Observational Constraints from Gamma-Rays

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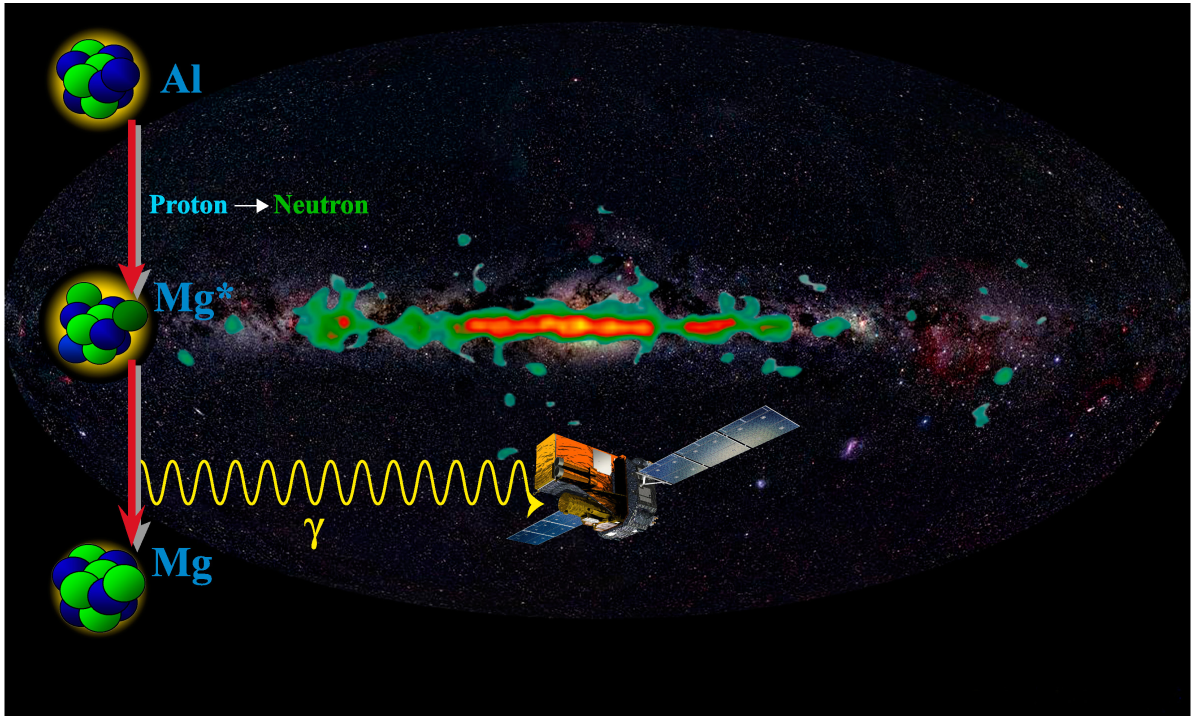
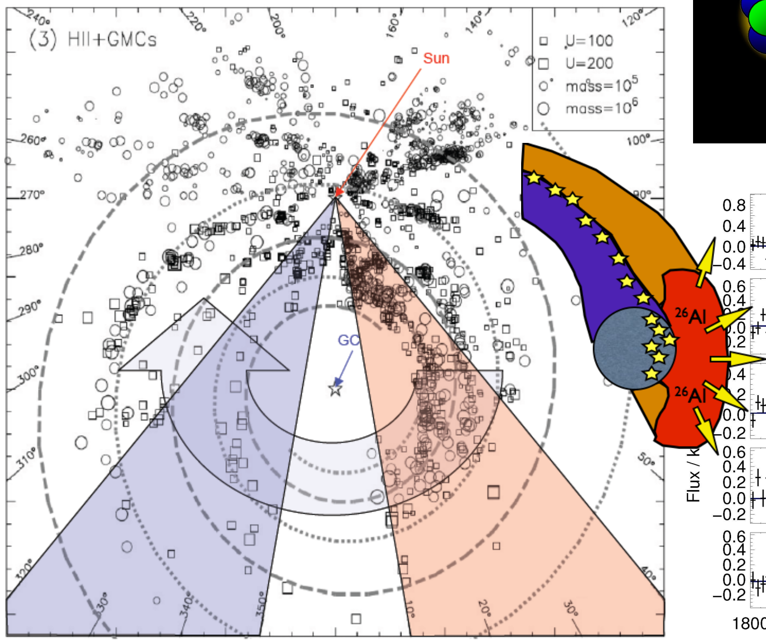
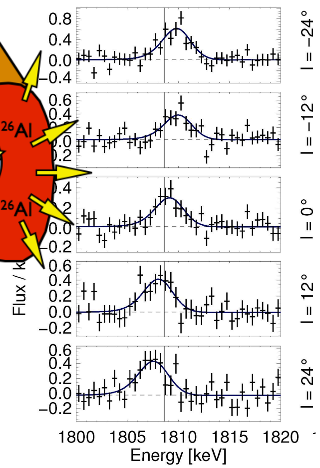
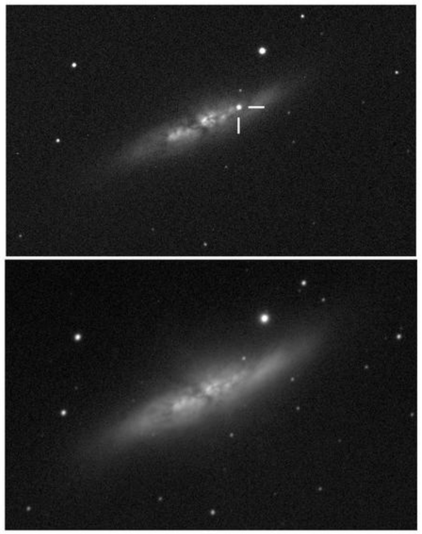
with
Martin Krause, Karsten Kretschmer, Thomas Siegert,
and ….. Breitschwerdt, Burkert, … Kroupa, …Preibisch…Vink, …

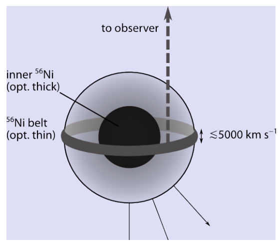
Massive Star Groups across the Galaxy, and Supernovae

