Massive-Star Groups: Nucleosynthesis and Feedback

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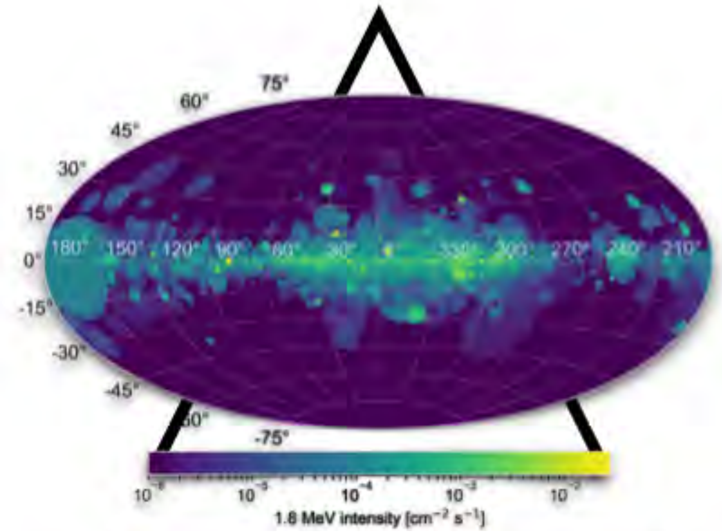
γ-ray Observations

and their

Interpretation



with work from Martin Krause, Karsten Kretschmer, Moritz Pleintinger, Thomas Siegert and others

Contents:

1. Insights from ^{26}Al gamma ray studies with INTEGRAL/SPI
2. The role of massive-star groups for ^{26}Al in the Galaxy
3. Population synthesis and a bottom-up description of the ^{26}Al in the Galaxy

Memories....

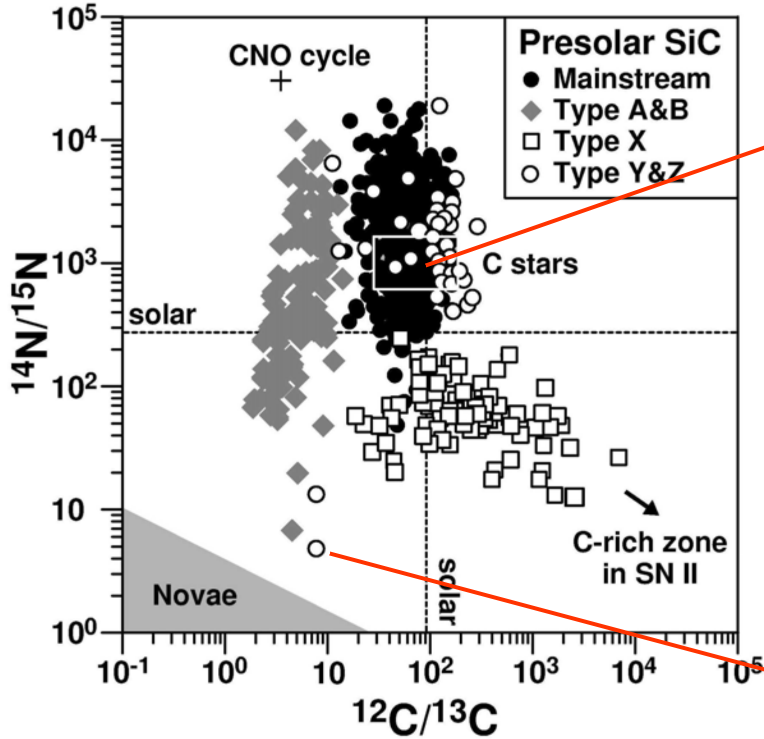
Happy Birthday, dear Maurizio!!!

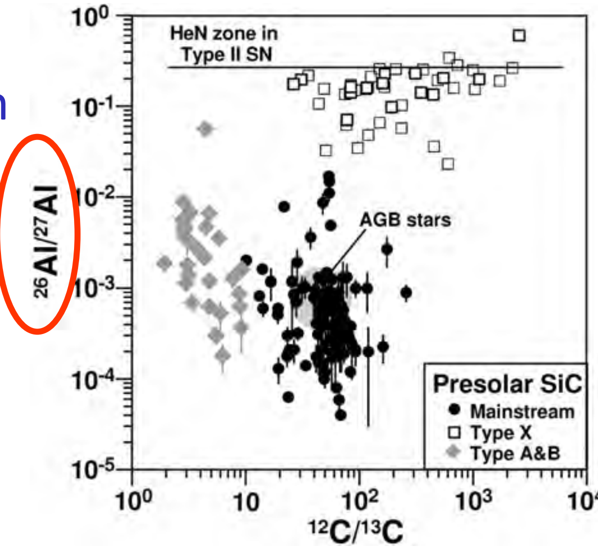
← 1 µm →

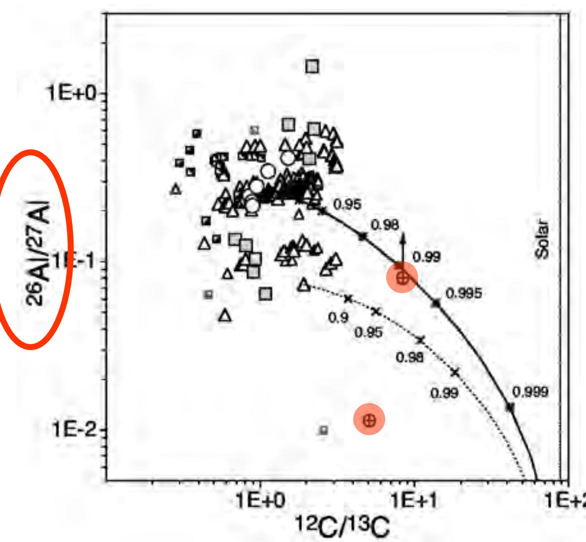
^{26}Al Sources: Hints from Presolar Grains

Isotopic Ratios in C,N,Si,...→ Source Type of Presolar Grain

- AGB Stars
- Supernovae
- Novae



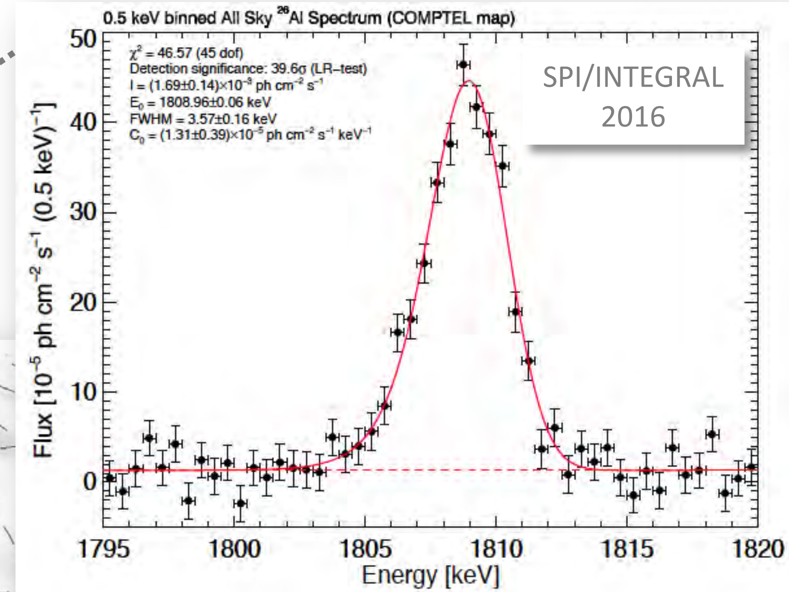


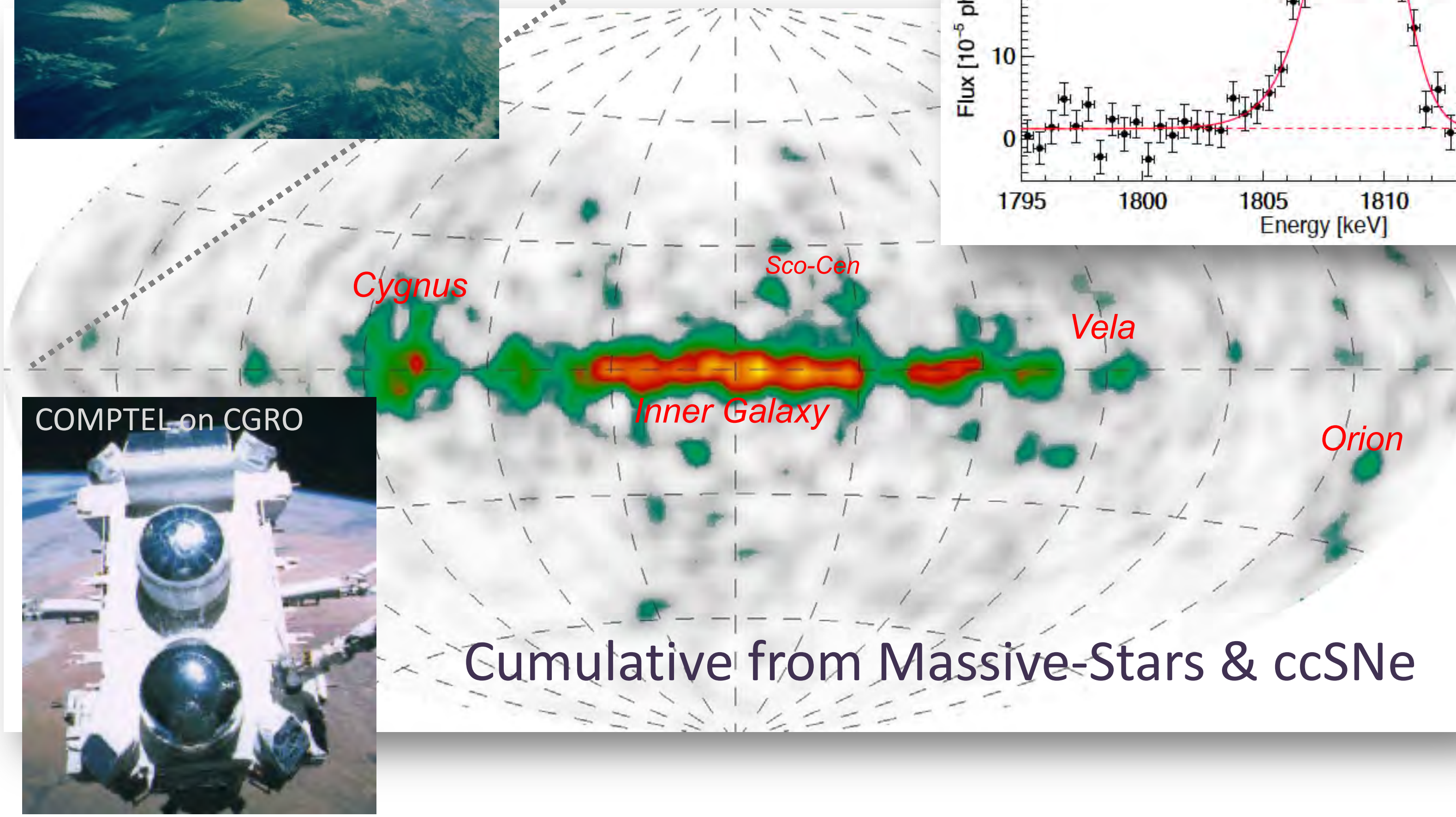


Amari, Nittler, Hoppe, Zinner, ... et al.

^{26}Al seen from ~ALL candidate source types: ccSNe, AGB stars, novae (when forming dust)

