Nucleosynthesis Gamma-Rays

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MPE Garching

Gamma-Ray Line Diagnostics
^{26}Al in the Galaxy
Prominent Regions of Recent Nucleosynthesis

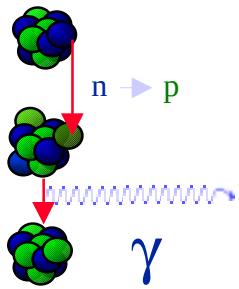
Origin of Cosmic Gamma-Ray Lines

Ref: e.g. Diehl & Timmes, 1998, PASP 110

Radioactivity

Nucleosynthesis Ashes Ejection into ISM, Decay of Unstable Isotopes

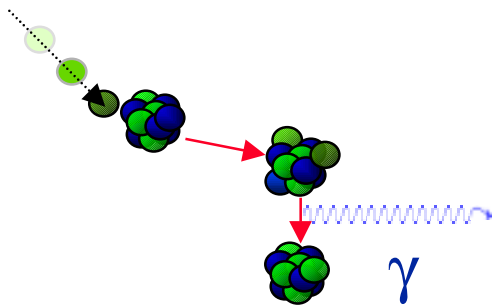
Isotope	Mean Lifetime	Decay Chain	γ-Ray Energy (keV)	Origin
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478	Novae
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*}+e^{+}$	158, 812; 847, 1238	Supernovae
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122	Supernovae
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275	Novae
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca^{*}+e^{+}$	78, 68; 1157	Supernovae
^{26}Al	$1.04\ 10^{6}$y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809	Stars, Supernovae, Novae
^{60}Fe	$2.0\ 10^{6}$y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332	Supernovae, Stars
e^{+}	.... 10^{5}y	$e^{+}+e^{-} \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511	(all above), jets, pulsars



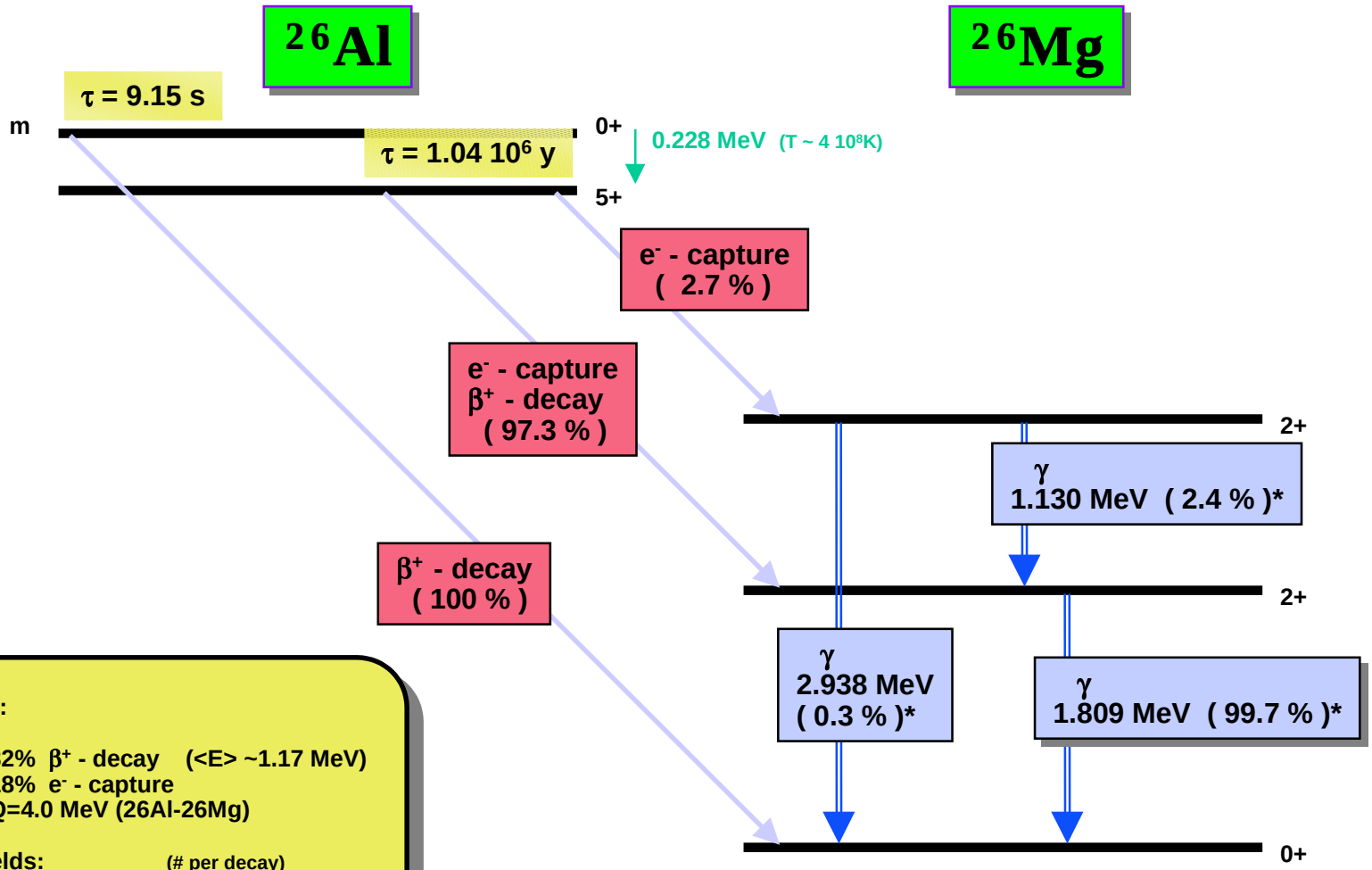
Nuclear Excitation

Energetic Collisions, e.g. Cosmic-Rays/Ambient Gas

Isotope	γ-Ray Energy (keV)
^{12}C	4438
^{16}O	6129
^{28}Si	1779
^{20}Ne	1634
^{24}Mg	1369
^{56}Fe	847



