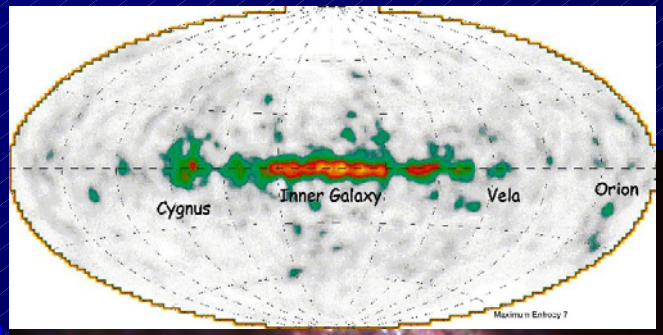
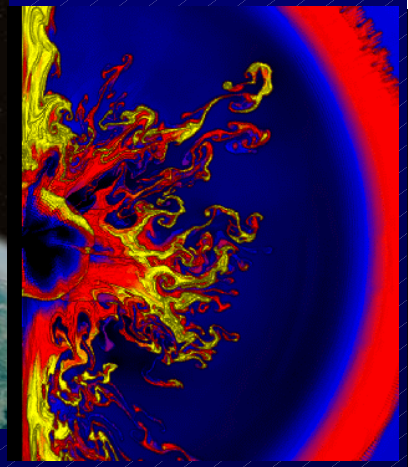
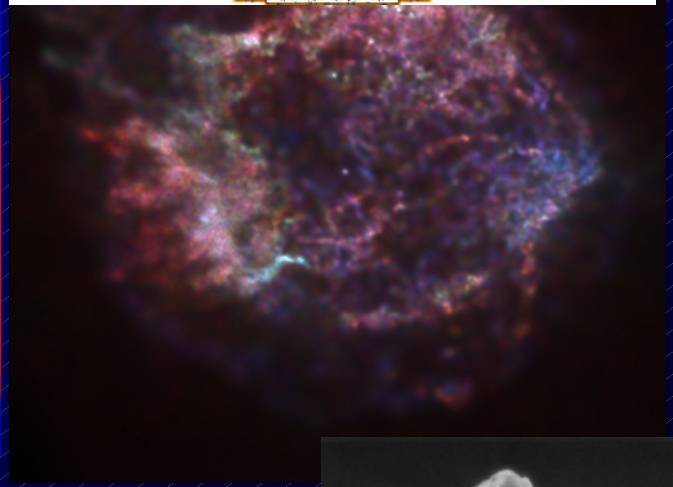
Current Galactic Nucleosynthesis

– Observations and their Interpretations –

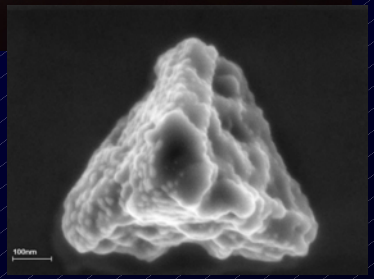
Roland Diehl
MPE Garching







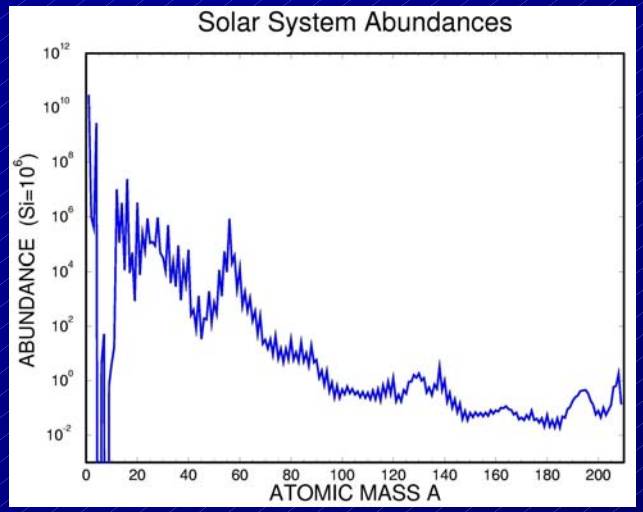
- Nucleosynthesis with Time
- Understanding Supernovae
- Massive Stars and ^{26}Al and ^{60}Fe

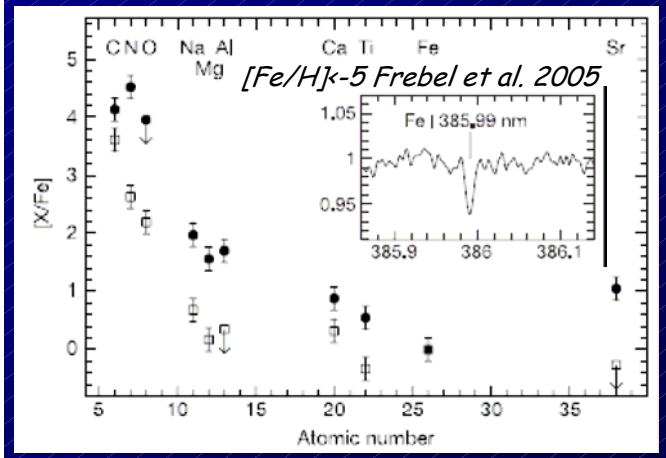


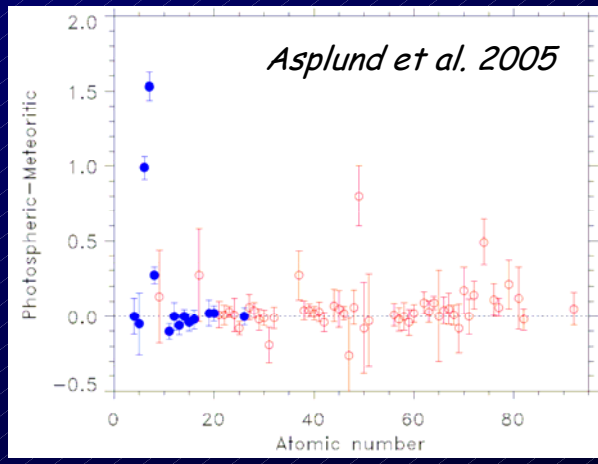
Cosmic Isotopes

Chemical Evolution of the Galaxy

- Abundances in Stellar Atmospheres





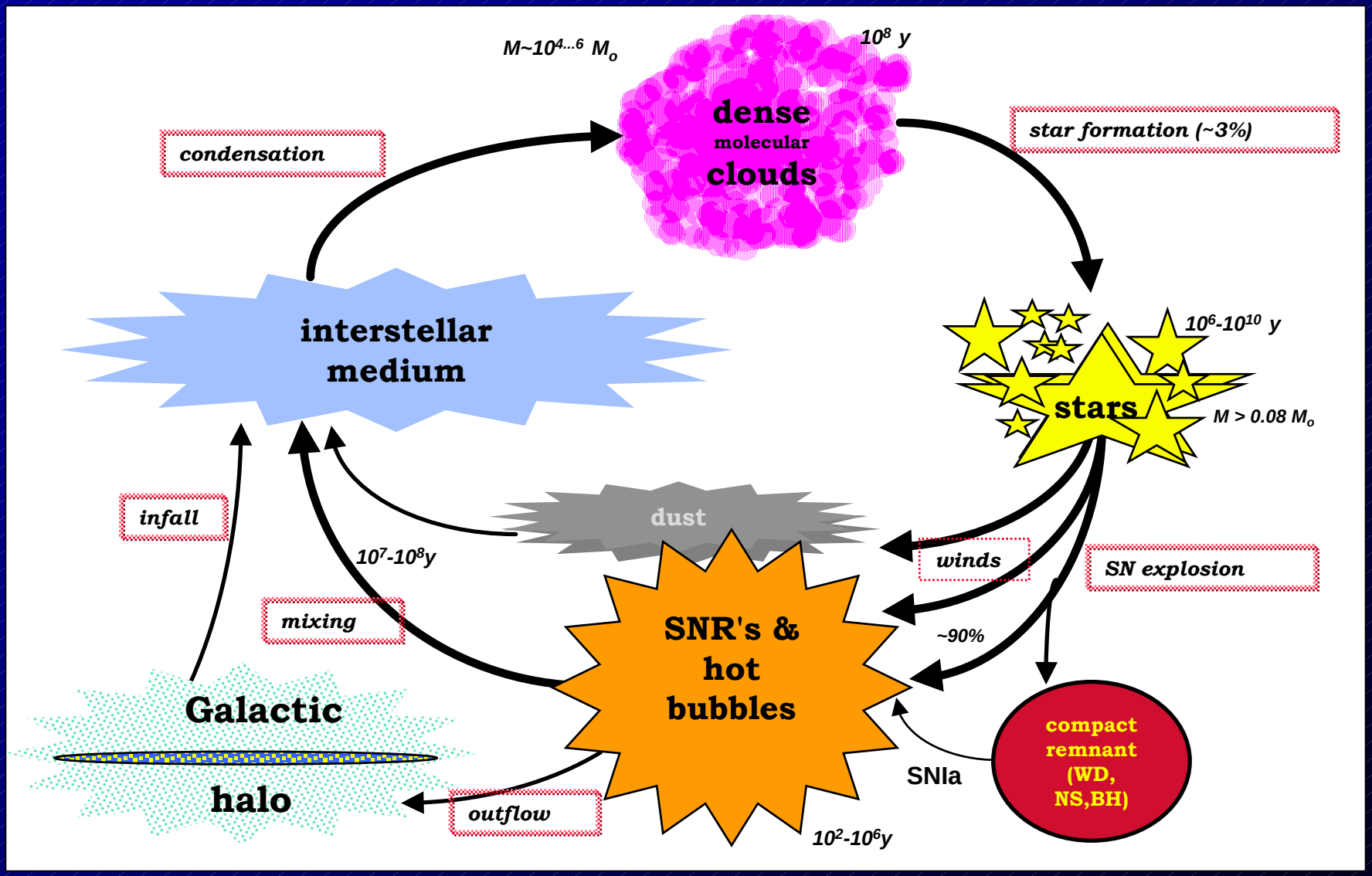


- Solar Abundances are Difficult to Assess
  - Main Components: X=0.7392, Y=0.2486, Z= 0.0122 *(Asplund et al. 2004)*

But, e.g.:

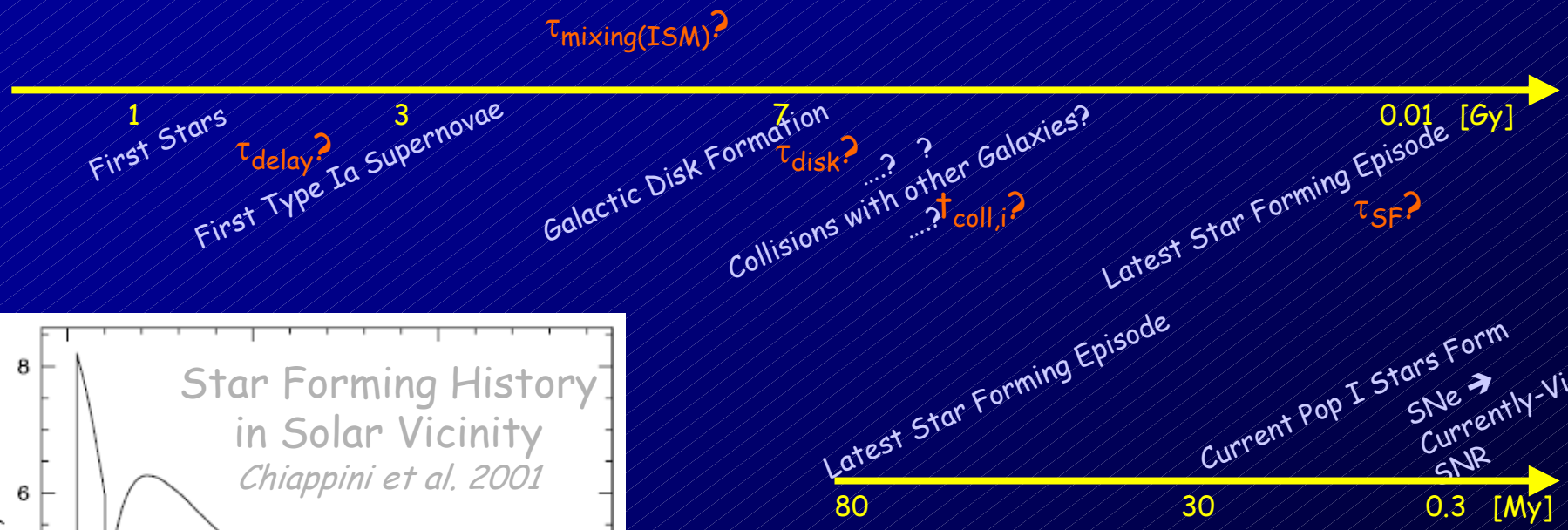
  - Metal Fraction Z/X: now 1.65%, was 2.75% *(Anders & Grevesse 1989)*
  - C Abundance: down by 0.17 dex, overall more consistent now

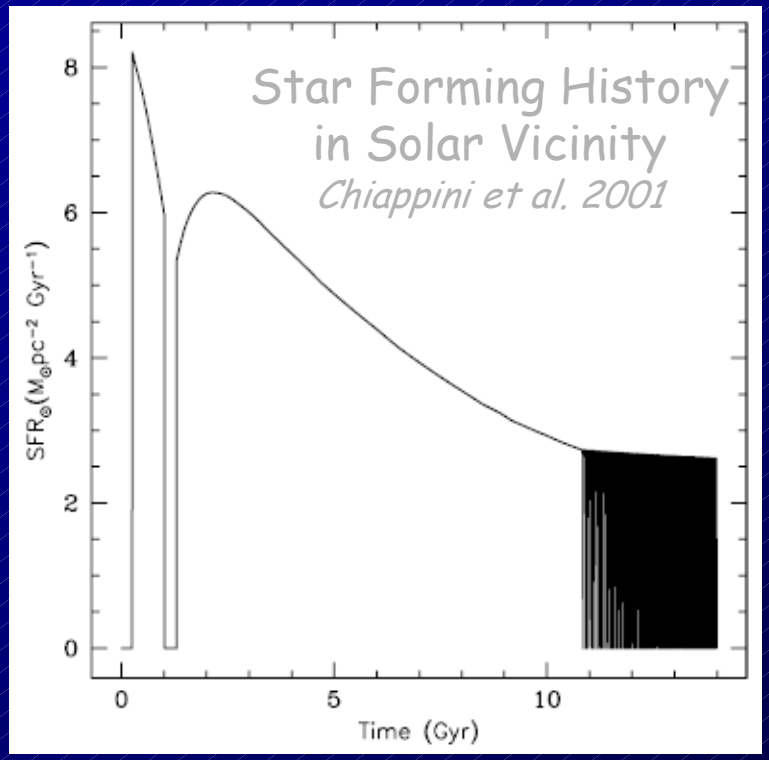
Astrophysical Cycles of Matter



- Associate Radiation Source Processes with Desired Astrophysical Parameter
  - e.g. Stellar-Atmosphere Abundance <-> SN Physics

Time Domains of Galactic Nucleosynthesis

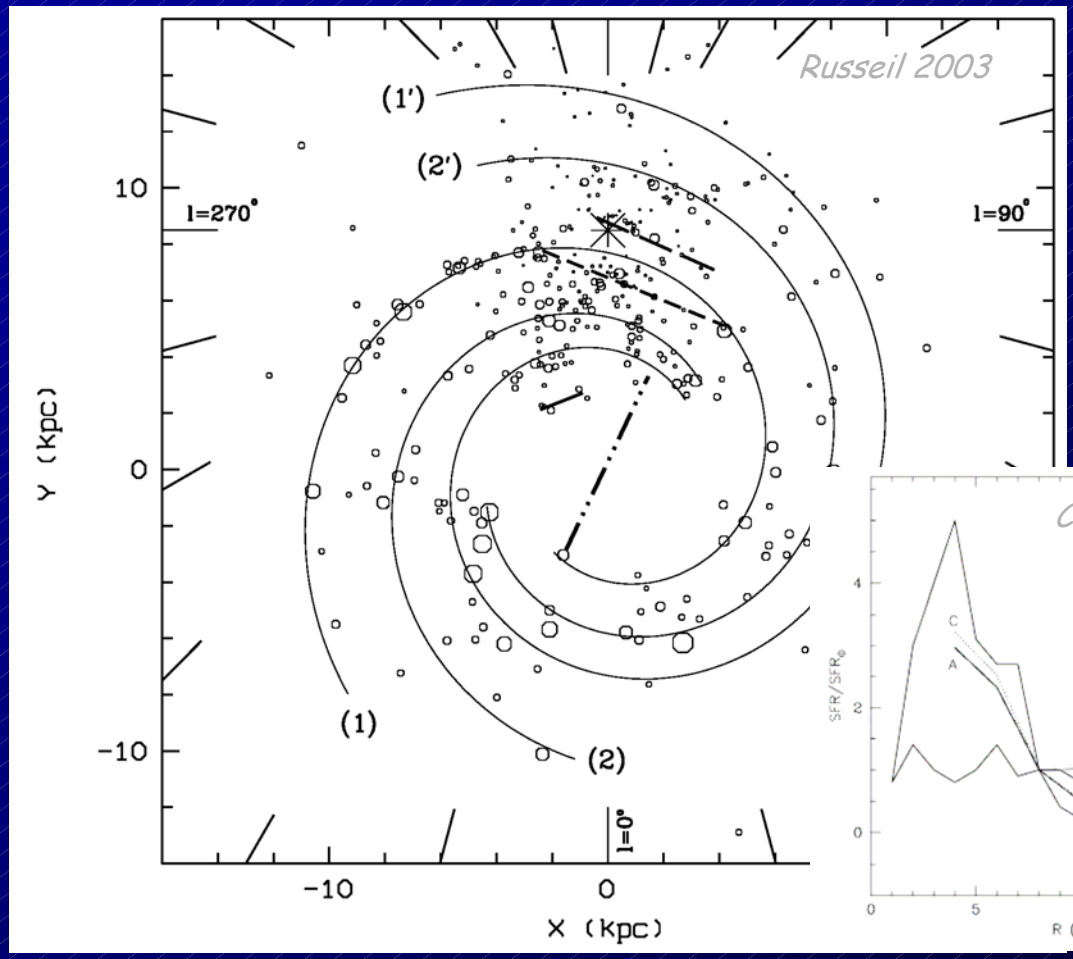


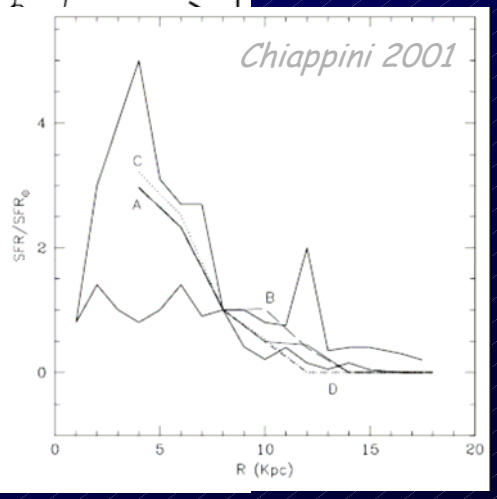


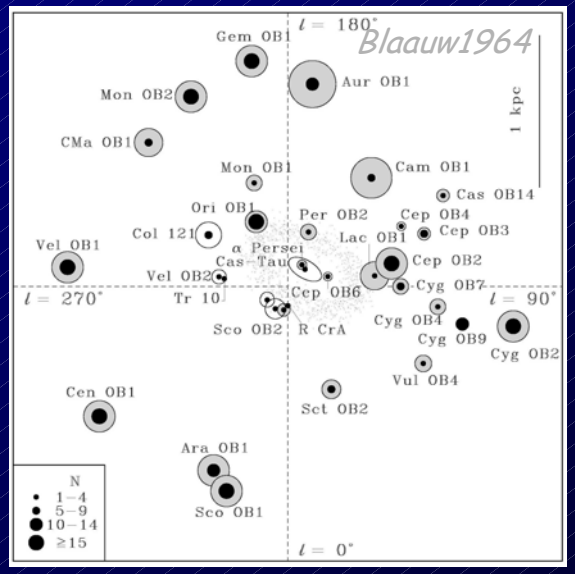
- ☆ We see…
  - ☞ Stars — Ages 0…13 Gy
  - ☞ SNR,Pulsars — Ages 0.03…30 ky
  - ☞ HII Regions — Ages 0…5 My
  - ☞ Parental Clouds — Ages 0.01…0.1 Gy
- ☆ …a highly fragmented and biased set of tracers

