Radioactivity Gamma-Rays and Galactic Structure

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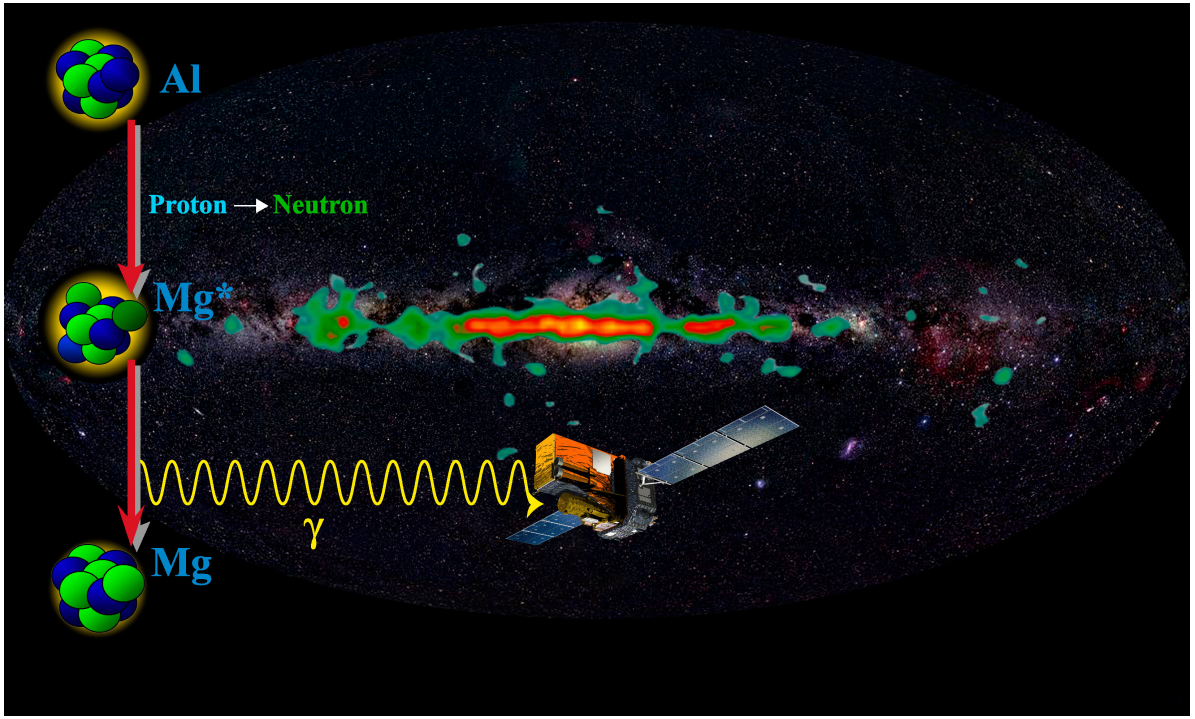
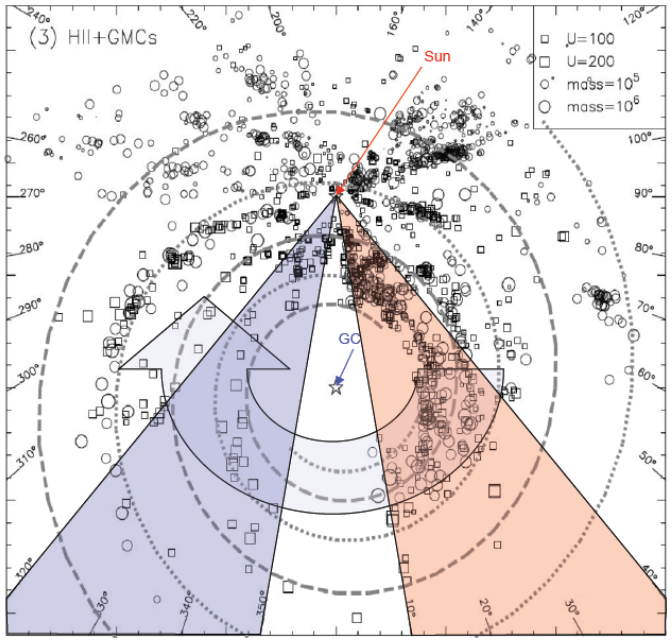
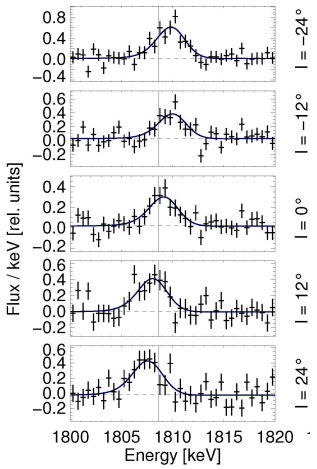
(MPE Garching, Germany)

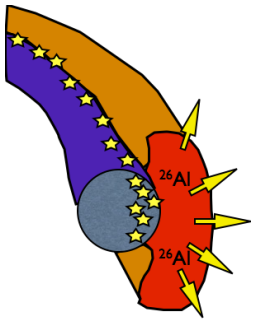
with
Martin Krause, Karsten Kretschmer, Thomas Siegert,
and ….. Breitschwerdt, Burkert, … Kroupa, …Preibisch…Vink, …

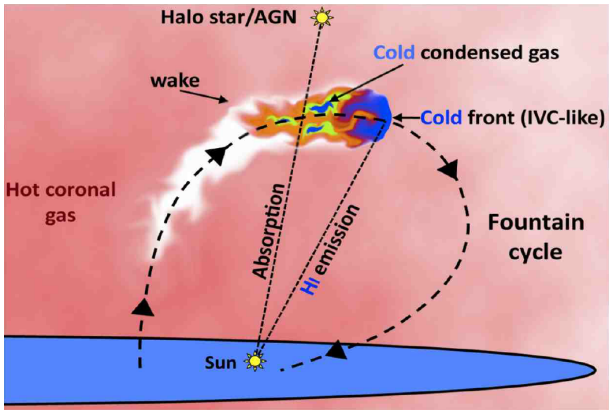
Massive Star Groups across the Galaxy











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

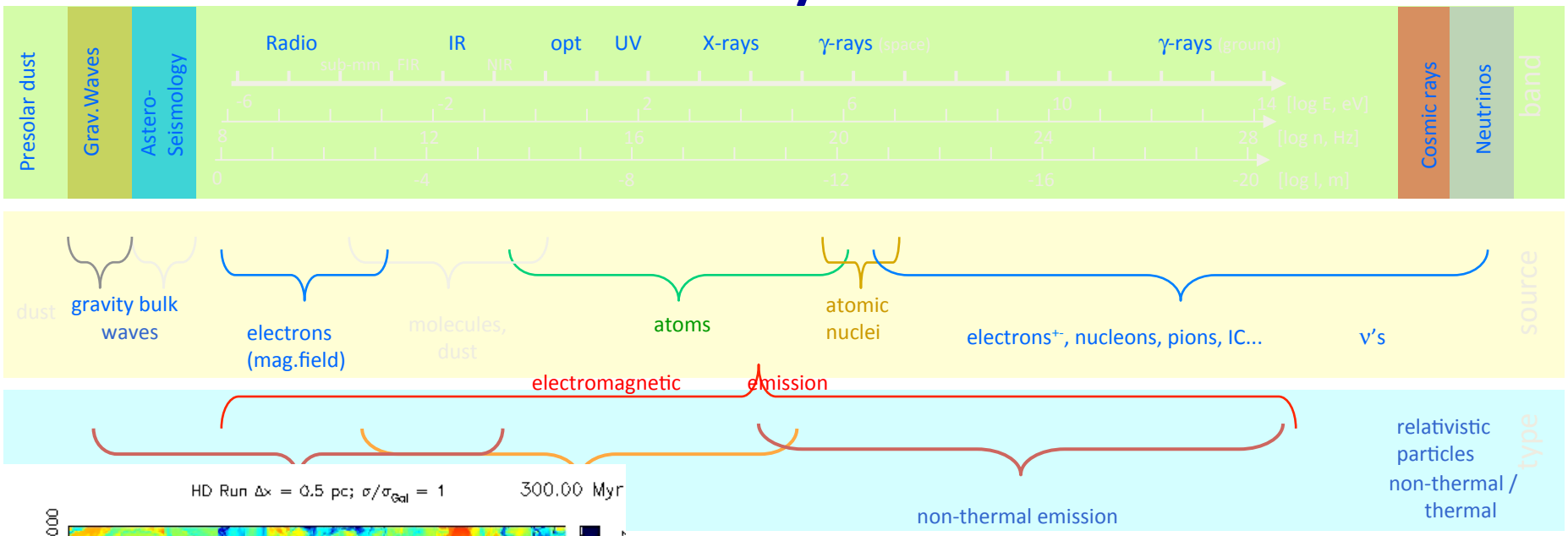
cumulative from many events

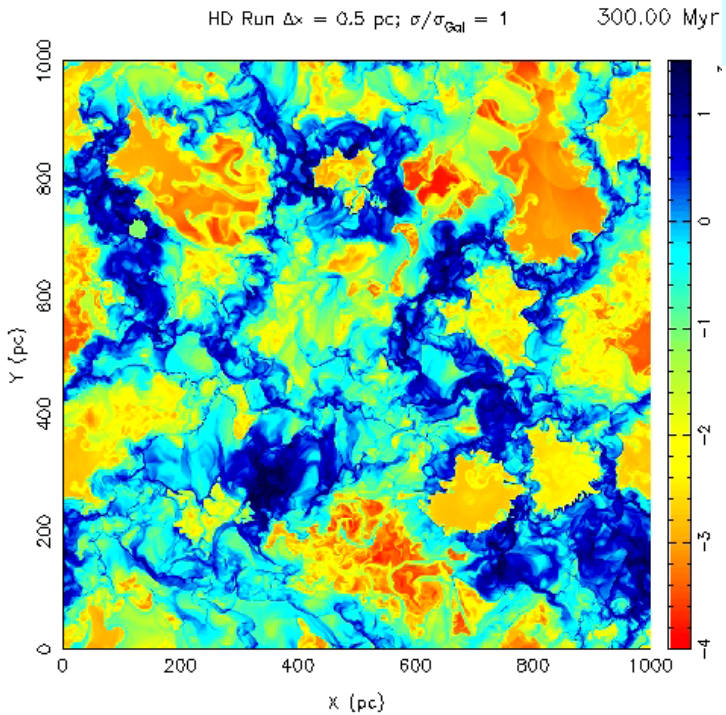
Radioactive trace isotopes are by-products of nucleosynthesis

Gamma rays detect brightest sources (>10^{-5} ph cm^{-2} s^{-1}) and thus

- complement other observables of stellar activity (formation/winds/explosions)
- trace ejecta amounts (not 'density'!) over the Myr time scale

Nuclear-line astronomy – a small "window"

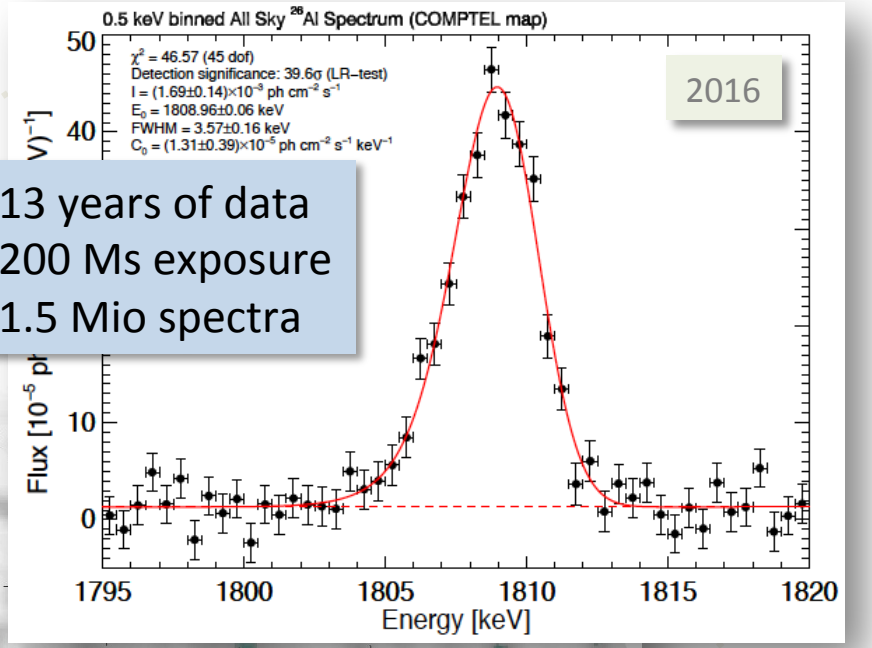




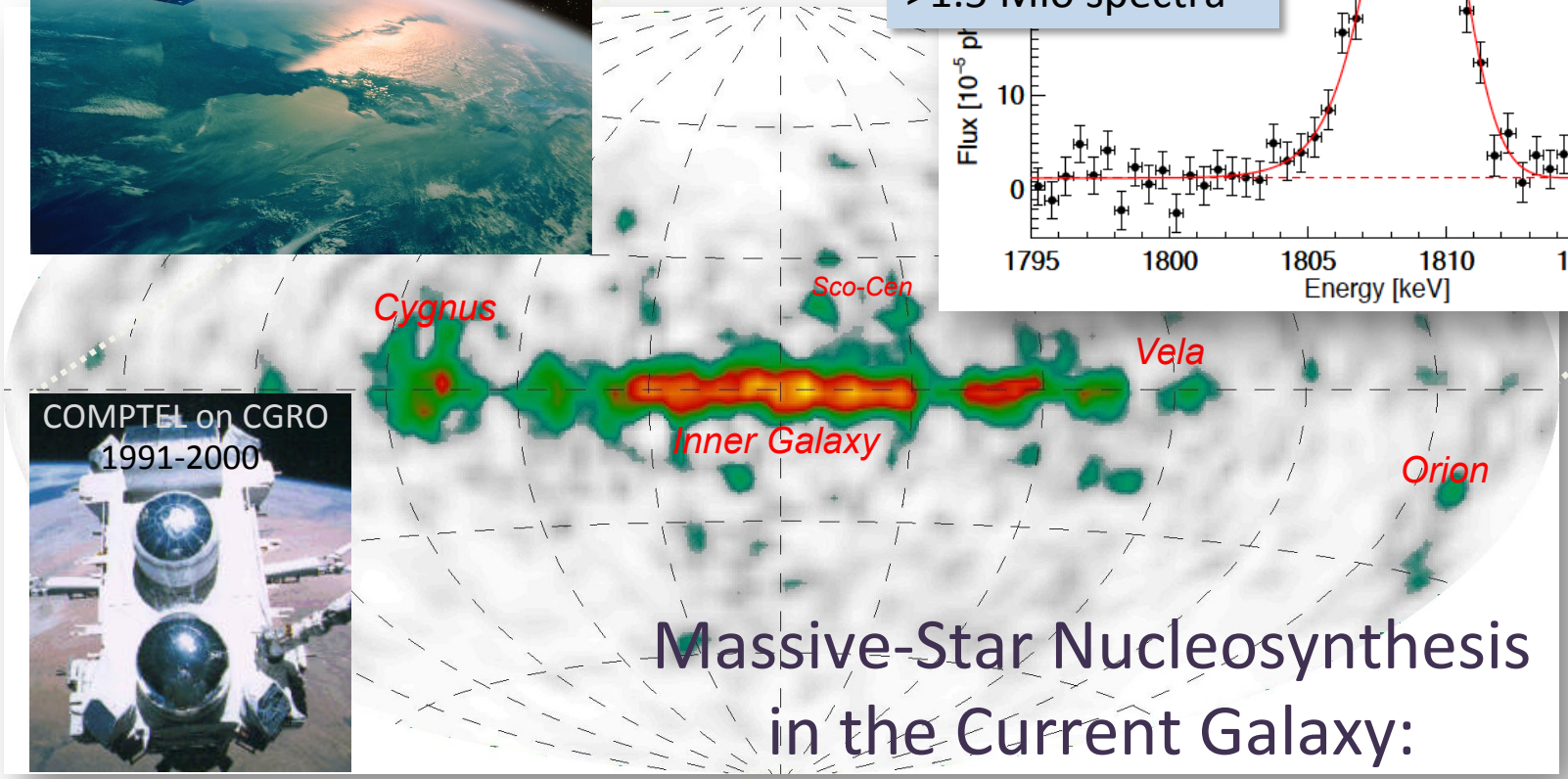
Where & how are ejecta produced?

