INTEGRAL School, Les Diablerets (CH), March/April 2000

"Radionuclides and Gamma-Ray Line Astronomy"

Invited Lectures
by
Roland Diehl
MPE Garching

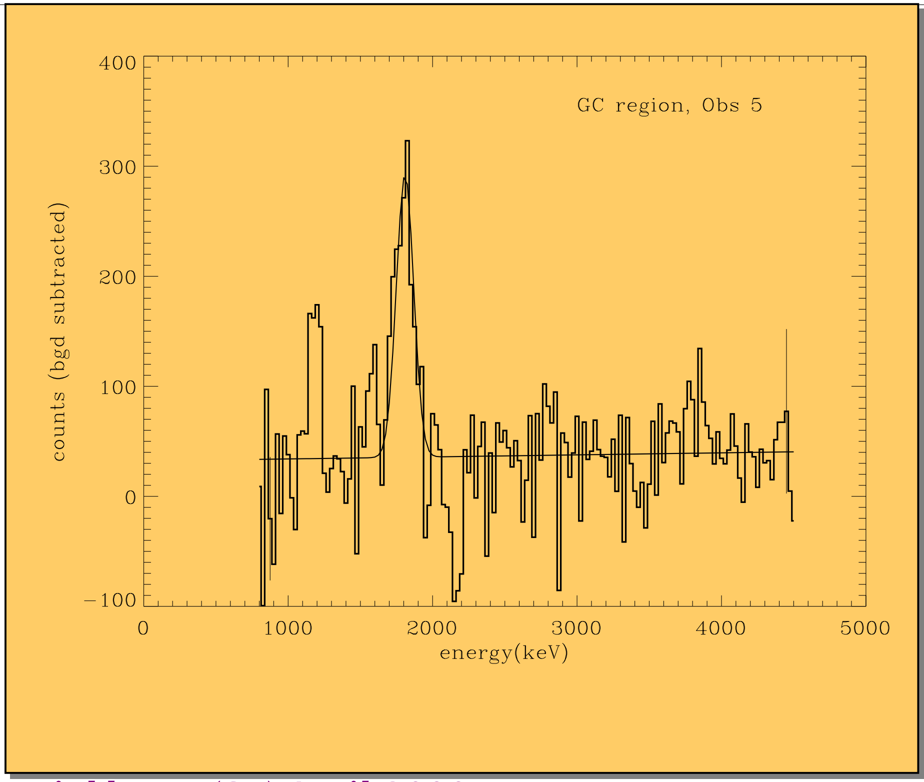
- Part I: Gamma-Rays and Nucleosynthesis
  - Nucleosynthesis Processes
  - Radioactive Decay
  - Cosmic Nucleosynthesis Sites
- Part II: Observed Cosmic Radioactivities
  - Supernovae
  - Diffuse Radioactivities & Various Connections

Part II

- **Observed Cosmic Radioactivities**
  - a) Supernovae
  - b) Diffuse Radioactivities

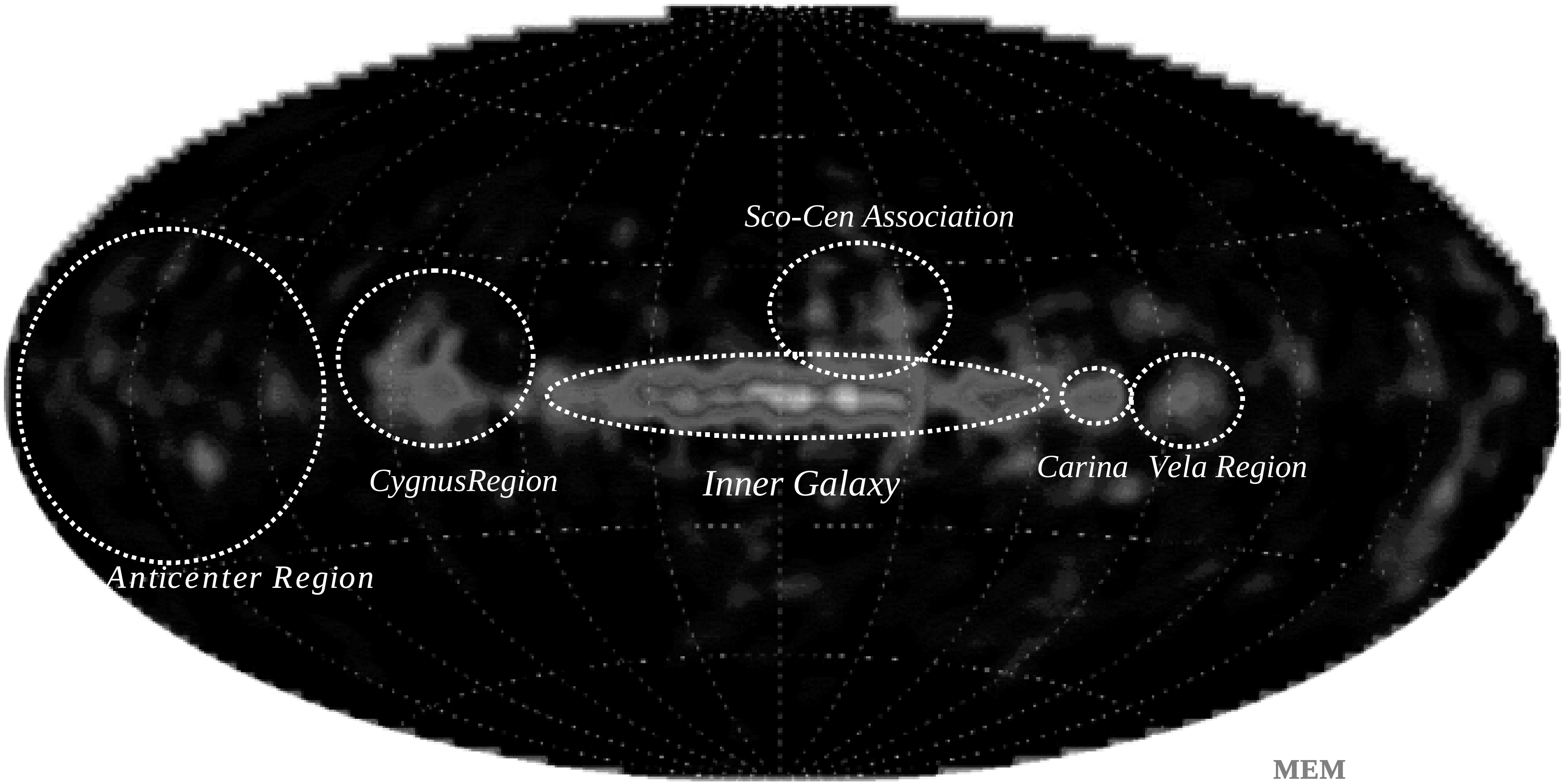
COMPTEL Measurement of ^{26}Al in 1.809 MeV Line

- **Instrumental Energy Resolution ~ 8% FWHM**
- **Measured Counts in 1.809 MeV Line (1.7-1.9 MeV):**
  - ☞ ~ 3000 from GC Region
  - ☞ ~ 90000 from all-Sky
- **Signal/Background Ratio ~2%**
- **Instrumental Background Modelled from Adjacent Energy Bands**
- **Spatial Resolution ~4° (= Response FWHM)**



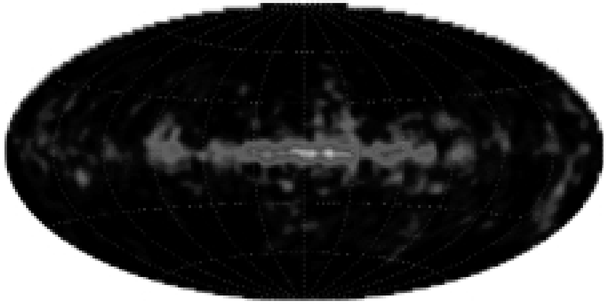
COMPTEL All-Sky Image at 1.8 MeV:

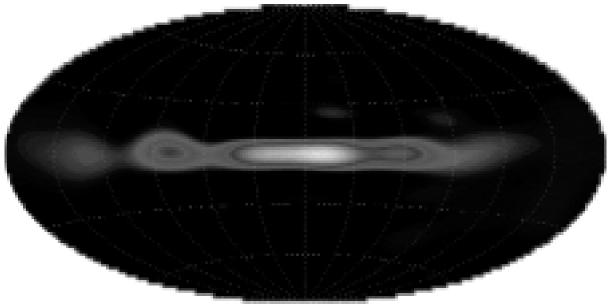
^{26}Al Nucleosynthesis in the Galaxy

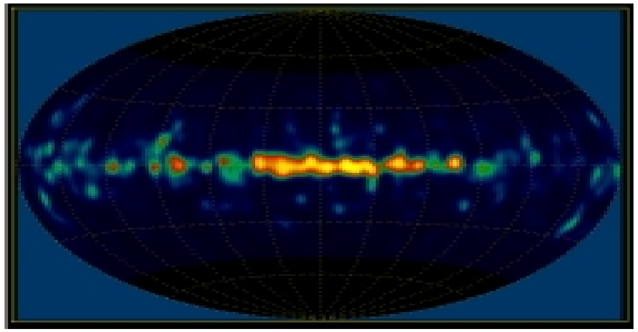


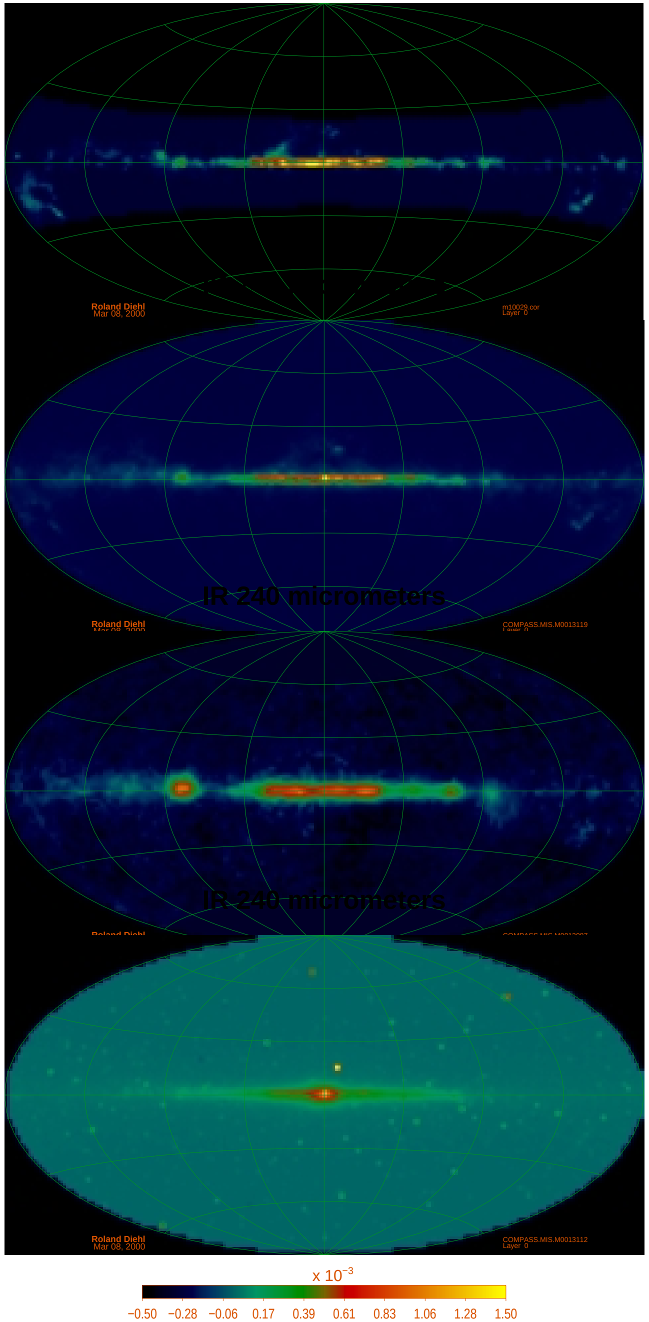
MEM
Phase 1-7

COMPTEL 1.809 MeV Maps and Possible Source Counterparts









CO map of molecular gas

IR map at 240 µm, dust

Radio map at 53 GHz, free electrons

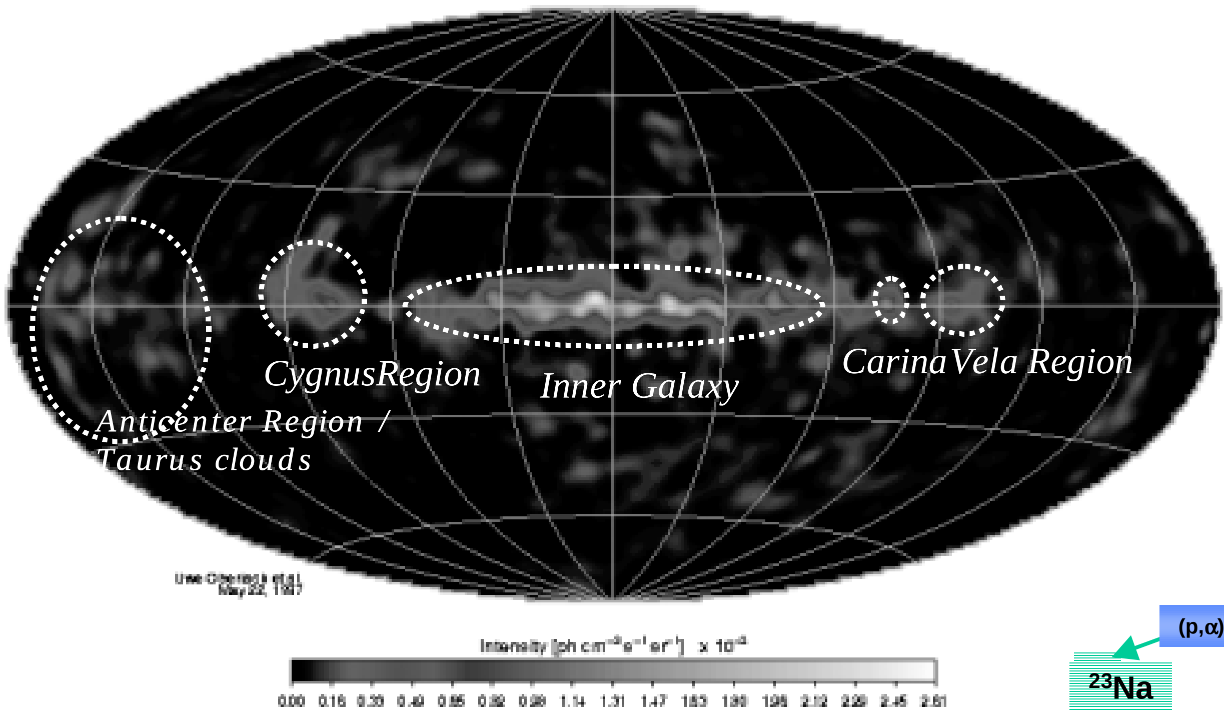
IR map at 3.5 µm, starlight

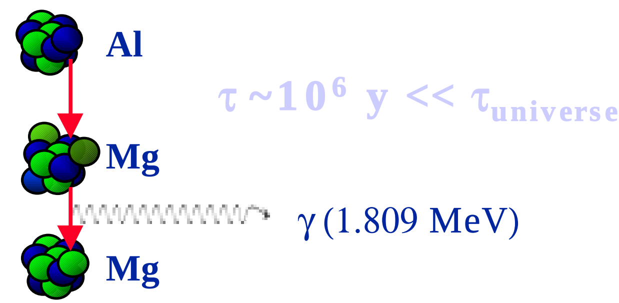
Different Imaging Methods
(ME, MREM, MLik)

