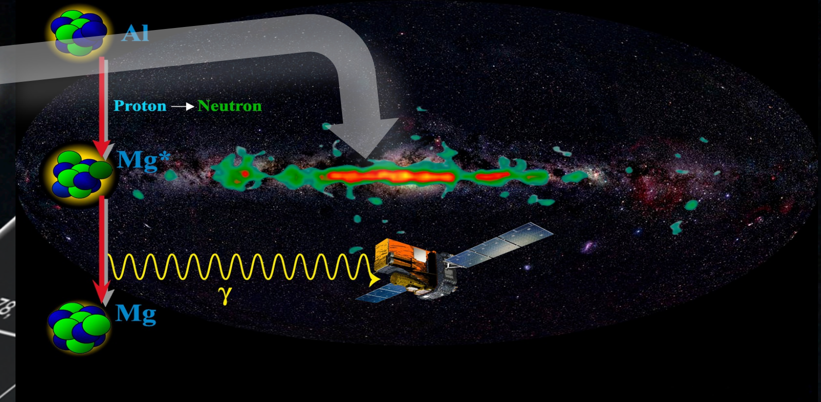


Cosmic radioactivities and Galactic gas dynamics

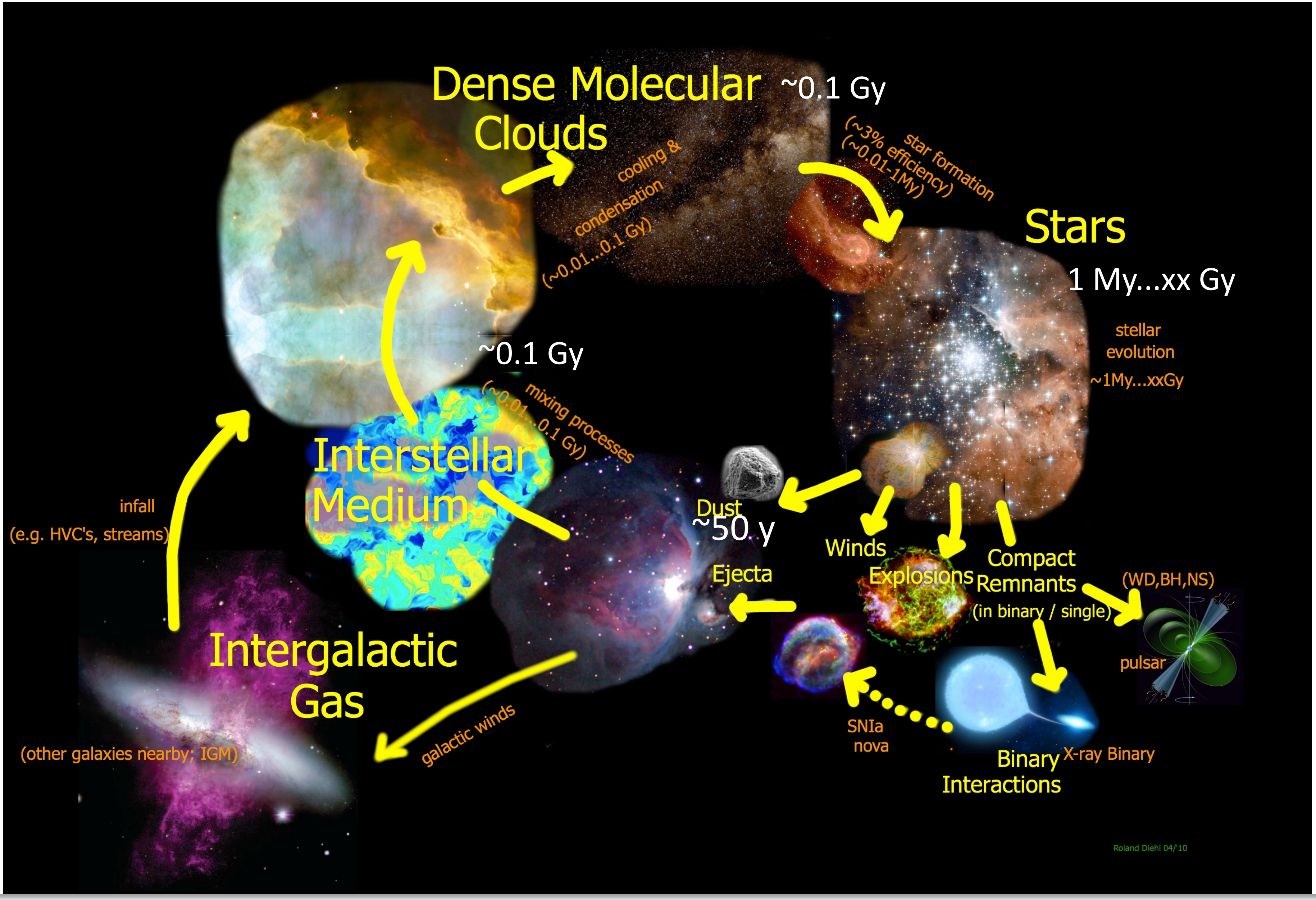
Roland Diehl
Technical University München and
MPE and Origins Cluster emeritus
Garching, Germany

Contents:

1. Star formation across times: Tracing feedback
2. Radioacivity and γ-ray observations
3. Nucleosynthesis Ejecta: Observing gas dynamics

with work from (a.o.)
Martin Krause, Karsten Kretschmer, Daniel Kröll,
Moritz Pleintinger, Thomas Siegert, Rasmus Voss, Wei Wang,r

The cycle of matter through star formation



Stars: formation, & their impact on ISM (My..Gy): "Feedback"*

*main issue in ISM sim last 10 years

Stars form from Giant Molecular Cloud Cores (~1% efficiency)

Most-massive stars evolve most rapidly and interact on surroundings within few Myrs

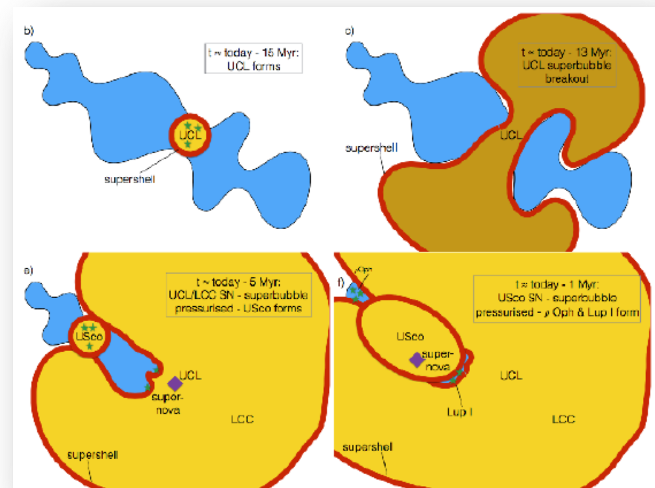
UV radiation from most-massive stars provides early feedback, winds form cavities

Overlapping wind cavities are energized by supernovae

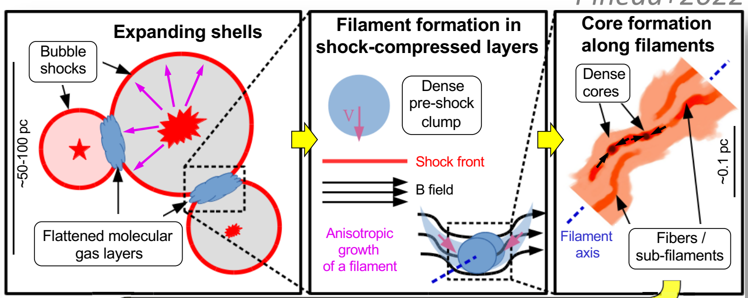
Star-forming clouds are eroded within few Myrs

Star formation is quenched, but some is triggered
in shocked-gas regions by such feedback

