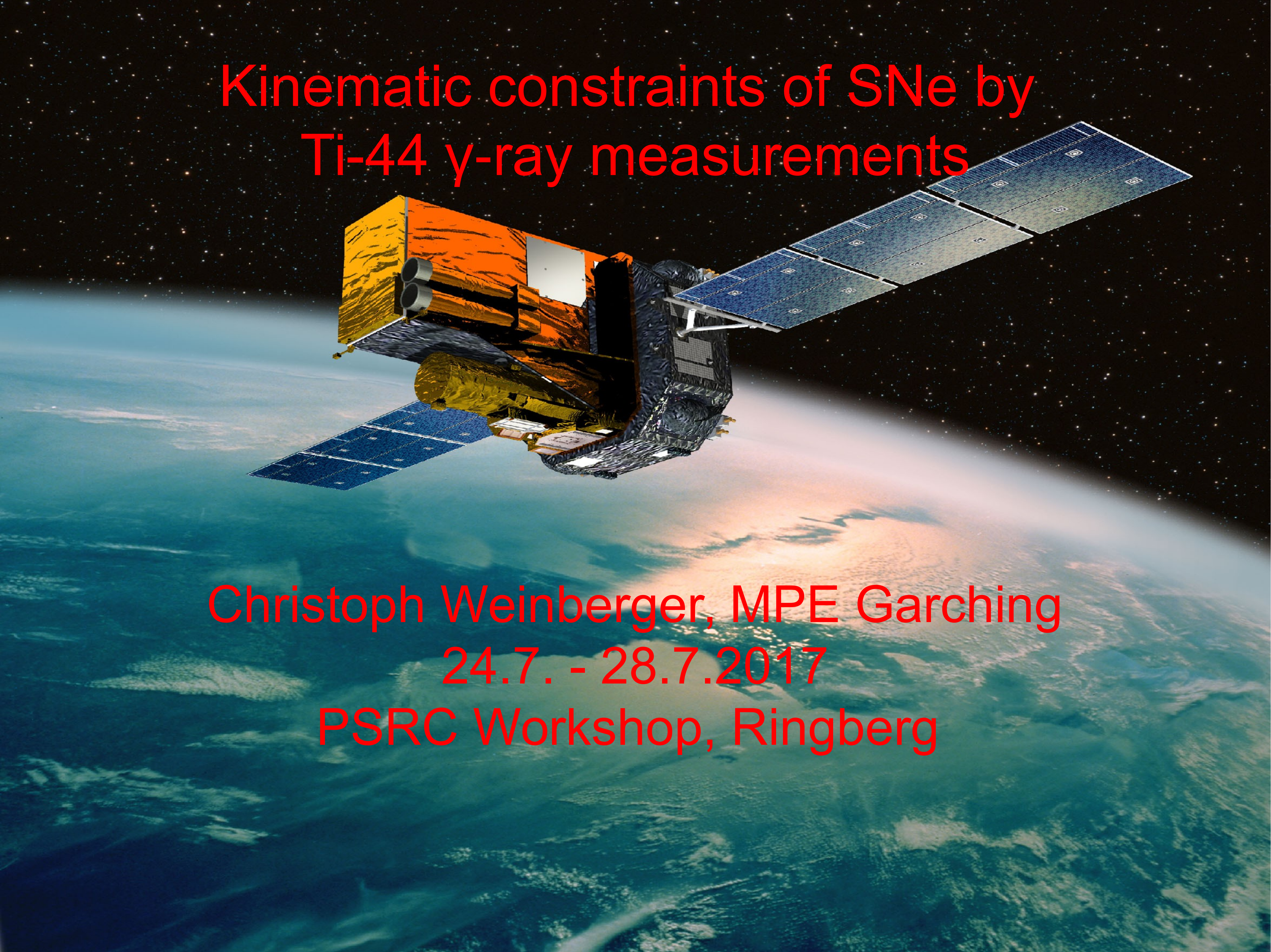


Kinematic constraints of SNe by Ti-44 γ-ray measurements

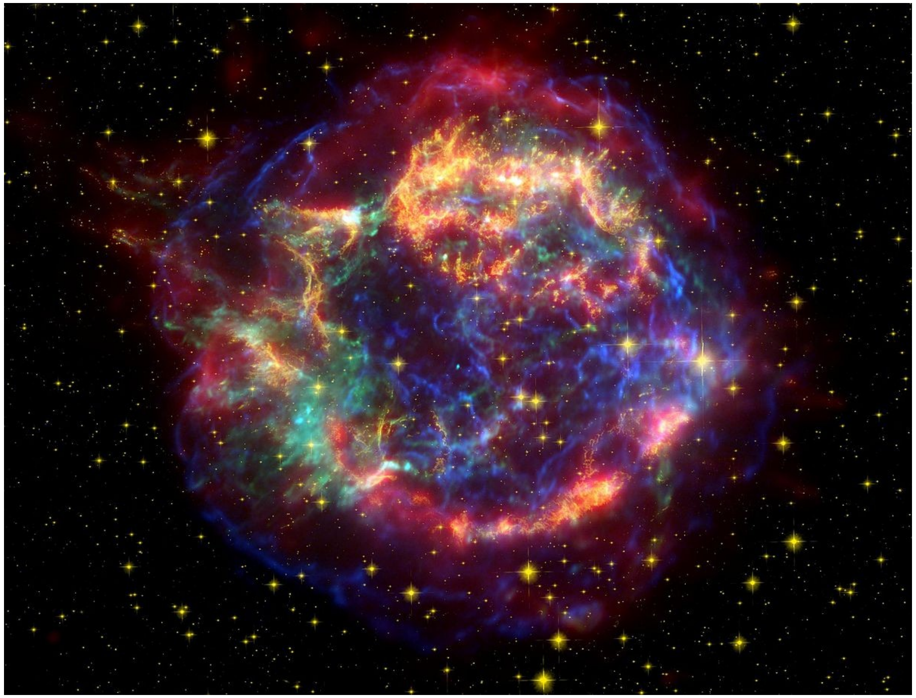
Christoph Weinberger, MPE Garching

24.7. - 28.7.2017

PSRC Workshop, Ringberg

Cassiopeia A

- Discovered 1947 as bright radio source
- Explosion date approximately 1680
- CC-SNIIb
- Progenitor 20-25M_{sun} star
- 3.4kpc distance to Earth



False color image:

