INTEGRAL and Cosmic Nucleosynthesis

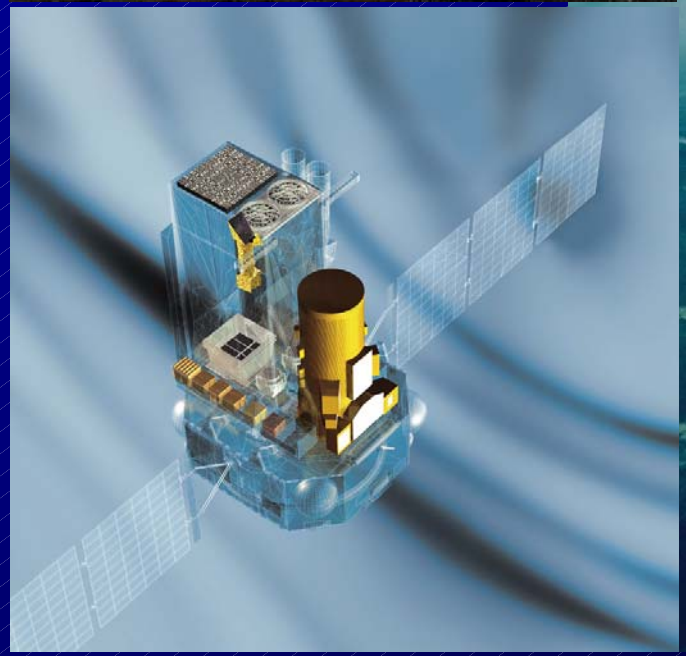
Roland Diehl

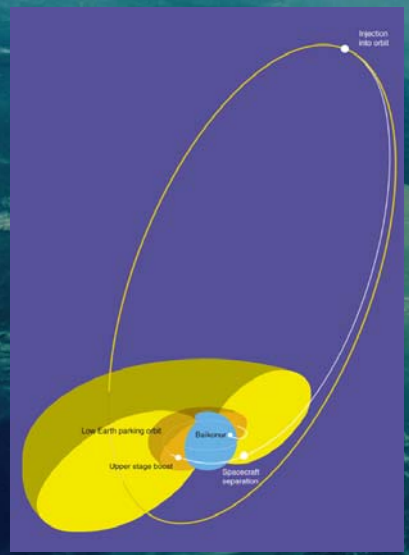
MPE Garching, Germany

- ☆ INTEGRAL and its Gamma-Ray Line Spectrometer
- ☆ ^{26}Al in the Galaxy
  - ☞ Astrophysics Issues
  - ☞ Status, incl. INTEGRAL
- ☆ other Diffuse Radioactivities
  - ☞ ^{60}Fe from SN
  - ☞ e+ Annihilation
- ☆ Supernova γ-rays

INTEGRAL The International Gamma-Ray Astrophysics Laboratory

- ESA Observatory (75% Open Program)
- 2002 -> 2008+
- Coded-Mask Gamma-Ray Telescopes
  - 2 main (imager, spectrometer)
  - 2 monitors





- 3-Day Orbit
- Excellent Performance

- Science:
  - Nucleosynthesis
  - Compact Stars
  - Active Galaxies
  - Gamma-Ray Bursts
  - ...

INTEGRAL Observations & Opportunities

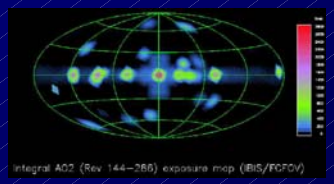
Core Program

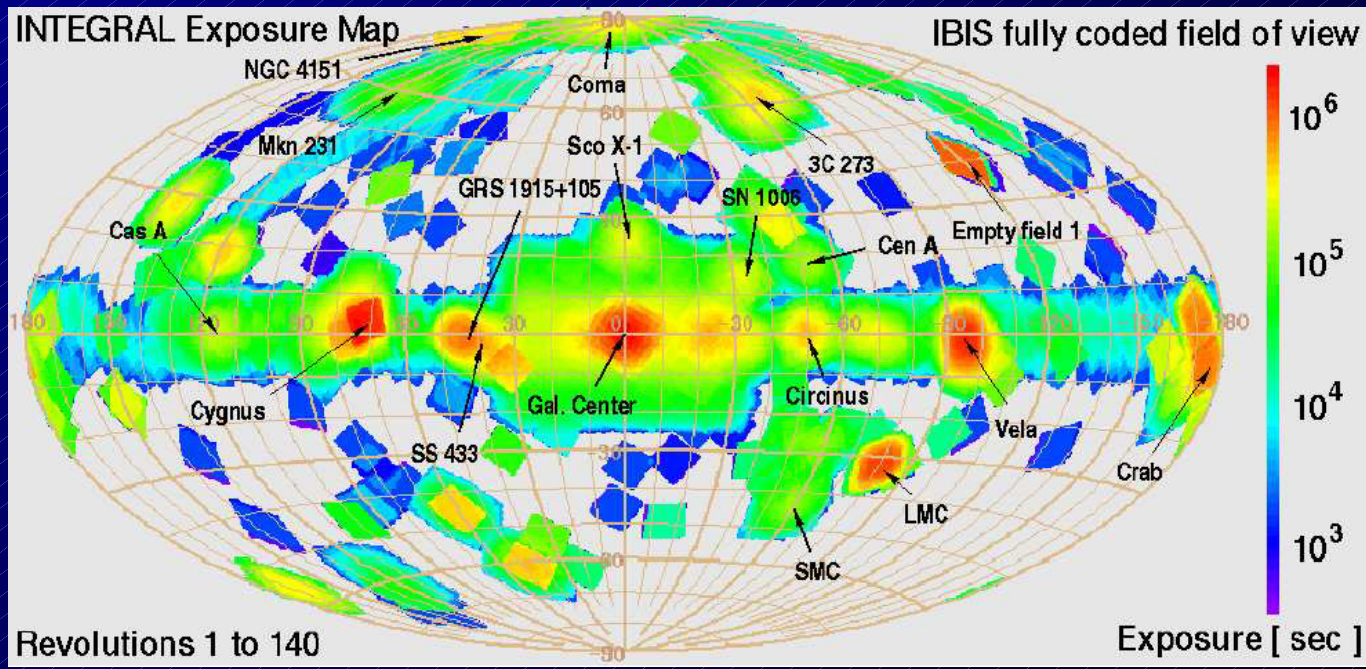
- ☆ Galactic-Plane Survey (weekly, 6° spaced sawtooth 21° incl)
- ☆ Galactic-Central-Region Deep Exposure (l=0±30°, b=0±20°)
- ☆ Pointed Observations (Vela Region, ToO)
- ☆ Dithering (Std: 5x5 pattern, 2° spacing)

Exposure ->

Opportunities

- ☆ AO-01
  February 2001
  for Dec '02-Dec'03
- ☆ AO-02
  September 2003
  for Dec '03-Dec'04
- ☆ ...
- ☆

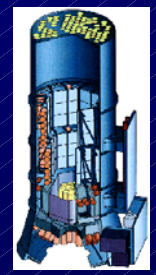




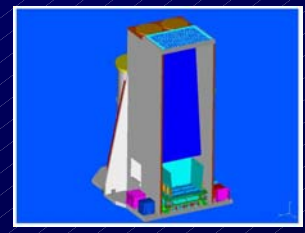
Mission Extended / Approved till 16 Dec 2008

INTEGRAL Scientific Payload ("Instruments")

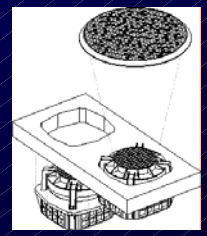
- SPECTROMETER "SPI"
  - ☞ Coded-Mask Telescope with 19-Element Ge Camera



- IMAGER "IBIS"
  - ☞ **Coded-Mask Telescope with fine CdTl and CsI Camera Planes**



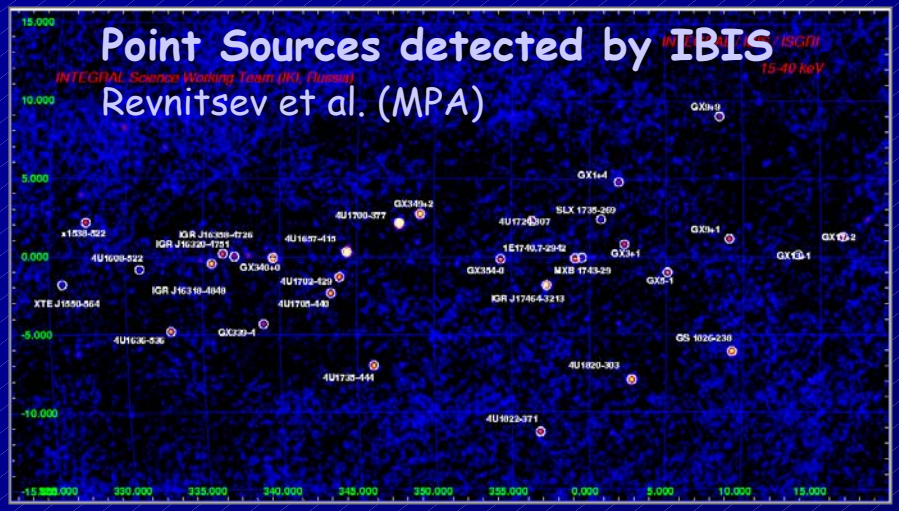
- X-RAY MONITOR "JEM-X"
  - ☞ Coded-Mask Telescopes with Imaging Microstrip Gas Detector

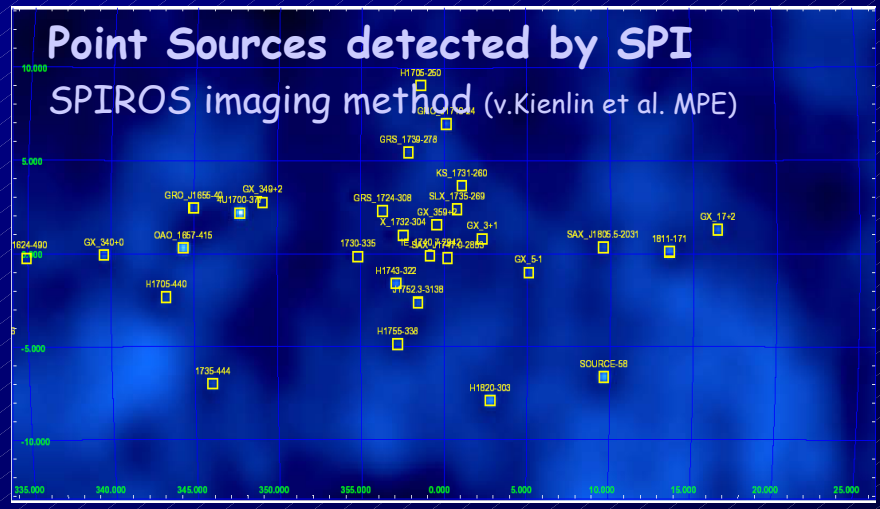


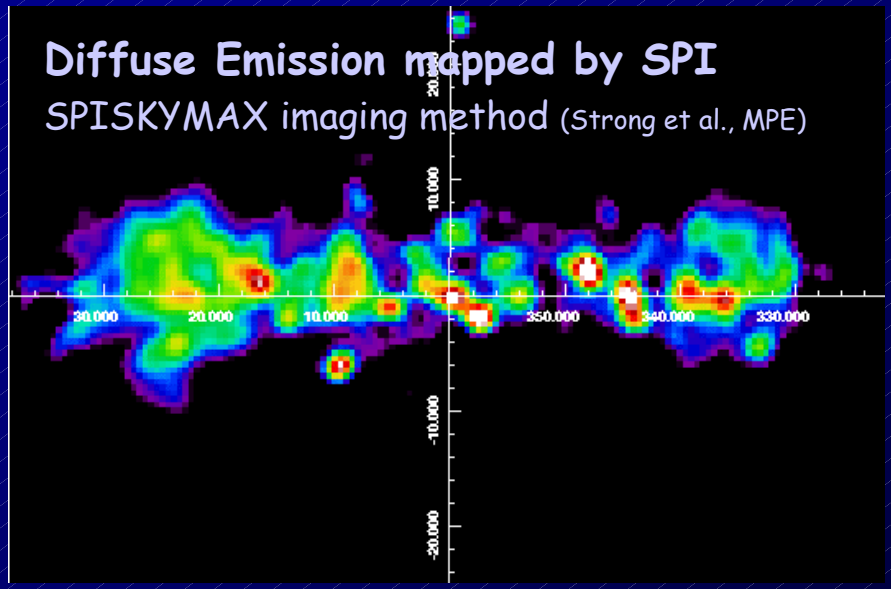
- OPTICAL MONITORING CAMERA "OMC"

- INTEGRAL SCIENCE DATA CENTRE "ISDC"

INTEGRAL's Gamma-Ray Source Survey







- Galactic Point Sources:
  - ☆ Accreting Binaries (Black-hole, NS)
  - ☆ Pulsars
  - ☆ ???
- Diffuse Galactic Emission
  - ☆ from Cosmic-ray / Gas Interactions
  - ☆ from Ensembles of Sources
  - ☆ from Galactic Nucleosynthesis
- plus
  - ☆ AGN, GRB, Solar Flares, ...

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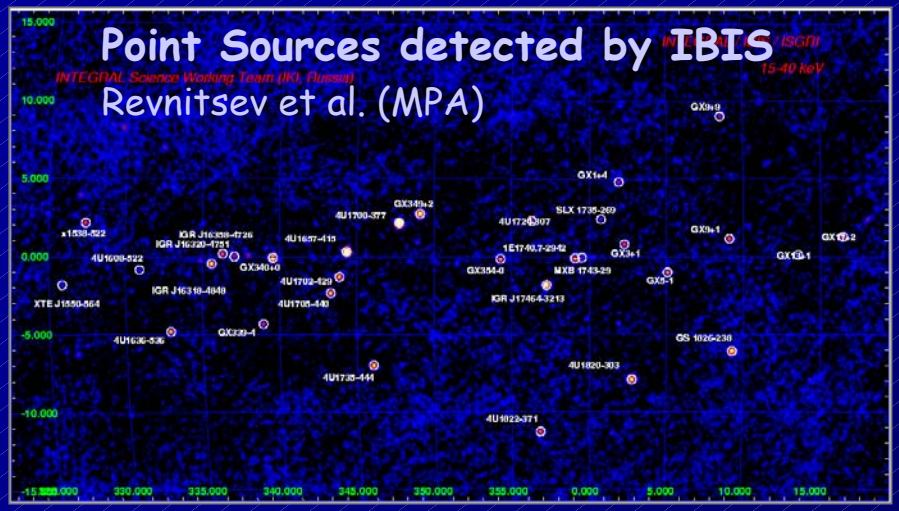

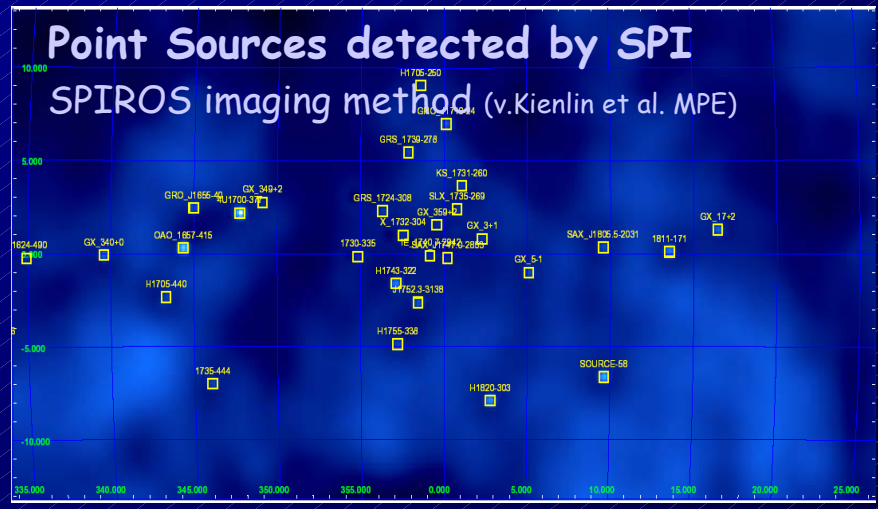

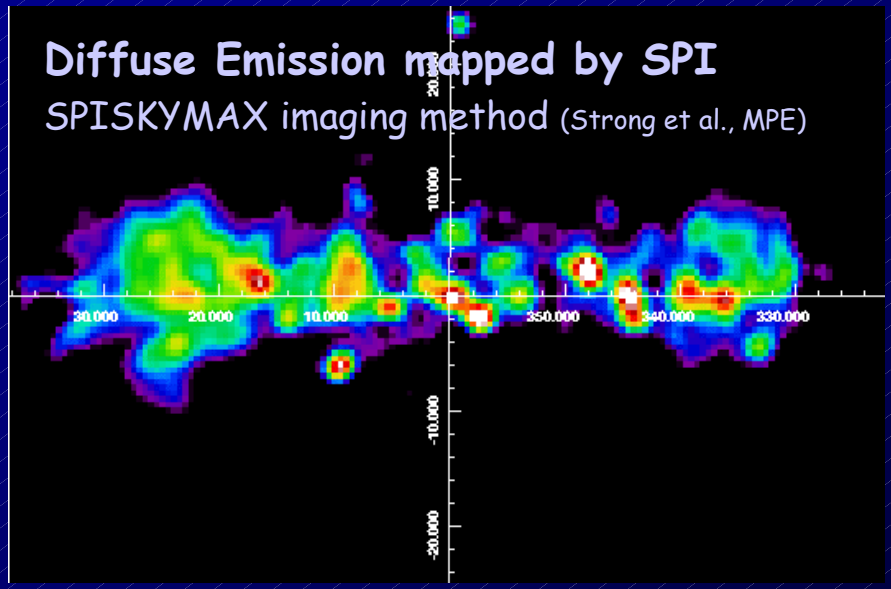

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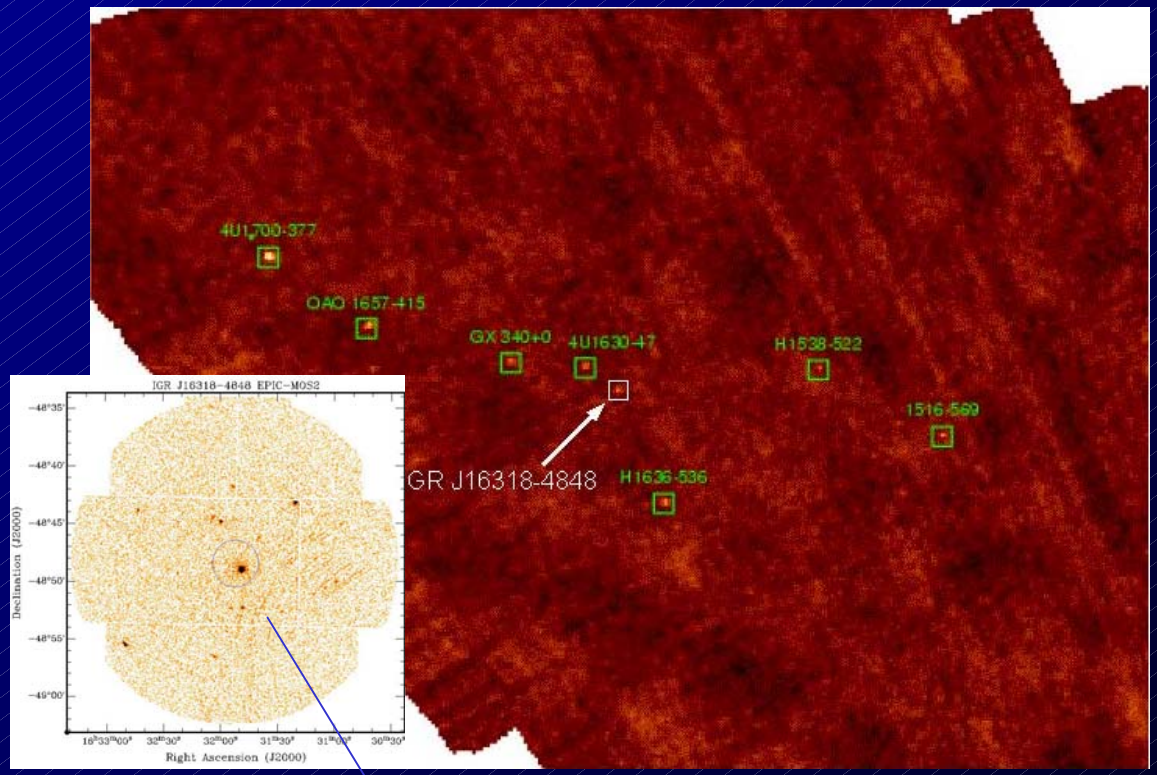
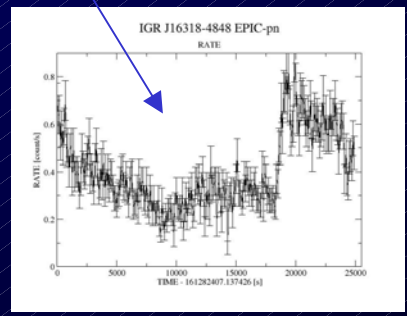
INTEGRAL Gamma-Ray Sources (IGR)

- **IGR J16318-4848**
  - Discovery Jan 2003 15-40 keV (ISGRI)
  - I~.05-.1 Crab, Variability δt~1000s
  - XMM/Newton ToO Discovers Weak X-ray Source
  - Highly Absorbed!
  - ...
- **IGR Sources:** (~2/month)
  - Mostly Soft Spectra, but Some Hard at >100 keV -> Pulsars, BH Candidates
  - Some Highly Absorbed (N_H~2 10^{24} cm^2)

-> New Class of Embedded Sources?