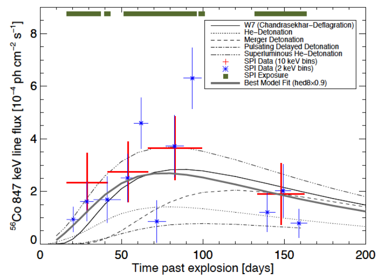






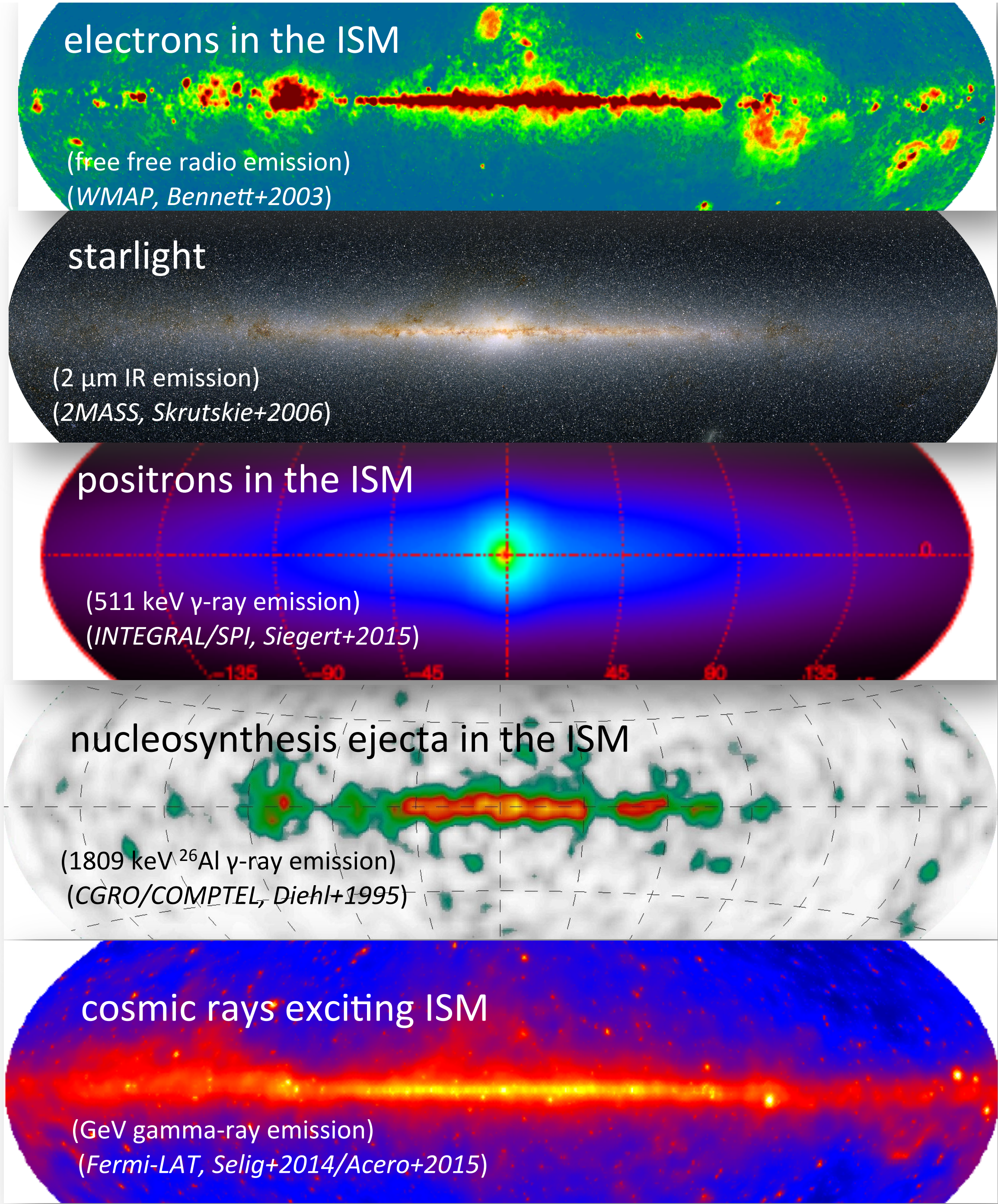




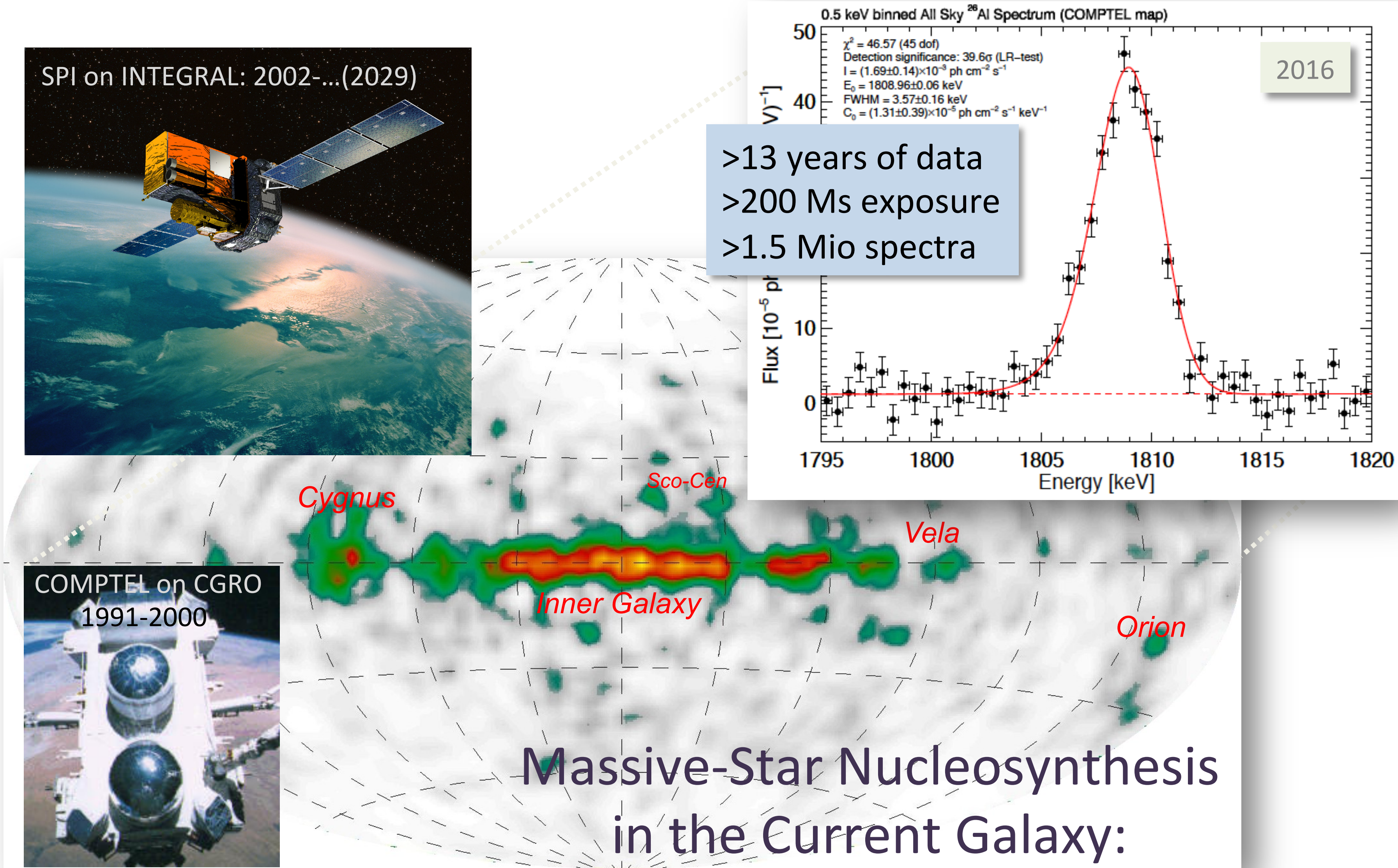


Special Messengers: ^{26}Al Radioactivity, Positrons

- Radioactivity provides a clock
- ^{26}Al radioactivity traces nucleosynthesis ejecta over ~few Myrs
- Such γ-ray emission is independent of density, ionisation states, …
- Positrons produce a characteristic spectrum upon annihilation
  → e^+ in the ISM



^{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

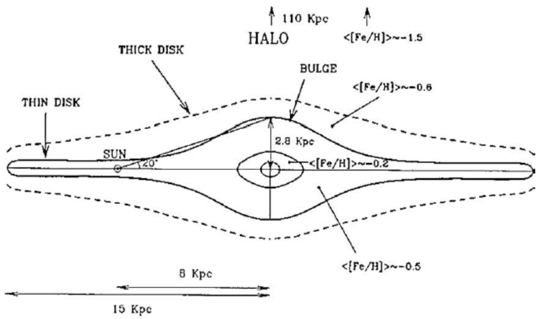
→ *Diehl et al., Nature 2006*
→ *Diehl et al., A&A 2010**
→ *Diehl et al., in prep. (2016)**