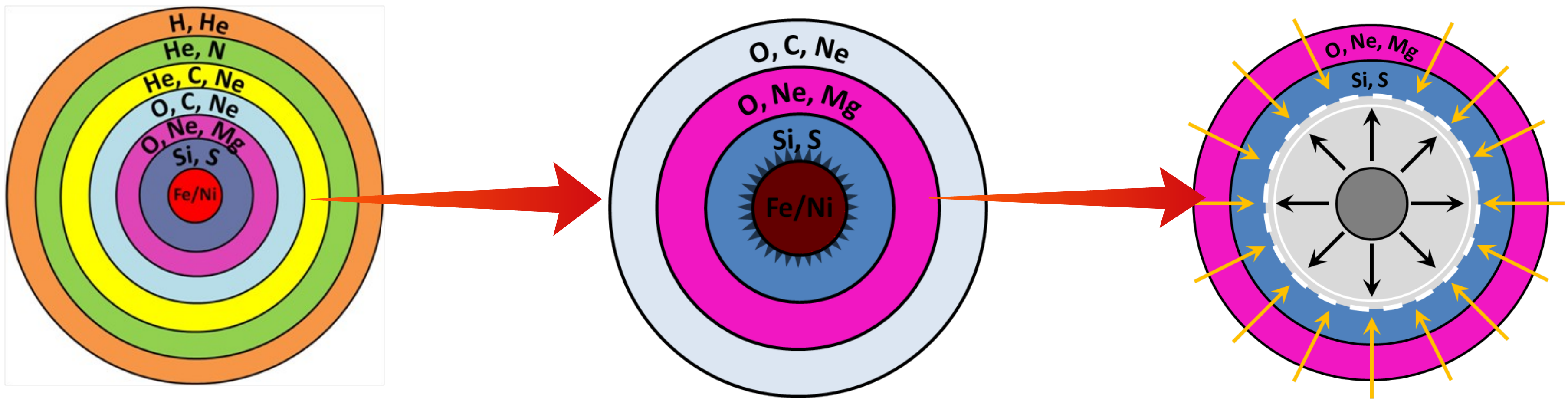
Orange: HST optical

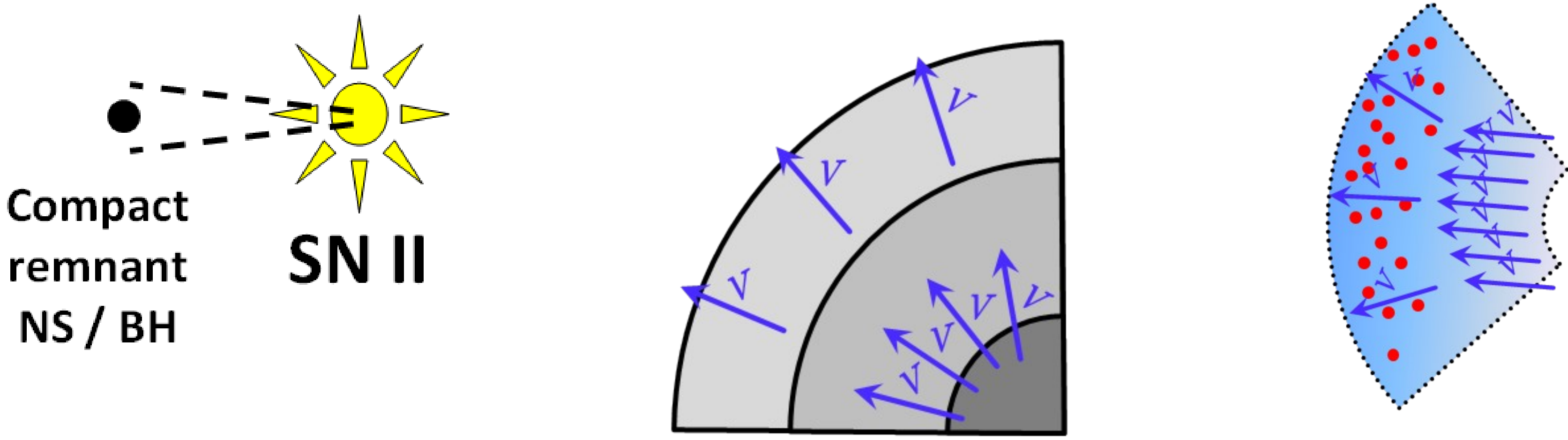
Red: Spitzer IR

Blue/Green: Chandra X-Ray

Core Collapse SNe

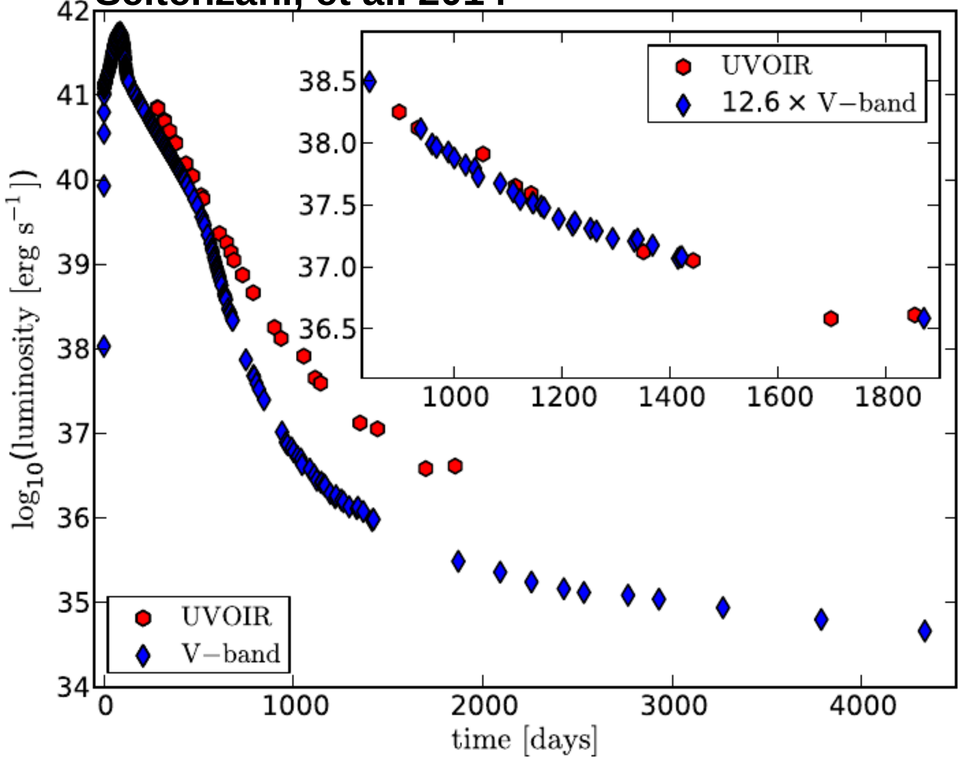
Supernovae Type II





Early Lightcurve (CC-SN)

Seitenzahl, et al. 2014

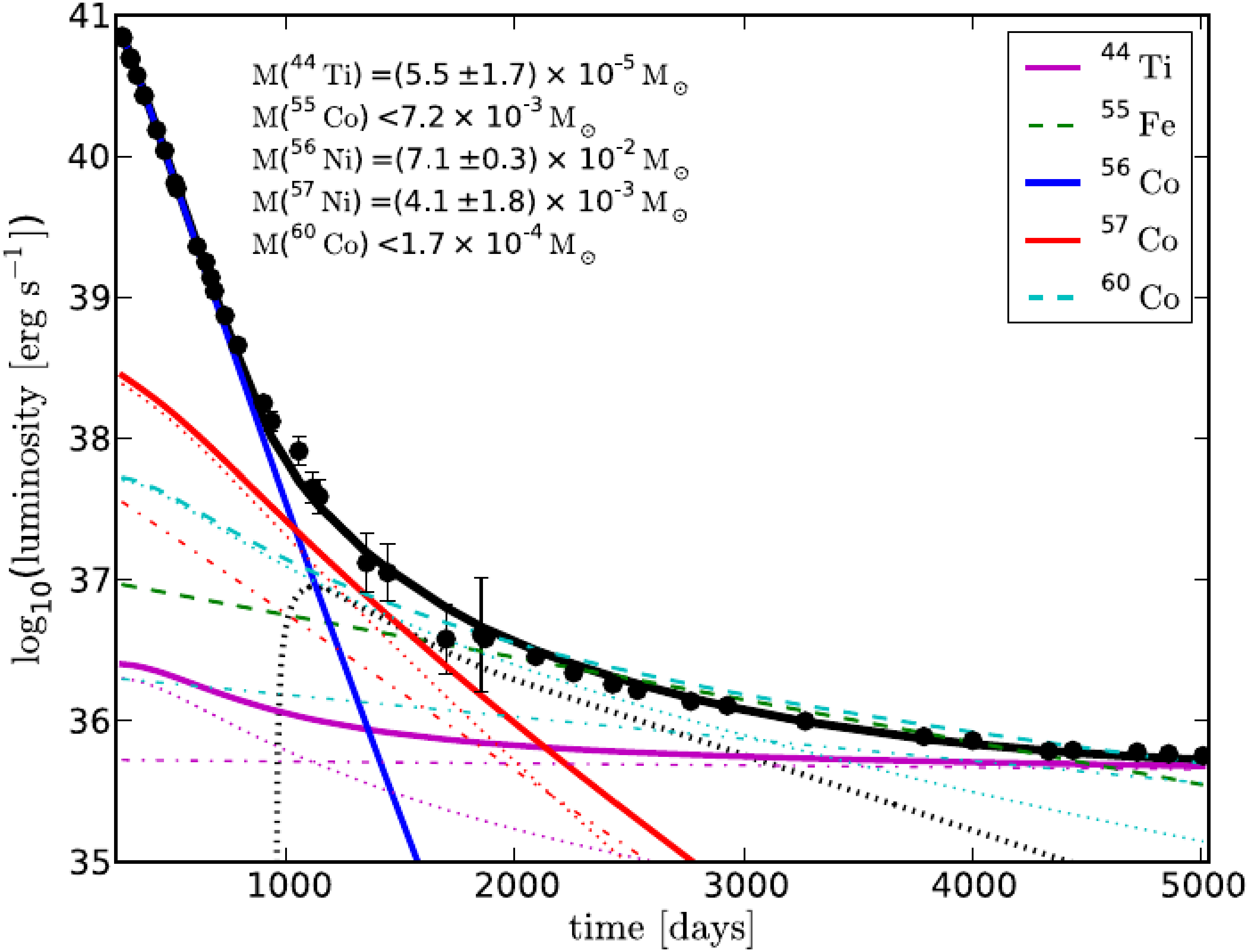


Early lightcurve:

- dominated by Ni-56 and Co-56 decay
- ~ $0.1M_{sun}$ Ni-56
- γ-rays from decay trapped in remnant → converted into heat
- Adiabatic expansion leads to reduction of optical depth → escape of γ-rays

