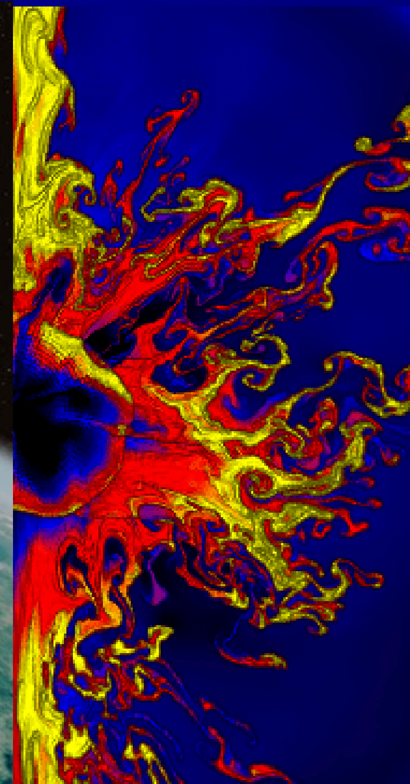
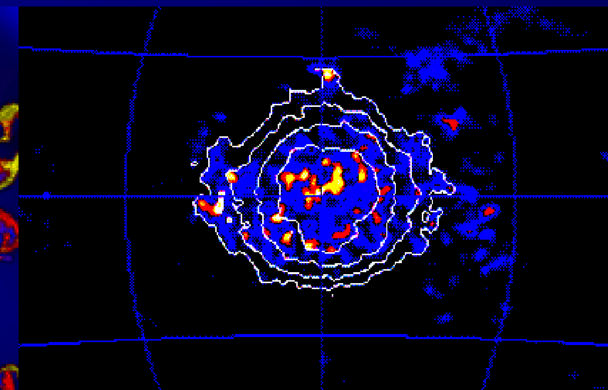
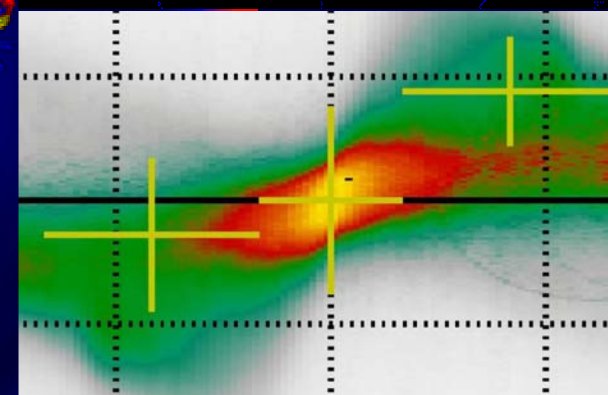
Nuclear Astrophysics with Gamma-Ray Line Observations

- Cosmic Gamma-Ray Spectroscopy Measurements and their Interpretations -

by Roland Diehl (MPE Garching, Germany)

Nucleosynthesis Sources / Study Objectives:

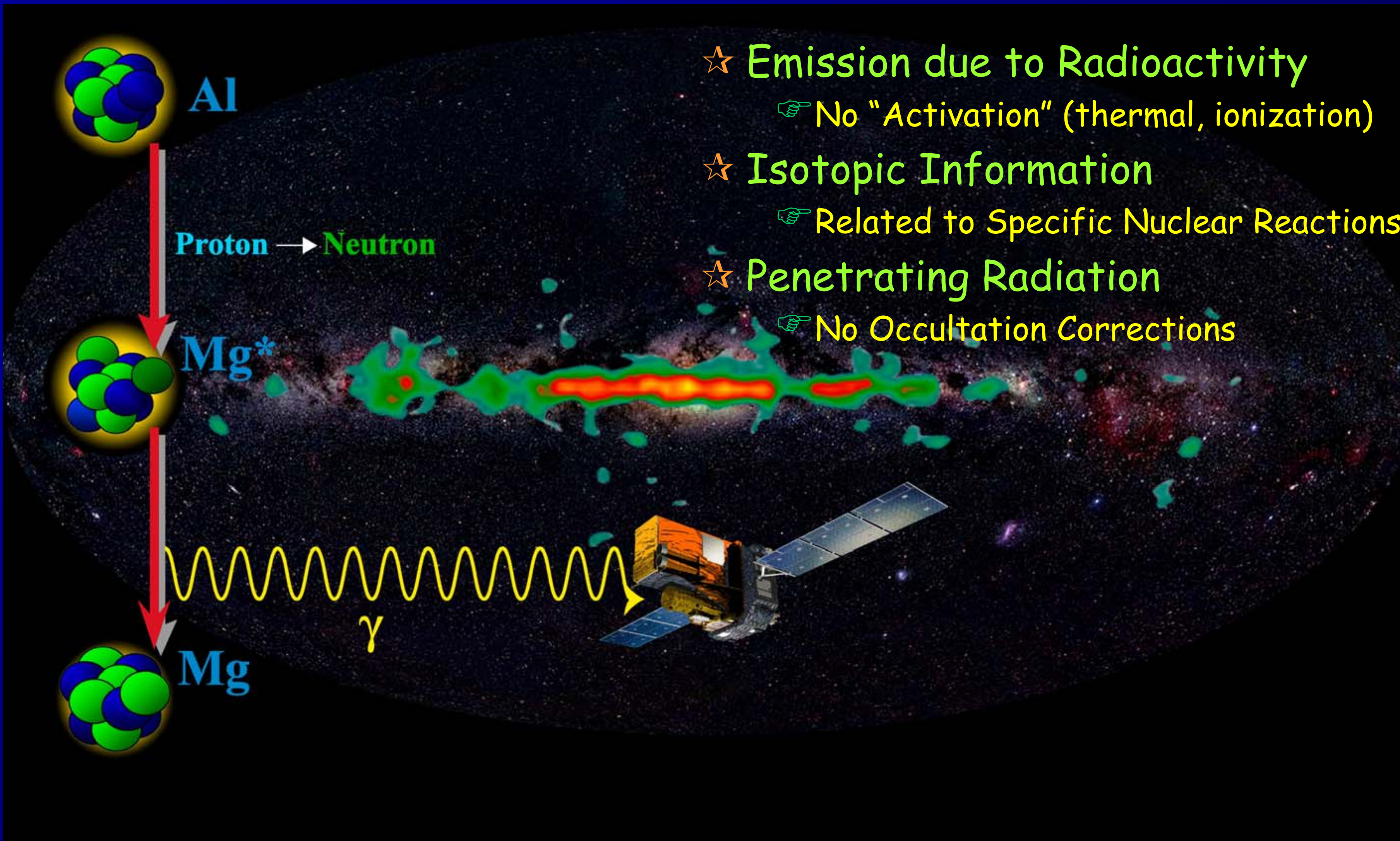
- ☆Supernovae
- ☆Massive Stars
- ☆Positrons

from work done with
H. Halloin, K. Kretschmer, A. Strong,
W. Wang (MPE), P. Jean, J. Knödlseder,
J.P. Roques, G. Weidenspointner (CESR),
C. Wunderer (UCB), H. Hartmann (CU),
& more INTEGRAL/SPI Team members

Nuclei in the Cosmos IX, CERN, 26 Jun 2006

Gamma-Rays: Messengers of Nuclear Physics
Special Characteristics:

- ☆ Emission due to Radioactivity
  - ☞ No “Activation” (thermal, ionization)
- ☆ Isotopic Information
  - ☞ Related to Specific Nuclear Reactions
- ☆ Penetrating Radiation
  - ☞ No Occultation Corrections



Gamma-Rays: Messengers of Nuclear Physics

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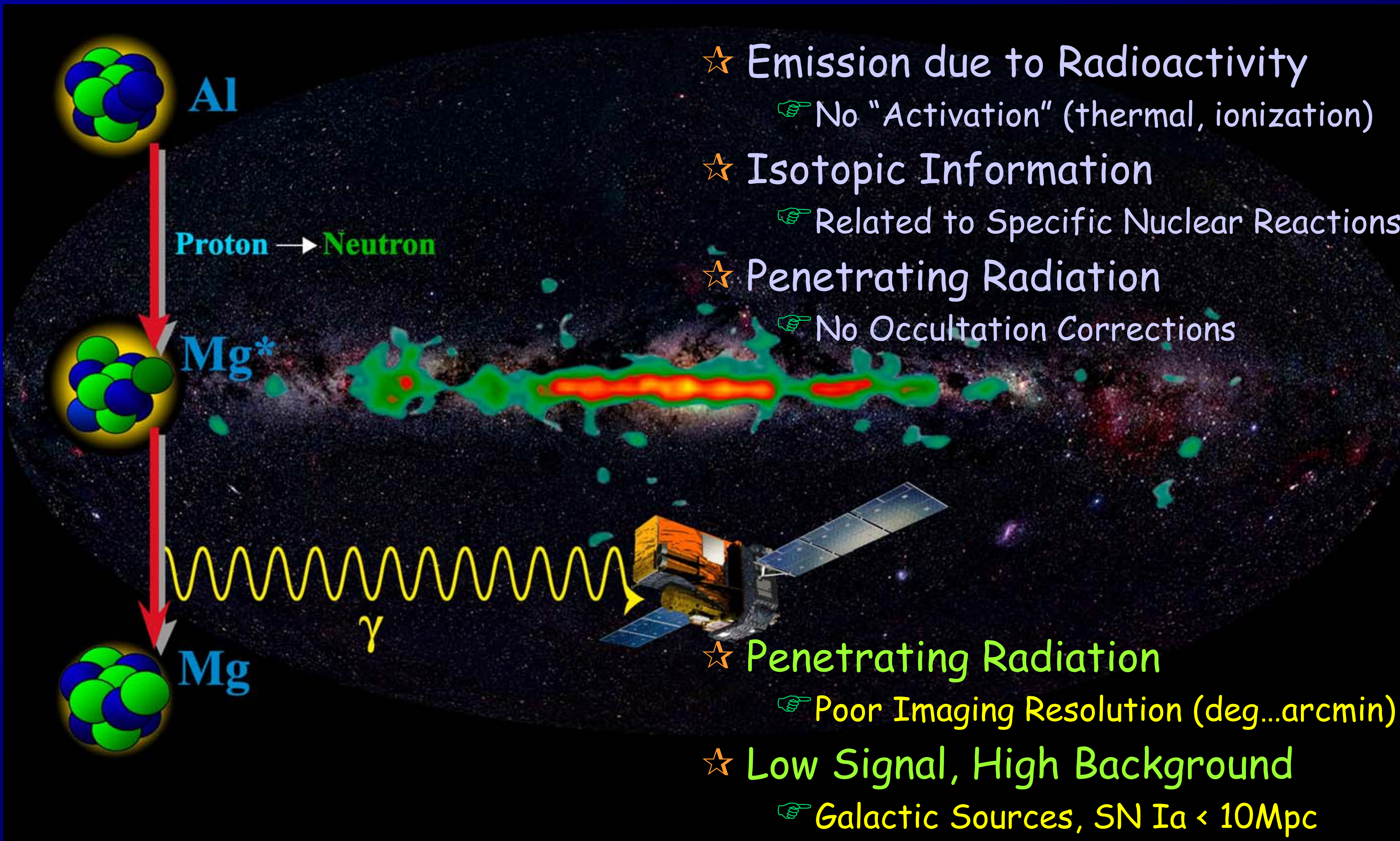

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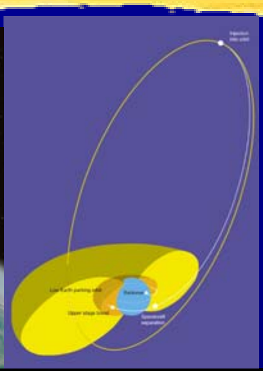
  - ☞ No Occultation Corrections
- ☆ Penetrating Radiation
  - ☞ Poor Imaging Resolution (deg…arcmin)
- ☆ Low Signal, High Background
  - ☞ Galactic Sources, SN Ia < 10Mpc

Gamma-Ray Lines for Nucleosynthesis Studies

- Radioactive Trace Isotopes as Nucleosynthesis By-Products
- For Gamma-ray Spectroscopy We Need:
  - Decay Time > Source Dilution Time
  - Yields > Instrumental Sensitivities

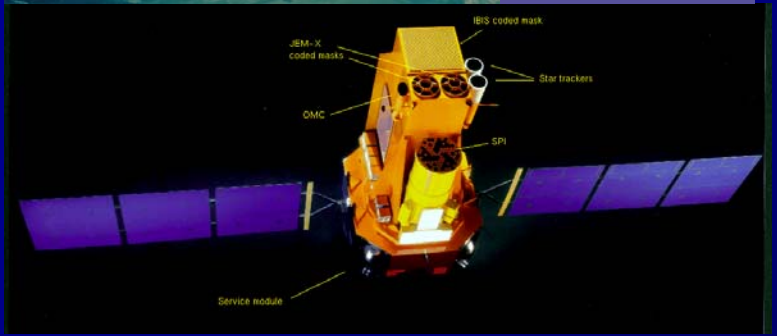
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	85 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	$2.0\ 10^{6}$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

INTEGRAL: Ge Spectrometer Works in Space!



