γ-Ray Spectroscopy of Cosmic Sources

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with
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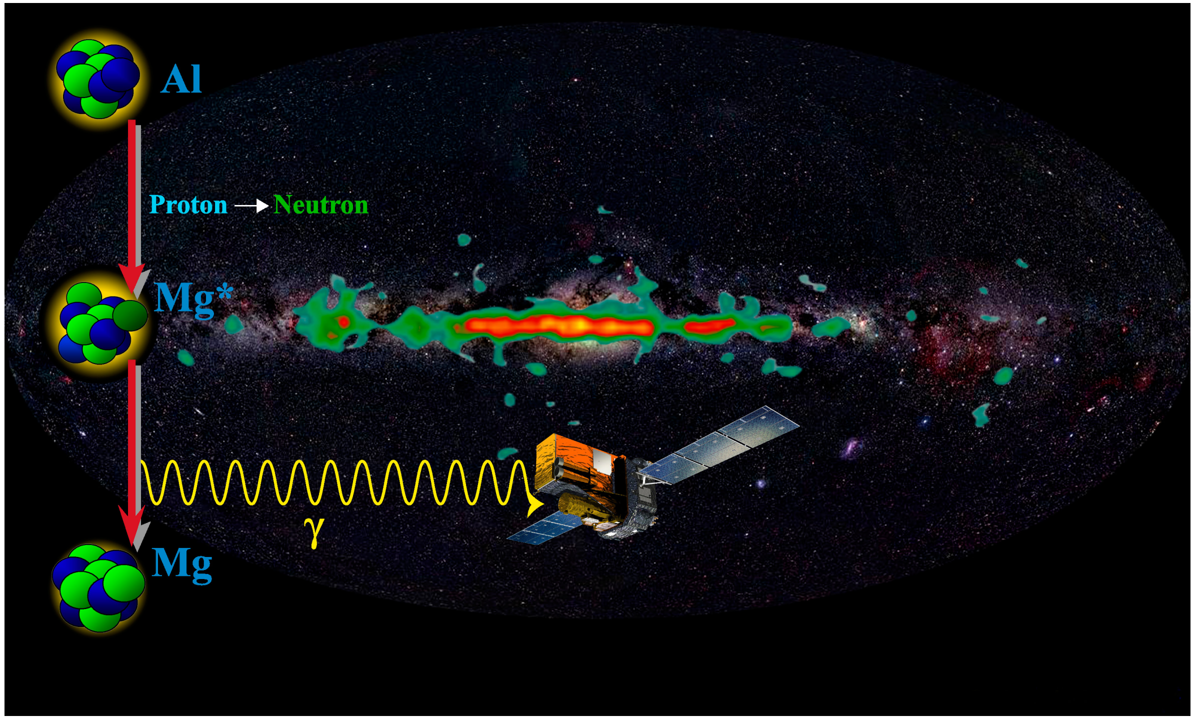
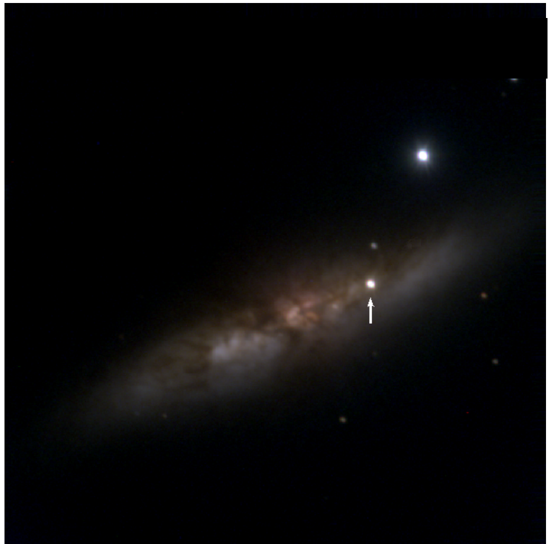
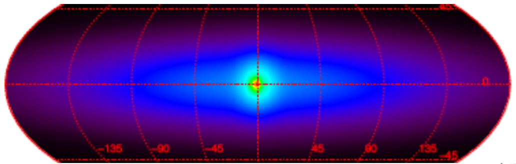
Massive Stars / Groups,

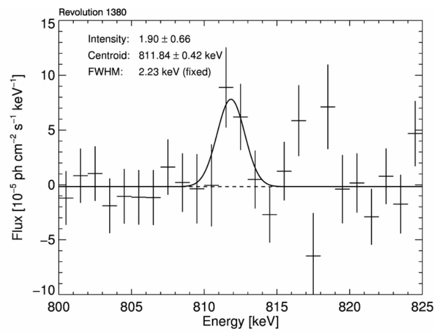
Positrons,

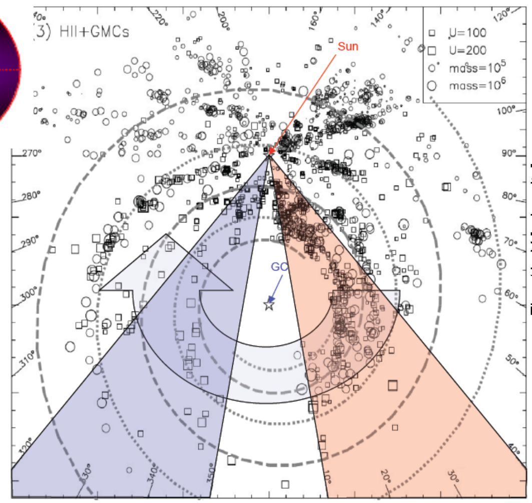
and Supernova Explosions

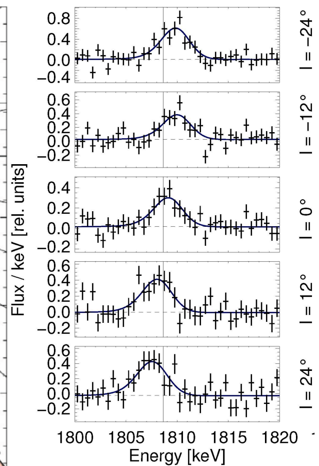




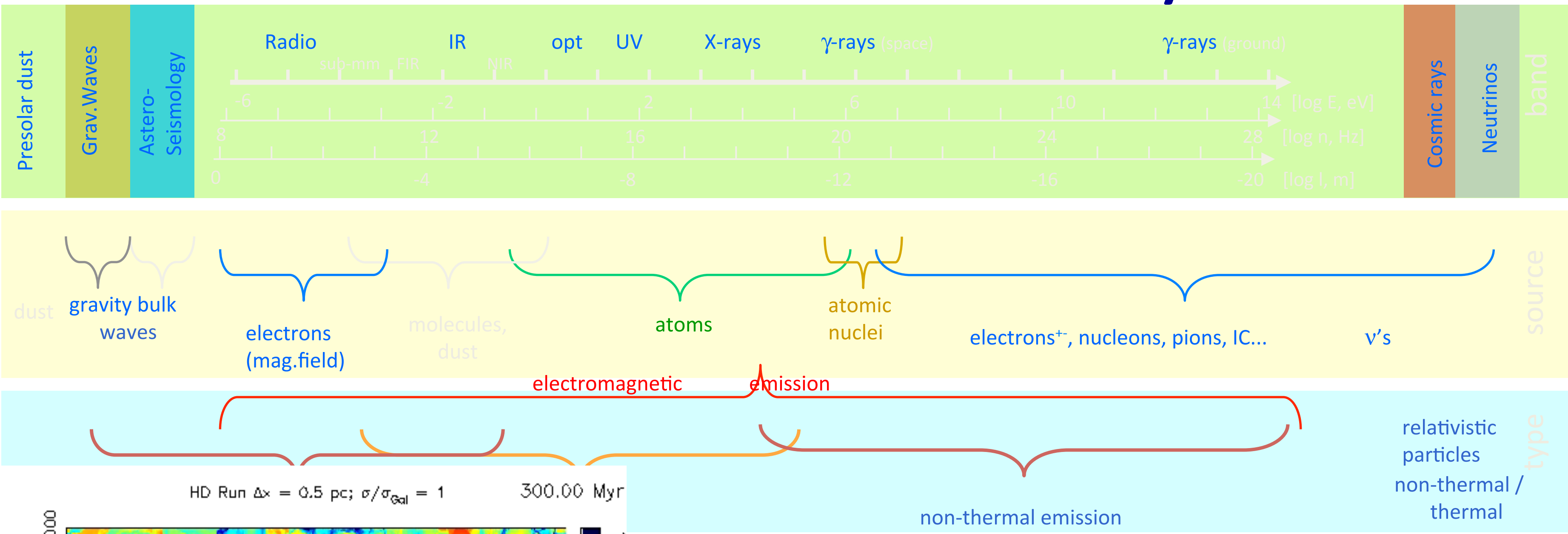


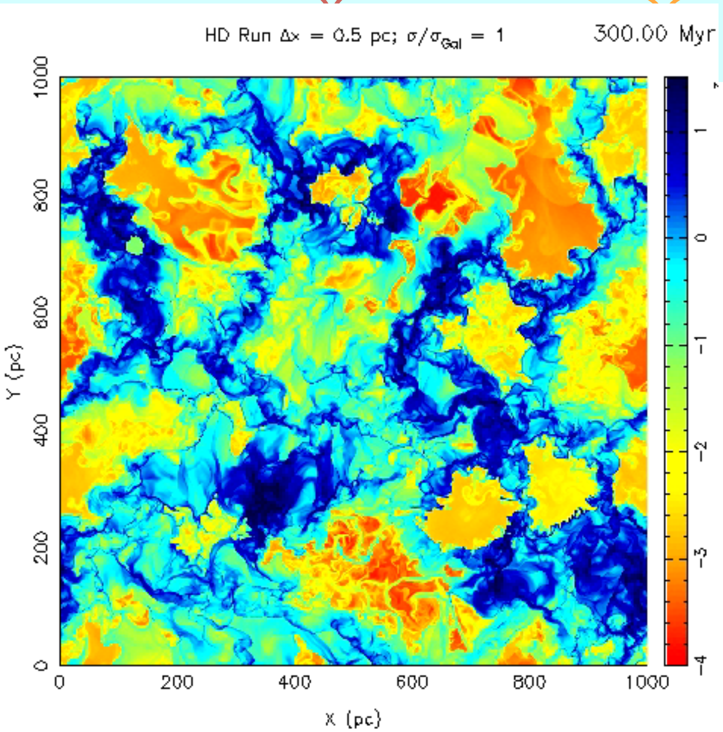






Nuclear-line astronomy





Where & how are ejecta produced?

How do ejecta move (My) before getting recycled?

Current Nuclear Gamma-Ray Line Telescopes

INTEGRAL

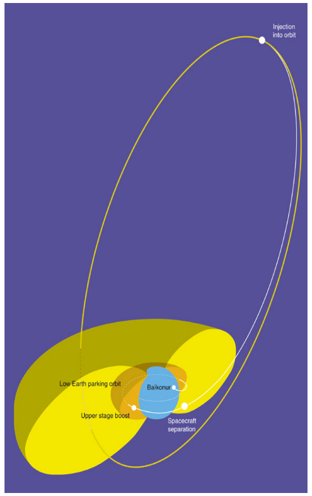
2002-(2018+..202x)

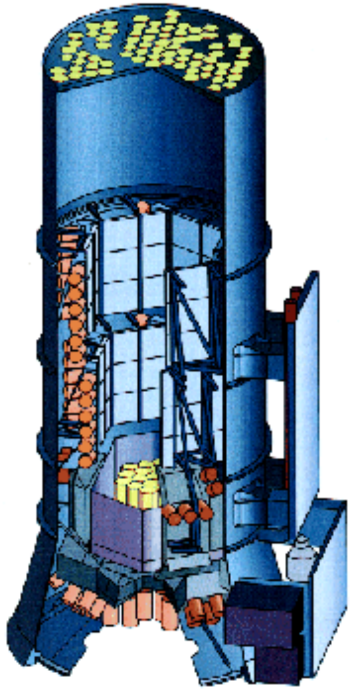
ESA

high E resolution

Ge detectors

15-8000 keV





NuSTAR (<80 keV!)