^{26}Al Radioactive Decay



^{26}Al Decay:

82% β^+ - decay (<E> ~1.17 MeV)
18% e^- - capture
Q=4.0 MeV (26Al-26Mg)

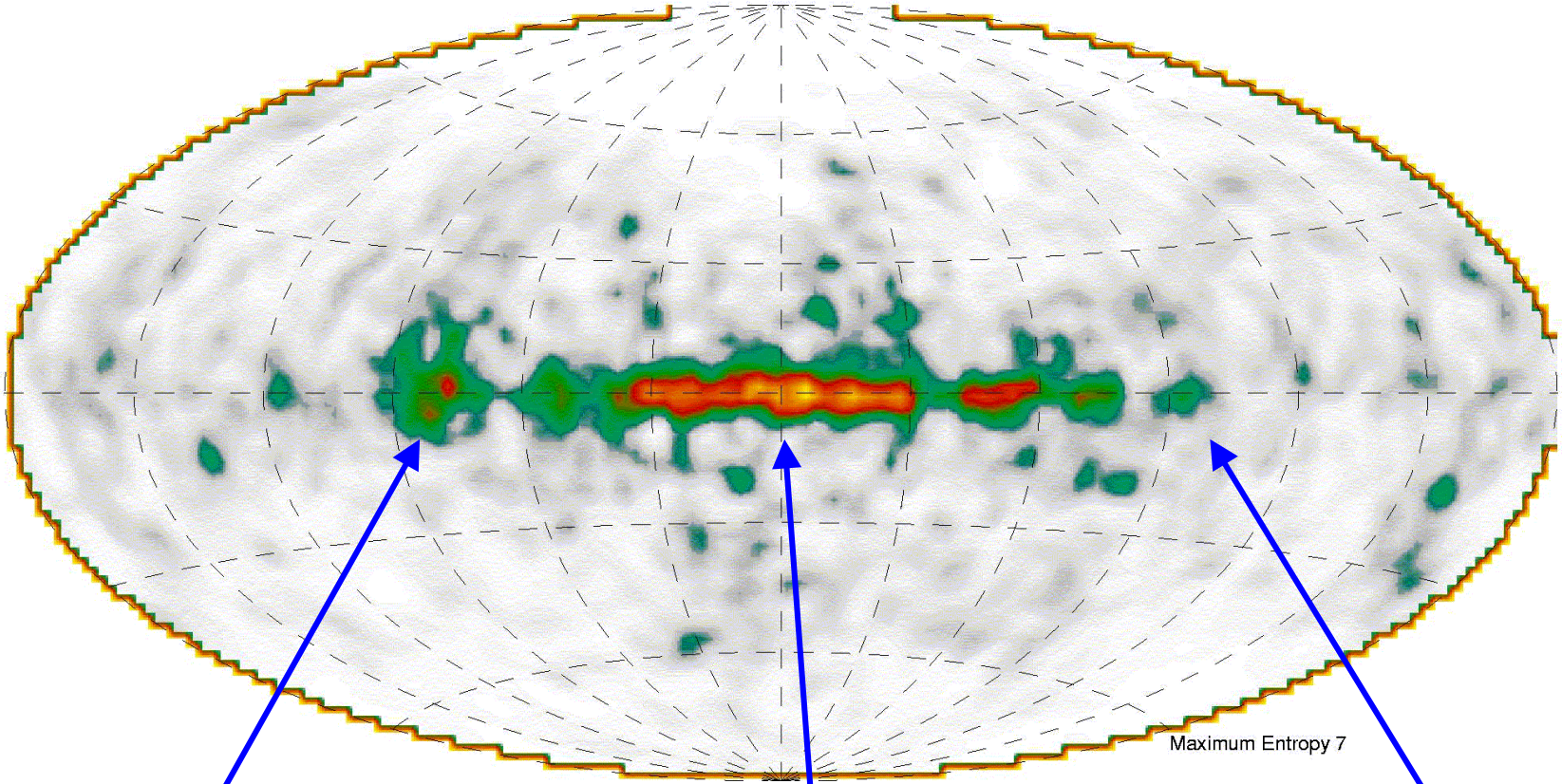
Photon yields: (# per decay)

0.511 MeV	1.622
1.130 MeV	0.024
1.809 MeV	0.997
2.938 MeV	0.003

* .= % are relative to one decay of ^{26}Al

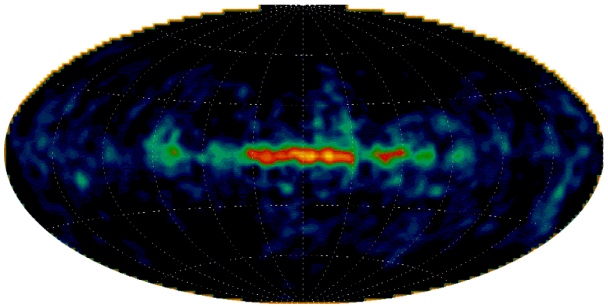
COMPTEL All-Sky Image at 1.8 MeV:

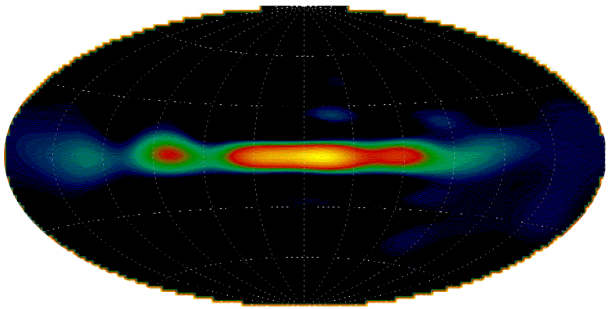
^{26}Al Nucleosynthesis in the Galaxy

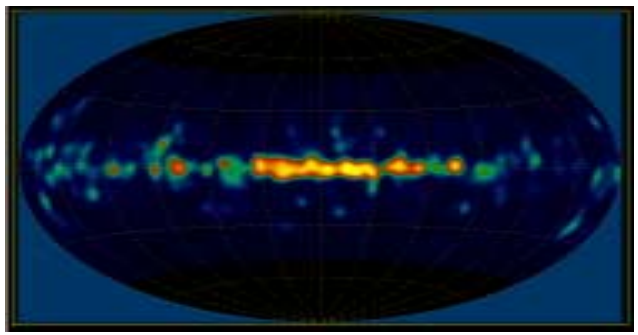


MEM Image.
Complete Mission (Phase 1-9)
(Plüschke et al. 2001)

