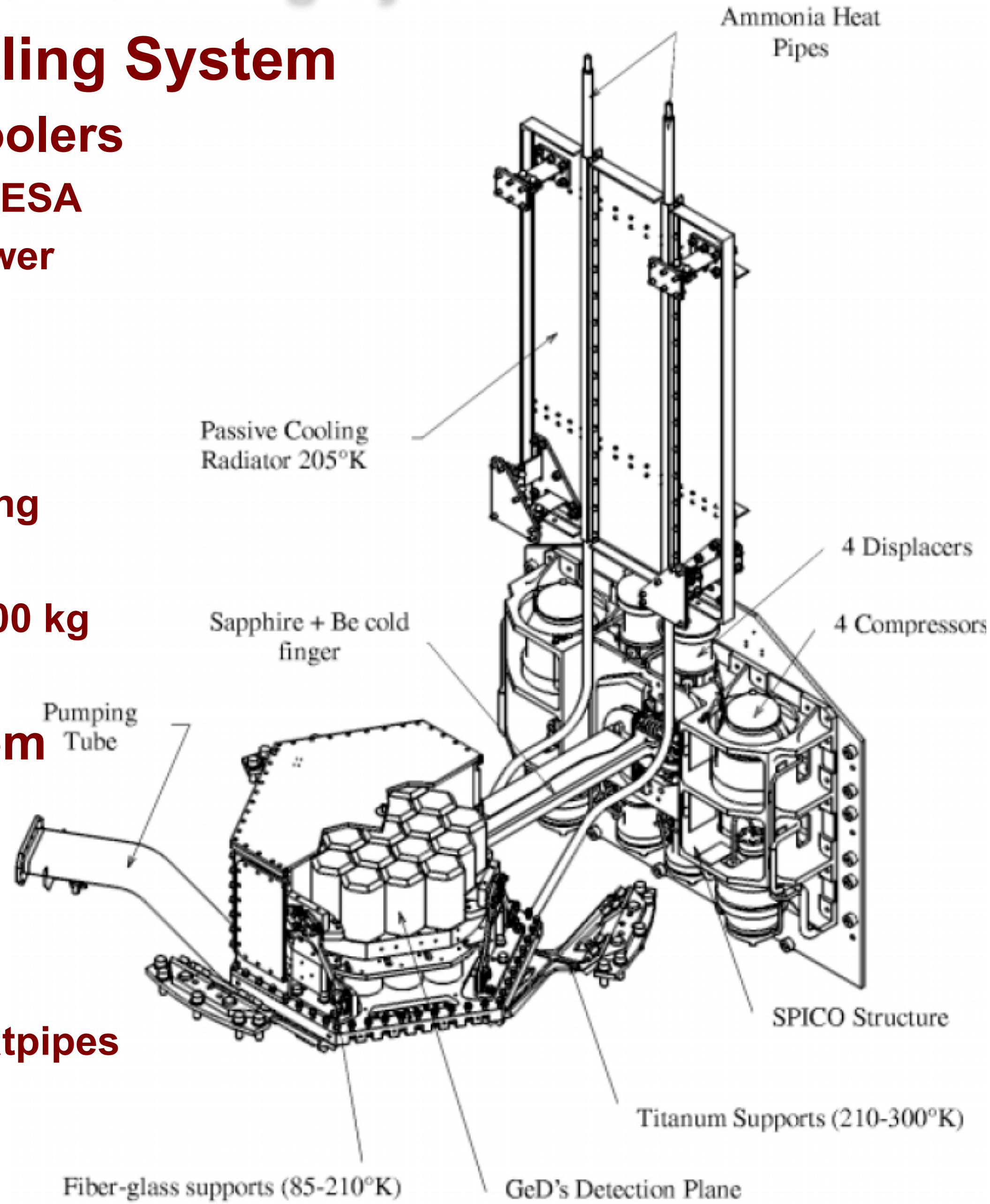
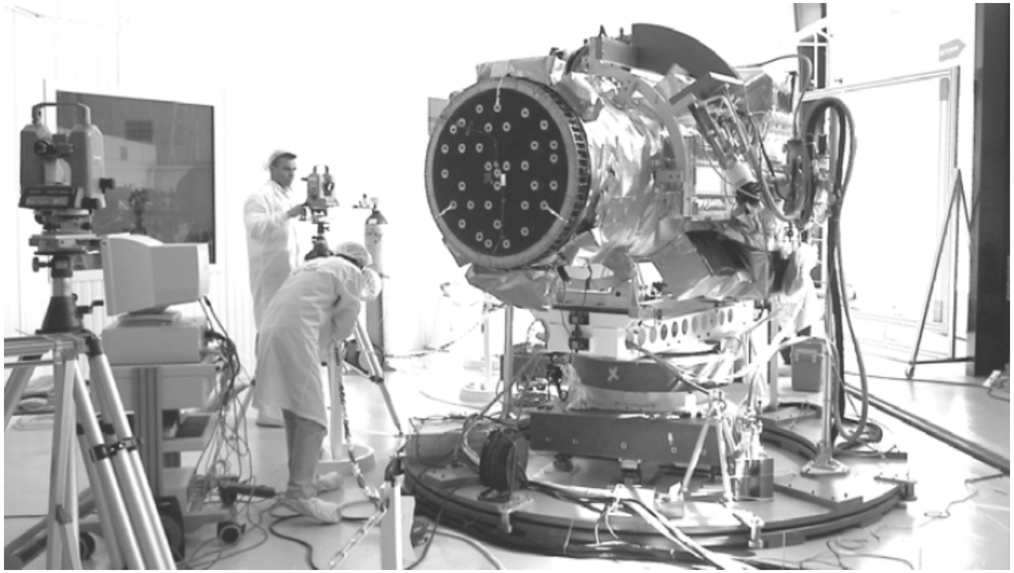
SPI Detector Cooling System

- **Electro-Mechanical Cooling System**
  - ☆ 4 mechanical (Stirling) coolers
    - ☞ Provided by MMS Astrium/ESA
    - ☞ Cooling to 80K, ~few W power
  - ☆ Detectors enclosed in Be housing (cold box)
    - ☞ Stabilization, passive cooling
    - ☞ Careful thermal insulation
    - ☞ Total weight of cryostat ~100 kg
  - ☆ Ammonia heat pipe system
    - ☞ Operated near freezing (196K)
  - ☆ Electronics Control
    - ☞ Antifreeze of Ammonia Heatpipes
    - ☞ Annealing

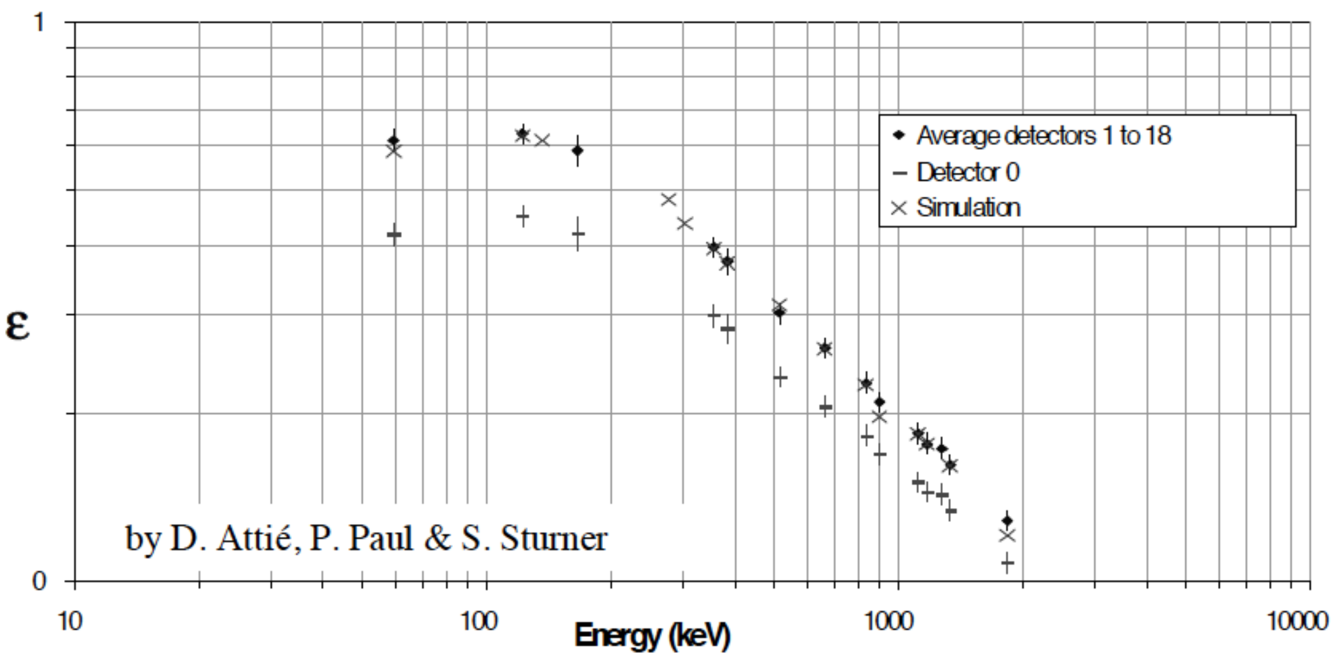


SPI Prelaunch Calibration

- **Bruyères Le Châtel**
  - ☆ **April 2001**
    - ☞ **108 h accelerator time**
    - ☞ **Also using strong radioactive sources**



  - ☆ **Results**
    - ☞ **Overall efficiency:**

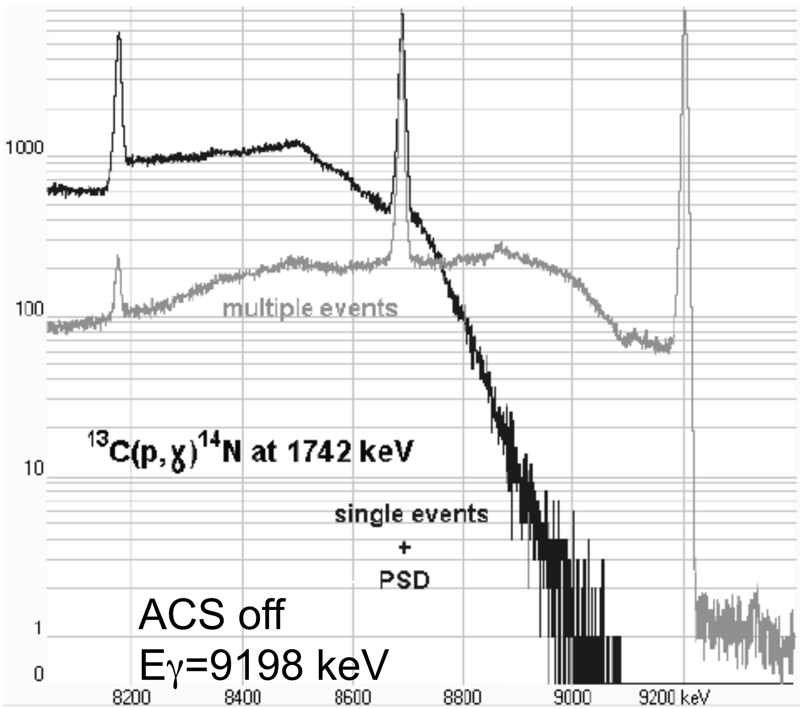


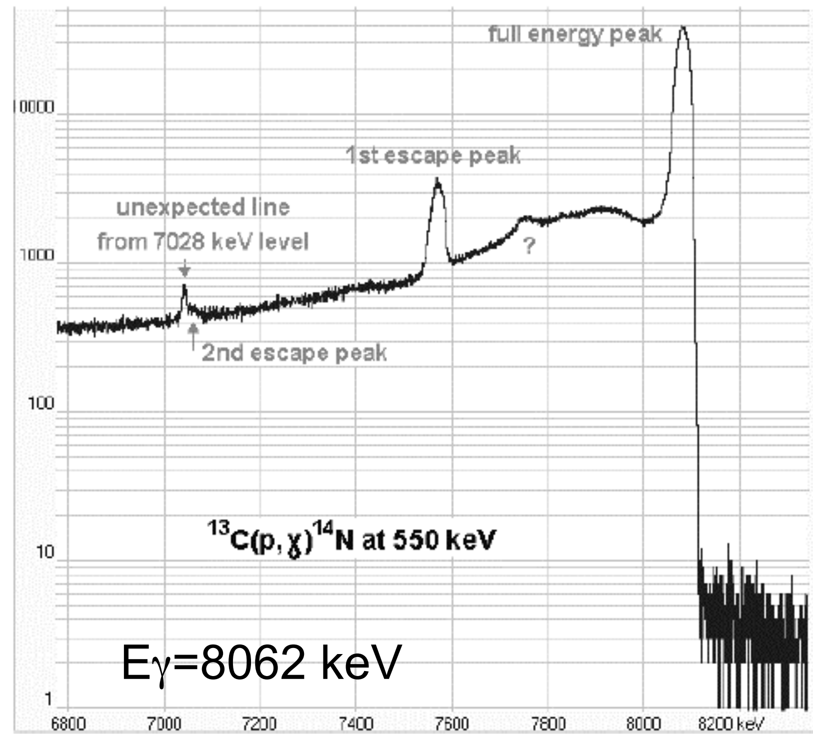
☞ *Attie et al 2003*

SPI Ground Calibration Data, Bruyères Le Châtel

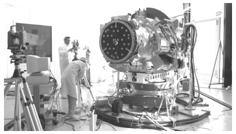
☆ Different Photon Sources from Nuclear Resonances

- ☞ $^{13}C(p,\gamma)^{14}N$ with narrow resonance at E_p 1742 keV, broad resonance at 550 keV



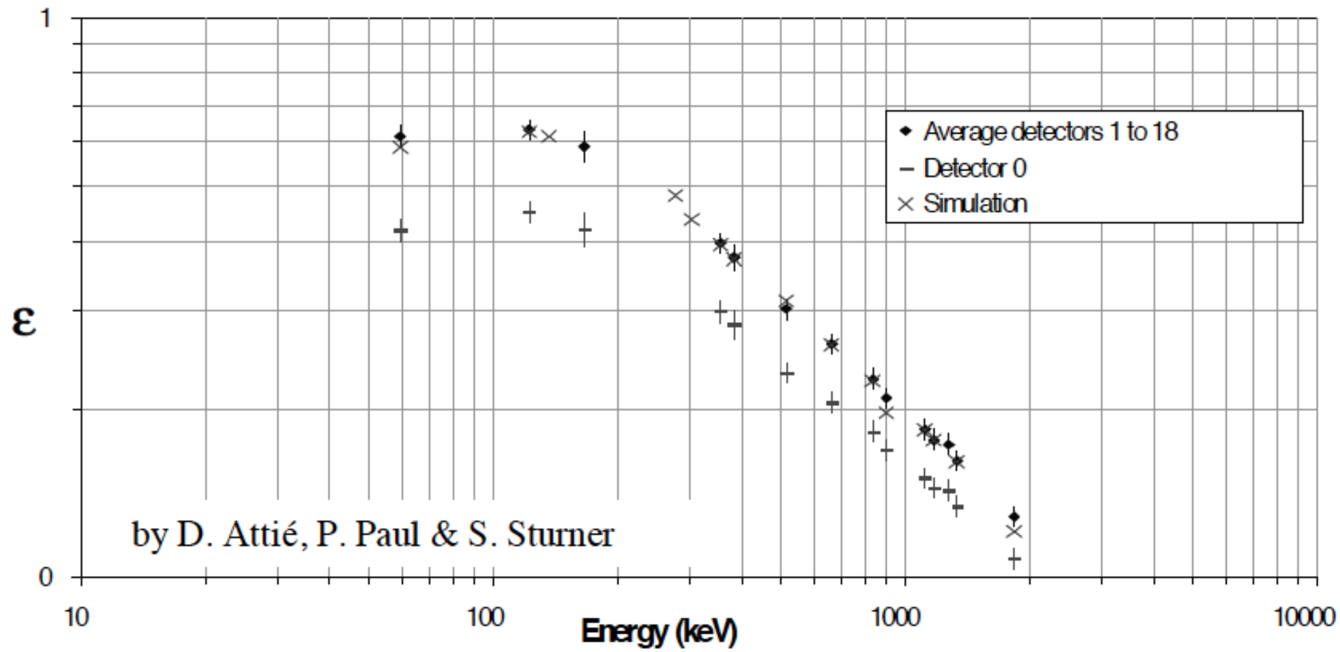


- ☞ SPI Detector Electronics 10-8000 keV
- ☞ Single- and Multiple-Detector Events

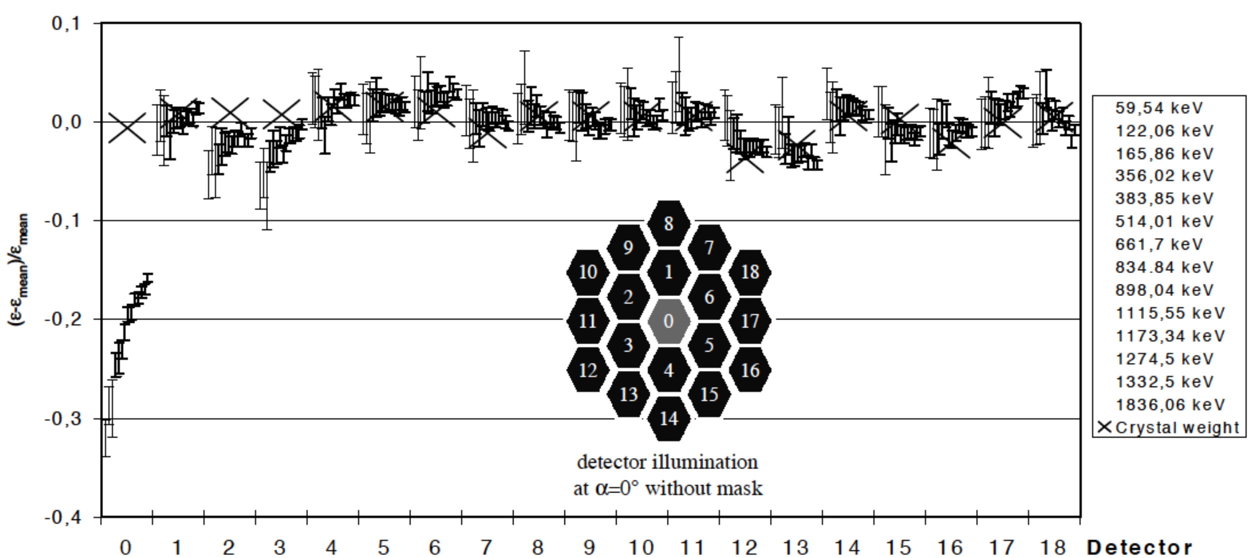


SPI Prelaunch Calibration Results

☆ **Overall efficiency:**

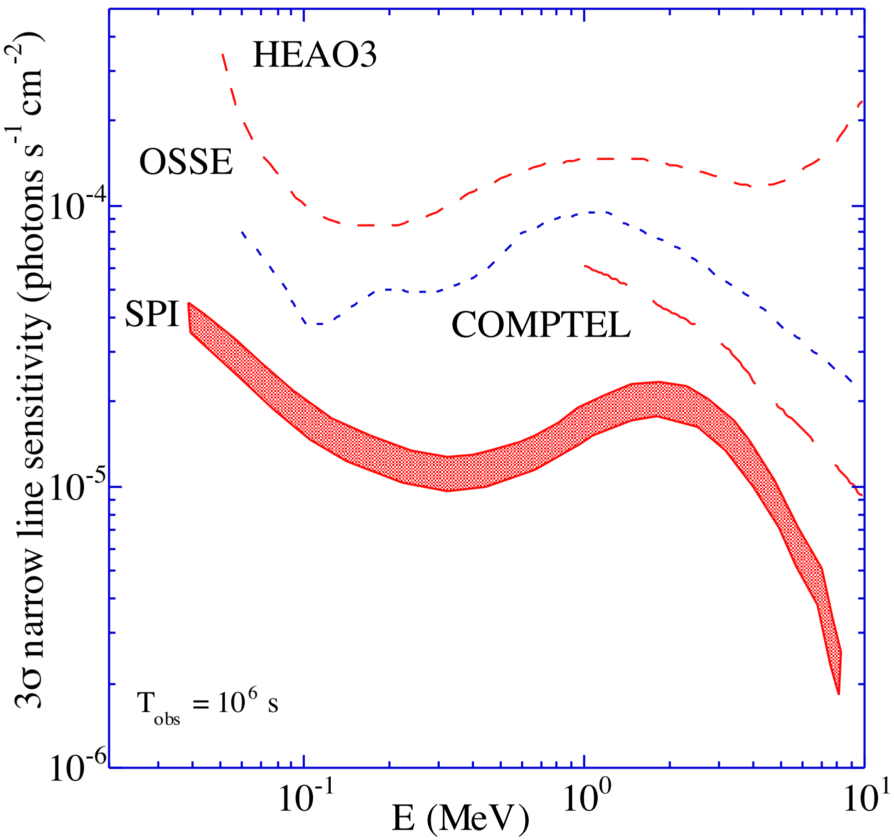


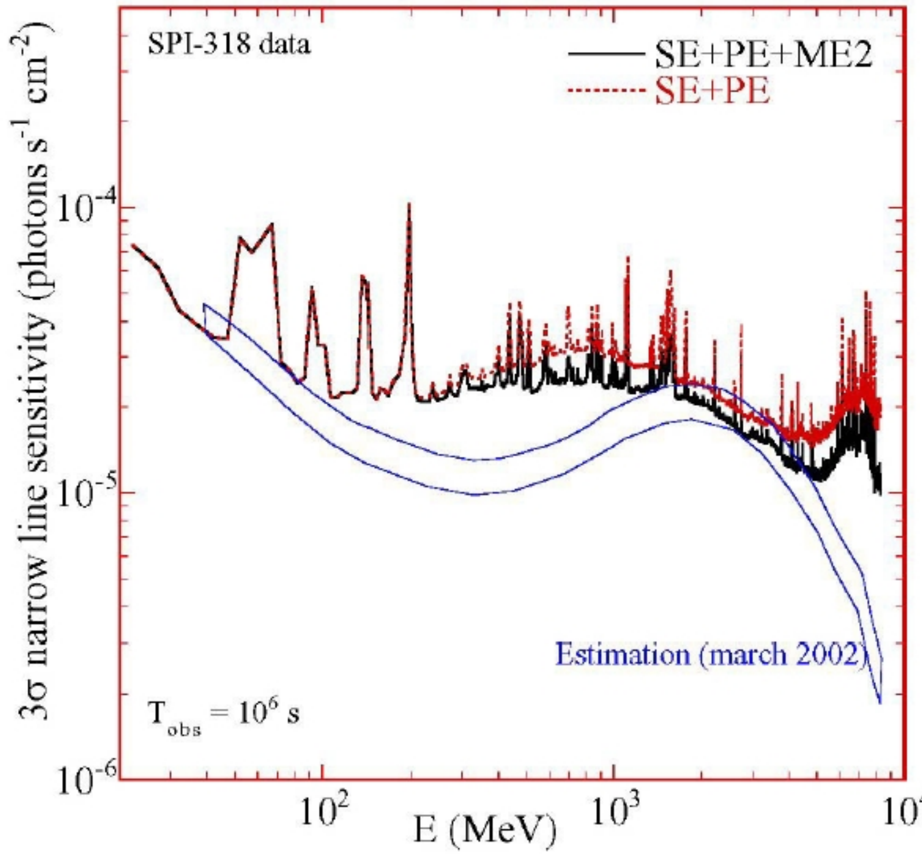
☆ **Detector Homogeneity:**



☞ *Attie et al 2003*

SPI Sensitivity for Gamma-Ray Lines





- The early estimate had ignored the instrumental line contributions
- Pulse Shape Rejection of background is less effective than estimated