Late lightcurve

Seitenzahl, et al. 2014



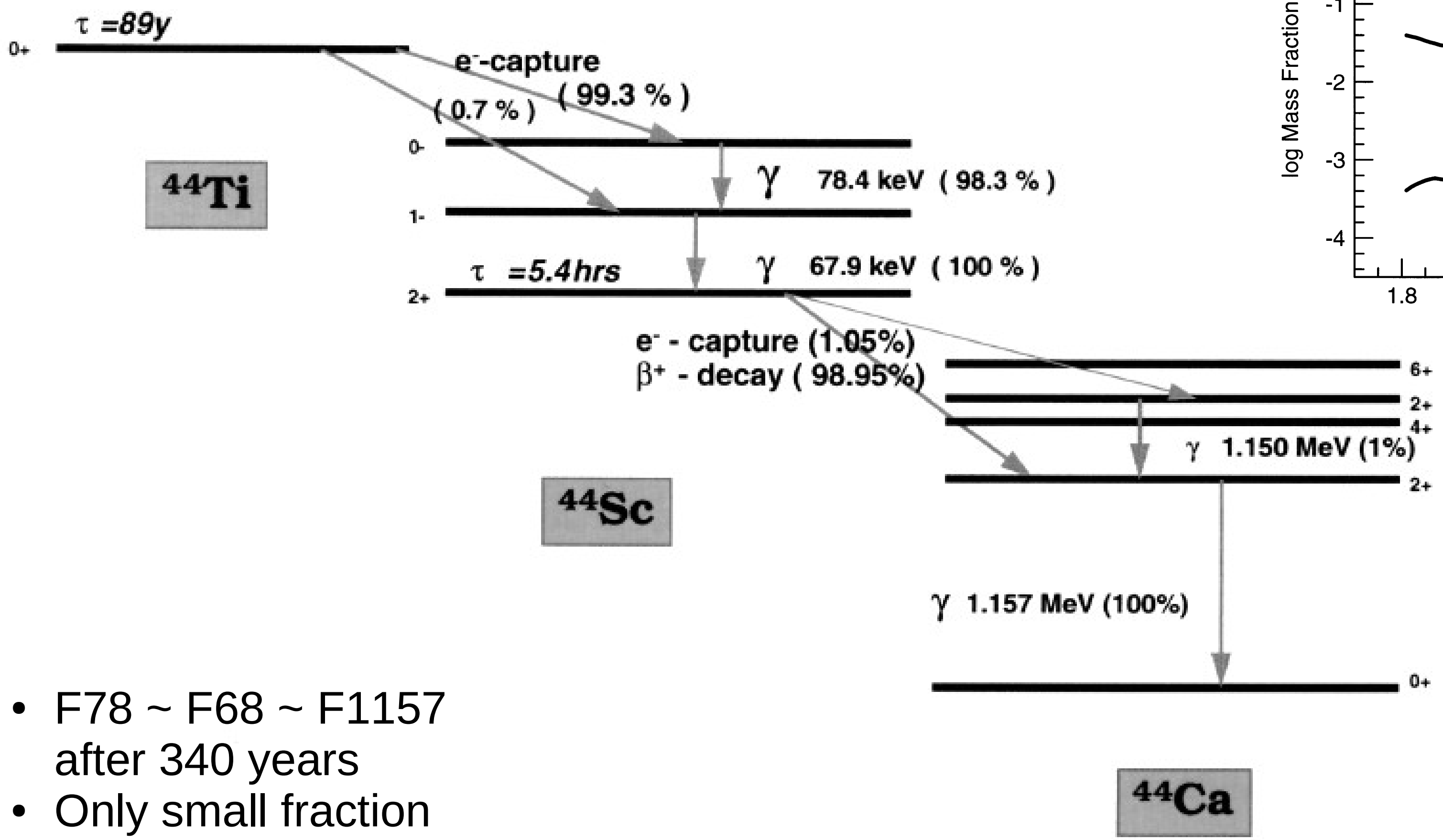
Bolometric luminosity dominated by

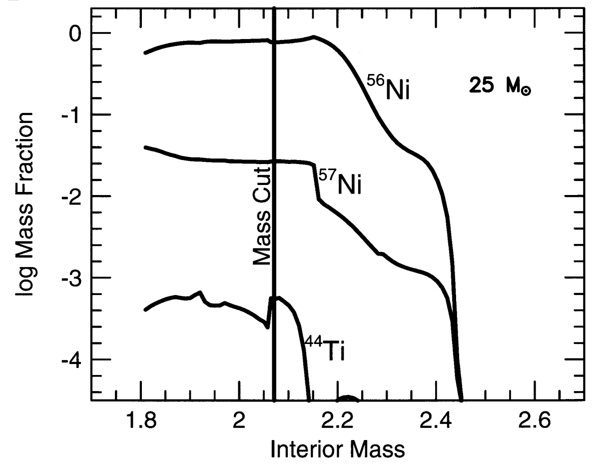
- Co-56 (t ~ 0-3a)
- Co-57 (t ~ 3-5a)
- Co-60 (t ~ 5-8a)
- Ti-44 (t > 8a)

Half life times:

Ni-56:	6d
Co-56:	77d
Co-60:	5.3y
Ti-44:	60y

Ti-44 Decay Chain

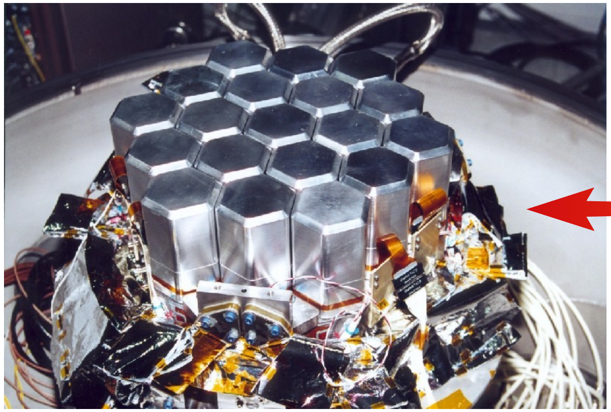




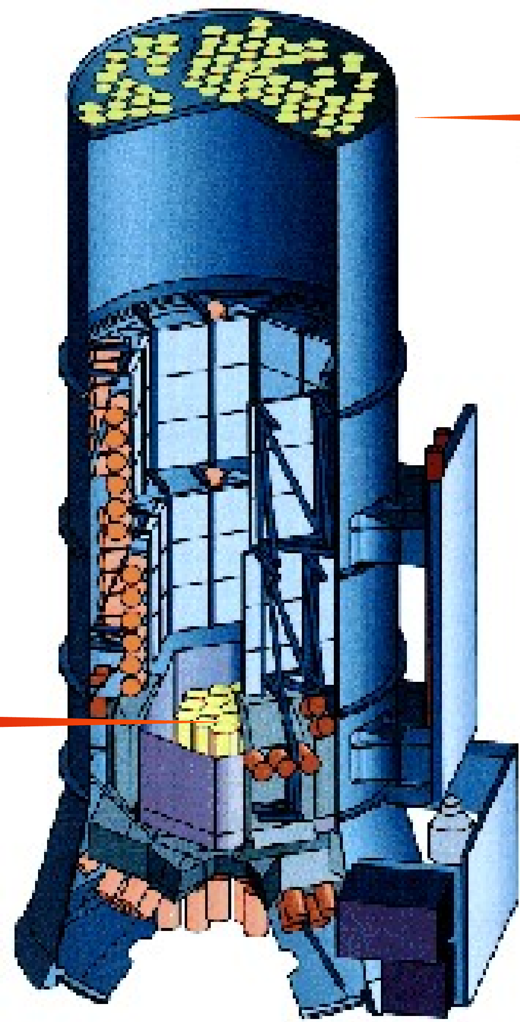
- F78 ~ F68 ~ F1157 after 340 years
- Only small fraction contributes to heating

γ-Ray Measurements with the Spectrometer on Integral

- 19 High purity Ge Detectors make up the SPI camera
- Energy range: 20-8000keV
- High energy resolution of 2.2keV FWHM at 662keV
- Integrated veto system
- Field of view: 16x16Deg



HPGE detector array



Coded Mask Telescope

Tungsten Mask

- γ-rays can not be focused → coded mask telescope:
- Source creates shadow-gram in detector array
- Spatial resolution: 2.6 Deg

Distinguish between background and Sky?

