SN® Afterglows in γ-Ray Lines

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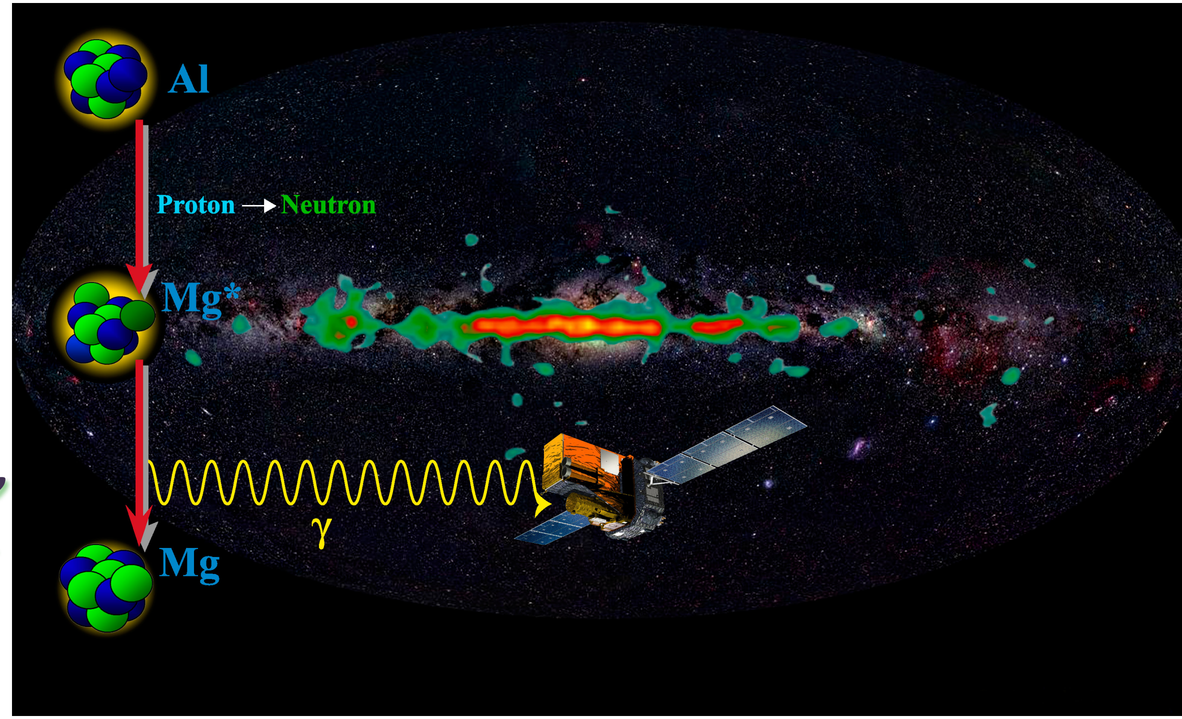
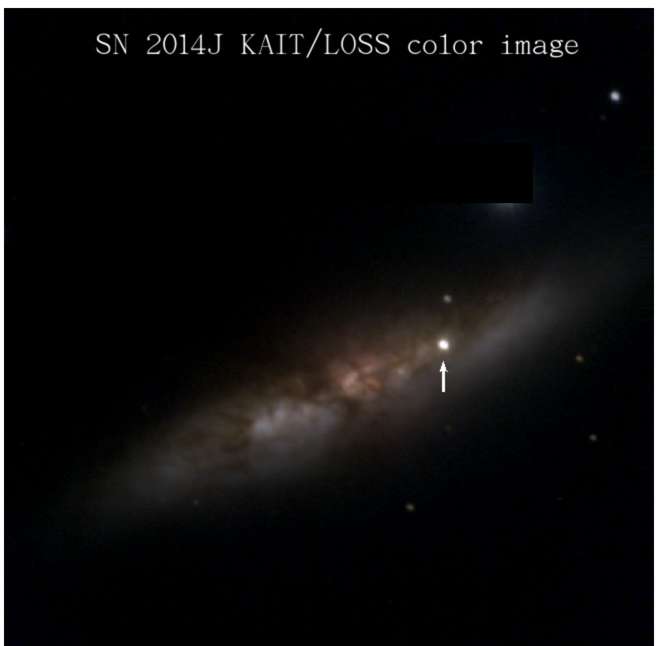
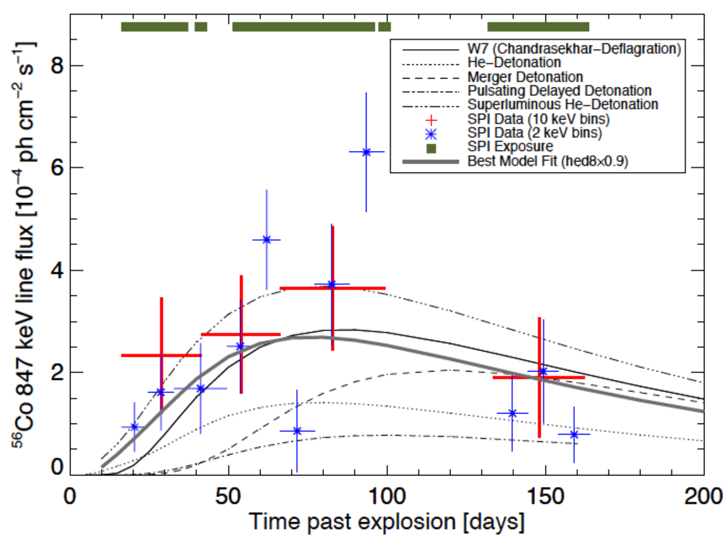
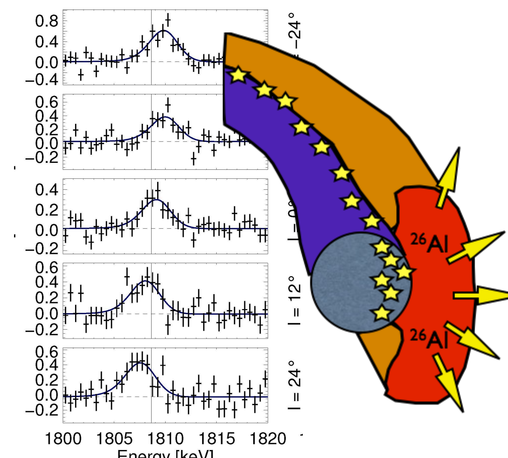
with
Thomas Siegert, Christoph Weinberger, Moritz Pleintinger, Daniel Kröll, Jochen Greiner, Xiaoling Zhang (MPE),
Martin Krause, Karsten Kretschmer, Keiichi Maeda, and many others at other institutions



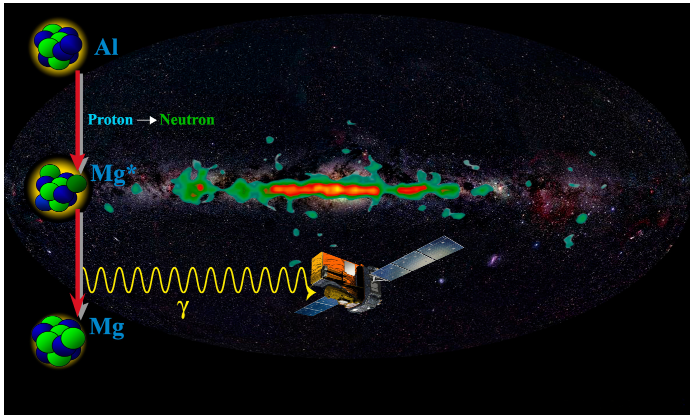
→ *Massive Stars / Groups, and Supernova Explosions*





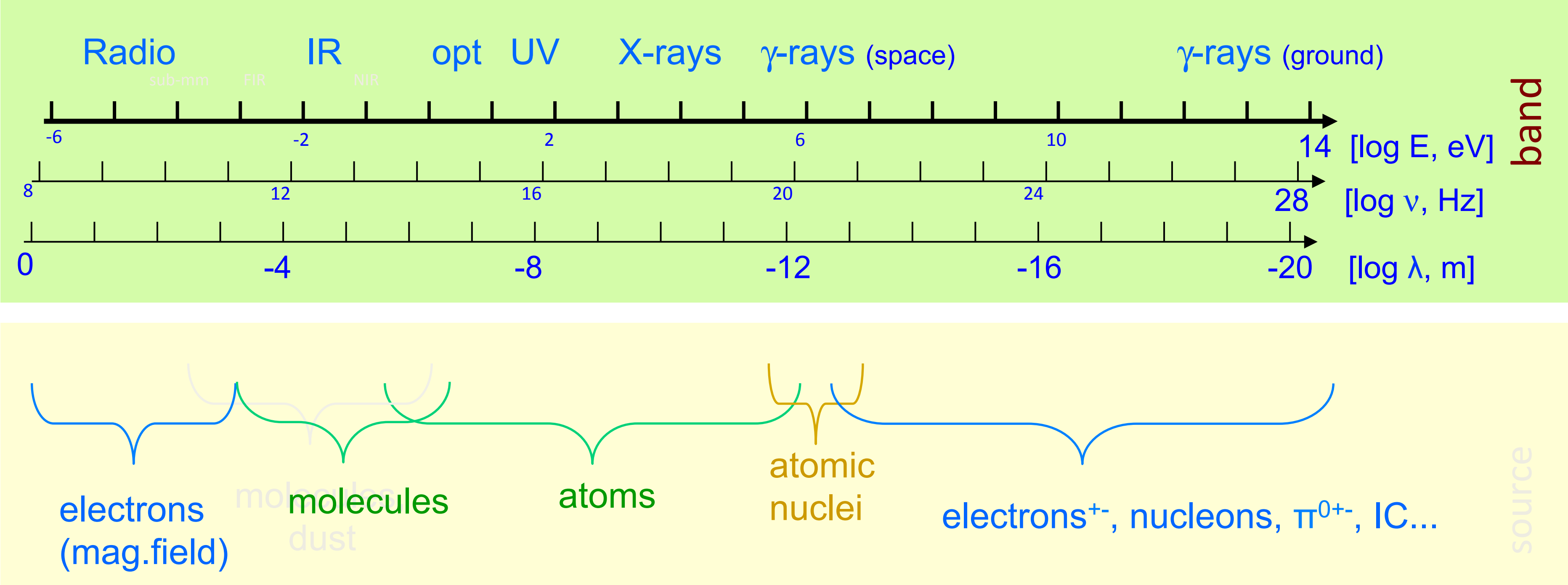


Nuclei: one of the astronomical messengers



Nuclear line transitions → atomic state ~irrelevant

Radioactive decay → a natural clock



Nuclear Gamma-Ray Lines from Supernovae

Radioactive trace isotopes are by-products of nucleosynthesis reactions

Released from the supernova explosion, we observe gamma-ray afterglows:

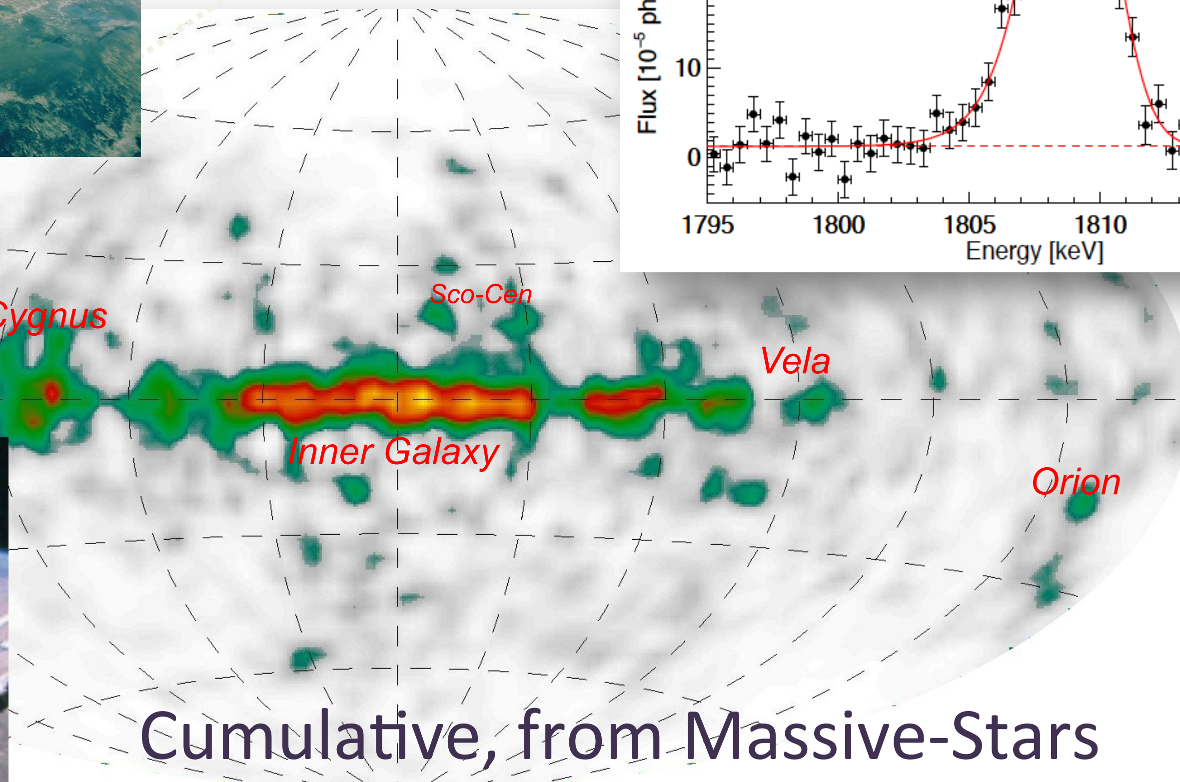
Isotope	*Mean Lifetime*	*Decay Chain*	*γ-Ray Energy (keV)*
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{44}Ti	85 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	1.04 10^6y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	3.8 10^6y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