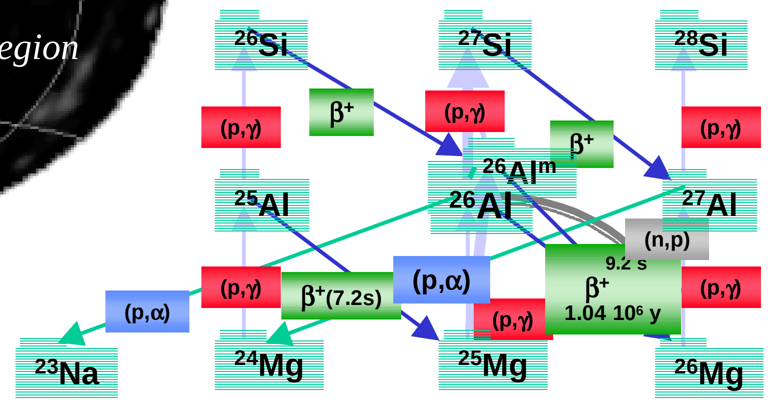
^{26}Al Candidate Source Objects

- Novae (O-Ne Enriched)
  - Hot Hydrogen Burning, T~few 10^8K
  - Yields: ~ 10^{-8} $M_\odot$ per event, ~ 0.4…5 $M_\odot$ for entire Galaxy
  - ☹ Enrichment Scenarios Uncertain, Overall Ejected Nova Mass Not Understood
- Supernovae (core collapse)
  - Explosive H Burning in O/Ne Shell, Explosive C Burning
  - Yields: ~ 10^{-5} … 5 10^{-4} $M_\odot$ per event, ~1-2 $M_\odot$ for entire Galaxy
  - ☹ Impact of Neutrino Spallation (↑), Na-Al Cycle Leak and Metastable ^{26}Al Decay (↓)?
- Wolf Rayet Stars
  - Hydrostatic H Burning (MS), Wind Phase ~x 10^6y Later → Product Release into ISM
  - Yields: ~ 10^{-4}… 10^{-5} $M_\odot$ per event, ~ 0.9 $M_\odot$ for entire Galaxy
  - ☹ Convective-Shell Boundary Mixing & Rotation Impacts Uncertain
- AGB Stars (massive AGB, M > 3 M_o)
  - H Shell Burning, eventually Hot Bottom Burning Contributions, Admixture of He Burning Products During Pulses
  - Yields: ~10^{-4}….10^{-8} $M_\odot$ per star (but over T~7τ_{26Al}), ~ 1 $M_\odot$ for entire Galaxy
  - ☹ Convective & Pulse Mixing Unceertain; Hot-Bottom Burning Uncertain

Nucleosynthesis in the Galaxy: ^{26}Al 1.809 MeV Gamma-Rays







First All-Sky Map in a Nucleosynthesis Line (COMPTEL) ⇒

- **Galactic Emission Dominates the 1.8 MeV Sky**
- **Significant Outer-Galaxy Features (Cygnus, Vela)**
- **Non-Smooth Emission Along Galactic Plane**
- **No Brightened Galactic Bulge (i.e., old stars)**

⇒ **Nucleosynthesis Occurs in the Present Epoch of Universe**

⇒ **Massive Stars are Dominating Sources of ^{26}Al**

Ref.: COMPTEL: Schönfelder et al., IEEE 1993; Gamma-Ray Lines: Diehl & Timmes, PASP 1998; 1.8 MeV Imaging: PhD Theses Oberlack 1998, Knödlseder 1998

Global Parameters of ^{26}Al Distribution

- **Method:**

  Variation of Parameters in First-Order Models

  ☞ **Scale Height ~130 pc (from Spiral-Arm Model)**

  ☞ **Galactocentric Scale Radius ~ 5 kpc (from Exponential-Disk Model)**

- **Method:**

  Uncertainty Limits from
  Fitted Coefficients of Different Relevant Models

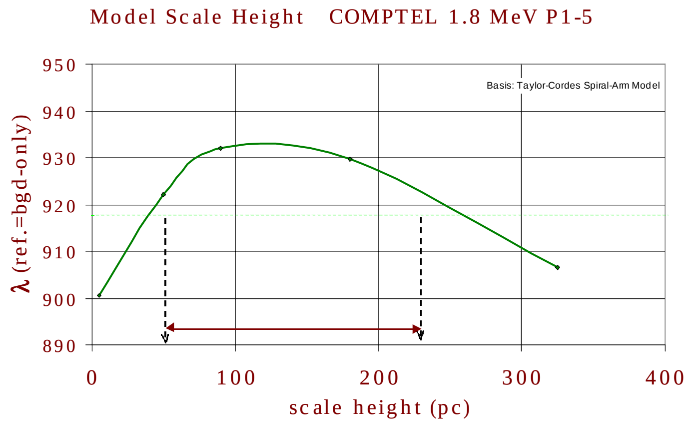
  ☞ **total ^{26}Al Mass ~2.2 M_o (+/- 0.15 M_o)**

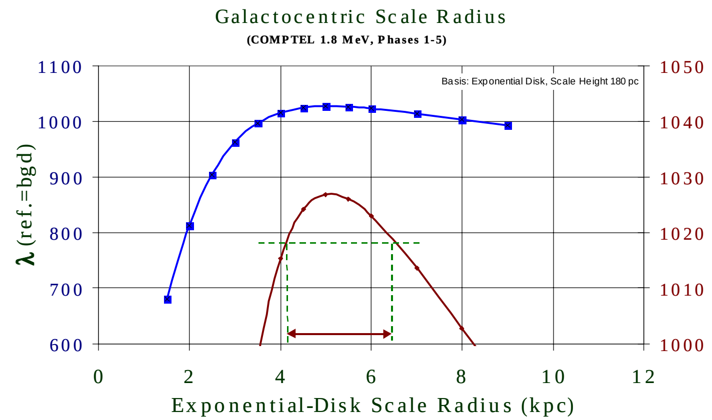
  (if only global, no local/localized 26Al assumed)

  ☞ **Galactic-Bulge Contribution < 0.18 M_o (2σ)**

  ☞ **General Spiral-Structure Significance >4σ**

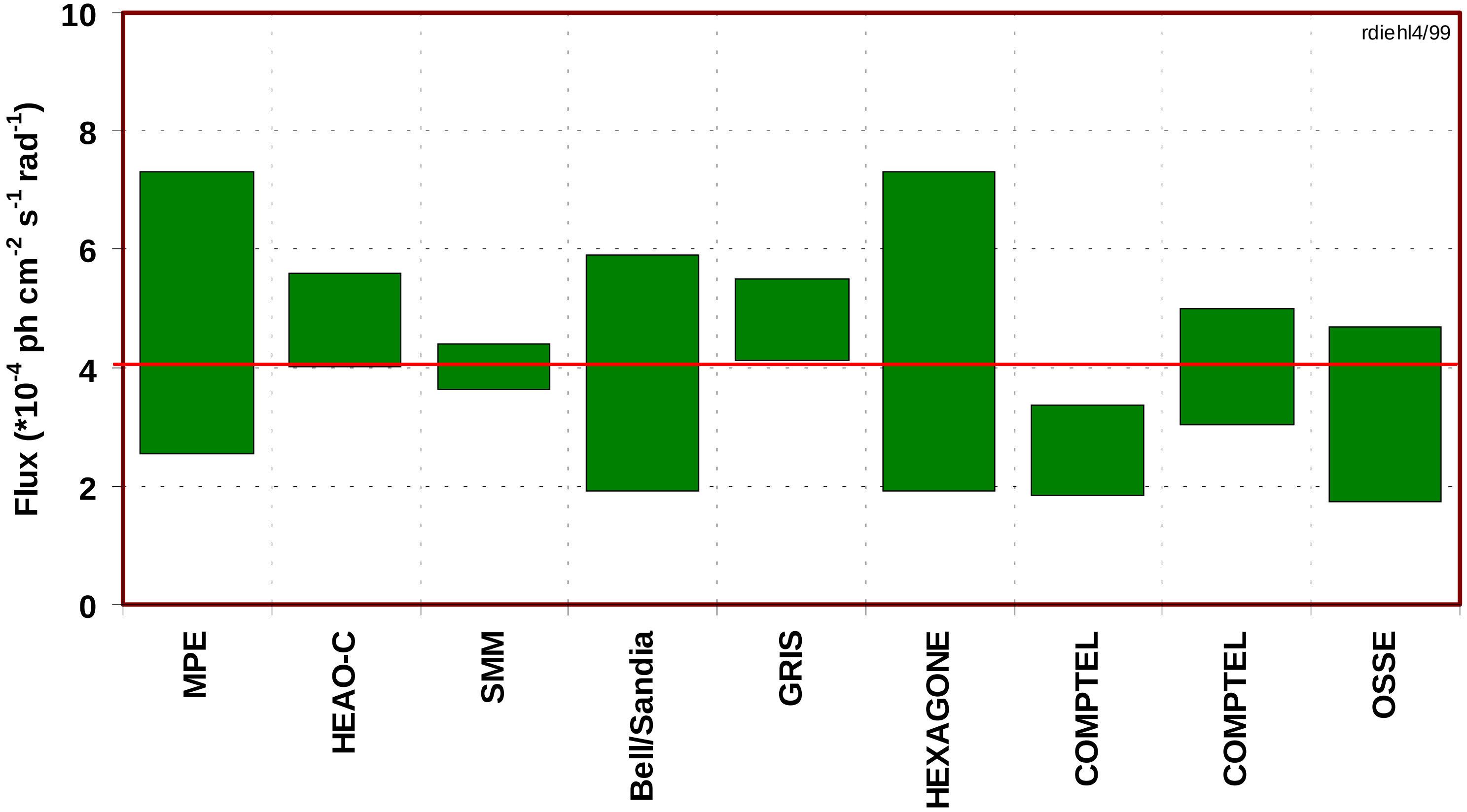
  ☞ **Spiral-Arm Component 0.5 M_o < $M_{26Alspiral-arms}$ < 2.5 M_o (2σ)**