γ-rays as a global Galactic tracer of ^{26}Al nucleosynthesis





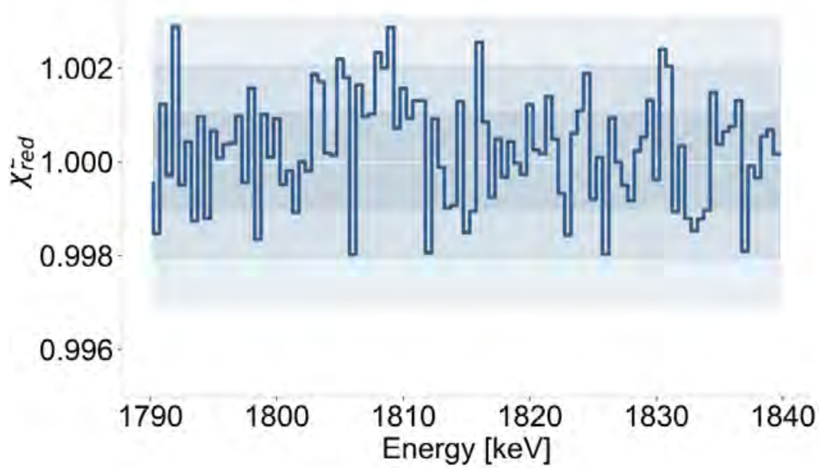
Diehl+2006;2018

Improved Sensitivity: New ^{26}Al all-sky spectrum

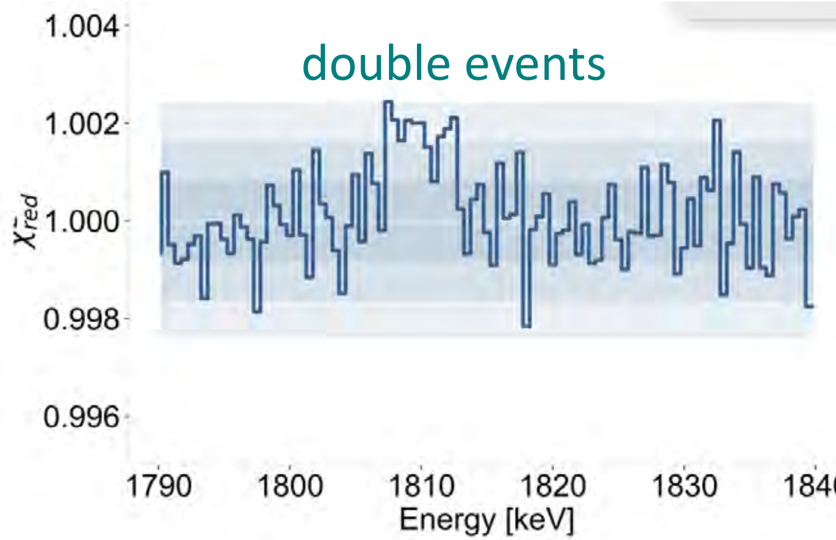
^{26}Al results from SE and DE in SPI

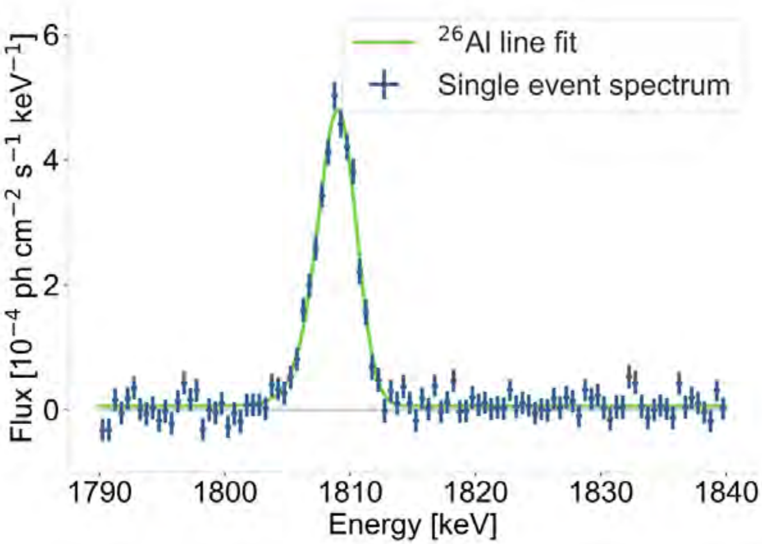
Pleintinger 2020; Diehl+ 2022

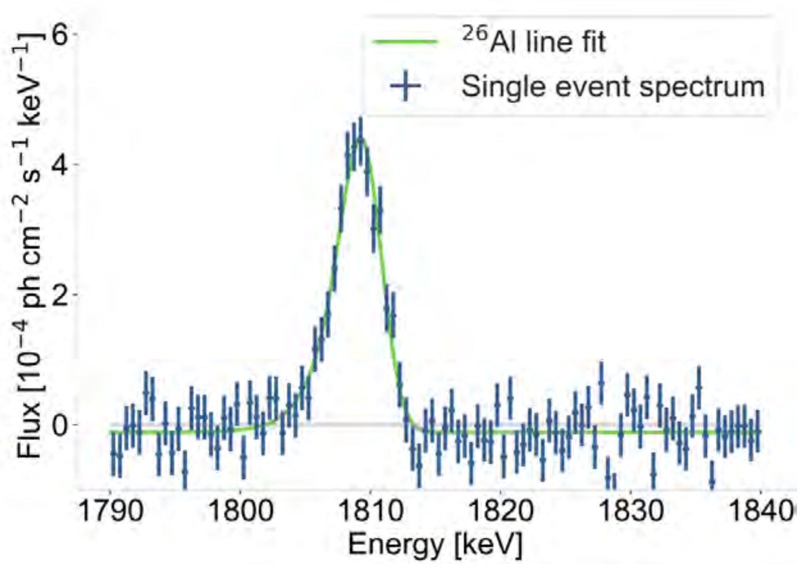
single events



double events



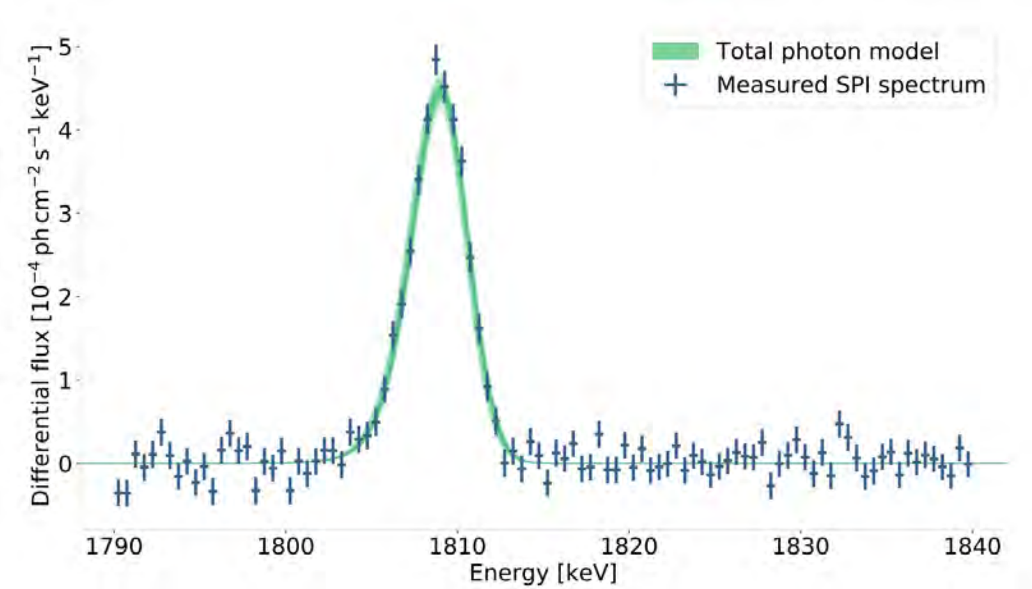


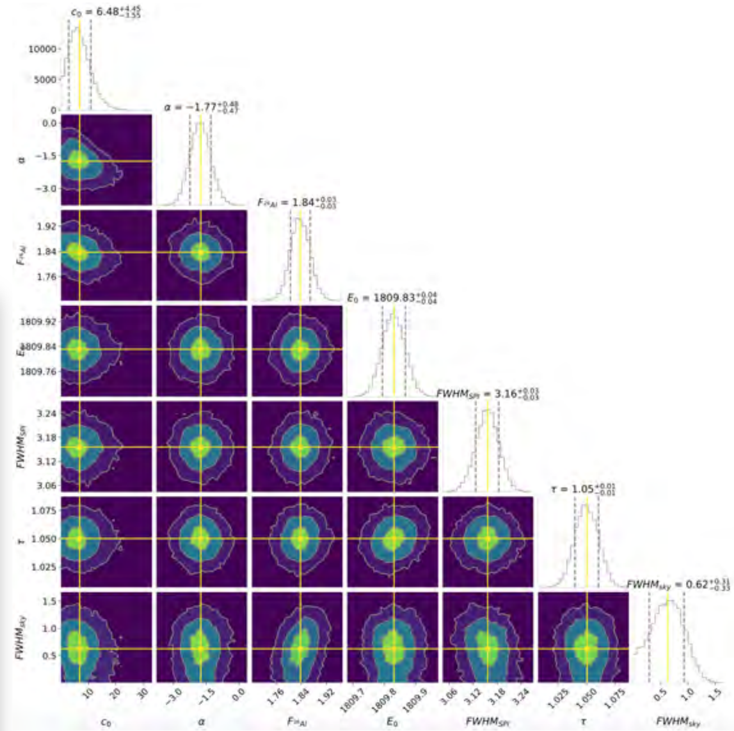


New ^{26}Al all-sky spectrum

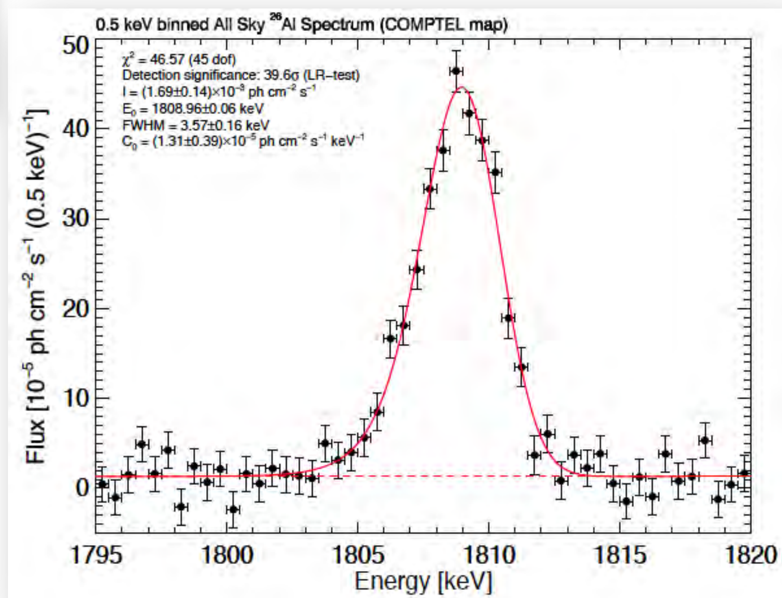
^{26}Al results from SE and DE: >58σ

Pleintinger 2020; Diehl+2022





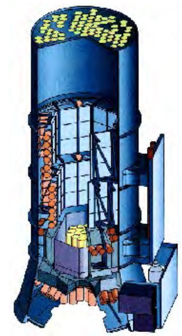
Siegert 2016



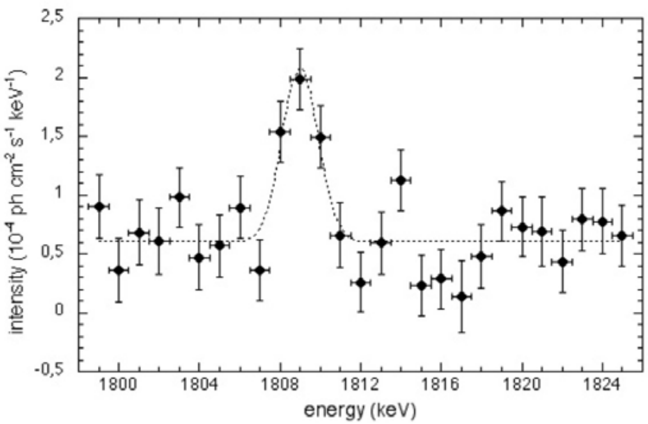
Radio-Isotopes with ~My lifetimes: ^{26}Al , ^{60}Fe