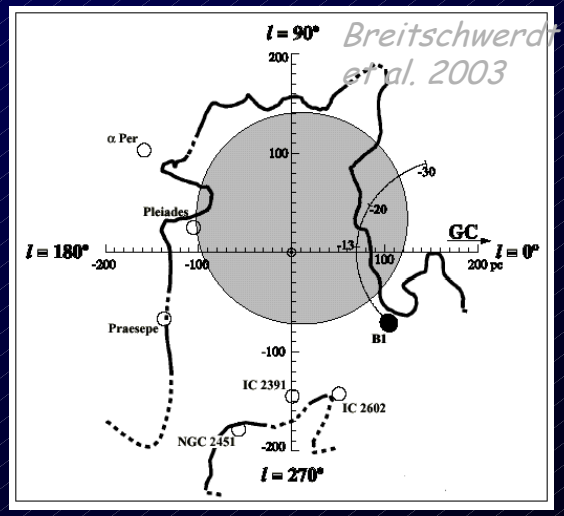
Nucleosynthesis Sources in the Galaxy

- Star Forming Regions in GMClouds along Spiral Arms
- Clustered Source Regions, Local Disks/Belts

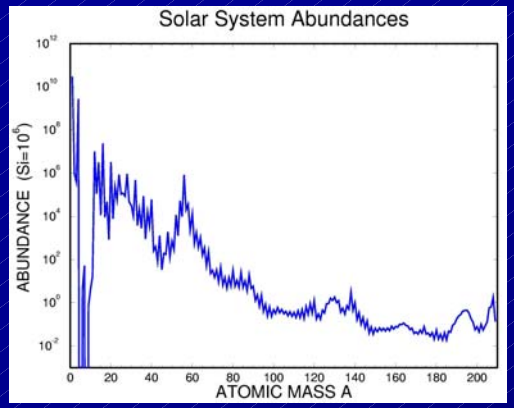


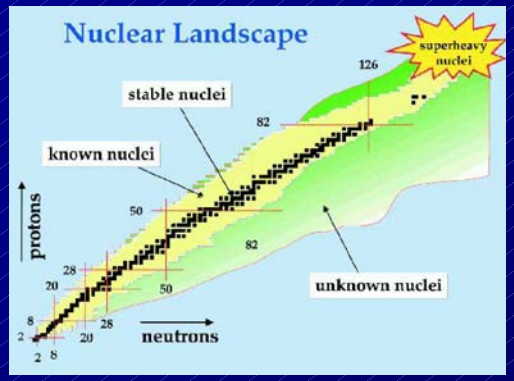






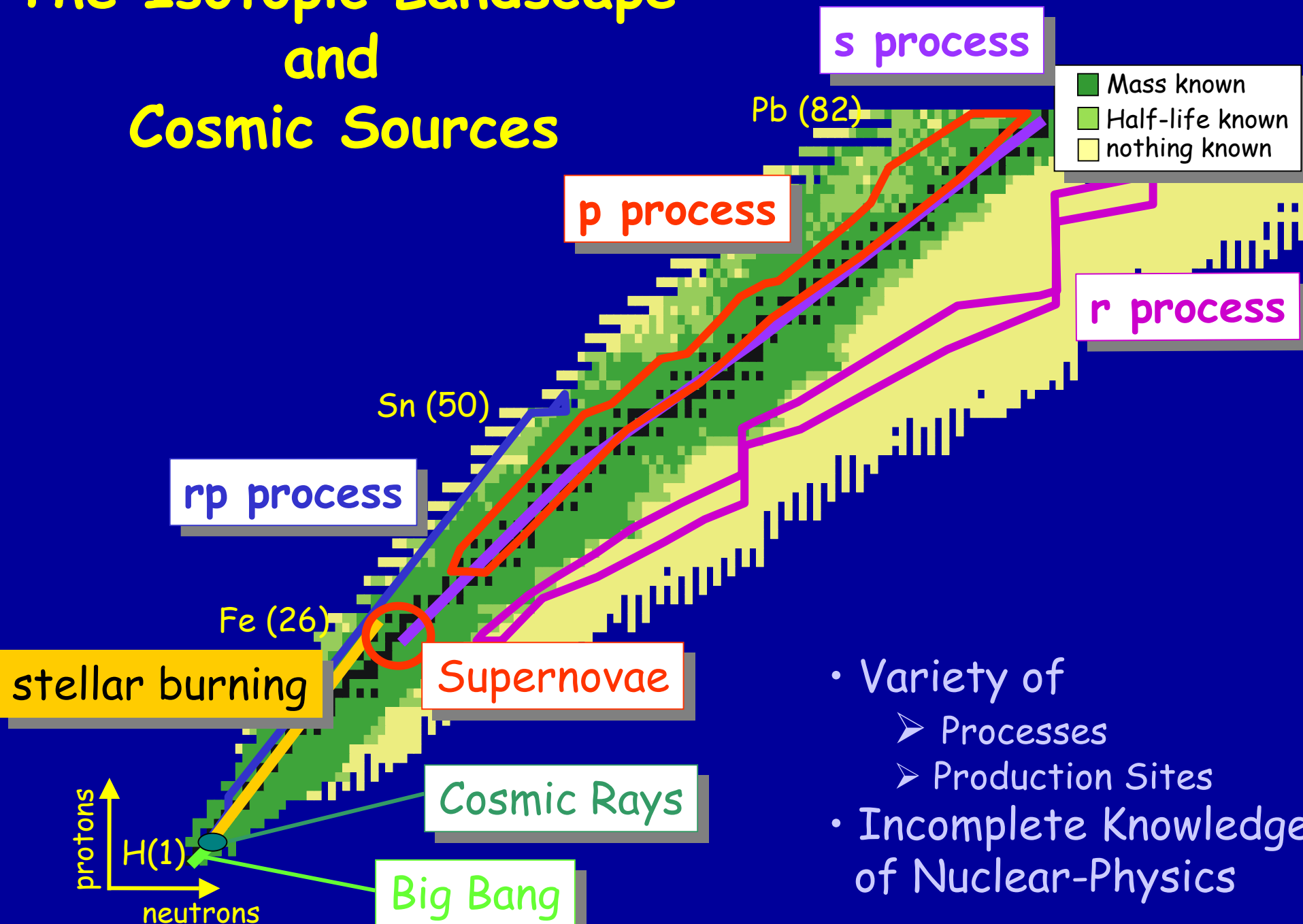
Nuclear Physics and Astrophysics





- Nuclear Structure, Nucleon Interactions
  - Coulomb Repulsion versus Strong Interaction
  - Collective Interactions, Clusters
- Reaction Paths far from Stability
  - No Data from Nuclear-Physics Experiments
  - Lessons on Nuclear Physics from Astronomy
- Cosmic Environments of Nuclear Reactions
  - Explosive Heating & Burning Zone Dilution
  - Longterm Evolutions in Stars (Convection) and Interstellar Medium ("chemical evolution")
- "Nuclear Astrophysics"

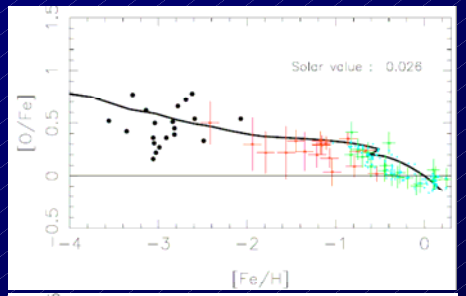
The Isotopic Landscape and Cosmic Sources

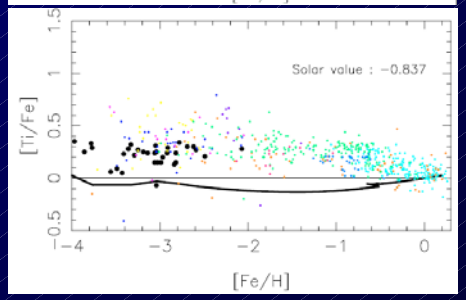


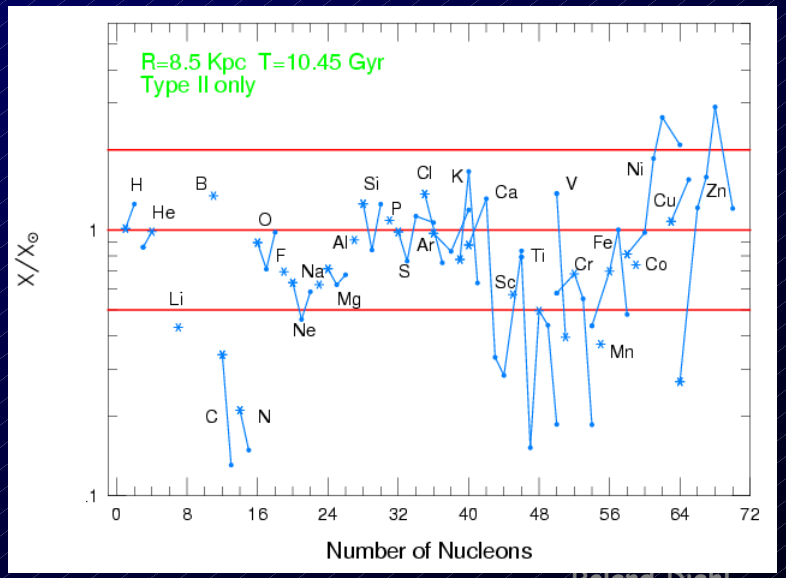
- Variety of
  - Processes
  - Production Sites
- Incomplete Knowledge of Nuclear-Physics

Chemical Evolution of the Galaxy

- Modeling Abundance Evolutions
  - ☆ Star Formation History
  - ☆ Source Yields
  - ☆ Mixing and Infall
  - ☞ Works for Some Elements, not for Others…
- Modeling Standard Abundances
  - ☆ (same ingredients)
  - ☞ Agreement is Good, ~Factor 2
- There are Missing Pieces…
  - ☞ Nuclear Reactions?
  - ☞ Stellar & SN Models?
  - ☞ Matter Cycling / ISM Flows?







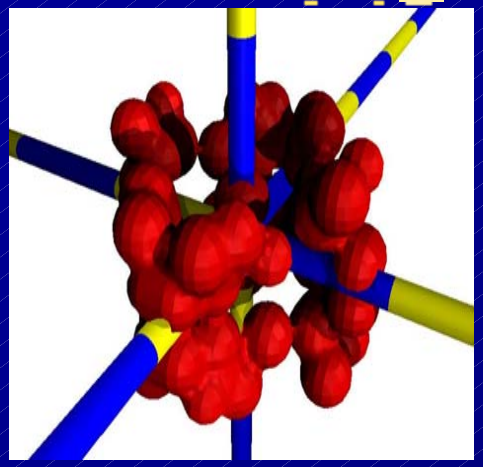
Gamma-Ray Lines for Nucleosynthesis Study

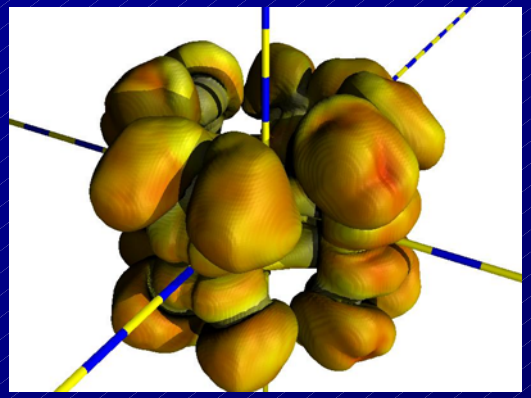
- Radioactive Trace Isotopes as Nucleosynthesis By-Products
- For Gamma-Spectroscopy We Need:
  - ☞ Decay Time > Source Dilution Time

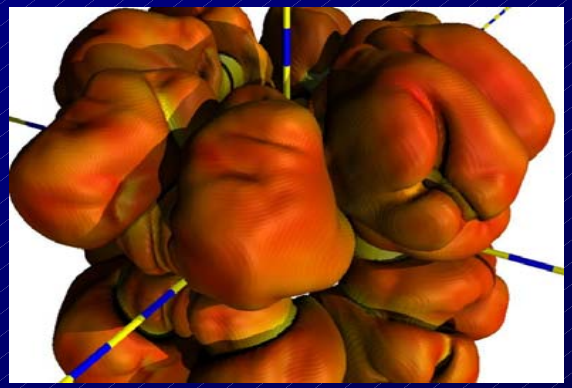
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*} + e^{+}$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*}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

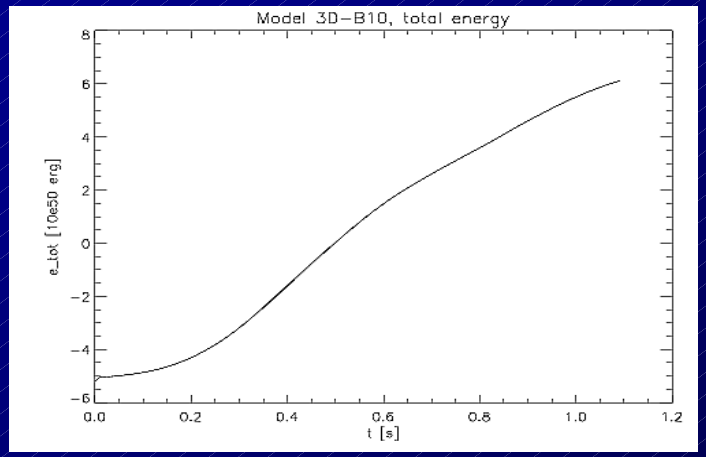
- Supernovae Type Ia

How Does a SNIa Explode?