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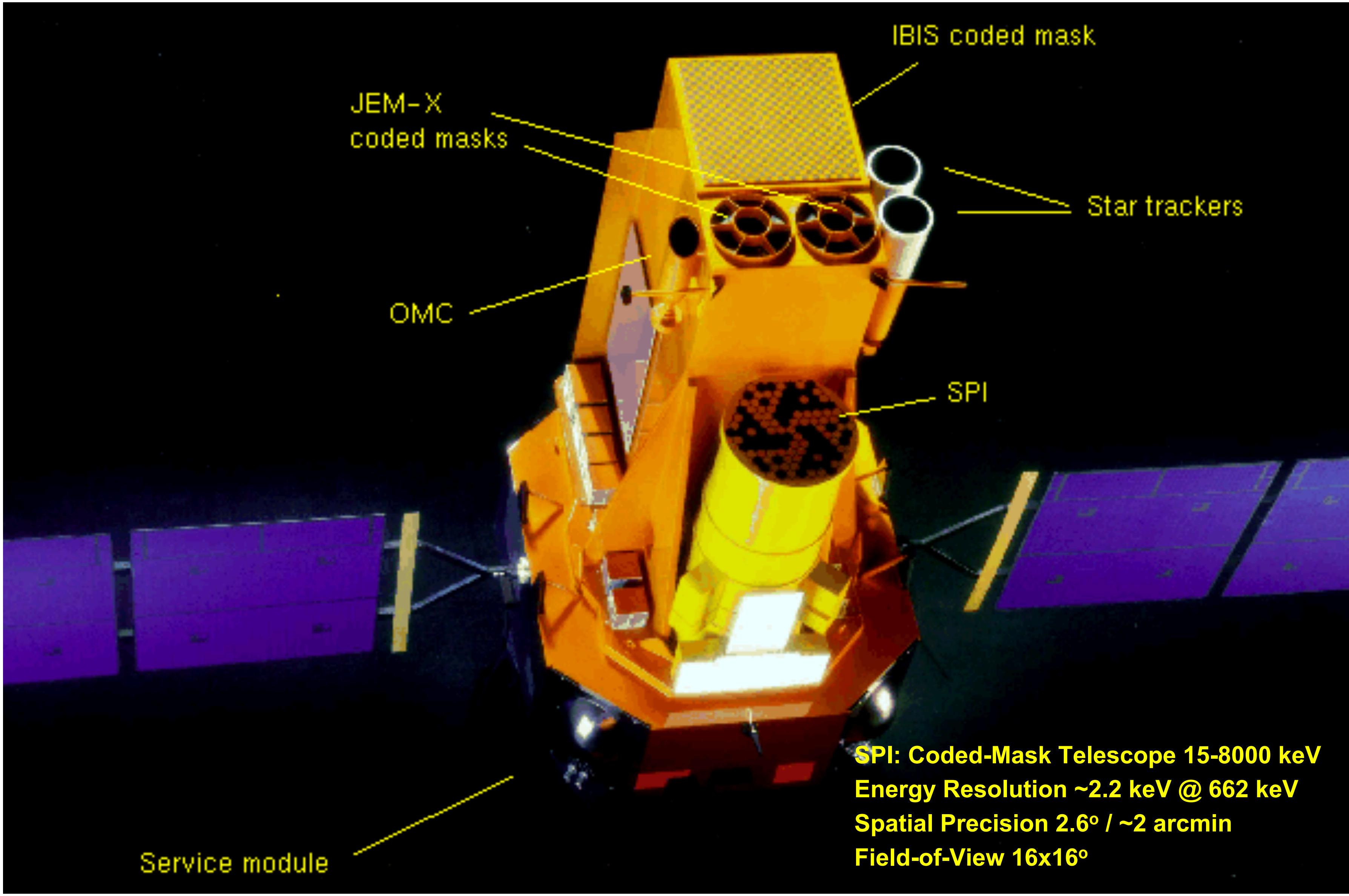
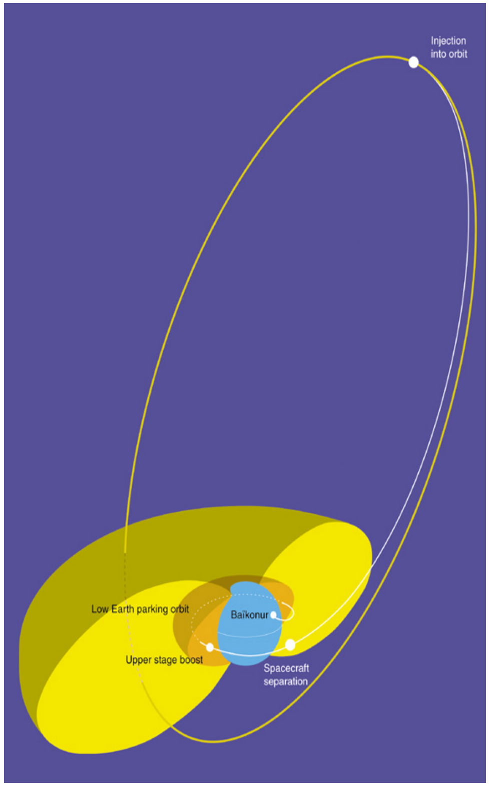
AGaDe Workshop, Garching (D), 2-5 Jun 2008

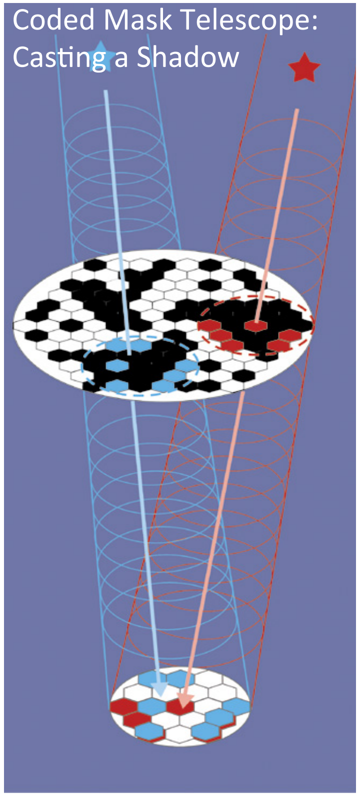
INTEGRAL and it's Ge γ-Spectrometer for Space

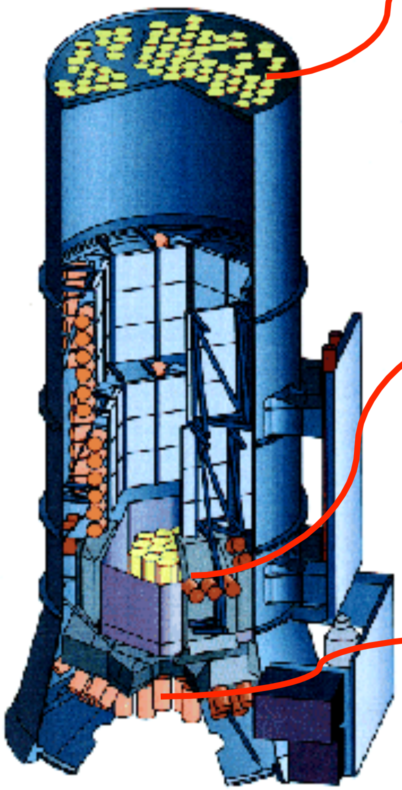


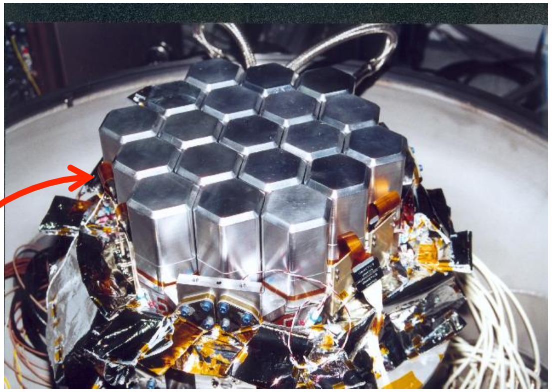
INTEGRAL: Ge γ-Spectrometry of Cosmic Sources

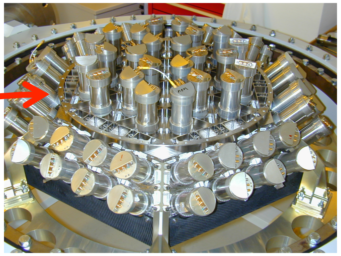
- **Coded-Mask Telescope**
- **19-element camera**
- **16° field of view, 2.7°**
- **20-8000 keV**







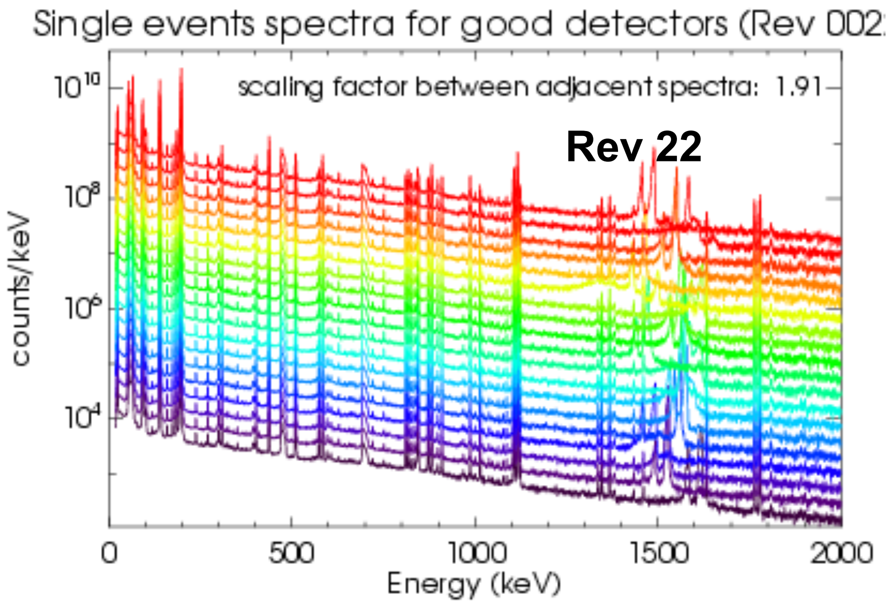


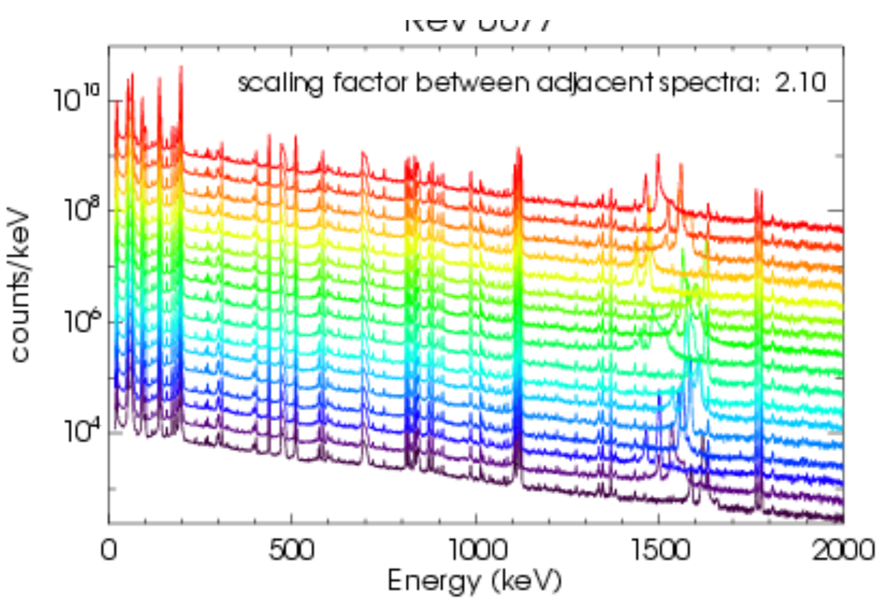


INTEGRAL: Ge γ-Spectrometry in Space!

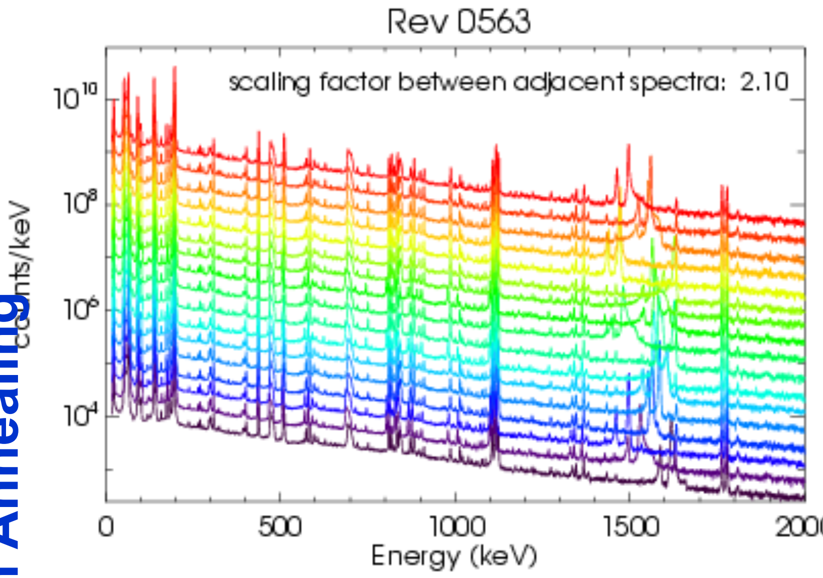
INTEGRAL/SPI Spectra (3 days)

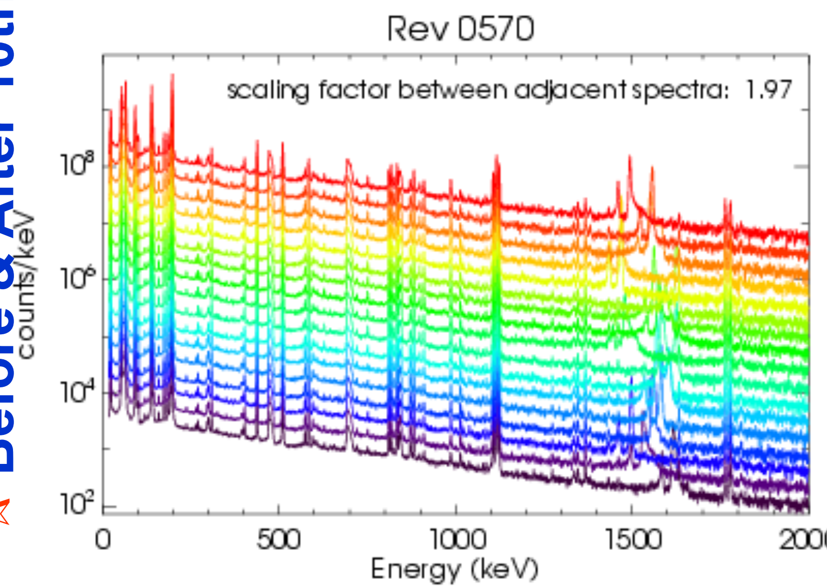
☆ **Early Mission & Present (5+yrs)**





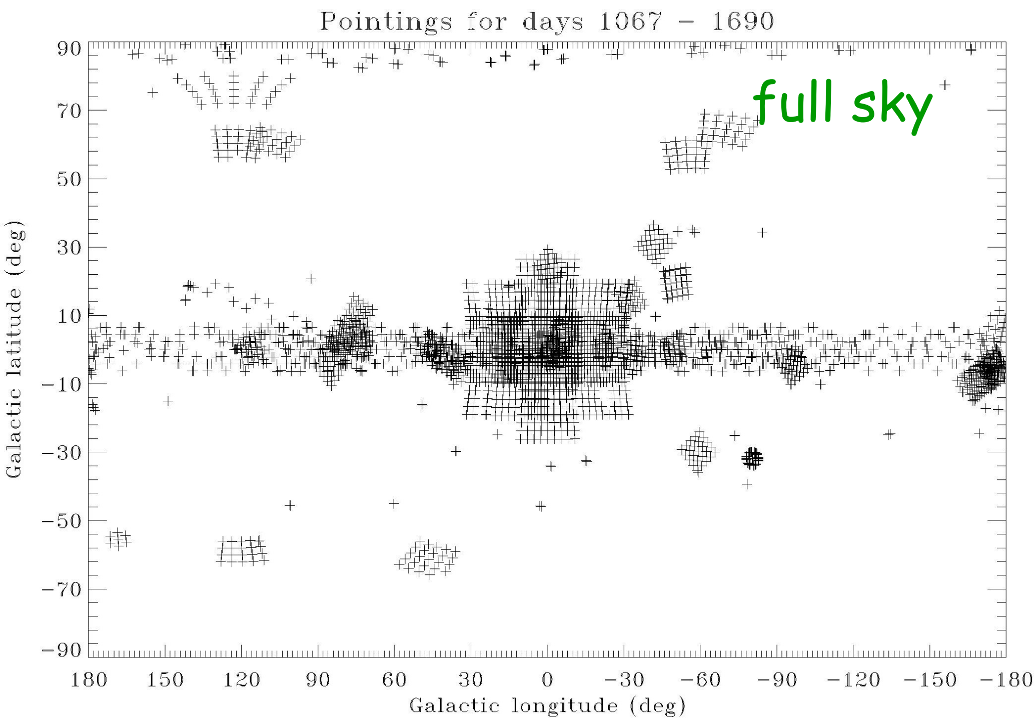
☆ **Before & After 10th Annealing**





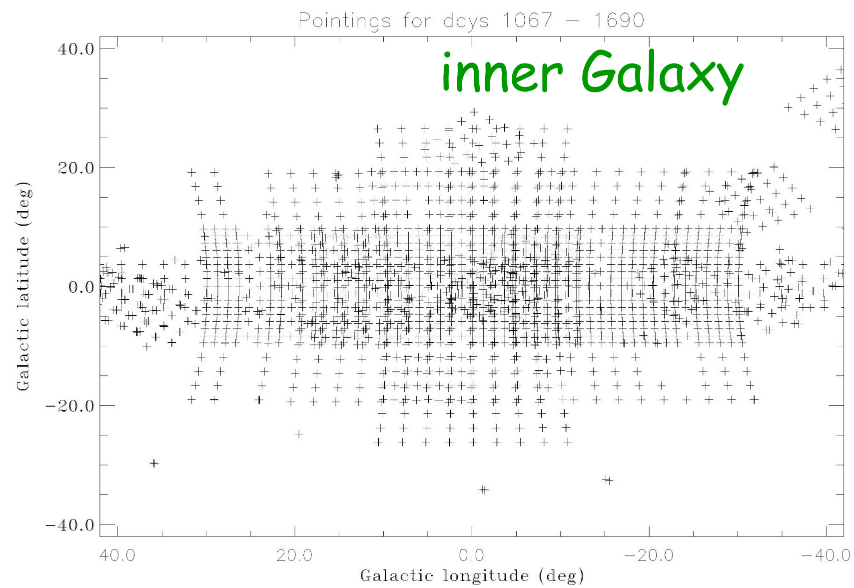
The INTEGRAL ^{26}Al Sky Survey

- **Pointing on Sky Varies in ~30 min Steps**

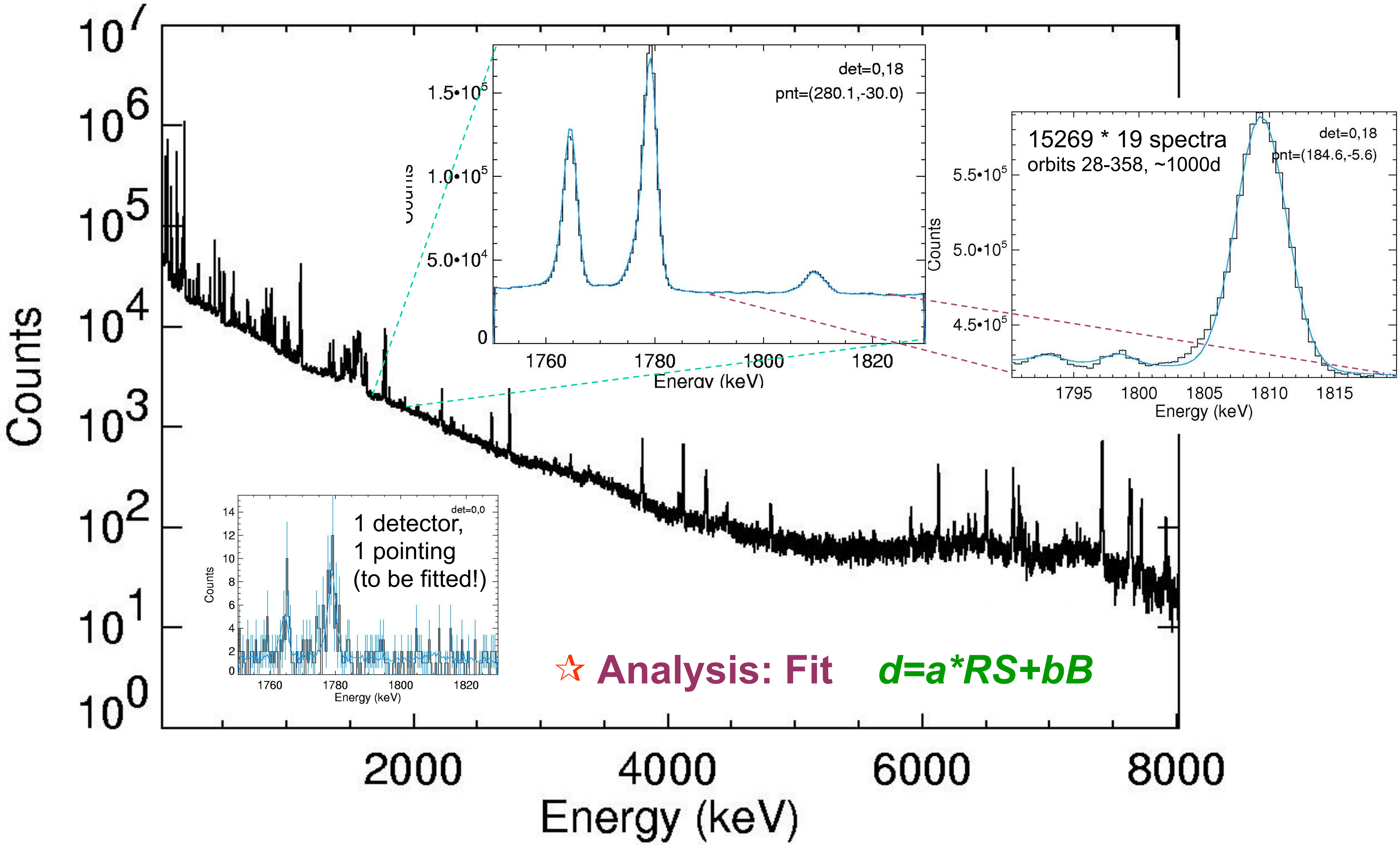


typically by ~2.1°
(PSF width ~3°)