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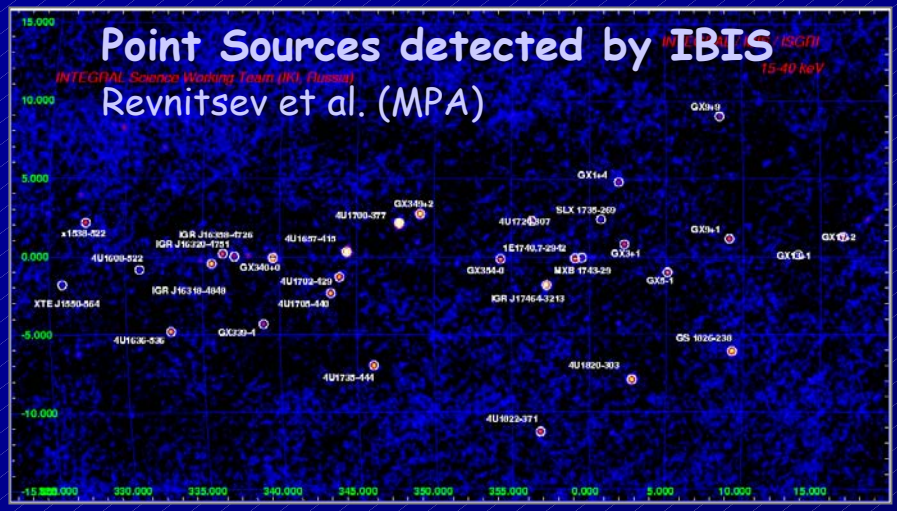

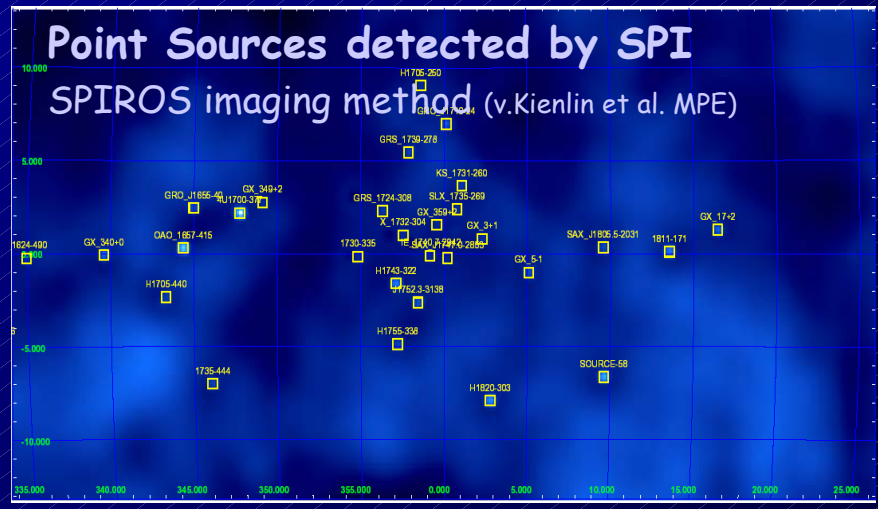

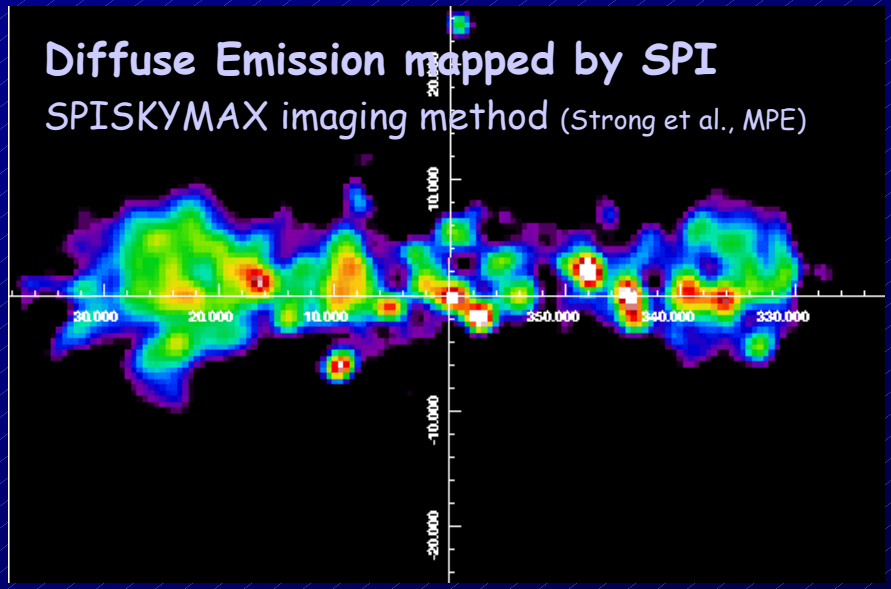

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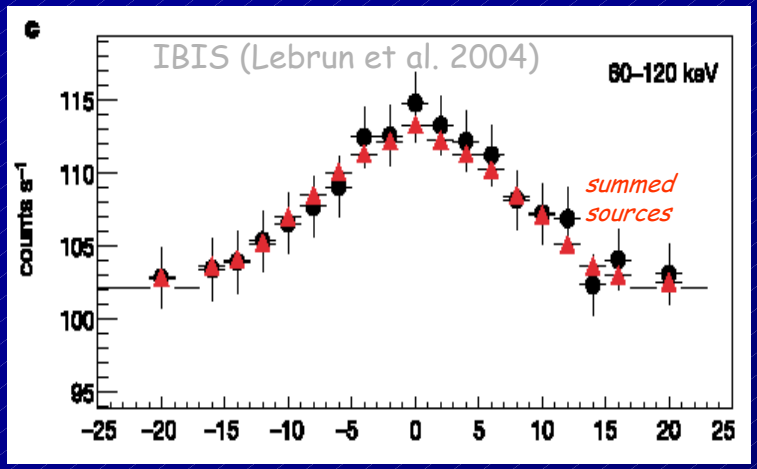
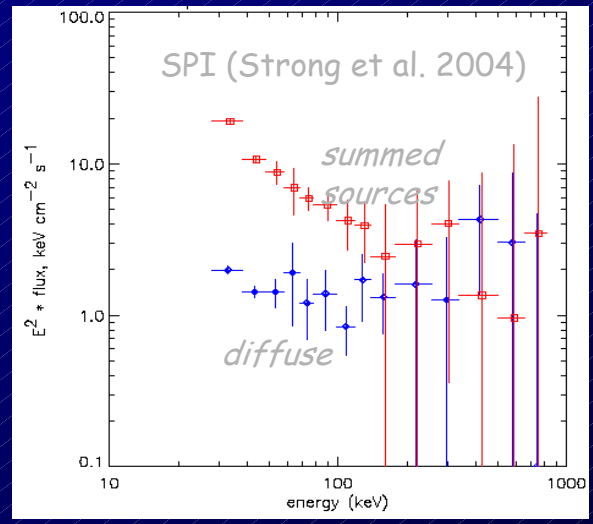
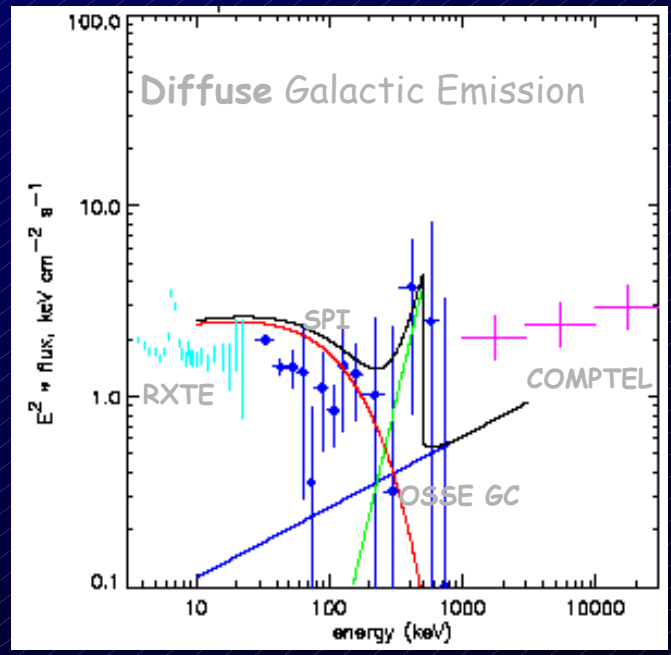
Diffuse Emission and Galactic Sources





- ☆ Diffuse Emission ??
  - ☞ Negligable/Absent (hard X-rays, IBIS)
  - ☞ Small but Significant (harder X-rays, SPI)
    - ☞ Large (~80%, X-rays, Chandra)
    - ☞ Evident (γ-rays, CGRO; Sources??)
- ☆ Origin?
  - ☞ Non-Thermal Bremsstrahlung?
    - Too Inefficient
  - ☞ Unresolved Sources?
  - ☞ Positron Annihilation?



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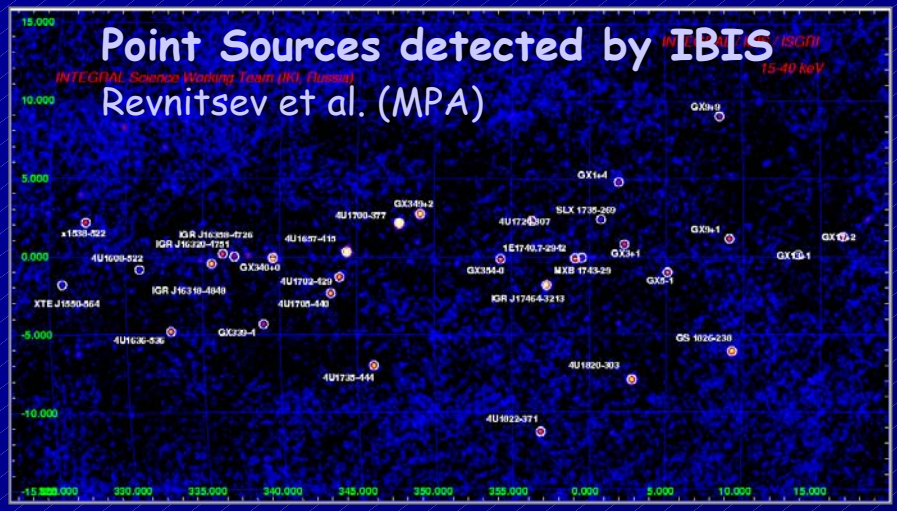

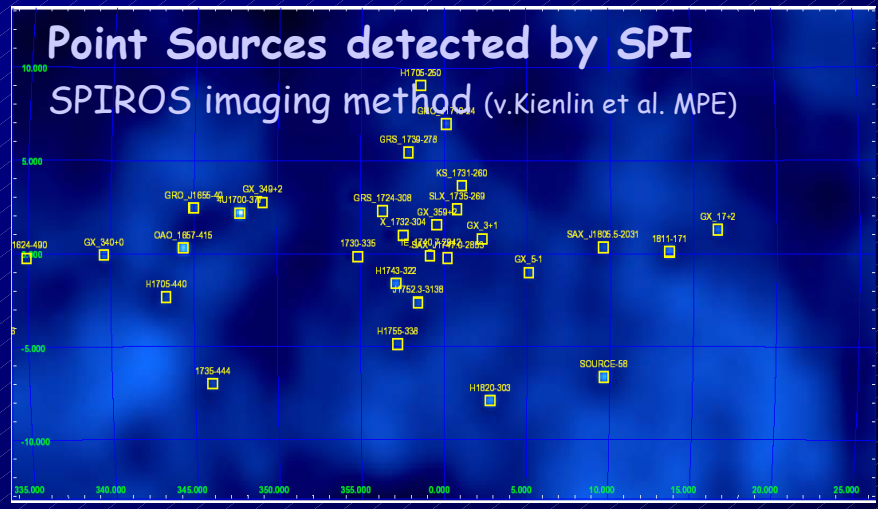

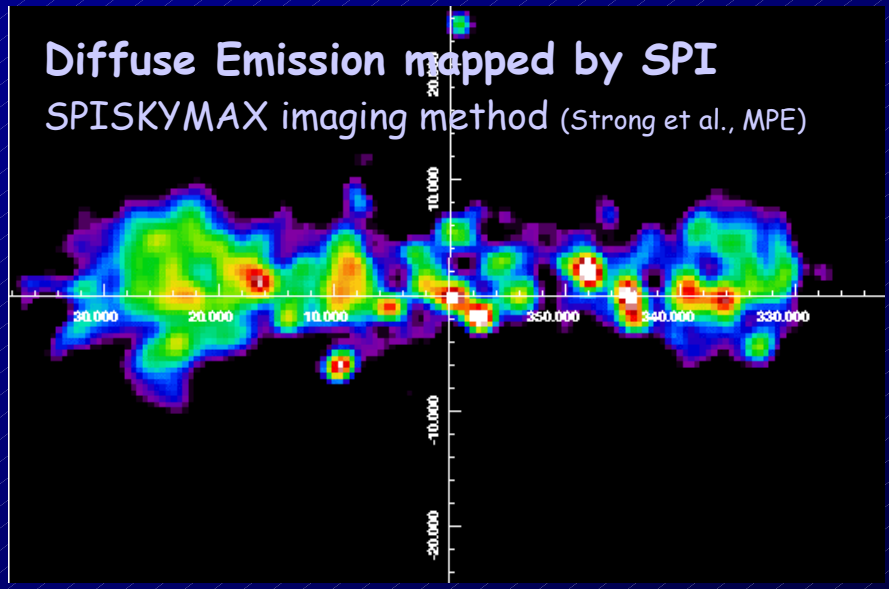

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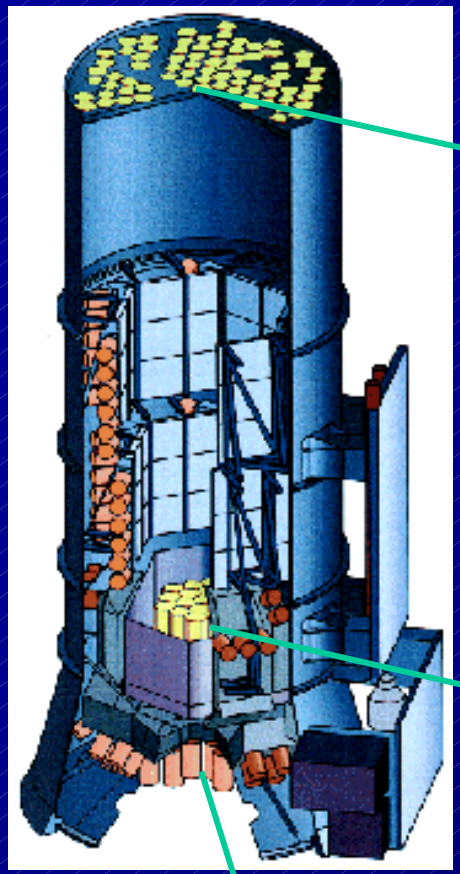
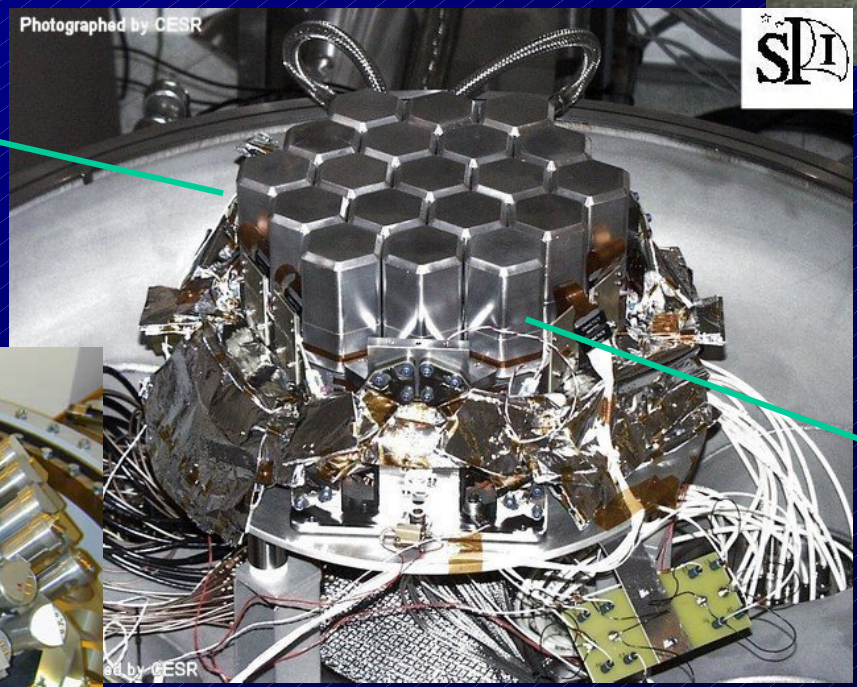
  - ☆ **from Galactic Nucleosynthesis**
- AGN

