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

“Radionuclides and Gamma-Ray Line Astronomy”

Invited Lectures
by
Roland Diehl
MPE Garching

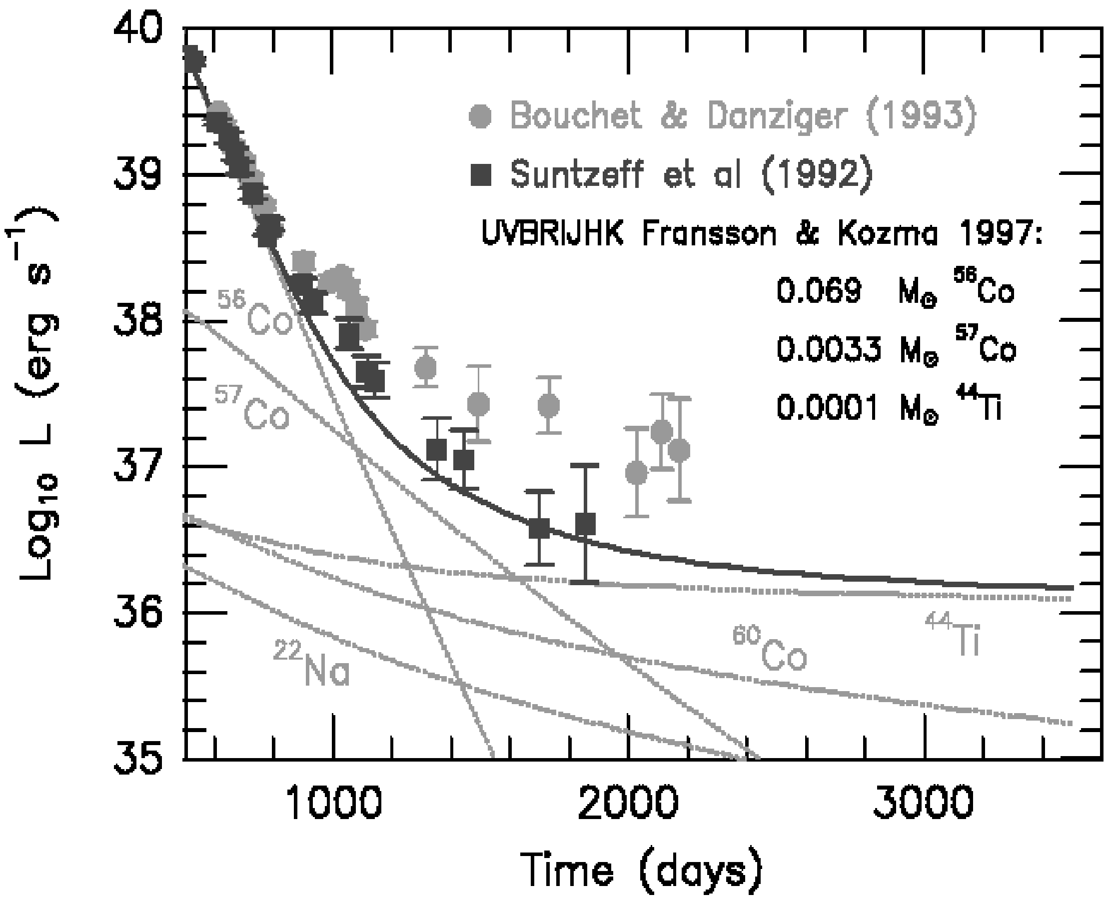
- Part I: Gamma-Rays and Nucleosynthesis
  - Nucleosynthesis Processes
  - Radioactive Decay
  - Cosmic Nucleosynthesis Sites
- Part II: Observed Cosmic Radioactivities
  - Supernovae
  - Diffuse Radioactivities & Various Connections

Part II

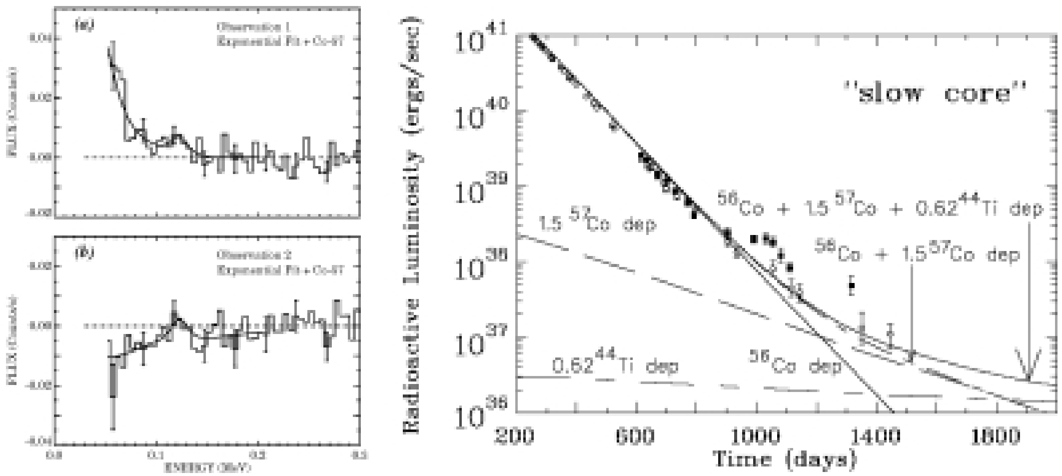
- **Observed Cosmic Radioactivities**
  - a) Supernovae
  - b) Diffuse Radioactivities

The Energy from Radioactivity in SN1987A

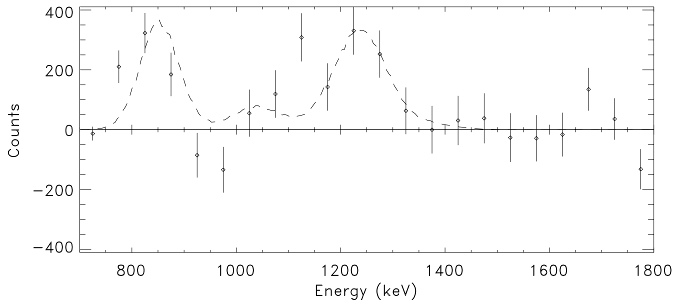
- **Early Light Curve Dominated by ^{56}Ni and ^{57}Co Radioactivity (Gamma-Ray Lines Detected by SMM and OSSE, respectively)**
- **Late Light Curve Power Source Unknown: ~10^{-4} M_o of ^{44}Ti? Pulsar?**
- **Detection by INTEGRAL Possible, if ^{44}Ti Source**



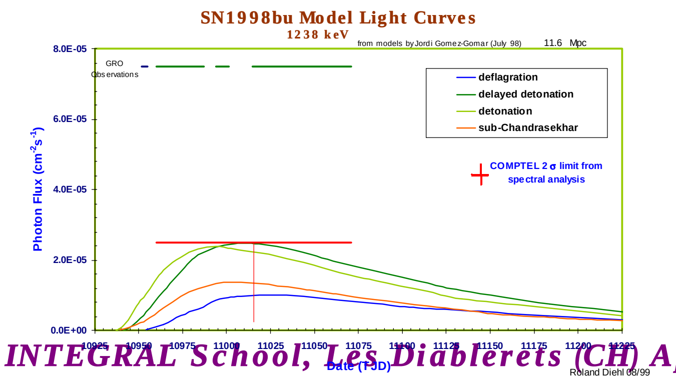
Supernovae: Constraints from Gamma-Ray Lines



(Kurfess et al. 1992; Clayton et al. 1992)