$$D = RxS + B$$

Problem: Data is background dominated →

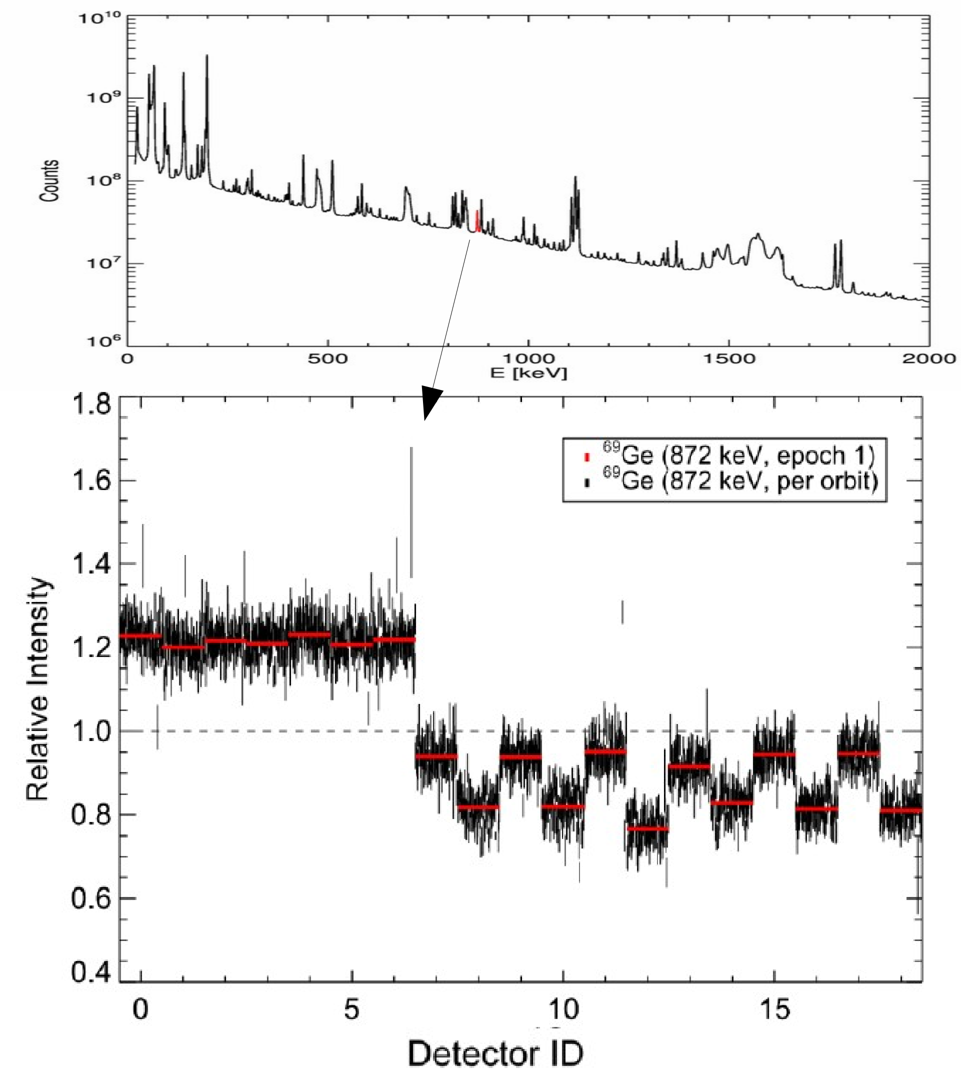
$$S = R^{-1}(D\text{-}B) = R^{-1}(0)$$

Simultanious determination of background and sky signal necessary

$$D = \alpha(RxS) + \beta B$$

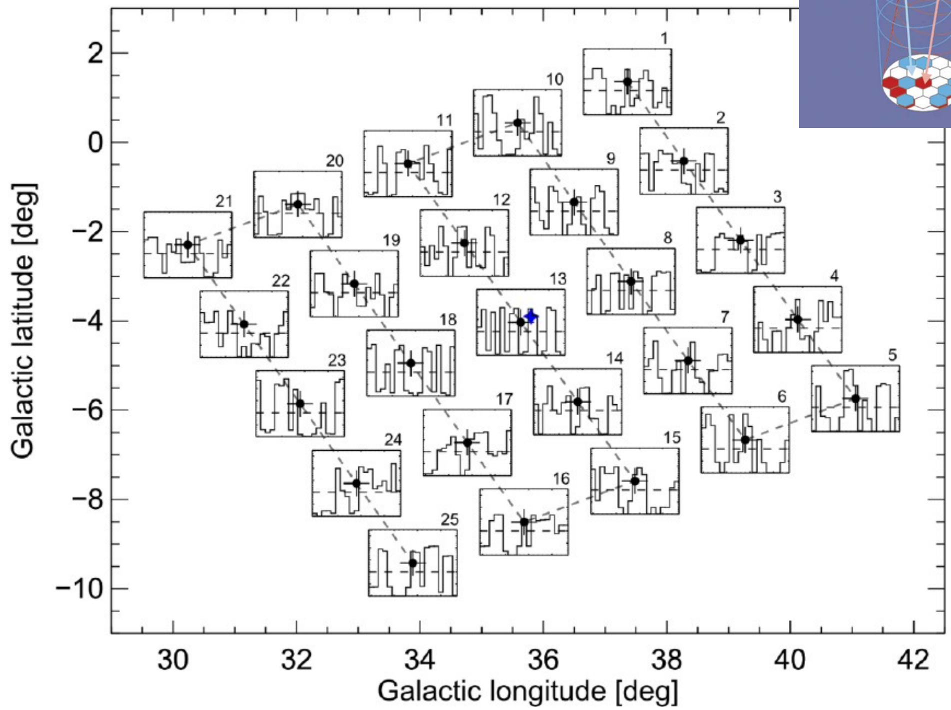
Elaborate background model that self consistently describes the physical processes in the satellite needed.

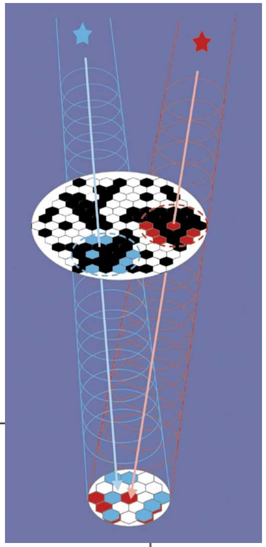
Detector Pattern



Background pattern remain constant in time

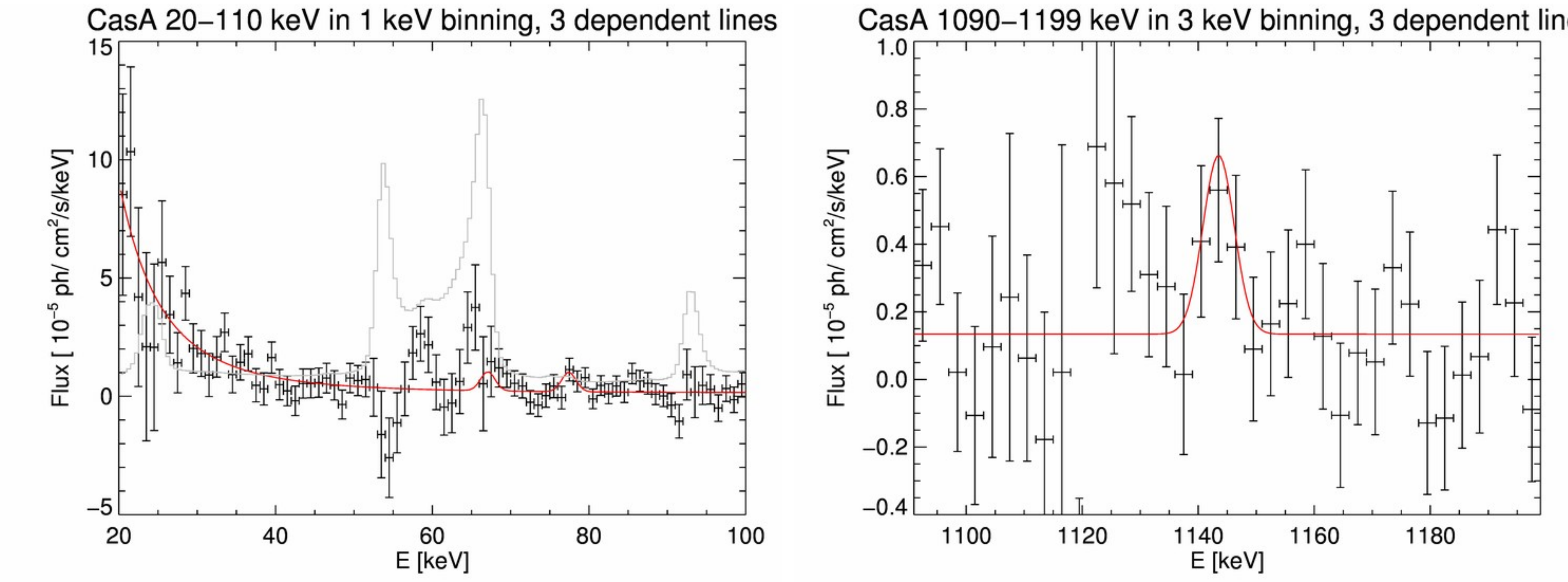
Sky pattern dependent on source location!





Distinguish between BG and Sky by disentangling the Sky and BG pattern simultaneously!