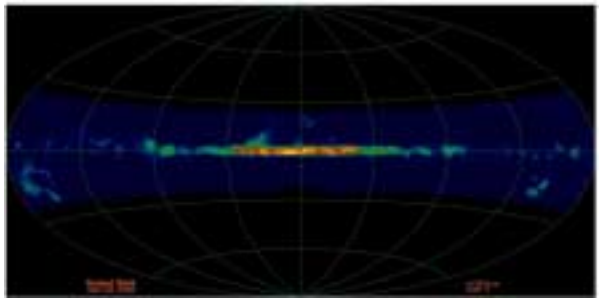
COMPTEL 1.809 MeV Maps and Possible Source Counterparts



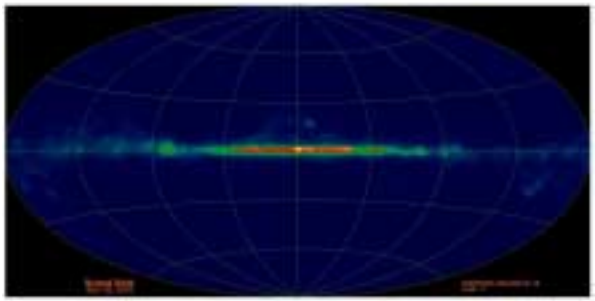




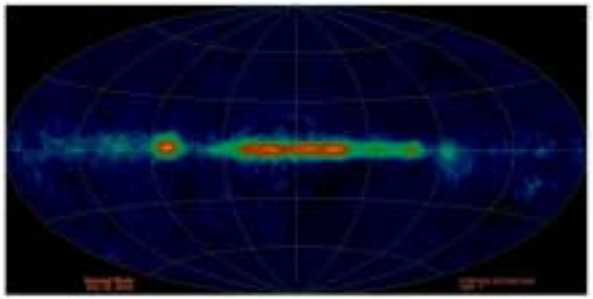
Different Imaging Methods
(ME, MREM, MLik)



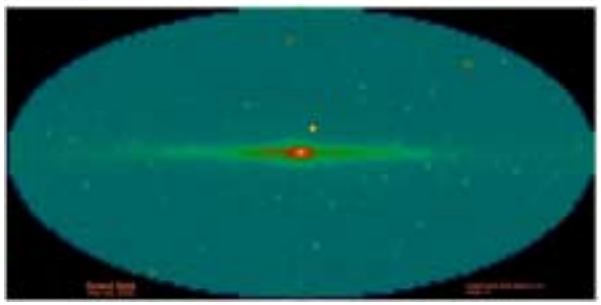
CO map of molecular gas



IR map at 240 μm, dust



Radio map at 53 GHz, free electrons



IR map at 3.5 μm, starlight

Model Fits ^{26}Al Tracers / COMPTEL 1.8 MeV: Results:

- Galactic Emission Clearly Detected (~32σ) , Disk Dominates
- Exponential Disk = Satisfactory Global Model
  (R_0=5 +-1 kpc, z_0=130 +-90 pc)
- Spiral Structure in Models = Significant Improvement (3.6σ)
- Dust / Gas / Free-Electron Distributions = Best Src Tracer
- Object Catalogues = No Improvement of Model (<3σ)
- Nearby Extended Models (Gould Belt, Loop I) = Not Conclusive (Shapes?) (<3σ)
- Total Amount of ^{26}Al in Galaxy: ~2 +-0.3 M_o

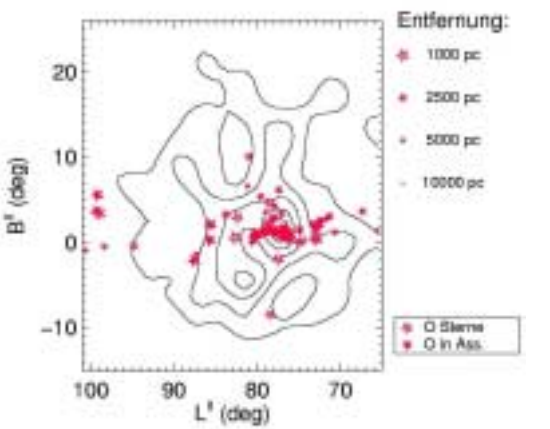
On the Massive-Star Origin of ^{26}Al

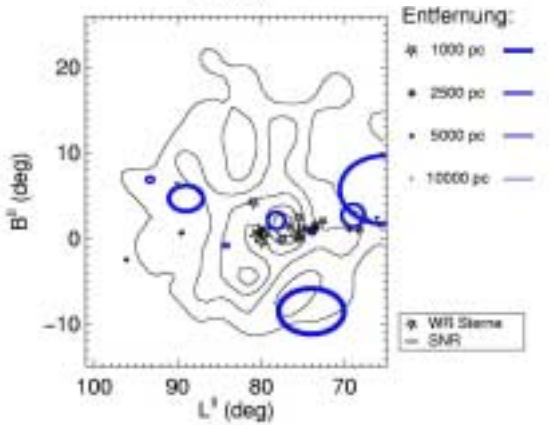
- 1.8 MeV Emission and Patterns of Massive-Stars
  - LMC Patterns, M31 Patterns
  - Nearby OB Associations
- ^{26}Al Disk Latitude Extent
  - > Gas, but < Old Population => “puffed up” by SN/Wind Ejection?
- 1.8 MeV Emission and Candidate-Source Tracers
  - Free-Electron Emission, i.e. Ionization by Massive-Star UV Photons
  - Warm Dust Emission, i.e., SN & O-Star Heating of IS Dust
  - Known Massive Star Locations, i.e. Young Clusters, WR & O Stars
  - Cosmic Ray Sources
- Consistency Checks on Massive-Star Outputs:
  - Line-of-sight integrated $I_{1.8MeV} = I_{free\text{-}free\_emission}$ ***(Knödlseder 1999)***
    => Plausible ~8 10^{-5} M_o Average Yield of ^{26}Al per “OV star”,
    Consistent total ^{26}Al Mass of ~ 2.4 M_o, ~10000 WR Stars in Galaxy
    But: => SN (II+Ib) rate ~ 1.8/100y (?)
  - Cygnus Region Predicted vs. Measured ^{26}Al ***(Plüschke et al. 2001)***
  - others (Orion, Sco-Cen) under detailed investigations