How do ejecta move (My) before getting recycled?

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



>13 years of data
>200 Ms exposure
>1.5 Mio spectra

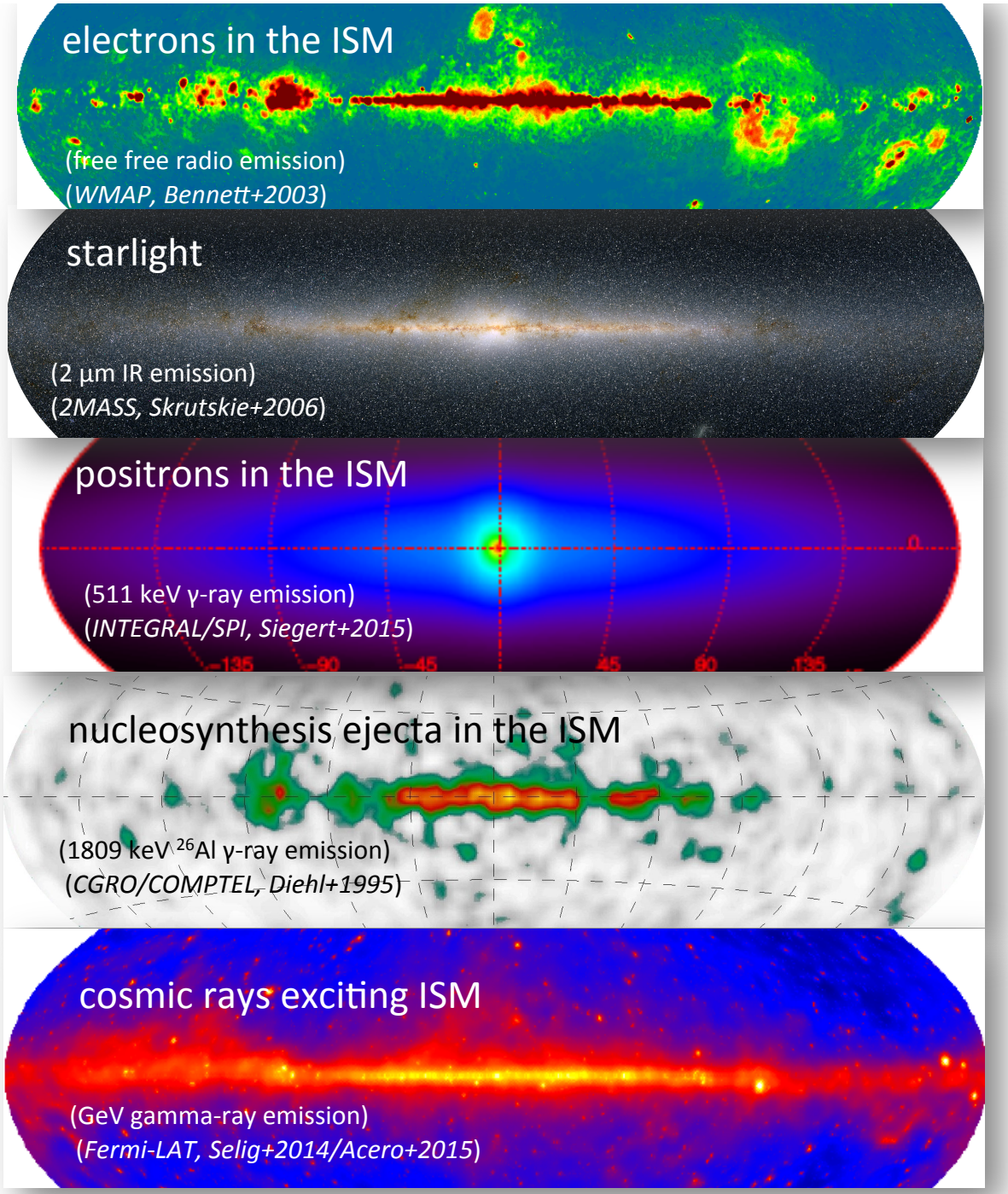


Massive-Star Nucleosynthesis in the Current Galaxy:

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

^{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, …



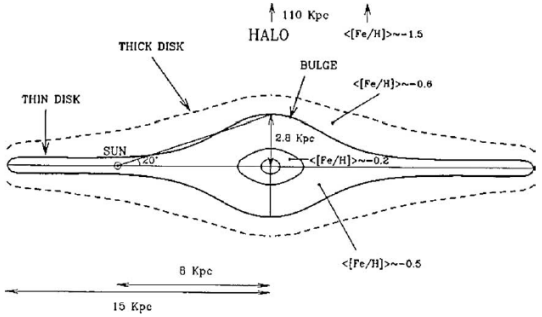
Using the ^{26}Al Line to Characterize the Galaxy's SN Activity

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

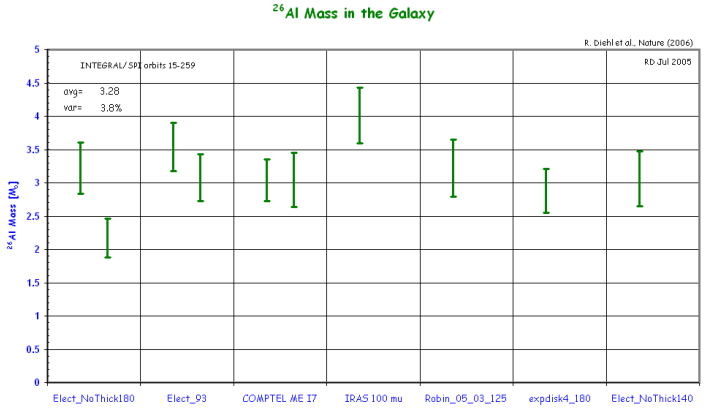
Measured Gamma-Ray Flux*

**) better account for foreground emission*

Galaxy Geometry



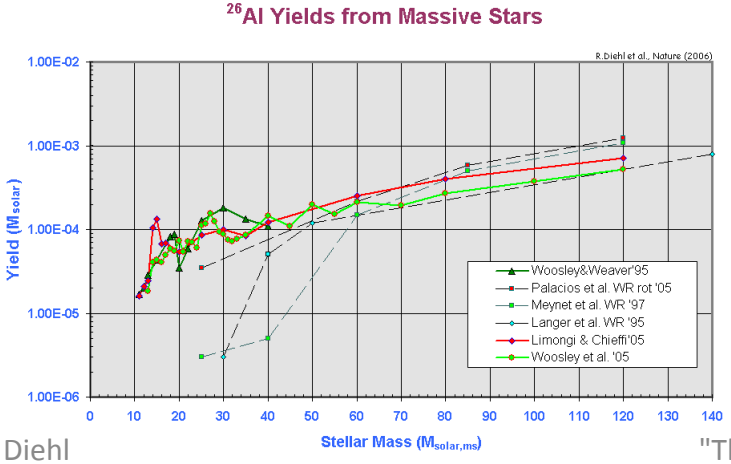
➤ ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

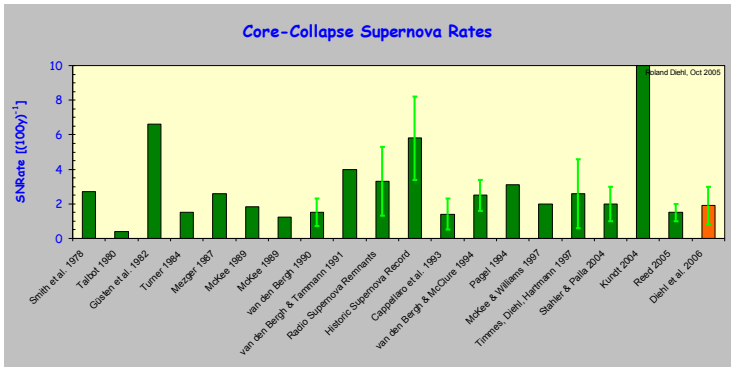


^{26}Al Yields per Star

Stellar Mass Distribution

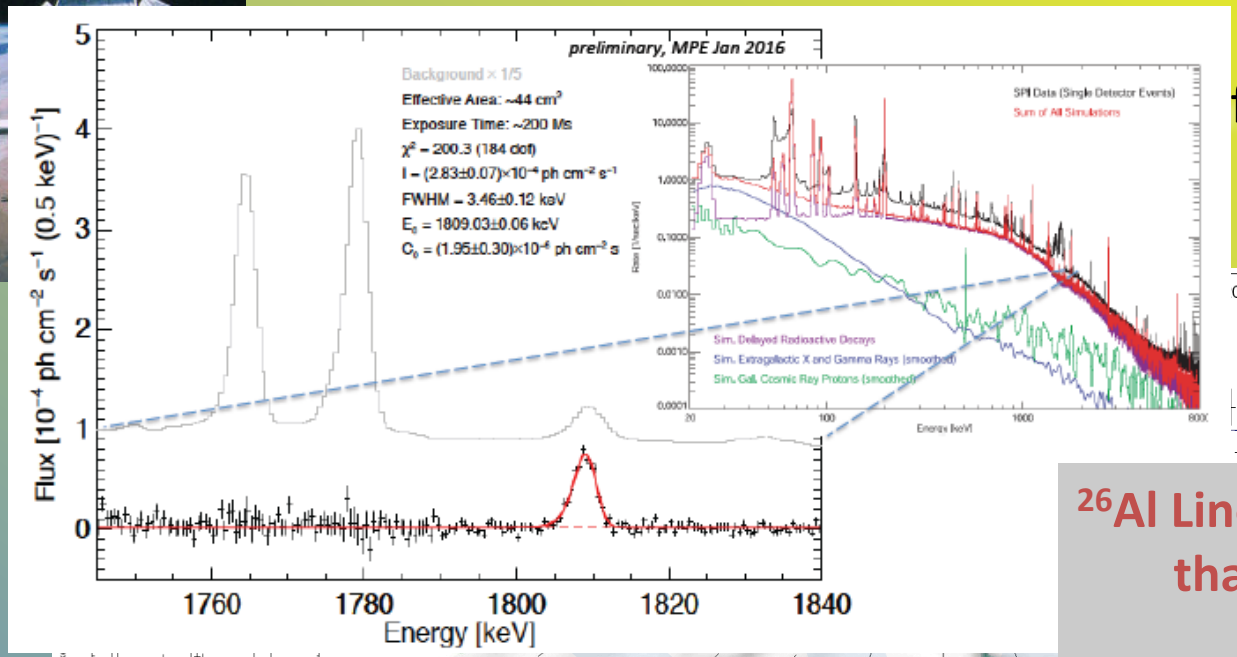
✓ cc-SN Rate = 1.3 (± 0.4) per Century

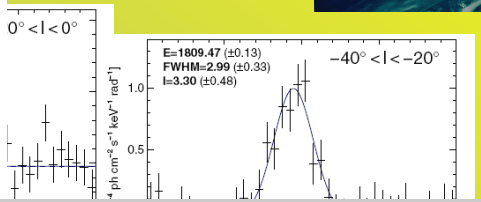




✓ Star Formation Rate = 2.8 $M_\odot$/yr

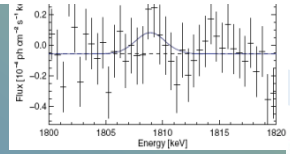
f the Galaxy

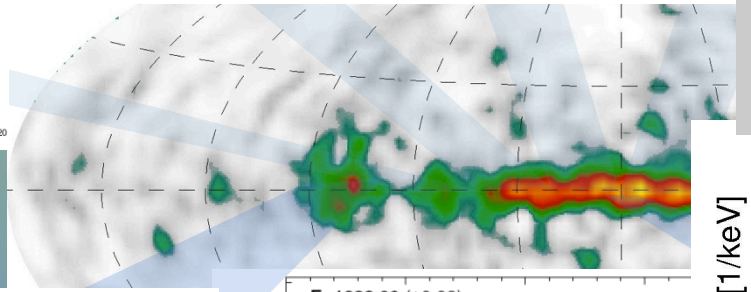


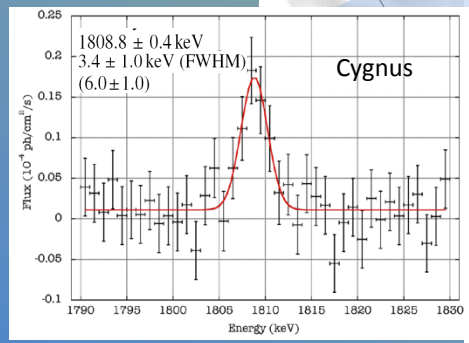


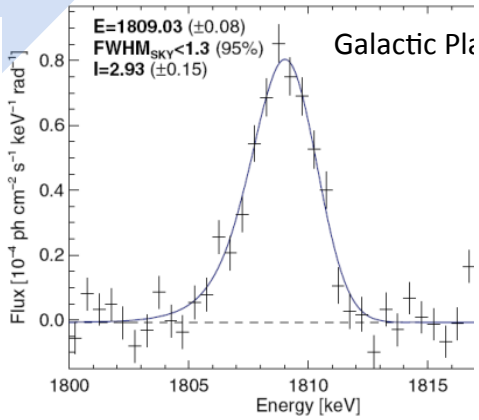
^{26}Al Line is "Narrow" (a little more than the instrumental)

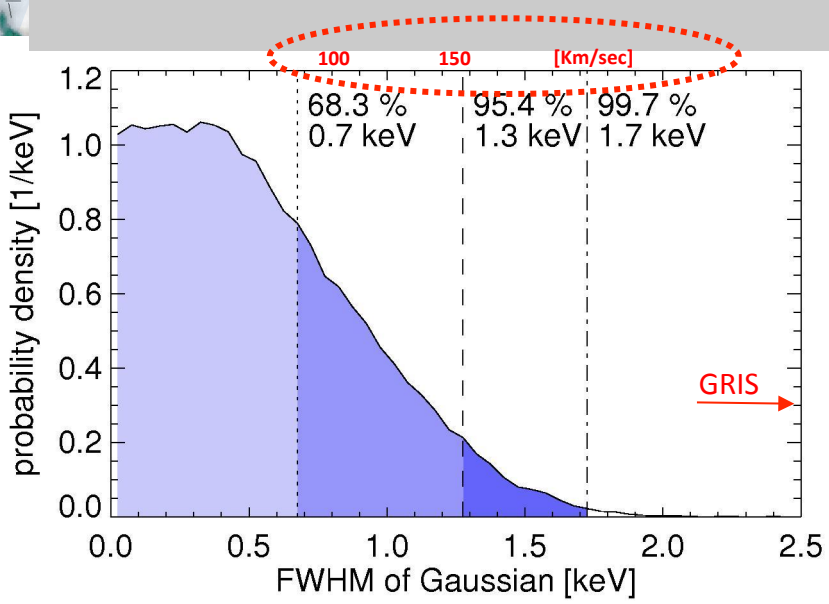
- **SPI: ~0.4 keV, <1.3 keV**
- **ISM velocities 25…150 km s^{-1}**