Ti-44 Line measurements



- Simultaneous fit of 3 lines (68,78,1157 keV centroid energy) and continuum emission
- Background mostly suppressed for lines (work in progress)
- Centroids blue shifted with $3494 \pm 1217\, km/s$

Ti44 mass and expansion velocity

- Total integrated flux:

$$F=\int A e^{-\frac{(x-E_0)^2}{2\sigma^2}}=\sqrt{2\pi}A\sigma$$

→ activity of source:

$$A(t)=\frac{4\pi d^2 F}{b}$$

$$A(t)=\frac{-\partial N}{\partial t}=N(t)\lambda$$

$$N(t)=N_0 e^{(-\lambda t)}=\frac{m_0}{44\,mu}e^{(-\lambda t)}$$

Mass determination:

$$m_0=\frac{A(t)\,44\,mu}{e^{-\lambda t}\lambda}=\frac{4\pi d^2 F\,44\,mu}{b\,e^{-\lambda t}\lambda}$$

ejected Ti44 mass:

$$m_0=1.20\pm0.91\cdot10^{-4}M_{sun}(78\,keV)$$

$$m_0=2.32\pm1.06\cdot10^{-4}M_{sun}(1157\,keV)$$

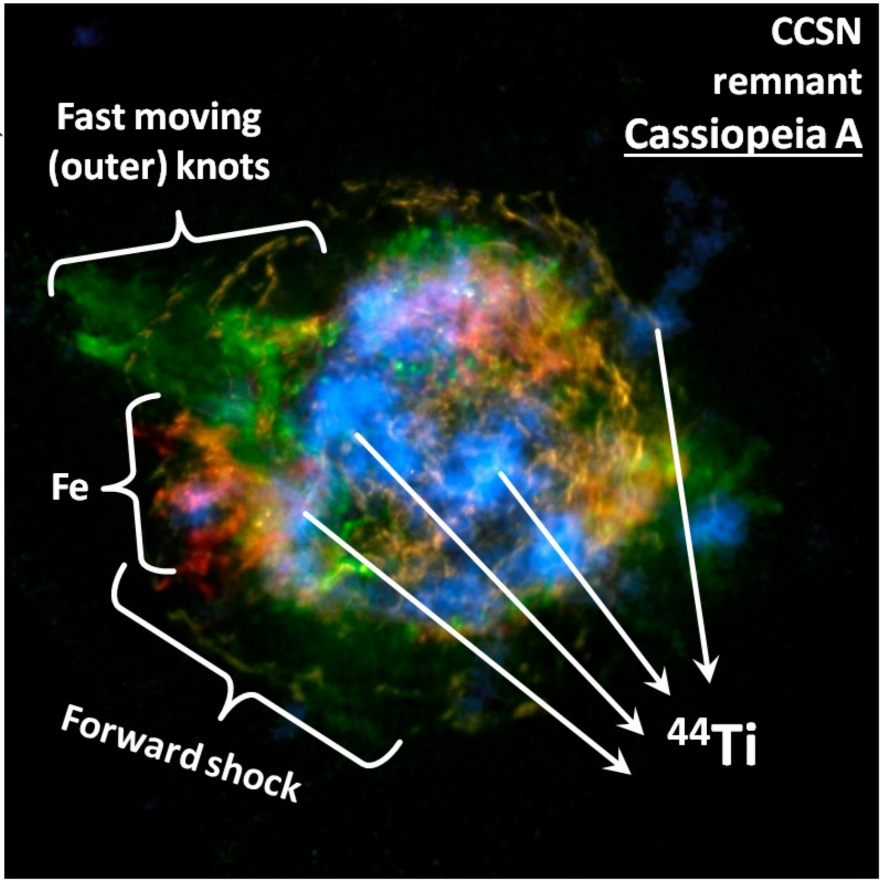
Expansion velocity ~ the measured width of the γ-line (Doppler broadening)

$$\Delta v=5039\pm3526\,km/s(78\,keV)$$

$$\Delta v=1484\pm331\,km/s(1157\,keV)$$

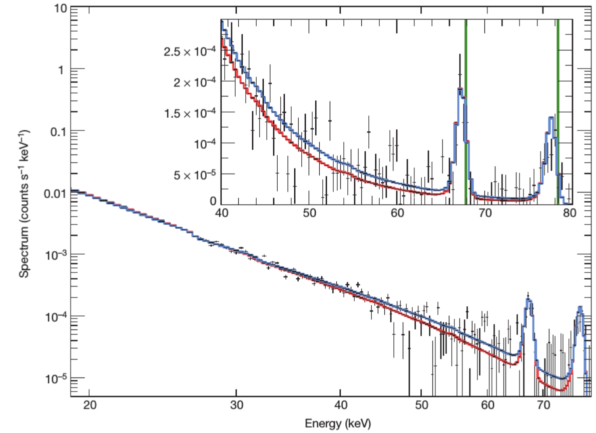
Resolved Ti-44 in Cas A

Grefenstette, et al. 2014

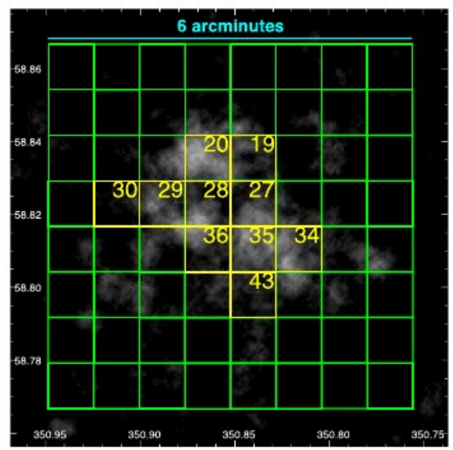


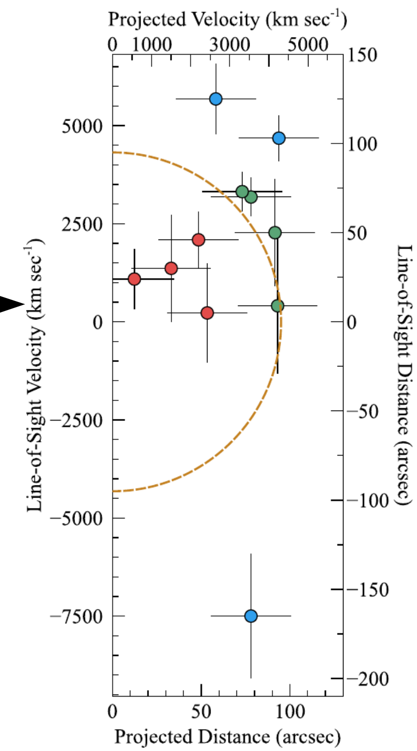
Doppler velocity:
-7500 km/s - +5200 km/s
→ possible assymetric explosion