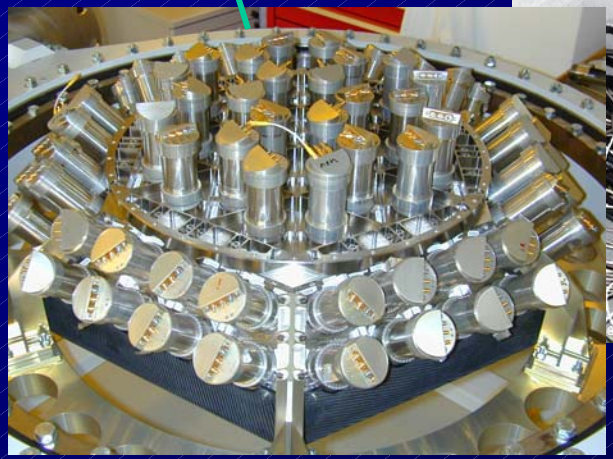
The SPI Spectrometer



Spectral Resolution
$E/\Delta E \sim 600$

$\Rightarrow$ Nuclear-Line Spectroscopy in Space

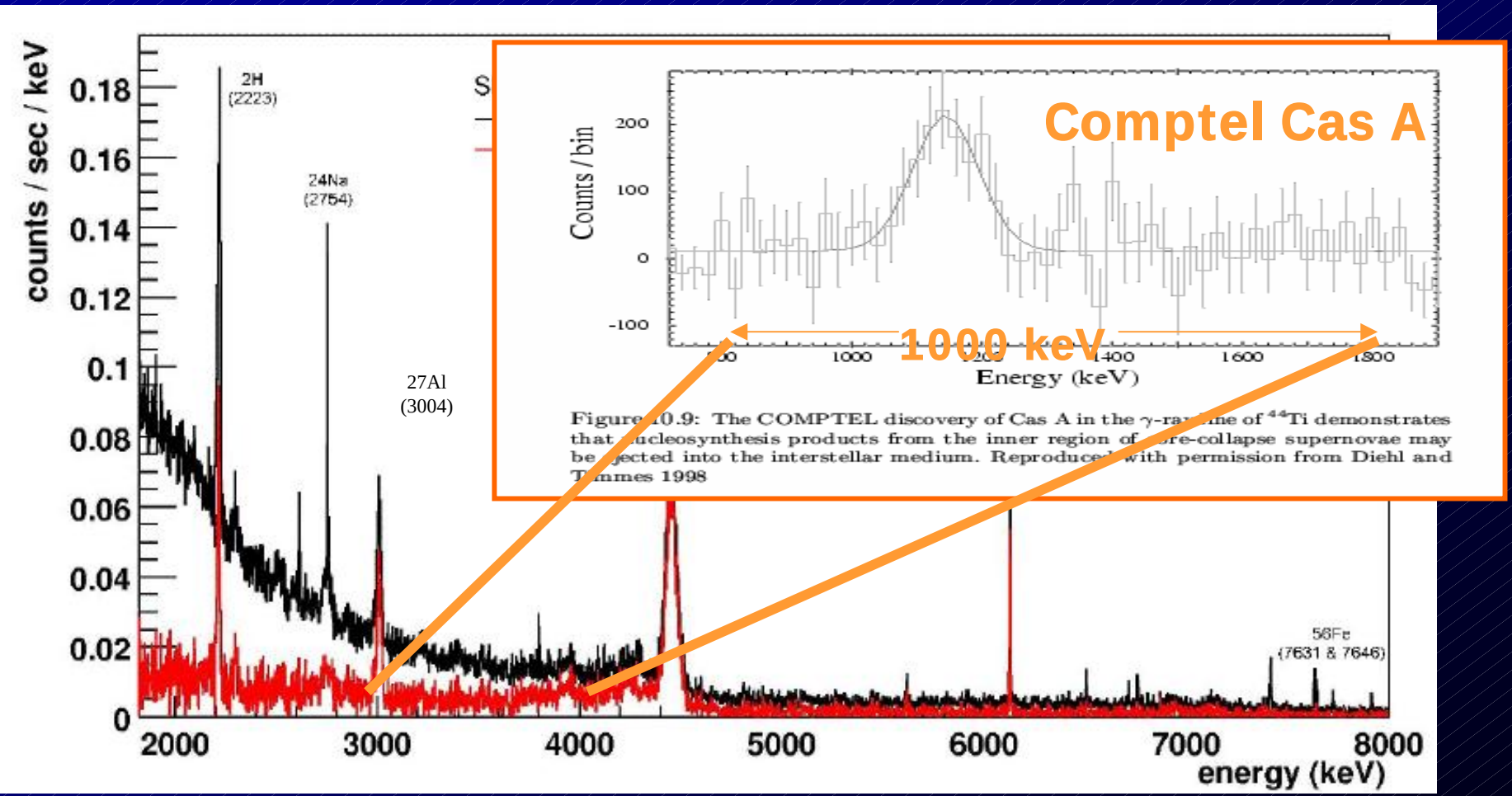




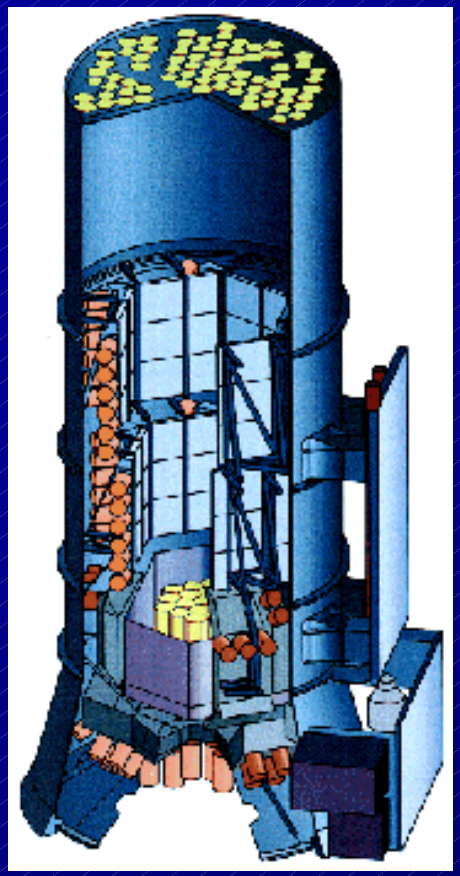
SPI: Spectroscopy in Gamma-Rays

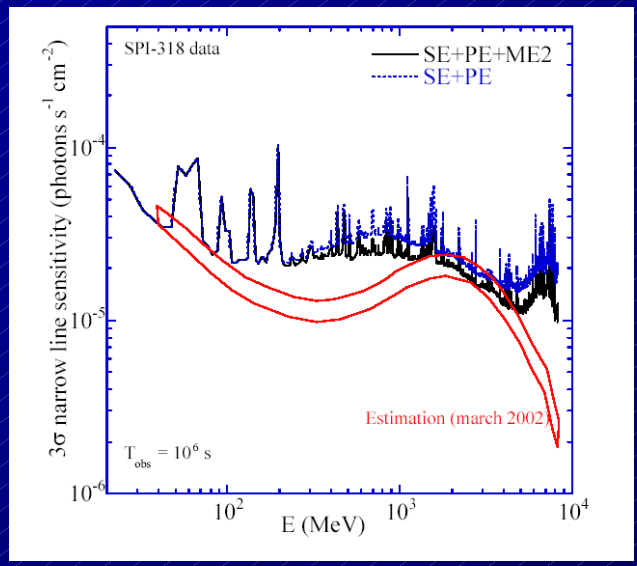
-> New Quality of γ-ray Data

local bgd, induced by particles from solar M5 flare on 9 Nov 2002

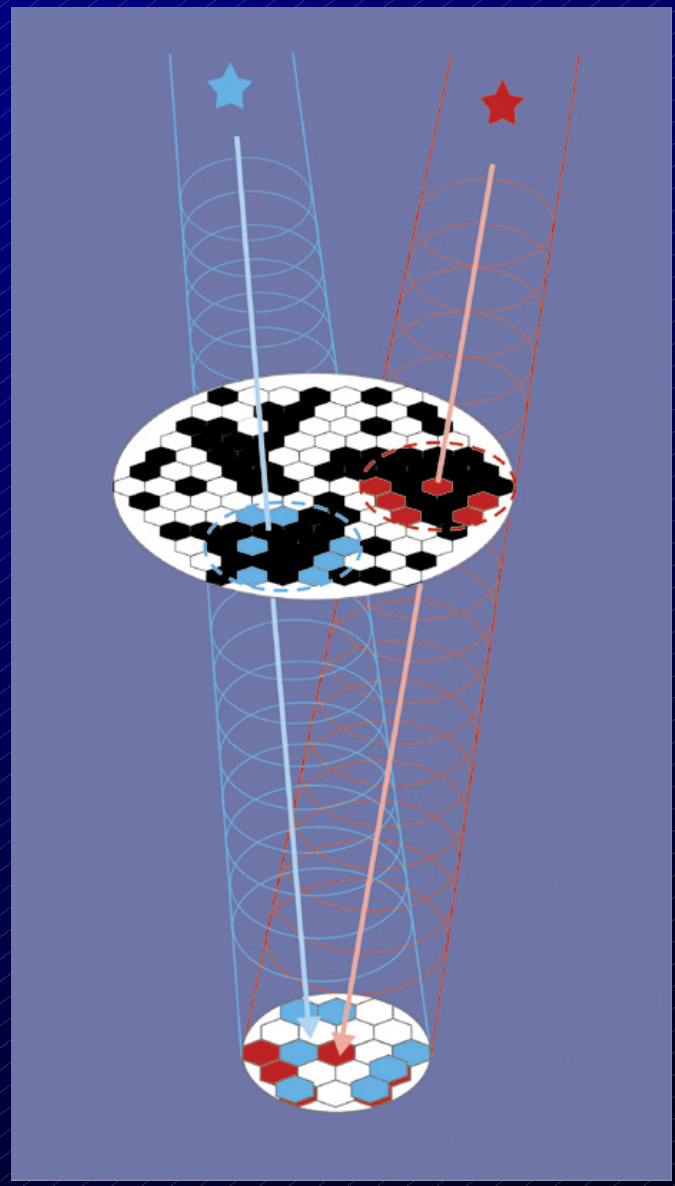


SPI Study of Diffuse Line Emission





...Finding the Shadowgram Pattern from Diffuse Emission at 0.005 Hz against a Background of 0.3 Hz

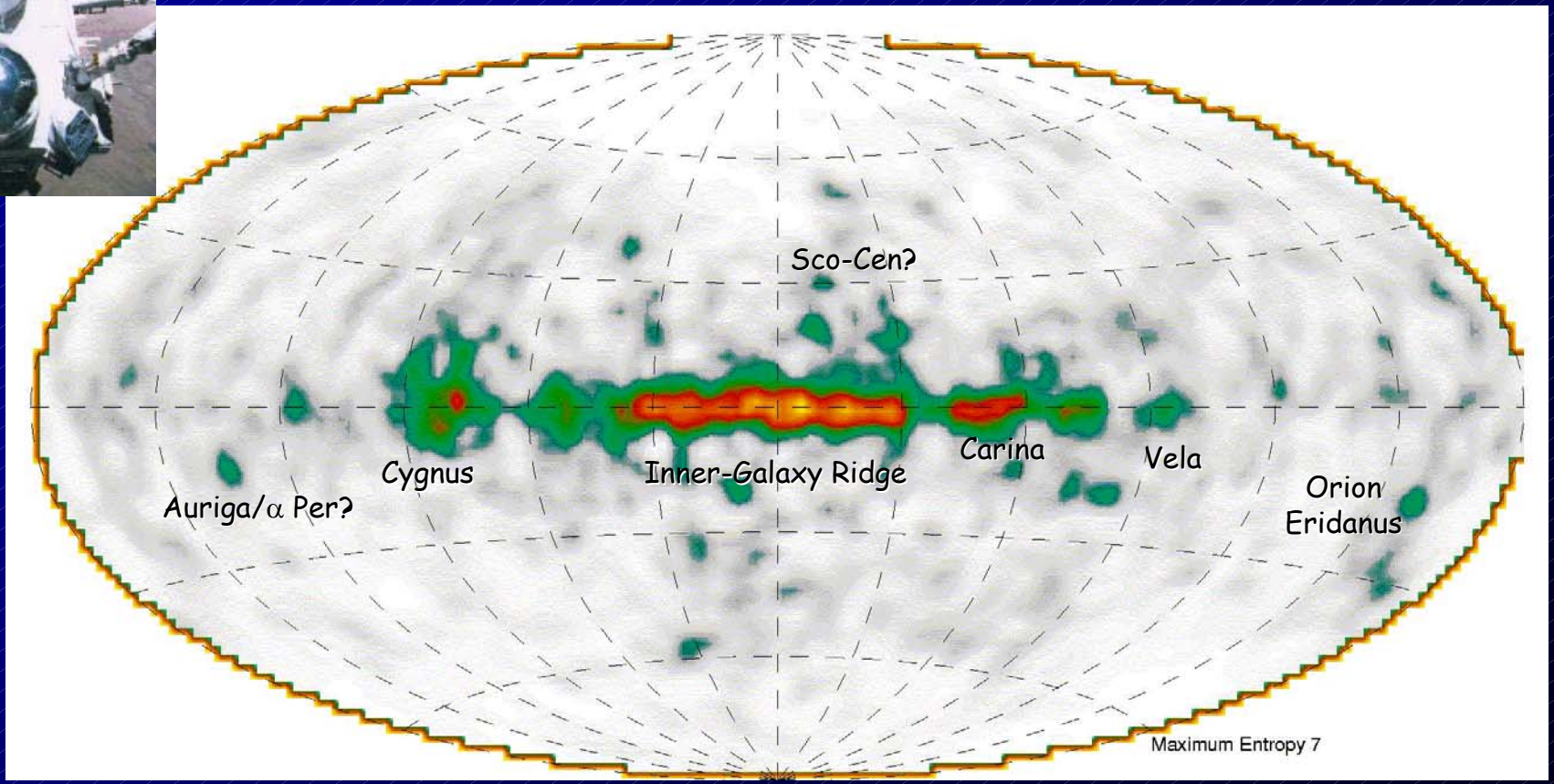


Analysis Team

- MPE (R.D., A. Strong, K. Kretschmer, ...),
  CESR (J. Knödlseder, P. Jean, V. Lonjou, G. Weidenspointner,...),
  GSFC (B. Teegarden, S. Sturner, K. Watanabe, ...),
  CEA (S. Schanne, B. Cordier, ...),
  UCB (C. Wunderer, ...), ***et al.***

The Sky at 1809 keV: ^{26}Al

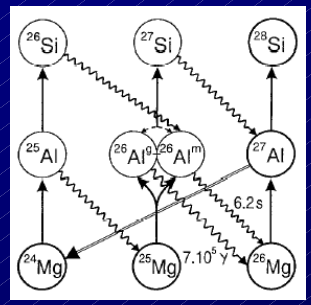
Recent Nucleosynthesis in the Galaxy ($\tau_{^{26}Al}$~1My)



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

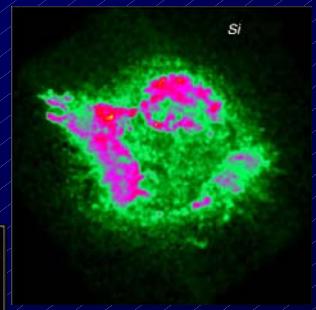
Candidate Sources of ^{26}Al

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



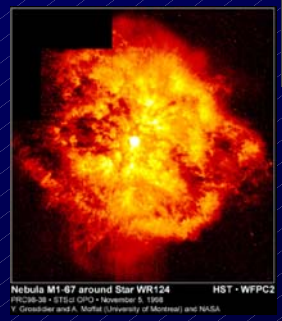
Core-Collapse Supernovae

- 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

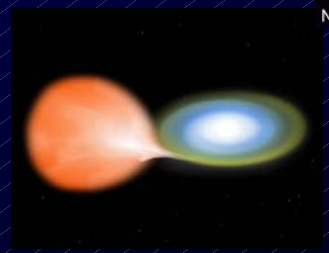


AGB Stars (M>4M$_{\odot}$)

- 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



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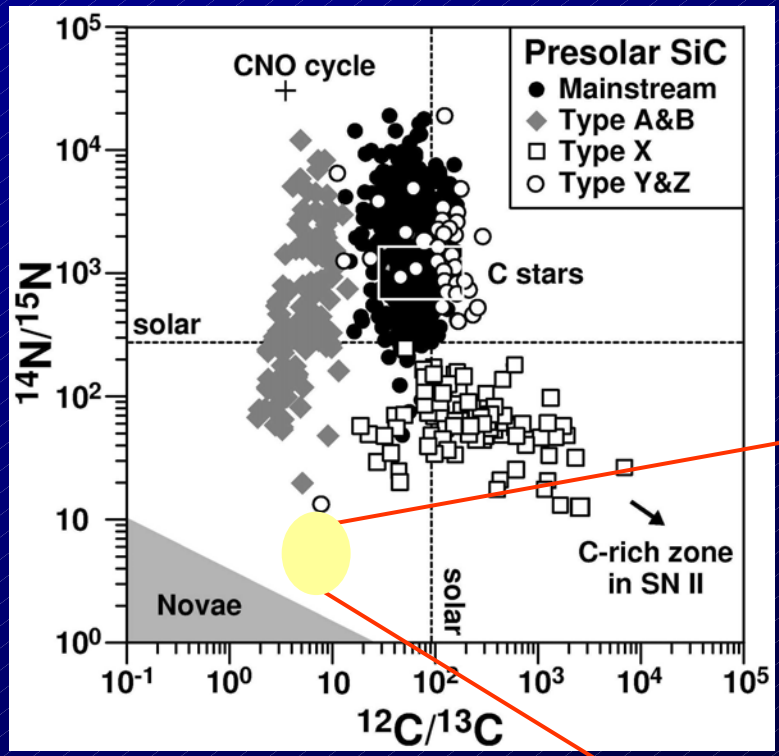
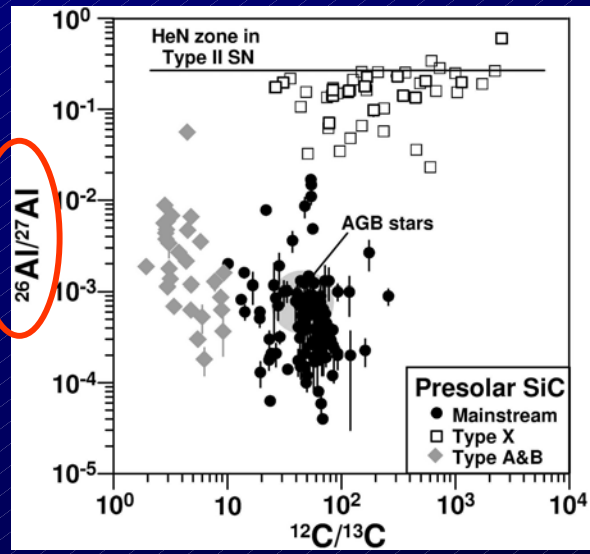
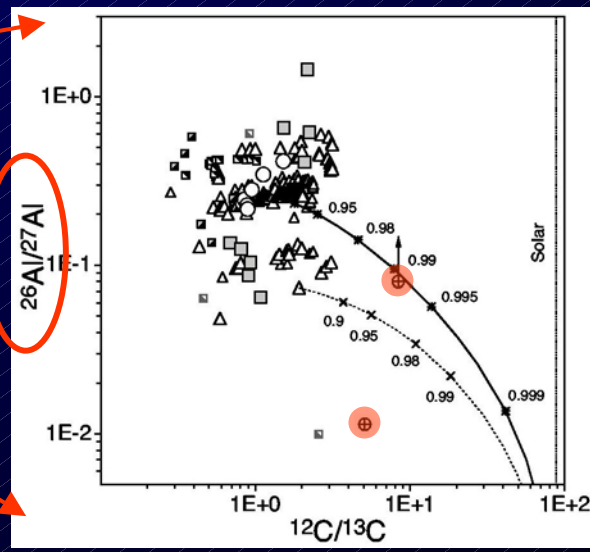
Hints from Presolar Grains