First's with INTEGRAL

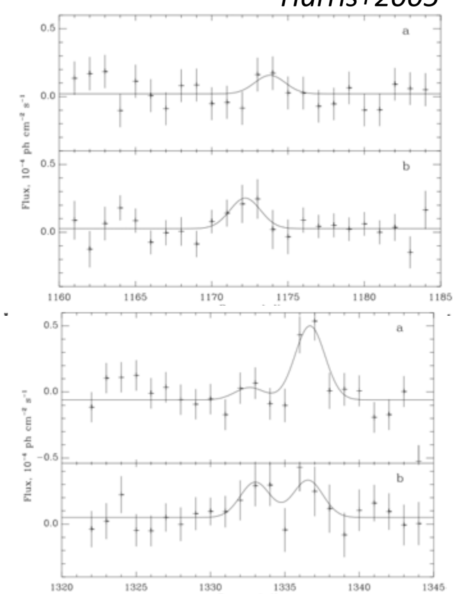
INTEGRAL/SPI



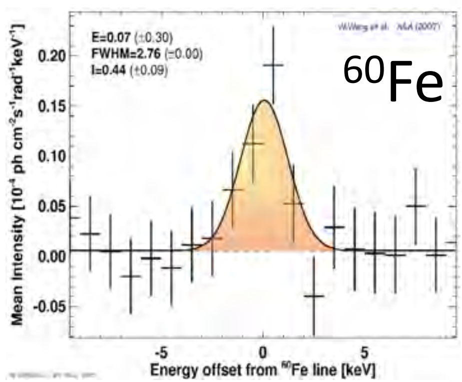
Diehl+2003



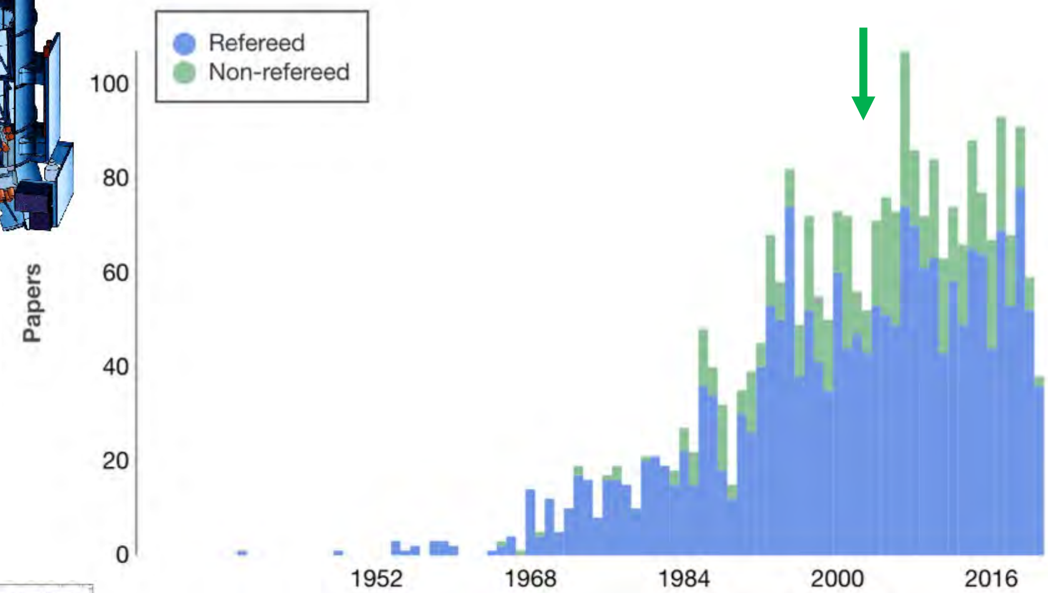
Harris+2005

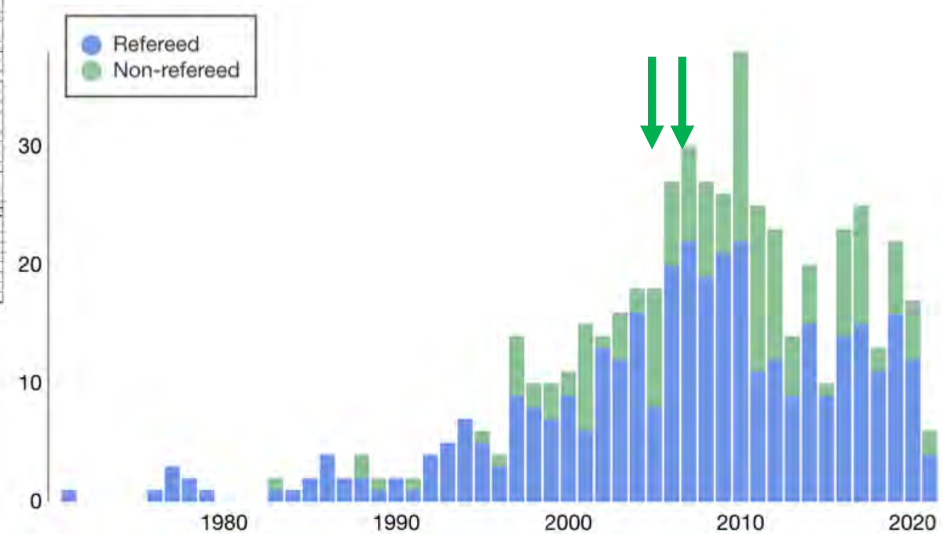


Wang+2007

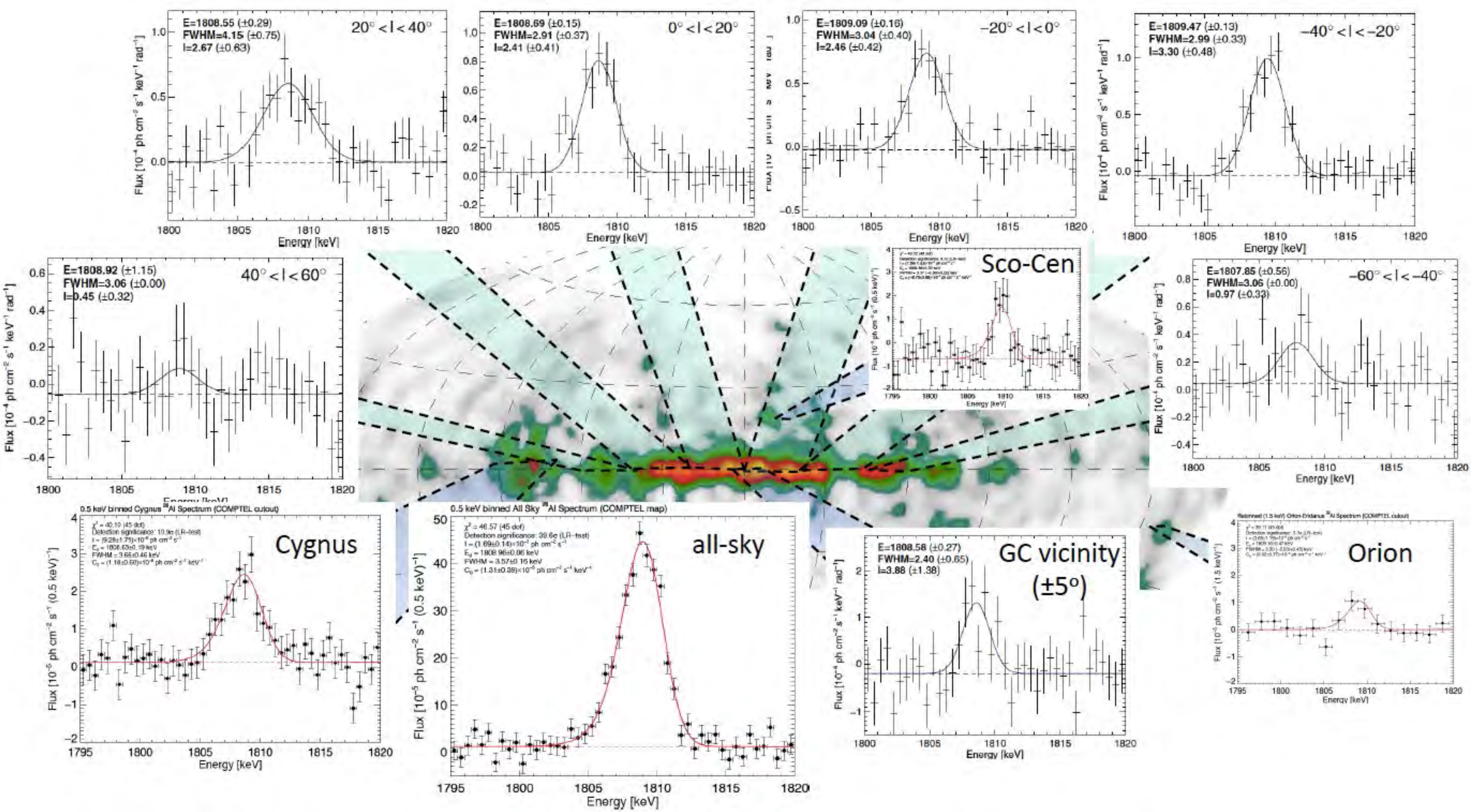


Record of studies in time

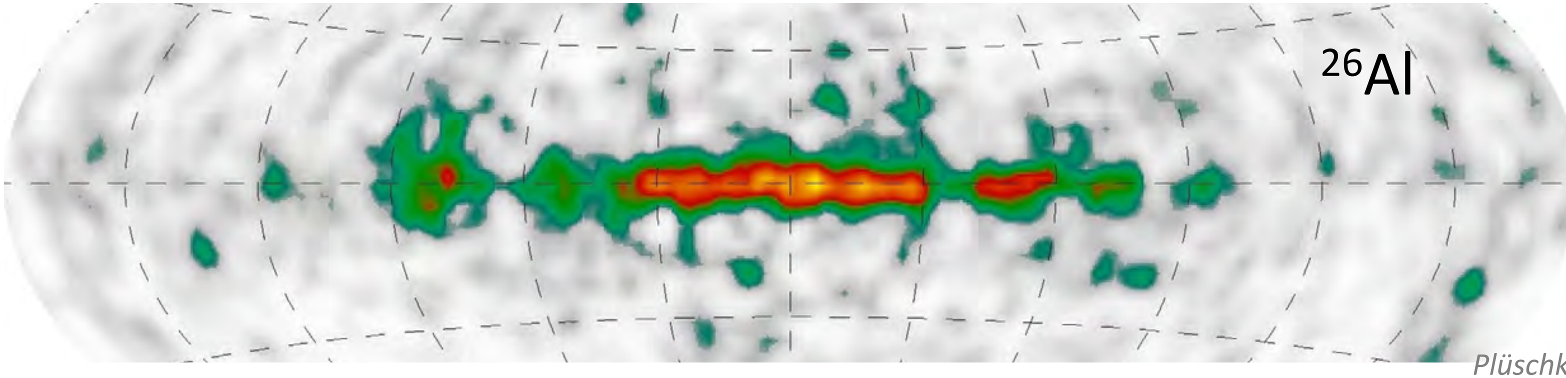




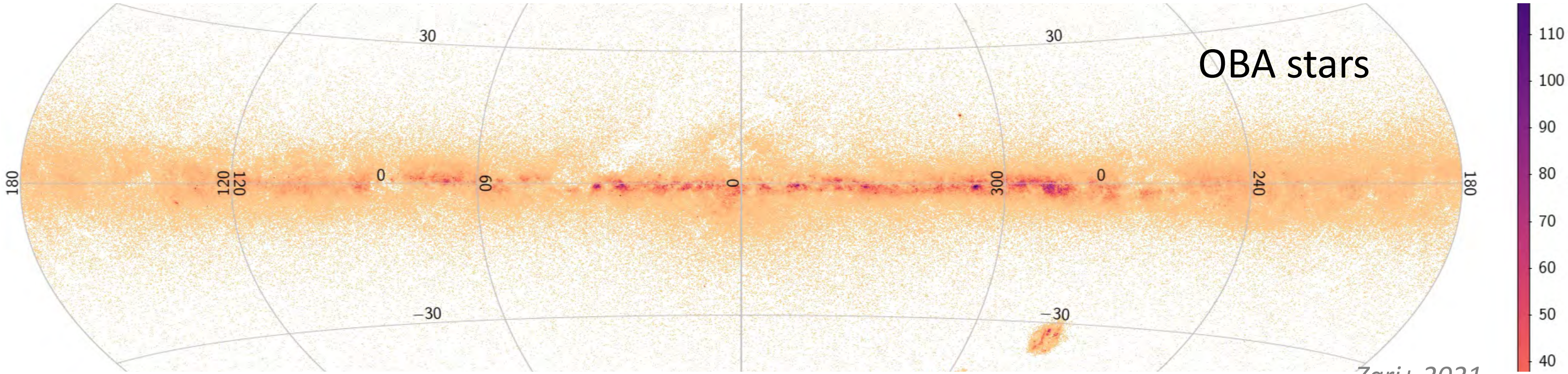
^{26}Al image and spectra along the plane of the Galaxy → regions characterised by massive-star groups



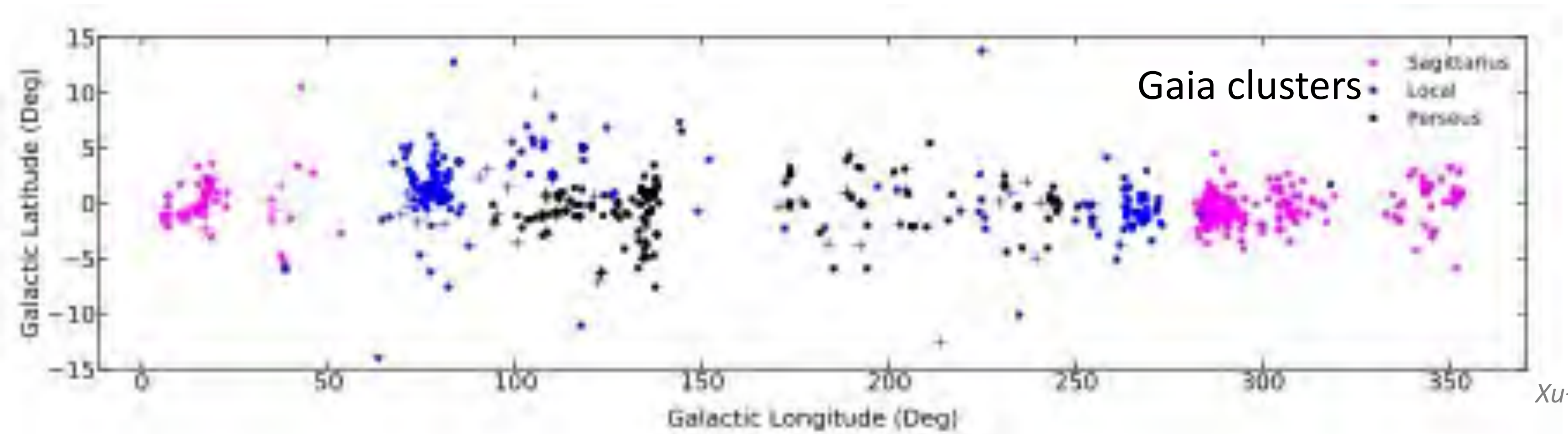
Massive-star and ^{26}Al radioactivity locations



Plüschke+ 2001



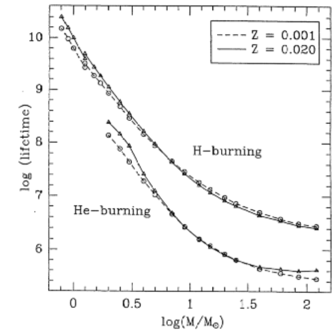
Zari+ 2021

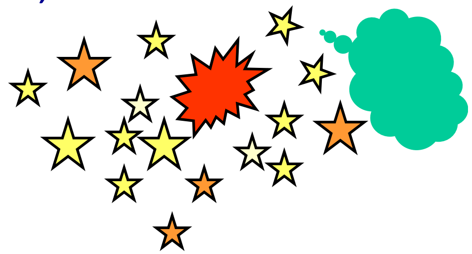


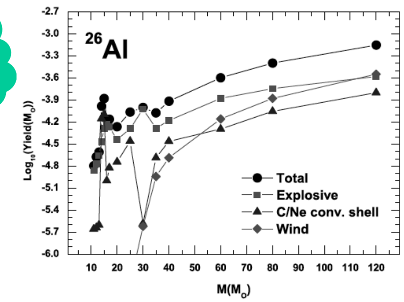
Xu+ 2021

Modelling a Massive-Star Group

- Implement Known Massive-Star Properties
  - ☆ Stellar Evolution Phases and their Durations
  - ☆ Characteristic Emissions in Radiation, Winds, new Nuclei

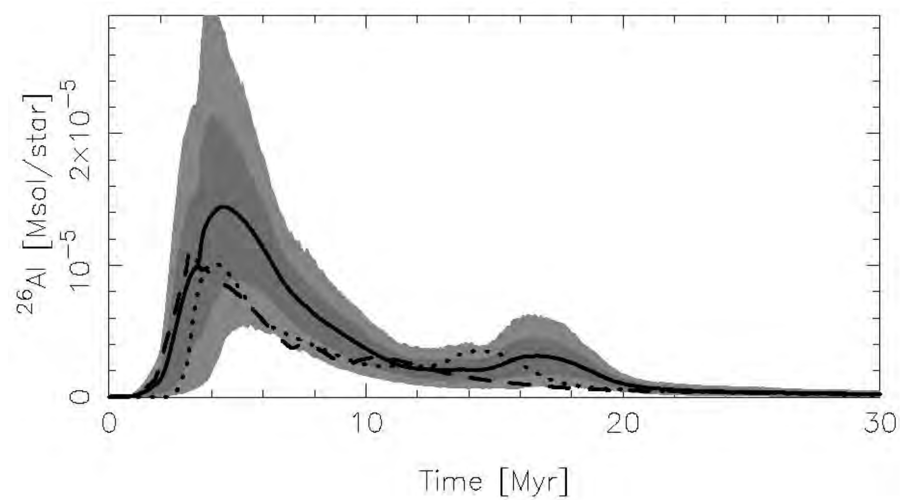






- Sample a Group of Stars
  → Assemble Group Properties
  - ☆ Time Profiles of Characteristic Emissions
  - ☆ Statistical Variations

Voss et al. 2009

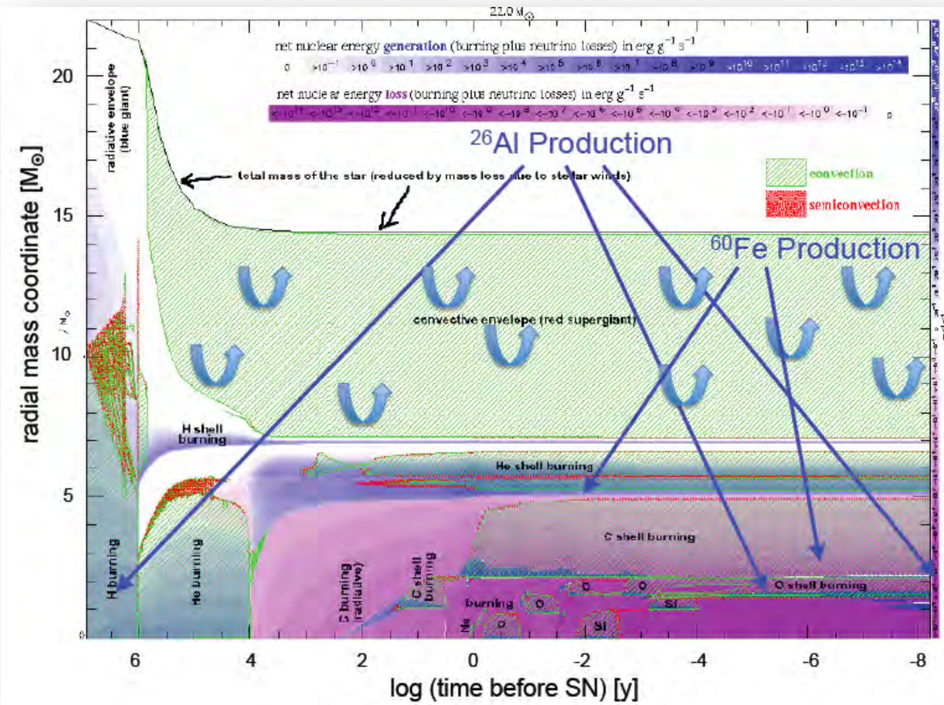


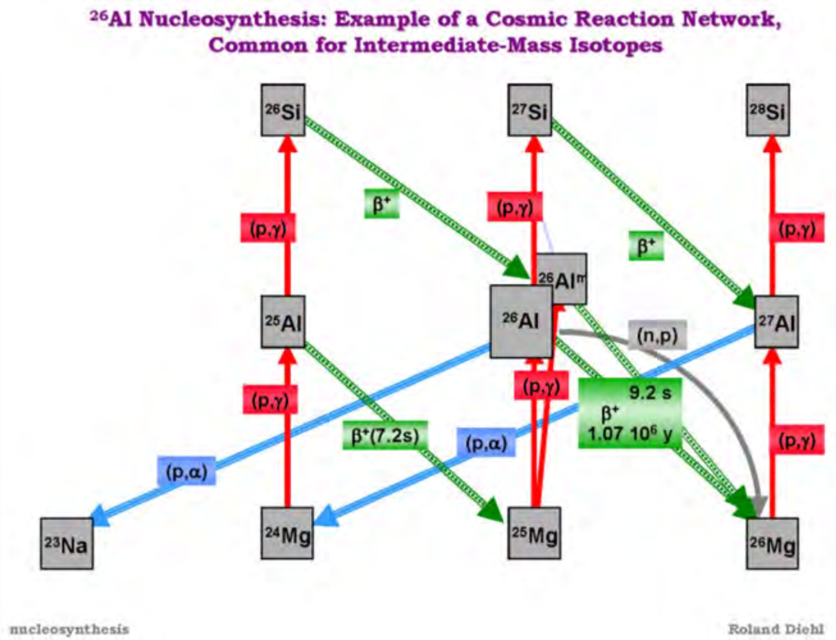
- *similar to Leitherer's STARBURST99, yet enhanced with nucleosynthesis ejecta*

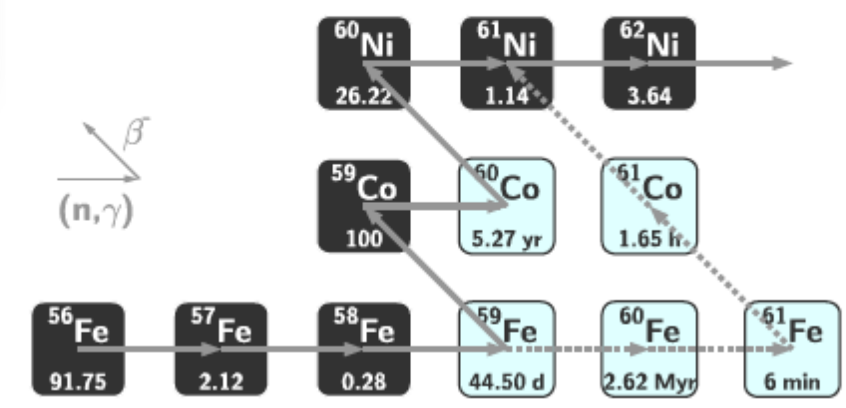
Nucleosynthesis in massive stars: ^{60}Fe, ^{26}Al

→ Two Messengers from Massive-Star Interiors with Different Origin!

ratio → cancel source distance knowledge







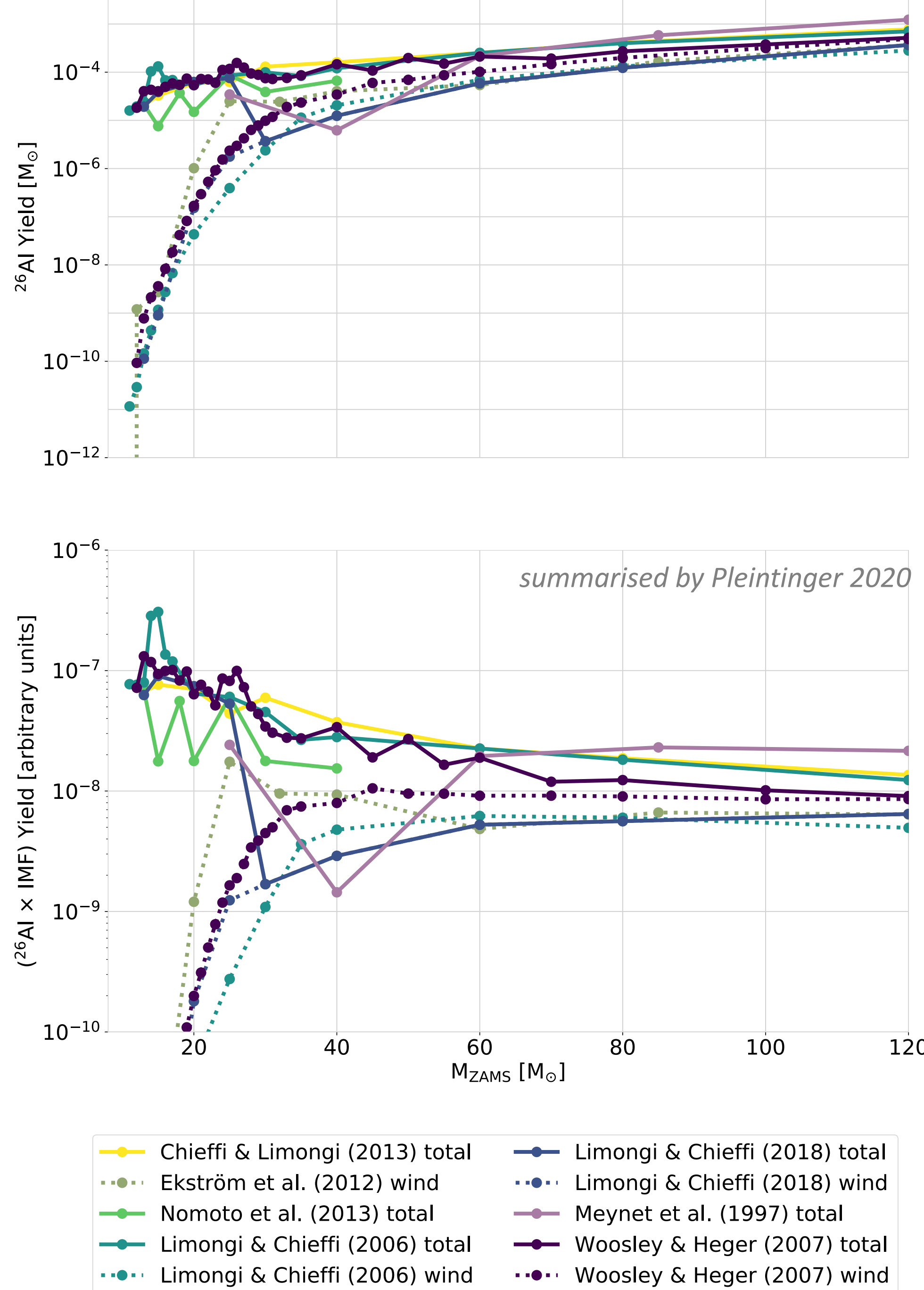
Processes:

Hydrostatic fusion
WR wind release
Late Shell burning
Explosive fusion
Explosive release

Charged-particle fusion
Neutron capture

Yields in ^{26}Al from massive-star models (wind & SN)

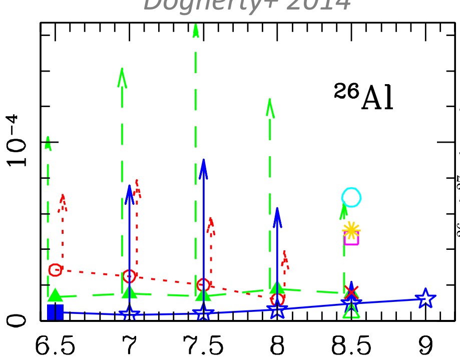
- about factor 5-10 differences among different model types/variants
- stars with M<35 $M_\odot$ dominate (when weighted with IMF)
- ~ few $M_\odot$ total



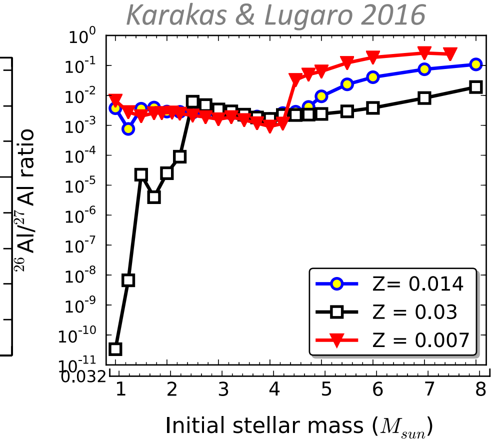
☆ Novae: ~0.1 $M_\odot$ total

☆ AGB stars: 0.05...0.12 $M_\odot$ total

Dogherty+ 2014



Karakas & Lugaro 2016

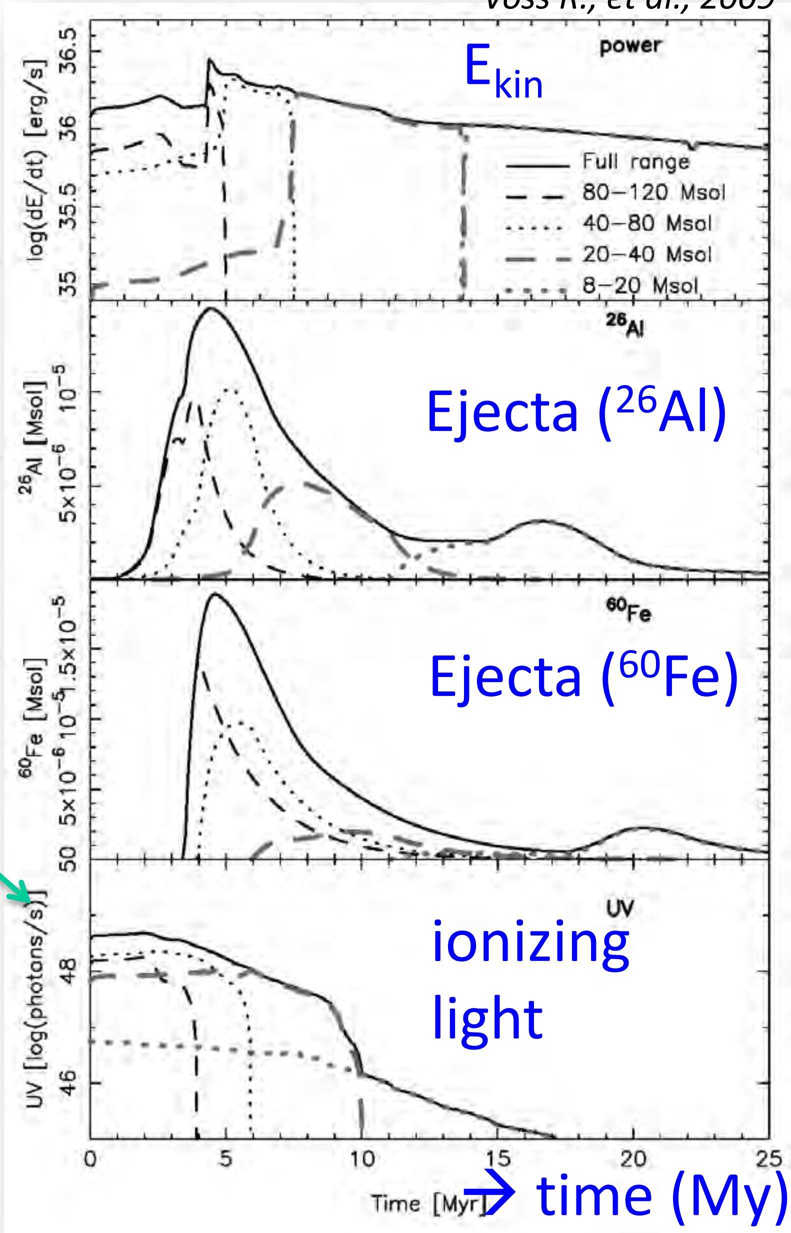


Massive-Star Groups

- 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



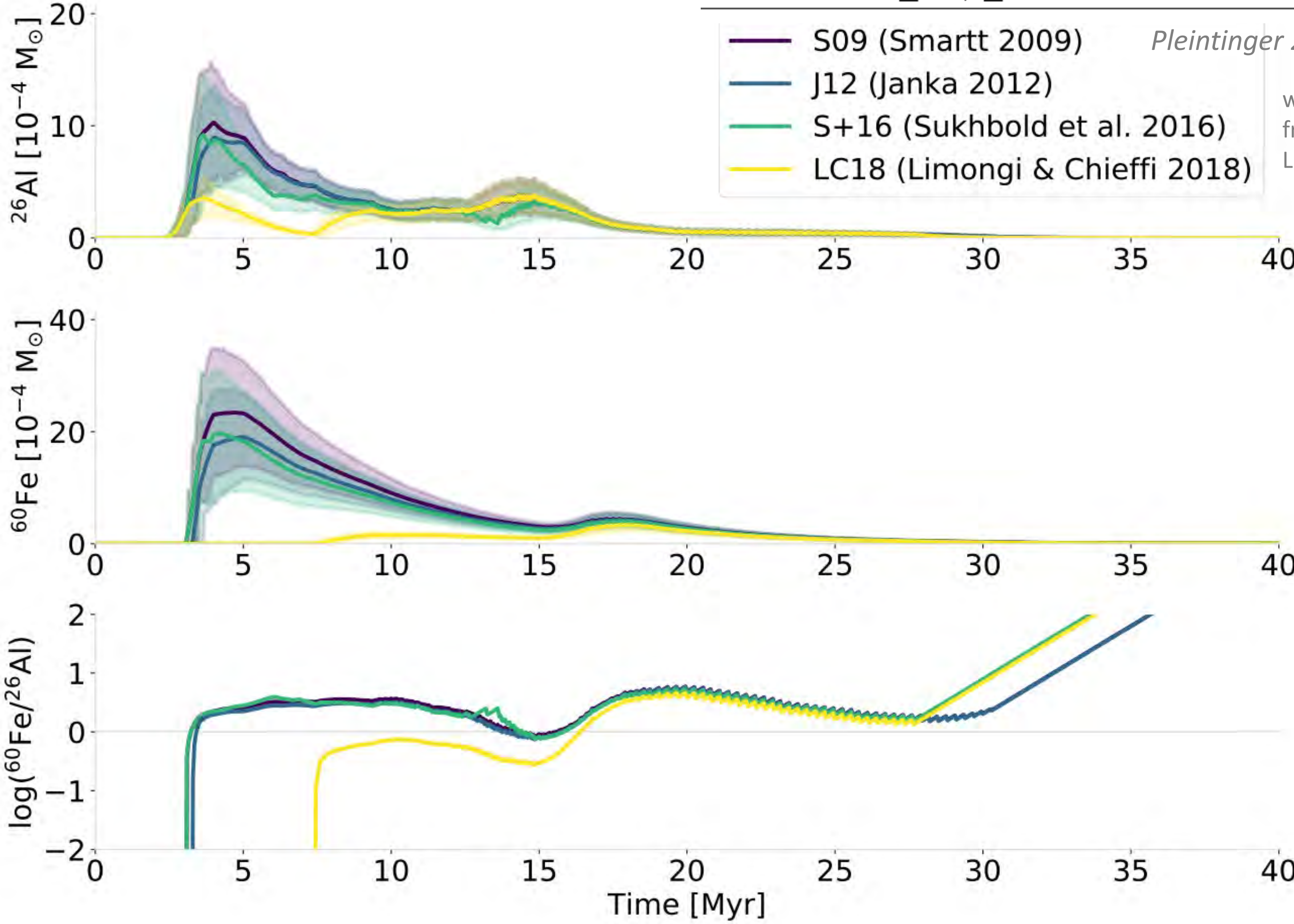
Population synthesis: impact of different inputs on groups

variation of explodability

Acronym	Exploding stellar models
S09	$M_* \geq 8$
J12	$8 \leq M_* \leq 100$ and $140 \leq M_* \leq 260$
S+16	Irregular islands and valleys of explodability
LC18	$8 \leq M_* \leq 25$

Pleintinger 2020; Siegert+2022

with basic yields from Limongi & Chieffi 2006



☞ contributions from early (i.e. most-massive-star) SNe reduced

Population synthesis: impact of different inputs

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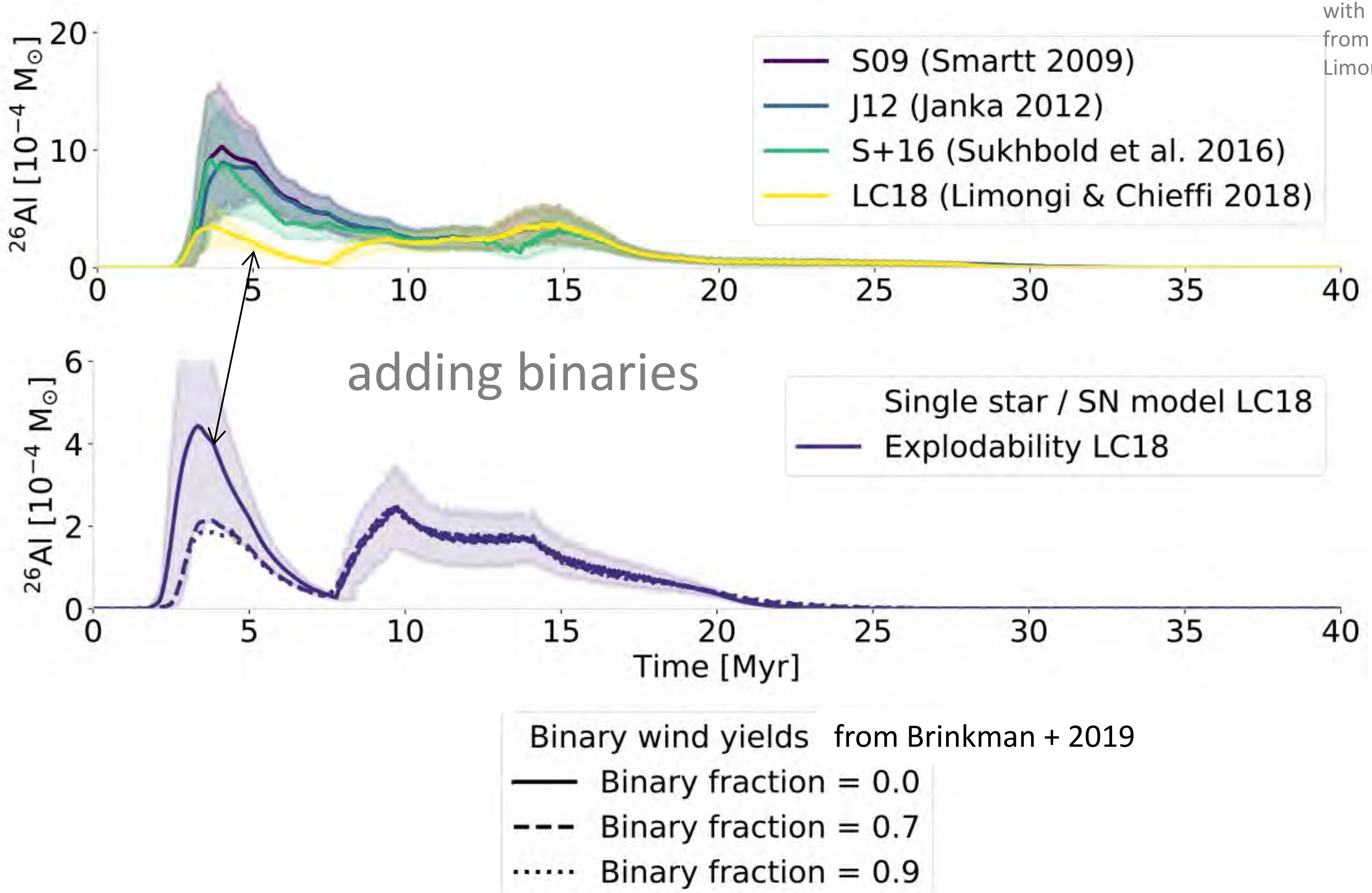
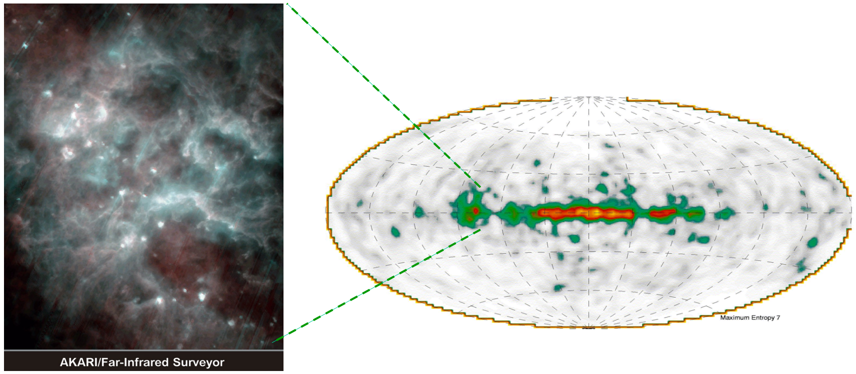
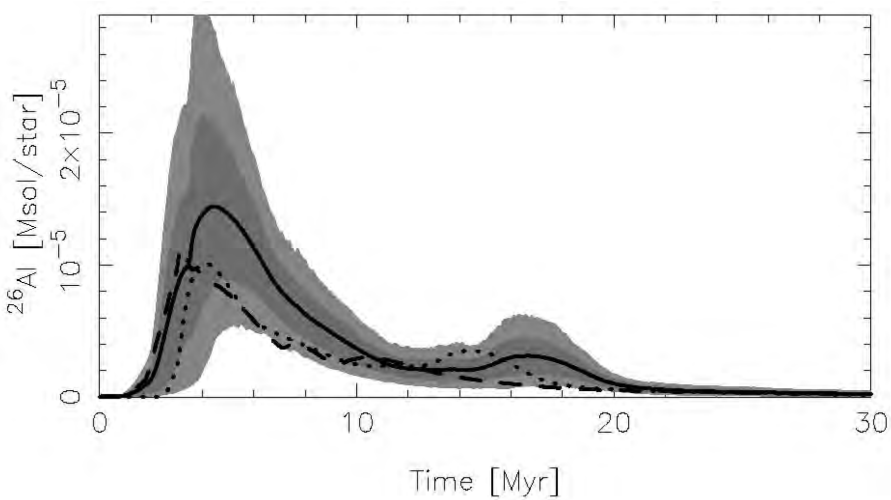
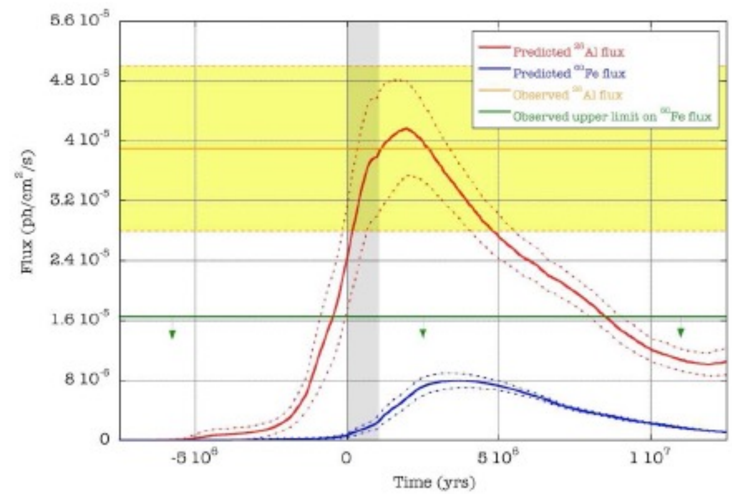