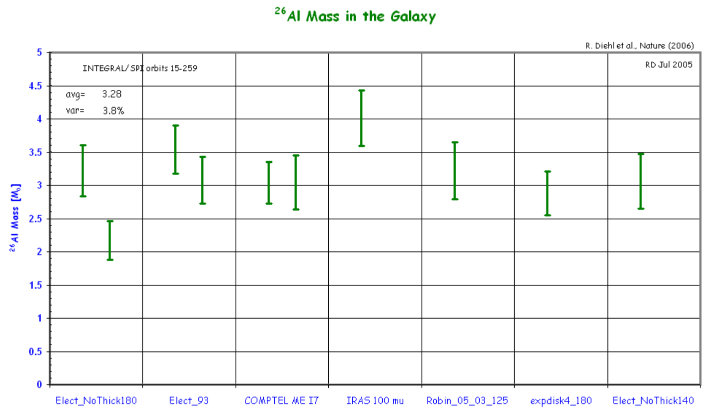
Measured Gamma-Ray Flux*

**) better account for foreground emission*

Galaxy Geometry

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

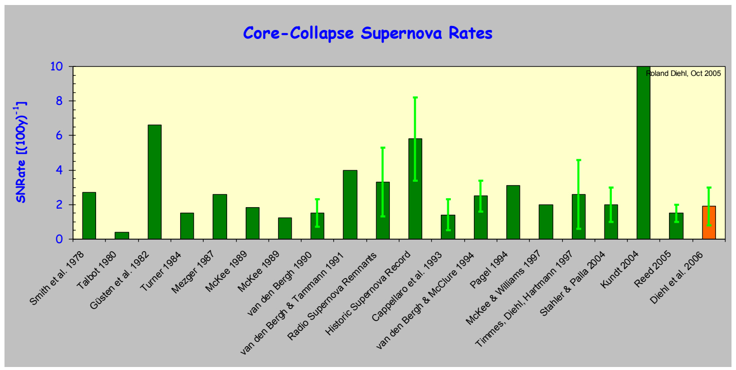


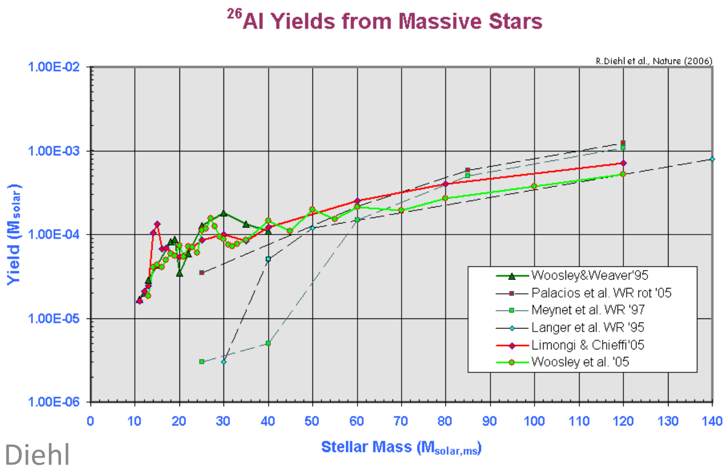


Stellar Mass Distribution,

^{26}Al Yields per Star

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

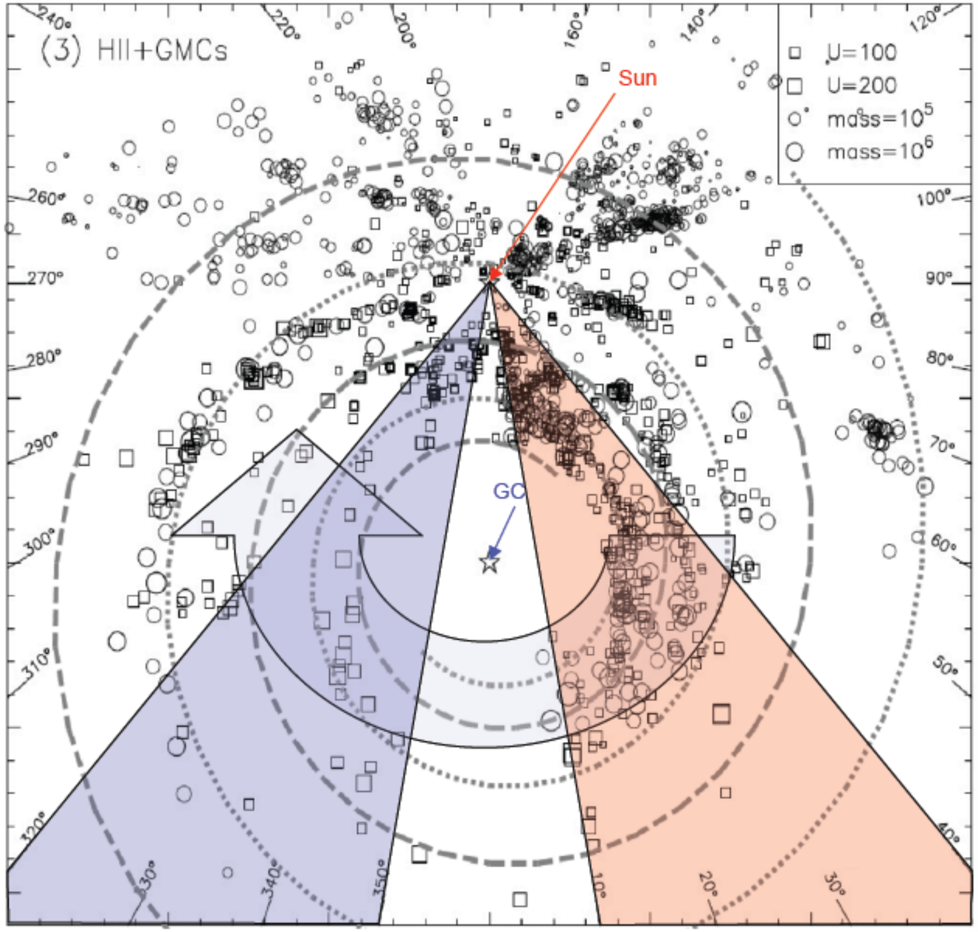


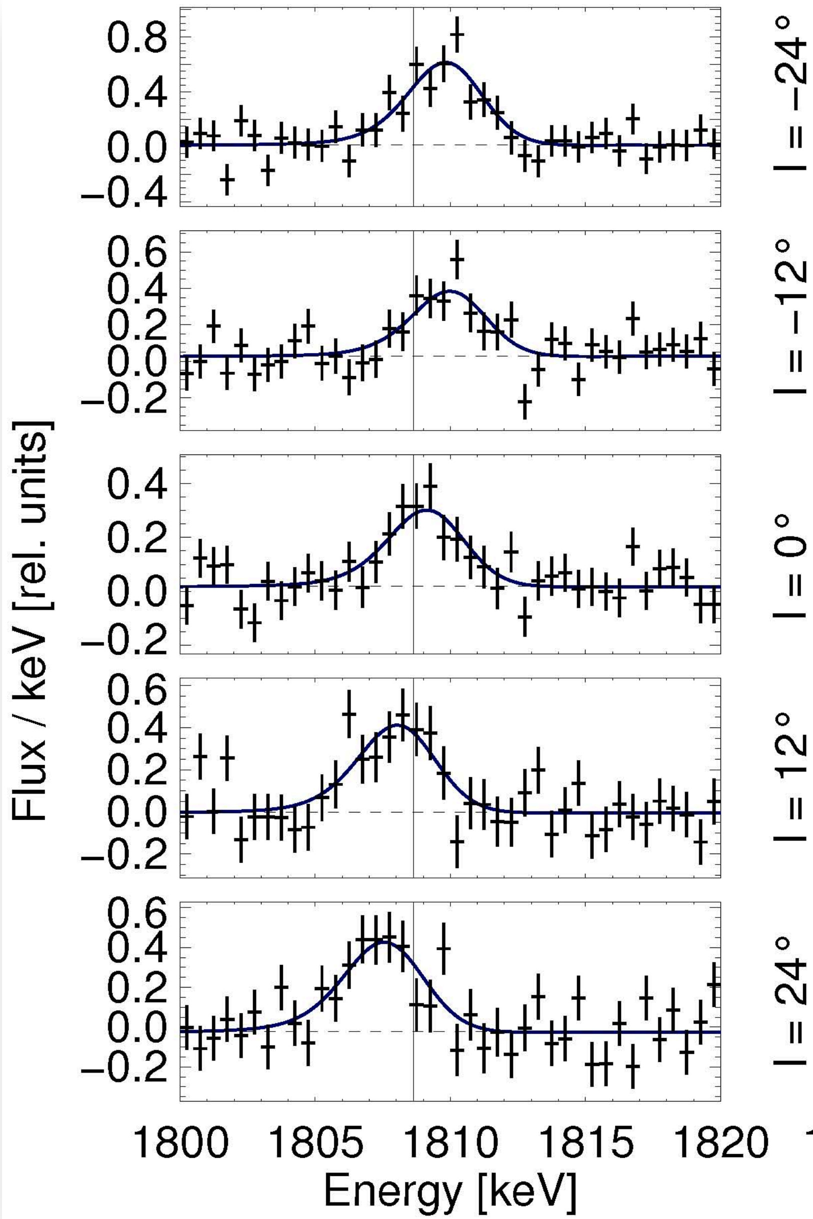


✓ Star Formation Rate = 2.8 $M_\odot$/yr

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

- Large-scale Galactic rotation

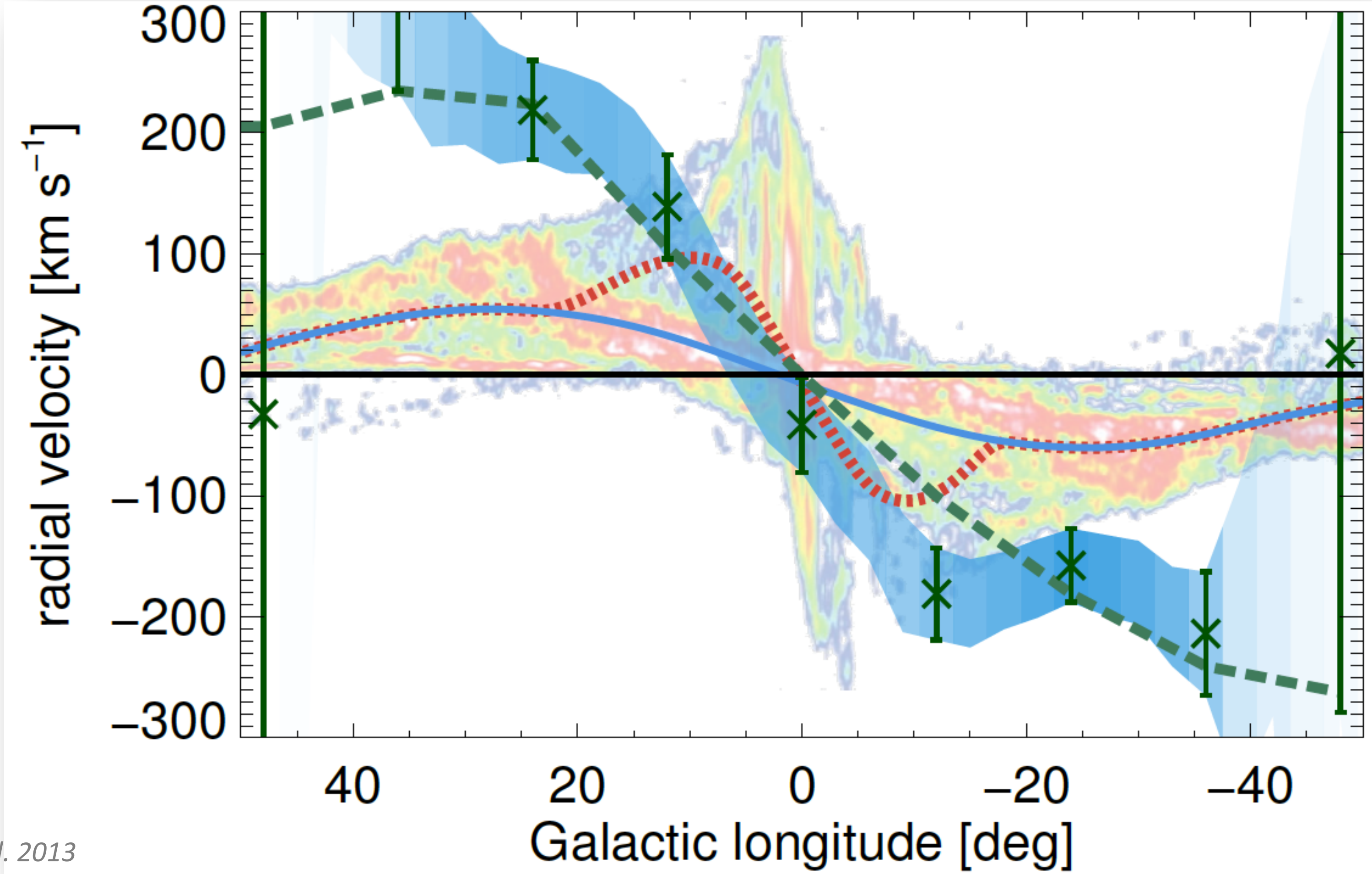




Kretschmer et al., A&A (2013)

The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



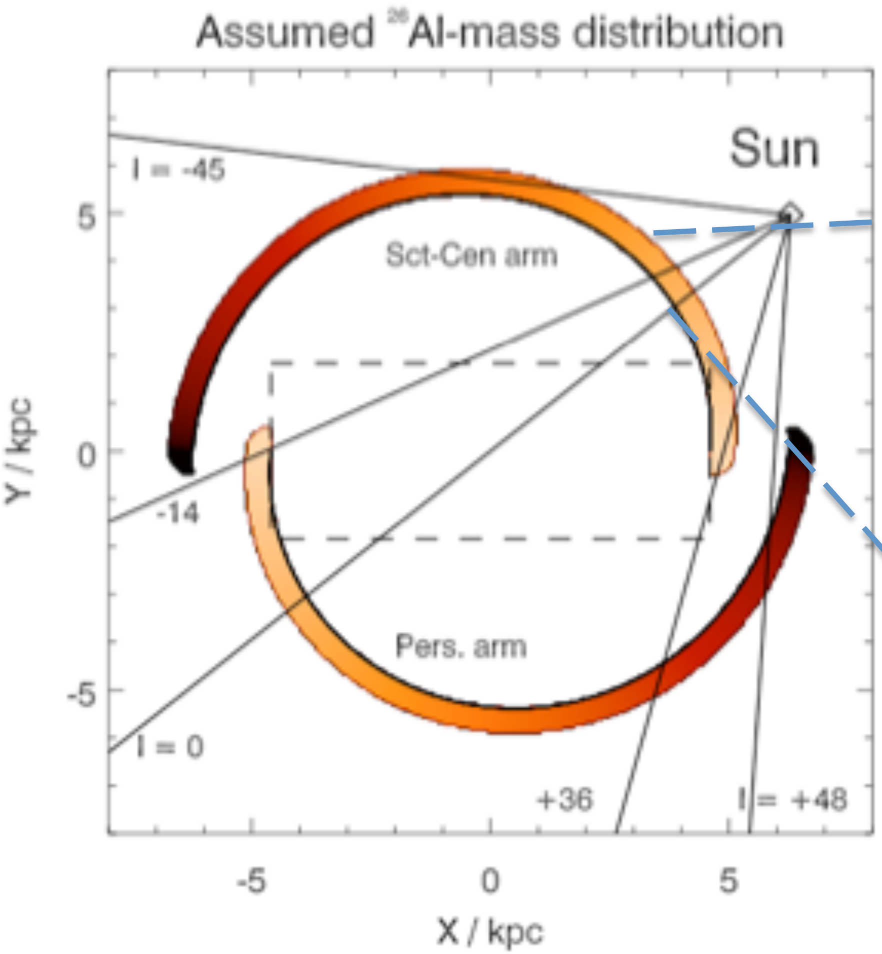
Kretschmer, Diehl, et al. 2013

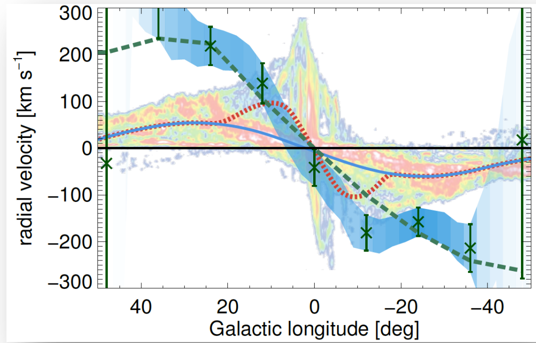
Kinematics of massive star ejecta in the Milky Way as traced by ^{26}Al

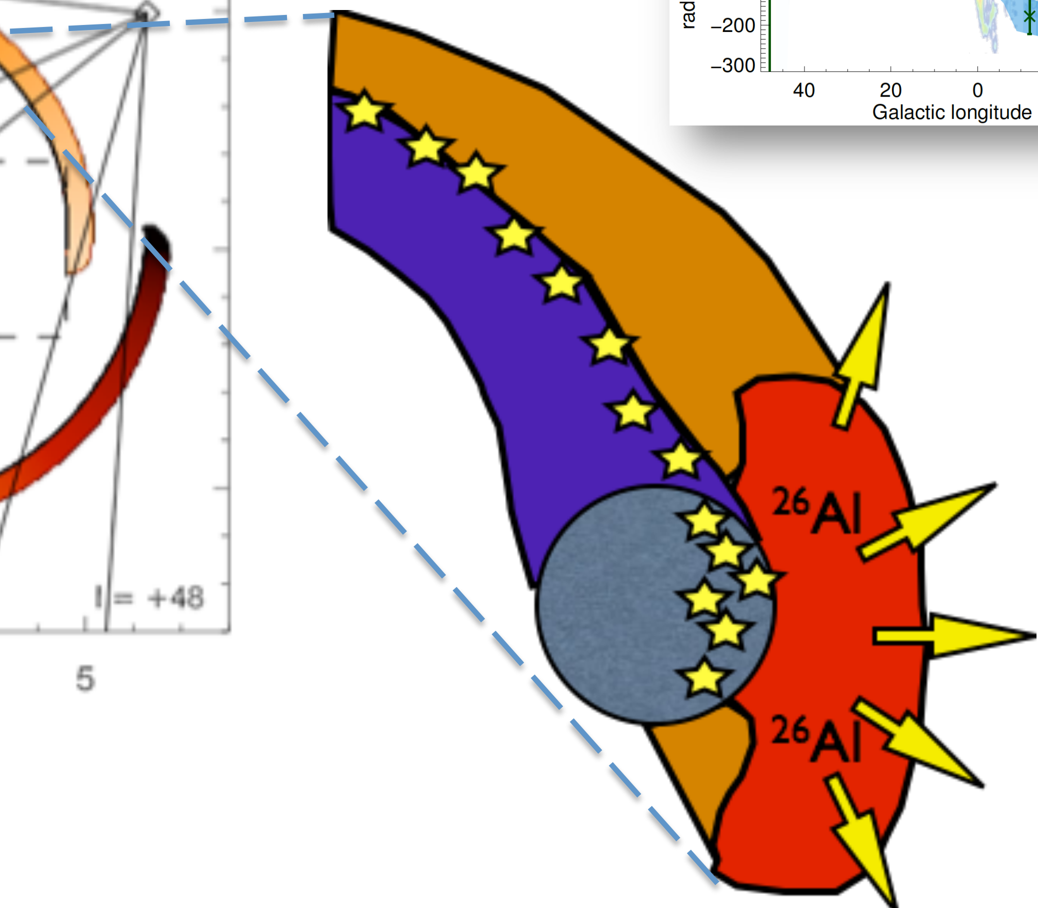
Karsten Kretschmer[1,2], Roland Diehl[2,3], Martin Krause[2,3], Andreas Burkert[4,3,2], Katharina Fierlinger[3,4], Ortwin Gerhard[2], Jochen Greiner[2,3], and Wei Wang[5]

