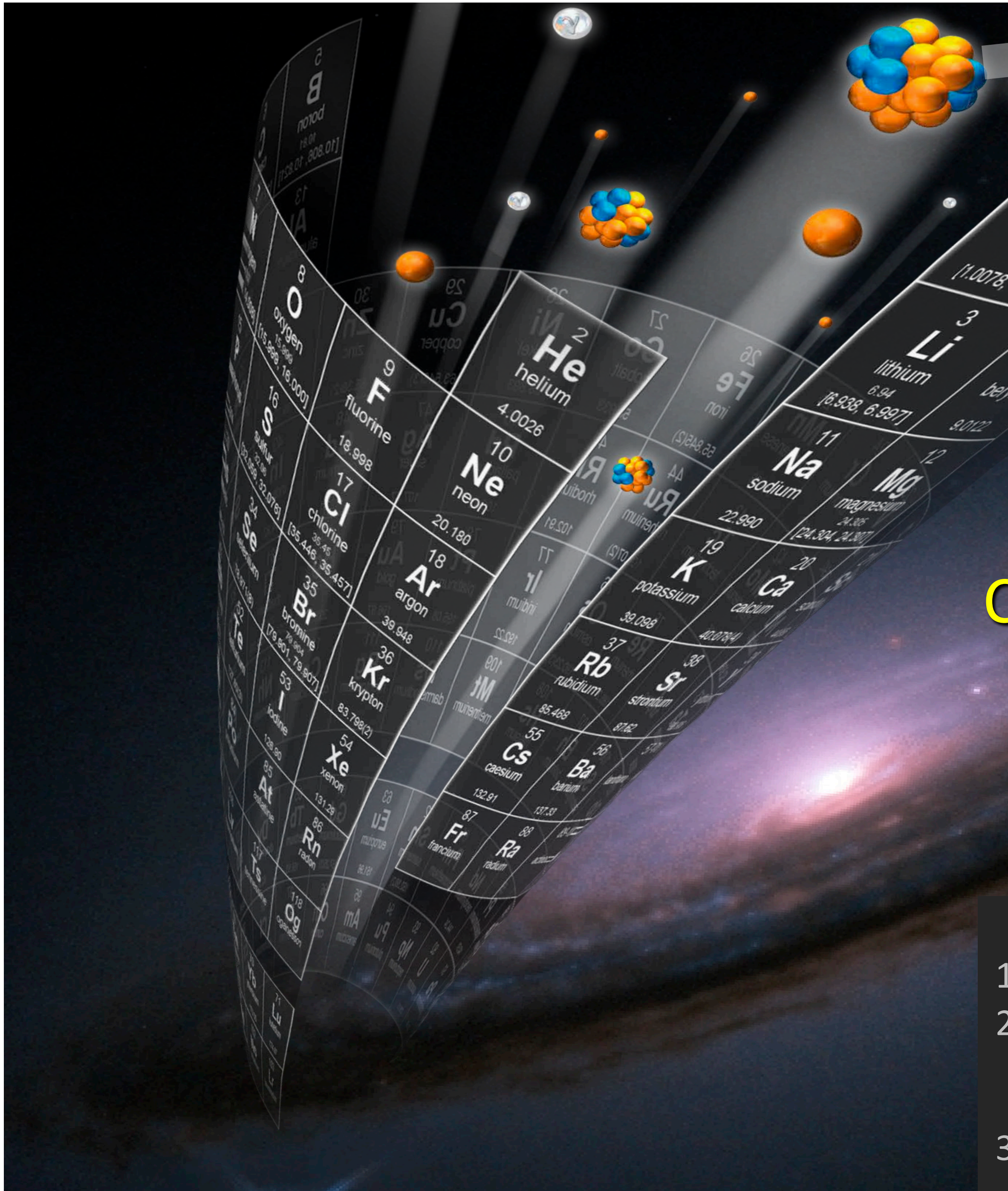
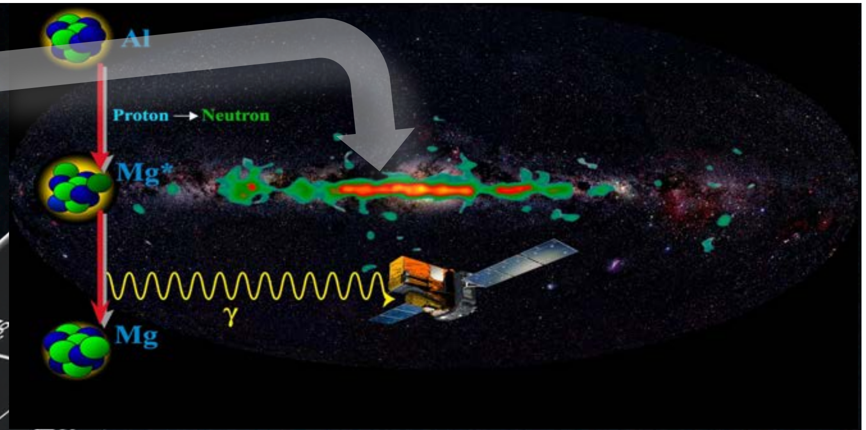




Tracing the Ejecta from Cosmic Nucleosynthesis

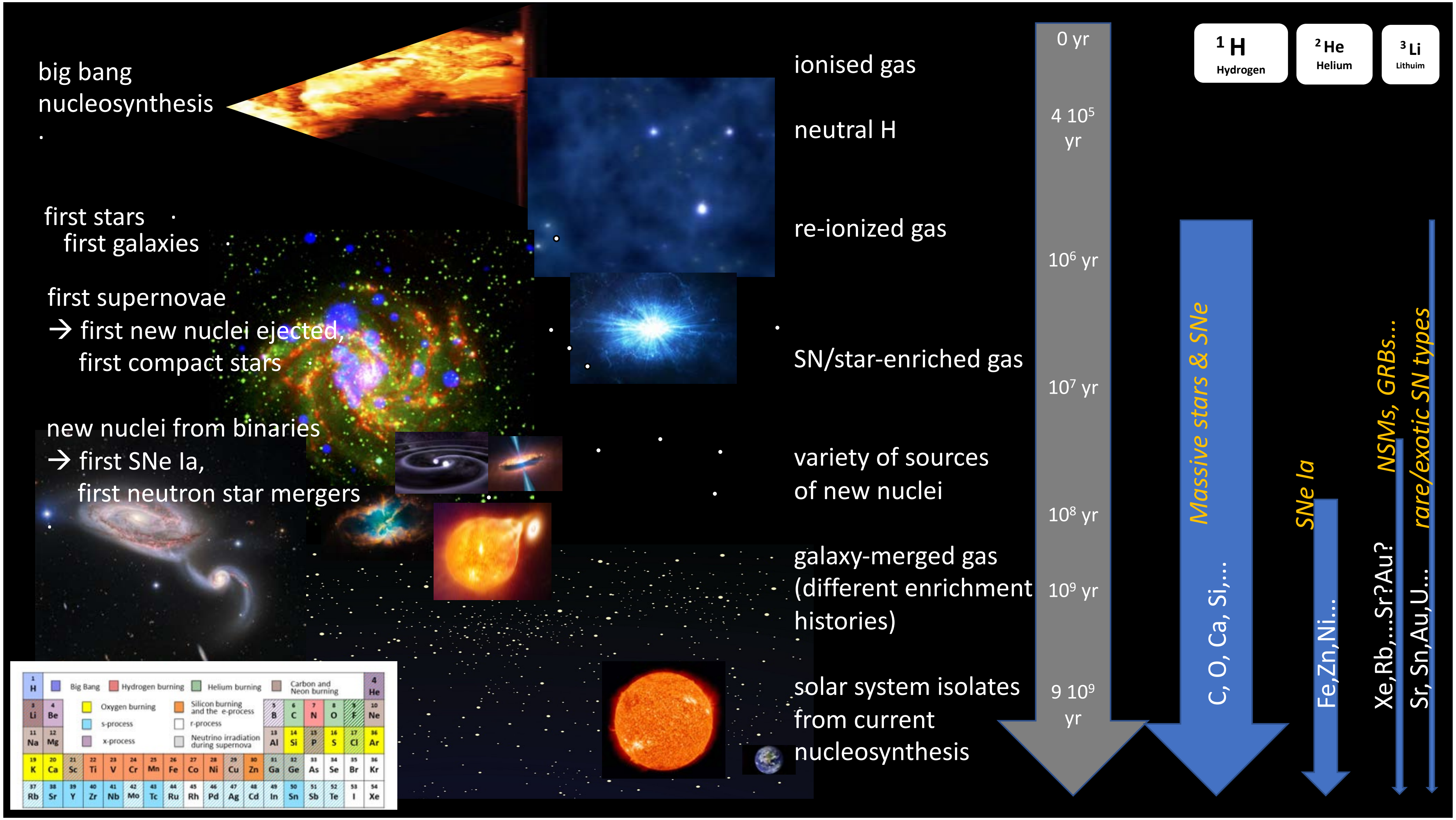
Roland Diehl
Technical University München and
MPE and Origins Cluster emeritus
Garching

Contents:

Figure: ChETEC 2021

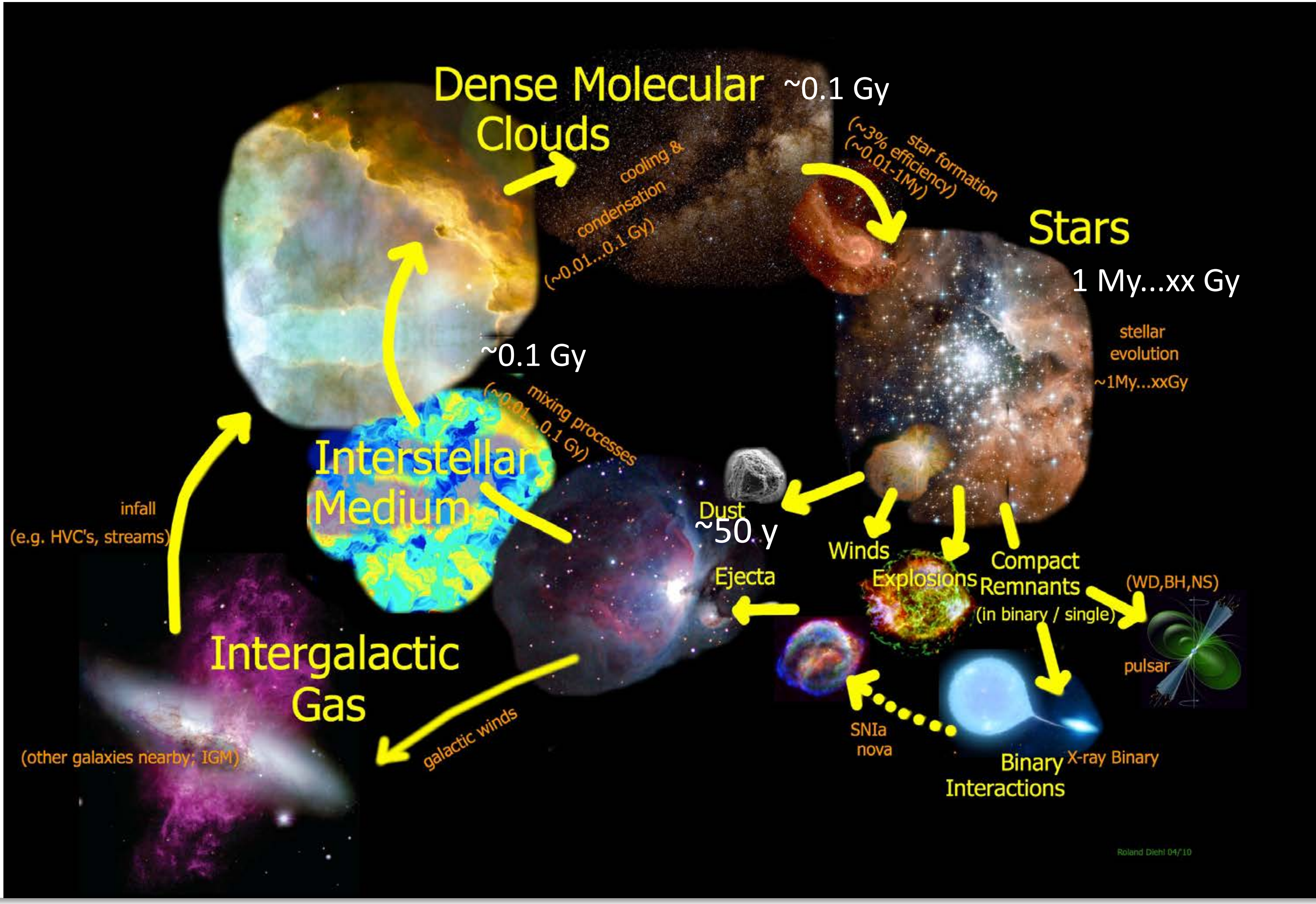
with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

The composition of cosmic matter evolves over time

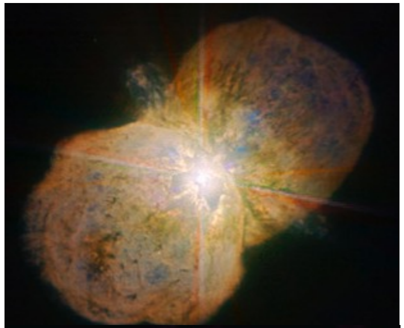


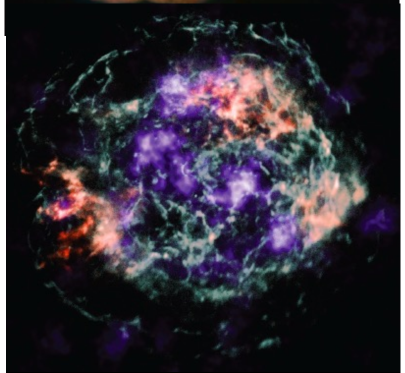
... a coarse picture of cosmic nucleosynthesis.

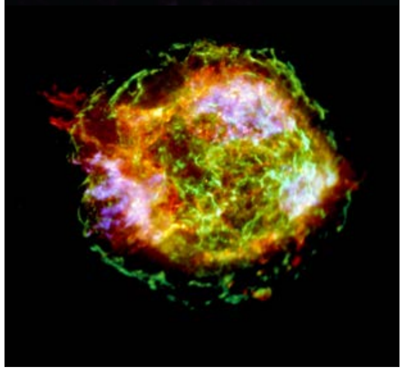
On-going Enrichments from Nucleosynthesis Sources

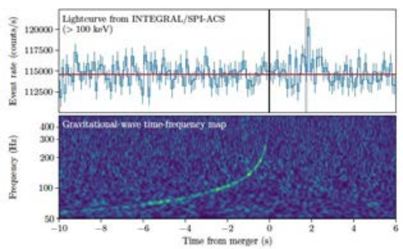


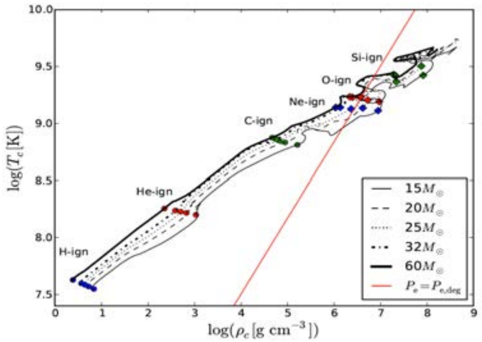
Cosmic nucleosynthesis sources

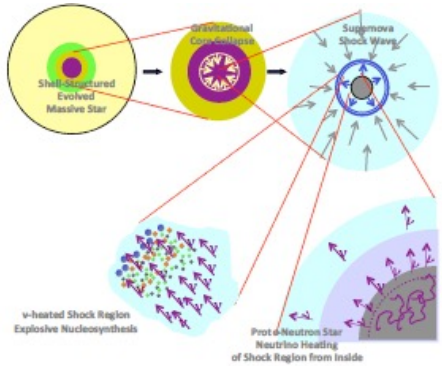


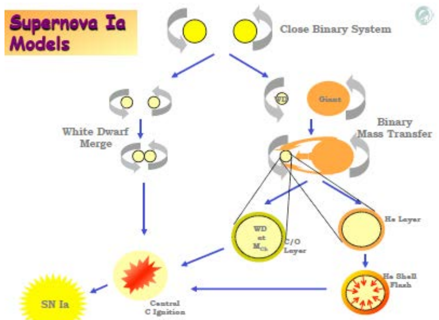




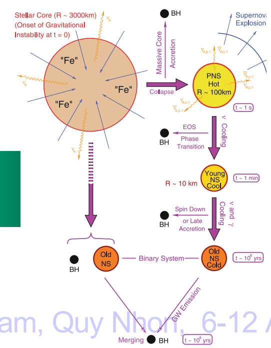








MERGING NEUTRON STARS



○ Nuclear fusion reactions power all stars

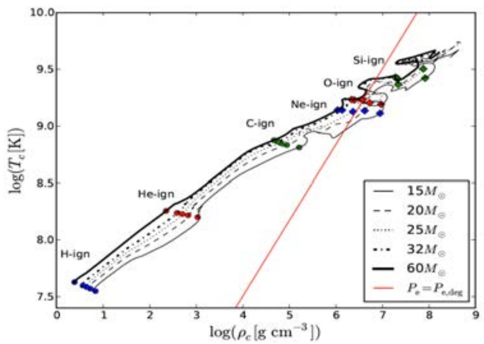
○ Many stars explode as a supernova at the end of their evolution

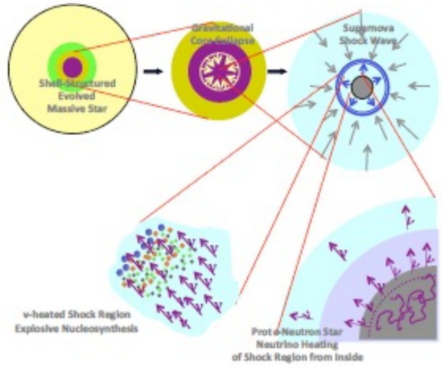
○ Some binary systems including white dwarf stellar remnants explode as a supernova

○ Some binary systems including neutron stars eventually merge to form a black hole

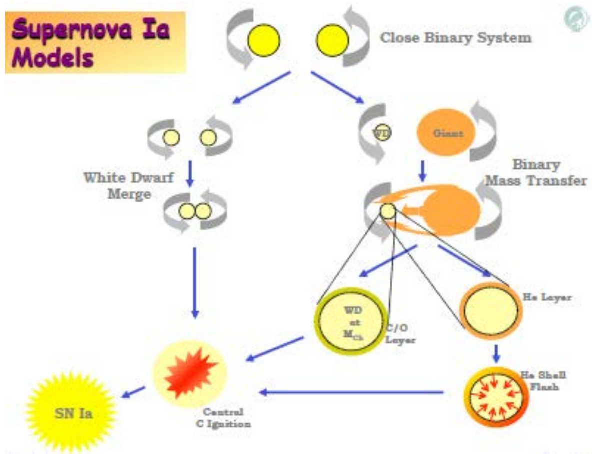
➢ How many new nuclei in ejecta??