17 October 2002:

06:41 Launch of Integral from Baikonur / Kasachstan

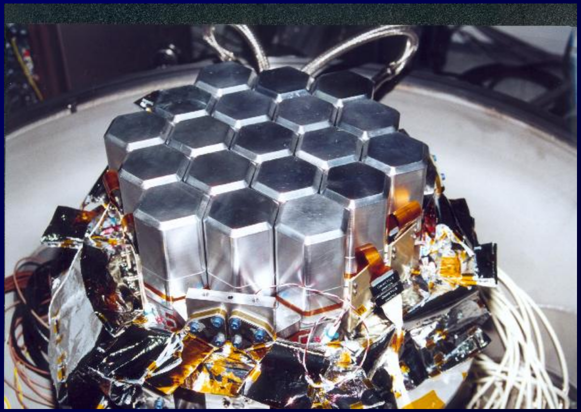


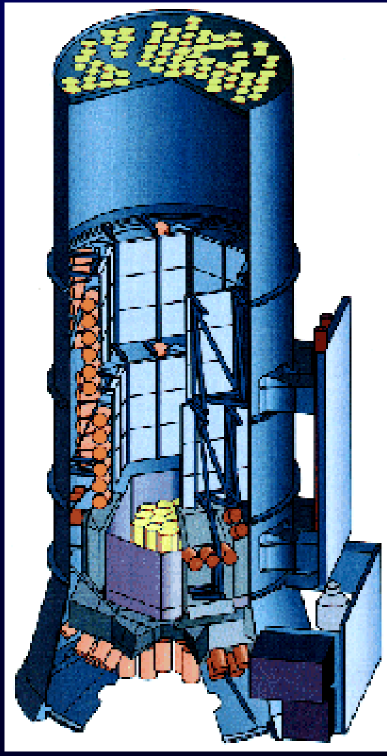
SPI: Coded-Mask Telescope 15-8000 keV

Energy Resolution ~2.2 keV @ 662 keV

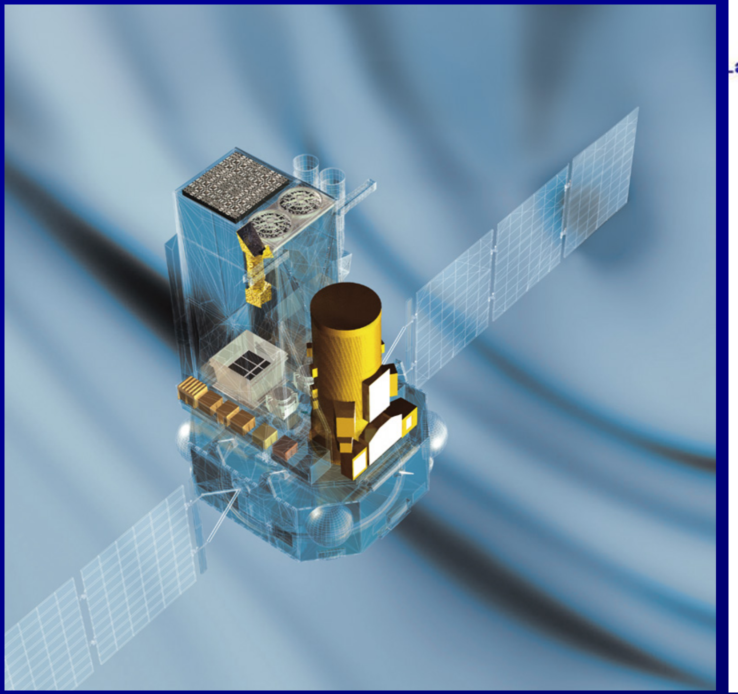
Spatial Precision 2.6° / ~2 arcmin

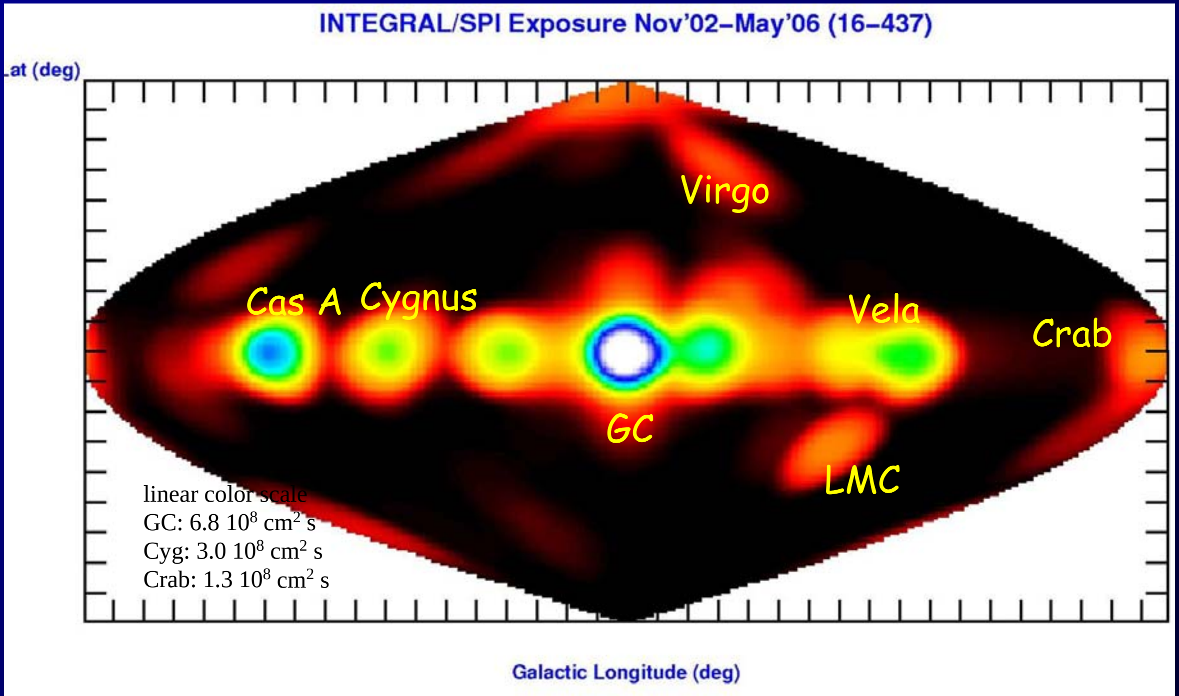
Field-of-View 16x16°





INTEGRAL Observations & Mission Status



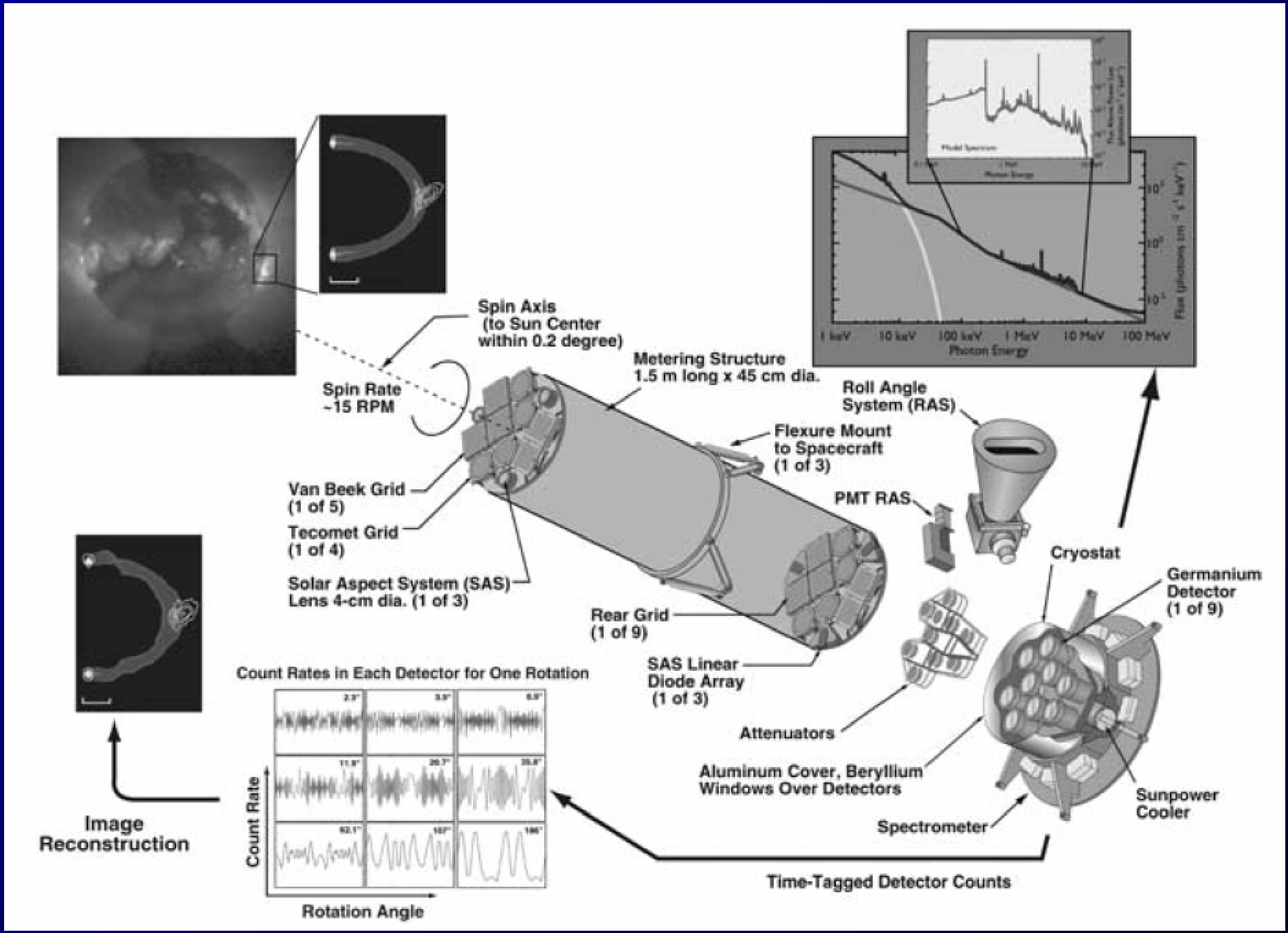


Status Today (Summer 2006):

- ☆ No Major Failures
- ☆ Diversity of Science Results
- ☆ ESA-approved Mission Horizon: 2008 (…>2010)

RHESSI:
The Ramaty High-Energy Solar Spectroscopic Imager

- ☆ Launch 5 Feb 2002
- ☆ Science Target: Particle Acceleration Processes in Solar Flares
- ☆ Instrumentation:
  - Imaging System (Rotating Modulator)
  - Spectrometer 9 Ge Crystals
- ☆ Solar + Some Cosmic Gamma-Ray Studies
  - Earth Occultation Imaging

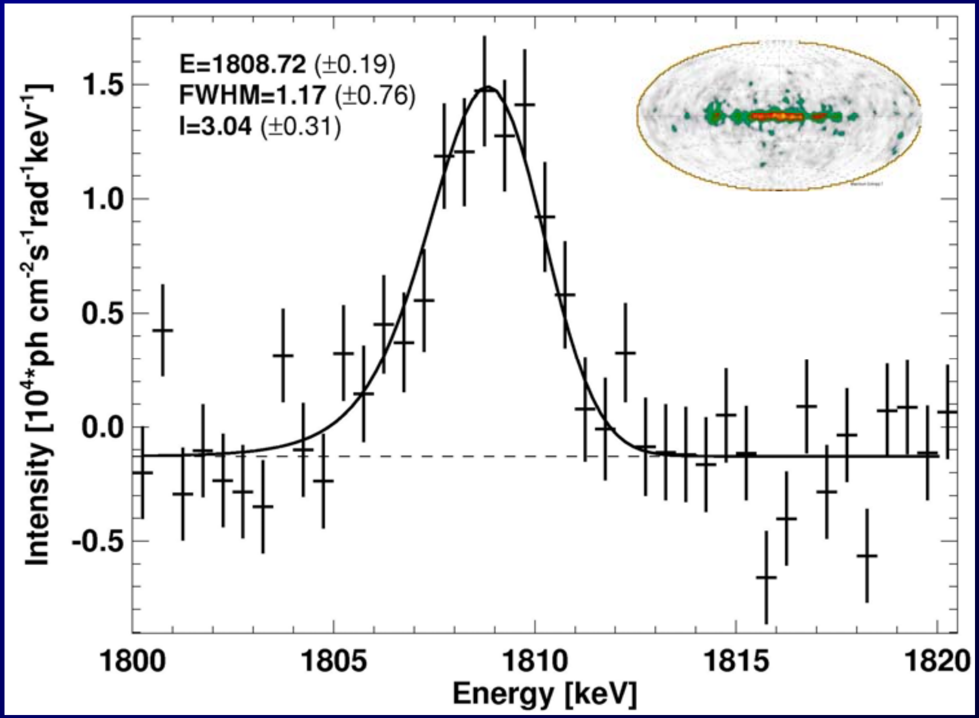


- PI: R.P. Lin
- Collaboration UCB, PSI, GSFC, ETH, ...
- NASA SMEX Mission

Result Summary

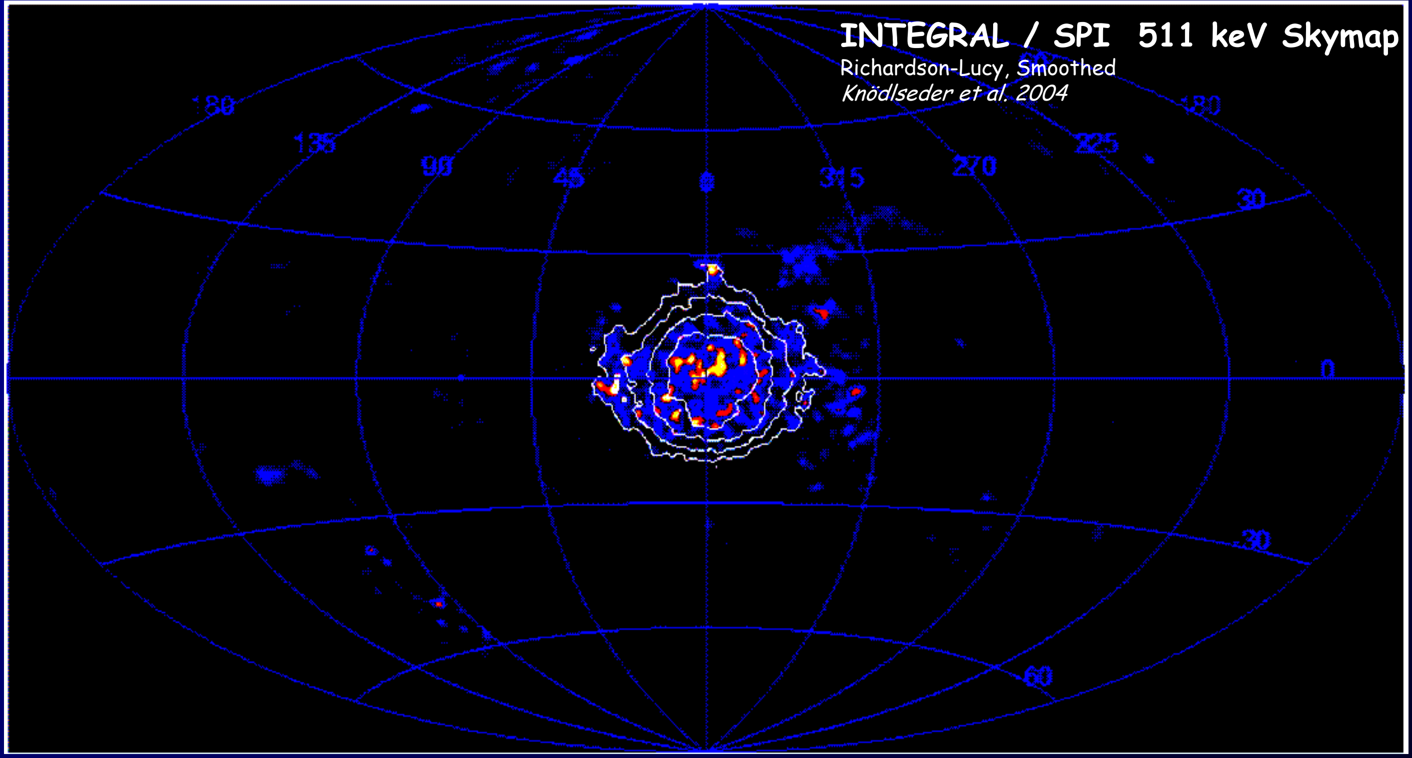
Spectra of ^{26}Al Emission Across Galactic Plane

- ☆ Galactic ^{26}Al Studies are in Progress for
  - ☞ Understanding Massive-Star Nucleosynthesis
  - ☞ Understanding Massive-Star Content & Actions in the Galaxy



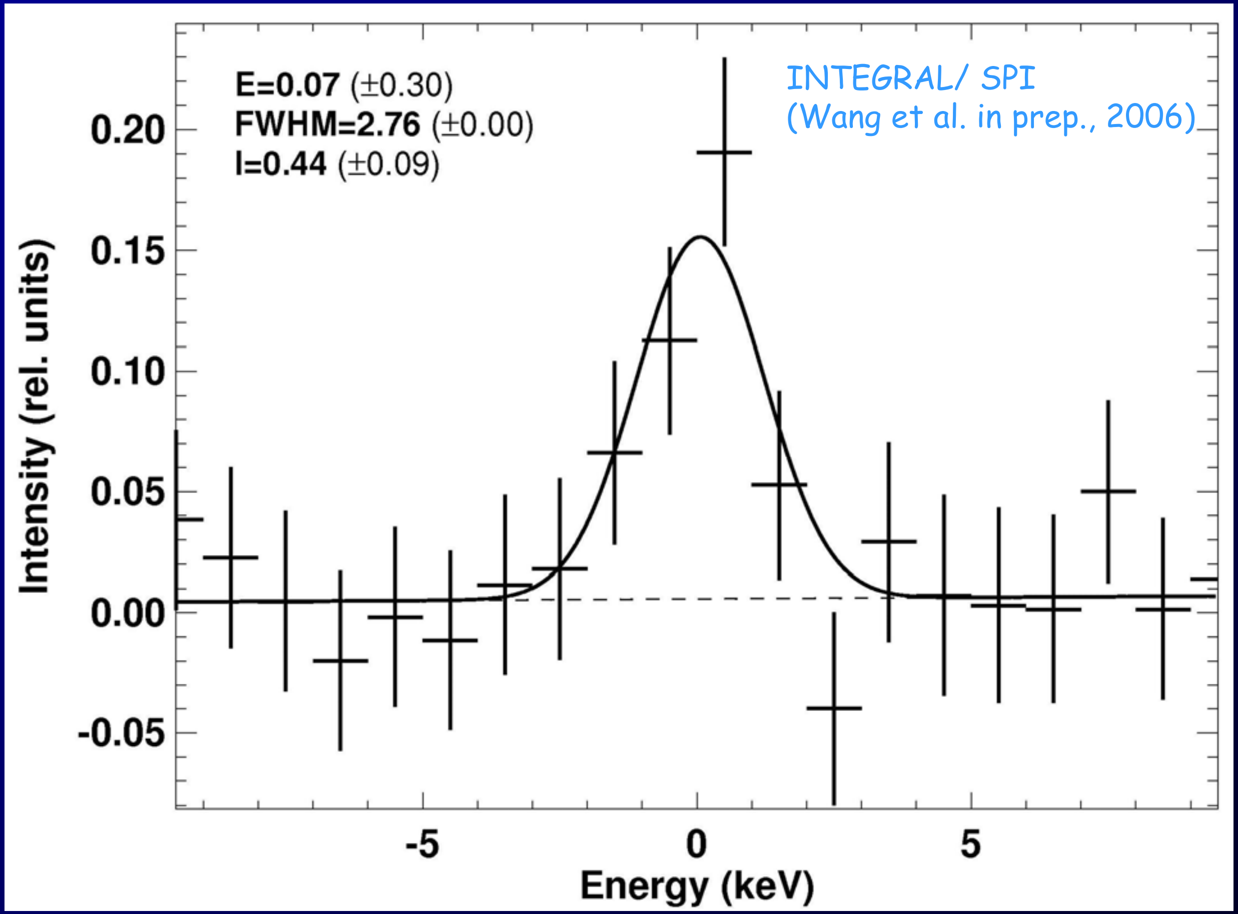
The Positron-Annihilation Sky is a Surprise

- ☆ Expected Galactic Sources of Positrons are Located Throughout the Galactic Plane and Disk
- ☆ Annihilation Gamma-rays Come Mainly from the Inner Galaxy