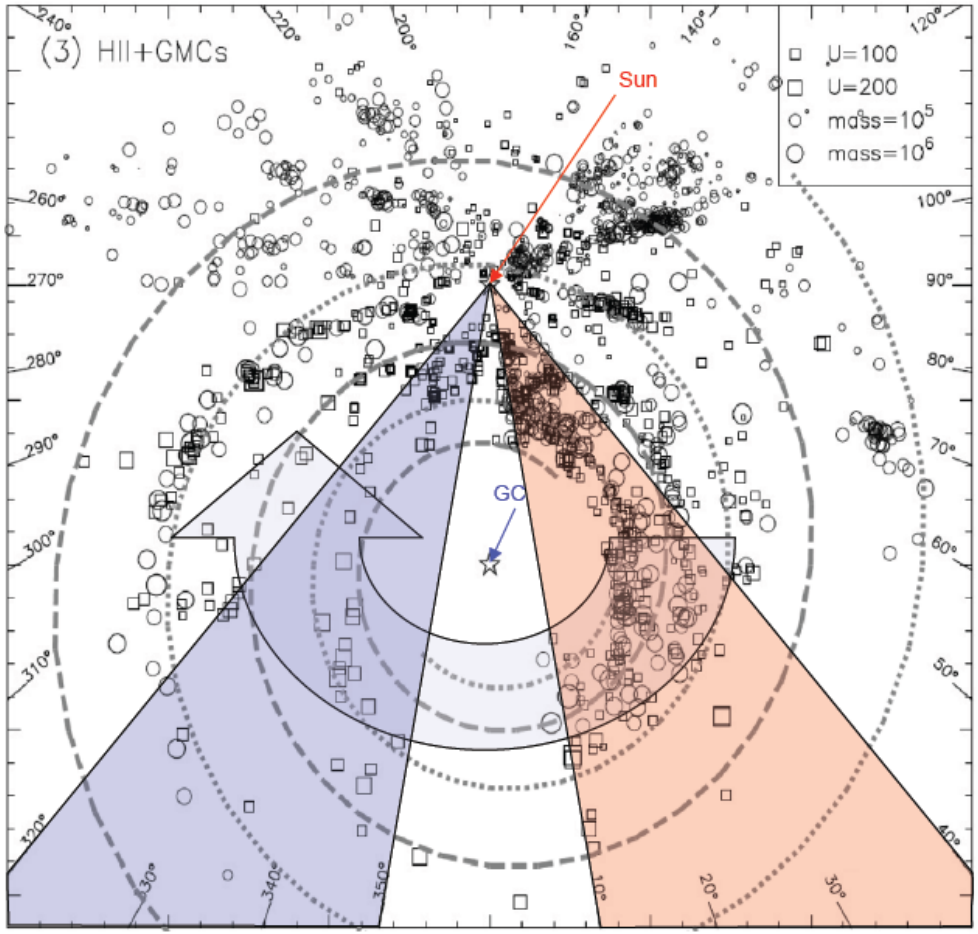


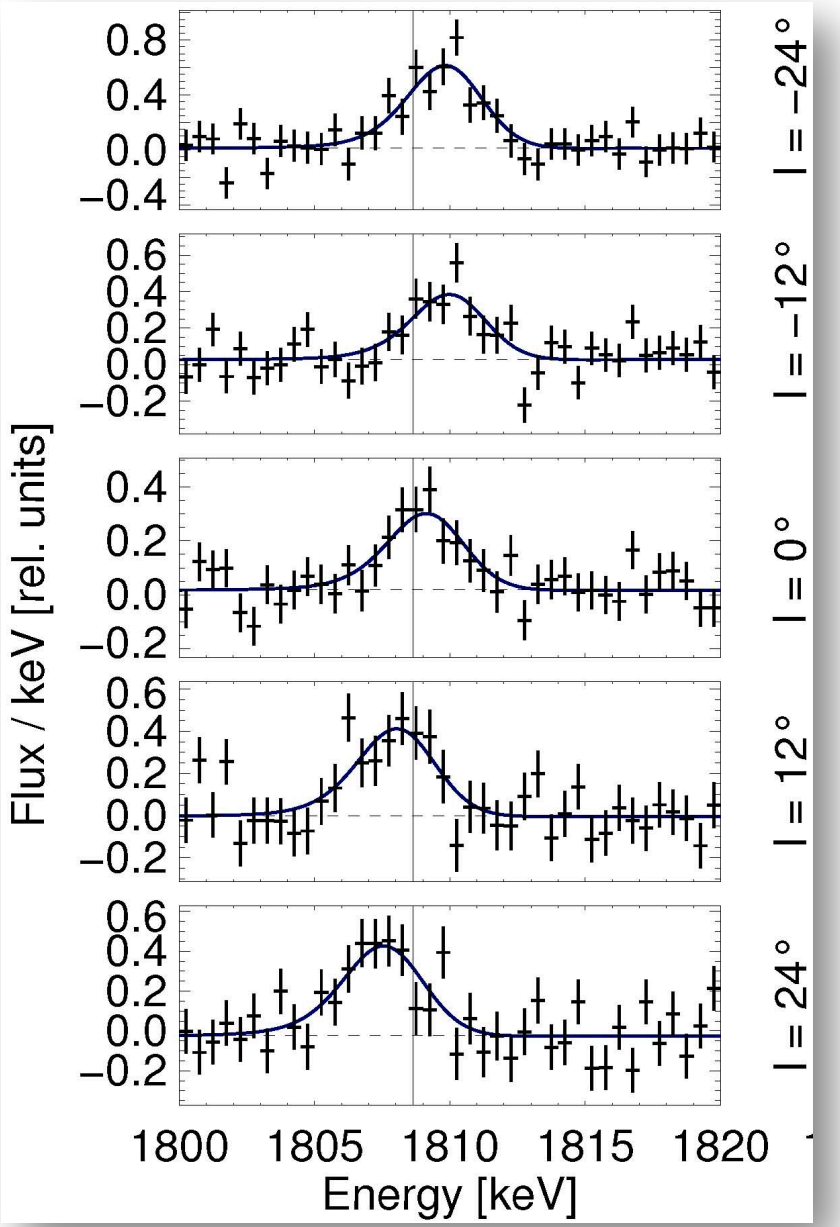




Views of SF in our Galaxy: ^{26}Al γ-rays

- Large-scale Galactic rotation

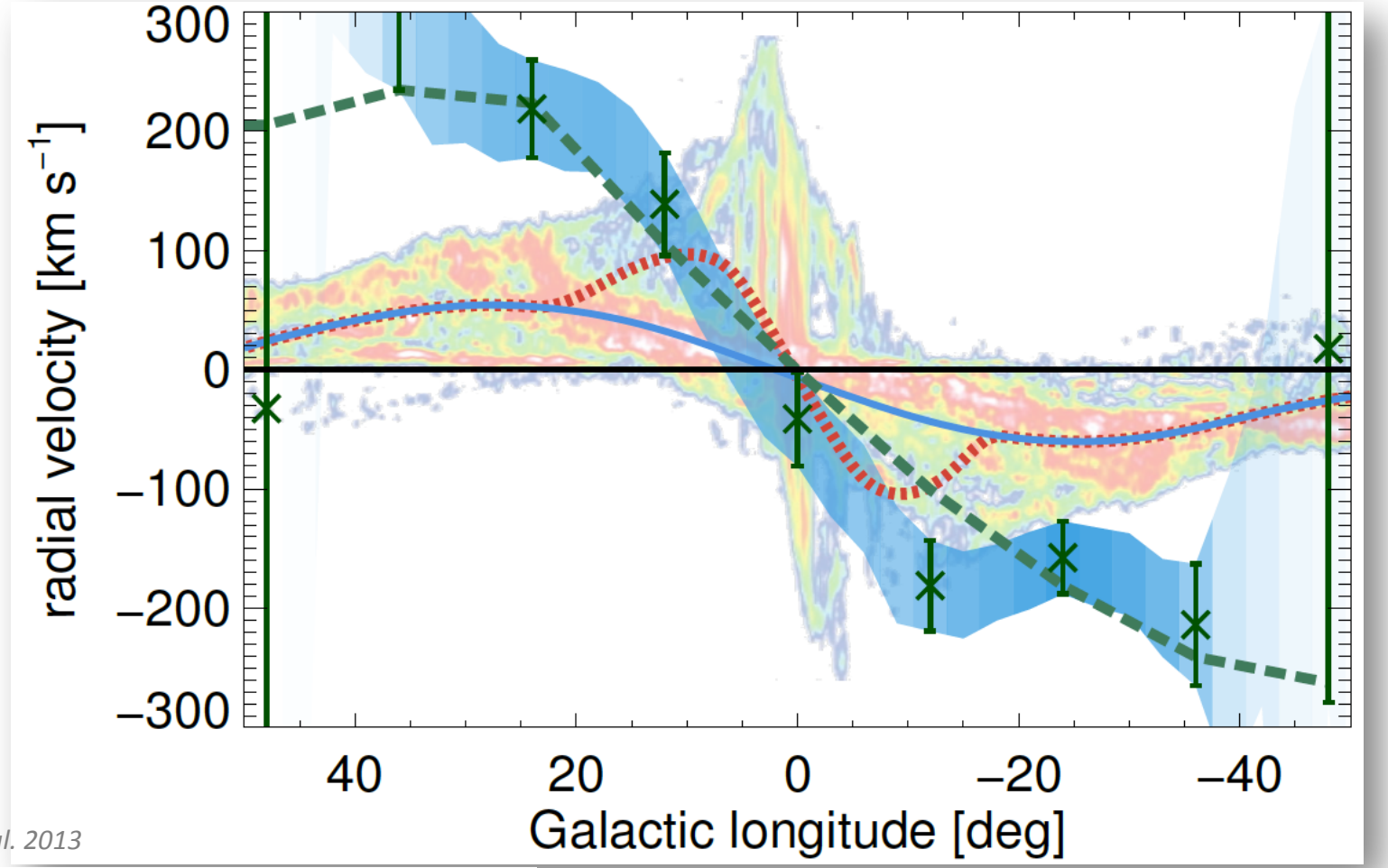




Kretschmer et al., A&A (2013)

The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



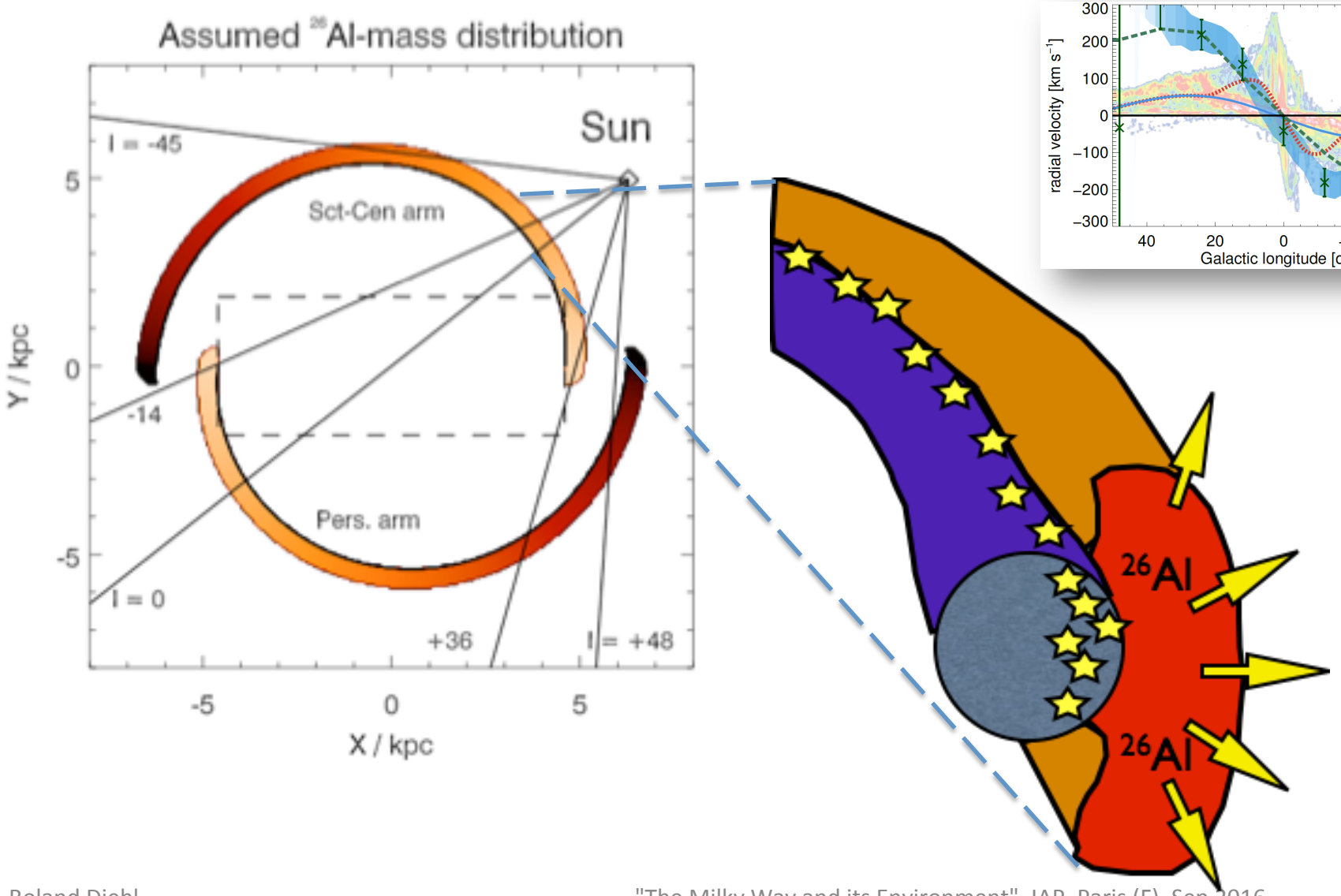
Kretschmer, Diehl, et al. 2013

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



^{26}Al in the Inner Galaxy: Excess Gas Velocities Seen in ^{26}Al

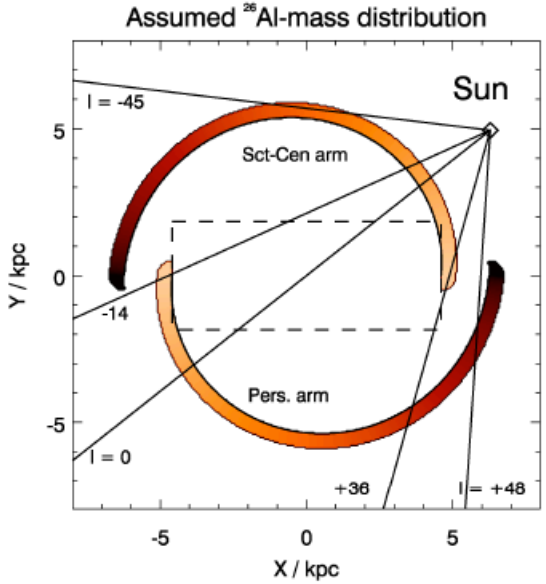
- Interpretation: One-sided Superbubble Blow-outs from Spiral arms' leading edges

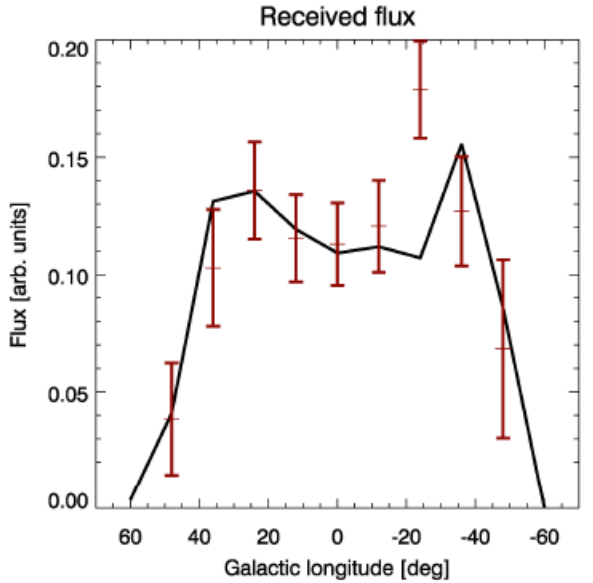
- Assume:

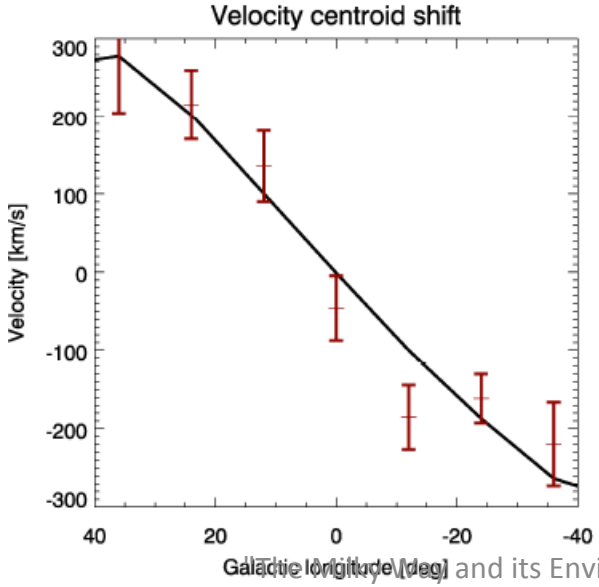
  Sources in Spiral Arms, pref. inner arms/ends