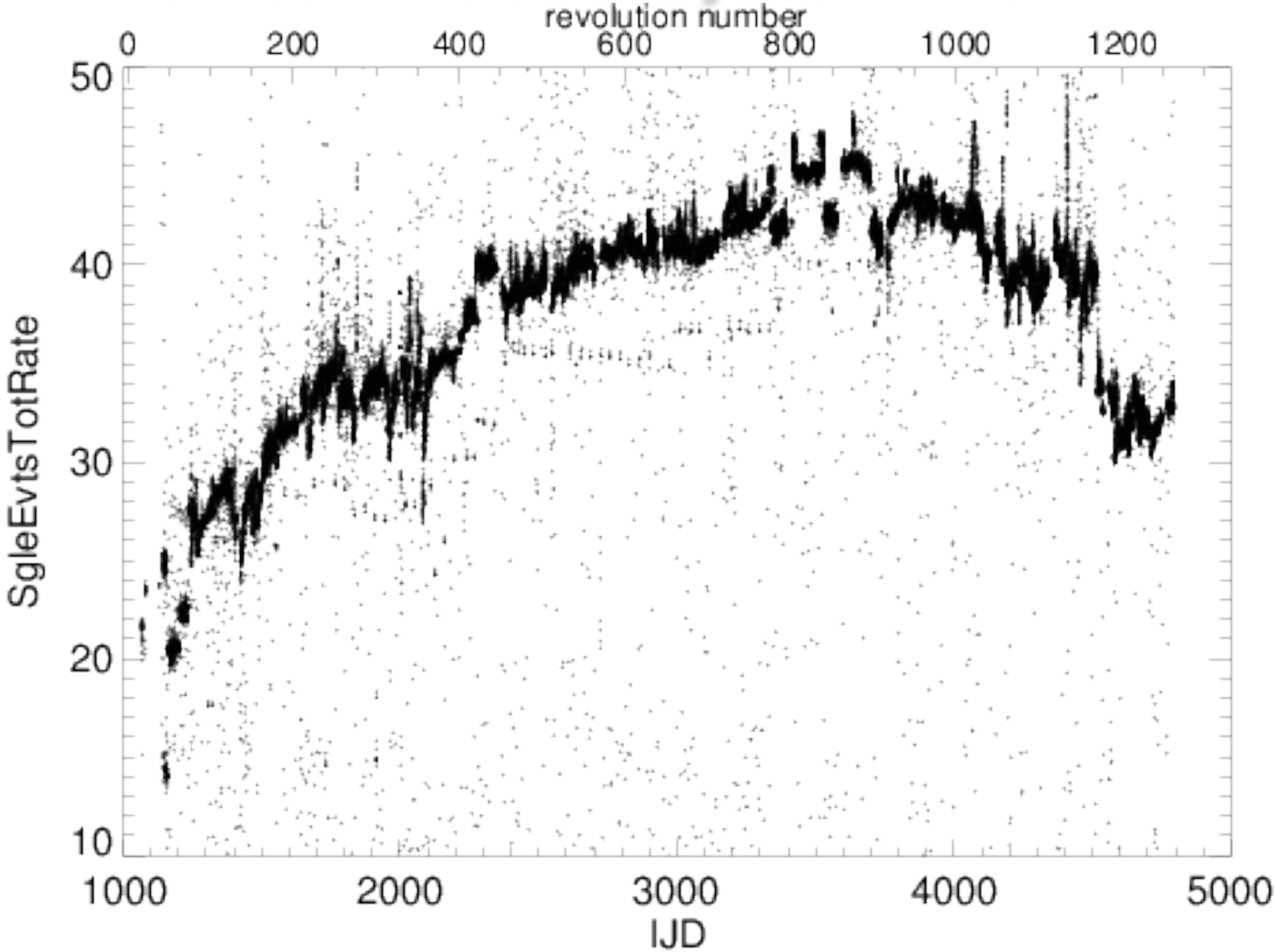
5x5 pattern = target obs



Energy Spectra: Characteristic Examples



SPI Count Rate History 2002 - 2013



SPI Count Rate History 2002 - 2013

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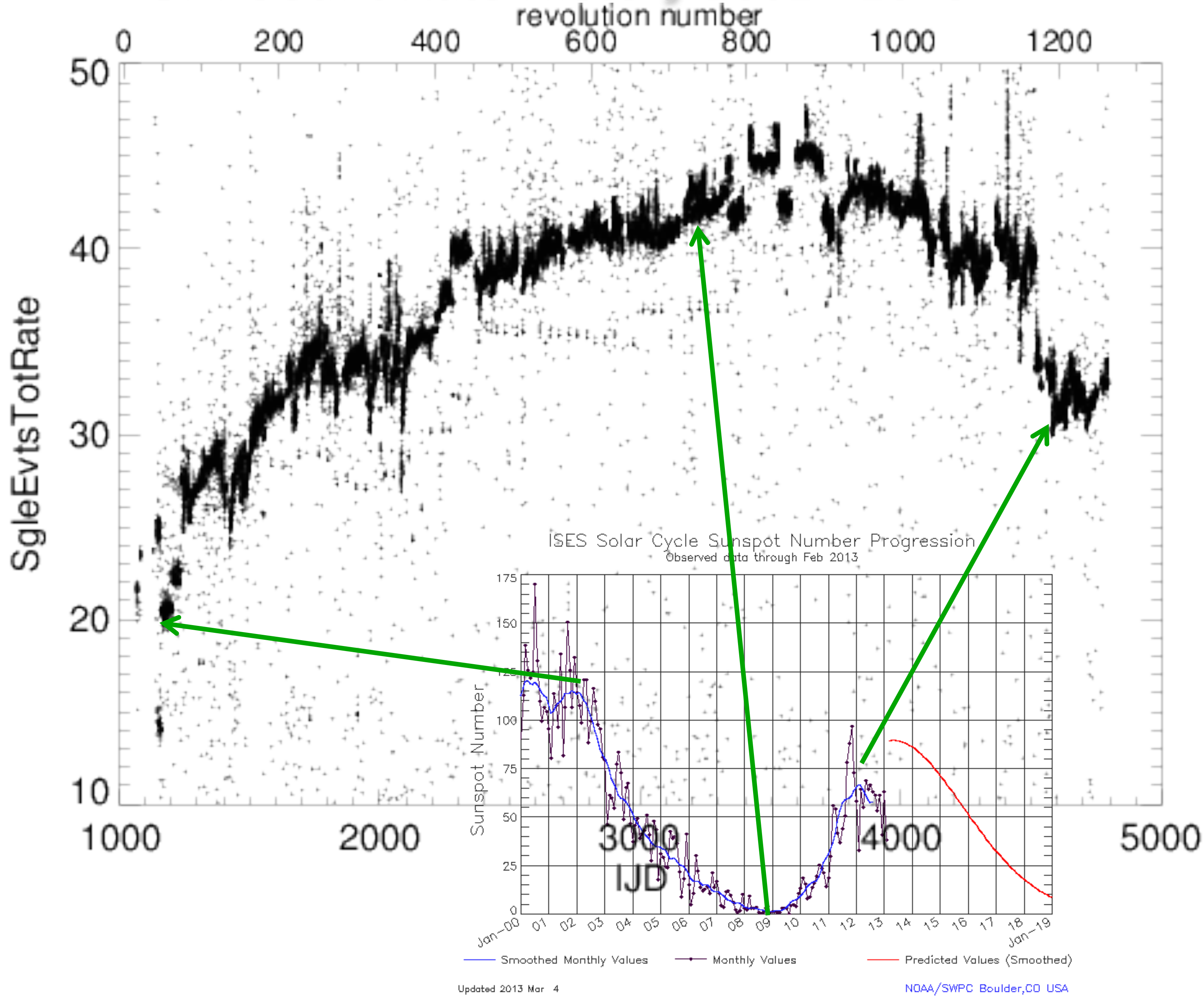

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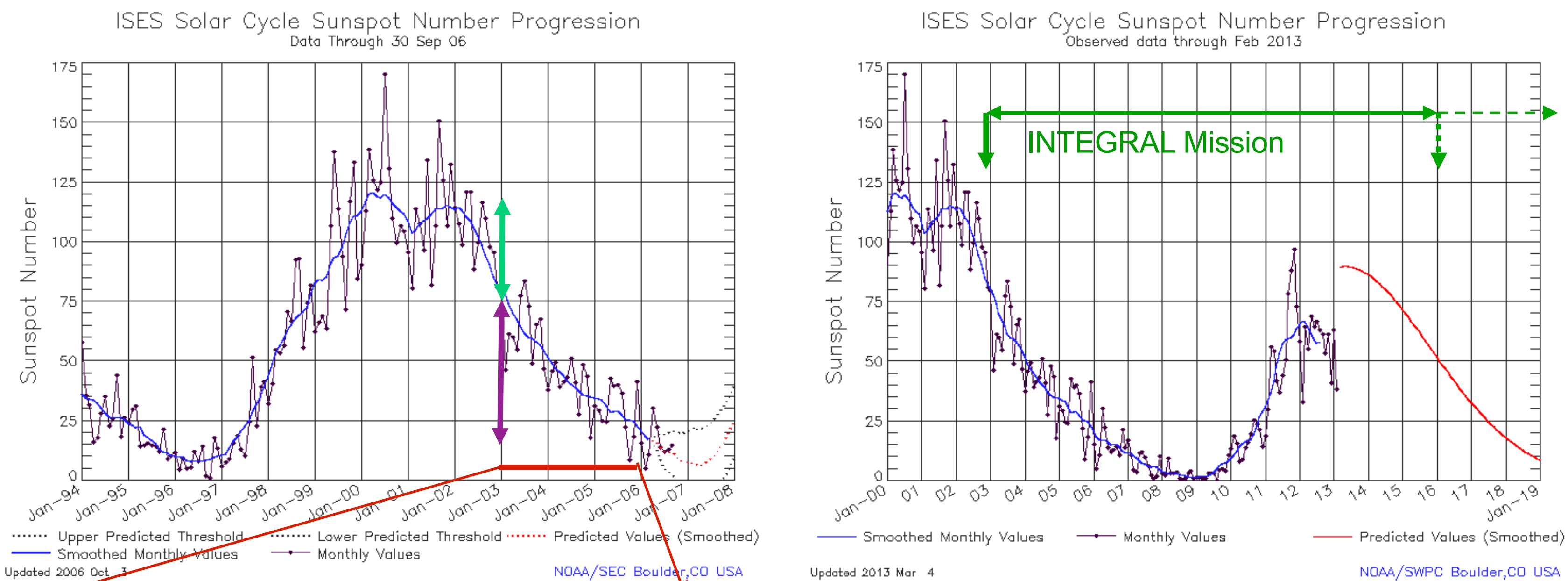
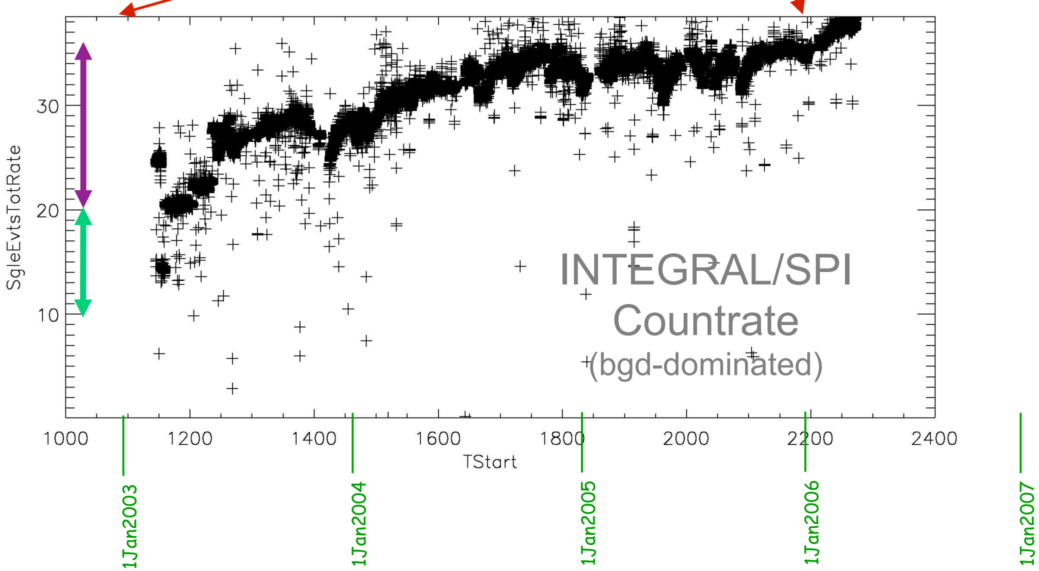
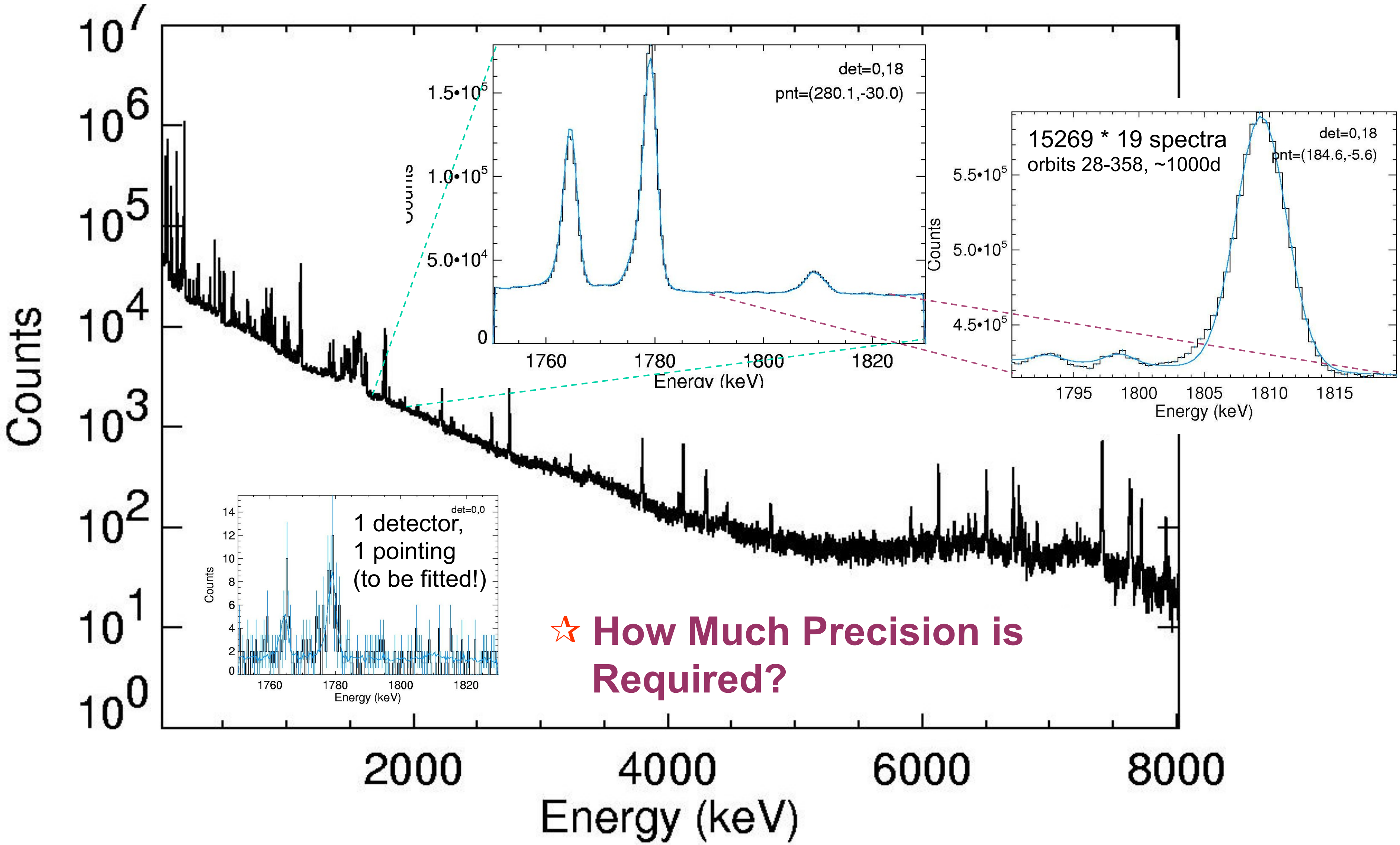
Solar Activity and SPI Background *(from study 2008)*



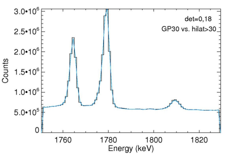


- ☆ **Prompt Background Follows Solar Activity**
- ☆ **Decrease Expected >2009**
  - ☞ **Unclear:**
    How Much of SPI's Background is 'Prompt' (versus 'activation')?

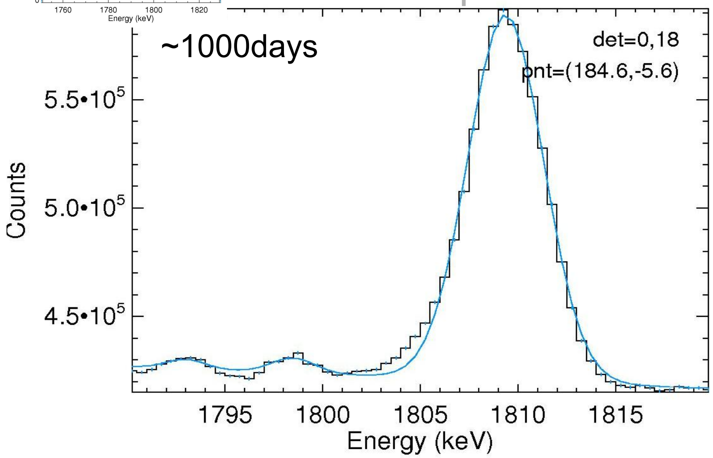
Energy Spectra: Characteristic Examples



Contaminations from Underlying or Nearby Instrumental Lines?