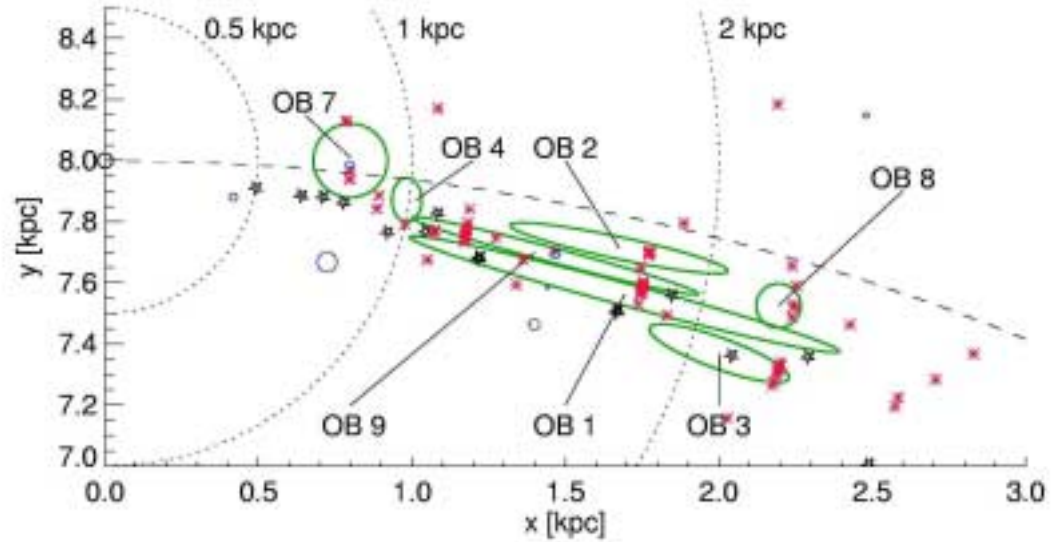
⇒ Plausible Massive Star Origin of ^{26}Al

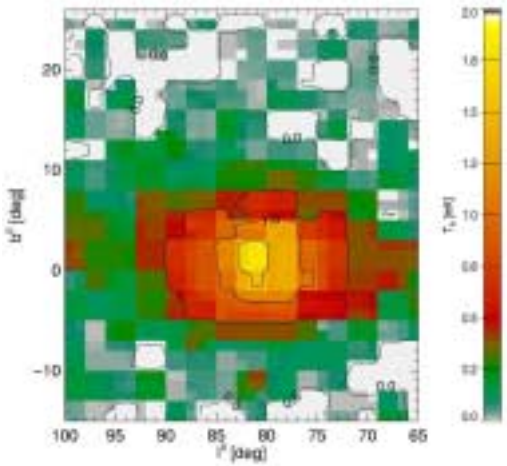
Massive-Star Activity in the Cygnus Region

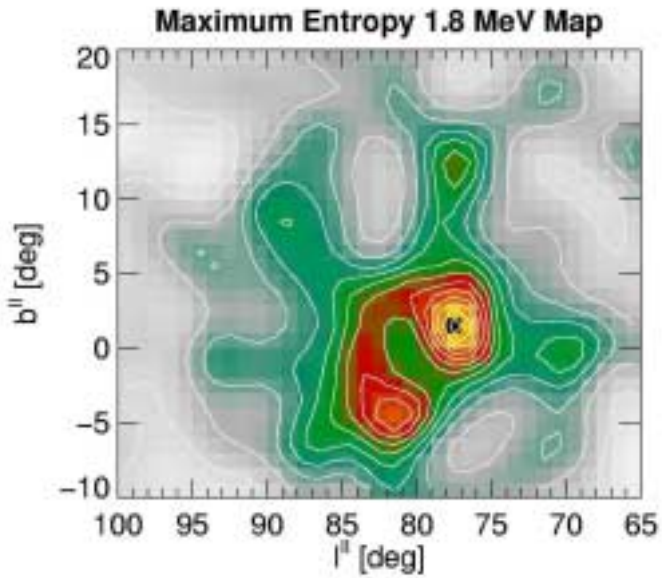
- 19 Supernova Remnants
- 23 Wolf Rayet Stars
- 9 OB Associations
- Prominent Free-Free Emission
- Prominent ^{26}Al Emission