How massive-star ejecta are spread out…

- Superbubbles blown into inter-arm regions



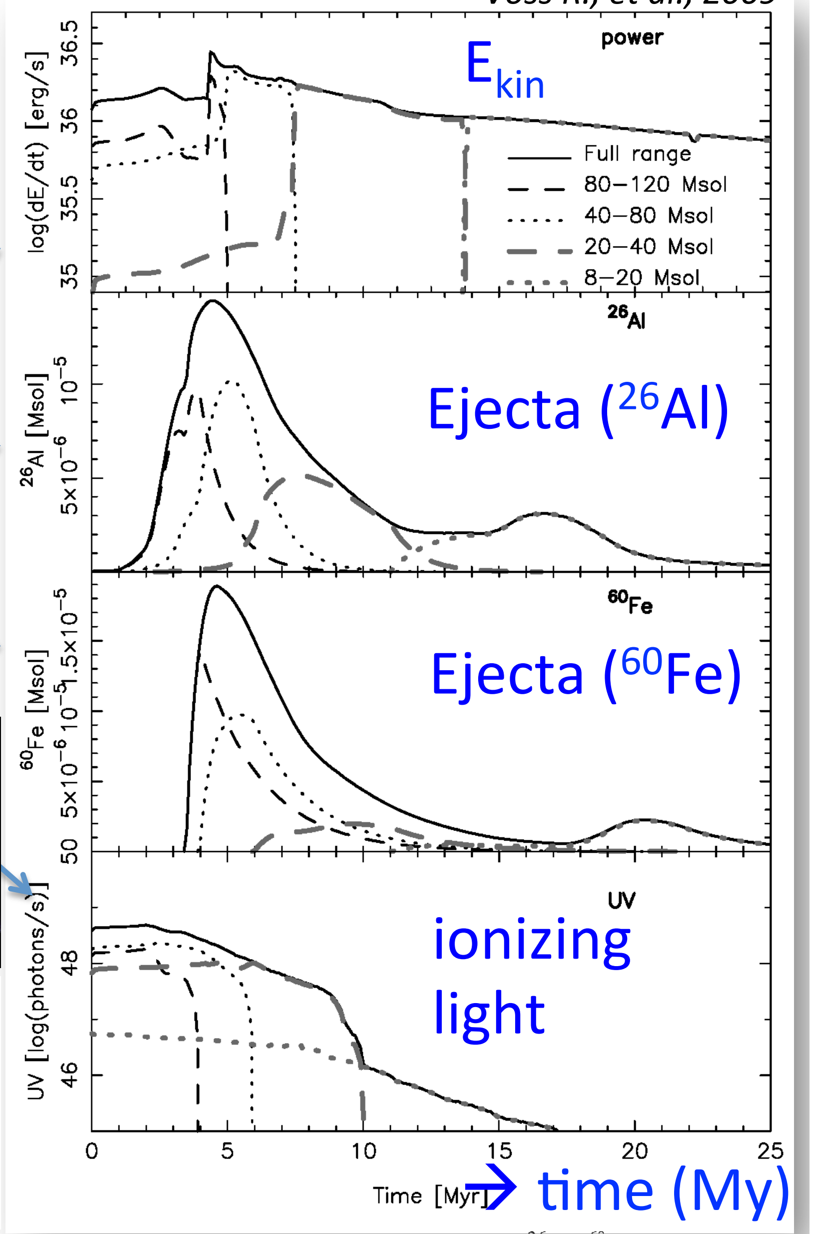


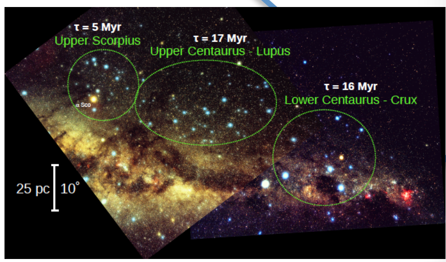


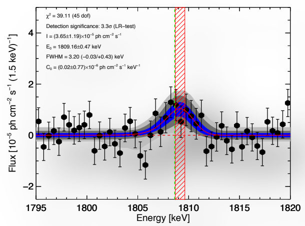
Massive-Star Groups

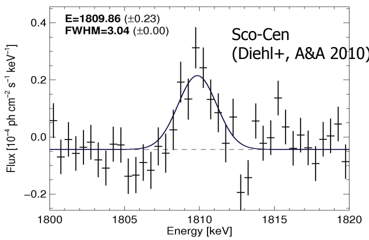
- The "outputs" of massive stars and their supernovae:
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation
- Observational constraints from:
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