'raw' spectra



SPI Instrumental Bgd Paper:
(Weidenspointner et al. 2003)

1778.961(8)	0.365(4)	$^{28}Al(\beta^-)^{28}Si$	1778.969(12)	blend
1805.8(3)	0.007(1)	?	?	blend
1808.7(1)	0.029(2)	$^{26}Na(\beta^-)^{26}Mg$	1808.66(3)	blend
		$^{26}Mg^*$	1808.66(3)	blend
1810.9(2)	0.017(2)	$^{56}Mn(\beta^-)^{56}Fe$	1810.772(17)	blend

1792.63 6	0.017 5	ε+β+
1792.63 22	0.0480 16	β-
1793.0 5	0.062 11	β-
1793 3	0.07 3	ε+β+
1793.0 2	0.124 25	ε+β+
1793.0 4	0.71 14	β-
1793.1 4	0.013 6	ε+β+
1793.10 20	0.22 4	ε+β+
1793.1 3	4.6 6	ε+β+
1793.12 7	0.11 5	β-
1793.12 7	0.618 25	β-
1793.17 15	0.20	ε+β+
1793.2 5	1.10 14	ε+β+
1793.21 7	2.61 17	ε+β+
1793.24 10	0.043 7	ε+β+
1793.25 25	0.0126 18	ε+β+
1793.3 3	0.035 14	β-

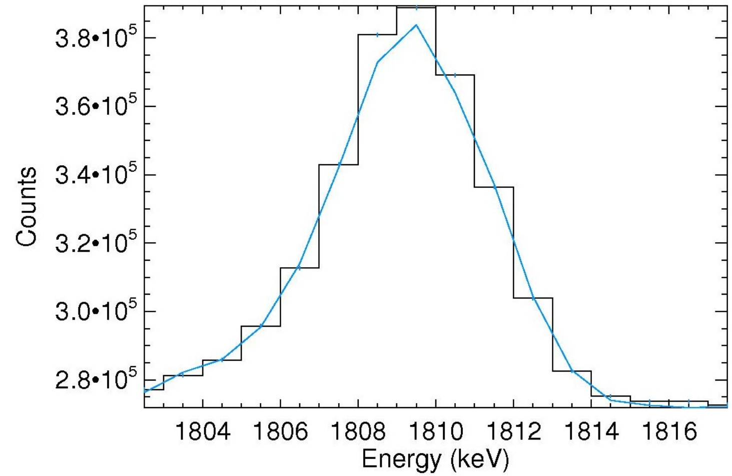
1808.65 7	99.76 4	ε+β+	7.17E+5 y 24	26Al
1808.7 5	0.087 17	ε+β+	17.9 m 3	151Dy
			9.4 s 7	183Hg
			7.3 m 1	103Cd
			24.5 s 2	137I
			22.13 m 19	44K
			51.5 m 10	167Lu
			19.5 m 1	179Re
			1.73 m 10	154Pm
1808.98 8	1.32 15	ε+β+	18.9 m 3	67Ge
1809	0.00024 19	β-	4.44 h 2	105Ru
1809.0 4	0.023 5	ε+β+	55.5 m 4	105Cd
1809.0	~0.24	ε+β+	1.83 m 6	147mTb
1809.0 3	2.5 2*	ε+β+	5.04 m 16	197mBi
1809.04 10	0.00369 8	β-	1.17 m 3	234mPa
1809.2 3	0.102 8	β-	24.94 s 6	141Cs
1809.2 4	0.18 5	β-	3.1 m 3	190Re
1809.2 3	0.32 6	β-	0.78 s 1	121Ag
1809.30 14	2.05 10	β-	6.49 s 7	138I
1809.42 22	0.0113 19	ε+β+	6.70 d 3	172Lu
1809.5 3	0.400 22	ε+β+	3.204 s 7	58Cu
1809.5 4	0.48 7	ε+β+	3.14 m 3	164Lu
1809.50 15	0.795 23	ε+β+	2.012 d 20	170Lu
1809.50 9	1.70 18	β-	2.10 s 2	123Cd
1809.6 4	0.020 5	ε+β+	59.7 s 6	93Ru
1809.7 3	0.53 7	ε+β+	21.1 s 2	149Ho
1809.8 6	0.098 20	ε+β+	17.5 h 1	152Tb
1809.8 3	2.7 4	ε+β+	4.17 s 10	151Tm
1809.9 3	0.00040 10	β-	17.005 h 4	188Re
1809.9 3	0.34 3	ε+β+	41.5 h 5	188Ir
1810.0 2	0.0070 5	ε+β+	3.66 m 2	128Cs
1810.0 2	0.043 5	ε+β+	5.41 h 5	209At
1810.1 4	0.5 2*	ε+β+	36.1 s 3	160Lu
1810.1 2	2.01 24	β-	2.3 s 1	101Zr
1810.20 18	0.038 5	β-	11.30 h 1	77Ge
1810.4 2	1.566 24	ε+β+	12.0 m 5	194Pb
1810.5 6	0.041 14	β-	2.68 h 2	150Pm
1810.5 4	0.14 9	β-	7.52 m 8	152mPm
1810.6 5	0.019 6	ε+β+	7.70 h 3	166Tm
1810.6 2	0.062 9	ε+β+	4.118 h 25	149Tb
1810.64 13	0.024 4	ε+β+	34.06 h 5	169Lu
1810.7 5	0.149 14	ε+β+	42.8 m 10	190Au
1810.7 5	0.149 14	ε+β+	42.8 m 10	190Au
1810.7 1	0.172 16	β-	122 s 3	230Ac
1810.7 10	5.9 3	β-	4.35 m 7	102mTc
1810.73 20	0.141 16	β-	3.15 m 4	89Kr
1810.772 17	0.640 10	ε+β+	77.27 d 3	56Co
1810.772 17	27.2 8	β-	2.5785 h 2	56Mn
1810.9 1	0.080 5	β-	12.44 m 7	151Nd

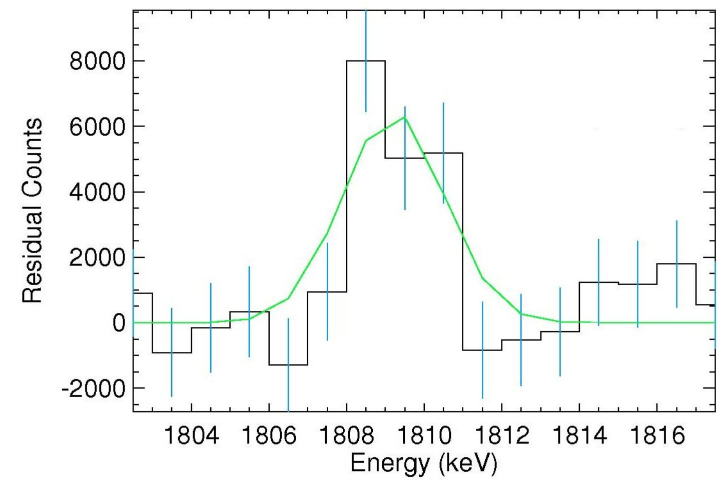
- **What are the Origins of Lines?**
  - ☆ **We care, because of characteristic time variations, e.g. after belt passages**
    - ☞ **This example: 19 Detectors fitted with 3 Gaussians & Exponential:**
      - 1793.0 keV 1.0 keV wide 21877 cnts
      - 1798.5 keV 1.1 keV wide 37829 cnts
      - 1809.4 keV 1.9 keV wide 1640280 cnts
  - ☆ **We are analyzing celestial ^{26}Al at**
    - **1808.65 keV, expecting ~300000 cnts**

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

→ A useful first-order check

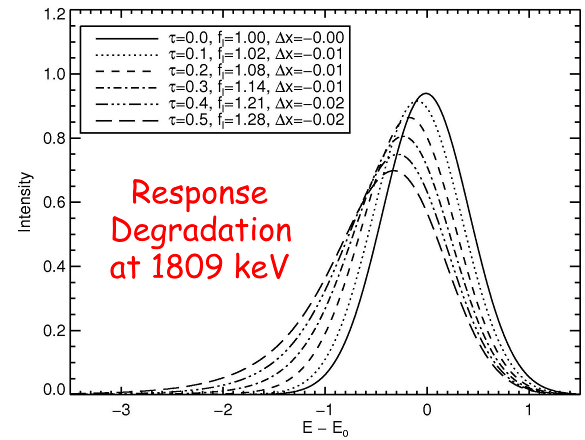


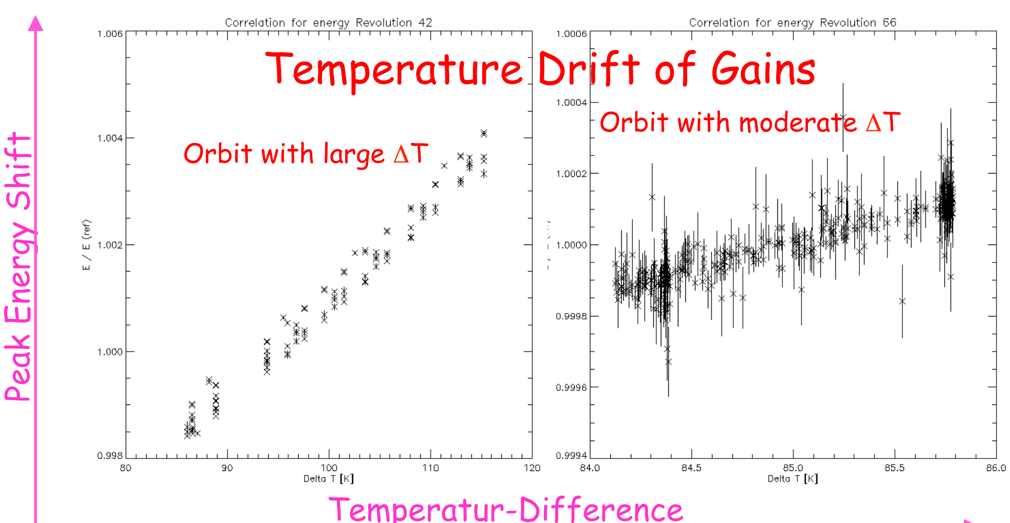


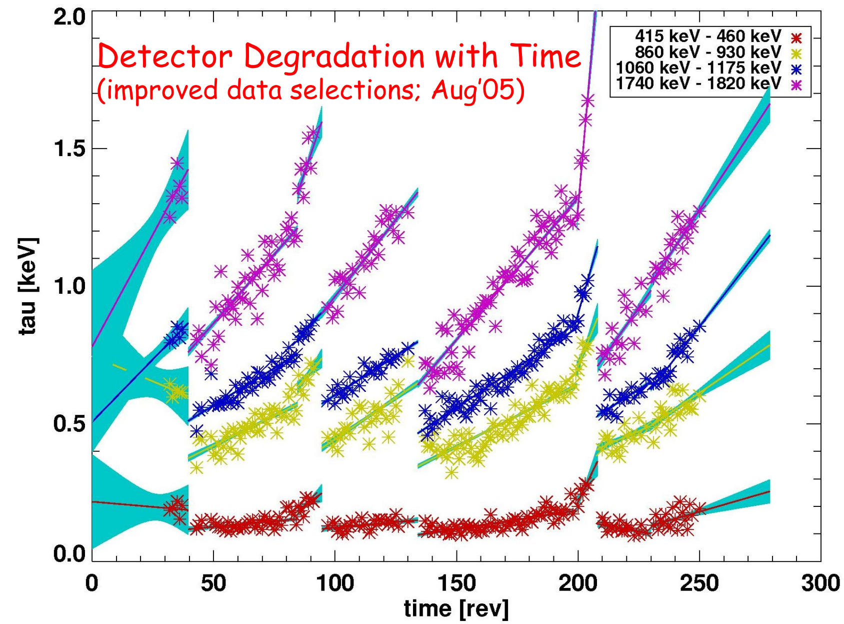
Value	Name	Error
1809.21	Centroid	0.11
1.30	Width	0.00
21024	Counts	1630
12.90	sigma of detection	

High-Resolution Spectroscopy with SPI

- **Cosmic-Ray Damage of Charge Collection**
  - ☆ Degradation with time
  - ☆ Annealings
- **Time-Variable Spectral Response**
  - ☆ **Line Shape = Convolution [Gaussian * Exponential]**
  - ☆ **Degradation Model (piece-wise linear)**
  - ☆ Next: Correct Short-term (<1 Orbit) Gain Variations with Detector Temperatures







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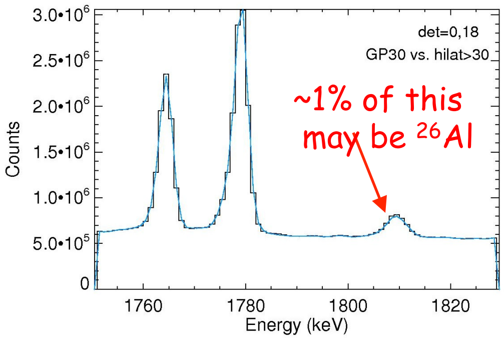
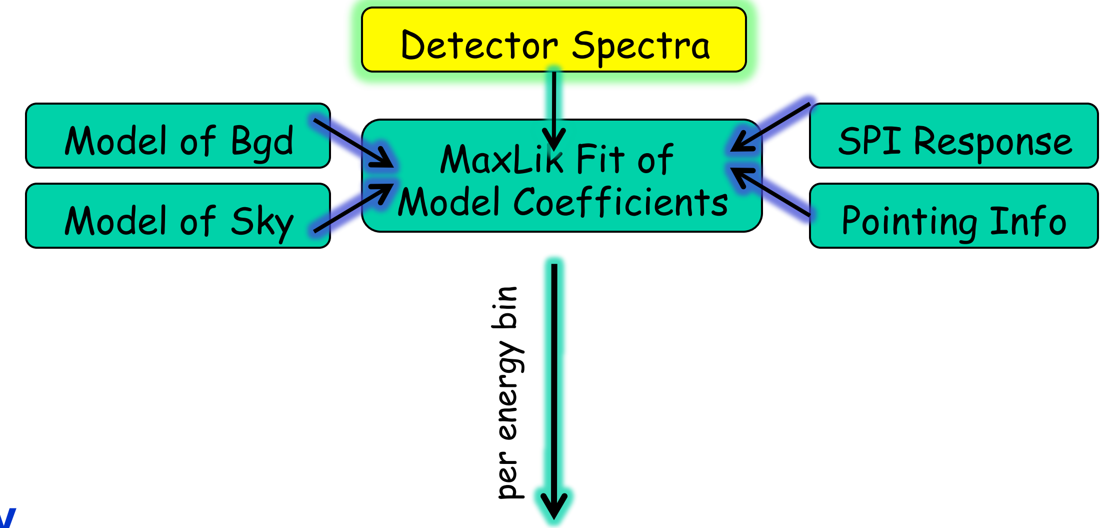
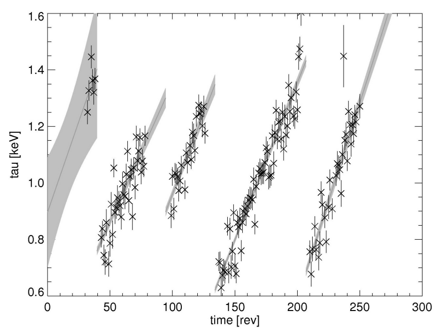
^{26}Al Line Analysis with SPI

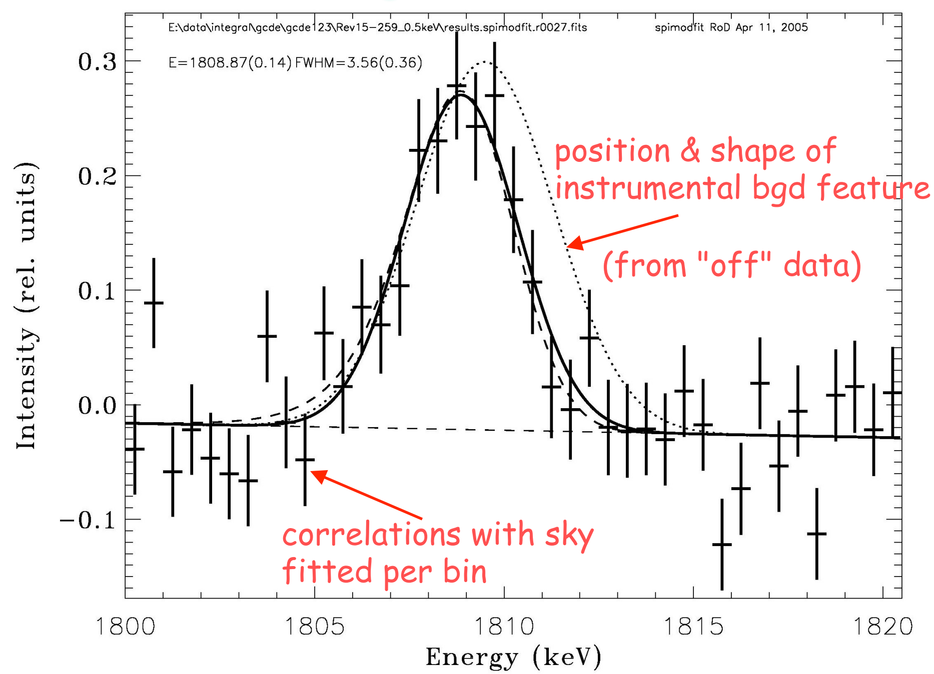




Analysis Method:

- ☆ **Fitting of Background and Sky Distribution Models in Fine E Bins**
- ☆ **Comparison to "predicted" Features, Shapes**





-> Detection of Celestial ^{26}Al

Nuclear Gamma-Ray Line Telescopes / Missions

☆ **Compton Gamma-Ray Observatory**

1991-2000

NASA

☆ **INTEGRAL Observatory**

2002-(2014+)

ESA

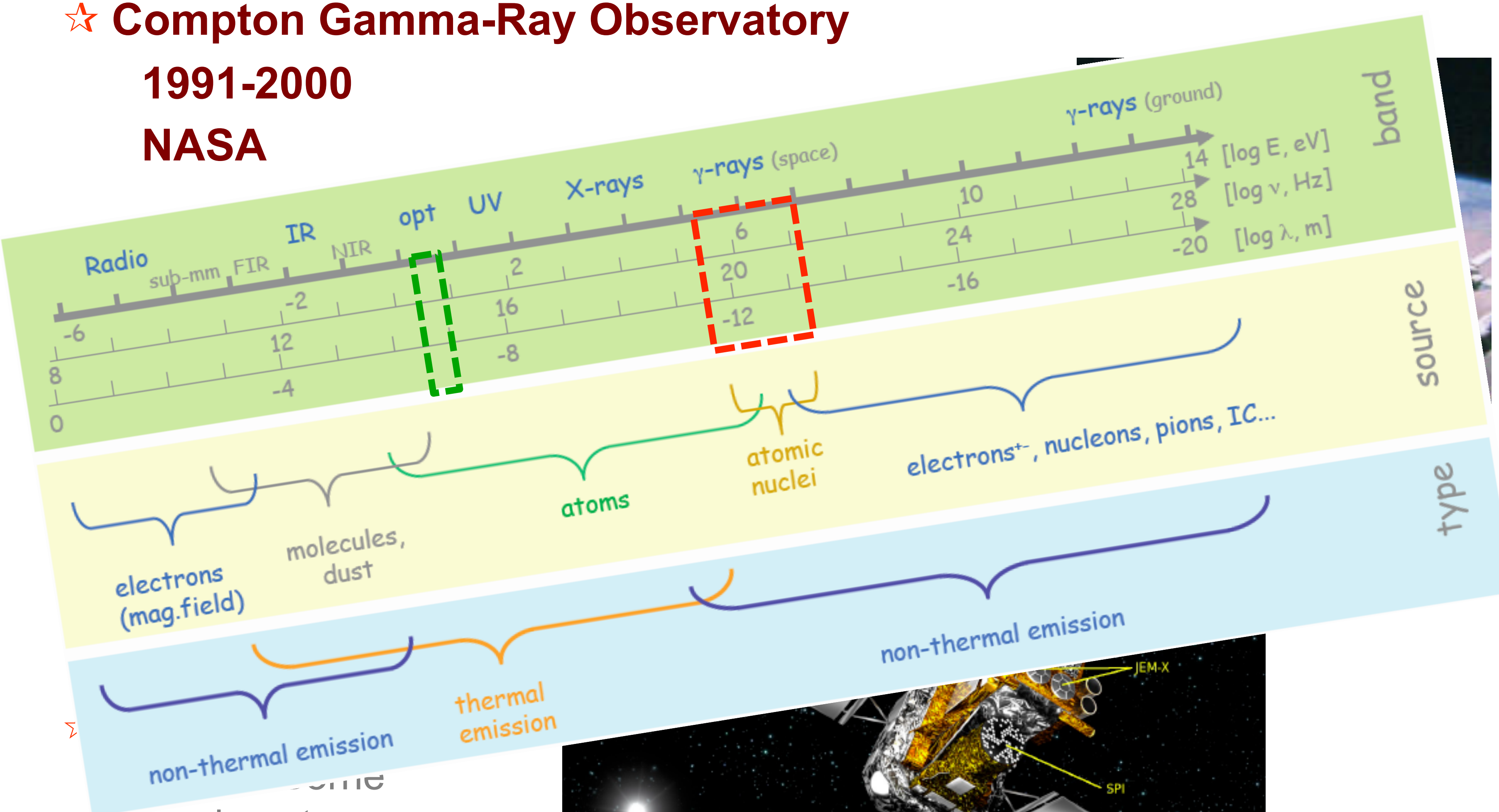
☆ Earlier Balloone-Borne Experiments

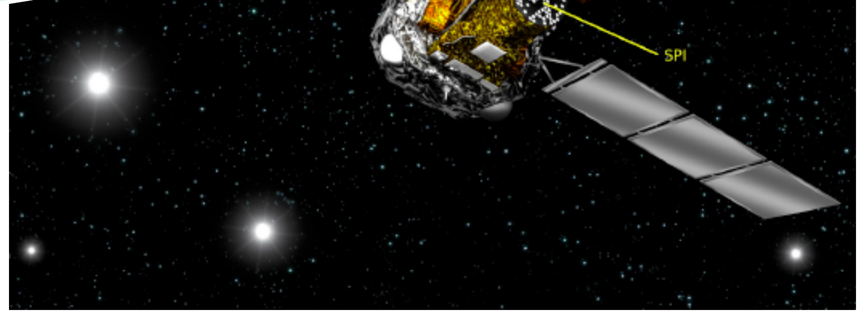
☆ HEAO-C

1978

Nuclear Gamma-Ray Line Telescopes / Missions

- ☆ **Compton Gamma-Ray Observatory**
  - **1991-2000**
  - **NASA**





- ☆ Experiments
- ☆ HEAO-C
  - 1978

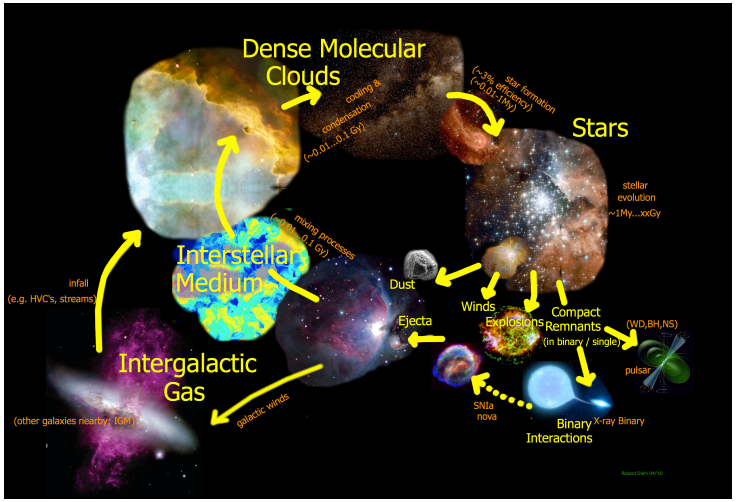
Radioisotope Gamma-Ray Lines and their Messages

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	1.04 10^{6}y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	3.8 10^{6}y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	…. 10^{5}y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511

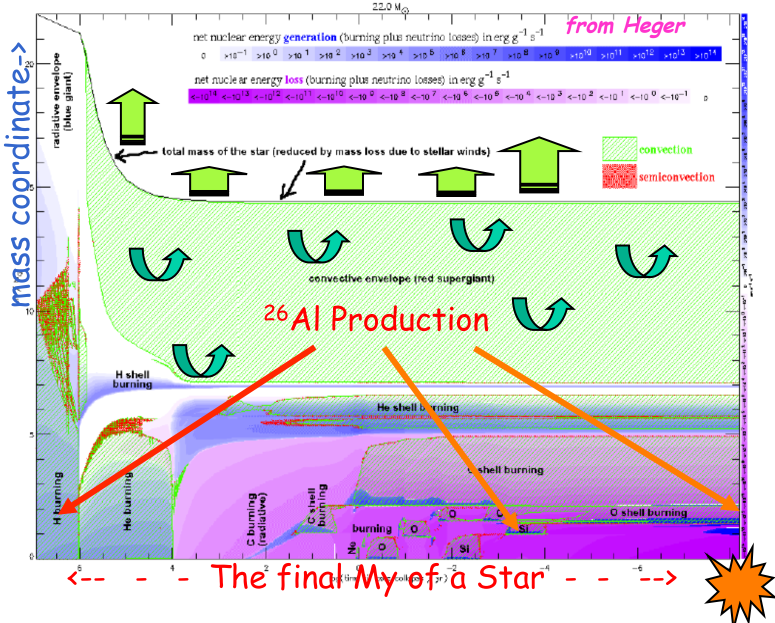
individual object/event

cumulative from many events

Massive-Star Interiors



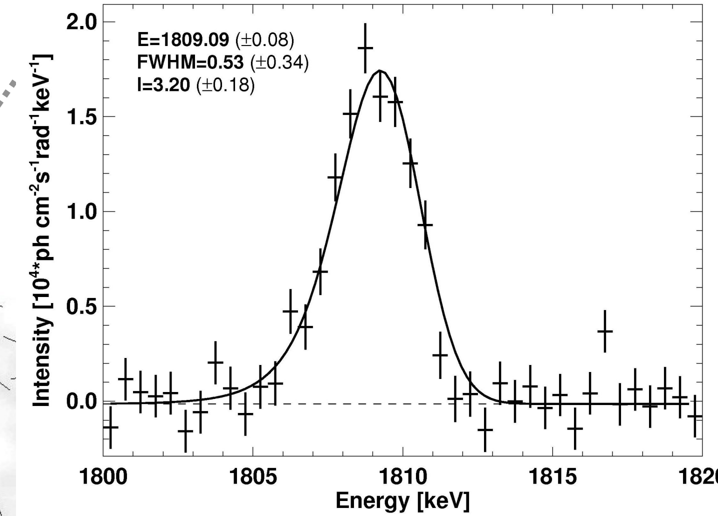
- ☆ **Massive Stars are:**
  - **Key Producers of Cosmic 'Metals'**
  - **Key Agents for Cosmic Evolution in Galaxies**