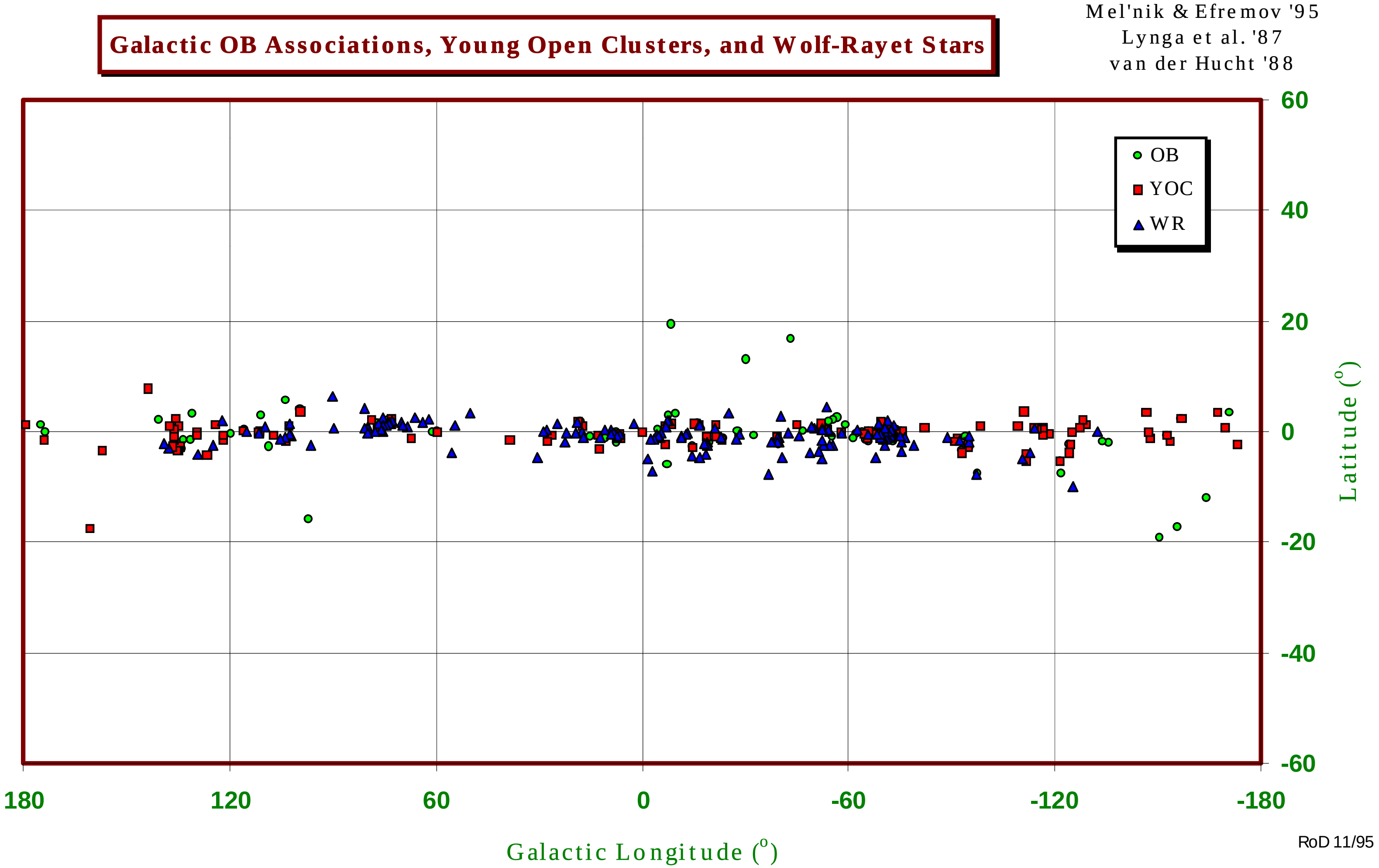
Fluxes in the 1.809 MeV ^{26}Al Line from Inner Galaxy

- Different Instruments Reflect Different Systematics
- Methods of Flux Determination Differs Among Instruments



INTEGRAL School, Les Diablerets (CH) April 2000 *© Roland Diehl*

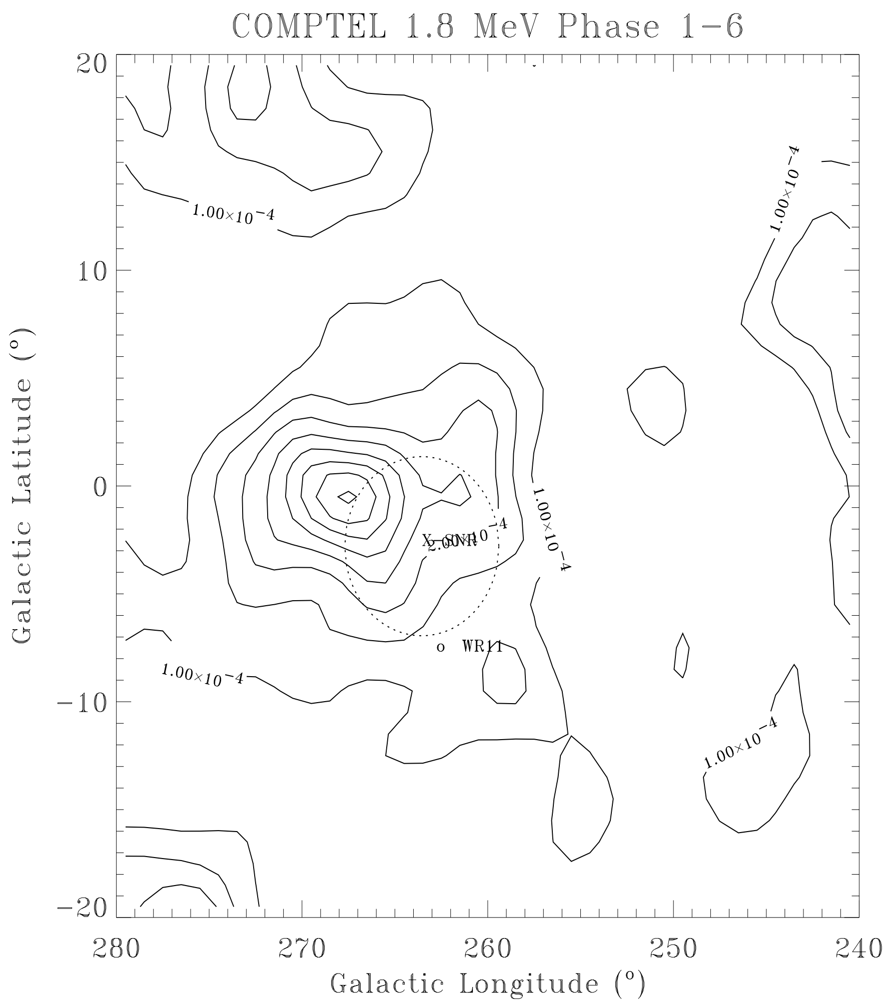
Galactic Distribution of Massive Stars: other Measurements



On the Massive-Star Origin of ^{26}Al

- Consistency Check on Massive-Star Outputs: *(Knödlseder 1999)*
  Equating line-of-sight integrated $I_{1.8MeV}$ to $I_{free-free\_emission}$
  =>
  - **Plausible ~8 10^{-5} M_o Average Yield of ^{26}Al per "OV star"**
  - **Consistent total ^{26}Al Mass of ~ 2.4 M_o**
  - **Plausible ~10000 WR Stars in Galaxy**
  - **But: => SN (II+Ib) rate ~ 1.8/100y (?)**
- Agreement of 1.8 MeV Emission Distribution with Source Tracers
  - **Free-Electron Emission Distribution (53 GHz COBE) , i.e., mainly from Ionization by Massive-Star UV Photons**
  - **Warm Dust Emission, i.e., from SN and Massive-Star Winds' Heating of IS Dust (>100 μm COBE)**
  - **Distribution of Known Massive Stars (i.e., Young Clusters, WR Stars, O Stars) (but: incomplete at d>3 kpc)**
- Irregular Patterns of Massive-Star Locations Observed in LMC, M31; Same as Overall Irregularity of 1.8 MeV Emission?
- ^{26}Al Disk Latitude Extent > Gas, But < Old Population (=> "puffed up" by SN/Wind Ejection?)

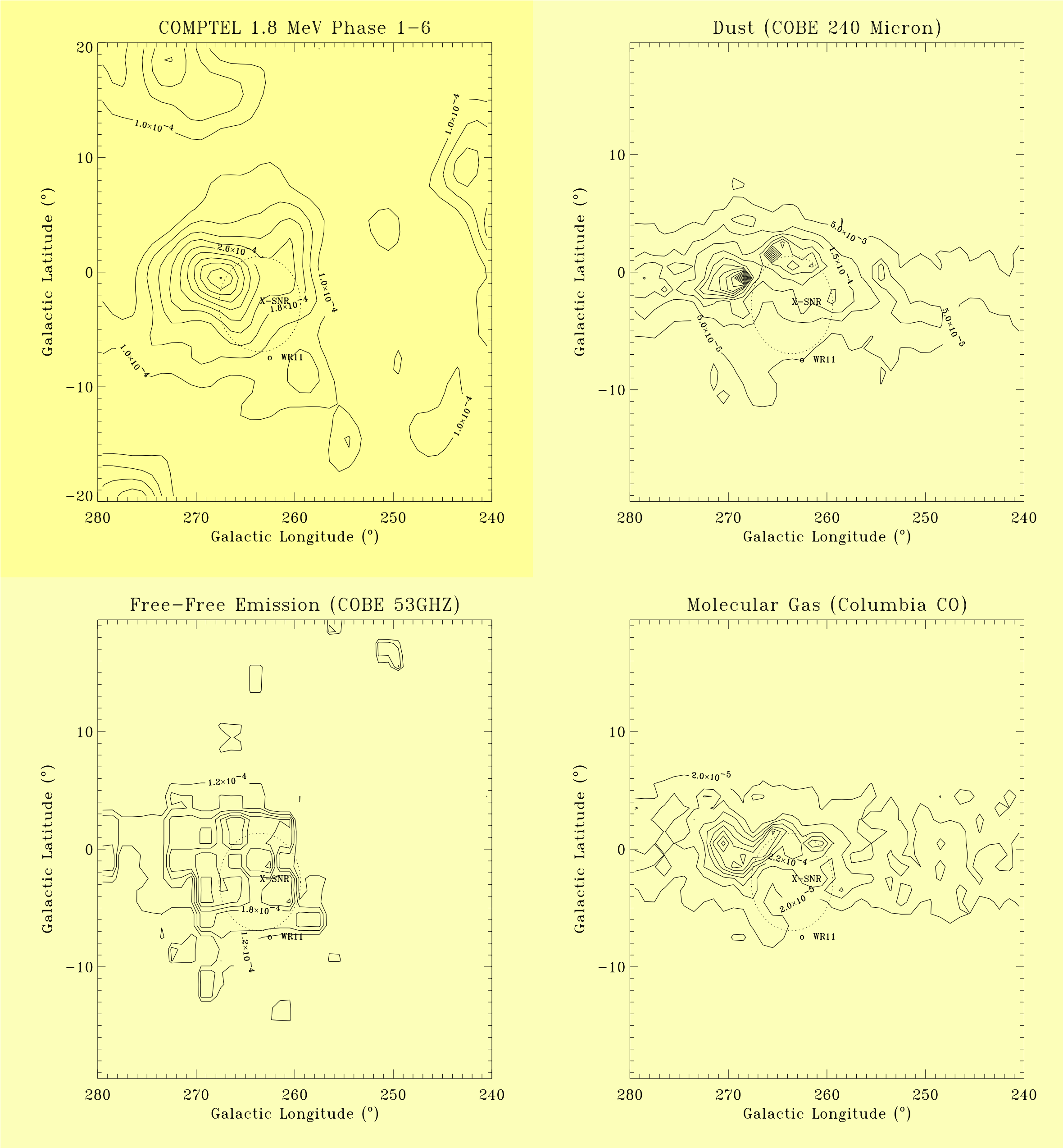
COMPTEL 1.8 MeV Image from Vela Region



- Extended Emission with Peak at l~267°/b~0°
- Significant Large-Scale Background Emission
- Which Stellar Groups/Regions Contribute (Distances?)?
- Does the Vela SNR Contribute Significantly?
- Does the RX J0852-4622 SNR Contribute Significantly? (Distance?)
- Note: $\tau_{26Al} \sim 10^6$ y, ⇨Multiple Events Likely

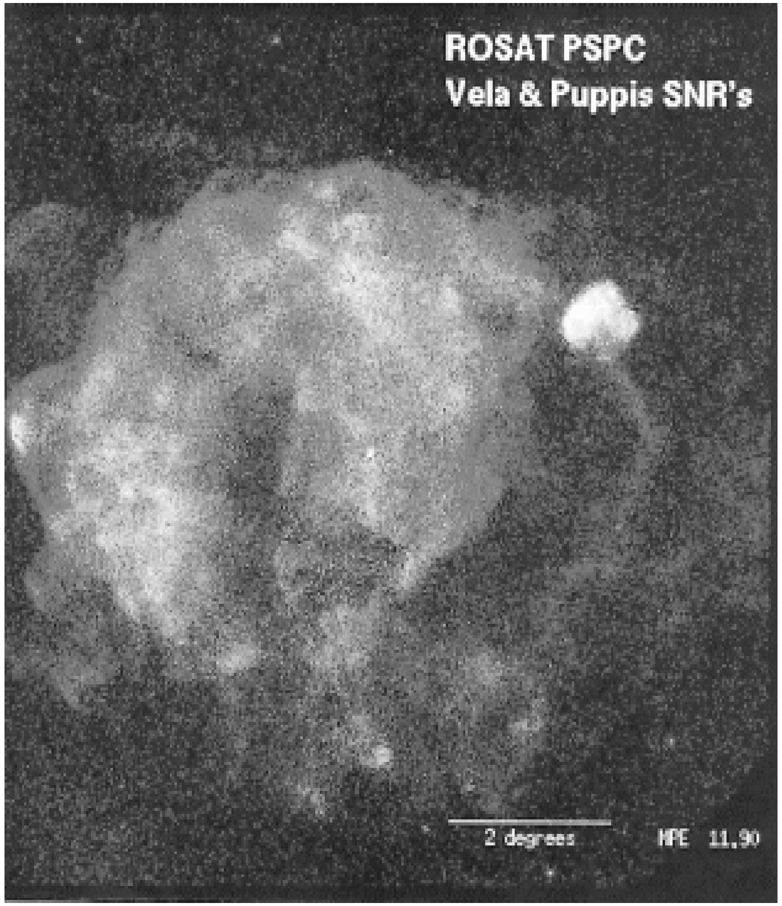
Image (MEM) of Vela Region from COMPTEL All-Sky Survey (Phases 1-6)