2012-(2018+) …

NASA

hard X ray

imaging <80 keV

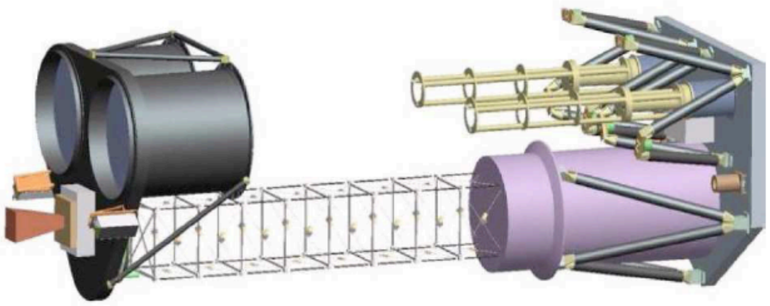


Fig. 1. NuSTAR telescopes in deployed configuration

Nuclear Gamma-Ray Lines

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	85 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	$3.8\ 10^6$y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	…. 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma..$	511, <511

individual object/event (^{7}Be – ^{44}Ti)

cumulative from many events (^{26}Al – e^+)

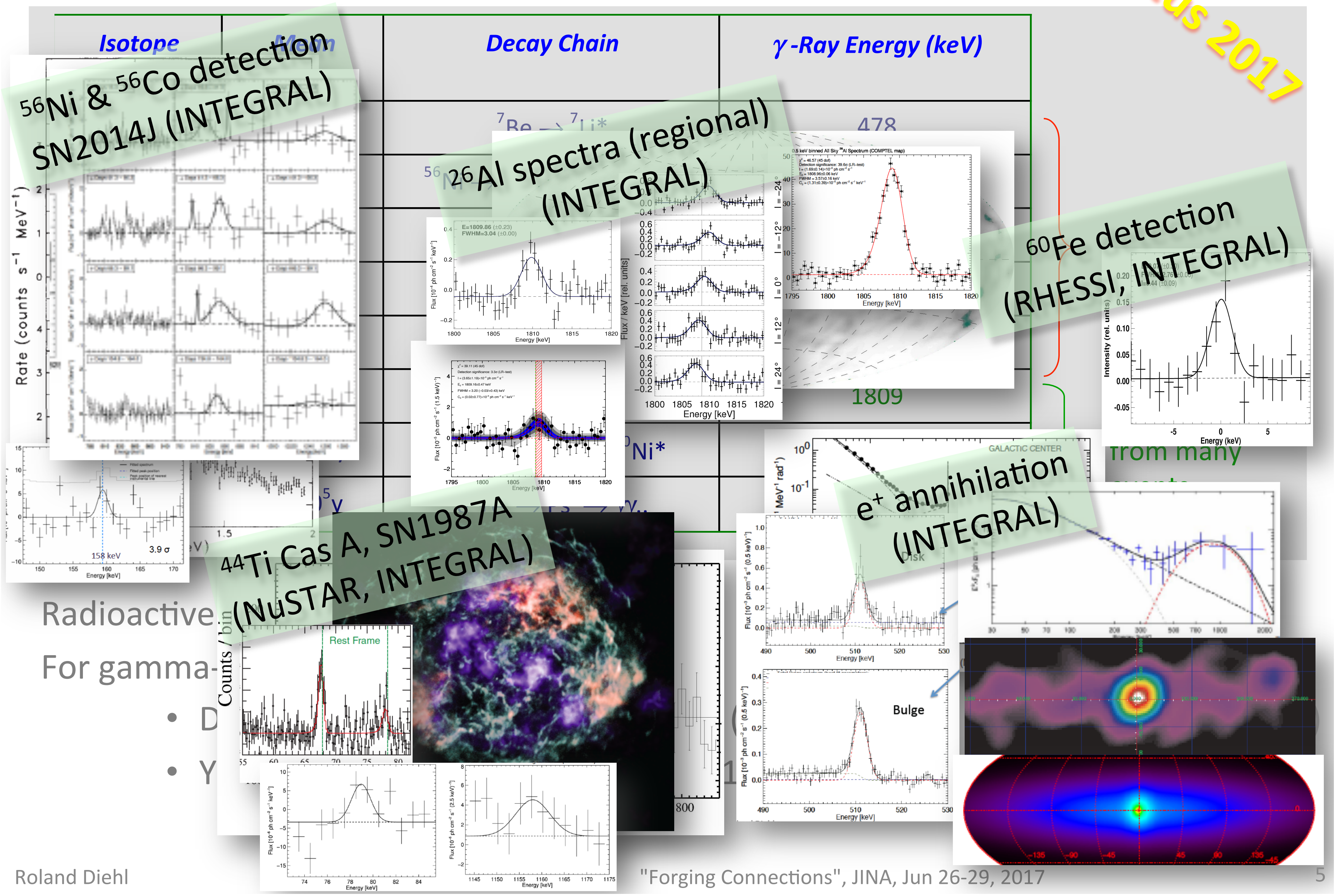
Radioactive trace isotopes are by-products of nucleosynthesis

For gamma-ray detections we need:

- Decay Time > Source Dilution Time (~weeks) (→ no < days lifetimes)
- Yields > Instrumental Sensitivities (10^{-5} ph cm^{-2} s^{-1}) (→ no elements > Fe)

Nuclear Gamma-Ray Lines

status 2017

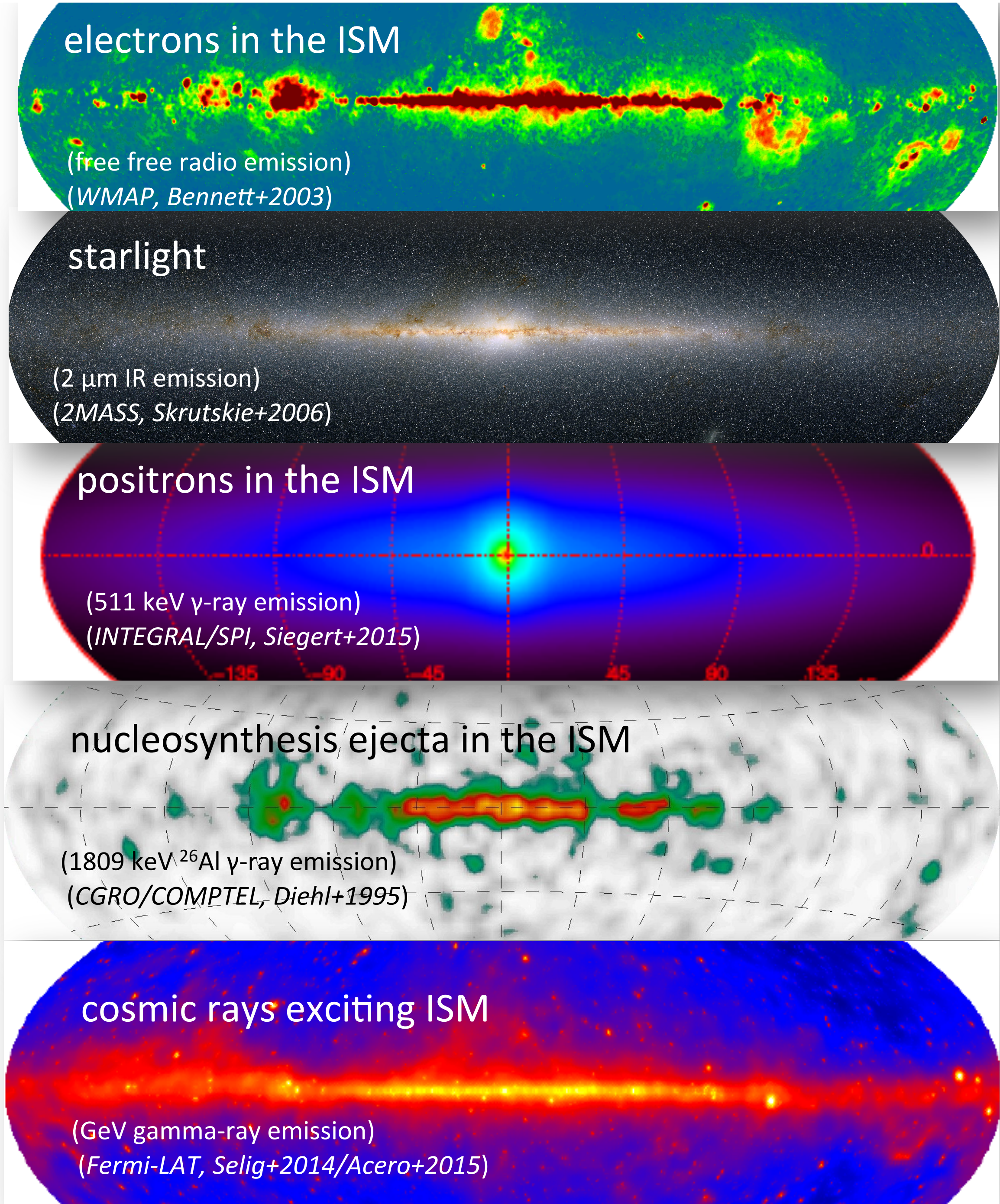


Summary

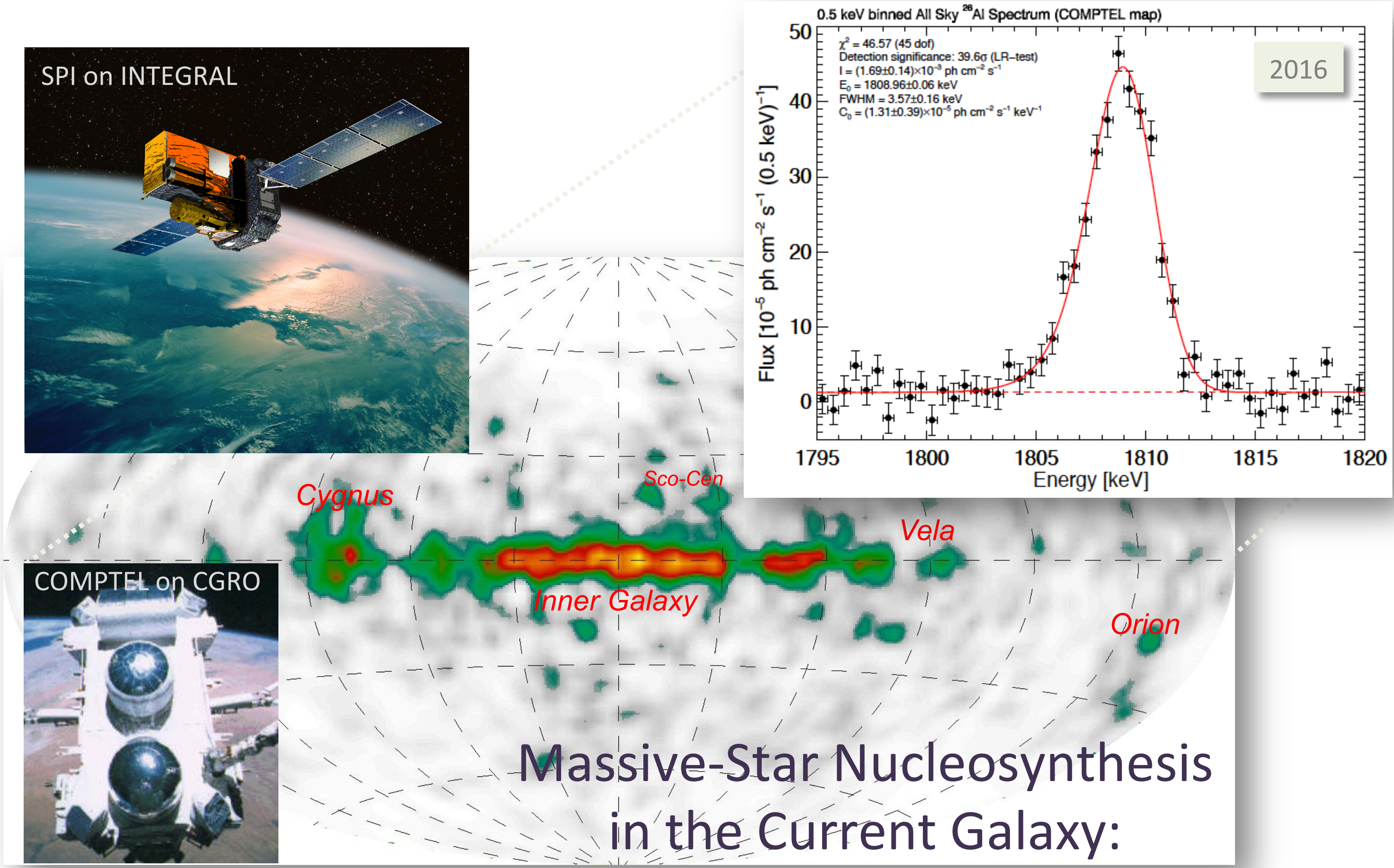
- ^{26}Al throughout the Galaxy→Superbubbles = hosts of nucleosynthesis ejecta from massive stars
- ^{26}Al in Sco-Cen, Orion → the dynamical ISM
- ^{60}Fe from ccSNe → structure of massive stars
- ^{56}Ni from SN type Ia → ignition, 3D morphology?
- ^{44}Ti from ccSNe: inner-region nucleosynthesis; kinematics of ejecta in SNR
- Positron annihilation → ??????
- Novae: Another "Lithium problem"??