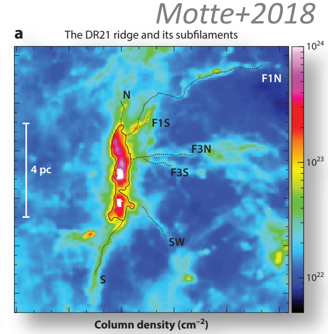
Krause+2018



Pineda+2022

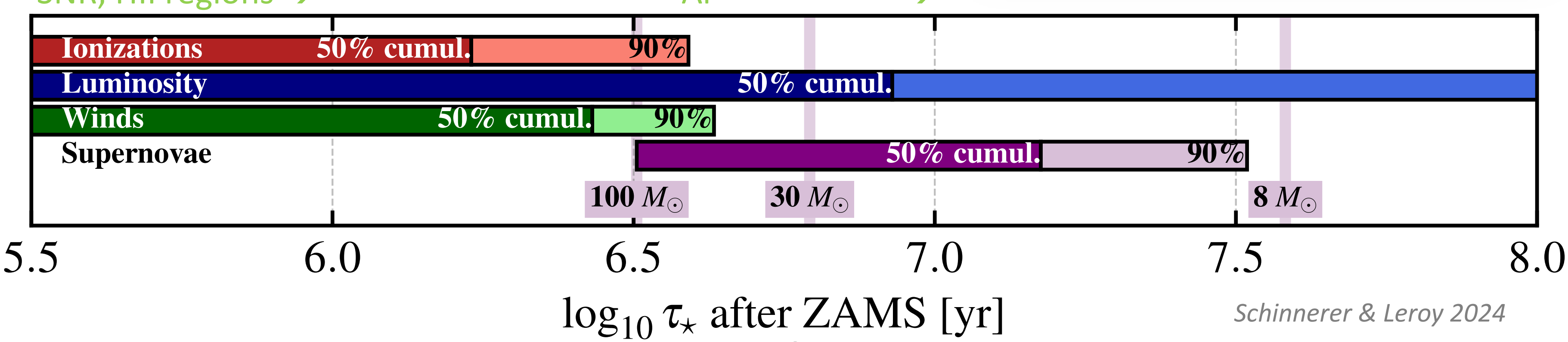


Motte+2018



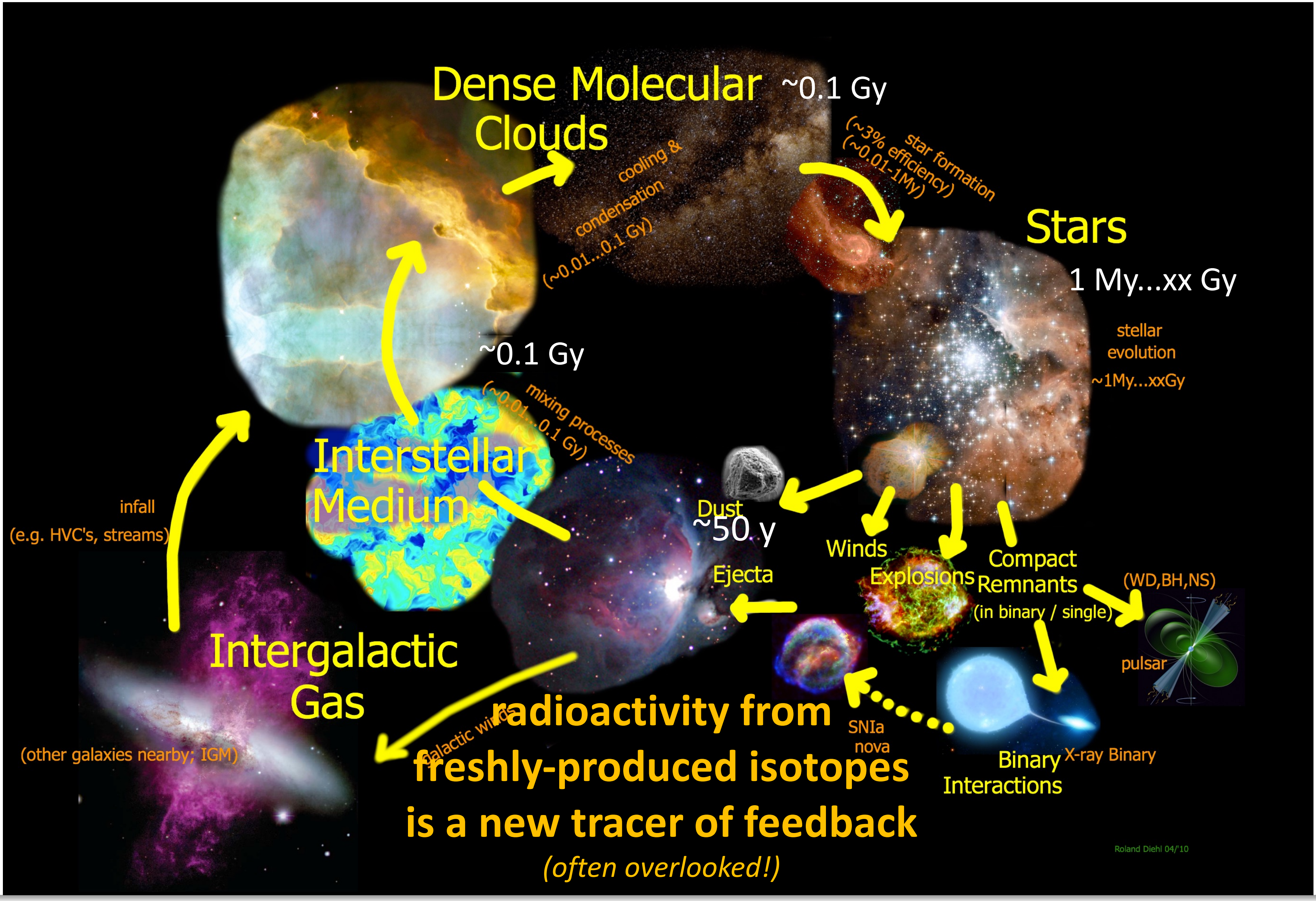
SNR, HII regions →

^{26}Al →

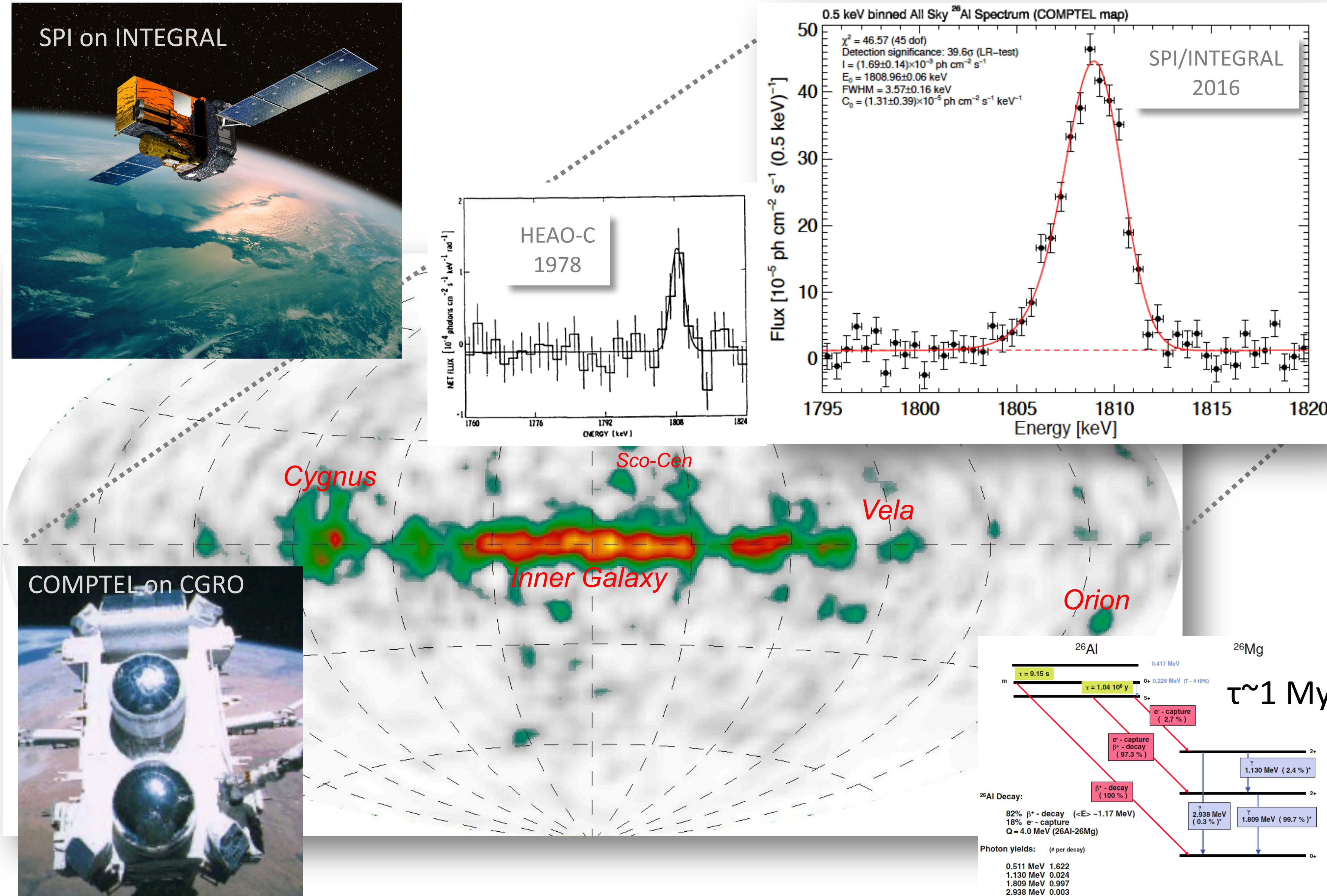


Schinnerer & Leroy 2024

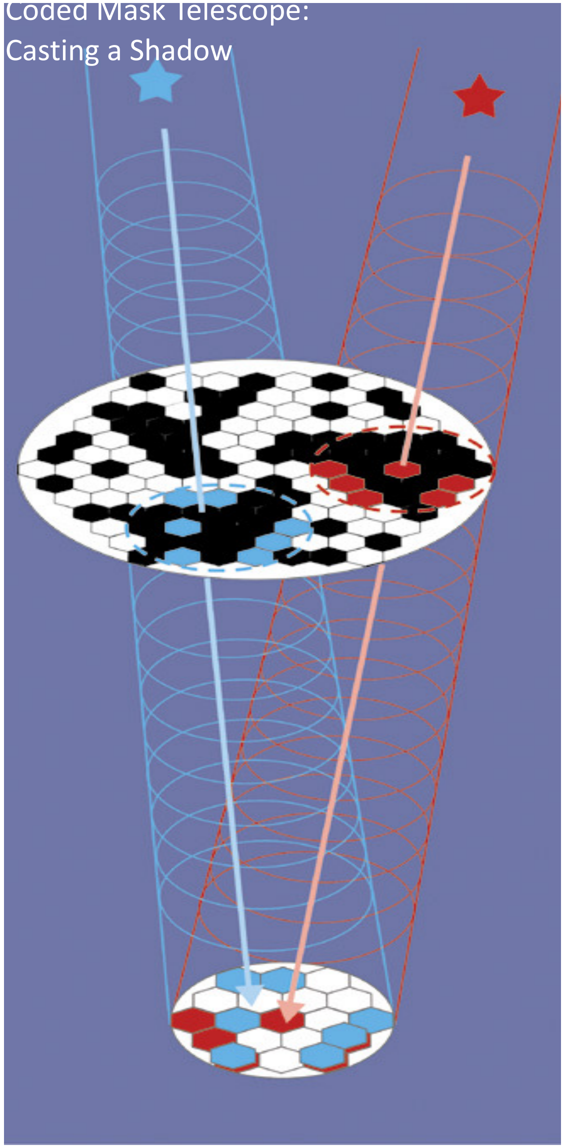
The cycle of matter through star formation



^{26}Al γ-rays from the Galaxy



INTEGRAL Cosmic Photon Measurements: The SPI Ge γ-Spectrometer



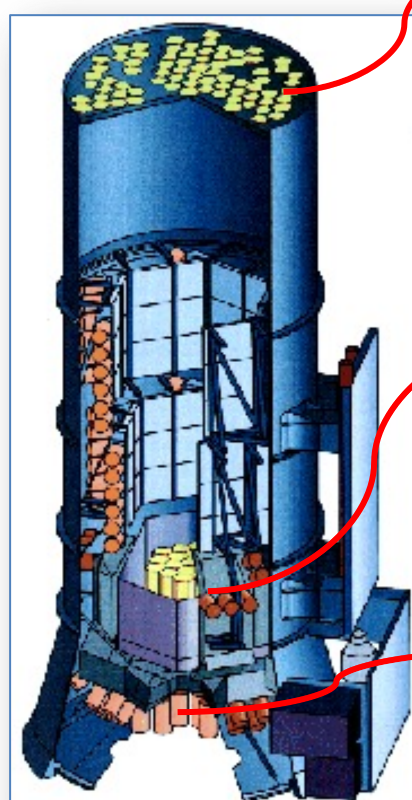
Coded-Mask Telescope

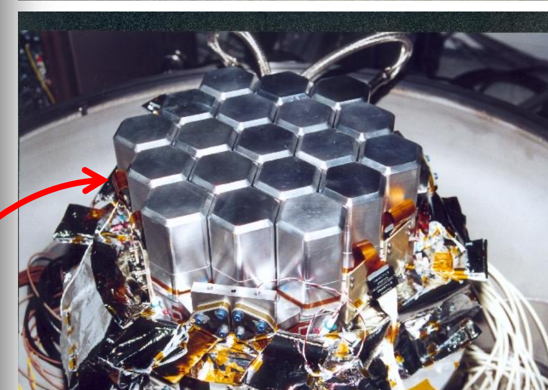
Energy Range 15-8000 keV

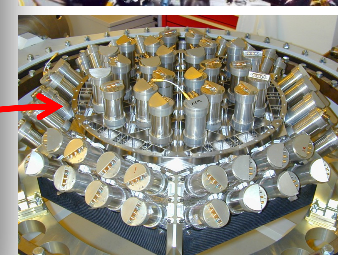
Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6º / ~2 arcmin