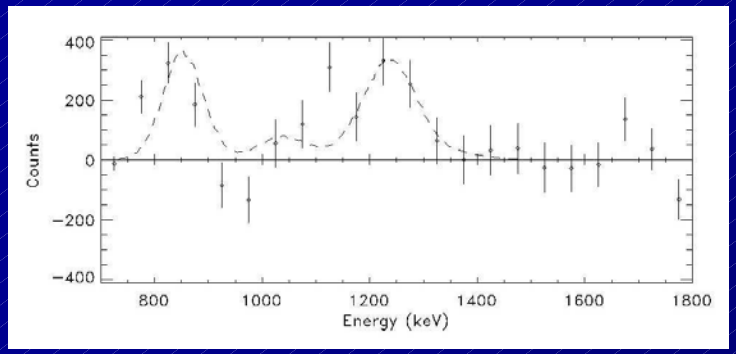


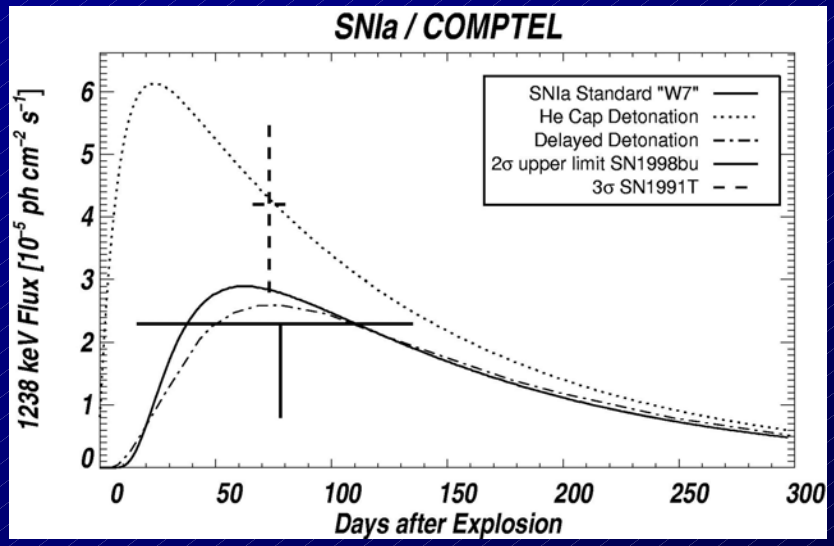




- C Ignition at M_{Ch} Limit (many ignition points??)
- Turbulent Flame Propagation
- WD Expansion -> Flame Extinction
- Issues: Rapid Time Scales!
  - Nuclear Burning C+O->^{56}Ni…
  - Expansion
  - Mixing
- Models:
  - **DET / DEF / DDT / PUL**
- ^{56}Ni and other Isotopes: ~Factor 2 Uncertain
- "Standardizable Candles" are not Understood

Gamma-Rays from Supernovae Ia

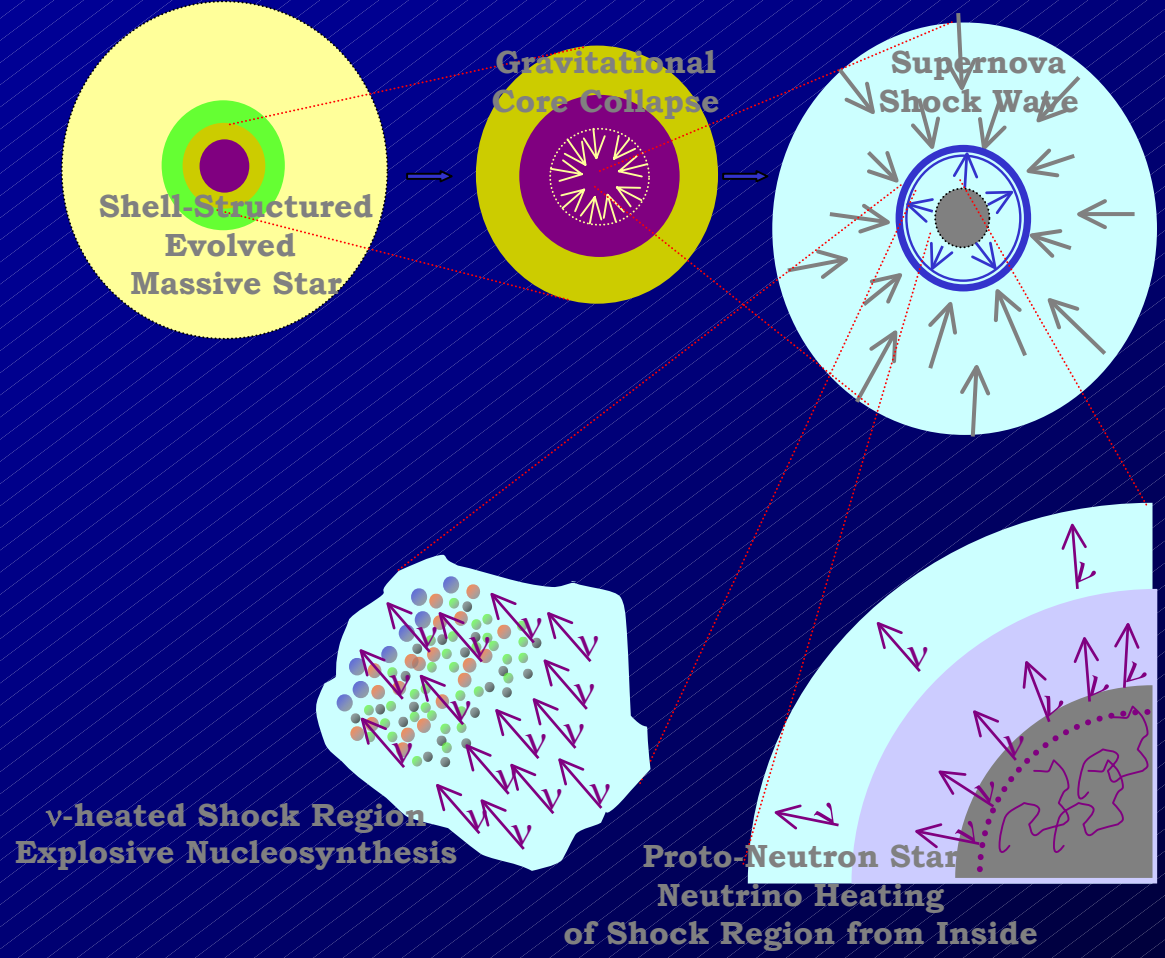




- Rarely SNIa ^{56}Ni Decay Gamma-Rays are Above Instrumental Limits (~10^{-5} ph cm^{-2} s^{-1})
  - ~2 Events / 9 Years CGRO
  - ~2 Events / 2 Years INTEGRAL Mission
- COMPTEL
  - ☞ Signal from SN1991T (3σ) (13 Mpc)
  - ☞ Upper Limit for SN1998bu (11 Mpc)
- The ^{56}Ni Power Source: 0.5 M_o of ^{56}Ni??
- Which Model?

- Massive Star Nucleosynthesis:
  - ☆ Core-Collapse Supernovae
  - ☆ Hydrostatic Burning

Core Collapse-Supernovae: The Model

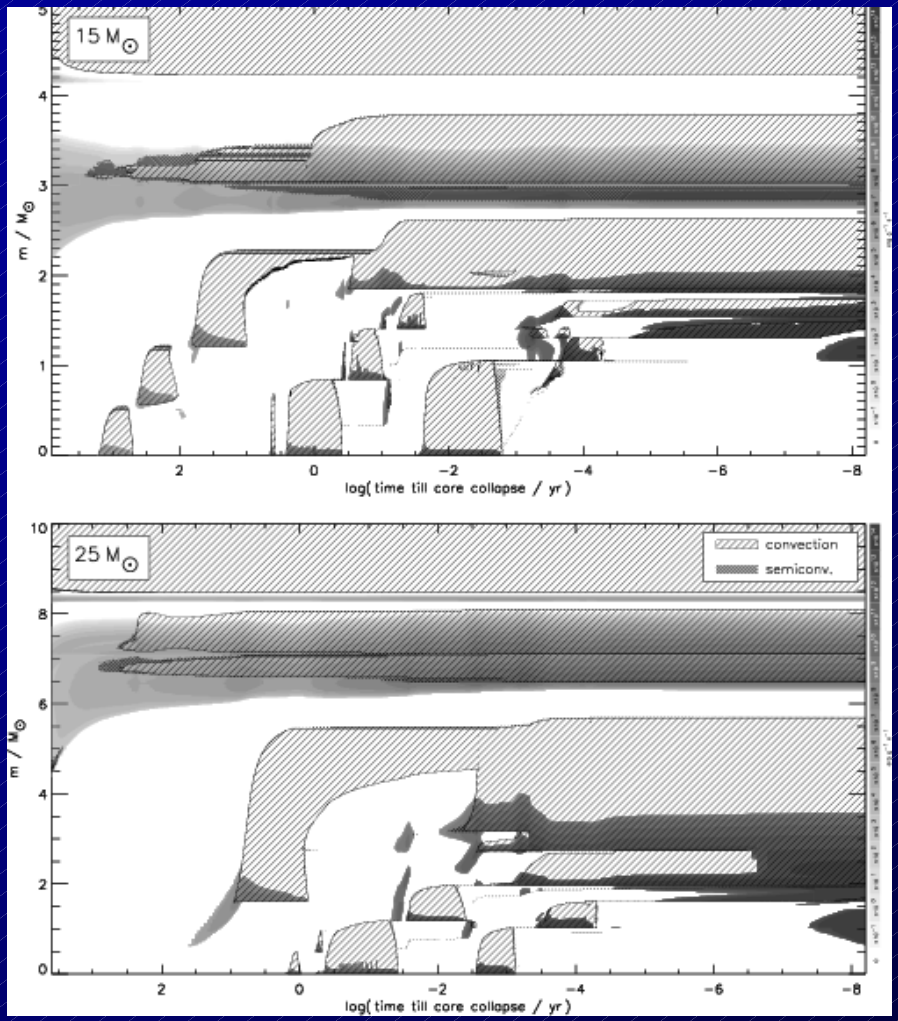


Empirical / Parametrized Models for Explosion (Explosion Energy, Mass Cut)

Nuclear Physics:
- ν Luminosities
  - PNS EoS, Pasta Phases
- Nucleosynthesis
  - Shock Region
  - Explosive

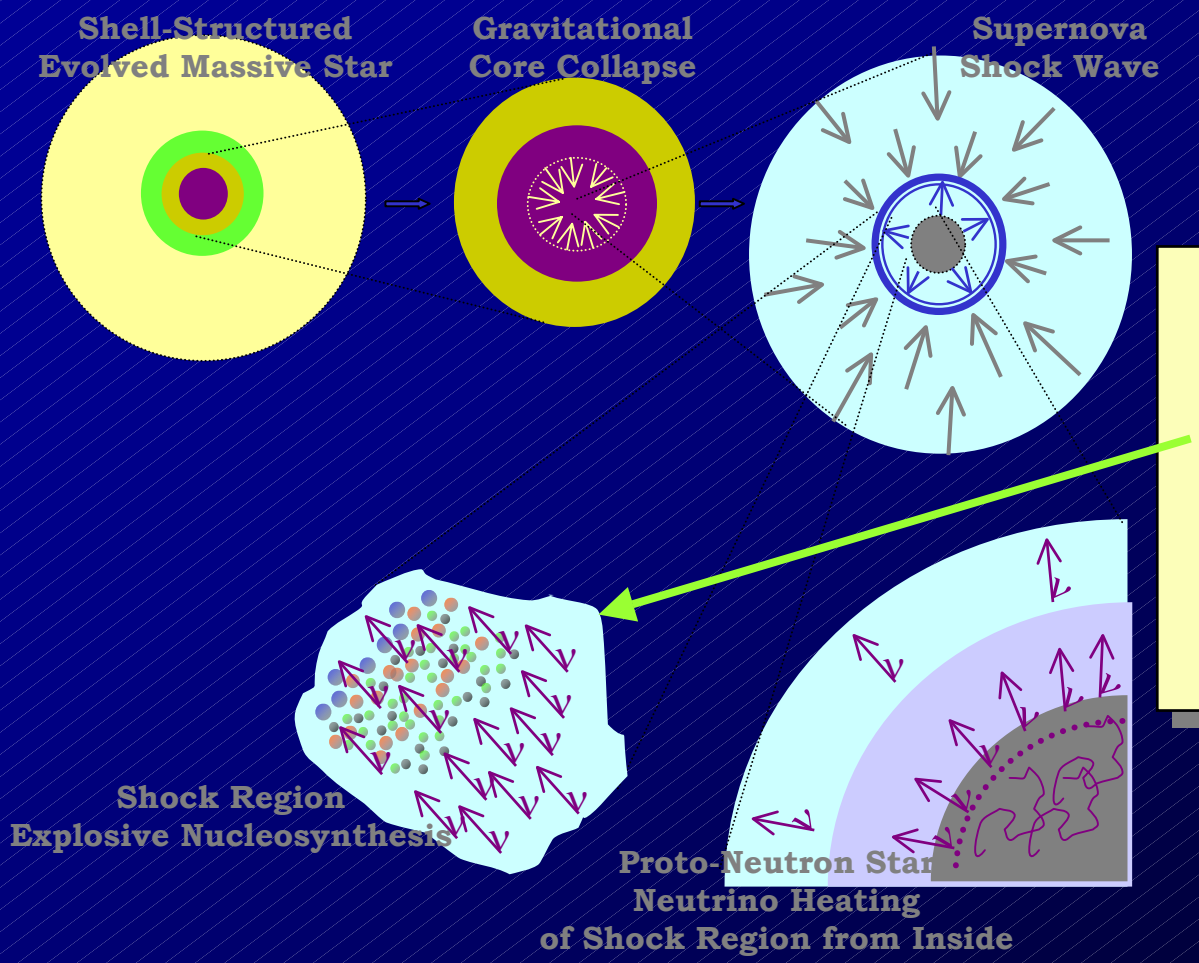
- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis

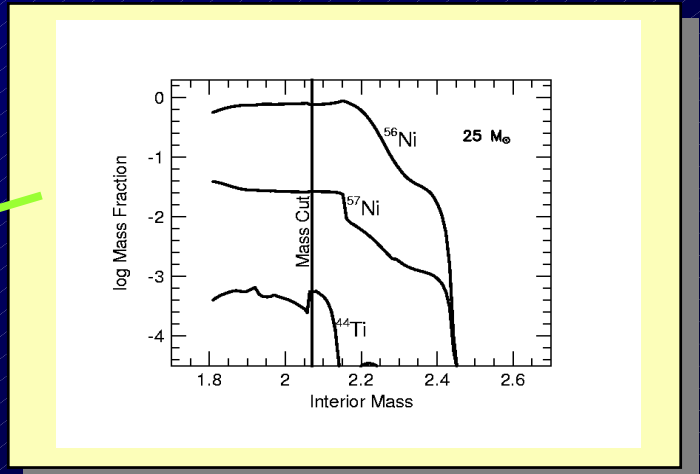
Stellar Structure in Late Phases of Massive-Star Evolution



- Episodes of Core and Shell Burning
- Impacts on Pre-SN Core Size & Composition
- Nucleosynthesis Products

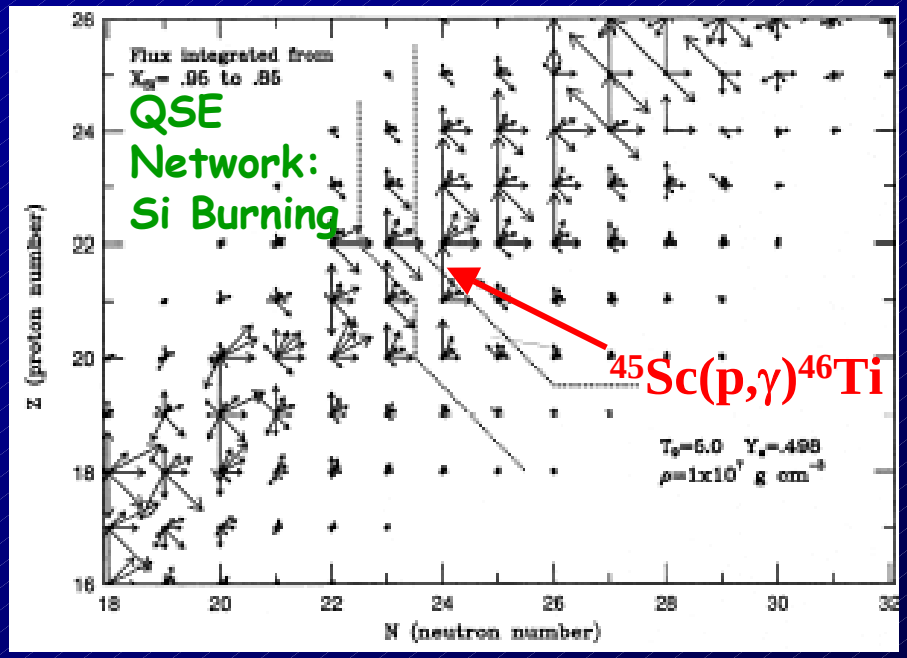
Issues in CC-Supernova Models

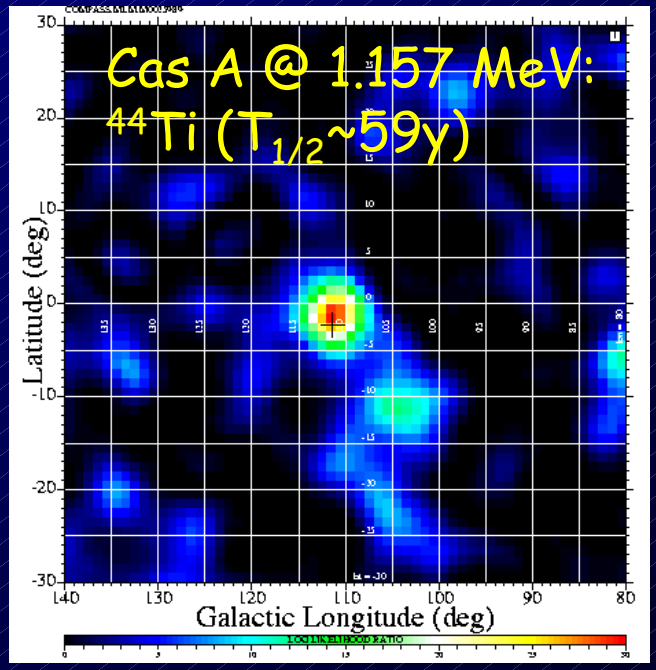




- 3D-Effects Important for Energy Budget AND Nucleosynthesis
- Location of Ejecta/Remnant Separation
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out, => Unique Probe (+Ni Isotopes)

Core-Collapse SN Nuclear Reactions -> ^{44}Ti

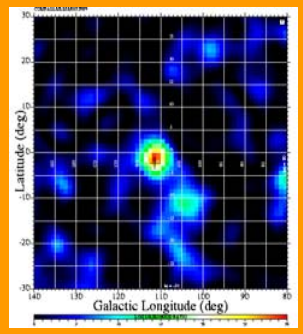


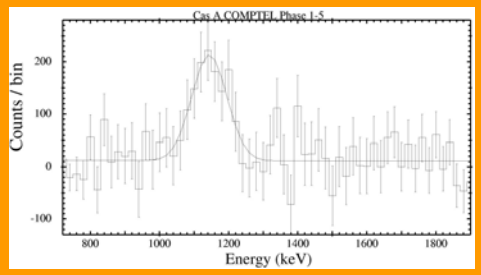


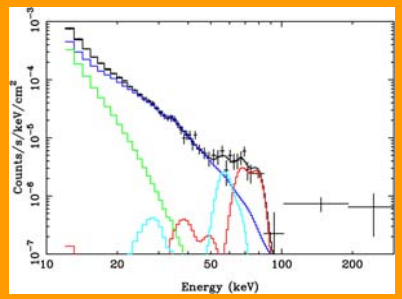
☆Complex Nuclear-Reaction Dynamics

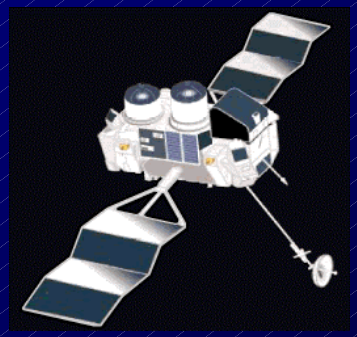
☞ Specific Isotopic Abundances as "Calibration Marks"

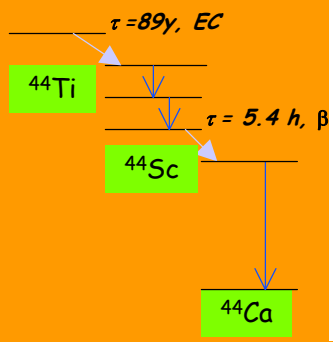
Core-Collapse Supernovae: ^{44}Ti from Cas A