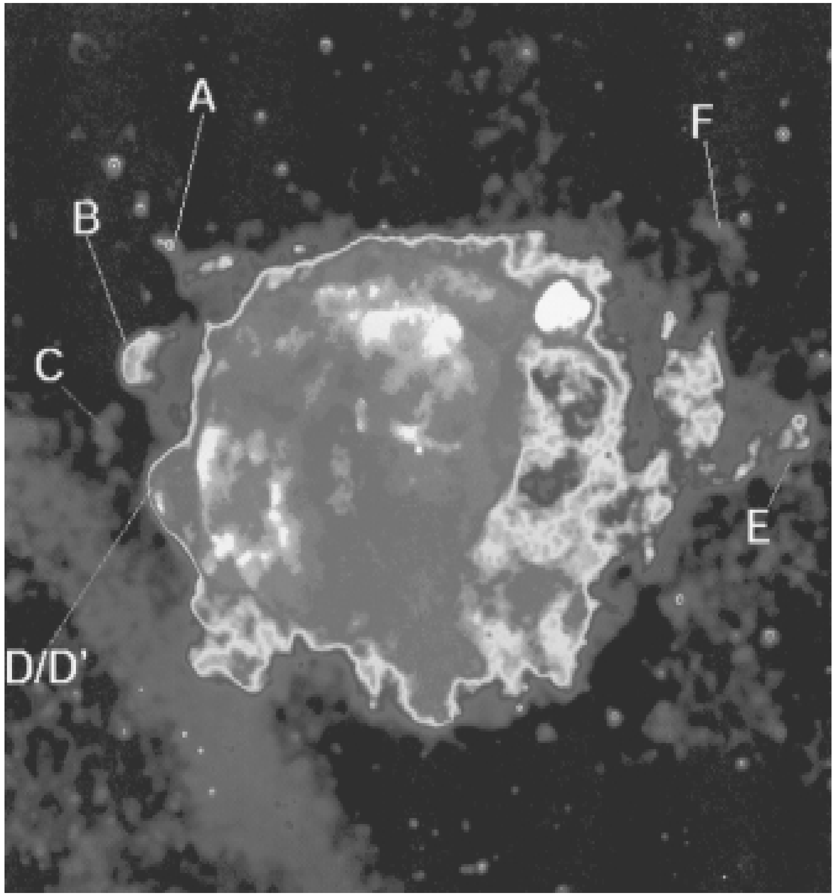
The Vela Region in ^{26}Al/1.8 MeV and ^{26}Al Tracer Candidates



- Dominating Gas Features Appear Active Nucleosynthesis Sites, with Active Ionization and Heated Dust

The Vela SNR in X-Rays

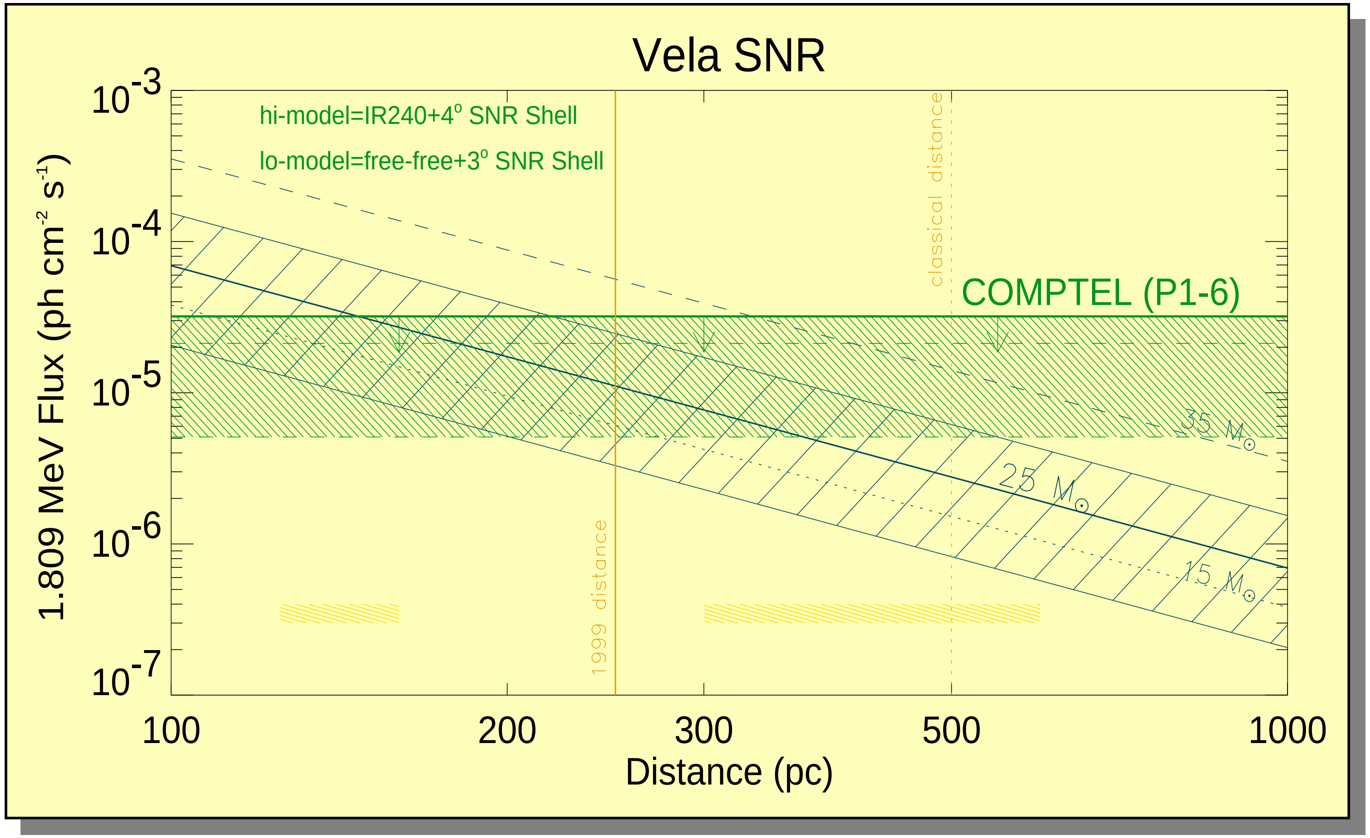




Ref: Aschenbach, Egger, & Trümper 1995 Natu

- **X-Ray Emission Diameter ~8.3°** (opt/rad:~5.5°)
- **PSR B0833-45 is Central Compact Remnant**
- **Thermal SNR** (kT~0.3 keV) **with Central Synchrotron Nebula** (Vela-X)
- **Protrusions** Extending ~degrees Beyond SNR: **SN Ejecta Clumps**
- $N_H = 0.3 \cdot 10^{21} cm^{-2}$

The Vela SNR and 1.809 MeV Emission

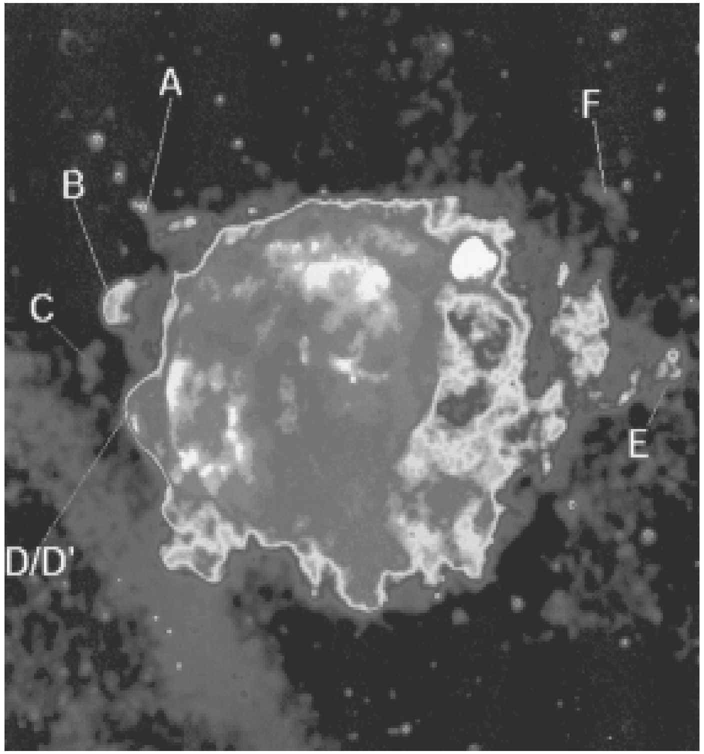


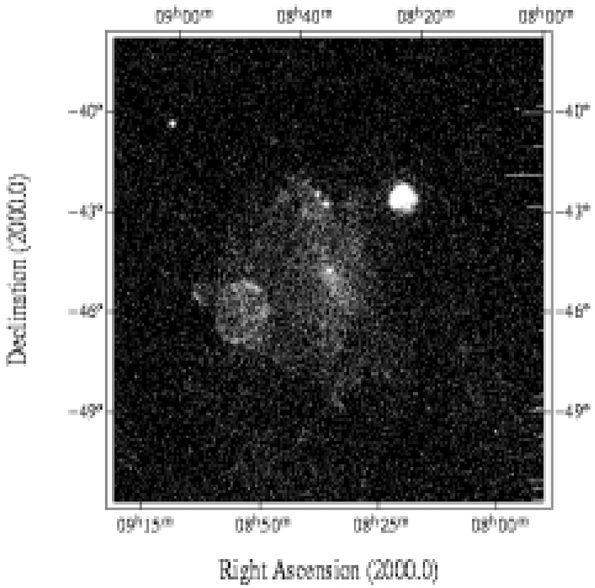
- Distance to Vela SNR:

  ~ 120 pc (Vela Pulsar Polar Cap X) ....**250**... 600 (Vela SNR Fragments & Kinematics) p
- SN II ^{26}Al Yields from Santa Cruz Models (WW'93; T et al '95)

=> Compatible with SNII Nucleosynthesis Models

A New X-SNR in the Vela Region





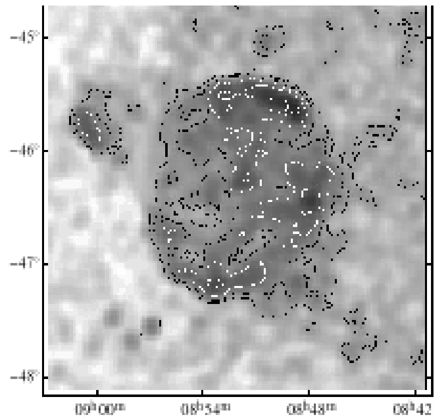
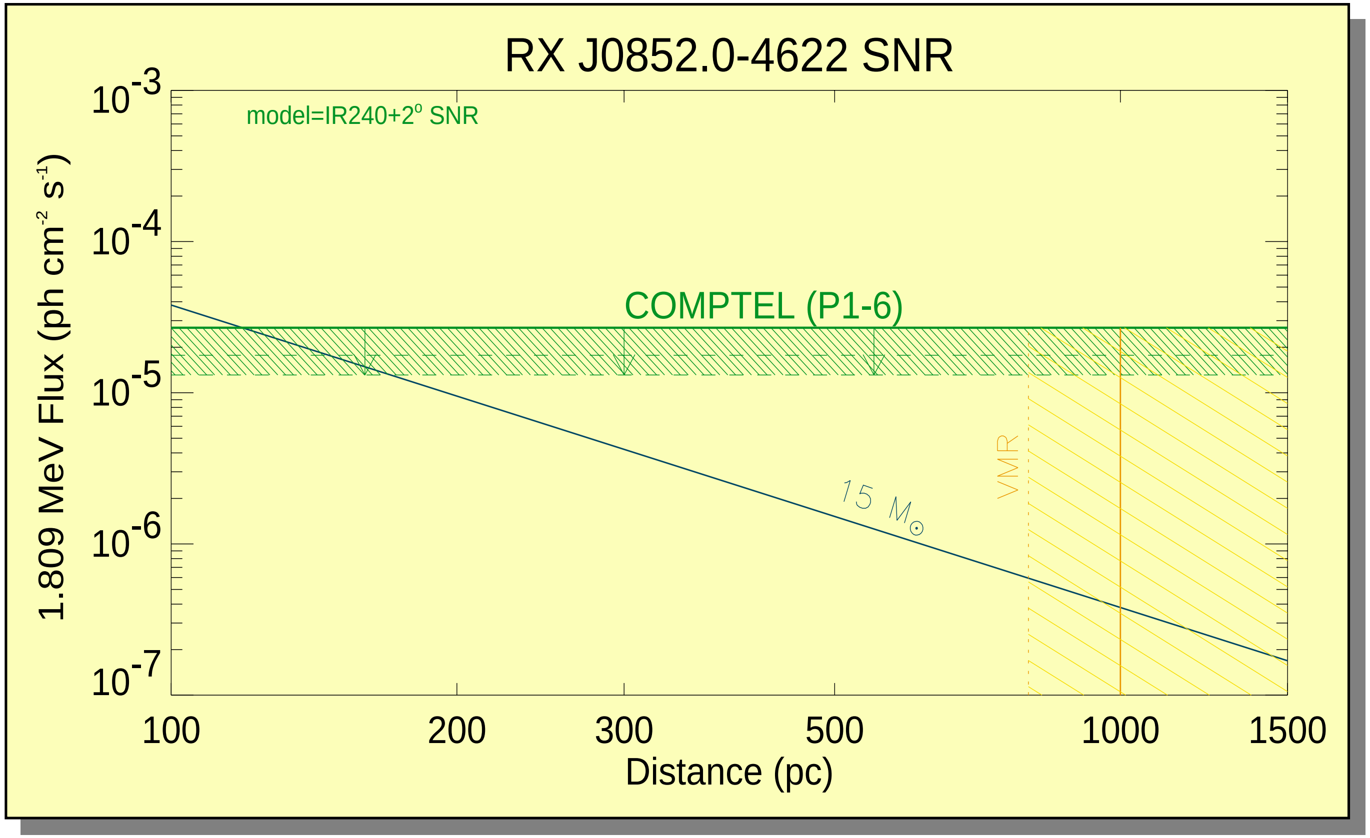


Fig. 1. Grey scale image of RX J0852.0-4622 for E > 1.3 keV. Coordinates are right ascension, declination of epoch 2000.0. Contour levels are (in black) 1.5, 2.3, (in white) 3.5, 5.2, 8.2, 9.2 in units of $10^{-[illegible]}$ PSPC counts $s^{-[illegible]}$ $arcmin^{-[illegible]}$.