Estimated Ti-44 mass:
$m_0 = 1.54 \pm 0.21 \cdot 10^{-4} M_{sun}$



Ti-44 interior to Fe shell
→ ejecta reversal





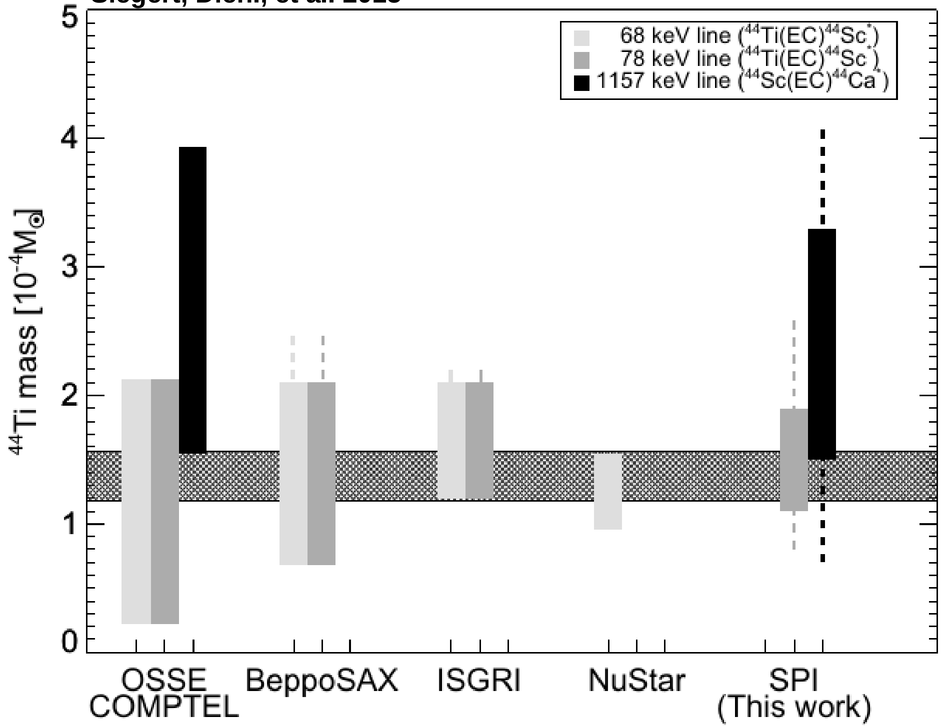
Grefenstette, et al. 2017

Red/Green:
X-rays by Chandra from heated Fe and Si/Mg

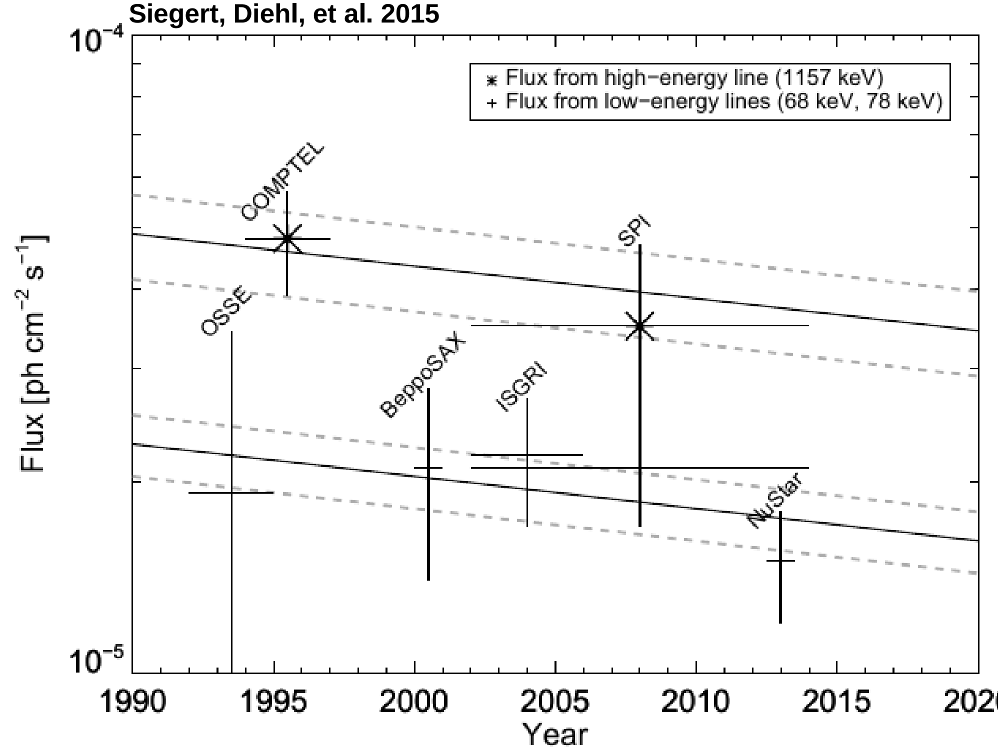
Blue:
Hard x-ray emisson from Ti-44 by NuStar

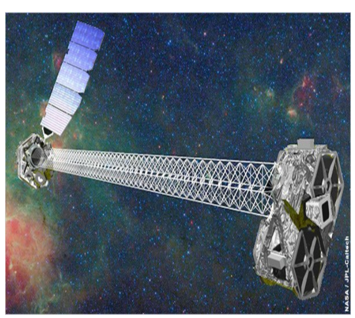
Mean ejecta mass

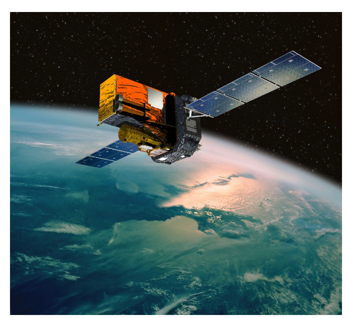
Siegert, Diehl, et al. 2015



Siegert, Diehl, et al. 2015





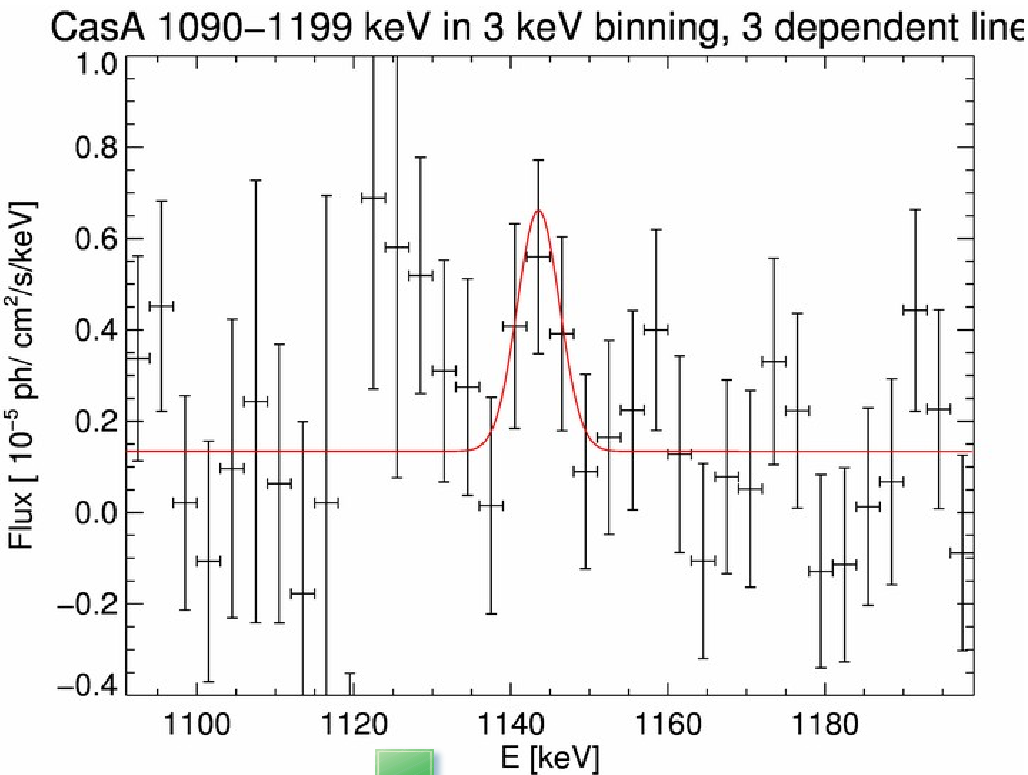


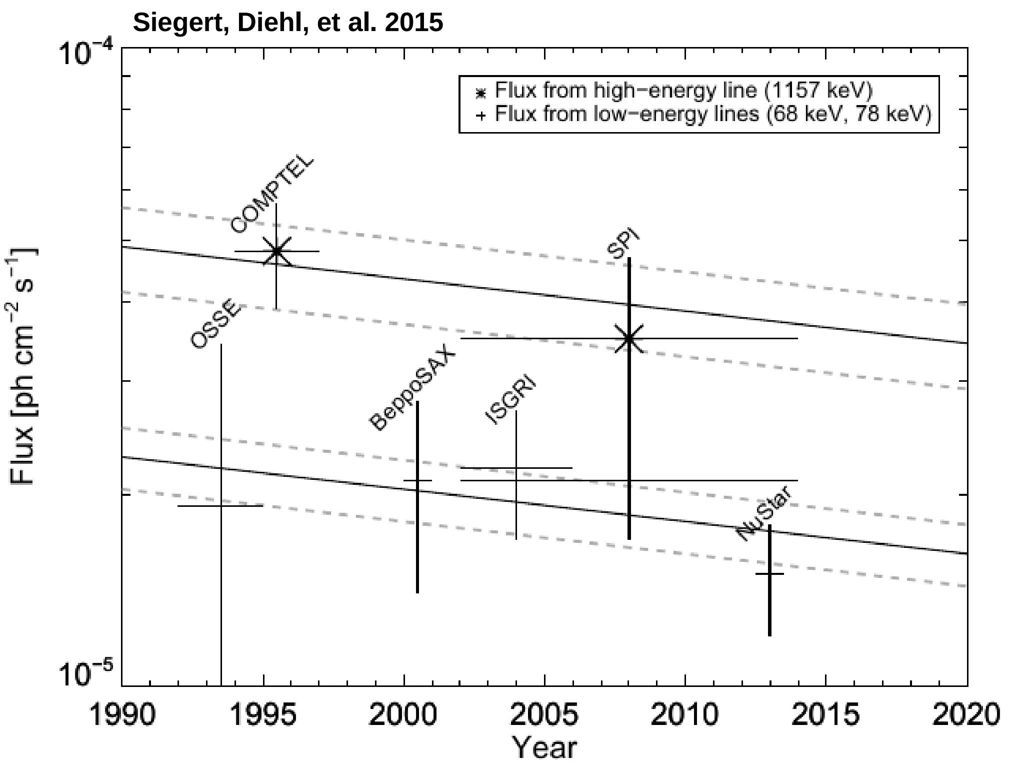
Weighted mean ejecta mass:

$$m_{Ti\,44} = 1.37 \pm 0.19 \cdot 10^{-4}\, M_{sun}$$

Synthesized ejecta yield can be directly measured with γ-rays!