Field-of-View 16x16º

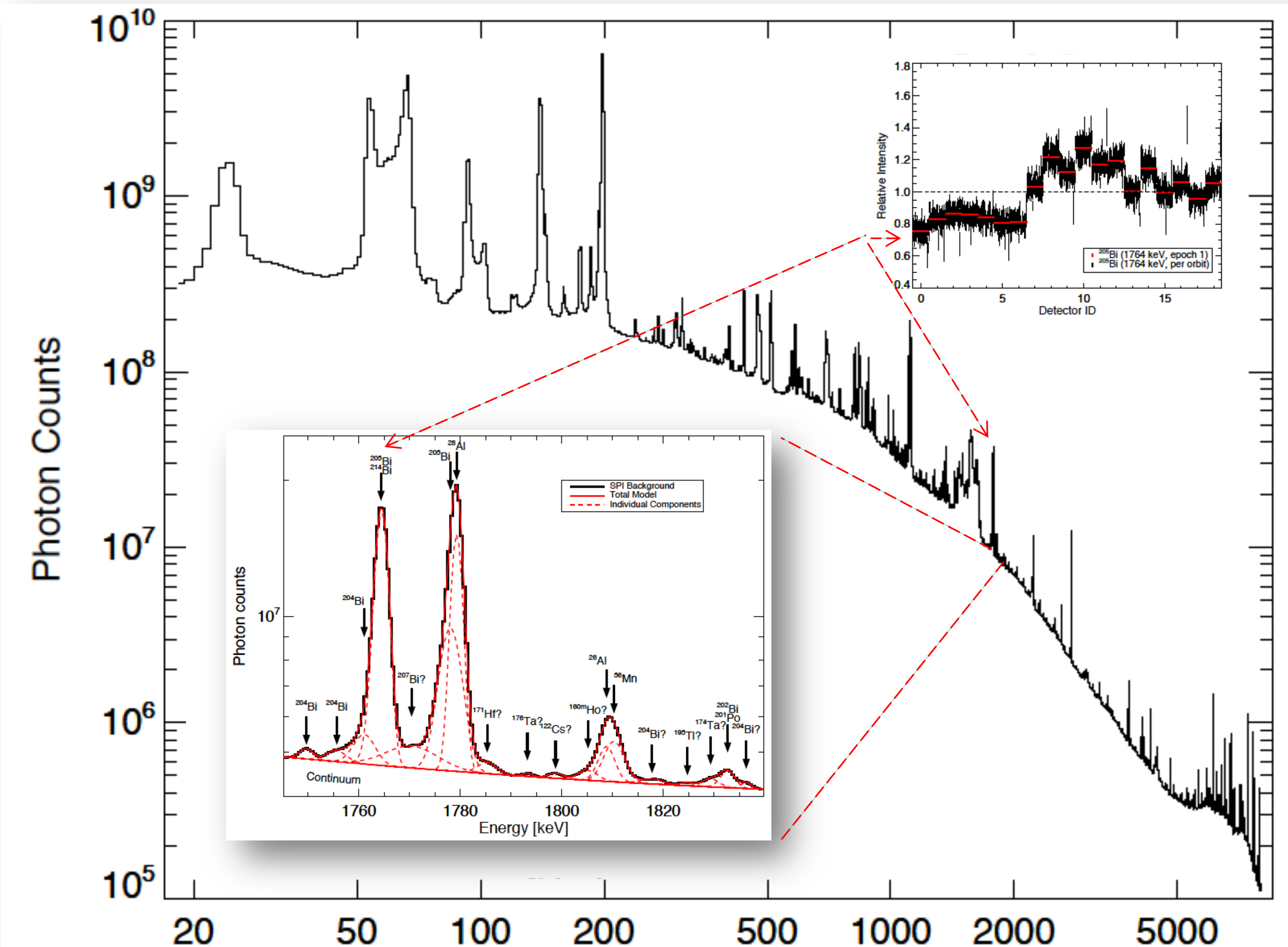






INTEGRAL/SPI Ge detector spectra

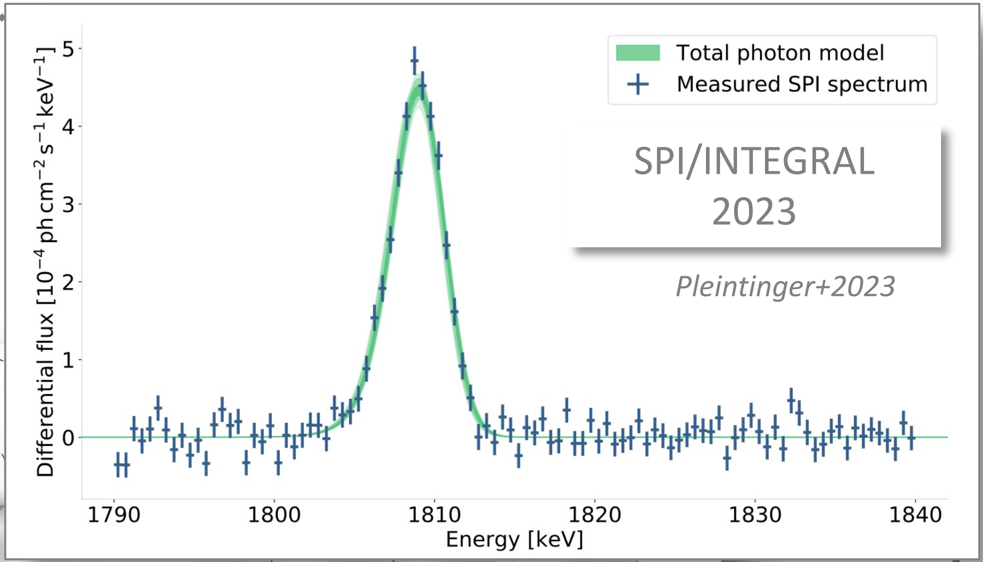
Dominance of instrumental background

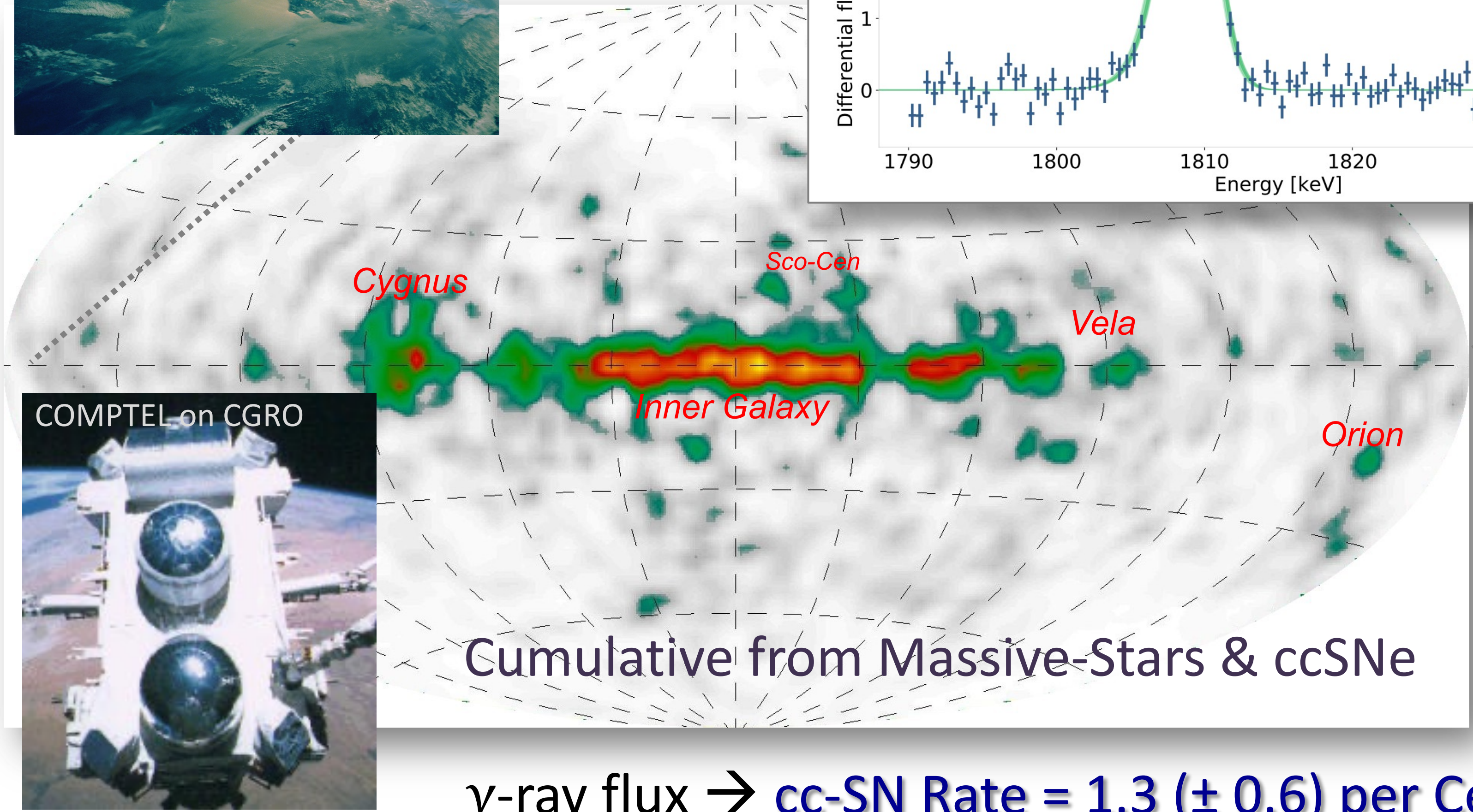


Modelled/understood at high precision

raw data for ^{26}Al analysis: ~100000 such spectra

^{26}Al γ-rays and the galaxy-wide massive star census





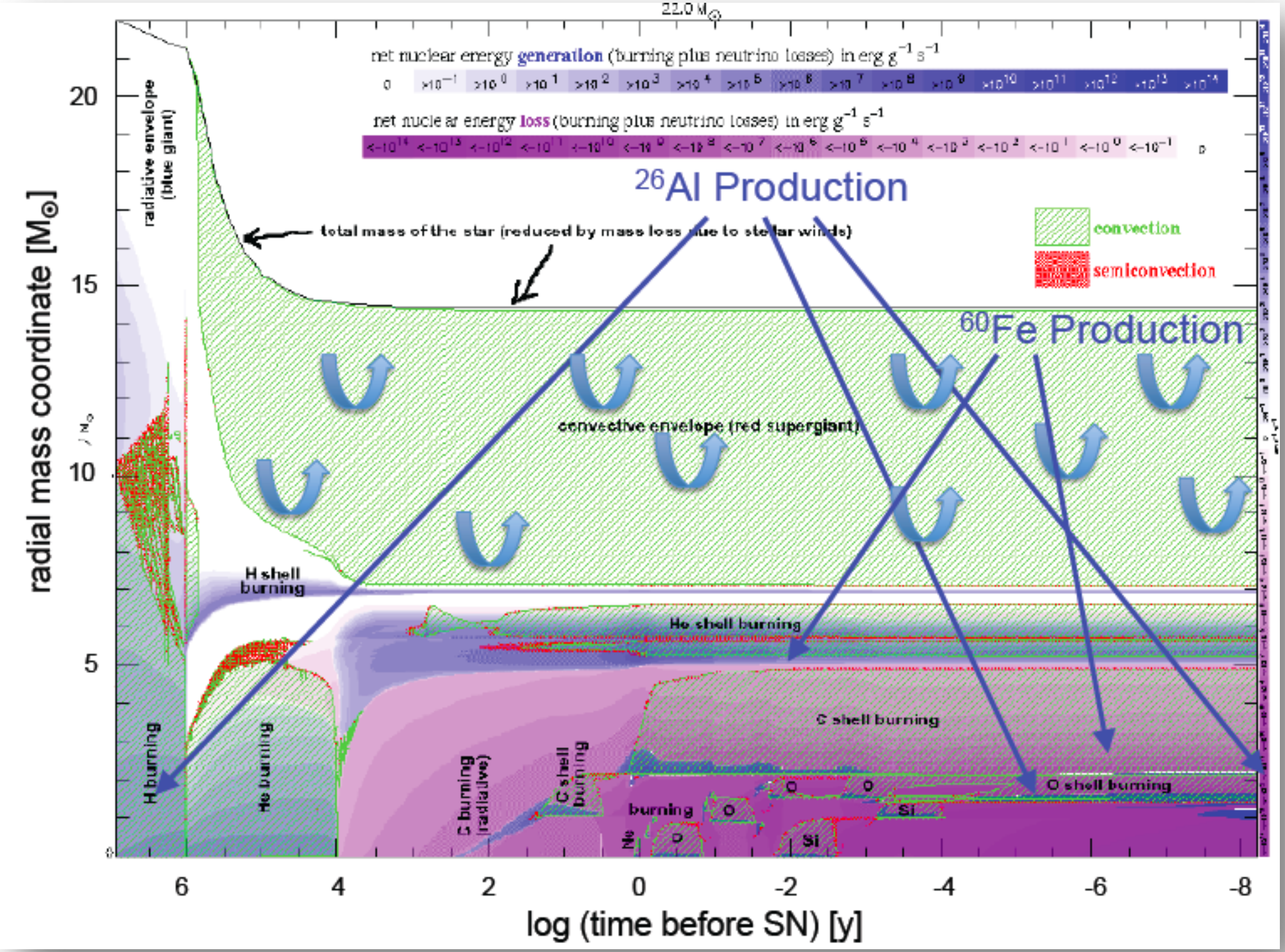
γ-ray flux → **cc-SN Rate = 1.3 (± 0.6) per Century**

Diehl+2006;2018

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

→ Messengers from Massive-Star Interiors!

…complementing neutrinos and asteroseismology!



Processes:

- ☆ *Hydrostatic fusion*
- ☆ *WR wind release*
- ☆ *Late Shell burning*
- ☆ *Explosive fusion*
- ☆ *Explosive release*

^{26}Al radioactive luminosity ~1 My → cumulative from many sources

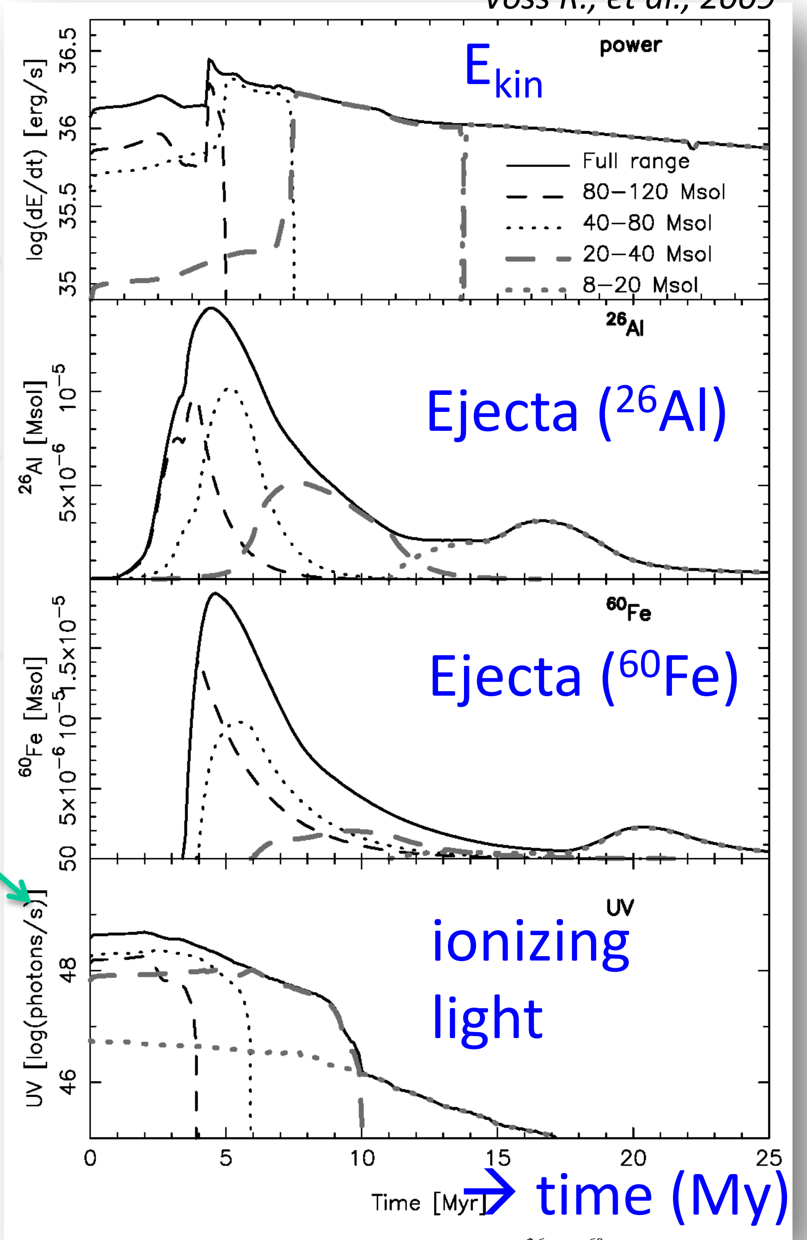
Massive-Star Groups: Modelling long-term phenomenae

- Model the "outputs" of massive stars and their supernovae from theory
  - Winds and Explosions
  - Nucleosynthesis Ejecta
  - Ionizing Radiation

- Get observational constraints from
  - Star Counts
  - ISM Cavities
  - Free-Electron Emission
  - Radioactive Ejecta

  ➔ *multi-wavelength studies!*

Voss R., et al., 2009



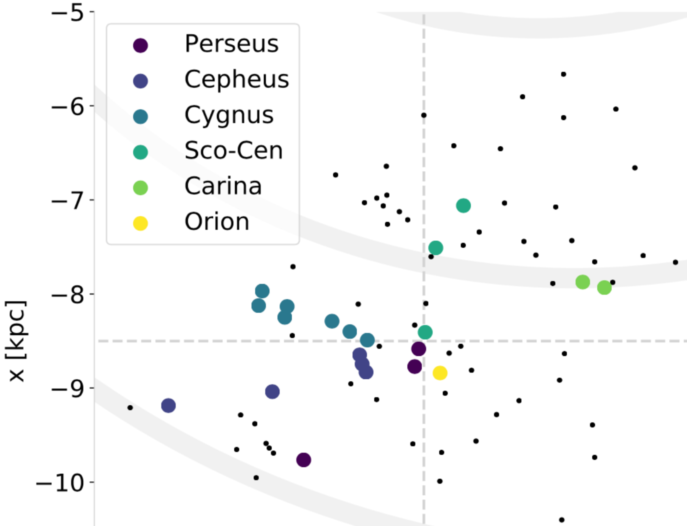
Diffuse radioactivity throughout the entire Galaxy to SPI data

Galactic Bottom-Up Modelling

- ☞ Use stellar evolution times and yields (wind, SN) → PopSyn
- ☞ Include knowledge about sources (known stellar groups, model)
- ☞ model spatial spreading, ray-trace gamma rays

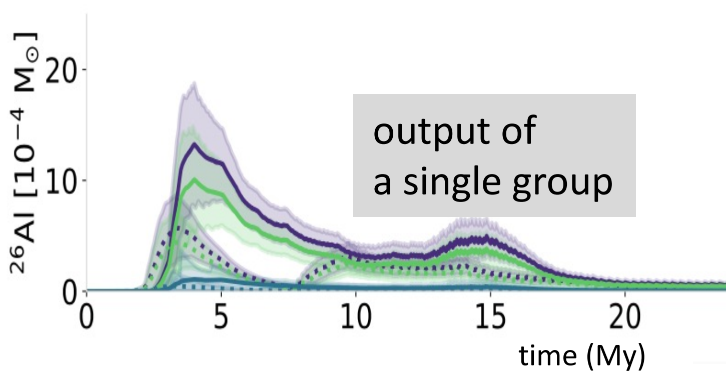
Pleintinger PhD thesis 2020 (see also Siegert+ 2023)