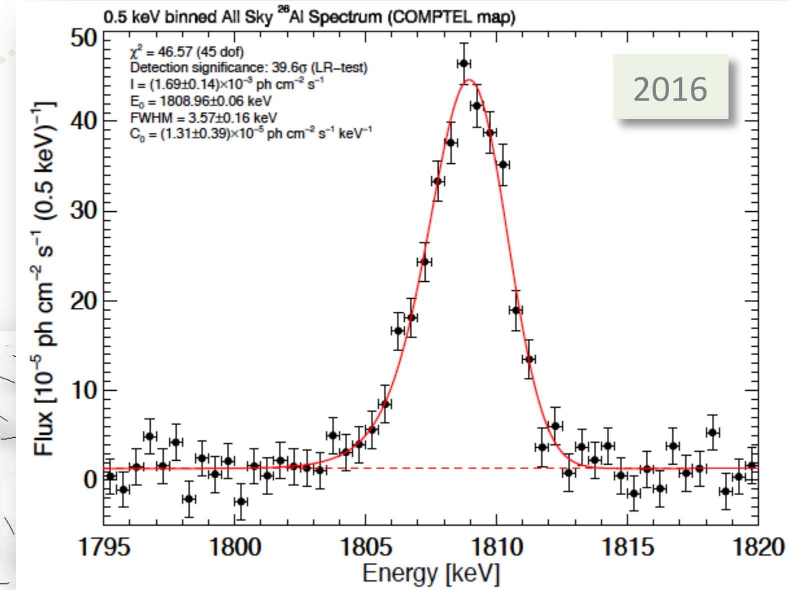
individual object/event

cumulative from many events

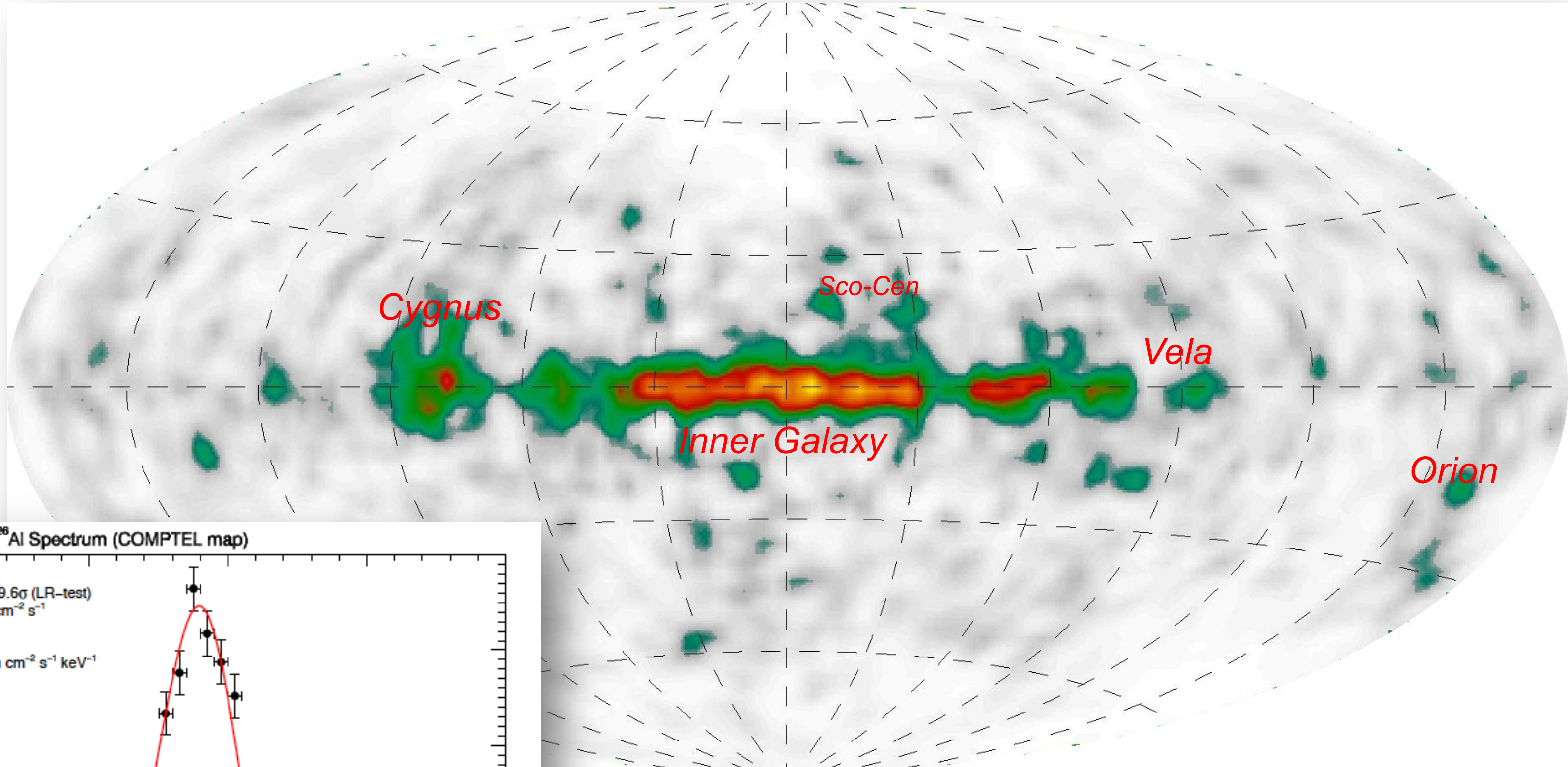
- Million years to ~one week (^{26}Al – ^{44}Ti – ^{56}Ni/^{56}Co)
- Typically 10^{-5} ph cm^{-2} s^{-1}

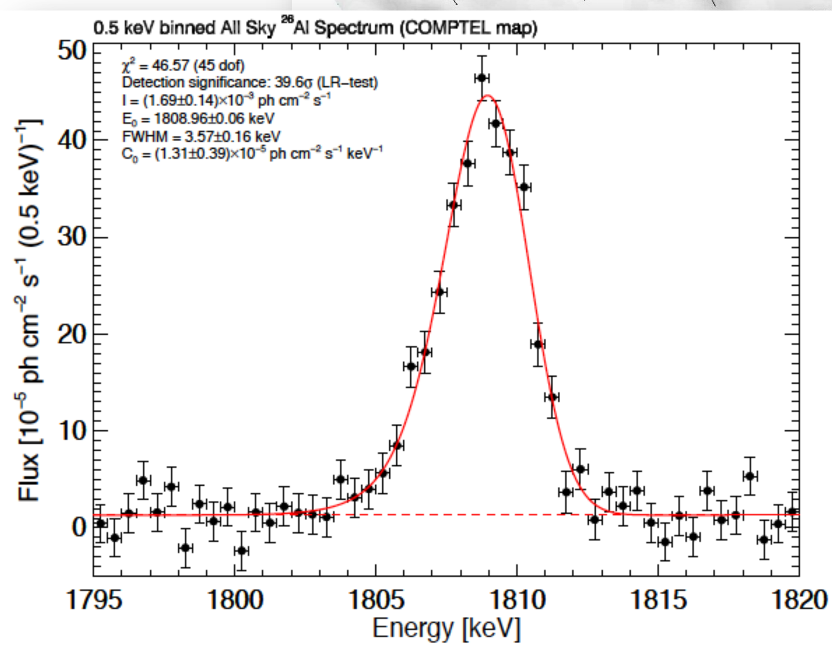
^{26}Al in our Galaxy: γ-ray Image and Spectrum





^{26}Al in our Galaxy: γ-ray Image and Spectrum





Current-Galaxy SN Ejecta (τ~My)

From ^{26}Al γ-rays in the ISM
→ ~2 $M_\odot$ of ^{26}Al in the Galaxy

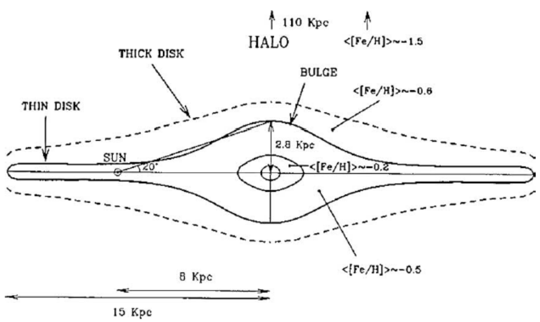
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2017)**

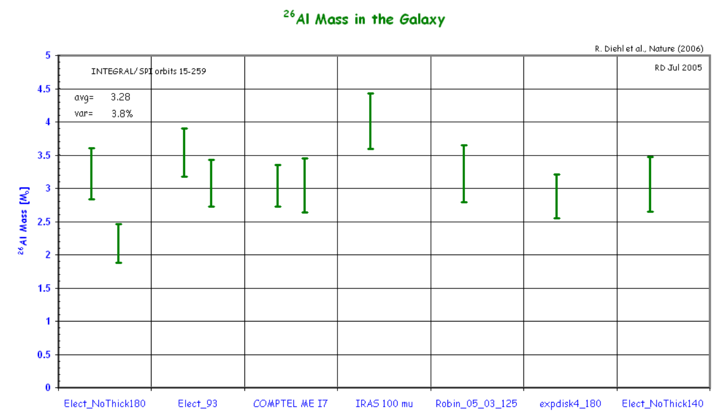
Measured Gamma-Ray Flux*

) better account for foreground emission

Galaxy Geometry

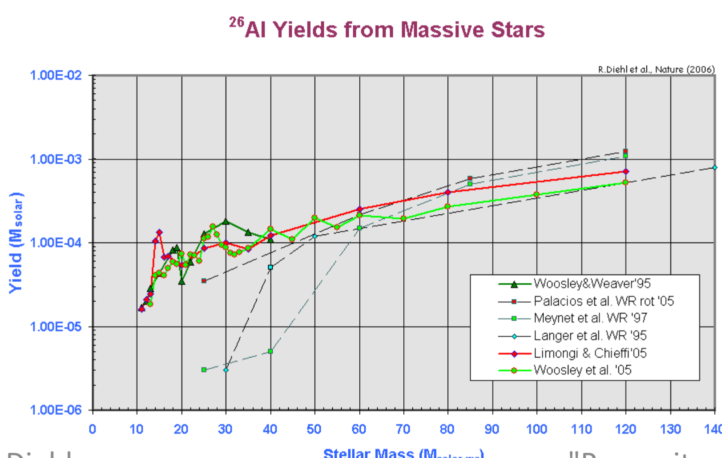


➢ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

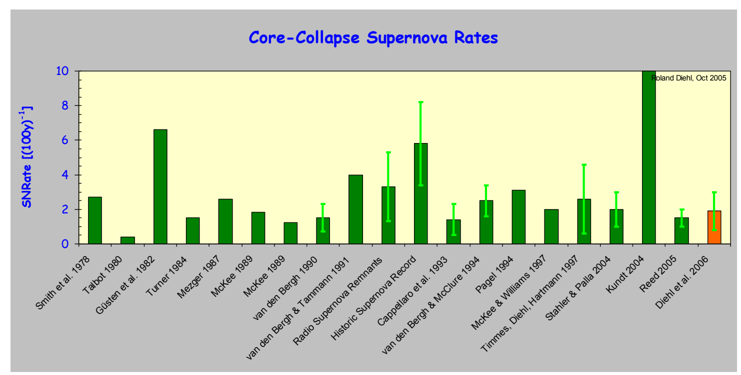


^{26}Al Yields per Star

Stellar Mass Distribution

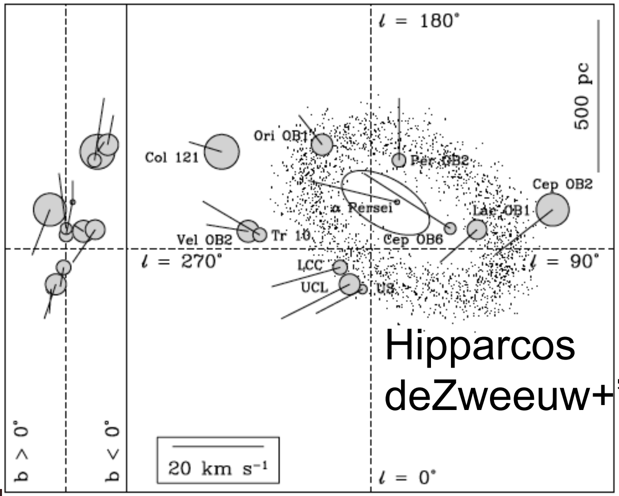


✓ cc-SN Rate = 1.3 (± 0.6) per Century

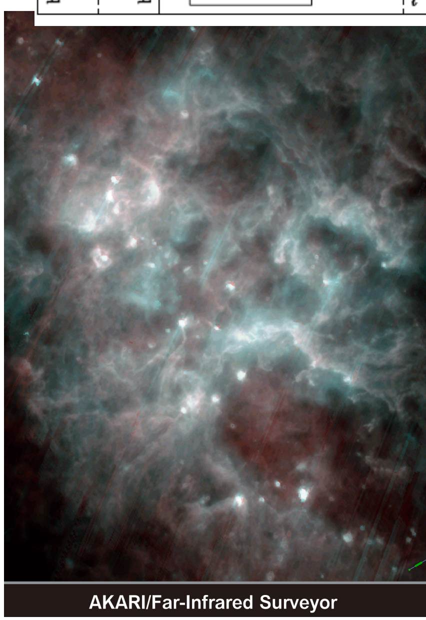


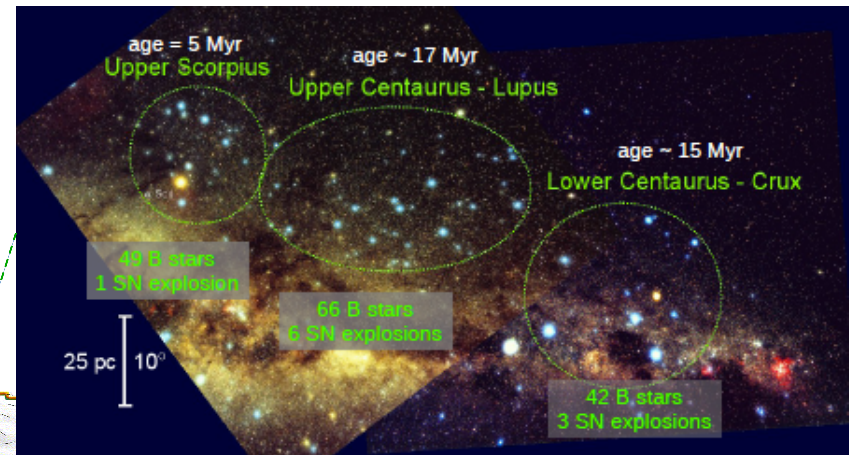
✓ Star Formation Rate = 2.8 $M_\odot$/yr

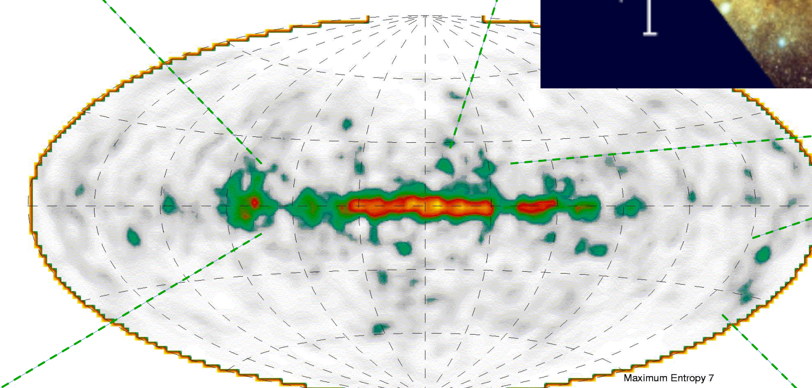
Resolving ^{26}Al Emission from Specific Groups of Stars