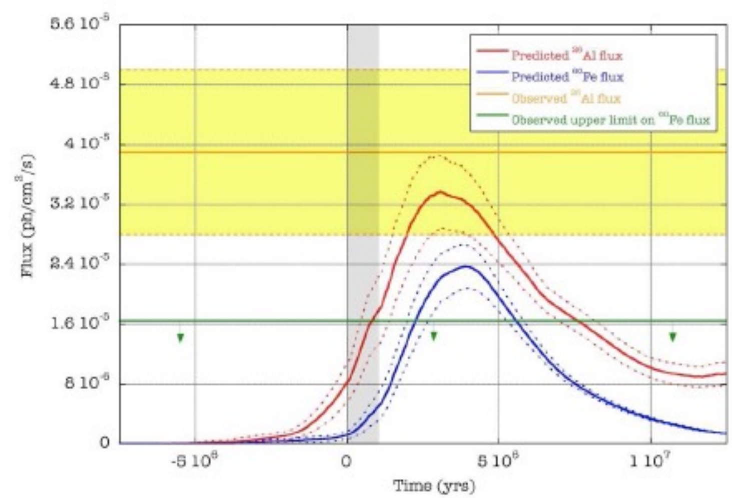
Testing our Models: Cygnus at its Specific Age and Metallicity



- ☆ Population Synthesis Application to Cygnus Region
  - ☞ Models for Solar Metallicity ~OK
  - ☞ If Lower Metallicity: Underprediction?
  - ☞ *Martin+ 2010*

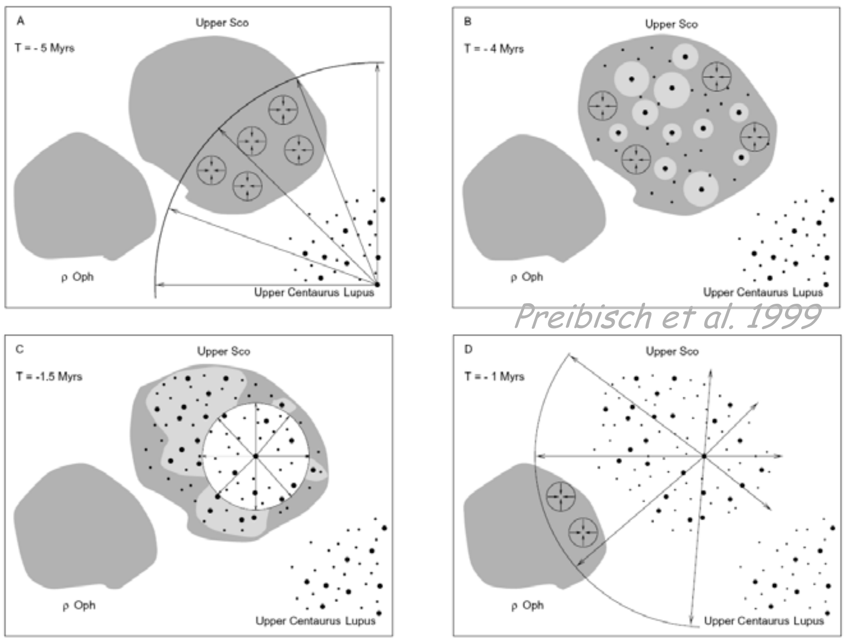




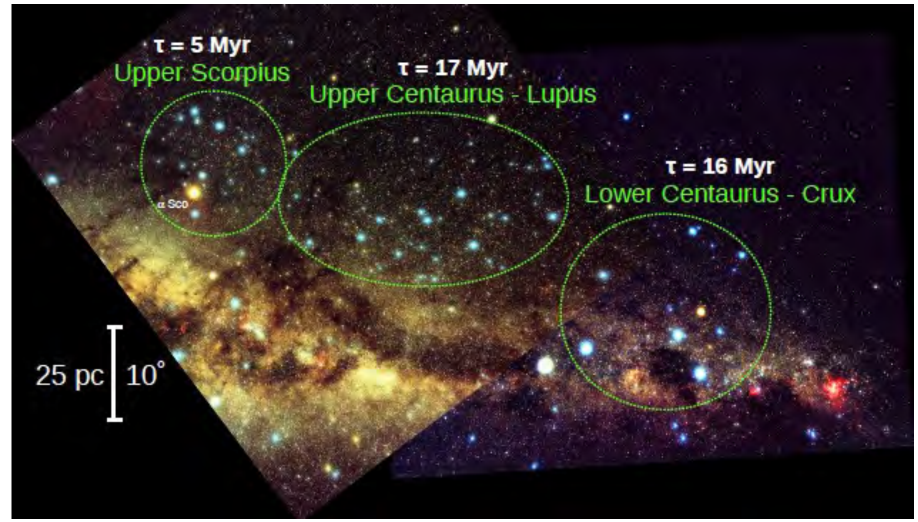


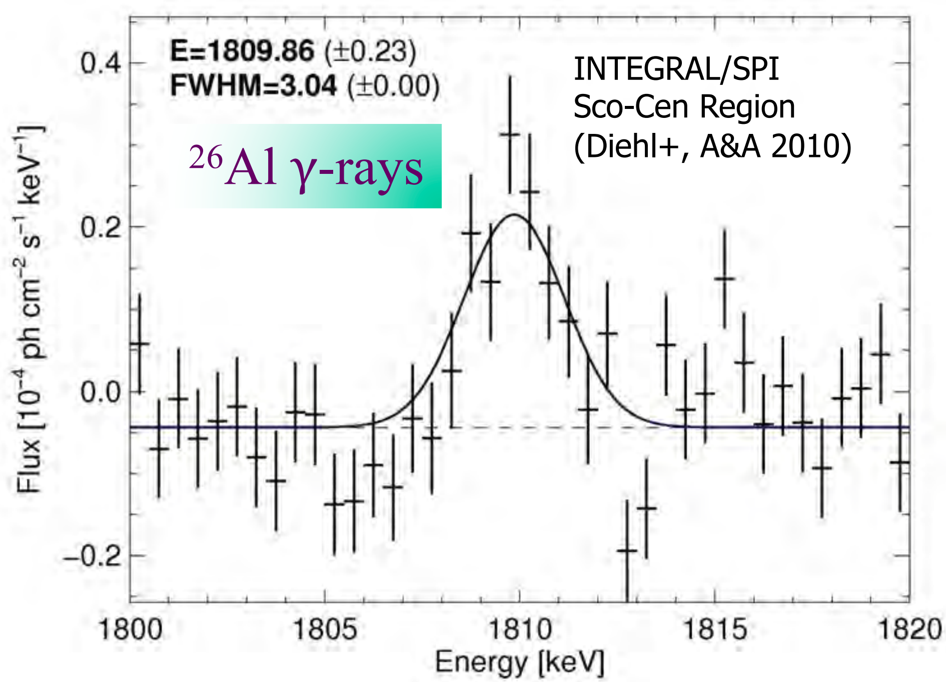
The Sco-Cen Association: Triggered Star Formation?

- Nearest OB Association (~120pc)
  - subgroups of ages 5, 16, 17 My
- Extended, Triggered Star Formation?



Preibisch et al. 1999





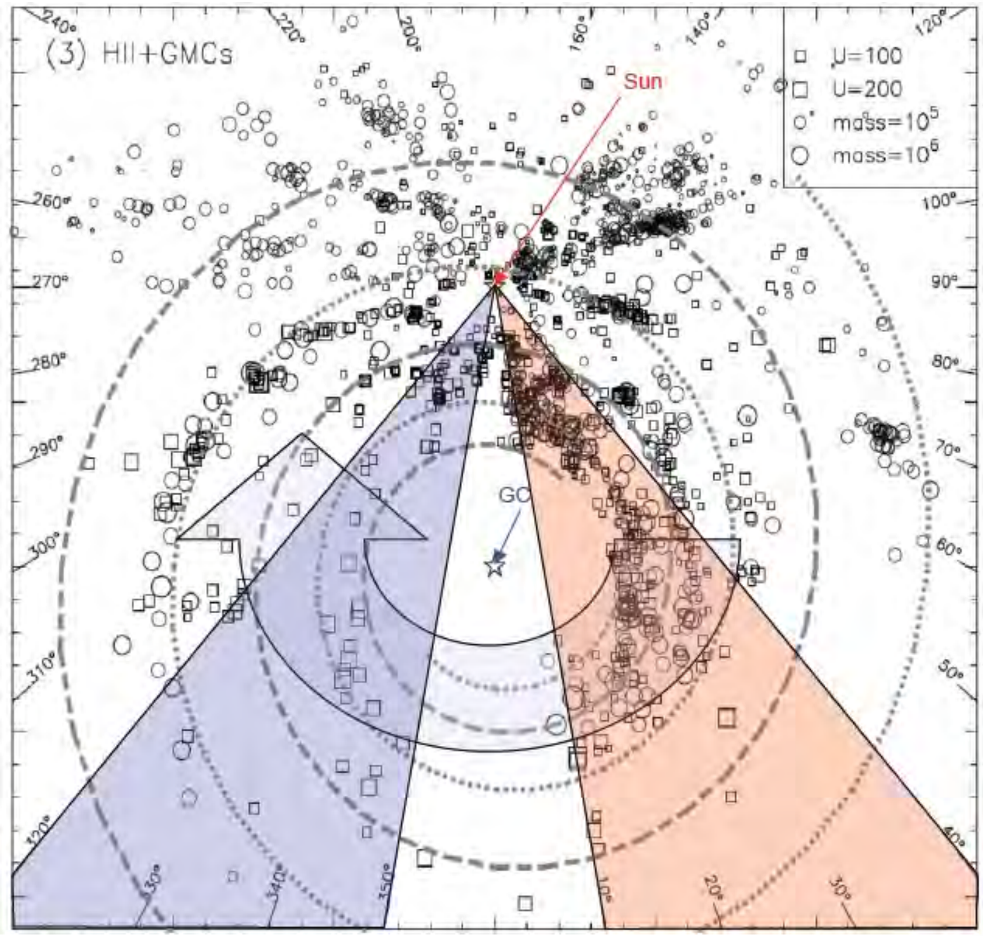
- **Compare Data with Population Synthesis**

  R. Voss, RD, et al., 2009, 2010, 2011

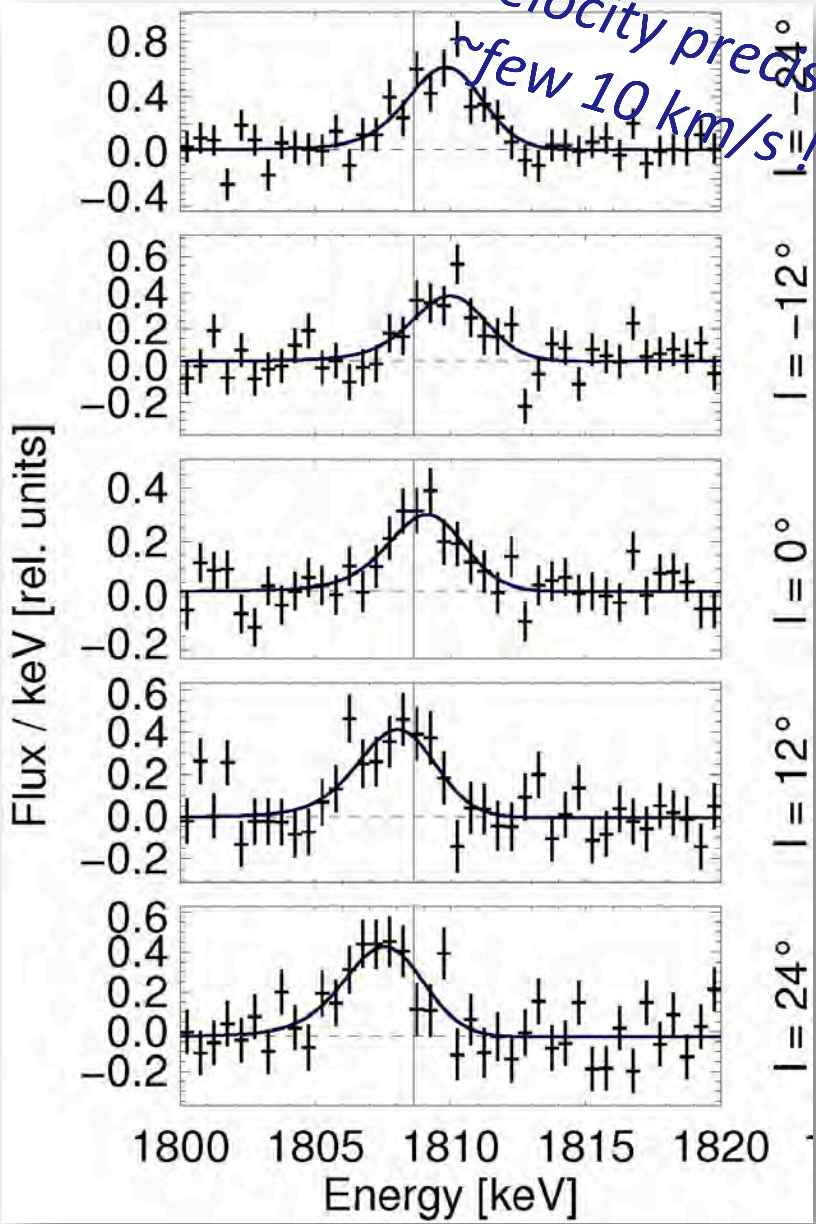
  - **Observed ^{26}Al Emission**
  - **Stellar Groups Ages & Richness**
  - **ISM Shell/Cavity Observables**

^{26}Al γ-rays trace kinematics at galactic scale

☞ Large-scale Galactic rotation



Kretschmer et al., A&A (2013)

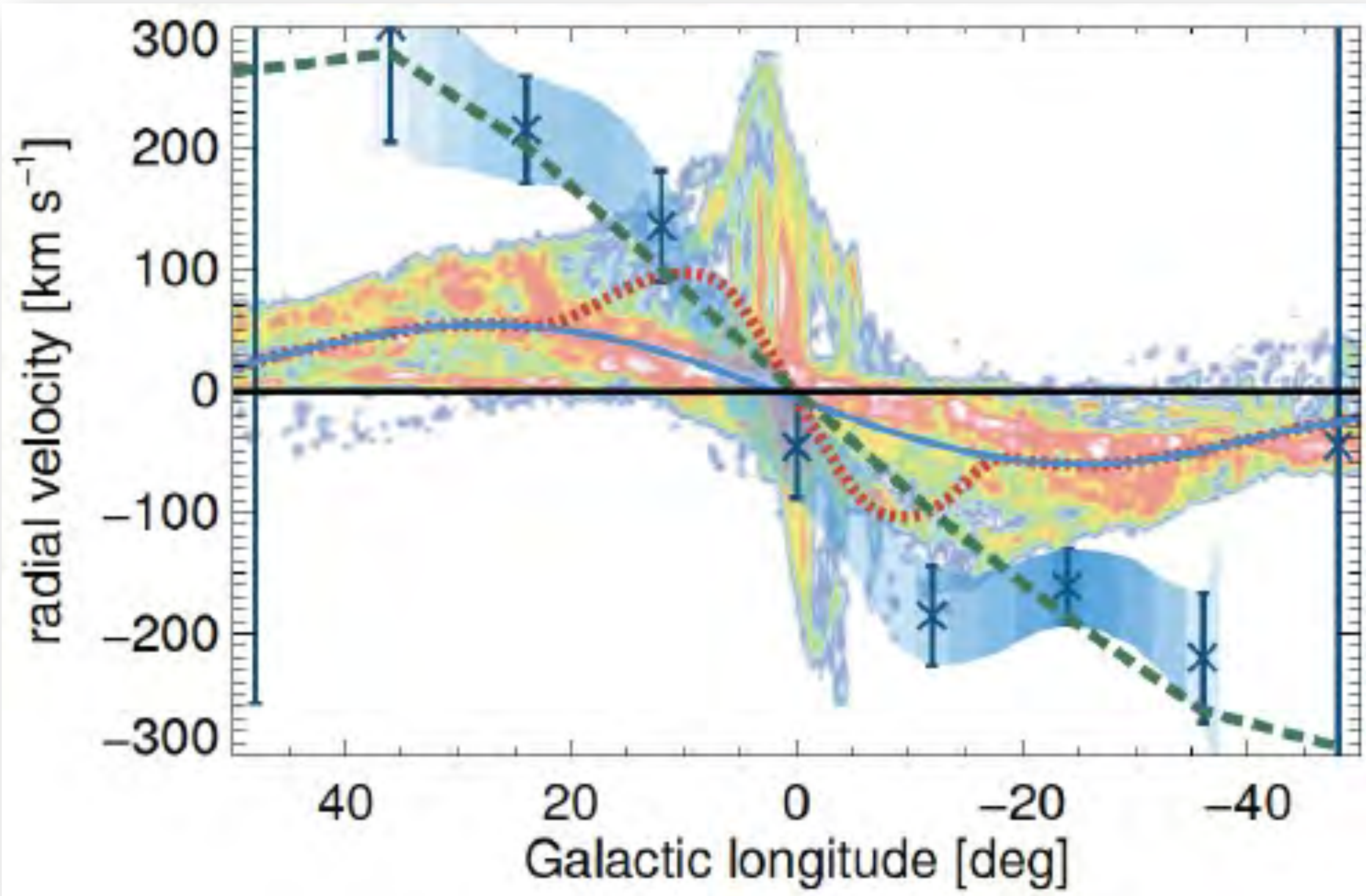


Velocity precision ~few 10 km/s !!