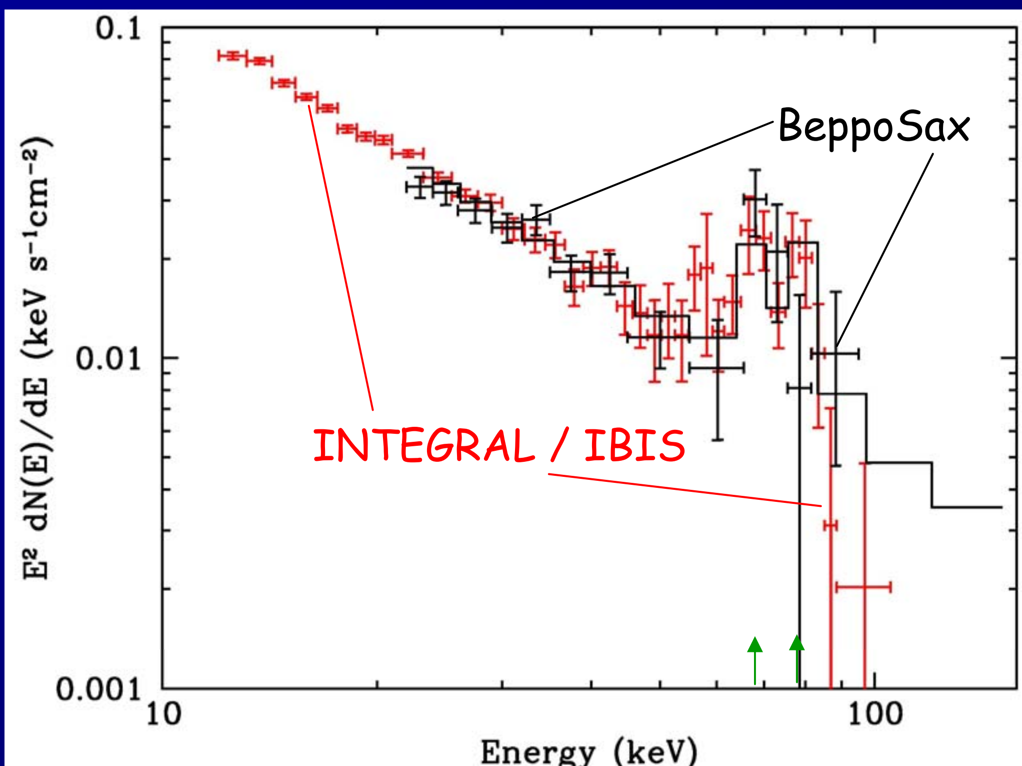
^{60}Fe Emission is Seen from the Galaxy

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



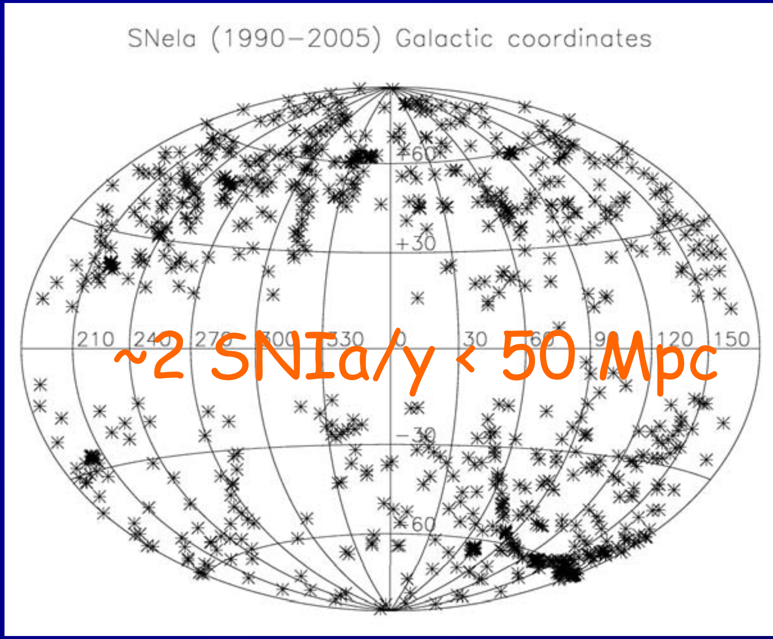
"^{44}Ti from cc-SNe" is Still an Open Issue

- ☆ Cas A is Still the Only Source Clearly Detected
- ☆ Non-Detection with SPI May Imply High ^{44}Ti Ejection Velocity

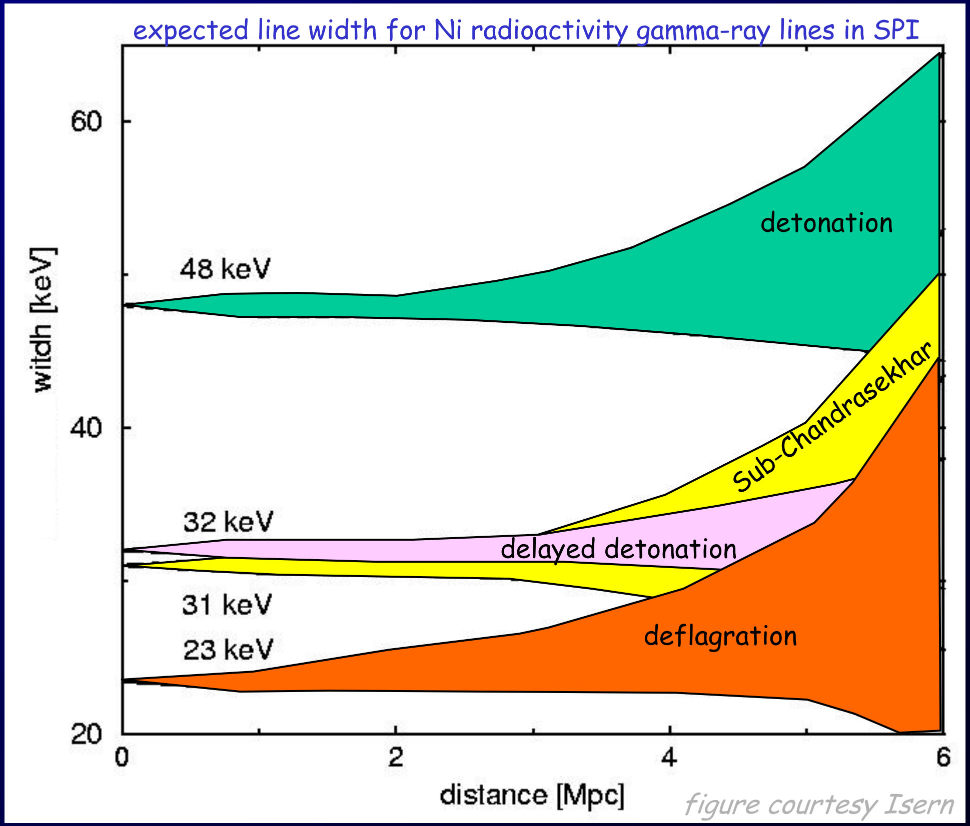


Vink et al. 2005

Still No Luck with SNIa Events

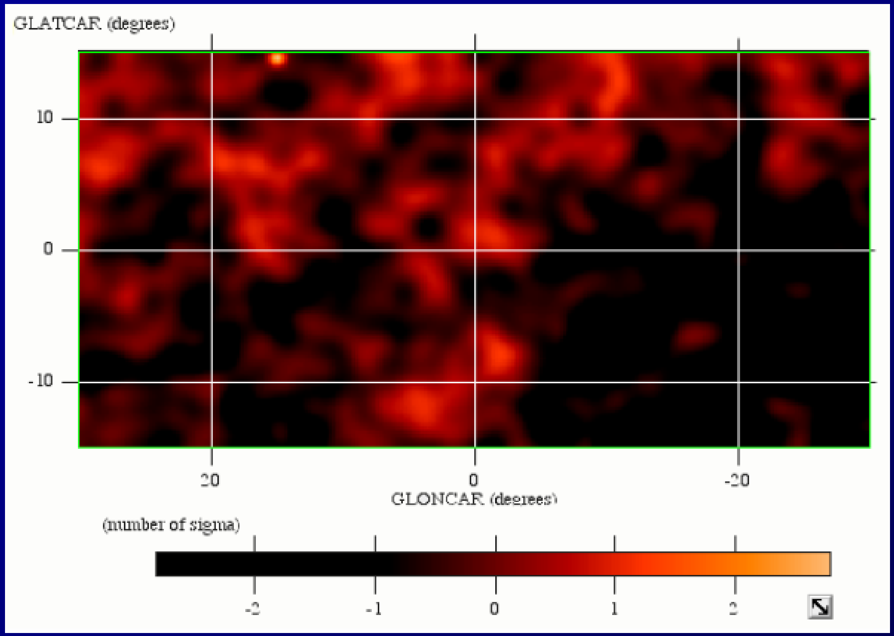


☆ Spectroscopy Can Discriminate Between Models only for Nearby (hence rare) SNe (<5 Mpc)

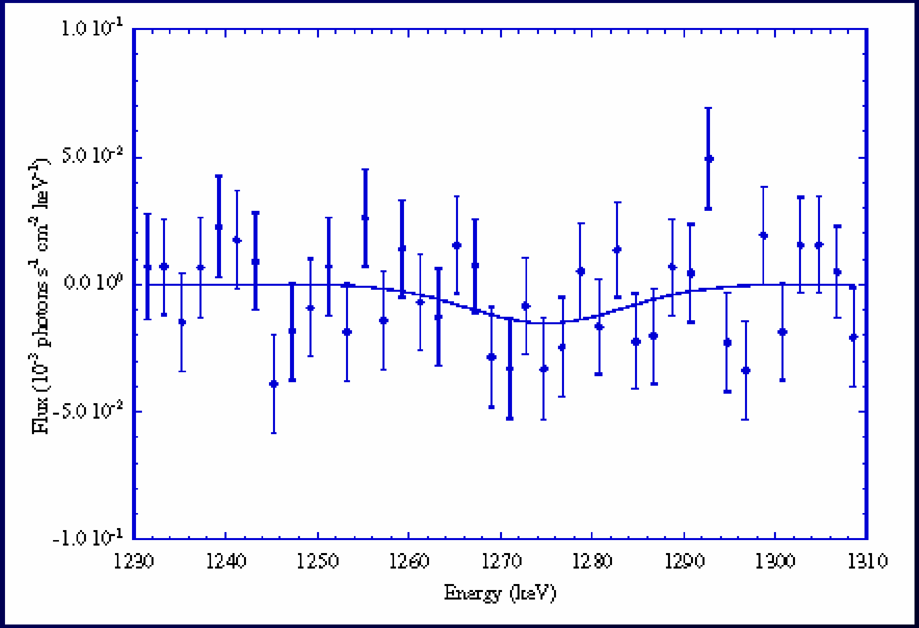


Still No Nova Lines Detected

- Expectations for I_{22Na} ~ Factor 10 Below Instrumental Sensitivities



^{22}Na Line:
SPI Galactic Bulge Skymap

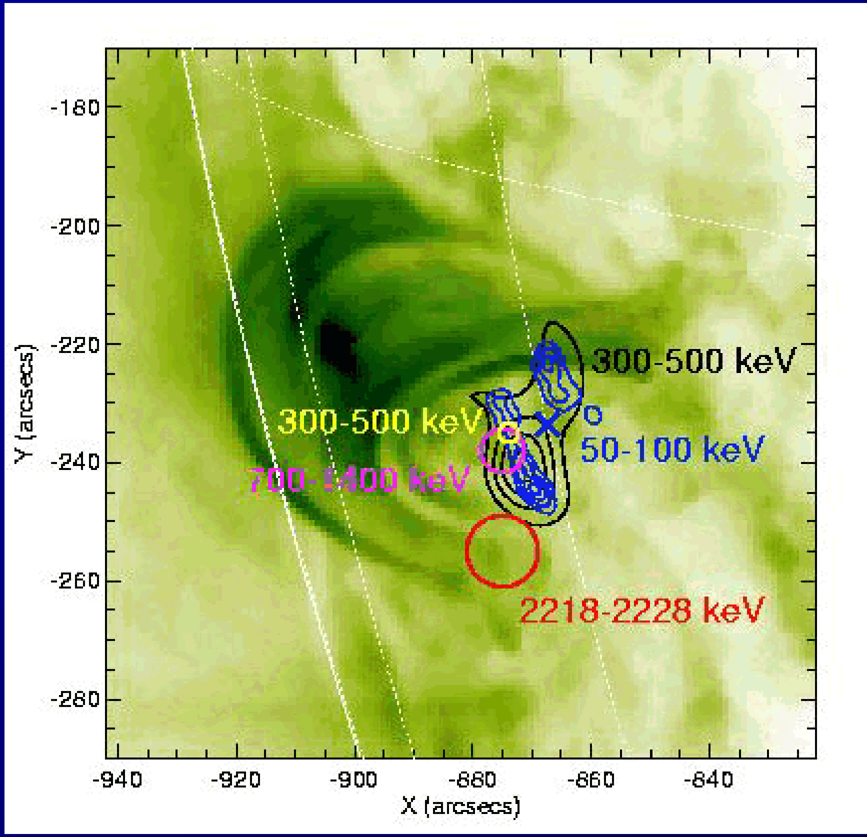


Jean et al. 2005

Testing for a Nova Galaxy Model

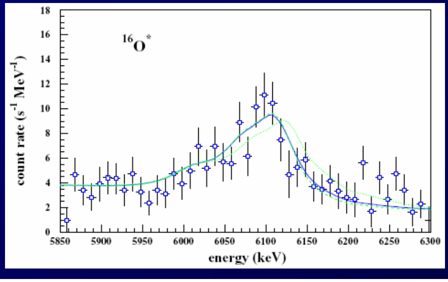
Gamma-Ray Lines Probe the Active Sun

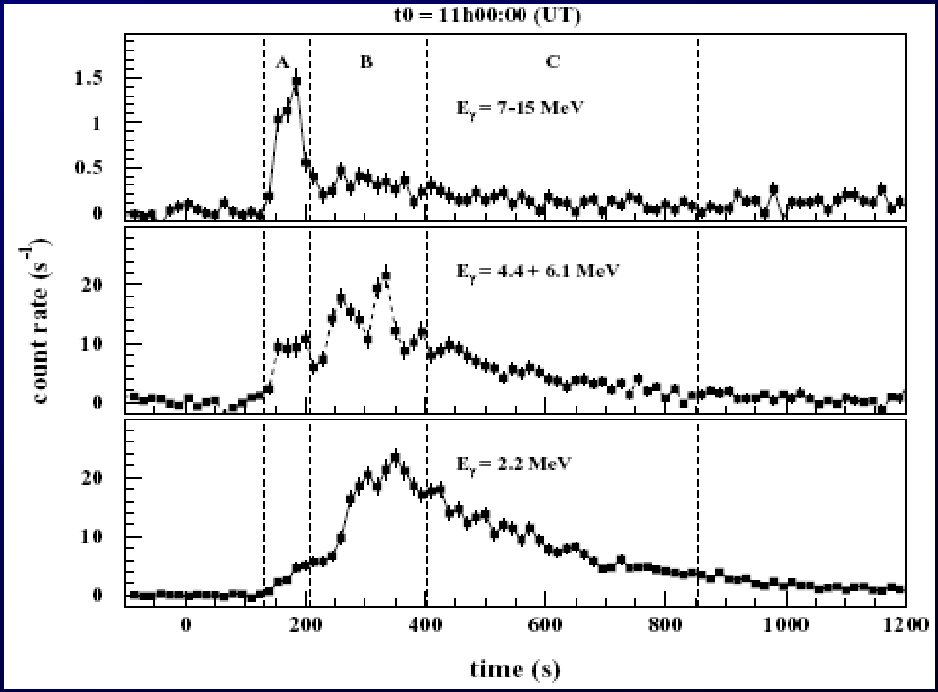
- Images of Flare Regions:
  - Different Locations for Electron and Ion Accelerations?



Hurford et al. 2003

- Temporal Evolution of Line Ratios, Line Shapes
  - Beam Geometries
  - C/O Ratio
  - ...