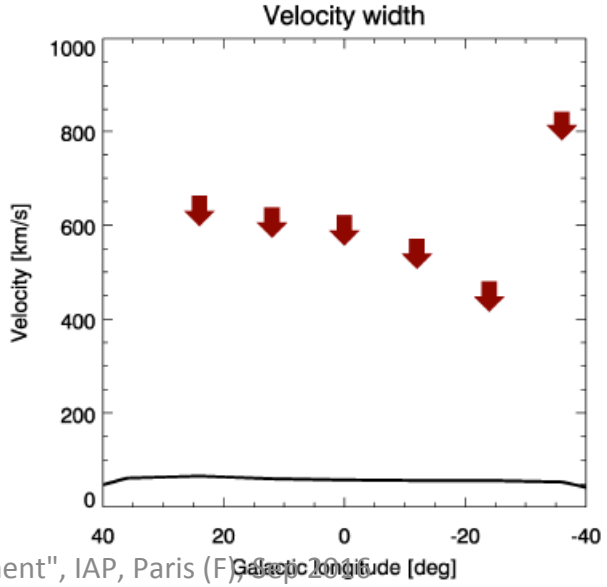
  ~200km/s blowout in direction between arms

  viewed from the Solar System position







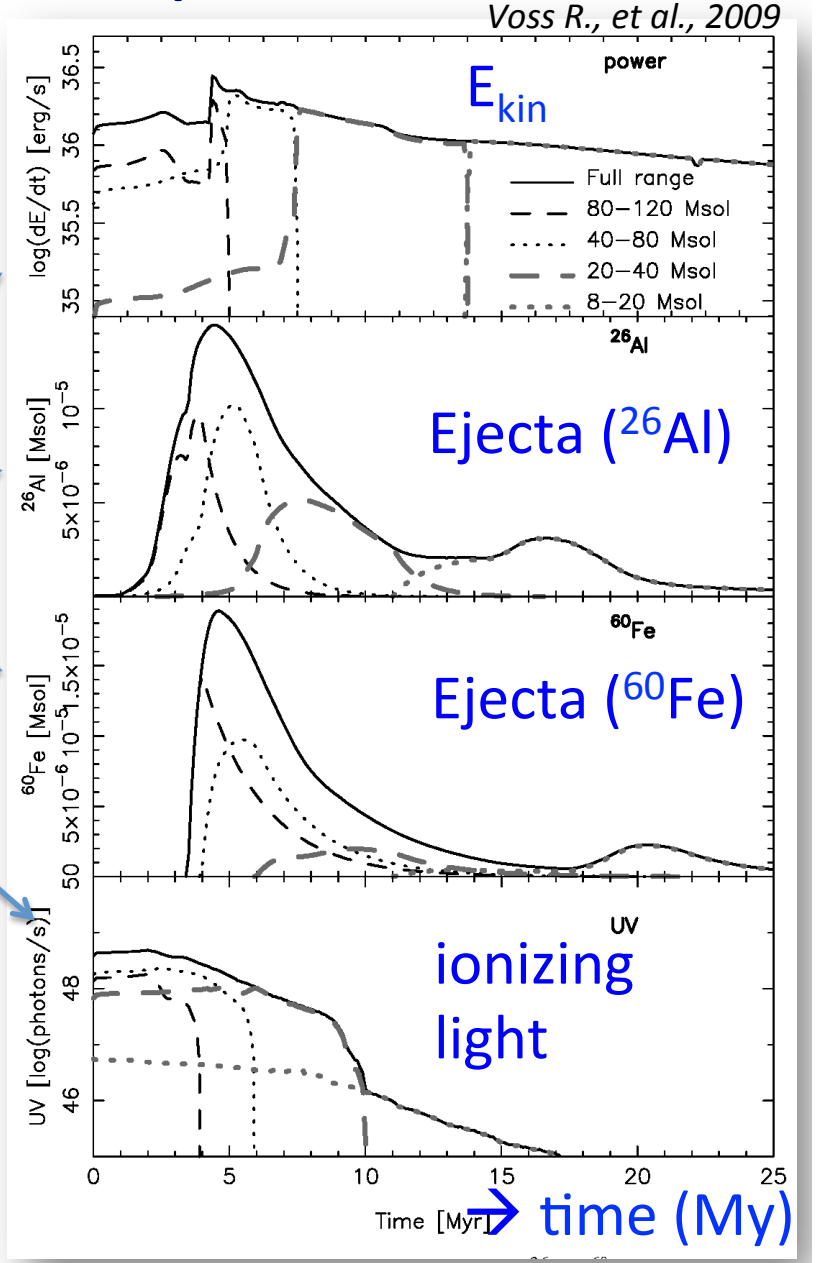


Massive-Star Groups

- 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

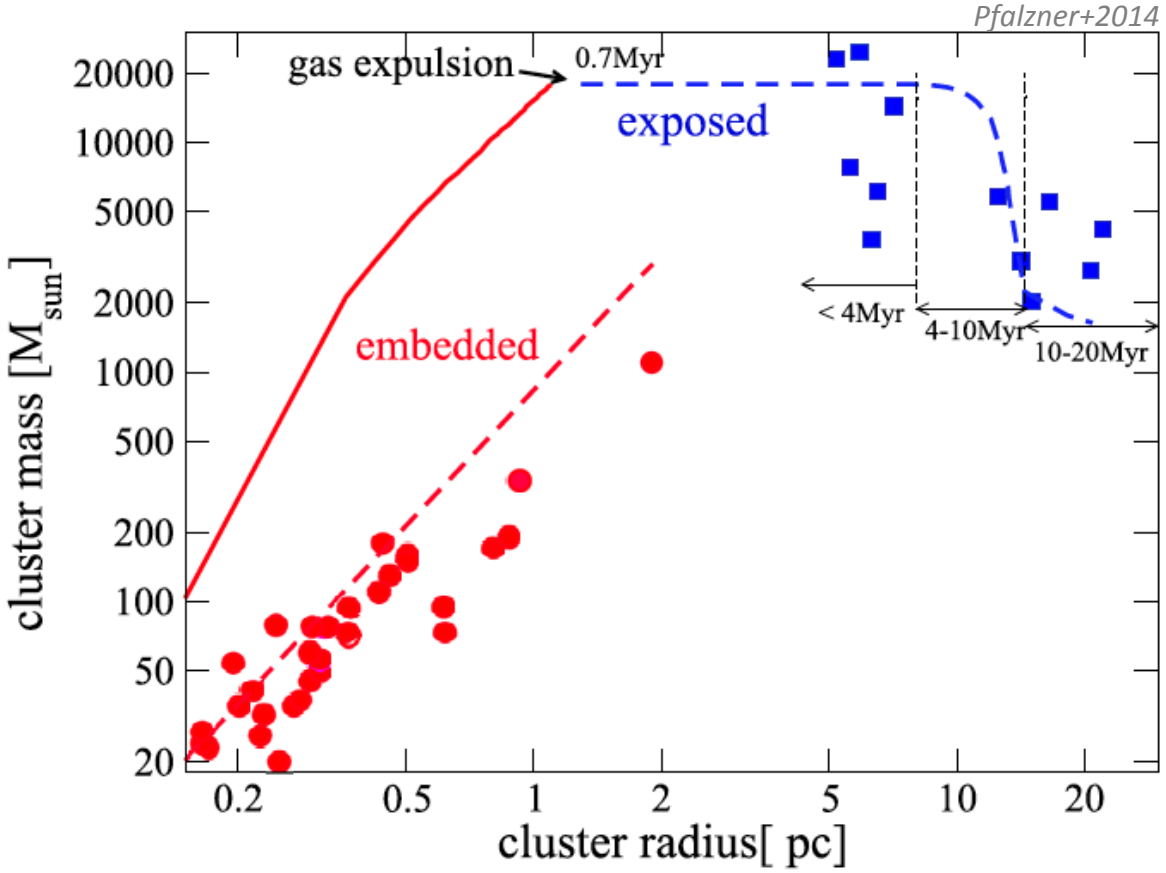


Massive-Star Cluster Birth & Evolution

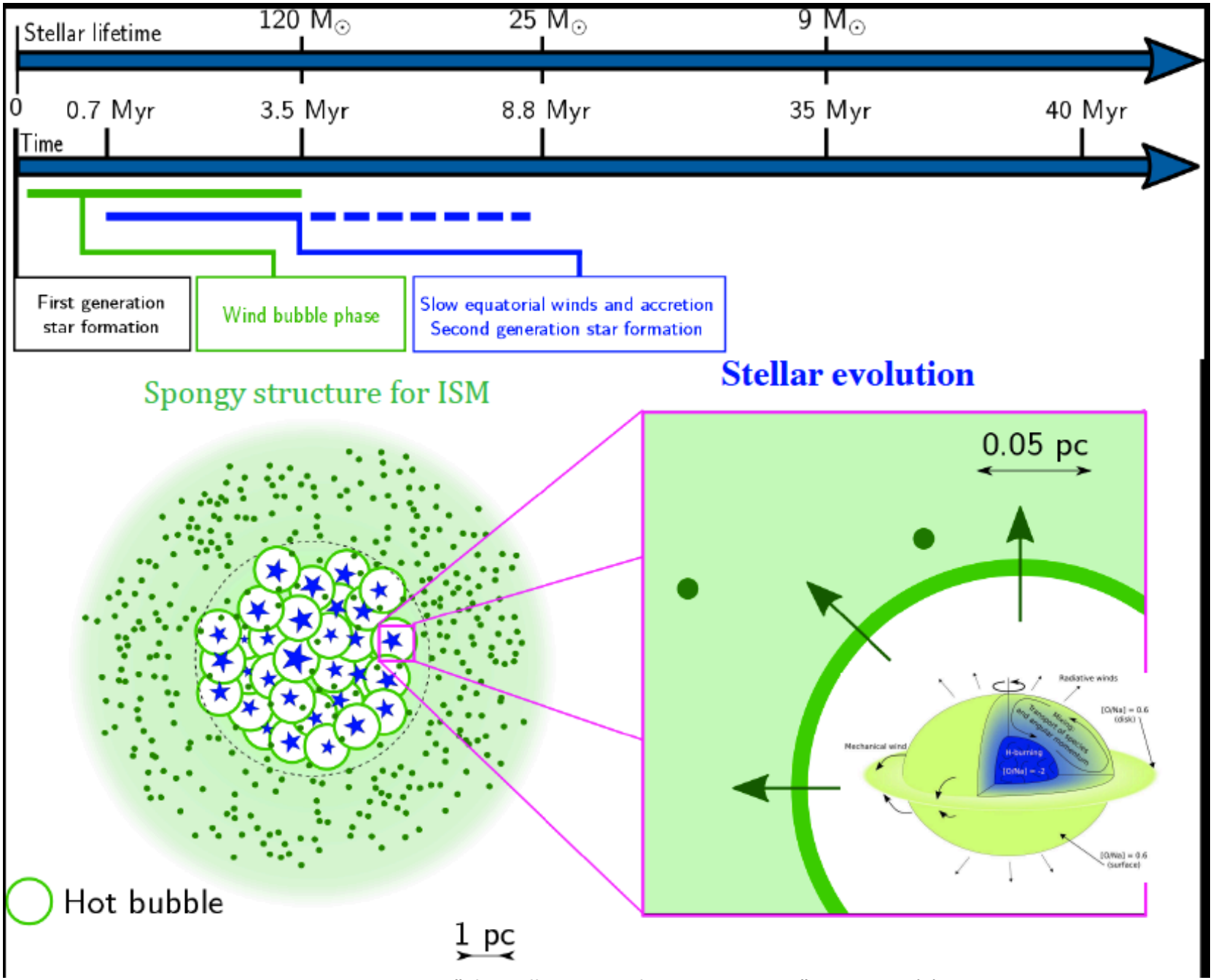
Issues: (…OC's, YMC's, GC's…)

- Formation monolithic or hierarchical?
- Role of initial gas mass?
- Role of gas expulsion?

- How does gas expulsion happen???

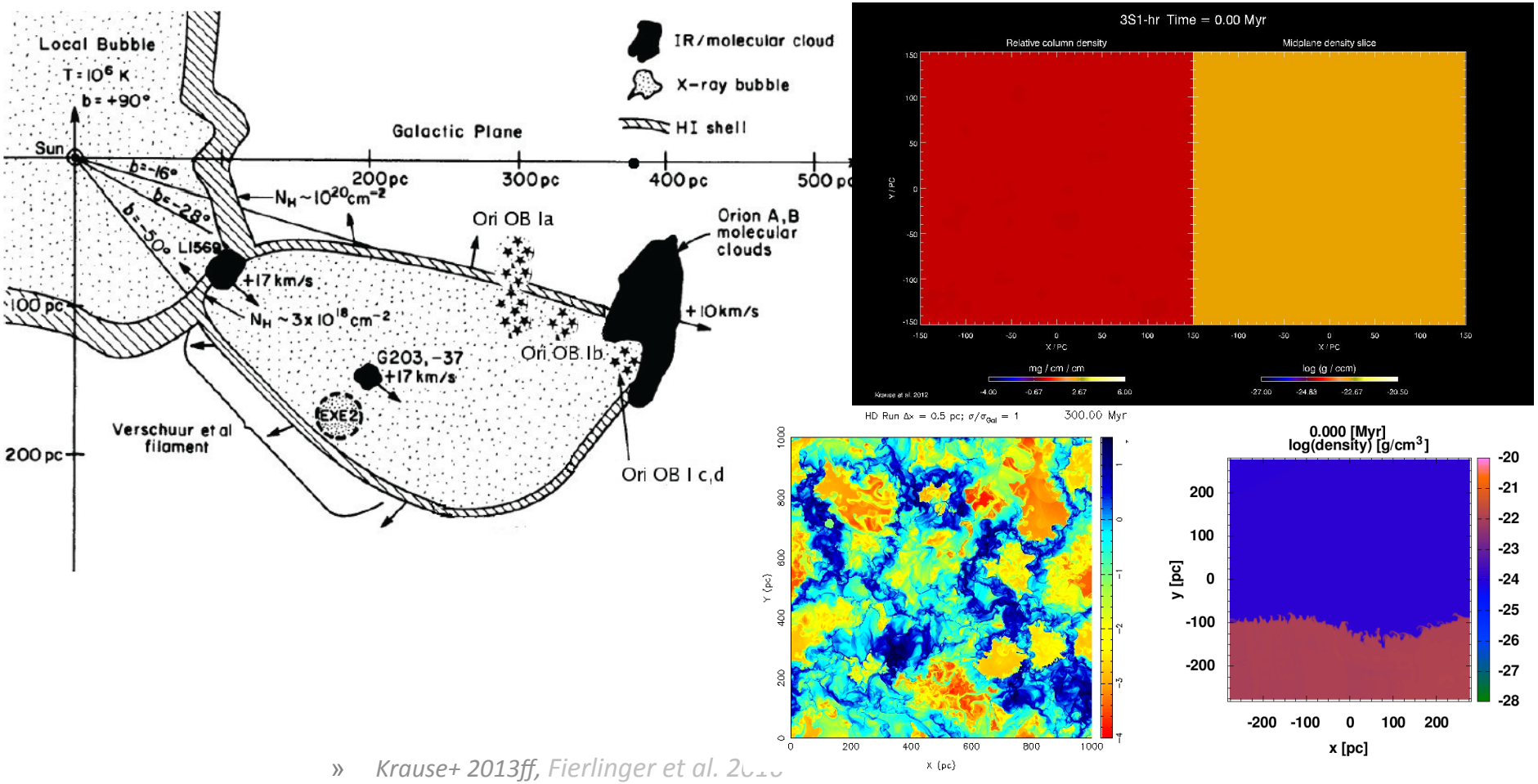


- *see also Banerjee & Kroupa 2015, Gentry+ 2016, Krause+2016, Li+2016, Pfalzner+2016, Yadev+2016, …*: an active field!