^{26}Al Radioactivity: Special Messengers

- Radioactivity provides a clock
- ^{26}Al radioactivity gamma rays trace nucleosynthesis ejecta over ~few Myrs
- Radioactive emission is independent of density, ionisation states, …



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



Massive-Star Nucleosynthesis
in the Current Galaxy:

Current Enrichment (~My) from ^{26}Al γ-rays

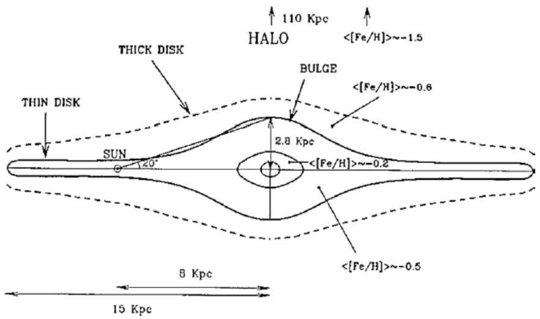
Using the ^{26}Al Line to Characterize the Galaxy’s SN Activity

→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2016)**

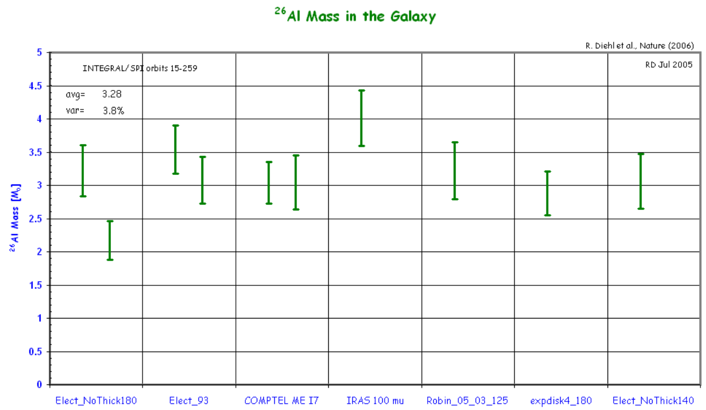
Measured Gamma-Ray Flux*

**) better account for foreground emission*

Galaxy Geometry

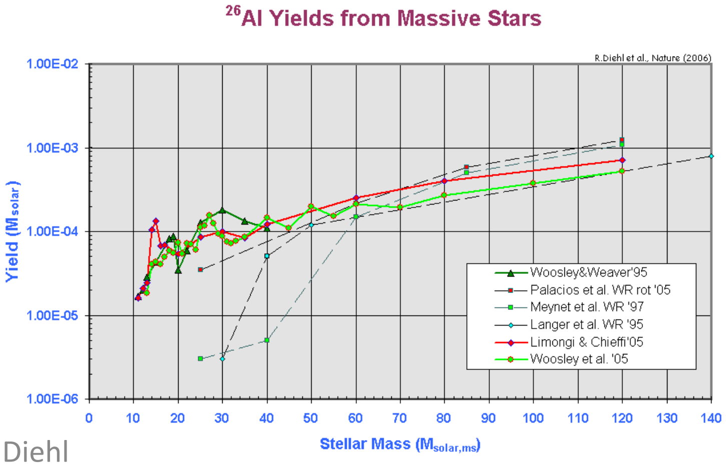


➢ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

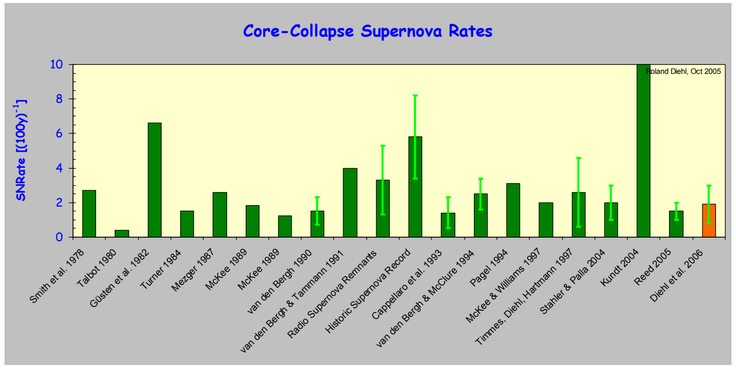


^{26}Al Yields per Star

Stellar Mass Distribution



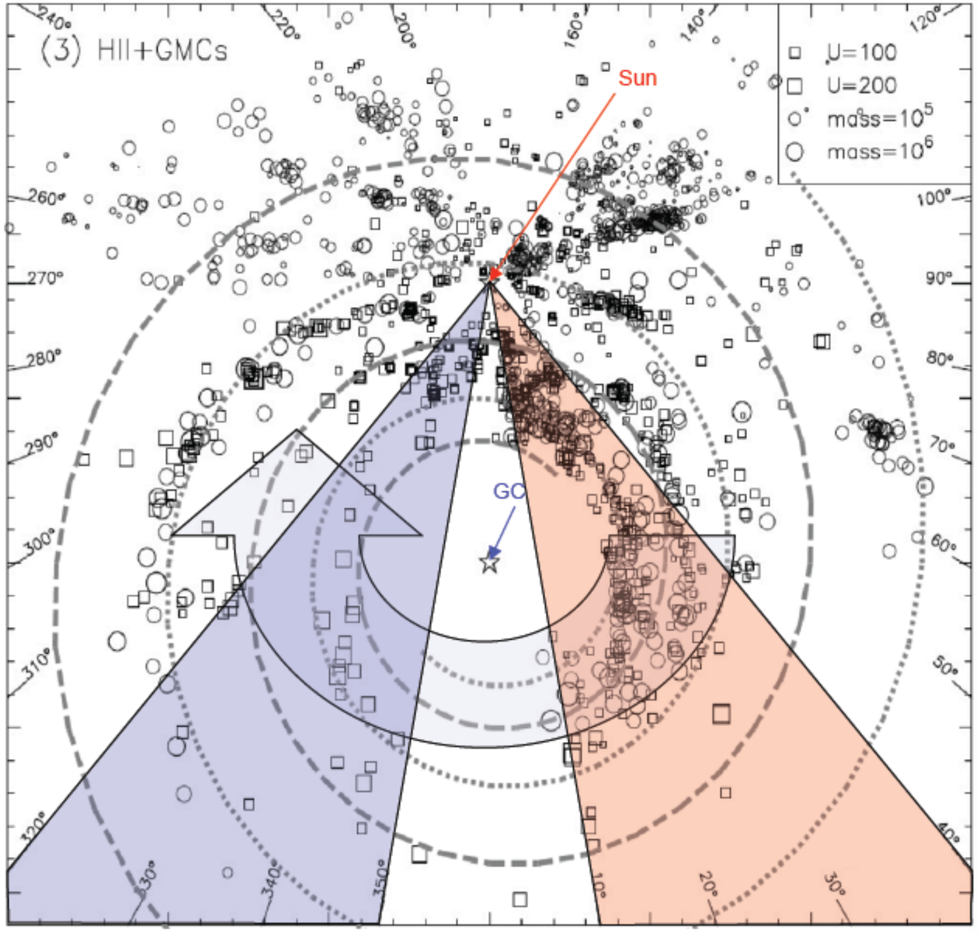
✓ **cc-SN Rate = 1.3 (± 0.4) per Century**

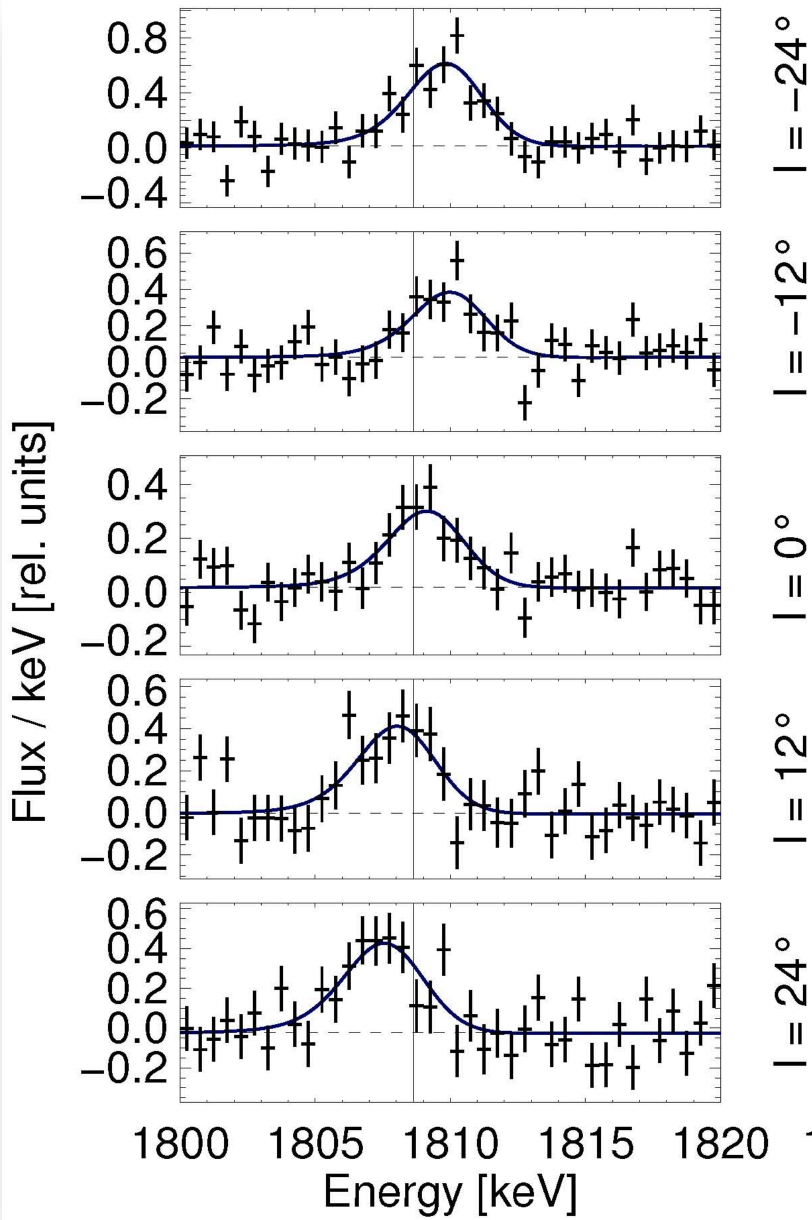


✓ Star Formation Rate = 2.8 $M_\odot$/yr

Views of SF in our Galaxy: ^{26}Al γ-rays

- Large-scale Galactic rotation

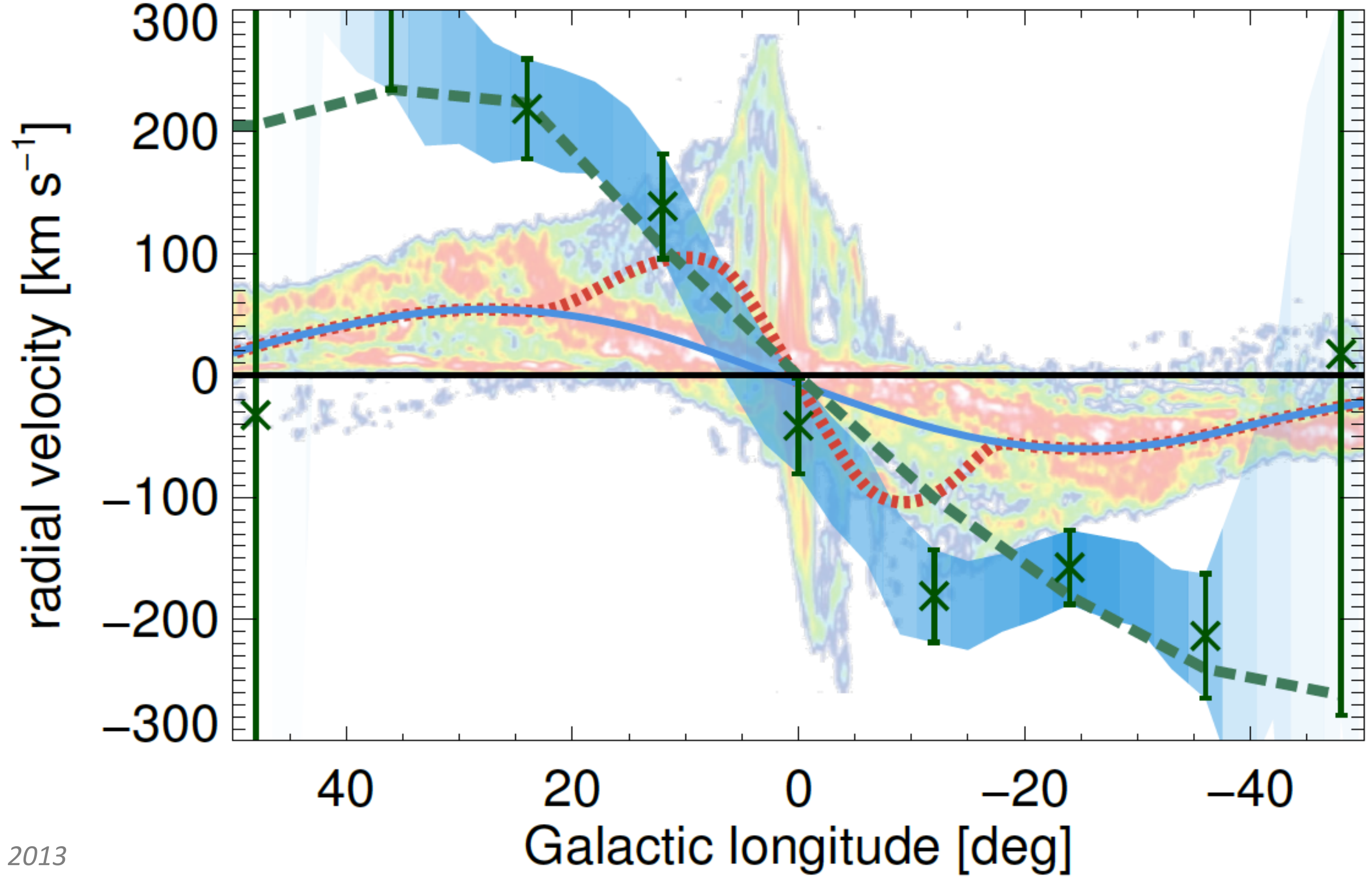




Kretschmer et al., A&A (2013)