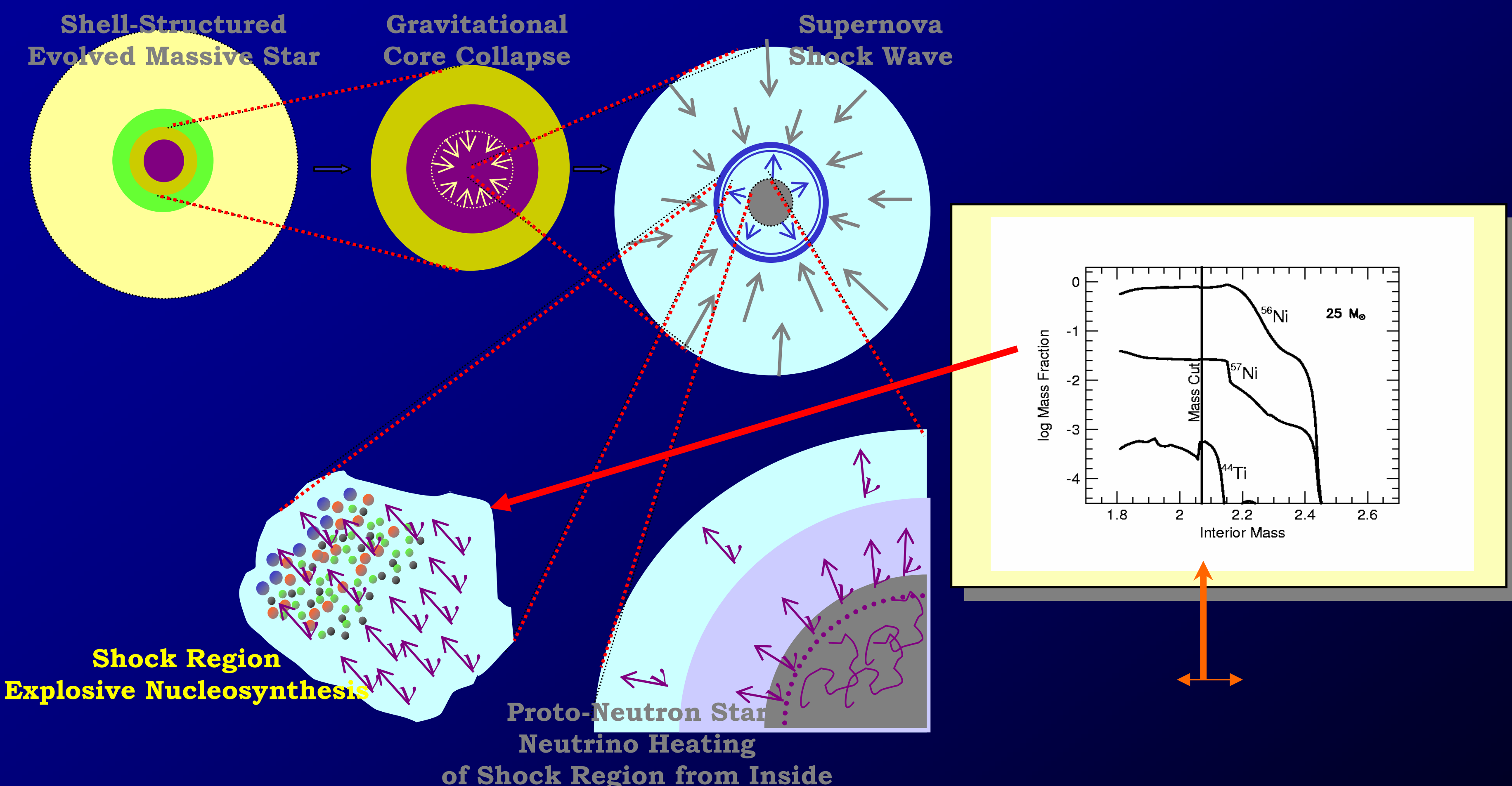


Kiener et al. 2005

Details...

(selected)

Nucleosynthesis in CC-Supernova Models and ^{44}Ti



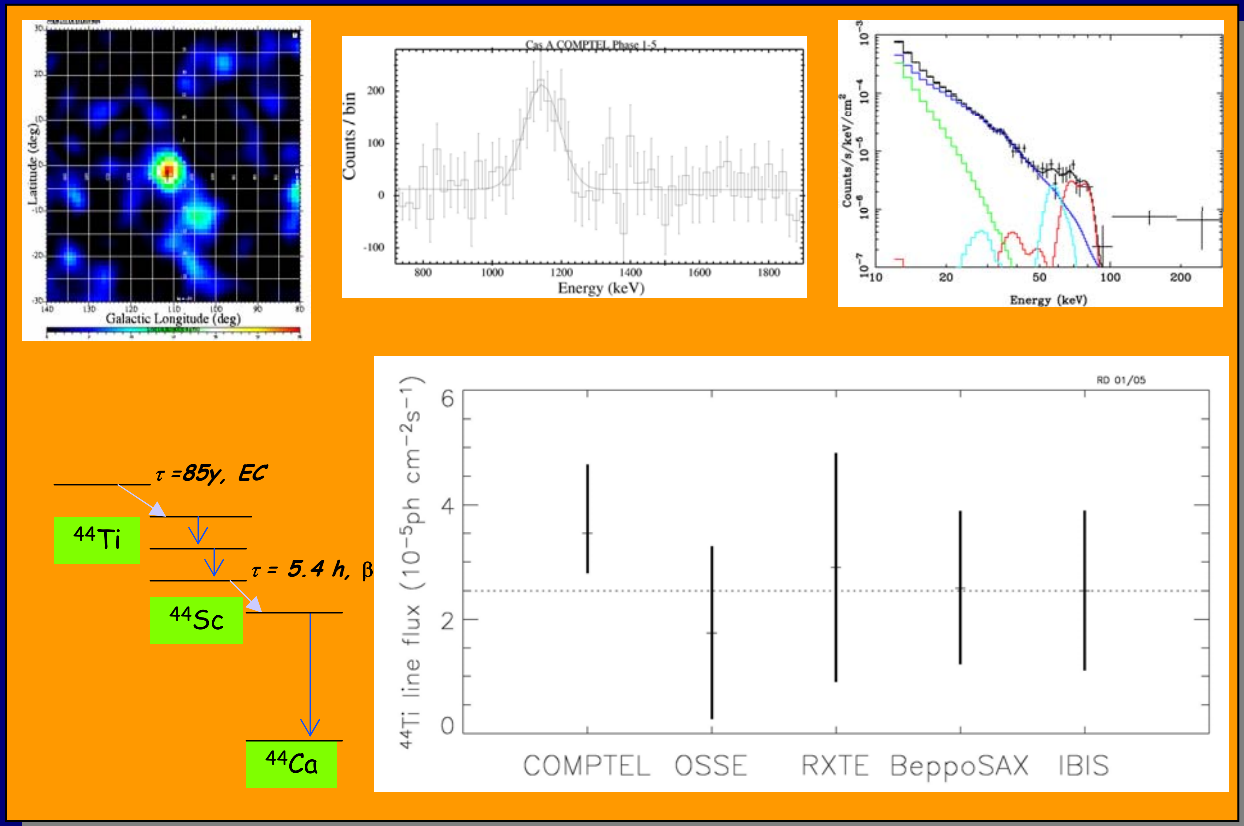
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out, => Unique Probe (+Ni Isotopes)

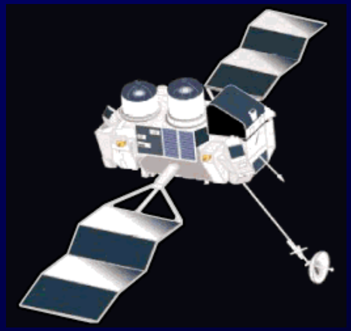
89 y	$^{44}Ti \rightarrow ^{44}Sc^* \rightarrow ^{44}Ca^* + e^+$	78, 68; 1157

^{44}Ti γ-rays from Cas A

τ=85y (Ahmad et al. 2006)

89 y	$^{44}Ti \rightarrow ^{44}Sc^* \rightarrow ^{44}Ca^* + e^+$	78, 68; 1157



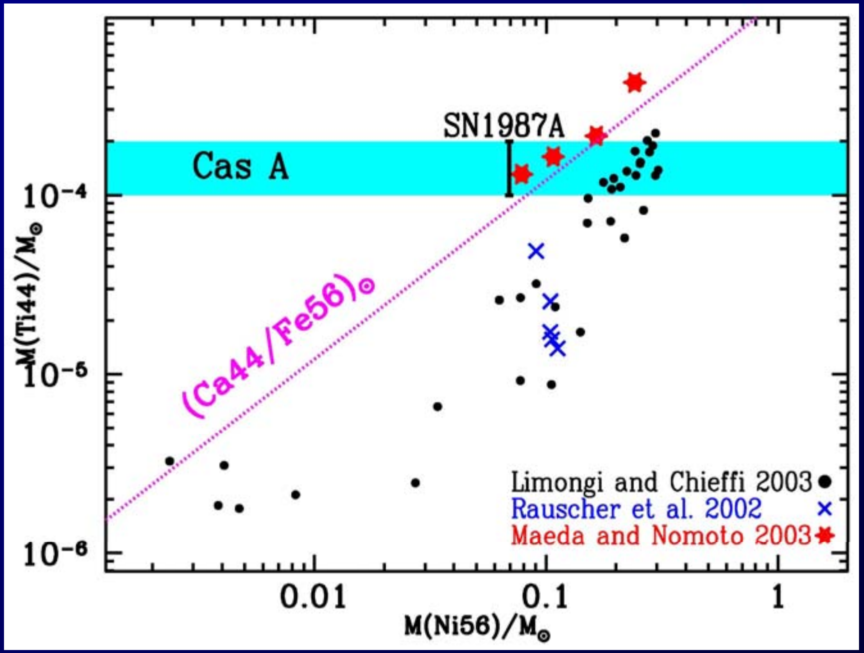


↳ ^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} M_o

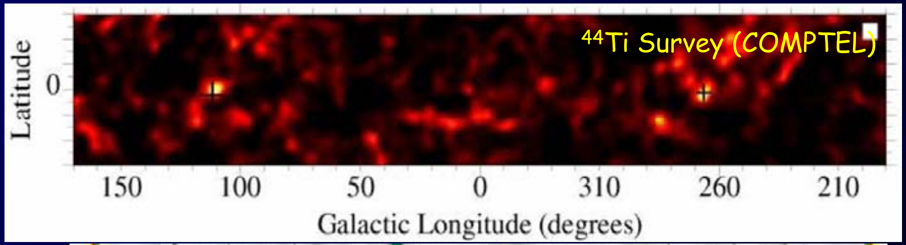
"Normal" Core Collapse Supernovae as ^{44}Ti Sources?

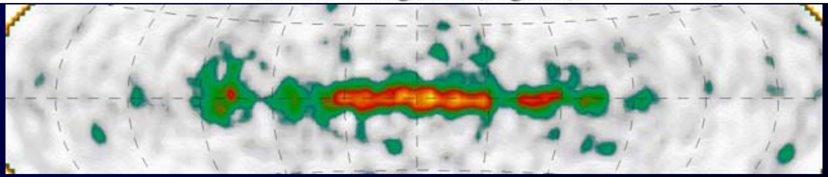
- ☆ ^{44}Ti vs. ^{56}Ni: Models compared to
  - ➢ Solar ^{44}Ca
  - ➢ SN1987A & Cas A

⇨ Only Non-Spherical Models Reproduce Observed ^{56}Ni/^{44}Ti Ratios



- ☆ Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)





"^{44}Ti from cc-SNe" is Still an Open Issue

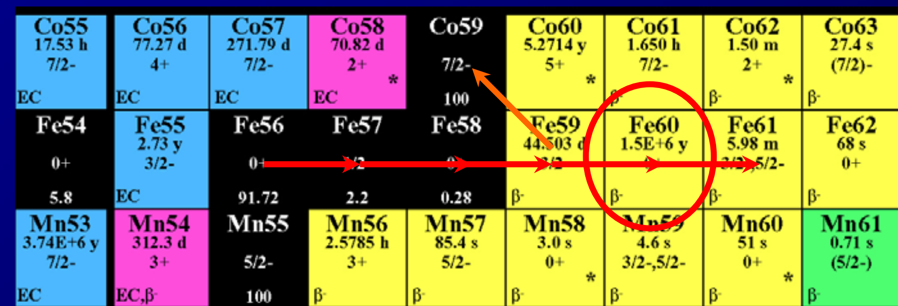
- ☆ Cas A is Still the Only Source Clearly Detected in γ-rays
  - ☞ 4 Independent Instruments
- ☆ Non-Detection with SPI May Imply High ^{44}Ti Ejection Velocity
  - ☞ Result from 3 Ms:
  - ☞ Broadened Line Would 'Drown' in SPI's Instrumental Background

Vink et al. 2005

  - ☞ (another 2.5 Ms to be analyzed)

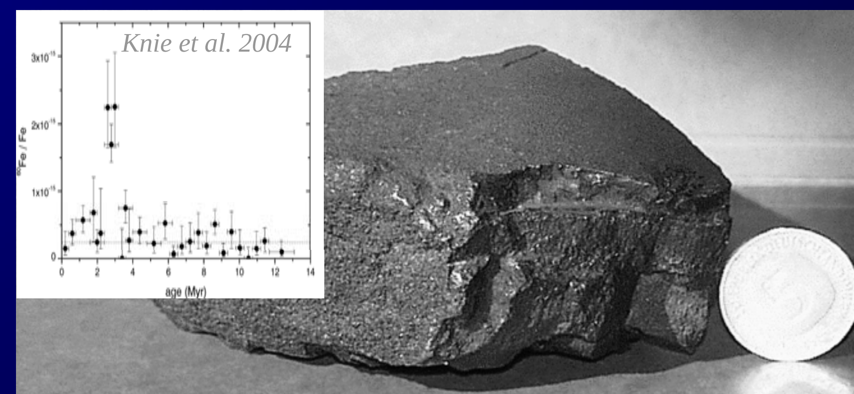
^{60}Fe: Why is it Interesting?

2.0 10^6y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332



☆ ^{60}Fe is Produced through Successive Neutron Captures

☞ r-Process Astrophysics…



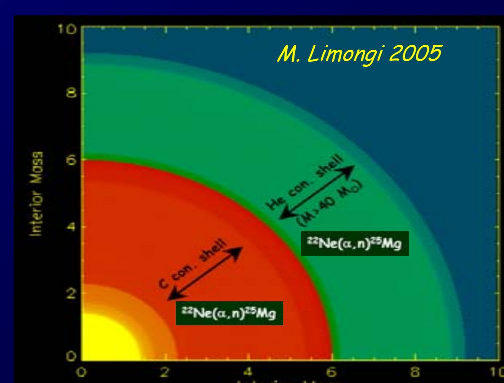
☆ ^{60}Fe has been Detected in Pacific Ocean Crust

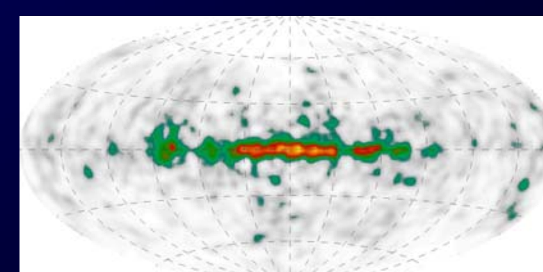
☞ Nearby SN ~2 My ago?

☆ Massive Stars are Likely Sources of ^{60}Fe

☞ Observable in the Galaxy (as ^{26}Al is)?