A second contributor?





$$F = 3.57 \cdot 10^{-5}\, ph\, cm^{-2} s^{-1}$$
$$m_0 = 2.32 \pm 1.06 \cdot 10^{-4}\, M_{sun} (1157\, keV)$$

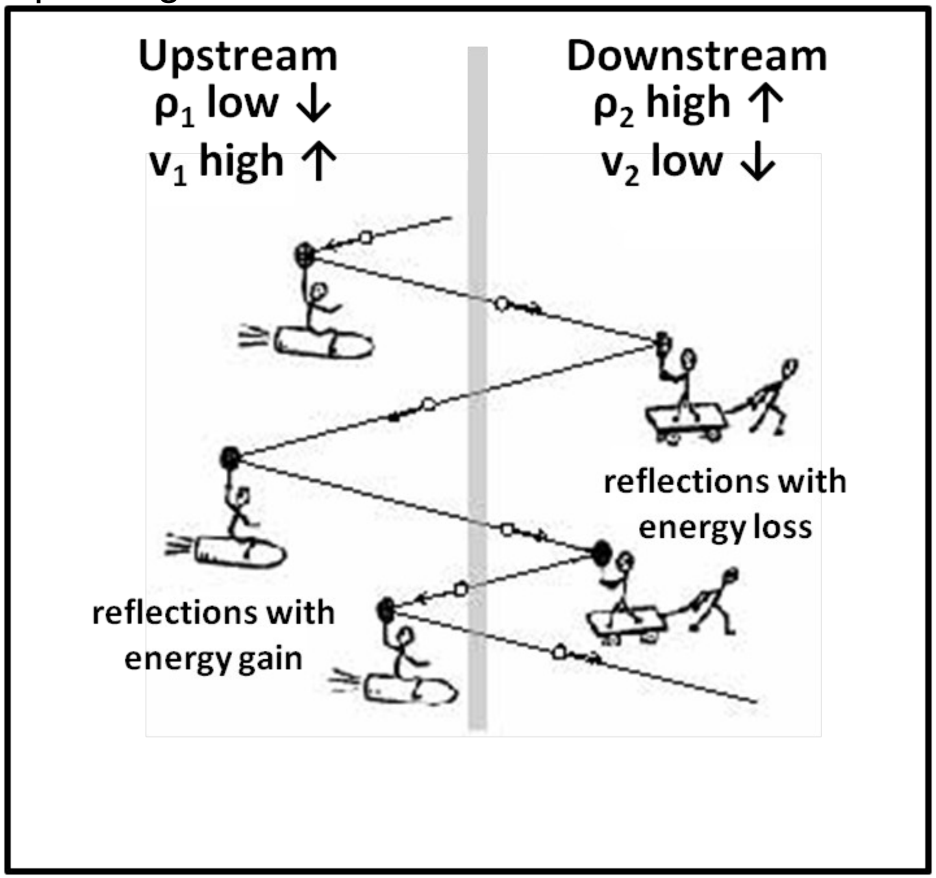
Flux of 1157 keV line systematically higher than 78keV line
Discrepancy of ~ $2.5 \cdot 10^{-5}\, ph\, cm^{-2} s^{-1}$
→ higher 'measured' ejecta mass for Ti-44 in the deexcitation line of *Ca-44 than *Sc-44
Second process needed to account for the increased flux in the high energy line

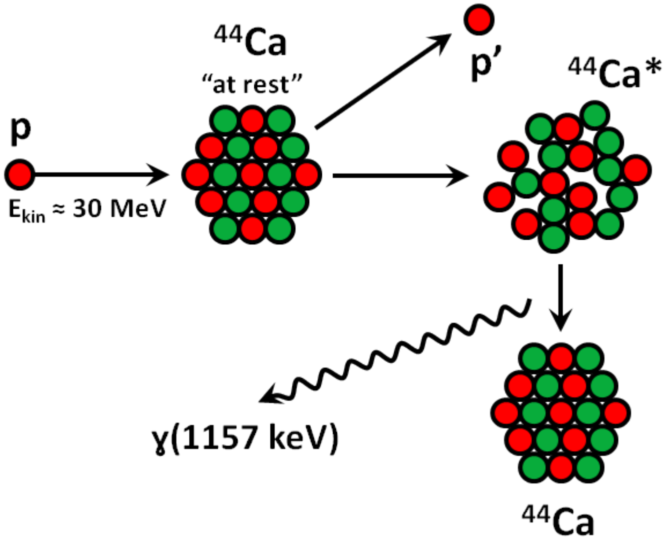
Second Contribution: Cosmic Ray Acceleration

Diffusive shock acceleration:

SN remnants are expected to be sites of particle acceleration

Particles go through repeated acceleration by passing the shock front

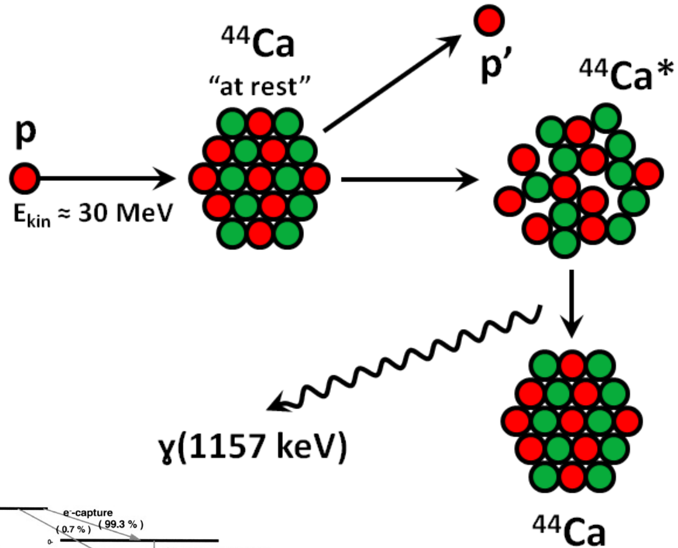


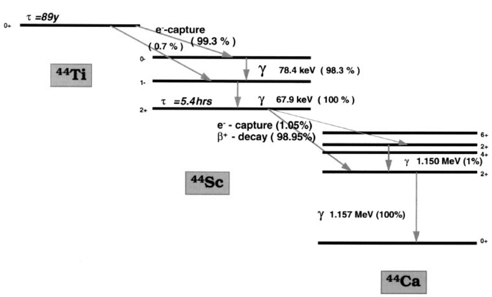


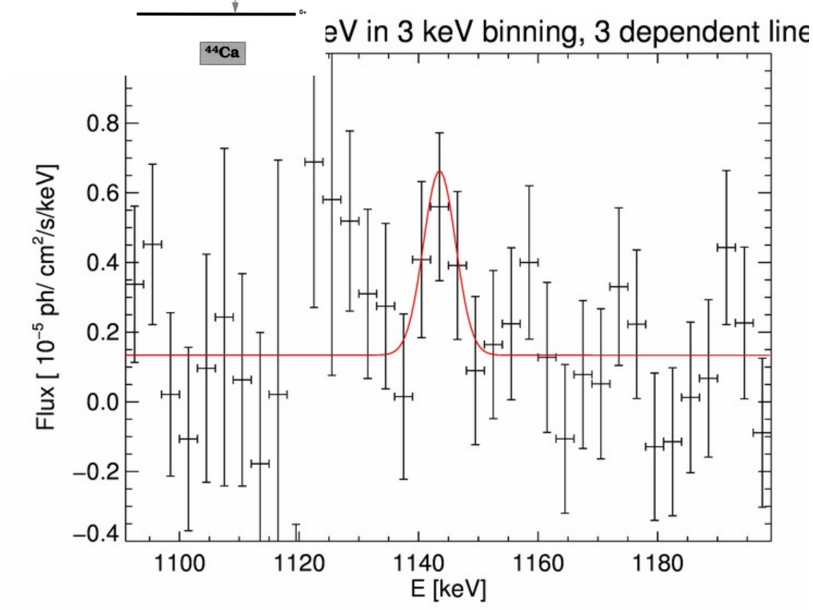
Accelerated particles scatter on target nucleus
Transition of nucleus into excited state
→ excited nucleus emits γ-ray with characteristic deexcitation energy