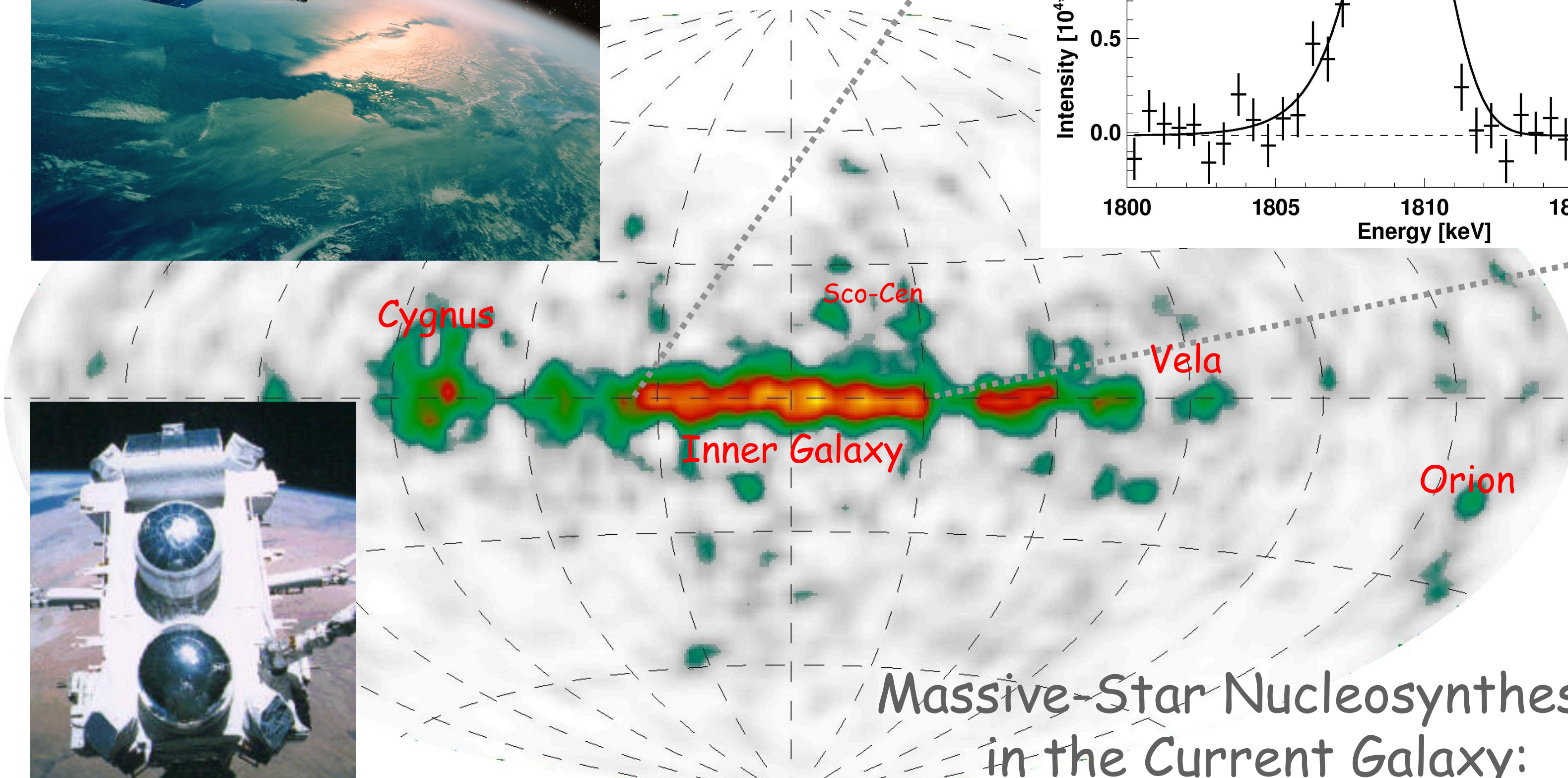


- ☆ **How does the Interior Structure Evolve in Late Stages?**
  - **Which "Shells" are Active?**
  - **Which Nuclei are Produced? (ejected?)**
  - **What are the Time Scales?**
  - **How does all this Depend on Rotation?**
  - **How does all this Depend on Metallicity?**

Main Sources of ^{44}Ti, ^{26}Al, ^{60}Fe

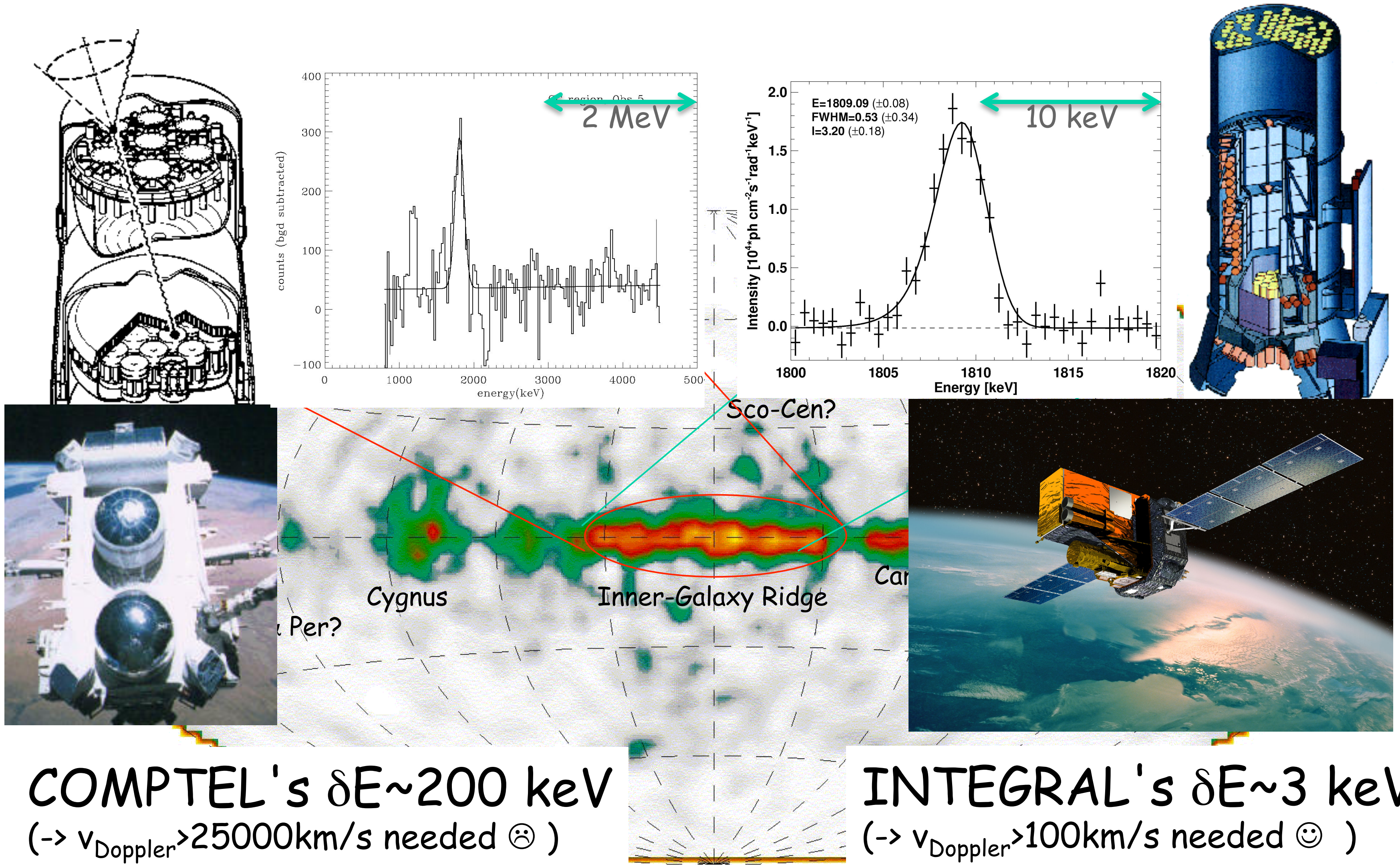
^{26}Al in our Galaxy: γ-ray Image and Spectrum





Massive-Star Nucleosynthesis
in the Current Galaxy:
Exploiting the Message from ^{26}Al γ-rays

CGRO (<2000) / INTEGRAL (>2002) Spectroscopy



COMPTEL's δE~200 keV
(-> $v_{Doppler}$>25000km/s needed ☹)

INTEGRAL's δE~3 keV
(-> $v_{Doppler}$>100km/s needed ☺)

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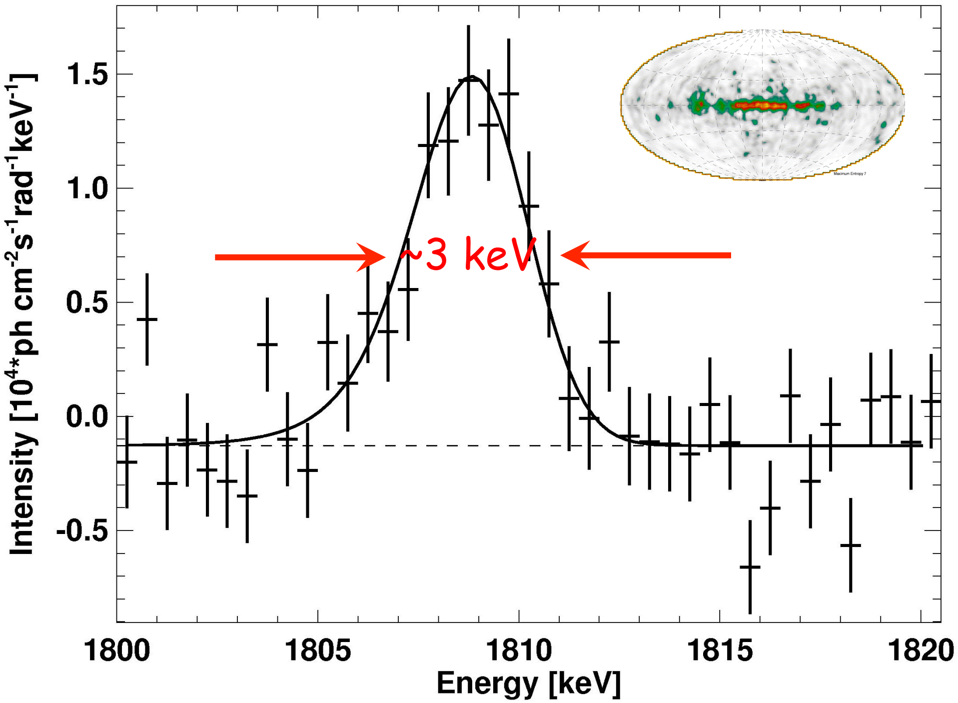
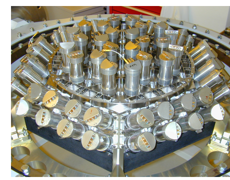
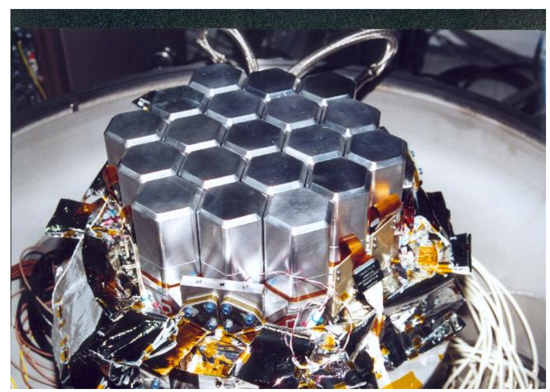
Ge Spectroscopy of ^{26}Al Line with SPI/INTEGRAL

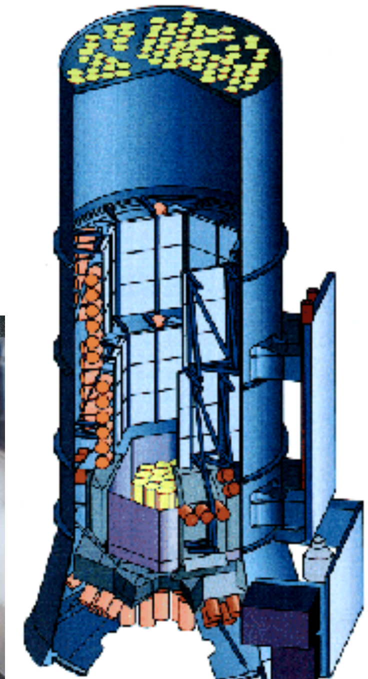
since Oct 2002

- ☆ **^{26}Al Glow of Inner Galaxy Confirmed, at ~Known Flux Level**
- ☆ **Line is Resolved, and not as broad as suggested** **(by GRIS)**
  - ☞ ***Diehl et al., Astron. & Astroph. (2006)***

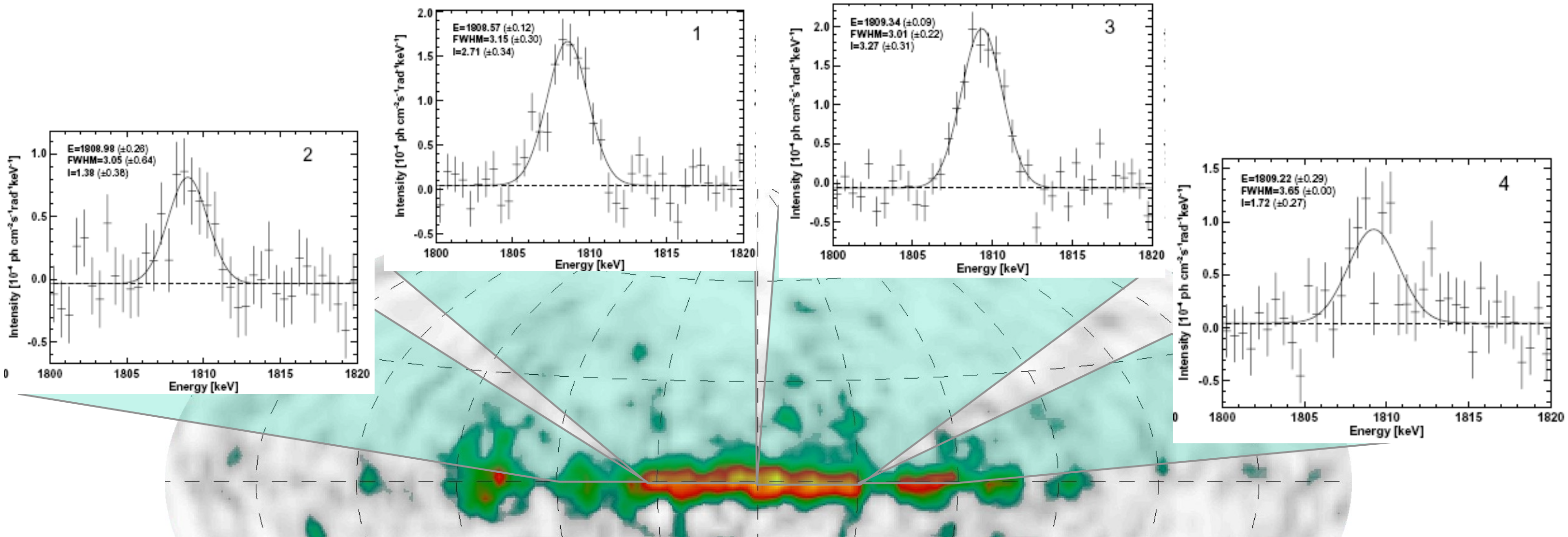




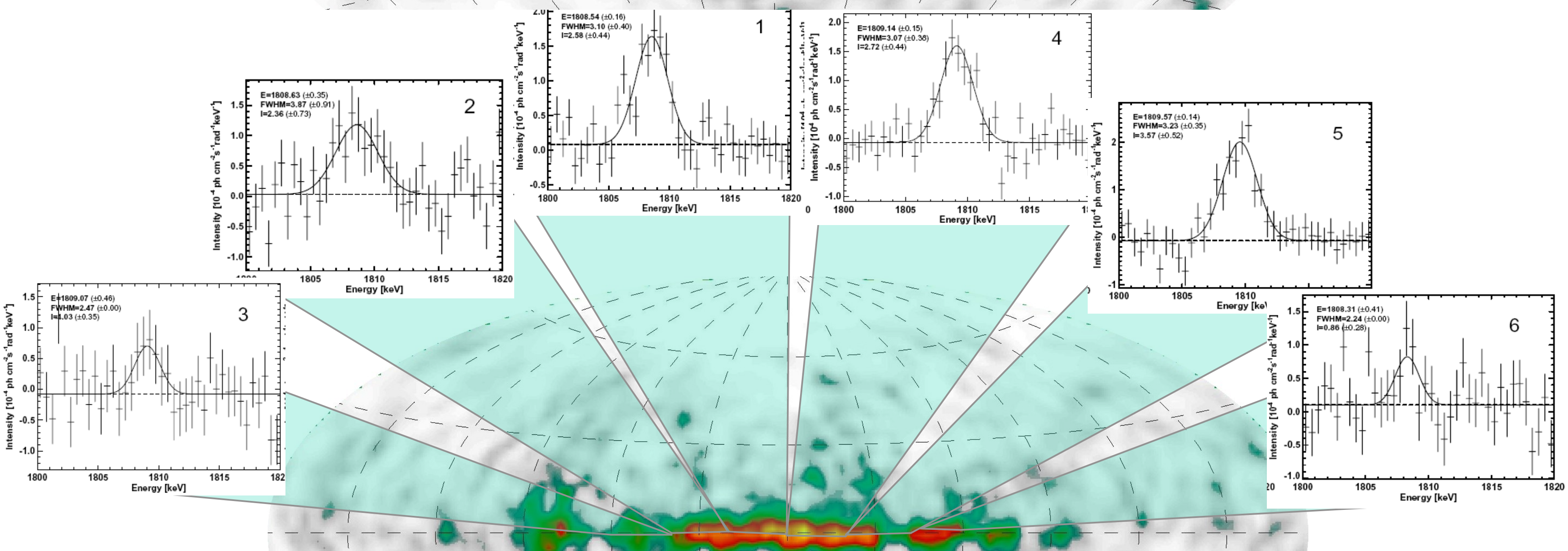




- ☆ **SPI Opened the '^{26}Al Line Spectroscopy' Science**
  - ☞ COMPTEL was superior wrt. Large-Scale Imaging



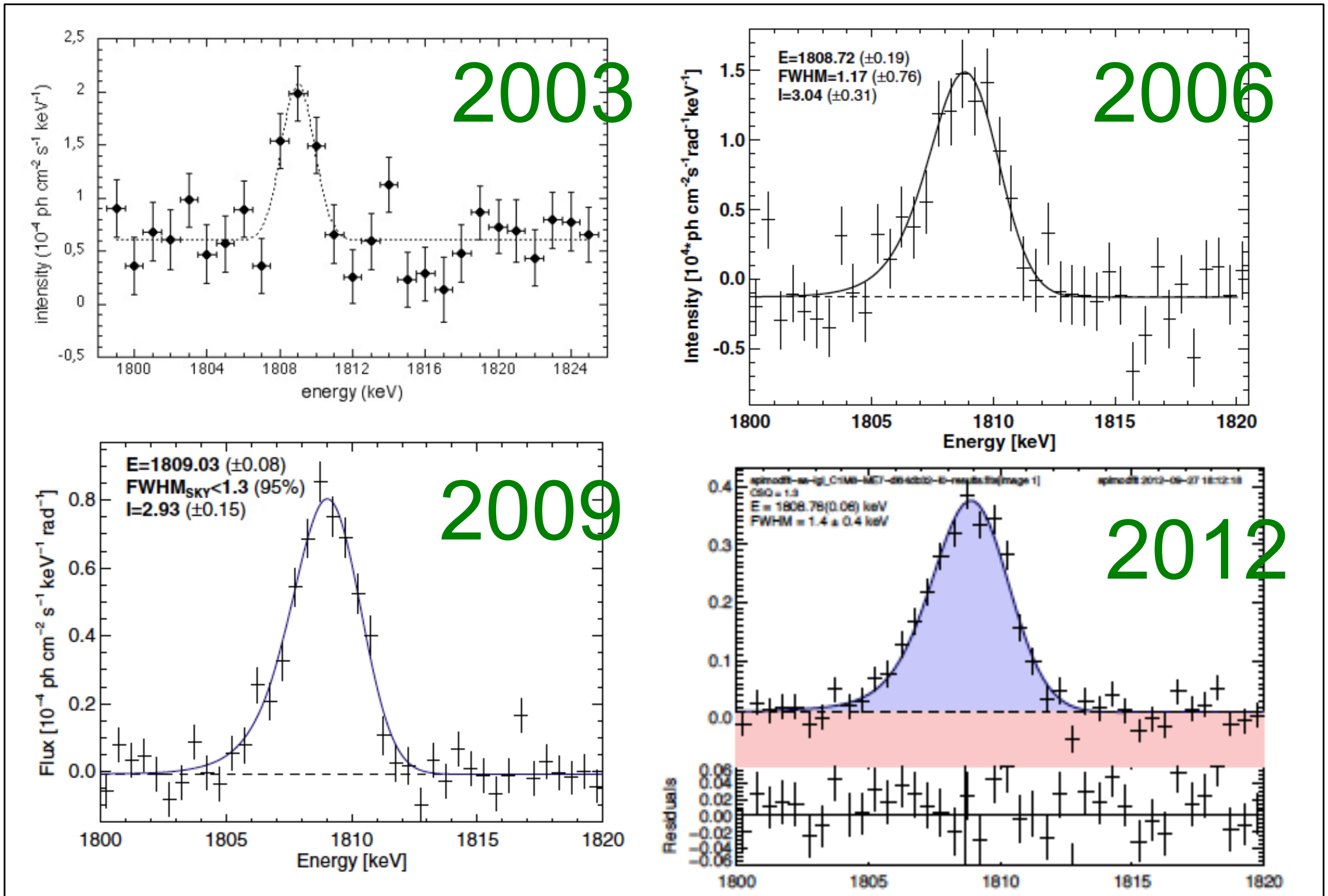
Now: Spectral Variation along the Plane of the Galaxy