- Isotopic Ratios in C,N,Si,...-> Source Type of Presolar Grain
  - ☆ AGB Stars
  - ☆ Supernovae
  - ☆ Novae



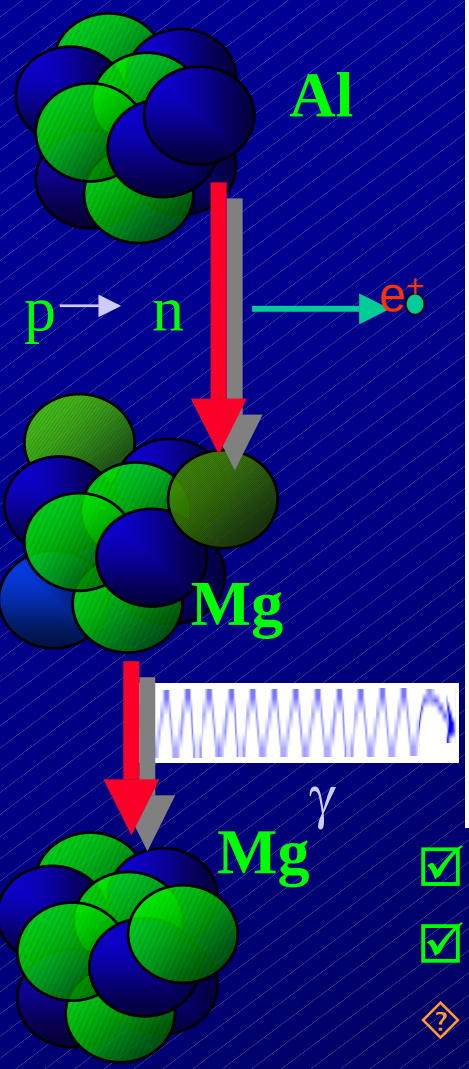
☞ Amari, Nittler, Hoppe, Zinner, ... et al.

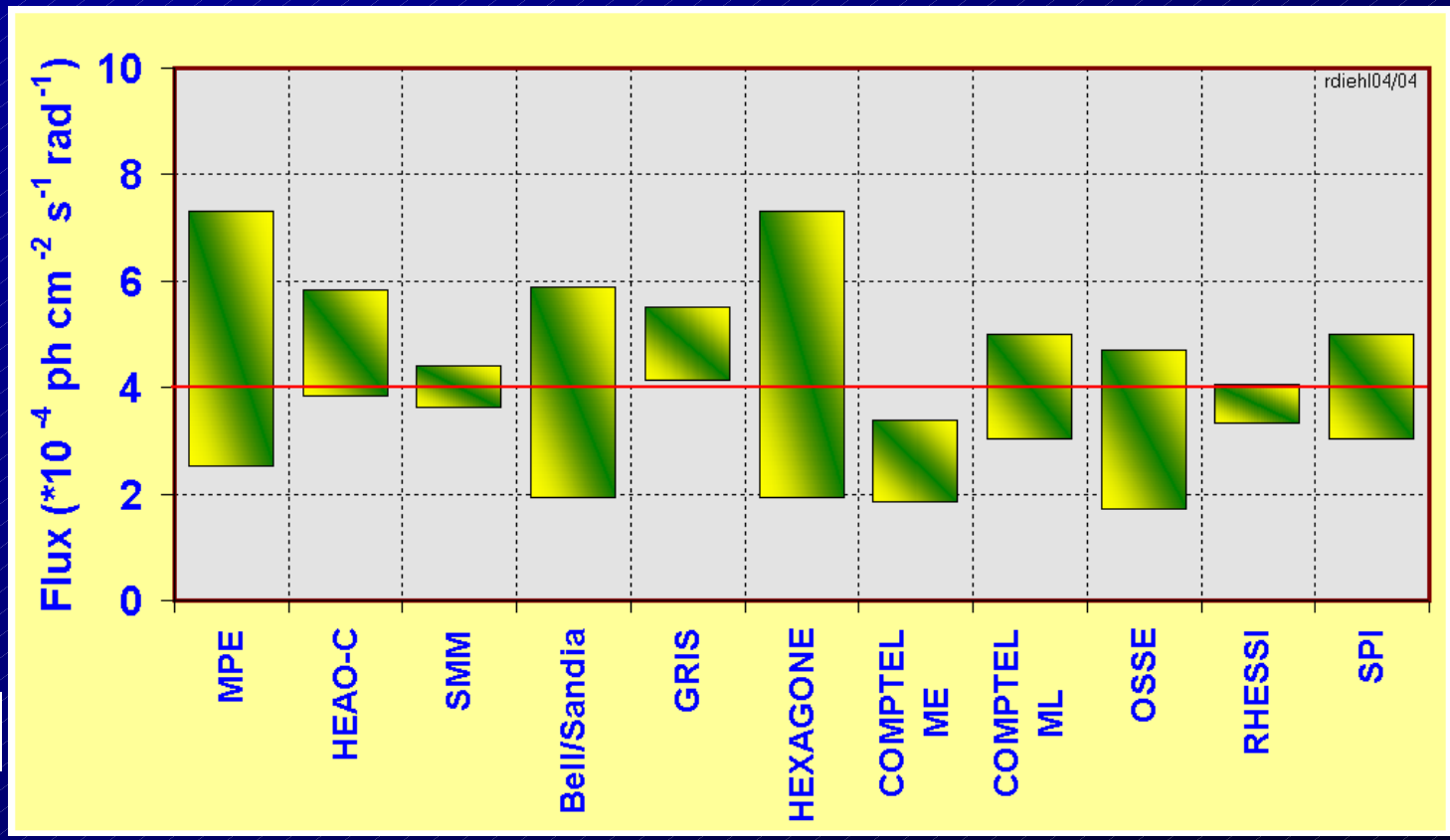




- ^{26}Al Found in ~ALL Candidate Sources

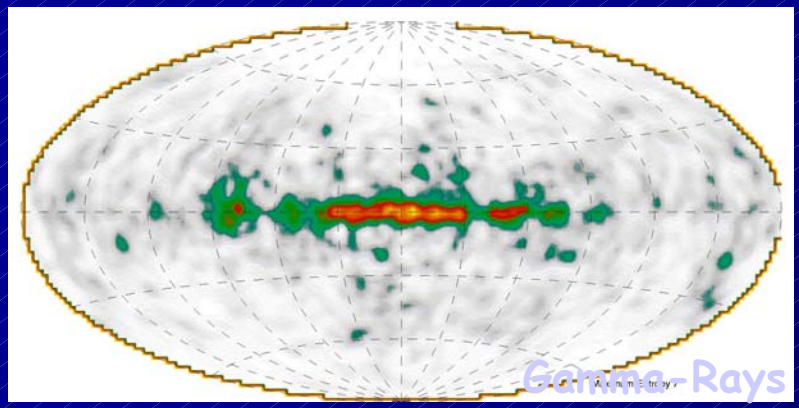
^{26}Al Gamma-Rays from the Inner Galaxy

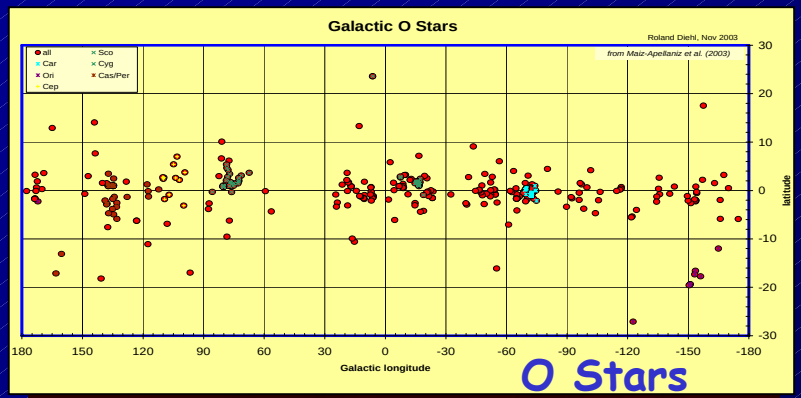


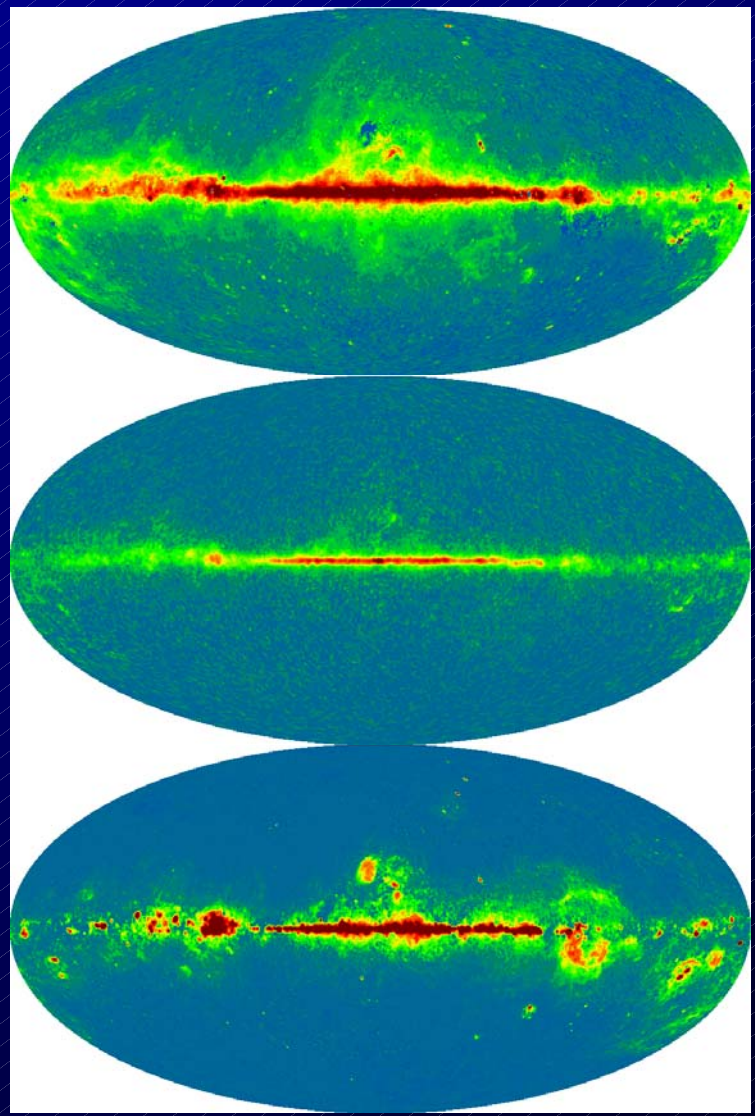


- ☑ Flux ~ 4.x ±1 10^{-4} ph cm^{-2} s^{-1} rad^{-1}
- ☑ Consistent with 2.x M_o of ^{26}Al in Galaxy
- ? Instrumental Systematics? (FoV, Bgd Method)
- ? Large-Scale Emission (local)?
- ☞ Need 3D Spatial Source Distribution

^{26}Al Comes Mainly from Massive Stars







Different Linear Combinations of Narrow-Band Radio Maps (WMAP)

Candidate Sources of ^{26}Al

Object	Yield ~2$M_\odot$?	Spatial Profile	ISM Ionization	Dust Grains
Novae	✓ ✗ ?	✗	✗	✓
AGB Stars	✓ ✗ ?	✓ ??	✗ ?	✓
WR Stars	✓	✓ ✗ ?	✓	✓ ?
cc-SNe	✗ ?	✓ ?	✓	✓

explosive H

shell H

H Burning

core H

core H

explosive O/Ne, ν Process

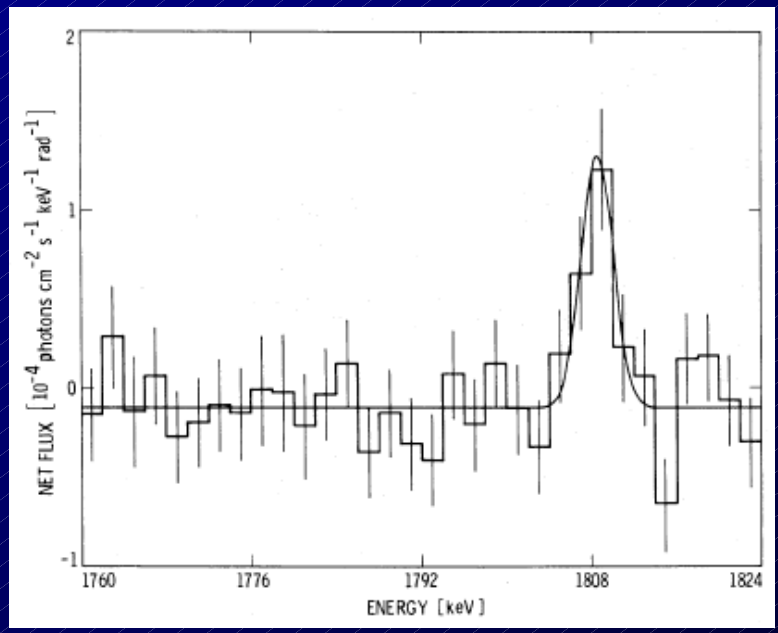
☞ Massive Stars !

☞ But: Which Phase ?

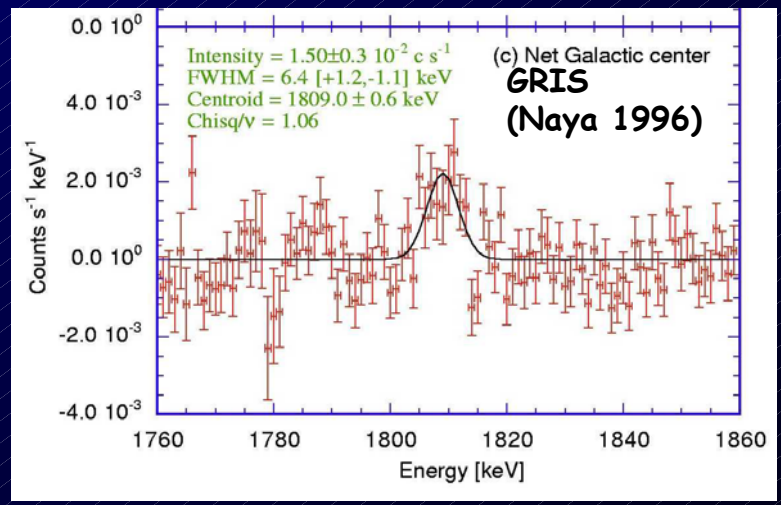
Which Process?

Previous Experiments: High-Velocity ^{26}Al?