The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



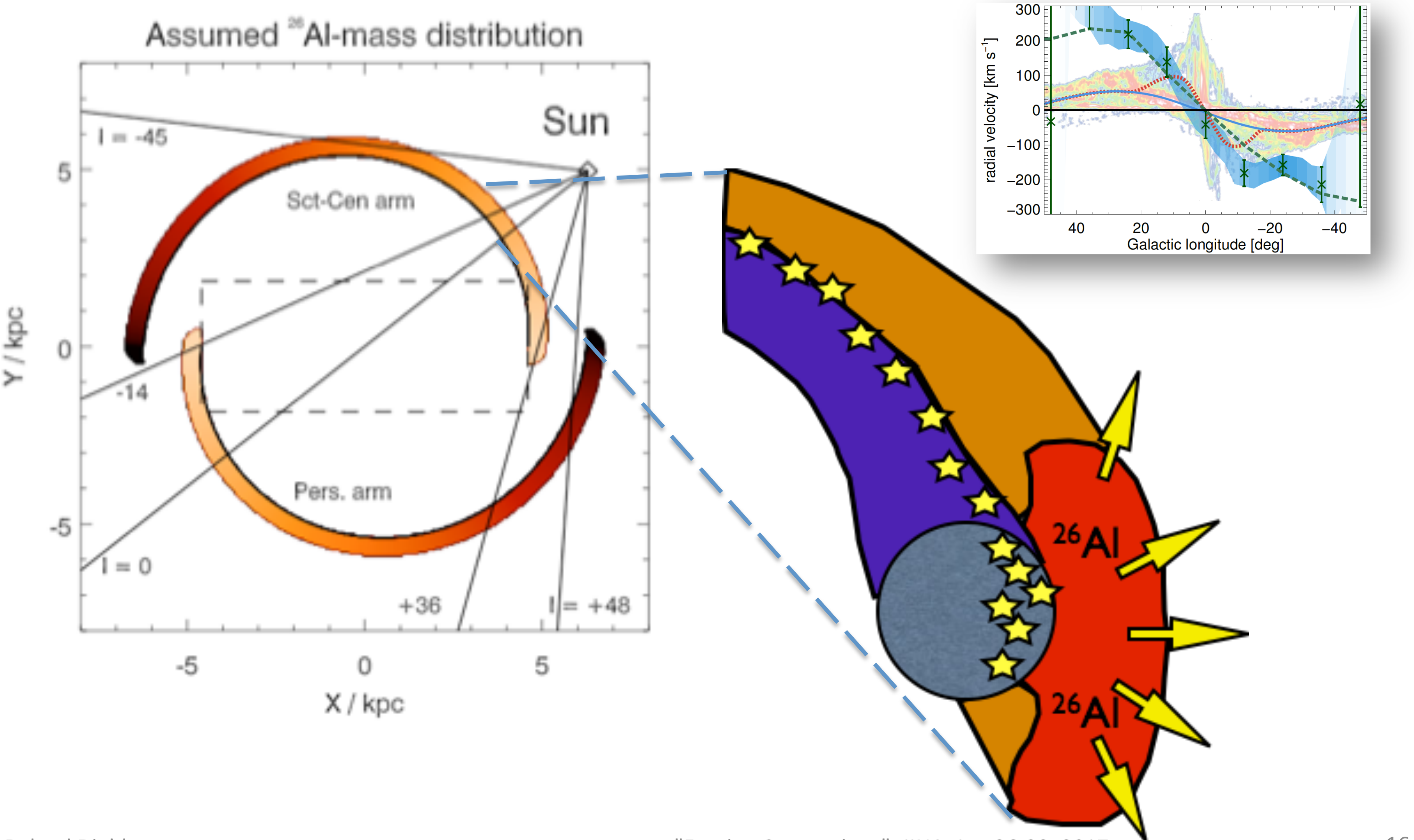
Kretschmer, Diehl, et al. 2013

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]

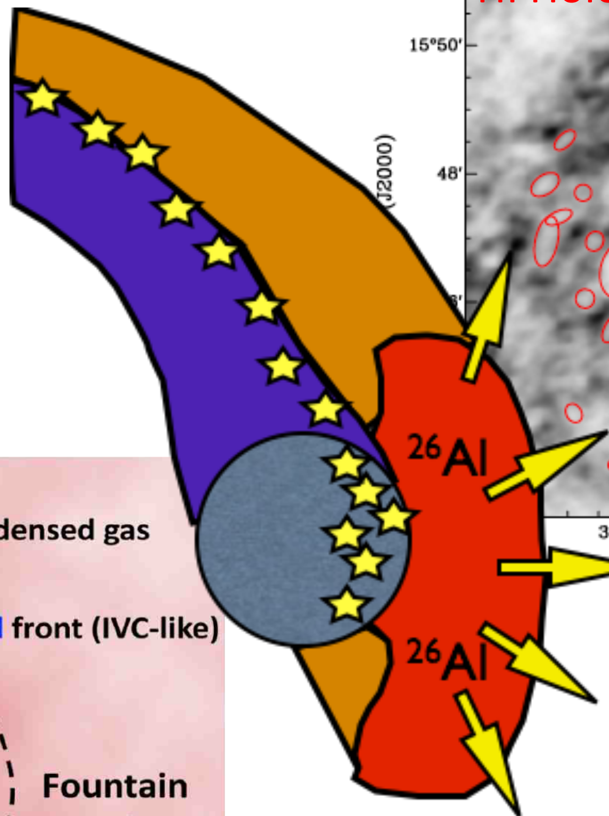
How massive-star ejecta are spread out…

- Superbubbles blown into inter-arm regions

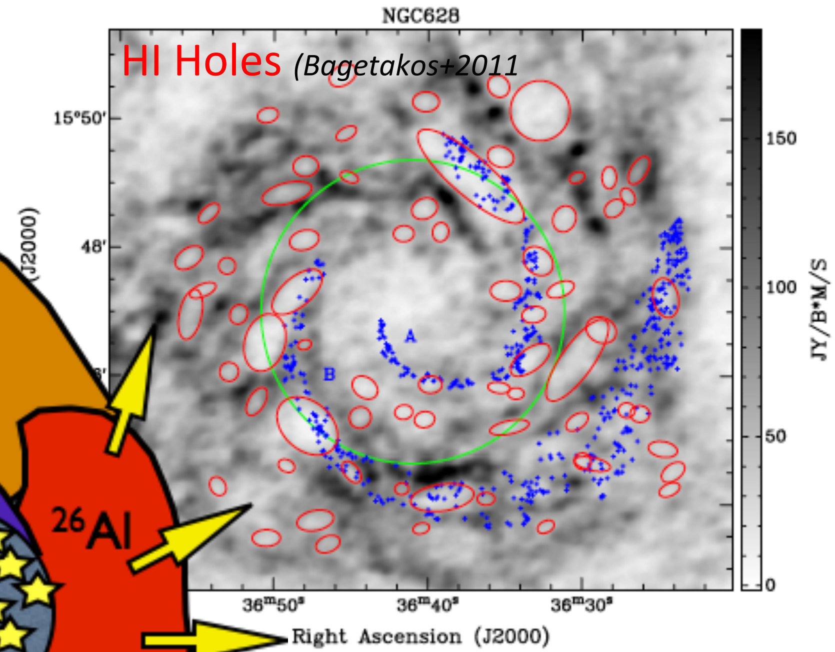


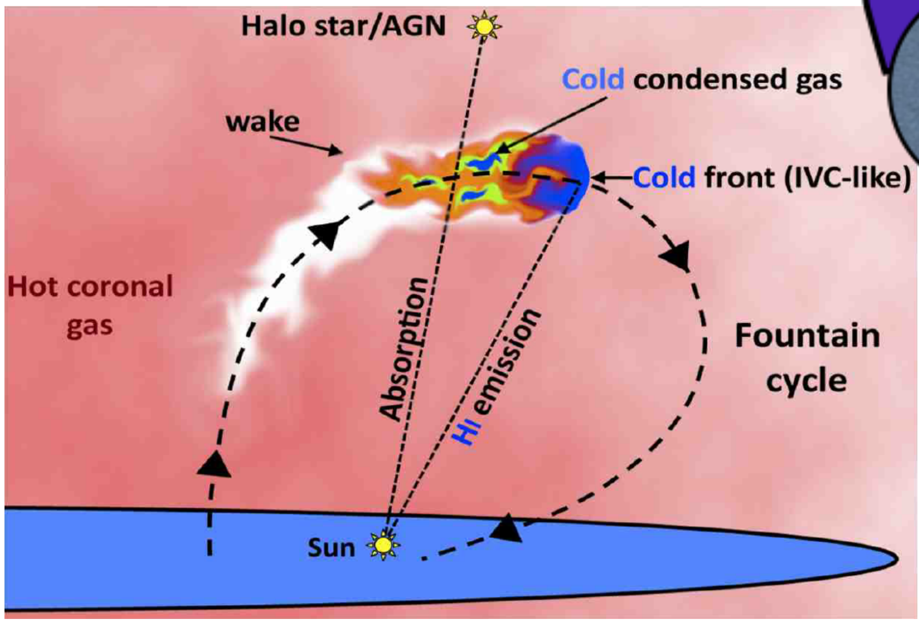
The Cycle of Gas in a Galaxy

- How the Galaxy's Disk and Halo "communicate"
  - Chimneys around massive-star groups eject gas into halo
  - Return time: IVC's?

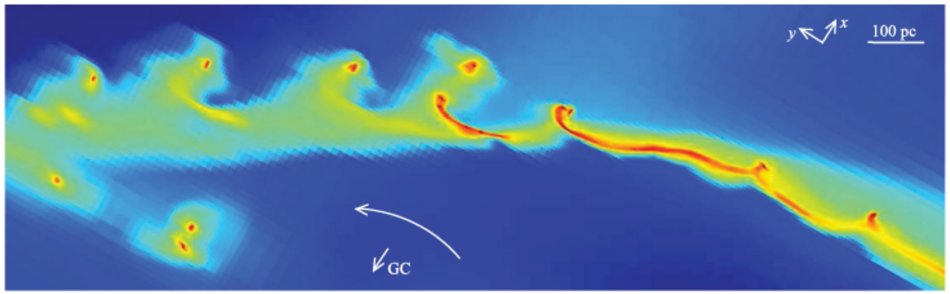


Renaud et al. 2014





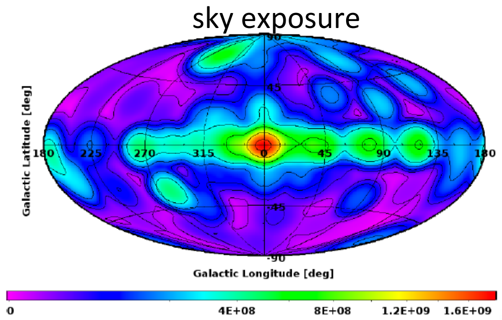
Marasco, Fraternai, & Binney 2011; Fraternali et al. 2013

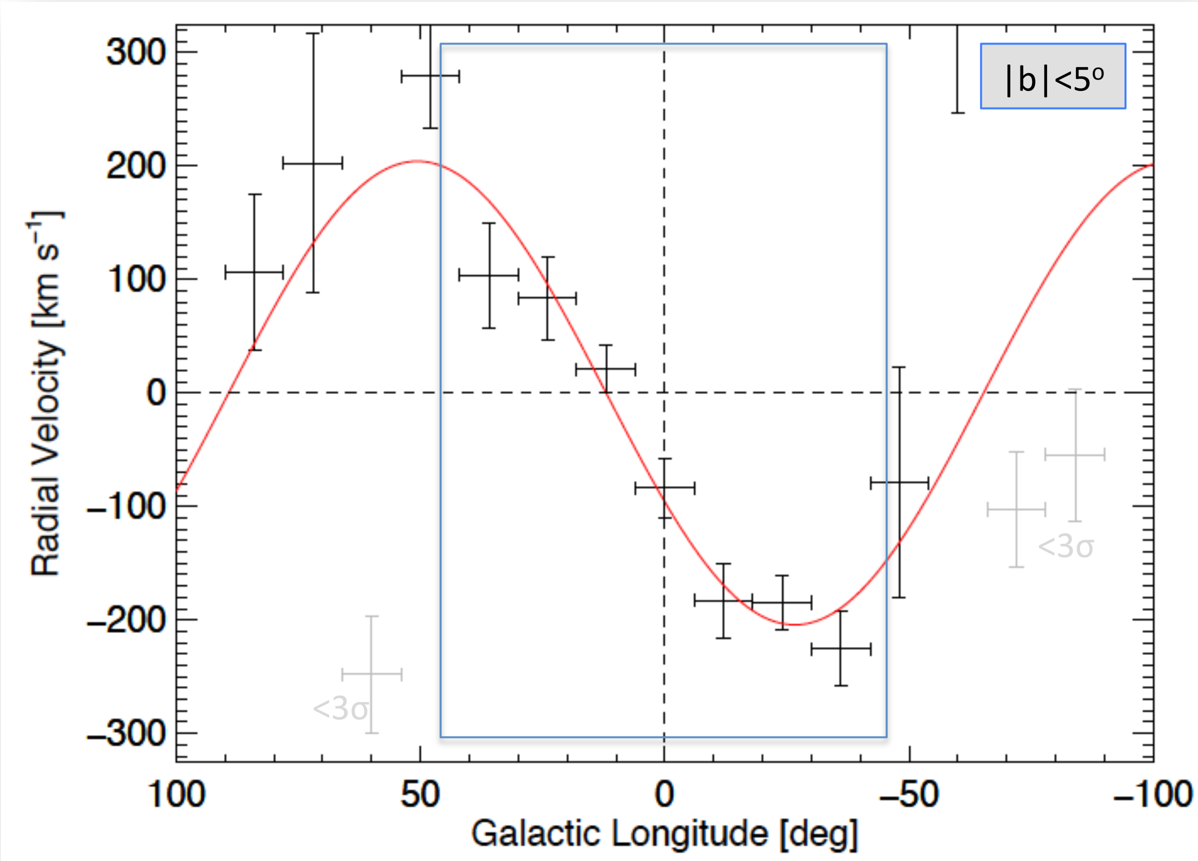


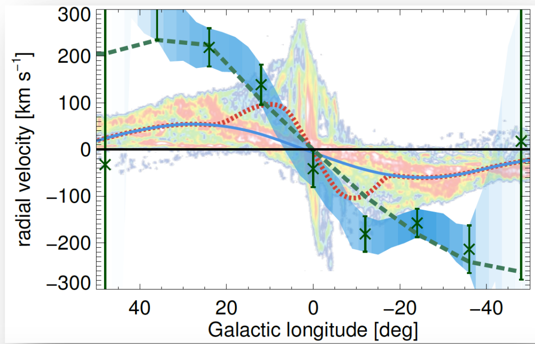
^{26}Al longitude vs. velocity: Update 2016