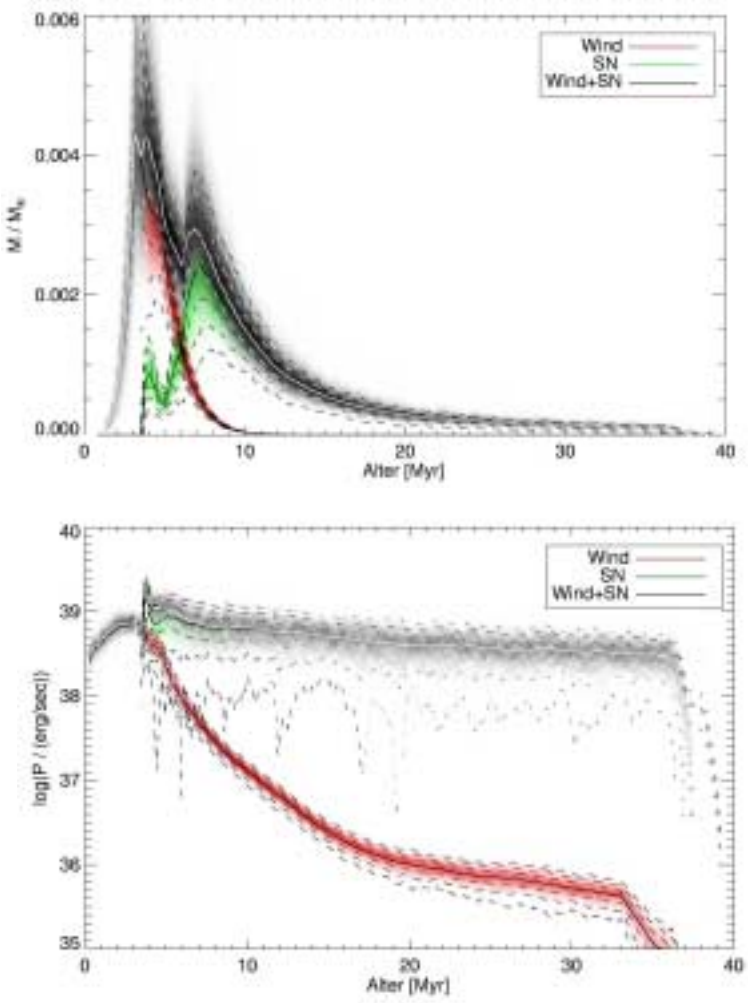


Understanding Massive Stars in the Cygnus Region: Modelling ^{26}Al Emission

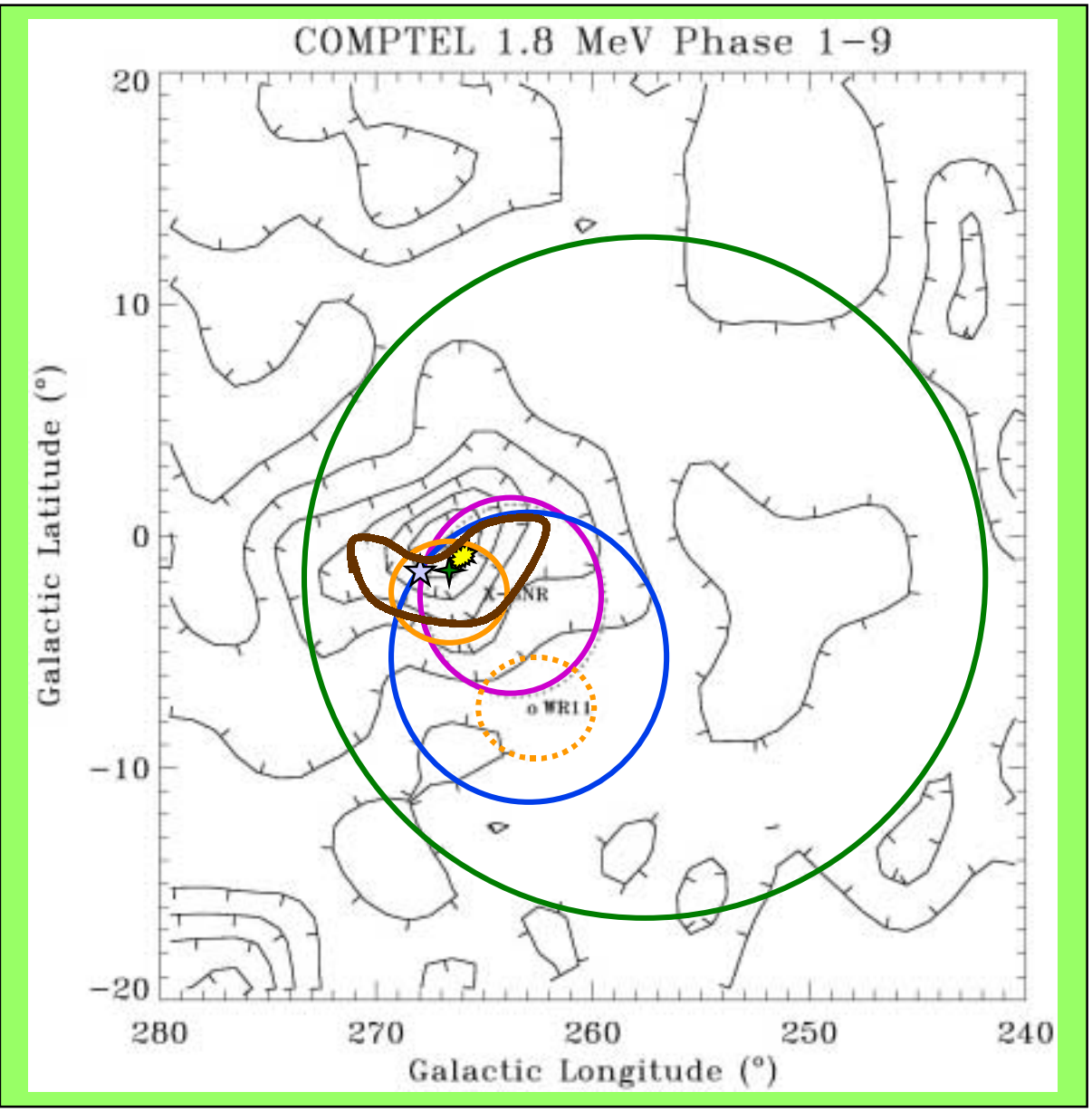
S. Plüschke, PhD Thesis, TUM 2001

- **Individual Known Sources + Population-Synthesis Model of OB Associations -> 1.8 MeV Expectations**