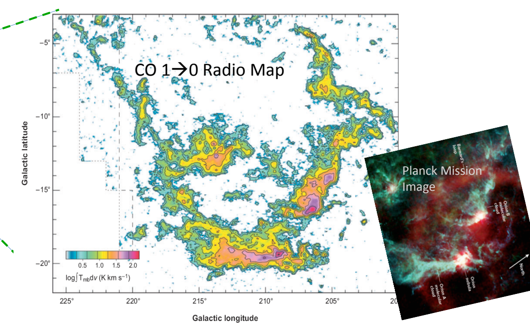


Hipparcos
deZweeuw+'99





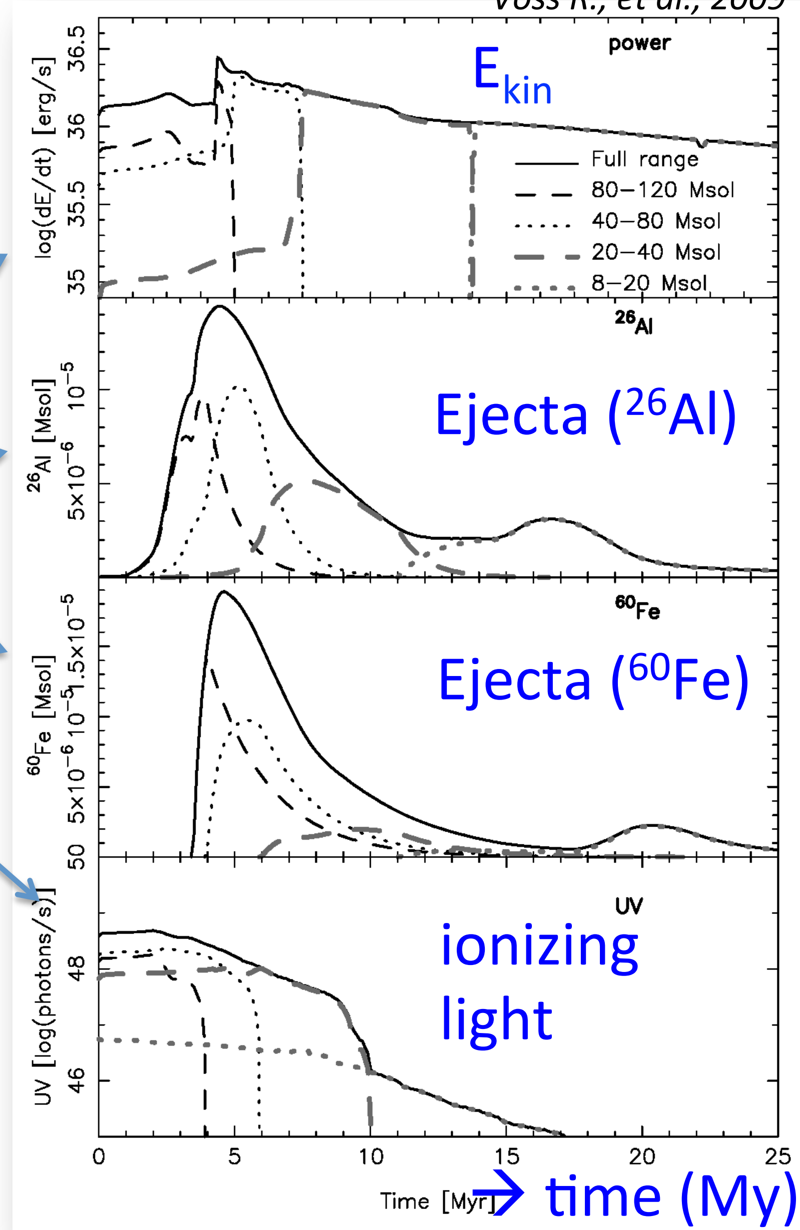




Massive-Star Groups and their SNe

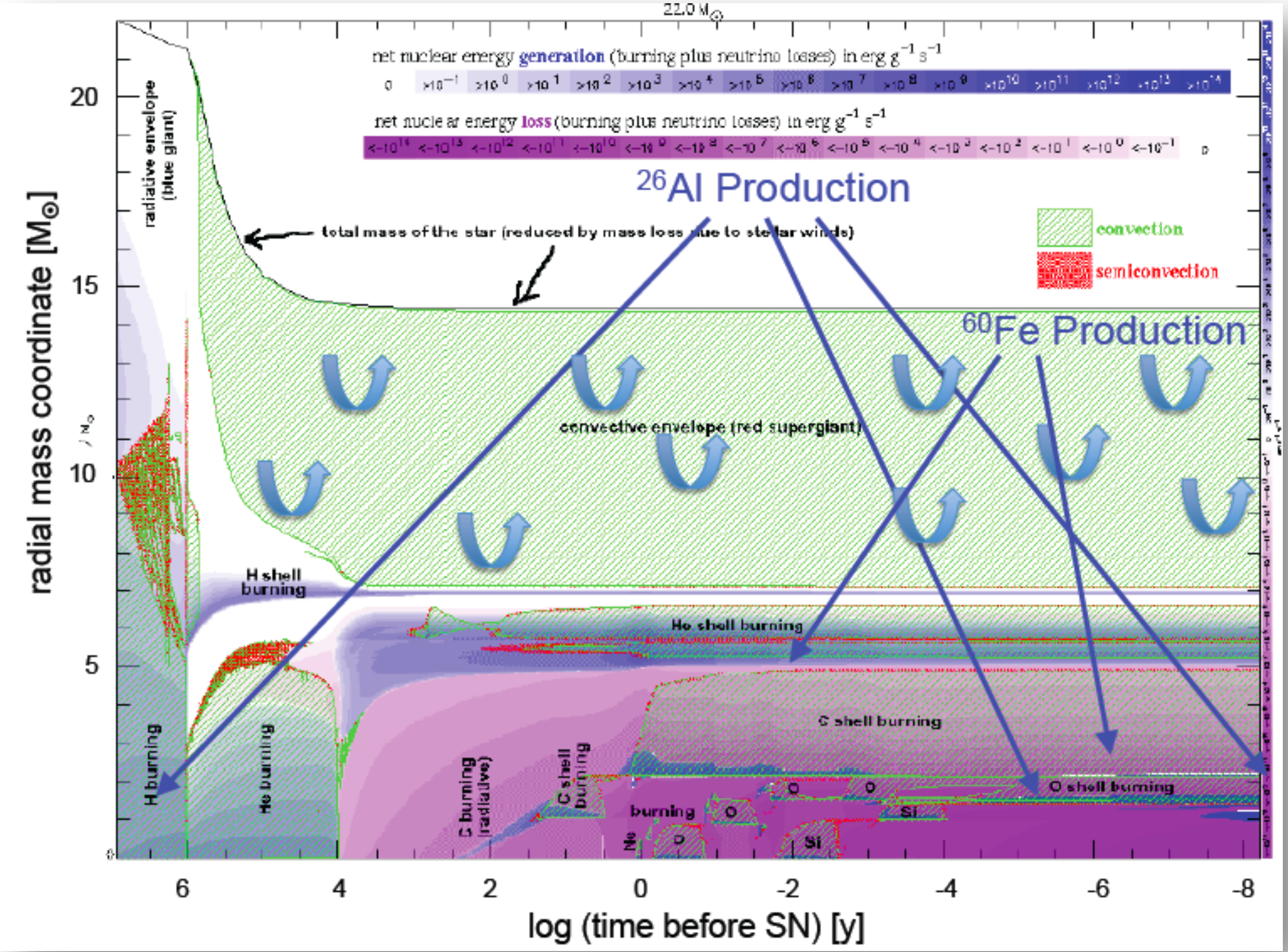
- The “outputs” of massive stars and their supernovae
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation

Voss R., et al., 2009



Radioactivities from massive stars: ^{60}Fe, ^{26}Al

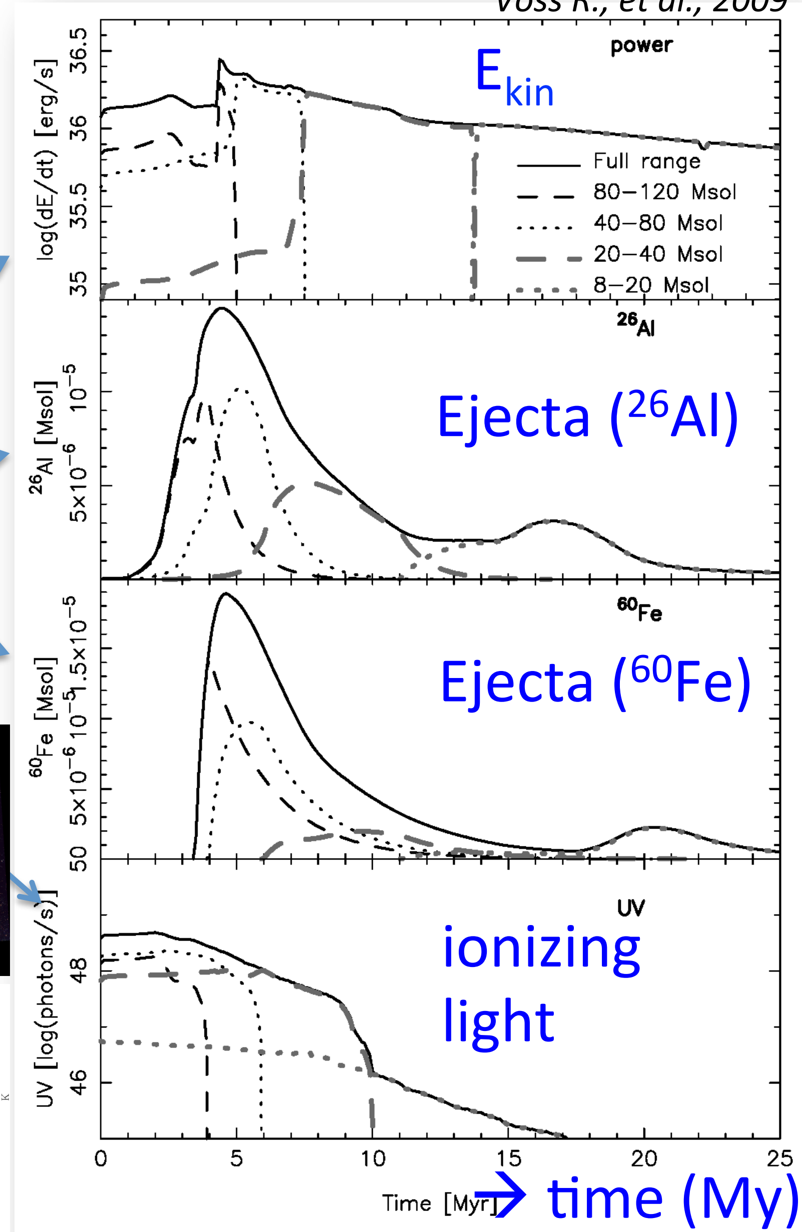
- Massive-Star Interiors
  (adapted from Heger)
  - *Hydrostatic fusion*
  - *WR wind release*
  - *Late Shell burning*
  - *Explosive fusion*
  - *Explosive release*

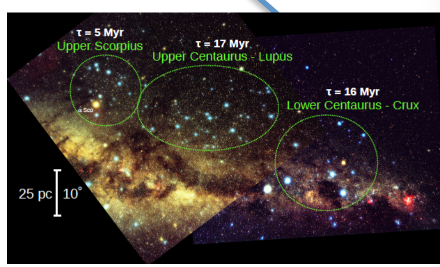


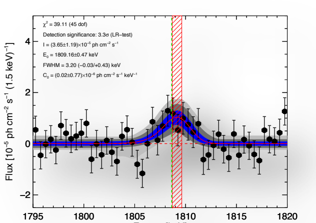
Understanding Massive-Star Groups

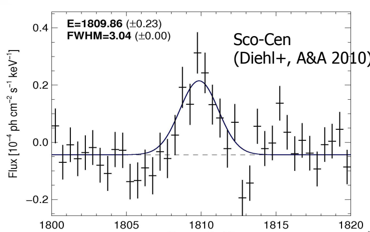
- We study the "outputs" of massive stars and their supernovae
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation
- We get observational constraints from
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

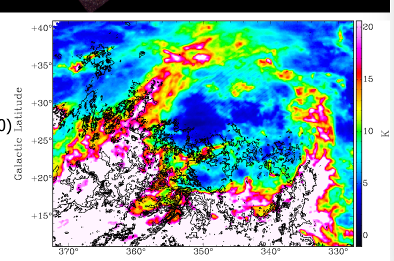
Voss R., et al., 2009





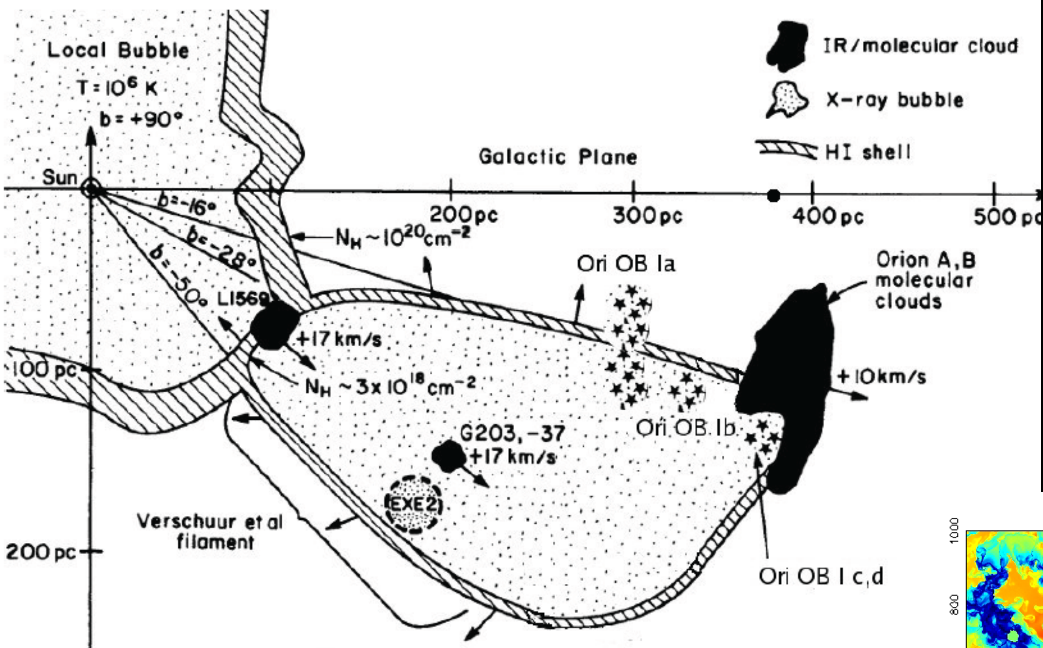


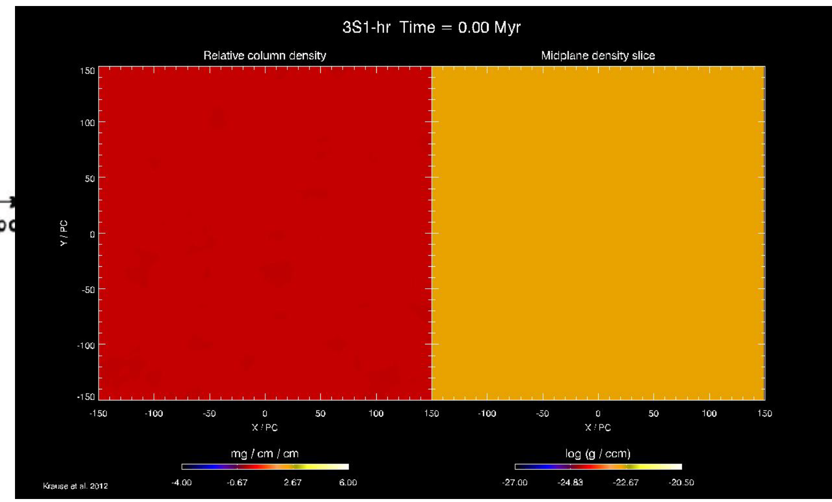


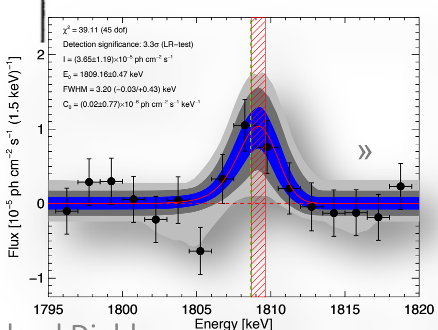


Supernova ejecta in the dynamic interstellar medium

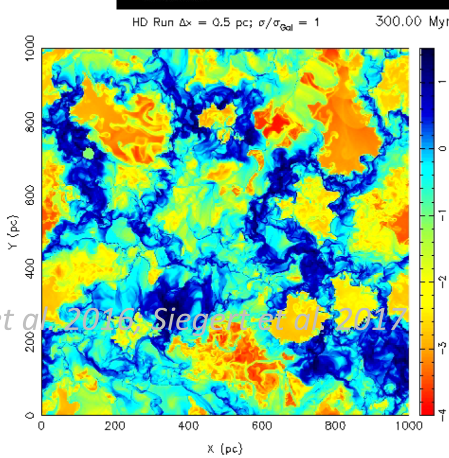
- ISM Dynamics ←→ Ejecta in SNR and (Super-)Bubbles
  - Multi-Messenger Obs & Simulations
    (Cygnus, Orion, Scorpius-Centaurus, Carina)