Environments for nucleosynthesis ejecta

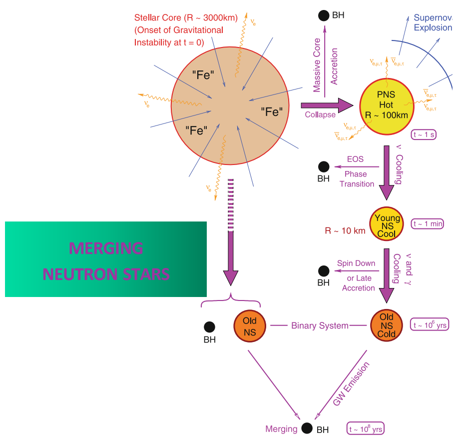




- ☆ Massive stars and ccSNe
  - ☞ typical $t_{evolution}$ ~ 1-100 My
  - ☞ molecular-cloud and superbubble environment

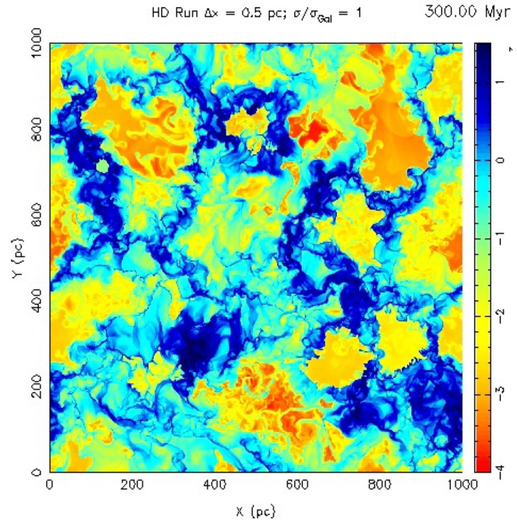


- ☆ Supernovae type Ia
  - ☞ typical $t_{evolution}$ ~ 0.x-1 Gy
  - ☞ outside star forming regions



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

Modeling stellar feedback (1)



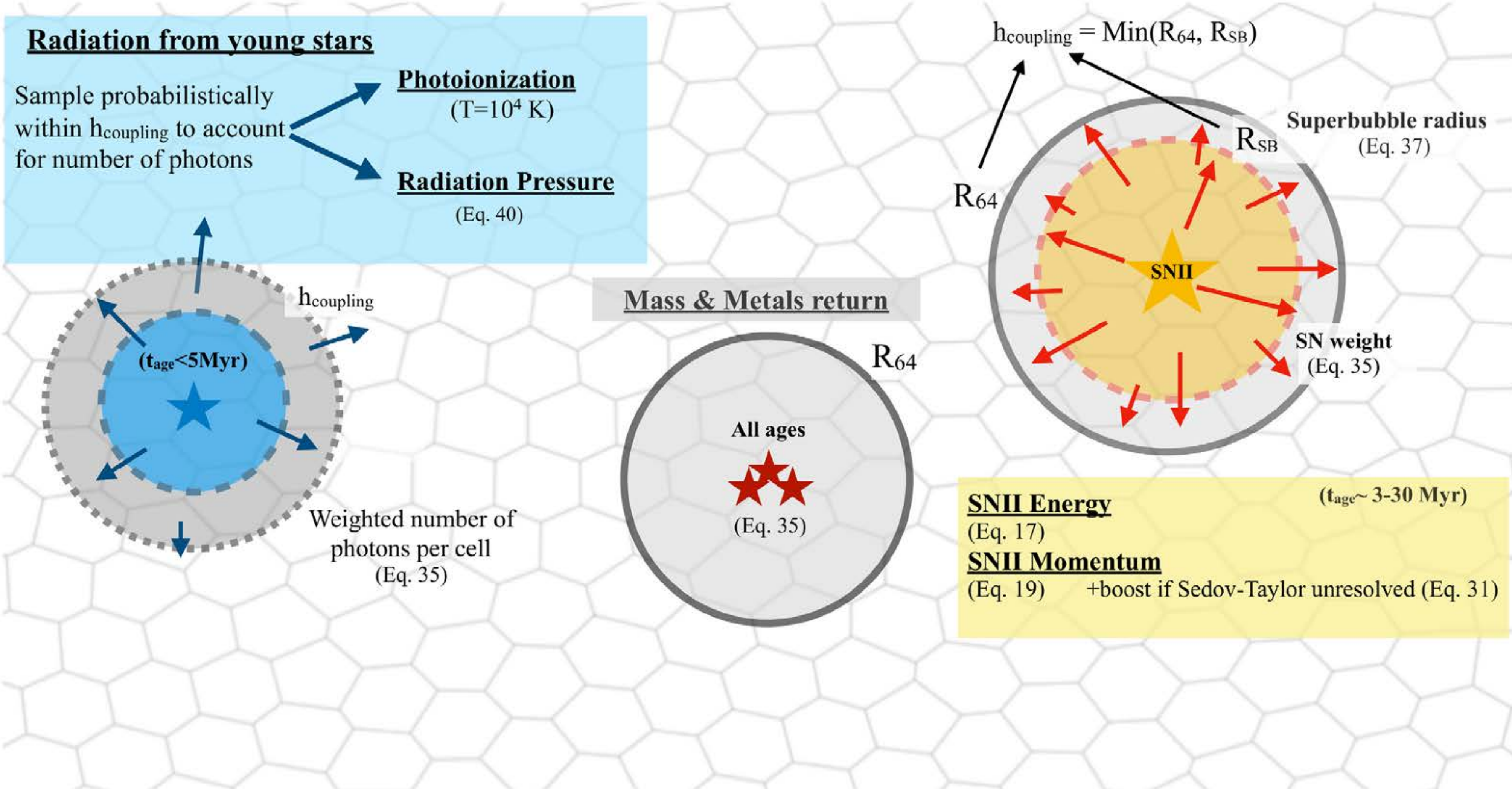
- The ISM plasma is highly complex
  - ☆ large reservoir of internal energy (ionization states, coupling to mag field & CRs)
  - ☆ shocks imply non-equilibrium physics, i.e. detailed solution of MHD equations
  - ☆ microscopic physics is coupled to large dimensions through plasma waves, mag fields, CRs
  - ☆ stellar actions (radiation, wind, explosions, rate, location) from other models
- Modeling alternatives:
  - ☆ Implement physical processes in 3D MHD Eulerian grid codes *(exact)*
  - ☆ Employ SPH modelling: spatial modeling replaced by mass modelling *(efficient)*
  - ☆ Hybrid models: *(~exact; ~efficient)* SPH plus particles randomly placed and with detailed physics
- Limitations:
  - ☆ 3D MHD is computationally expensive → resolution limited
  - ☆ SPH cannot properly treat shocks and tenous hot phase
  - ☆ Hybrid models often use subgrid physics models

Breitschwerdt & deAvillez 2021

Modeling stellar feedback (2)

- Example of a hybrid code: AREPO
  Key processes of photoionization and kinetic energy injections

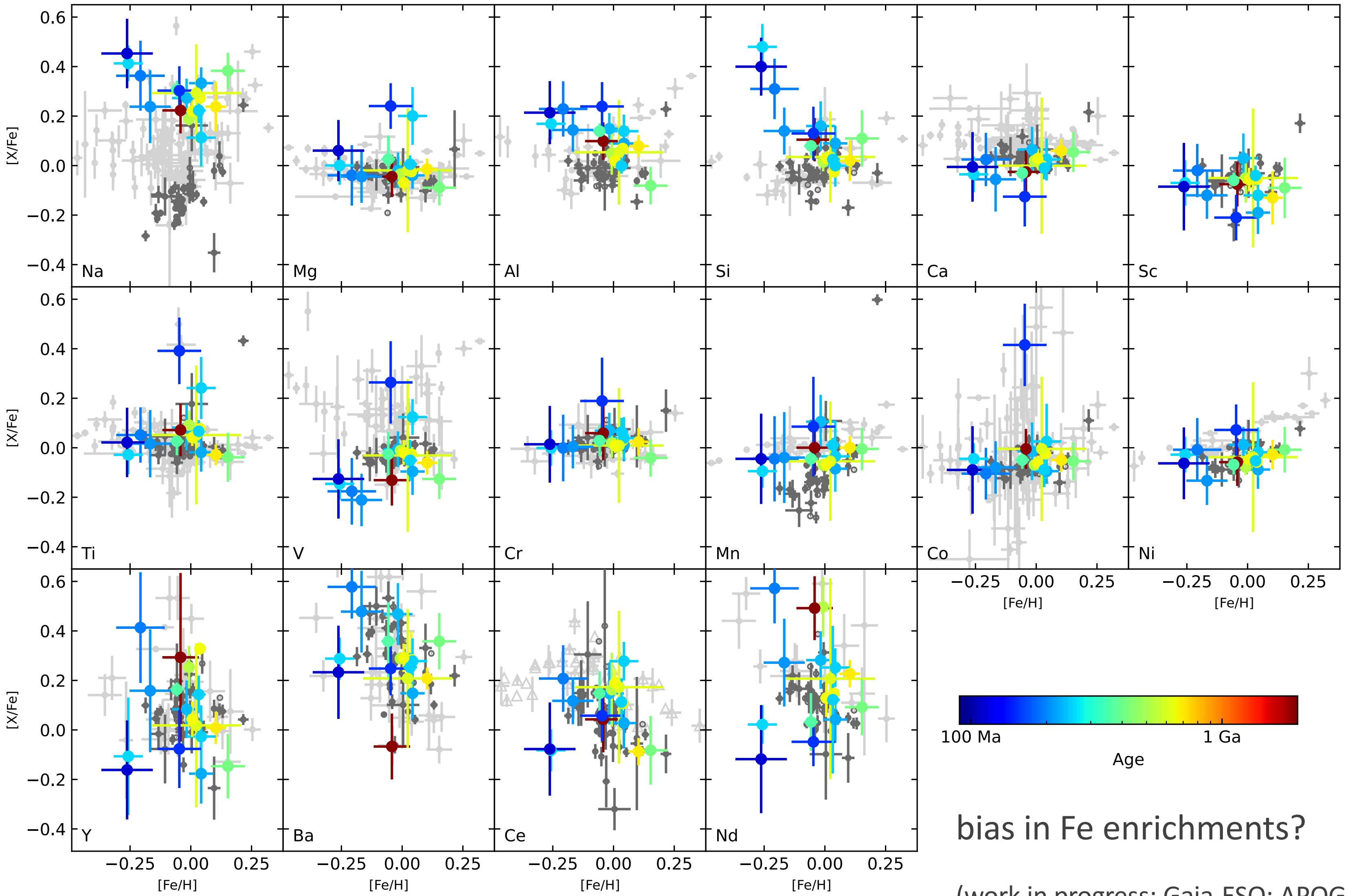
Marinacci+2019



Inhomogeneities of chemical enrichments?

- Open-cluster abundances show deviations for youngest clusters

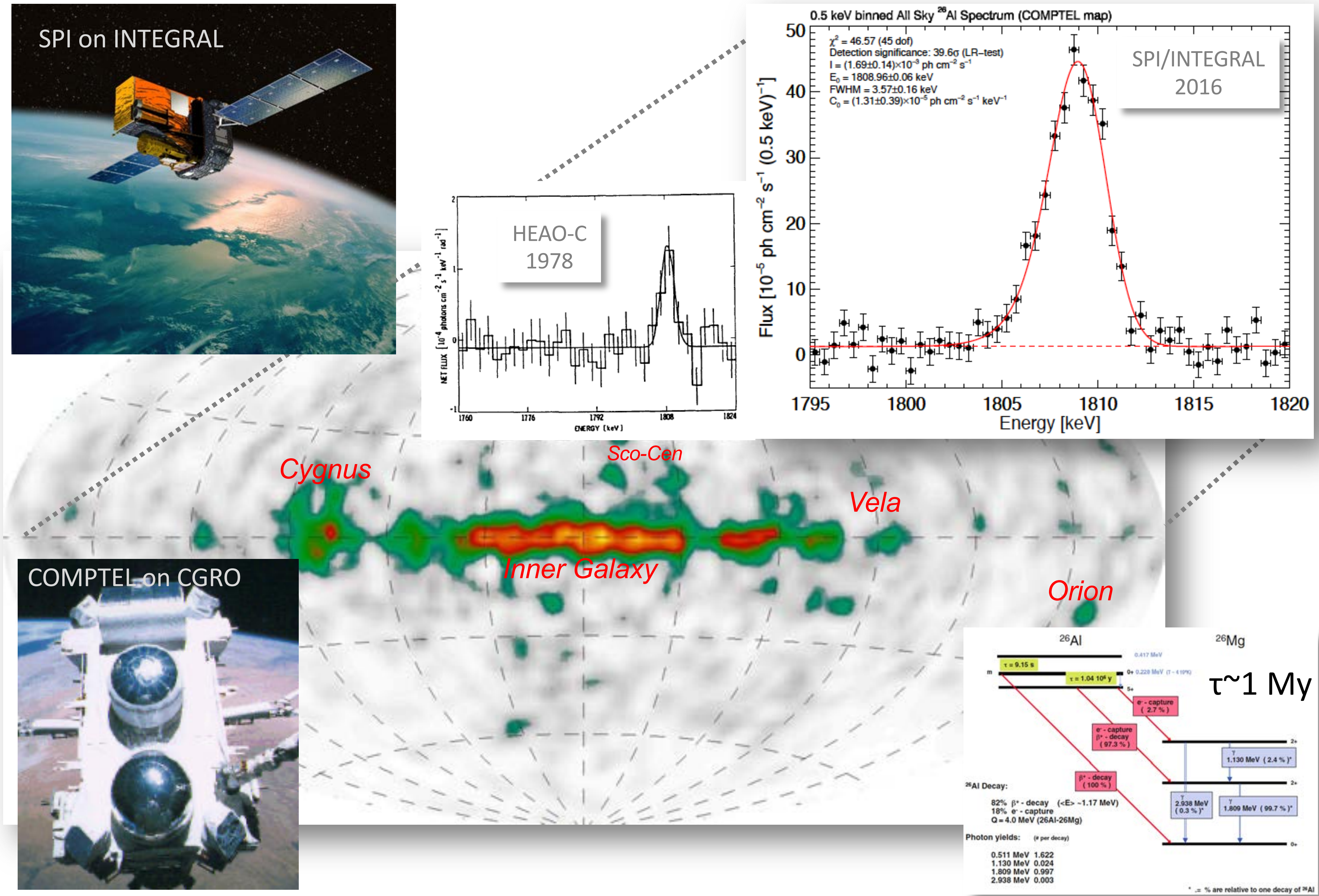
Carrera+2022



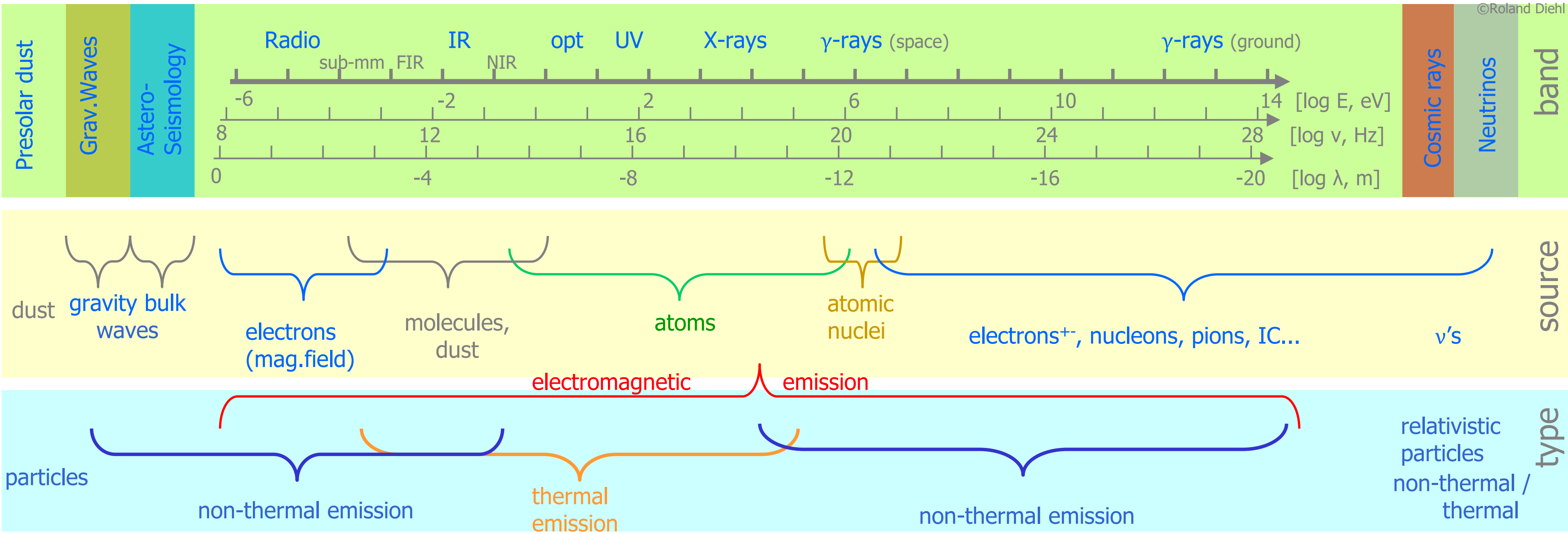
bias in Fe enrichments?

(work in progress; Gaia-ESO; APOGEE; ...)