☞ **Compare Two Isotopes from Same Sources!**

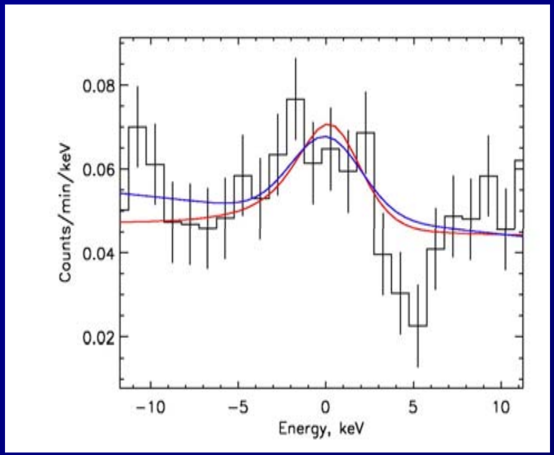


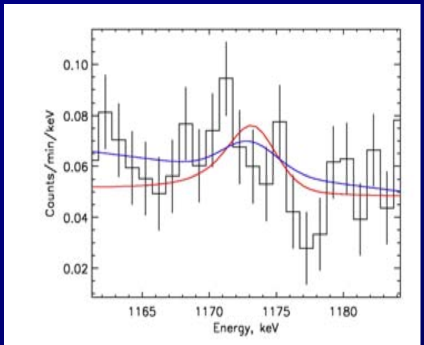


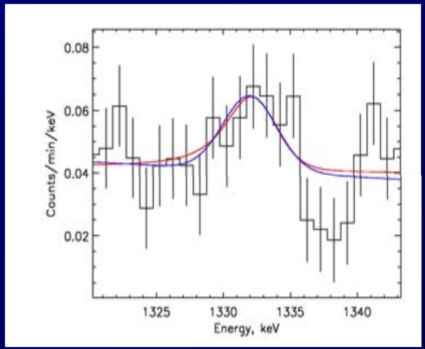
First ^{60}Fe Indications from the Galaxy with RHESSI & SPI/INTEGRAL

RHESSI

- ☆ 2.6 σ Detection
  - ☞ *Smith 2004*
- ☆ $I=0.63_{\pm 0.5}\ 10^{-4}$ ph cm^{-2} s^{-1}
  - ☞ *Smith 2005*

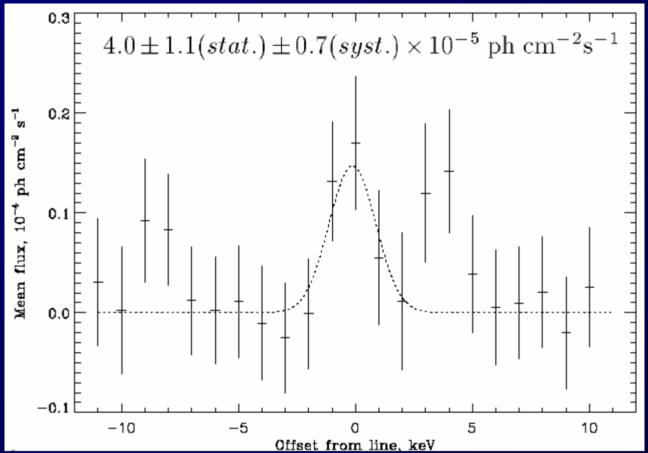


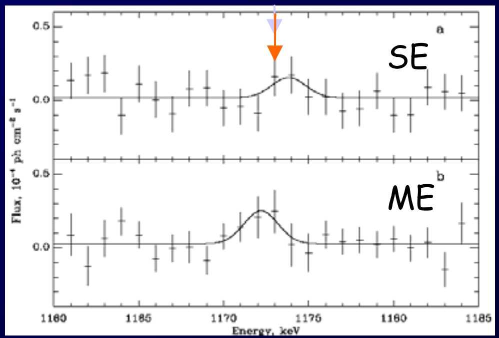


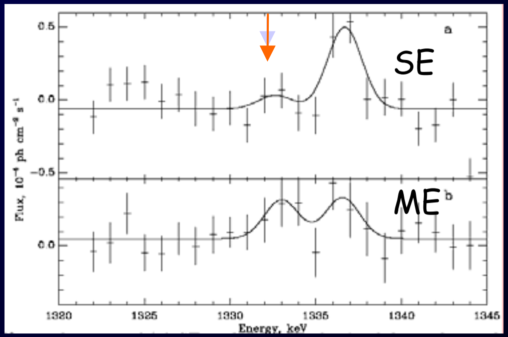


SPI

- ☆ 3 σ Detection
- ☆ $I=0.4_{\pm 0.2}\ 10^{-4}$ ph cm^{-2} s^{-1}
  - ☞ *Harris et al. 2005*

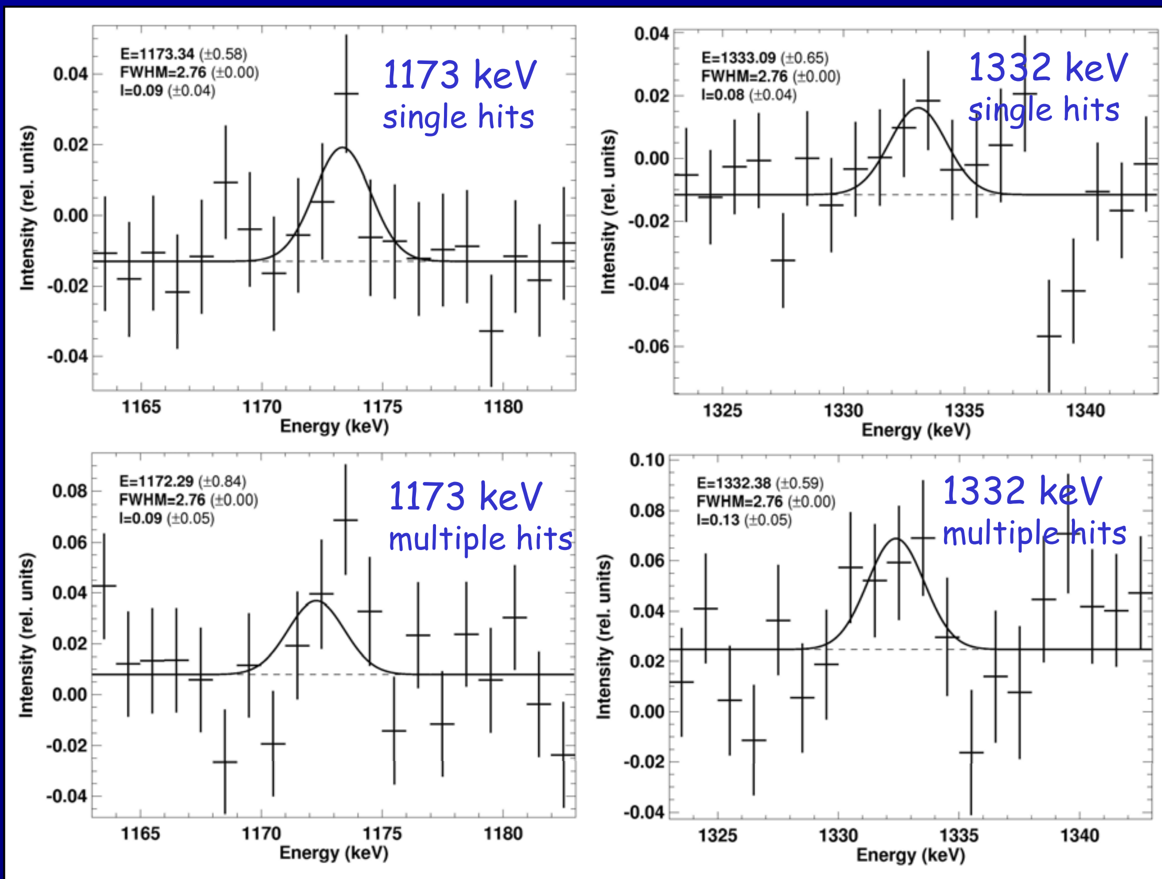


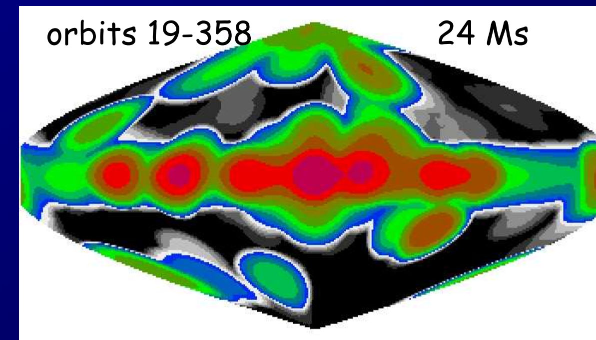


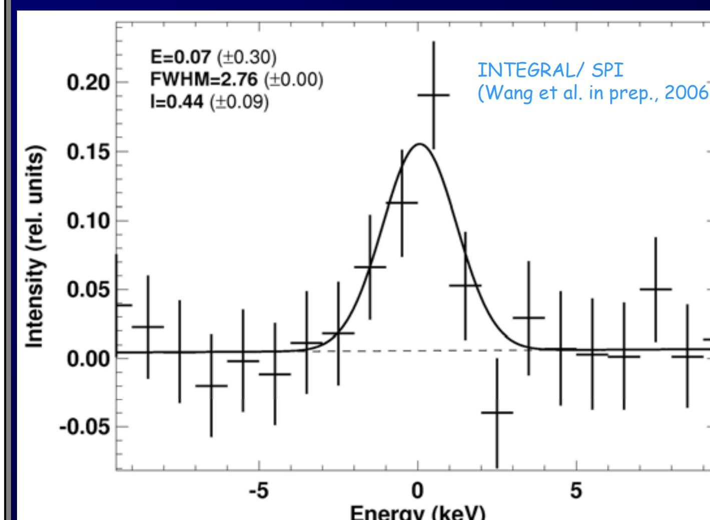


^{60}Fe Gamma-Rays: SPI Update

June 2006





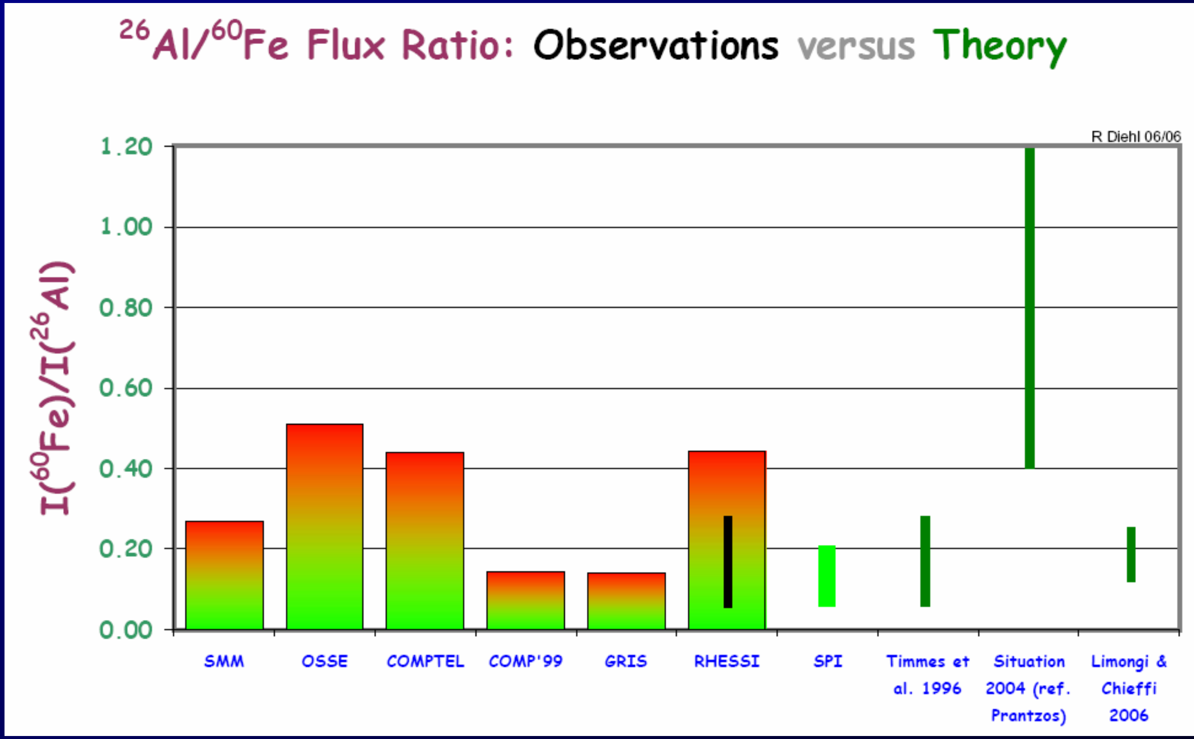


- ☆ Four independent measurements ⇨ 4.9 σ significance (combined)
- ☆ Reduced systematics from instrumental lines
- ☆ ^{60}Fe/^{26}Al γ-ray Intensity Ratio 14.8 (±6) %

^{60}Fe from Massive Stars: Observations vs. Theory

2.0 10^6y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332

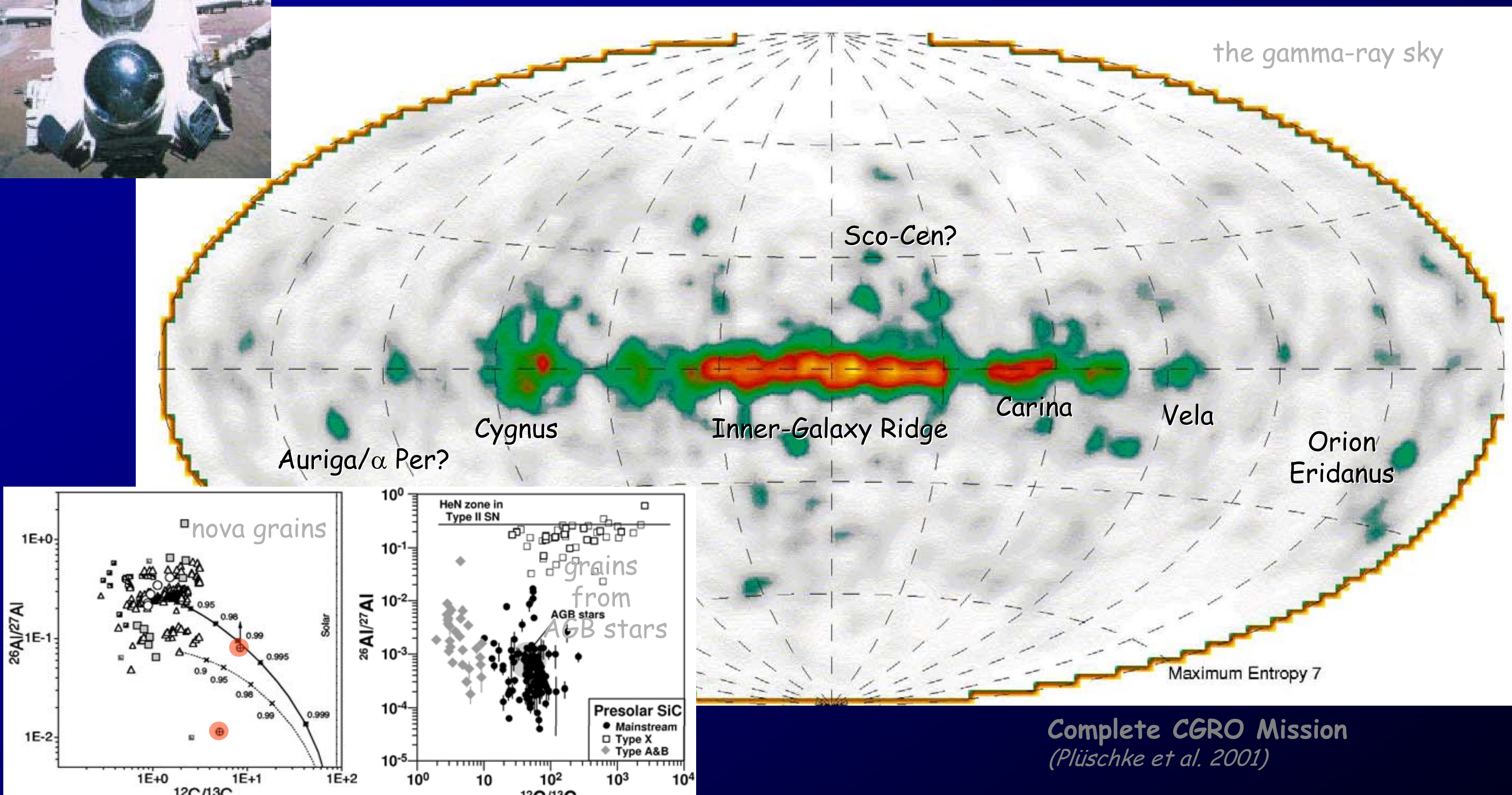
- ☆ **Improved Models Agree with Data on $^{60}Fe/^{26}Al$ γ-Ray Intensity Ratio**
  - ☞ **But: Uncertainties are Large**
    - ☞ Marginal / Non-Imaging Detections -> Ratio <0.3; Massive Stars?
    - ☞ Revised Yields Had Led to Higher Predicted Ratios ~1.0
    - ☞ Revised Stellar Models Again Reduced Predicted Ratios



- ☆ Assessments Needed:
  - ☞ Stellar Models
  - ☞ Nuclear Physics
  - ☞ Gamma-Ray ^{60}Fe Signal Origin