- **Model Ingredients:**
  - Stellar Evolution Tracks (Geneva/Meynet) [-> L(t), T(t), $^{dm}/_{dt}$(t)]
  - Nucleosynthesis Yields WR, SN
  - Stellar Wind Model(s)
  - Initial Mass Function
  - Sample Statistics Analysis
- **Model Predictions:**
  - ^{26}Al Gamma-Ray Luminosity (t)
  - EUV Luminosity (t)
  - Kinetic-Energy Ejection (t)
- **Consistency Checks**
  - Details of Population Evolution (e.g. STARBURST99)
  - Modelling Free-Free Emission from Same OB Associations Model
  - Estimation of OB Association Ages from ^{26}Al Emission
  - Estimation of Cygnus Region Kinematics from Massive-Star Winds & SNae



The Candidate ^{26}Al Sources in the Vela Region

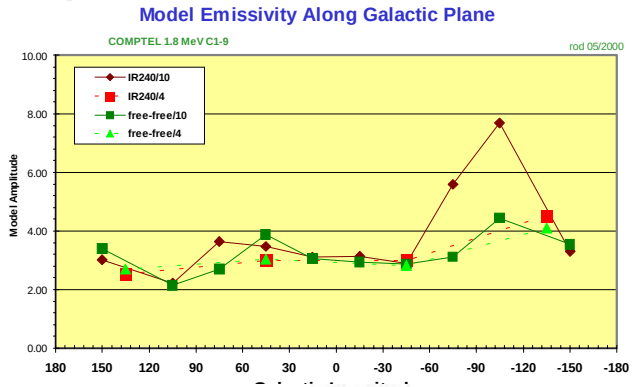


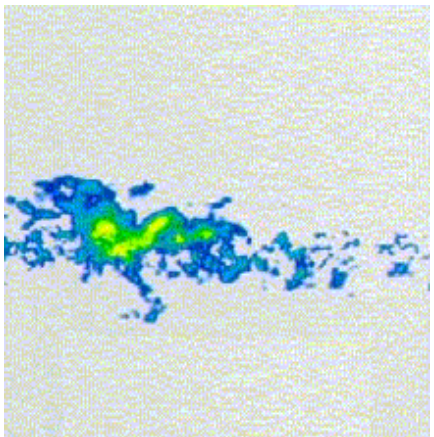
- Possible Sources:
  - Molecular Ridge
  - RCW38
  - Vela R2, OB2
  - Vela SNR
  - ^{44}Ti SNR (266.5/-1.5)
  - X-SNR (266.2/-1.2)
  - γ^2Velorum/WR11
  - IRAS Vela Shell/OB2
  - Gum Nebula

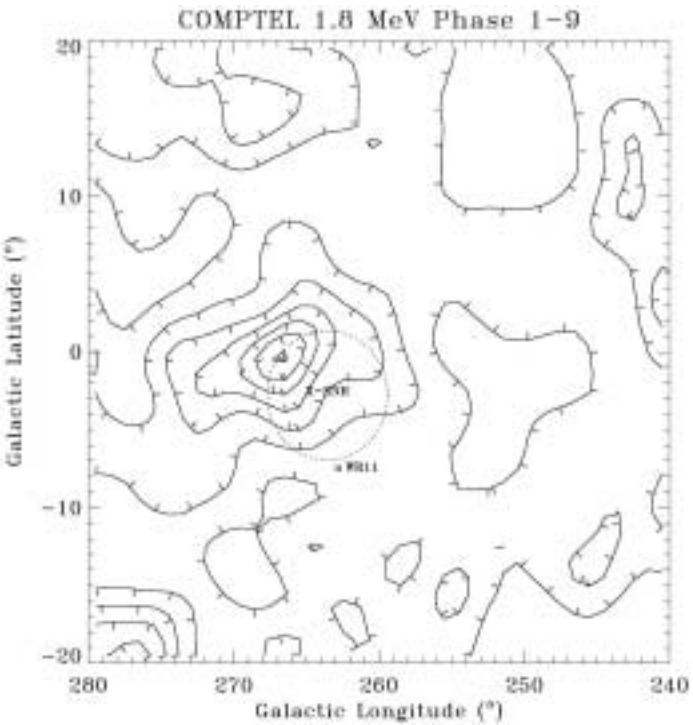
- Active Region towards Edge of Molecular Ridge?

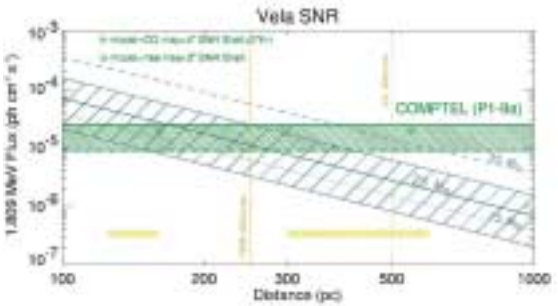
Vela Region ^{26}Al Study

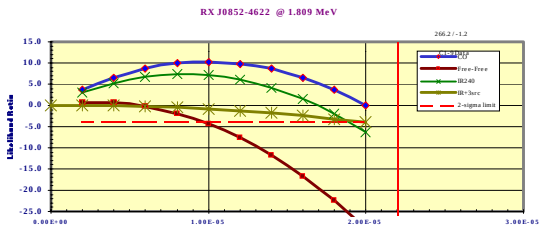
- **Vela Molecular Ridge Appears Relatively Active (t~10^{7}y) (Brightest HII Regions; SNR; Excess ^{26}Al)**
- **Source Objects' ^{26}Al Contributions not Detectable Individually**
- **Vela SNR and WR11 Distances Known (250 and 259 pc) => Limit & Calibrate Nucleosynthesis Models**