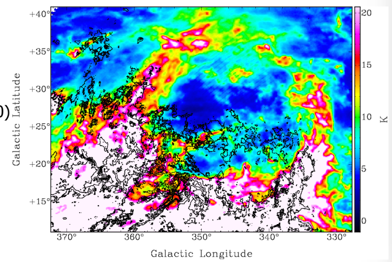
Voss R., et al., 2009







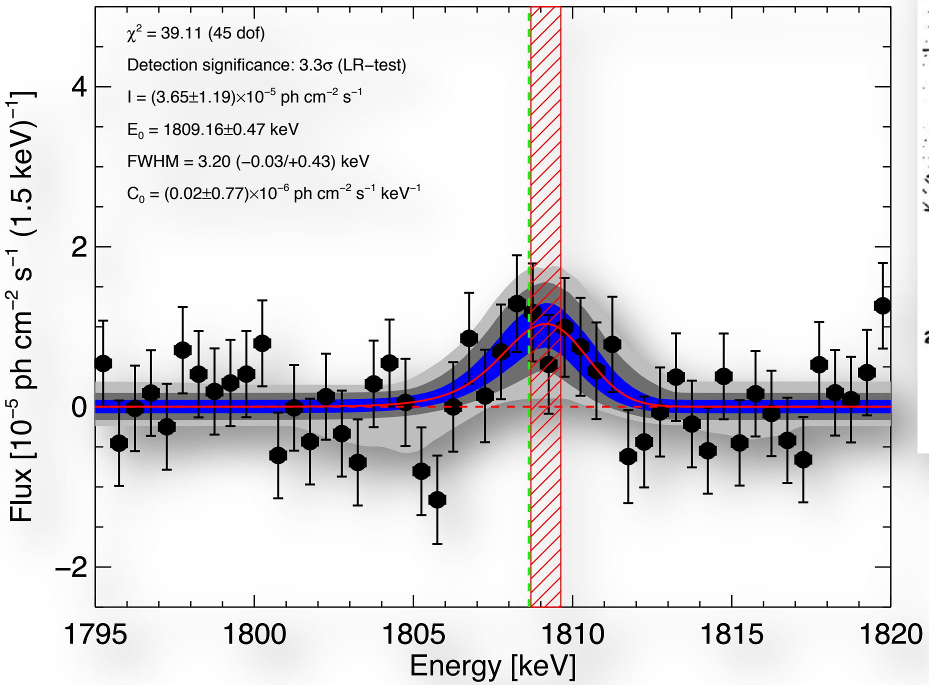


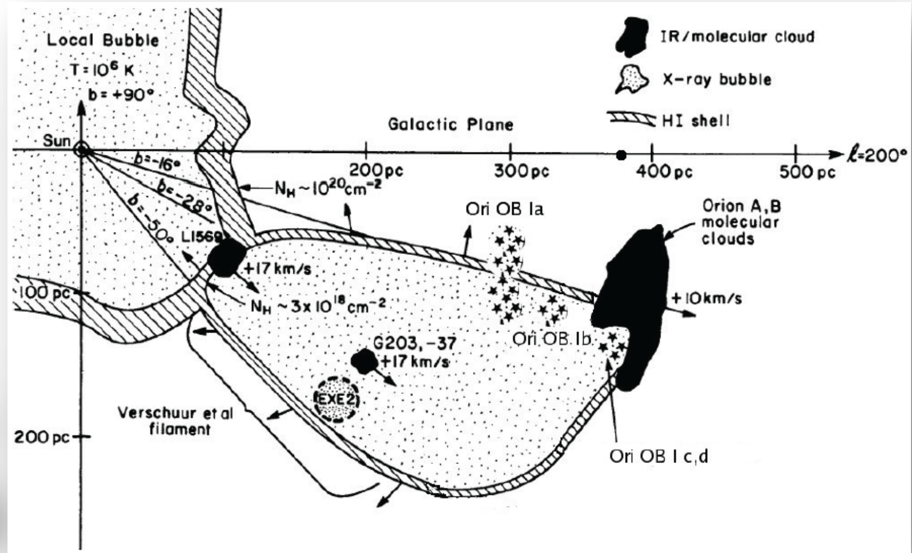


^{26}Al in Orion

- Now also detected with SPI/INTEGRAL

Siegert & Diehl (2016), arxiv 1609.08817





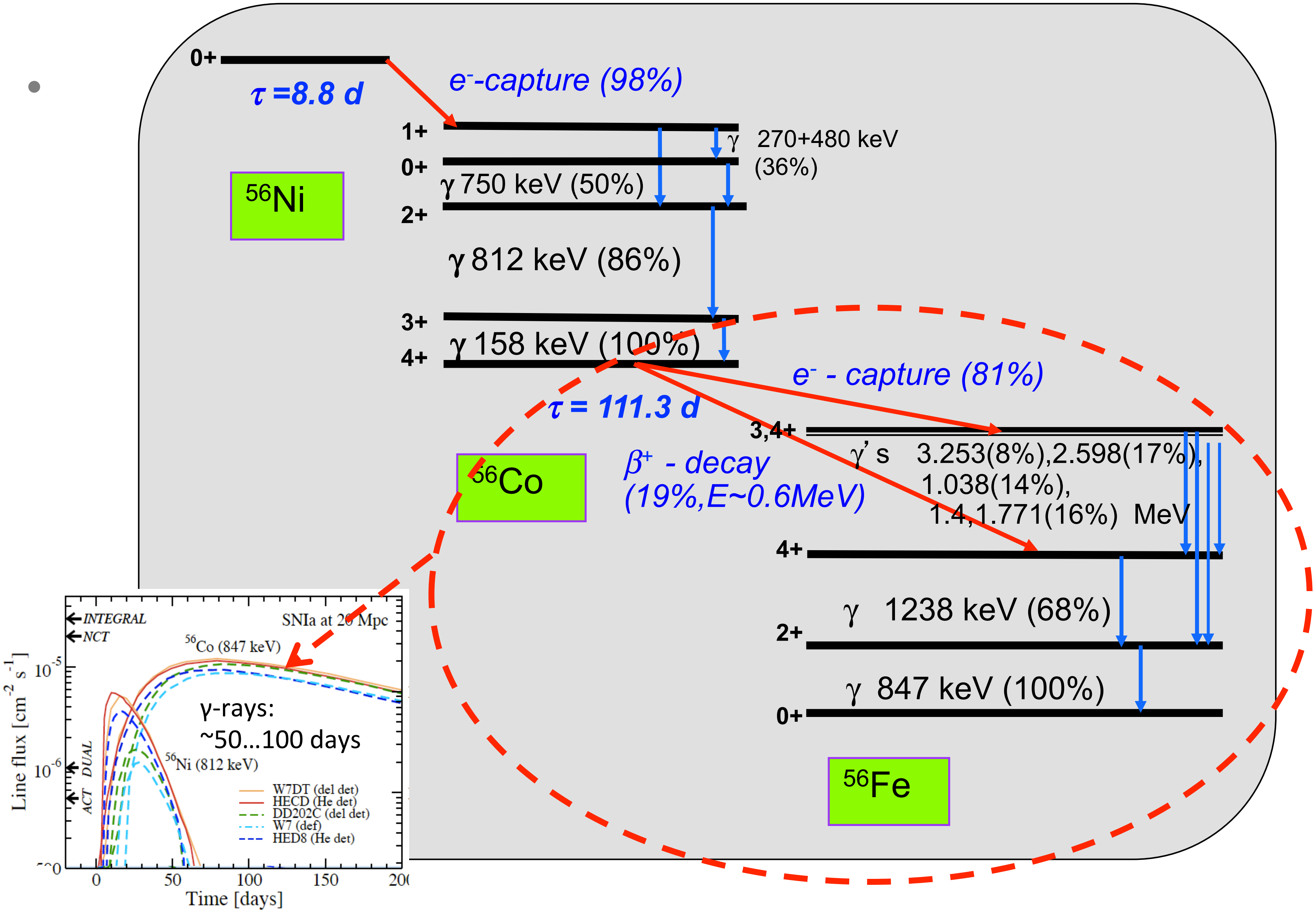
→ Ejecta kinematics?? ← blue shift; velocity broadening?

Radioactivity gamma rays (τ ~My):

→Much of the nucleosynthesis ejecta are not instantaneously recycled into new stars

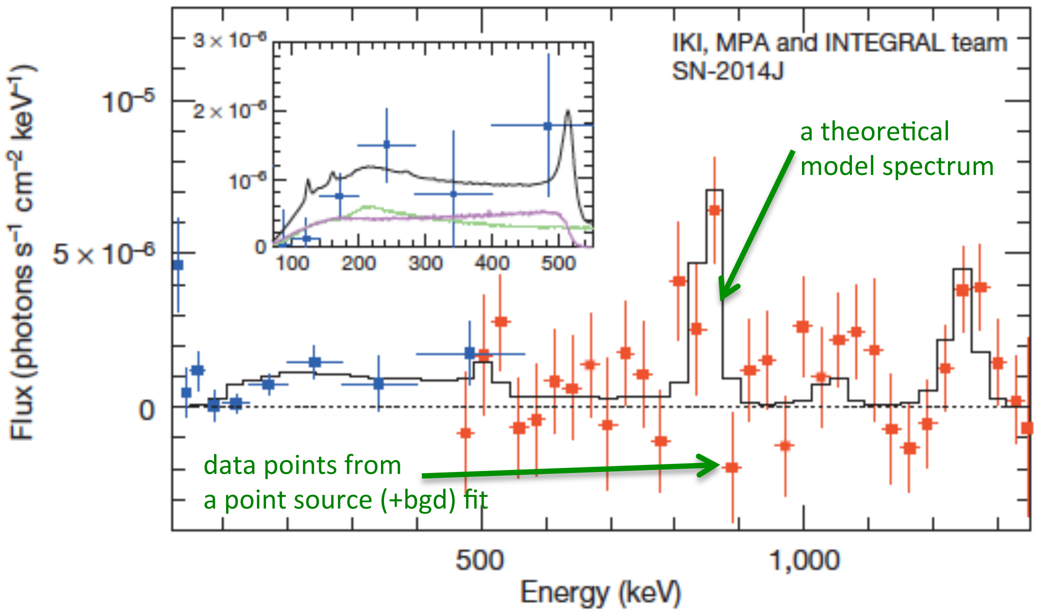
- →Superbubbles
- →Role of halo clouds?