→ model for ^{26}Al data, with astrophysical parameters

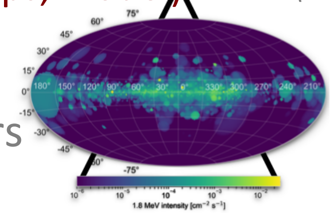


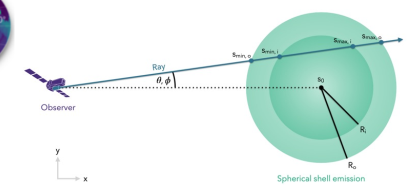
MC sampling of distant groups

locations of nearby groups

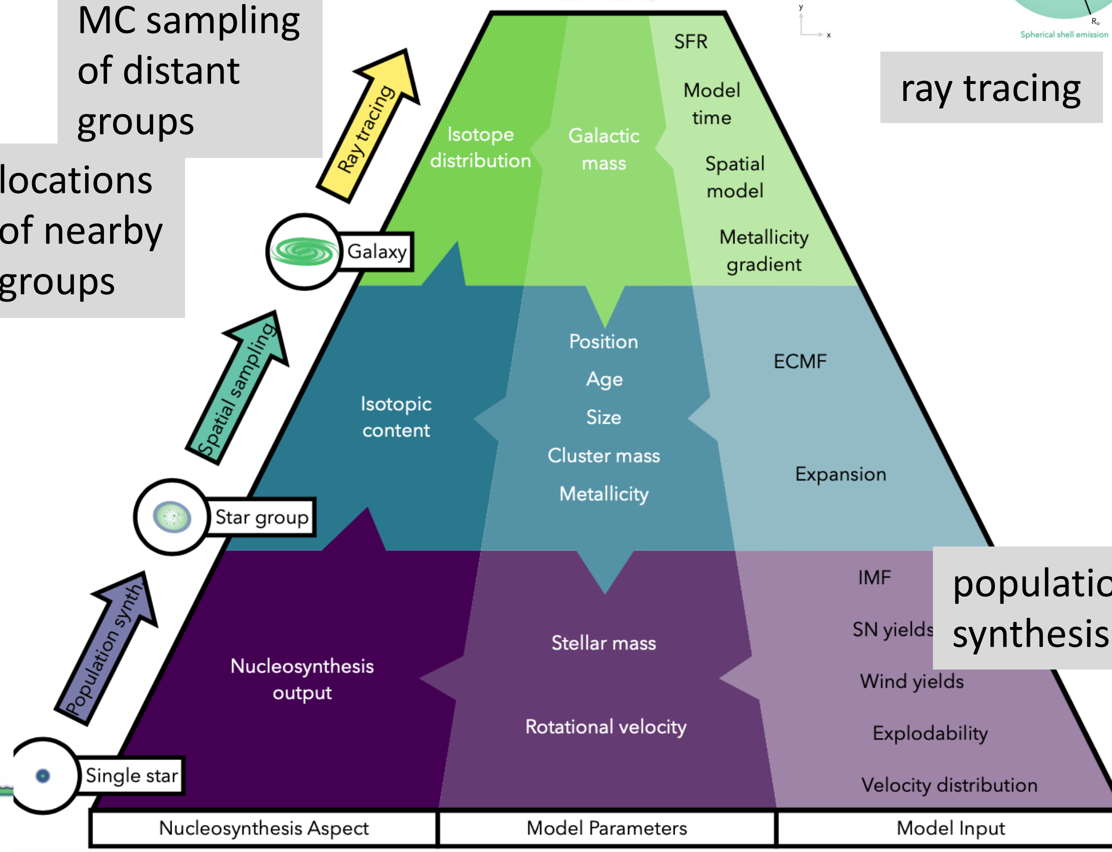


output of a single group





ray tracing

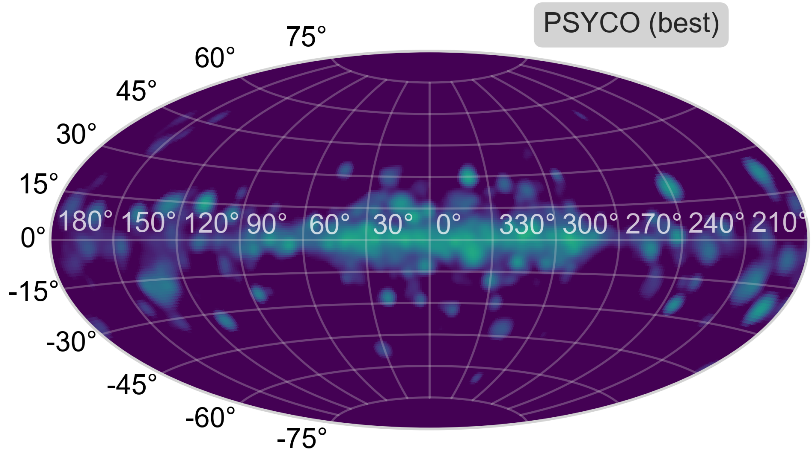


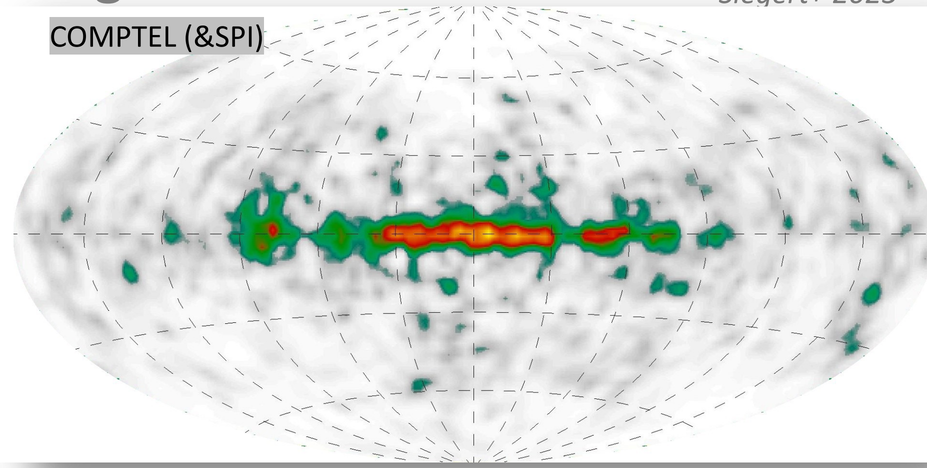
population synthesis

Diffuse radioactivity throughout the Galaxy

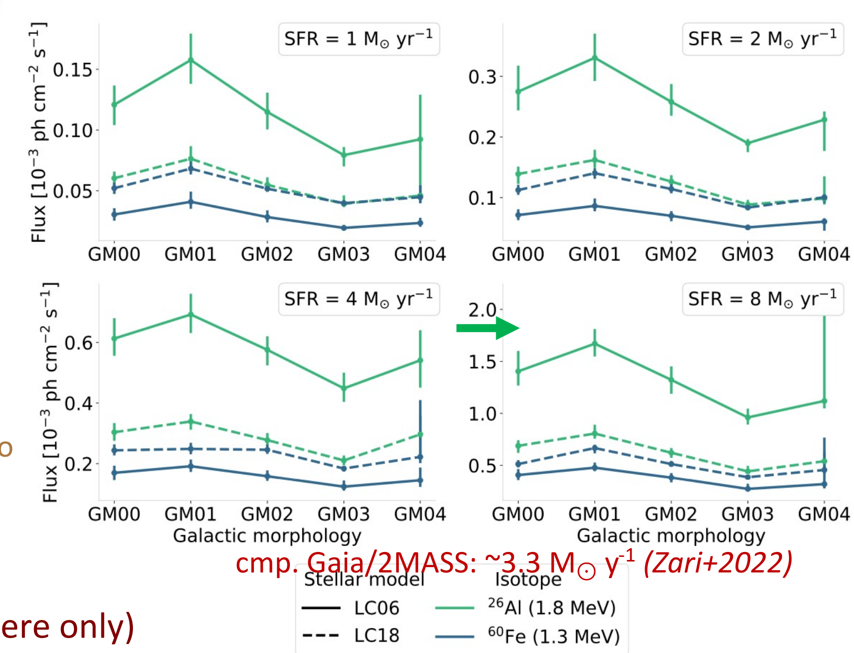
Galactic Population Synthesis Modelling versus observations

Pleintinger 2020
Siegert+ 2023





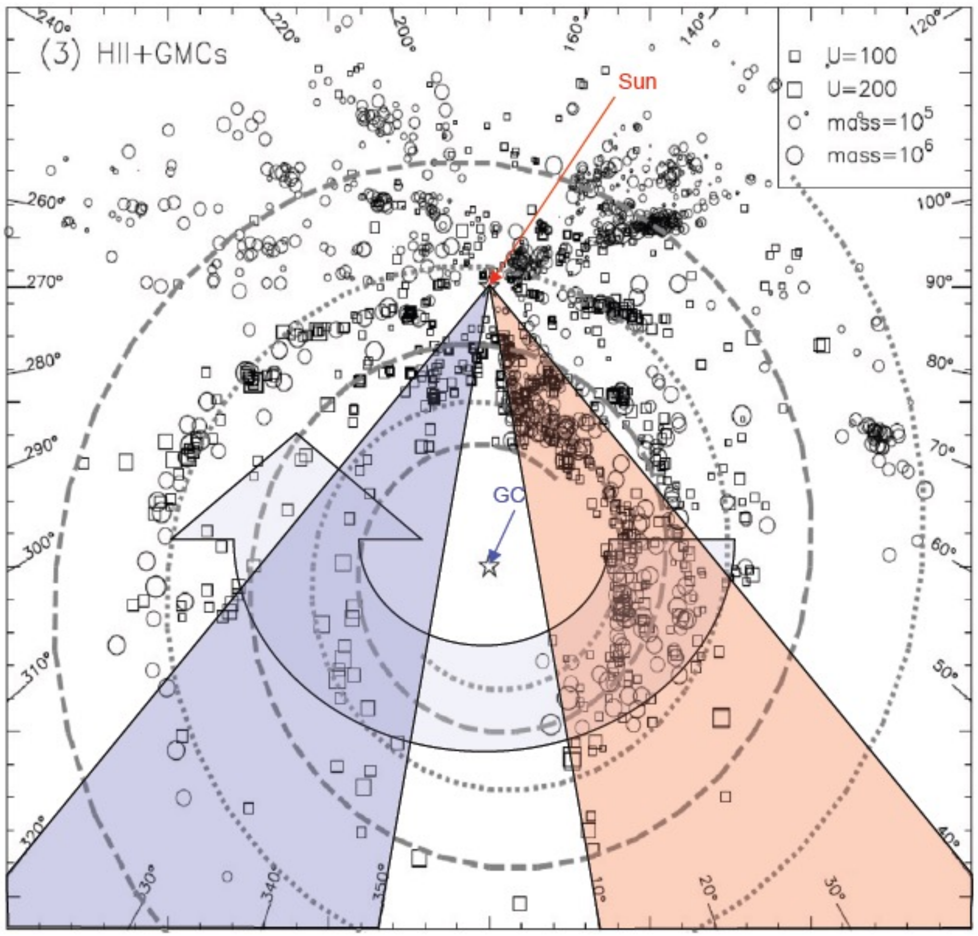
- PSYCO modeling: (30000 sample optimisation)
  → best: 4-arm spiral 700 pc, LC06 yields, SN explosions up to 25 $M_\odot$
- SPI observation: → full sky flux $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1}
- flux from model-predicted ^{26}Al:
  → $(0.5..13)\ 10^{-4}$ ph cm^{-2} s^{-1} → too low
  - Massive-star yields: see disc. in Diehl+2021; Battino+2024 → astro
  - Contributions from AGB stars and novae??
- Best-fit details (yield, explodability) depend on superbubble modelling (here: sphere only)



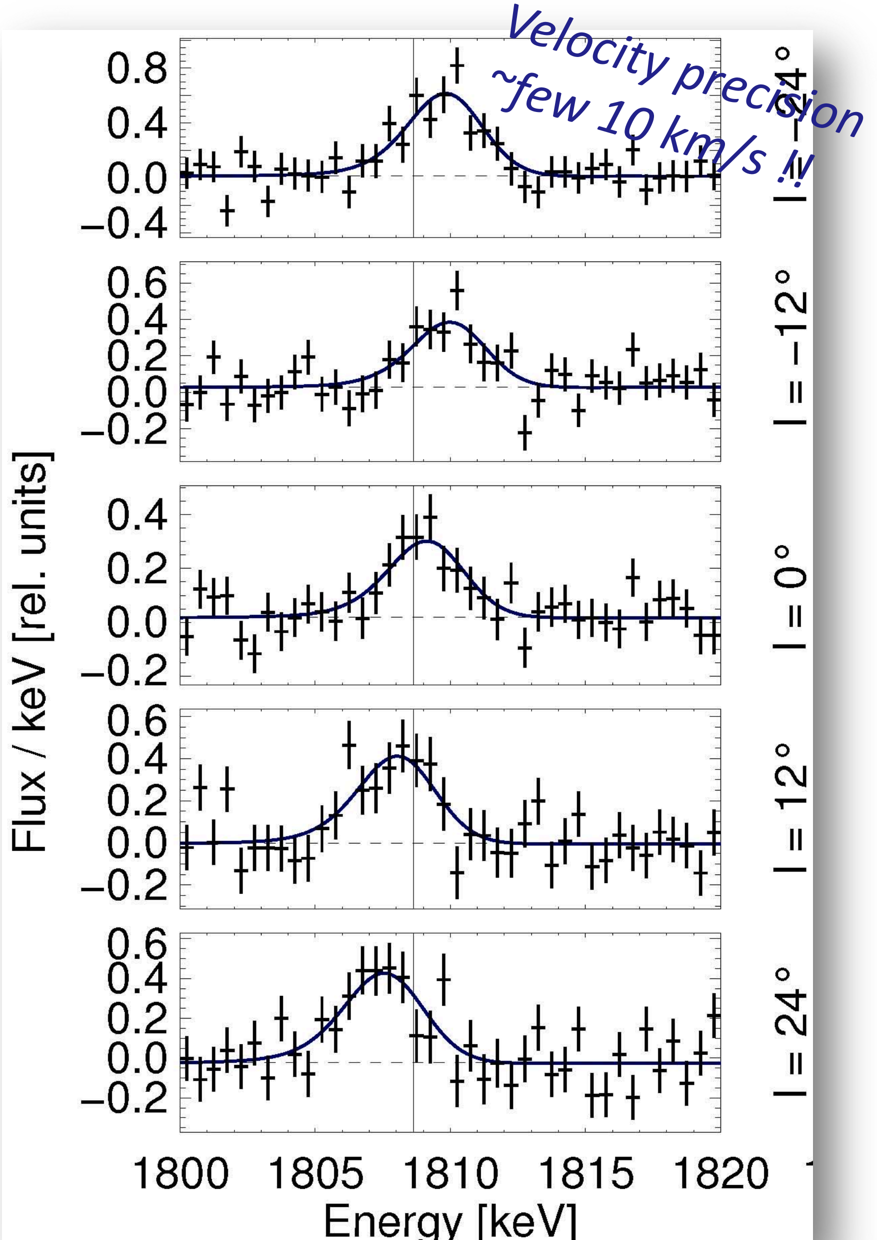
cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{-1} *(Zari+2022)*