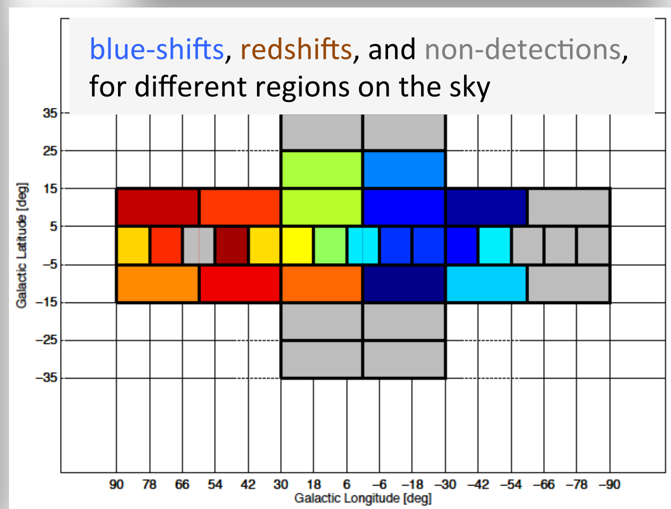
13 years of data (9), improved methods

→ confirm ~same characteristics









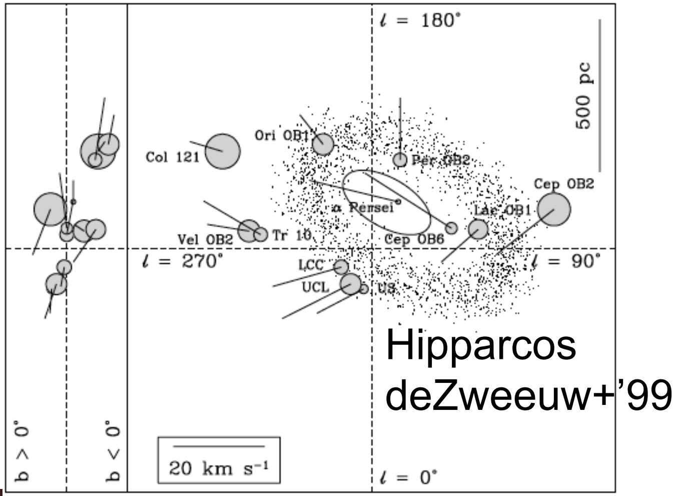
Resolving ^{26}Al Emission from Specific Groups of Stars

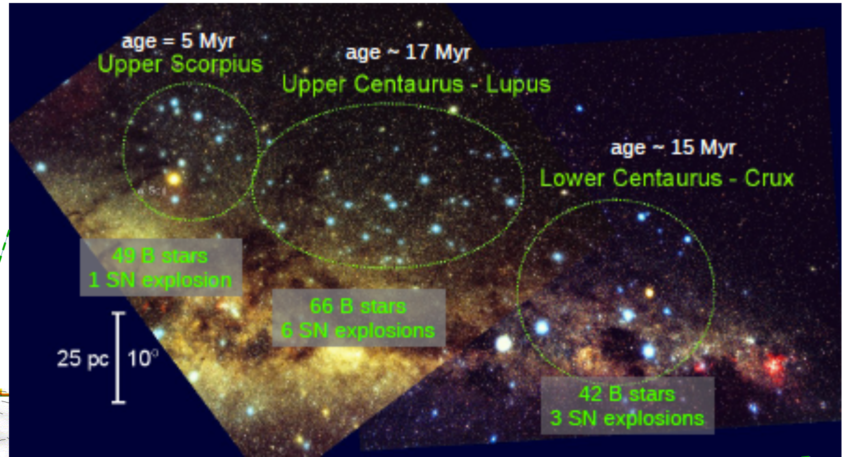
Groups of Stars:

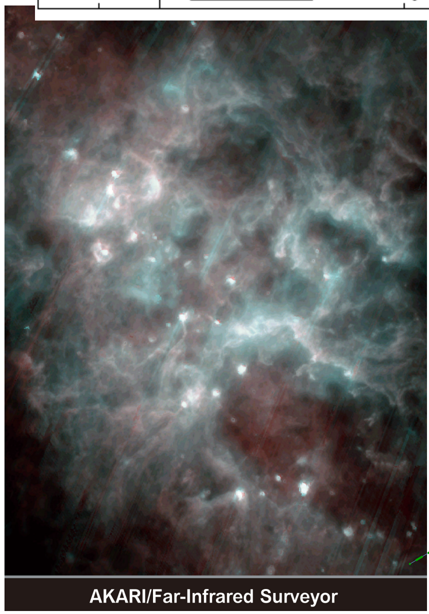
Test our Models for Consistency

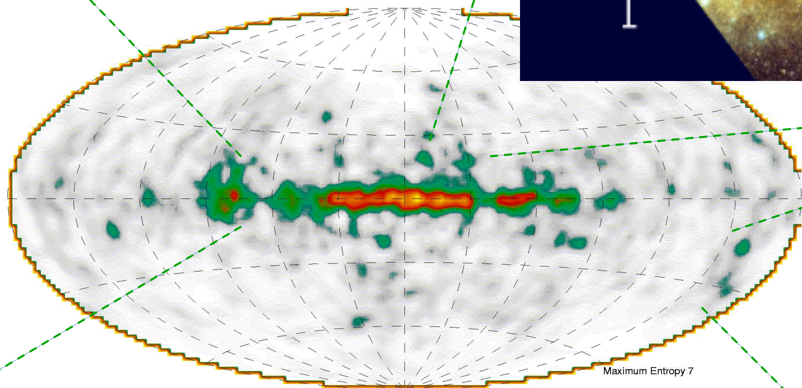
Separate WR-Wind from SN yields

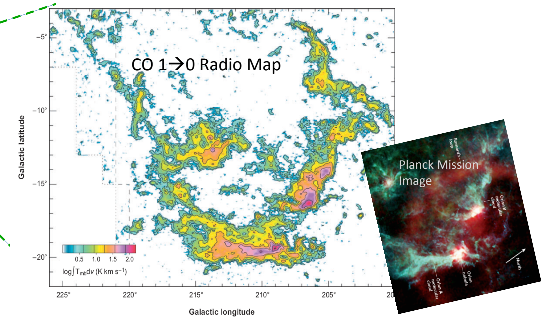
Measure ejecta kinematics







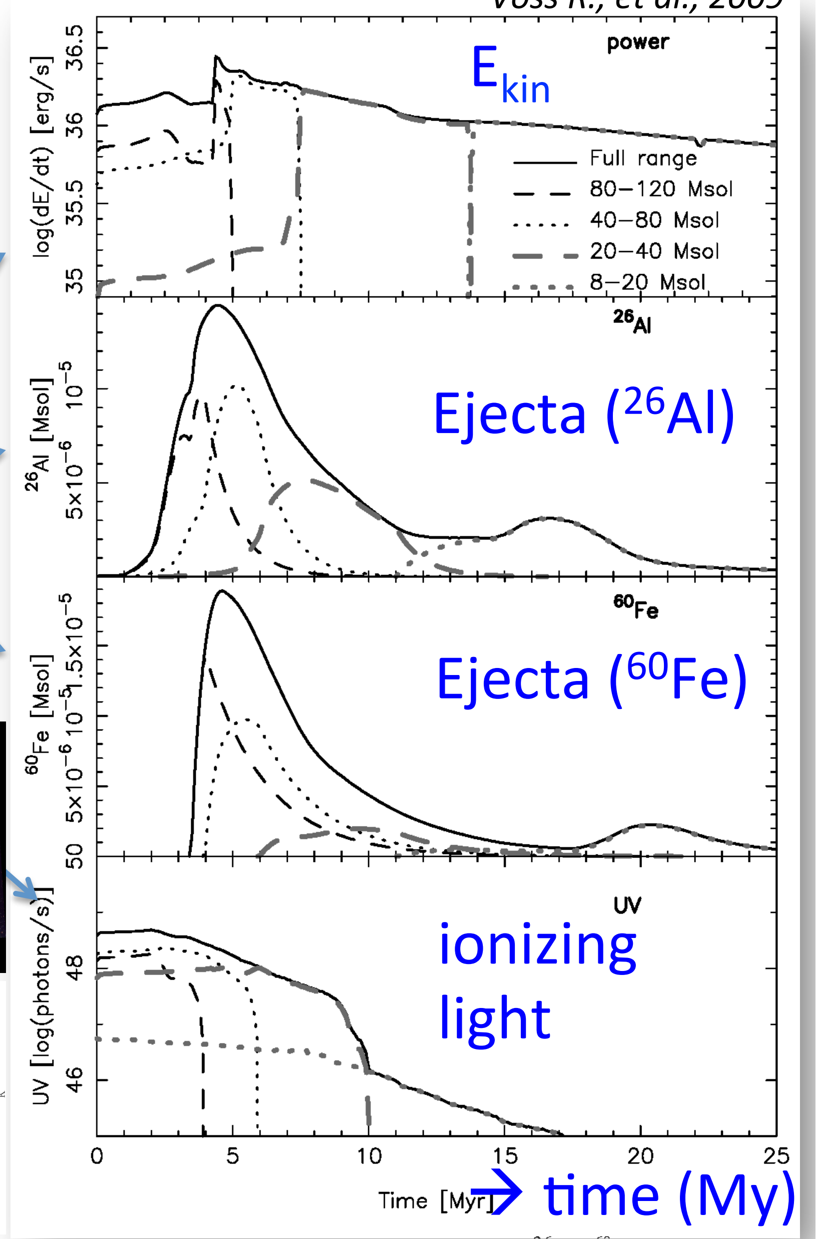


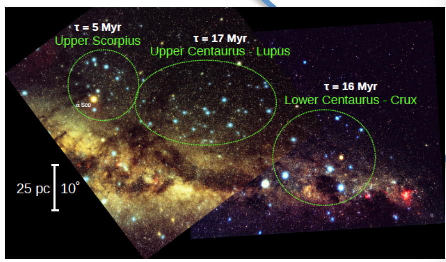


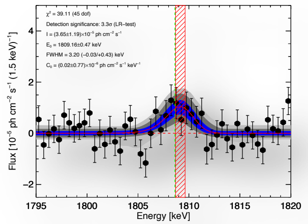
Massive-Star Groups

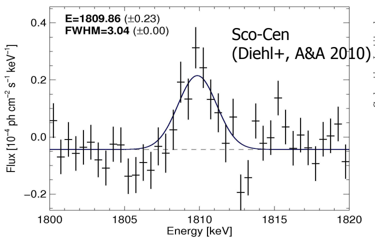
- We study the “outputs” of massive stars and their supernovae
  – Winds and Explosions
  – Nucleosynthesis Ejecta
  – Ionizing Radiation
- We get observational constraints from
  – Star Counts
  – ISM Cavities
  – Free-Electron Emission
  – Radioactive Ejecta