The longitude-velocity diagrams: ^{26}Al shows a new aspect

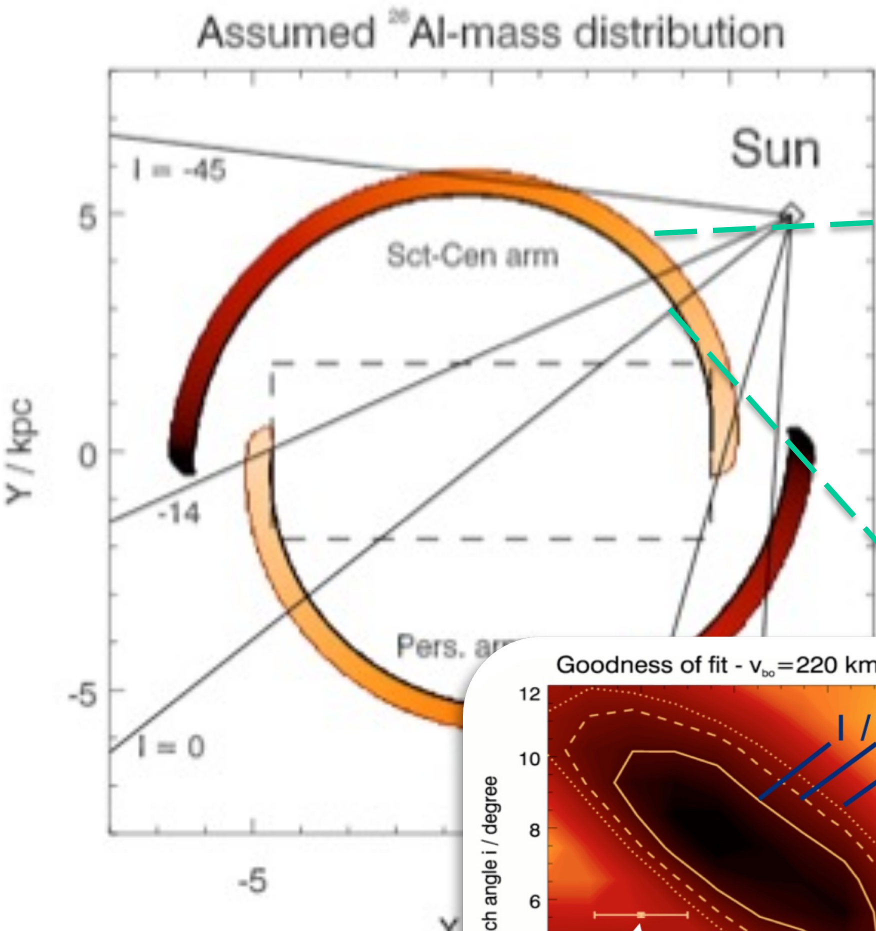
excess velocity ~200 km s^{-1} wrt CO gas and masers seen for massive-star ejecta!

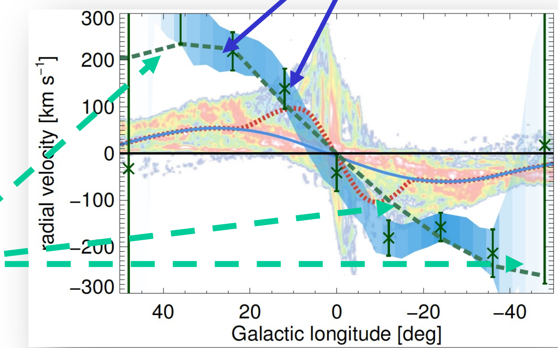
Kretschmer et al., A&A (2013)



How massive-star ejecta are spread out…

Superbubbles blown into inter-arm regions

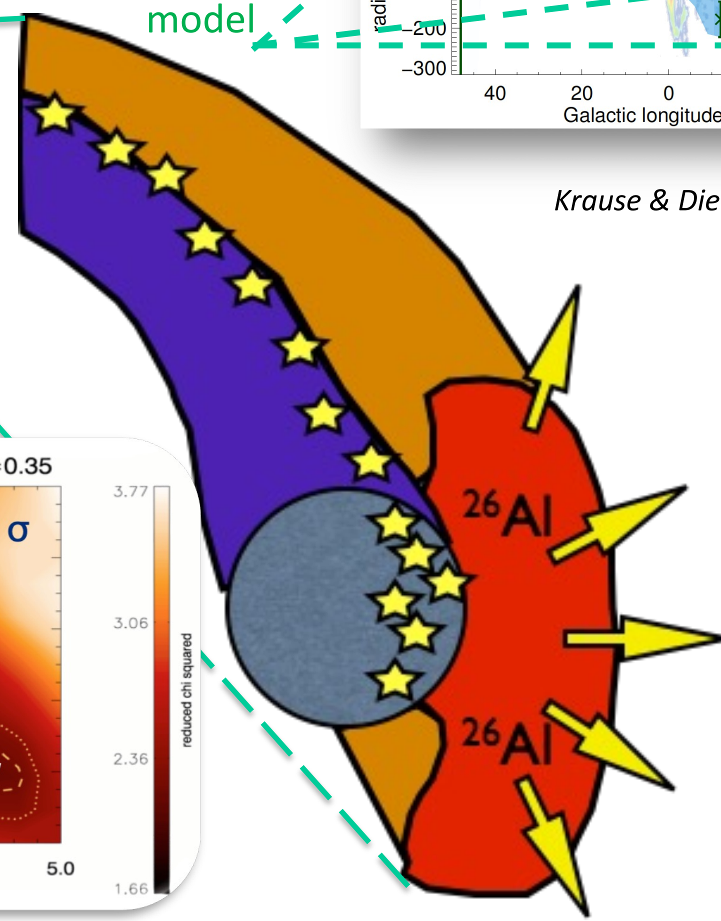




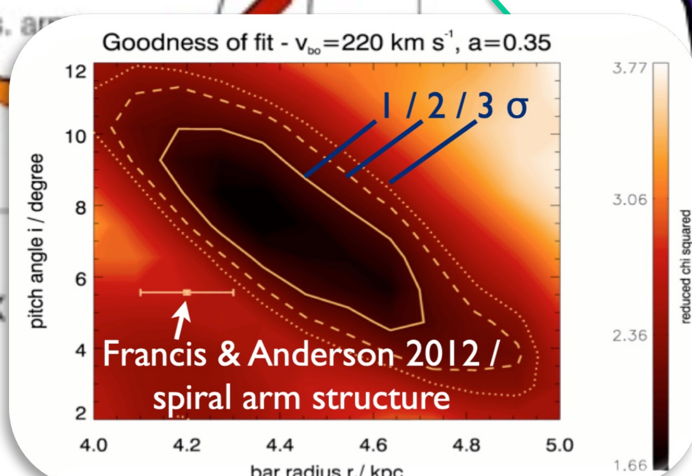
SPI/INTEGRAL data

simple geometry model

Krause & Diehl, ApJ (2014)



fit spiral par's as well!



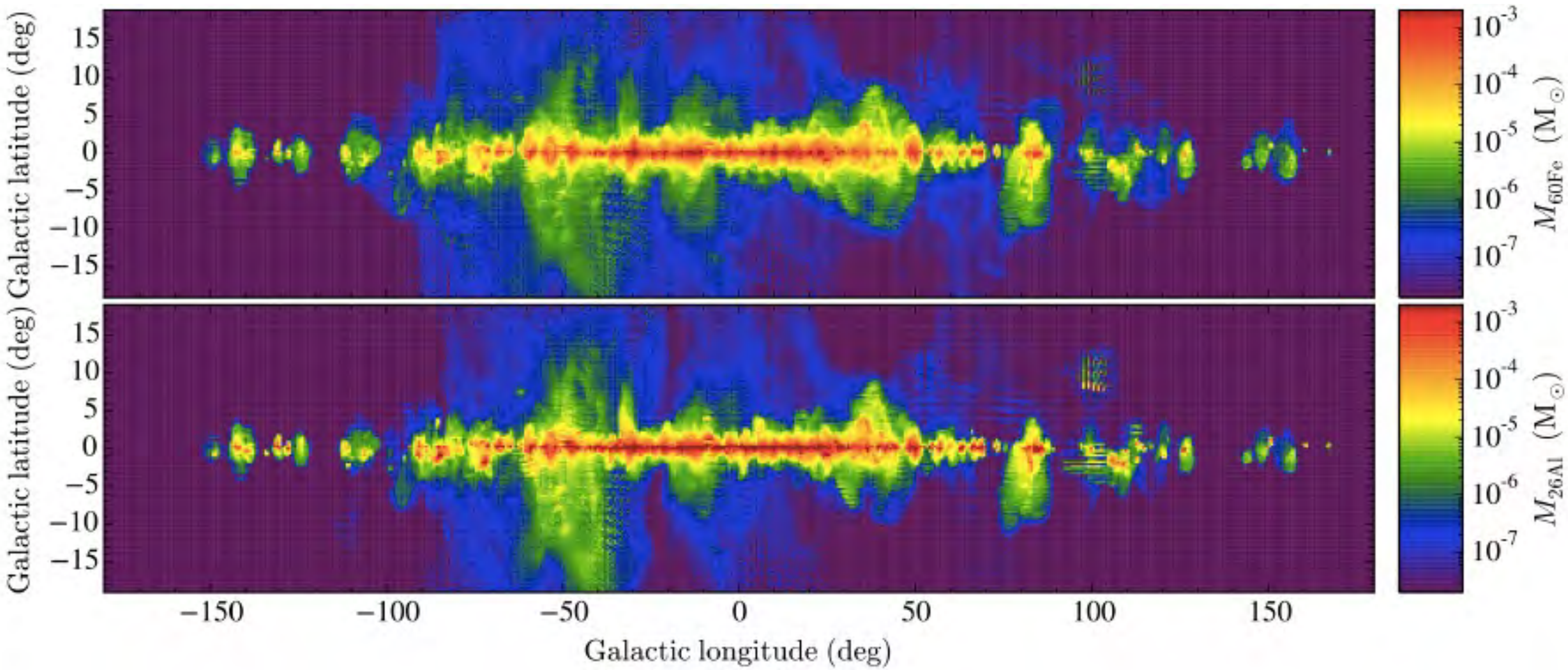
^{26}Al trajectories in simulations

3D hydrodynamical simulations on kpc scales have become feasible
(with sufficient resolution to trace nucleosynthesis events):

- ☆ 128^3 cells, cell size 7.8 pc (more-precise than cosmological simulations, but still crude)
- ☆ starting fom 'current galaxy' model (Tasker&Tan 2009), no bulge nor spiral arms initially
- ☆ star formation by Toomre criterion on single cells, efficiency set tp 1%

→ 'map' of a simulated galaxy in radioactive ^{26}Al (and ^{60}Fe)

Fujimoto+ 2018



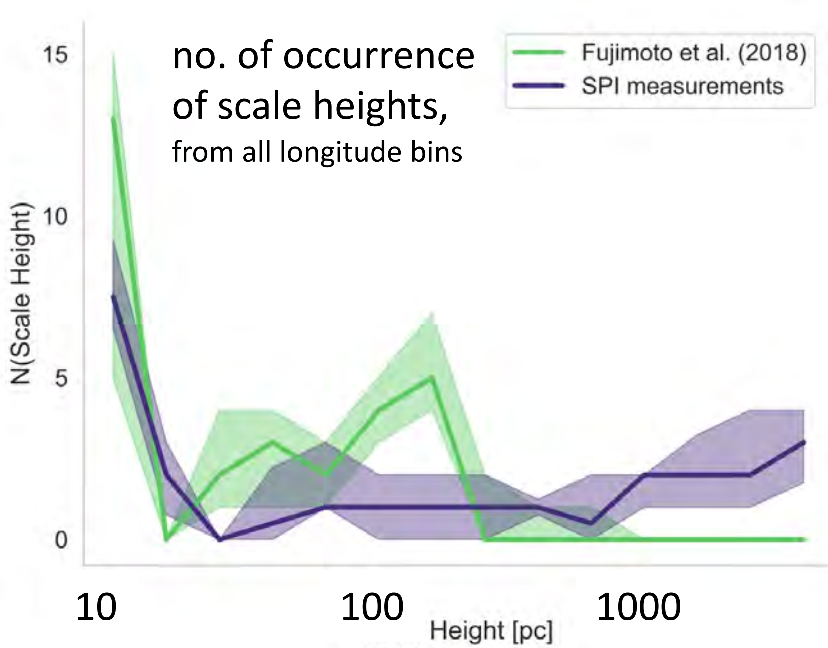
Comparing Observations with Simulations

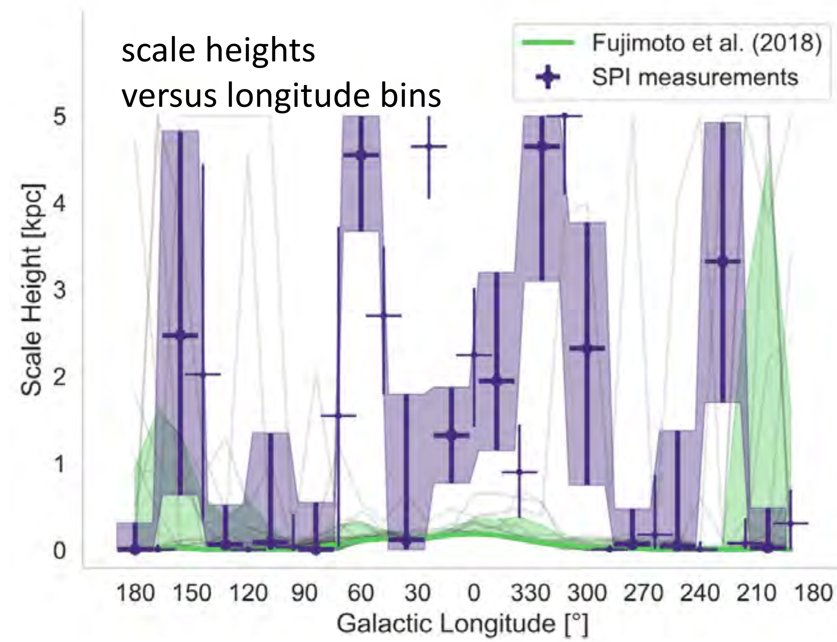
Pleintinger+ 2019

Biases on both ends:

- ☆ Simulations adopt an idealised Galaxy from a general viewpoint
- ☆ Observations are from the Solar-system viewpoint, nearby environment may be special

Use projections that eliminate those biases and focus on general characteristics of the large-scale ISM