^{26}Al in the Galaxy: Massive-Stars… and more

1.04 10^6y	$^{26}Al \rightarrow ^{26}Mg^* + e^+$	1809



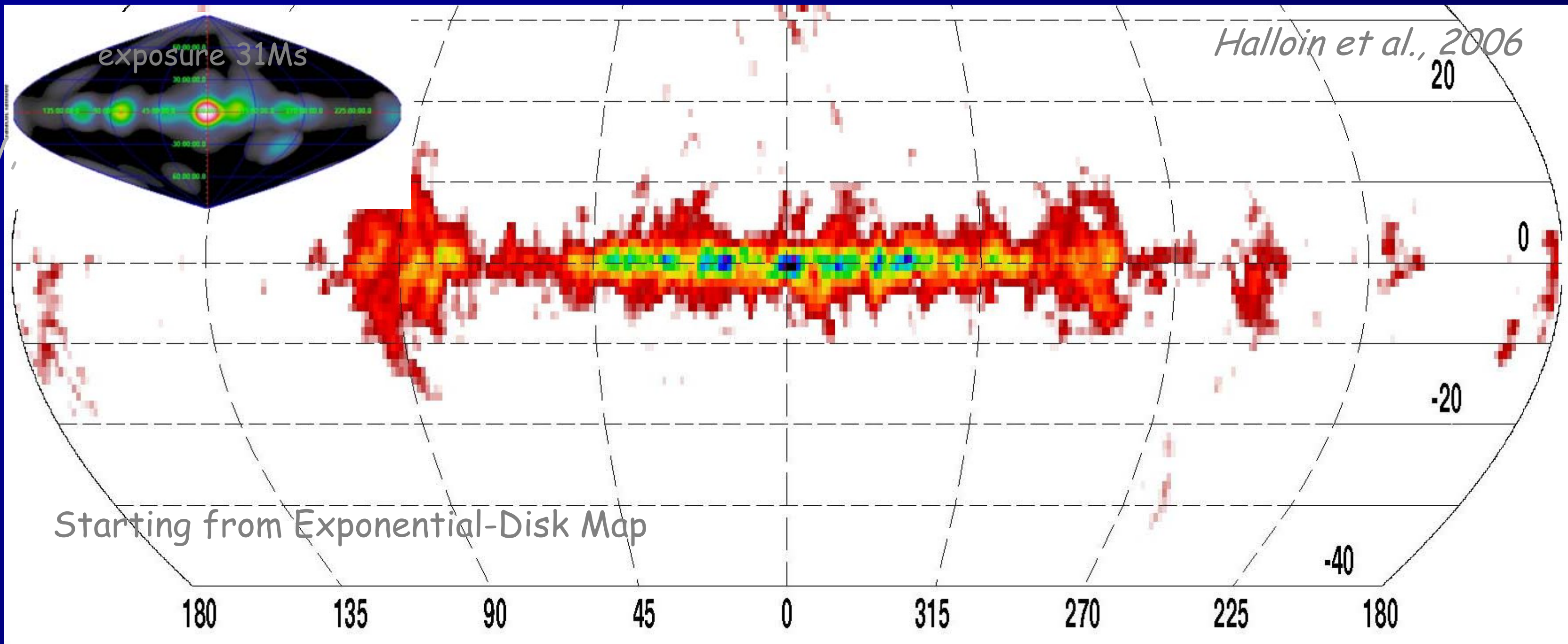
Complete CGRO Mission
(Plüschke et al. 2001)

Imaging the ^{26}Al Sky with SPI

RL Imaging Method

1805-1811 keV, SE+DE

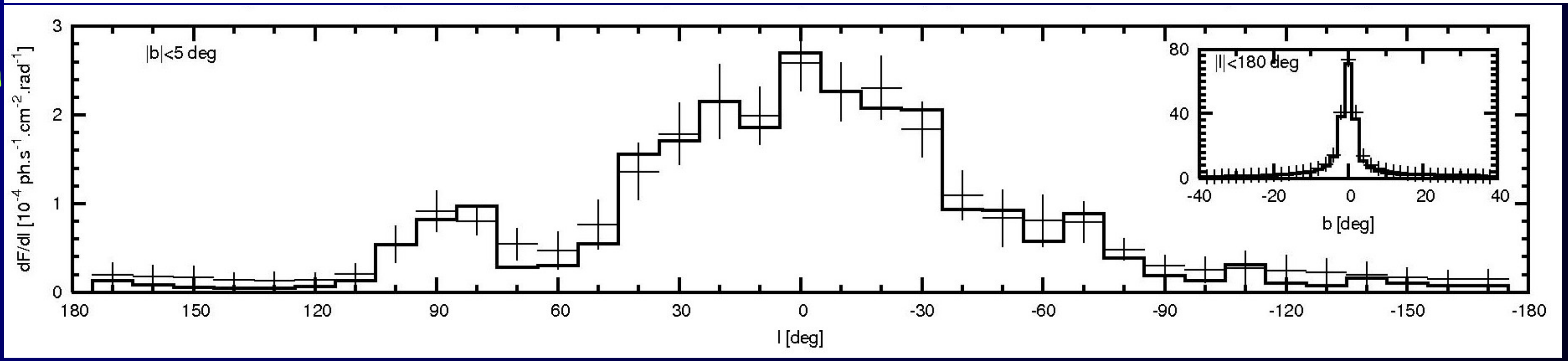
Bgd from orthog. Tracers



Extended inner-Galaxy Ridge

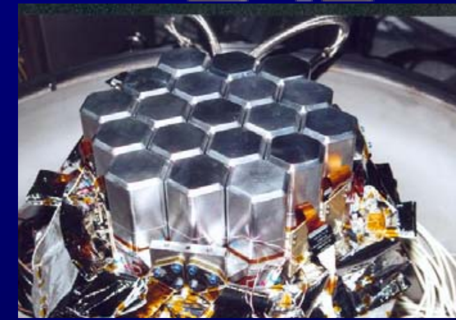
Cygnus Region

4th Quadrant Slightly Brighter than 1st

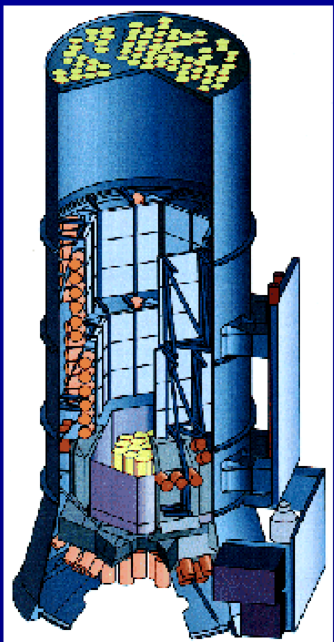


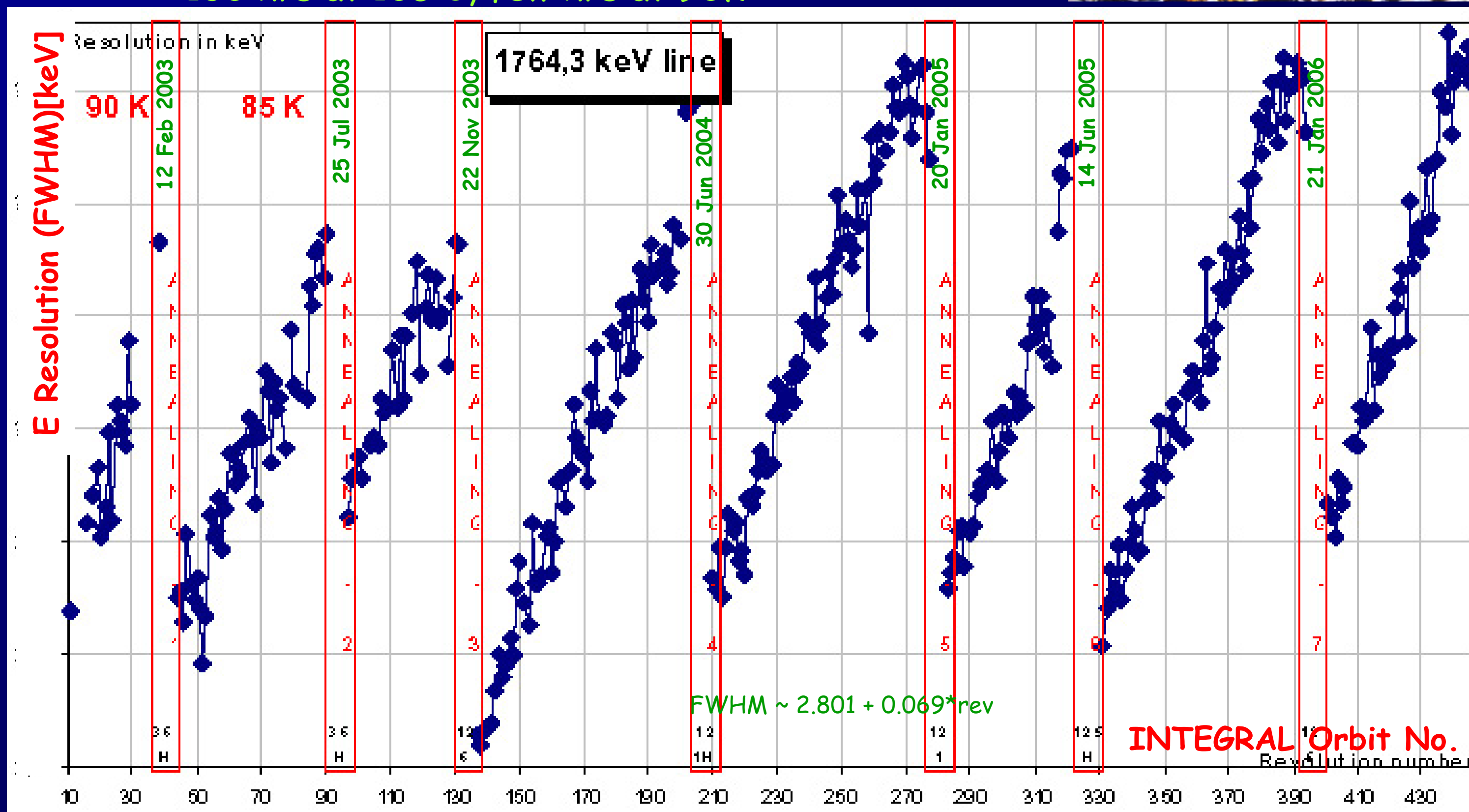
Roland Diehl

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



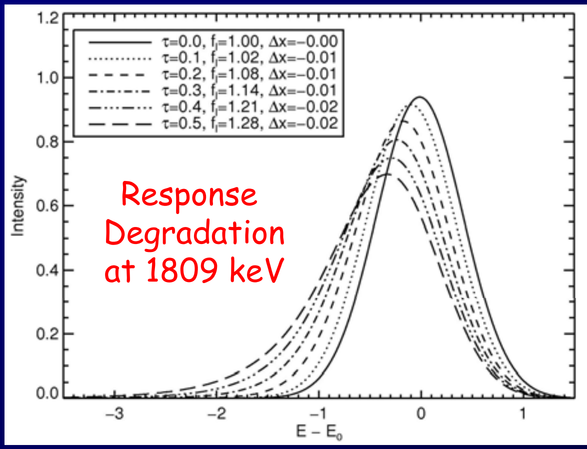
- Cosmic-Ray Bombardement -> Crystal Degradation
  - ~2% per Orbit, ~20% in 6 Months (@1 MeV)
- Annealing
  - ~130 hrs at 105°C, few hrs at 90K

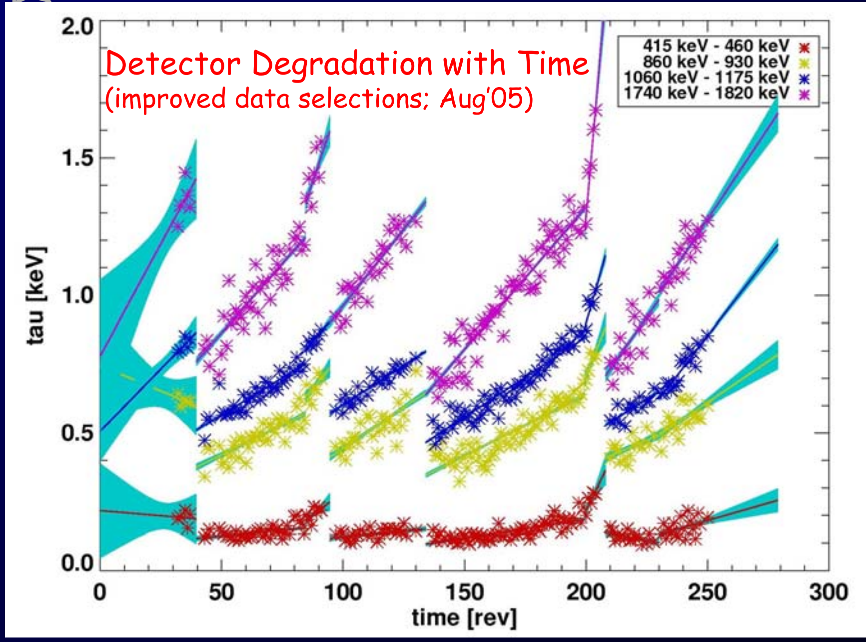


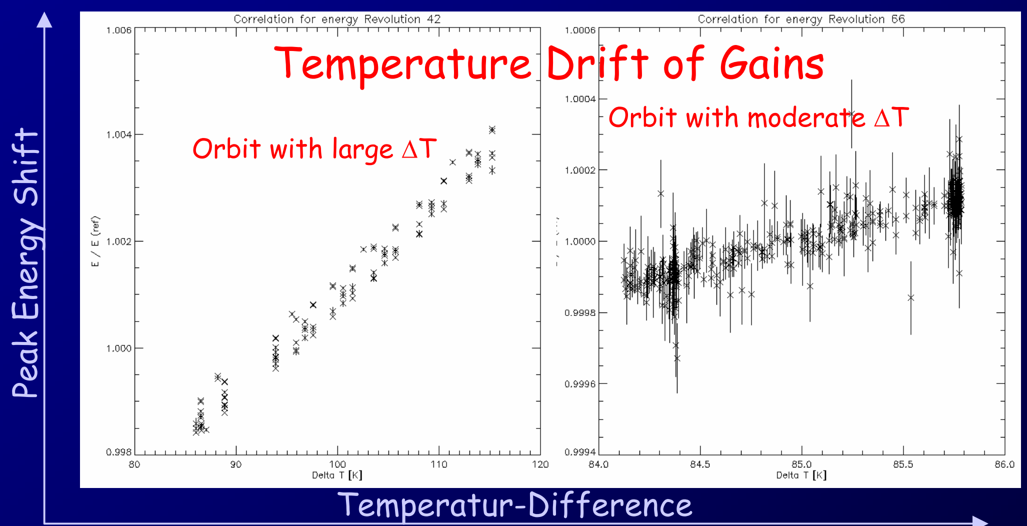


High-Resolution Spectroscopy with SPI

- 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

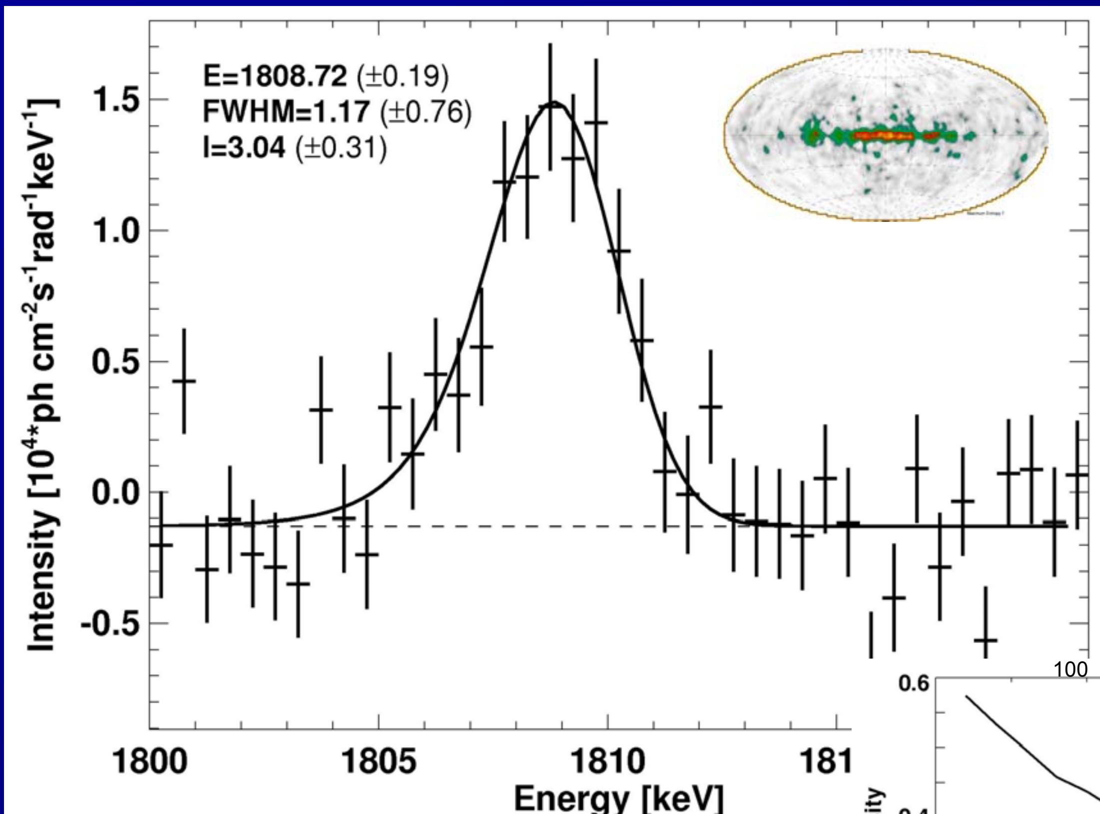






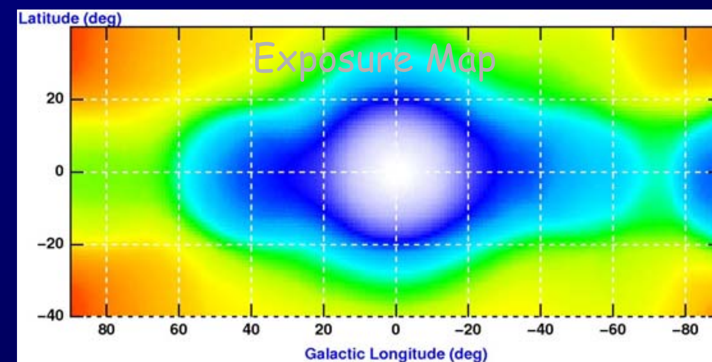
^{26}Al Line Shape from the Inner Galaxy