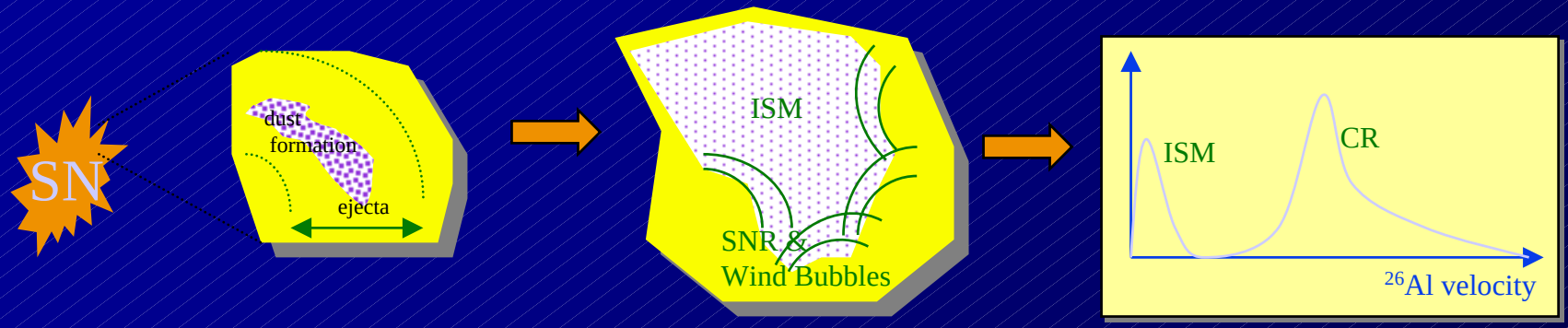
- ☆ HEAO-C Satellite Ge Detector
  - ☞ ^{26}Al Line Discovery (5σ)
  - ☞ Line Width ~Instrumental (<3 keV)
  - ☞ Mayoney et al., 1982, 1984



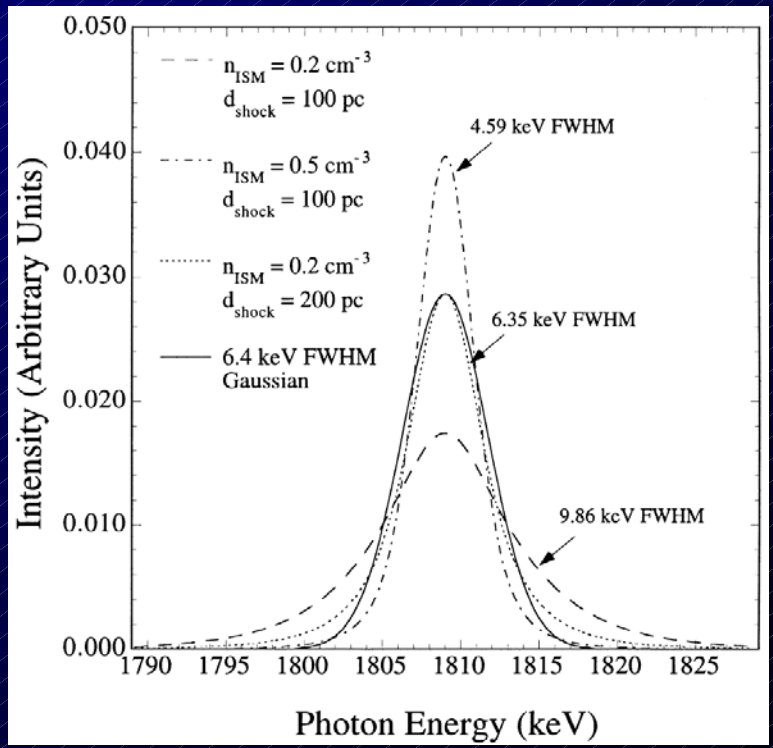
- ☆ GRIS Balloone-Borne Ge Detector
  - ☞ ^{26}Al Line Measurement (7σ)
  - ☞ Line Width >Instrumental, Intrinsic Width 5.4 keV (≅540 km s^{-1} over 10^6 years!)
  - ☞ Naya et al. 1996



^{26}Al After Injection into the ISM



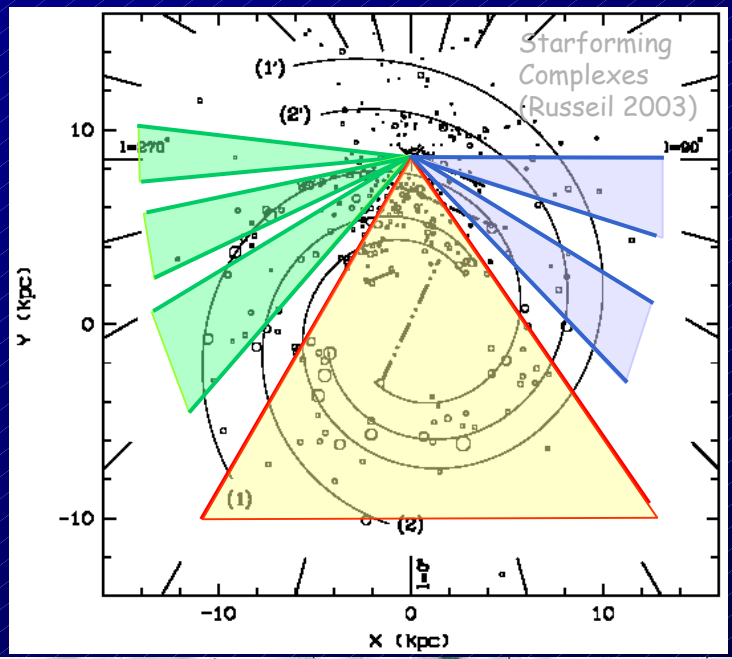
- ☆ Dust Condensation Likely
  - ☞ Al ~most refractory species
  - ☞ Presolar grains measurements
- ☆ Gas and Dust Dynamics Decoupled?
  - ☞ Dust Grains Penetrate SN Shells
  - ☞ Ejection Velocity Maintained?
- ☆ Dust Destruction in Adjacent Swept-Up / SN Shells
  - ☞ Re-Acceleration of ^{26}Al in Dense Clusters of Massive Stars

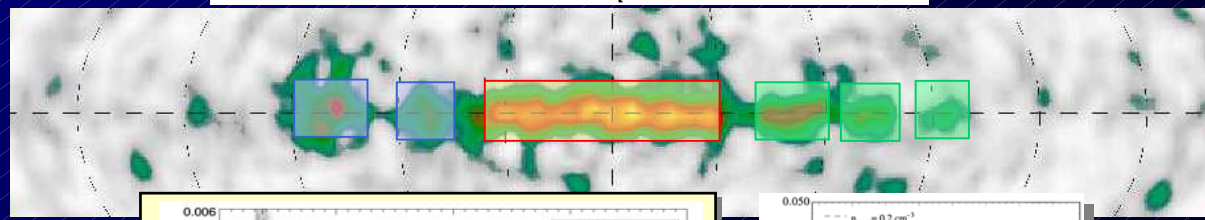


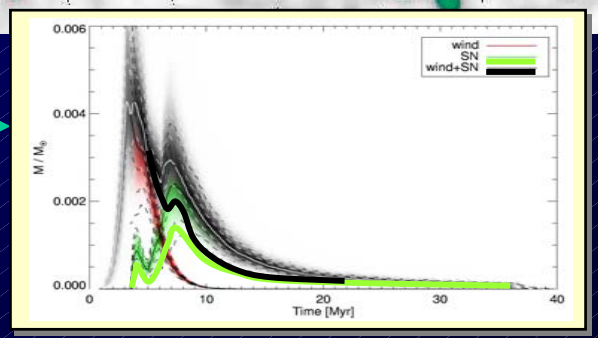
- ☞ Chen et al. 1997
- ☞ Sturner & Naya 1999

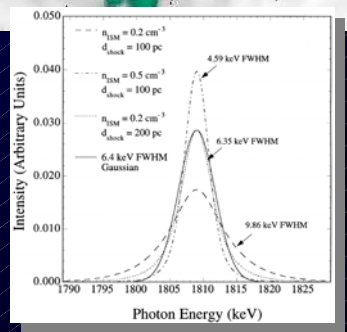
^{26}Al Sources: Localized Studies

- ☆ Irregularity Along Plane of Galaxy
- ☆ Correlated to Galactic Structure
  - ☞ Spiral Arms
  - ☞ Star-Forming Complexes
- ☆ Prominent Lines-of-Sight:
  - ☞ Inner Galaxy
  - ☞ Directions with Many SFR's
  - ☞ Nearby Source Regions
    - Cygnus
    - Vela





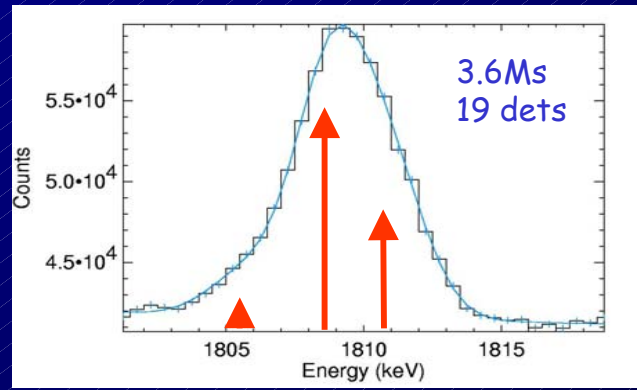


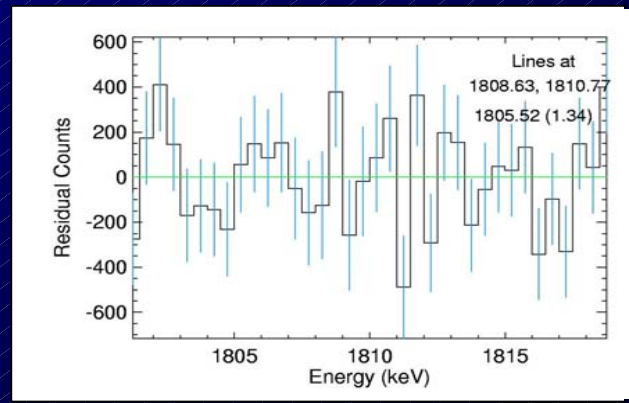


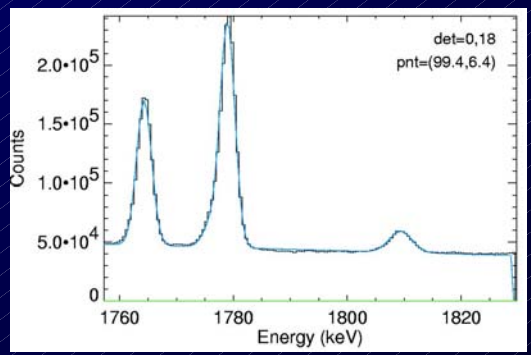
-> Plüschke et al., 2001; Cerviño et al. 2002

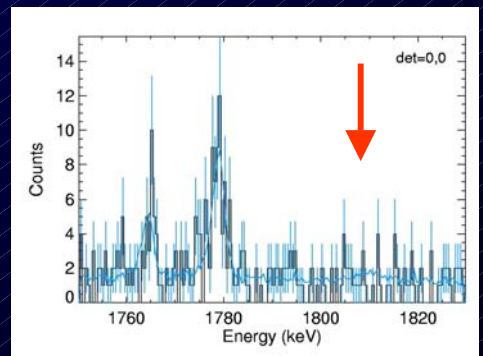
Ge Detector Spectra from SPI

- ☆ Spectral Feature at ~1809 keV:
  - ☞ Complex of Instrumental Lines
    - 1808.63 keV ^{26}Mg, $^{26/27}$Na (^{27}Al (p,α)+ n capture activation)
    - 1810.77 keV ^{56}Co, ^{56}Mn
    - 1805.5x keV? (degradation / origin tbd)
  - ☞ Variable Activation
    - Radioactivity Build-Up
    - CR Flux Variations (Belts, Sun)
  - ☞ Expected ^{26}Al Signal: ~2-4%
- ☆ Analysis Challenges
  - ☞ Understand Background
    - ON/OFF Re-Normalizations
    - Activation History
    - Line Identifications
  - ☞ Model / Fit Background Properly
  - ☞ Low-Number Statistics
    - >40000 Spectra (GCDE 1+2)
  - ☞ Imaging Spectroscopy
    - ON/OFF Spectra Checks
    - Fitting Model Skymaps
    - Iterative Deconvolutions



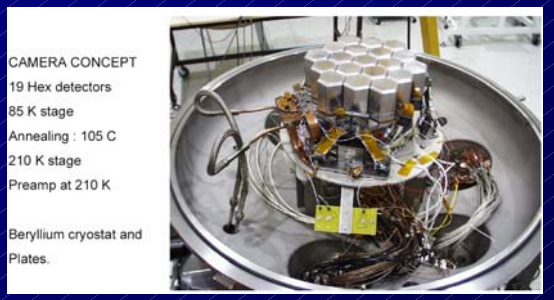




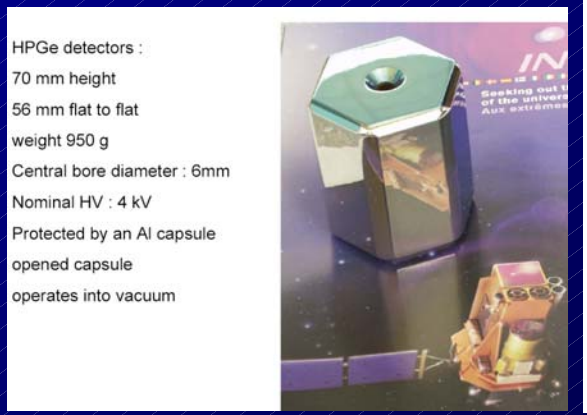


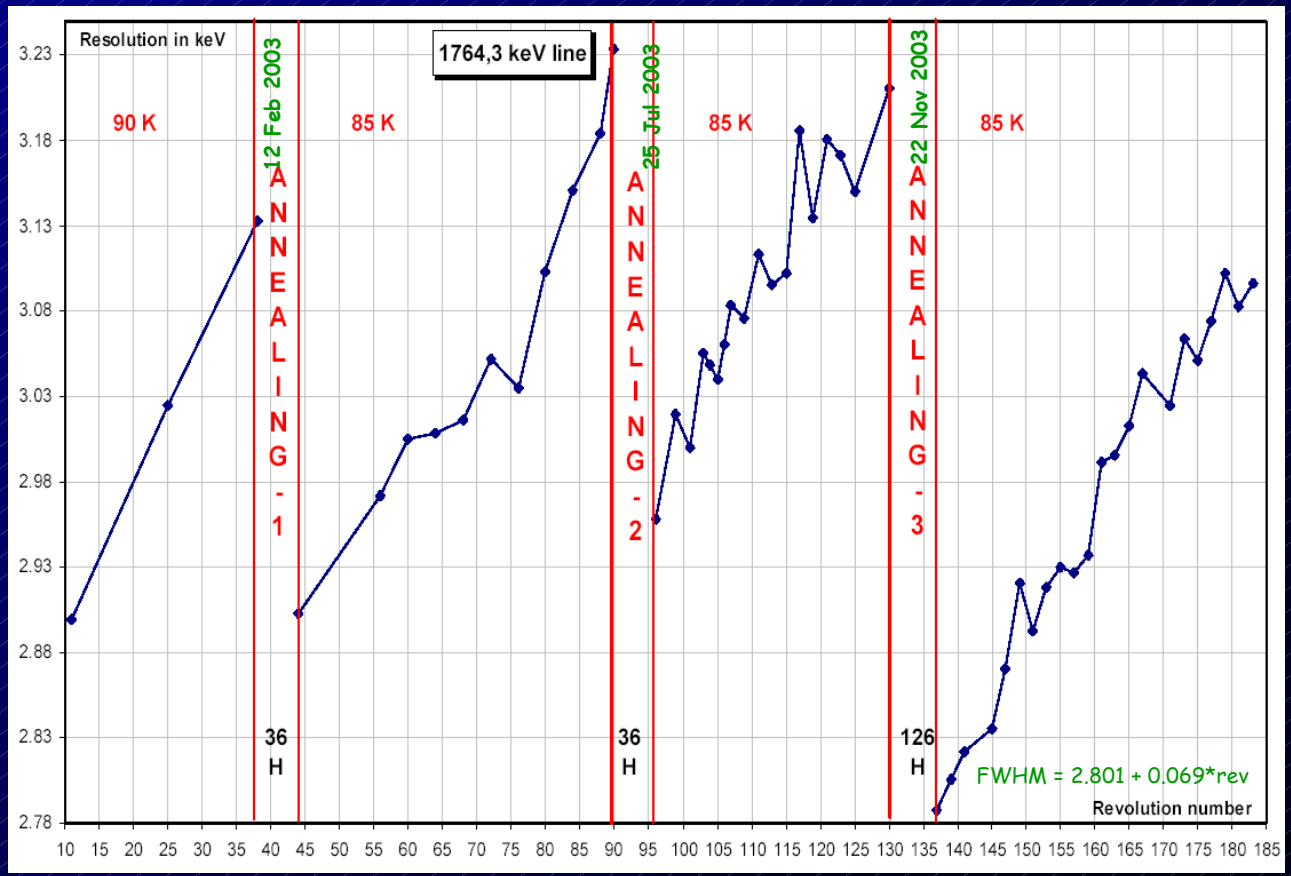
Maintaining High Spectral Resolution

- **Degradation**
  - ~2% per Orbit, ~20% in 6 Months (@1 MeV)
  - ~35% Slower at 85K

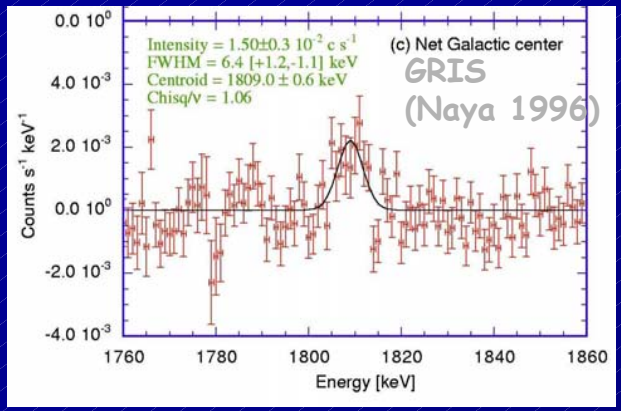


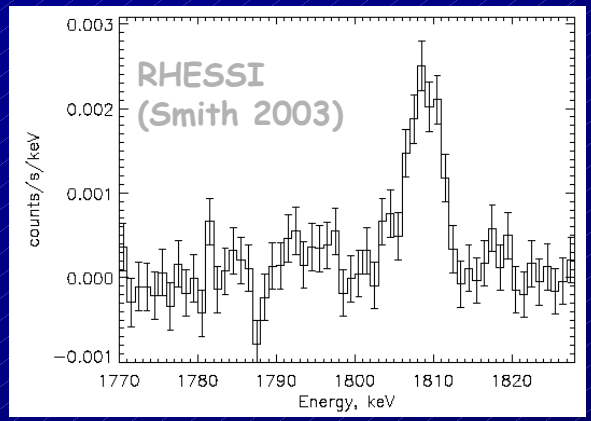
- **Annealing:**
  - 126(36) hrs at 105C
  - Few hrs at 90K

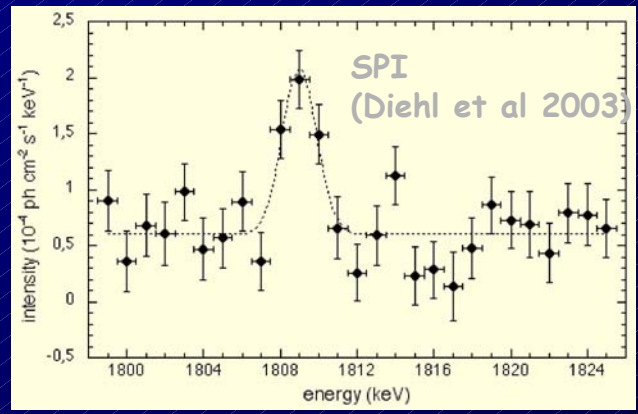




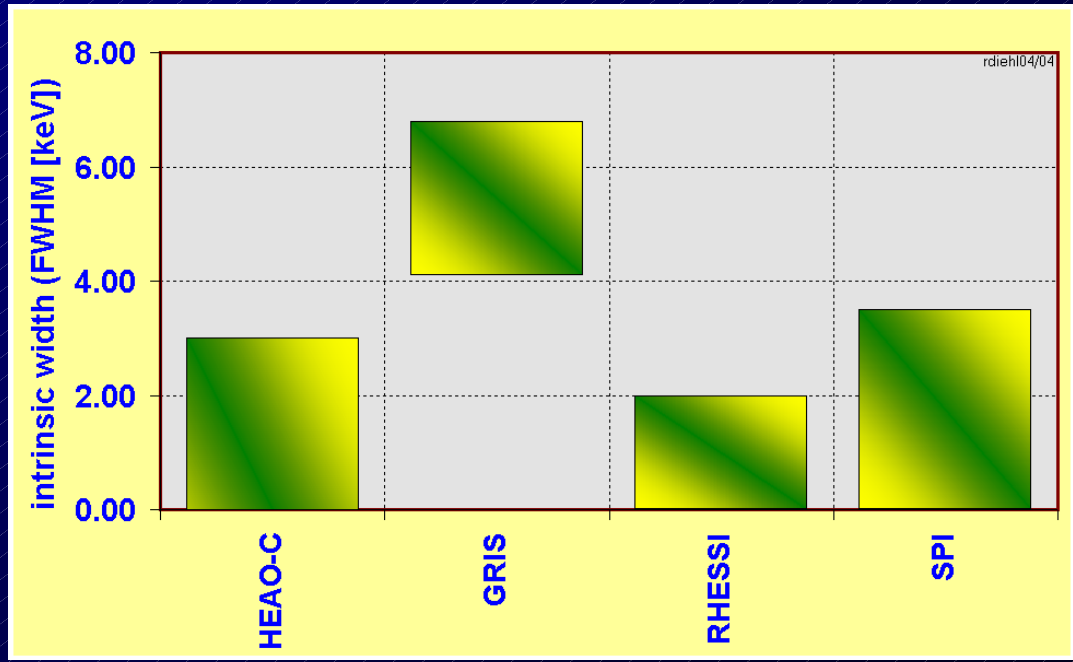
^{26}Al Line Width: Velocity of ^{26}Al in ISM







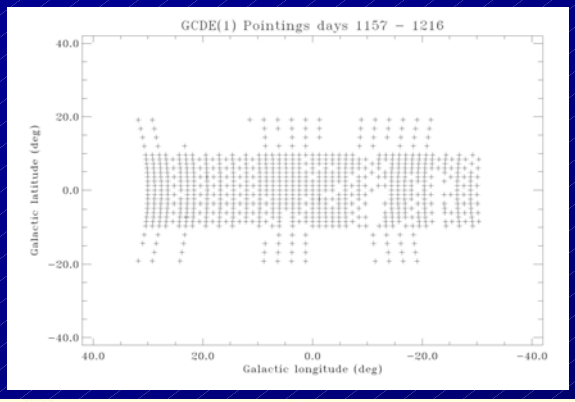
- Broad Line was Difficult to Understand
  - ^{26}Al on Dust?
  - Huge ISM Cavities?
  - *Chen et al. 1997*
- Issue Dissappeared?