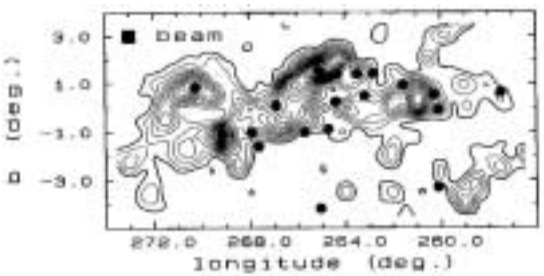


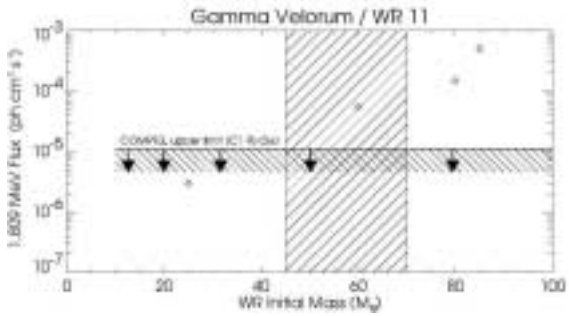












Orion/Anticenter Region:
OB Stars, Gas Clouds, and ^{26}Al Gamma-Rays

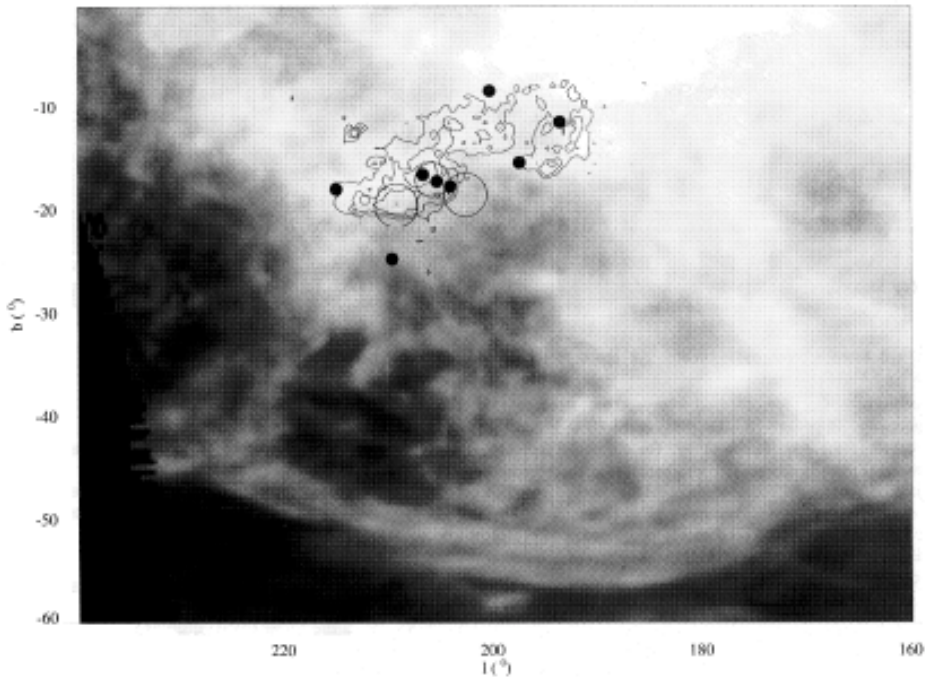
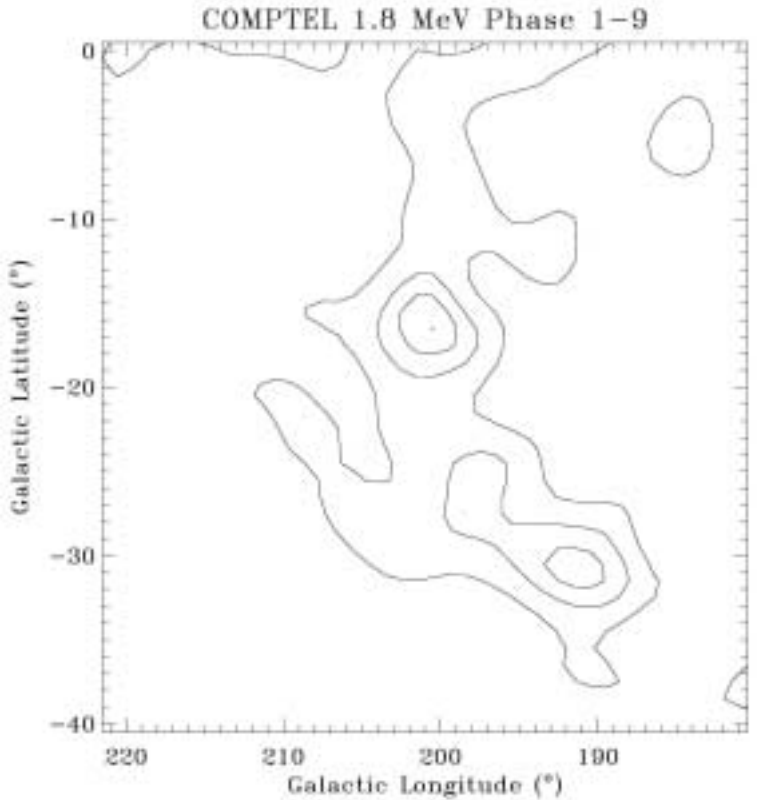


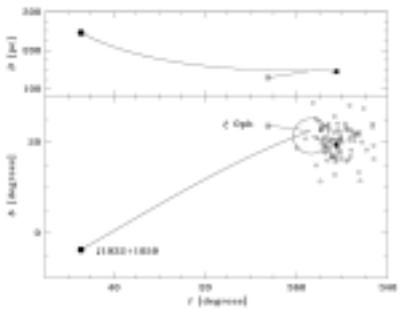
Fig. 7. The position of the Orion OB1 association with respect to the H I shell. The grey scale image is a logarithmically scaled representation of integrated H I emission in the velocity interval $-1\ \mathrm{km\,s^{-1}} \leq v_{LSR} \leq +8\ \mathrm{km\,s^{-1}}$. The contours outline the 100 μm (IRAS) emmission from the Orion A and B molecular clouds (the ring around $(l, b) = (195°, -12°)$ is the λ-Orionis ring). The dots show the brightest stars in the Orion constellation. The circles show the positions of the three main subgroups of Orion OB1. From right to left are shown 1a, 1b and 1c