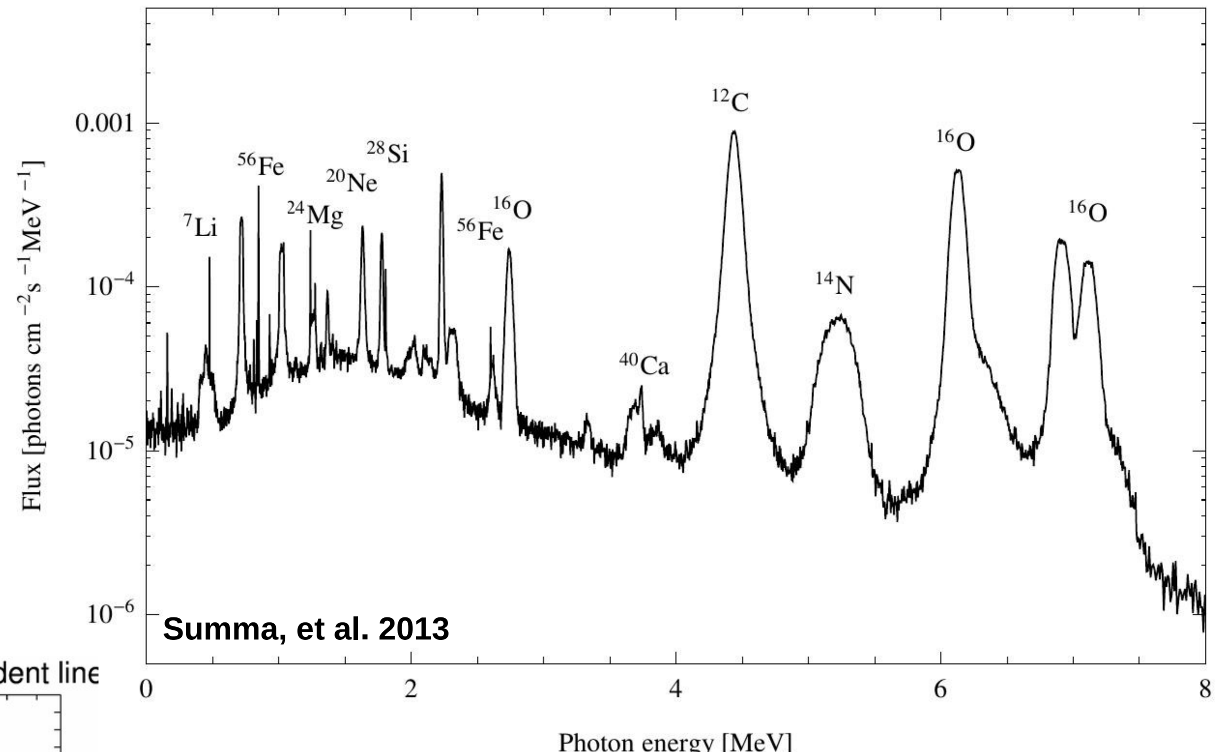
γ-ray deexcitation lines give opportunity to probe young SN remnants as particle accelerator laboratories

Cosmic ray induced deexcitation lines









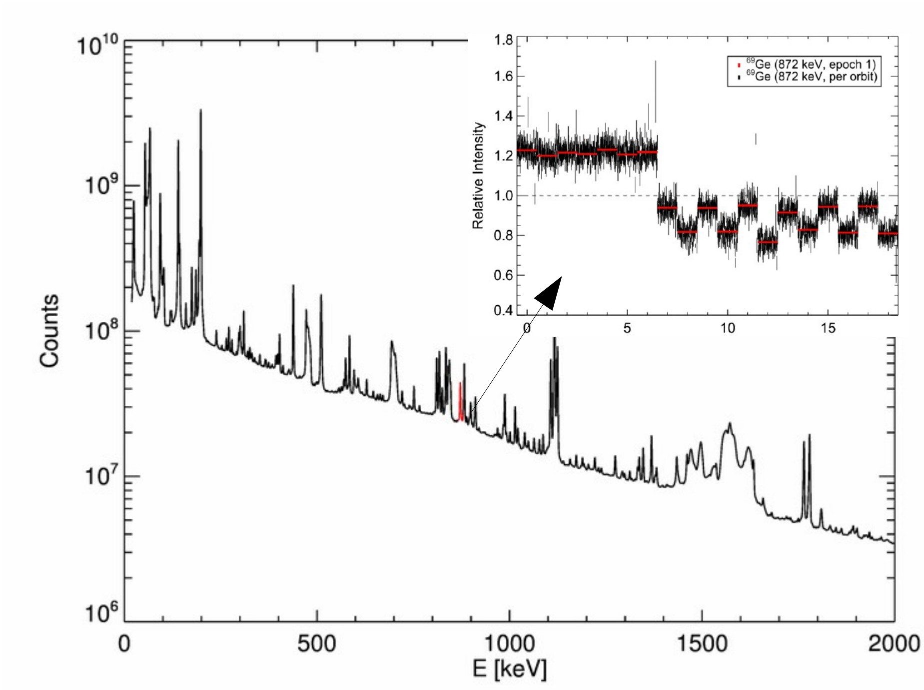
Deexcitation lines for most stable isotopes in ejecta

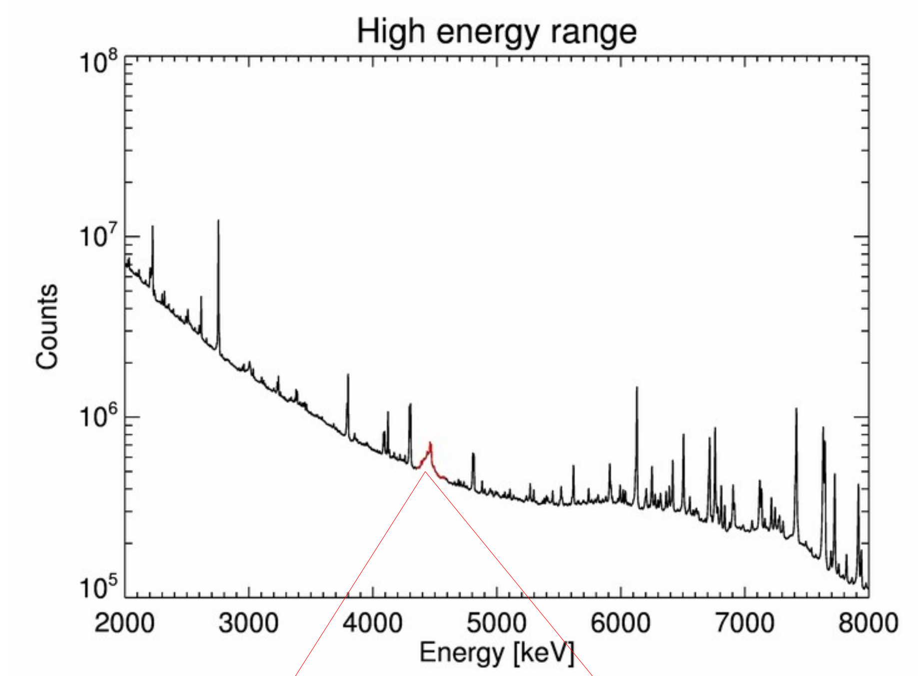
Strongest lines:

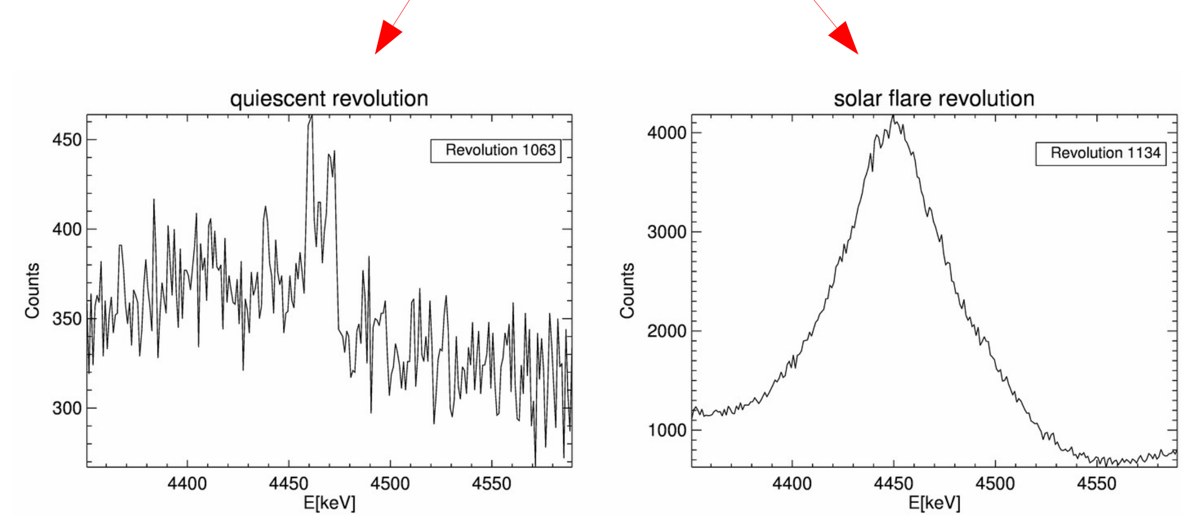
- C-12 at 4434keV
- O-16 at 6128keV

Problem: No background model so far

High Energy Range Background Modeling







Low energy range (E < 2000keV):

- Lineshape/detector pattern constant in time

High energy range (E > 2000keV):

- Significant influence of lineshapes due to solar flare
- Detector pattern not constant

High energy background model opens possibilities to study not only CR excitation!

Summary/Conclusion

- Observation of Ti-44 in Cas A in two x-Ray and γ-Ray lines:

  → verifies previous sudies

- Precise mass determination:

$$m_{Ti\,44} = 1.37 \pm 0.19 \cdot 10^{-4}\, M_{sun}$$

- Lines are Doppler broadened:

  → SNR expanstion velocity between 1150 and 8500 km/s

- Flux discrepancy between 78/1157keV line:

  → additional contribution to flux due to nuclear excitation by LECR