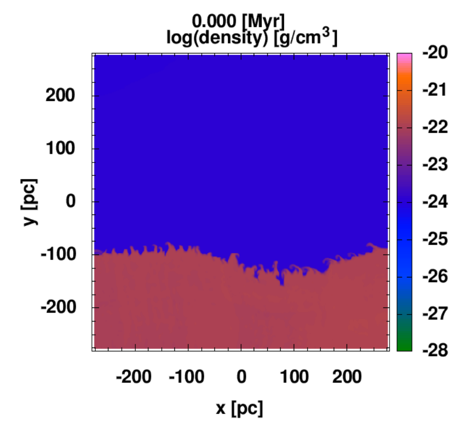






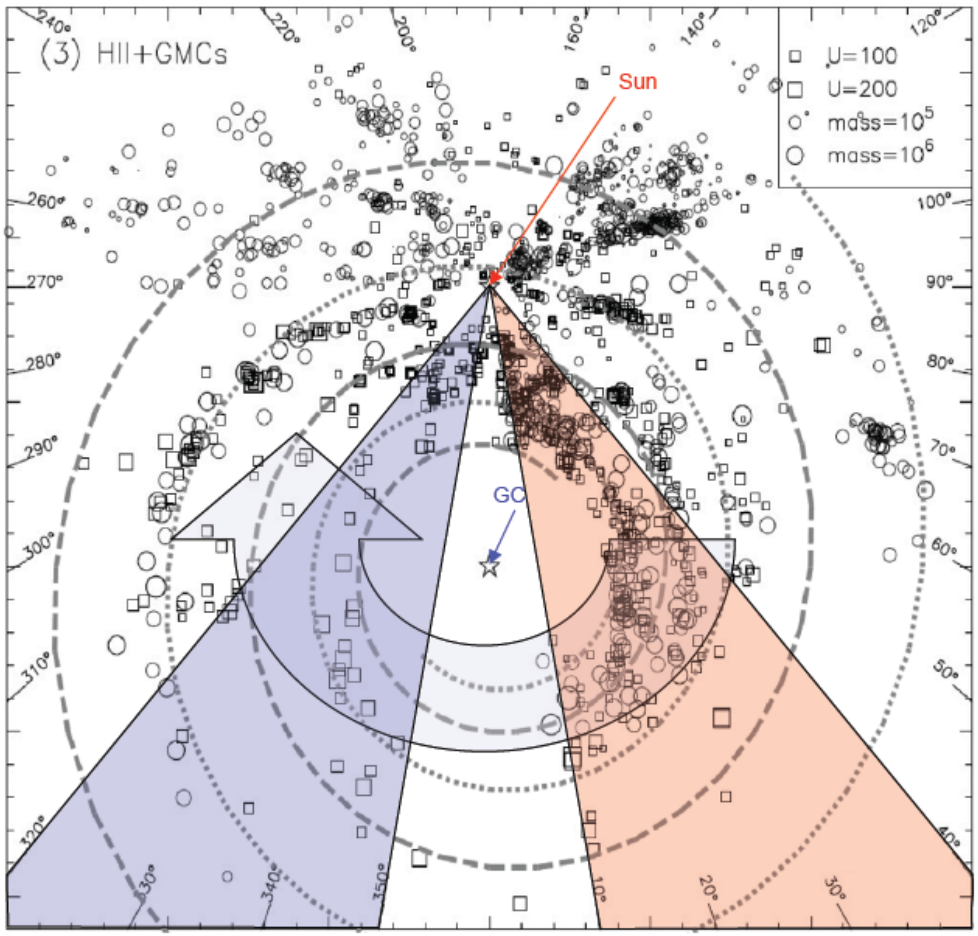
Krause+ 2013ff, Fierlinger et al. 2016, Siegert et al 2017

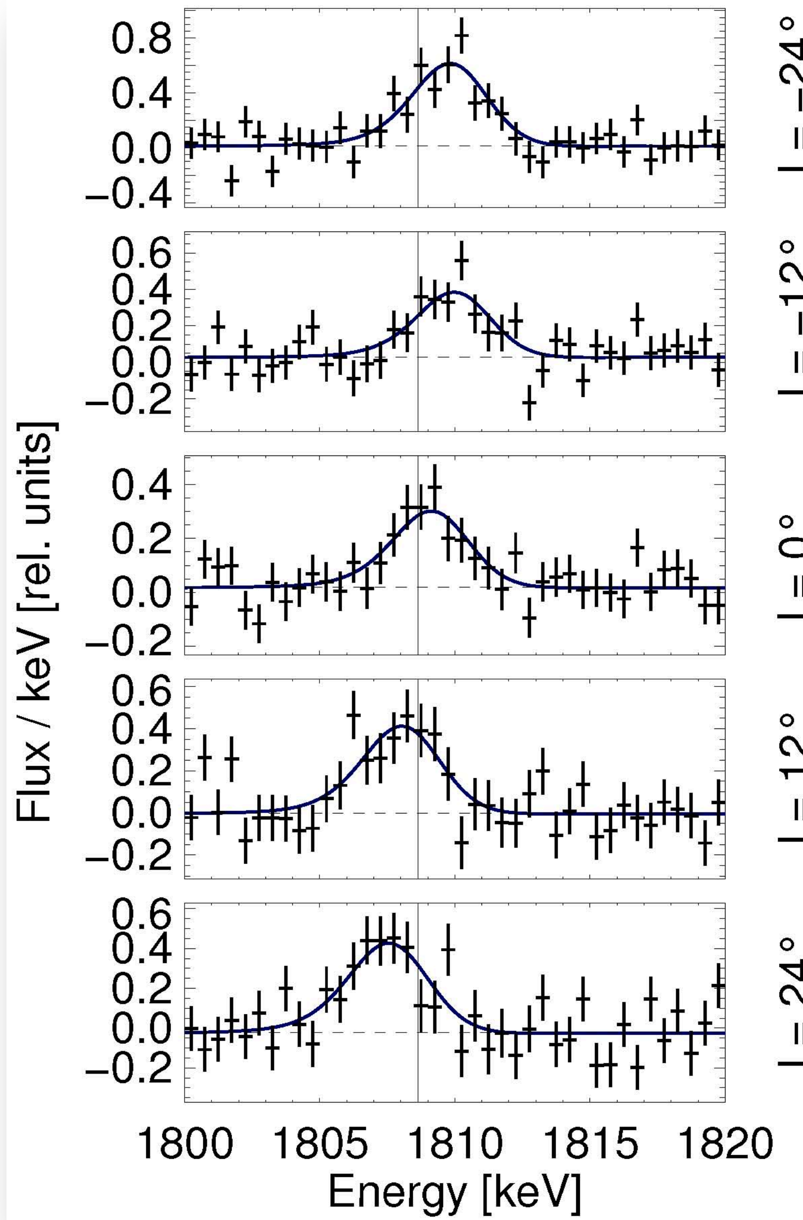




Massive Star Groups in our Galaxy: ^{26}Al γ-rays

- Large-scale Galactic rotation

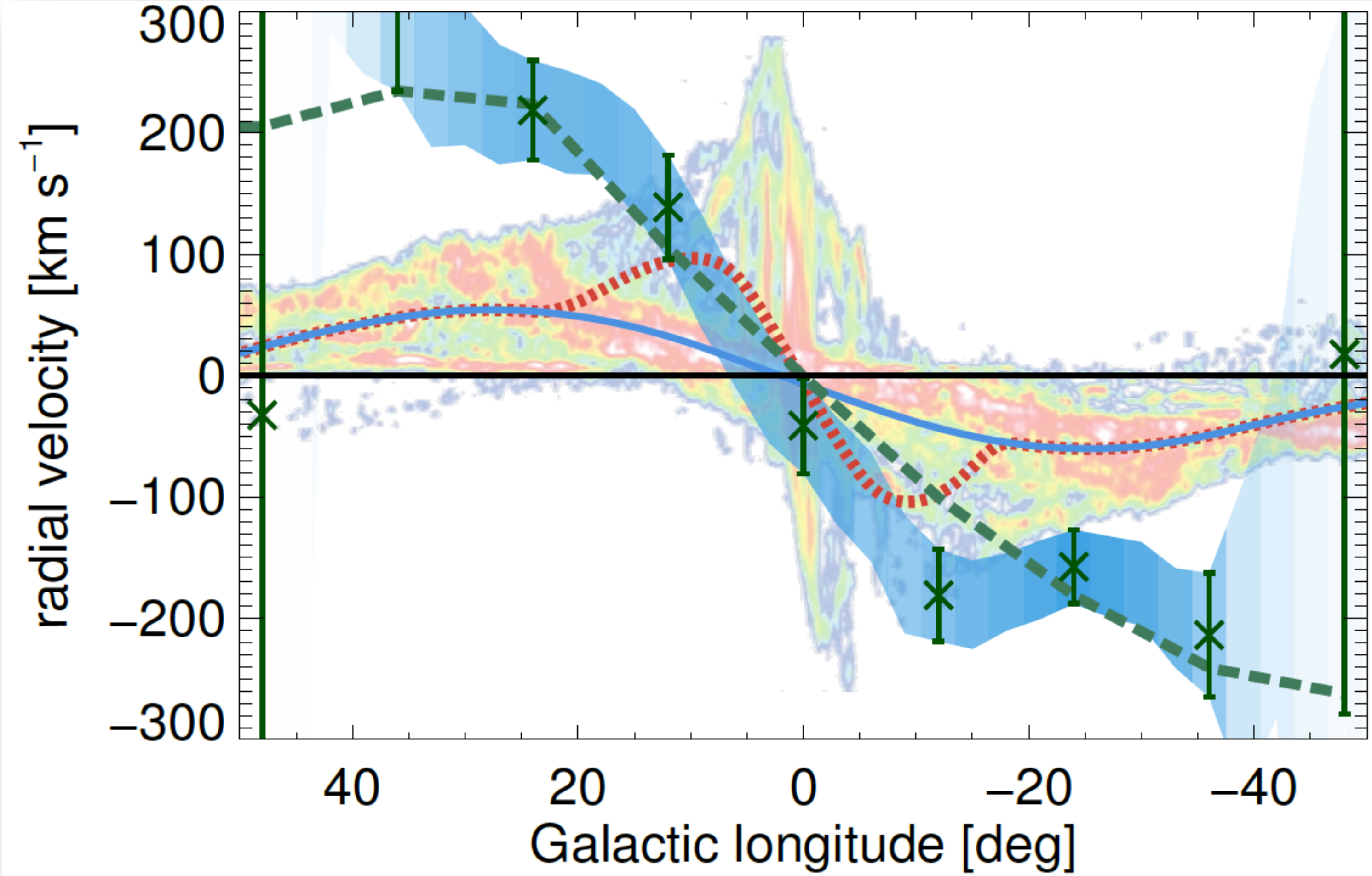




Kretschmer et al., A&A (2013)

The velocities versus Galactic longitude

- Excess velocity seen for ^{26}Al ejecta versus, e.g., CO!

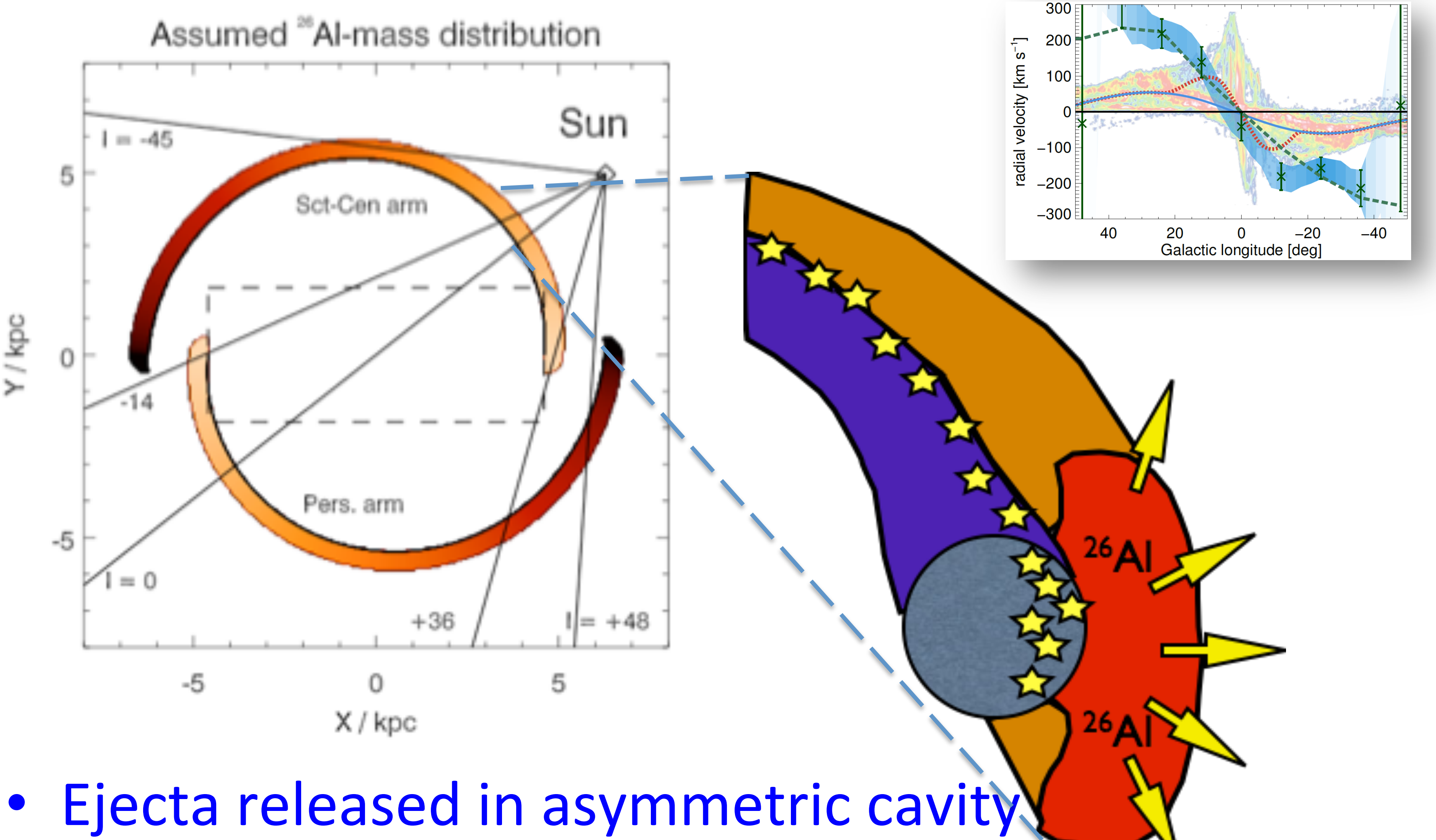


Kinematics of massive star ejecta in the Milky Way as traced by ^{26}Al

Karsten Kretschmer[1,2], Roland Diehl[2,3], Martin Krause[2,3], Andreas Burkert[4,3,2], Katharina Fierlinger[3,4], Ortwin Gerhard[2], Jochen Greiner[2,3], and Wei Wang[5]