☆ **Spatially-Resolved ^{26}Al Signals are Weak (again)**

Measuring the ^{26}Al Gamma-Ray Line from the Galaxy

- **Increasing Exposure** (Oct 2002…. Today)
  → Improved Statistical & Systematic Precision



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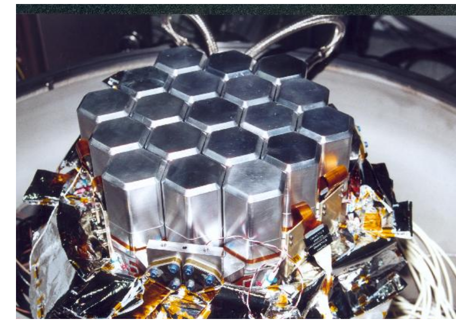
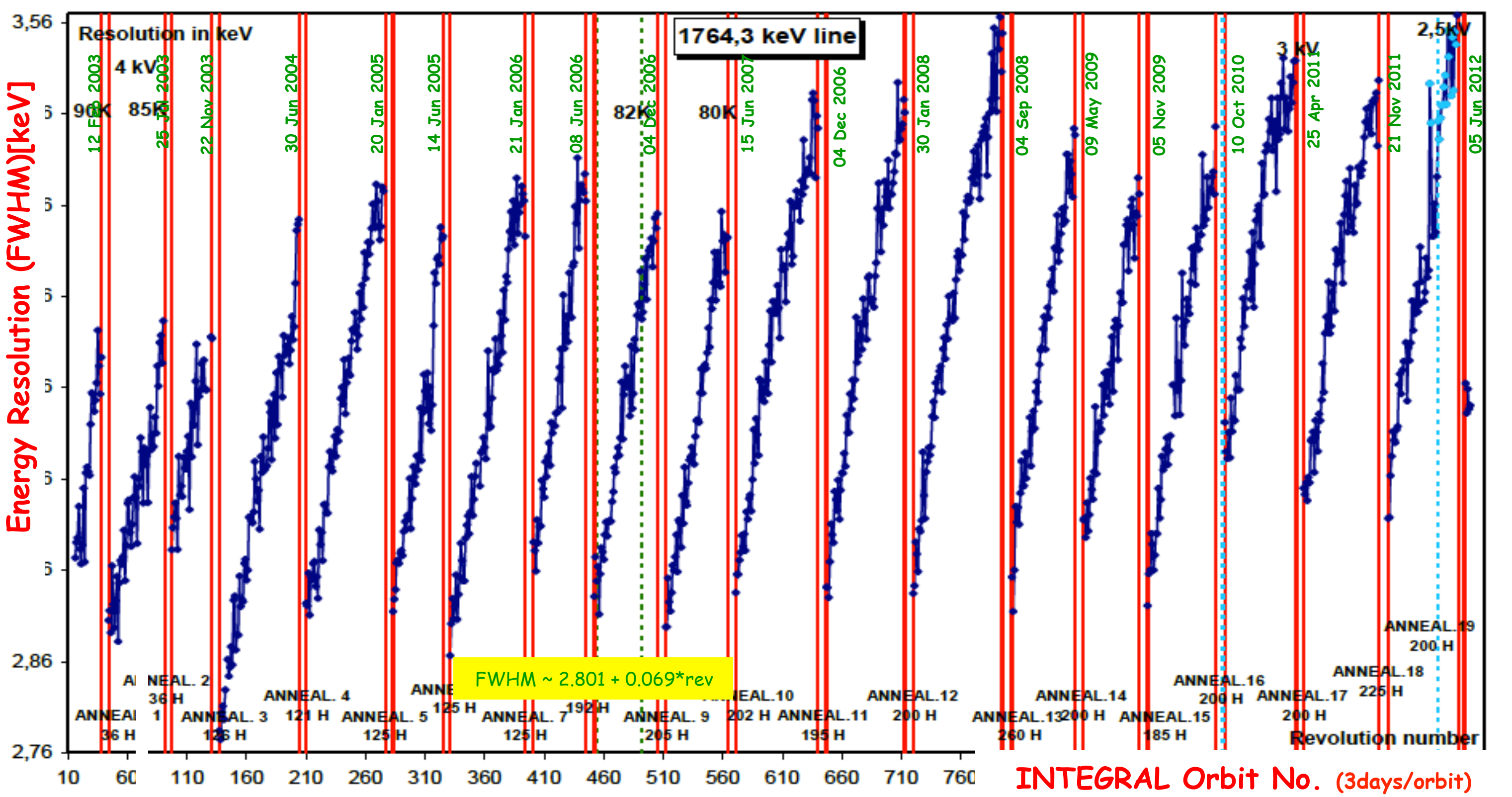
High-Resolution Gamma-Ray Spectroscopy Maintained in Space: SPI on INTEGRAL

- **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



✓19 Annealings Successfully Completed (Jul 2012)

✓15 of 19 Detectors Operational with Fine Resolution



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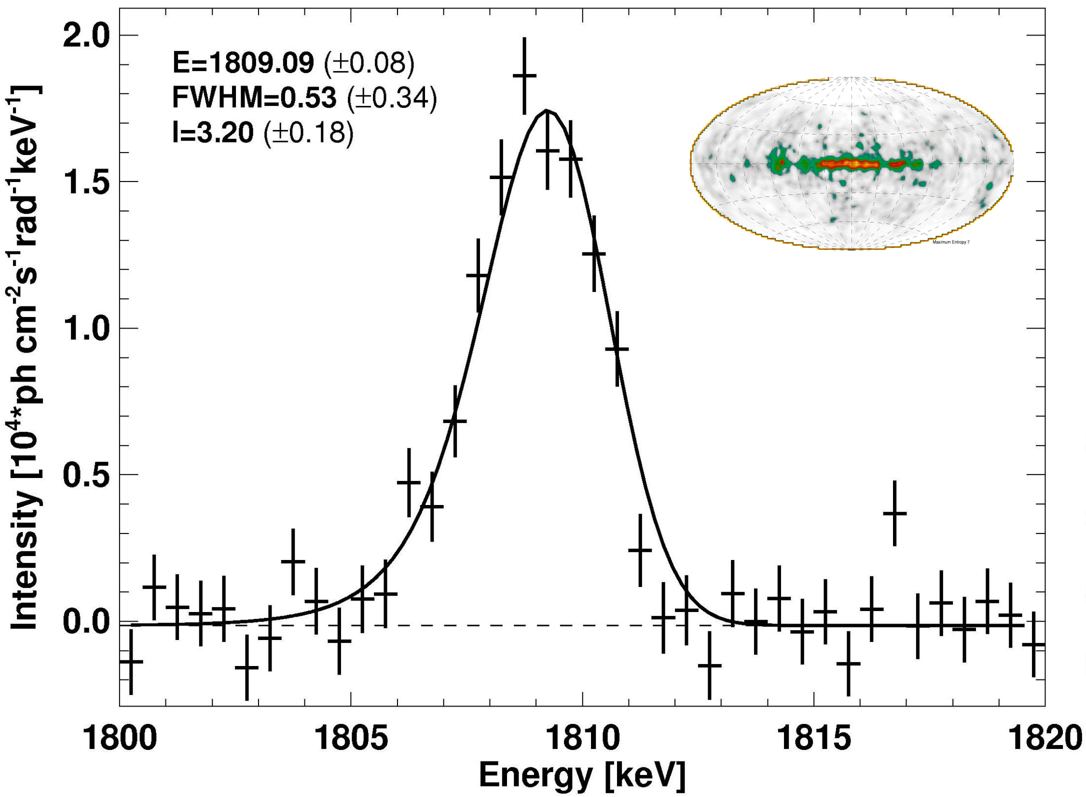
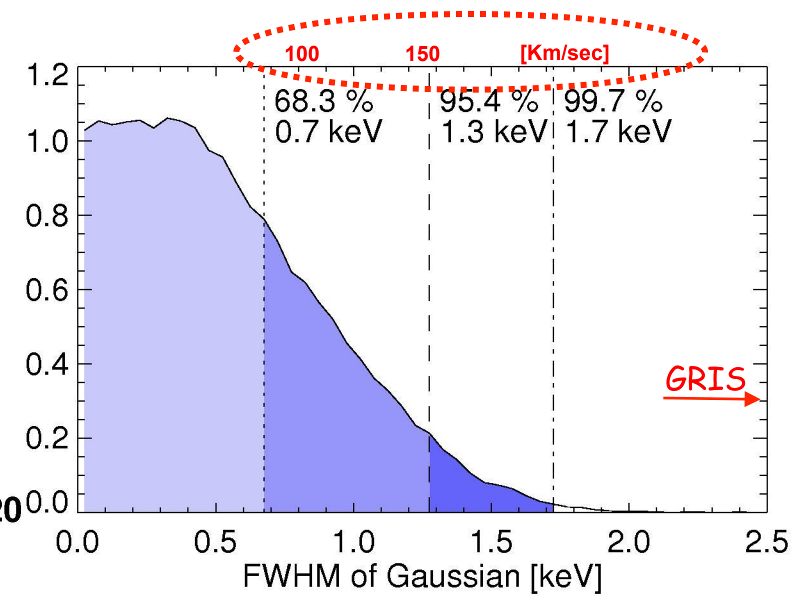
How Wide is the Celestial ^{26}Al Line?

- **SPI Response * Celestial Line -> Actually-Observed Line Feature**
- Fit Expected Spectral Signature to the Sky&Bgd-Fitted Spectral Signal
- Perform Statistical Uncertainty Analysis (Monte Carlo Markov Chain)

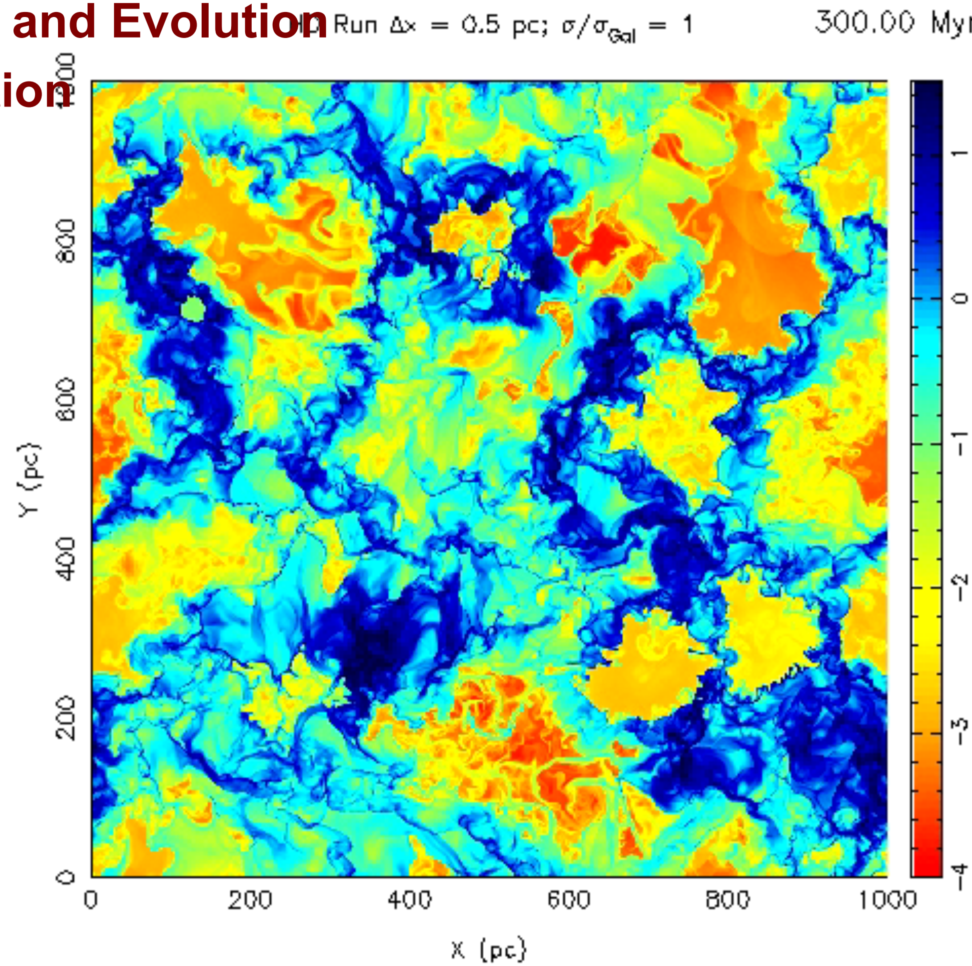


Celestial Line Width Constraint



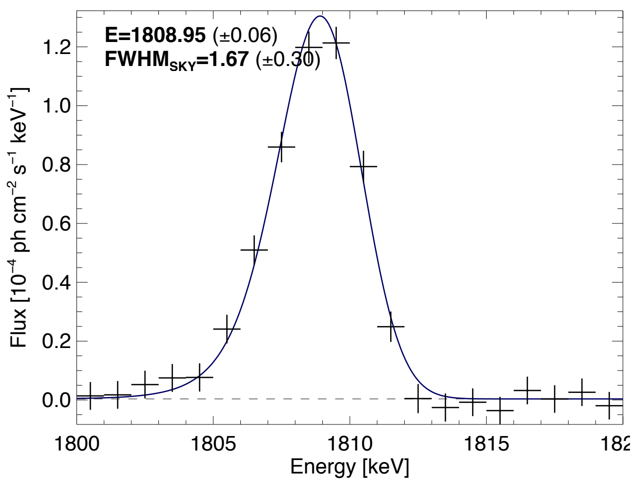
-> Data up to mid 2006; W.Wang et al., in prep.
Line Width Probability Distribution by K.Kretschmer

- **The ISM is a non-Equilibrium and Highly-Dynamic Medium**
  - ☆ **No ‘Pressure equilibrium’ (‘phases’)**
    - ☞ **Numerical Simulations of ISM (MHD 3D)**
      - – **Large-Scale Dynamics and Evolution**
      - – **MC Outflows, Destruction**
      - – **Energy Feedback into ISM**

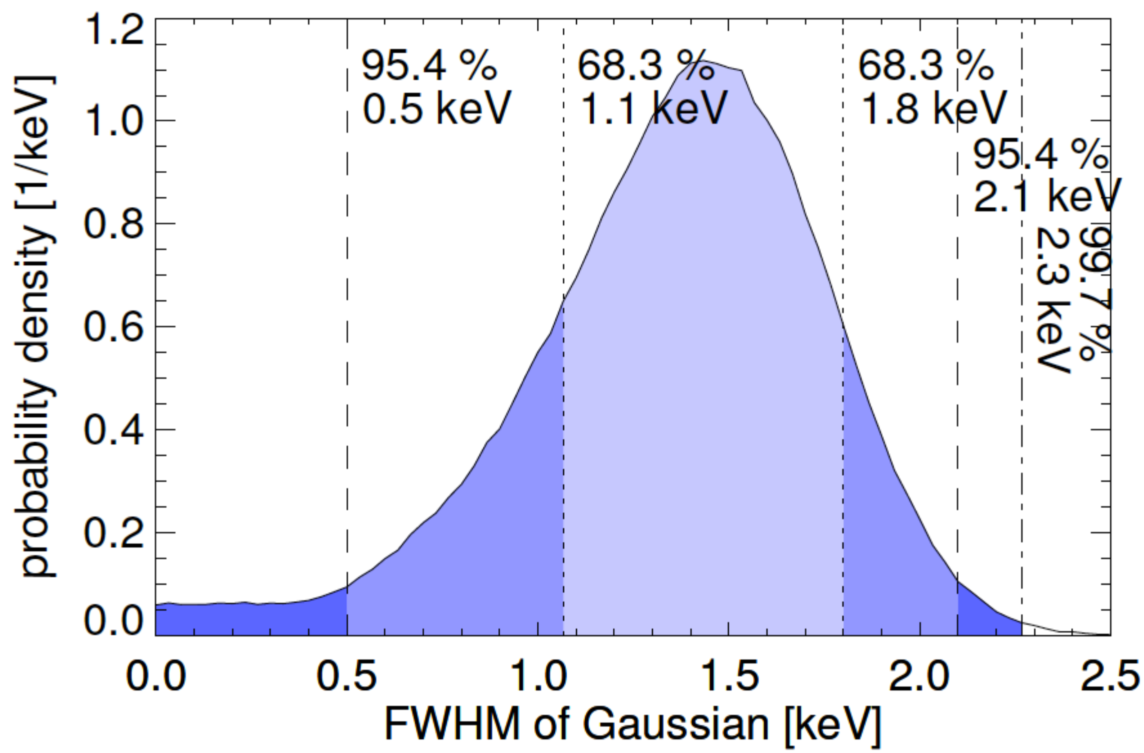


Measuring the ^{26}Al Gamma-Ray Line in Detail

- **Line Width:** (from 10 years of data, up to rev 1240) *(Diehl et al. 2013)*
  - ☆ **Account for Instrumental Line Width (~3 keV)**
  - ☆ **Extract Additional (astrophysical) Broadening → Doppler velocity**



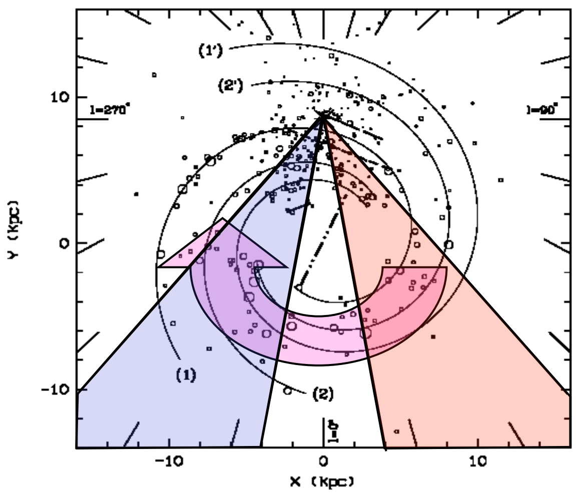
☞ **~1.4 ±0.35 ±0.3 keV**
Consistent with Expectation from Galactic Rotation (~1.35 keV)

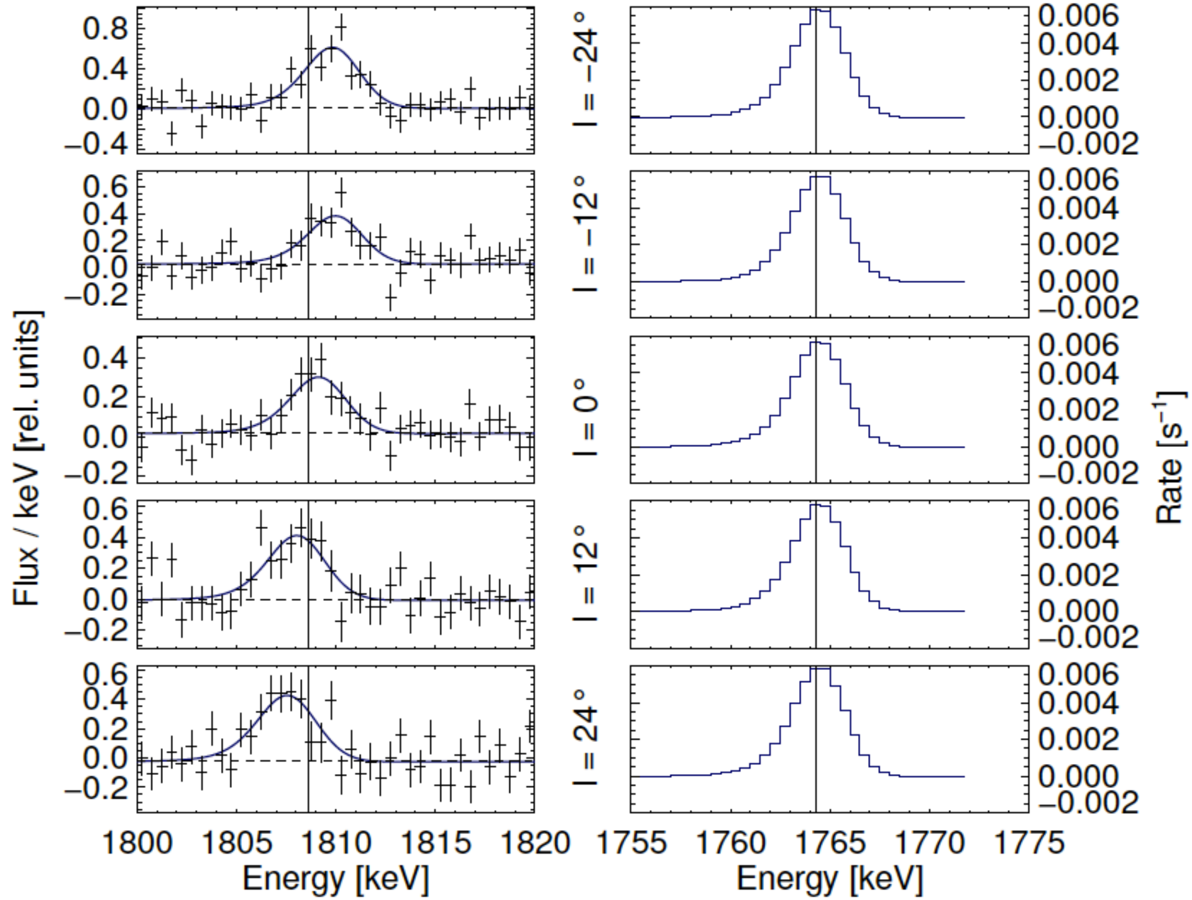


175 $_{\pm 45}$ km s^{-1}

Spatially-Resolved Spectroscopy

- **Analyze Line Shape and Position for Different Directions**
  - ☆ **Galactic Rotation**