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

☞ Large-scale Galactic rotation



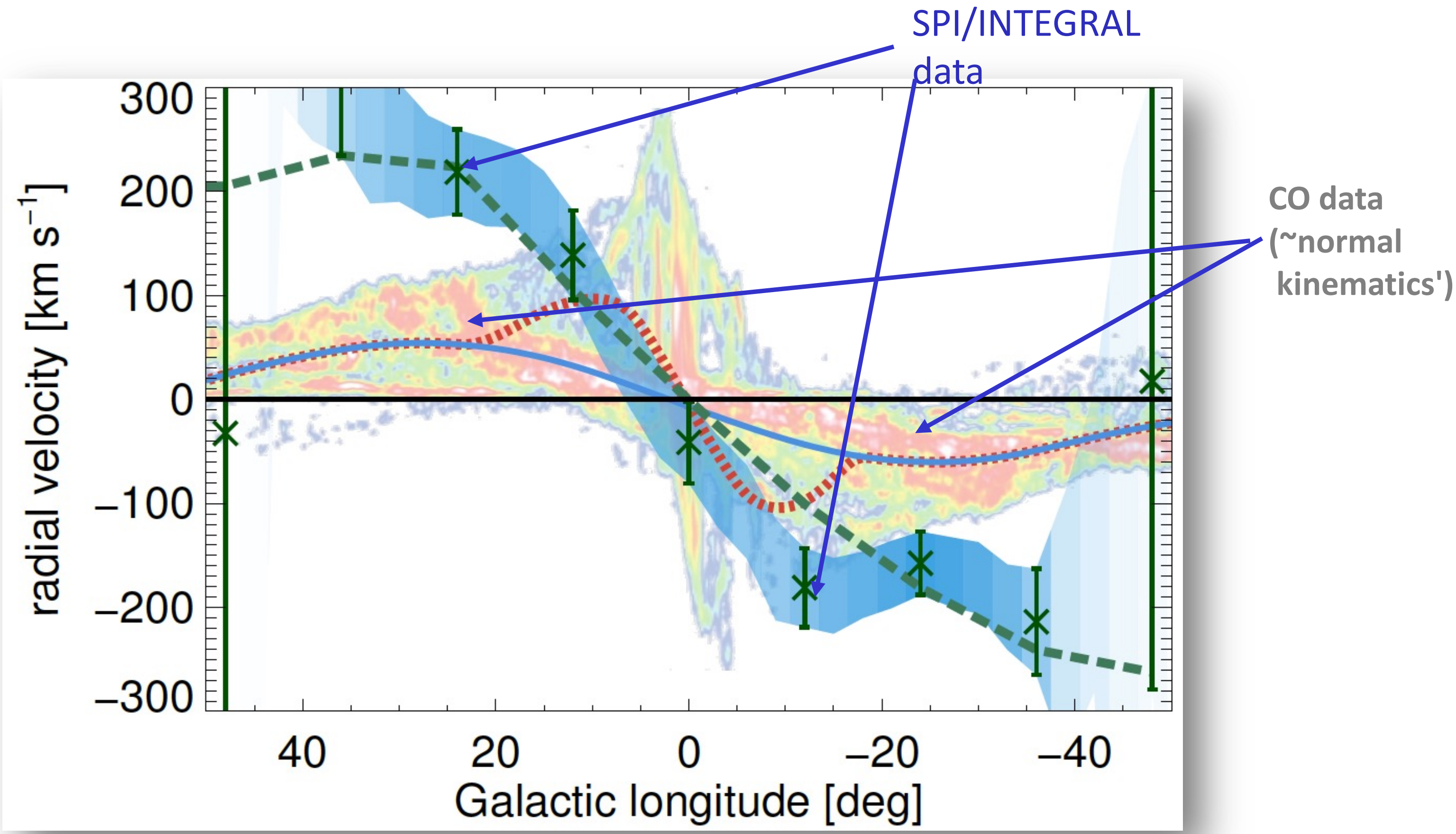
Kretschmer et al., A&A (2013)



How massive-star ejecta are spreading…

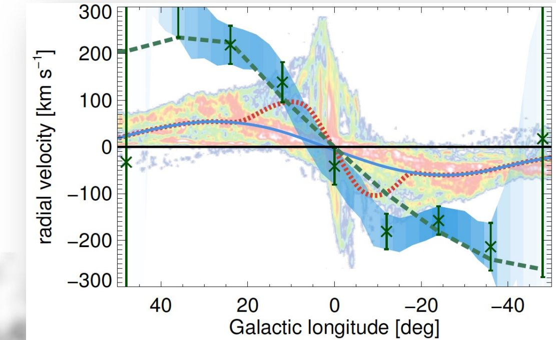
- ^{26}Al shows apparently higher galactocentric rotation (?)

Kretschmer+(2013)

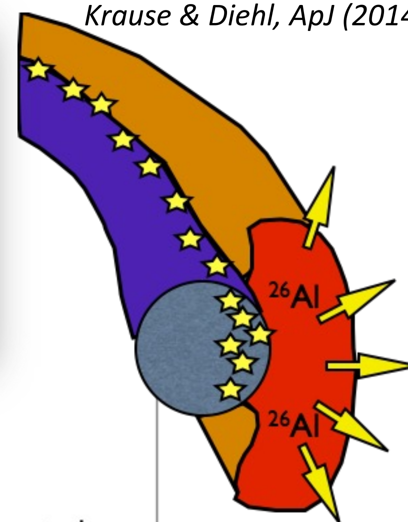


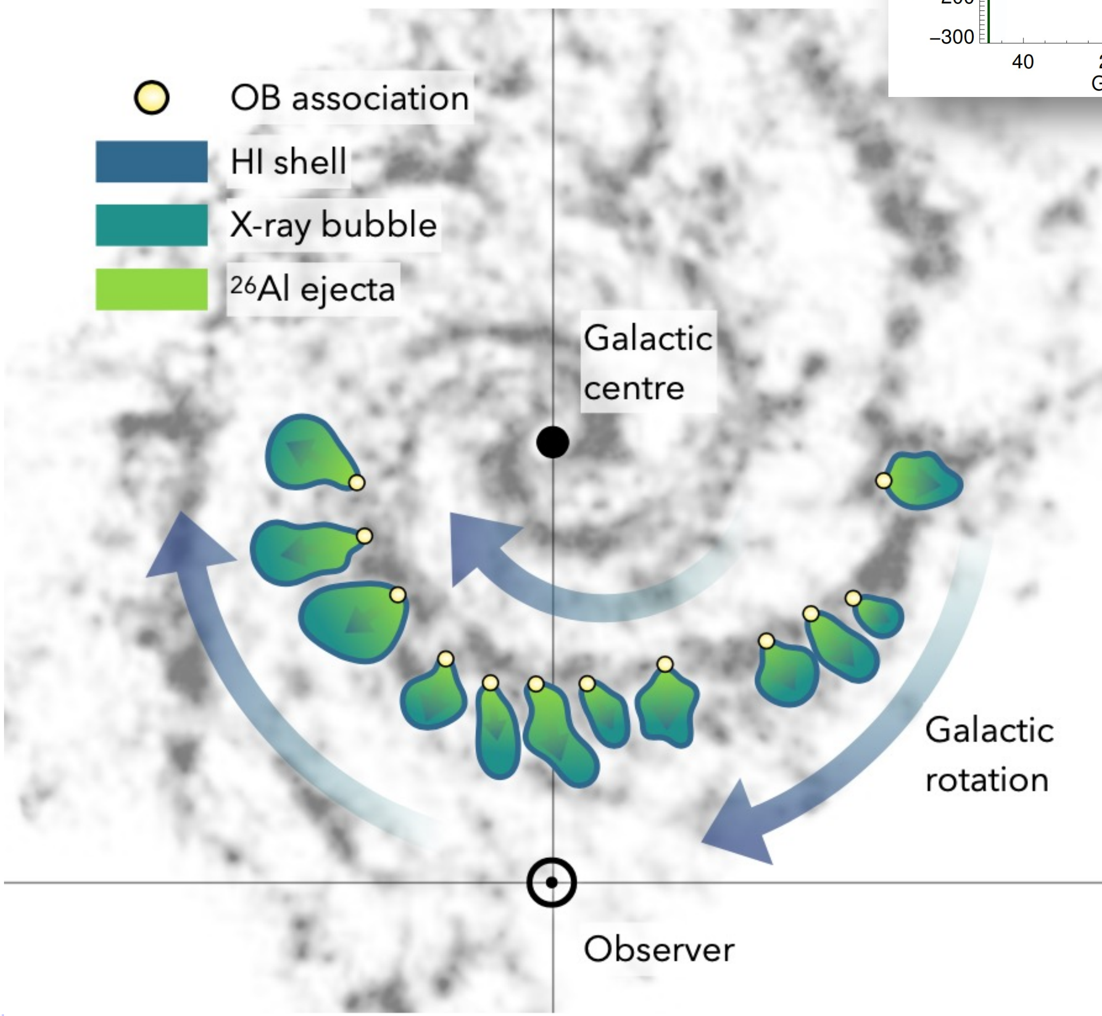
How massive-star ejecta are spreading…

Superbubbles extended away from massive-star groups



Krause & Diehl, ApJ (2014)





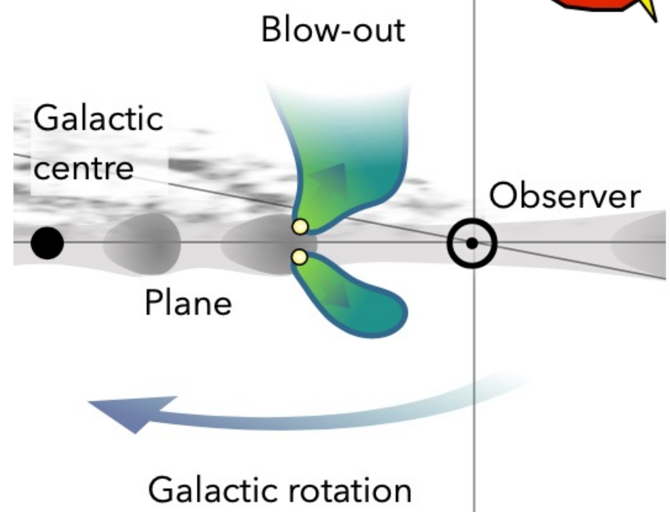


Illustration by M. Pleintinger (2020)

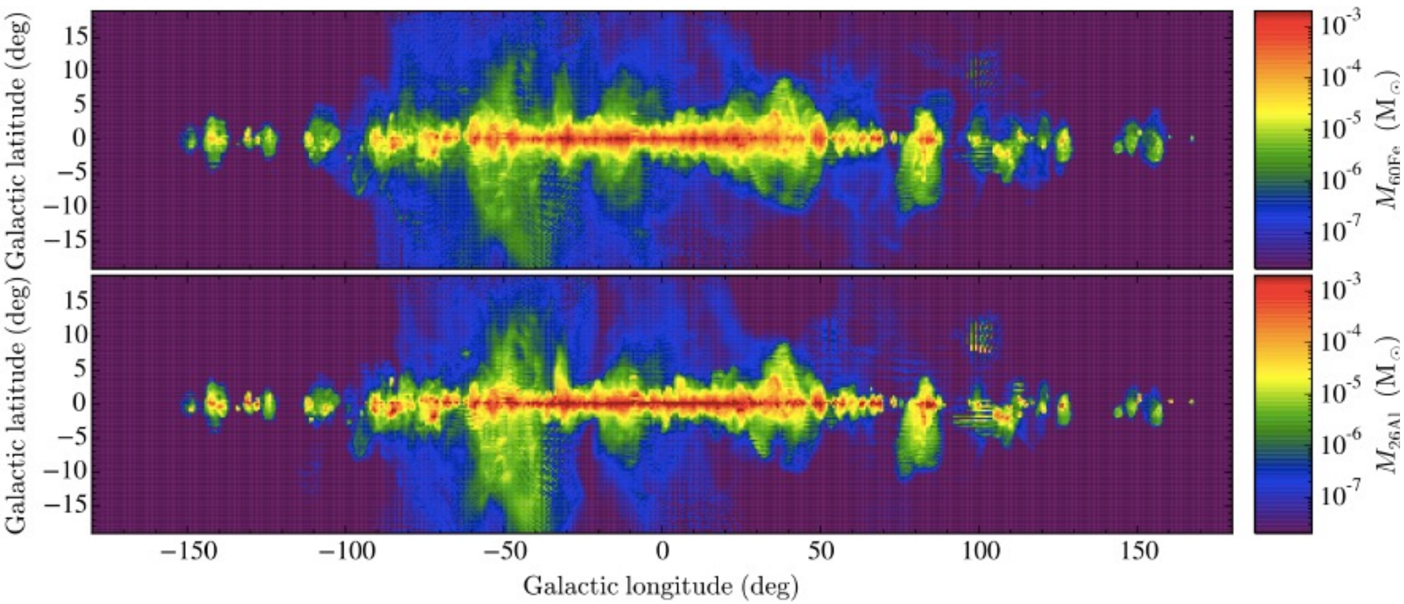
^{26}Al trajectories in simulations

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

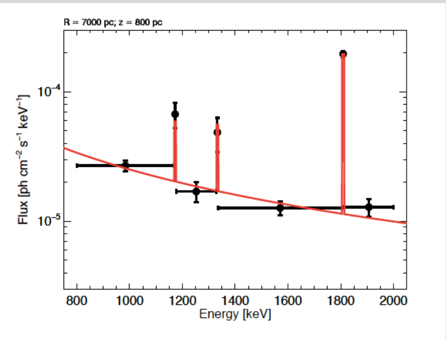
- ☆ 128^3 cells, cell size 7.8 pc (more-precise than cosmological simulations, but still crude)
- ☆ starting fom 'current galaxy' model (Tasker&Tan 2009), no bulge nor spiral arms initially
- ☆ star formation by Toomre criterion on single cells, efficiency set tp 1%