^{56}Ni radioactivity: Decay chain, γ rays, e^+

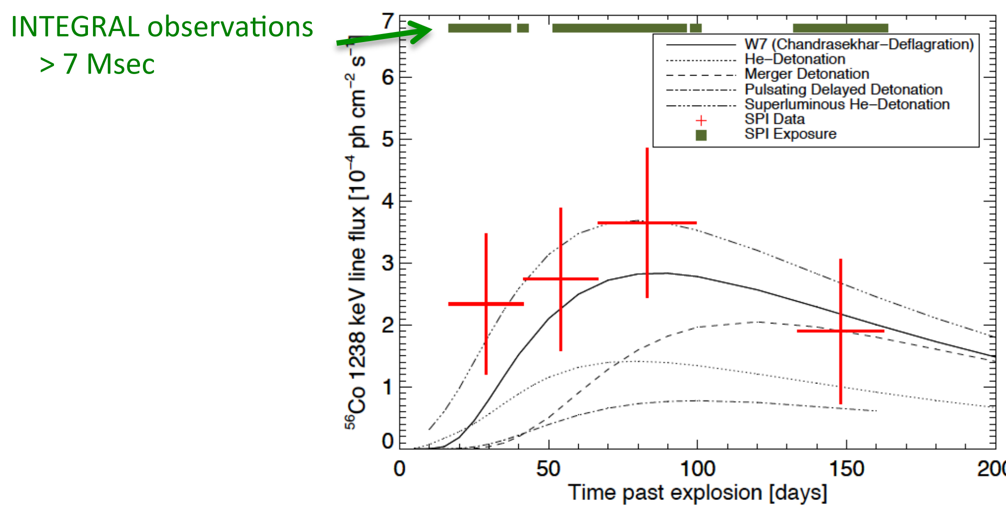


SN2014J data Jan – Jun 2014: ^{56}Co lines

- Detection of 847 and 1238 keV lines from ^{56}Co decay at days 50-100



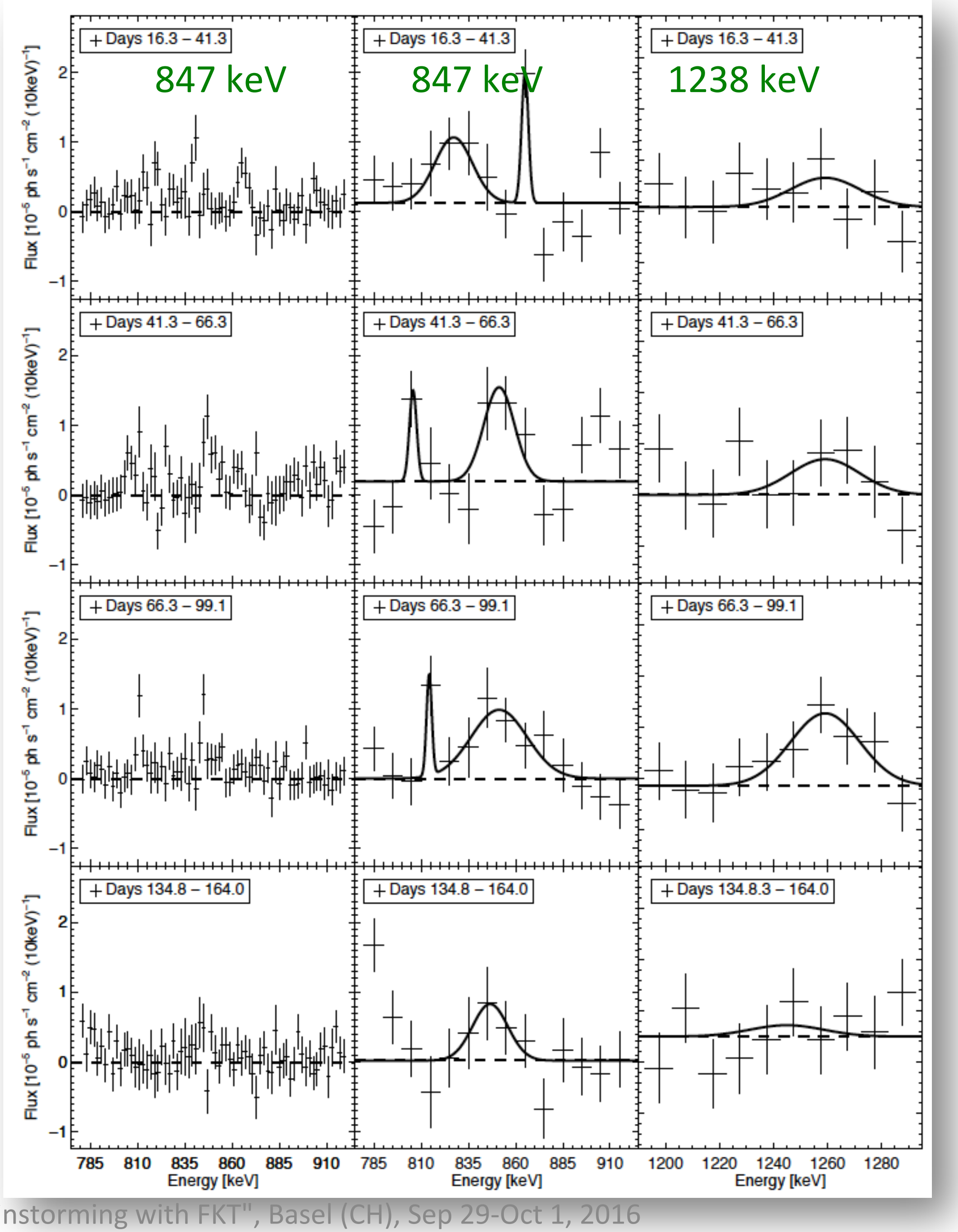
- Confirmation of our SN Ia model



  - *Churazov et al., Nat, 2014*
  - *Diehl et al., A&A 2015*

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

- The ^{56}Co decay lines
- Different spectral binning
- Different epochs



→ Observed:
a structured and
evolving spectrum

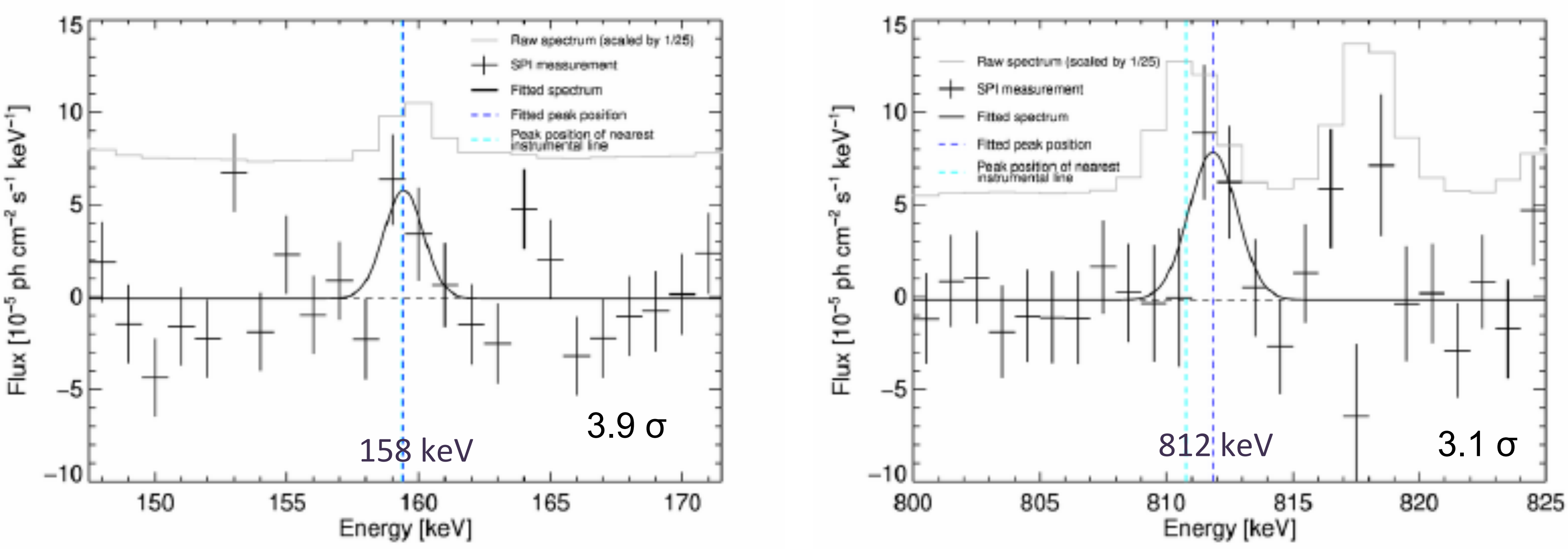
- expected:
gradual appearance
of broadened ^{56}Co lines
  - *Diehl et al., A&A (2015)*

SN2014J: Early ^{56}Ni (τ~8.8d)

Spectra from the SN at ~20 days after explosion

– Clear detections of the two strongest lines expected from ^{56}Ni

Diehl et al., Science (2014)



– Intensities:

(1.14 ±0.43) 10^{-4} ph cm^{-2} s^{-1} (158 keV line)

and (1.91 ±0.67) 10^{-4} ph cm^{-2} s^{-1} (812 keV line)

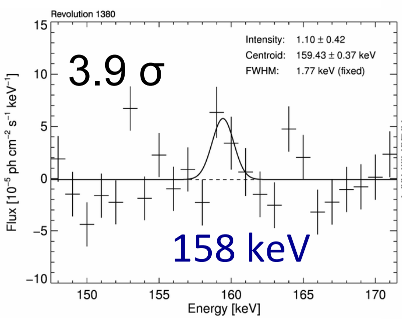
– Corresponding ^{56}Ni mass (backscaled to explosion): ~0.06 $M_{\odot}$

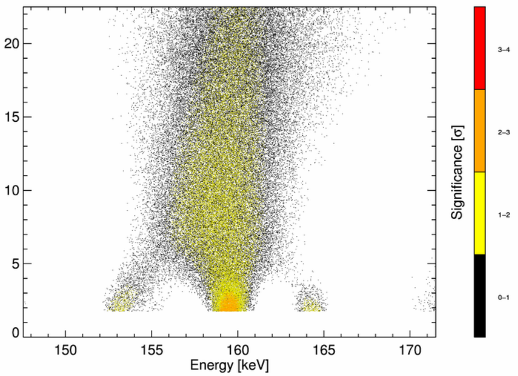
SN2014J: Early ^{56}Ni (τ~8.8d)

… and also an underlying broad line?

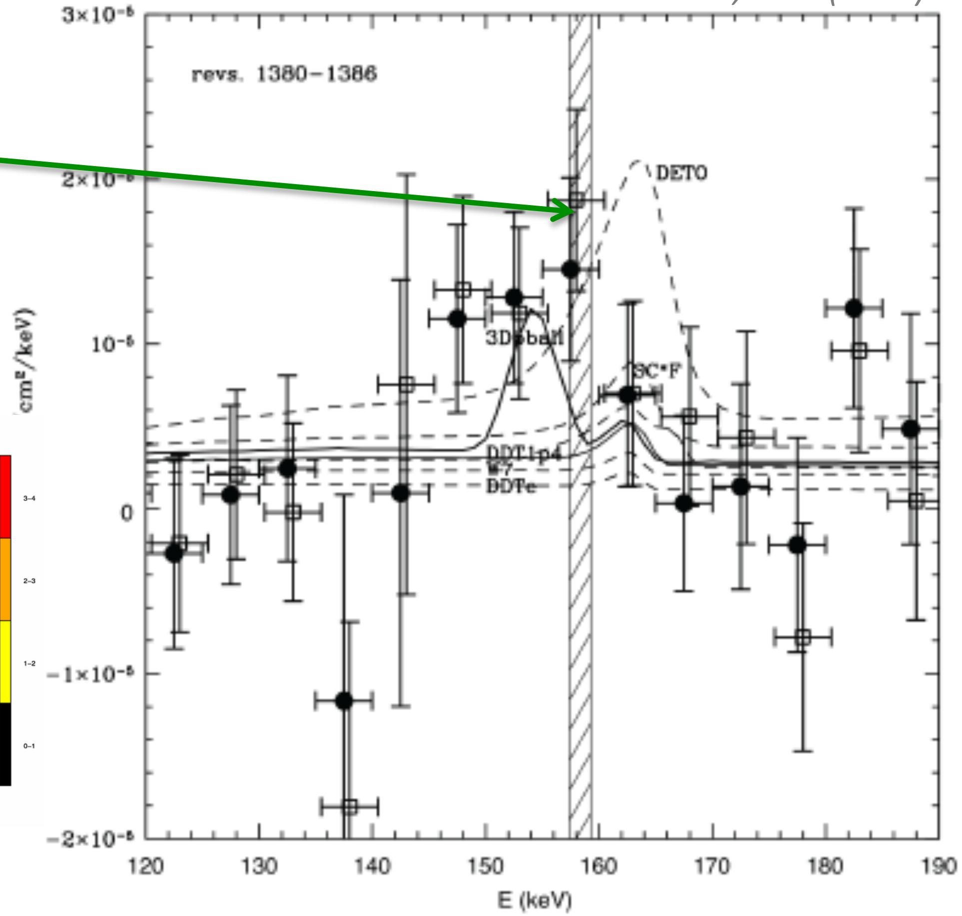
– Broad-bin analysis:

→ ^{56}Ni mass estimate (backscaled to explosion): ~0.08 $M_\odot$





Isern et al., A&A (2016)

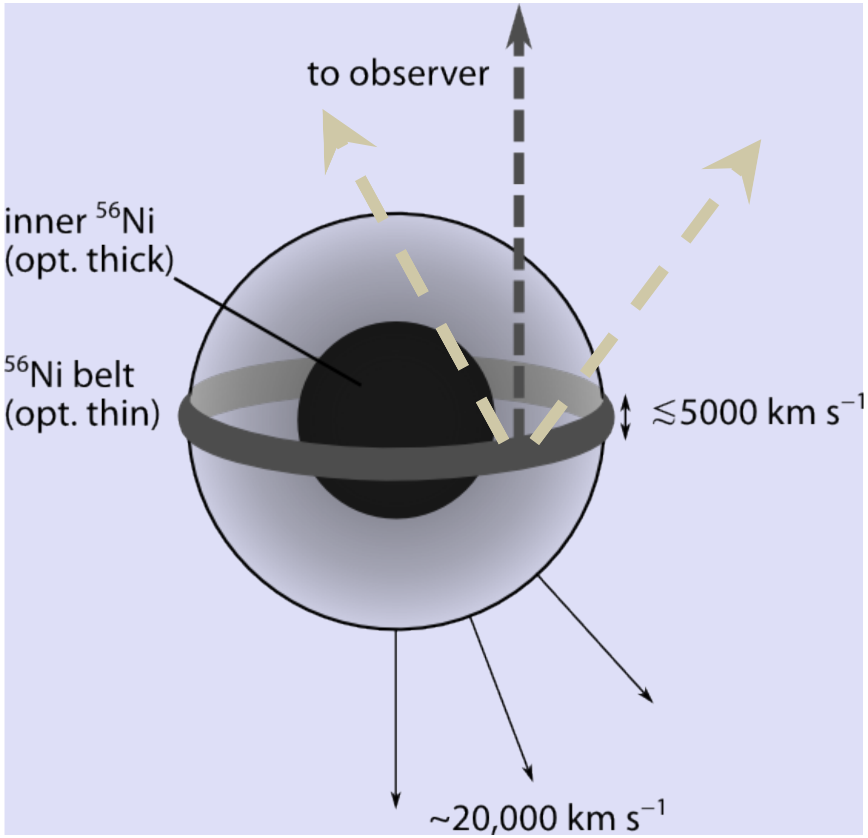


=> γ-rays show ^{56}Ni near/at the surface!

SN2014J: An unusual (triggered) explosion?

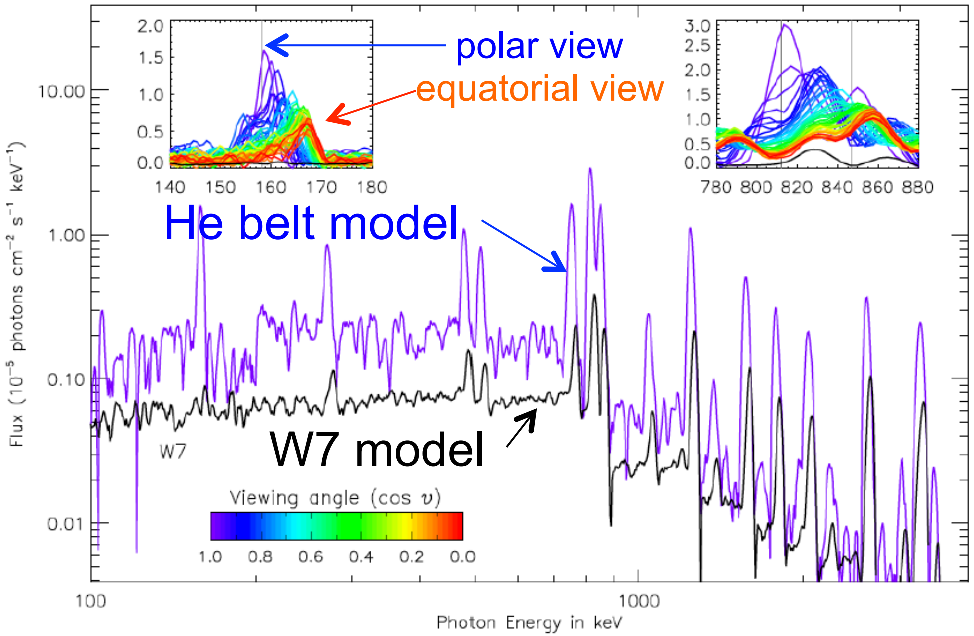
- A belt of He accreted from the companion star → He explosion, triggering the SNIa explosion of the CO white dwarf ($M<M_{ch}$)

Science Vol. 345 (2014)



Simulating how an exploding belt of accreted He would be observed in gamma-rays:
Polar viewing → unshifted lines
Equatorial viewing → blue shift