^{26}Al γ-rays from the Galaxy



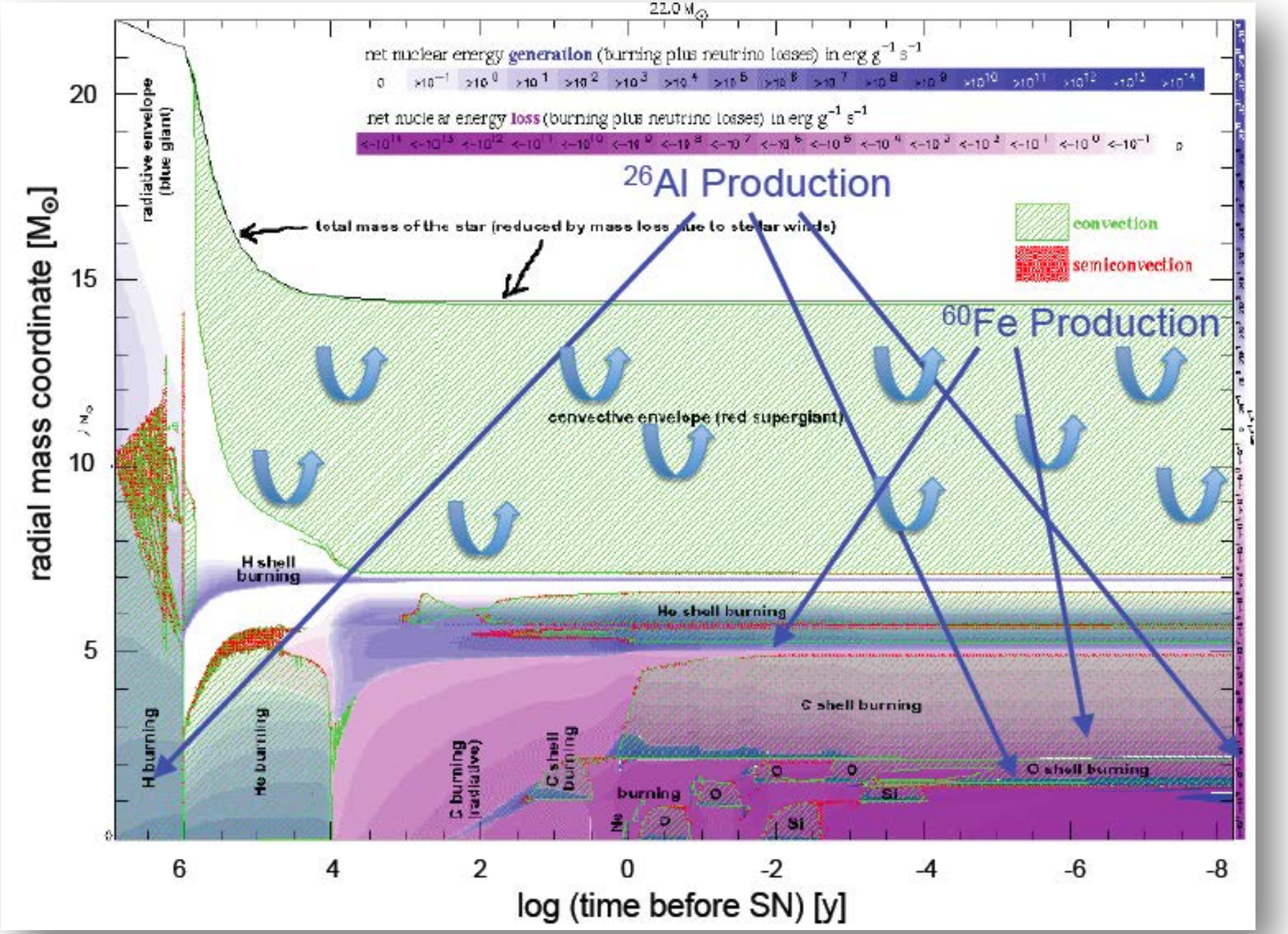
Astronomy across the cosmic messengers



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

→ Messengers from Massive-Star Interiors!

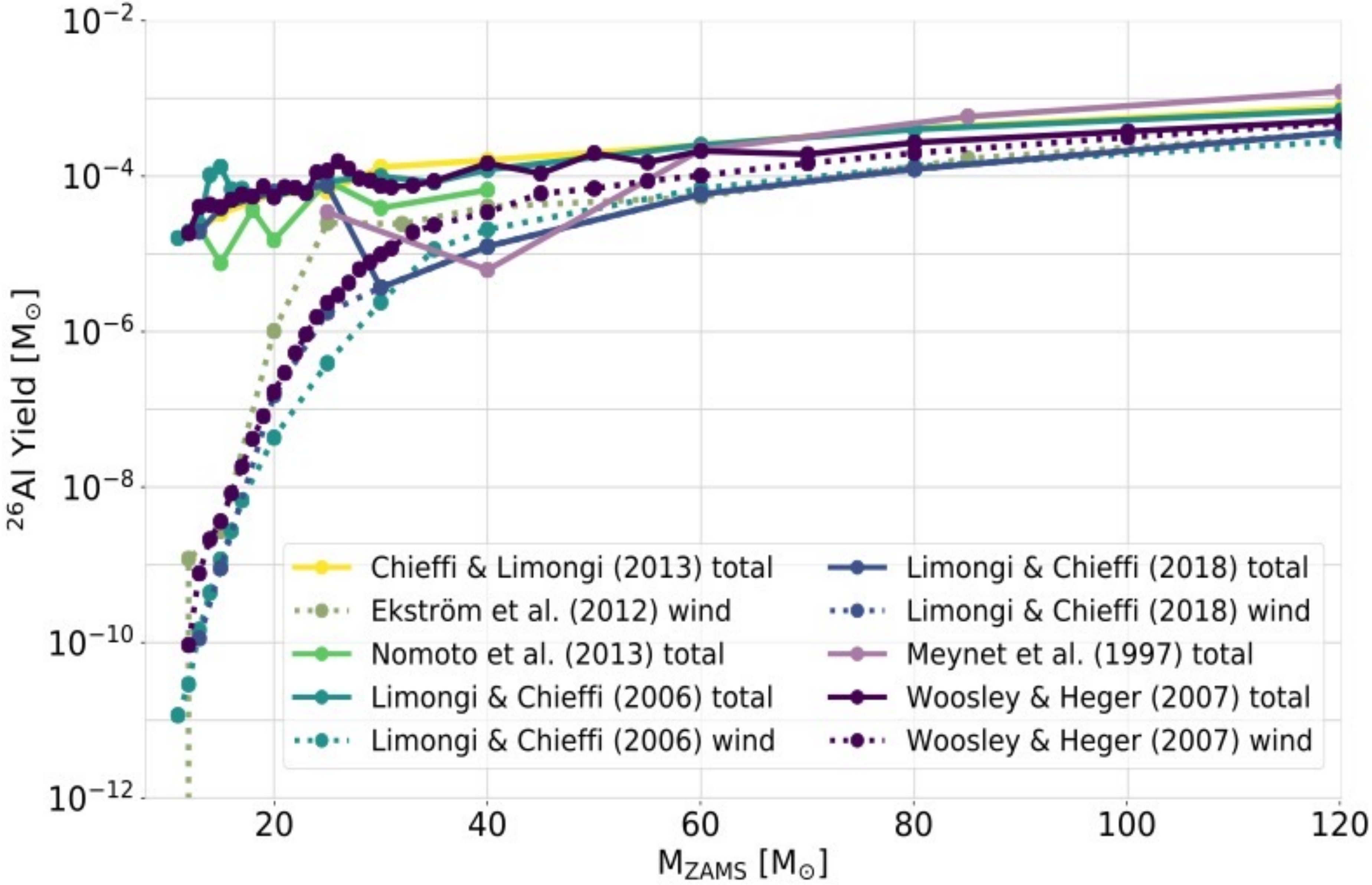
...complementing neutrinos and asteroseismology!



Processes:

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

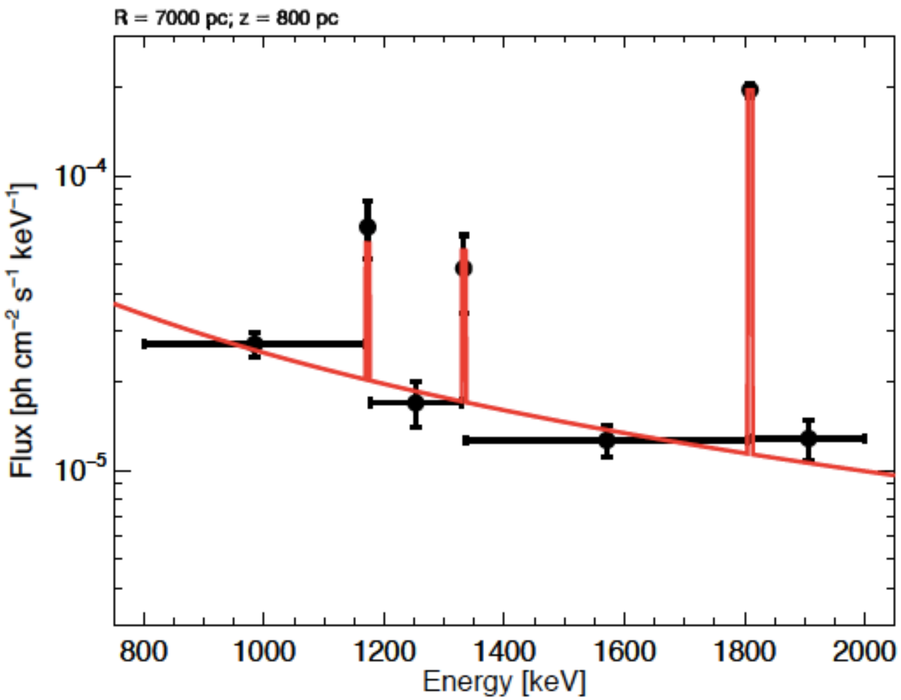
^{26}Al Yields versus mass, for massive stars and their SNe



☞ ccSNe dominate for lower-mass range,
winds dominate over explosive ejecta for more-massive stars

Diffuse gamma-ray emission from ^{60}Fe in the Galaxy

^{26}Al and ^{60}Fe analysis with same INTEGRAL dataset (15+ years) and models



^{60}Fe emission too faint for imaging etc

Variability study on ^{60}Fe/^{26}Al ratio

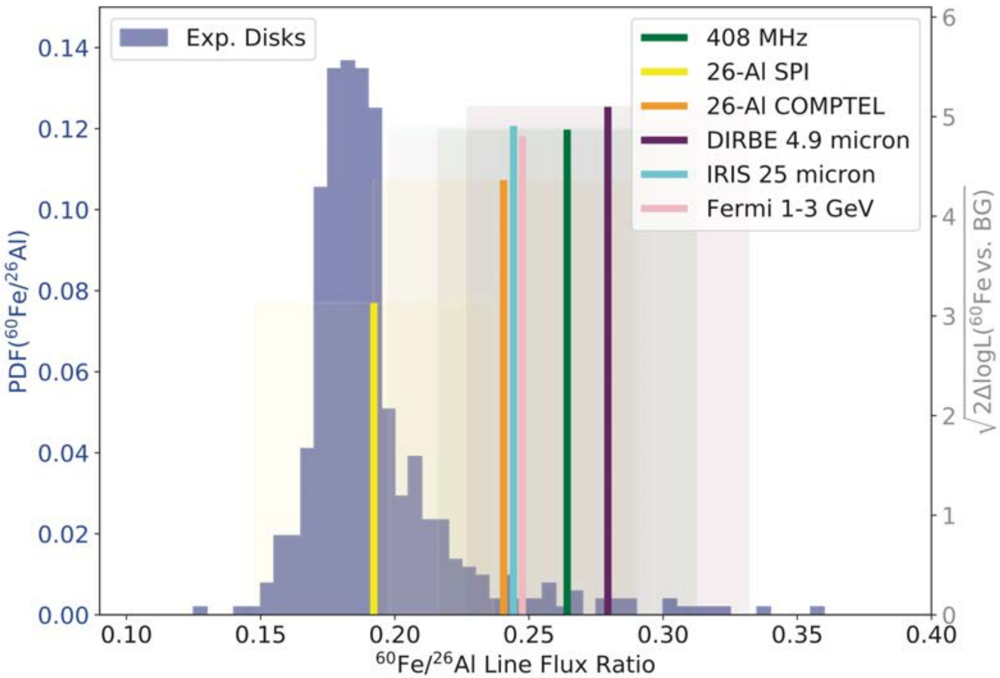
(systematics!)

➔ ^{60}Fe/^{26}Al < 0.4 in Galaxy

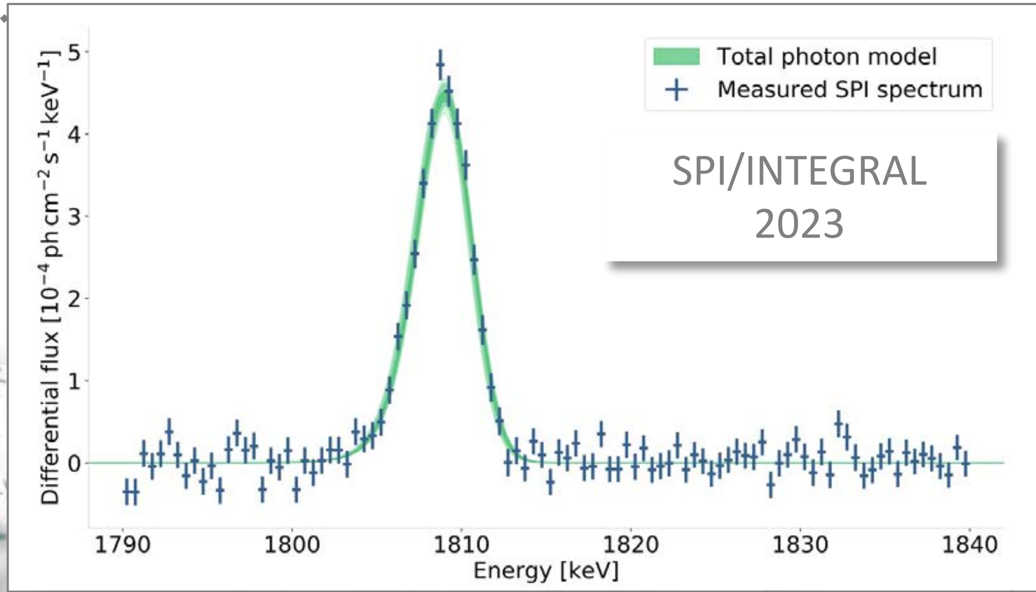
cmp theory: 0.2...1,

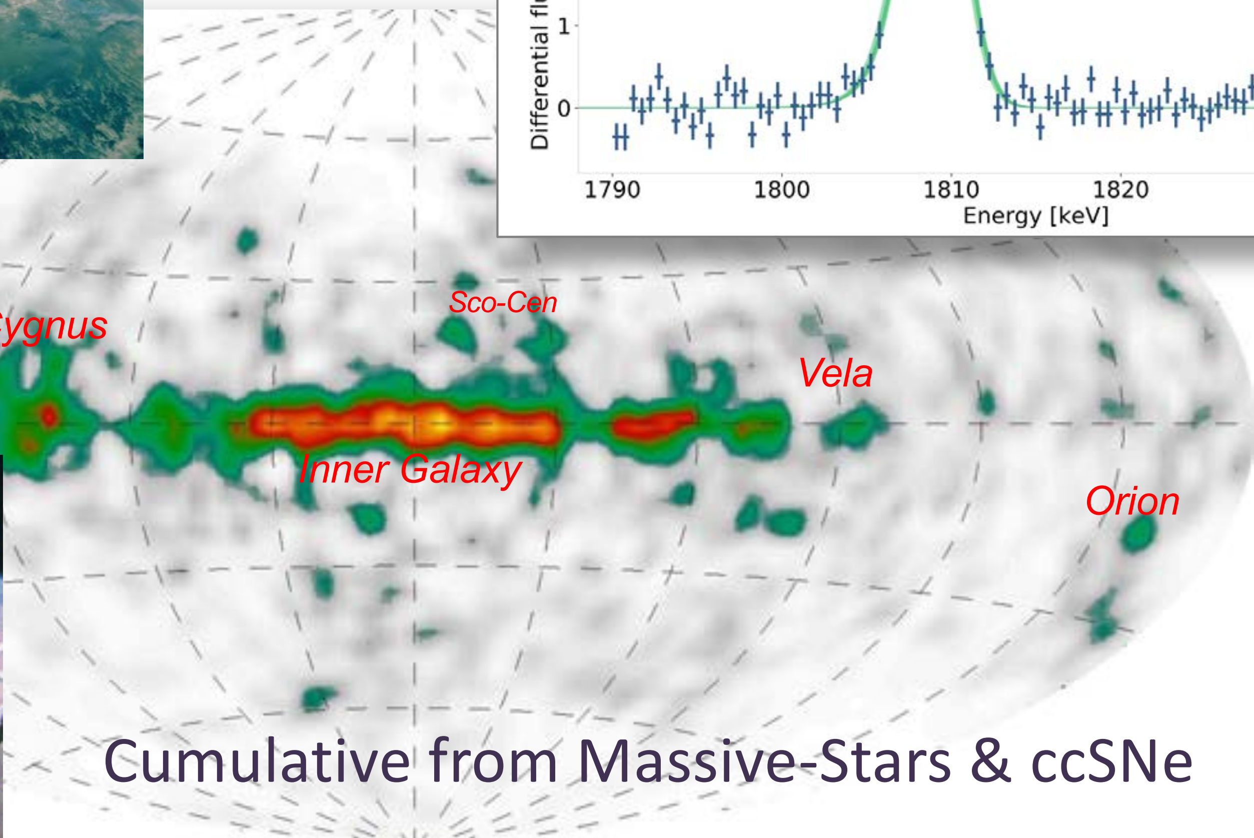
and oceancrusts: >0.2

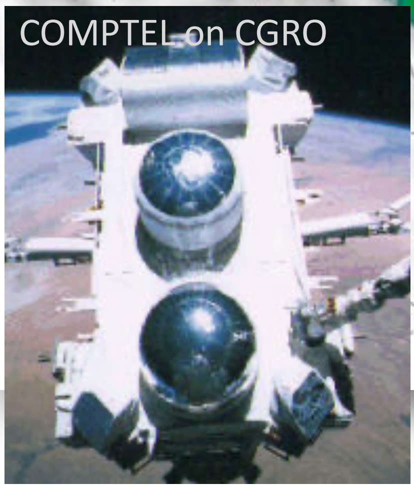
Wang+ 2020



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







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

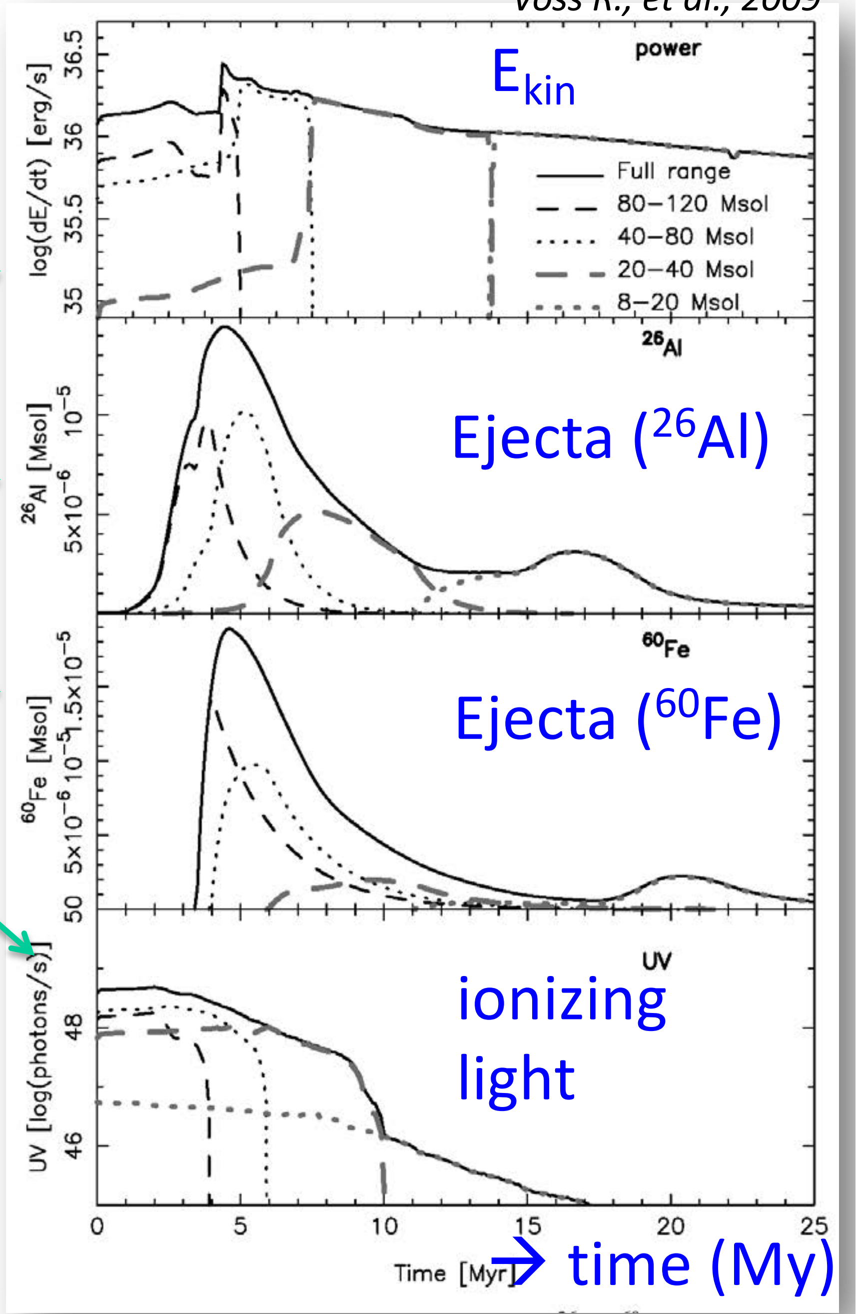
Diehl+2006;2018

Massive-Star Groups: Population Synthesis

- We model the "outputs" of massive stars and their supernovae from theory
  - 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