How massive-star ejecta are spread out…

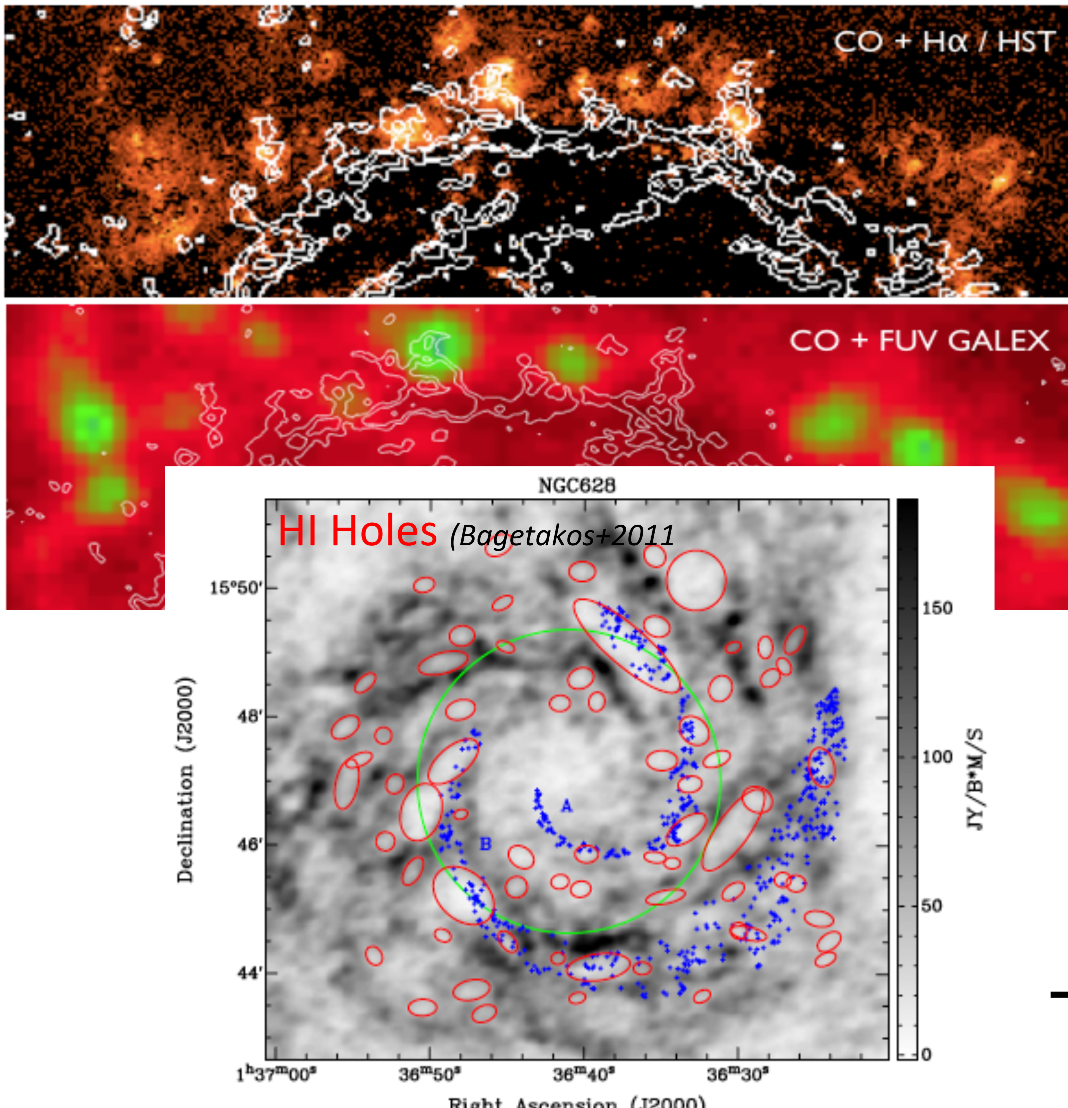
- Superbubbles blown into inter-arm regions



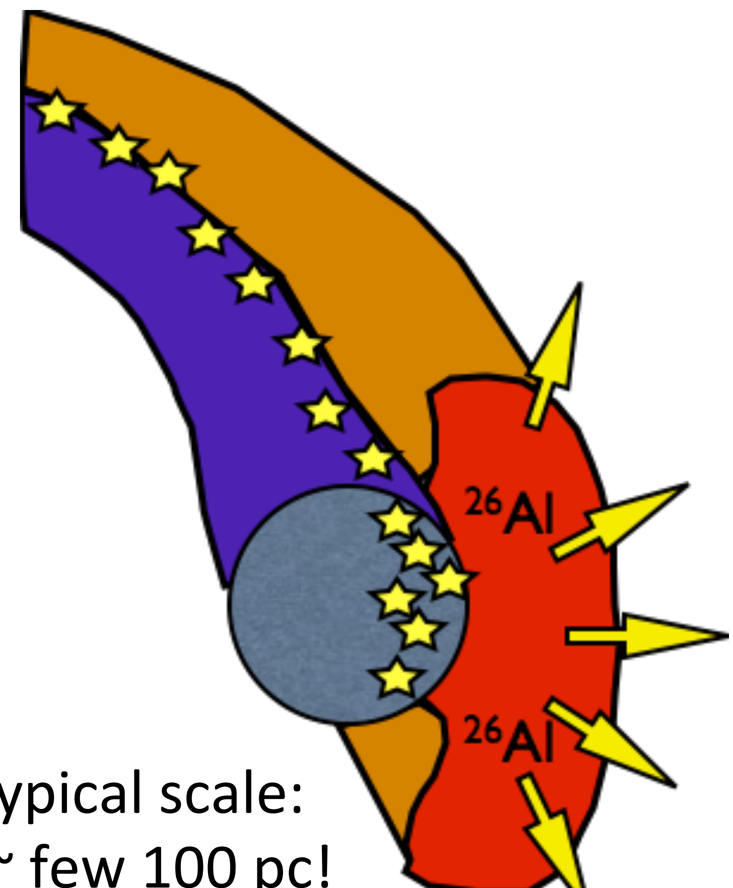
- Ejecta released in asymmetric cavity

How ejecta are spread out on the My scale…

- SN ejecta are in superbubbles, preferentially (not SNR!)

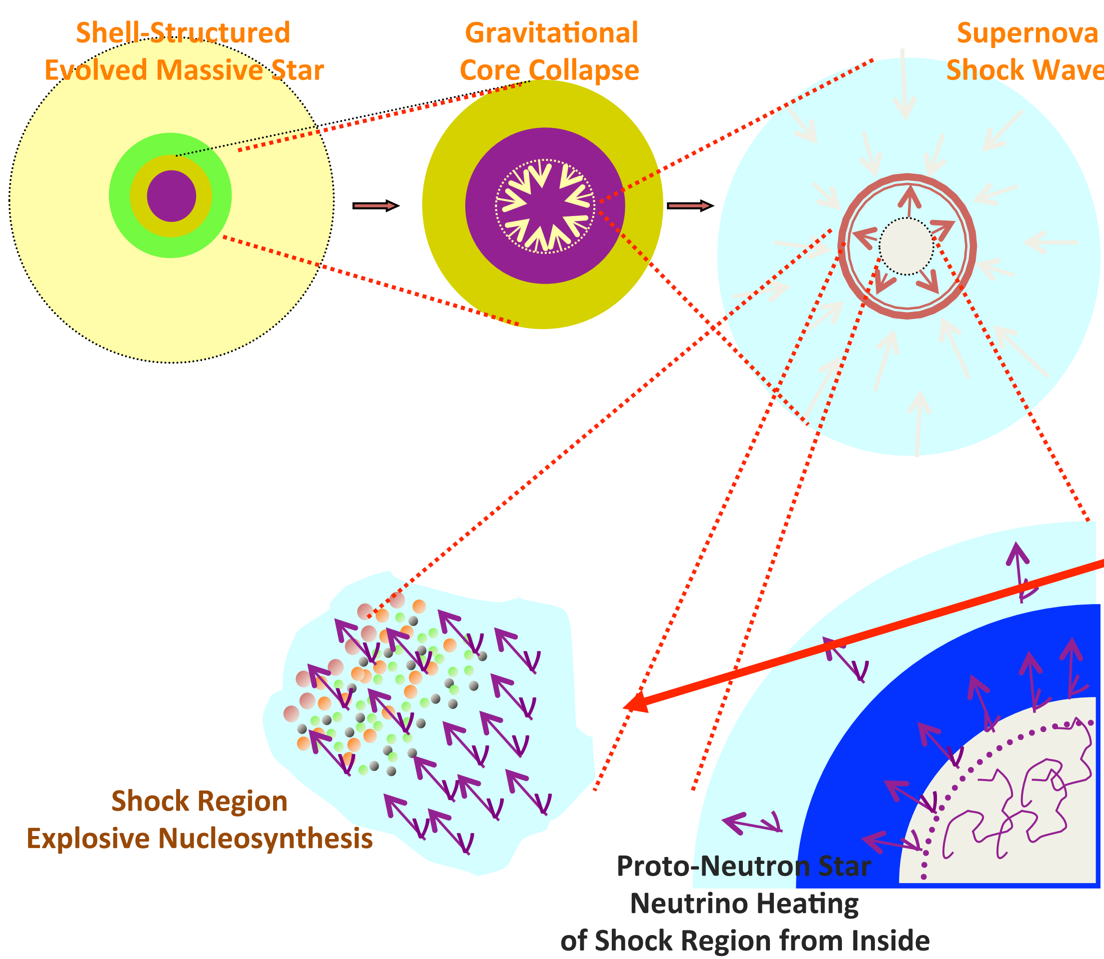


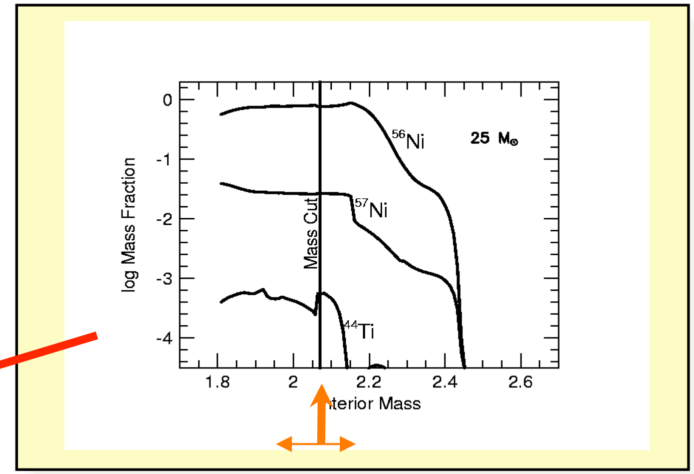
…seen in other galaxies.

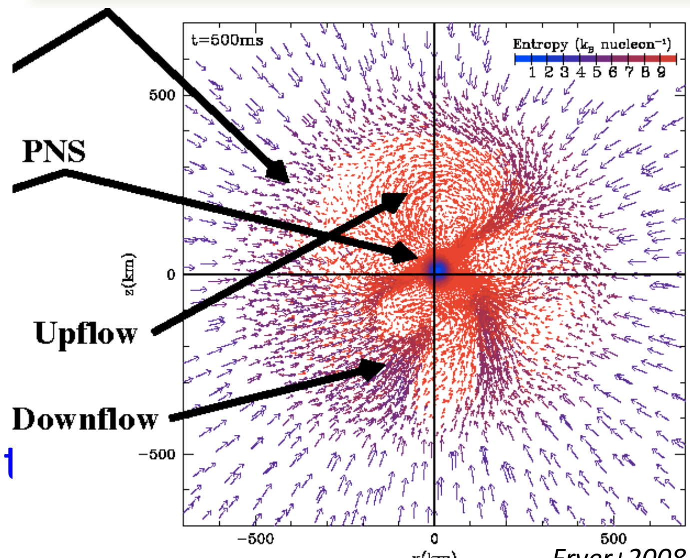


→typical scale:
~ few 100 pc!

Nucleosynthesis in CC-Supernova Models and ^{44}Ti





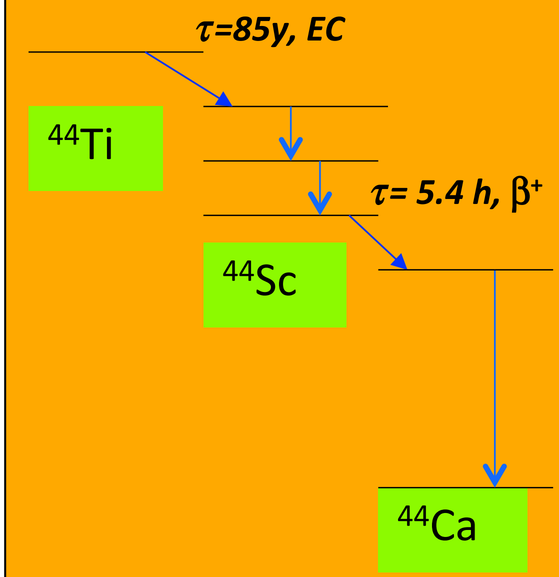


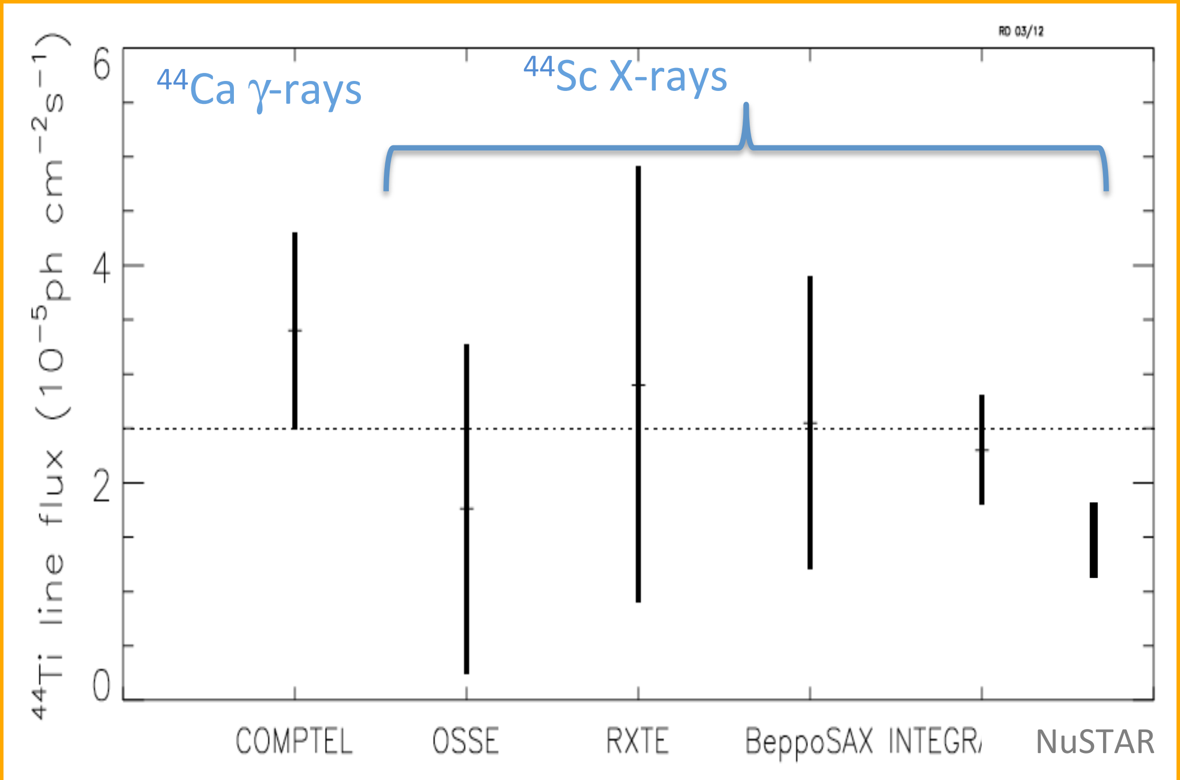
Fryer+2008

- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out

  => Unique Probe (+Ni Isotopes)