-> *Diehl et al., A&A 2006*

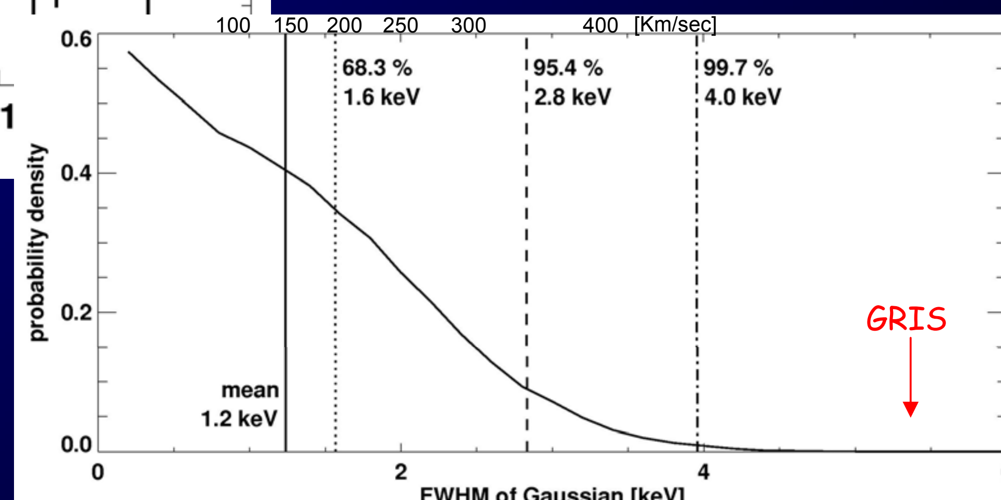


Data:

Orbits 15-259 (1.5y)
16 Ms
4Ms at GC



- The ^{26}Al Line is "Narrow" (~instrumental width)
  - SPI: 0.2…1.2 keV, <2.8 keV
  - ISM velocities 25…150 km s^{-1}

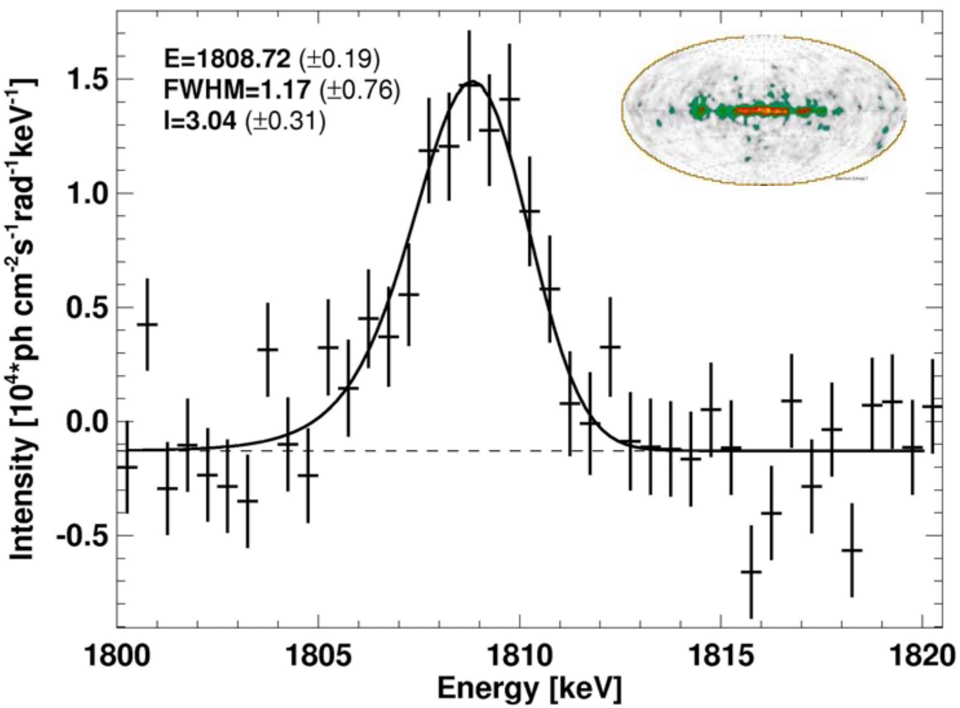


Update: ^{26}Al from the Galaxy

June 2006

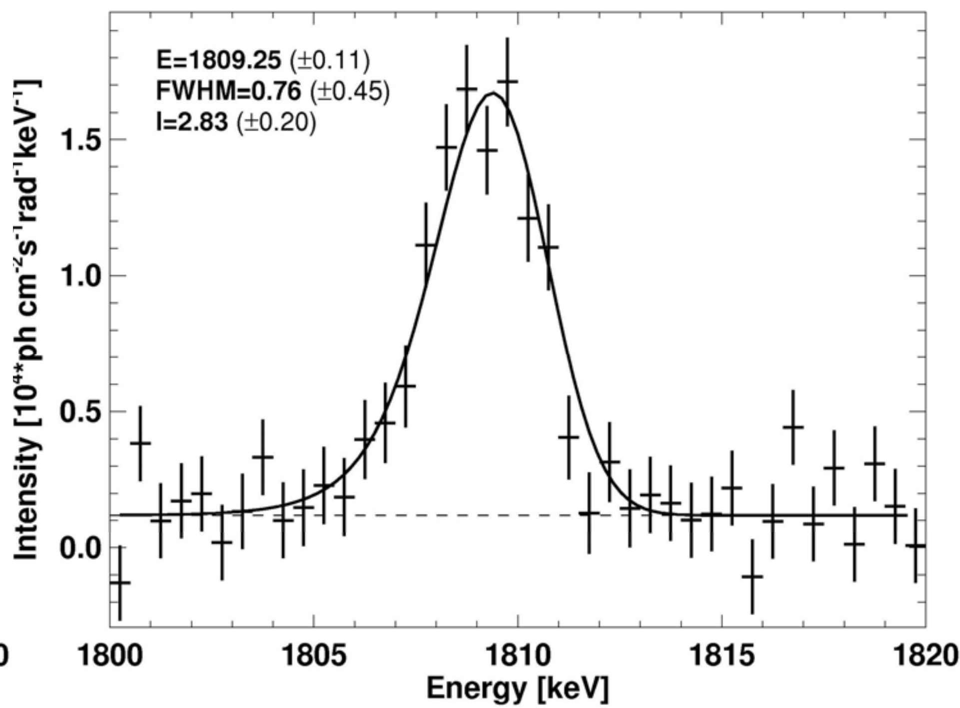
☆ Orbits 15-259

☞(27 Nov 2002 - 28 Nov 2004)



☆ Orbits 39-358

☞(7 Feb 2003 - 21 Sep 2005)



☆ No Changes in Results:

☞Intensity ~3 10^{-4} ph cm^{-2} s^{-1} rad^{-1}

☞Narrow Line

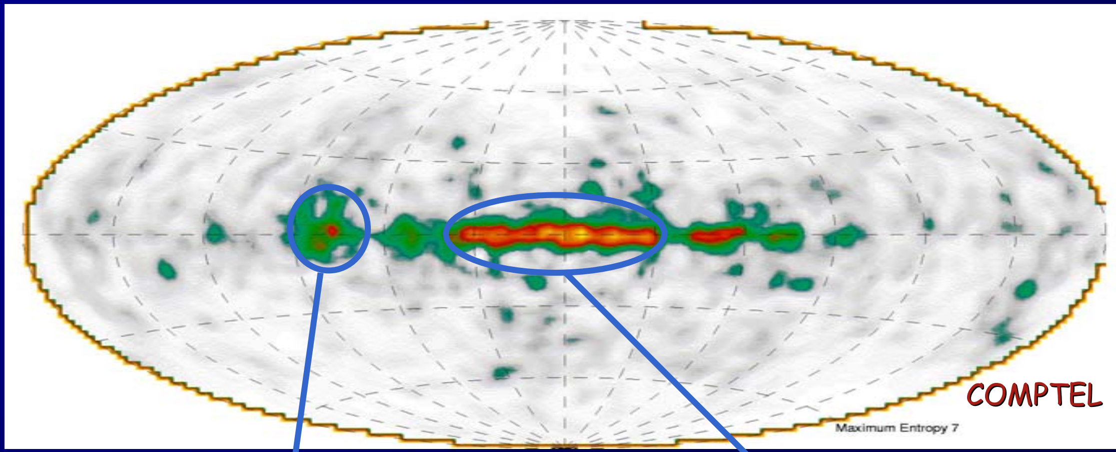
☞This Data Sample:

- Avoid Data with Changing Instrument Configurations
- Stabilize Background Model with More & Homogeneous Data

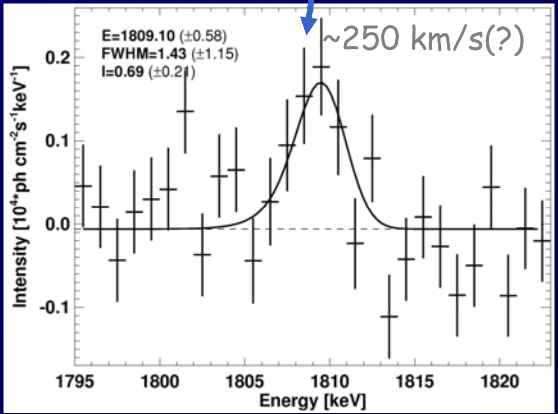
^{26}Al Line Shapes for Different Regions

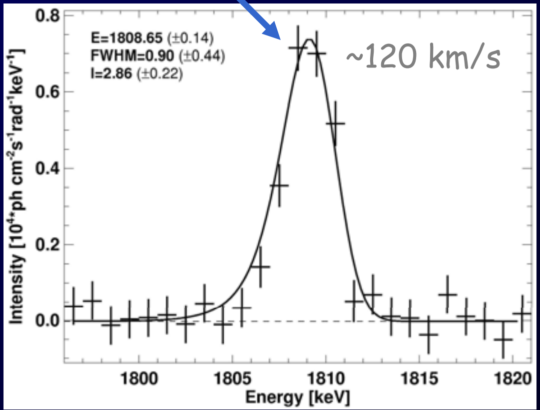
1.04 10^6y	$^{26}Al \rightarrow ^{26}Mg^* + e^+$	1809

- ^{26}Al Reflects Sources of Nucleosynthesis ($\tau \sim 10^6$y)
- COMPTEL Imaging -> Massive Stars are Dominating Sources



- Decay in ISM -> narrow line
- Large Cavities -> broad line
- Young Clusters -> broad line

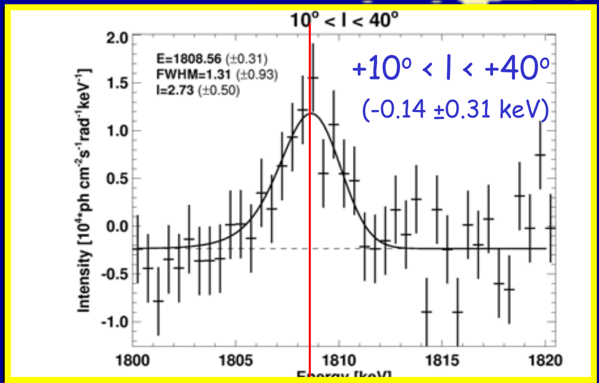


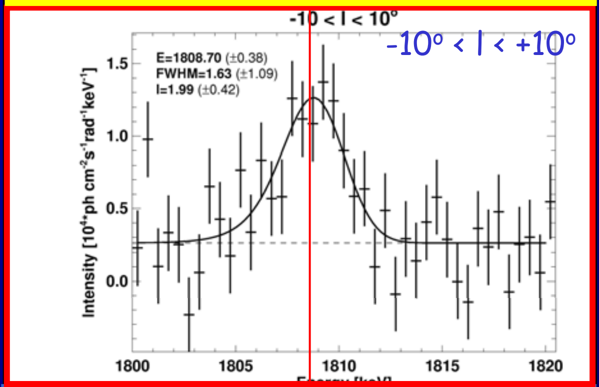


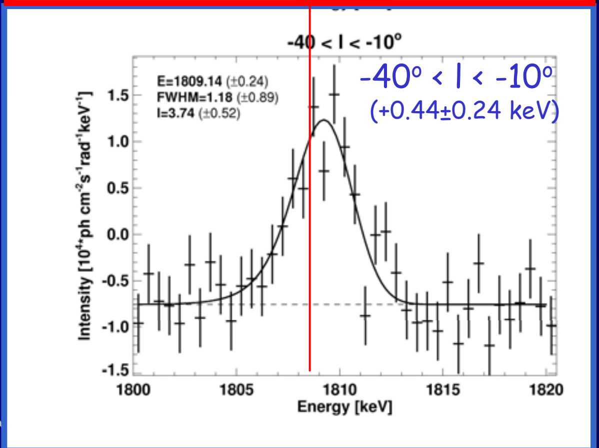
INTEGRAL/SPI Task: Spectroscopy for ^{26}Al Source Regions