Stellar lifetime
120 M⊙
25 M⊙
9 M⊙
0
0.7 Myr
3.5 Myr
8.8 Myr
35 Myr
40 Myr
Time
First generation star formation
Wind bubble phase
Slow equatorial winds and accretion
Second generation star formation
Spongy structure for ISM
Stellar evolution
0.05 pc
Radiative winds
Mechanical wind
H-burning
Hot bubble
1 pc

Nucleosynthesis Ejecta and Dynamics of Interstellar Medium

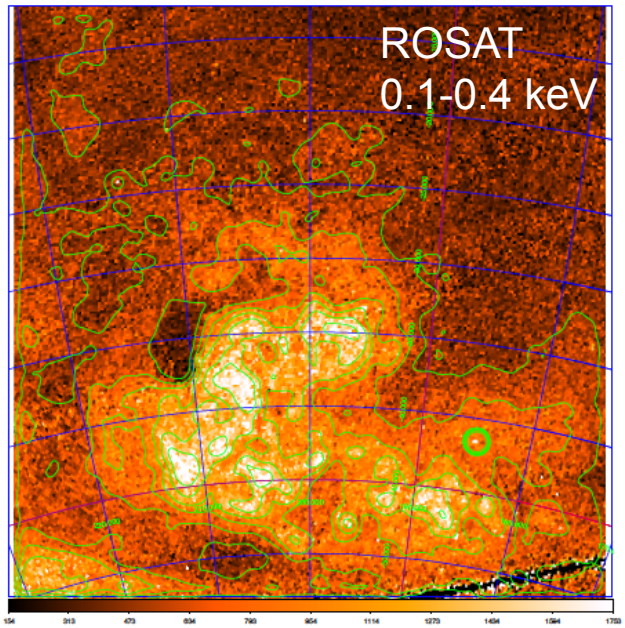
- ISM is Highly-Dynamic → Ejecta in (Super-)Bubbles
  - Study Specific Regions in Detail (Cygnus, Orion, Scorpius-Centaurus, Carina)

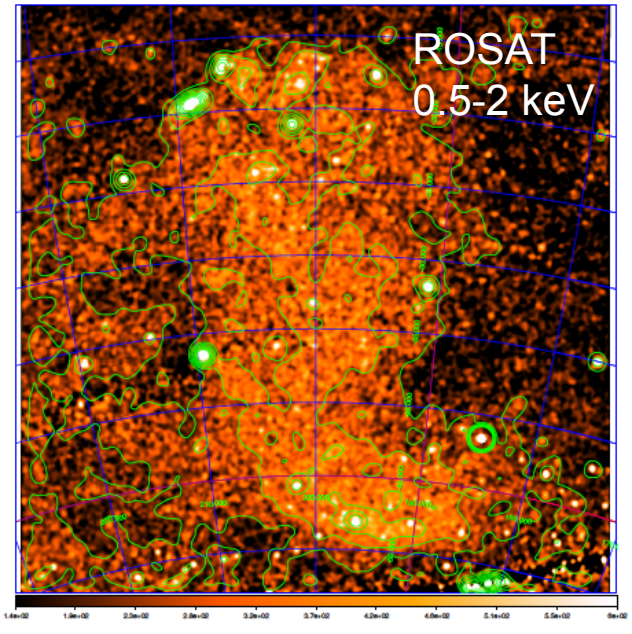


» *Krause+ 2013ff, Fierlinger et al. 2016*

Understanding the Eridanus Superbubble

- X-ray Emission, size, ^{26}Al





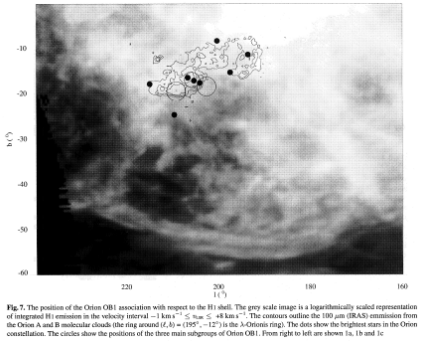
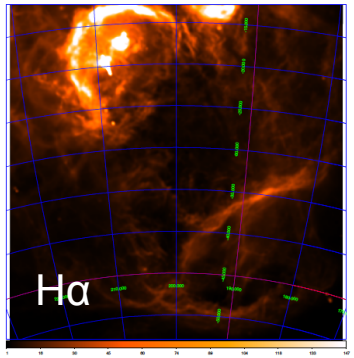
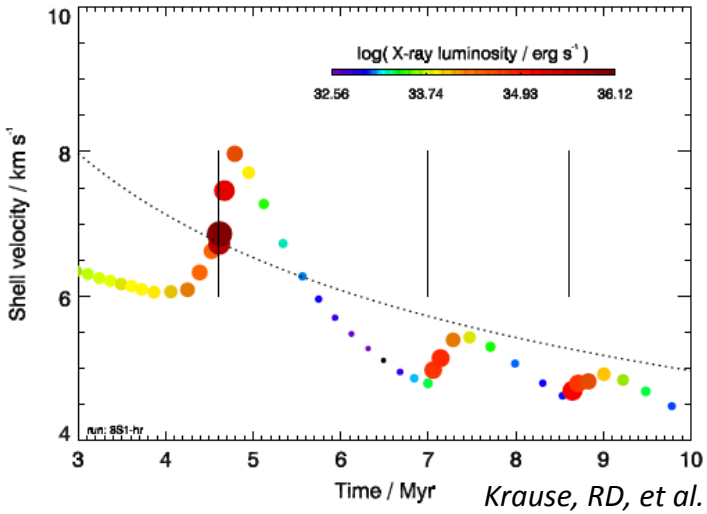


Fig. 7. The position of the Orion OB1 association with respect to the H I shell. The grey scale image is a logarithmically scaled representation of integrated H I emission in the velocity interval $-1\ \mathrm{km\,s^{-1}} \leq v_{\mathrm{LSR}} \leq +8\ \mathrm{km\,s^{-1}}$. The contours outline the 100 μm (IRAS) emmission from the Orion A and B molecular clouds (the ring around $(l, b) = (195°, -12°)$ is the λ-Orionis ring). The dots show the brightest stars in the Orion constellation. The circles show the positions of the three main subgroups of Orion OB1. From right to left are shown 1a, 1b and 1c



– Temporal X-ray brightenings after SN energy injections
– spatial oscillations

superbubble with two off-center supernovae

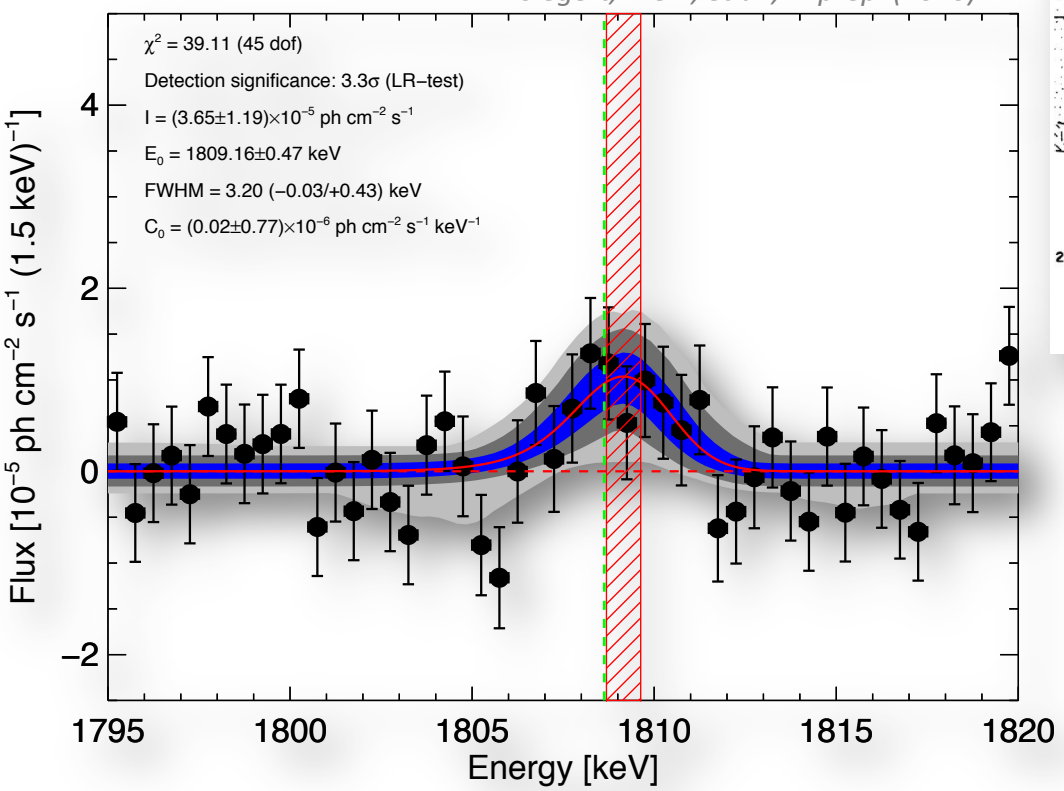


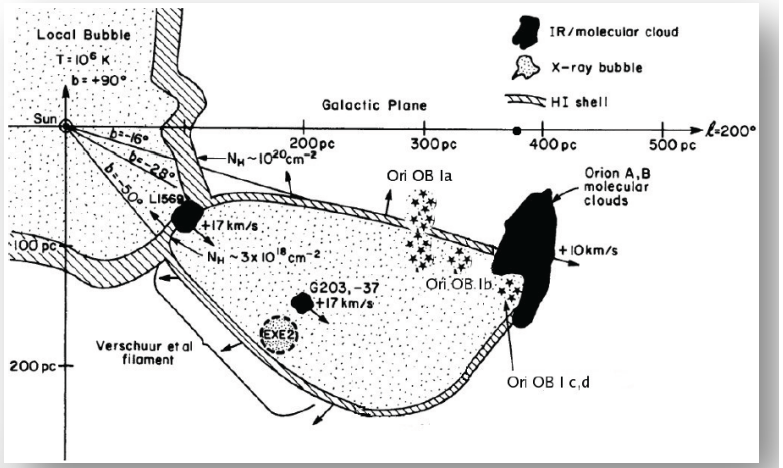
Krause, RD, et al. 2015

^{26}Al in Orion

- Now also detected with SPI/INTEGRAL

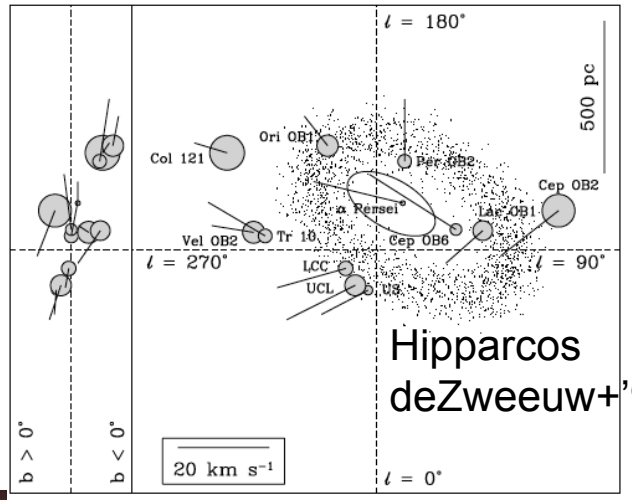
Siegert, Diehl, et al., in prep. (2016)





– Kinematics?? → blue shift; velocity broadening?

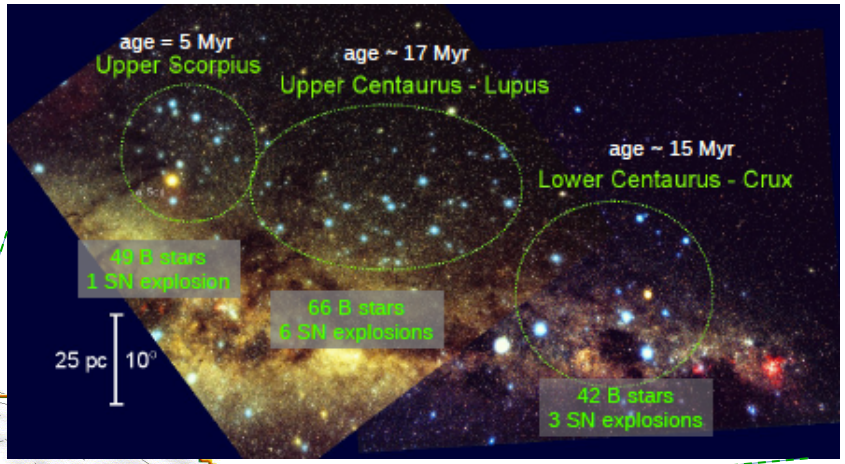
Resolving ^{26}Al Emission from Specific Groups of Stars

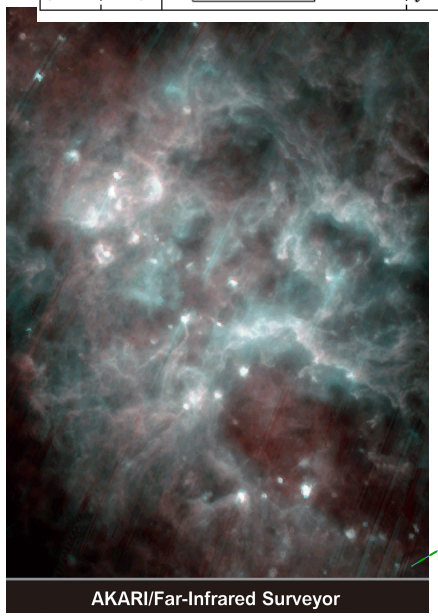


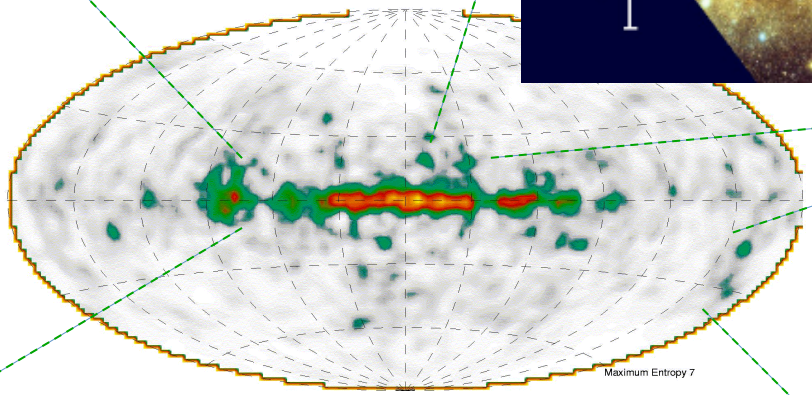
Hipparcos
deZweeuw+'99

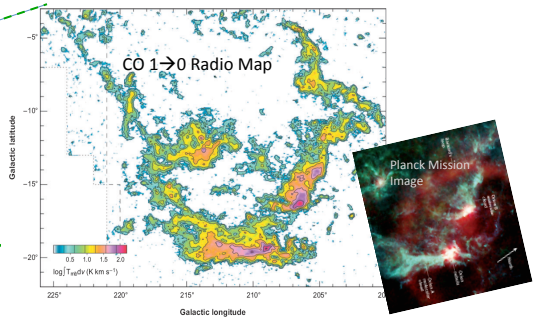
Nearby and/or rich Groups of Stars:

Test our Models for Consistency









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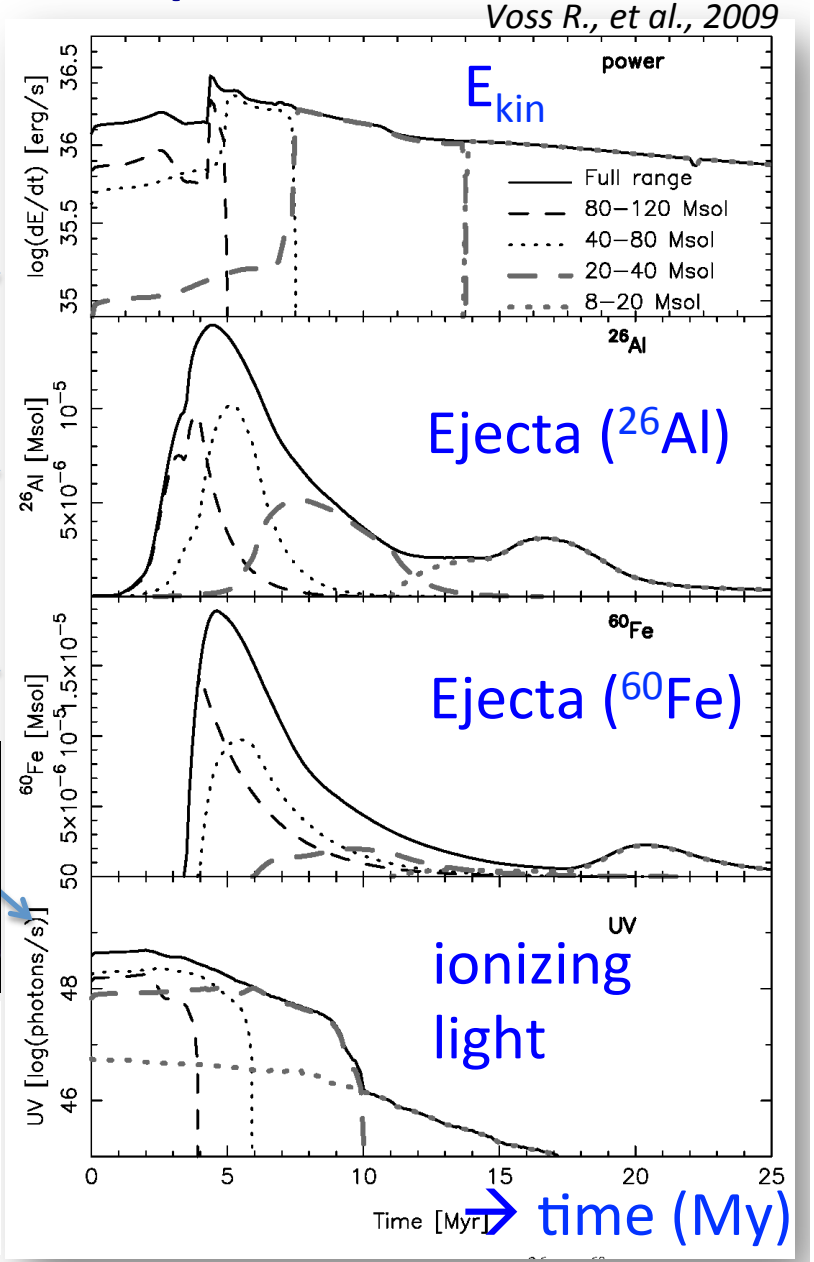
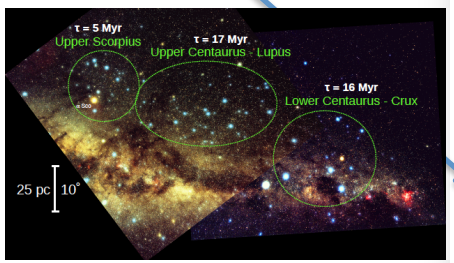
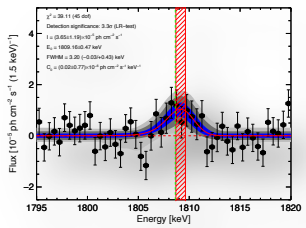
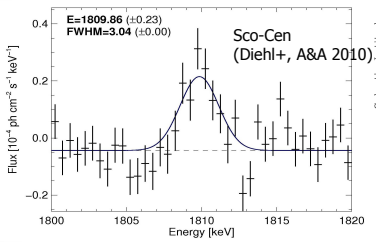
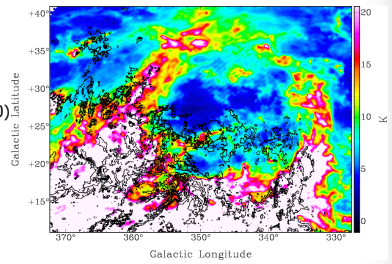