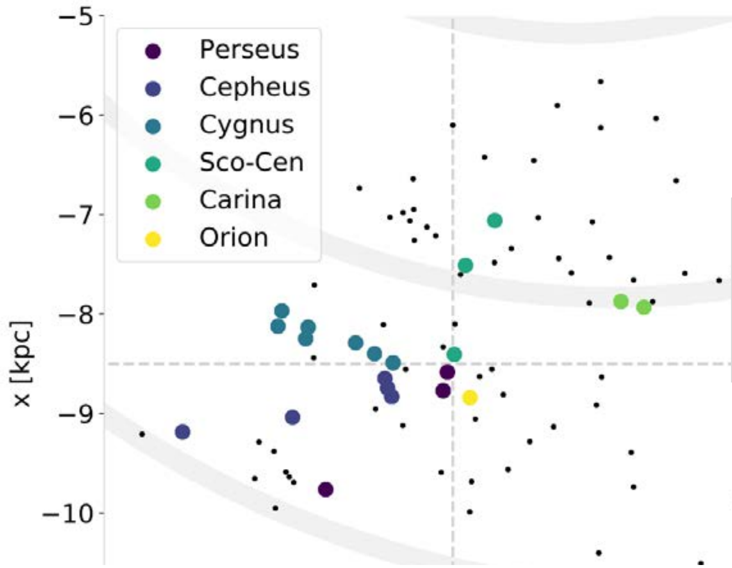
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling

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

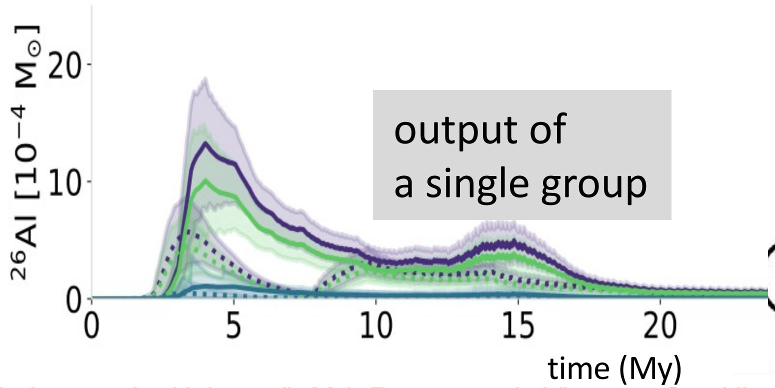
→ bottom-up model for the ^{26}Al observations

Pleintinger PhD thesis 2020
(see also Siegert+ 2023)

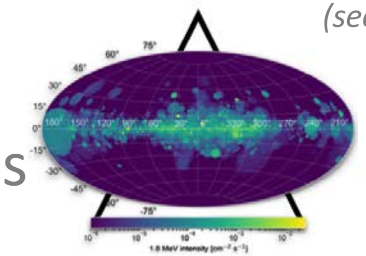


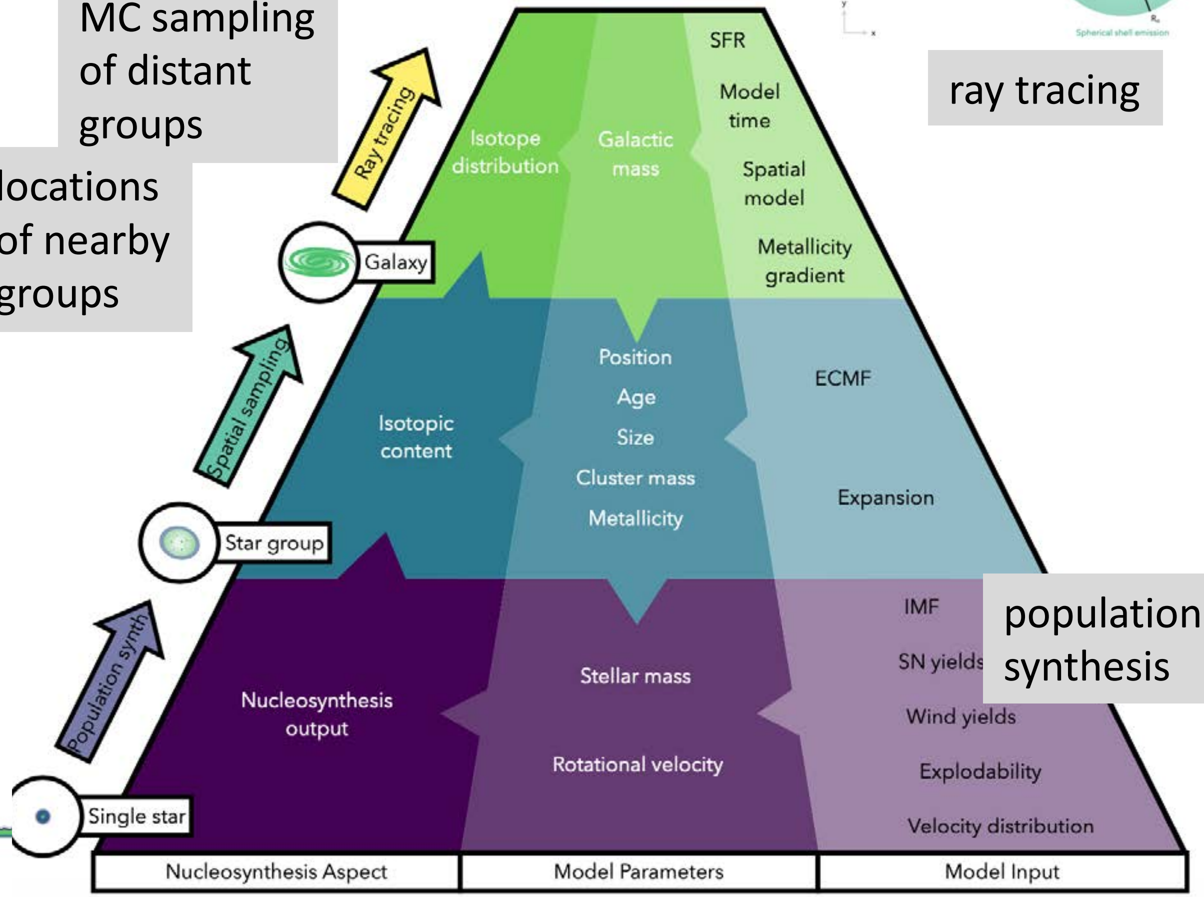
MC sampling of distant groups

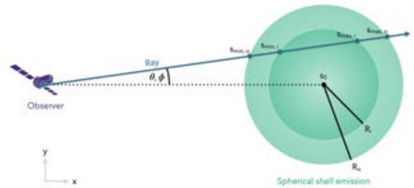
locations of nearby groups



output of a single group







ray tracing

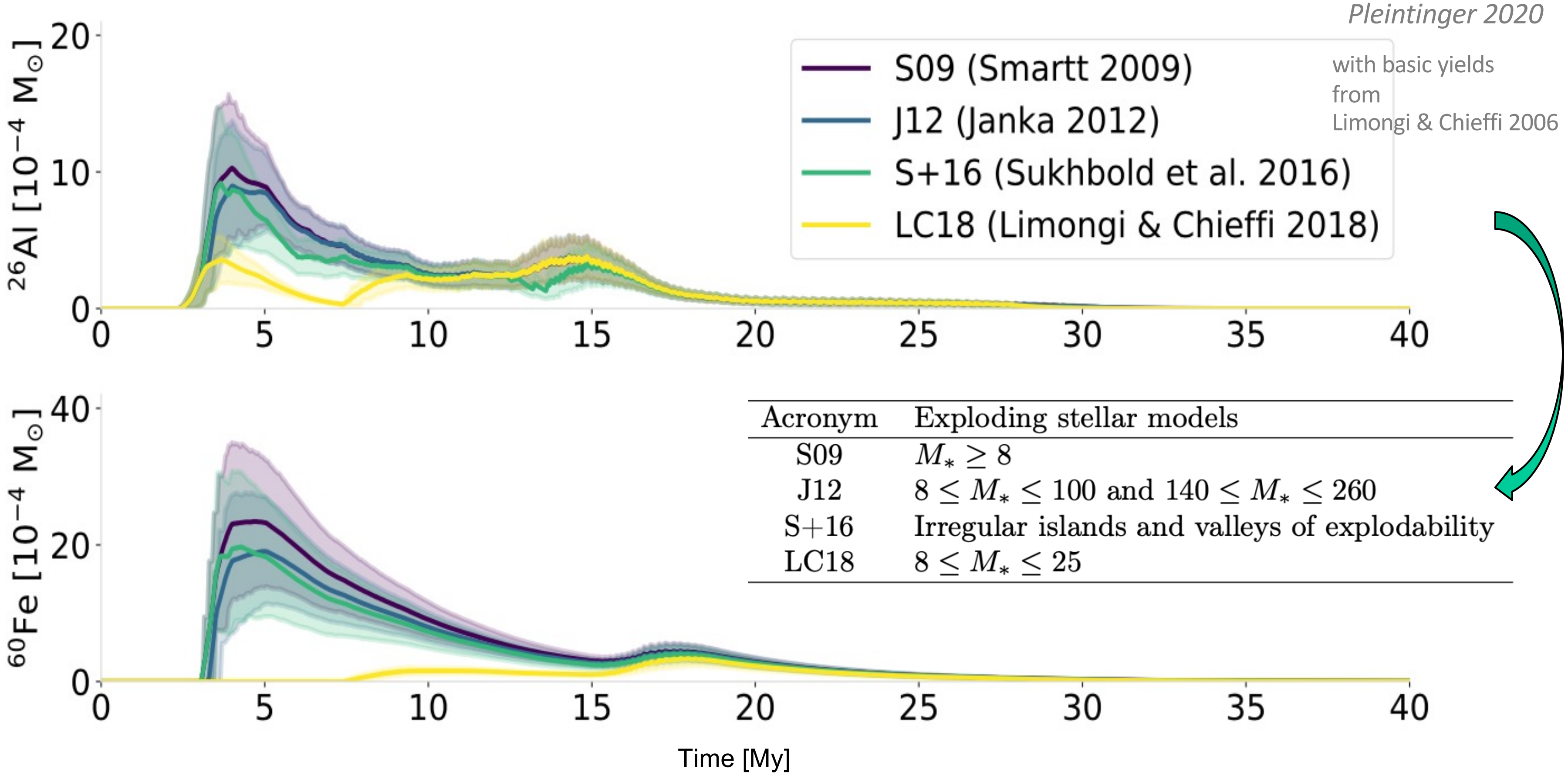
population synthesis

Population synthesis: impact of different inputs on groups

variation of explodability *(i.e.: not all stars of high mass make a SN!)*

Pleintinger 2020

with basic yields from Limongi & Chieffi 2006

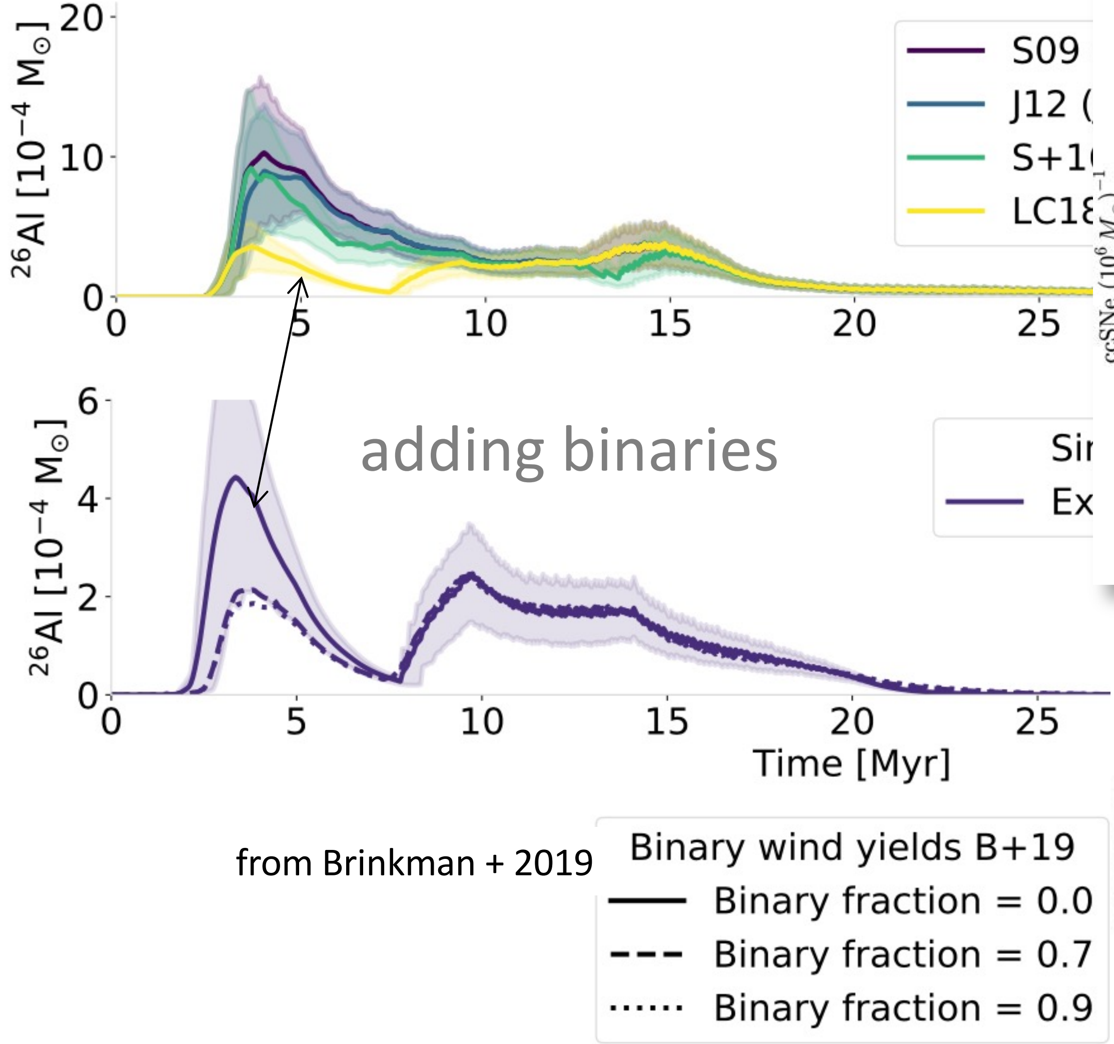


Acronym	Exploding stellar models
S09	$M_* \geq 8$
J12	$8 \leq M_* \leq 100$ and $140 \leq M_* \leq 260$
S+16	Irregular islands and valleys of explodability
LC18	$8 \leq M_* \leq 25$

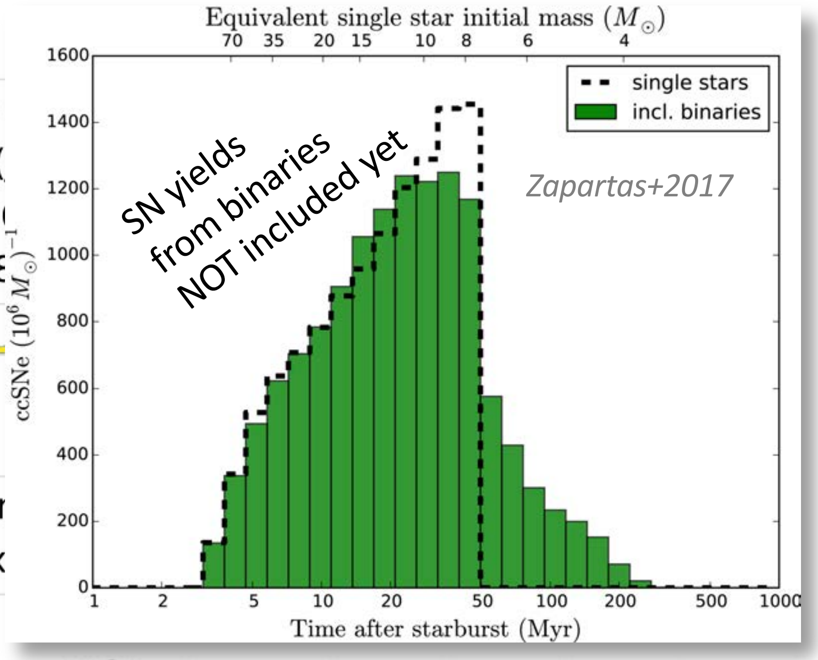
☞ contributions from early (i.e. most-massive-stars') SNe eliminated if non-exploding