^{44}Ti γ-rays from Cas A



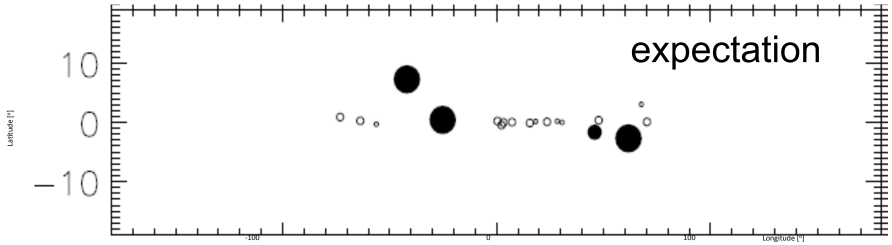


↳ ^{44}Ti Ejected Mass ~1.23 $_{\pm 0.25}$ 10^{-4} $M_\odot$

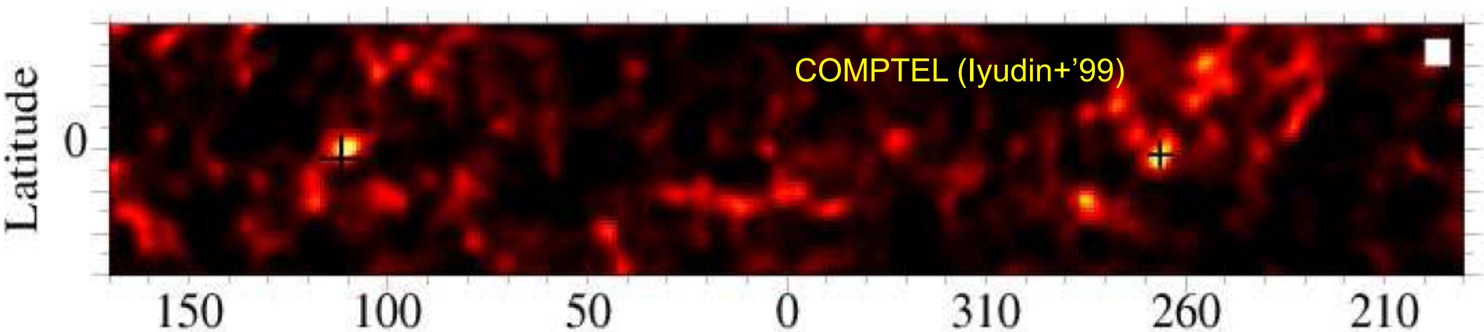
→ see talk by Chris Weinberger

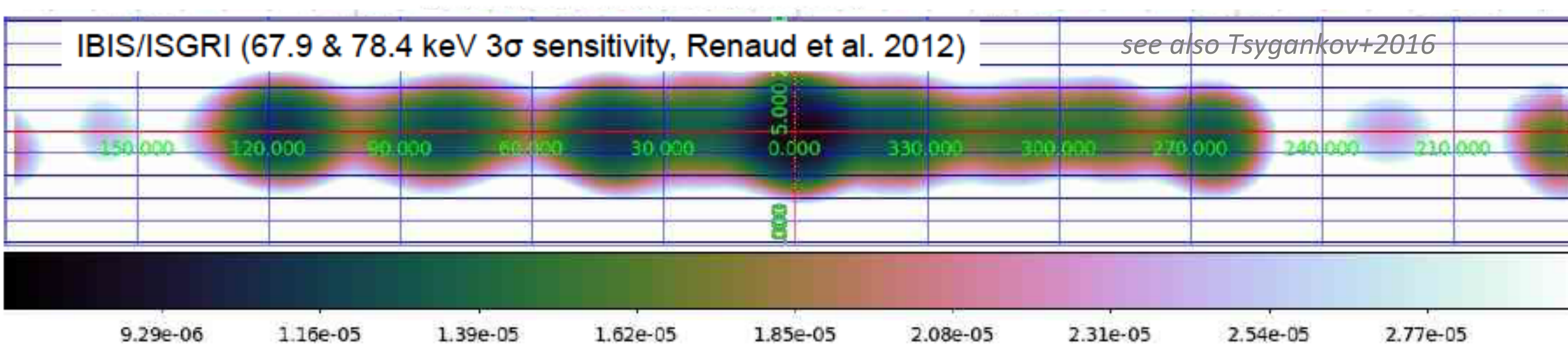
Are all Core Collapse Supernovae ^{44}Ti Sources?

- ☆ Cas A is the ONLY Source Seen in our Galaxy
- ☆ Sky Regions with Most Massive Stars (inner Galaxy) are ^{44}Ti Source-Free
- ☆ We would expect to see > a few of such sources!

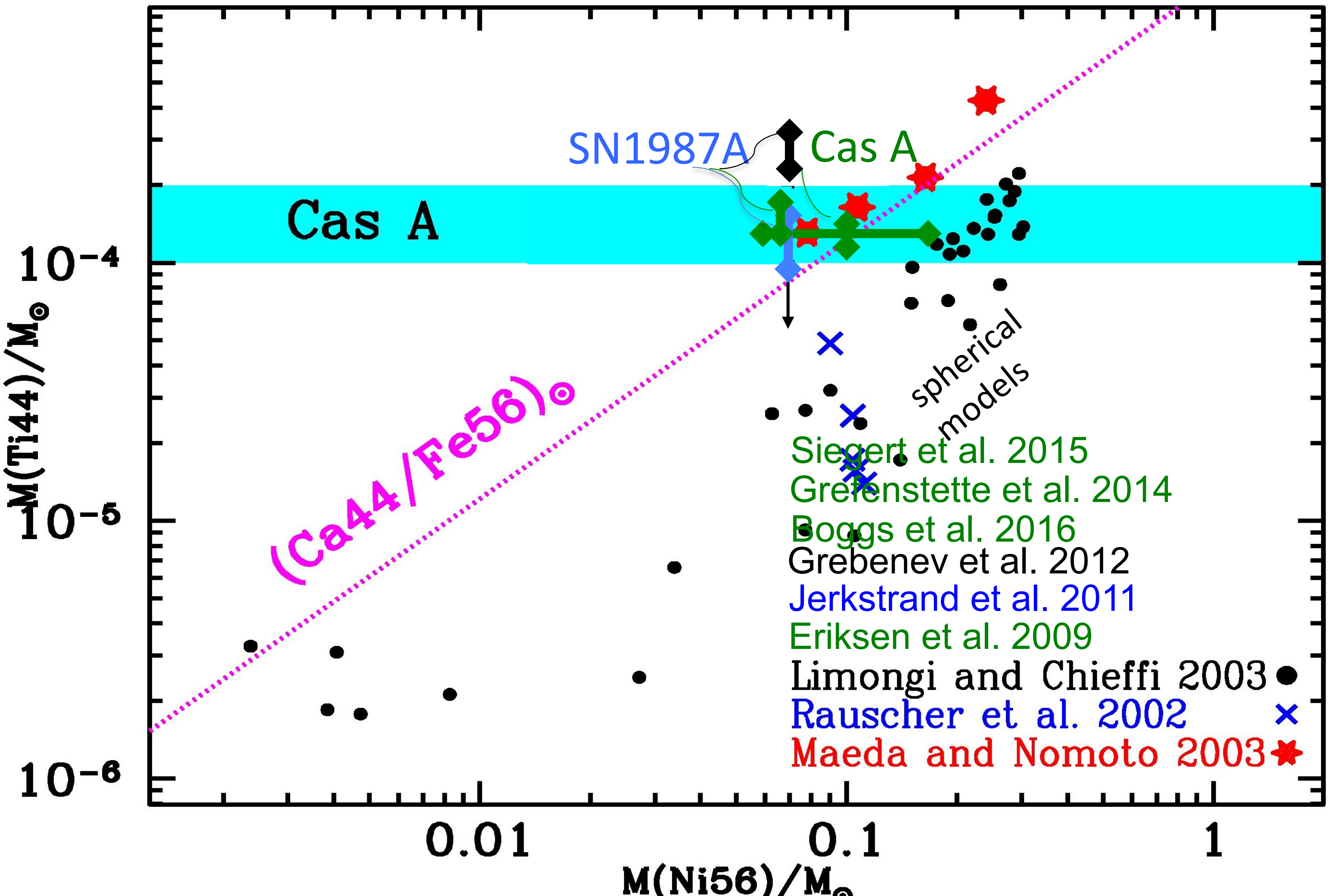


The et al. 2006*; see also Dufour & Kaspi 2013*





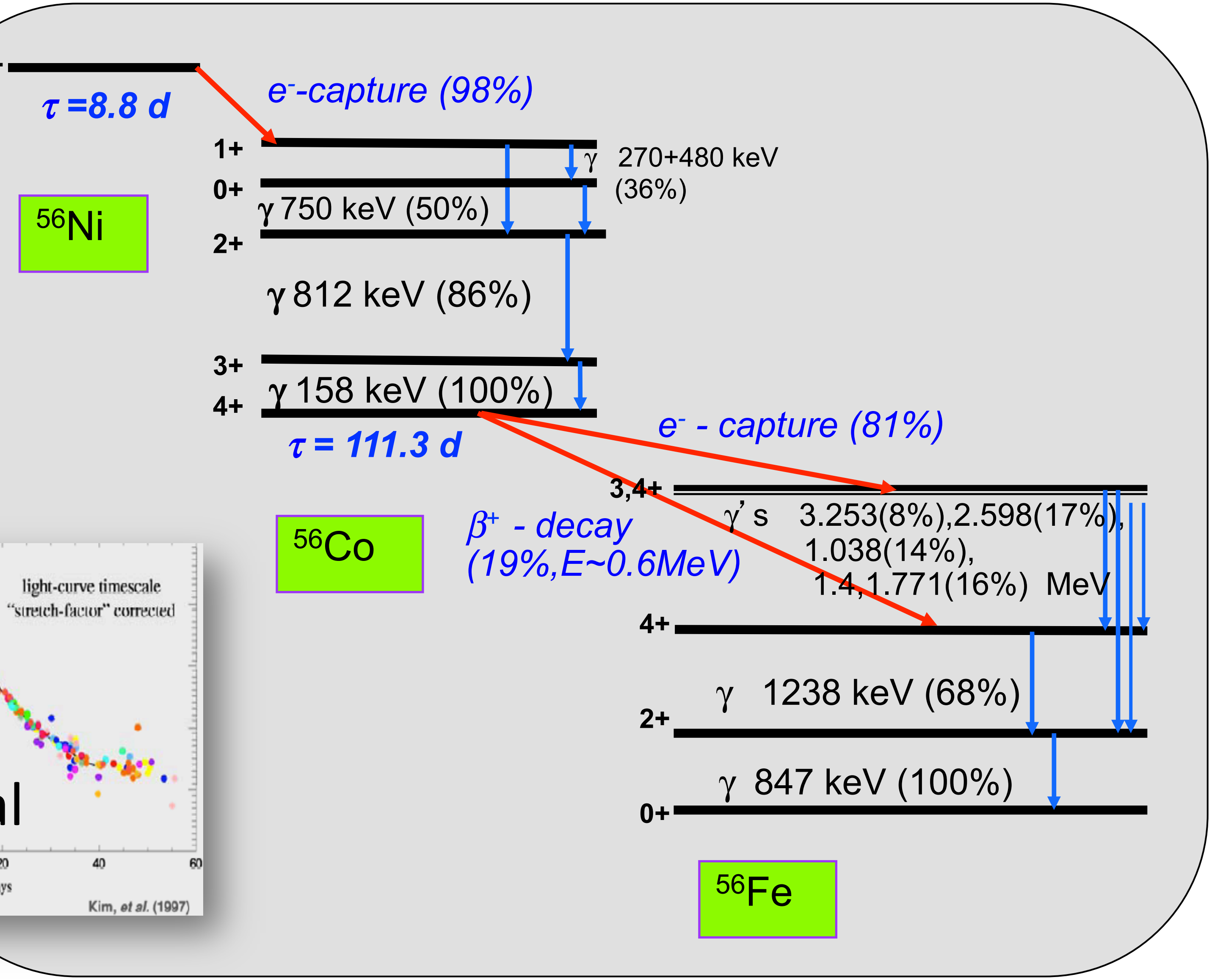
“Abnormal” Supernovae as ^{44}Ca (=^{44}Ti) Sources?

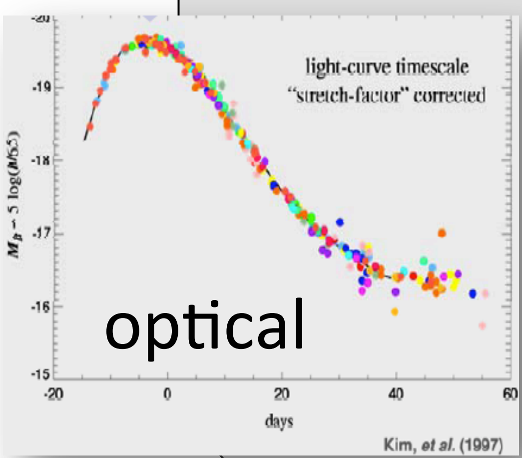


⇨ Only Non-Spherical Models Seem to Reproduce Observed ^{56}Ni/^{44}Ti Ratios

⇨ *The et al. 2006*

^{56}Ni Radioactivity Decay Chain and Gamma-Rays





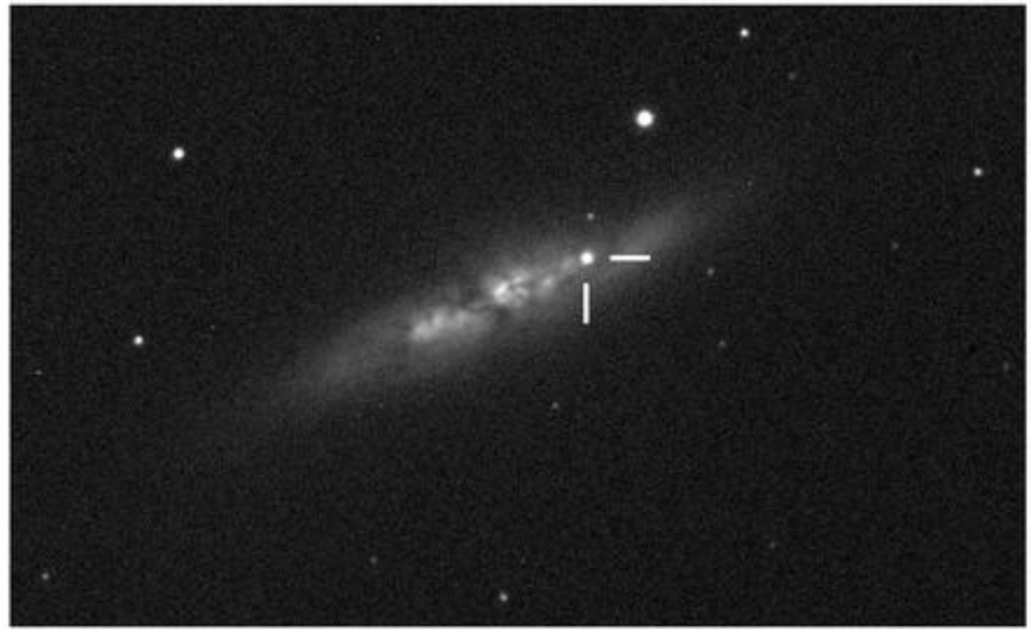
- Nuclear BE release 0.6$M_\odot$ C,O→^{56}Ni: ~1.1 10^{51} erg (>2*BE_{WD})

SN2014J: Discovery of ^{56}Ni γ-ray lines

SN Ia in M82

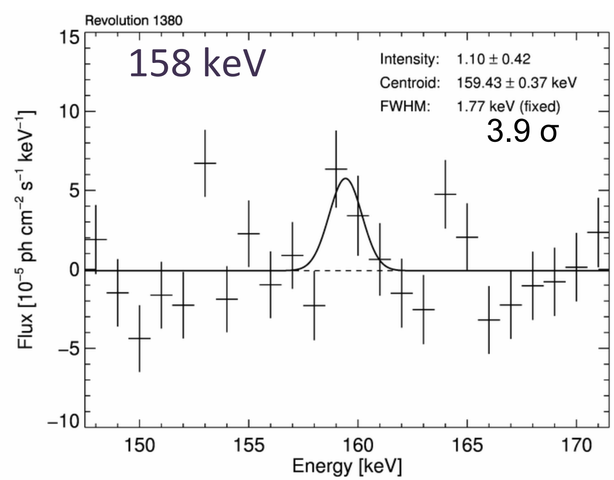
(Starburst Galaxy)

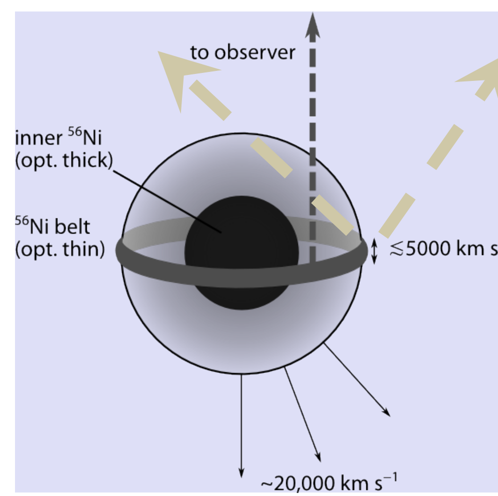
- Discovered 22 Jan 2014
- Likely Explosion Date:
  14 Jan 2014 (14.75 +/-0.3d)
- Distance 3.3….3.53 Mpc,
  l=141.41°, b=40.56°
- Closest SN Ia in 40 y!