Galactic Rotation and the ^{26}Al Line

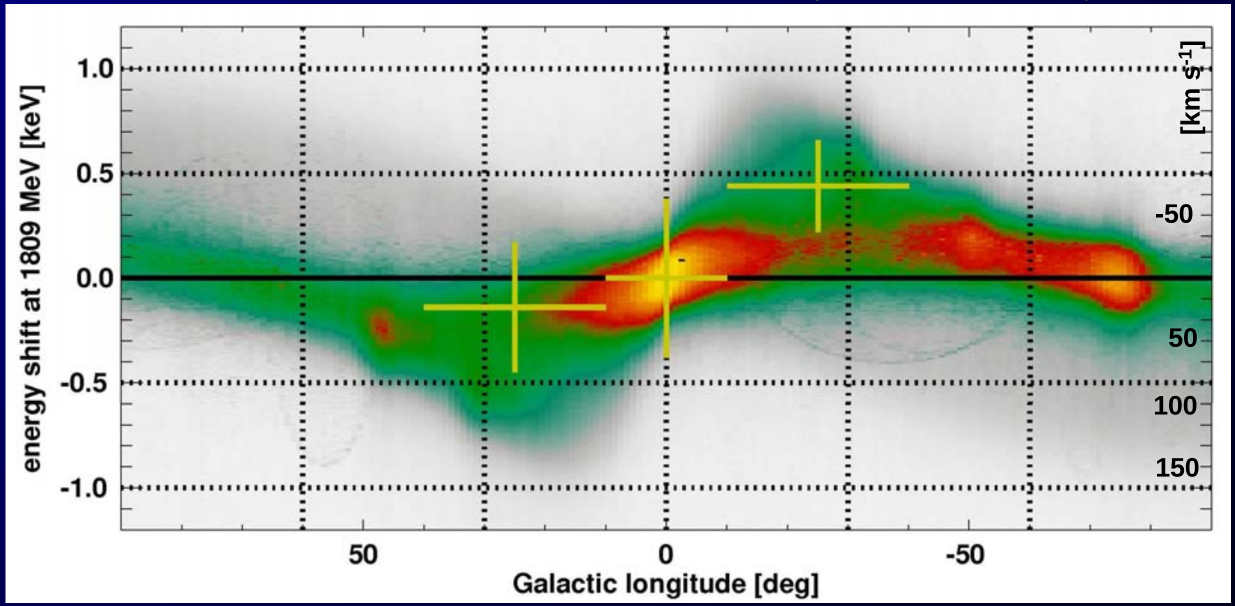
-> *Diehl et al., Nature 2006*



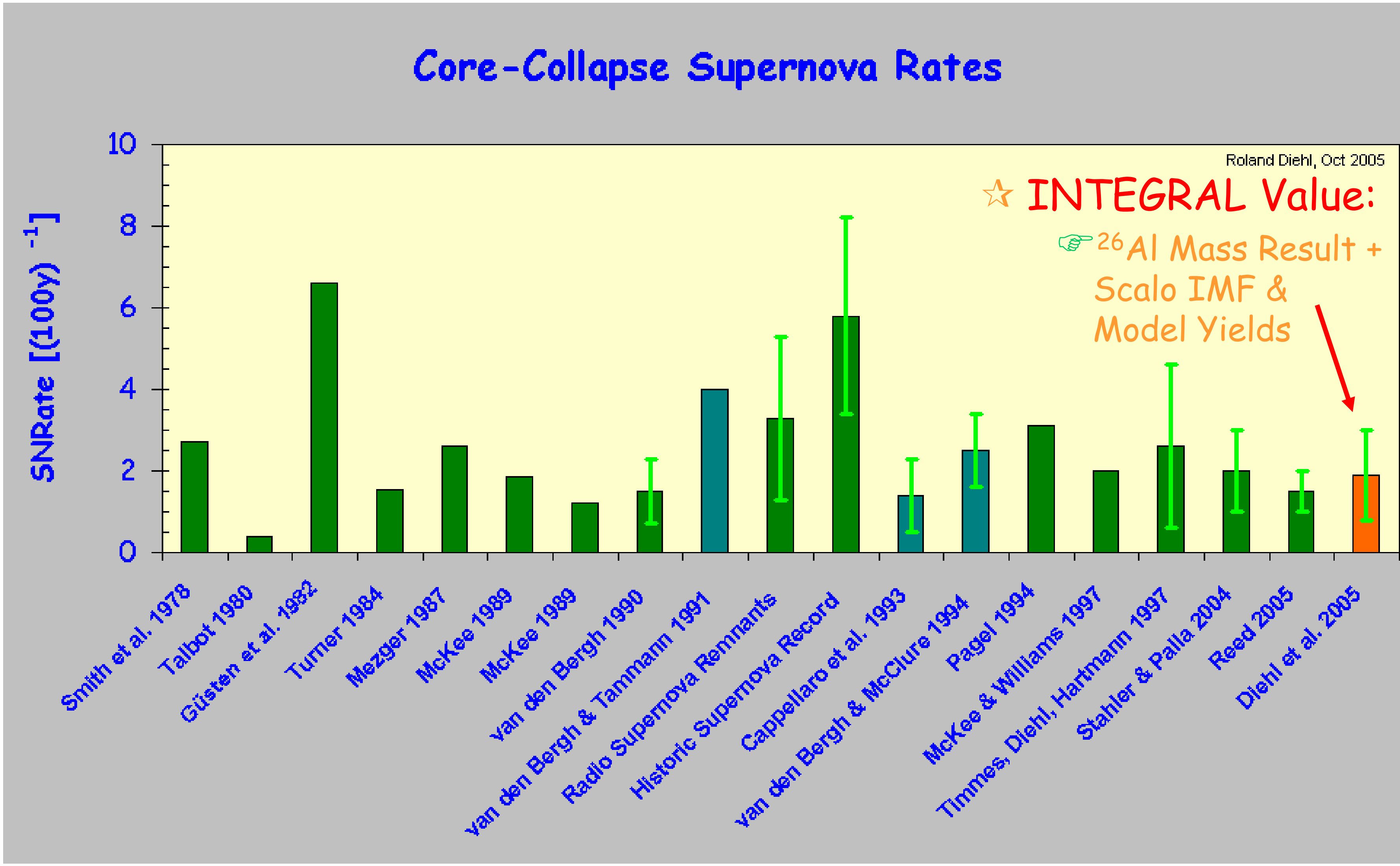




- ☆ Galactic Rotation Affects the Line Centroid ~as Expected
  - ☞ Consolidation: These sources are NOT Localized
  - ☞ Basis for GALACTIC ^{26}Al Amount Determination using geometrical / tracer models
- ➢ Measurements of
  - ✓ ^{26}Al Mass in Galaxy = 2.8 (±0.8) $M_{\odot}$
  - ✓ cc-SN Rate = 1.9 (± 1.1) per Century

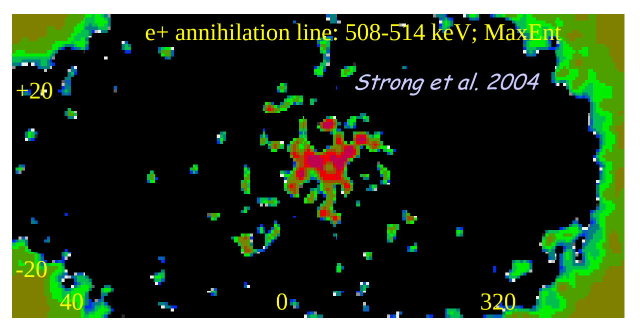


Galactic Supernovae from Massive Stars



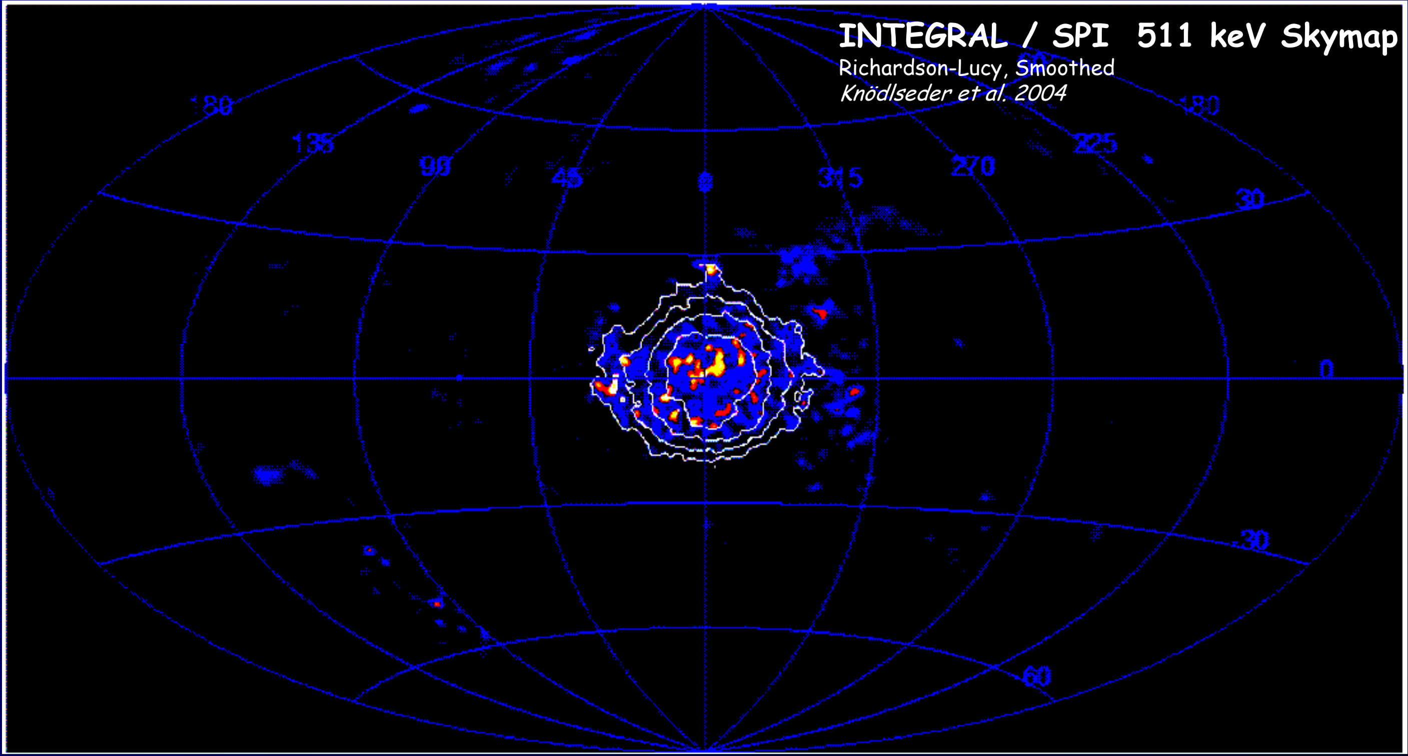
Annihilation of Positrons in the Galaxy

…. 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511



511 keV Line Emission Imaging with SPI:

- Extended, ~bulge-like Emission (δl~8°,δb~8°)
- No/Weak Disk Emission Seen; No "Fountain"



Positron Budget and Annihilation Gamma-Ray Flux

.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

☆ Gamma-Ray Observations

- 511 keV Line Flux from Galactic Bulge: $I=1.03 \pm 0.06\ 10^{-3}$ ph cm^{-2} s^{-1}
- 511 keV Line Flux from Galactic Disk: $I=0.7 \pm 0.4\ 10^{-3}$ ph cm^{-2} s^{-1}
- Ps Continuum Fluxes Consistent with 511 keV Line ($fract_{ps\text{-}annih}=0.92 \pm 0.09$)
- Bulge Brightness > Disk Brightness, but total $I_{disk} \sim 3 \pm 2\ 10^{-3}$ ph cm^{-2} s^{-1}

☆ Nucleosynthesis

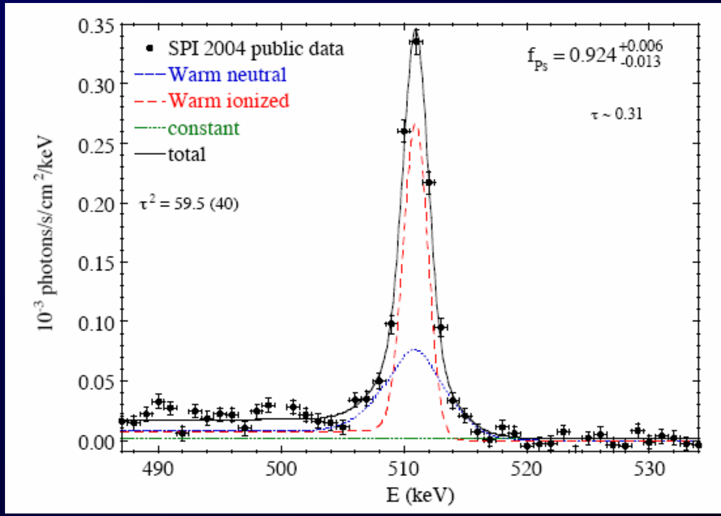
- ^{26}Al e^+ Production: $I \sim 0.2\ 10^{-3}$ ph cm^{-2} s^{-1}
- SNIa e^+ Production: $I \sim 5\ 10^{-3}$ ph cm^{-2} s^{-1}
- cc-SN e^+ Production: $I \sim 0.8\ 10^{-3}$ ph cm^{-2} s^{-1}
- Novae small

☆ Others

- Binaries ?
- Pulsars ?
- Dark-Matter Annihilations ?

☆ Positron Production in Galaxy is Sufficient to Explain I_γ

- **Morphology!?!**



Annihilation of Positrons in the Galaxy

…. 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

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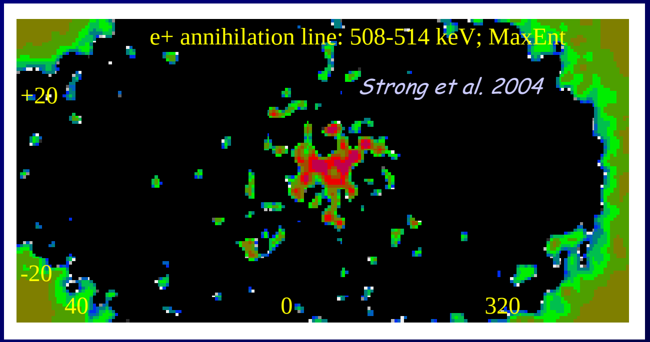
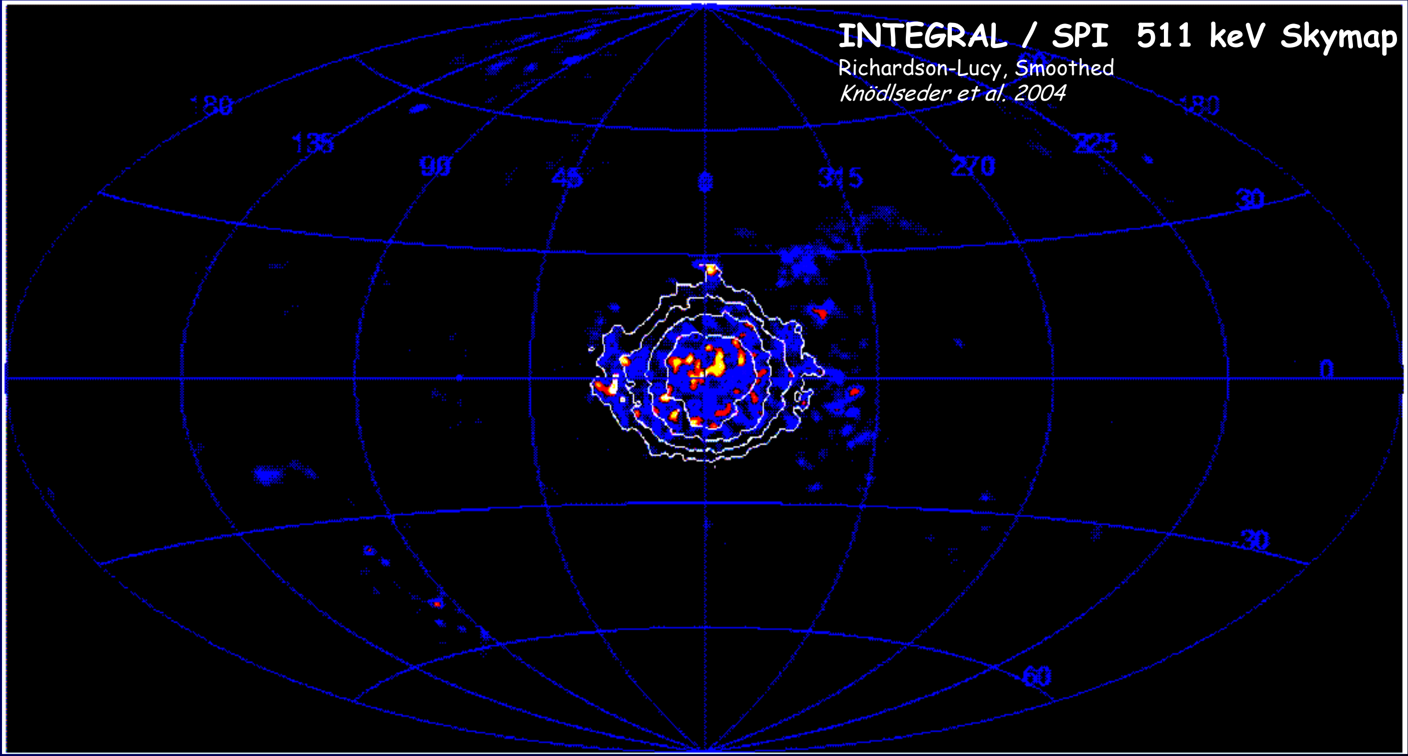
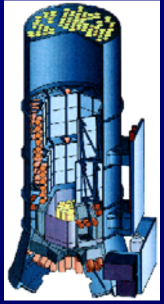


-> Not from Young Stars (Minor Contribution)

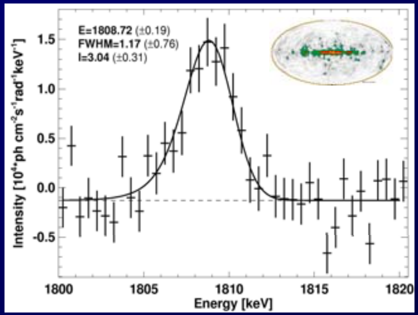
- Old stellar population!
- Dark-Matter Annihilations?
- Positron Transport from Disk Regions to Inner Galaxy?



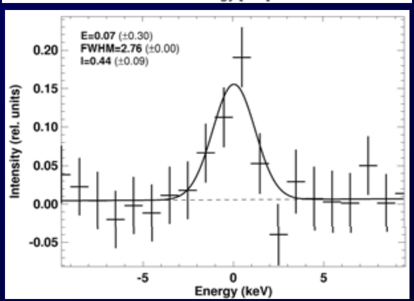
Summary:
Nuclear Astrophysics with Gamma-Ray Line Observations



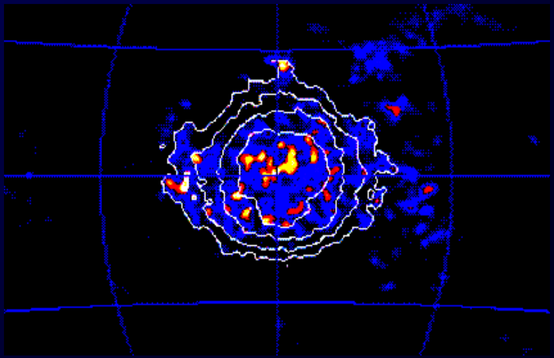
- Ge Spectroscopy Opened a New Stage for Nuclear Astrophysics



- ^{26}Al in the Galaxy Reveals Massive-Star Activity



- $^{60}Fe/^{26}Al$ Ratio Constrains Massive-Star Nucleosynthesis Models
- Positron Annihilation Poses Puzzle for Additional Sources or Large-Scale Positron Transport



- Studies of 3D Effects in Supernovae Interiors Still Lack Good Measurements (& Luck)