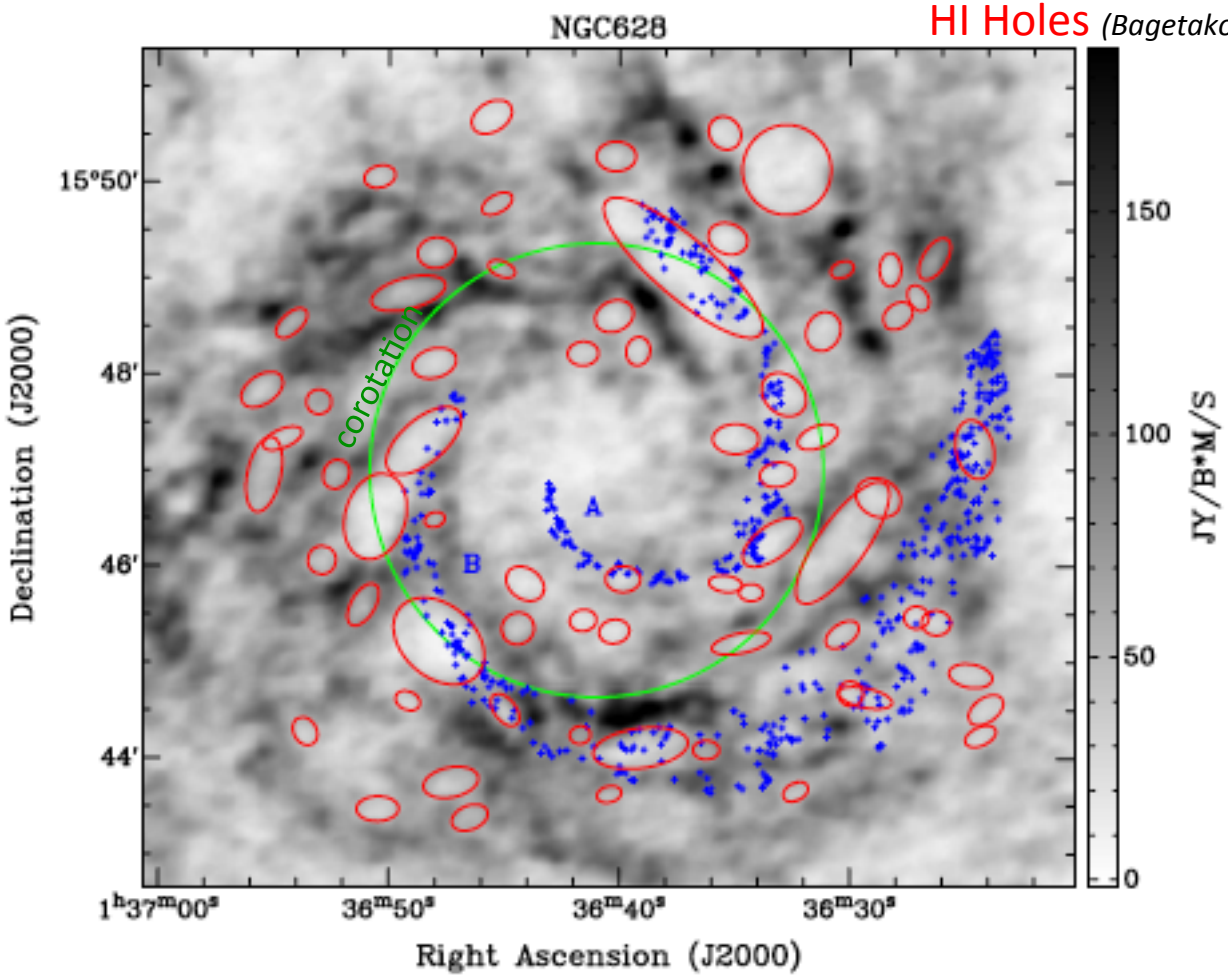


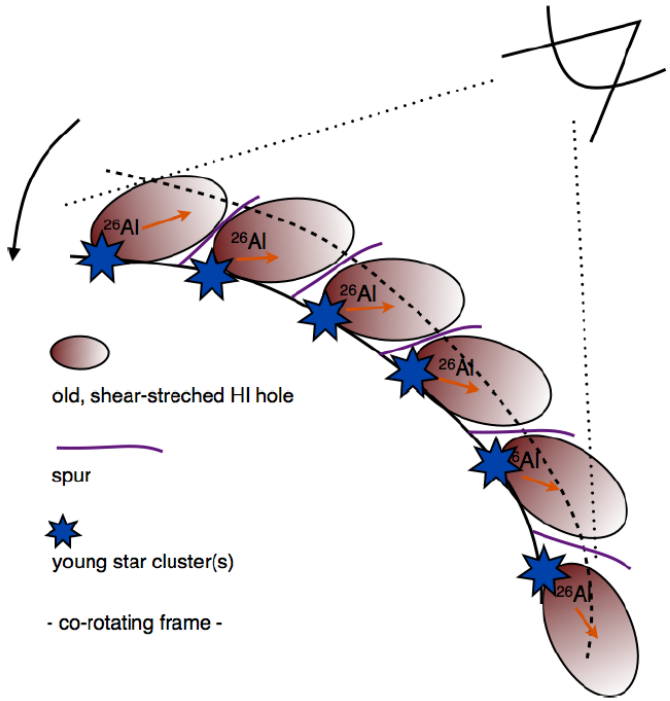




Superbubbles and HI Holes

- ^{26}Al Ejecta Streaming into HI Holes Between Arms

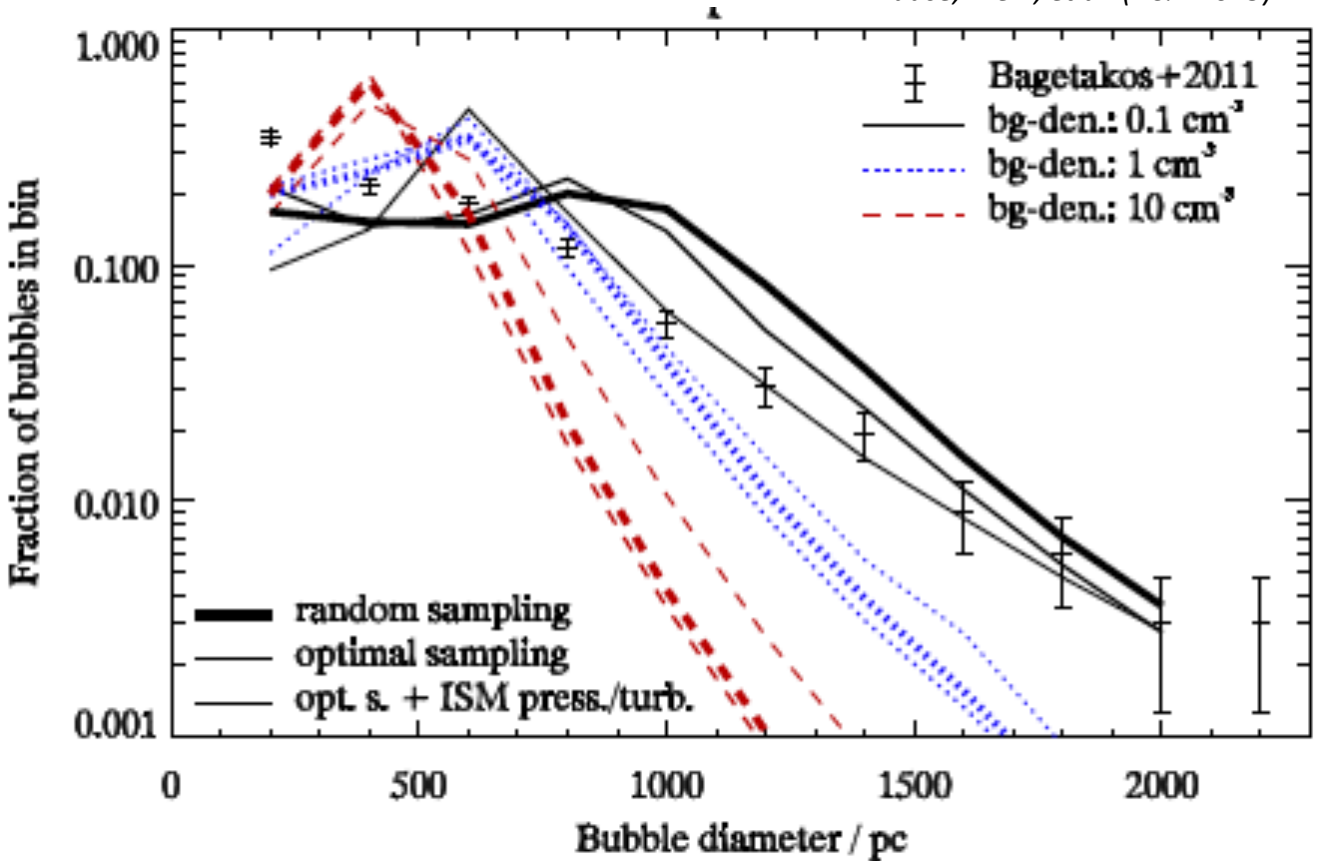




How do HI "holes" (~SB's) compare with this?

- PopSyn → Ejected E_{kin} from Star Clusters → SB size
  - Depends on ambient ISM density

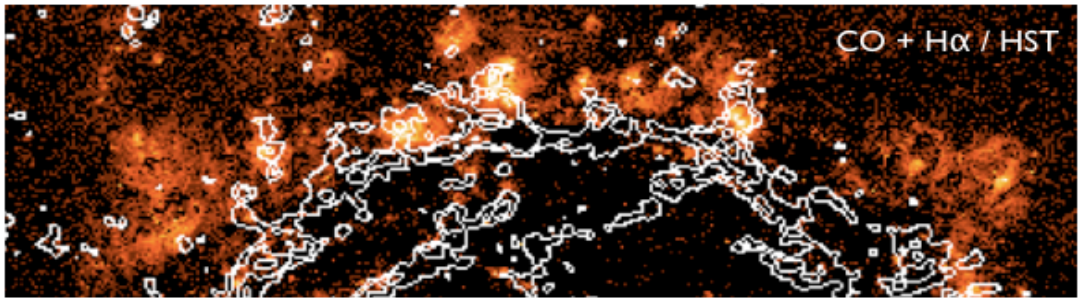
Krause, Diehl, et al. (A&A 2015)

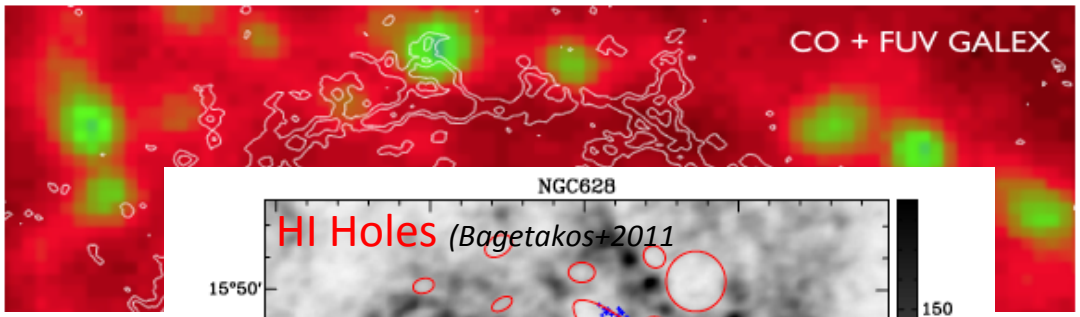


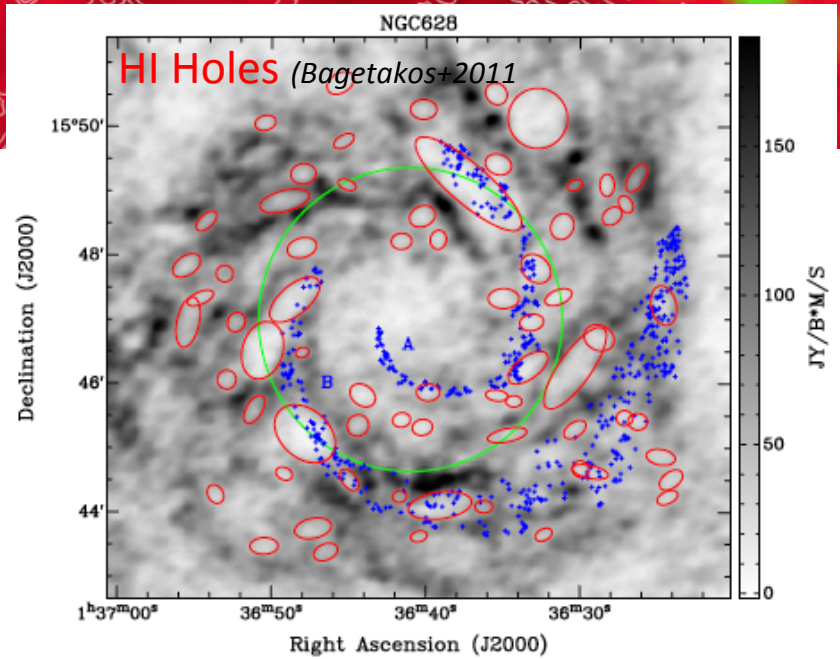
– Low-density environments are required to make large SBs

How massive-star ejecta are spread out…

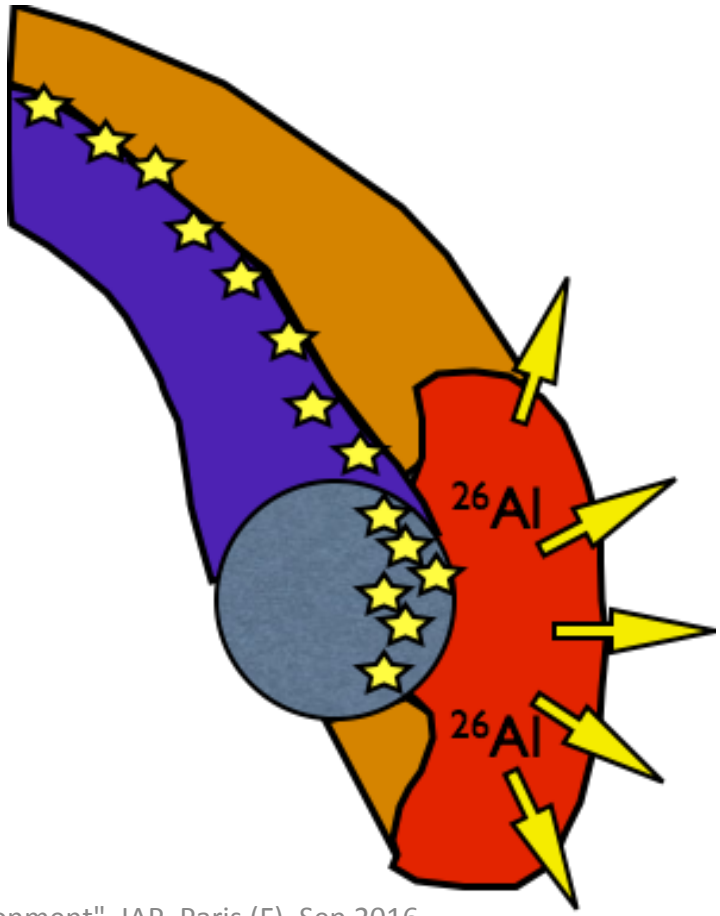
- Superbubbles blown into inter-arm regions