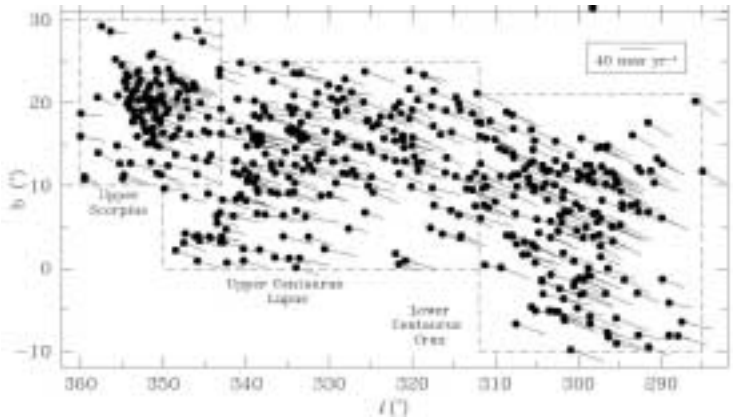
- Orion OB1:
  - Association of Massive Stars, 4 Subgroups (a-d)
  - Ages ~7-12, 5, 3, 1 My
- Eridanus Cavity:
  - Blown by Orion OB1 Massive Stars, Age ~5.5 My
- ^{26}Al Production from Massive Stars:
  - Ejection into ISM from WR Winds & SN
  - Decay Time 1 My, 1.809 MeV Maximum ~4 My after Star Formation

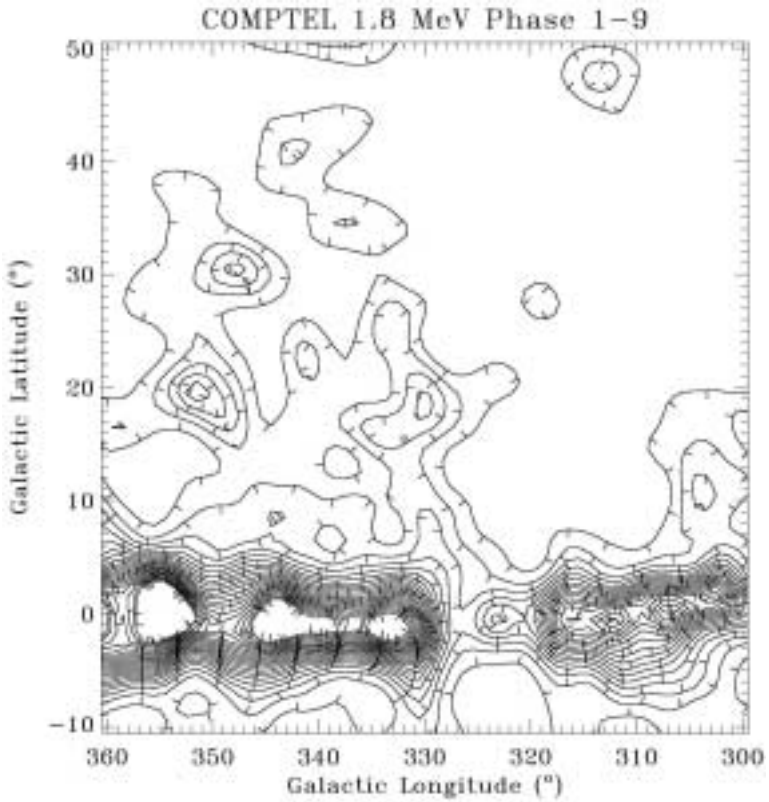
Sco-Cen Region

- **Nearest Active Star-Forming Region**
  - Distance ~118-145 pc
- **Three Major Subgroups:**
  - Upper Scorpius, Age 5-6 My
  - Upper Centaurus Lupus, Age 10 My
  - Lower Centaurus Crux, Age 4 My
- **HI Loops:**
  - SN Activity in Sco-Cen Responsible for Loop I
  - SN Bubbles' Interaction Triggered Star Formation (e.g. UCenLup SN 12 My ago –> USco Passage 5 My ago)
- **ζ Oph Runaway O Star**
  - from USco (~1 My ago) or UCenLup (3 My)
  - Associated with PSR J1932+1059? (at USco 1 My ago, d_{now}~560 pc -> SN Ejected ζ Oph?)



- **^{26}Al From Massive Stars?**
  - COMPTEL 1.809 MeV Image is Suggestive
  - Analysis in Progress





Summary: ^{26}Al in Localized Regions of the Galaxy

- **Cygnus Region Study**
  - Extended Emission, ~as Expected from OB Association Morphology
  - Reveals/Confirms Exceptional Nature of Cyg OB2
  - New Insights on Star Formation History and Richness
- **Vela Region Study**
  - Extended Emission, Prominent 'Point' Sources Not Dominating
  - Vela SNR At/Below Detection Limits (even INTEGRAL) (Size!)
    γ^2Vel / WR11 Not Detected - A Challenge for WR Nucleosynthesis Models
  - RX J0852-4622 Could Be Significant Contributor (but degenerate with VMR)
  - Vela Molecular Ridge Appears Active Star Formation Region
- **Orion/Eridanus Study**
  - Extended Emission, Offset from Orion OB1 / Massive Stars
  - Morphology of Eridanus Bubble is Suggestive:
    - 'Venting' of Massive-Star/SN Ejecta into Superbubble
    - Proximity and Extent of Visible ^{26}Al ~Consistent with Models (tbc)
- **Sco-Cen Study**
  - Interesting 1.8 MeV Emission Features, Plausible Source Candidates....
  - Being Investigated.....
- **Gould Belt Study**
  - Combining 1.8 MeV Emission Features from Orion, Sco-Cen, others below threshold?
  - Being Investigated..... Spatial Emission Model Biases are Difficult to Assess....