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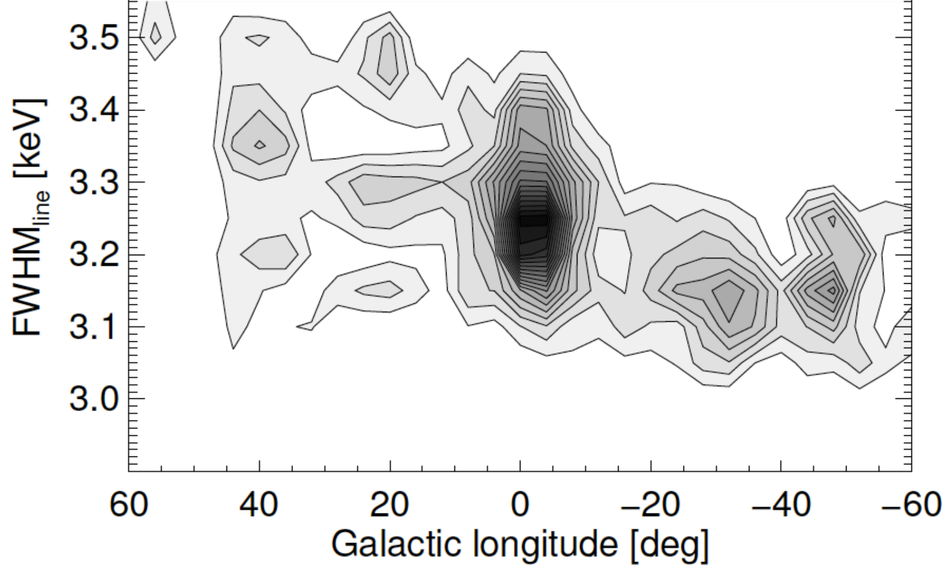
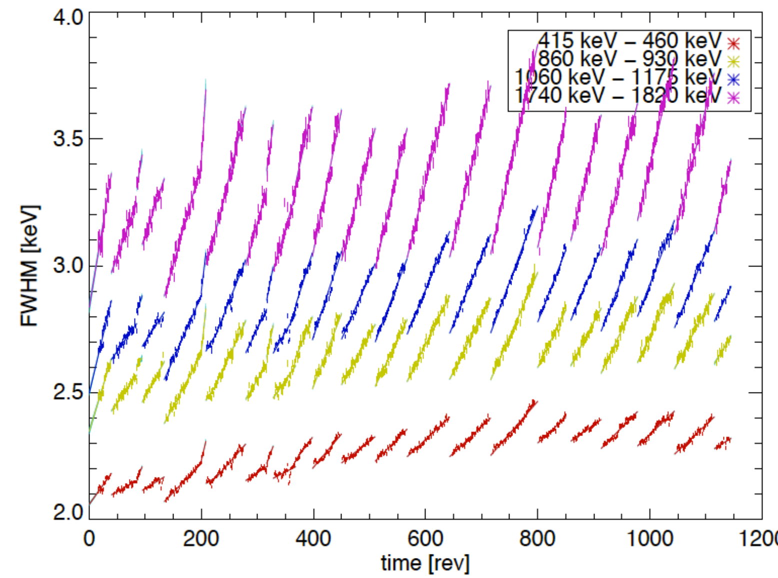
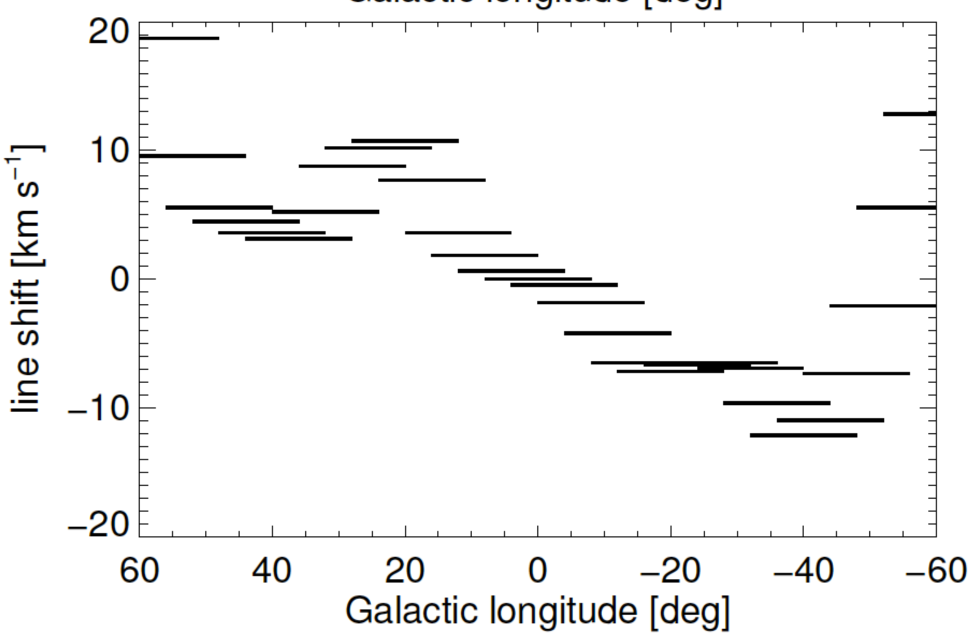
^{26}Al in the Inner Galaxy: Spectral Response in RoI's

☞ **Are there systematic response variations which could mimic a longitude-velocity trends?**

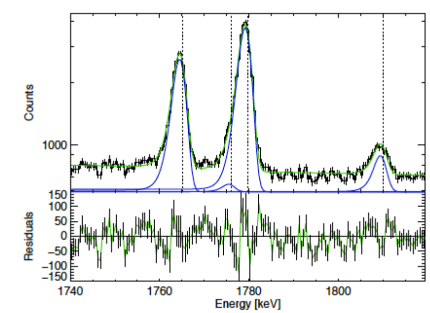






Modelling SPI's response

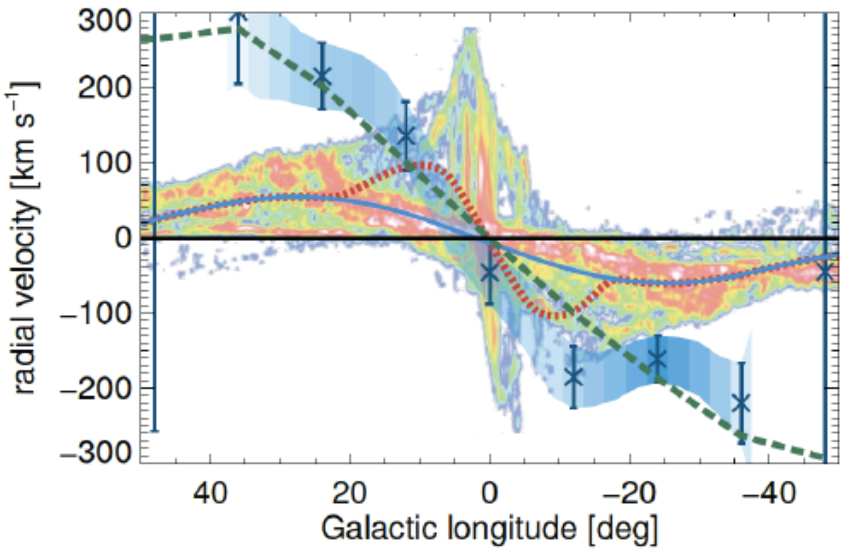
- Radiation damage causes asymmetric line with low-energy tail
- Good fit results obtained with a convolution of Gaussian and truncated exponential



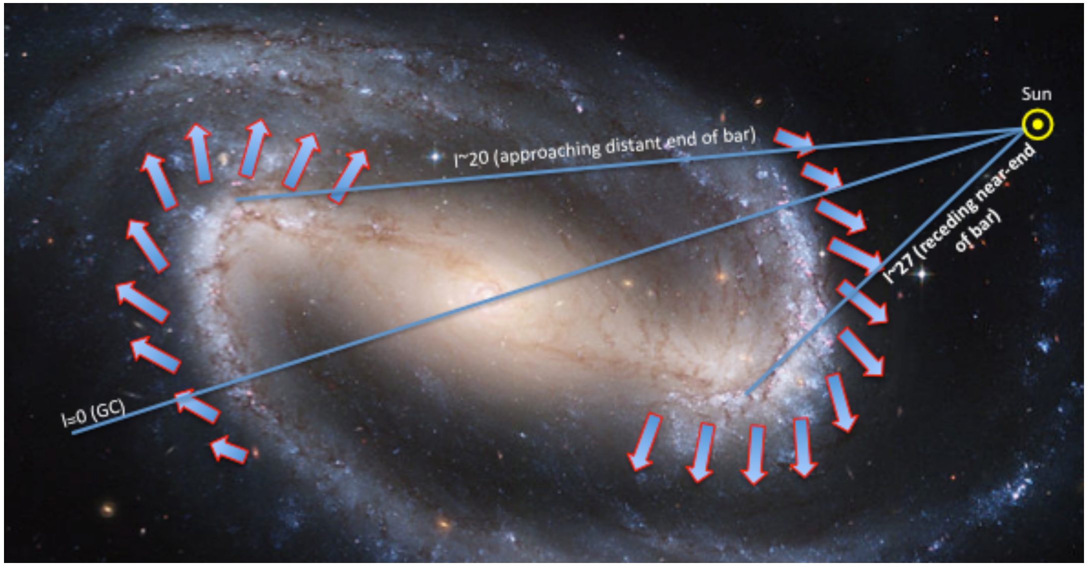
$$I(E) \approx \int_0^{\infty} \exp(-E'/\tau) \cdot \exp\left(\frac{(E+E'-E_0)^2}{2\sigma^2}\right) \mathrm{d}E'$$

Motion of Hot Gas in the Inner Galaxy – ^{26}Al

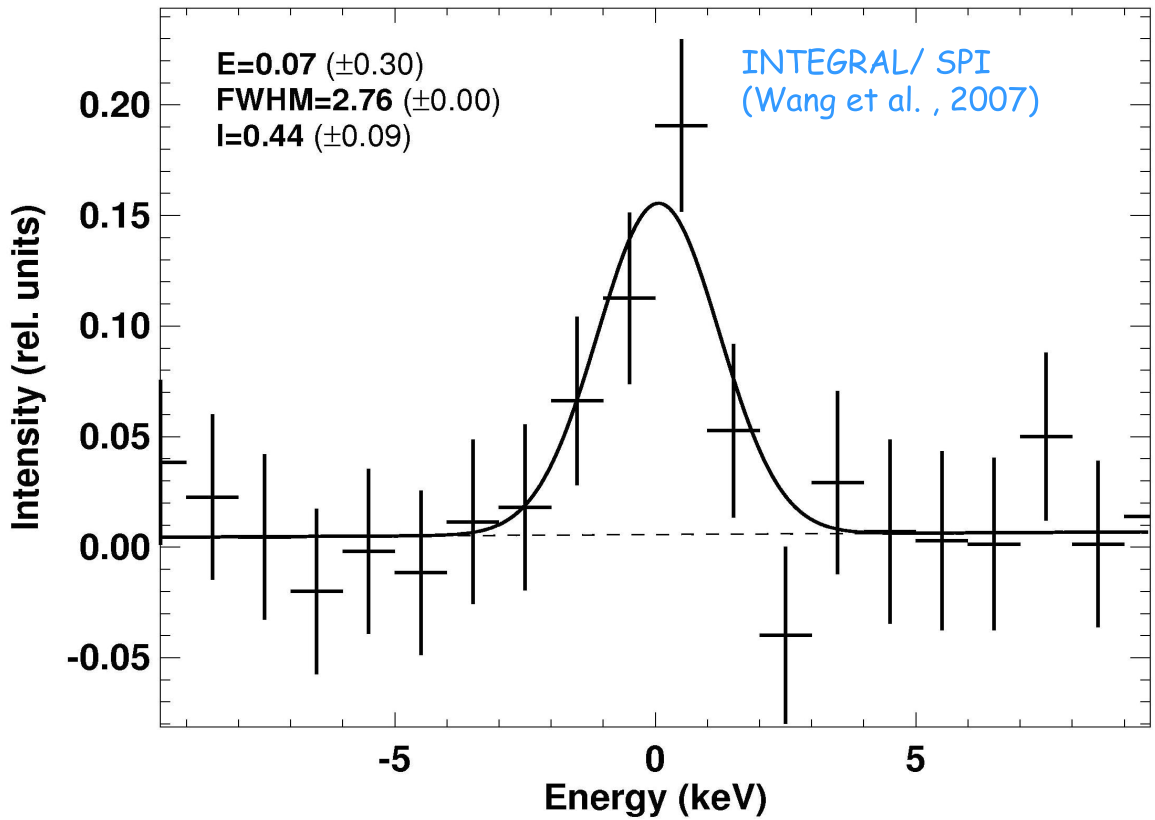
- **Hot gas streaming away from star-forming clouds**

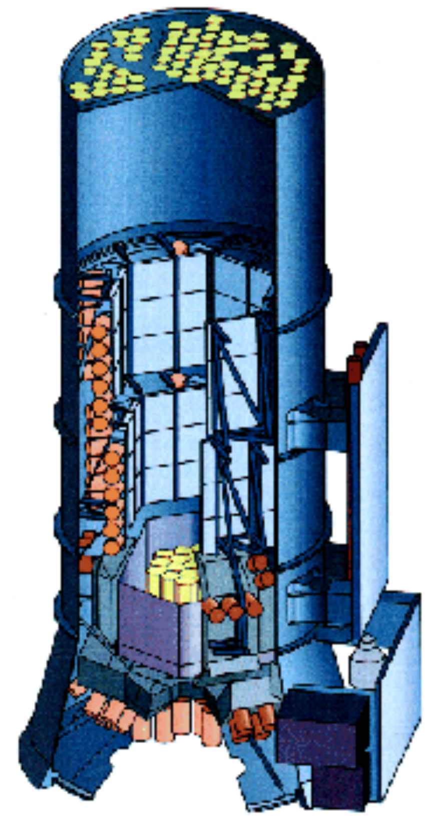


enhanced star formation in spiral arms; gas/parental-cloud momenta incur one-sided outflow (forward, i.e. following & enhancing bulk velocity)



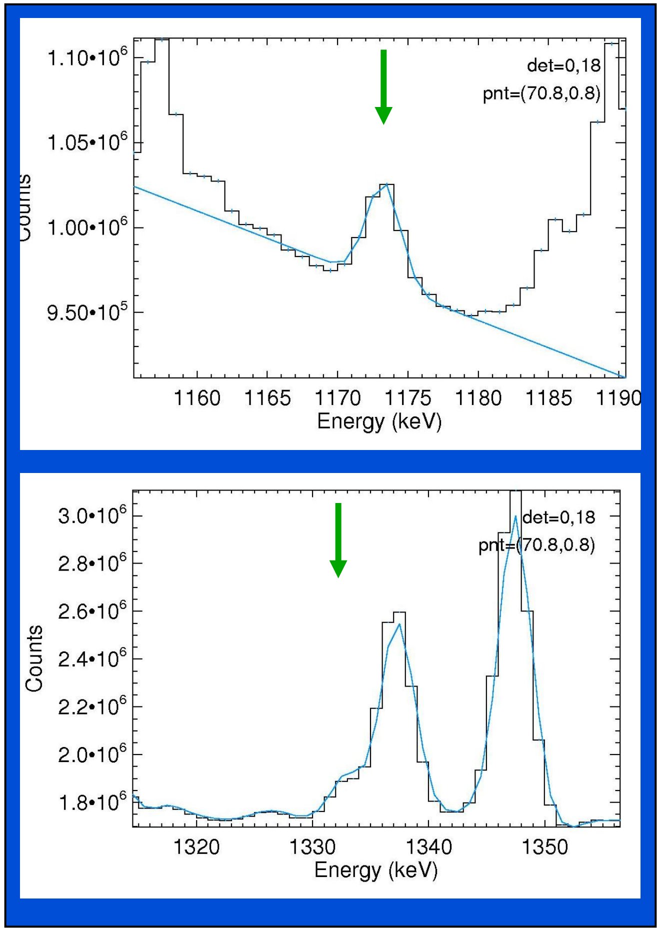
^{60}Fe Emission is Seen from the Galaxy

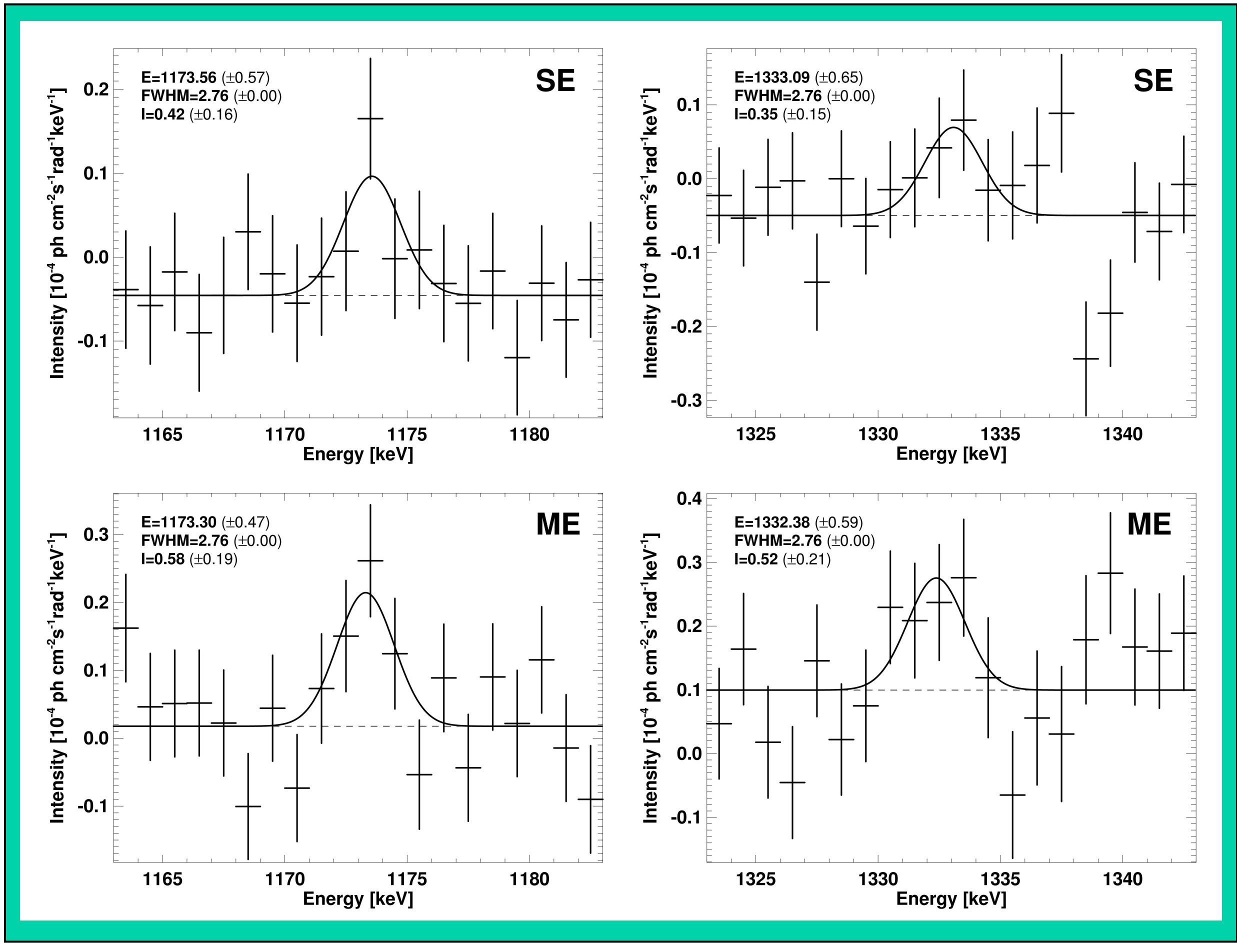




- ☆ **Gamma-ray Signal Now Beyond 'Hints'/'Limits'** (5σ)
- ☆ **^{60}Fe/^{26}Al Emission Ratio ~15%**

Science Result: ^{60}Fe

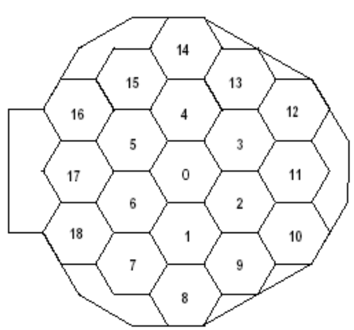




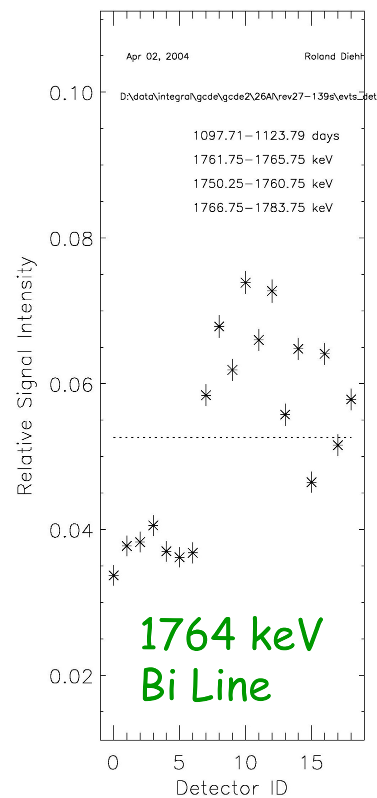
- ☆ **Marginal Result**
  - ☞ **Problematic Instrumental Lines**
    - – **^{60}Co Buildup, 1337 keV Ge Line**

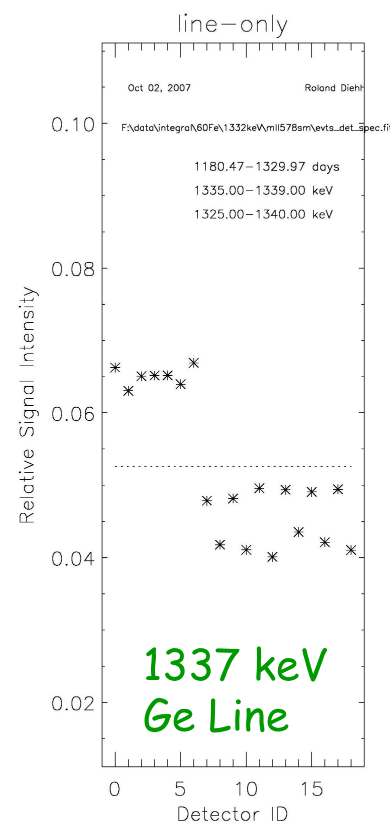
"Imaging" Bgd: Interior, or from Outside