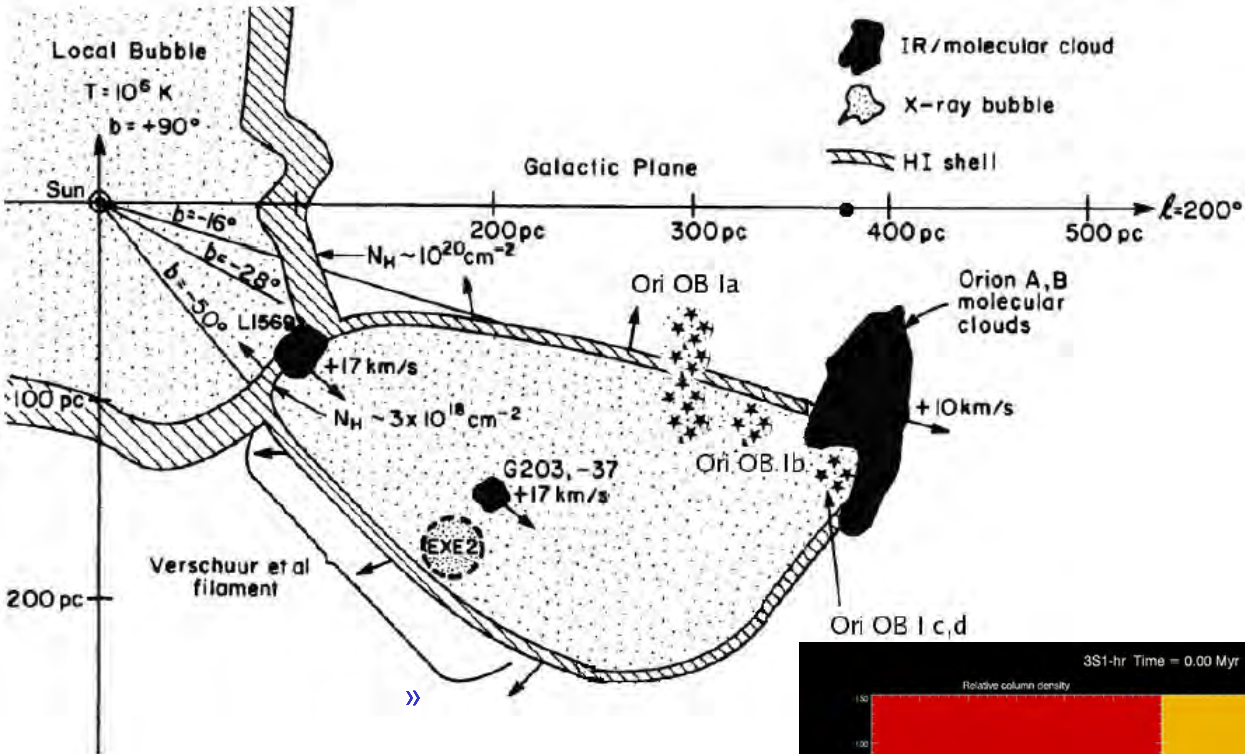


→ the differences are significant: larger 'chimneys' in observations

Ejecta and cavities blown by stars & supernovae

ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

here: the Orion region with the Eridanus cavity



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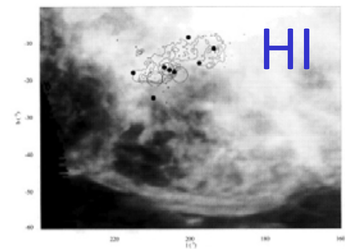
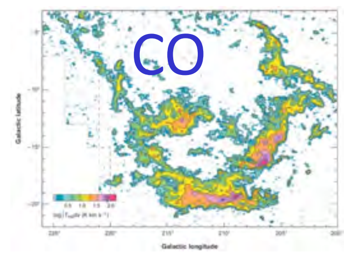
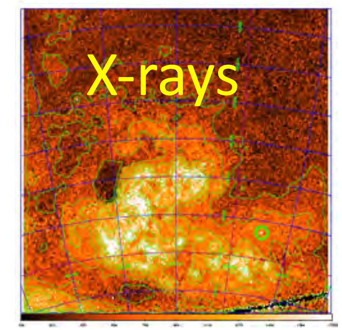
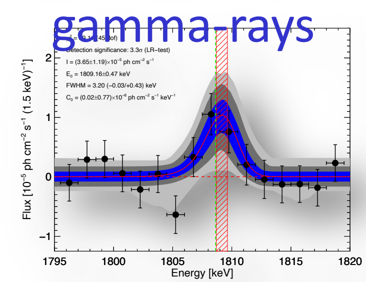
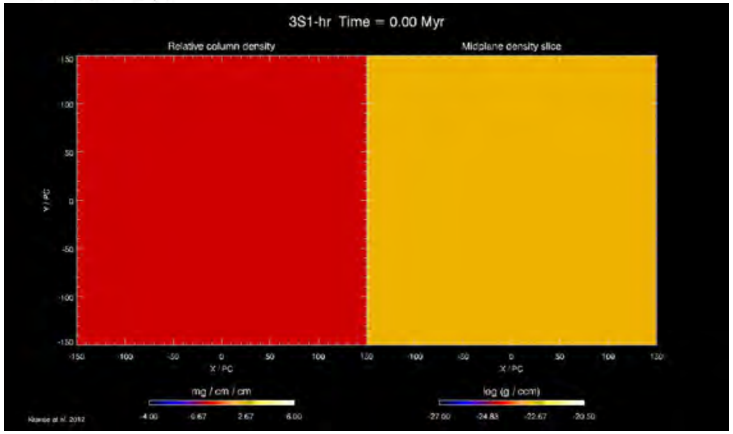








Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003

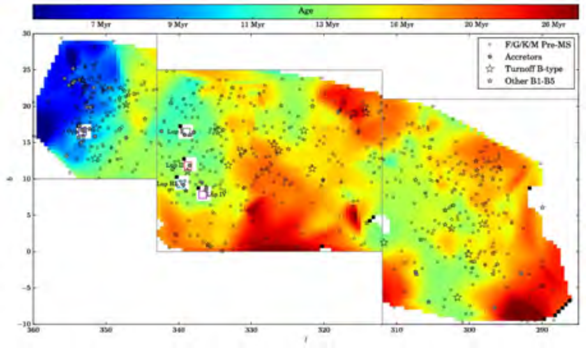


3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff

Stellar feedback in the Sco-Cen region (d~140 pc)

The stellar population covers a wide age range

no clear coeval subgroups, rather SF ongoing for ~15+ My



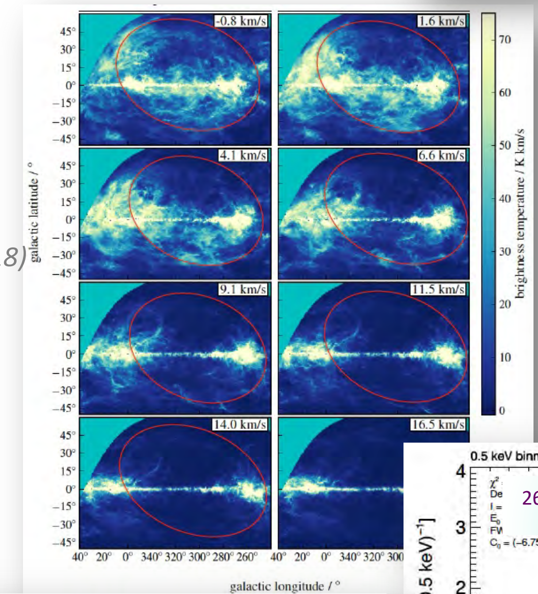
The interstellar medium holds
a network of cavities

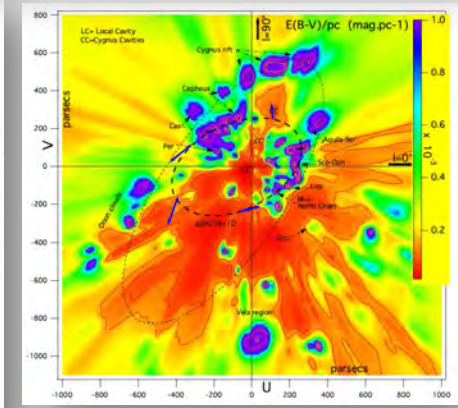
ISM dynamics is not easy to unravel

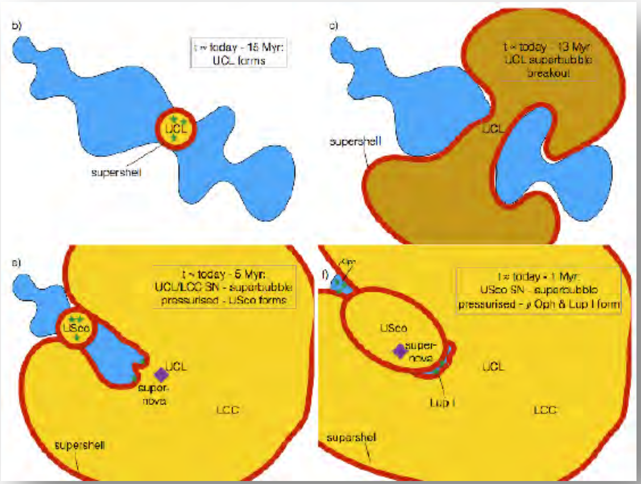
^{26}Al $_{(t\sim1My)}$ appears widely spread;
can we measure the flow?

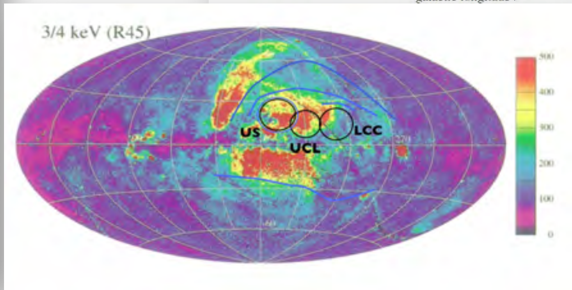
→ *"surround & squish"* *M. Krause+ A&A (2018)*

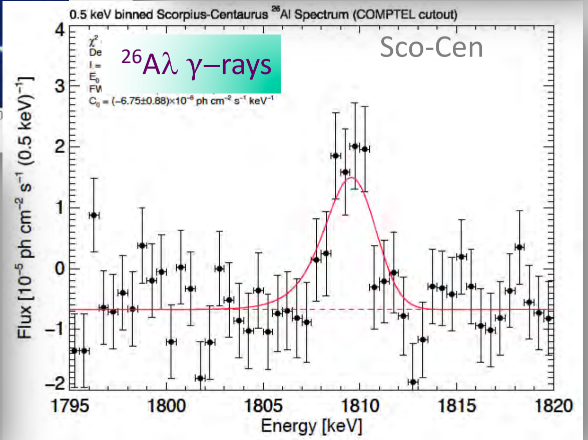
rather than "triggered" star formation







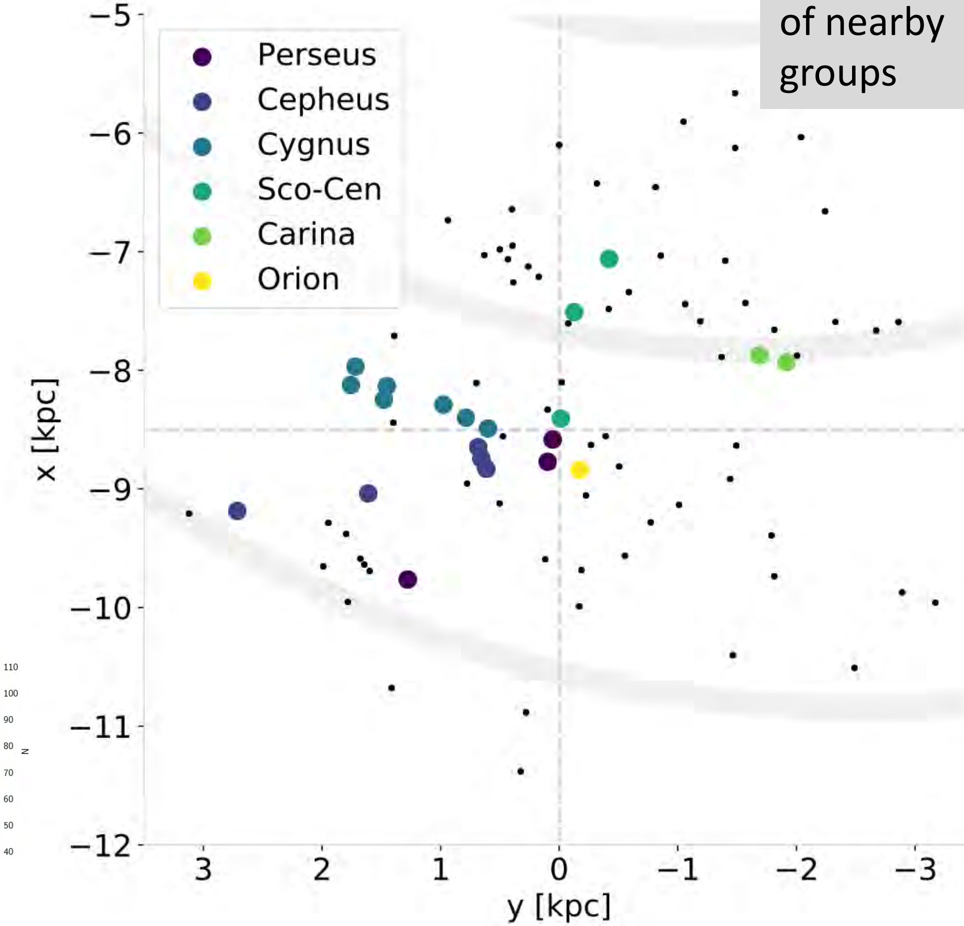




Locations of Massive-Star Groups

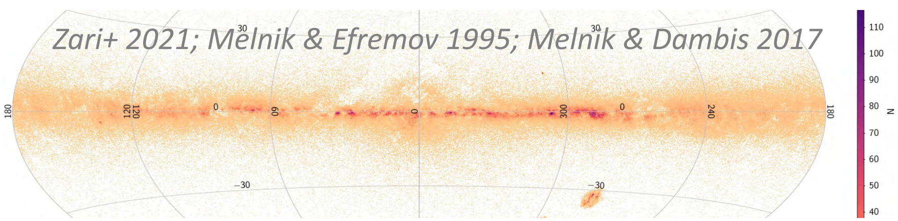
- Nearby groups: well-constrained
  - ☞ location, age, masses

locations of nearby groups



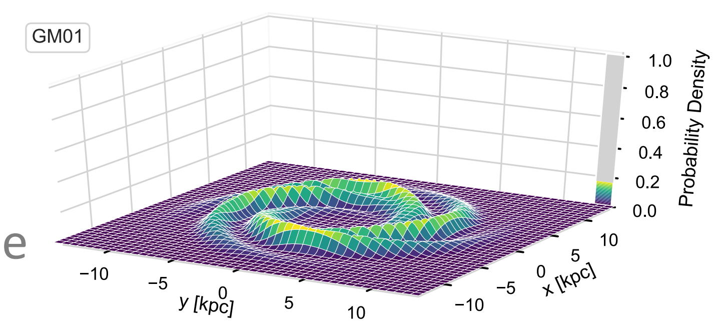
- Galaxy at large:
  - ☆ catalogues (few kpc)
    - ☞ sample mass fct and ages

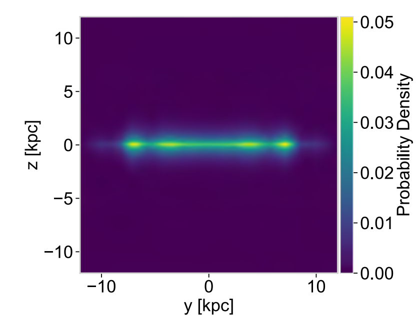
locations of distant groups



Zari+ 2021; Mělnik & Efremov 1995; Melnik & Dambis 2017

  - ☆ geometrical models (>7 kpc)
    - ☞ sample locations, mass fct, ages





always assume spherical volume

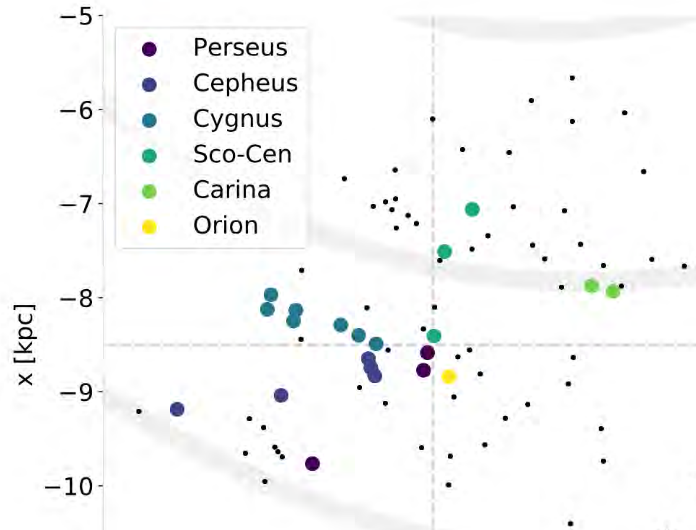
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling

- Use stellar / SN yields and evolution times
- Include knowledge about sources (stellar groups)
- Include known groups; sample unknown groups

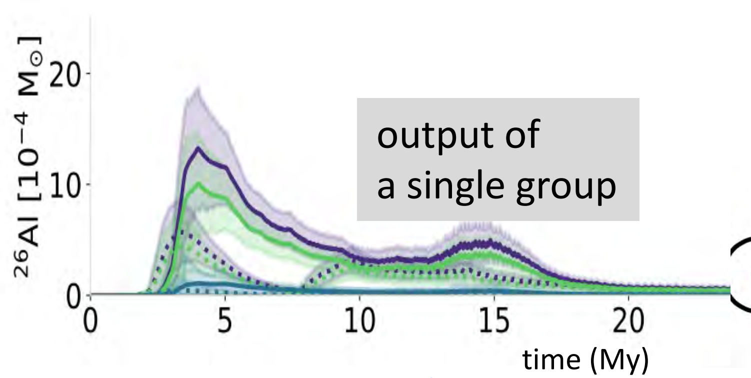
Pleintinger PhD thesis 2020; Siegert+ 2022