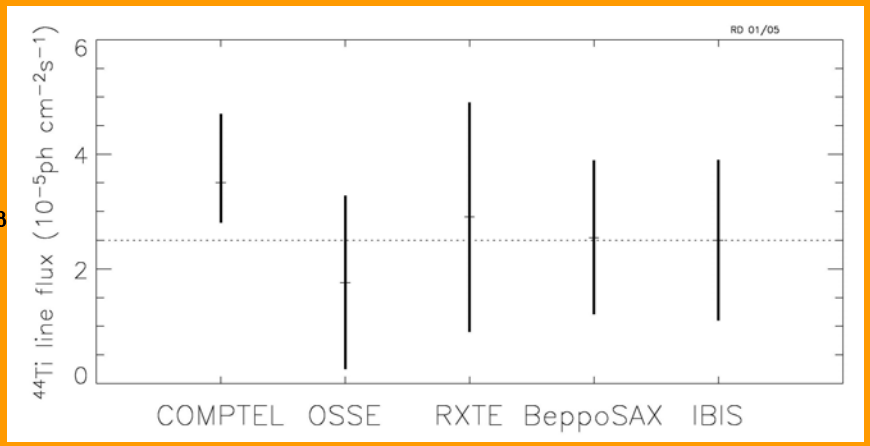












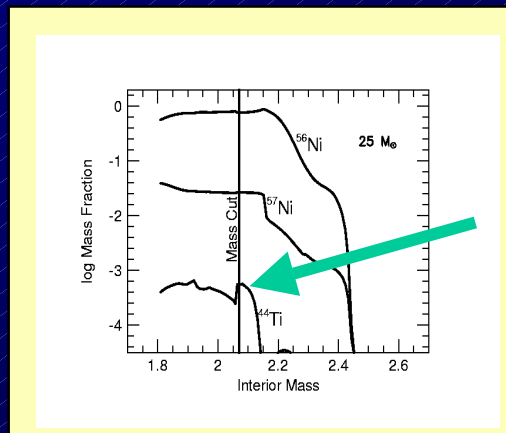
Detections:
- Iyudin et al. 1994: COMPTEL 1.157 MeV
- Vink et al. 2001; 2005:
  SAX & IBIS 68/78 keV

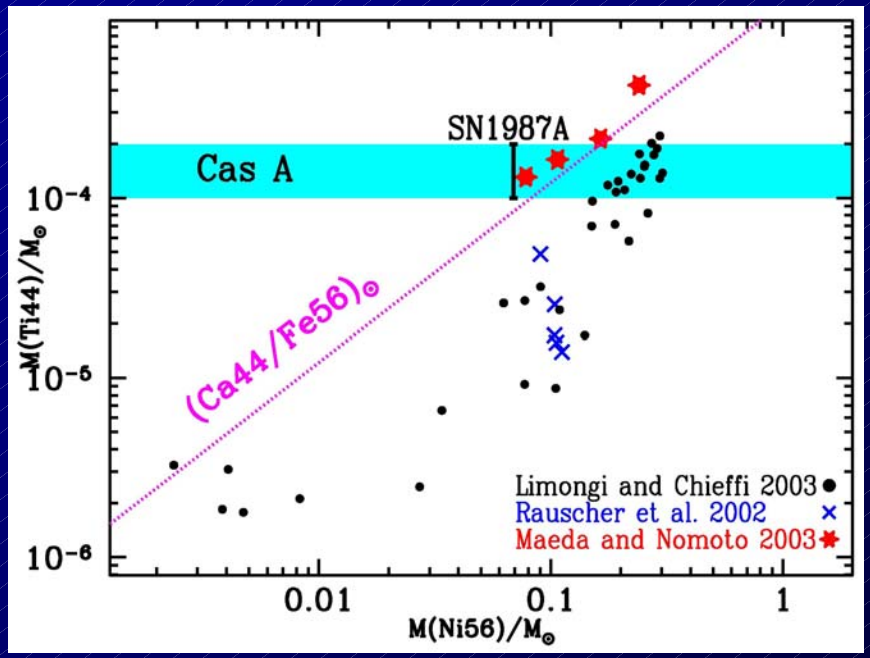
Comparable Upper Limits by RXTE, OSSE

- ^{44}Ti Decay: τ~89y -> Young SNR
- Difficult γ-Ray Region (78, 68, 1157 keV) -> Uncertain I_γ , I_X
- -> ^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} M_o

Core Collapse Supernovae: ^{56}Ni and ^{44}Ti

- Consistency of cc-SN Model: Cas A vs. …
  - ☆ ^{44}Ti from Models/SN1987A/γ-Rays, vs. ^{56}Ni
  - ☆ Only Non-Spherical Models ★ Reproduce Observed Ratios



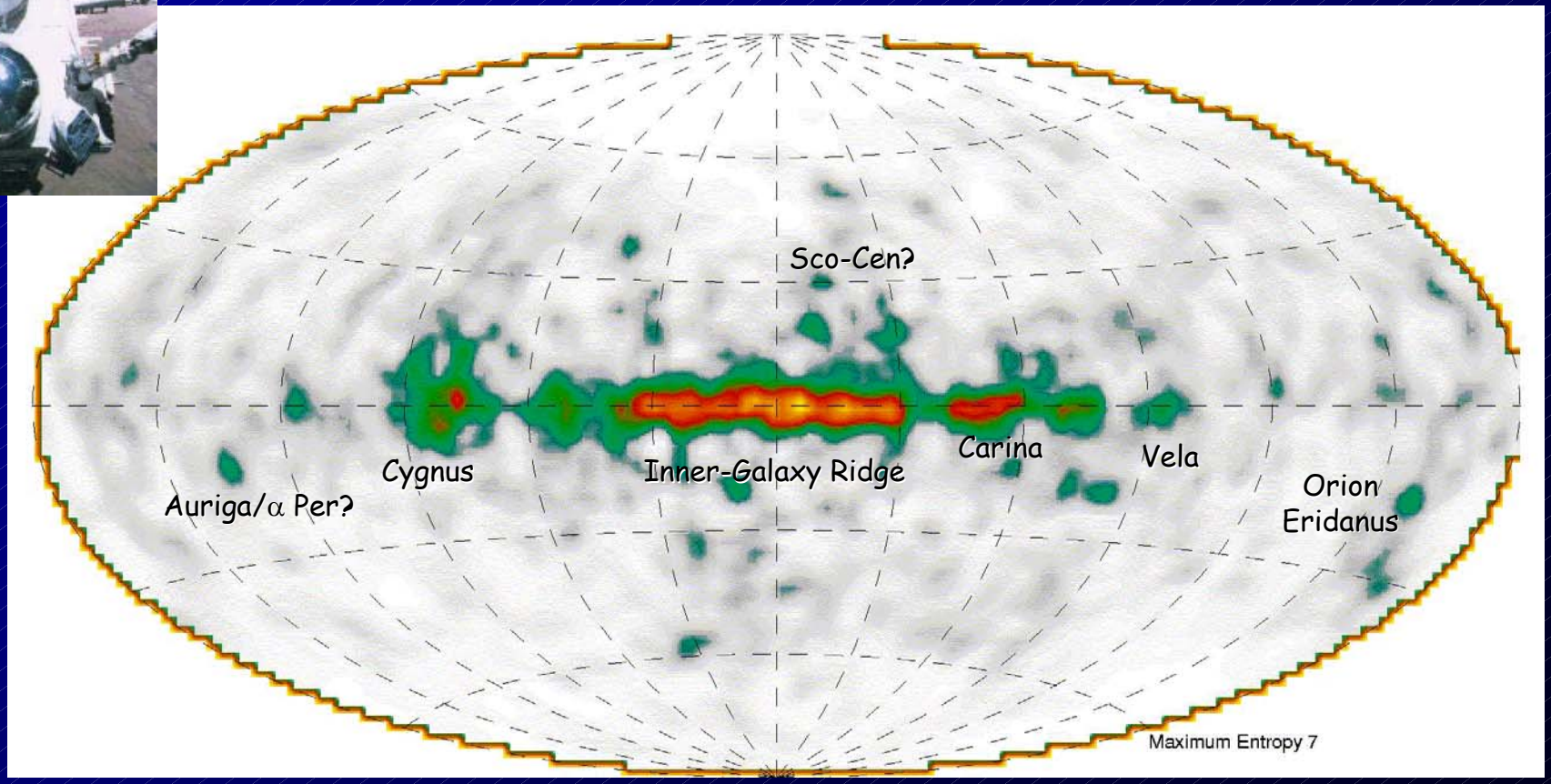


Aspherical explosions?? (->GRB)

Need Event Statistics, ^{44}Ti Spectra

Spatial Distribution of Nucleosynthesis in the Galaxy

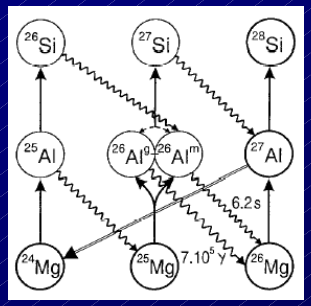
The Sky at 1809 keV: ^{26}Al

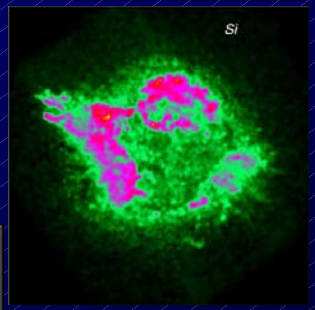


Complete CGRO Mission
(Plüschke et al. 2001)

Candidate Sources of ^{26}Al

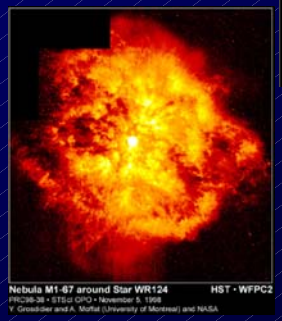
- p-rich Environment -> H Burning
- Seed Nuclei (Ne-Na group or Mg)
- Ejection of Nuclear Ashes (Wind, Explosion)





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

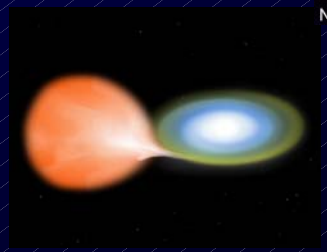


Massive Stars in their Wolf-Rayet Phase

- Core H-Burning -> ^{26}Al Production During ~10^5y 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

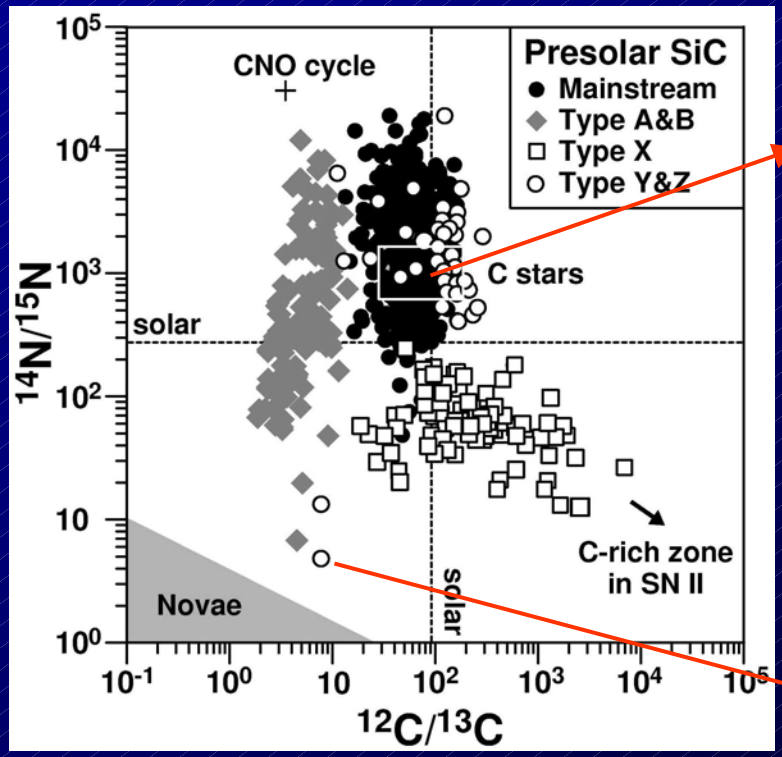


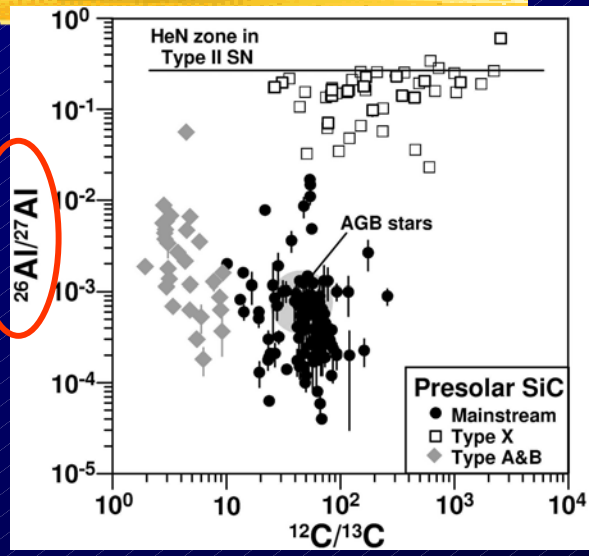
Novae

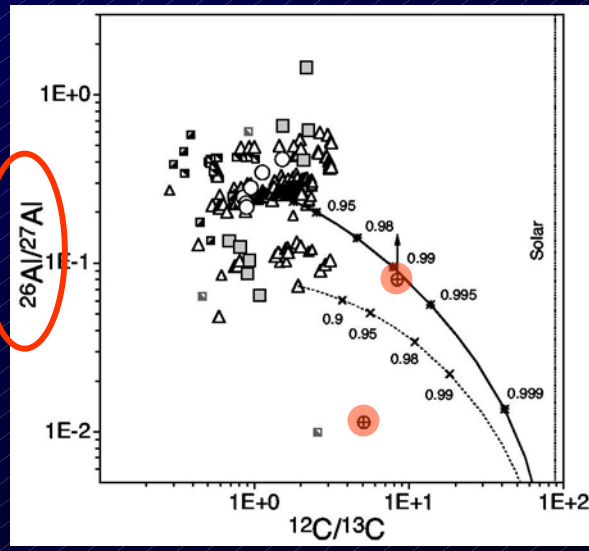
- H Accretion onto White Dwarf
- Explosive H Burning with Seed Nuclei Admixture

Hints from Presolar Grains

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





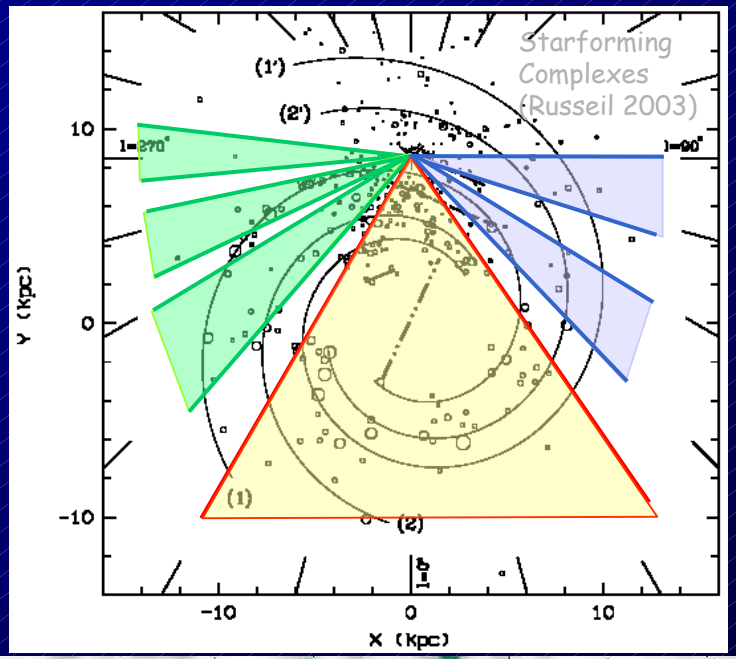


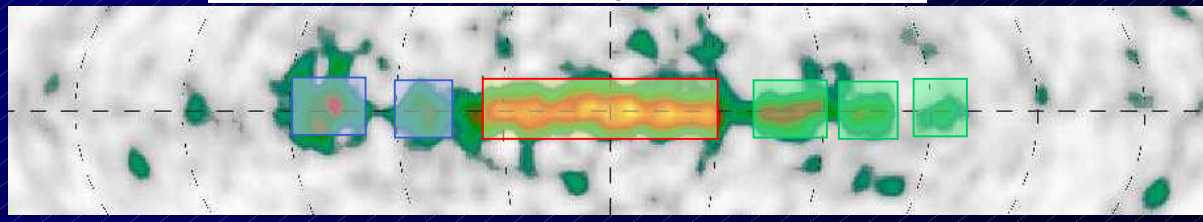
☞ Amari, Nittler, Hoppe, Zinner, … et al.