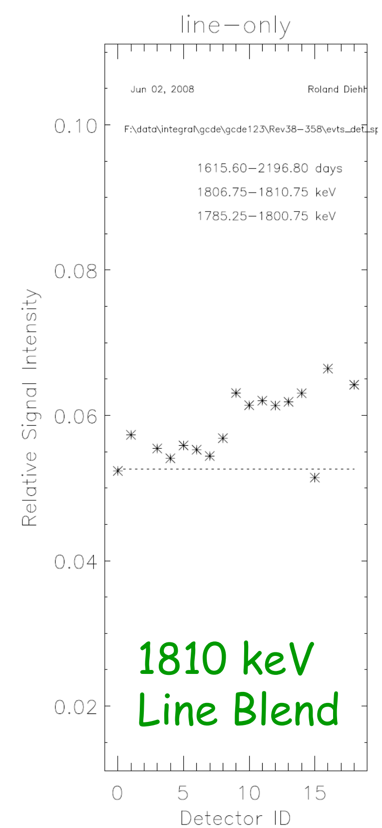
- **SPI 19-Ge Detector Arrangement within BGO Shield**
  - ☆ **Use Relative Contributions to Signal per Detector**
    - ☞ **Homogeneous Irradiation & Performance <-> Equal Shares**
  - ☆ **Hints for Location of Bgd Source**
    - ☞ **Discriminate among Candidates**



Top PA 1 array view



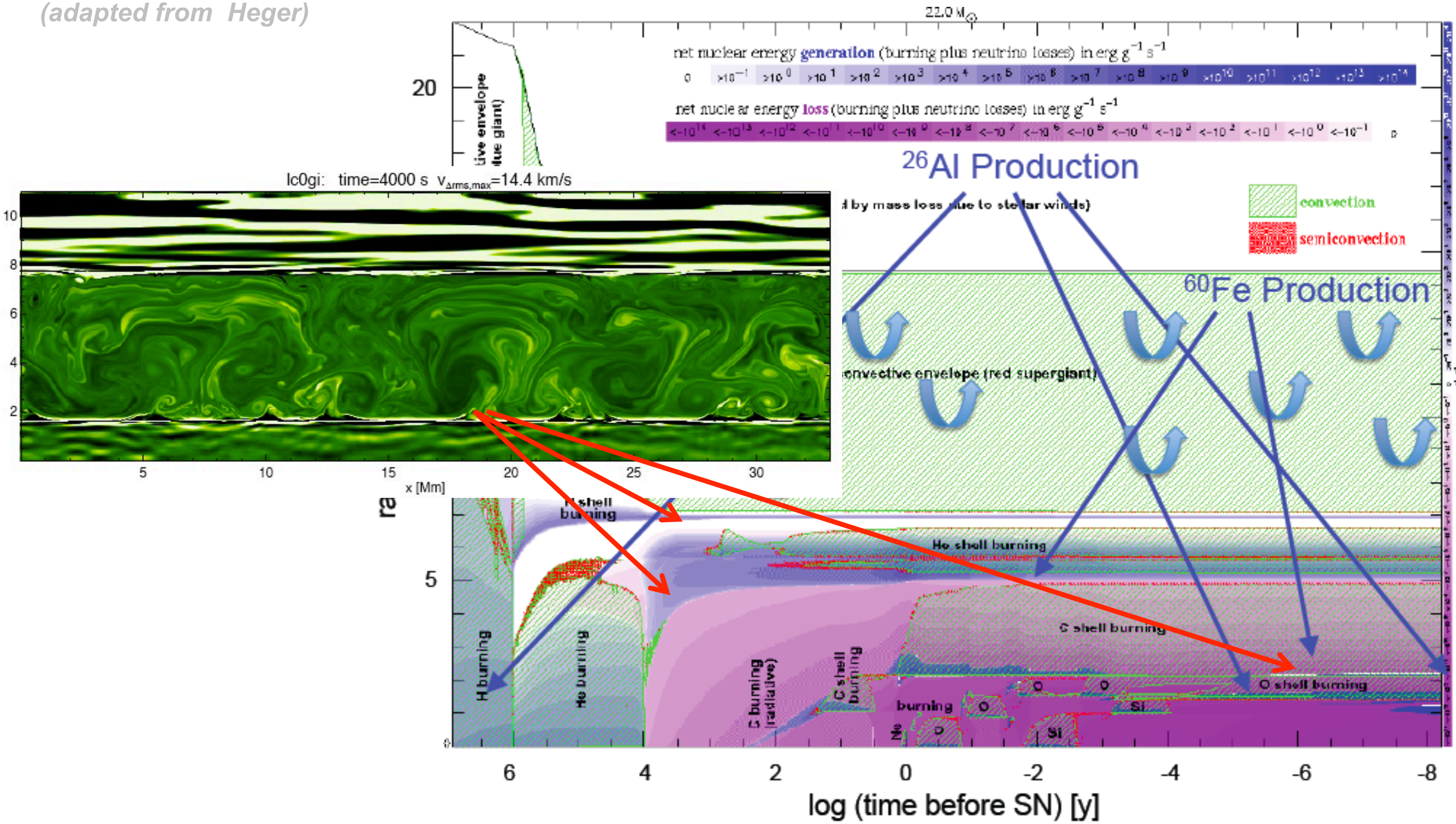




Massive-Star Structure Diagnostics: $^{60}Fe/^{26}Al$ Ratio

- Two Isotopes from Same Source Type → Eliminate Astronomical Bias
- Production-
  Site Detail

(adapted from Heger)



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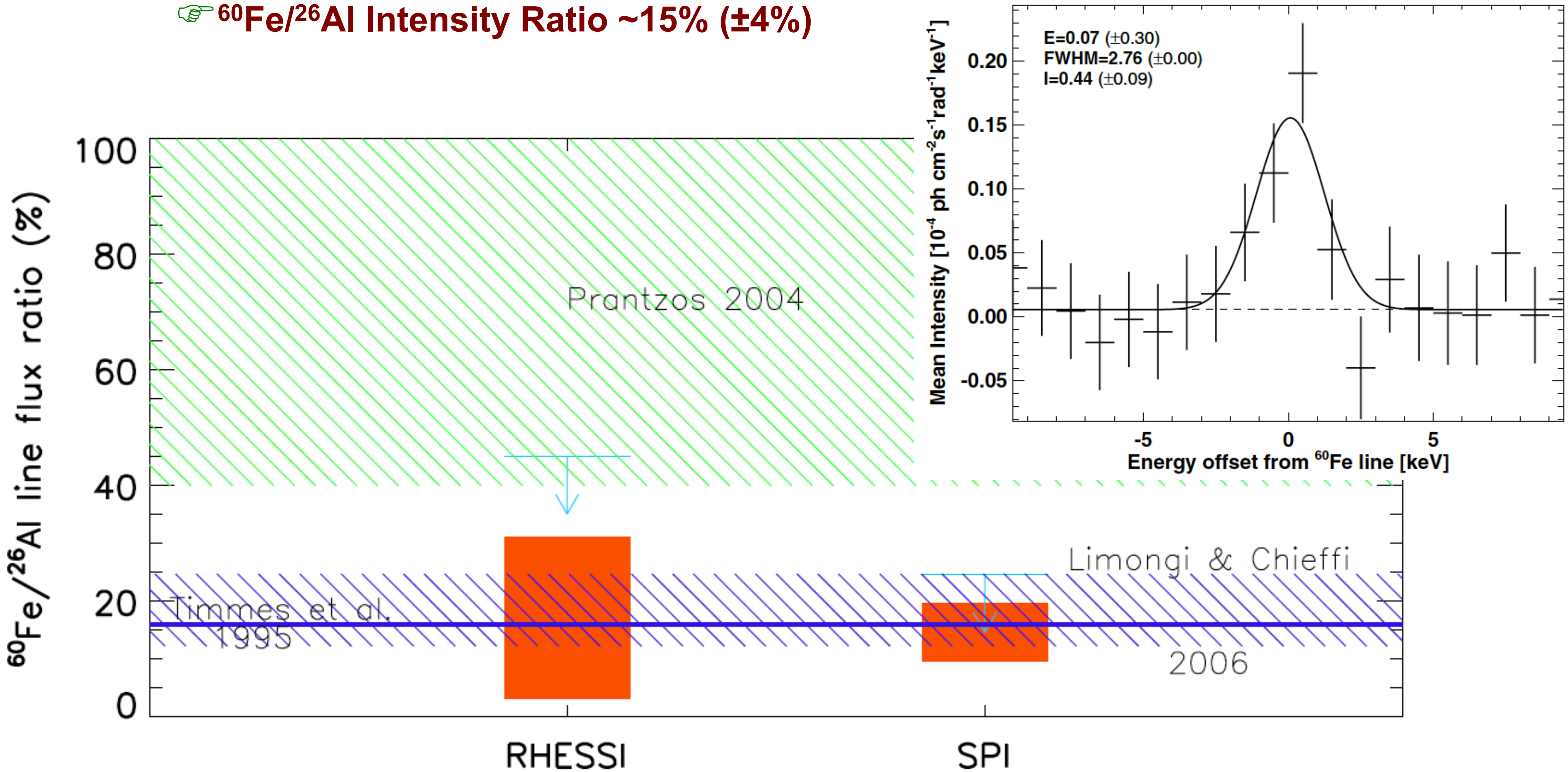
^{60}Fe in the Current ISM

- **Gamma-Ray Observations: RHESSI, INTEGRAL**

☞ **^{60}Fe/^{26}Al Intensity Ratio ~15% (±4%)**

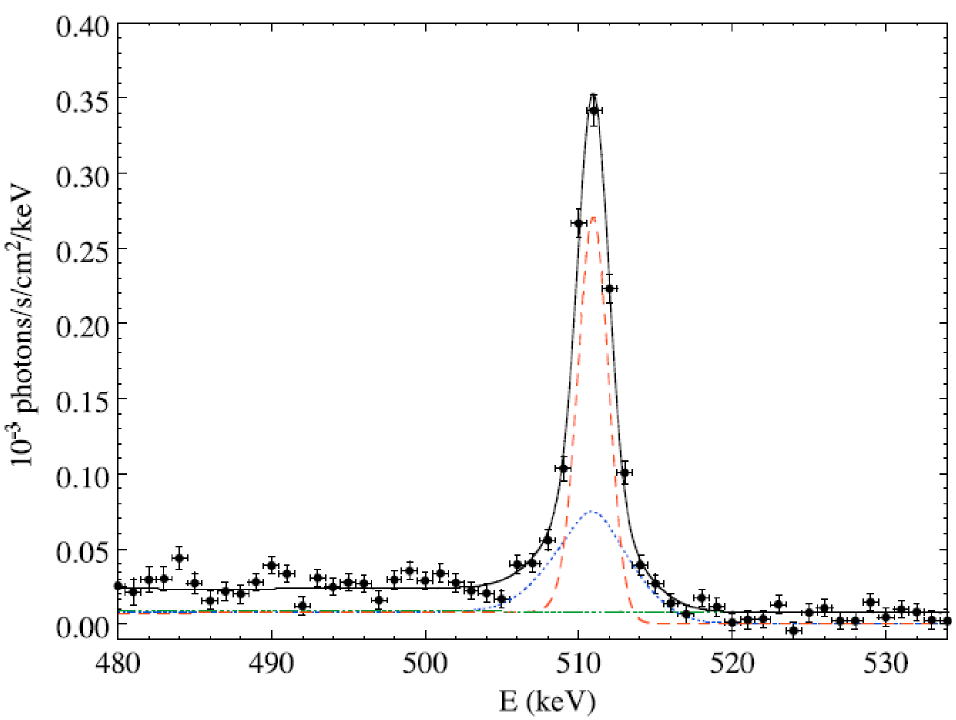


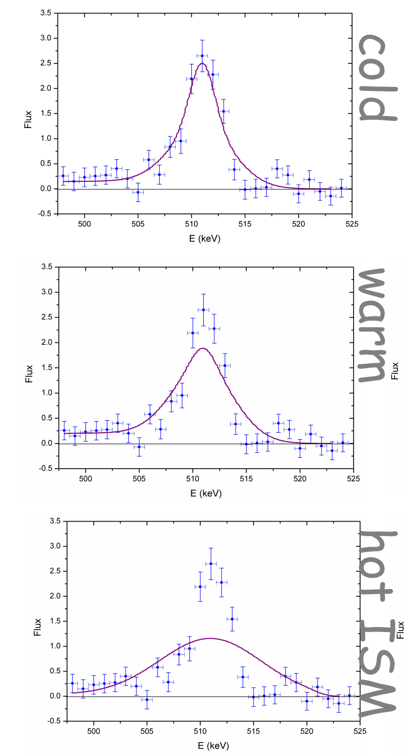
☞ **^{60}Fe/^{56}Fe isotope ratio in current ISM = 1.5 10^{-7}**

– **using M_{ISM}=4.95 10^9 $M_\odot$ and SAD 7.5 and M_{26Al}=2.25 $M_\odot$ → M_{60Fe}~1.2 $M_\odot$**

e⁺ Annihilation Conditions and the Line Width

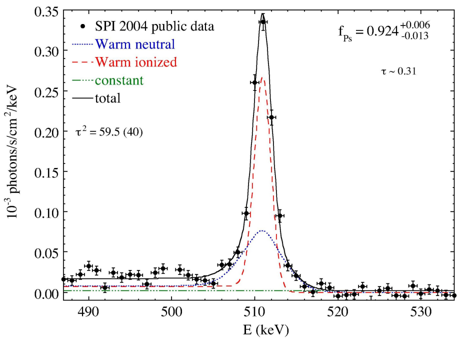
- ☆ e⁺ annihilation → 511 keV photons (+continuum)
- ☆ **Annihilation Environments:**
  - ☞ In-Flight -> broad line
  - ☞ Hot ISM -> broad line
  - ☞ Warm&Cold ISM -> narrow line
  - ☞ On Dust Grains -> narrow line

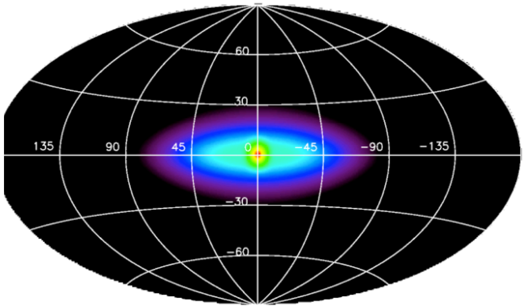


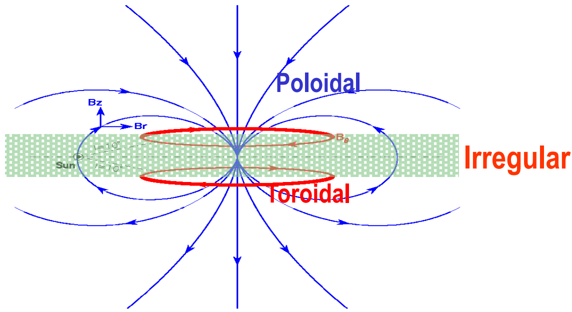


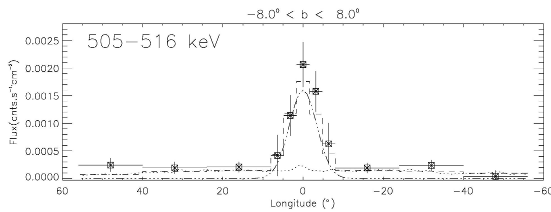
Galactic Positron Annihilation: Summary

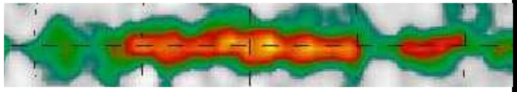
- ☆ **Annihilation γ-Rays are a New Astronomical Domain / Window**
- ☆ **Galactic-Disk Emission: More-than-enough Sources, probably Nucleosynthesis; Bulge Emission: a Puzzle**
- ☆ **Positron Transport and Annihilation Environment Diagnostics → Cosmic-Ray and ISM Astrophysics**
- ☆ **Spatial Profile of 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**

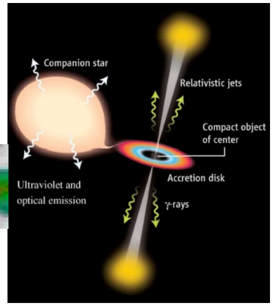




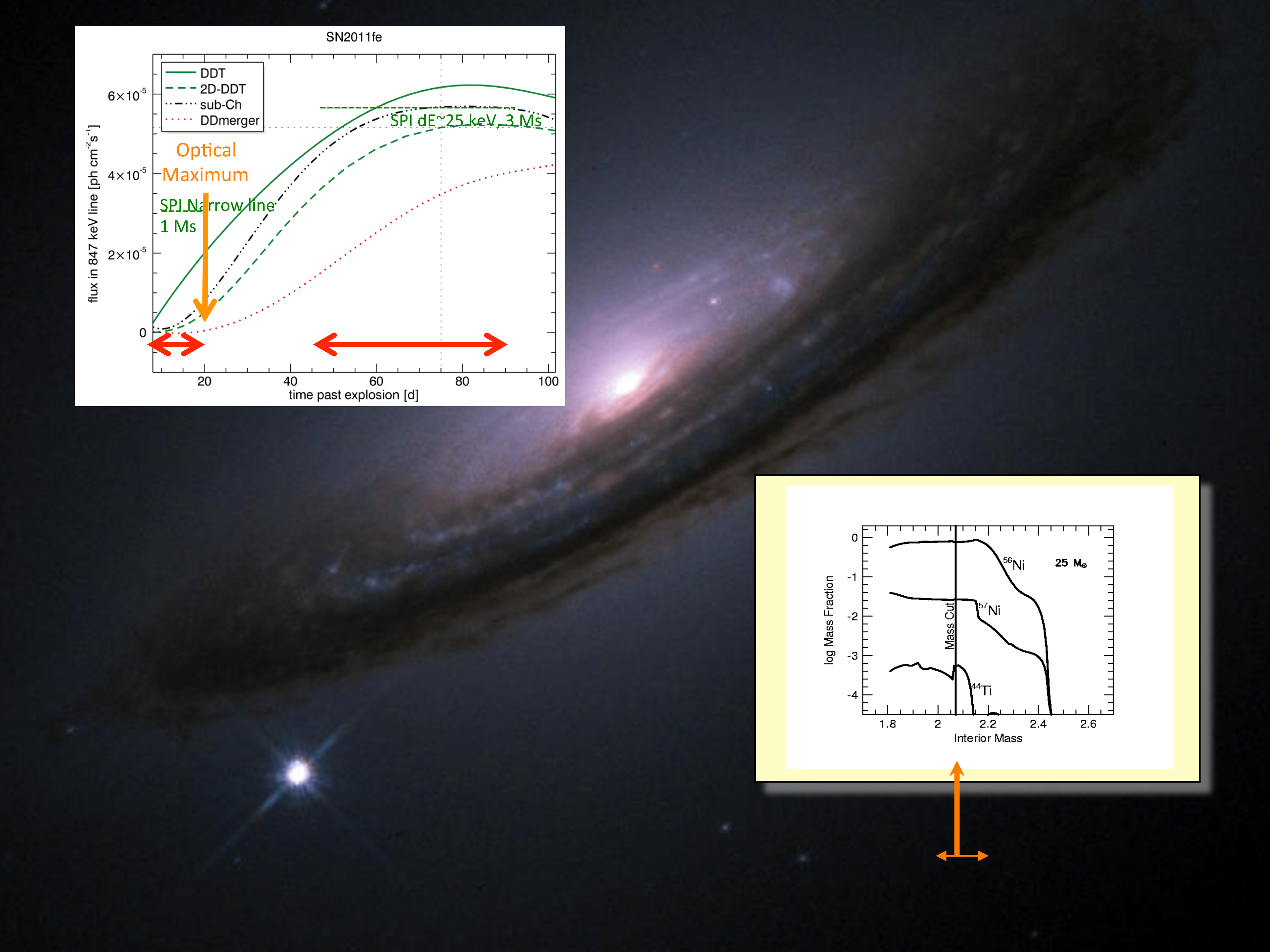




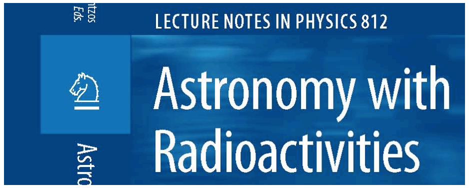




Roland Diehl

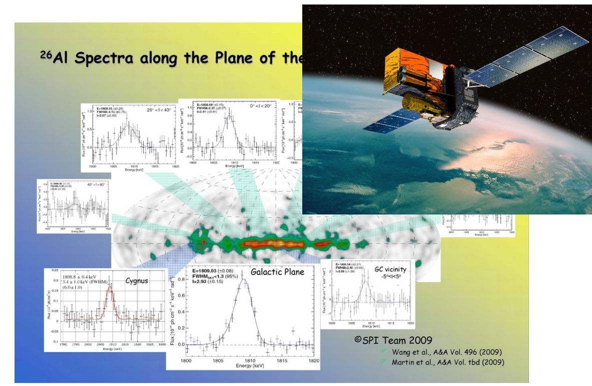


SN2011fe
DDT
2D-DDT
sub-Ch
DDmerger
6×10^-5
4×10^-5
2×10^-5
0
flux in 847 keV line [ph cm^-2 s^-1]
Optical
Maximum
SPI Narrow line
1 Ms
SPI dE~25 keV, 3 Ms
20
40
60
80
100
time past explosion [d]
0
-1
-2
-3
-4
log Mass Fraction
56Ni
25 M⊙
57Ni
Mass Cut
44Ti
1.8
2
2.2
2.4
2.6
Interior Mass

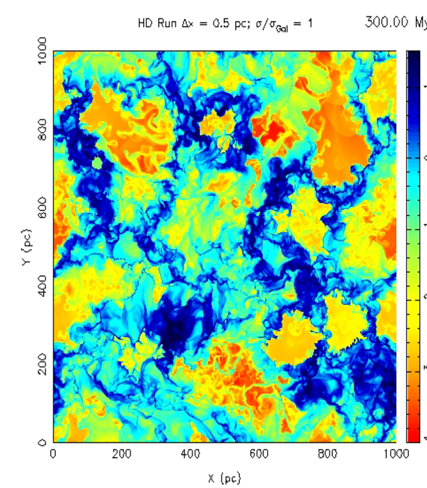


Ge Spectroscopy of Cosmic Radioactivities
Summary

- ☆ **Radioactivity provides a unique / different astronomical tool**
  - ☞ **Intensity change only due to radioactive decay**
  - ☞ **Thermodynamic gas state unimportant**



- ☆ **Ge provides Spectroscopy (line shapes)**
- ☆ **Supernova interiors:**
  - ☞ **SNIa brightness evolution and ^{56}Ni yield calibration**
  - ☞ **Core collapse evolution into an explosion with ^{56}Ni and ^{44}Ti production**
- ☆ **Massive-star shell structure and evolution:**
  - ☞ **^{26}Al production in core H burning and late shell burning, ^{60}Fe production in C and He shells**



- ☆ **Chemical evolution uncertainties:**
  - ☞ **ISM state and dynamics around positron sources, and around massive-star regions**