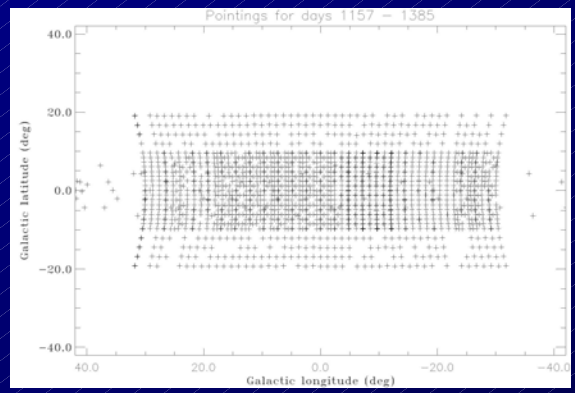


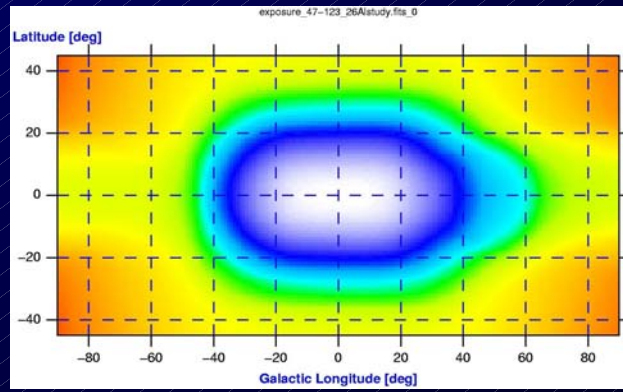
SPI's Inner Galaxy Survey

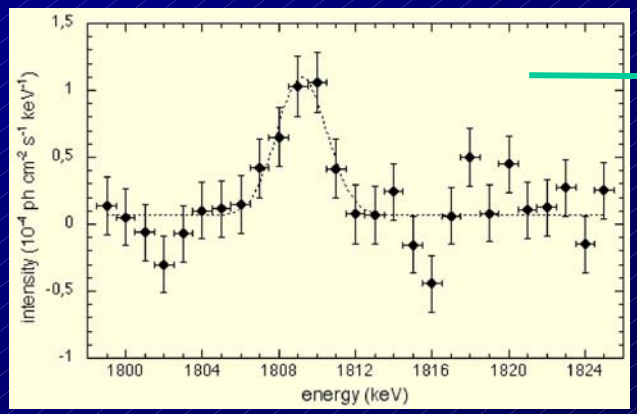
INTEGRAL Core Program: "GCDE"

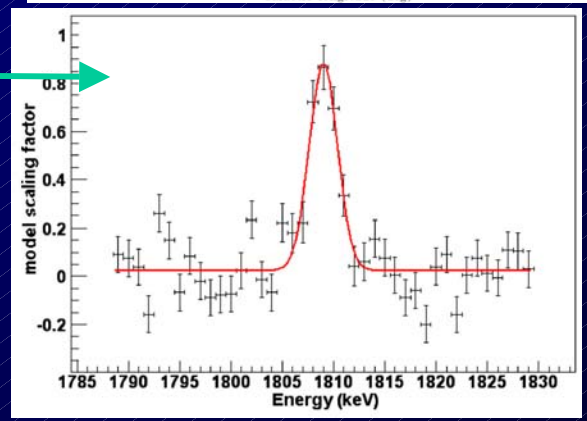
- ☆ Science Exposures
  - ☞ GCDE1: ~1 Msec
  - ☞ GCDE1+2: ~3.6 Msec







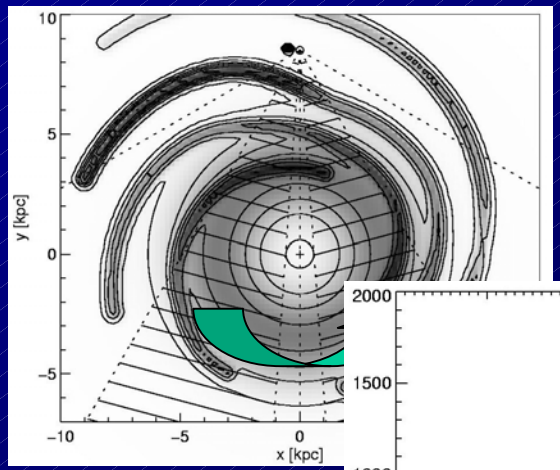


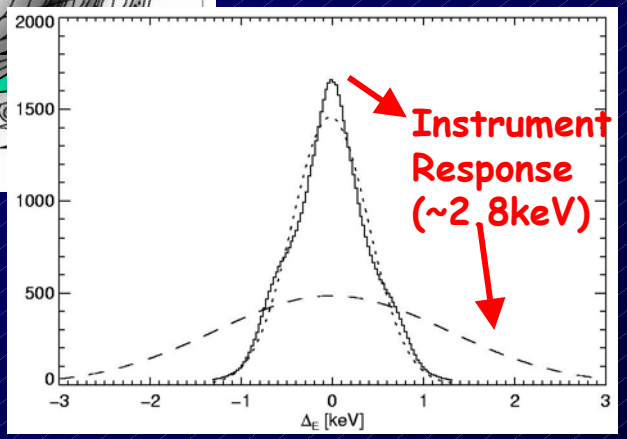


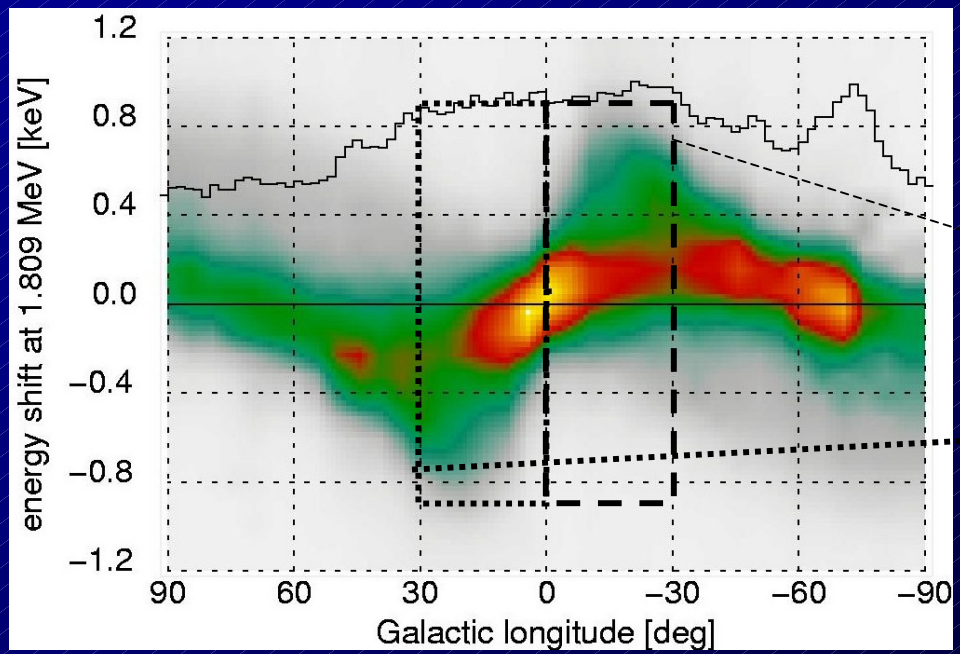
- ☞ Detailed Re-Analysis in Progress (Bgd Model, Systematics Checks…)

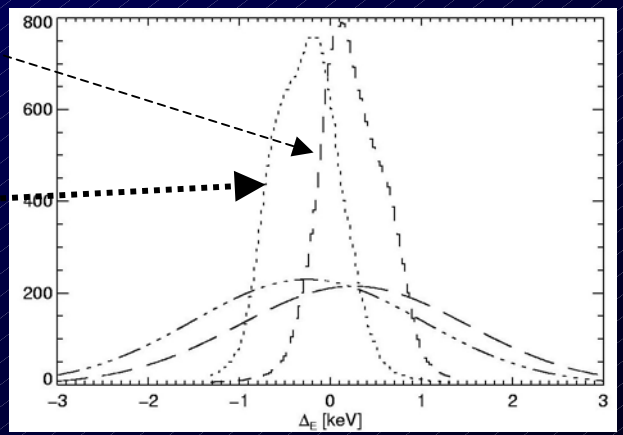
Galactic Rotation and ^{26}Al Source Measurements

- ☆ Line Centroid <-> Rotation
- ☆ East/West Shift ±0.25 keV
- ☆ Detectable with SPI Ge Detectors ?



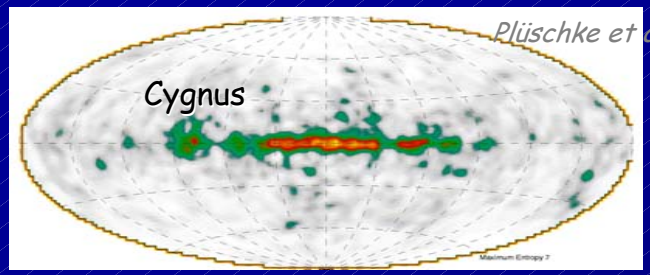




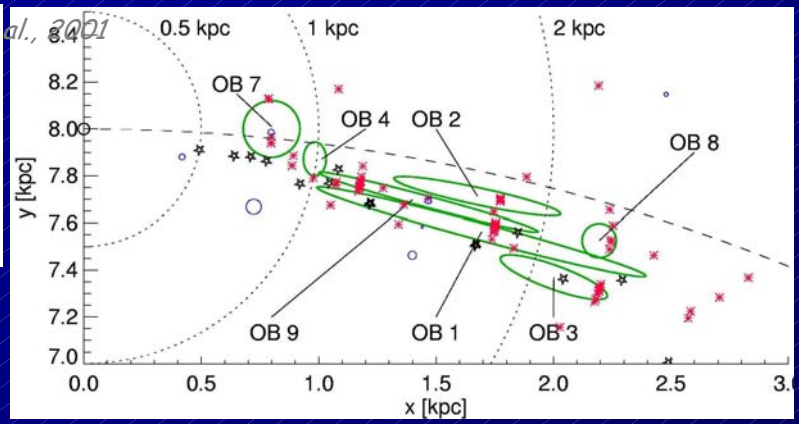


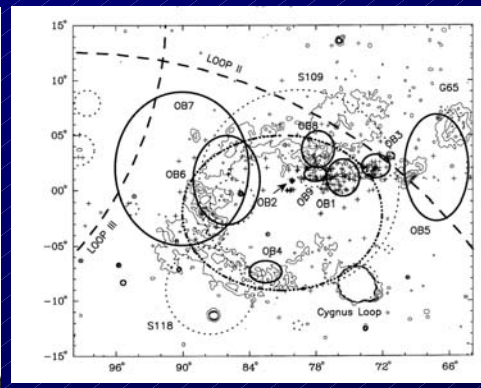
☞ *Kretschmer et al. 2003 & Poster here*

The Cygnus Region



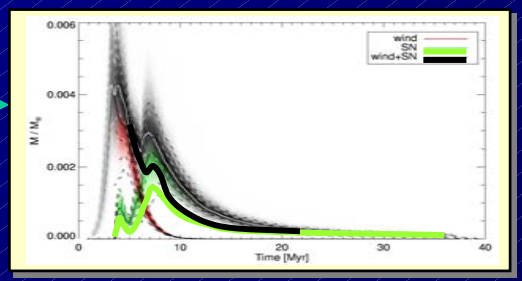
Plüschke et al., 2001





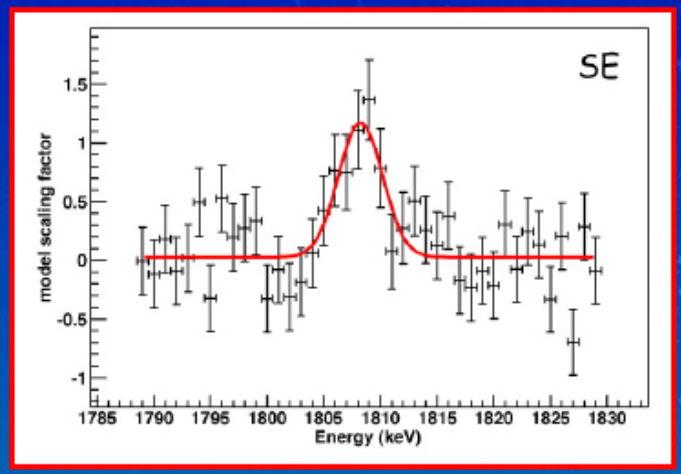
☆ Well-Confined Candidate Sources

- ☞ 9 OB Accociations
- ☞ Cyg OB2 Dominating
- ☞ Test Laboratory for Age Discrimination of Sources



-> Plüschke et al., 2001; Cerviño et al. 2002

Knödlseder et al., 5th INTEGRAL Workshop 2004

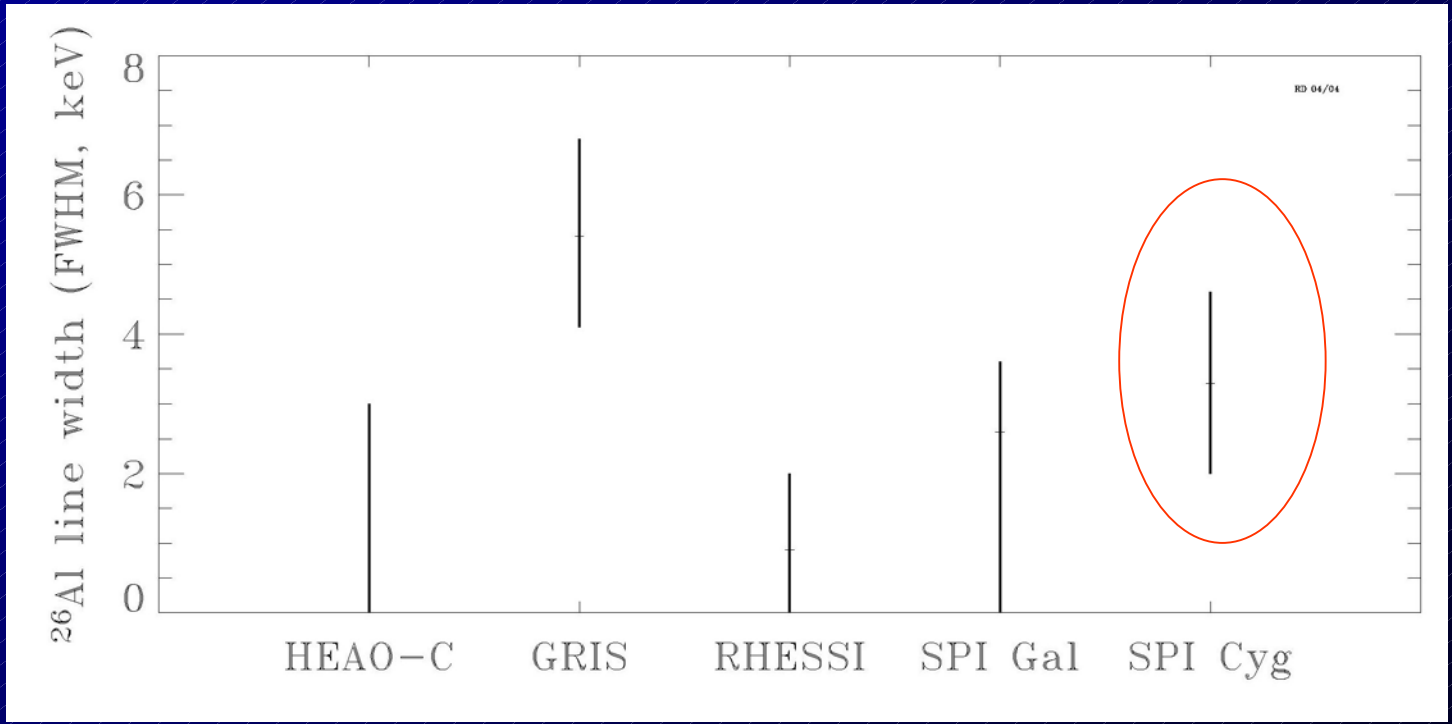


Flux : $(7.2 \pm 1.8) \times 10^{-5}$ ph cm^{-2} s^{-1}
Position : 1808.4 ± 0.3 keV $\Rightarrow v_{rad} = -41 \pm 50$ km s^{-1}
Width : 3.3 ± 1.3 keV $\Rightarrow \Delta v = 550 \pm 210$ km s^{-1}

DRAO radio image of ionising massive star clusters in Cygnus X that are at the origin of the ^{26}Al production detected by SPI

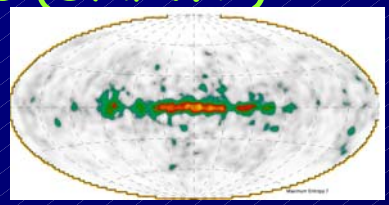
Cygnus: Young Clusters of Massive Stars

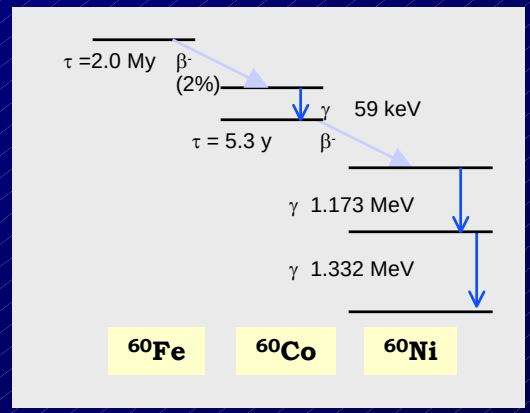
- ☆ Indications of Moderate Line Broadening
  - ☞ ~300 km s^{-1}
- ☆ Cyg OB2: High Density of Massive Stars
  - ☞ Wind Interactions, Large Hot Bubbles??