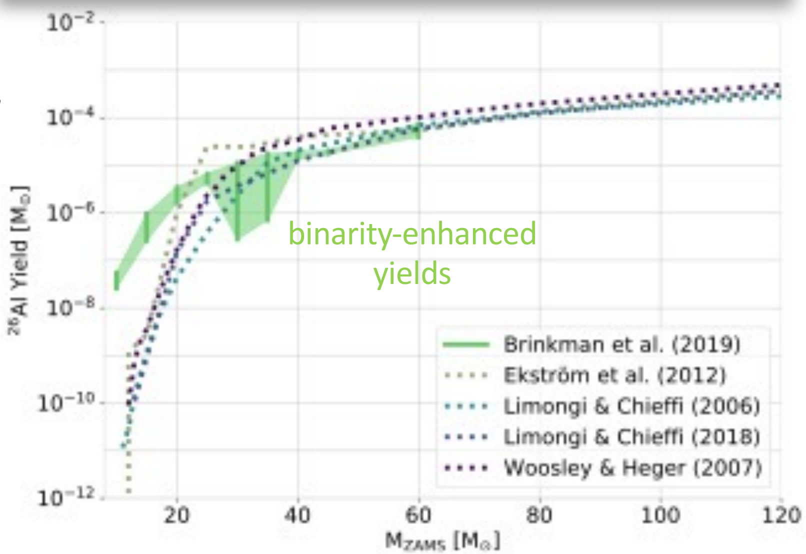
Population synthesis: impact of different inputs

variation of explodability



from Brinkman + 2019



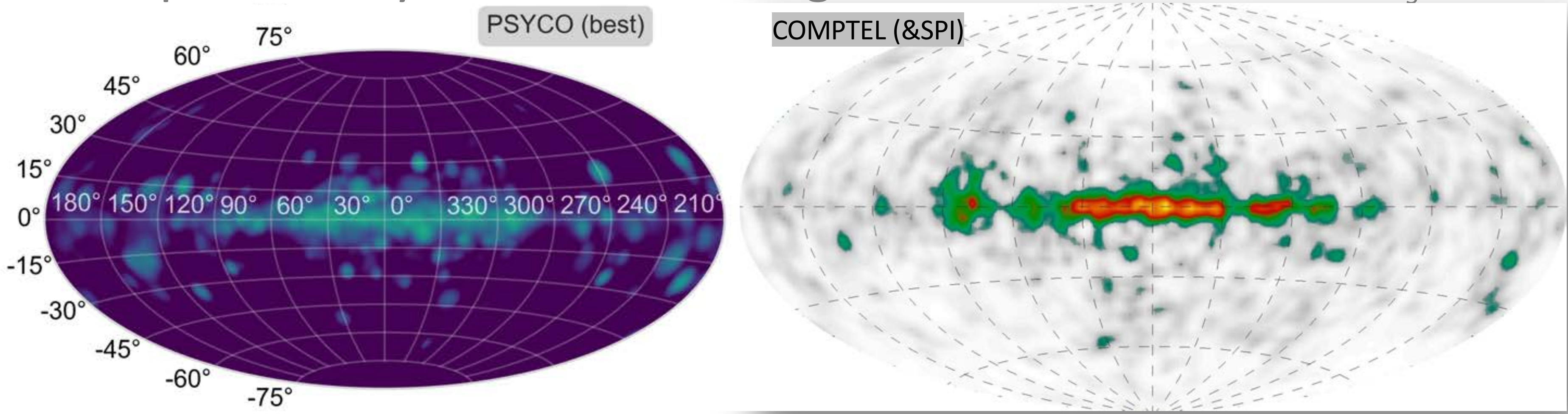


☞ contributions from early (i.e. most-massive-star) SNe reduced

Diffuse radioactivity throughout the Galaxy

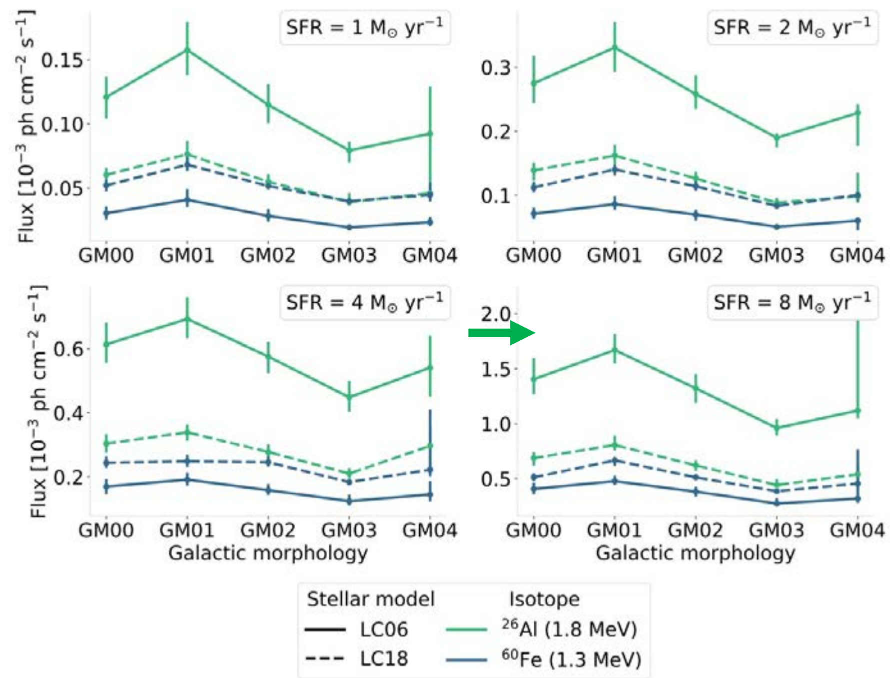
Galactic Population Synthesis Modelling versus observations

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
- Best-fit details (yield, explodability) depend on superbubble modelling

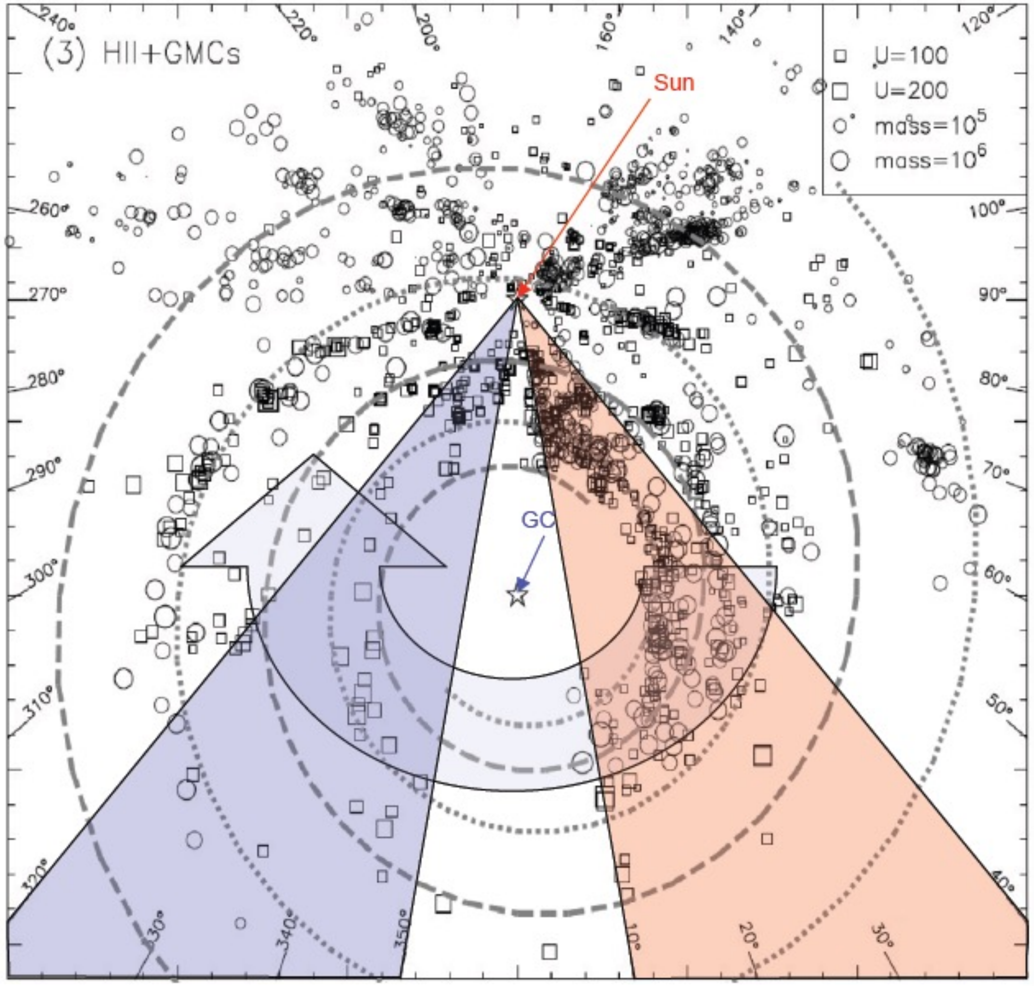
  (here: sphere only)

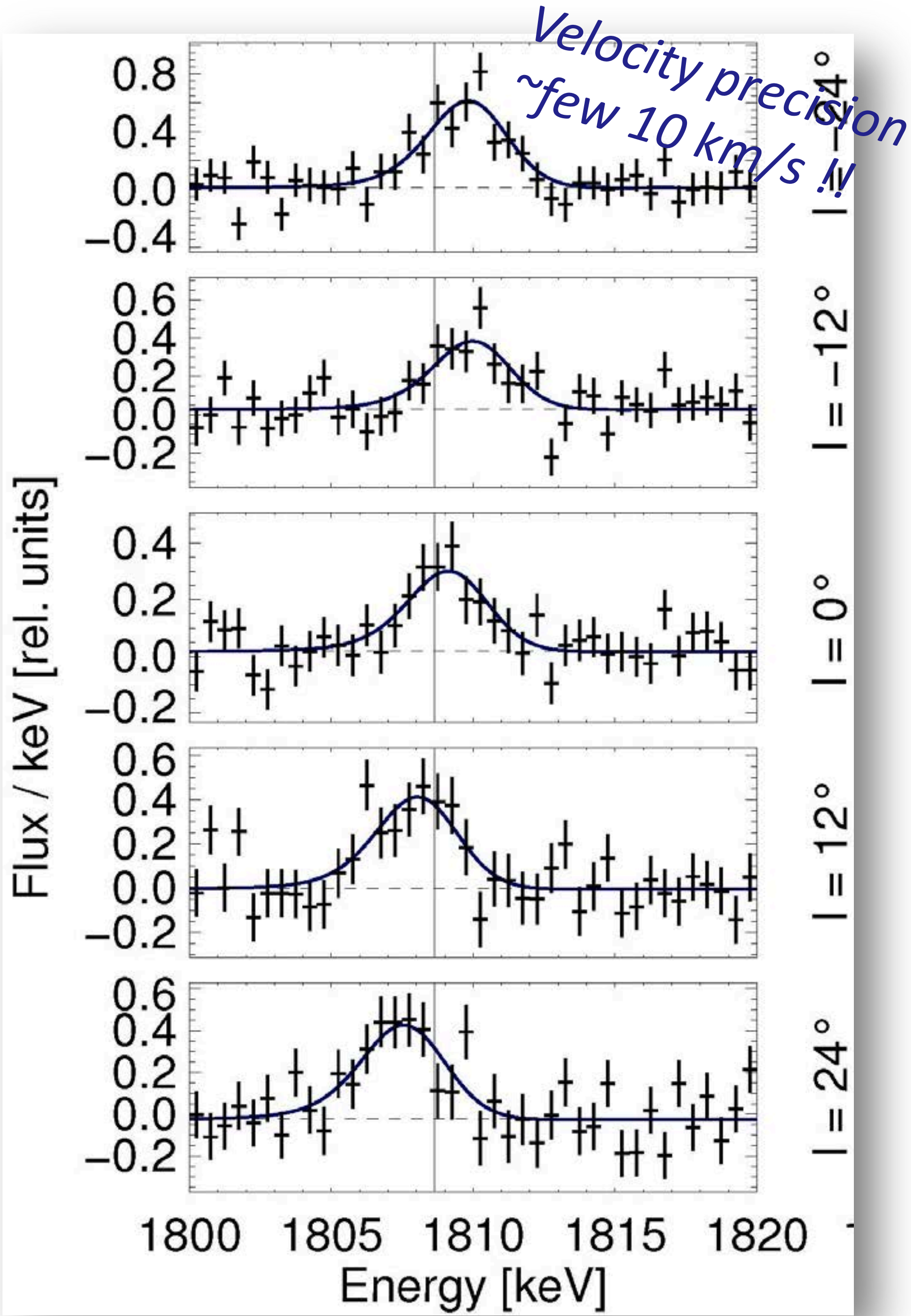


cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{-1} *(Zari+2022)*

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

☞ Large-scale Galactic rotation



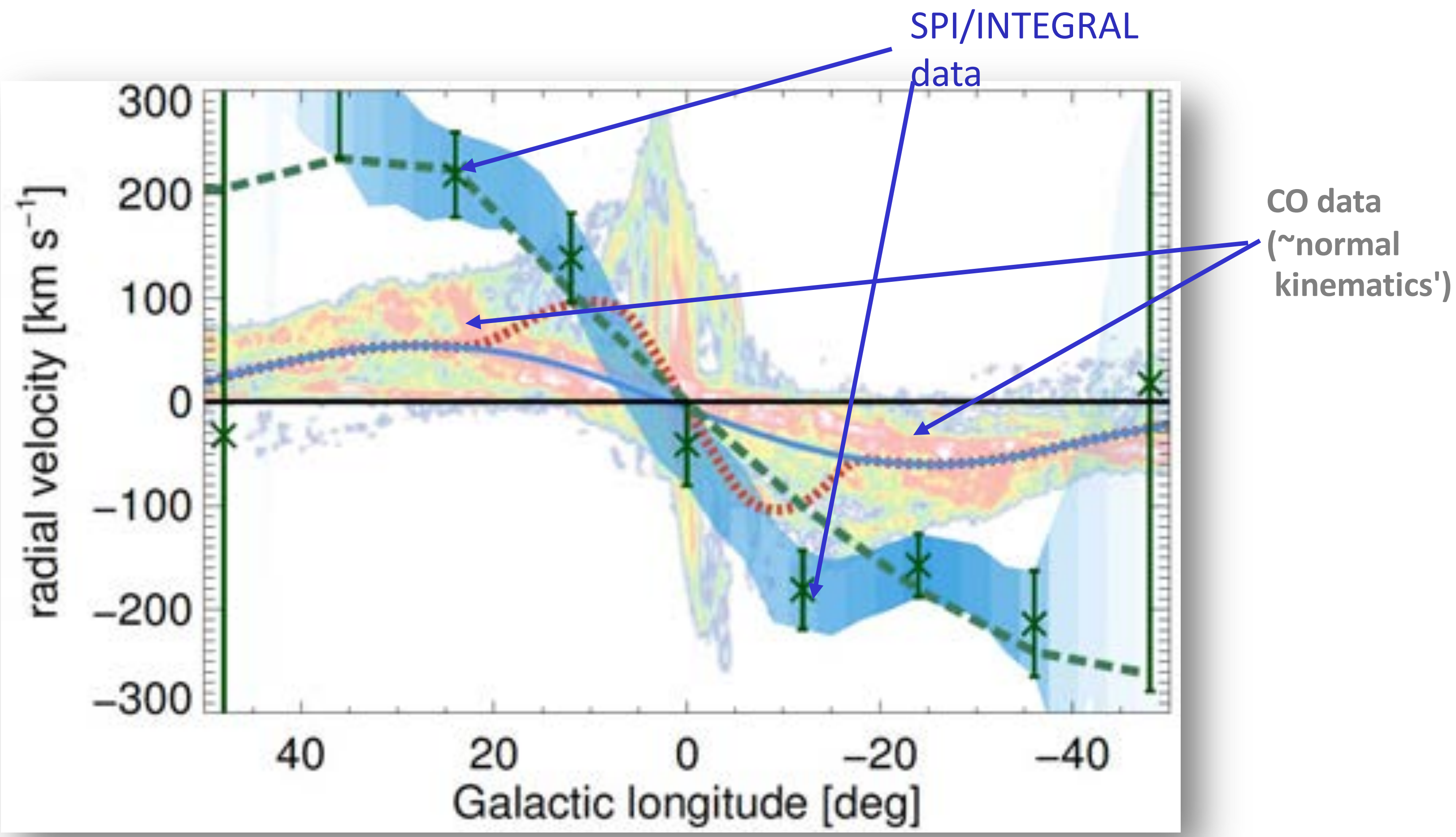


Kretschmer et al., A&A (2013)

How massive-star ejecta are spreading…

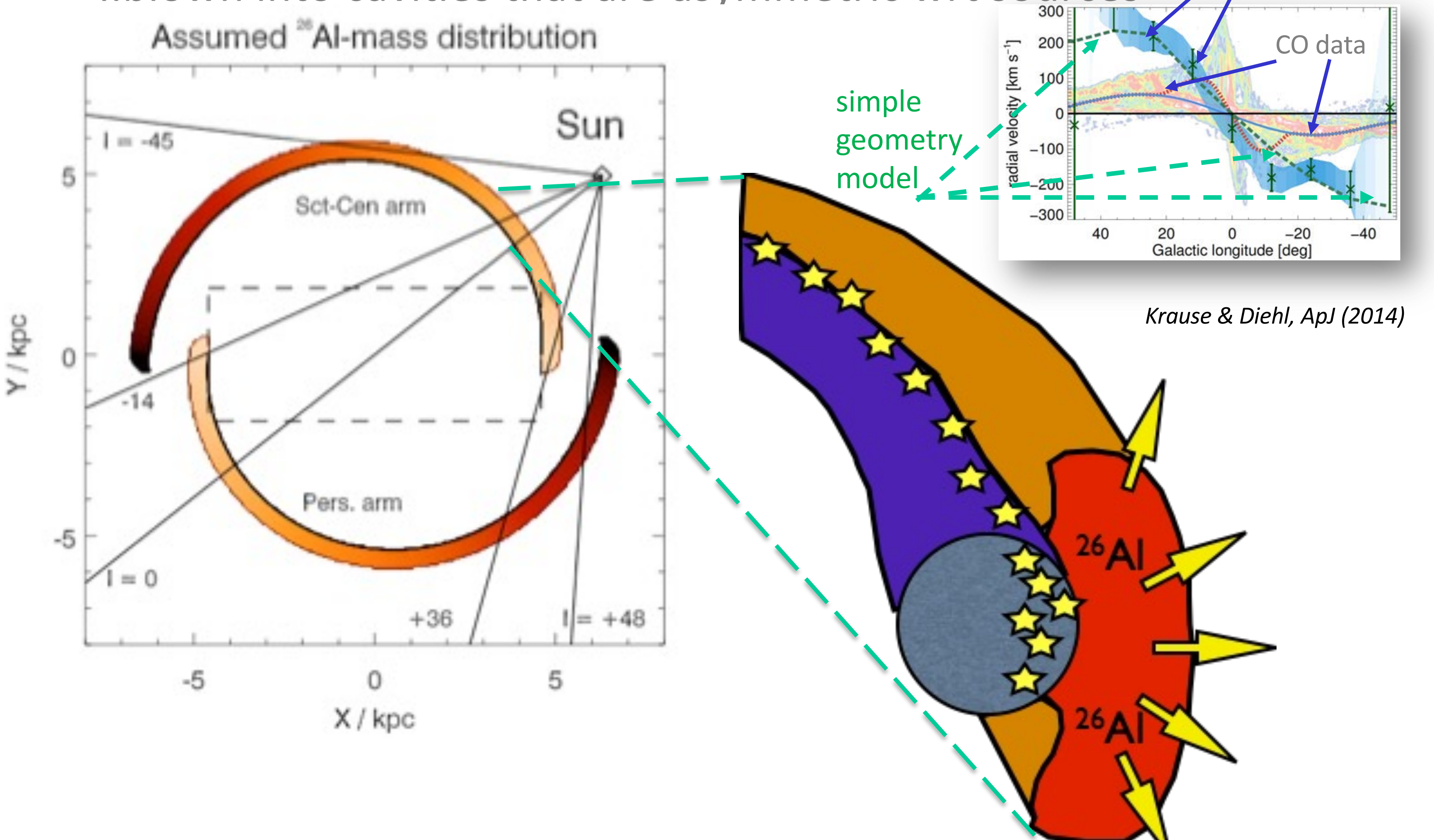
- ^{26}Al shows apparently higher galactocentric rotation (?)