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

Large-Scale Appearance of ^{26}Al Sources

- ☆ 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

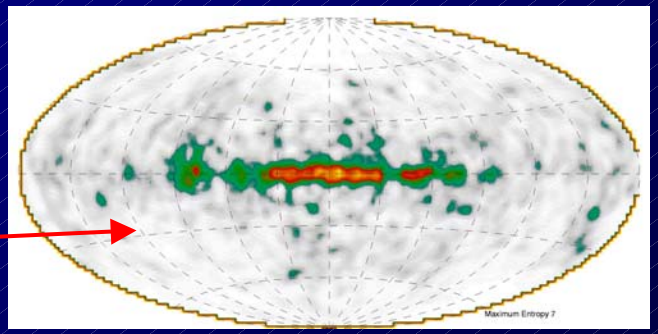


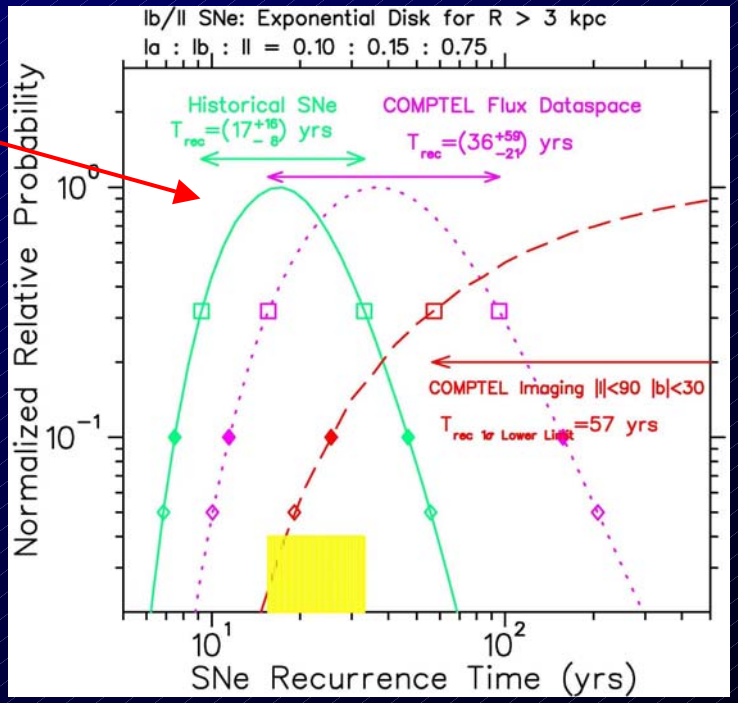


Search for ^{44}Ti from Galactic cc-Supernovae

The et al., 2000

- No ^{44}Ti Sources in Inner Galaxy
  - ☆ Parent Distribution of Sources ~ ^{26}Al
  - ☆ Monte-Carlo Study
    -> ^{44}Ti SNR Number Low
  - ☆ Small-Number Statistics?
  - ☆ Observational Bias?
  - ☆ Metallicity Anticorrelation?





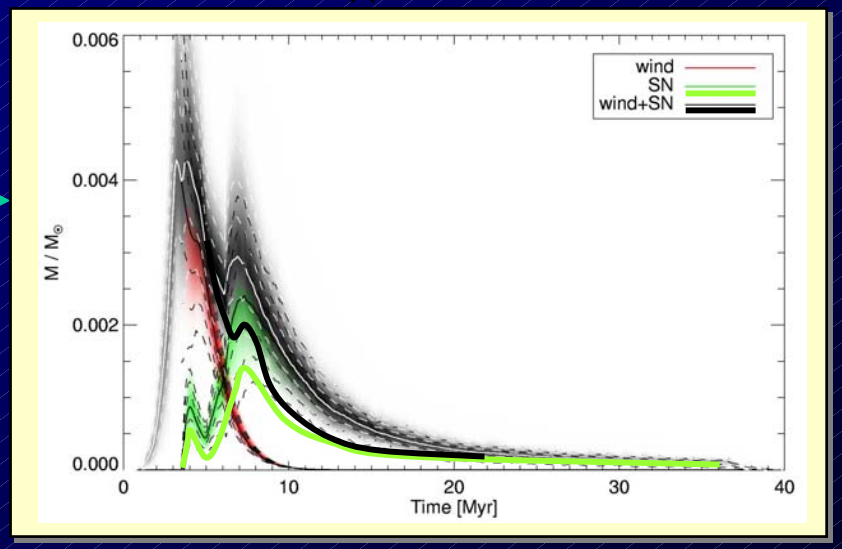
➢ Massive Stars are a Variety (^{26}Al, ^{44}Ti)

The ISM around Massive Stars:
How are Nucleosynthesis Products Fed Back?

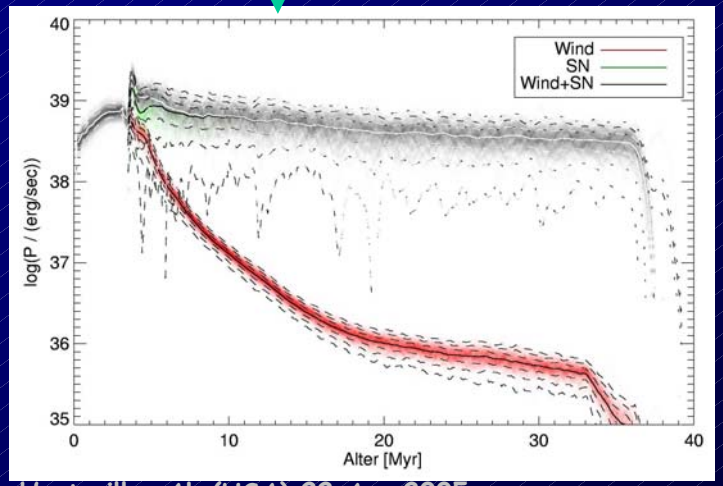
Modelling Massive-Star Groups

S. Plüschke, PhD Thesis, TUM 2001

- Model Ingredients:
  - Stellar Evolution
  - Stellar Wind Model(s)
  - Initial Mass Function
  - Nucleosynthesis Yields WR, SN
  - Sample Statistics Analysis
- Model Predictions:
  - ^{26}Al Gamma-Ray Luminosity (t)
  - EUV Luminosity (t)
  - Kinetic-Energy Ejection (t)

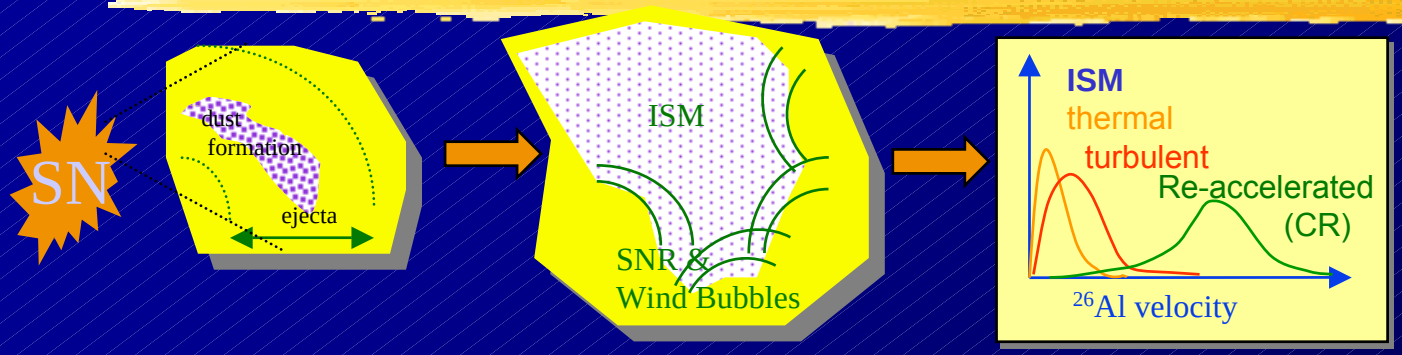


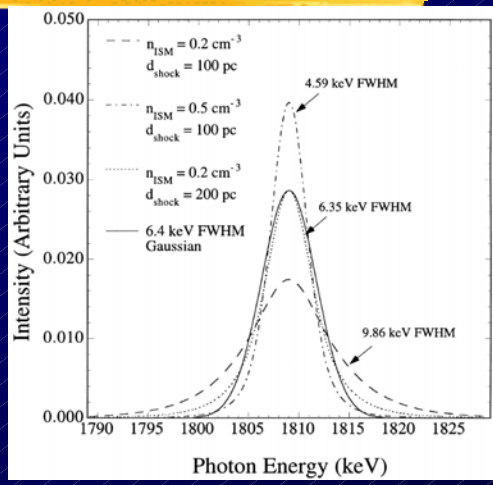
-> Plüschke et al., 2001; Cerviño et al. 2002



-> Localized-Source Consistency Checks

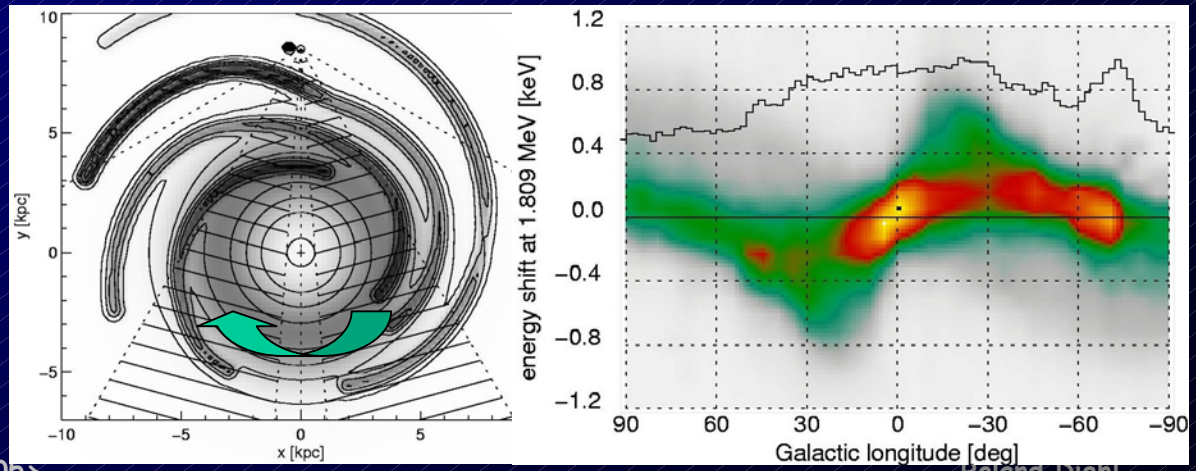
^{26}Al Line Shape Astrophysics



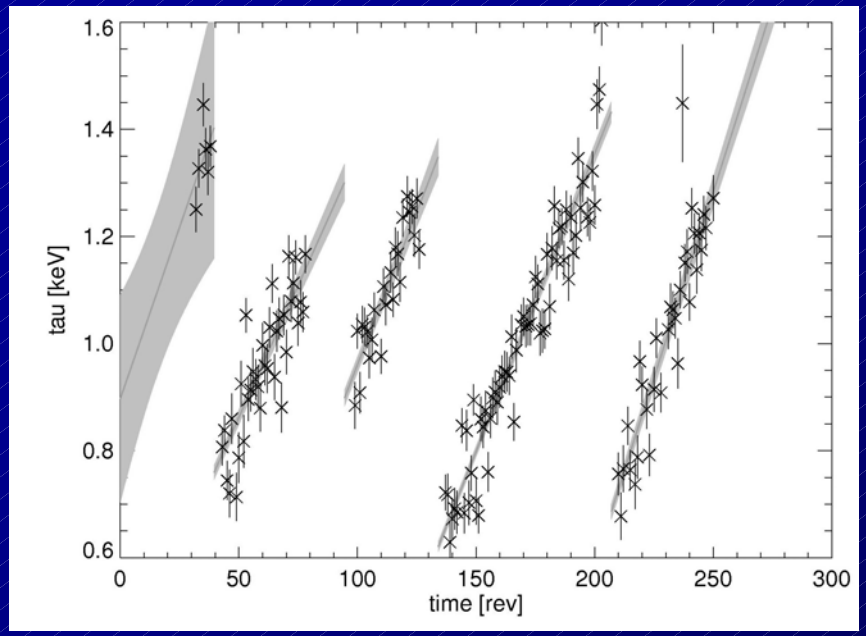


- Ejection and Slowing-Down of ^{26}Al from Sources
  - ^{26}Al Ejected into Hot Cavities (WR Winds, …)
    -> ISM Turbulence <-> Line Width
  - ^{26}Al Condensed on Dust, Re-accelerated -> High-Velocity Tail?
    - *Chen et al. 1997; Sturner & Naya 1999*

- Galactic Rotation
  - ^{26}Al Sources in Spiral Arms, Along Line-of-Sight
    -> ^{26}Al Source Location Along LoS
    - *Gehrels et al. 1996; Kretschmer et al. 2003*

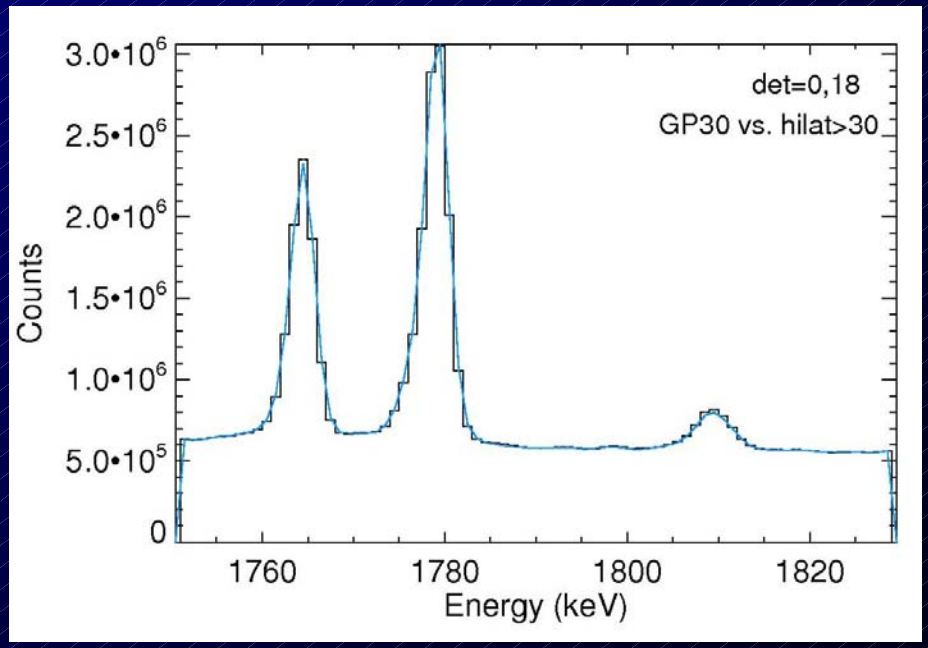


^{26}Al Line Spectroscopy from SPI Observations



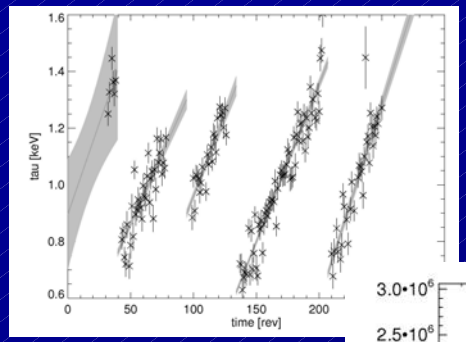
- Variable Instrumental Resolution

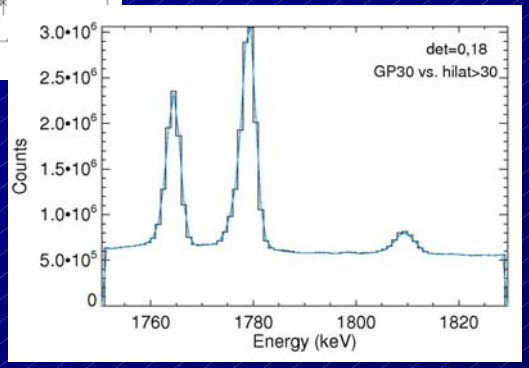
- ☆ Underlying Broad Background Feature
  - ☆ ^{26}Al Signal ~ 1% of total



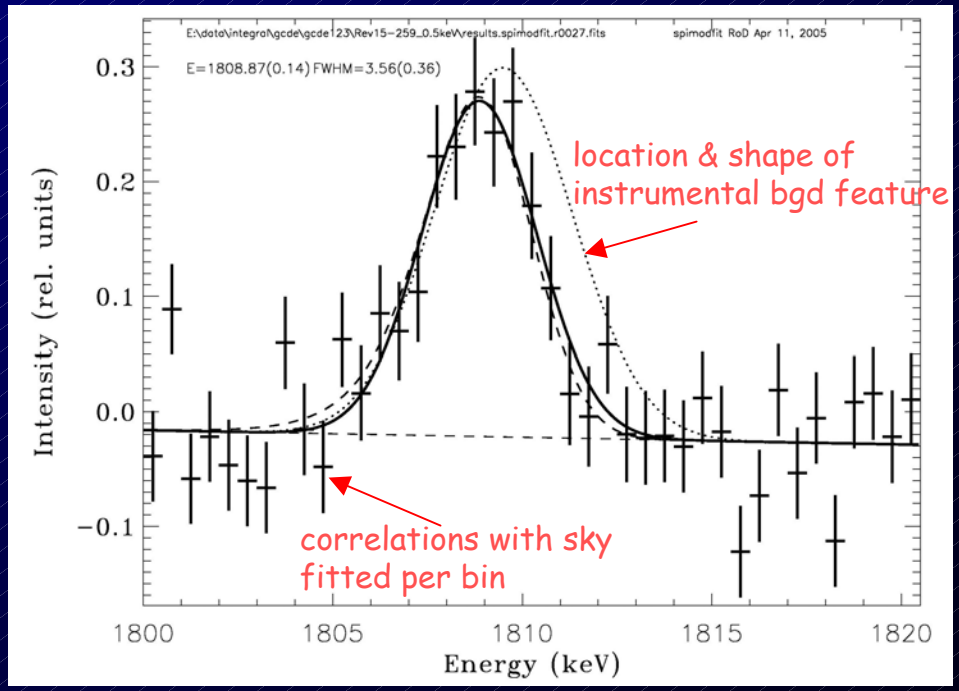
- ➢ Analysis Method:
- ☆ Fitting of Background and Sky Distribution Models in Fine E Bins
- ☆ Comparisons to "predicted" Features/Shapes