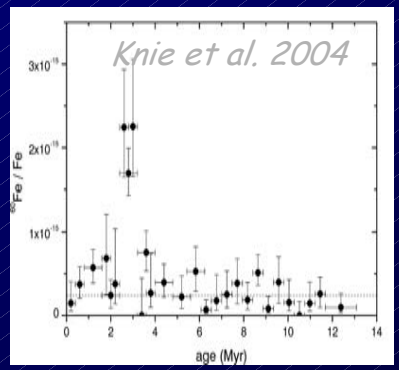


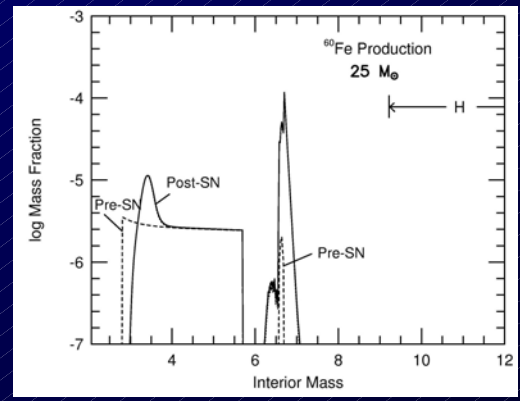
Diffuse ^{60}Fe in the Galaxy

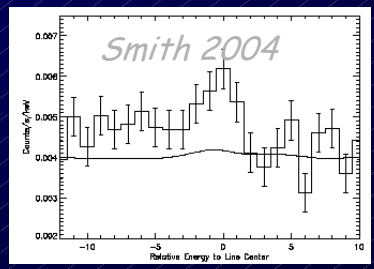
- ^{60}Fe Produced by n Capture on ^{56,58}Fe in cc-SN
  (O-Ne Shell, Base of He Shell)
- ~No ^{60}Fe During WR Phase
- -> Diagnostic of ^{26}Al Sources (SN/WR)
  - Distributed as ^{26}Al?
- Detection on Earth
  - Nearby SN 2.8 My ago?
- RHESSI Detection (?)
  - Significance 2.6 σ
  - 10.1 ± 3.8% of ^{26}Al Intensity

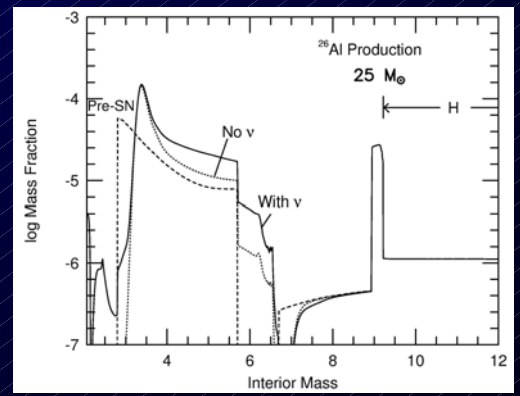


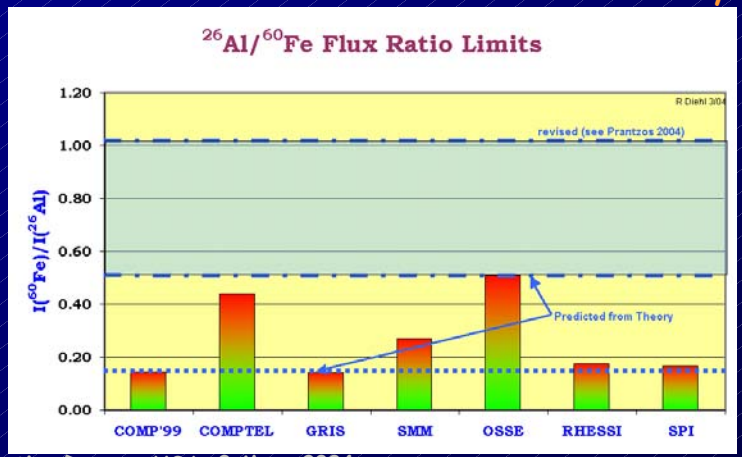












Annihilation Gamma-Rays from the Inner Galaxy

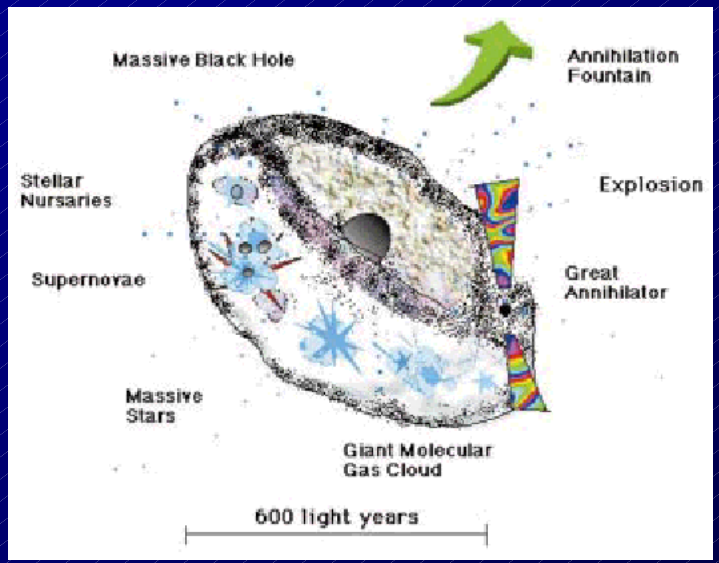
Roland Diehl

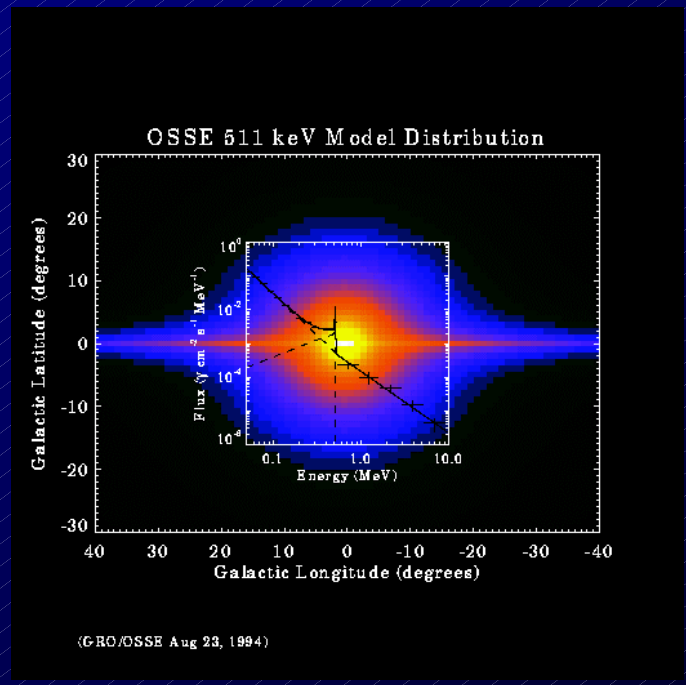
Positrons from Nuclear Reactions

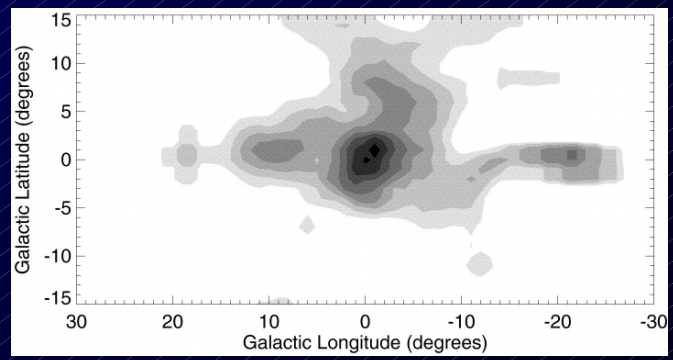
- Annihilation Gamma-Rays @ 511 keV
- OSSE Map of Inner Galaxy

->

- ☆ Nucleosynthesis, Galactic-Disk Sources
- ☆ Other Exotic Sources? ("PLE"?)







CGRO-OSSE
ref's:
Purcell et al. 1997;
Kinzer et al. 1998;
Milne et al. 1999

Positron Sources in Inner Galaxy

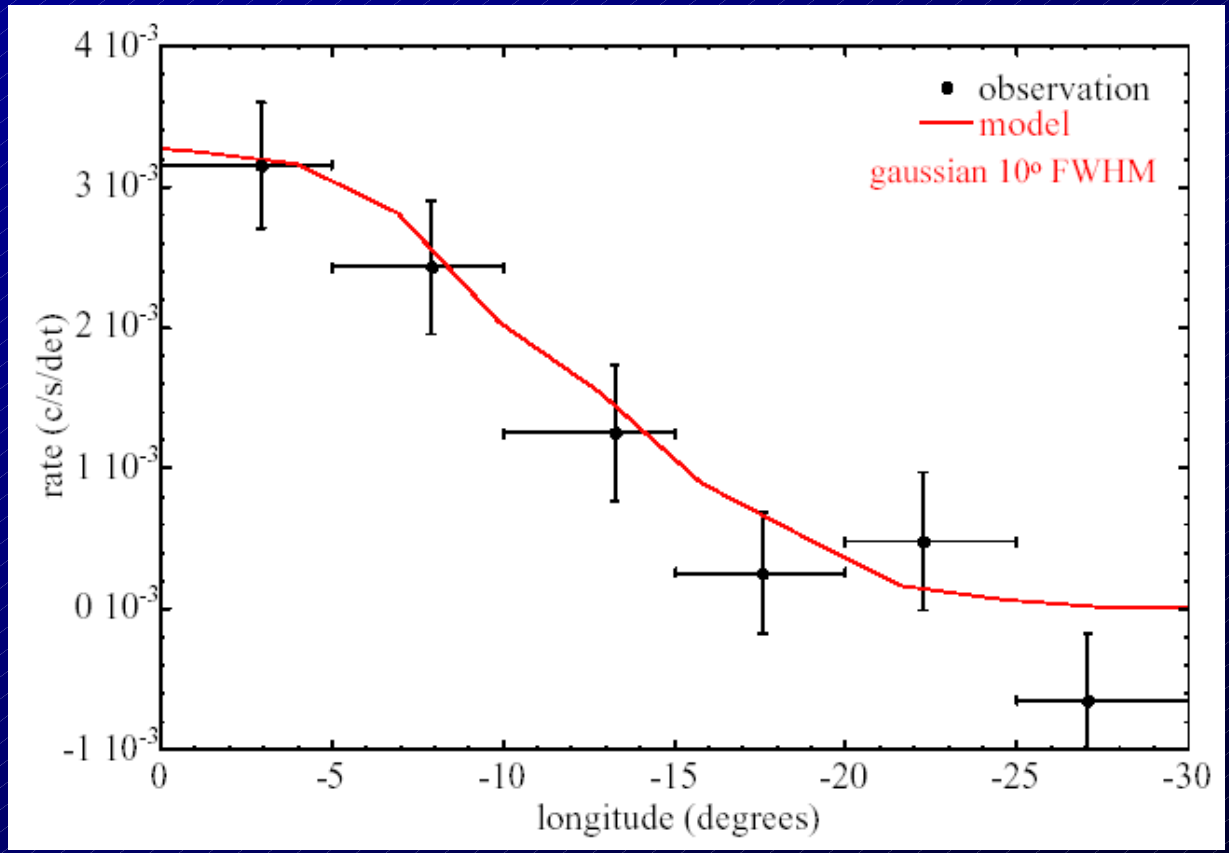
- ☆ Radioactivity from Nucleosynthesis
  - ☞ ^{26}Al from Various Sources
  - ☞ ^{56}Co from Supernovae Ia
  - ☞ Various β+ Decays from Novae
- ☆ Pulsars
- ☆ Accreting Binaries
- ☆ Cosmic-Ray Interactions with Ambient Gas
  - ☞ π+...

- ☆ Positron Annihilation:
  - ☞ Need e- and Momentum Balance
  - ☞ Lifetime Depends on ISM / CSM (->10^5 y?)

- ☆ *Spatial Distribution???*

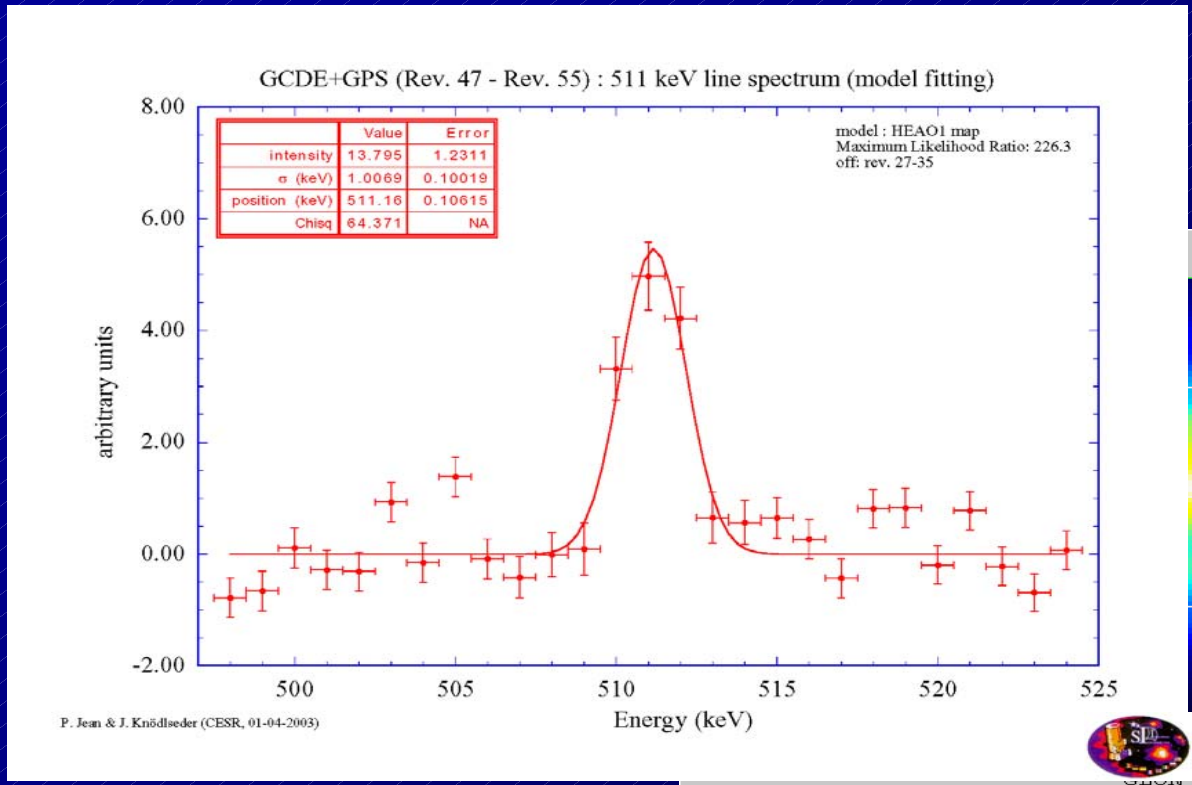
511 keV Emission Morphology

- ☆ Confirm ~Gaussian Fall-Off with FWHM~10°
  - ☞ *Jean et al., 2003*



- ☆ Speculations about Sources Adding to Radioactivities
  - ☞ *GRB/Hypernovae* *(Casse et al. 2003)*
  - ☞ *Dark-Matter Annihilation* *(Boehm et al. 2003)*

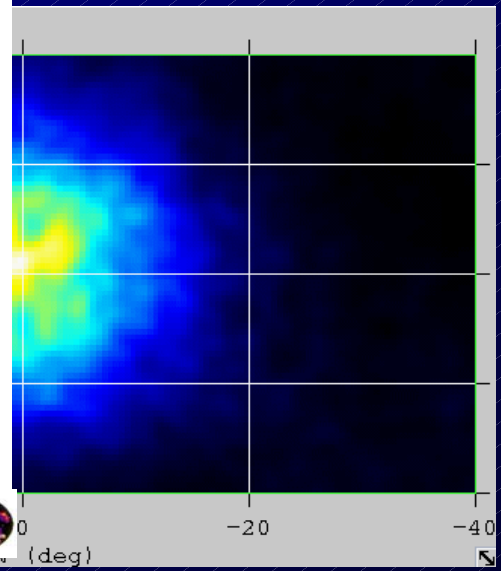
SPI: e^+ Annihilation in the Inner Galaxy



INTEGRAL/SPI: 6.1+/-1.1 x 10^{-4} $cm^{-2}s^{-1}$

CGRO/OSSE: 6.5+/-1.5 x 10^{-4} $cm^{-2}s^{-1}$

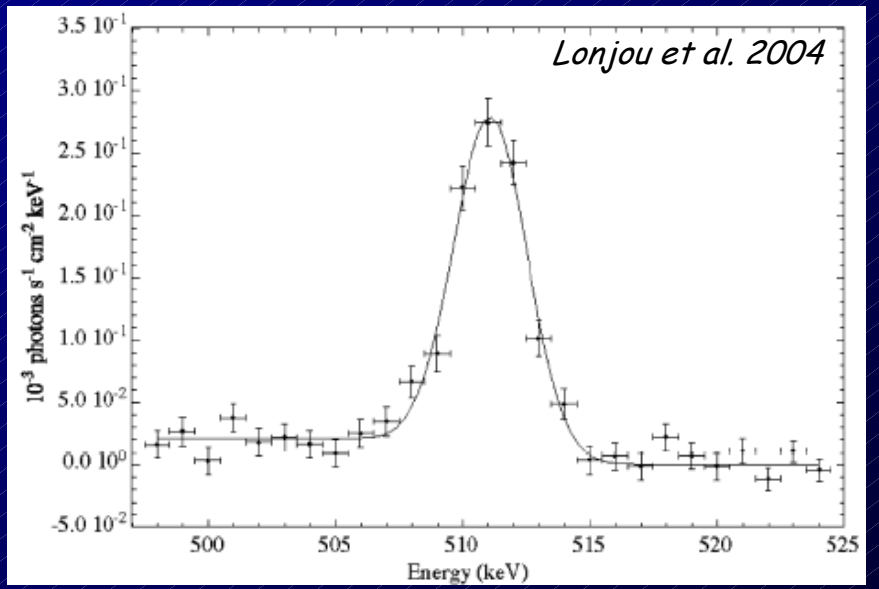
Jean et al 2003
Knödlseder et al. 2003



- Annihilation of e^+ (from Radioactivity, Pulsars, Jet Sources…)
  - ☆ Annihilation Line at 511 keV, ~ as Expected
  - ☆ Emission Region ~Extended without Major Structure