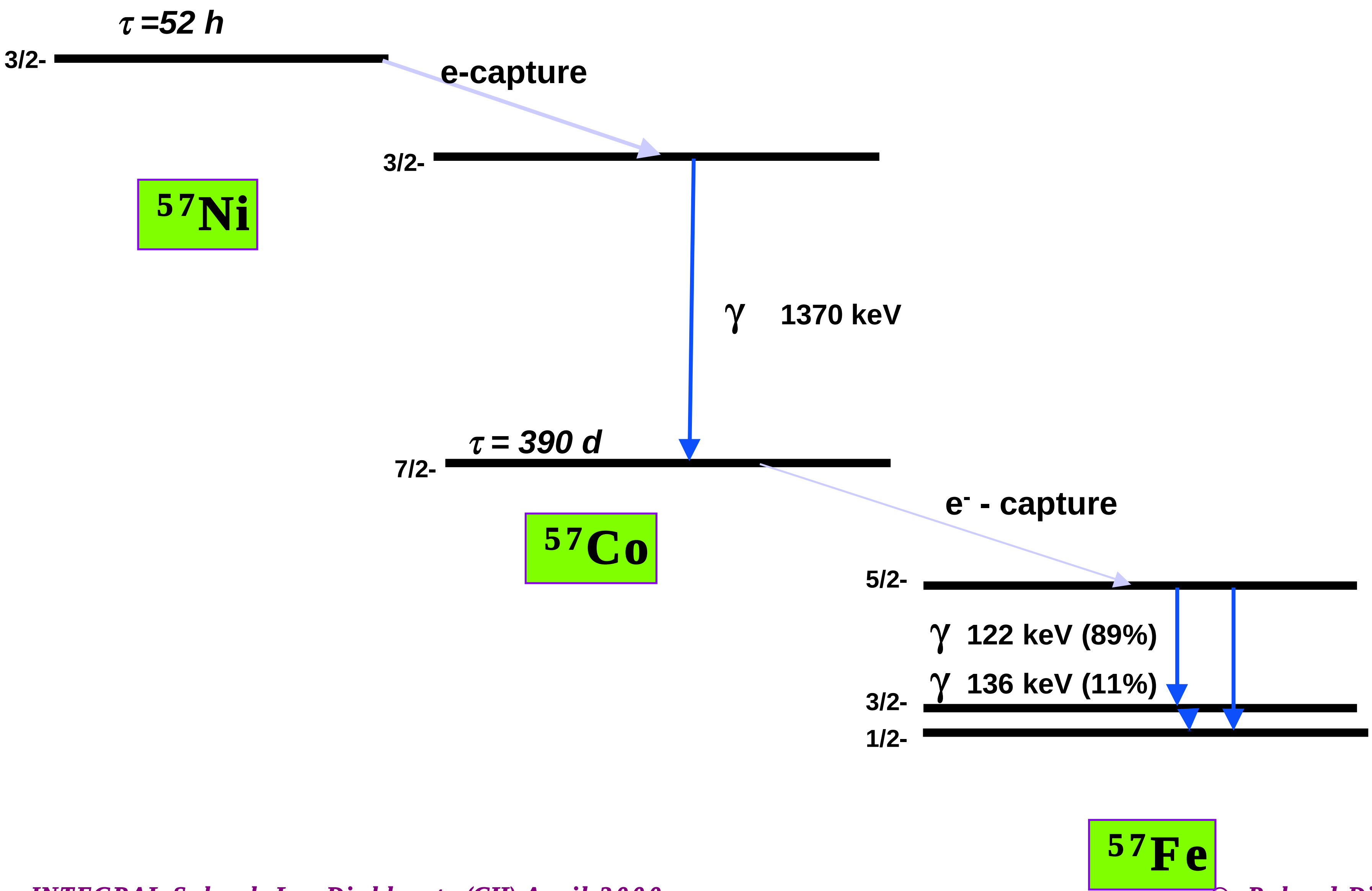


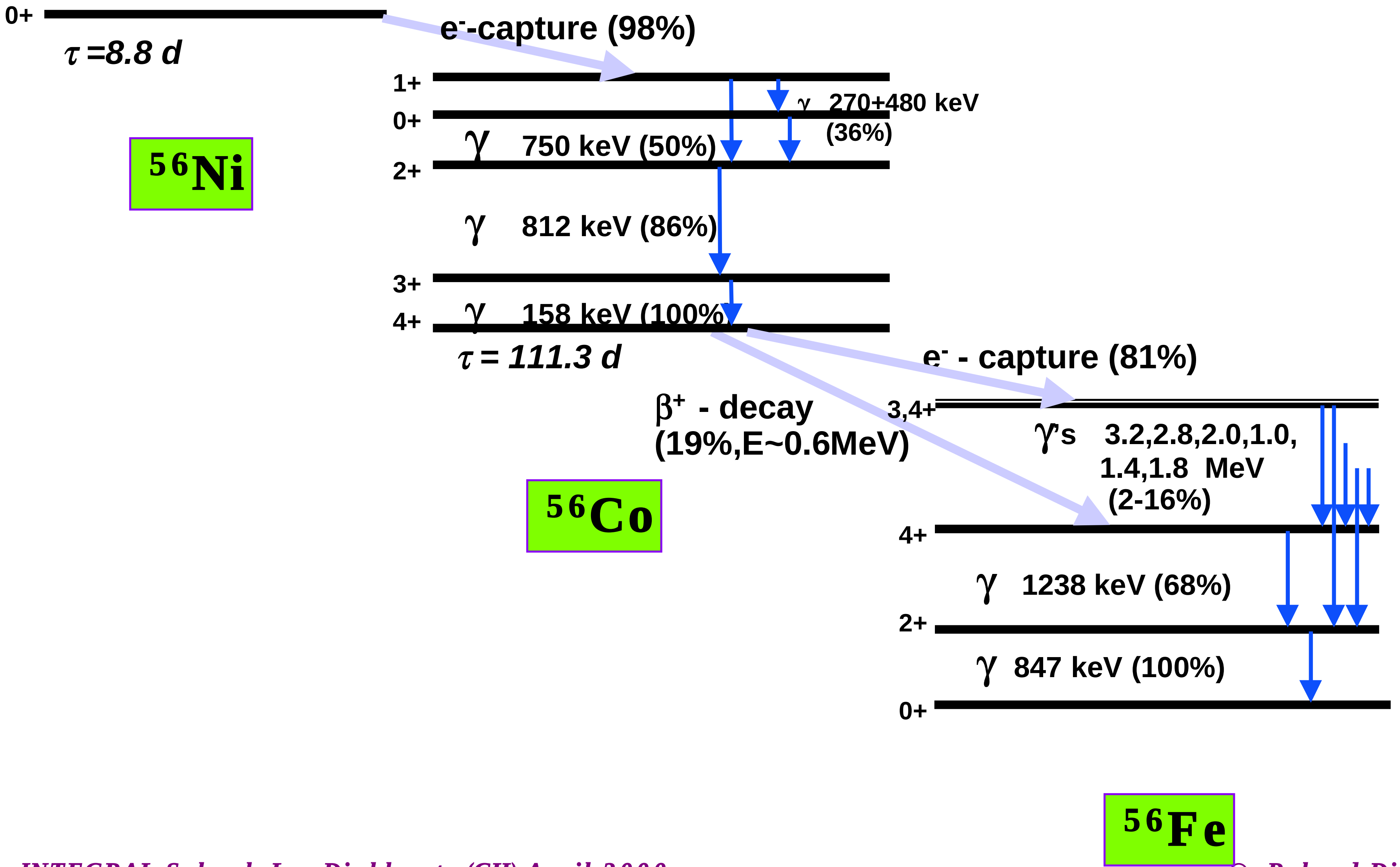
(Morris et al. 1995;1997)



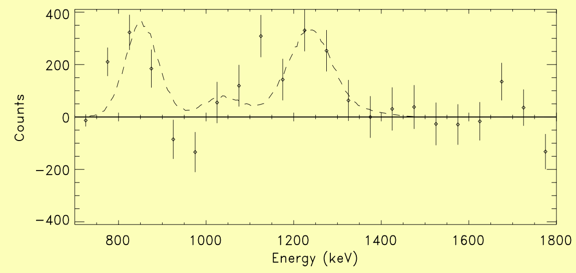
(Leising et al. 1999; Georgii et al. 1999)

- **SN 1987A**
  - **Core-Collapse; d~55kpc**
  - **Early ^{56}Ni Lines** **(SMM & balloons)** **–> Enhanced Mixing**
  - **^{57}Co Lines (OSSE)** **–> [^{57}Ni/^{56}Ni] ratio ~1.5-2 [^{57}Ni/^{56}Ni]$_{solar}$**
- **SN 1991T**
  - **Peculiar SNIa; d~17Mpc**
  - **Indication of ^{56}Co Lines** **(COMPTEL)** **–> M_{Ni}~0.6-3.3 M_o**
- **SN1998bu**
  - **SNIa; Unusually-high Reddening; d~8-12 Mpc**
  - **Limits on Lines** **(OSSE; COMPTEL)** **Constrain Models**

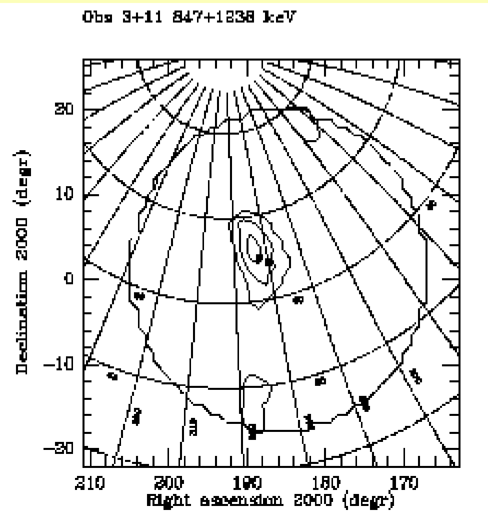

τ =52 h
3/2-
e-capture
3/2-
57Ni
γ 1370 keV
τ = 390 d
7/2-
57Co
e- - capture
5/2-
γ 122 keV (89%)
γ 136 keV (11%)
3/2-
1/2-
57Fe


0+
τ =8.8 d
56Ni
e⁻-capture (98%)
1+
0+
2+
γ 270+480 keV
(36%)
γ 750 keV (50%)
γ 812 keV (86%)
3+
4+
γ 158 keV (100%)
τ = 111.3 d
56Co
β⁺ - decay
(19%,E~0.6MeV)
e⁻ - capture (81%)
3,4+
γ's 3.2,2.8,2.0,1.0,
1.4,1.8 MeV
(2-16%)
4+
γ 1238 keV (68%)
2+
γ 847 keV (100%)
0+
56Fe

^{56}Co Line Indications from SN1991T in COMPTEL Data



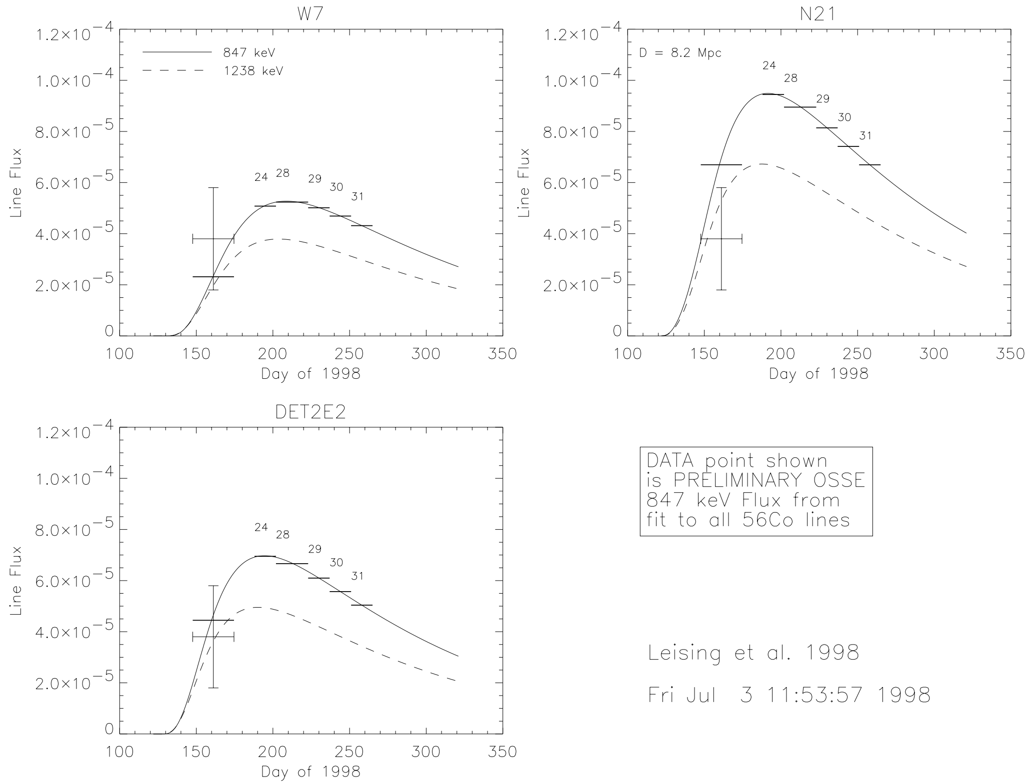
- **SN1991T:**
  - in NGC4527 on 10 Apr 1991
  - Distance 9.... 17 Mpc
  - Peculiar SNIa
    early: no Si absorption, Fe emission instead;
    overluminous;
    late: ~standard SNIa
- **COMPTEL Observation Result:**
  - Observations at Days 66-79, 176-190
  - 3.3σ from combined Observations in 847 and 1238 keV Lines
  - Flux:
    8.9 (±3.4 ±2.7) 10^{-5} ph cm^{-2} s^{-1} (combined)
    5.3 10^{-5} ph cm^{-2} s^{-1} (847 keV only)
    3.6 10^{-5} ph cm^{-2} s^{-1} (1238 keV only)
  - Inferred ^{56}Ni Mass: ~ 2 M_o (0.62...2.0...3.3 Mo)



- Large Uncertainties of Model Yields (Variety of Types) & Gamma-Ray Measurement

SN 1998 bu

- **Discovery on May 9.9, 1998**(Villi),
  Ia Identification on May 14(no H lines; SiII absorption at max; Meikle et al.; Ayani et al.),
  SN Event Inferred on May 1..2 (from Plate Post-Discovery on May 3)
- **Host Galaxy M96 / NGC 3368** (RA 10 46.8 Dec 11 50; l=234.5, b=57.0)
- **~Closest SNIa: D~8...12 Mpc** (D_{98bu}~0.7 D_{91T})
  (Ceph.8.2; Tully-F.~8.1; HST-Ceph.11.6±0.8; PN 9.6±0.6)
- **"Standard" Type-Ia Lightcurve & Spectra in IR,U,V,B; <V_{Bmax}>=11.89**
- **Extinction A_V~0.94 ±0.2 mag; Unusual Reddening (Host Galaxy Dust?)**



CGRO Observations:

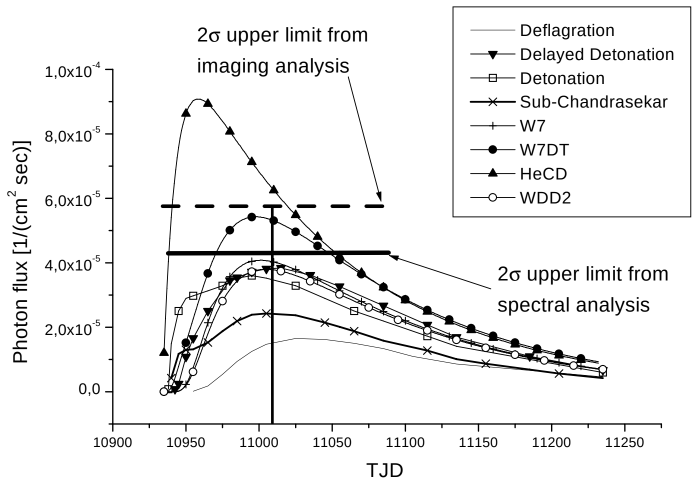
721.5	19May-22May	03	234.4/57.0
723.5	27May-02Jun	06	230.1/55.2
725.5	02Jun-16Jun	14	230.2/55.2
726.5	16Jun-23Jun	07	230.2/55.1
727.7	30Jun-07Jul	07	239.0/58.8
728.5	21Jul-11Aug	21	231.6/55.8
729.5	11Aug-25Aug	14	231.6/55.8
730.5	25Aug-08Sep	14	236.3/55.3
731.5	08Sep-22Sep	14	232.3/58.7

SN1998bu: COMPTEL Limits on ^{56}Ni Decay Lines

☞ 847 keV Line

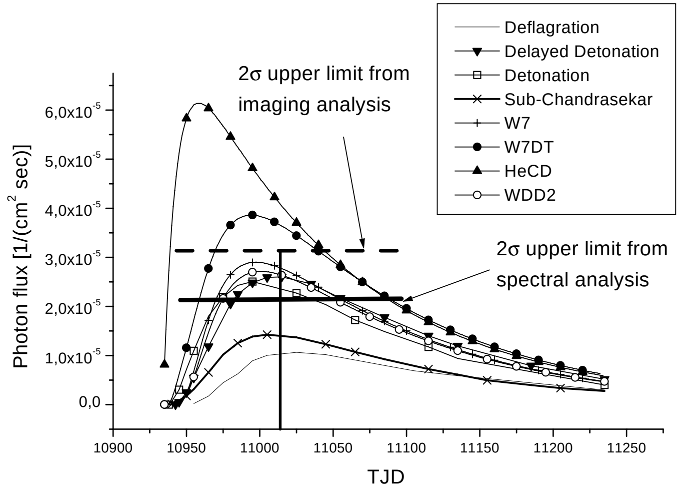
(for 11.3 Mpc)

- ☞ $I_{spectral} < 4.1\ 10^{-5}$ ph cm^{-2} s^{-1}
- ☞ $I_{imaging} < 5.8\ 10^{-5}$ ph cm^{-2} s^{-1}
- ☞ **$I < 5\ 10^{-5}$ ph cm^{-2} s^{-1}**



☞ 1238 keV Line

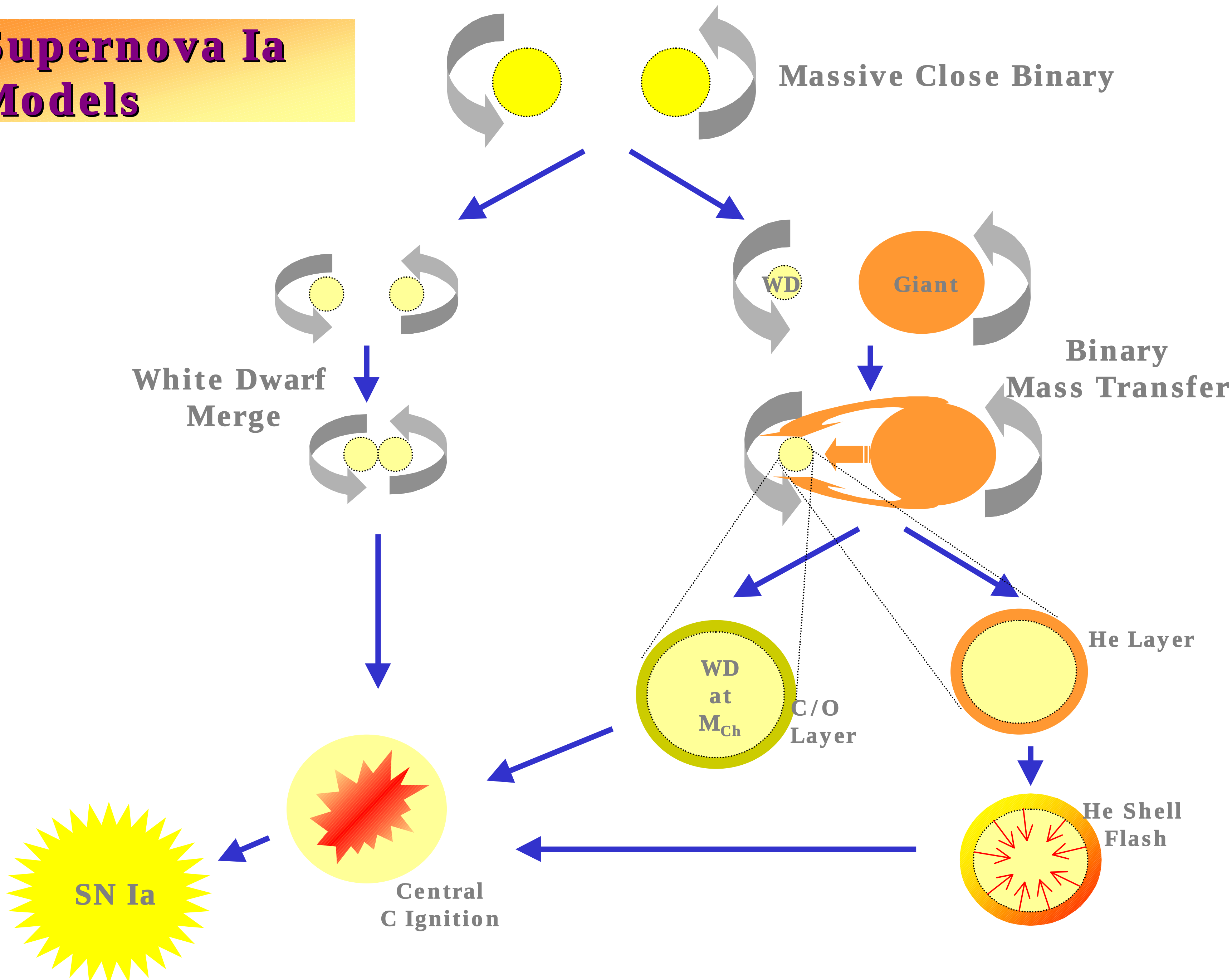
- ☞ $I_{spectral} < 2.3\ 10^{-5}$ ph cm^{-2} s^{-1}
- ☞ $I_{imaging} < 3.2\ 10^{-5}$ ph cm^{-2} s^{-1}
- ☞ **$I < 3\ 10^{-5}$ ph cm^{-2} s^{-1}**



- **"Fast" Models (He Cap, W7DT) Unlikely**

Georgii et al., AIP (Proc. 5th Comp.Symp.) 2000

Supernova Ia Models

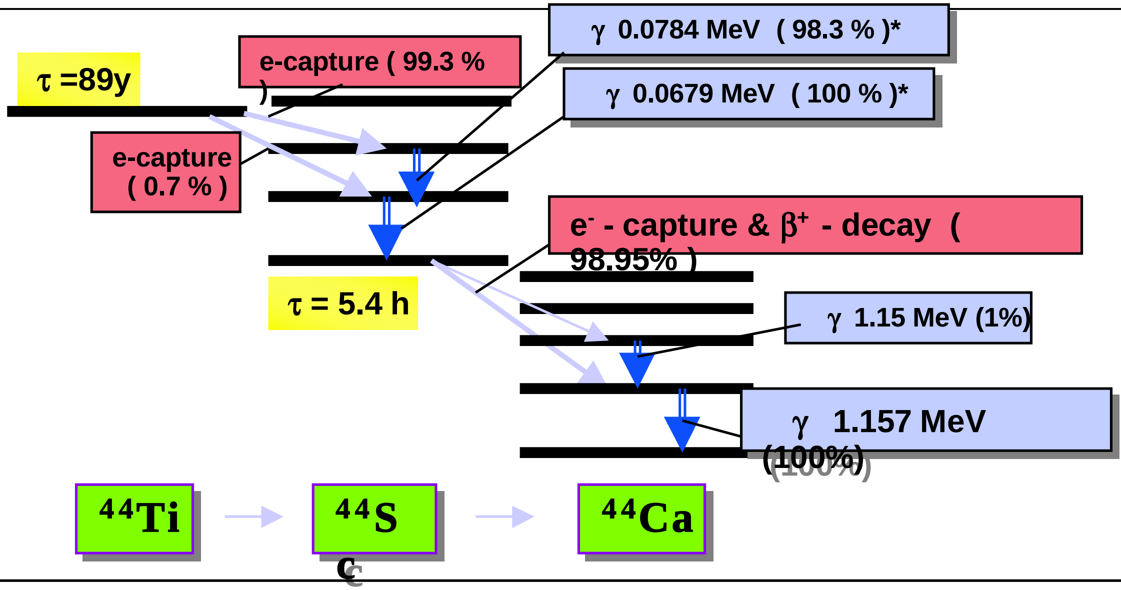


^{44}Ti Decay as Nucleosynthesis Probe

- Decay Scheme:

  → 3 gamma-ray lines

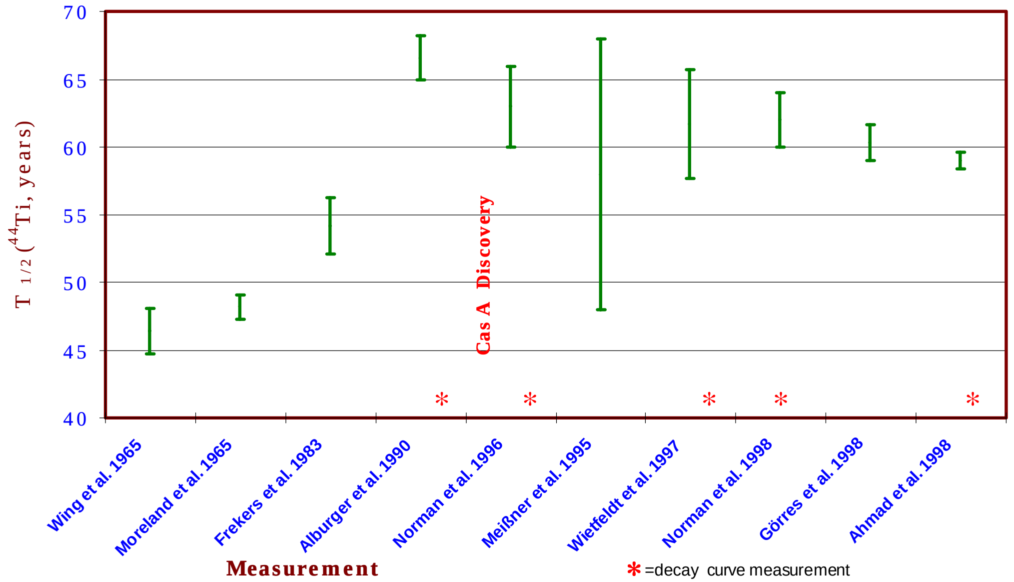
⇒ Probe of Individual Supernova Events!