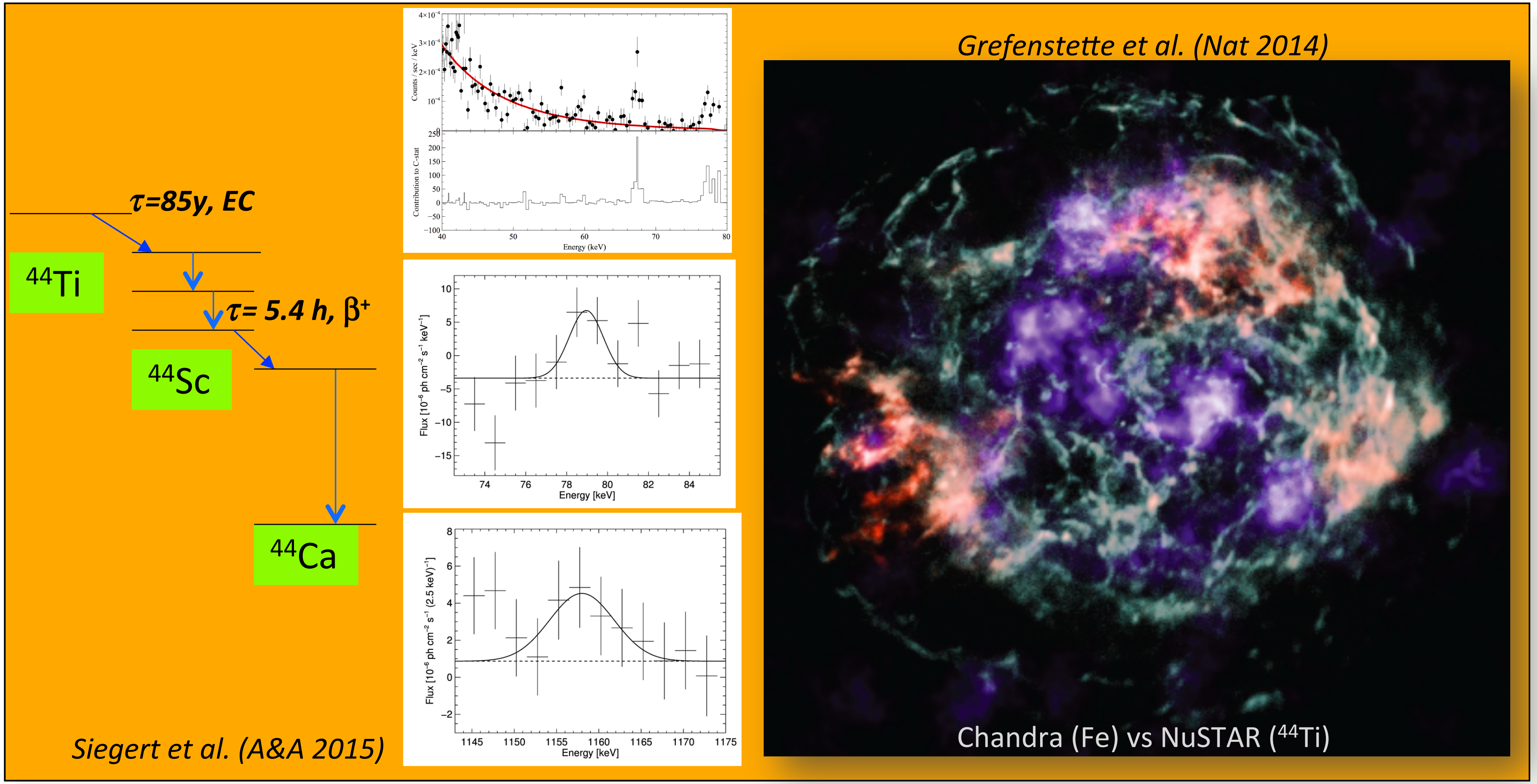
Markus Kromer



^{44}Ti γ-rays from Cas A (NuSTAR & INTEGRAL)

t=85y (Ahmad et al. 2006)

89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157

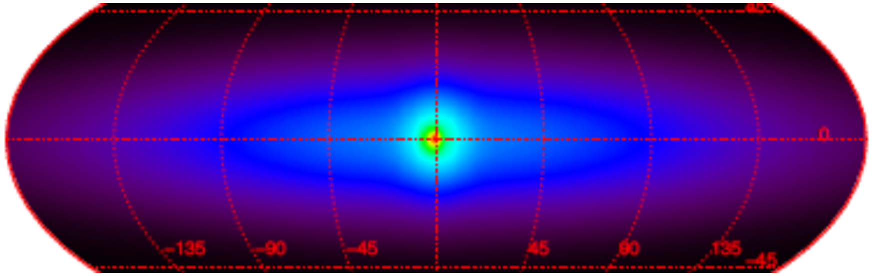


- ^{44}Ti Ejected Mass ~1.23 ±0.25 10^{-4} $M_\odot$
- Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)

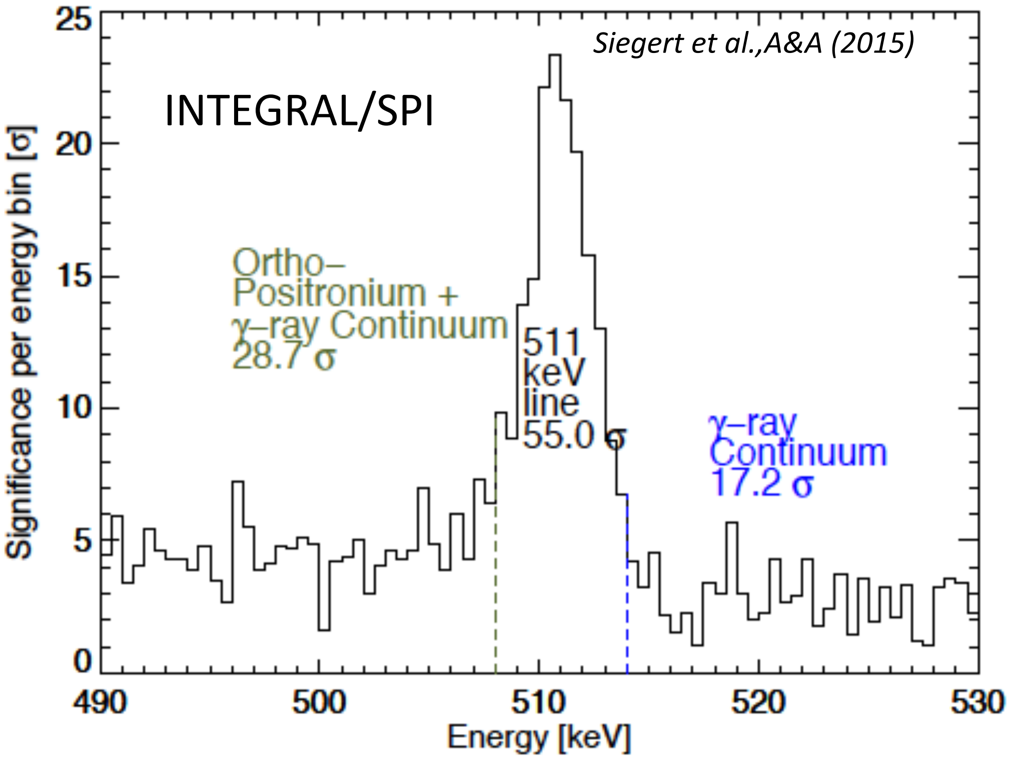
Supernova Explosions

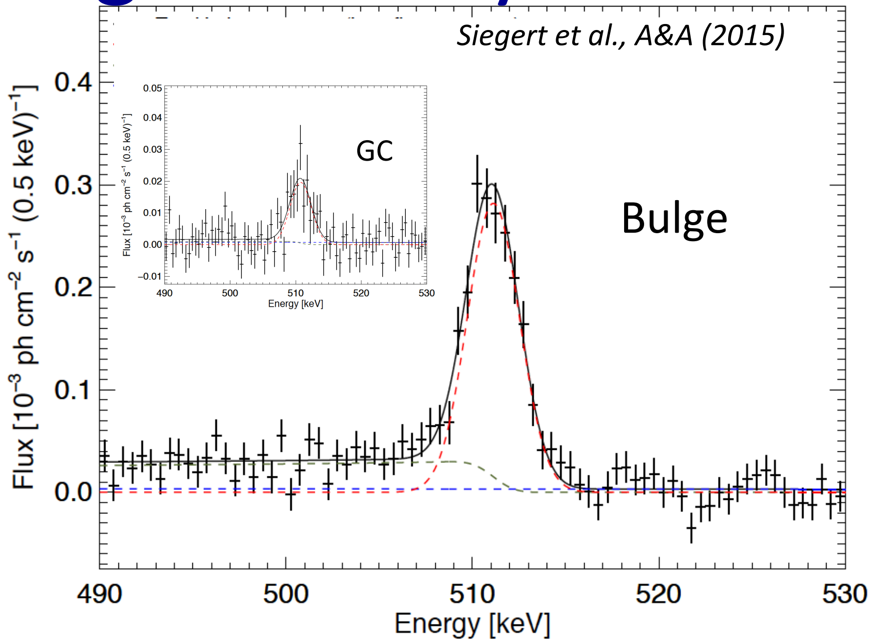
- Radioactive ejecta distribution within expanding SN may be more irregular than many models show