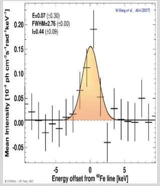
→ 'map' of a simulated galaxy in radioactive ^{26}Al (and ^{60}Fe)

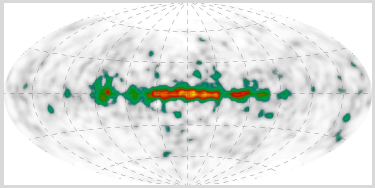
Fujimoto+ 2018



observations







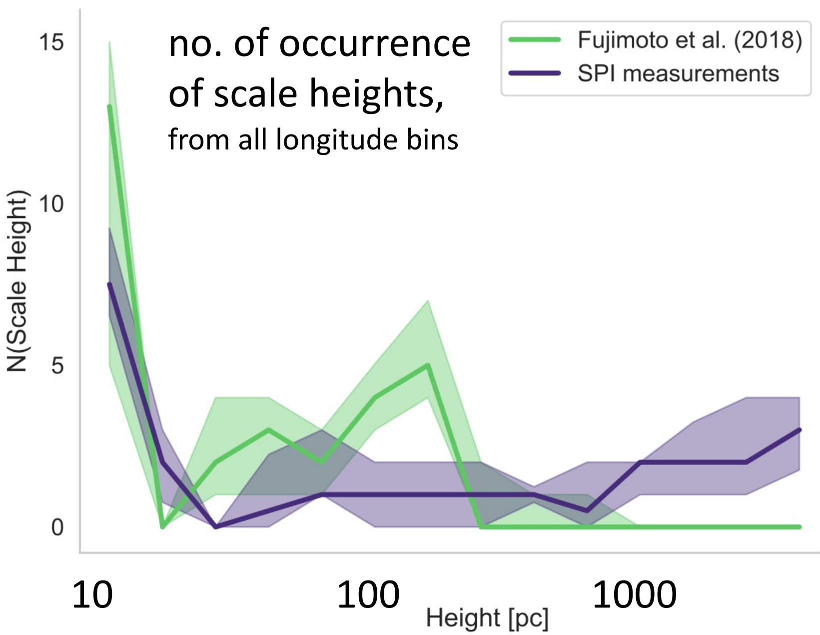
Comparing Observations with Simulations

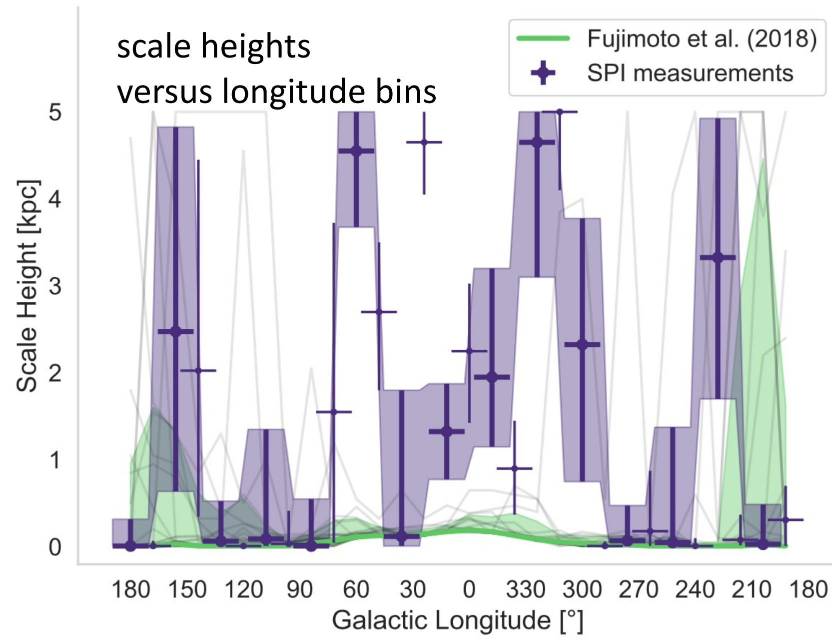
Pleintinger+ 2019

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

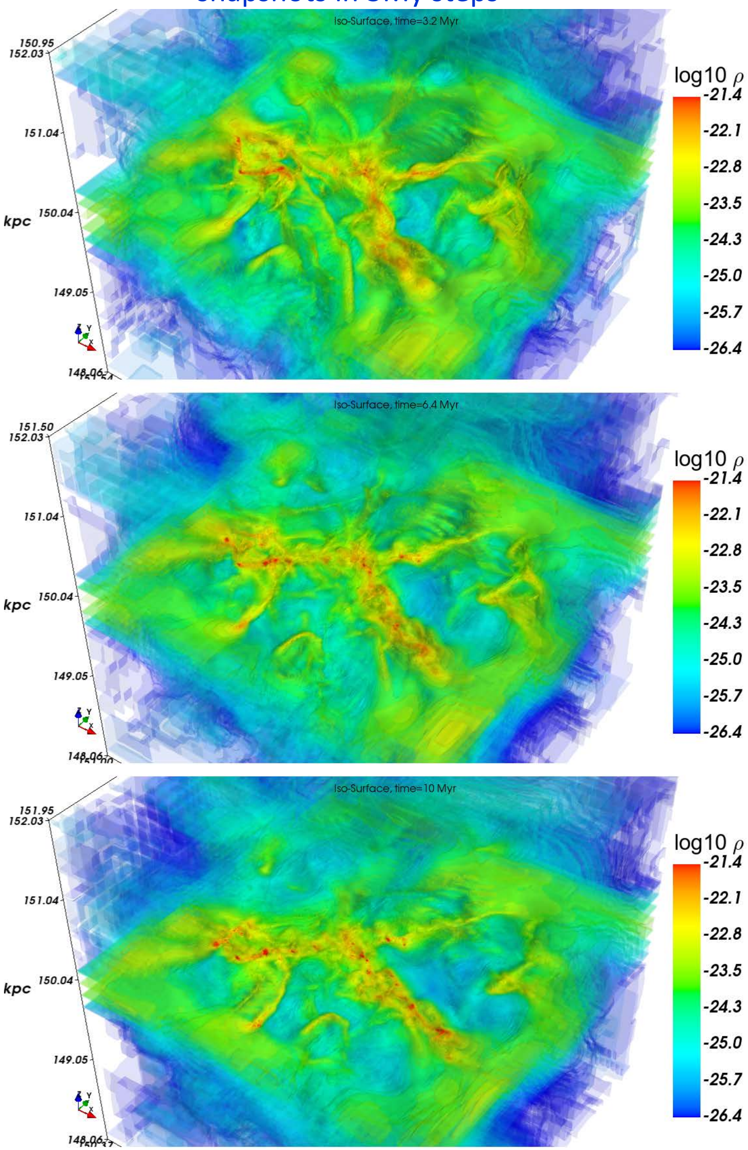




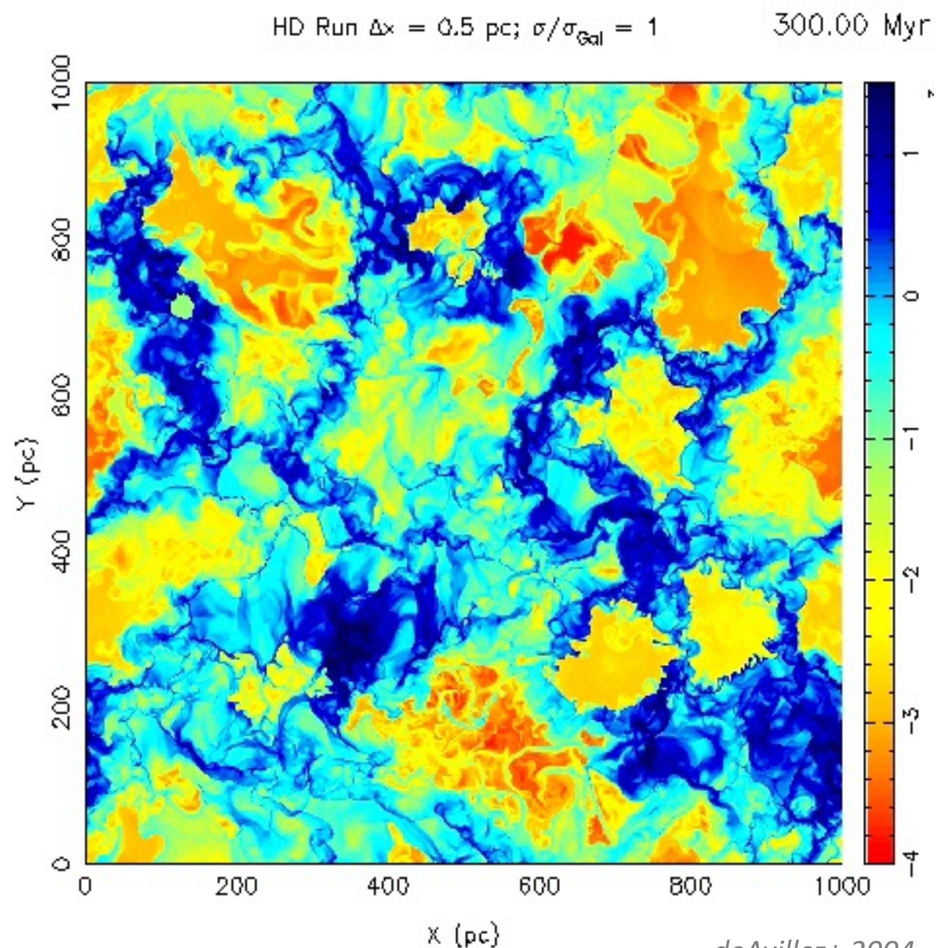
→ differences are significant: larger 'chimneys' (SBs) in observations

Superbubbles in the dynamic interstellar medium: Simulations

snapshots in 3My steps



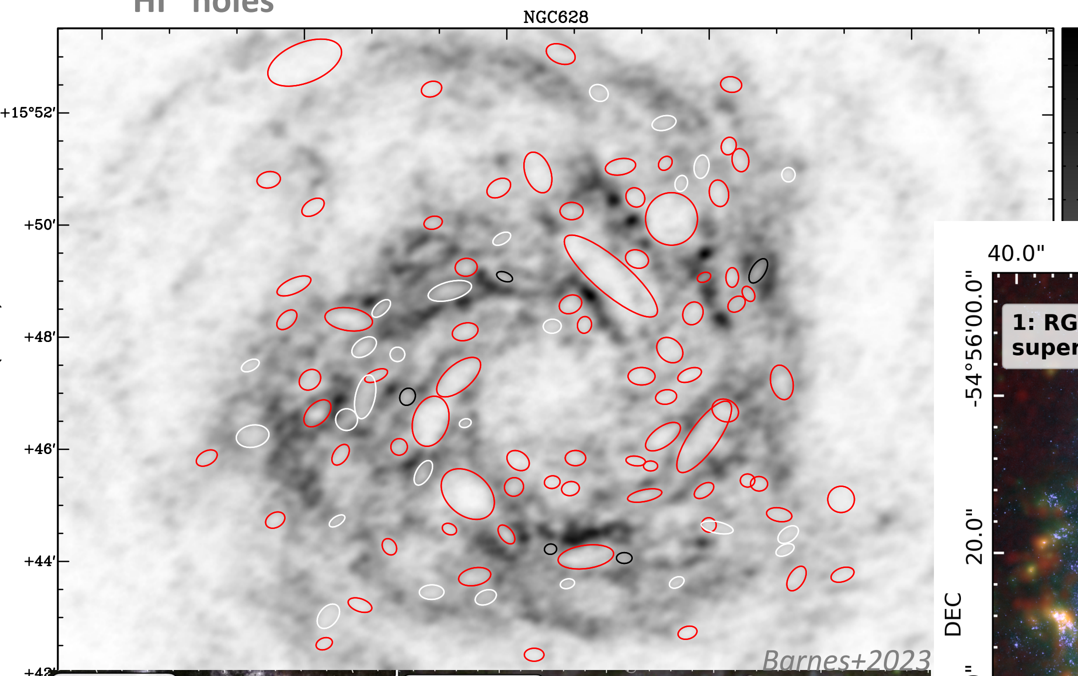
Pudritz+ 2024



deAvillez+ 2004

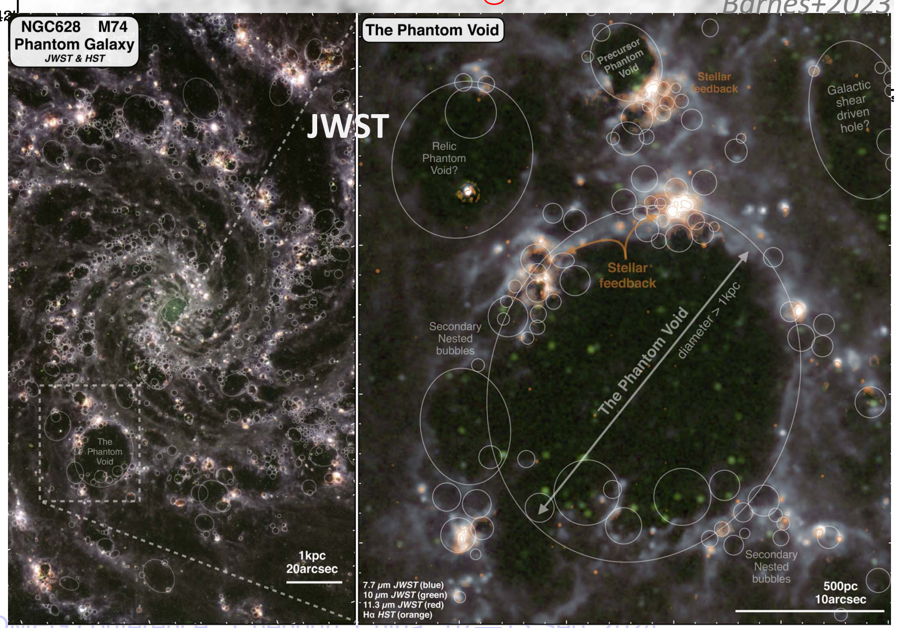
Superbubbles observed in other galaxies

HI 'holes'