- Decay Time:

  (Laboratory Measurements)

  now settled to 89y!

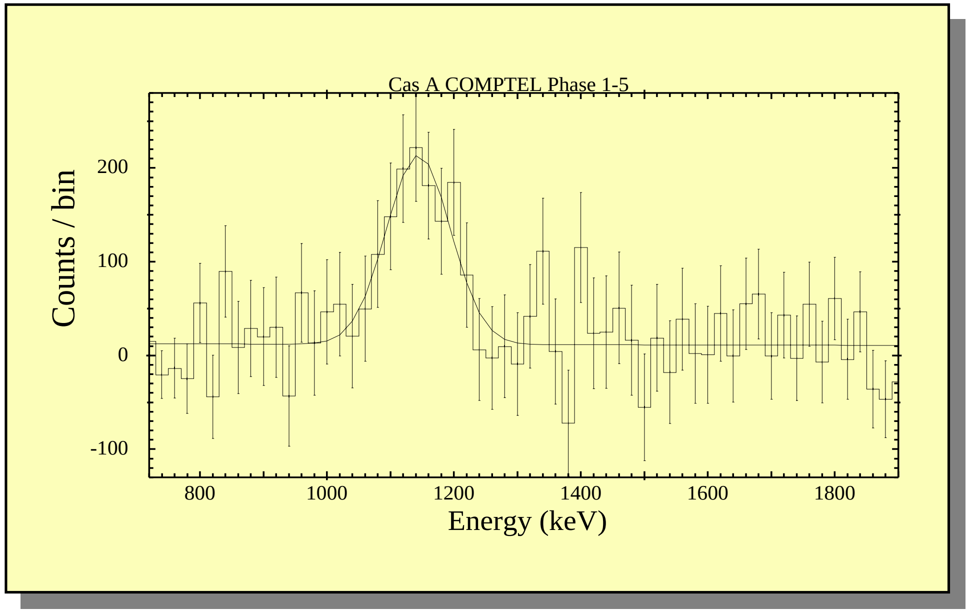


- ^{44}Ti Decay in SNR: EC Suppression through Ionization?

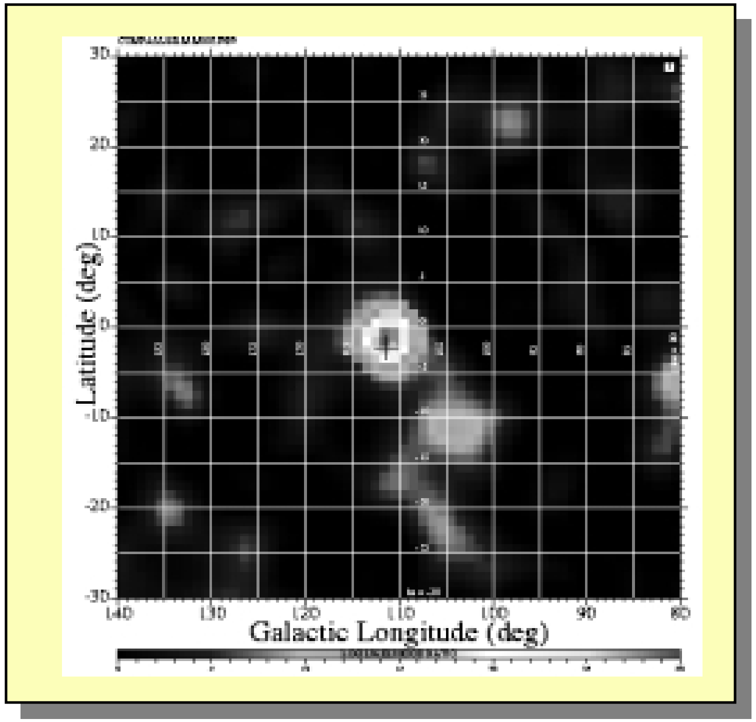
Core Collapse Supernovae: Cas A

- ☞ 1.157 MeV ^{44}Ti Line Detection (<6σ) by COMPTEL
- ☞ Likelihood Map Peaks @(l=111°/b=-1°)(±3°) = Cas A
- ☞ 1.157 MeV Flux   4.2 (±0.9) 10^{-5} ph cm^{-2} s^{-1}
- ☞ Consistent with OSSE 1.7 (±1.4) 10^{-5} and RXTE 2.9 (±2.0) 10^{-5} Flux Values

- Direct Proof of ^{44}Ti Production in CC-SNae
- Pioneering Detection of Young SNR in ^{44}Ti Gamma-Rays

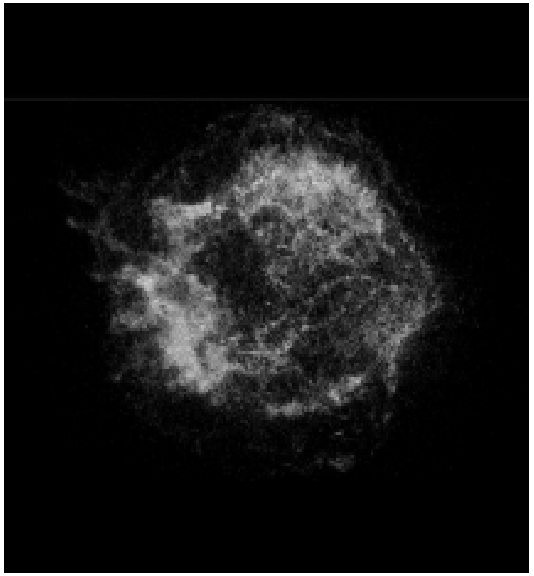


A. Iyudin et al., A&A 1994; ESA-SP 382 1997



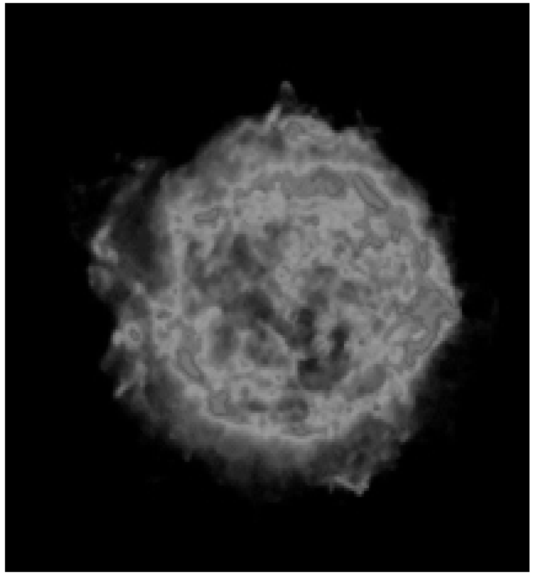
Cas A: Studies of SN Blastwave / ISM Interactions

- SNR Reverse Shock –> Hot SNR Bubble (X)
- Fermi Acceleration at Shock Discontinuity (R,X,γ)
- Heating of Dense Clumps/Filaments (Lines)

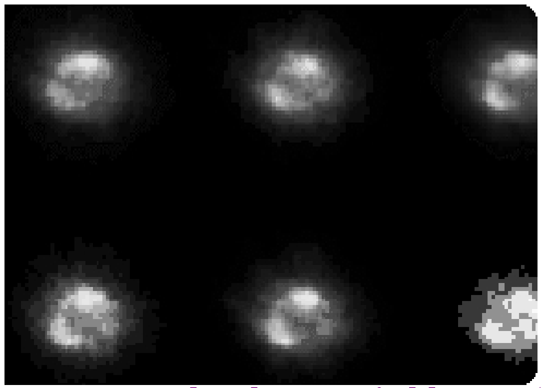


X-Cont (temperature)

Optical - Lines

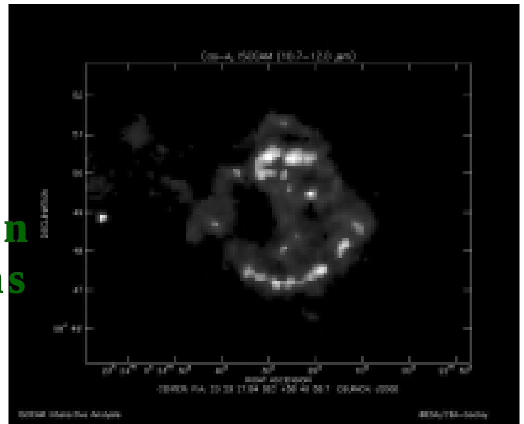


Radio-Continuum



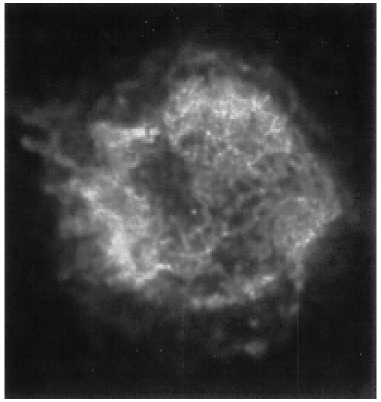
X-Lines

Diagnostics of
- Blast Wave Evolution
- Ejecta & CSM Composition
- Thermalization Conditions



IR-Lines

X-Ray Spectroscopy Cas A



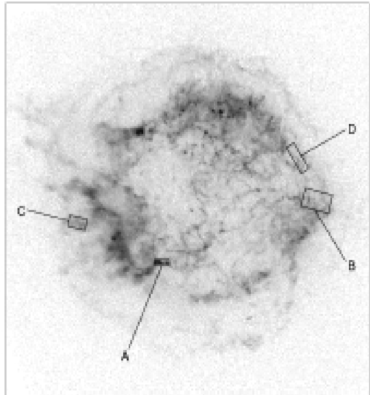


FIG. 2.—Broadband unsmoothed *Chandra* X-ray image of Cas A using a square-root intensity scaling. The spectral extraction regions in our study are indicated.

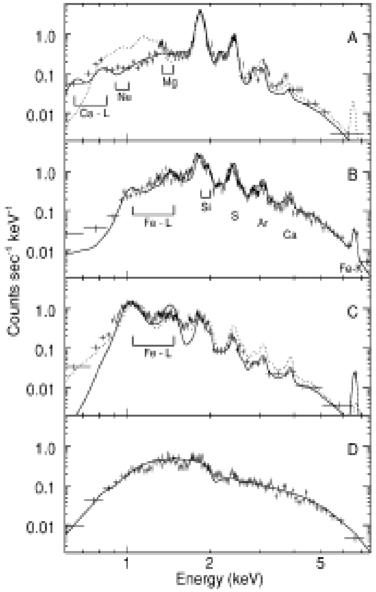


FIG. 3.—Energy spectra from several regions in Cas A as indicated in Fig. 2. The horizontal error bars show the widths of the energy bins, and the vertical ones indicate the statistical error on the measured event rate; systematic errors are not included. Superposed on the data points are smooth curves of simulated *Chandra* ACIS-S spectra. The simulations for regions A, B, and C are of a shock-heated plasma with NEI fractions absorbed by line-of-sight interstellar material. The dotted curves in regions A and C and the solid curve in region B assume abundances corresponding to explosive incomplete Si burning. A considerably better match for region A uses O-burning abundances (*solid curve*). The solid curve for region C is more Fe-rich; i.e., the Si, S, Ar, and Ca abundances are reduced by factors of 5 or more from their values in incomplete Si burning. The solid curves for regions A, B, and C have temperatures of 2.5, 2.5, and 2.8 keV, ionization timescales of 2.5 × 10[illegible], 7.9 × 10[illegible], and 7.9 × 10[illegible] cm[illegible] s, and column densities of 0.9 × 10[illegible], 2.3 × 10[illegible], and 1.5 × 10[illegible] atoms cm[illegible], respectively. All the models for regions A, B, and C also include significant amounts of continuum emission from material with a lower atomic number. The solid curve for region D is an absorbed power-law model with a photon index of 2.6 and a column density of 1.3 × 10[illegible] atoms cm[illegible].