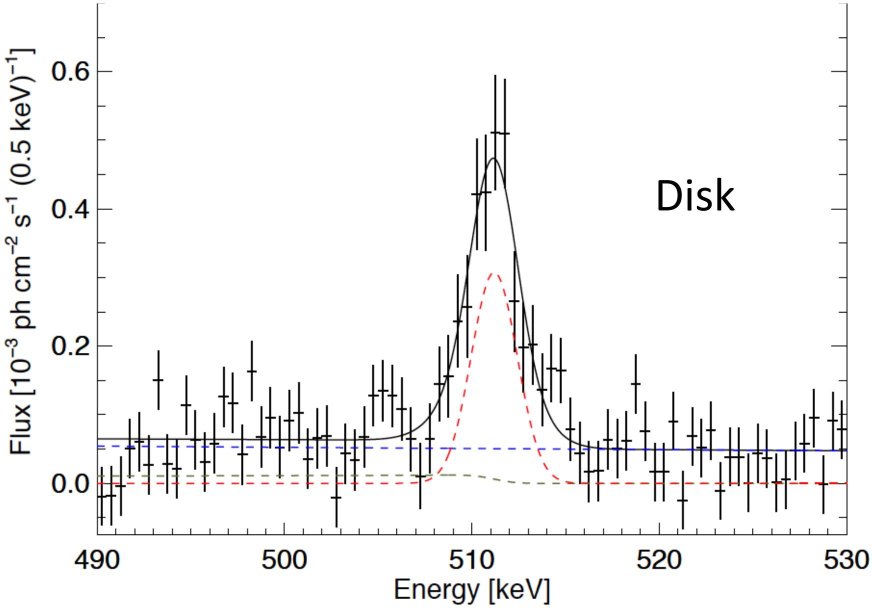
Positron annihilation gamma rays



– Derive/discriminate spectra from different regions

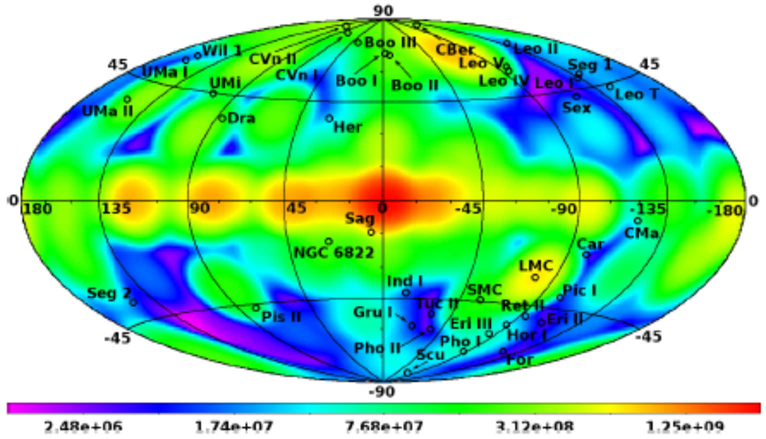


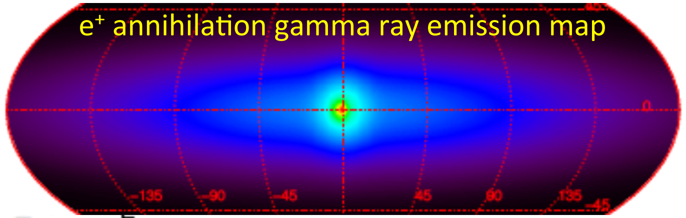




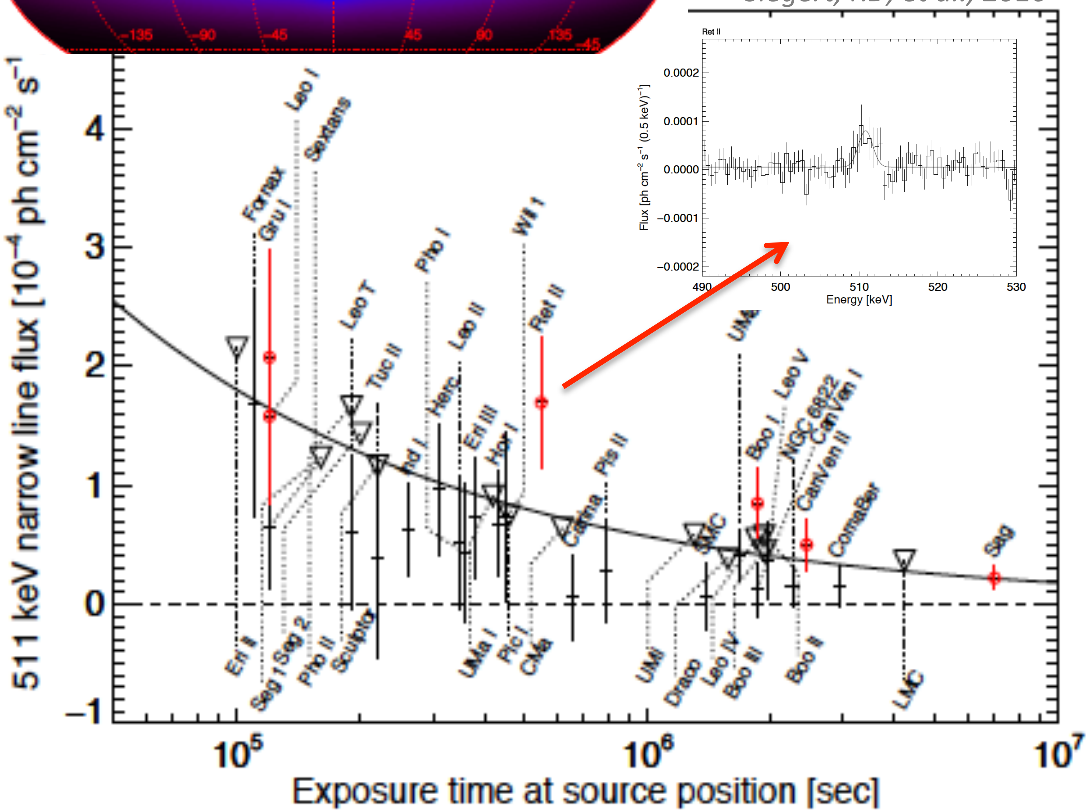
Positron Annihilation in a dSph Galaxy

Search for 511 keV emission in nearby dSph galaxies





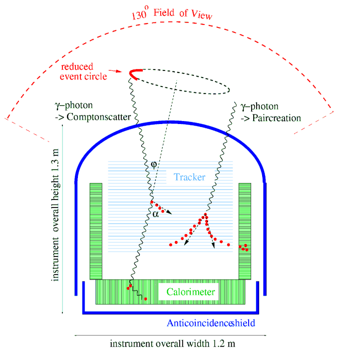
Siegert, RD, et al., 2016

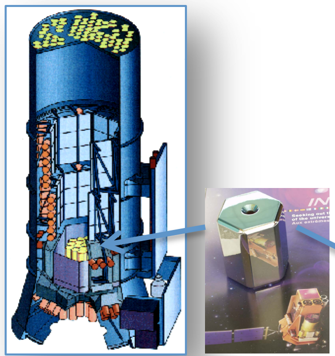


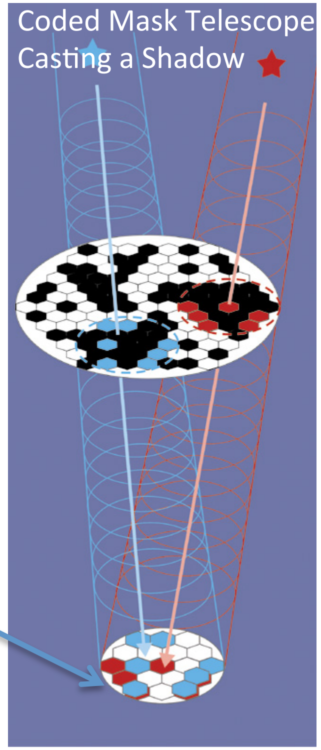
- Absence of significant detections excludes DM as e^{+} source
- Detection of Ret II:
  → stellar e^{+} !! $(3.7 \pm 1.2) \times 10^{43}\ e^{+}\ s^{-1}$

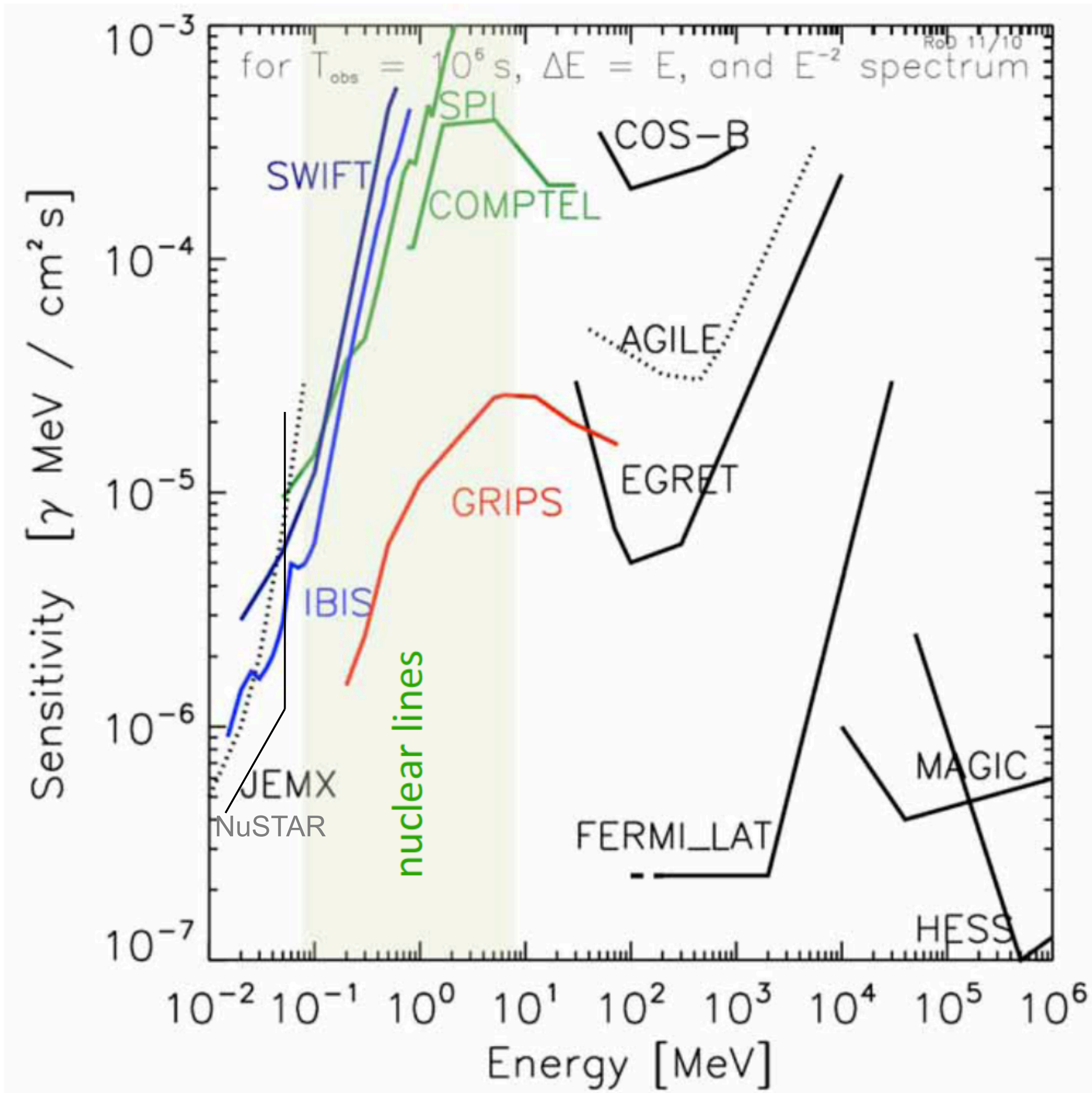
High-Energy Telescopes & Sensitivities

- “Gamma-Ray” Range
  ~10-12 Decades
  - Different Techniques Across the HE Band
  - Challenge: Nuclear-Line Regime



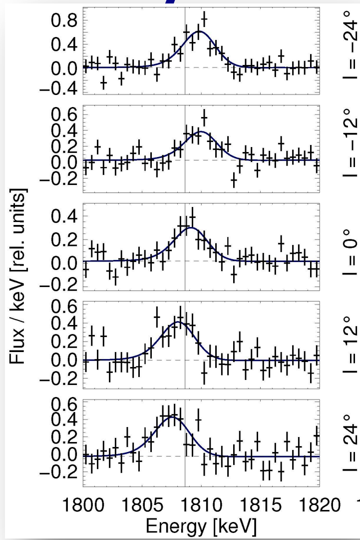






INTEGRAL mission: into 2020ies (2029); no others planned

Gamma Ray Observations: Summary



- Radioactivity γ-rays provide a unique / different view
  - Radioactivity traces diluted ejecta over Myrs
- ^{26}Al gamma rays show an apparently higher velocity of large-scale galactic rotation
  - Radioactive decay and ejecta flow → asymmetry
    → Superbubbles blows towards spiral-arm leading part
  - Ori-Eridanus cavity extends away from molecular clouds, ^{26}Al seems to flow towards us in Orion
- Supernovae expose their radioactive interiors 'clumpy': ^{26}Al, ^{60}Fe
  - SN2014J showed ^{56}Ni at its outskirts: not easy for models
  - Cas A ejecta are clumpy (^{44}Ti)
- Positrons open new perspective through annihilation gamma rays ^{26}Al, ^{60}Fe
  - The Galaxy shows e^+ must come from several sources; but not from DM
  - e^+ signals in SN2014J and in a microquasar are first 'source proofs'