The 1.809 MeV Emission and RXJ0852-4622



- Distance to RX J0852-4622:

  ~ 120 pc (COMPTEL 26Al Map) ....1000 (VMR)... 1500 (ROSAT X Spectrum) pc
- SN II ^{26}Al Yields from Santa Cruz Models (WW'93; T et al '95)

=> Unclear if Significant or Dominating Contributor

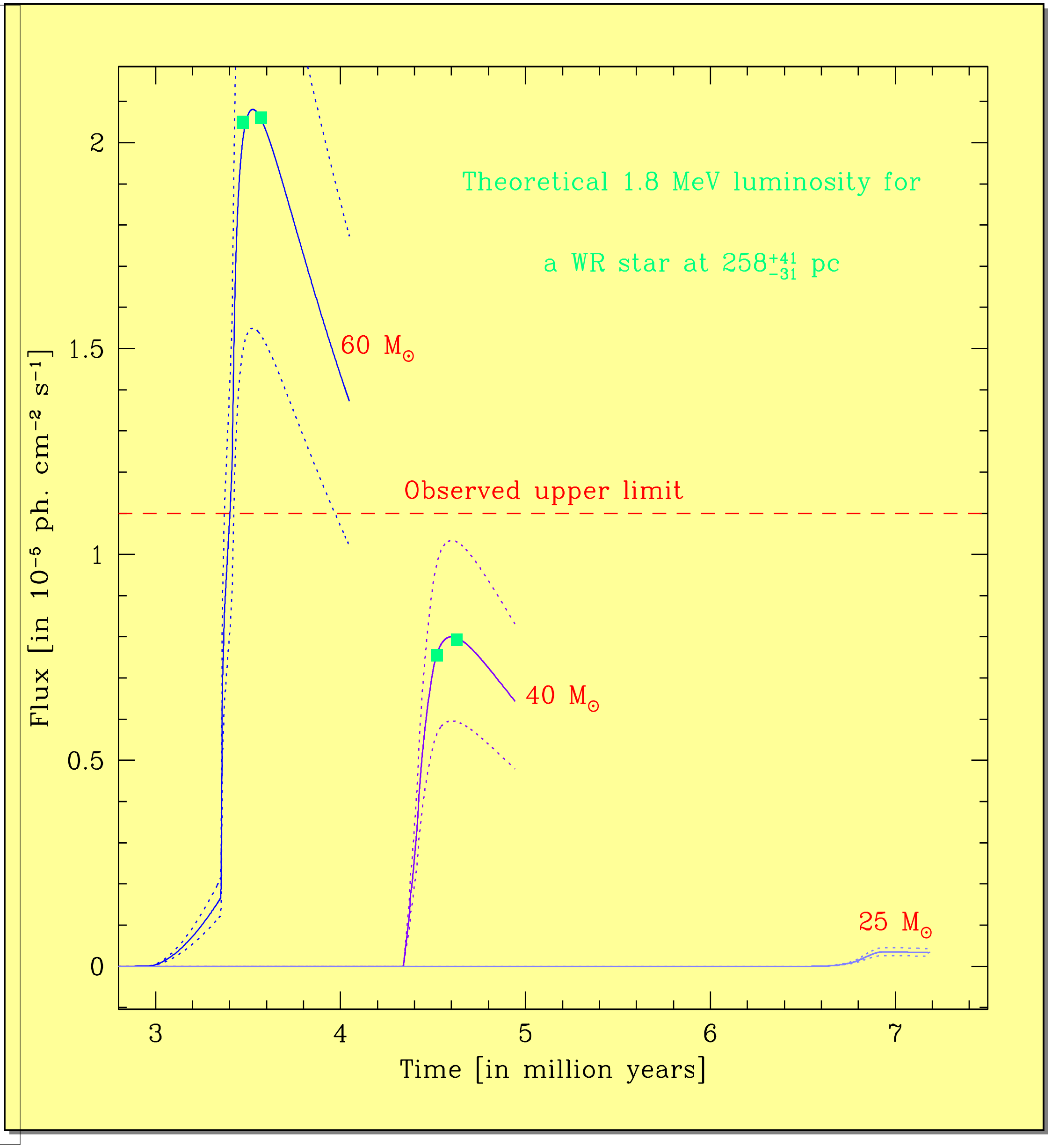
Constraints on WR11 from It's ^{26}Al Yield

- Ejected Amount of WR Nucleosynthesis Products is a Function of:
  - ☞ Initial Mass & Metallicity
  - ☞ Stellar Model (Convection Treatment, Rotation)
  - ☞ Stellar Wind (=WR Phase)

=>

- Compare Expected WR11 Light Curve in 1.809 MeV γ's to COMPTEL Observations
- Extract Independent Mass & Age Constraints

(Diehl, Meynet, Prantzos, et al., in preparation)



The γ^2 -Velorum System

Distance: 258 (+41; - 31) pc — Nearest WR Star to Sun!

Components: Wolf-Rayet Star "WR11", ~ 50 M_o (=$M_{initial}$; present mass = 9±2 M_o; WC8)

O Star ~ 35 M_o (=$M_{initial}$; present mass =30±2 M_o; O7.5)

other Parameters: System Age < 6 My, O Star Age ~3.6±0.2 My
OB2 (d~410 pc) ~10-30 My

γ-Ray Constraints:

$I_{1.8 MeV}$ < 1.1 10^{-5} ph cm^{-2} s^{-1}

M_{26Al} < 6 10^{-5} M_o

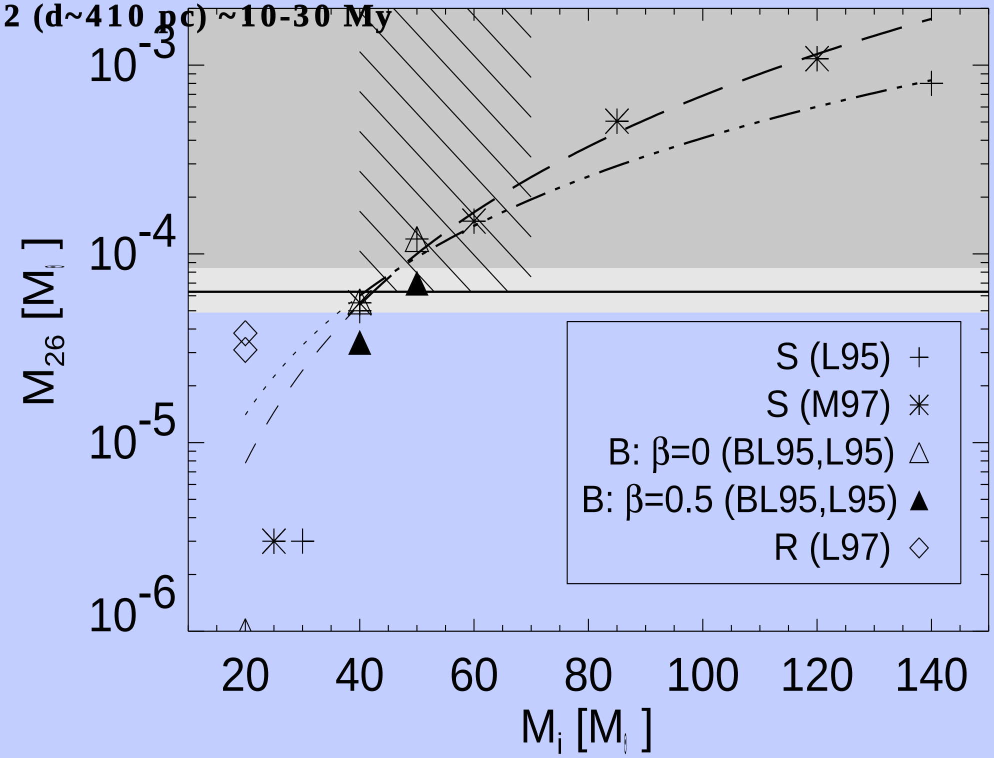
Models:

(Meynet et al. 1997; Langer et al. 1995; 1997)

M_{26Al} ~ 10^{-4} M_o (3 10^{-5} .... 3 10^{-4} M_o)

Results Depend on:

- Convection Assumptions (S)
- Binarity (B)
- Stellar Rotation (R)
- Time within Evolution



(Oberlack et al., A&A 1999)

The Vela Region at 1.8 MeV

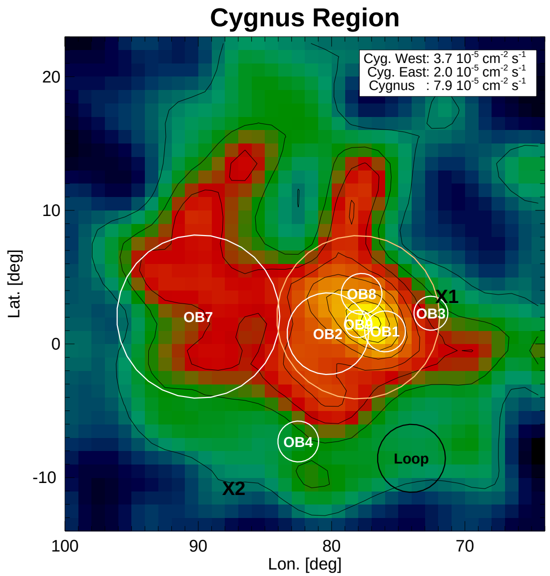
- Extended Emission from ^{26}Al with Peak at l~267°/b~0°
- Vela SNR Emission ~as Expected (& Not Dominating)
- RX J0852-4622 SNR Contribution Unclear (Distance?)
- Contribution from γ^2Velorum/WR11 Lower Than Expected
- ^{26}Al Emission Peak Coincides with Other Objects and Signs of Nucleosynthesis Activity in the Region

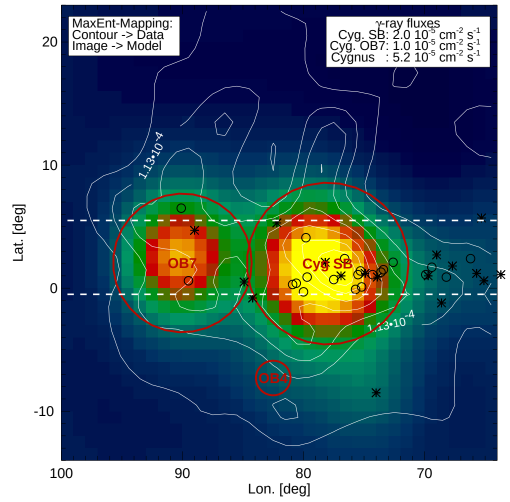
  Edge of Vela Molecular Ridge = Very Active Region?

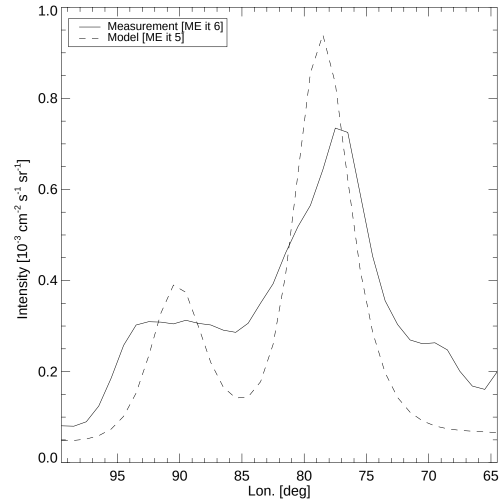
COMPTEL/R. Diehl et al., Sep 1998

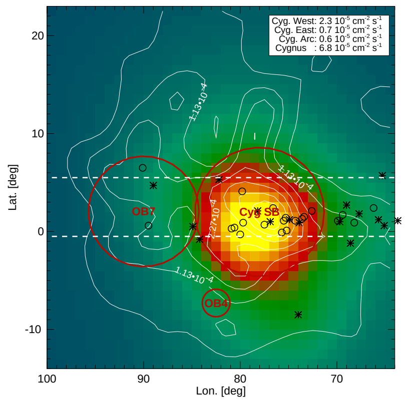
Cygnus Region ^{26}Al Emission

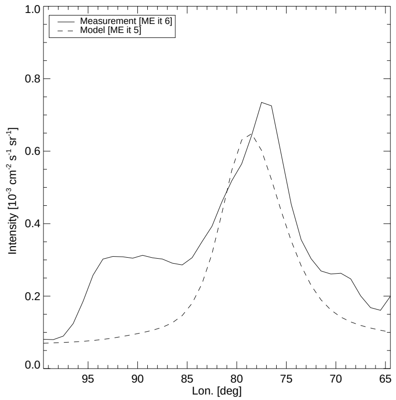
- **1.809 MeV Emission (6σ): I~8 10^{-5} ph cm^{-2} s^{-1}**
- **Candidate Sources:**
  - **7 OB Associations**
  - **17 WR stars**
  - **21 SNR's**
- **Assemble the ^{26}Al Emission from Source Models**
  - **Association Ages**
  - **Model Consistency Check**