→ bottom-up model for the ^{26}Al observations

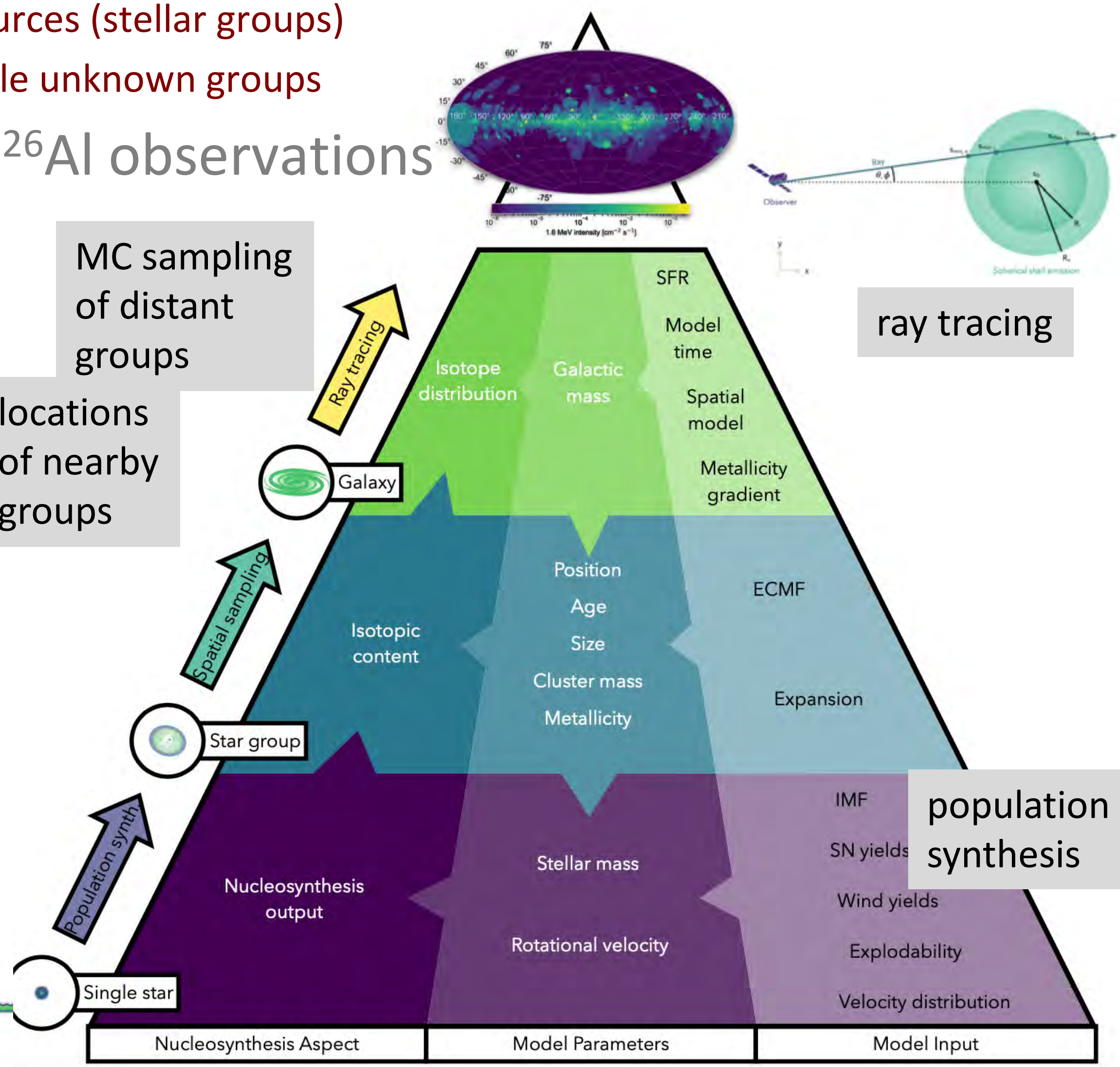


MC sampling of distant groups

locations of nearby groups



output of a single group

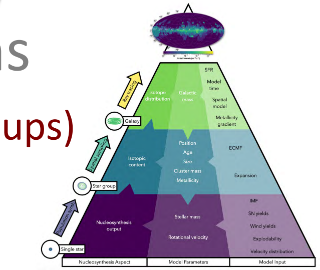


ray tracing

population synthesis

Diffuse radioactivity throughout the Galaxy

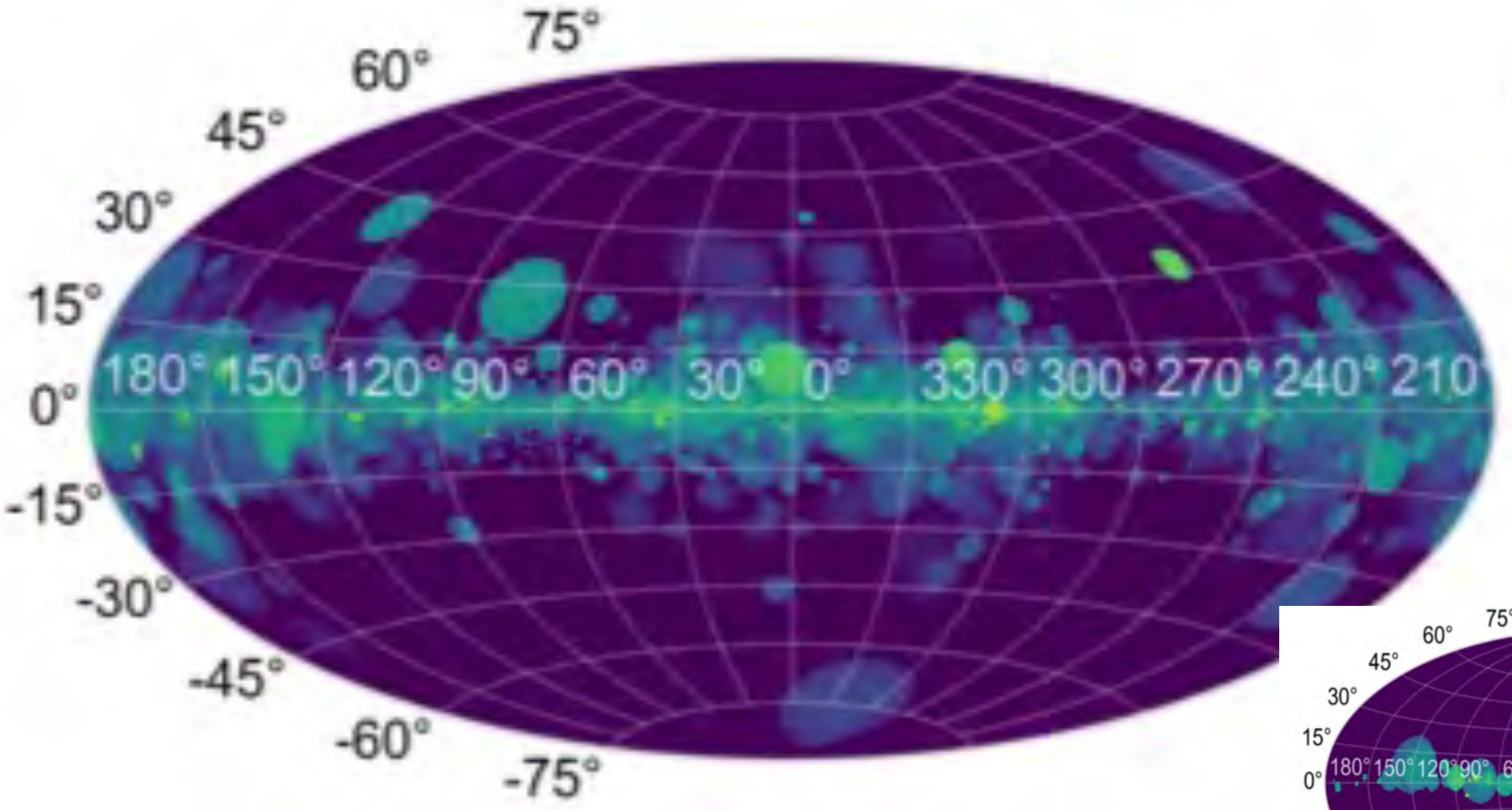
Pleintinger 2020; Siegert+ 2022

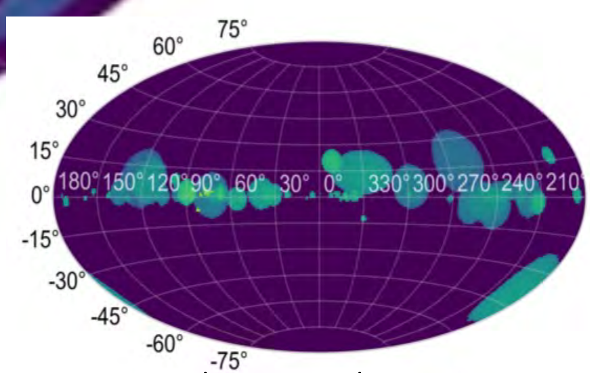


Galactic Pop Syn Modelling (bottom-up) for ^{26}Al observations

☞ stellar groups sampled from different galaxy morphologies (plus known groups)

☆ prominent nearby sources and a diffuse bgd glow



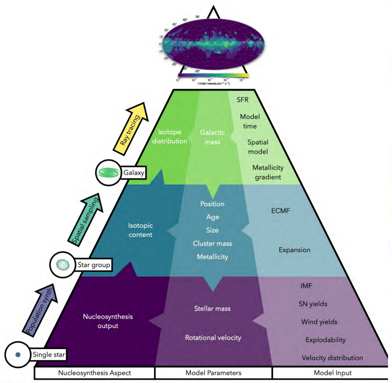


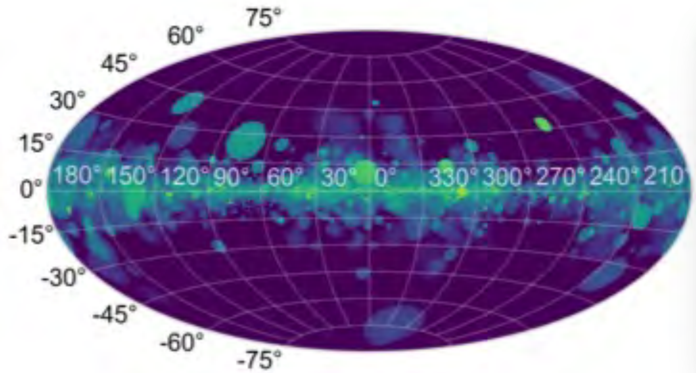
known nearby groups

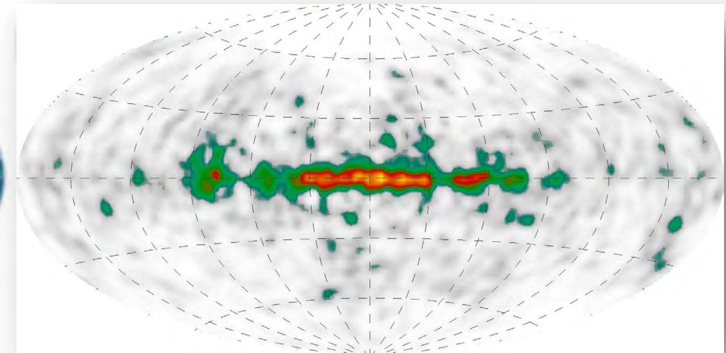
Diffuse radioactivity throughout the Galaxy

Pleintinger 2020
Diehl+ 2022
Siegert+ 2022

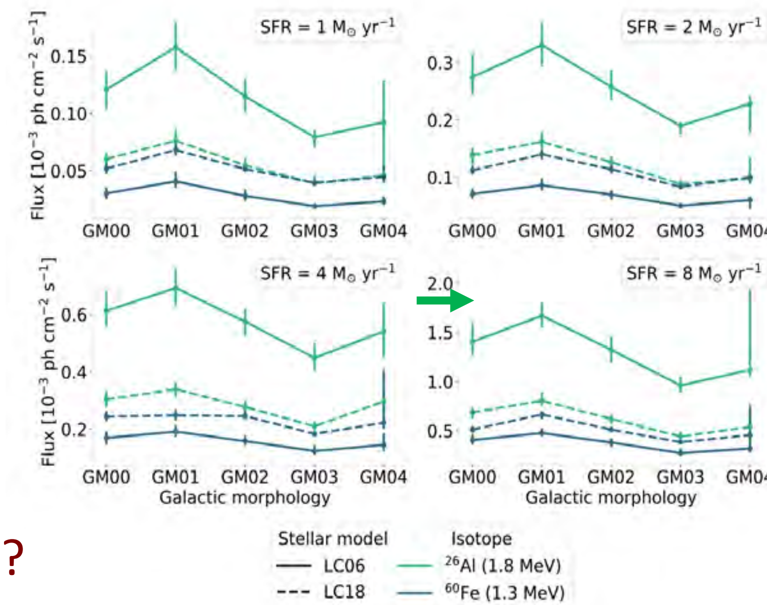
Galactic Population Synthesis Modelling versus observations







- observed full sky flux:
  $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1} ;
  → model-predicted ^{26}Al ~ too low
- up-scaling with star formation rate
  → values plausibly too high
- additional forground emission?
  (a young superbubble having engulfed us)?
- contributions from AGB stars (>50 My)?



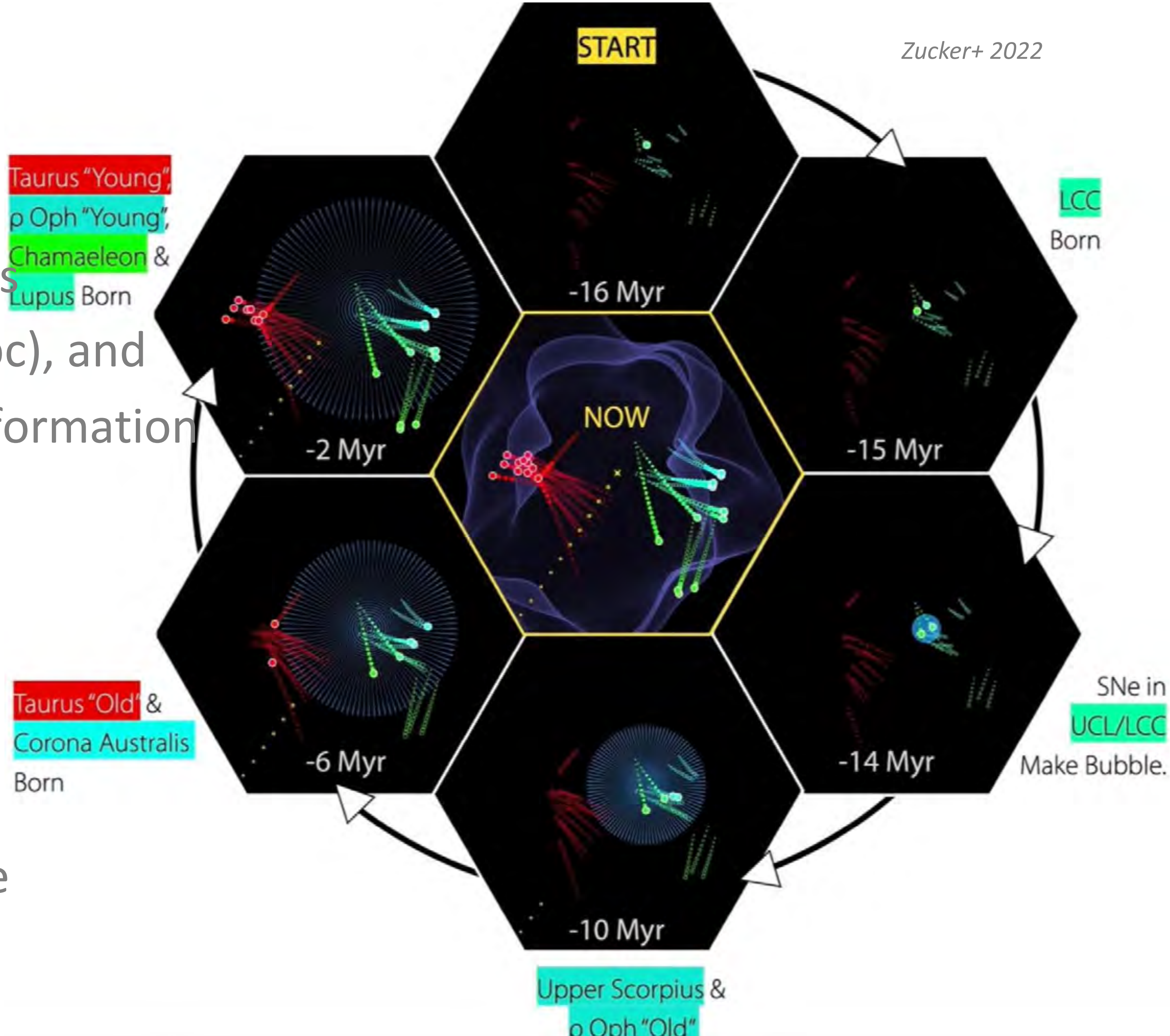
The local (super-)bubble

tracing back stellar motions

→ central cluster creates cavity (~200 pc), and triggers star formation at outskirts

bubble size

→ energy input from ~14 SNe at 1 SN/My



Massive-Star Groups - Summary

- ☆ INTEGRAL/SPI provides detailed observations of Galactic ^{26}Al
  - ~20 yrs of exposure, all SPI triggers used
    → 58 σ signal, all-sky flux 1.8 10^{-3} ph cm^{-2} s^{-1}
  - Galactic ^{26}Al mass estimate (geometrical models): 1.2-2.4 $M_\odot$
  - ^{26}Al velocities larger than expected → sources create superbubbles → ^{26}Al ingestions into pre-blown cavities
- ☆ Population synthesis of massive-star groups as a tool
  - 'PSYCO' predicts ^{26}Al ejection history over ~30 My
  - Inclusion of Galactic source distribution → bottom-up map
- ☆ Comparison between observations and population synthesis and simulations → massive-star group scenario plausible
  - discrepancies in detail: observed cavities larger, observed flux larger
- ☆ Varied messengers complement each other
  - Radioactivity provides a unique and different view on ejecta diffusion (→ recycling)
  - A next gamma-ray telescope (light-weight Compton telescope) is a dream 2040+; COSI-SMEX 2026?; INTEGRAL will end 2029