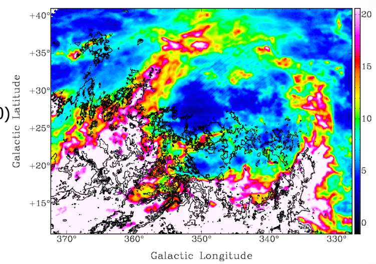
Voss R., et al., 2009



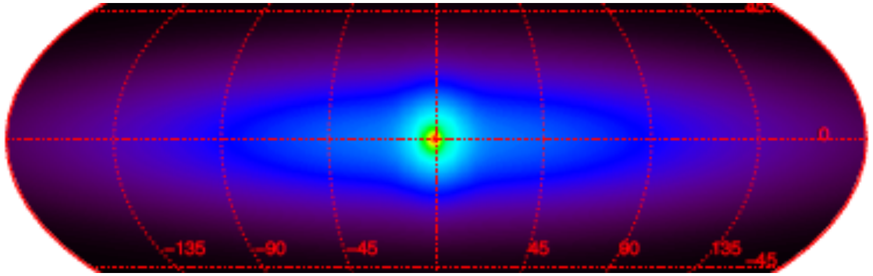




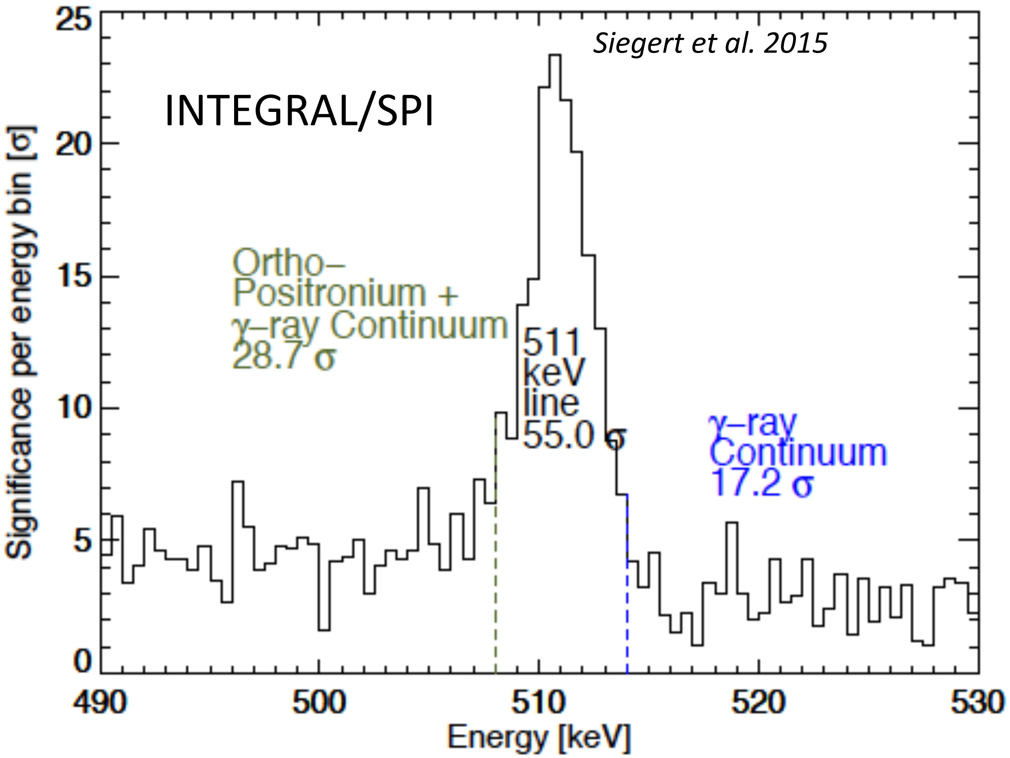


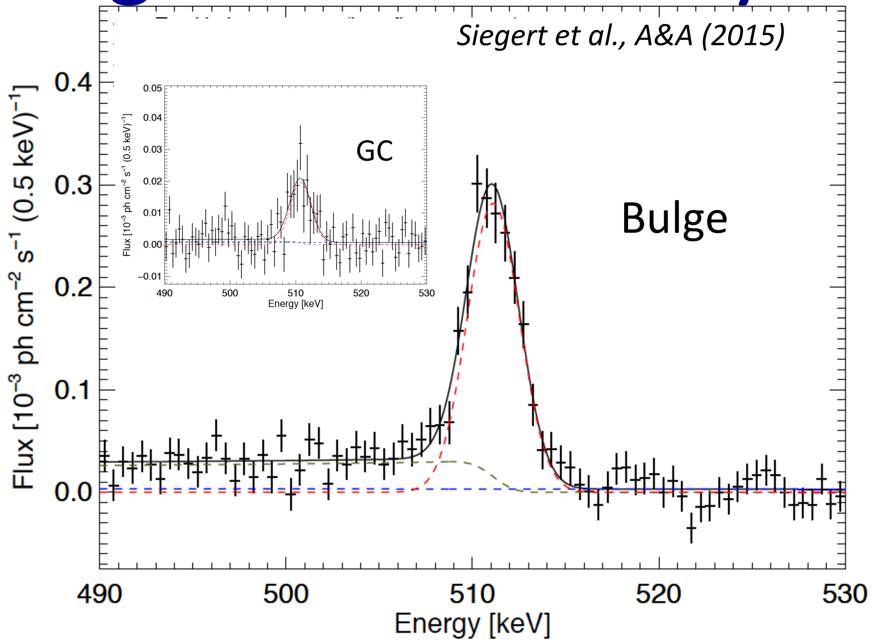


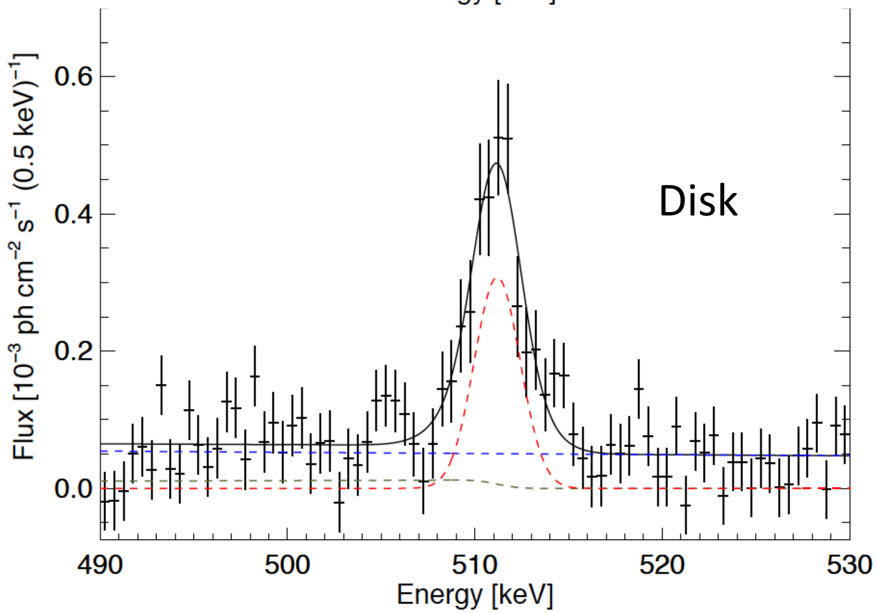
Positron annihilation throughout the Galaxy



– Derive/discriminate spectra from different regions





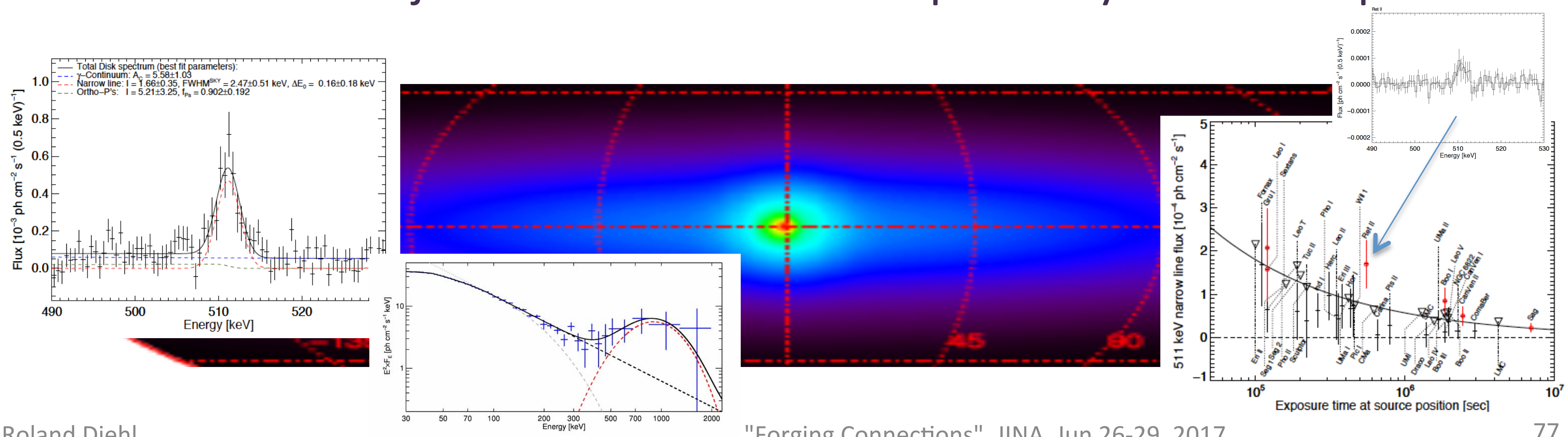


Understanding the 511 keV Line Emission

After 12 y of measurements and various different analyses

- *Knödlseder+ 2005, Jean+ 2005, Weidenspointner+ 2008, Bouchet+ 2011, Skinner et al. 2013, 2015a,b, Siegert+ 2016a,b*

- None of the plausible candidate sources produces morphology
- The disk appears quite extended / thick → e^+ outflows?
- Sources:
  - Only ^{26}Al is an established e^+ source/injector
  - Dark matter contributions are unlikely/small
  - Injections from pulsars, microquasars (!), SNe, novae, …
    all are plausible. How then the bulge enhancement?
- Positron injection and annihilation probably are 'decoupled'

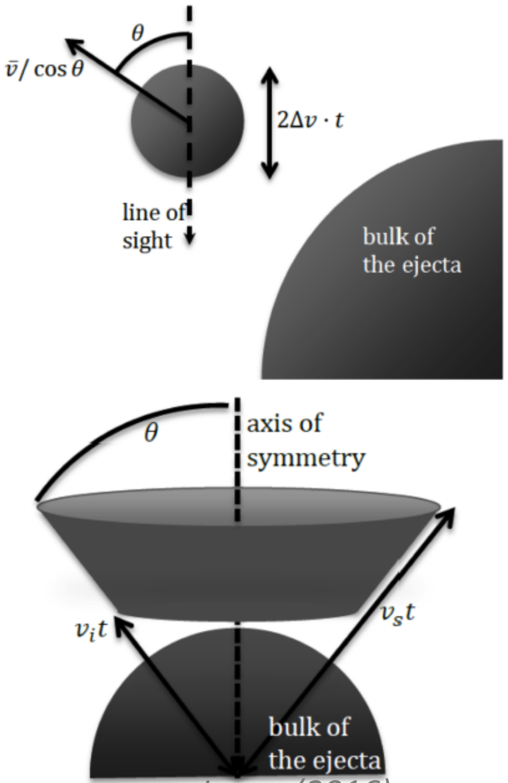


- Supernovae

SN2014J: An unusual explosion?

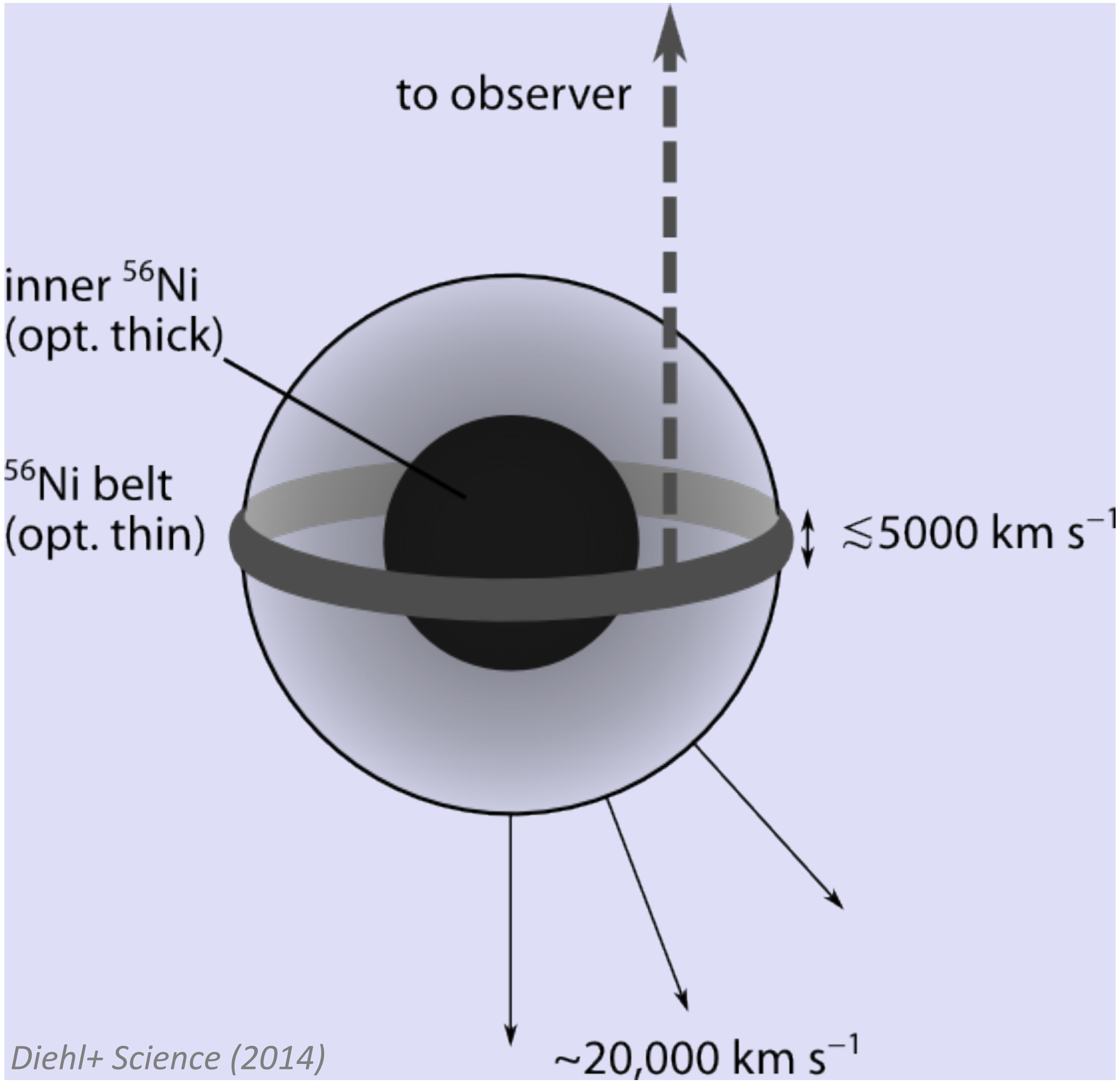
- SN2014J had significant ^{56}Ni near the surface