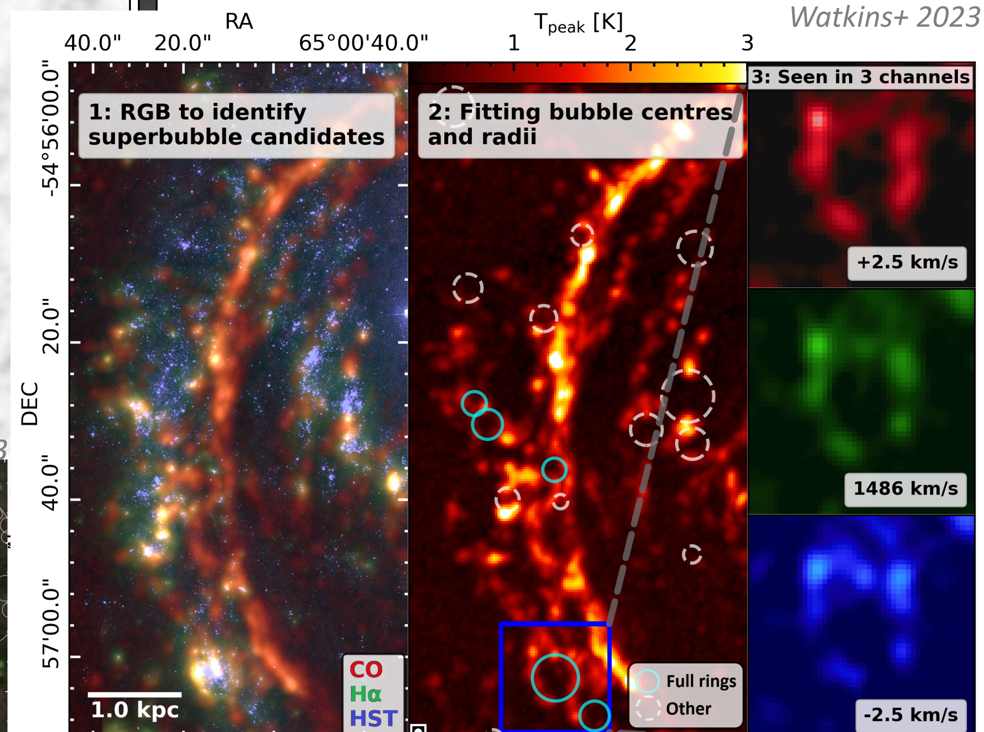
Bagetakos+ 2011

Barnes+2023



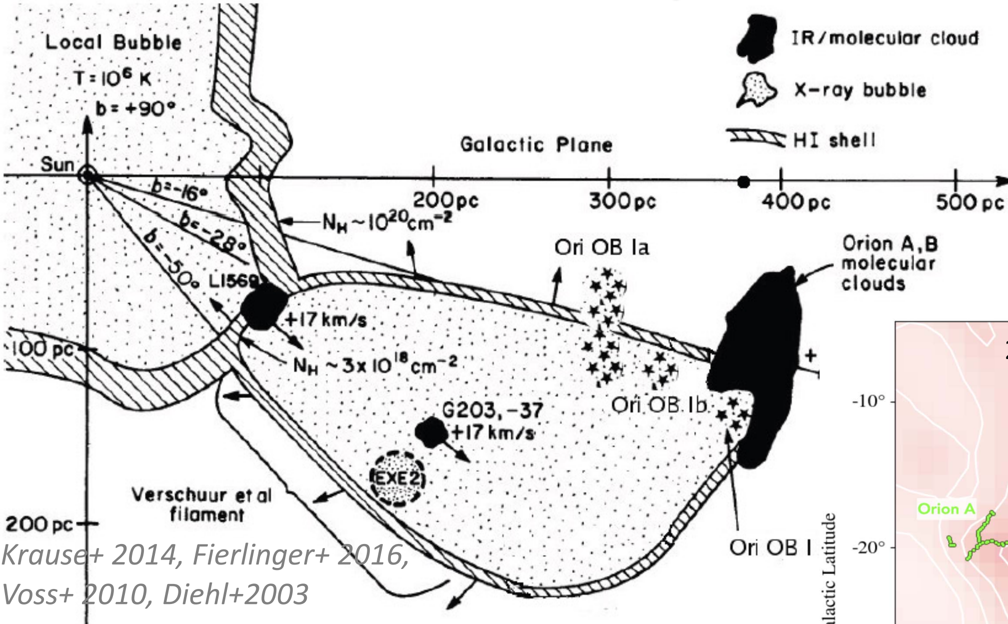
PHANGS

Watkins+ 2023

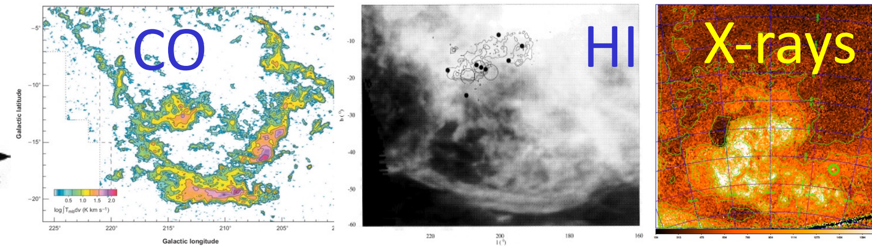


- all SF-galaxies show such large cavities (superbubbles)

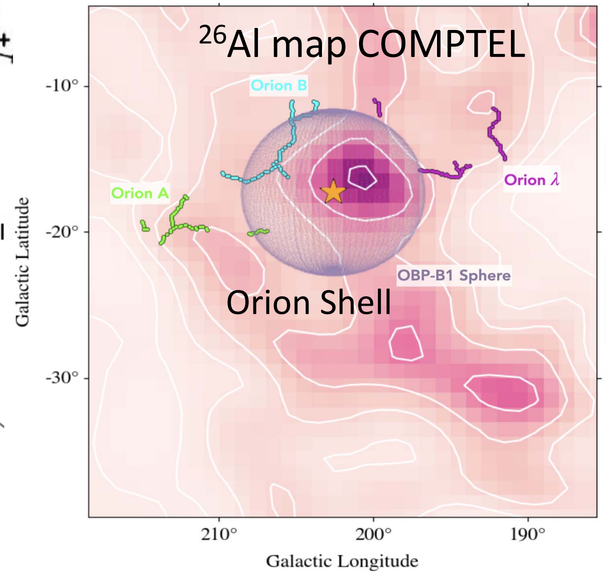
Orion-Eridanus: A superbubble blown by stars & supernovae



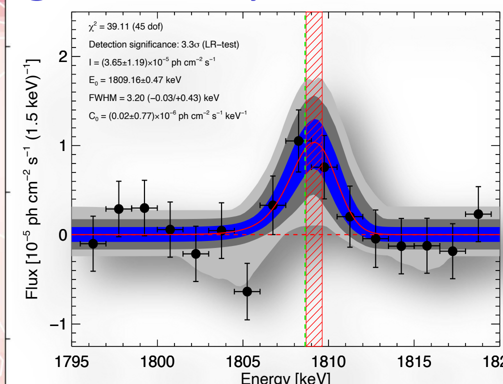
Krause+ 2014, Fierlinger+ 2016, Voss+ 2010, Diehl+2003

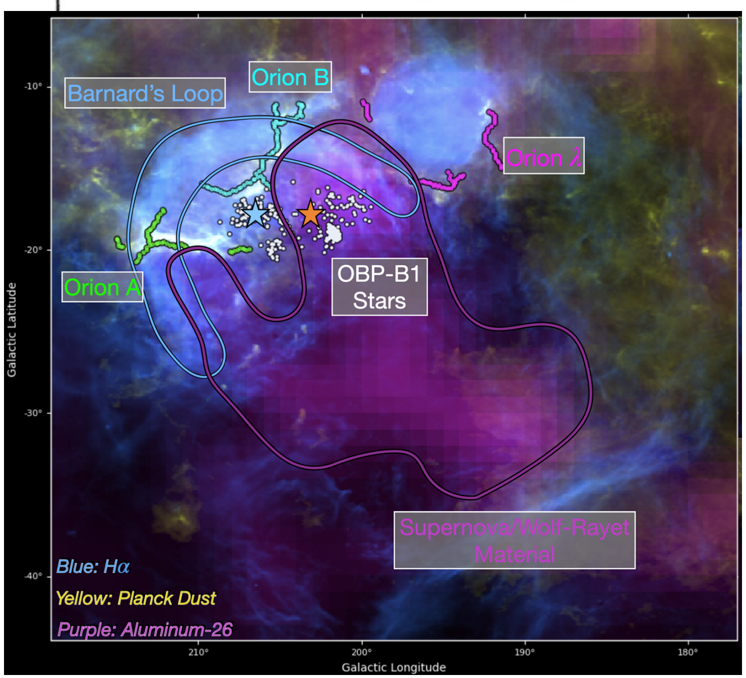


Diehl+2002; Foley+2023



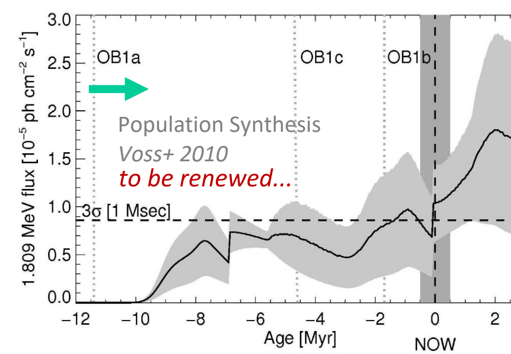
gamma-rays





Foley+2023

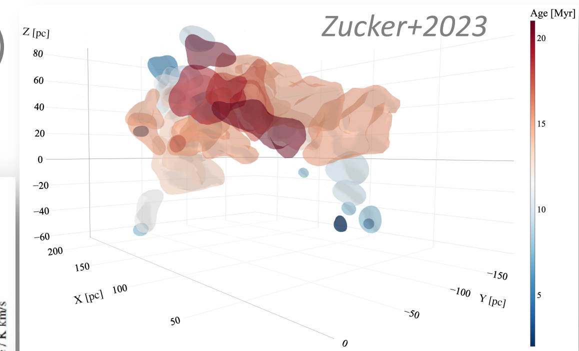
Shells driven by stars & SNe
→ Ejecta kinematics in a (super-)bubble



Stellar feedback in the nearerst massive-star region (Sco-Cen)

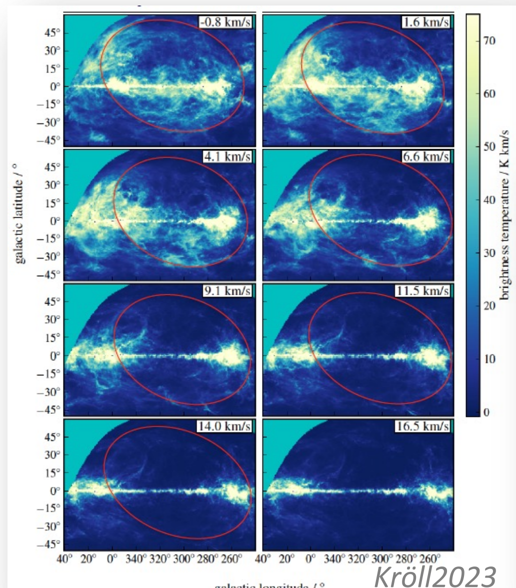
The stellar groups and population known (kinematics)

no clear coeval subgroups, SF ongoing for ~15+ My; distance~140pc)



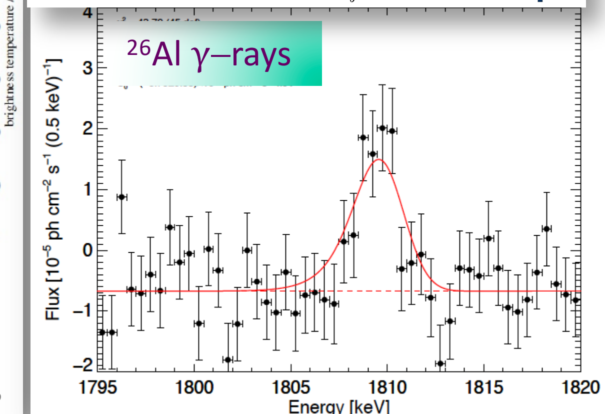
The interstellar medium holds a network of cavities

ISM dynamics is not easy to unravel



^{26}Al (t~1My) is detected (distributed)

→ can we measure the flow?