^{26}Al Line Spectroscopy from SPI Observations





- Variable Instrumental Resolution
- ☆ Underlying Broad Background Feature

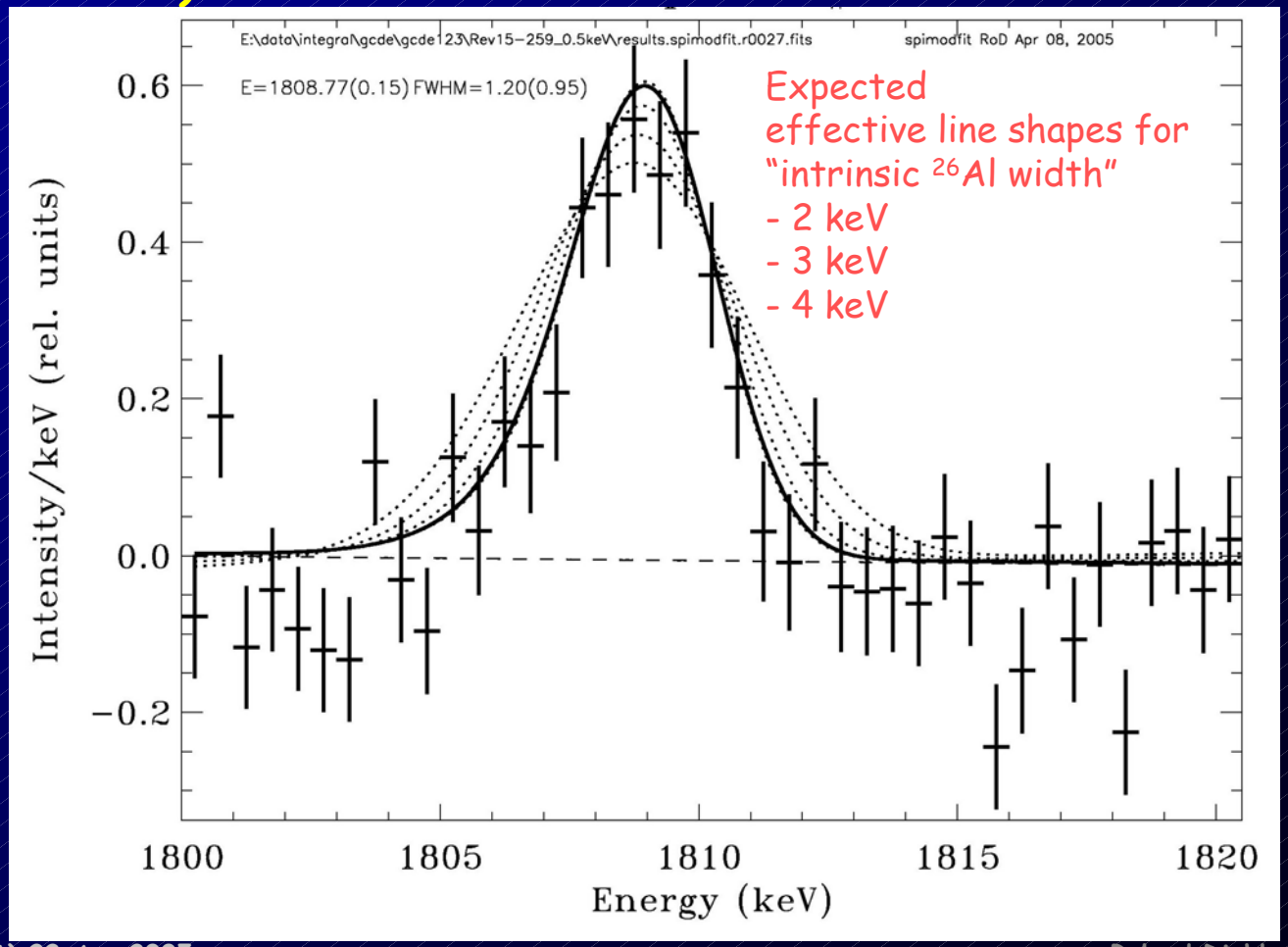


- ➢ Analysis Method:
- ☆ Fitting of Background and Sky Distribution Models in Fine E Bins -> ~16σ Detection of ^{26}Al
- ☆ Comparisons to "predicted" Features/Shapes

Roland Diehl

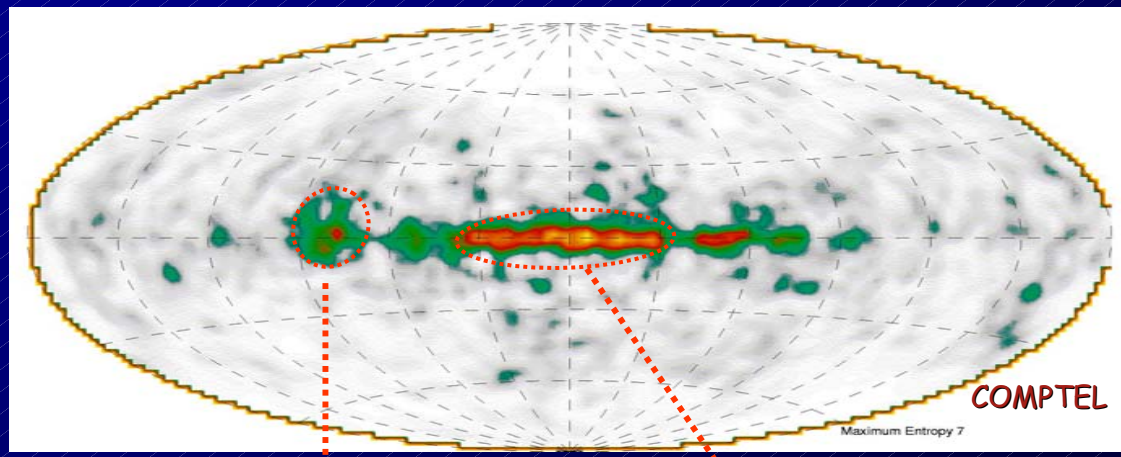
^{26}Al in the Inner Galaxy

- Generally, the ^{26}Al Line is "Narrow" (~instrumental width)
  - SPI: 1.2 ± 0.9 keV

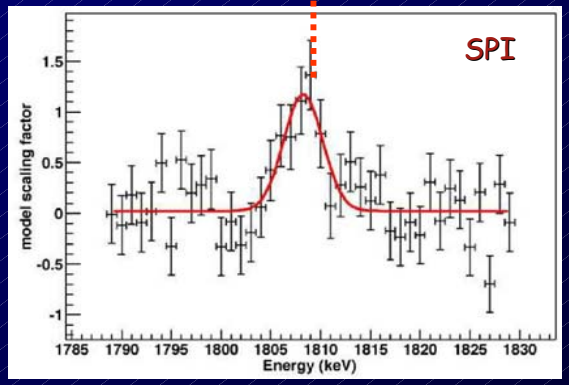


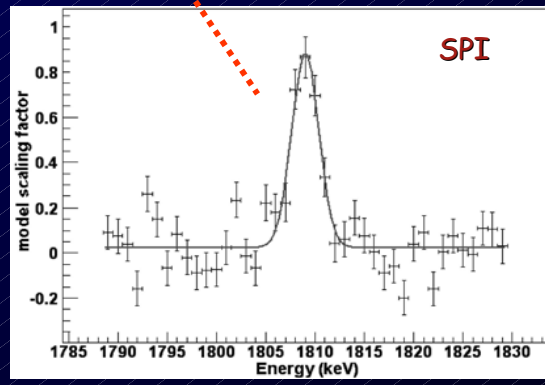
Nucleosynthesis in the Current Galaxy: ^{26}Al

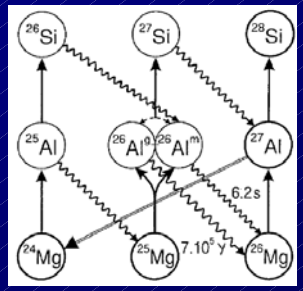
- ^{26}Al Reflects Sources of Nucleosynthesis ($\tau \sim 10^6$y)
- COMPTEL Imaging -> Massive Stars are Dominating Sources



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







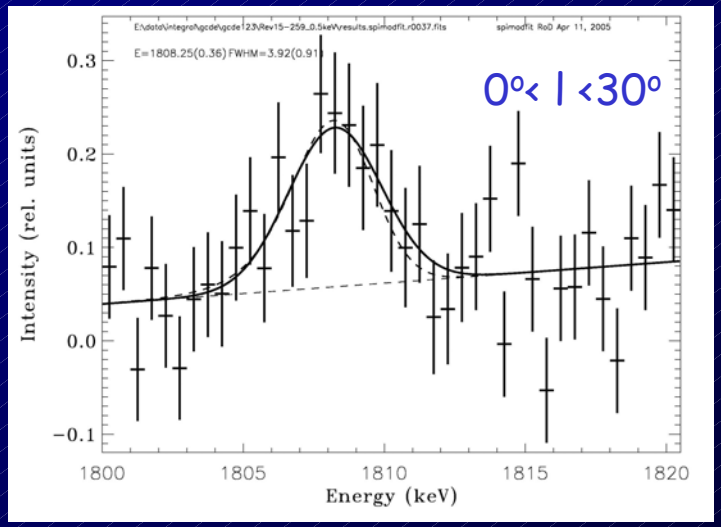
H Burning

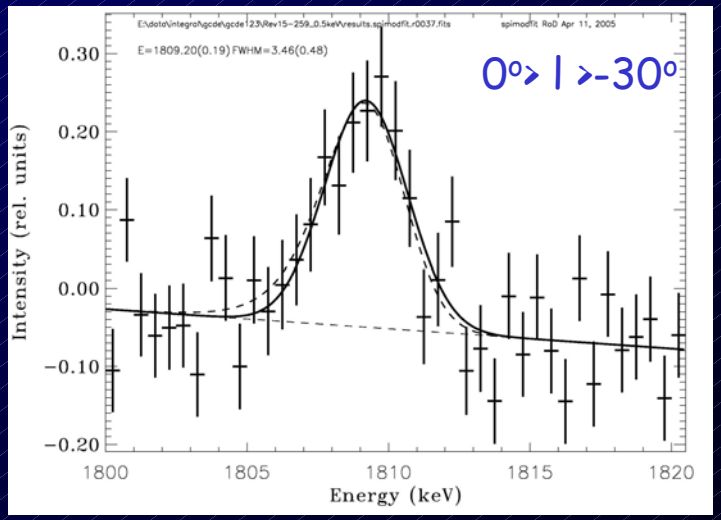
INTEGRAL/SPI: Add Fine Spectroscopy!

^{26}Al Spectroscopy Science: Inner Galaxy

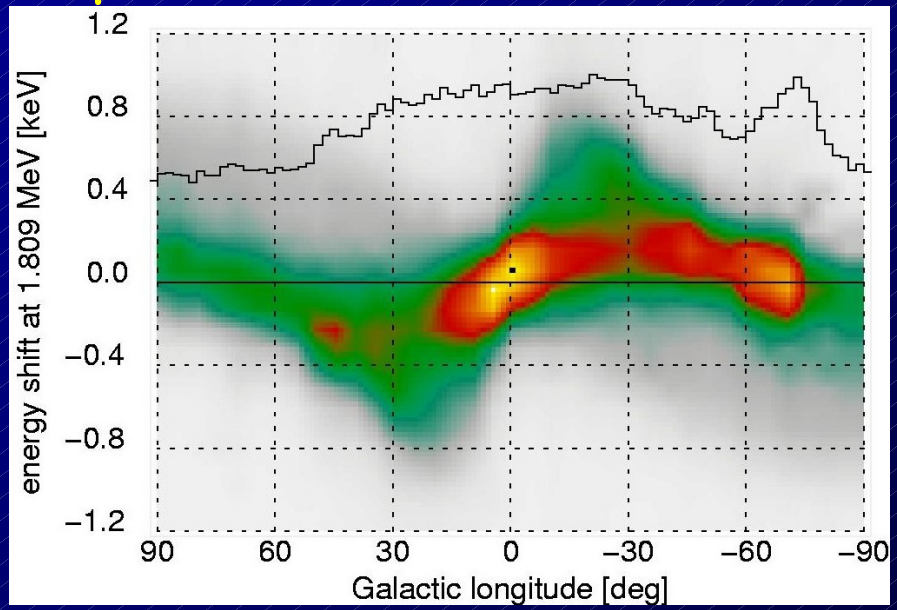
- ☆ Line Width -> Doppler Broadening
  - ☞ Galactic Rotation
  - ☞ Interstellar Turbulences

SPI:





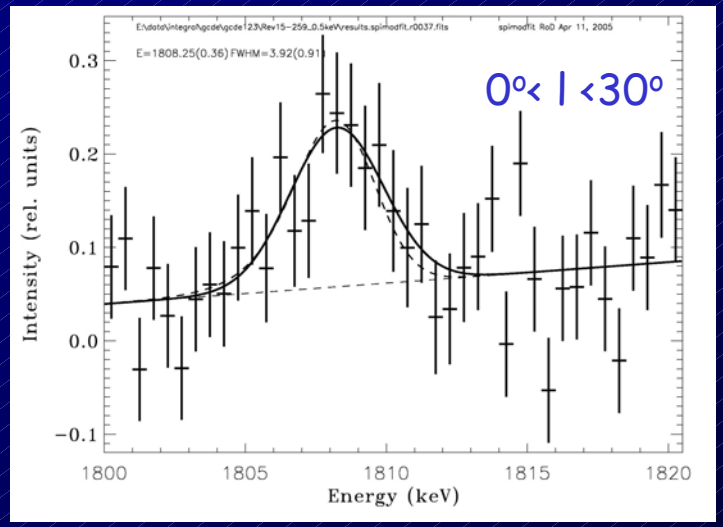
Expectations:

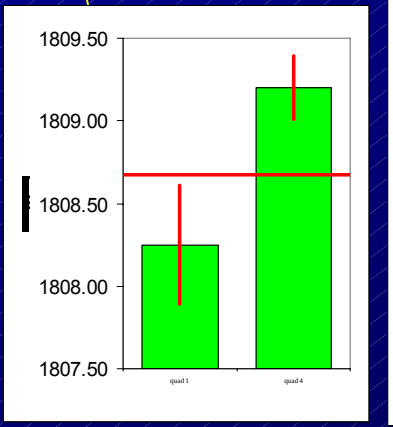


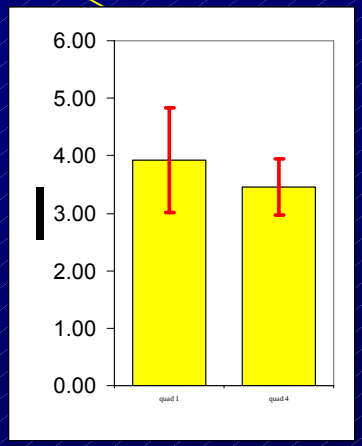
^{26}Al Line in Inner Galaxy : Detail

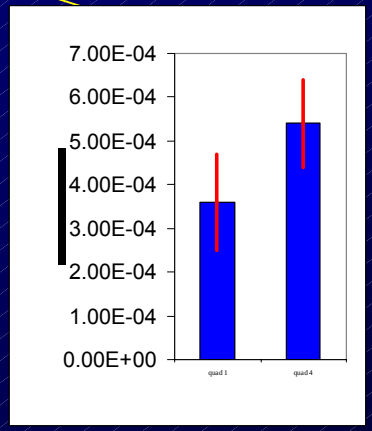
☆ Differences in I,FWHM not (yet) Significant:

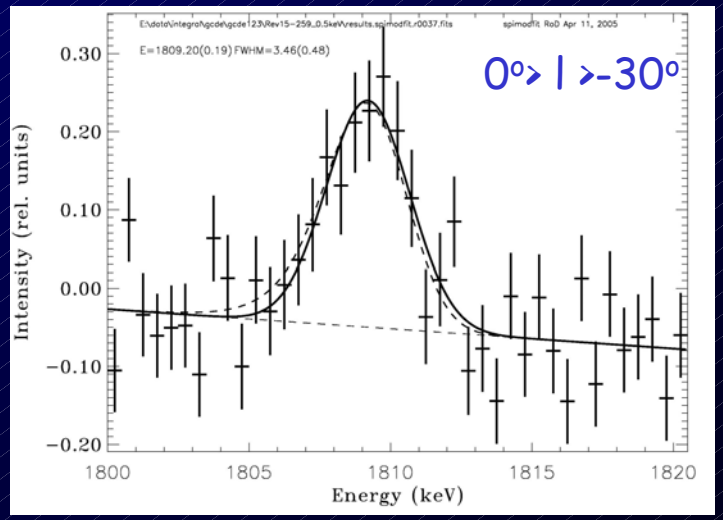
	quad 1		quad 4	
E_line	1808.25	0.36	1809.20	0.19
FWHM	3.92	0.91	3.46	0.48
I_line	3.59E-04	1.10E-04	5.40E-04	9.94E-05







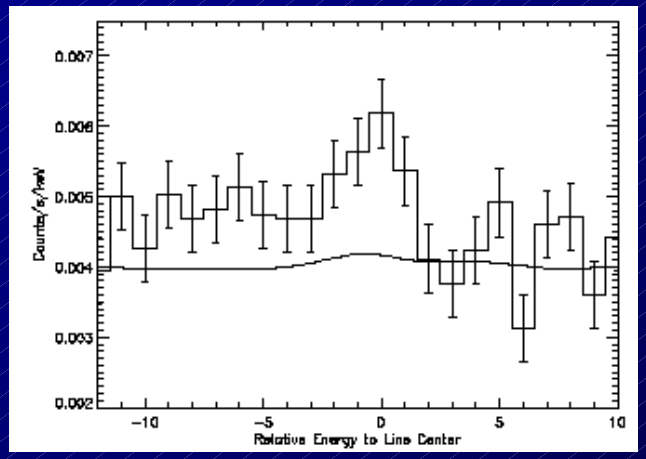


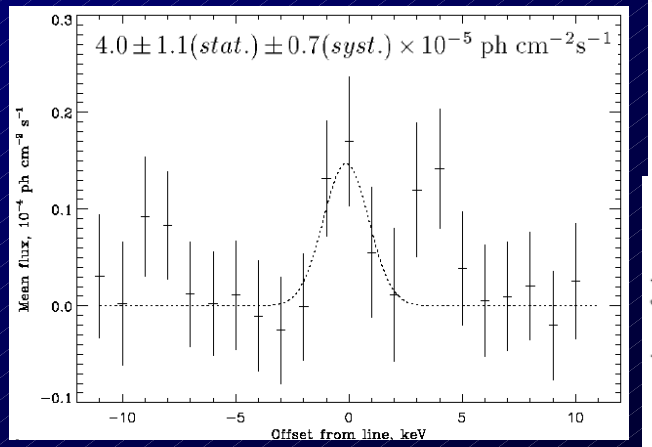


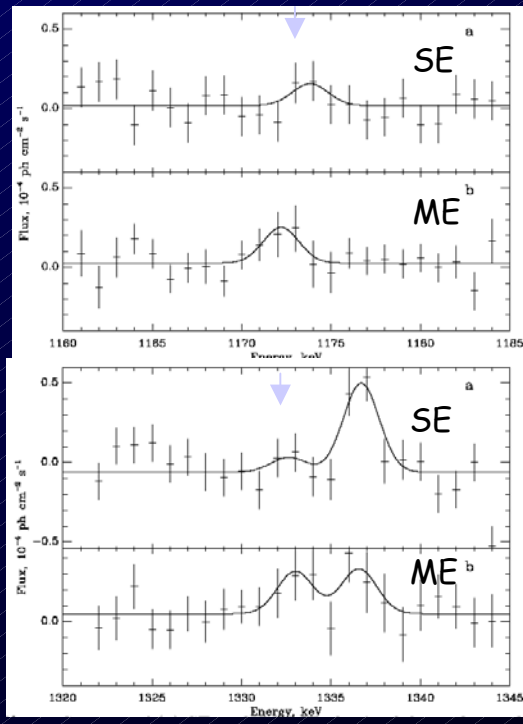
☆ Rotational Line Shifts ~ok (tbc)