Possible geometries of outer ^{56}Ni:



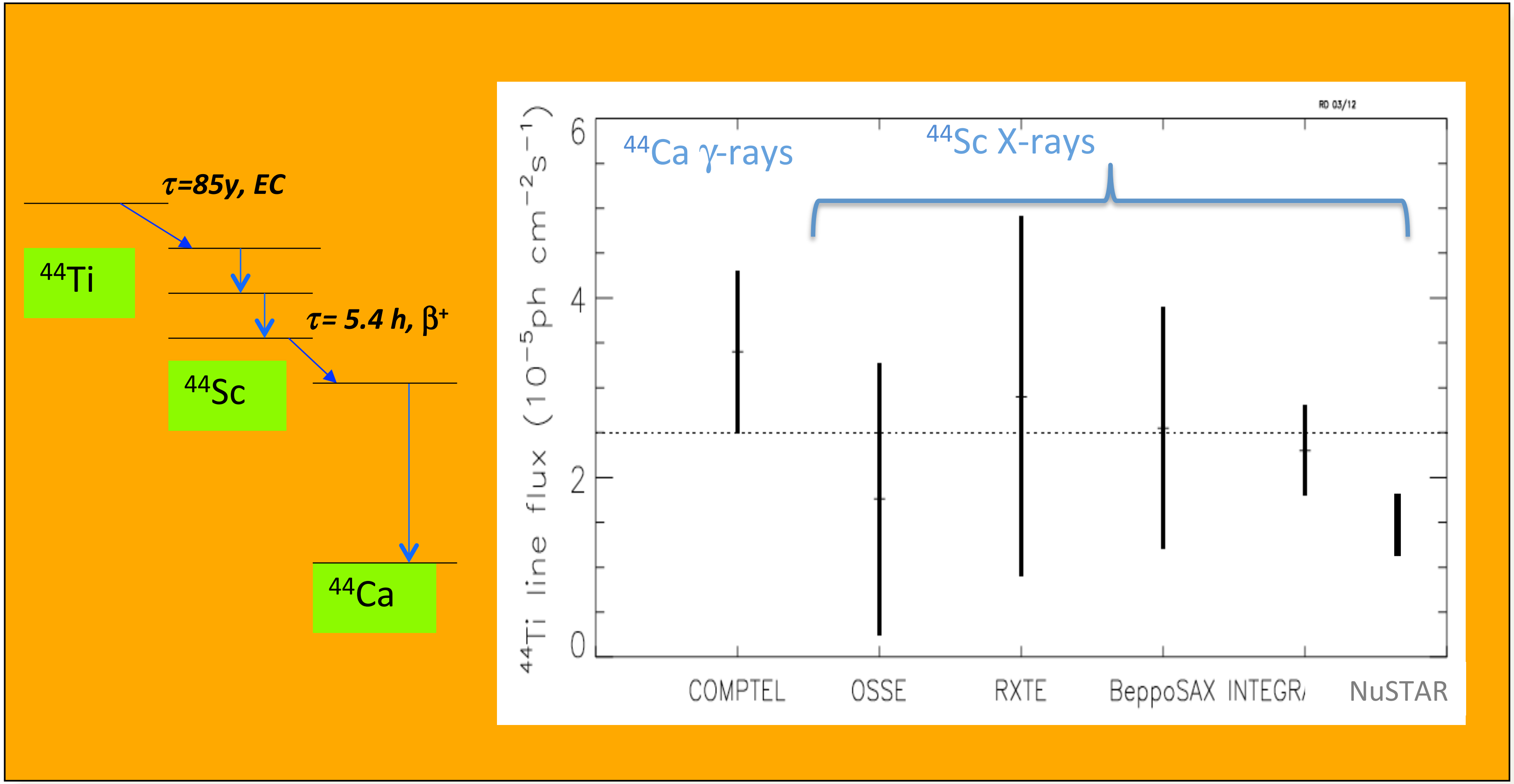
Isern+(2016)

A belt of He accreted from the companion star → He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)



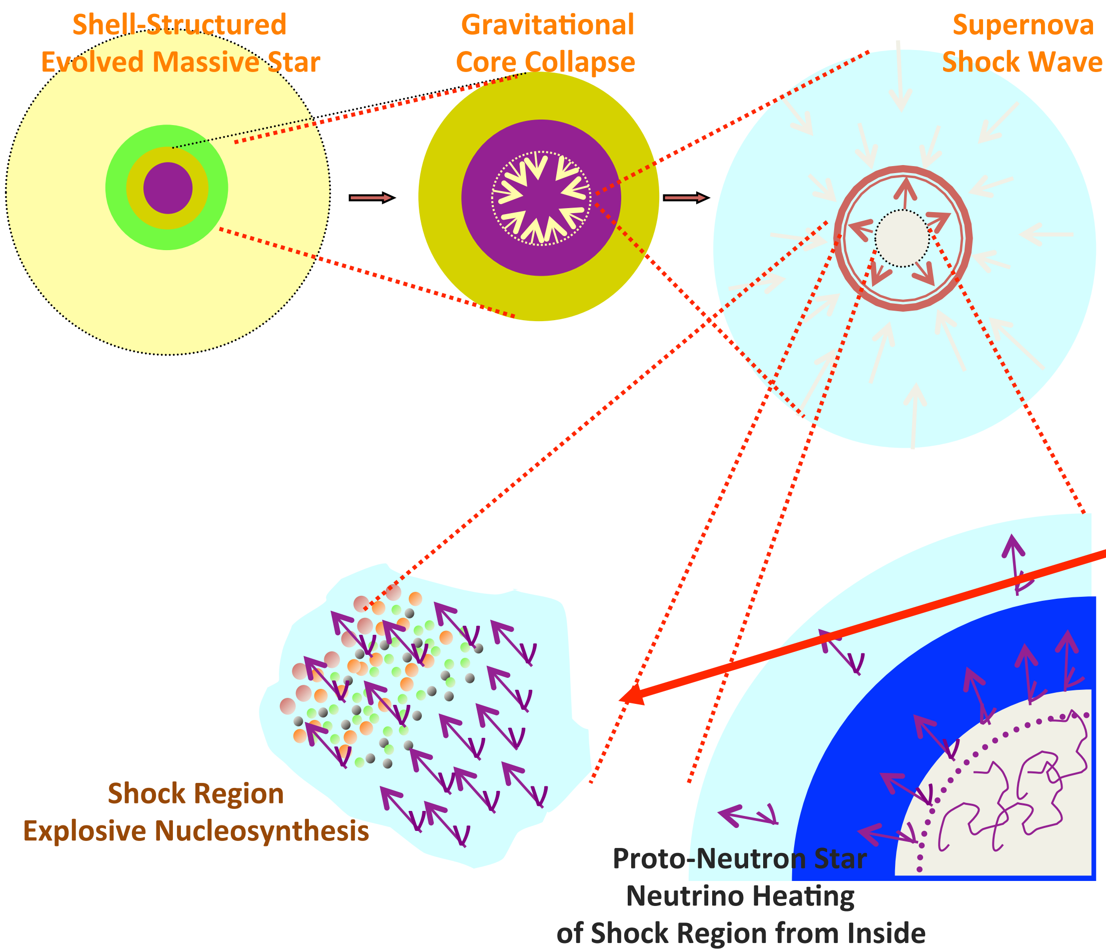
Diehl+ Science (2014)

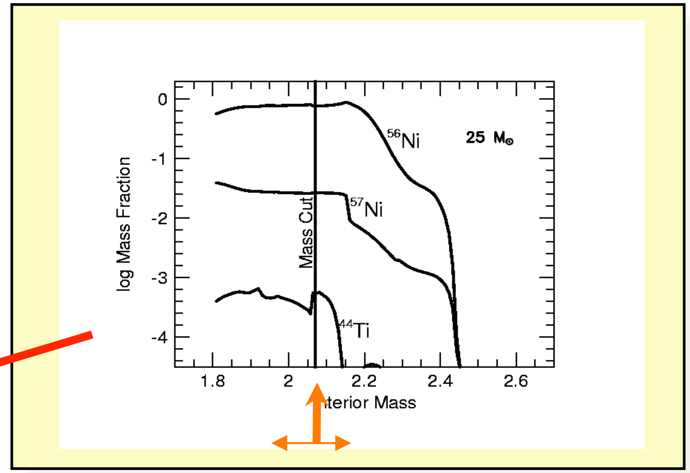
^{44}Ti γ-rays from Cas A

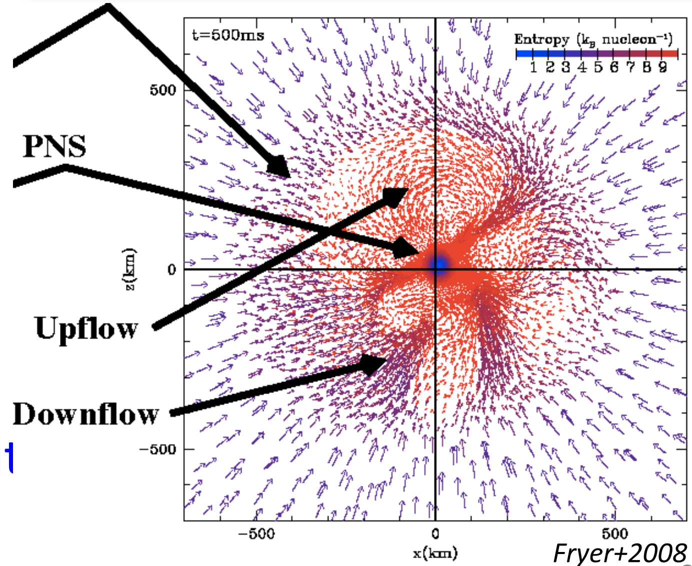


↳ ^{44}Ti Ejected Mass ~1.23 $_{\pm 0.25}$ 10^{-4} $M_\odot$

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







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

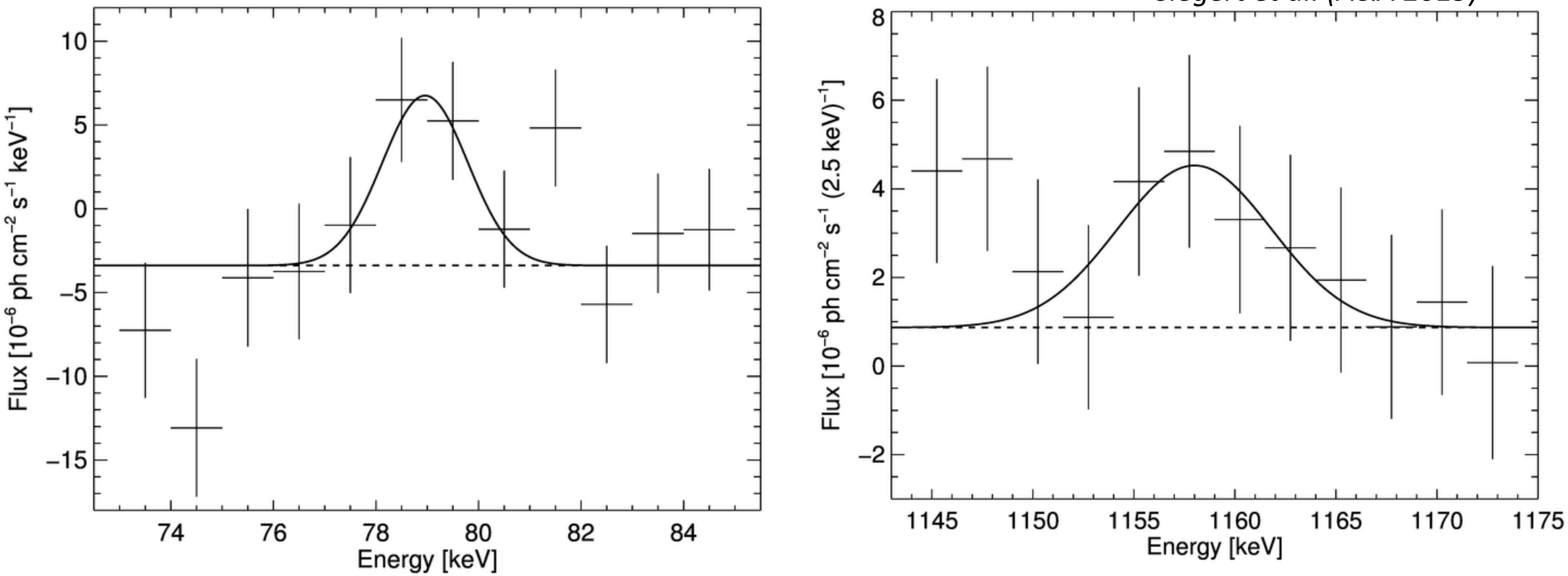
  => Unique Probe (+Ni Isotopes)