- **X-Ray Lines Reveal Clumps with Large Ejecta Enrichments**
- **SNR Inhomogeneity Requires Mixing / Turbulence During Explosion**

Ref.: Hughes et al., ApJ 528, 2000 (Chandra Observation)

IR Spectroscopy of Cas A

NeII Line (dotted line) **and Silicate Line** (full line) **Images of SNR**
(over optical color image) (from ISOCAM, Douvion et al. A&A, 2000)

- **Ne (and Ar, S) found in (same) Fast-Moving Knots / Ejecta Clumps**
- **(Optical Spectroscopy: O, S, Ar Incompletely Mixed in Knots)**
- **Anticorrelation of NeII and Silicates**

=> Macroscopic but Heterogeneous Mixing of SNR During/Before Dust Formation?

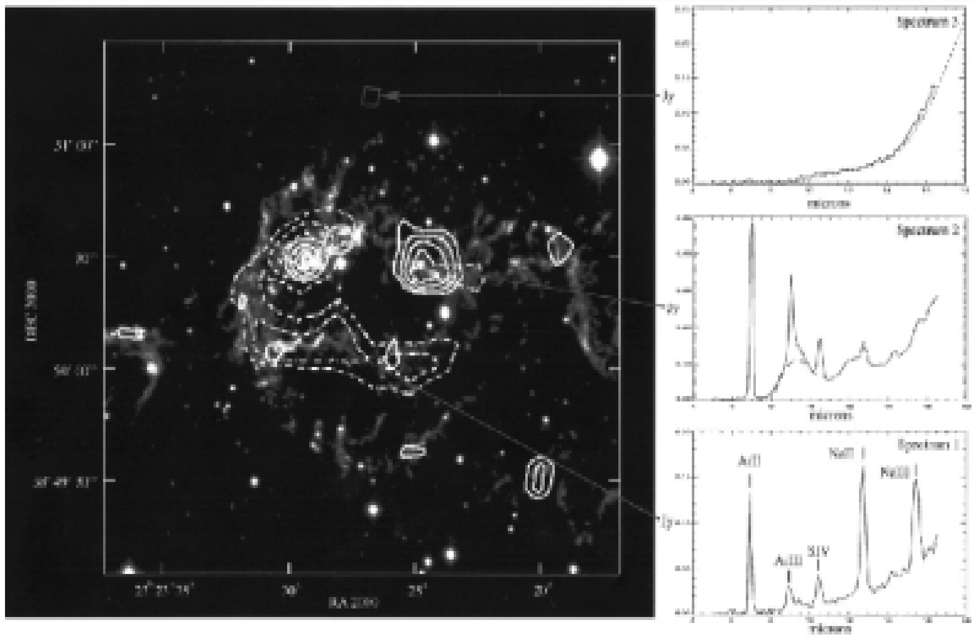


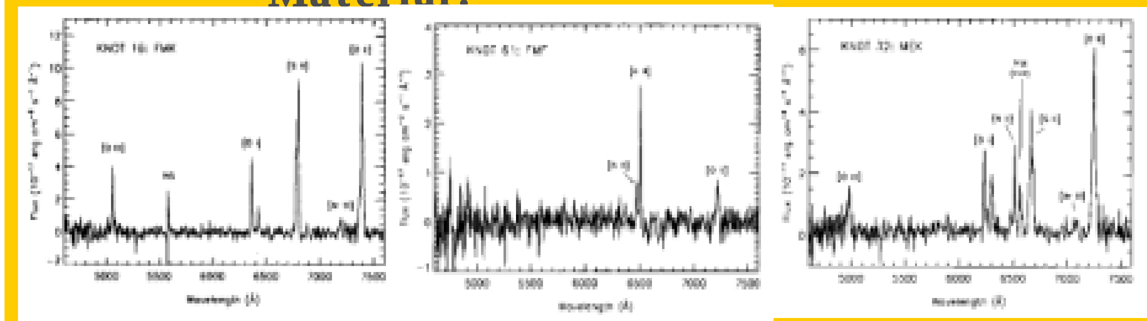
Fig. 1. Contour maps of the [Ne II] line emission (dotted contours) and of the 9.5 μm silicate dust emission (full contours) overplotted onto an optical image of the Cassiopeia-A supernova remnant. At each contour level the flux is divided by a factor 1.5; (instrumental ghost effects were taken into account to limit the lower contours of neon). The neon line and silicate emission are deduced from spectra such as those on the right of the image (see text). The spectra have been obtained with ISOCAM at a spatial resolution of 6″ × 6″; the ISOCAM pixel corresponding to the spectrum is represented on the image by green squares. The optical image has been obtained with the SIS instrument at CFHT.

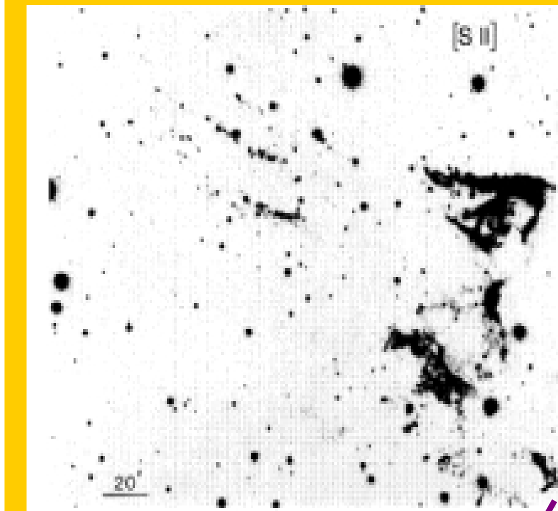
Cas A Asymmetries and Jet

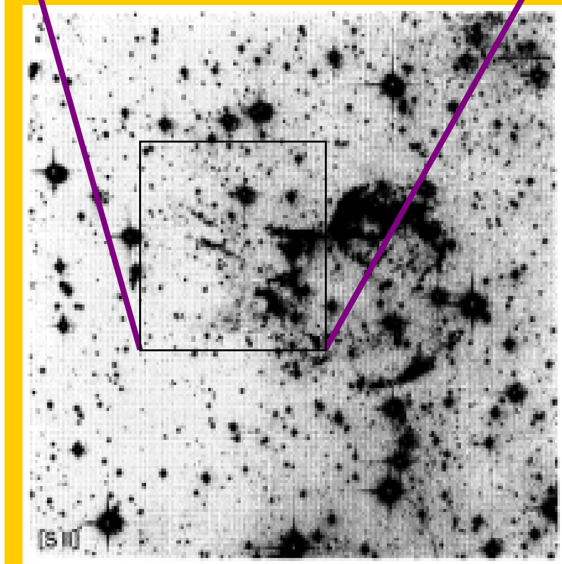
- ## Jet Properties
  - In NE Edge of SNR
  - Extending 3’ Beyond SNR
  - 25^{o} Opening Angle, ~6^{o} out of Plane of Sky
  - 7000 km/s < v < 13000 km/s
  - O, S, Ar Line Emission Knots; some N-rich Knots

  e.g. Fesen & Gunderson ApJ 1996

- ## Ejecta Plumes of SN?
  - Fast-Moving Knots: Mantle/Core Material?
  - Fast Moving Flocculi: Envelope Material?