Kretschmer+(2013)



How massive-star ejecta are spreading…

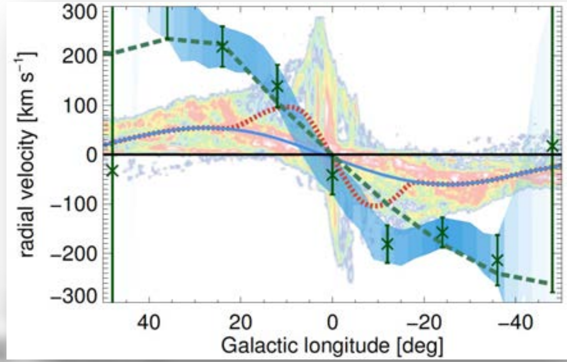
- ^{26}Al shows apparently higher galactocentric rotation (?)
- ..blown into cavities that are asymmetric wrt sources

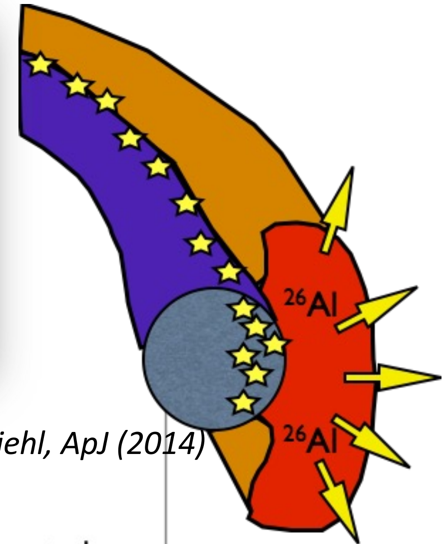


Krause & Diehl, ApJ (2014)

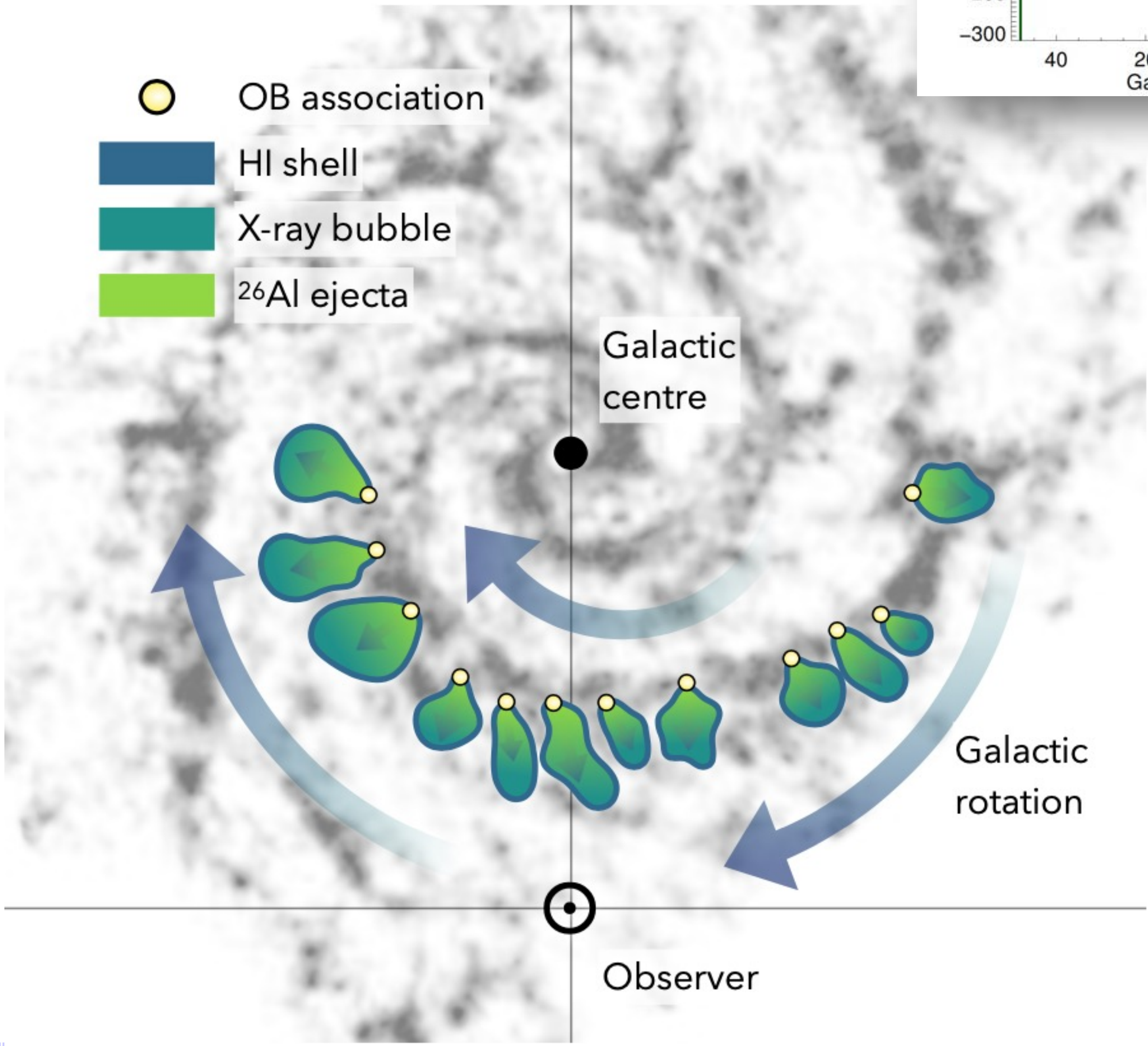
How massive-star ejecta are spread out…

Superbubbles extended away from massive-star groups





Krause & Diehl, ApJ (2014)



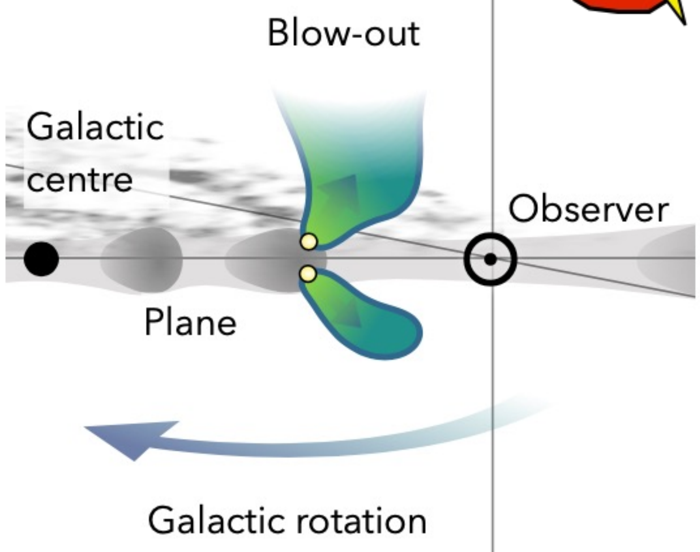
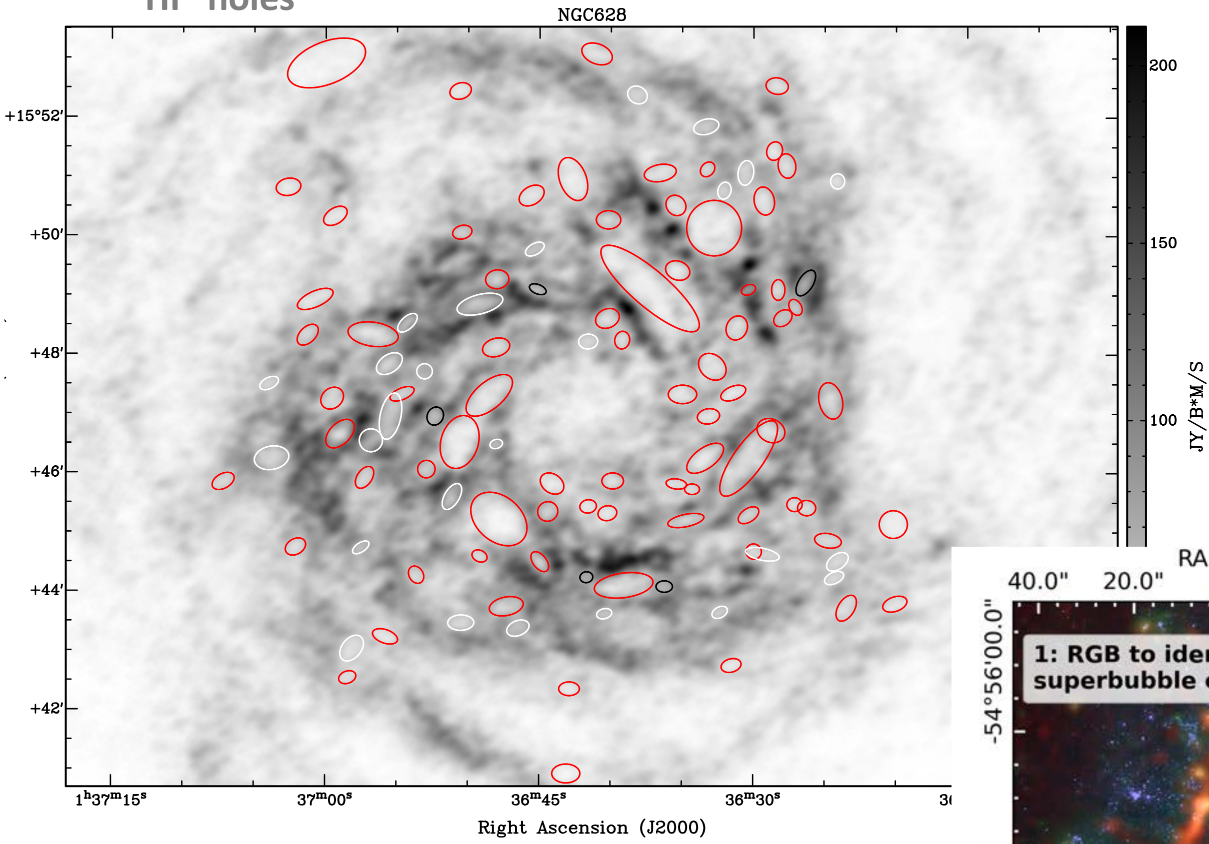


Illustration by M. Pleintinger (2020)

Superbubbles observations in other galaxies

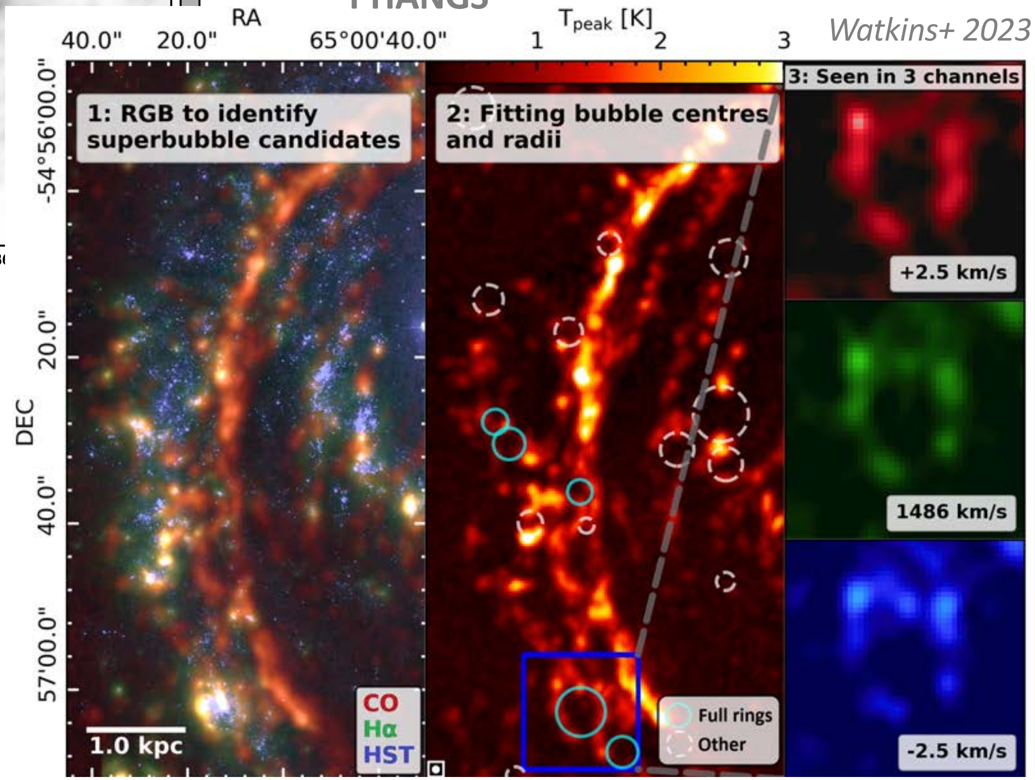
HI 'holes'