511 keV Emission Line: Flux, Shape

- ☆ *Since Jul 2003:*
  - ☞ *Improved Bgd Modeling*
  - ☞ *Imaging & Spectral Study*



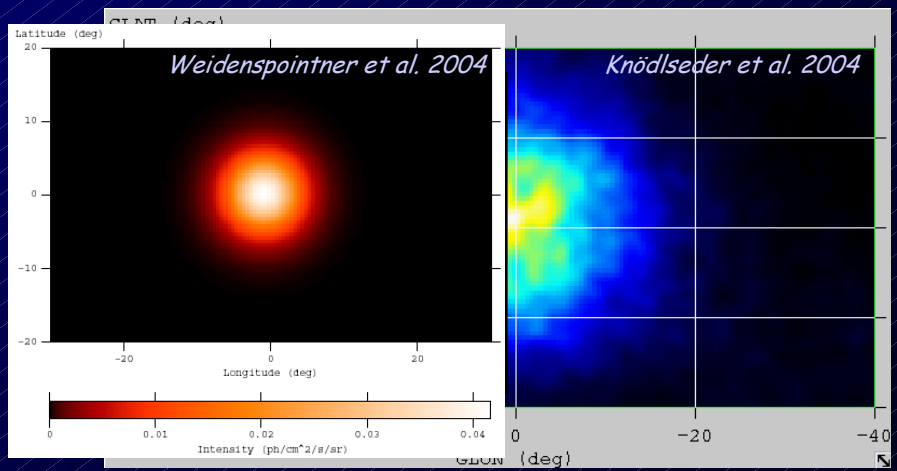
Results

- ☆ Spectral Line:
  - ☞ $I = 0.96\ ^{+0.21}_{-0.14}\ 10^{-3}$ ph cm^{-2} s^{-1}
  - ☞ FWHM = $2.76\ ^{+0.30}_{-0.33}$ keV

- ☆ Morphology:
  - ☞ 6…12° (2σ, FWHM)
  - ☞ Bulge/Disk > 0.8

->

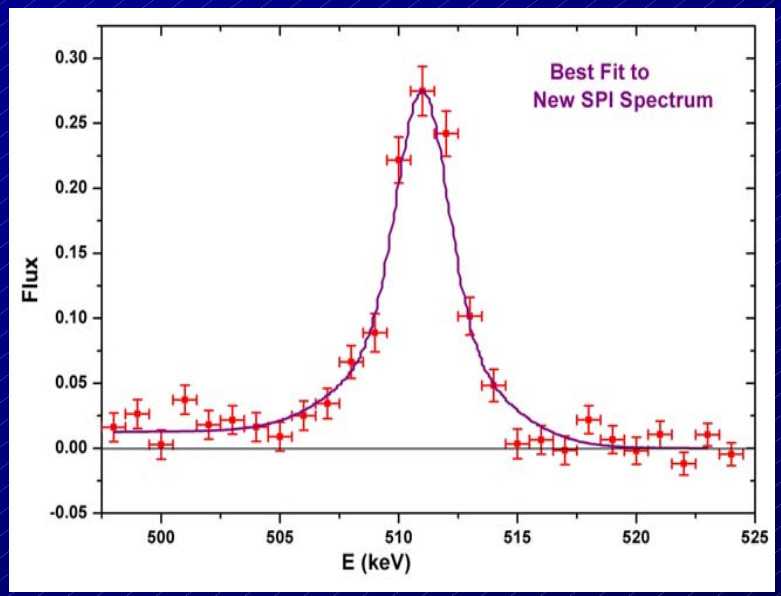
- ☆ Annihilation Rate (@GC)
  - ☞ $1.4\ ^{+0.6}_{-0.4}\ 10^{43}$ s^{-1}

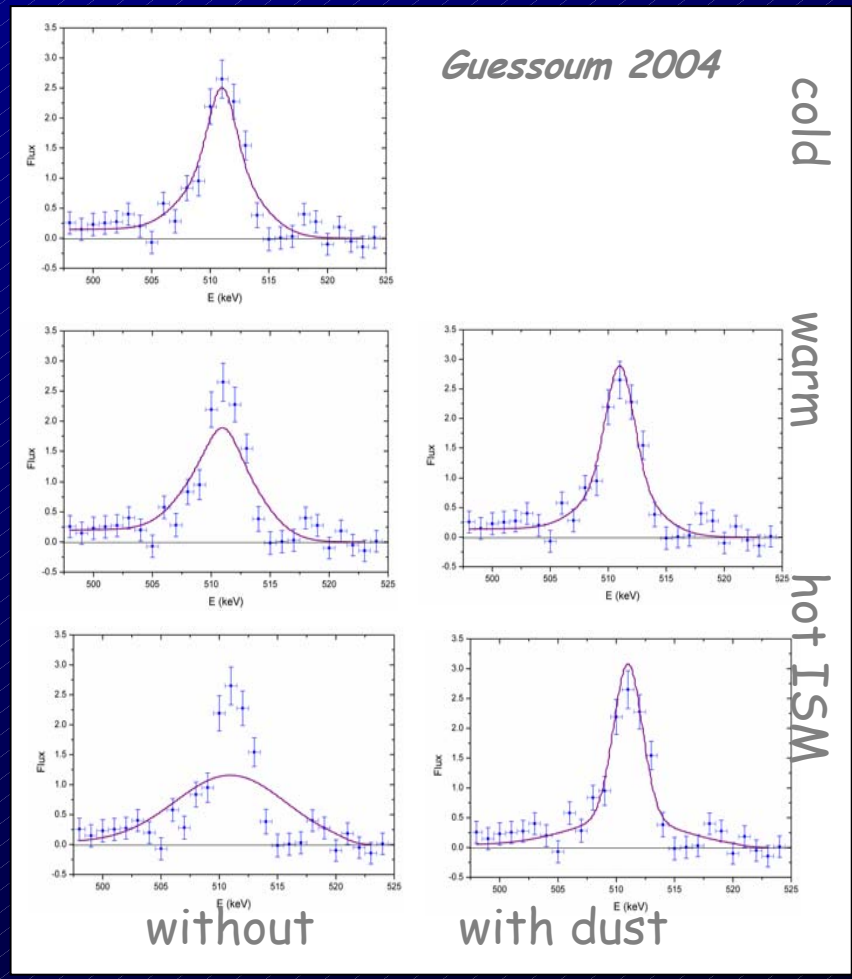


Annihilation Conditions: Which ISM Phase

- Diversity of Annihilation Processes:
  - Direct Annihilation with Free or Bound e-
  - Formation of a Positronium Atom
  - At MeV Energies
  - After Slowing Down
  - On Surfaces of Dust

☞ Momentum Balance <-> Line Width

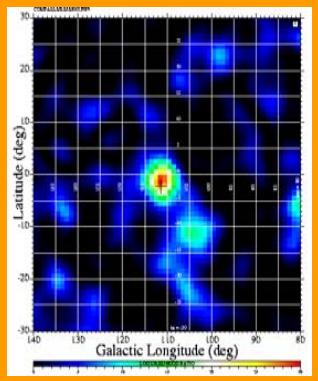


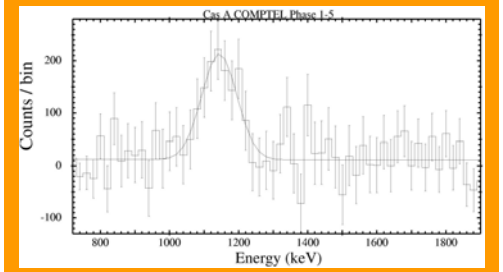


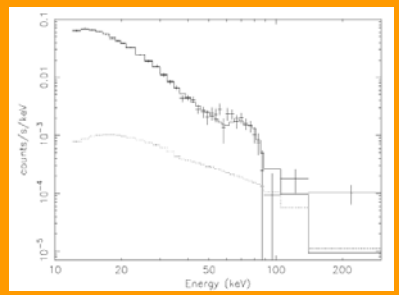
Cold	Warm Neutral	Warm Ionized	Hot	Dust
0.20 ± 0.25	0.00 ± 0.20	0.10 ± 0.30	0.20 ± 0.25	0.50 ± 0.20

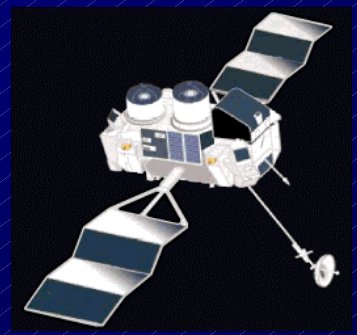
Supernova Nucleosynthesis

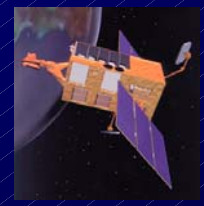
Core-Collapse Supernovae: ^{44}Ti from Cas A

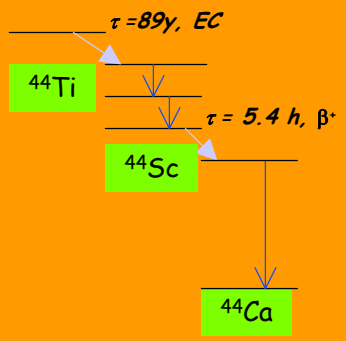


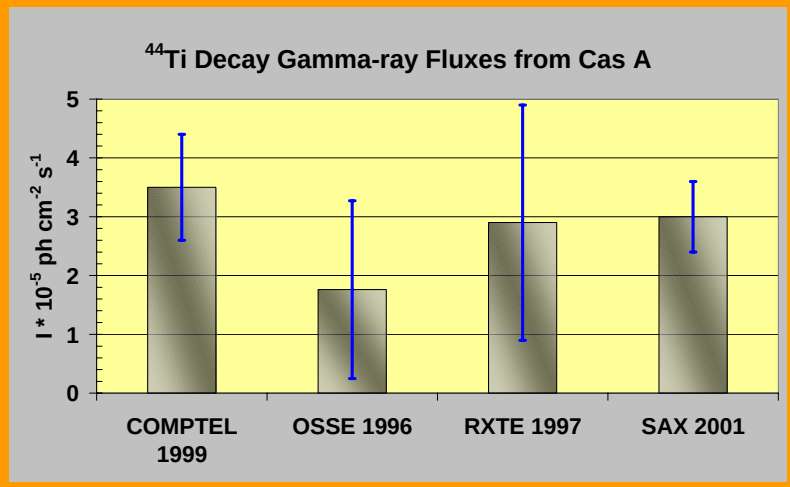












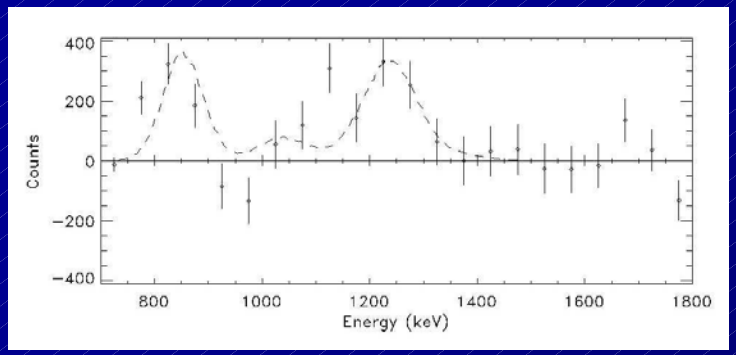
SPI Analysis in Progress

- ^{44}Ti Decay: τ~89y
- Difficult γ-Ray Region (78, 68, 1157 keV)
- -> ^{44}Ti Ejected Mass > Models (?)

-> Young SNR
-> Uncertain Iγ
~0.8-2.5 10^{-4} M_o

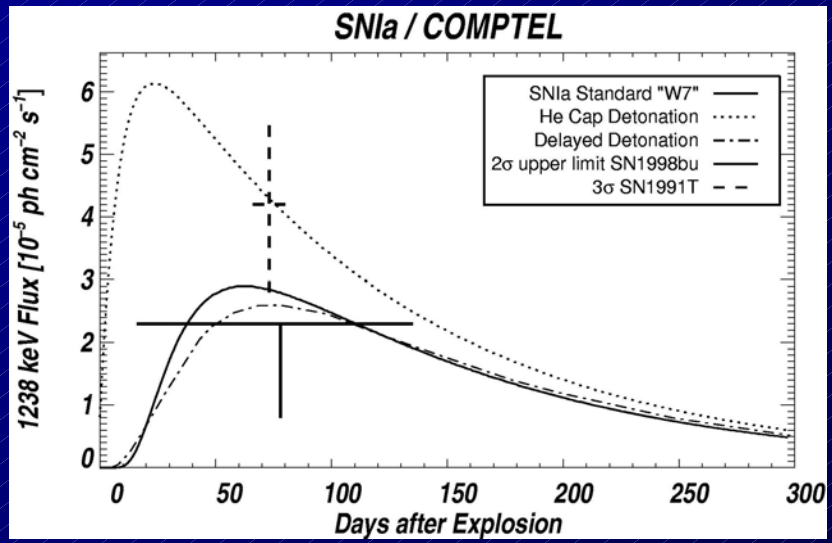
Roland Diehl

Gamma-Rays from Supernovae Ia



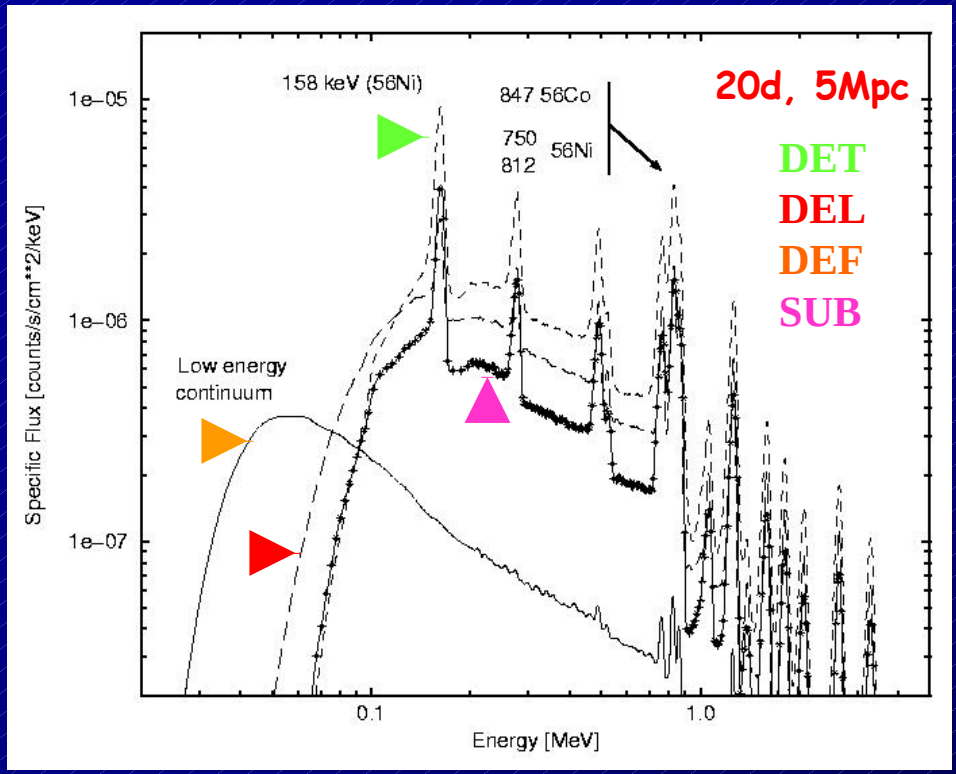
- Rarely SNIa ^{56}Ni Decay Gamma-Rays are Above Instrumental Limits (~10^{-5} ph cm^{-2} s^{-1})
  - ~2 Events / 9 Years CGRO
  - ~1 Event / Year INTEGRAL Mission?

- **COMPTEL**
  - **Signal from SN1991T (3σ) (13 Mpc)**
  - **Upper Limit for SN1998bu (11 Mpc)**

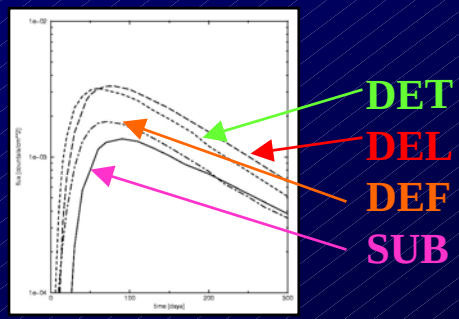


- The ^{56}Ni Power Source: 0.5 $M_\odot$ of ^{56}Ni ??
- Which Burning Profile and Mixing ?

SNIa Model Type Diagnosis through γ-Rays



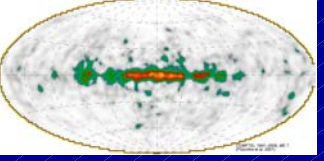
Isern, 2001; 2003



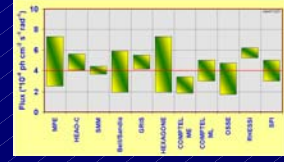
- Deflagration Model: No Lines (^{56}Ni Burried)
- Other Models: Prominent ^{56}Ni Lines
- ^{56}Ni Most Prominent in SUB/DET, LE Continuum Stronger in DEF/DEL (low-Z Elements)

- Light Curves Very Similar Among Models
- Line Profiles, too

- INTEGRAL Awaits Opportunity (~1/yr)



Summary



- SPI ^{26}Al Results Confirms Previous Measurements
  - ☆ Line Intensity in Inner Galaxy ~4 10^{-4} ph cm^{-2} s^{-1}
  - ☆ Inner Galaxy and Cygnus are Bright Emission Regions
  - ☆ 1809 keV Line is Not (much) Broadened
- SPI Positron Annihilation Mapping Has Begun
  - ☆ Intensity and Crude Distribution are as Expected
  - ☆ A Grain Component is Required to Explain Line Shape
- Issues Remain
  - ☆ ^{26}Al from Massive Stars: as Giants, WR Stars, or SN ?
  - ☆ Positron Annihilation: Symmetric Bulge? Disk Component?
  - ☆ See ^{44}Ti from SN1987A?
  - ☆ SNIa Model Discrimination from ^{56}Ni?
  - ☆ ^{22}Na from Novae?
- INTEGRAL Will Advance Nucleosynthesis Studies
  - ☆ ^{44}Ti Line Profile Measurements for Cas A
  - ☆ Resolving the ^{26}Al View Towards the Inner Galaxy
  - ☆ Sources and ISM Dynamics / Morphology in Source Regions
  - ☆ Annihilation Conditions in Nucleosynthesis Regions