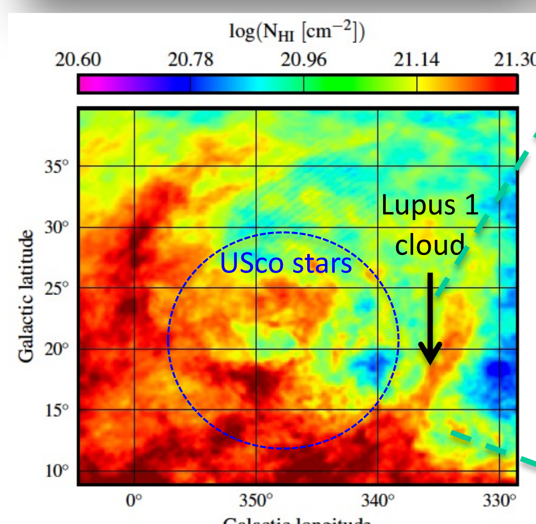
Star formation is seen (Lupus)

→ colliding shell boundaries

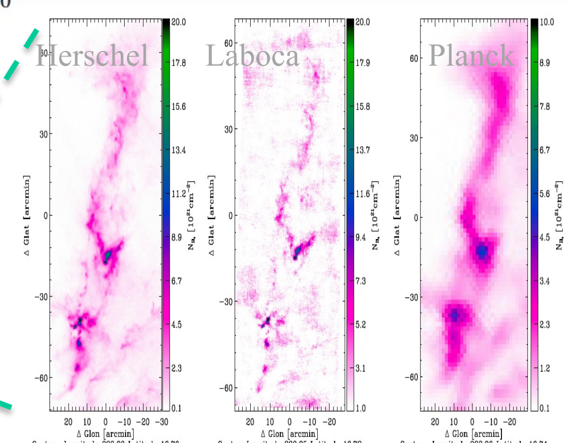
→ *"surround & squish"*

rather than "triggered" star formation

Krause+2018



Gaczkowski+2016; Roccatagliata+ 2017

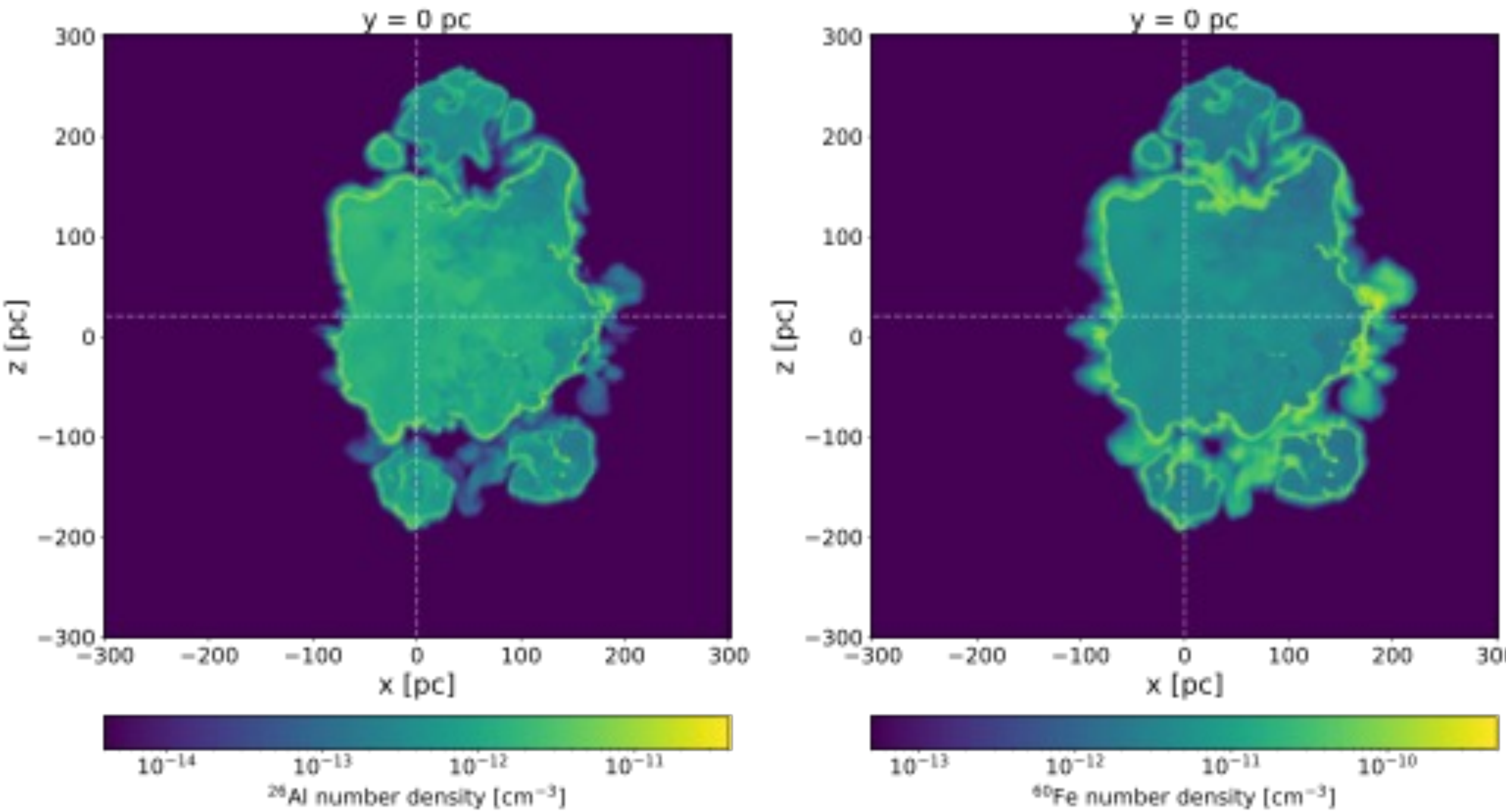


^{26}Al and ^{60}Fe in the Local Bubble

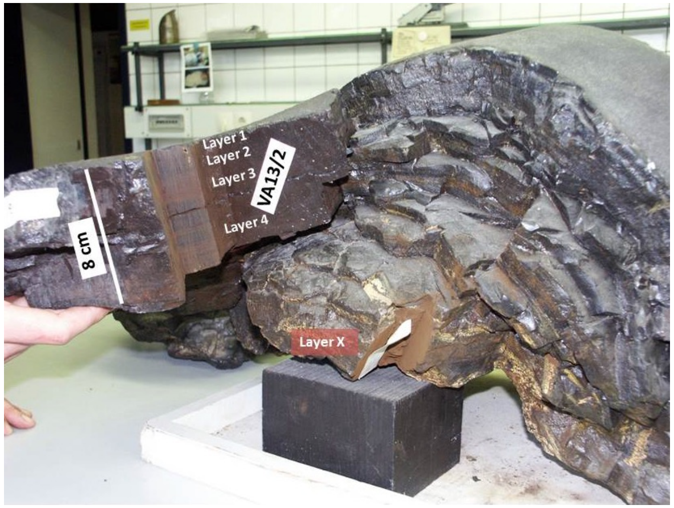
3D hydro simulations of Local Bubble evolution

^{26}Al predominantly in hot bubble interiors, ^{60}Fe deposition at bubble walls

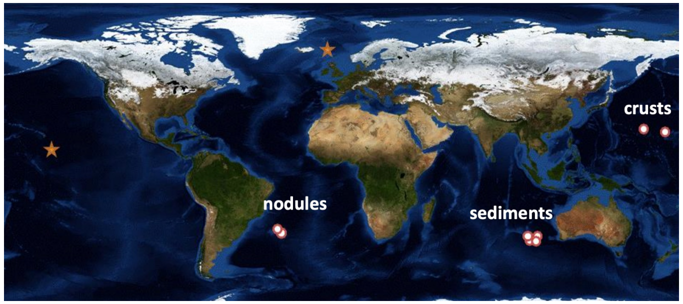
Siegert, Schulreich+,2024



^{60}Fe and ^{244}Pu from nearby nucleosynthesis found on Earth

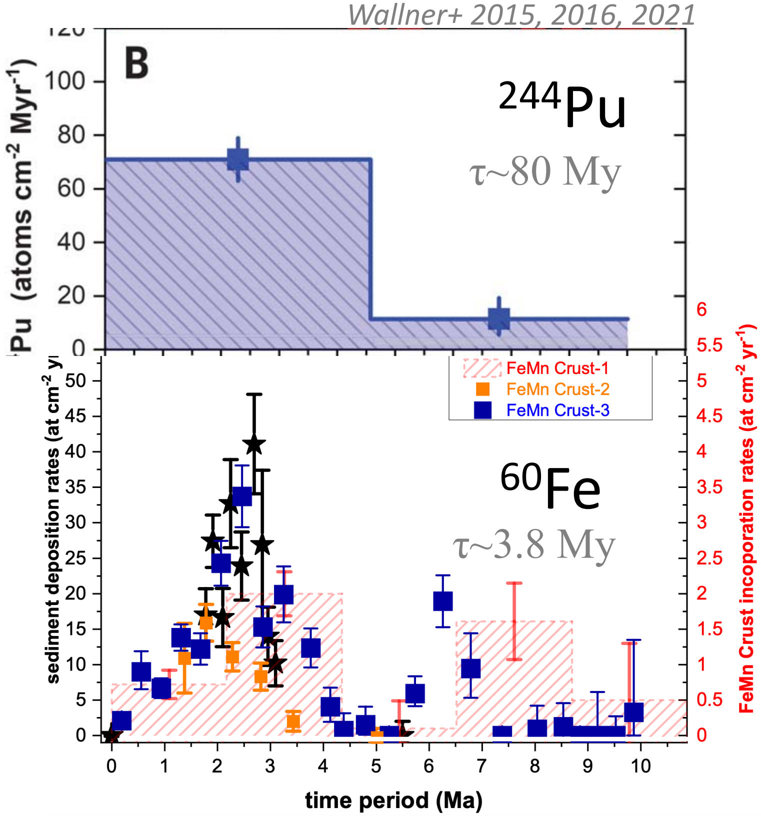


Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ...



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021

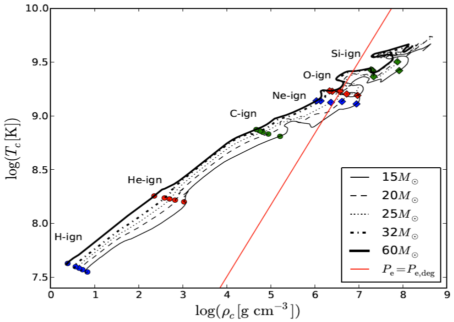


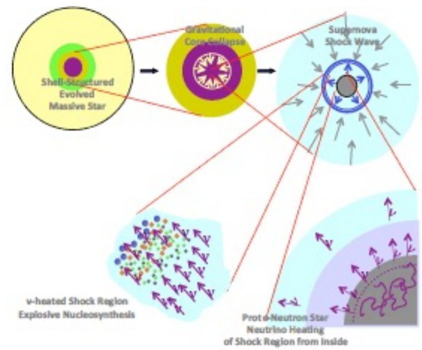
peak of radioactivity influx
≈3 & 6-8 My ago!

What are its sources?

How did these traces of nucleosynthesis get here?

➔Different environments for nucleosynthesis ejecta

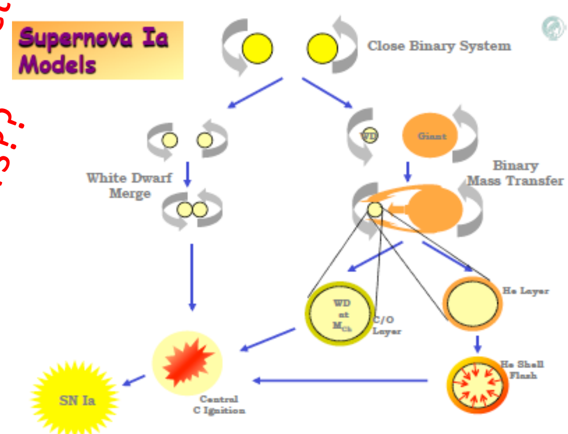




☆Massive stars and ccSNe

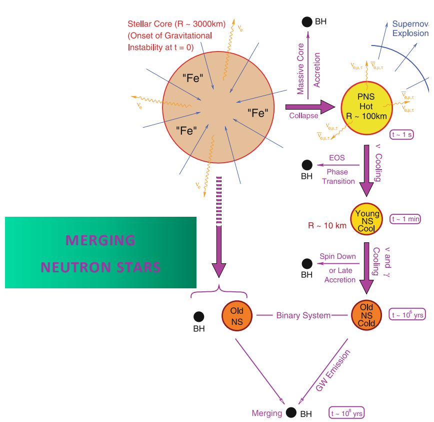
- ☞ typical $t_{evolution}$ ~ 1-100 My
- ☞ molecular-cloud and superbubble environment

how are nucleosynthesis ejecta incorporated into stars??



☆Supernovae type Ia

- ☞ typical $t_{evolution}$ ~ 0.x-1 Gy
- ☞ outside star forming regions

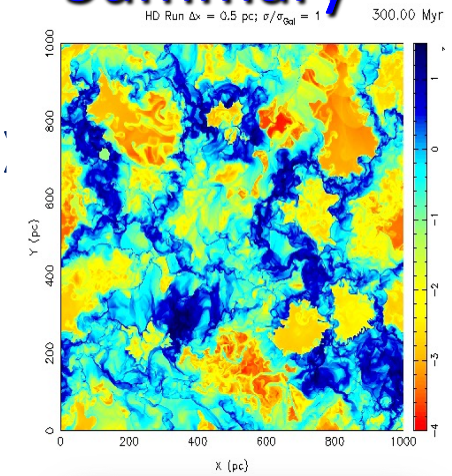


☆Compact-binary mergers

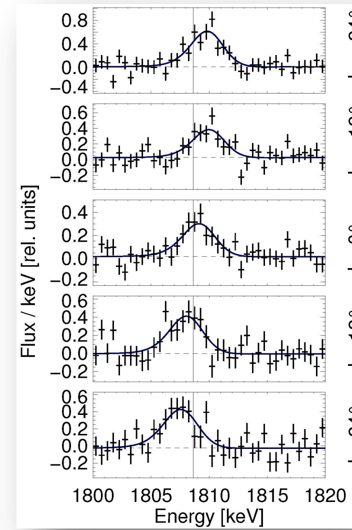
- ☞ typical $t_{evolution}$ ~ 1-x Gy
- ☞ away from galactic disk

☆*Note: ISM is mixed by SNe!*

Galactic Dynamics and Nucleosynthesis Ejecta - **Summary**



- ☆ Cycling of cosmic gas through sources and ISM is a challenge
  - ☞ Source afterglows reach aut to ~years (SNe) or few 10,000 y (SNR)
  - ☞ ^{26}Al is a new useful tracer with radioactive lifetime Myrs



- ☆ ^{26}Al gamma-ray spectroscopy shows new aspects
  - ☞ ^{26}Al preferentially appears in superbubbles
    → massive-star ejecta are rarely due to single WR stars or SNe
  - ☞ several massive-star groups are consistent with this view
  - ☞ the local cavities around the Sun reflect the Sco-Cen group and its activities
  - ☞ bottom-up modelling suggests ^{26}Al γ rays from large sky area (~Sco-Cen history)
  - ☞ ^{60}Fe is a second radio-isotope for such study seen in γ rays, found on Earth from nearby nucleosynthesis