Bagetakos+ 2011

PHANGS

Watkins+ 2023

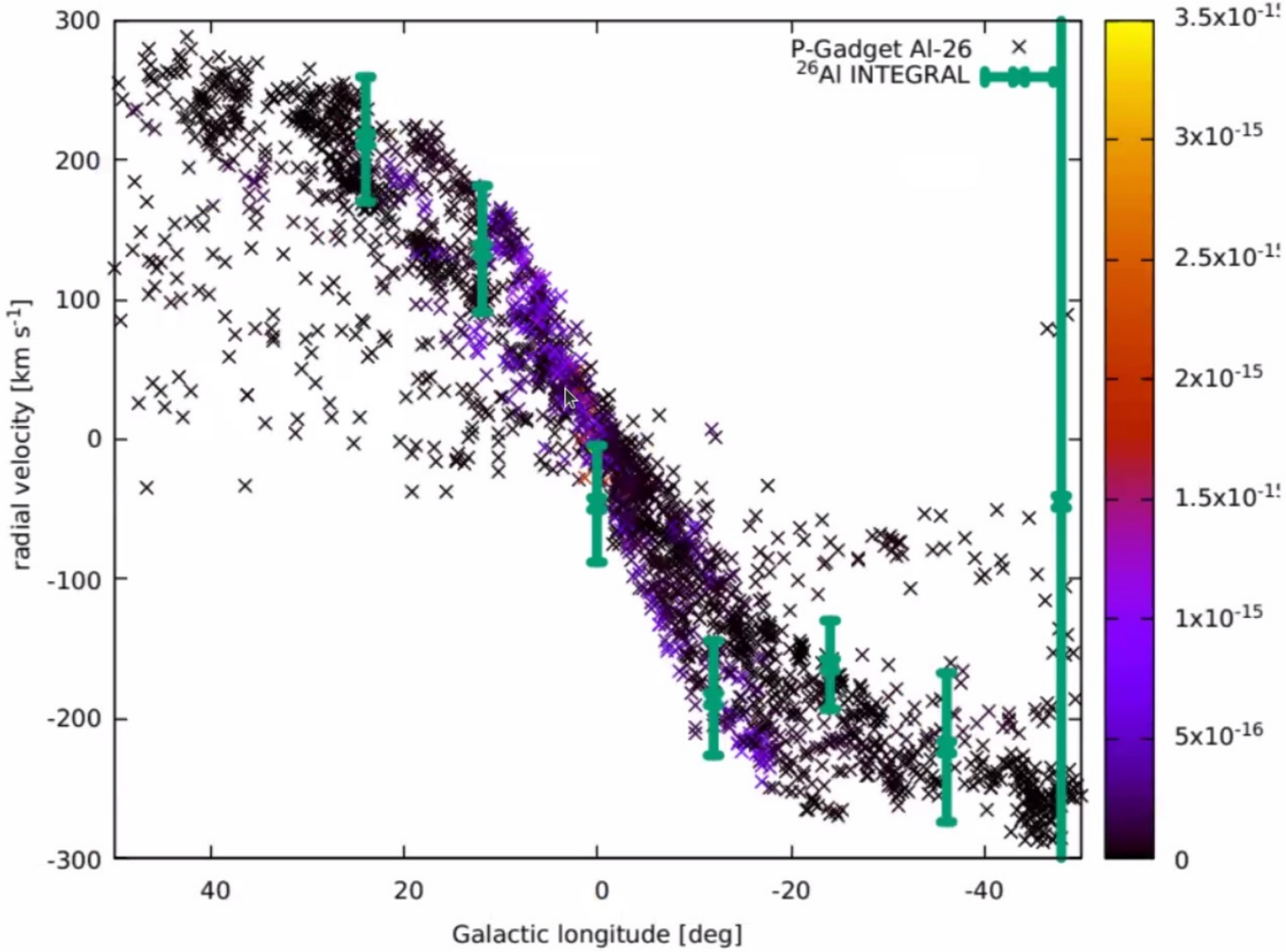


Simulations of (inhomogeneous) galactic evolution

→ ejecta with excess velocities appear naturally within a spiral galaxy

3D SPH simulation: analyze velocities in typical SF regions

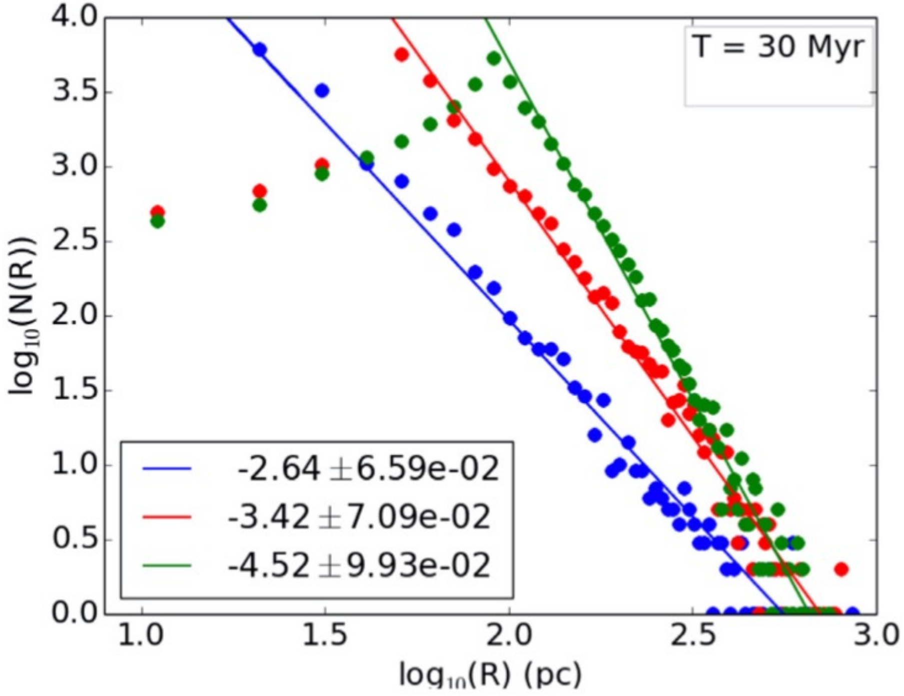
Wehmeyer & Kobayashi 2021

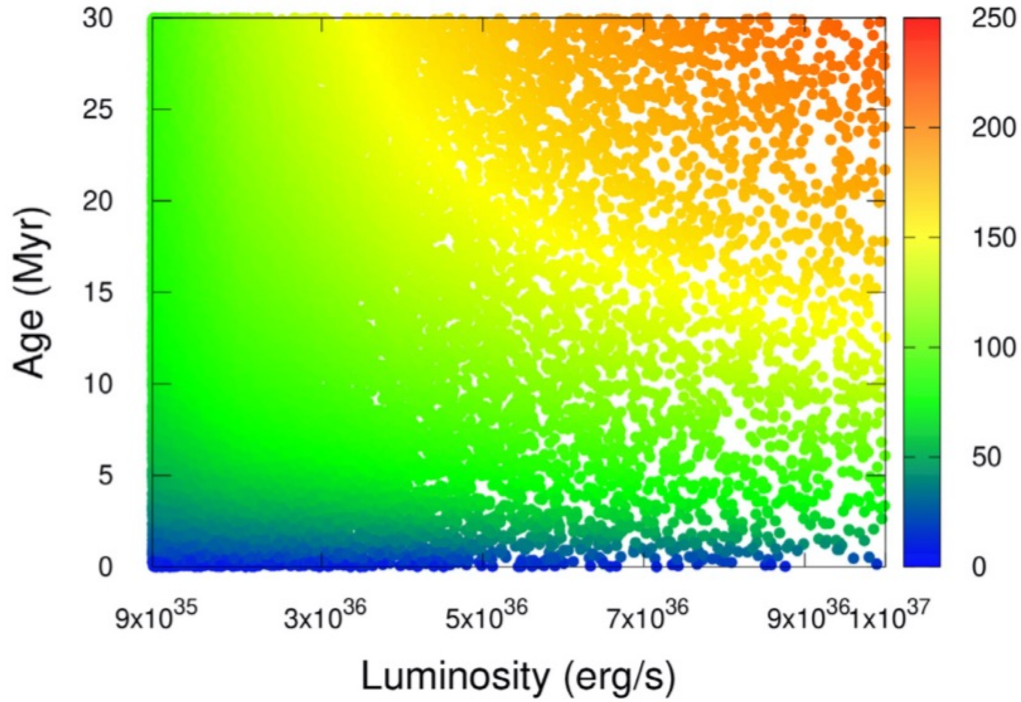


Stellar Feedback – insights from theory & simulations

- Stellar feedback is main driver of ISM and the baryon cycle
- Superbubbles are major elements / observable consequences

Nath+2020; see also Kruissen+

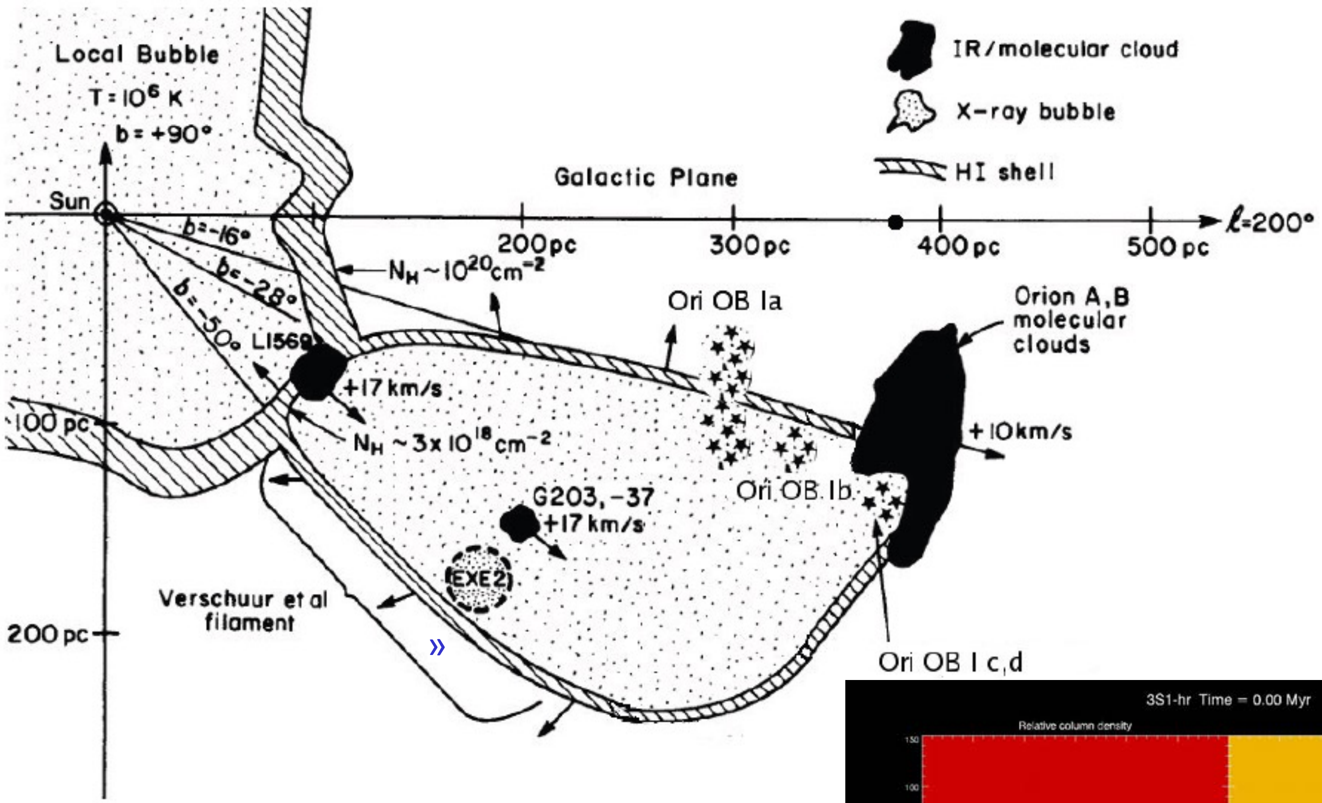


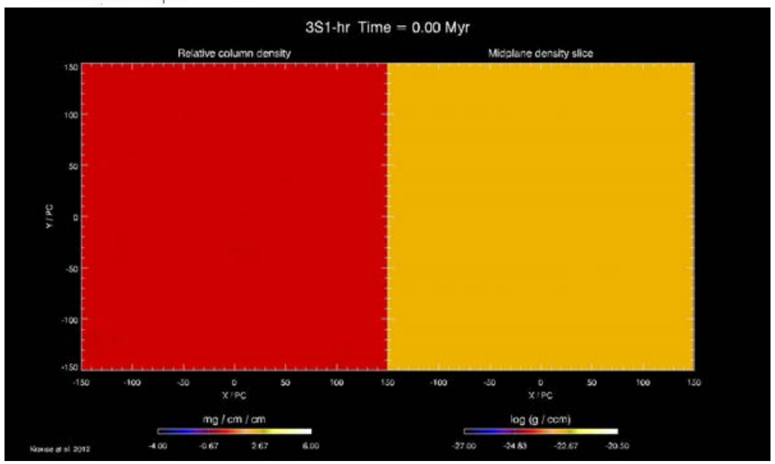


- Typical superbubble sizes extend to kpc
- Next-generation star formation occurs on the SB scale (~300 pc)

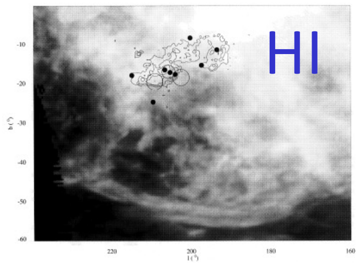
Orion-Eridanus: A superbubble blown by stars & supernovae

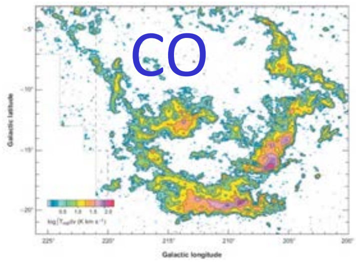
ISM is driven by stars and supernovae → Ejecta commonly in (super-)bubbles

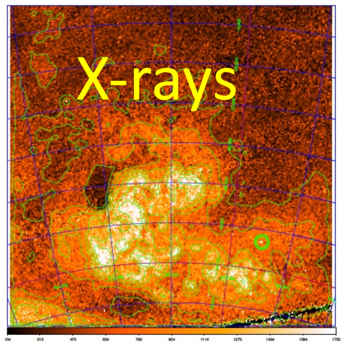


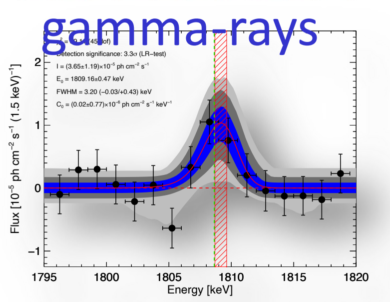


3D MHD sim, 0.1..0.005 pc resolution
Krause+ 2013ff





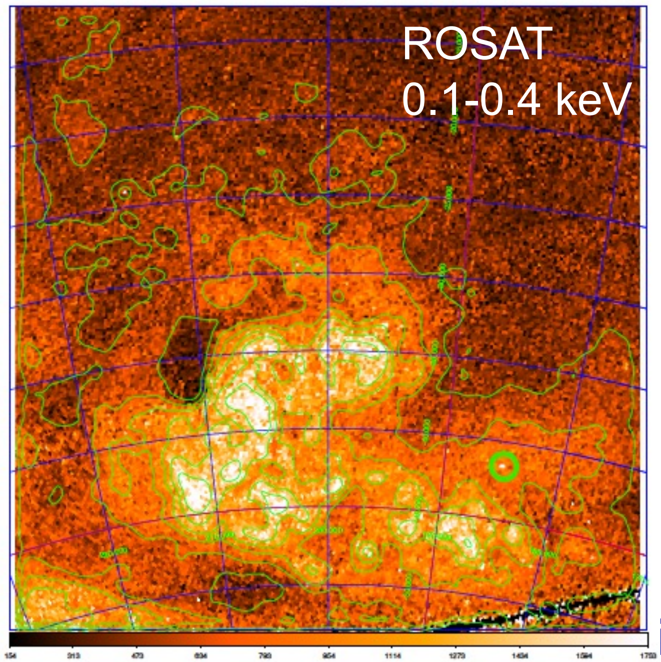


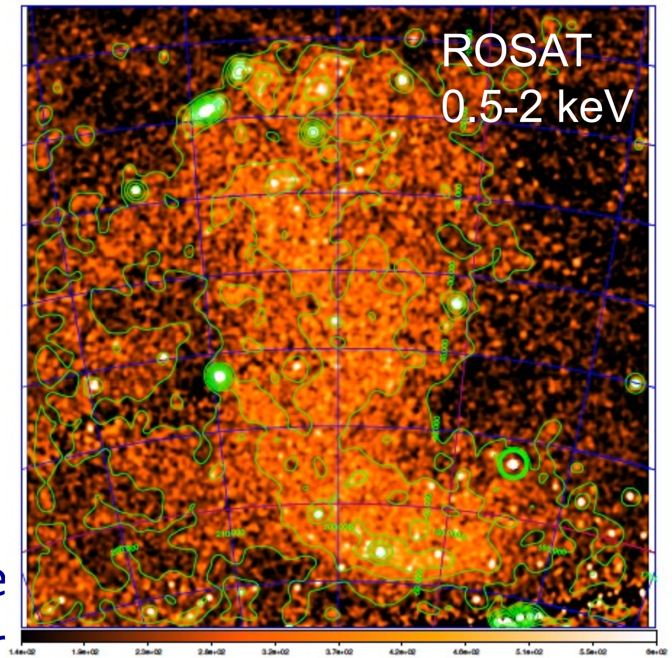


Krause+ 2014, Fierlinger+ 2016,
Voss+ 2010, Diehl+2003

Understanding the Eridanus Superbubble

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





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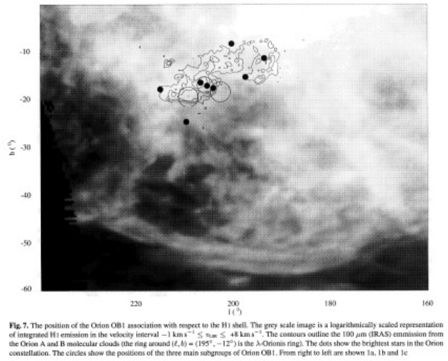
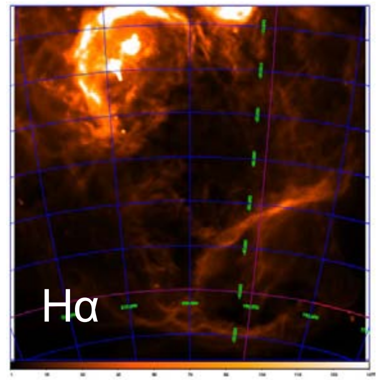
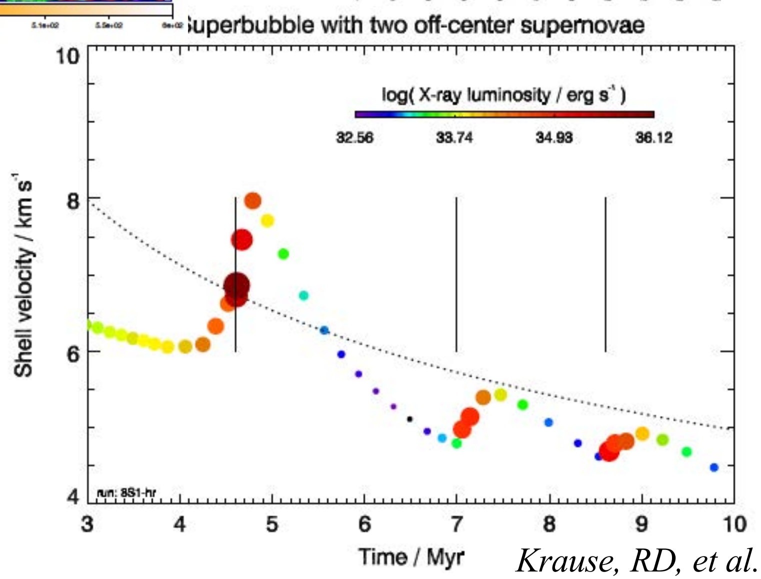






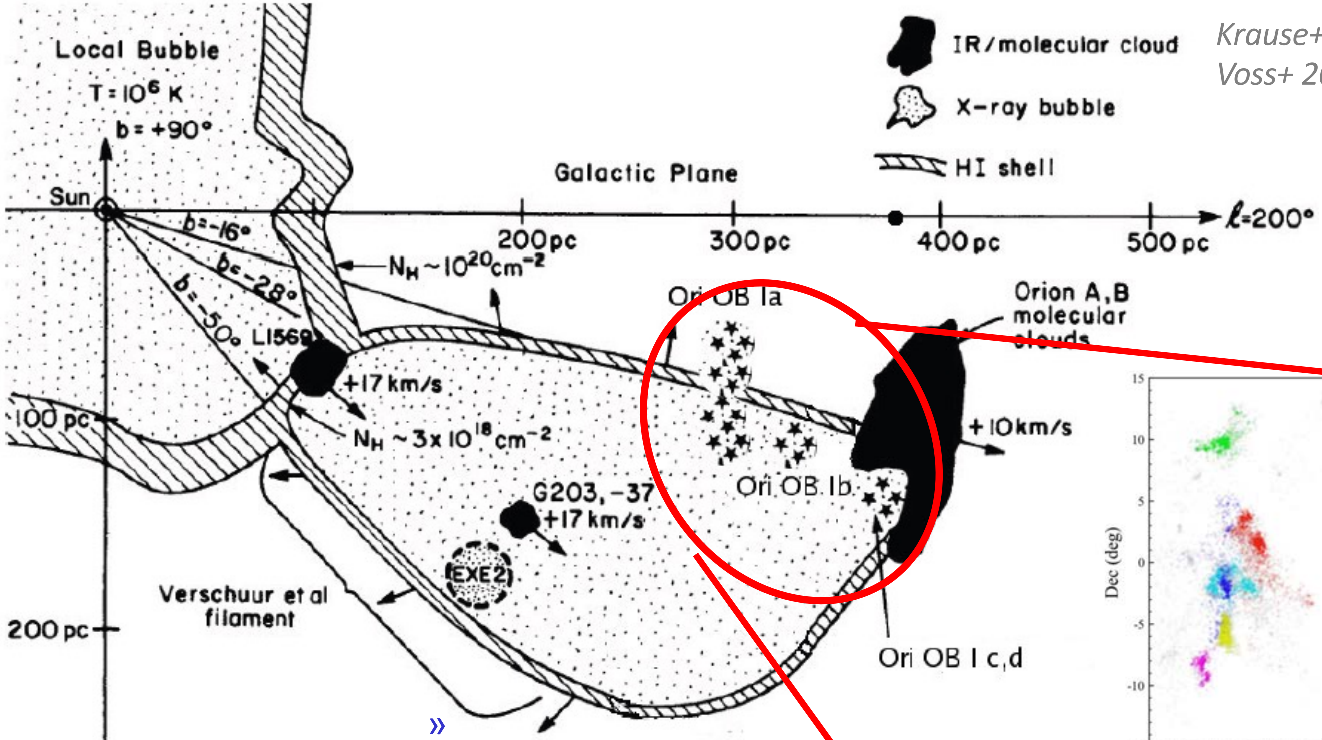
☆ spatial oscillations

Krause, RD, et al. 2015

Stars, structures, & shells

ISM is driven by stars and supernovae

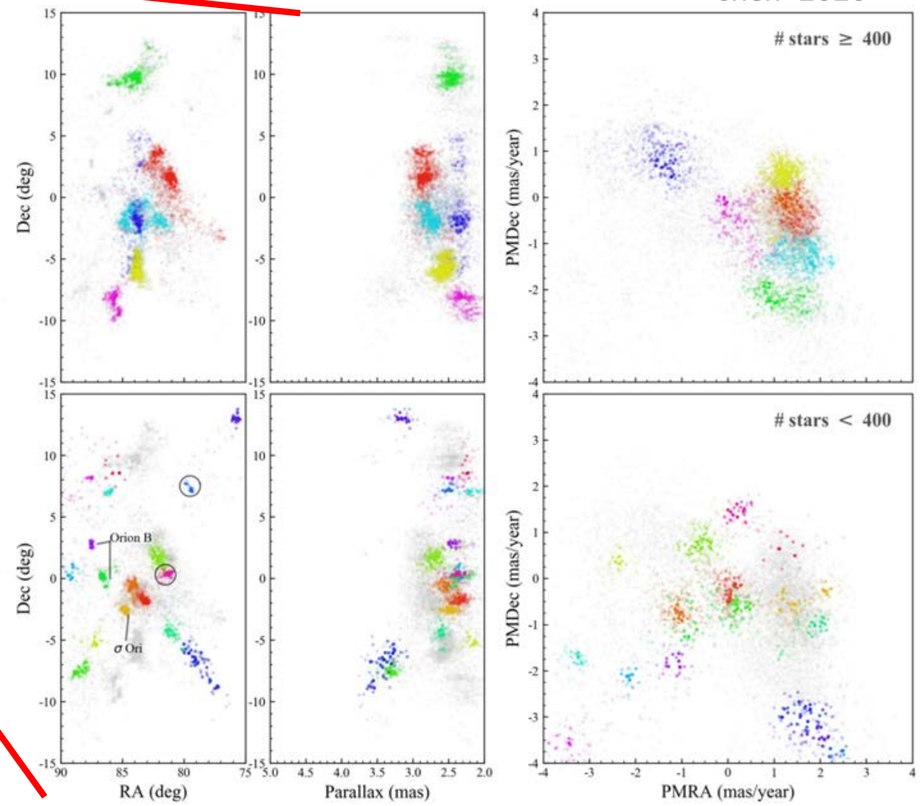
→ Use stellar census for estimation of driving energy & nucleosynthesis (^{26}Al)