^{56}Ni γ rays seen early

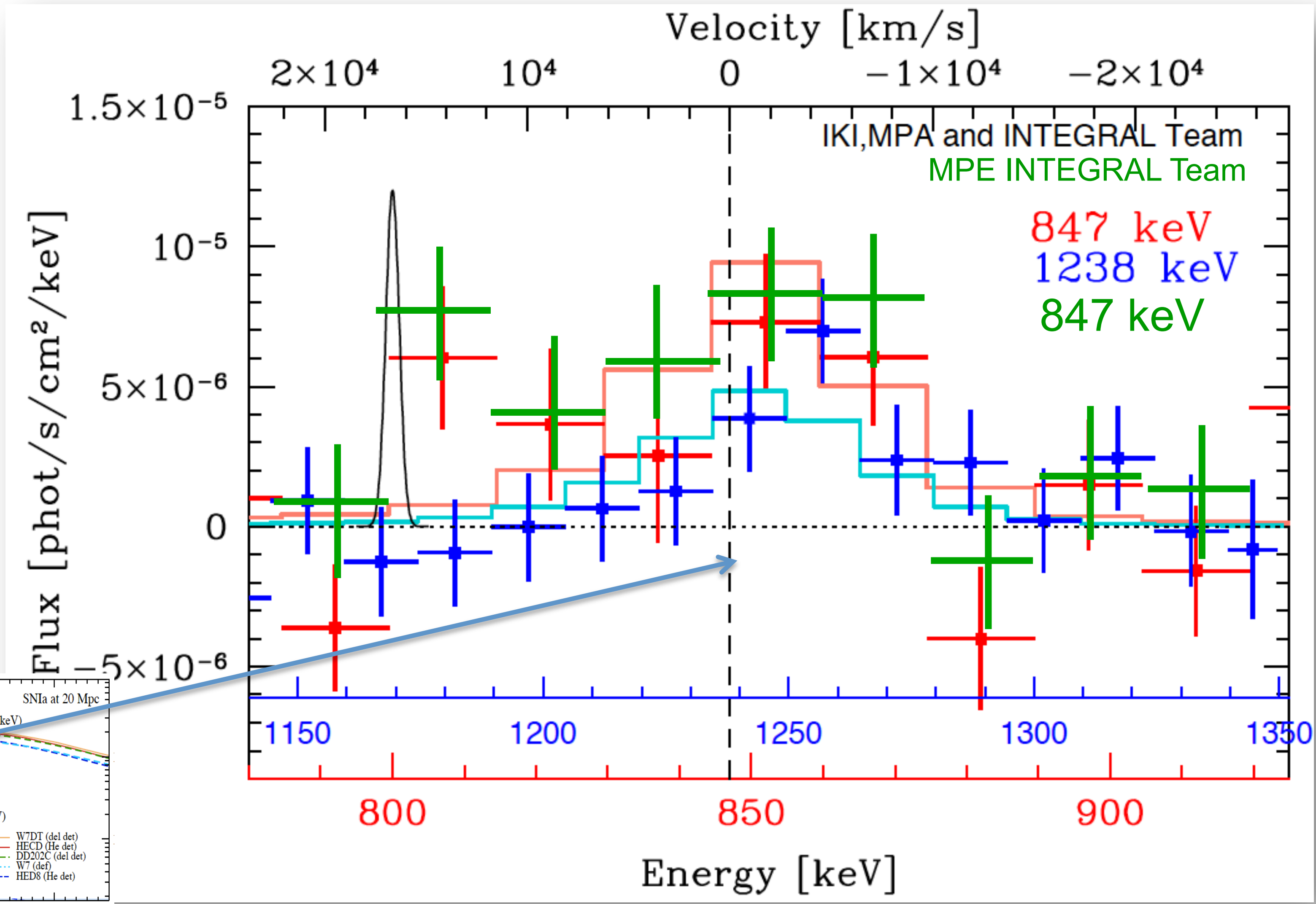
- Envelope still thick to γ-rays → surface ^{56}Ni
- Lines not shifted
  → He in orbital plane, off plane aspect angle

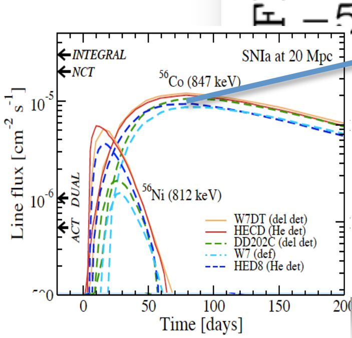




Longterm Data: Broad Lines from ^{56}Co!

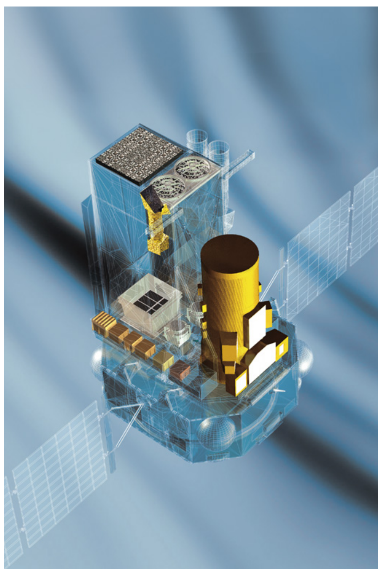
- INTEGRAL Obs from 31 Jan till 26 Jun 2014

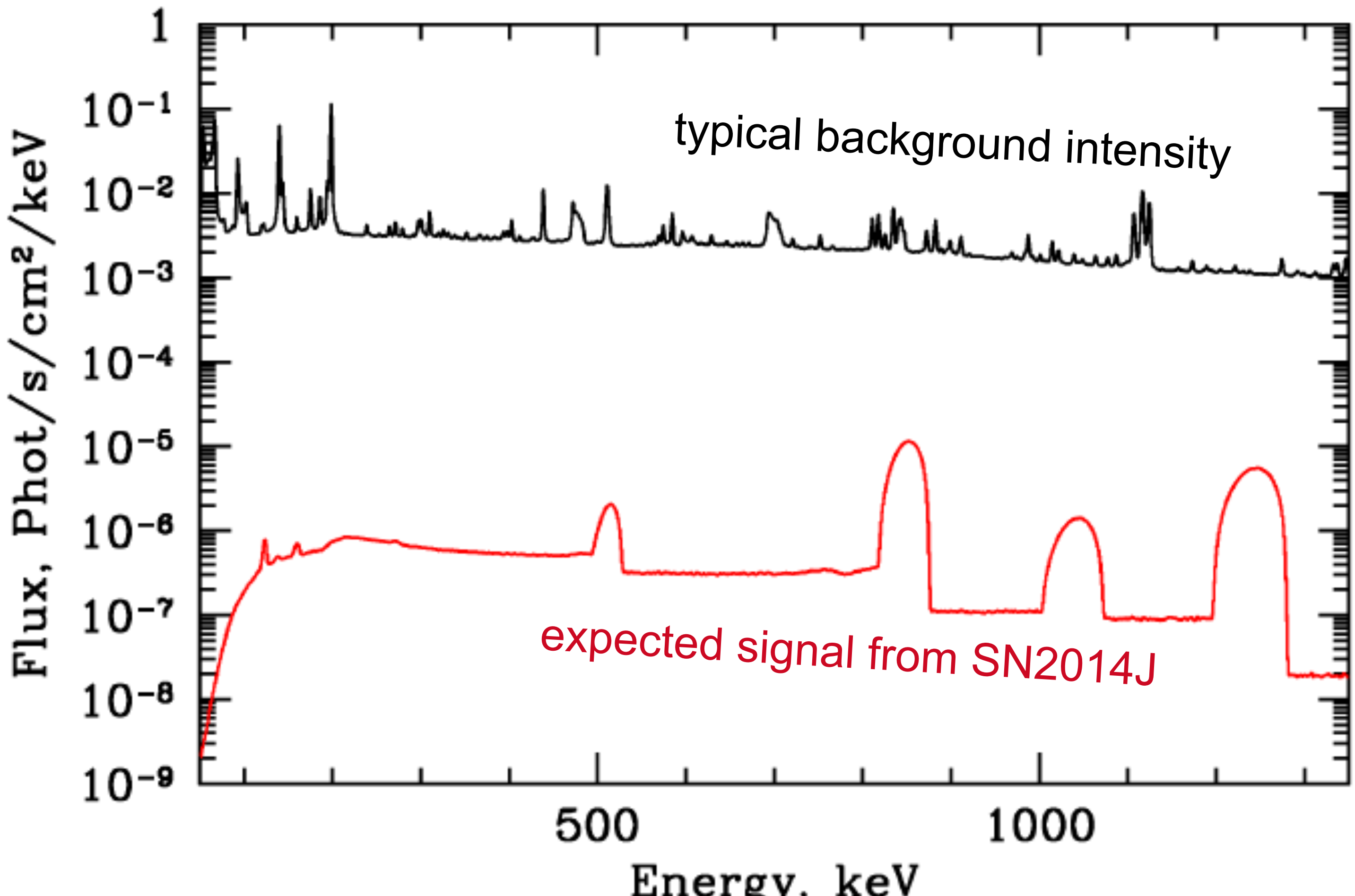




The Challenge of Finding Cosmic Gamma-Rays

- Current Gamma-Ray Telescopes Have Large Intrinsic Background
  - Cosmic Ray Activation of Spacecraft and Instrument





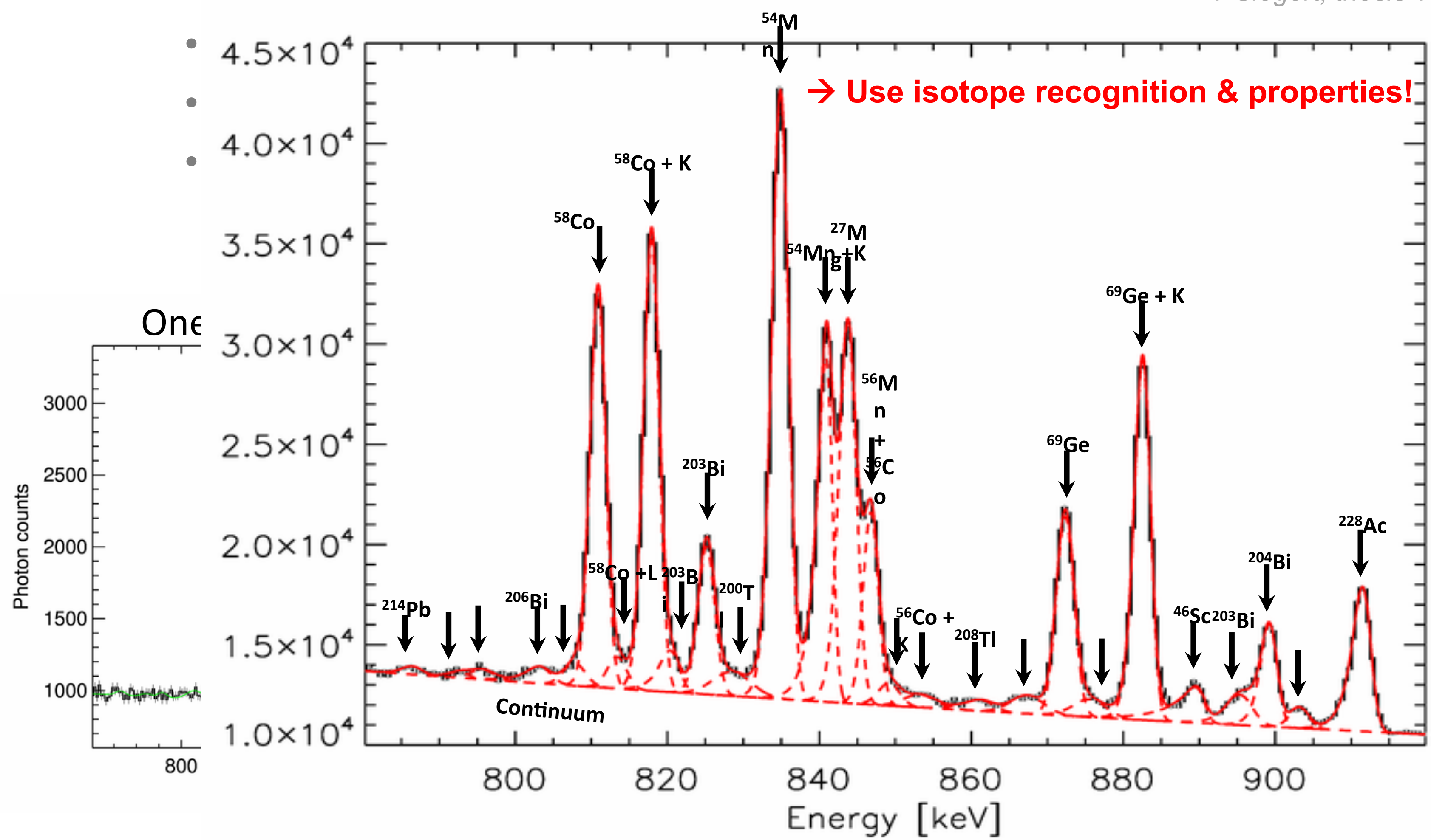
from Churazov et al., 2014

SN2014J Data Analysis

new

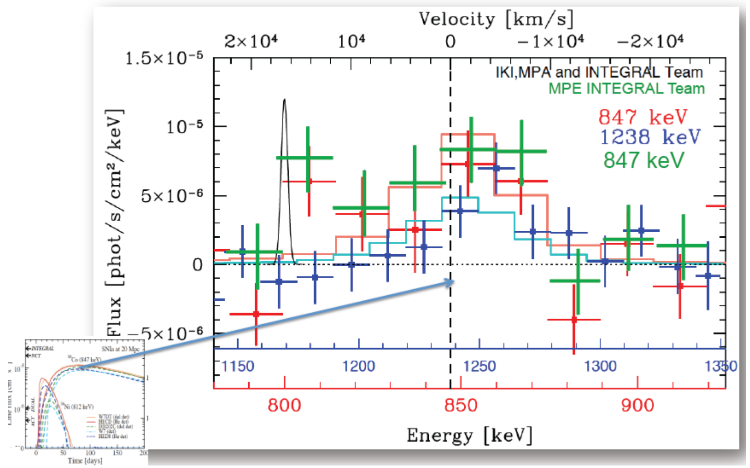
– Background modeling from detailed mission data spectroscopy
→ exploit physics of lines → consistent high-resolution model

T Siegert, thesis TUM (2013)