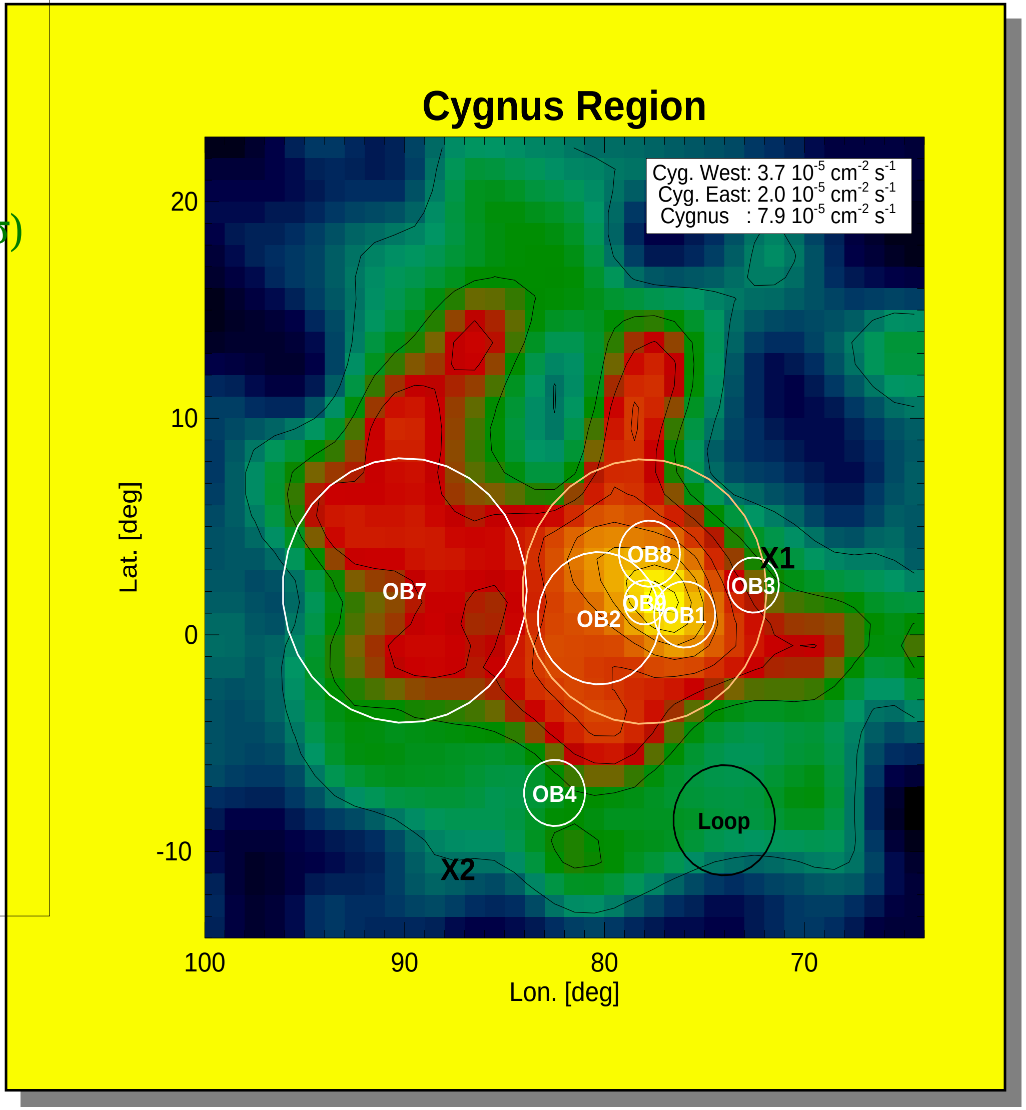
1.8 MeV Gamma-Rays from the Cygnus Region

- COMPTEL Phases 1-7
  Imaging Analysis:

  Emission from Entire Region
  F~ 7.9 (±1.2) 10^{-5} ph cm^{-2} s^{-1} (6σ)

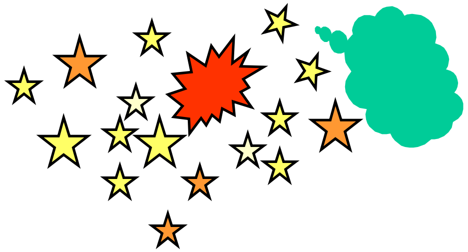
- Cygnus Region Objects:
  Cygnus Superbubble
  Cygnus OB Associations
  WR Stars and SNR Along LoS

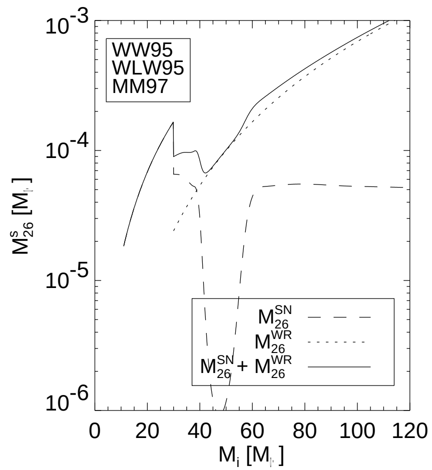
- OB Associations at Peak of their
  1.8 MeV Lightcurve?



Modeling Time-Dependent ^{26}Al Content of Star Clusters

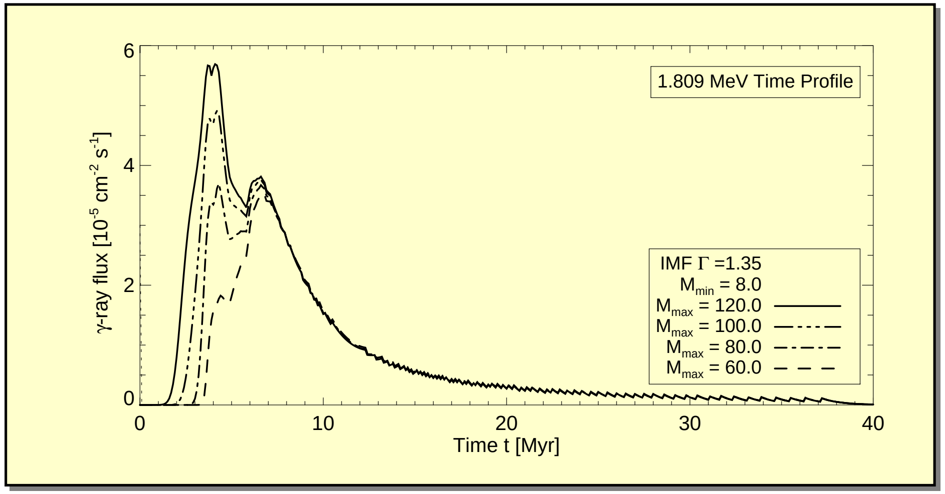
- Stellar Content (IMF)
- Stellar Evolution
  - ☞ Lifetime
  - ☞ WR Phase
- ^{26}Al Yields per Star





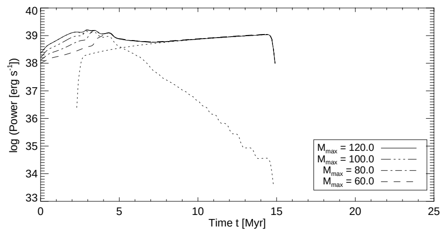
yields

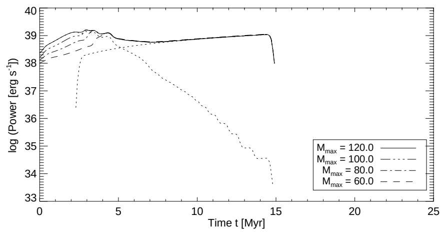
- 1.809 MeV “Light Curve” for an OB Association



plus

- other Observables
  - ☞ UV Light Output
  - ☞ Kinetic Energy





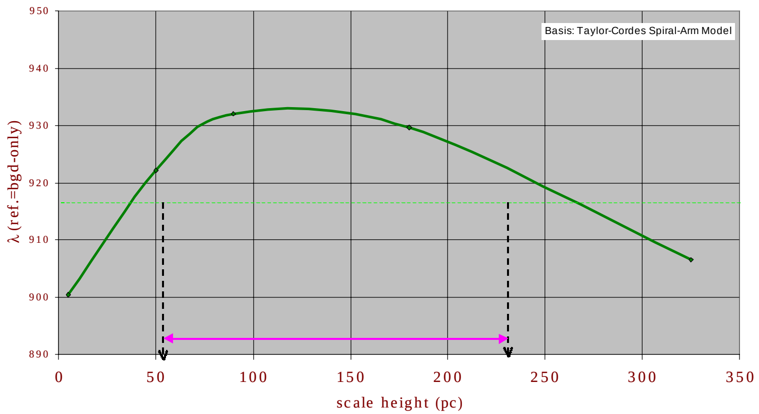
–> *Plüschke et al., 2000*

Massive Stars & Nearby Candidate ^{26}Al Source Regions

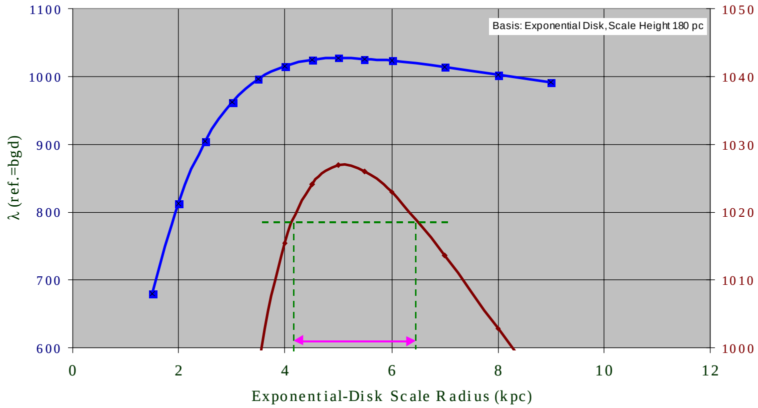
Diehl R., Knödlseder J., Oberlack U., Bennett K., Bloemen H., Hermsen W., Ryan J., Schönfelder V., von Ballmoos P.

- Issue: Are Massive Stars the Dominant ^{26}Al Producers?
- Method: Test (on COMPTEL 1.8 MeV Data) Distributions from:
  - Galaxy-Wide Tracers
  - Nearby Regions

Model Scale Height COMPTEL 1.8 MeV P1-5

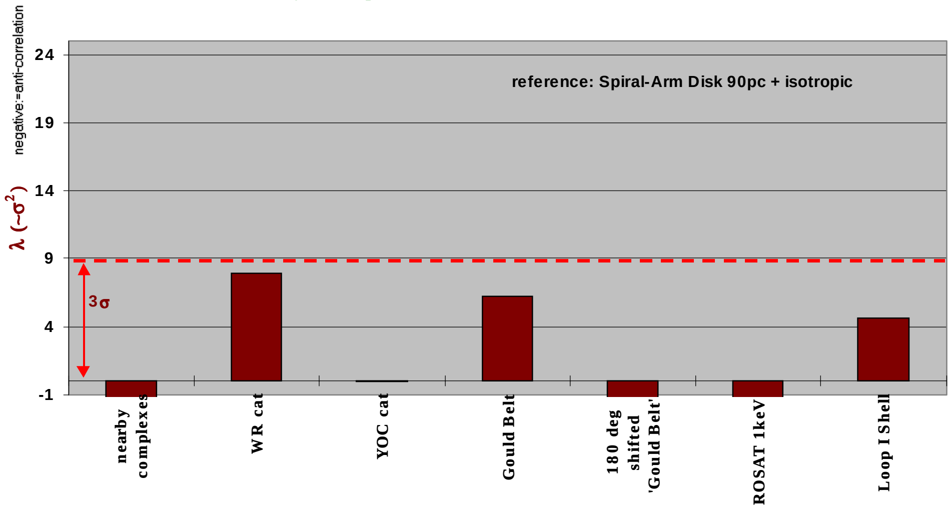


Galactocentric Scale Radius
(COMPTEL 1.8 MeV, Phases 1-5)

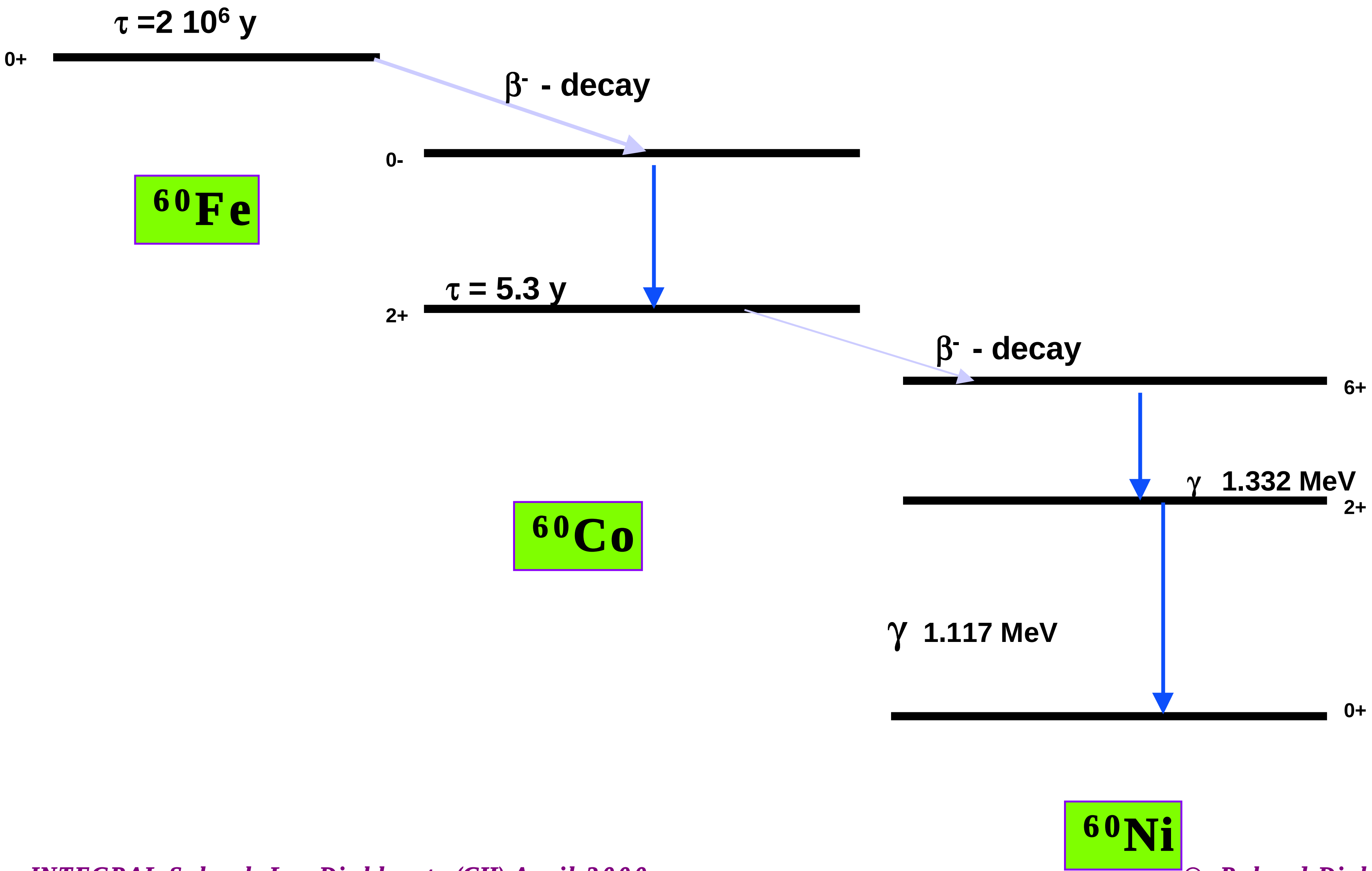


- **Results:**
  - **Galaxy-Wide: Disk $R_0$5kpc,$z_0$130pc**
  - **Spiral Structure**
  - **Nearby Regions Not (yet) Detected**