SPI Re-Analysis of Cas A for ^{44}Ti

Using cumulative data from >12 years,
and a new instrumental-background treatment

→ We see the 78 keV and 1157 keV line emission

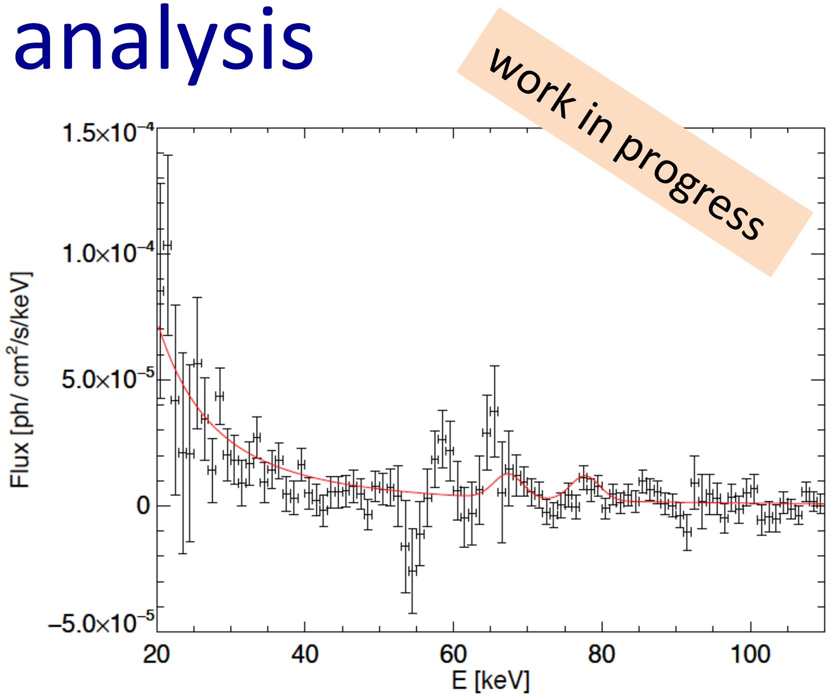
Siegert et al. (A&A 2015)

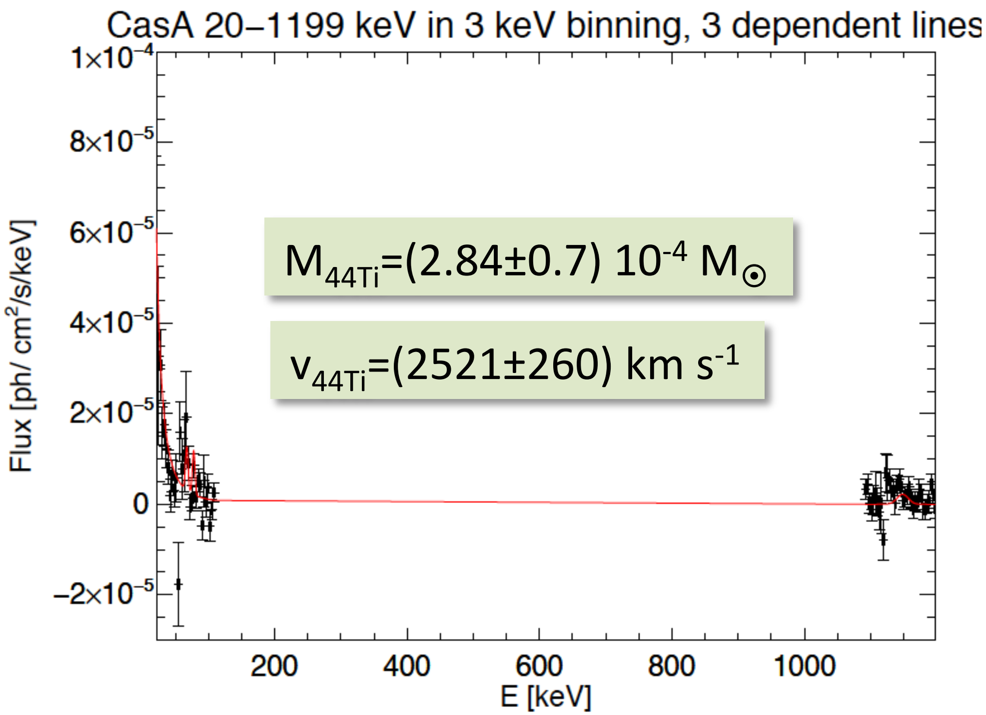


– Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)

Update: 3-line analysis

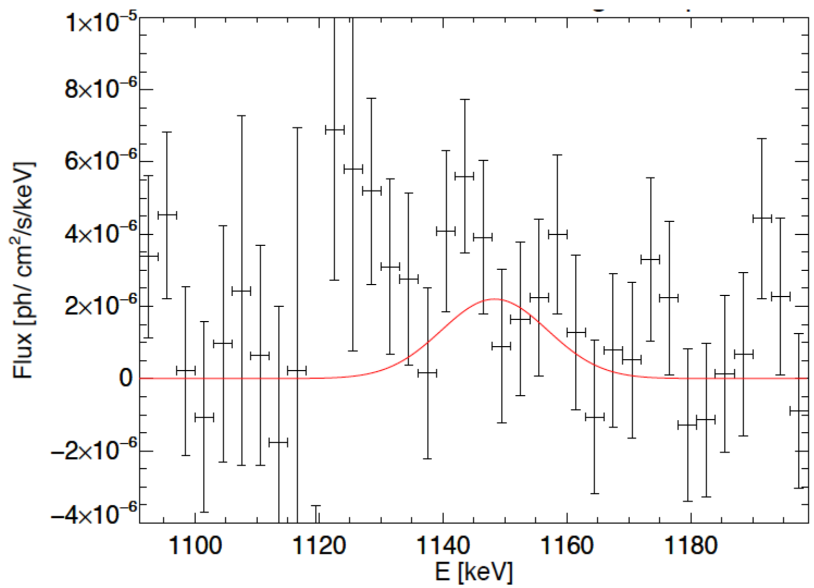
- INTEGRAL Deep Exposure Program 2016-2017
  - » additionally 2 Msec of Cas A & Tycho region; currently: ~8.6 Ms
- Refined analysis (Weinberger+, preliminary)
  - » use templates for blended-lines background features
  - » constrain ^{44}Ti through 3-line set (one line amplitude + cont fitted)





M_{44Ti}=(2.84±0.7) 10^{-4} $M_{\odot}$

v_{44Ti}=(2521±260) km s^{-1}



Update: 3-line analysis

work in progress

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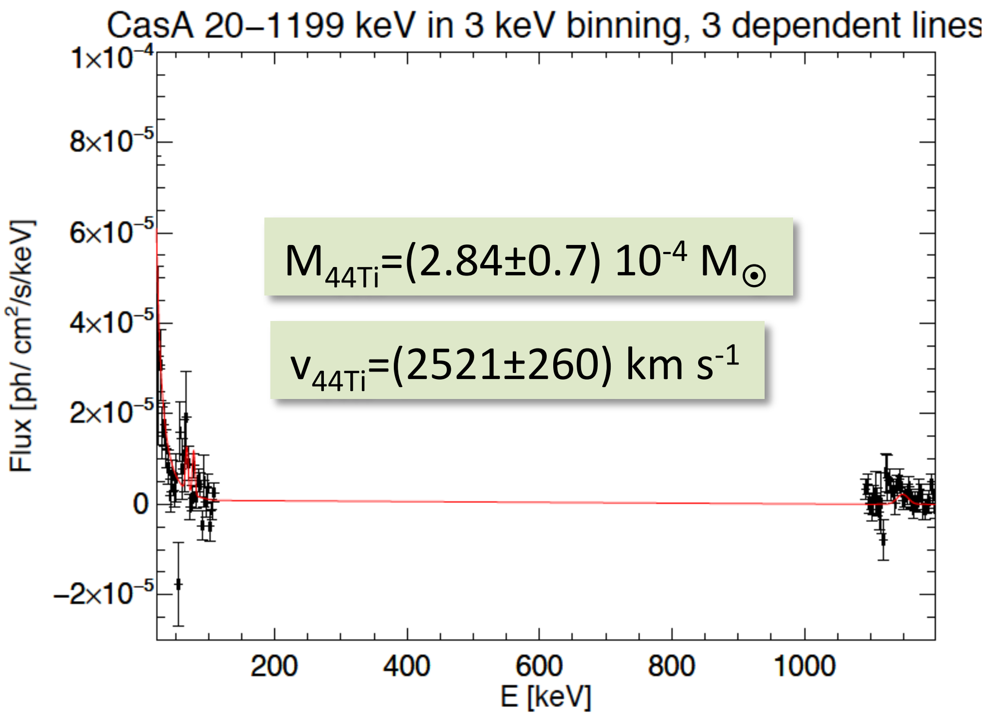
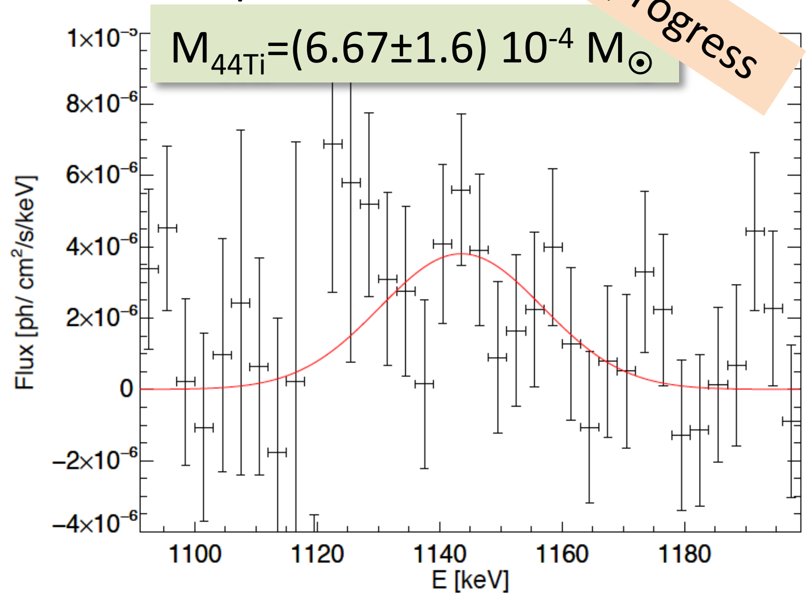
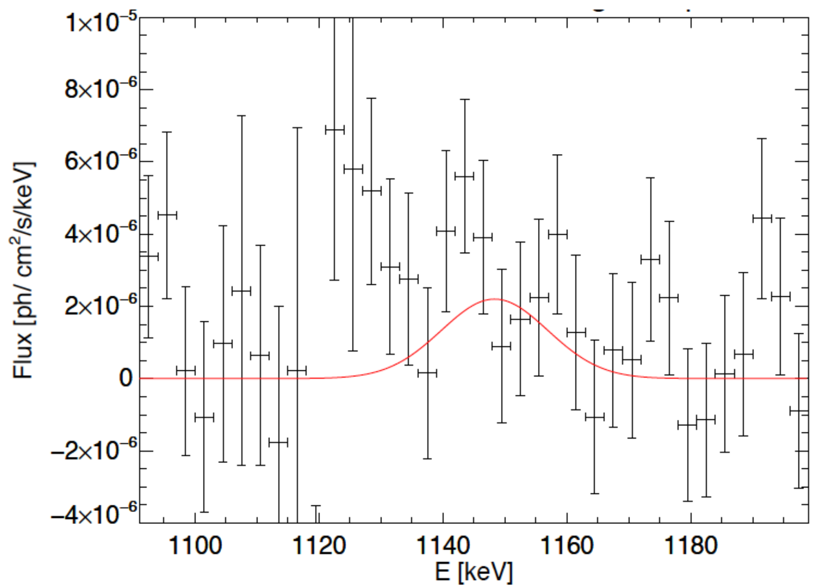


Independent →





Nuclear Gamma-Ray Lines....

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	85 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	$3.8\ 10^{6}$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

individual object/event

cumulative from many events

....include exciting news.

Thank you for staying with me!

Summary

- ^{26}Al throughout the Galaxy → Superbubbles = hosts of nucleosynthesis ejecta from massive stars
- ^{26}Al in Sco-Cen, Orion → the dynamical ISM
- ^{60}Fe from ccSNe → massive star shell burning, n src
- ^{56}Ni decay diagnostics from SN type Ia: ignition, 3D?
- ^{44}Ti from ccSNe: inner-region nucleosynthesis; kinematics of ejecta in SNR
- Nuclear de-excitation lines as probe of CR sources
- Positron annihilation: Sources? ISM, CR transport??
- Novae: Another "Lithium problem"?