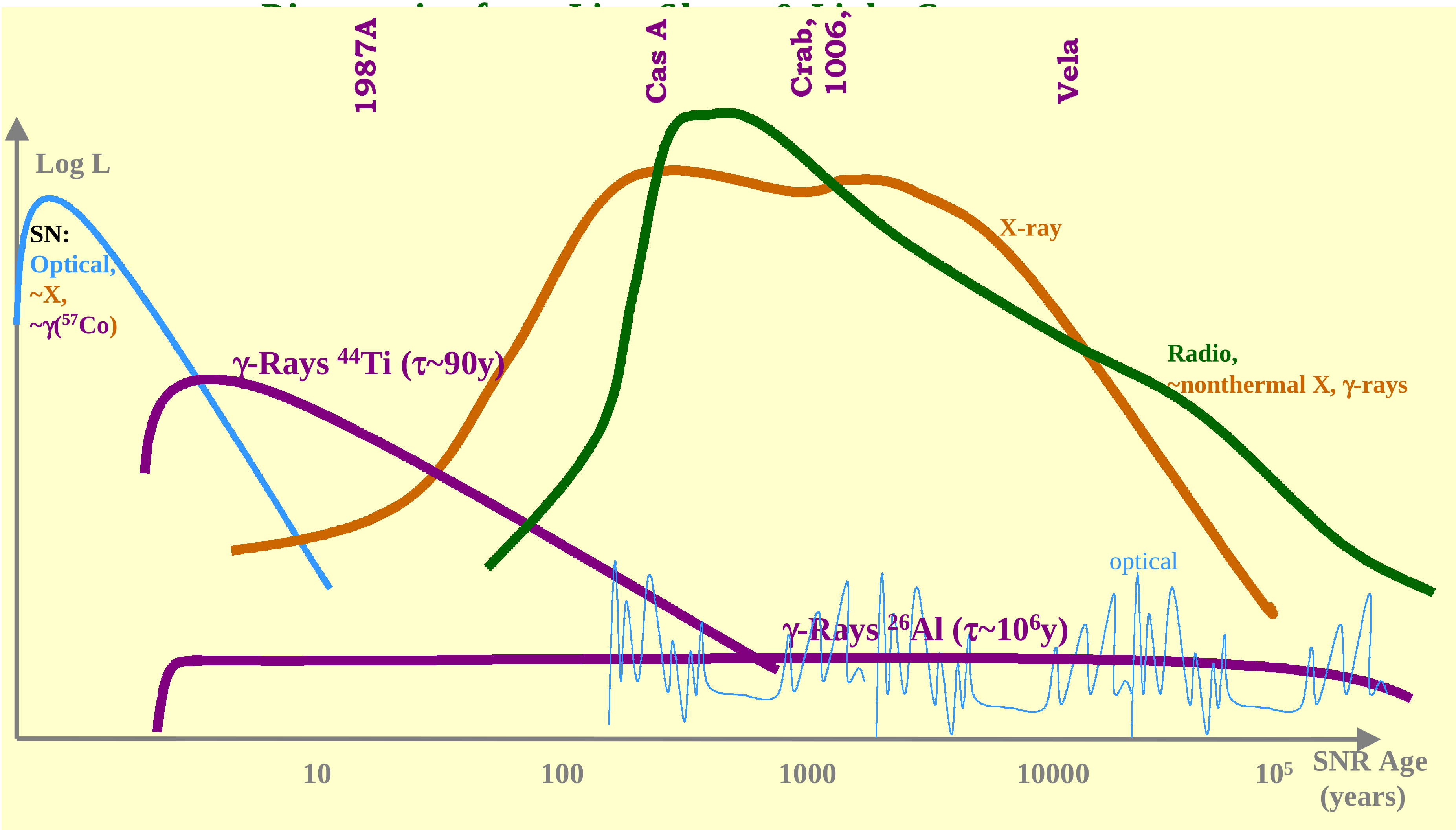




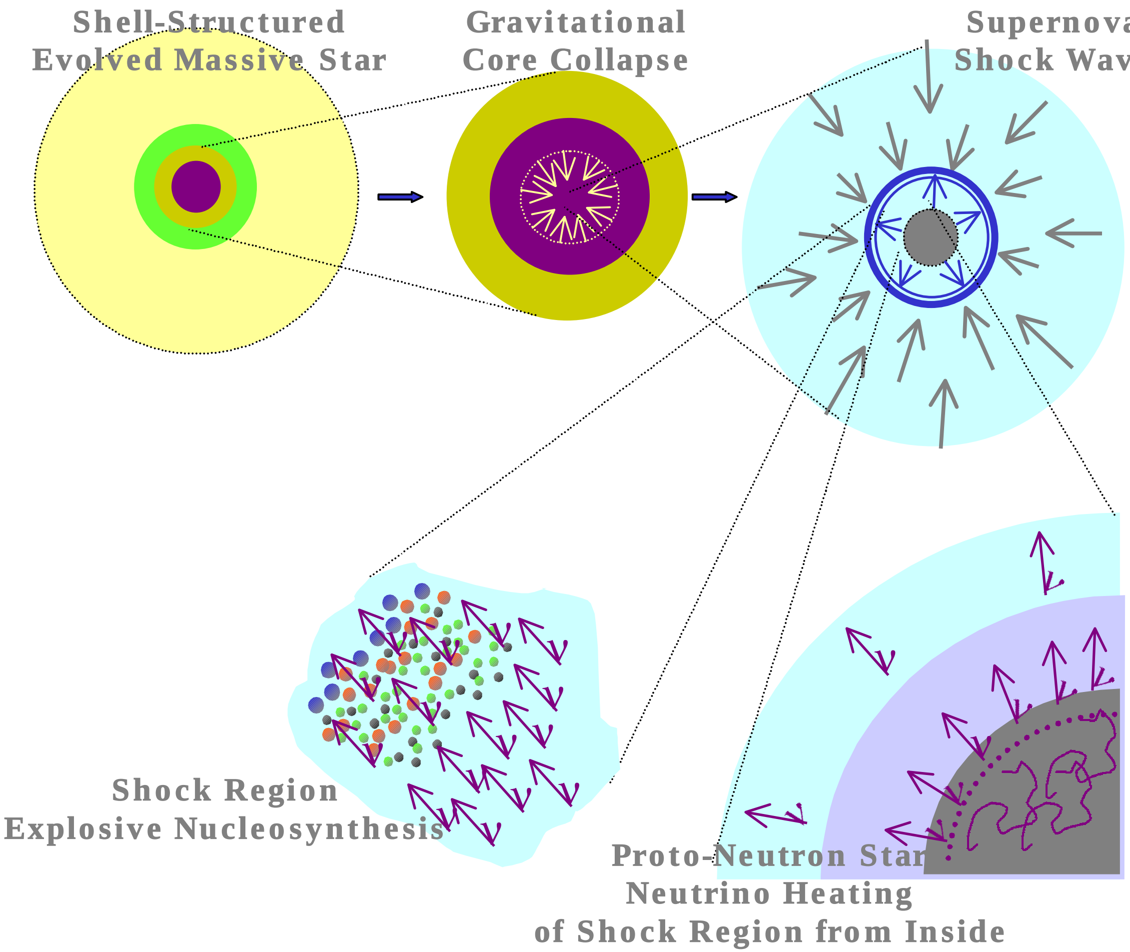
Supernova Remnants: Evolutionary States

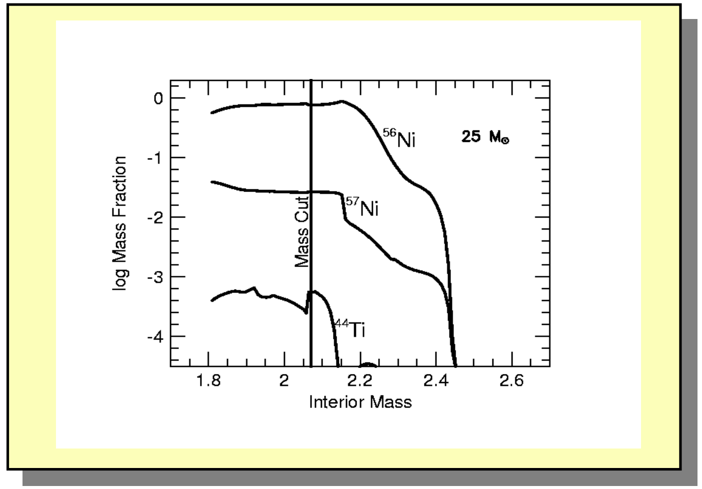
Gamma-Rays Can Extend Presently-Favourable X/R/O Regime:

- Search for New SNR



Issues in CC-Supernova Models



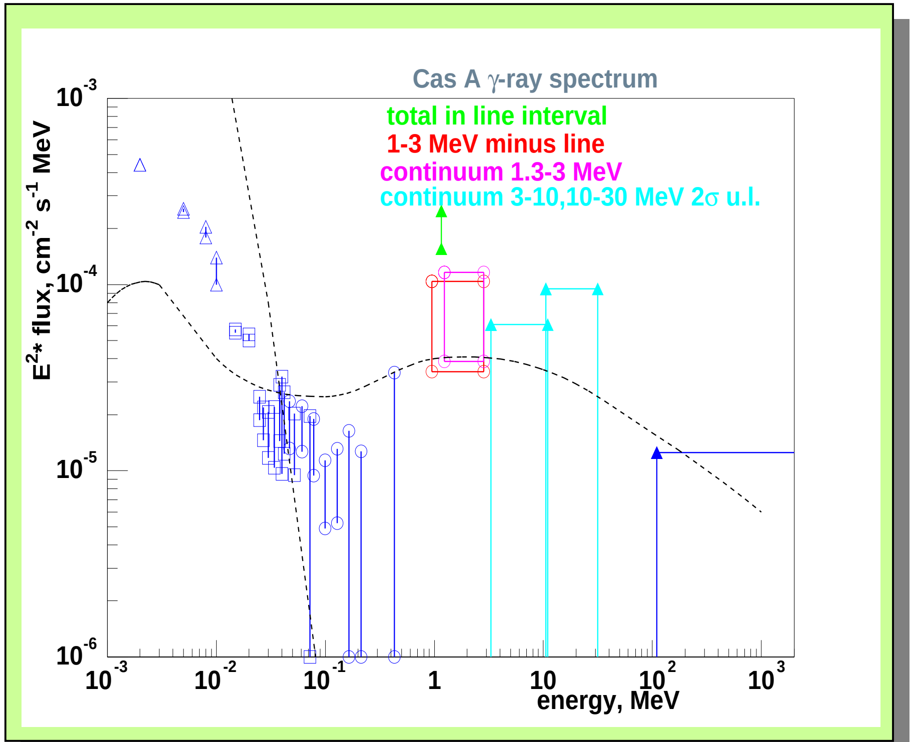


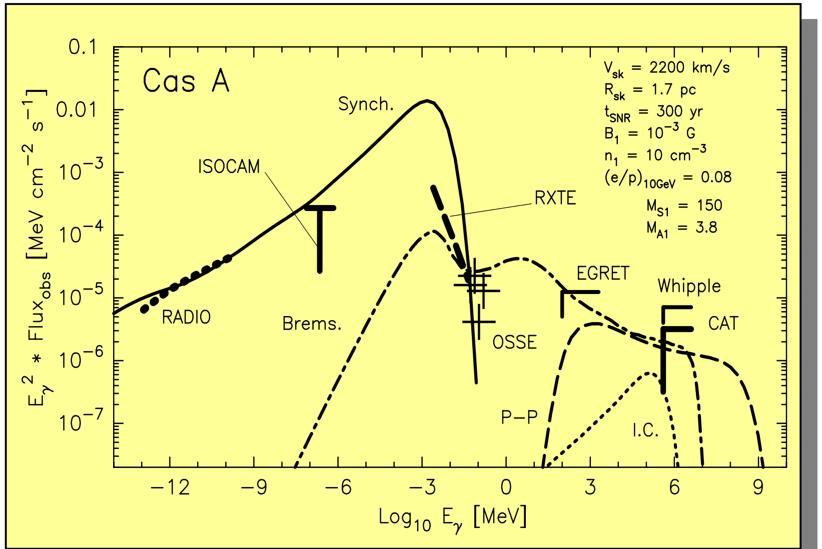
- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis
- Location of Ejecta/Remnant Separation
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out, => Unique Probe (+Ni Isotopes)

Continuum MeV Gamma-Rays from Cas A

❍ Hard X-Ray/MeV Gamma Regime Measurements

- ☞ RXTE Non-Thermal X-Rays from SN 1006 (Allen et al. 1997)
- ☞ OSSE Powerlaw Emission from Cas A (The et al. 1998; 1999)
- ☞ COMPTEL MeV Continuum Emission Study (Strong et al. 1999)





❍ SNR Model (e.g. Ellison et al. 1999)