SN2014J data Jan – Jun 2014: ^{56}Co lines

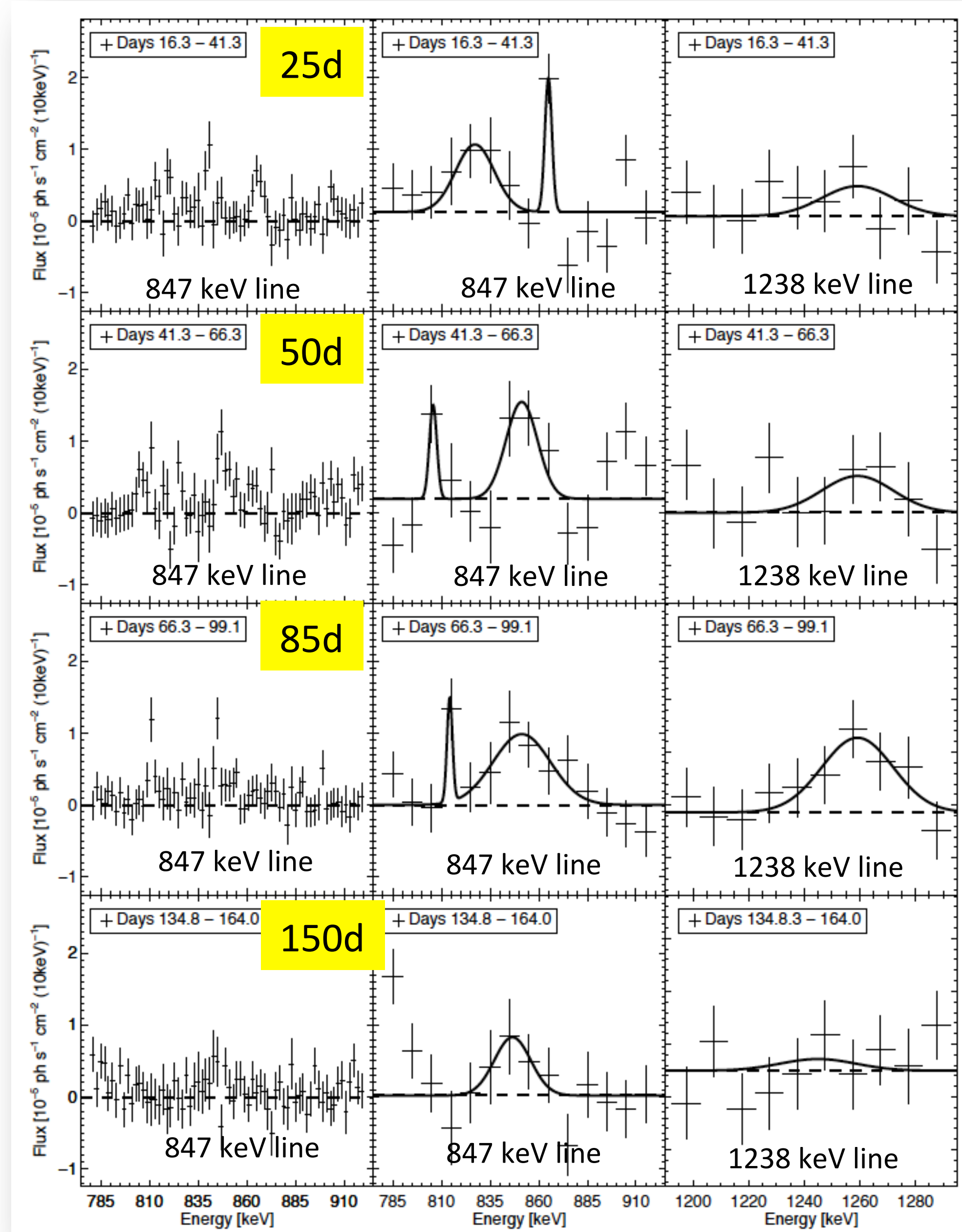
- Doppler broadened ✓



- Split into 4 time bins
- Coarse & fine spectral binning

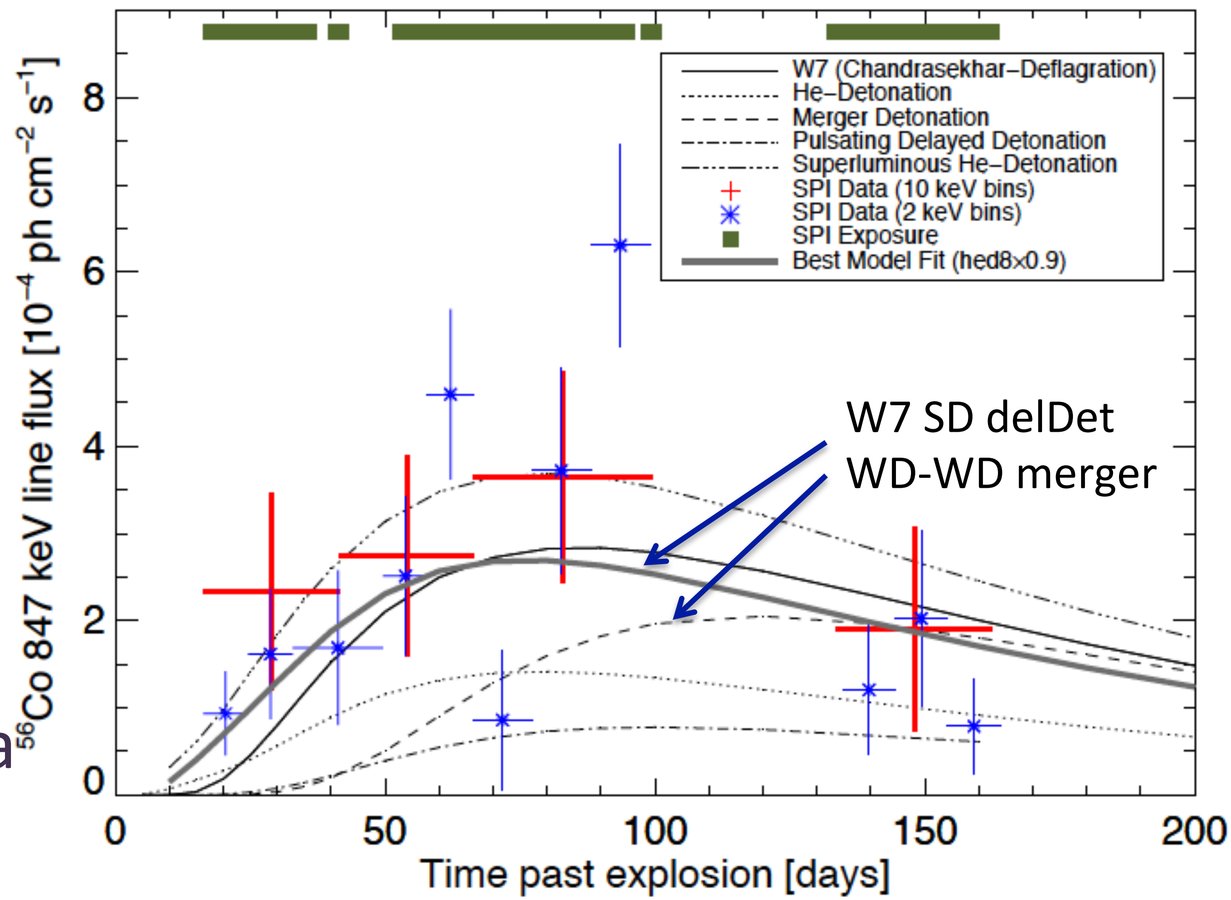
→ Observe a structured and evolving spectrum

- expected: gradual appearance of broadened ^{56}Co lines
  - *Diehl et al., A&A (2015)*



SN2014J data Jan – Jun 2014: 847 keV ^{56}Co line

– smooth(??) brightness evolution?



→Compare high/low res data to models

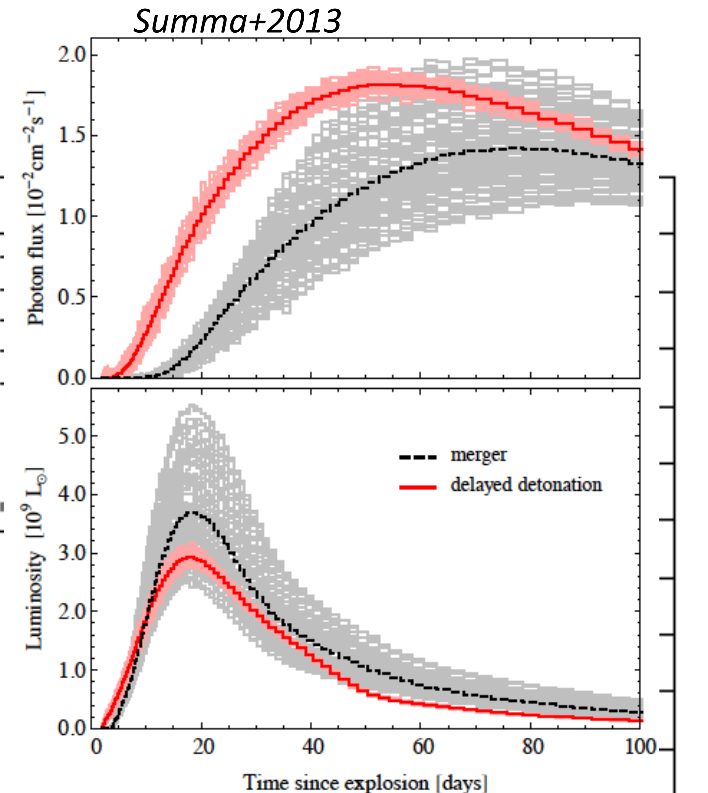
– ^{56}Ni mass (fitted): 0.49 $_{+/-0.09}$ $M_\odot$

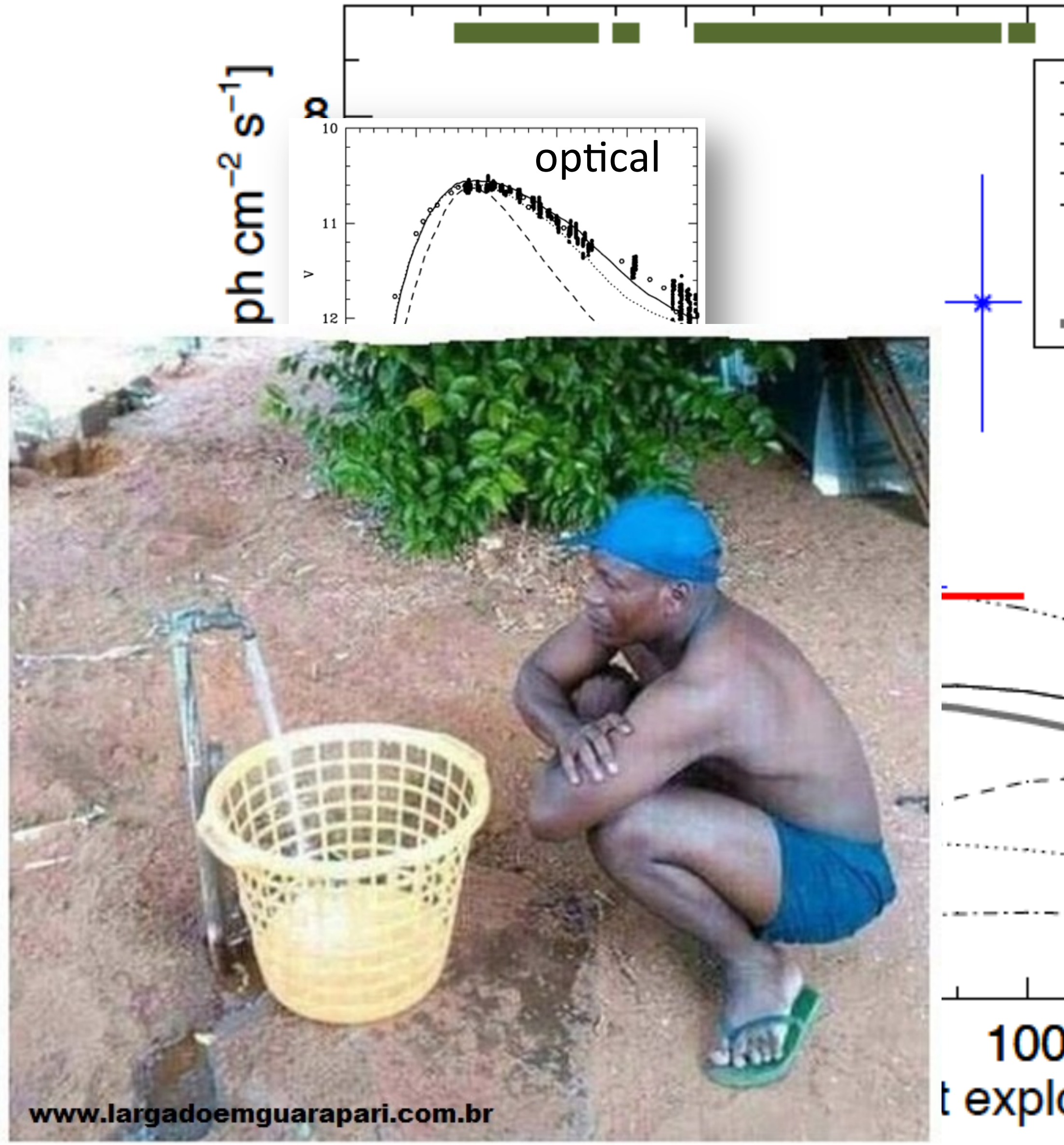
(cmp from bol. Light → 0.42 $_{+/-0.05}$ $M_\odot$

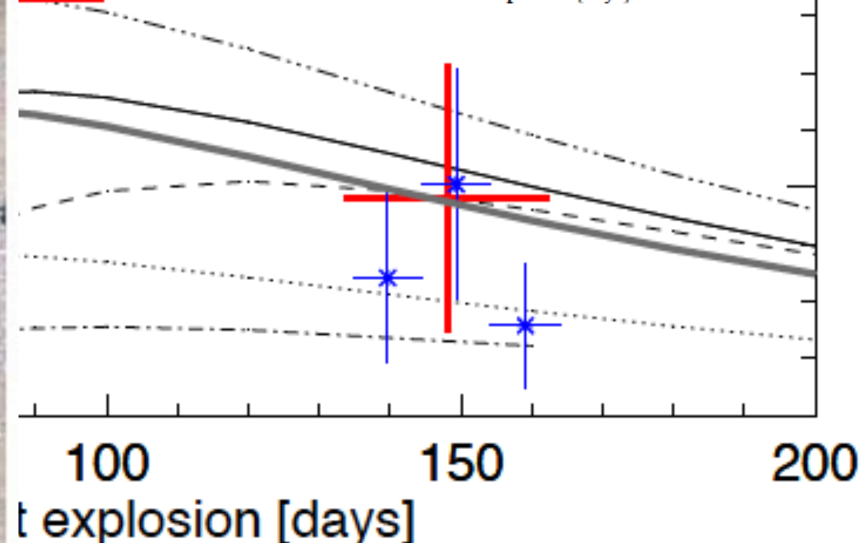
from models → 0.5 $_{+/-0.3}$ $M_\odot$

- *Diehl et al., A&A 2015*

Bolometric supernova light

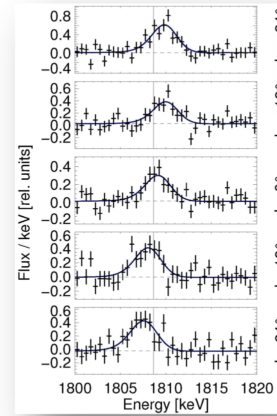


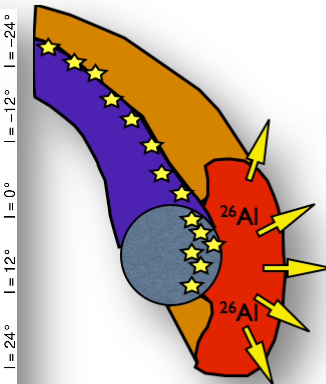




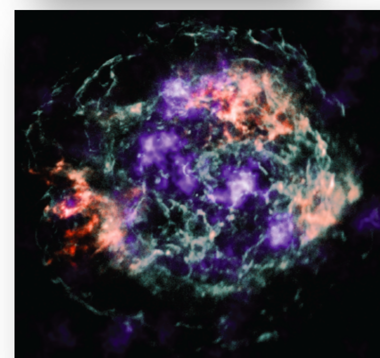
Summary: γ-rays from supernovae

- ^{26}Al throughout the Galaxy show that superbubbles hosts and re-cycle ejecta from Sne





- ^{44}Ti origins must be from rare sources (<< SN rate)



- ^{56}Co γ-ray emergence from SN2014J indicates 'porosity' / 3-dimensional structure