^{60}Fe Detections with RHESSI & SPI/INTEGRAL

- RHESSI
  - 2.6 σ Detection
  - I=0.91 ±0.31 10^{-4} ph cm^{-2} s^{-1}
    - *Smith 2004*
- SPI
  - 3 σ Detection
  - I=0.4 ±0.2 10^{-4} ph cm^{-2} s^{-1}
    - *Harris et al. 2005*

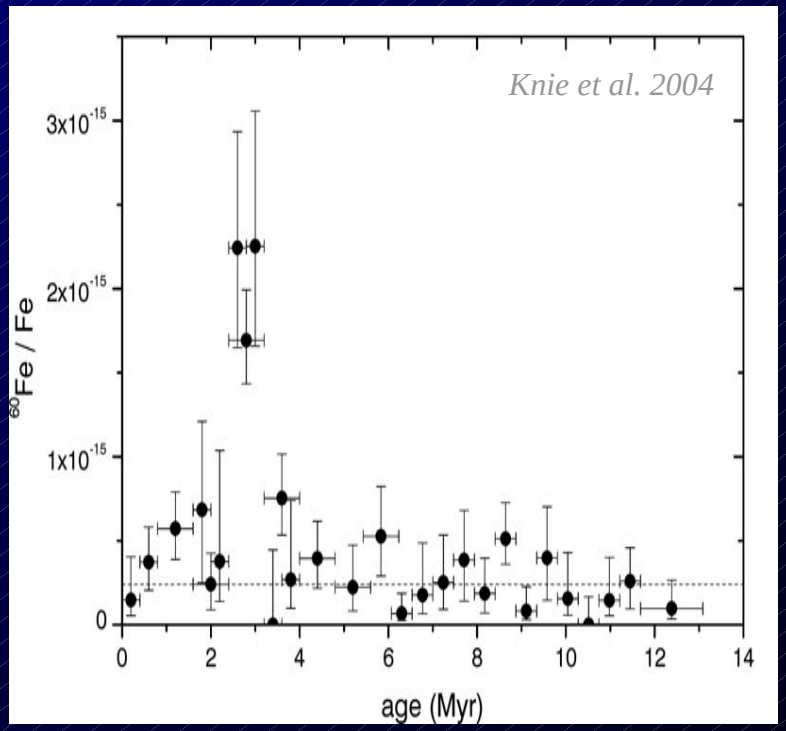






Terrestrial ^{60}Fe Detection

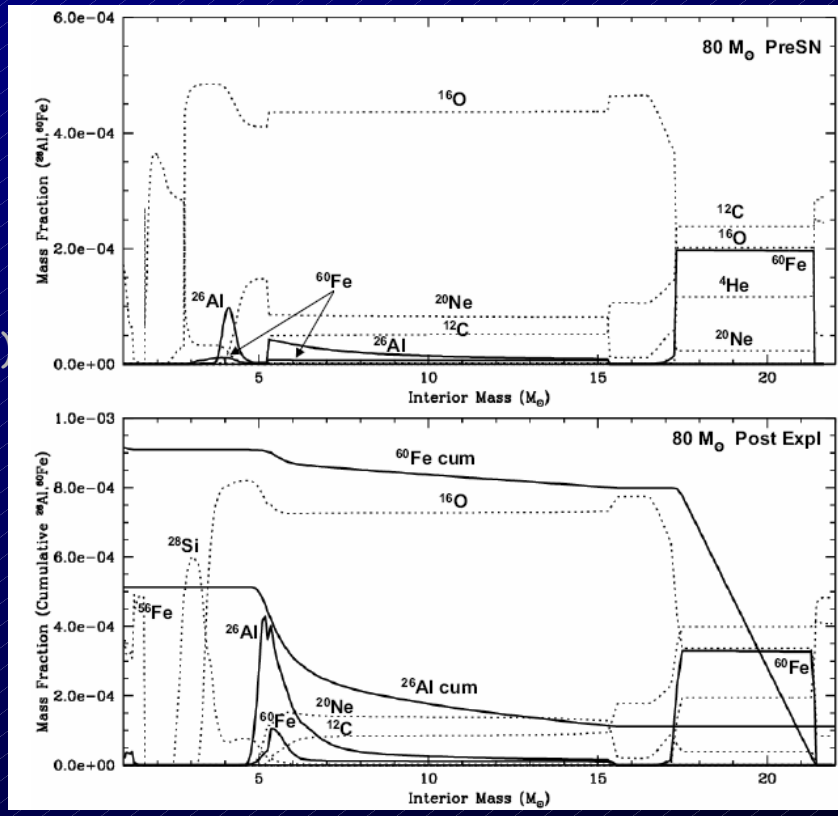
- Current Terrestrial Record:
  - ☆ Ocean Crust Analysis
    - ☞ Slow, Fe-rich Growth (2mm/My)
    - ☞ Dating with CR-Produced ^{10}Be
    - ☞ AMS Atom Counting
  - ☆ Nearby SN 2.8 My ago?



☆ *NB: This is NOT the ^{60}Fe we see in the Galactic ISM in γ-rays!*

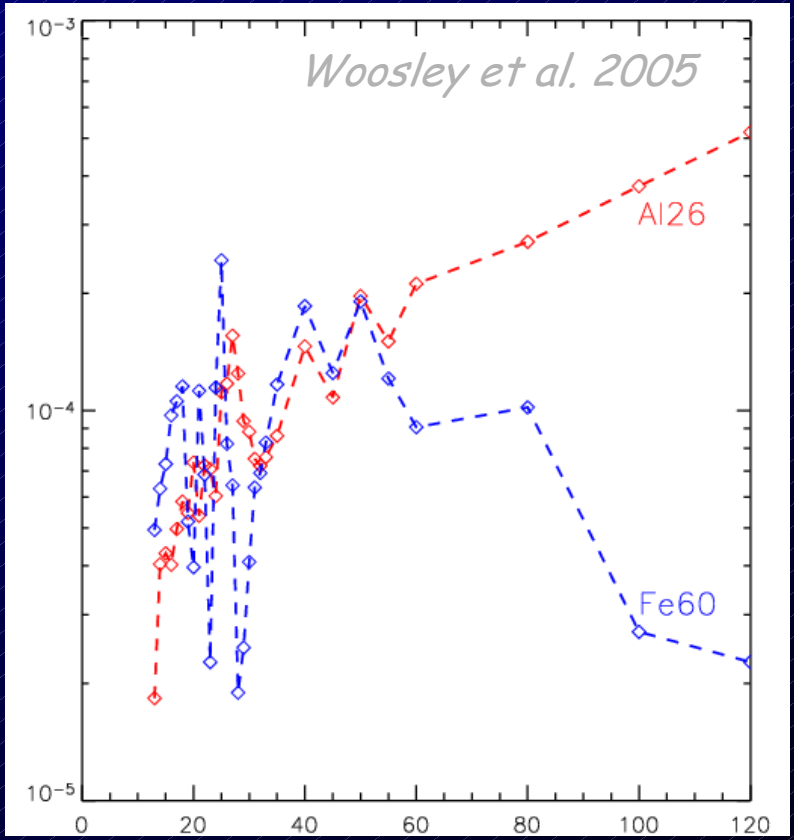
Two Radioactivities from Massive Stars: ^{26}Al and ^{60}Fe

- Production Sites
  - Hydrostatic Core & Shell Burning
  - Explosive Burning
- Ejection
  - (Late) Wind Phases ($^{dM}/_{dt}$~10^{10} x solar)
  - SN Explosion
- Main Processes
  - ☆ ^{25}Mg(p,γ)^{26}Al — H burning
  - ☆ ^{58}Fe(n,γ)^{59}Fe(n,γ)^{60}Fe — n capture
- Net Yields?
- ISM Yield Ratios?
  - ☆ 0.7 (25M$_o$) … 1.8 (80M$_o$) (e.g. Chieffi & Limongi 2005)
  - ☆ 0.14 (GCE Model) (e.g. Timmes et al. 1995)

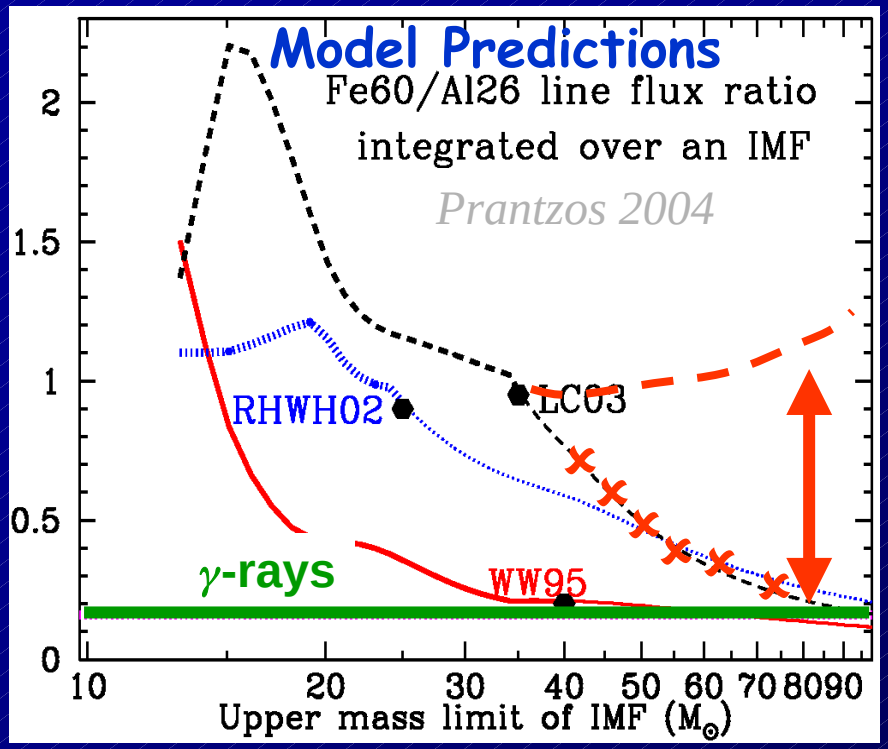


Updated Massive-Star Synthesis (^{26}Al, ^{60}Fe)

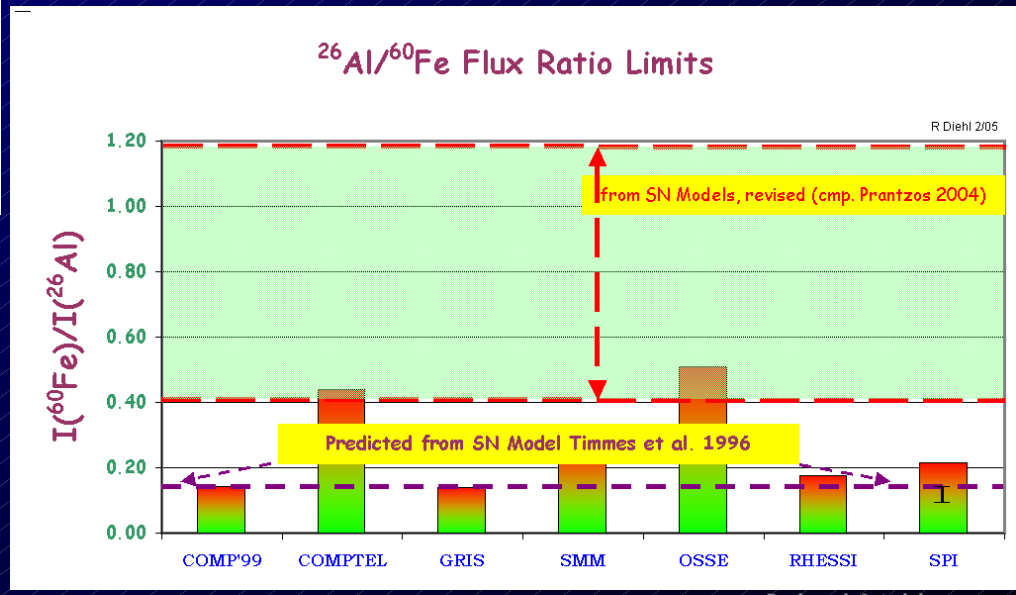
- Follow Stellar Evolution Consistently
  - ☆ Hydrodynamic Structure Evolution
  - ☆ Nuclear Energy Generation
  - ☆ Mass Loss Phases
  - ☆ Supernova Progenitor and Explosion
- Calculate a Complete Set of Stars (Mass Range)
  - ☆ Find Structural Discontinuities (Shell Burning; NS/BH; WR)
  - ☆ Cover IMF Range Well



The ^{60}Fe Puzzle



- ☆ No Source Would Bring the ^{60}Fe/^{26}Al Gamma-Ray Intensity Ratio Close to Measurement Constraints! (~Factor 3…5!)
  - ☞ Model Sample Statistics (LC)?
  - ☞ SN not a Significant ^{26}Al Source?
  - ☞ Nuclear Physics?



Uncertainties:

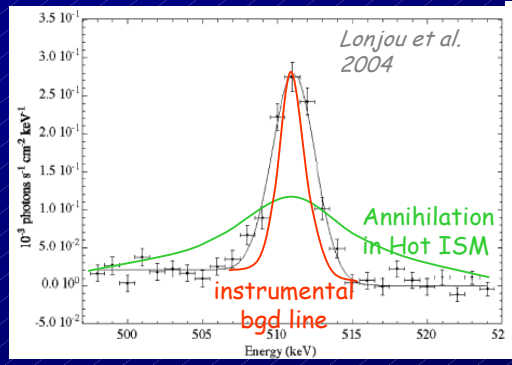
- n Capture Cross Sections for Fe Isotopes ^{59}Fe, ^{60}Fe
- β Decay Rate for ^{59}Fe
- Development of Hot-Base He Shell, C Shell
- n Source Activation

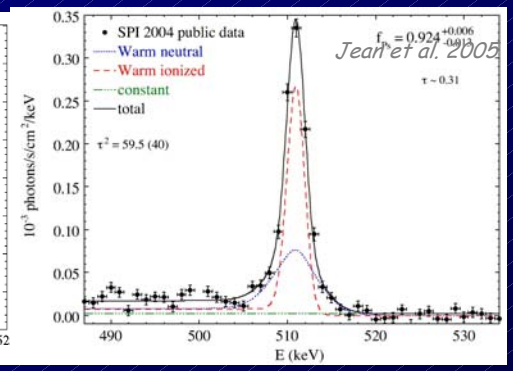
Annihilation of Positrons in the Galaxy

☞ See talk J.P. Roques

Astrophysics:

- Positron-Source Variety in Inner Galaxy
  - Nucleosynthesis Sources (SNIa, …)
  - Pulsars, Binaries, Jet Sources
  - Light Dark Matter Annihilations
- Annihilation in Diluted ISM ($\tau \sim 10^5$y)





Results (INTEGRAL / SPI) :

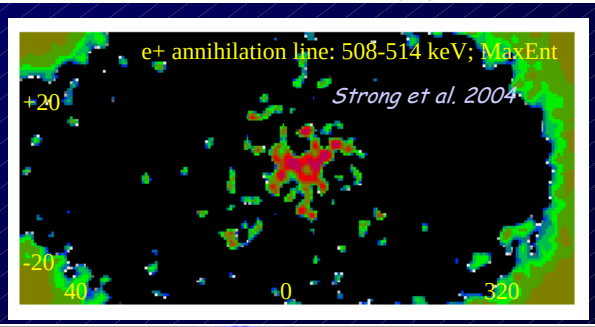
511 keV Line Characteristics :

- I = 0.96 10^{-3} ph cm^{-2} s^{-1}

-> Annihilation Rate (@GC) 1.4 10^{43} s^{-1}

- Broadened Line: Deconvolved FWHM = 2.76 keV
- Expectation: Hot-ISM->~4 keV, Grains->~2 keV

-> Annihilation in Warm ISM Phase

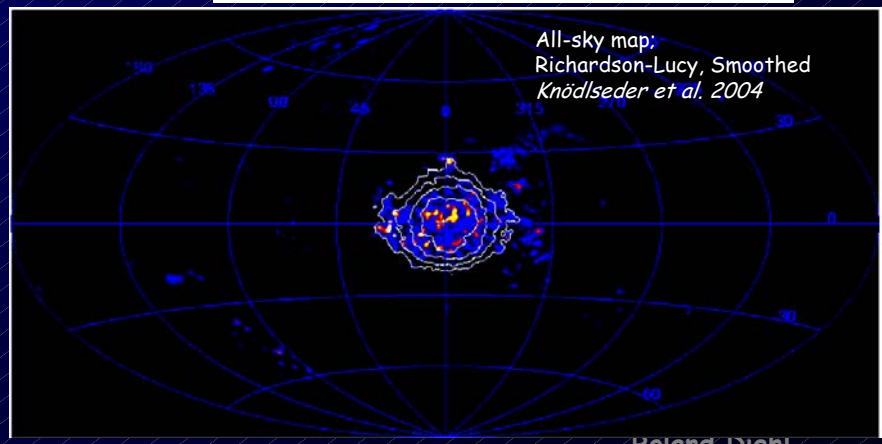


511 keV Line Emission Morphology:

- **Extended, ~bulge-like Emission** ($\delta l \sim 8^o, \delta b \sim 8^o$)
- **No/Weak Disk Emission Seen; No "Fountain"**