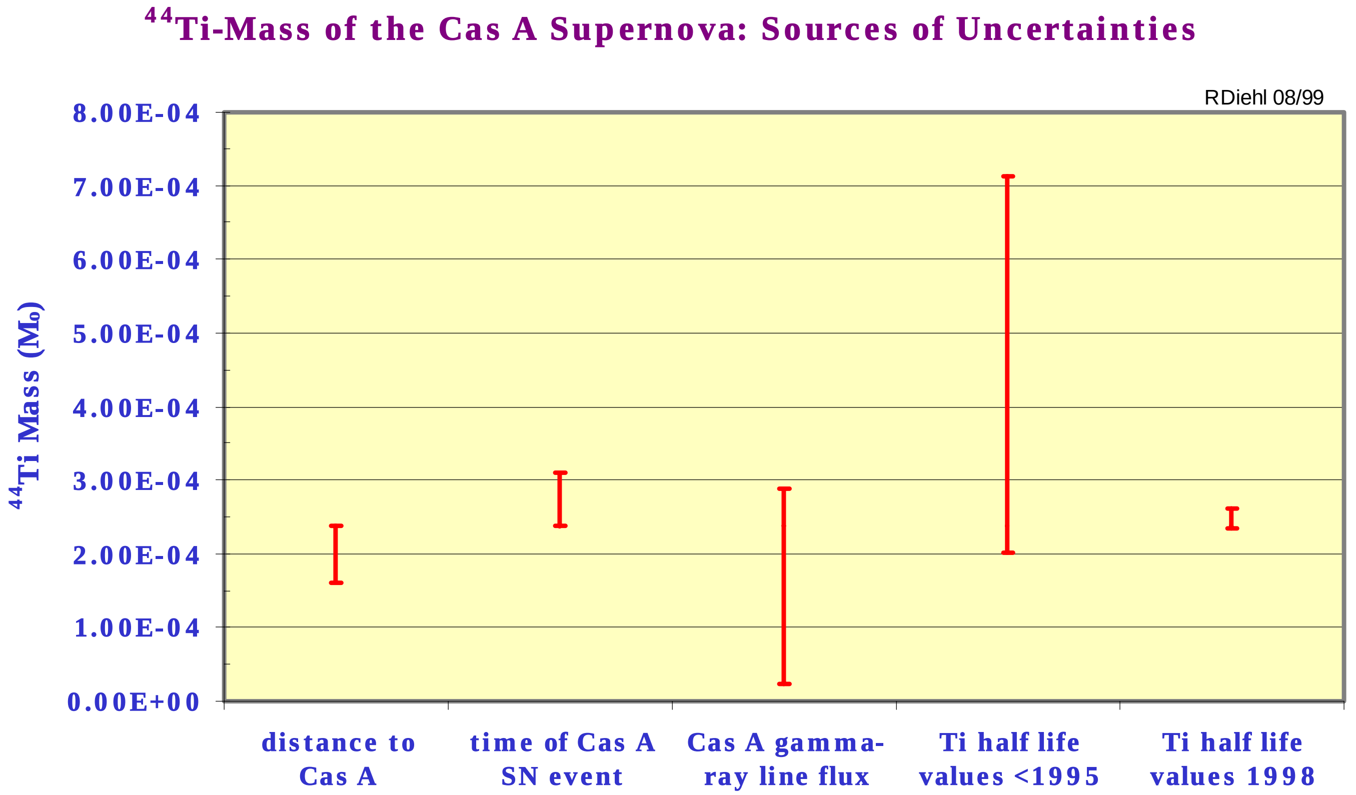
☹ **Continuum Turnover in MeV Regime?**

☹ **Bremsstrahlung or Synchrotron Emission?**

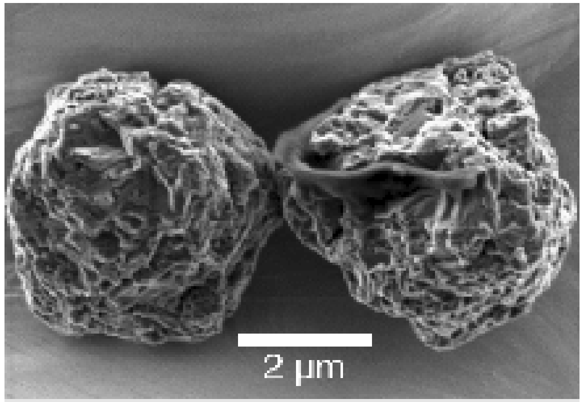
The ^{44}Ti Mass Produced by the Cas A Supernova

Derived ^{44}Ti Amount Depends on

☞ Date of Explosion	AD1680
☞ Distance to Cas A	3.4 kpc
☞ ^{44}Ti Radioactive Lifetime	89y ($T_{1/2}$ 60y)
☞ Measured Gamma Ray Intensity	1...4 10^{-5} ph cm^{-2} s^{-1}



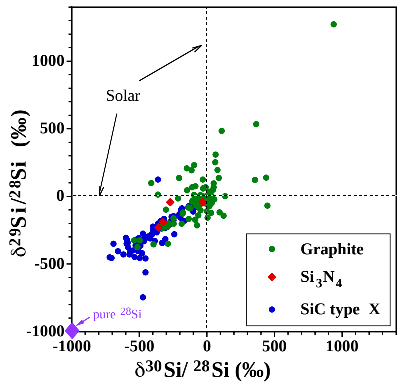
Silicon Carbide Grains



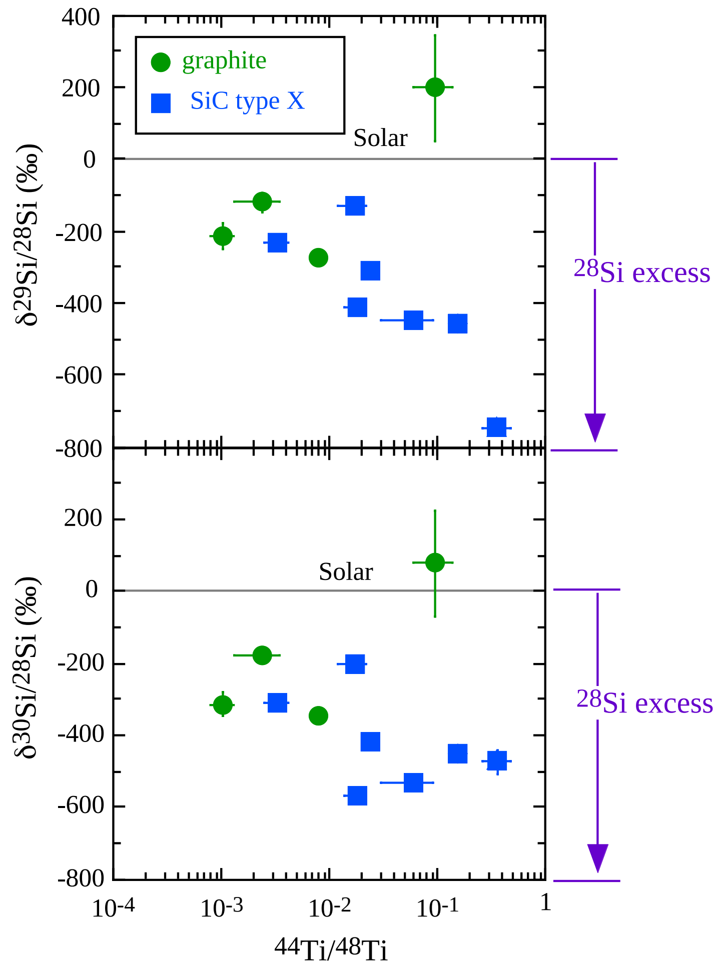
Scanning electron microscope image of presolar silicon carbide grains from the Murchison meteorite. It is thought that these grains formed in the atmosphere of a red giant star, survived the formation of our solar system, and were transported to earth intact inside of this meteorite; hence, they preserve within them the signature of the environment in which they were created. The signature is the precisely measured relative abundances of isotopes of zirconium and molybdenum. Other grains or aggregates of grains contain other heavy elements. Their abundances can be compared to the signature calculated from various models for red giant stars. Precise neutron capture cross sections are required if such comparisons are to be used for improving stellar models.

(Photo courtesy of Andrew Davis, University of Chicago.)

Supernova Grains: ^{44}Ti and ^{28}Si Enrichements



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



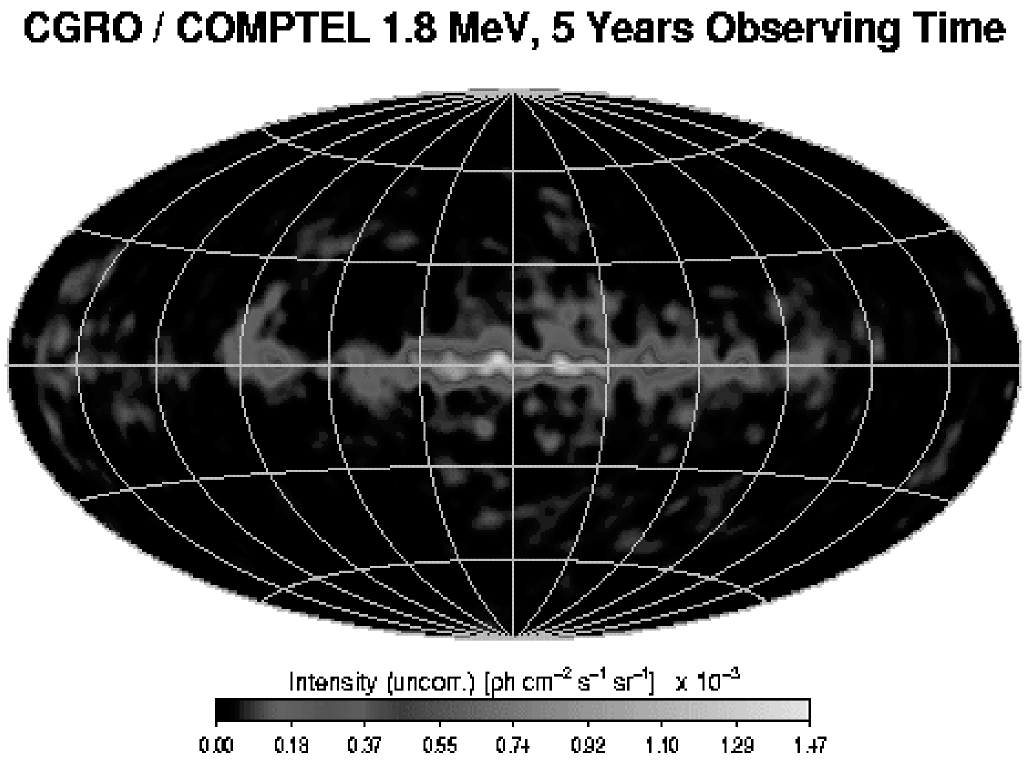
$\delta^iSi/^{28}Si$ (‰) = (($^iSi/^{28}Si)_{Grain}/(^iSi/^{28}Si)_{Solar}$-1)×1000

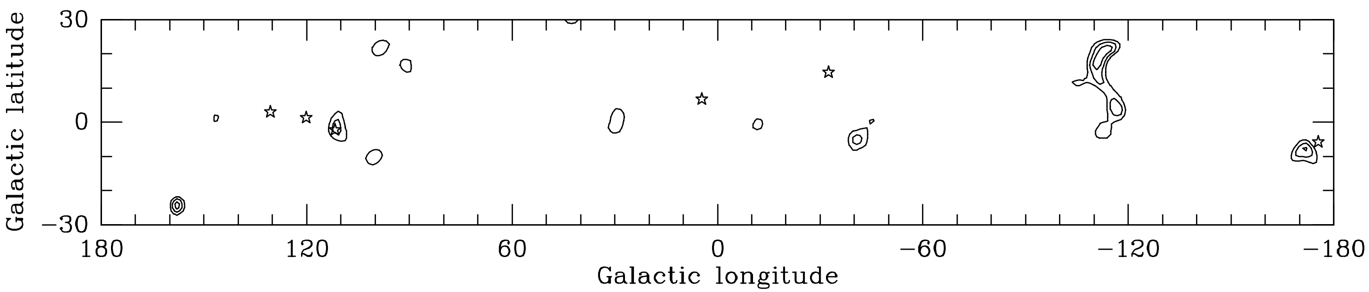
- **Nuclear Burning Should Produce Neighbouring Isotopes at ~Similar (factor 10) Abundances**
- **Excess in α-Multiples Indicates α-Rich Freeze-Out**

=> Supernova Origin

=> Supernovae Produce and Eject ^{44}Ti

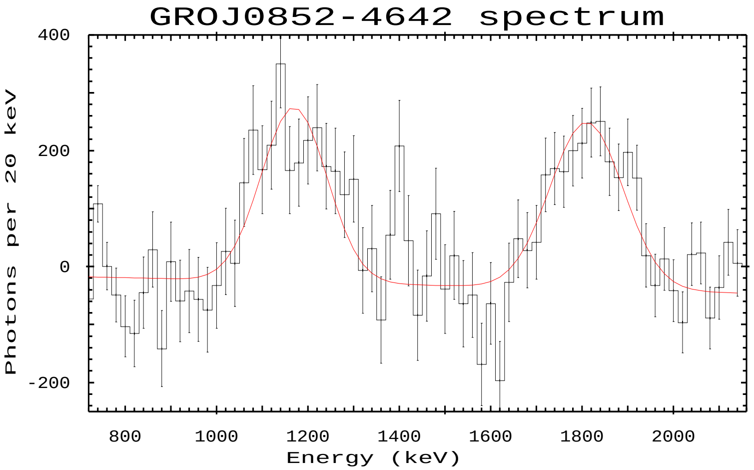
Why Are We Seeing So Few ^{44}Ti SNae?