Fits of Nearby Component Models, COMPTEL 1.8 MeV P1-5

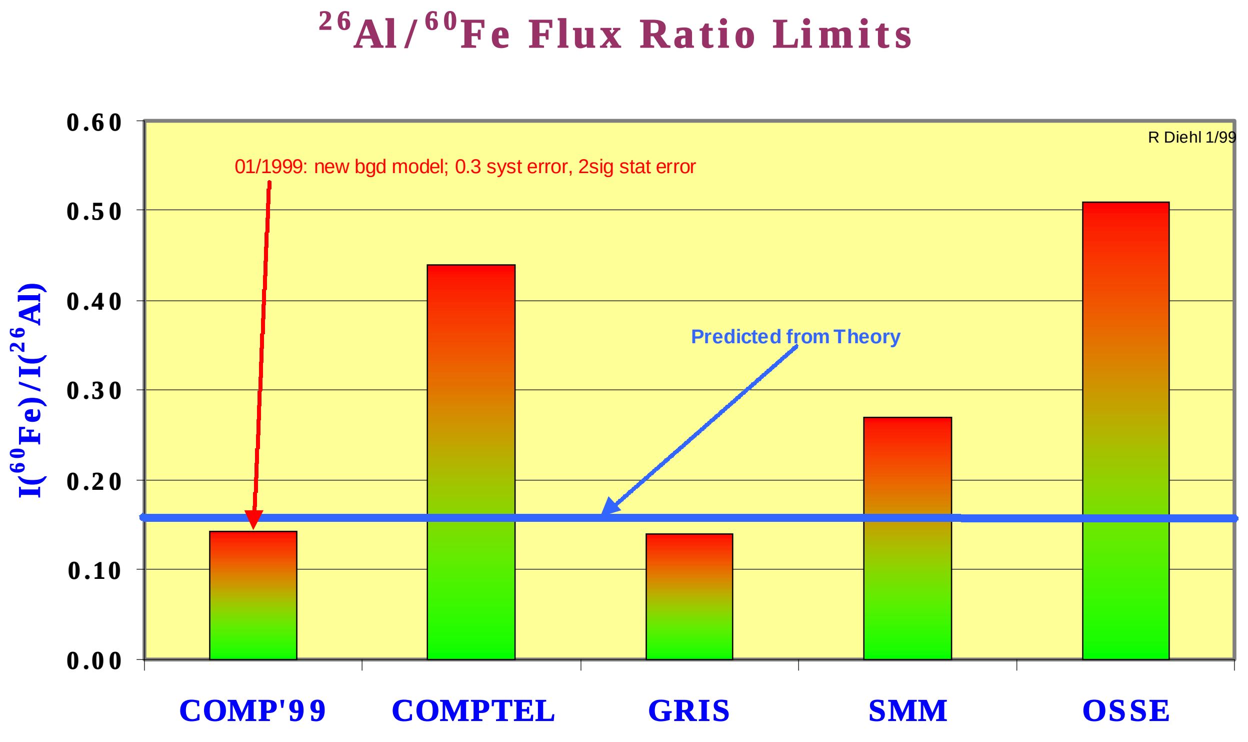


^{60}Fe Decay



τ =2 10⁶ y
0+
β⁻ - decay
0-
60Fe
τ = 5.3 y
2+
β⁻ - decay
6+
γ 1.332 MeV
2+
60Co
γ 1.117 MeV
0+
60Ni

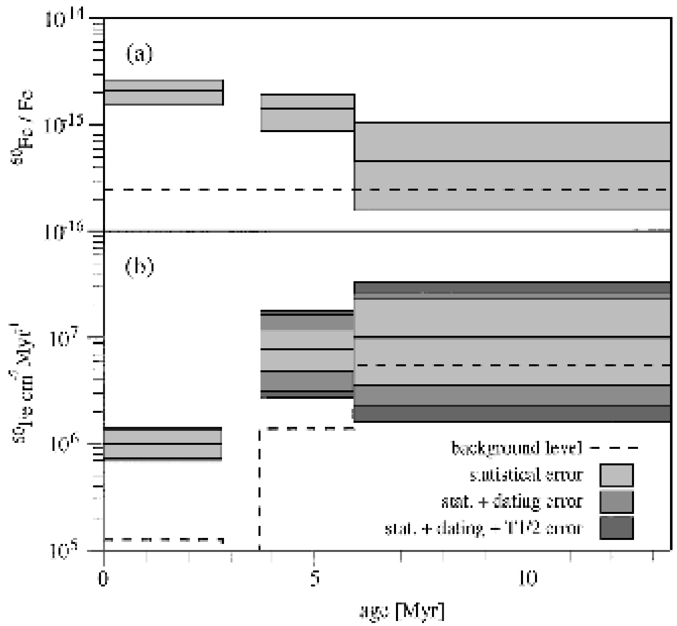
^{26}Al and ^{60}Fe:
Diagnostics for ^{26}Al from SNII versus WR



^{60}Fe in Solar System

Knie et al., PRL 83, 1999

- **Deep-Ocean Ferromagnetic-Crust Isotope Analysis**
  - Slowly-Growing Sample from South Pacific Floor (enriched cosmic contributions), 3 layers of 20 mm total, depth 1300m, Age Determination by Co (0-2.8/3.7-5.9/5.9-13.4 My)
  - **23 ^{60}Fe Events Identified from Accelerator Mass Spectroscopy** (14/7/2 events per layer)
  - **=> I~ 1..7..9 10^6 ^{60}Fe cm^{-2} My^{-1}**
  - **Potential Sources:**
    - CR Spallation in Earth Atmosphere
    - CR Spallation in Interstellar Dust
    - n Capture Sequences (?)
    - Cosmic Supernovae ~10^{-4} $M_\odot$ per SN
  - Cosmic-Ray Spallation in Earth Atmosphere (^{84}Kr(p,11p14n)^{60}Fe) Constrained from ^{36}Cl (^{40}Ar(p,2p3n)^{36}Cl) to I<10^4 ^{60}Fe cm^{-2} My^{-1}
  - Interstellar Spallation Contribution (^{62}Ni, ^{64}Ni) Constrained to <4 10^4 ^{60}Fe cm^{-2} My^{-1}



⇒ **Supernova Ejecta ??**

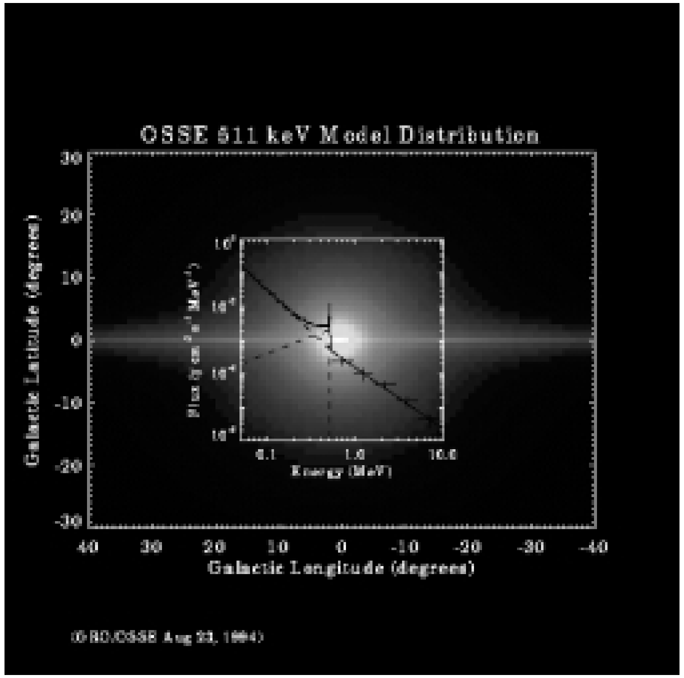
d~30pc ($v_{SNEjecta}$>$v_{SolarWind}$) **/ T_o~5 My**

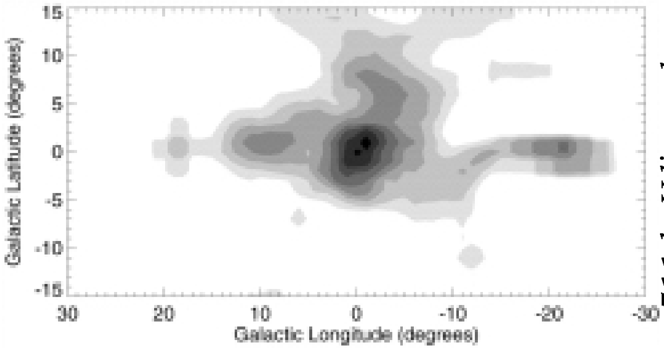
Positron Sources in the Galaxy

Source	disk	bulge
• Radioactivities		
○ Thermonuclear Supernovae (^{60}Co)	??	40-100%
○ Core-Collapse Supernovae		
^{44}Ti	12-24%	??
^{26}Al	10%	5-12%
○ Novae (^{7}Be, ^{22}Na)	<2%	5-12%
• Black-Hole Sources / Jets	??	??
• Pulsars	<10%	??

–> Expected Disk Emission (central sr) ~5-10 10^{-4} ph cm^{-2} s^{-1}

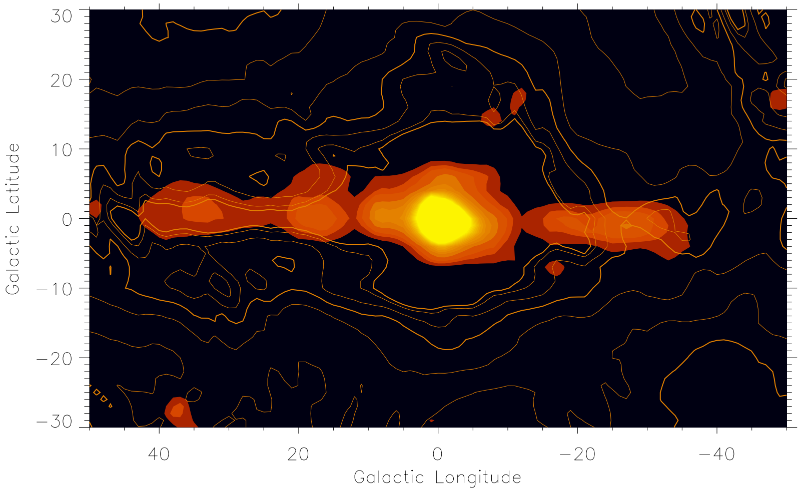
Annihilation Gamma-Rays from the Inner Galaxy





511 keV line-only

- $I_{full\text{-}map} \sim 2.2\ 10^{-3}$ ph cm^{-2} s^{-1}
  Annihilation Rate ~ $3.3_{\pm 0.5}\ 10^{43}$ e^+ s^{-1}
- Ps Fraction $0.97_{\pm 0.03}$
- Extended Diffuse Emission with Bright Bulge and Faint Disk Emission
  $I_{bulge} \sim 3.3\ 10^{-4}$ ph cm^{-2} s^{-1},
  $I_{disk} \sim 10^{-3}$ ph cm^{-2} s^{-1} (~10*^{26}Al e^+)
  $I_{gaussian,16deg} \sim 9\ 10^{-4}$ ph cm^{-2} s^{-1}
- No Point Source (1E1740.7-29.42)
- No Time Variability
- Indication of Northern 'Fountain'
- Improved Constraints from 511+Ps γ's



total annihilation emission (continuum with 511 keV line)