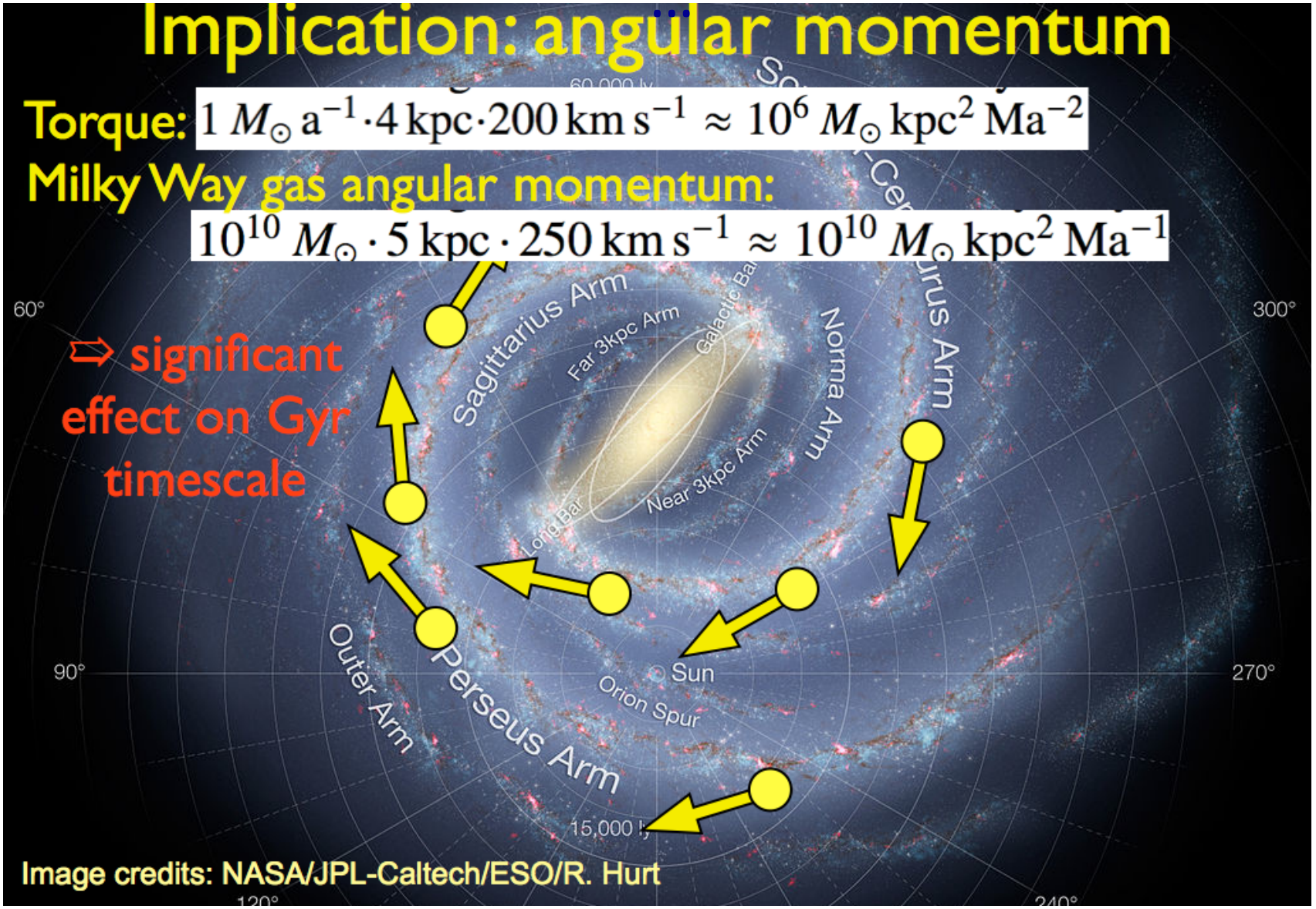




…seen in other galaxies.



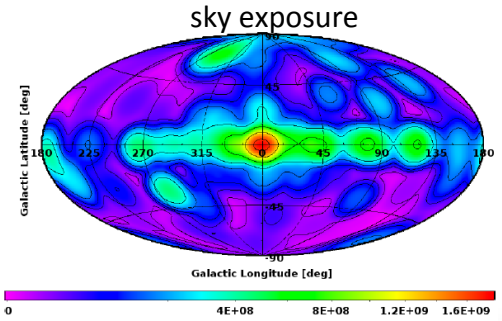
How Massive-Star Feedback May Impact Galactic Flows

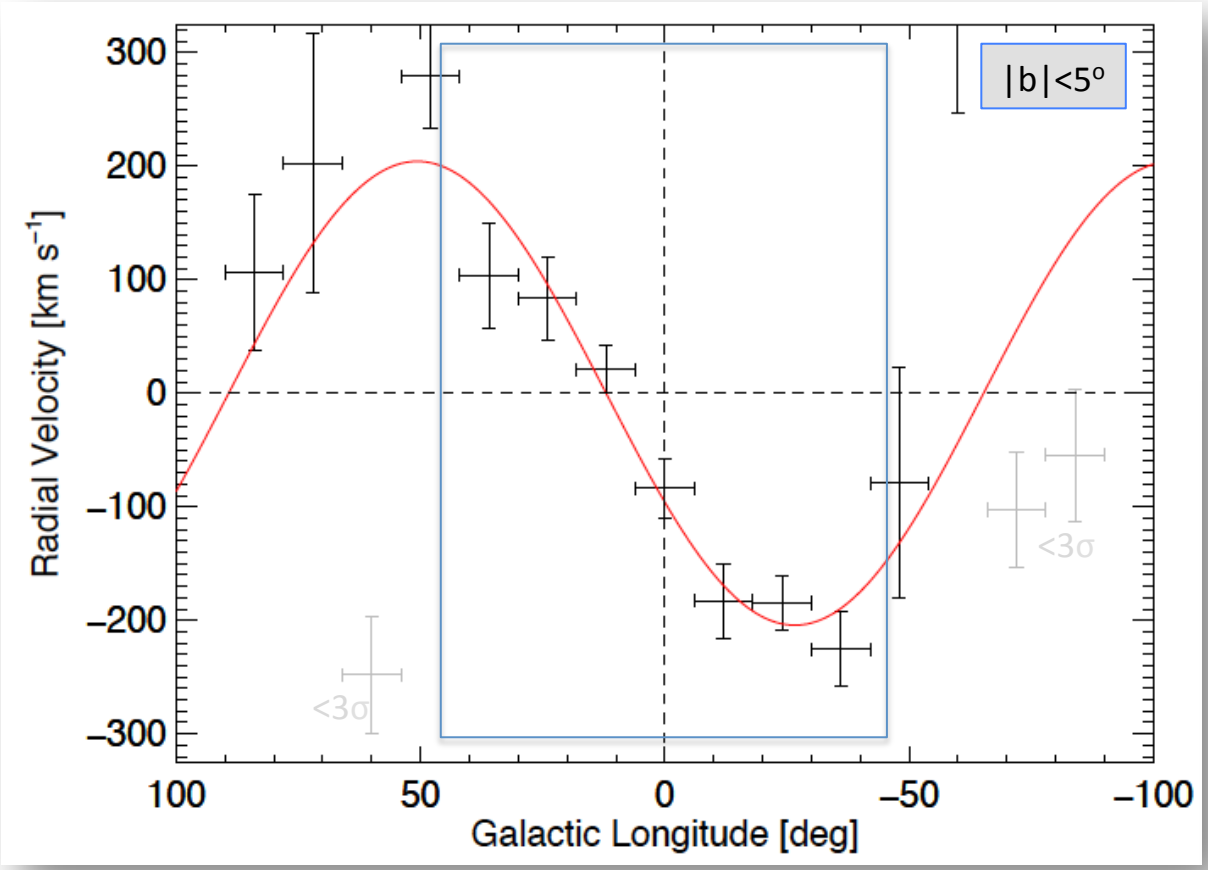


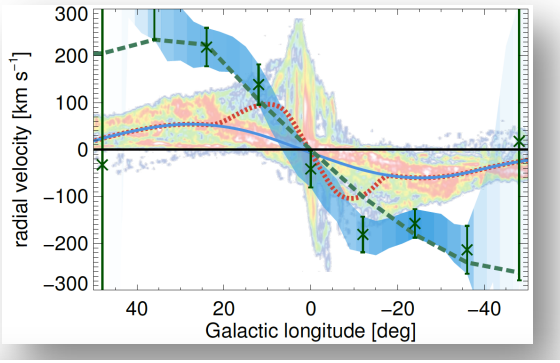
^{26}Al longitude vs. velocity: Update 2016

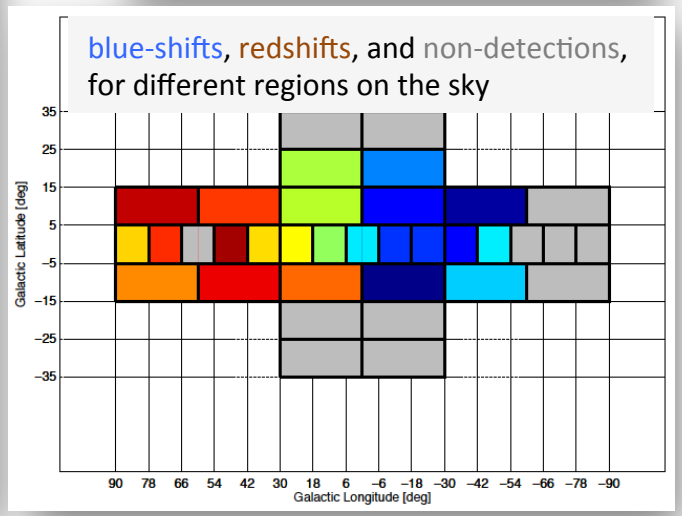
13 years of data (9), improved methods

→ confirm ~same characteristics





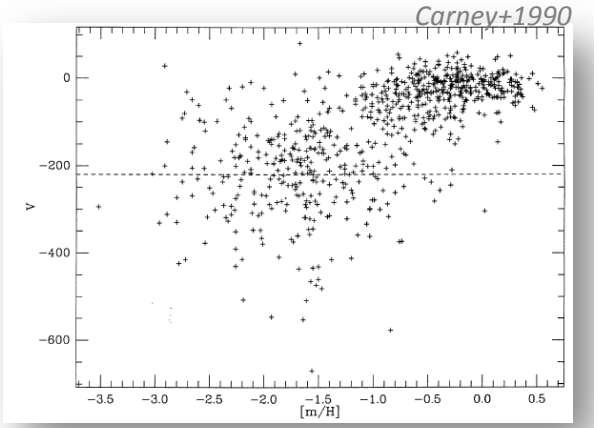


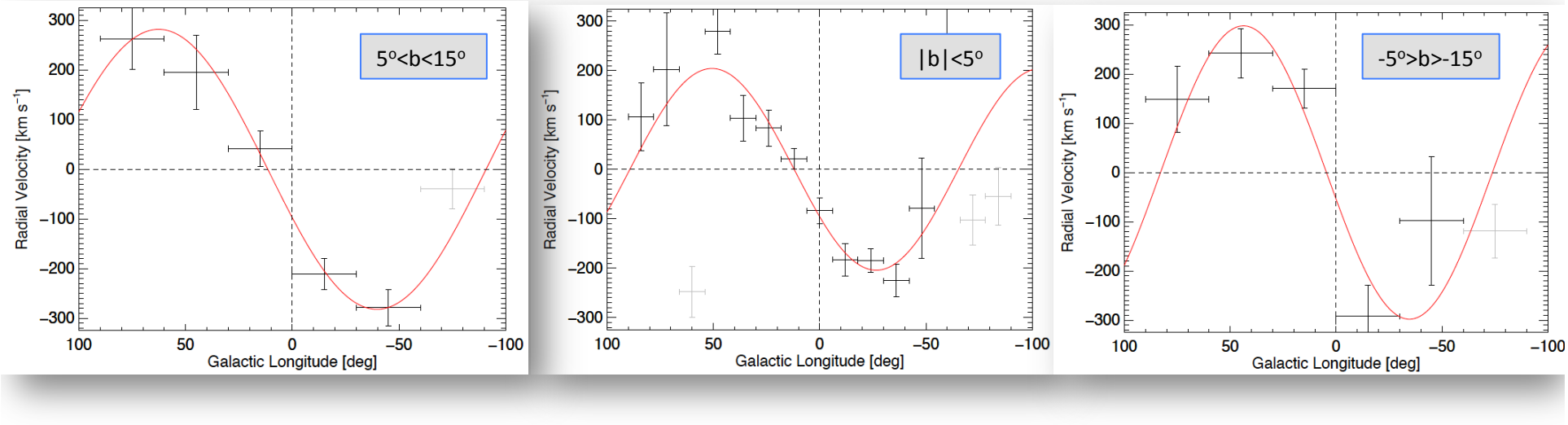


^{26}Al longitude vs. velocity: Update 2016

latitudinal dependency: disk vs halo region

→ asymmetries (?) wrt disk & center

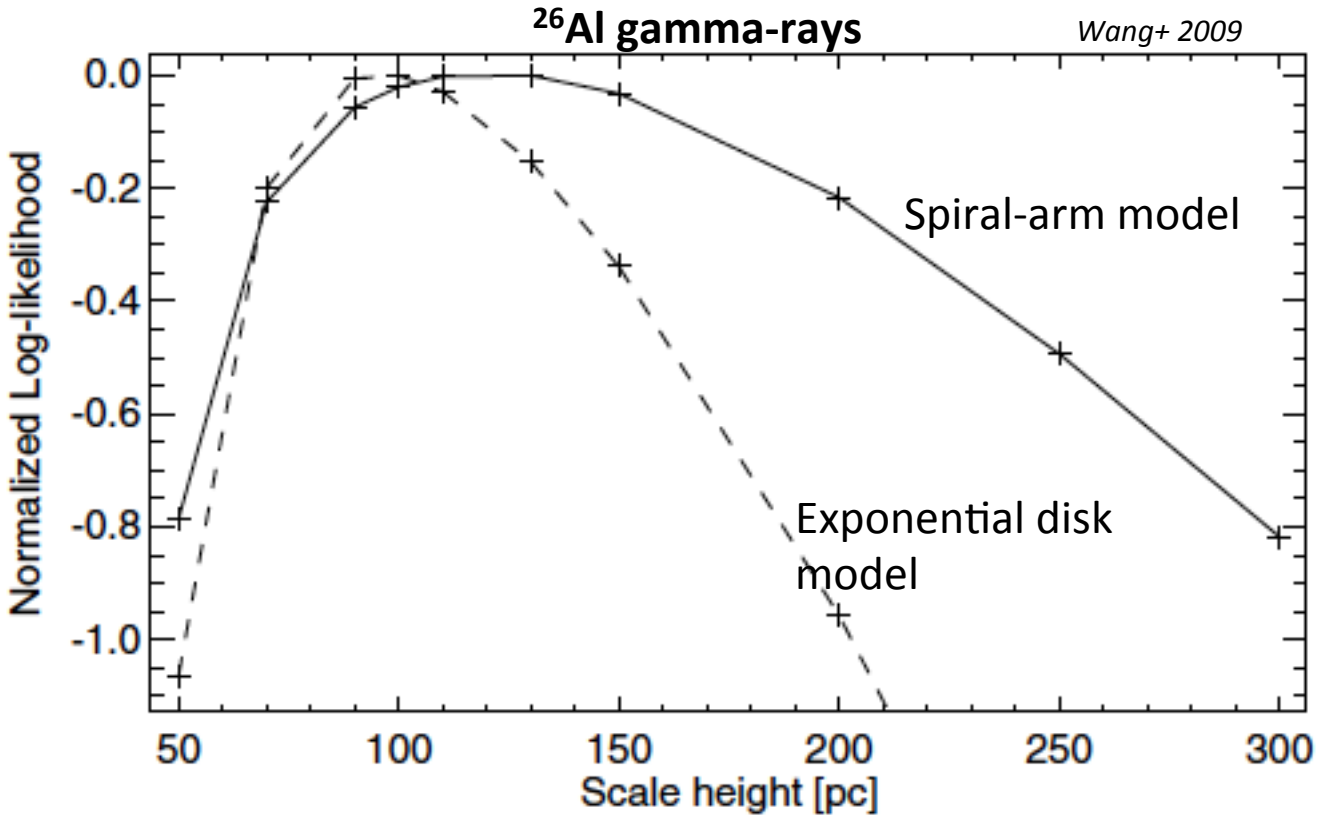




→ foreground emission (Scorpius-Centaurus)?