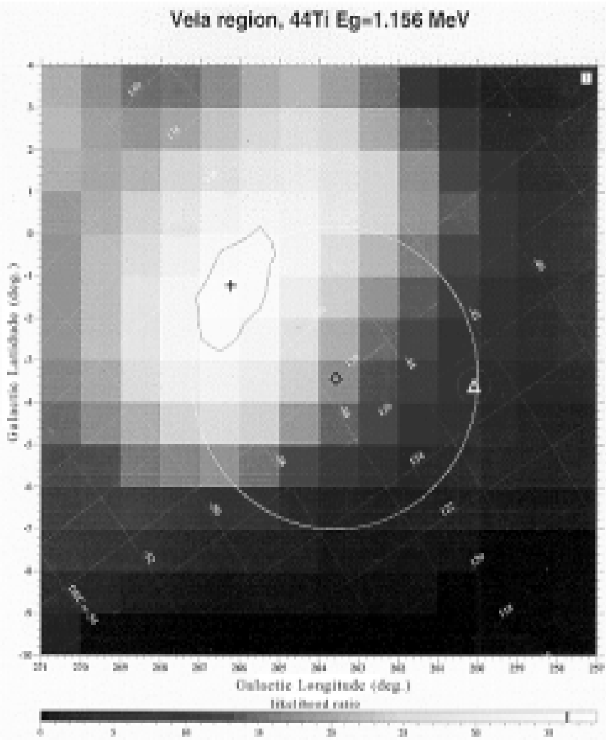




A New ^{44}Ti Supernova Remnant in Vela?

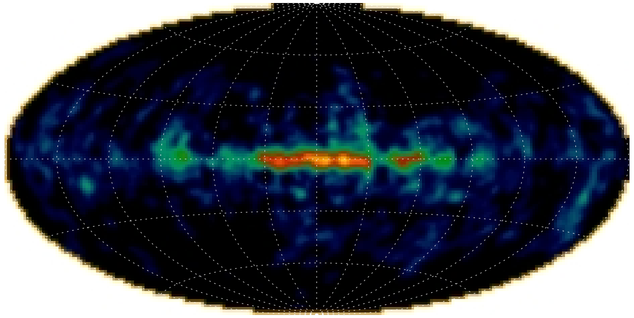
- COMPTEL Spectral Analysis
  - Using Extended Signal as Background
  - Scans along Plane of Galaxy
  - => 1.16 MeV Line Excess in Vela Region
- COMPTEL Imaging Analysis
  - Using Adjacent-Energy Background
  - Excluding Partially-Disfunct Detector Modules
  - Application of MEM All-Sky Imaging
  - => Indication of Point Source at/coincident with RX J0852-4622
- Uncertainties:
  - Instrumental Background Model
  - Underlying Galactic Continuum Emission
  - Imaging Method
  - –> Consistency Checks & Forther Study Required
- Assessments: **(Sep 1999)**
  - Vela Region Result not Robust Against Different Analysis Approaches and Data Selections, unlike Cas A ^{44}Ti Detection
  - For RX J0852.0-4622: Evidence of a ^{44}Ti Signal at ~2-4σ Significance
  - Independent Discovery of a ^{44}Ti SNR (GRO J 0852.0-4622) Cannot Be Claimed

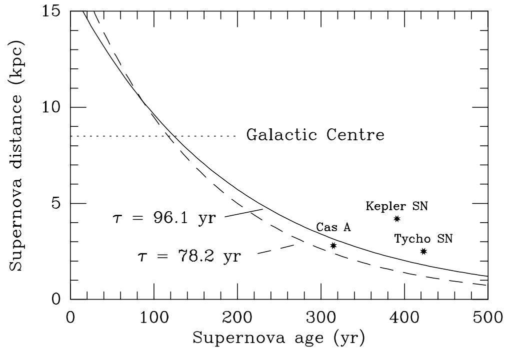


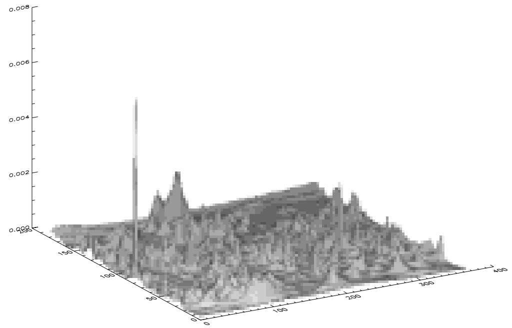


SN Search in ^{44}Ti

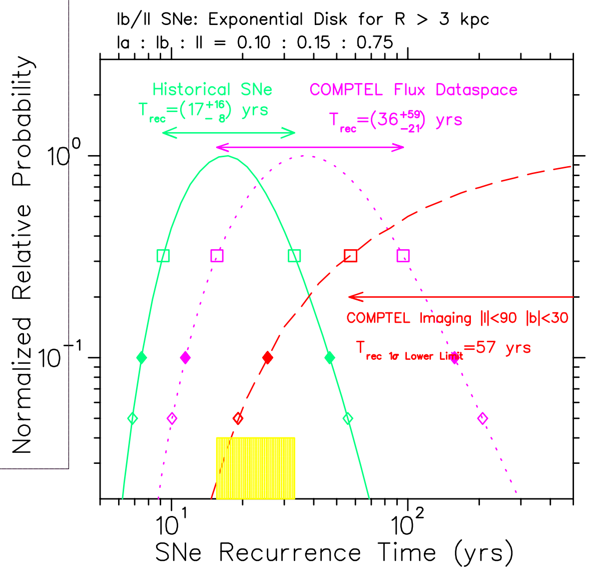
- **With SN Rate ~1/30y Expect Several ^{44}Ti Sources From Massive Stars**







- **Select Clean Region of COMPTEL ^{44}Ti Dataset (±90° l_{II}) to Derive SN-Rate Limits from MC Simulations**



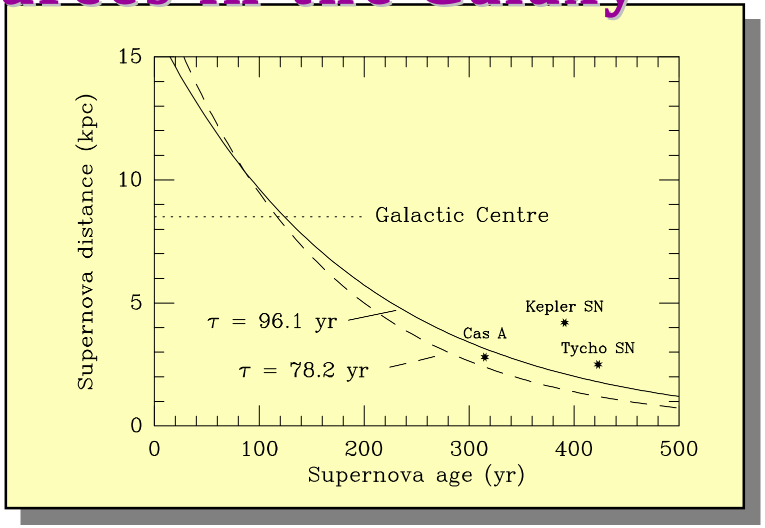
☞ **^{44}Ti Ejecting SN are Relatively Rare**

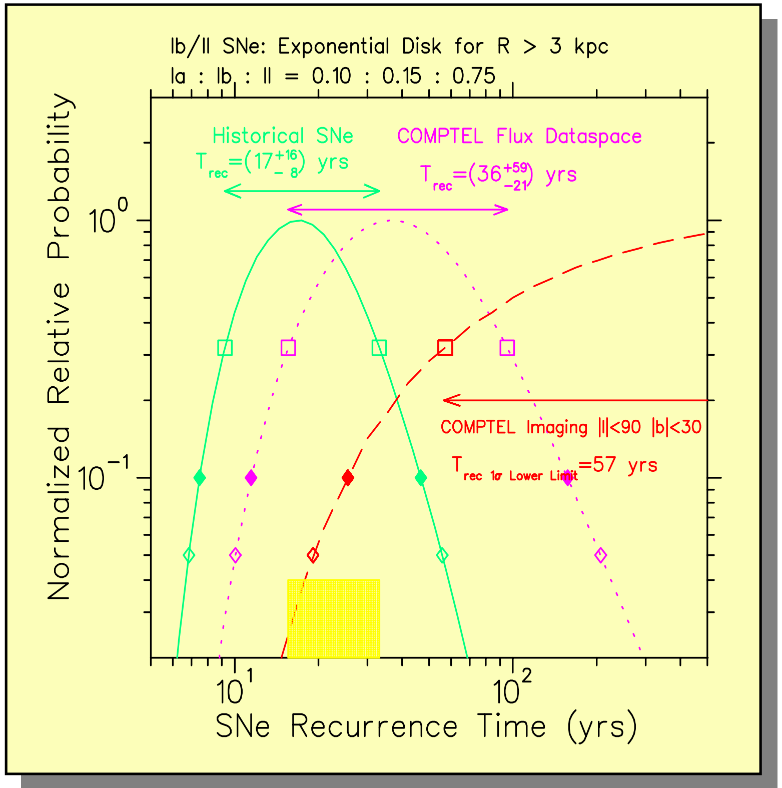
COMPTEL Search for ^{44}Ti Sources in the Galaxy

- If ^{44}Ti was Typical for Core-Collapse Supernovae:
  → Expect 3-4 Sources

- COMPTEL Imaging Searches for ^{44}Ti Line Sources
  → Cas A (Consolidated)
  Vela Region (Candidate)
  → < 3 Candidate Sources

- Monte Carlo Simulations with ^{44}Ti Model Yields per SN Type, Galactic Extinction Model, Optical Historic Record, COMPTEL Data Constraints
  → Opt. SN Frequency ~ 17 y
  ^{44}Ti SN Frequency > 17 y
  → ^{44}Ti Ejection is Not Typical





C. Dupraz et al. 1997; A. Iyudin et al. 1999; The et al. 1999

^{44}Ti Gamma-Rays and Massive Stars

- COMPTEL Survey Finds ≤ few ^{44}Ti Sources
- Cas A and SN1987A Produce ≥ Expected ^{44}Ti (≥ 5 10^{-5} M_o)

- Core-Collapse Supernovae are No ^{44}Ti Sources on Average
- Exceptional Events Produce Galactic ^{44}Ca (^{44}Ti)

- Cas A: Expect Co-Produced ^{56}Ni Ejection
  (Bright Light Curve) => ??
- Asymetries Observed in Ejecta / SNR / Winds

- What Is the Impact of Progenitor Evolution?
  (Rotation, Asymmetries)