-> Young Stars make Minor Contribution

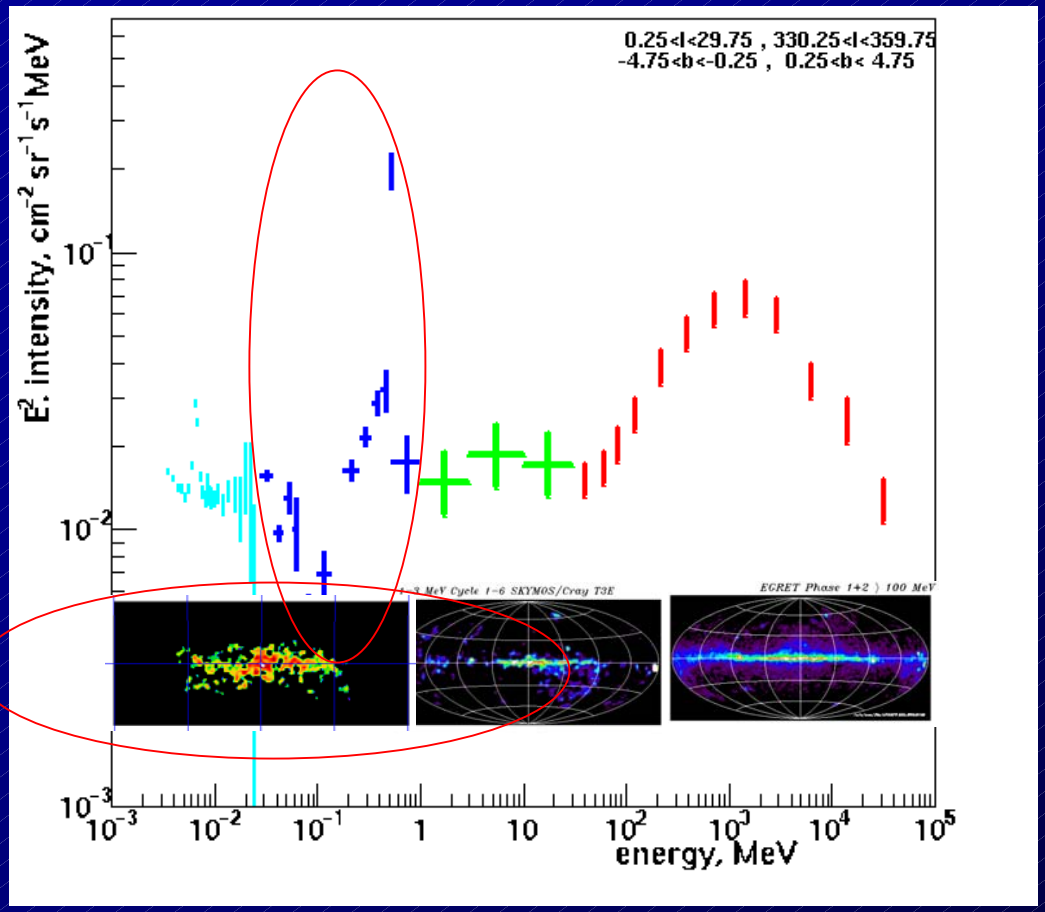
- **Old stellar population! Dark-Matter Annihilations?**



Summary: Galactic Nucleosynthesis

- Supernova Mechanisms May Greatly Benefit from Good Measurements of ^{56}Ni (SNIa) and ^{44}Ti Decays (cc-SN)
- Diffuse Radioactivities (^{60}Fe and ^{26}Al) are a Diagnostic Tool for Massive-Star Nucleosynthesis
- Cavities around Massive-Star Clusters are ~as Expected: ^{26}Al Line is "Narrow"
- Doppler Effects from Galactic Rotation for ^{26}Al
- ^{60}Fe Yields are ~Factor 3…5 below Expectation: Nuclear-Physics Measurements Needed!

The Galactic Ridge in X/Gamma-Rays



- Over 8 Decades in Energy
  - ☆ Spectra
  - ☆ Images

- ☞ A "Mine" of Information about High-Energy Processes in
  - ☞ ISM
  - ☞ Point-like Sources

The Galactic Plane with SPI

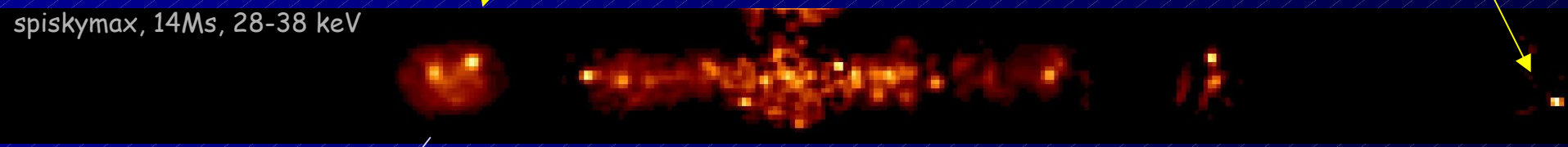
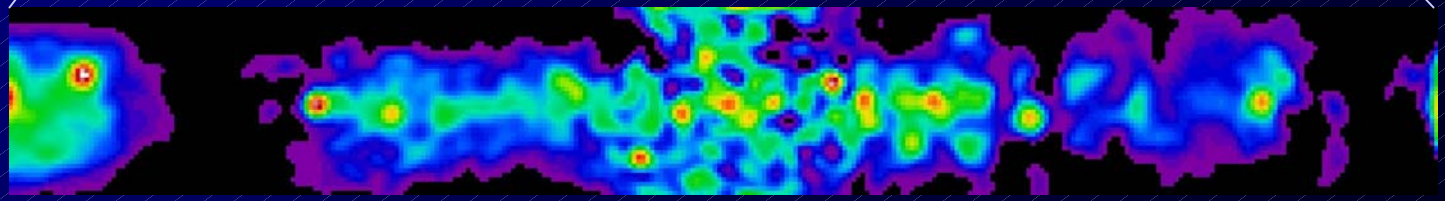
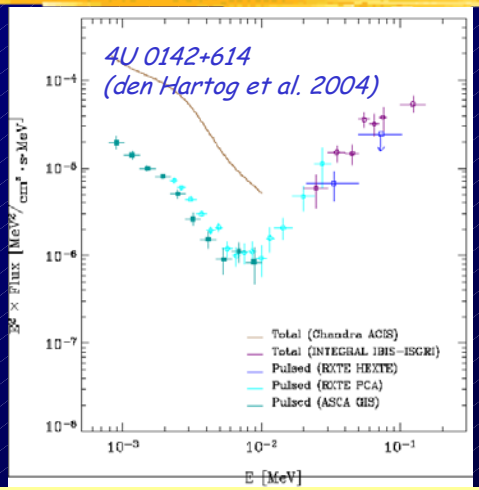


Image from 2 years of SPI Galactic-Plane Survey
(A. Strong et al., 2005)

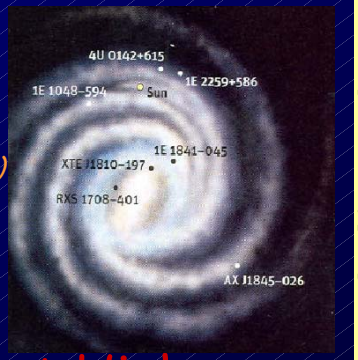


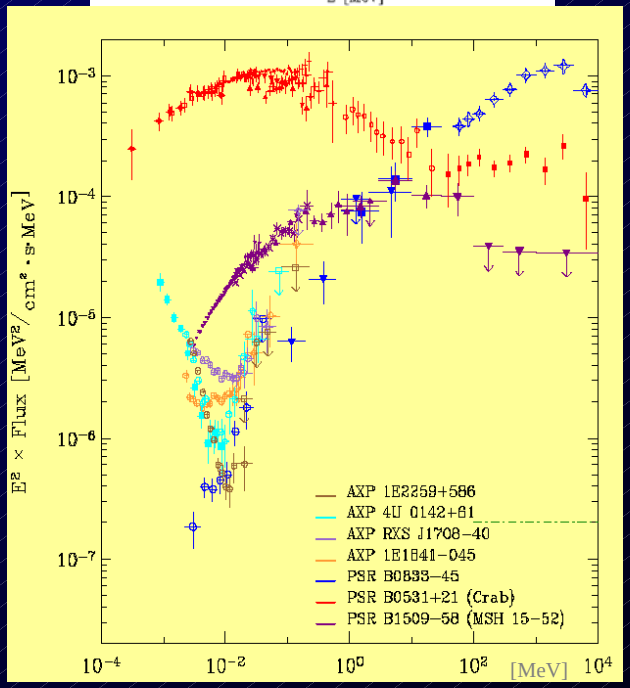
Gamma-Ray Emission from Neutron Stars: AXP's

- Anomalous X-ray Pulsars: *(e.g. Kaspi 2004)*
  - Periods in 5-12 sec range, spinning down
  - Located in young disk of Galaxy
  - Very soft spectra (kT~keV), $L_x \sim 10^{35}$ erg s^{-1}.
  - Not powered by rotation:
    X-ray power L_x > rotational energy loss
  - Not powered by accretion: steady spin down, no variability of emission, exept: SGR-like outbursts



- INTEGRAL Discovers More Such Sources, Surprisingly, at >10 keV
  - 1E 1841-045 *(Molkov et al. 2004, Bassani et al. 2004)*
  - 1RXS J170849-400910 *(Revnivtsev et al. 2004)*
  - 4U 0142+614 *(den Hartog et al. 2004)*
  - IGR J00234+6141 *(den Hartog et al. 2005)*

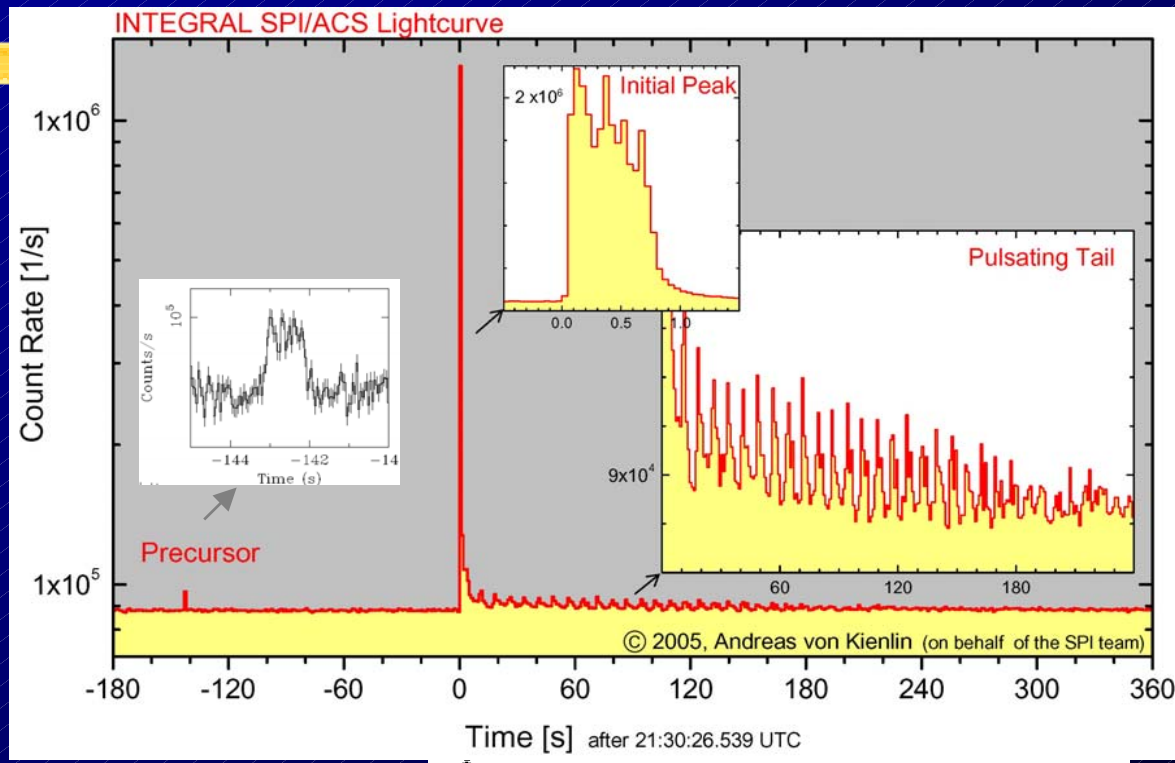


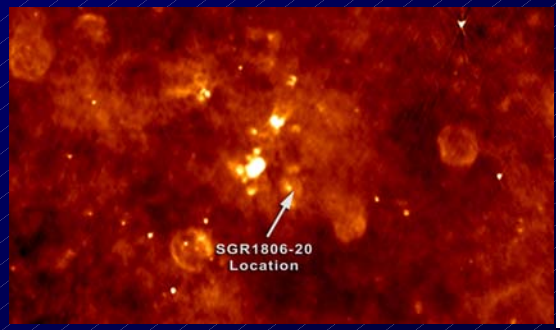


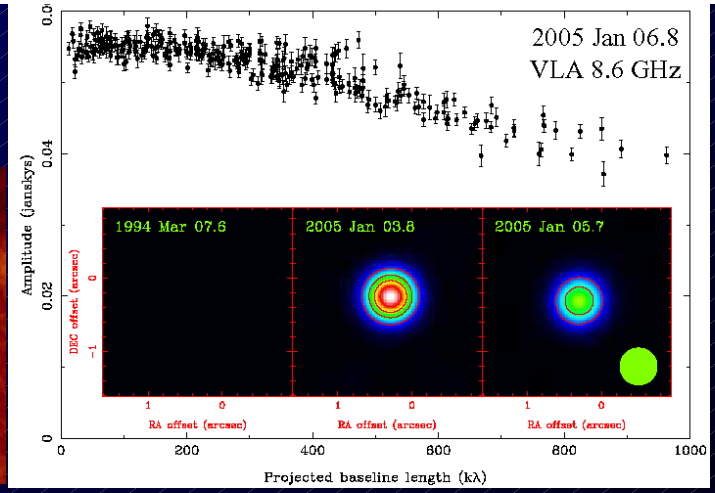
- AXP's Spectra Now Show Significant High-energy Emission Tail with Hard Spectrum
  - New Window to Study Magnetars B~$10^{14...15}$G!

Soft Gamma-Ray Repeaters / SGR 1806-20

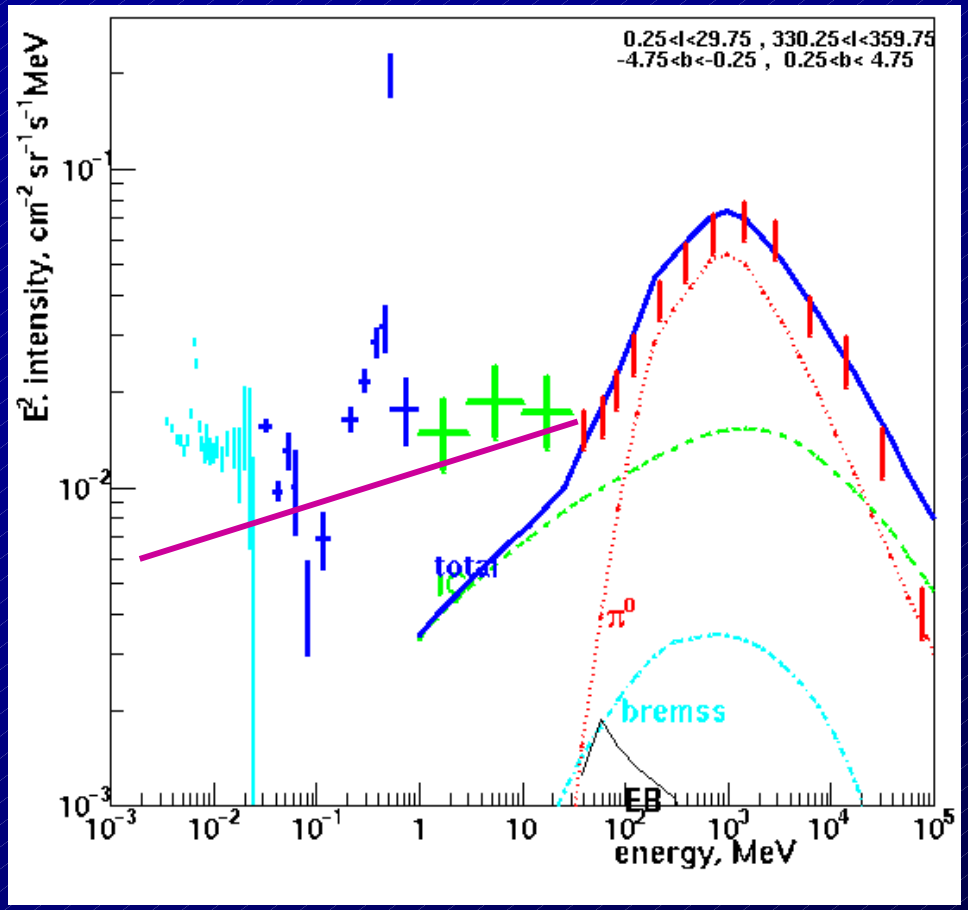
- SGR 1806-20
  - ☆ Giant Flare 27 Dec '04
    - ☞ INTEGRAL/SPI-ACS, RHESSI, SWIFT, Mars-Odyssee…
    - ☞ 7.56 sec pulsations (NS rotation?)
    - ☞ Precursor at -143 s
    - ☞ $E_{total,\ flare} \sim 10^{46}$ erg! (100* other SGRs)
    - ☞ $E_{peak}/E_{tail} \gg$ other SGRs
  - ☆ IR and Radio Afterglows
    - *(VLT, Israel et al. 2005; VLA, Gaensler et al. 2005;)*
    - ☞ *Expanding polarized radio nebula ($v_{exp} \sim 0.3$ c)*
    - ☞ *~4 10^{43} erg in particles*
  - ☆ *Example of a "Short-Duration" GRB??*







Low-Energy Gamma-Rays in Inner Galaxy



- ☆ CR Interactions with ISM
  - ☆ Pion Production
- ☆ CR Interactions with Starlight
  - ☆ Inverse Compton
- ☆ Positron Annihilation
  - ☆ 511 keV Line, Ps Continuum
- ☆ Compact Accreting Sources
  - ☆ Thermal Hot Plasma
  - ☆ Non-thermal Tails
- ☆ New Sort of Hard Sources
  - ☆ Particle Accelerators
    - ☆ AXP's
    - ☆ In-situ CR e- Acceleration

Exciting Times for High-Energy Astronomers

- Mapping Positron Annihilation
- Measuring Doppler Effects on ^{26}Al
- Constraining ^{60}Fe and ^{26}Al from Massive Stars
- Detecting Hard Tails in X-ray Sources (AXP's…)
- Discovering Embedded Binaries

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