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

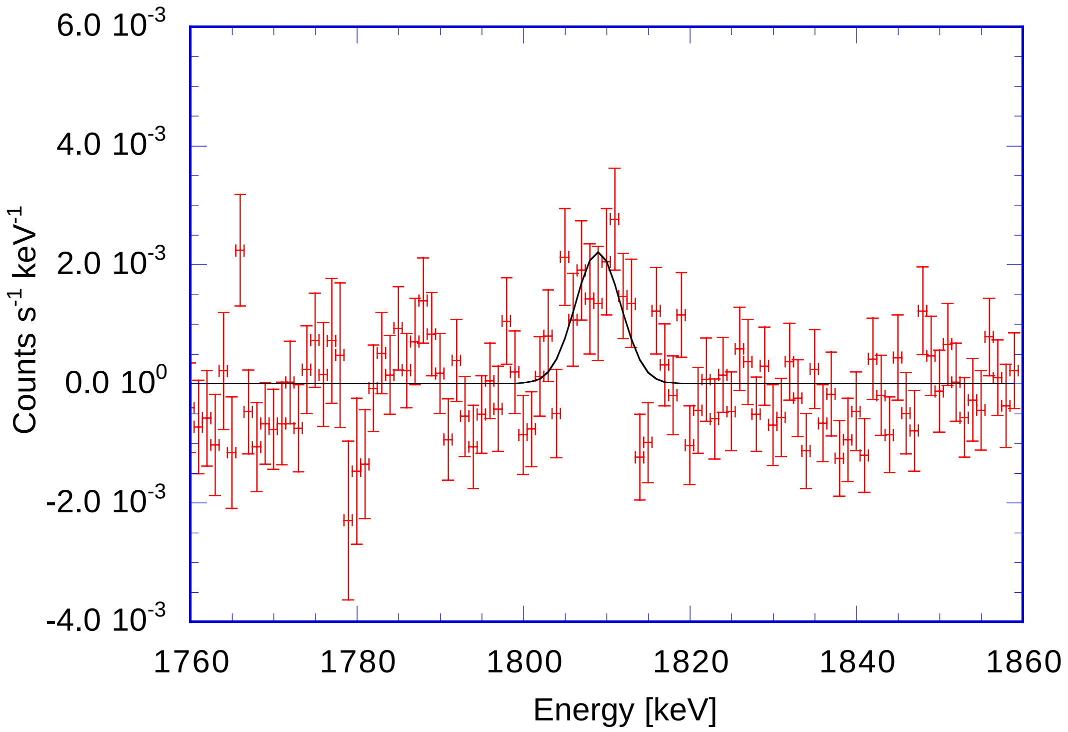
Gamma-Ray Line Shape Diagnostics

Line Shaping Processes:

☝ **Galactic Rotation Contribution is Small**
(< 1.7 keV)

☝ **Thermal Broadening Requires Very High Temperature**
$\sim 10^8$K, or kT~10keV

☝ **Kinetic Broadening is Measurable above ~ 100 km/s, Can Be Diagnostic for Acceleration and SN Ejecta**



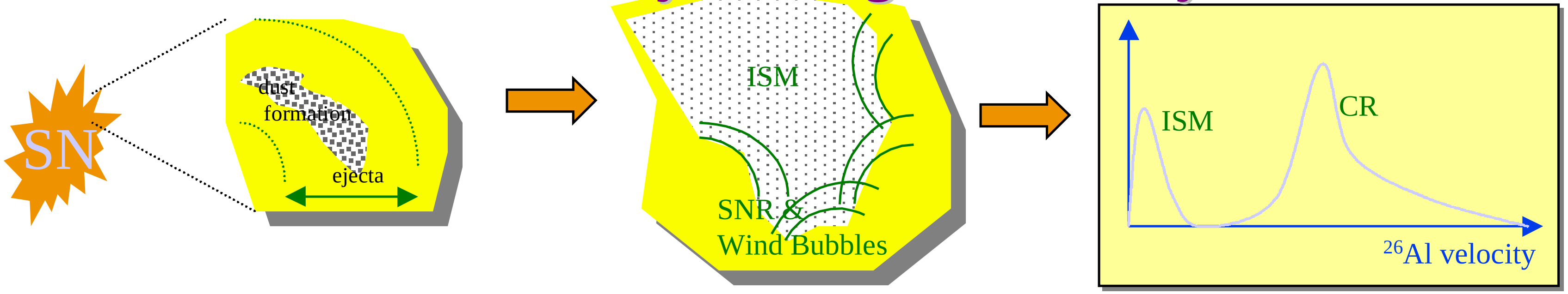
Measurement Example ^{26}Al:

GRIS Balloone-borne Ge Detector Galactic-Plane Scans (100º fov) J. Naya et al., Nature, 1996)

⇨ **Line Width ~6.4 ±1.2 keV, > Instrumental**

⇨ **5.4 keV Doppler Equivalent: ~540 ±140 km/s**

^{26}Al Decay at High Velocity



General Considerations on ^{26}Al Ejecta:

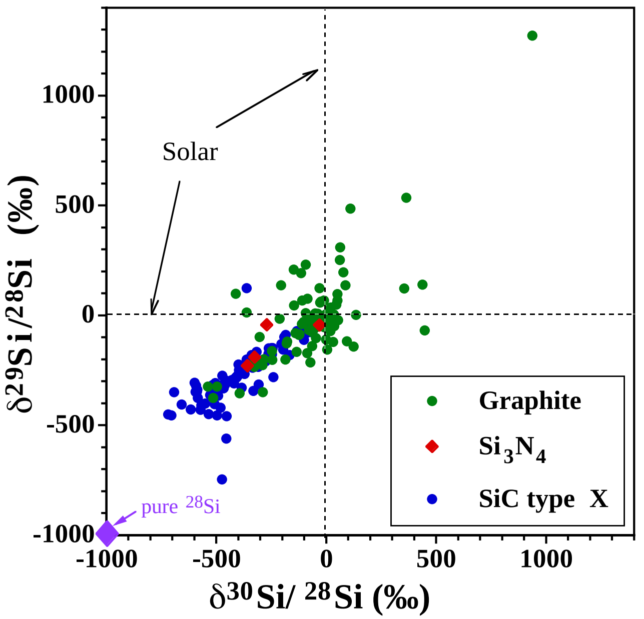
- Time Scales: $\tau_{SNR\ Evolution}$ 10^5y; $\tau_{26Al\ Decay}$ 10^6y; $\tau_{Stellar\ Associations}$ ~10^7y
- Aluminium is Refractory, Condensation onto Dust Grains is Likely
- Grain Formation in Core-Collapse Supernovae is Known (SN1987A Opt/IR Lightcurve)
- Dust Particles can be Decomposed in SNR/Wind Shocks
- SNR/Wind Shocks are Acceleration Sites for Energetic Particles / Cosmic Rays (e.g. SN1006)
- Atomic ^{26}Al would be Slow ($\tau_{Coulomb\text{-}Losses}<10^4$ y), Dust Mass-to-Charge Ratio allows $\tau_{Coulomb\text{-}Losses}$~$10^7$ y

Model: ***(see Chen et al. 1997; Ellison et al. 1997; Sturner & Naya 1999)***

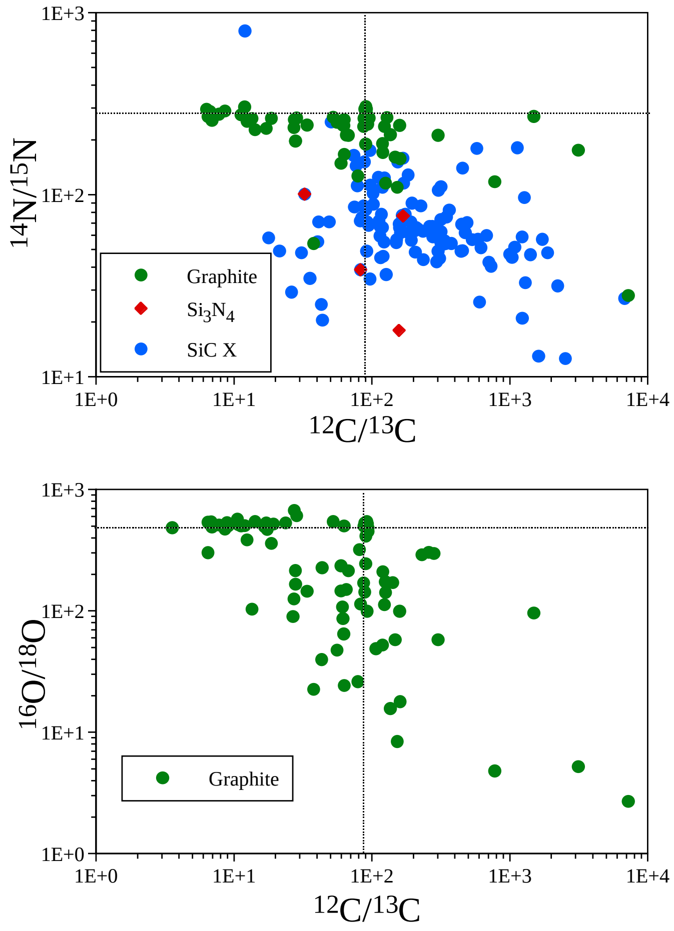
- ^{26}Al is Predominantly Embedded in SNII Dust Grains
- Grains may catch up with SN Shock, or else Leave the Late SNR with ~Initial Velocity into ISM
- Dust Grains Spend Significant Time in Dilute ISM: Atom/Dust Collisions Determine Grain Energy Losses $\tau_{Collisions}$~$100/N_H$ y
- Shock Acceleration May Produce Dust at Velocity up to 10^4 km/s

Isotopic Patterns: Si

- Analysis of Isotopic Abundances for Individual Grains in the Laboratory
- Correlations Reflect Grain Production Environment



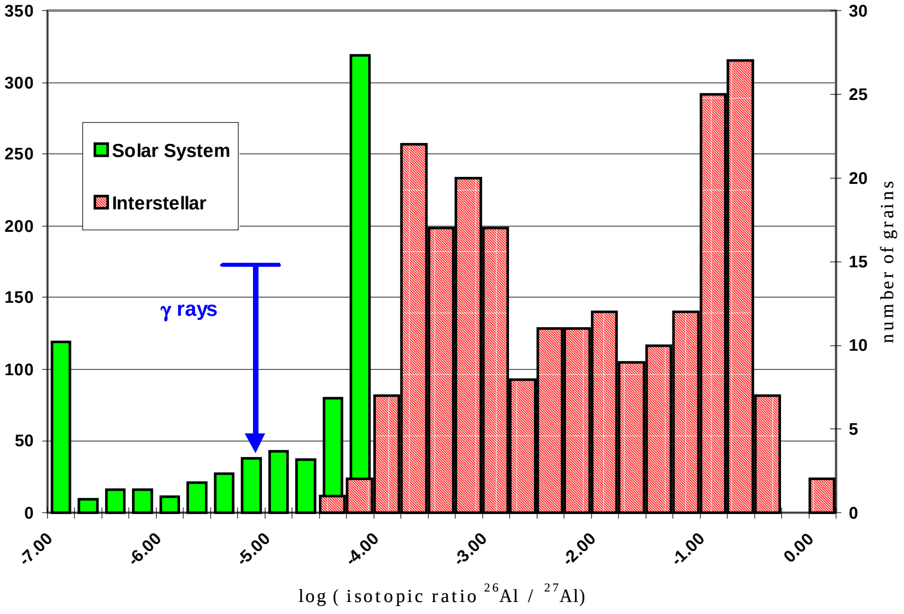
$\delta^{i}Si/^{28}Si$ (‰) = $((^{i}Si/^{28}Si)_{Grain}/(^{i}Si/^{28}Si)_{Solar} - 1)\times 1000$



^{26}Al/^{27}Al Isotopic Ratio

- Isotopic Ratio is Typical for Production Environment

- Meteoritic Samples (Solar System) ^{26}Al/^{27}Al ~ 5 10^{-5}
- Meteoritic Samples (Interstellar Grains) ^{26}Al/^{27}Al ~ 10^{-5}…1
- Gamma-Ray Measurement (ISM) ^{26}Al/^{27}Al ~ 1 10^{-5}
  (Assuming Solar ^{26}Al/^{27}Al in 4 10^{9} M_o ISM, 2 M_o of ^{26}Al)
- SNII Production with Chemical Evolution ^{26}Al/^{27}Al ~ 3 10^{-6}
  **(Assuming SN Production Ratio ^{26}Al/^{27}Al 6 10^{-3},
  Chemical Evolution with Infall k=4)**



after MacPhersson et al. 1995

Achievements in Gamma-Ray Line Astronomy

- Radioactivity is Diagnostic Tool for SNae & Novae

  SN1987A, SN1991T, SN1998bu, Cas A, WR11, Vela SNR; Nova Velorum

- Maps of Diffuse Radioactivity from Galaxy & All-Sky Available (few deg)

  1.809 MeV, 511 keV, (1.16 MeV, ...)

- Individual & Peculiar Source Regions Established and Being Studied

  GC Region (+Fountain), Inner Galaxy, Galactic Disk & Bulge, Vela & Cygnus Region, etc.

- Energetic-Particle Collisions Can Be Studied through Nuclear-Excitation Lines

  Solar-Flare Spectra (SMM, OSSE, COMPTEL)

Awaited Gamma-Ray Line Contributions

- Early-Lightcurve ^{56}Ni Lines from a SN Ia
- ^{22}Na from Novae, Early 511 keV Flash, ^{7}Be
- 1809 keV Emission Region Localization (3D)
- ^{26}Al Mass in the Galaxy - Decomposed Sources
- ^{60}Fe Correlation with ^{26}Al?
- Positron Decay Map of the Galaxy (~511 keV)
- ^{12}C & ^{16}O Excitation Lines from CR/ISM
- Line Shapes, Line Shapes, Line Shapes....

Nucleosynthesis Studies with Gamma-Ray Lines:
Summary

- **Radioactivity Gamma-Rays Provide** Unique Data **About:**
  - ☞ **Energy Source of SN Light Curves**
  - ☞ **Inner Regimes of Core-Collapse Supernovae**
  - ☞ **Massive-Star Distribution in the Galaxy**

- **Gamma-Ray Line Details are** Part of the Study of**:**
  - ☞ **Nucleosynthesis Reaction Cycles**
  - ☞ **SN Explosion Mechanism & 3D Effects**
  - ☞ **Stellar Convection Zone Detail**
  - ☞ **Evolution of Young Supernova Remnants**
  - ☞ **Cosmic-Ray Origin**

- Achievements:
  - ☞ Maps **of Radioactivity in ^{26}Al (t~10^6y) and e+ Annihilation**
  - ☞ Detections **of SN Radioactivity in ^{56}Ni, ^{57}Ni, ^{44}Ti**
  - ☞ **Detailed Astrophysics** Studies **of**
    - » **Young SNR Cas A (^{44}Ti)**
    - » **Localized Massive-Star Regions**