Measuring the Latitude Extent of Ejecta Flow

- scale height ~130 pc (CO: ~50 pc)



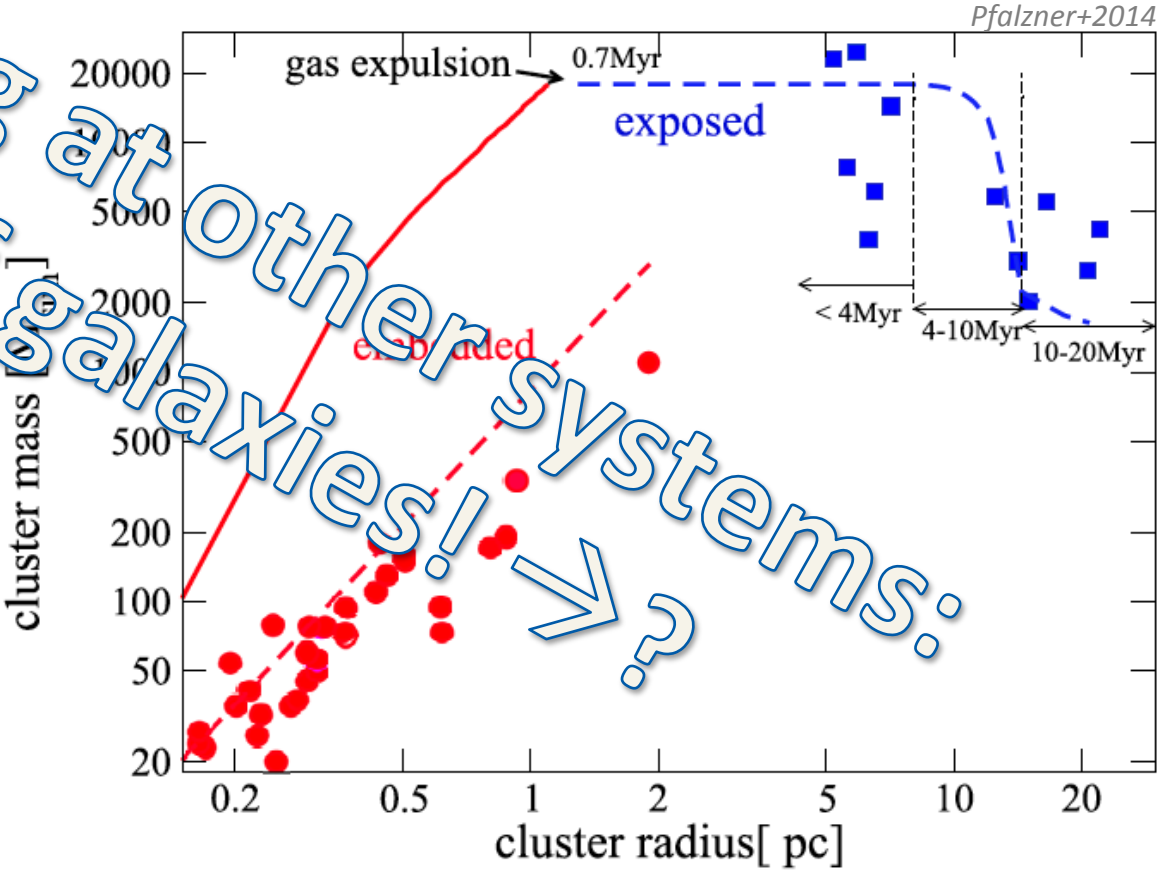
Massive-Star Cluster Birth & Evolution

Issues: (…OC's, YMC's, GC's…)

- Formation monolithic or hierarchical?
- Role of initial gas mass?
- Role of gas expulsion?

…looking at other systems: Dwarf galaxies! → ?

- How does gas expulsion happen???



- *see also Banerjee & Kroupa 2015, Gentry+ 2016, Krause+2016, Li+2016, Pfalzner+2016, Yadev+2016, …*: an active field!

Stellar population evolution in small systems

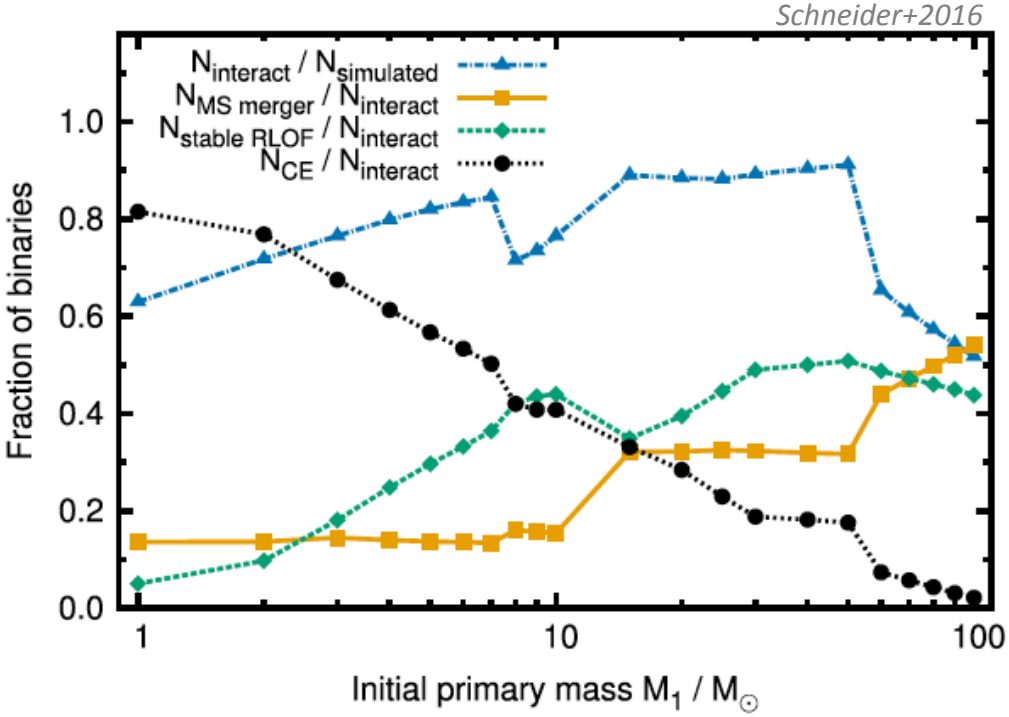
- Gas expulsion, stellar interactions, and binary system actions likely quench star formation quickly
- What remains??

  … Issues:

  - Only first star generation? (low Z → massive?)
  - Dispersed, i.e. only central objects currently identifyable
  - Nucleosynthetic fingerprint?
  - Important role of binaries → NS mergers? BH binaries?

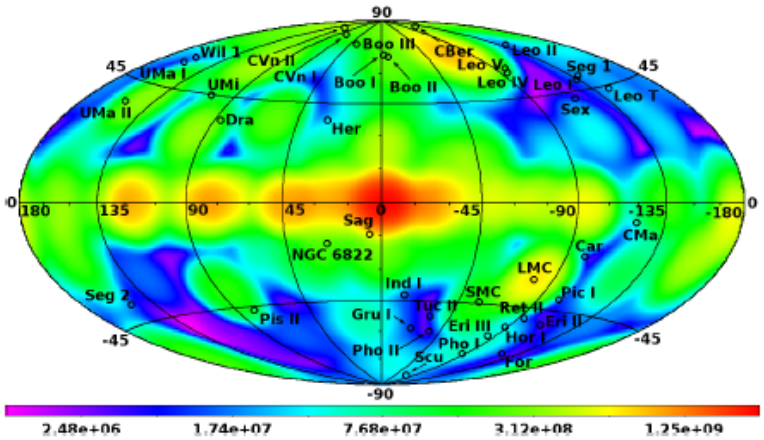
  – e.g., dSph's…

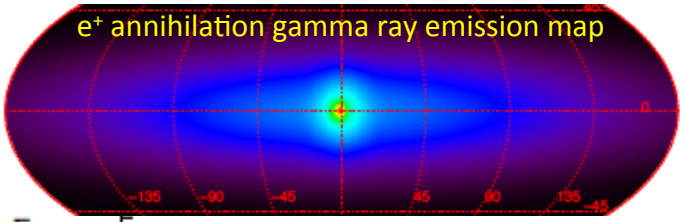
Schneider+2016



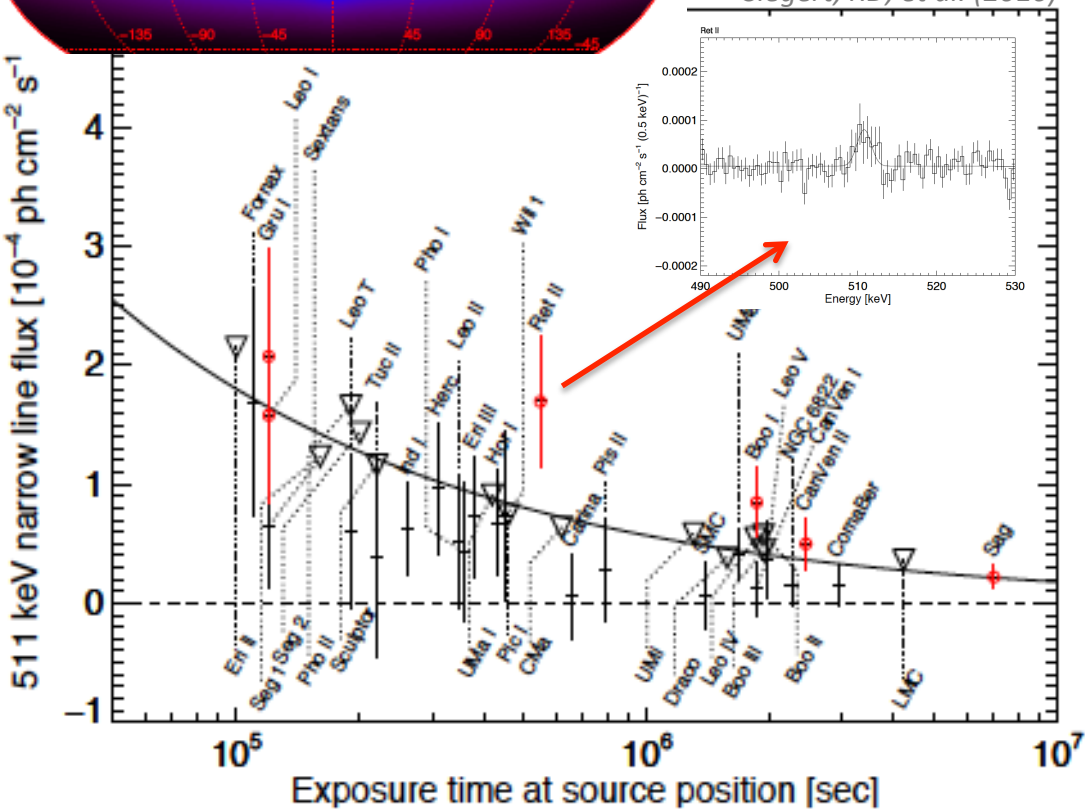
Positron Annihilation in a dSph Galaxy

Search for 511 keV emission in nearby dSph galaxies





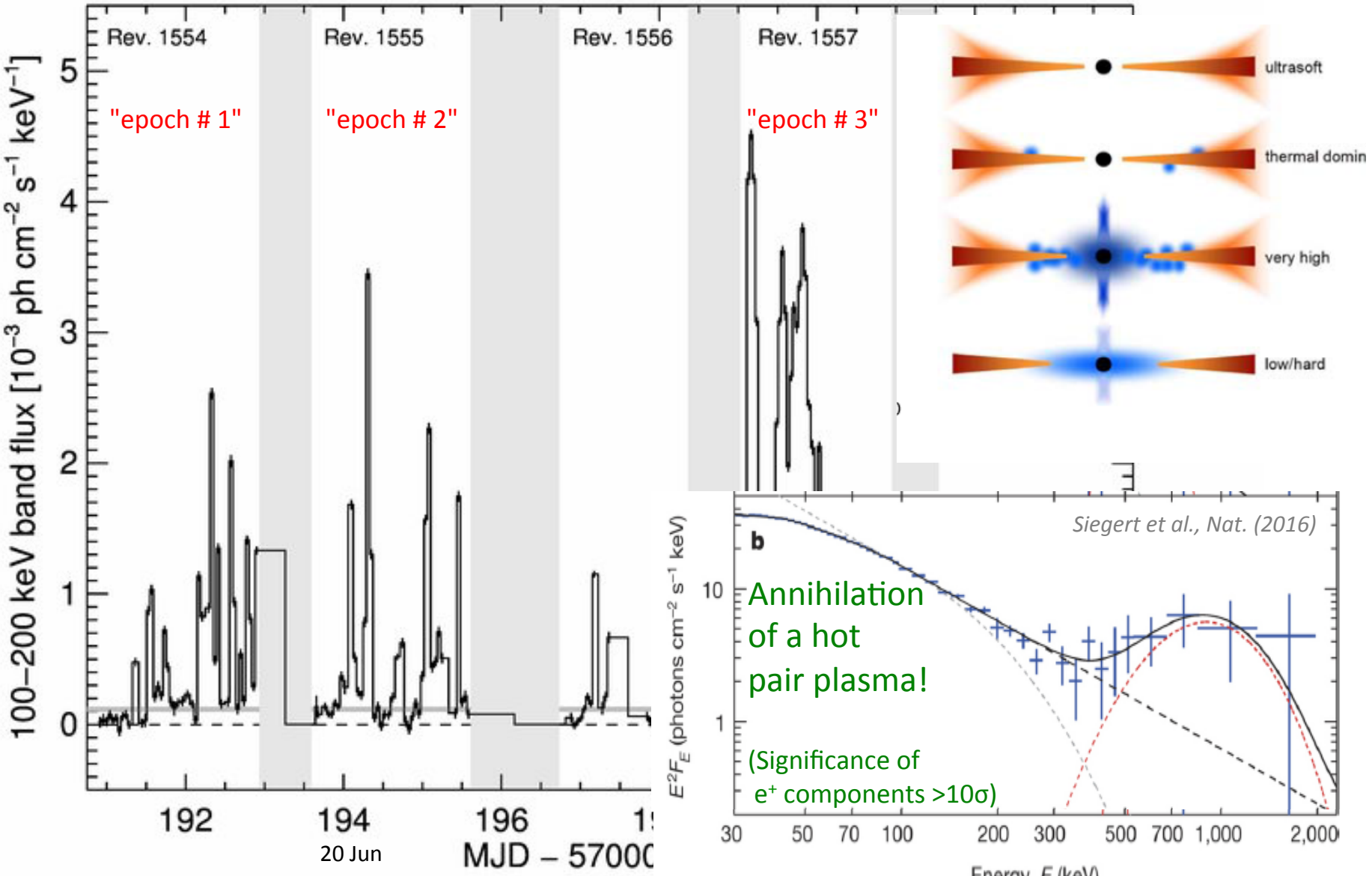
Siegert, RD, et al. (2016)



- 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}

Flaring of Microquasar V404 Cyg Jun 2015 → γ's from e^+!



→ This is example of a binary system providing e+ for long (Gy) times

Radioactivity Views of the Galaxy: 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
- Superbubbles are major agents of feedback: ^{26}Al, ^{60}Fe
  - Overlapping cavities lead to large superbubbles
  - Radiative cooling becomes less effective for later SN
- Radioactivity complements Galactic-structure studies
  - ^{26}Al, ^{60}Fe, positrons,…