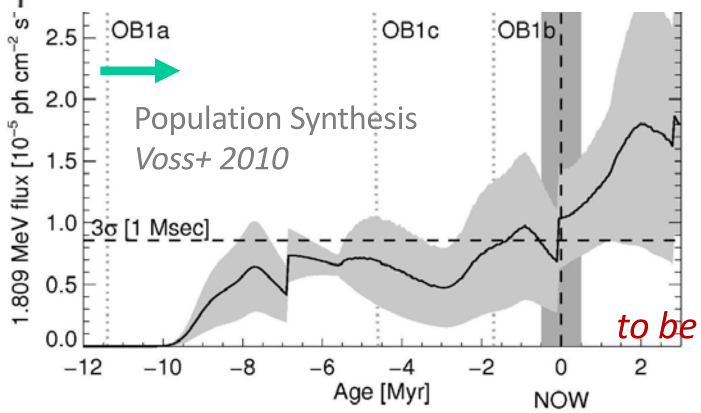


Krause+ 2014, Fierlinger+ 2016, Voss+ 2010, Diehl+2003

Gaia parallax analyses
→ 22 stellar groups
-150pc<MCs<50pc

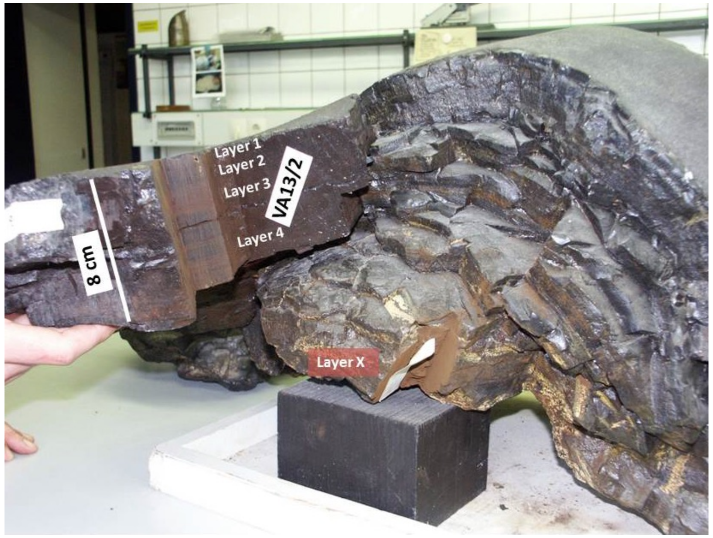
Chen+2020



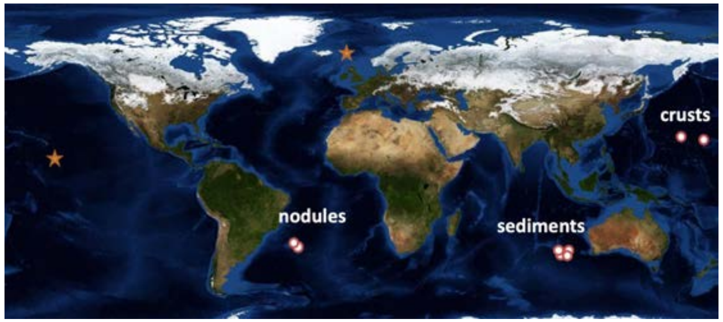


to be renewed...

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

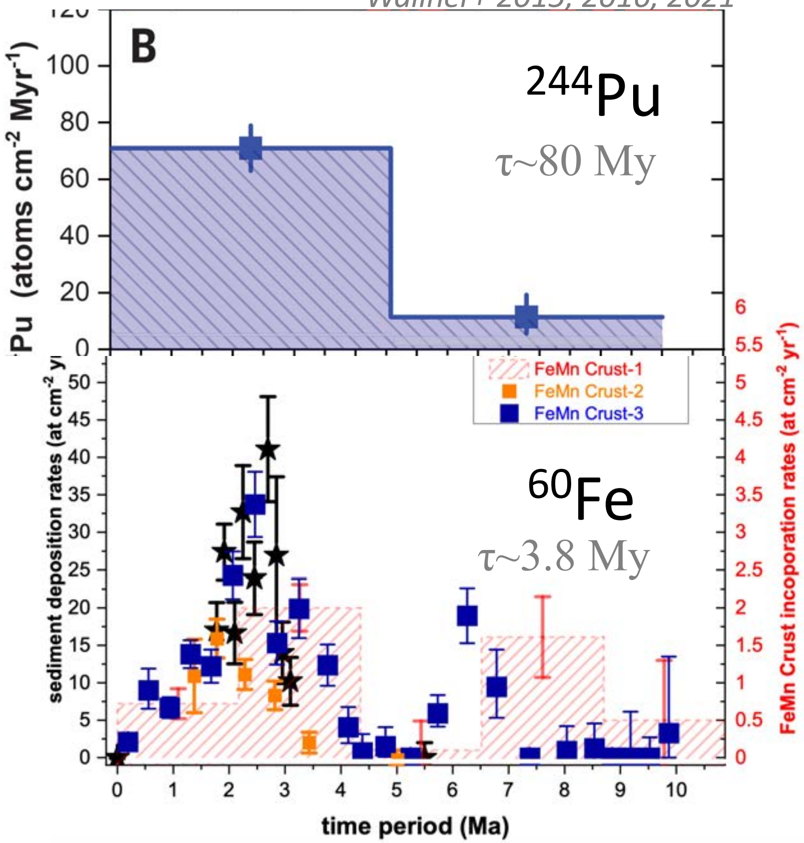


Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ...



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021



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

What are its sources?

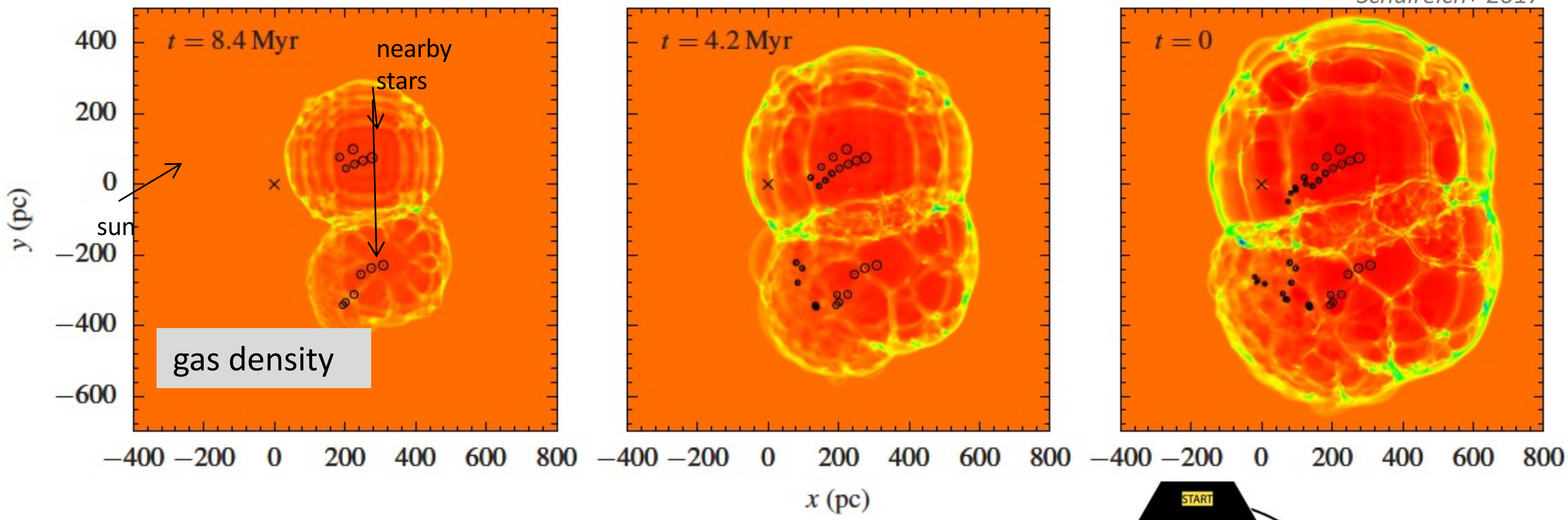
How did these traces of nucleosynthesis get here?

^{60}Fe on Earth from recent nearby supernovae?

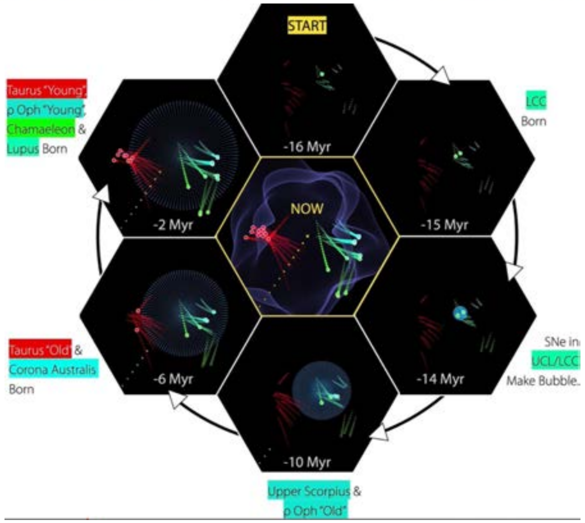
The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions within LB → ejecta flows reach the Solar System

Schulreich+ 2017



see also Zucker+ 2022
for a recent update on the Local Bubble and the Sco-Cen SN activity, confirming this local superbubble interpretation with dust cloud maps and Gaia data

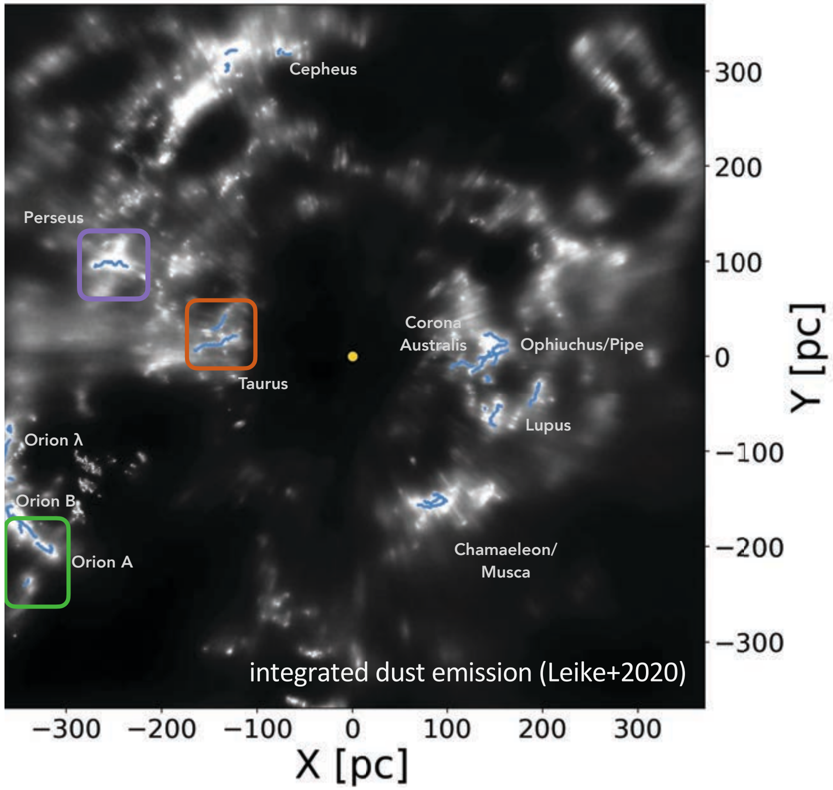


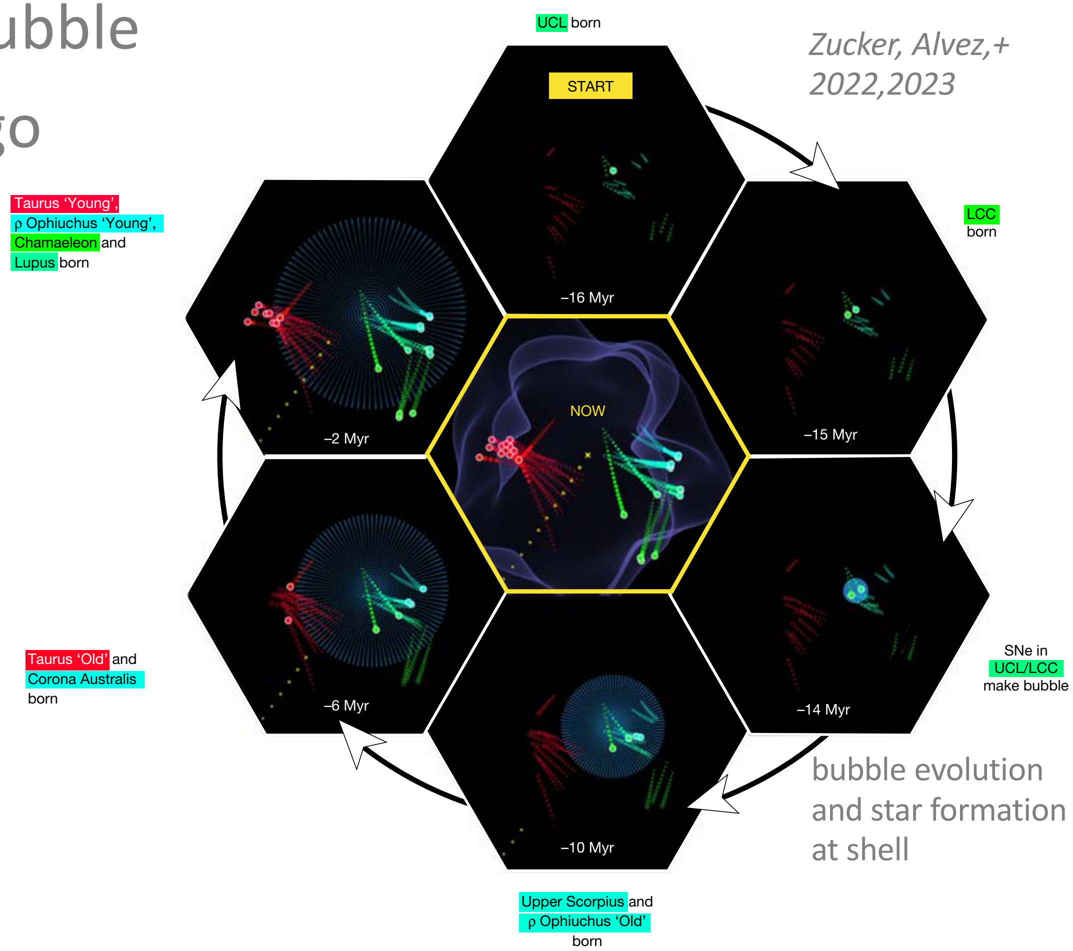
Recent nearby supernovae and the Local Bubble

The Sun is (now) located inside a hot cavity (the "Local Bubble")

SN explosions created the Local Bubble

The Sun entered the LB ~10 My ago





Zucker, Alvez,+ 2022,2023

bubble evolution and star formation at shell

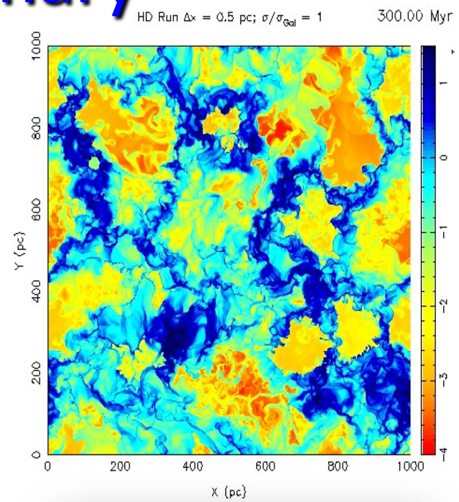
ISM dynamics and trajectory of the Sun lead to encounters with SB wall and quenching of the heliosphere from cloud encounters

→ nucleosynthesis ejecta flows can reach the Solar System

Tracing Nucleosynthesis Ejecta - Summary

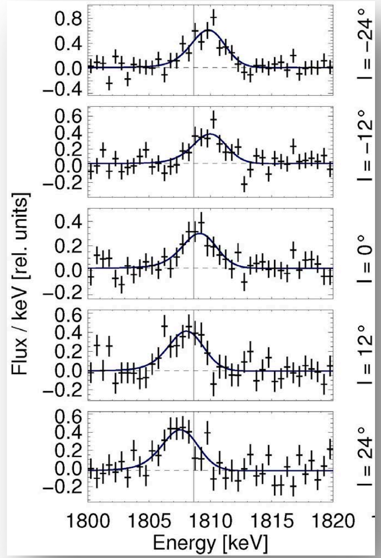
☆ Cycling of cosmic gas through sources and ISM is a challenge

- ☞ Source afterglows reach aut to ~years (SNe) or few 10,000 y (SNR)
- ☞ ^{26}Al with radioactive lifetime Myrs extends these traces



☆ ^{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
- ☞ ^{60}Fe is a second radio-isotope, and even found on Earth from nearby nucleosynthesis → get a detailed local view



☆ Varied messengers complement ISM studies of ejecta

- ☞ Radioactivity provides a unique and different view on cosmic isotopes (via gamma rays, stardust, CRs, sediments)