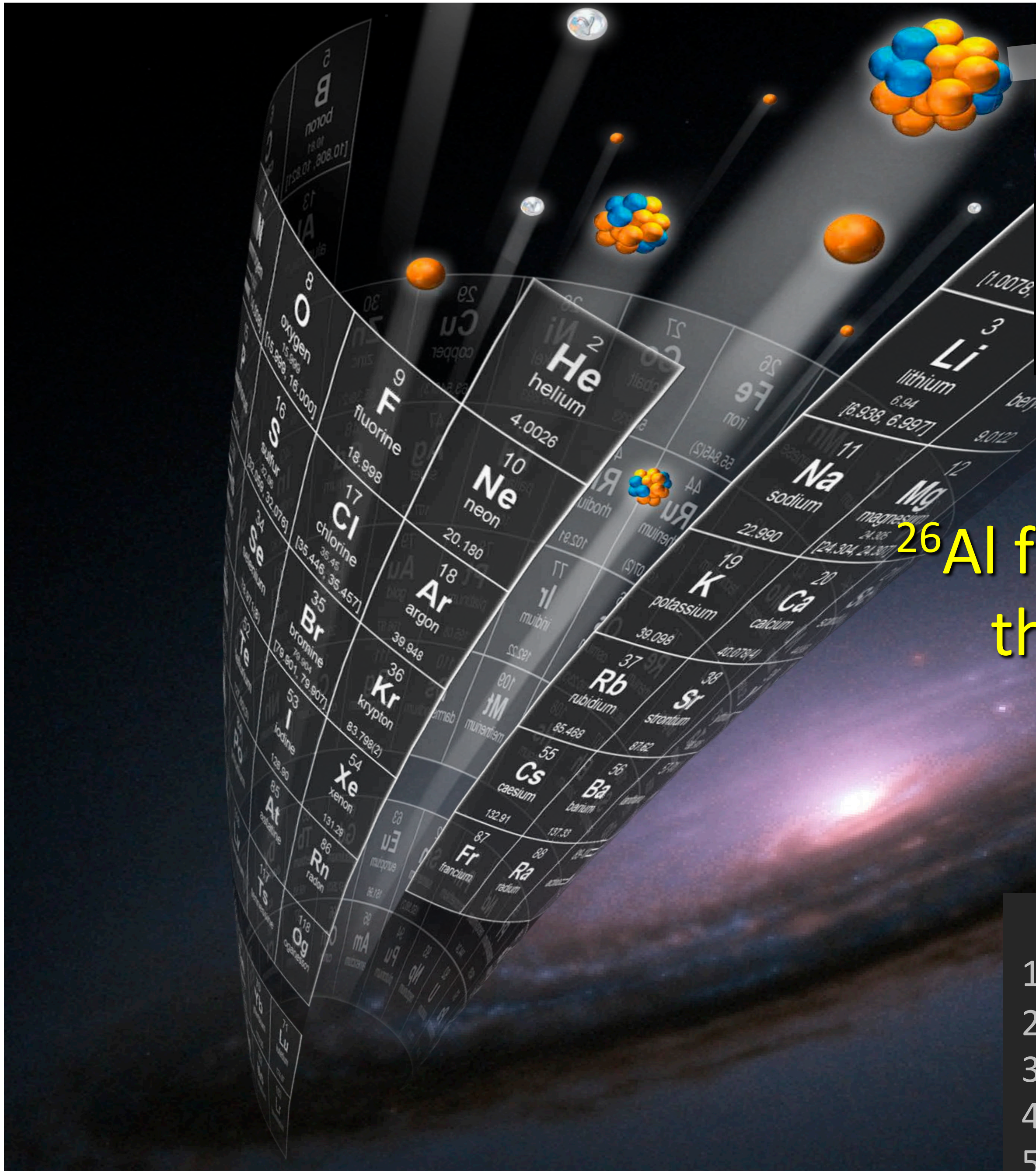
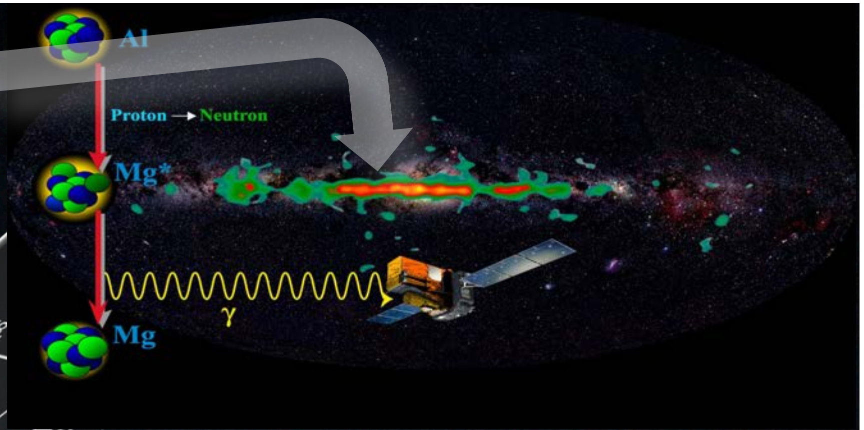




^{26}Al from massive-star clusters: theory and observations

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

Contents:

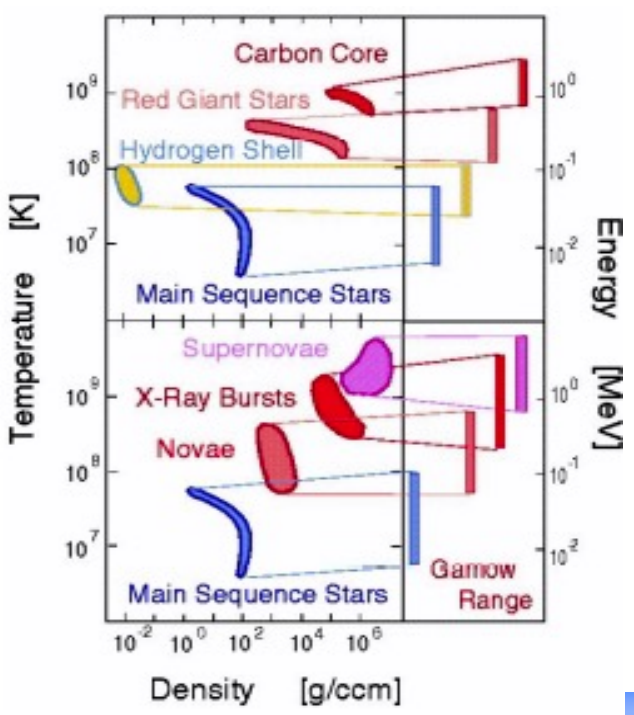
with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

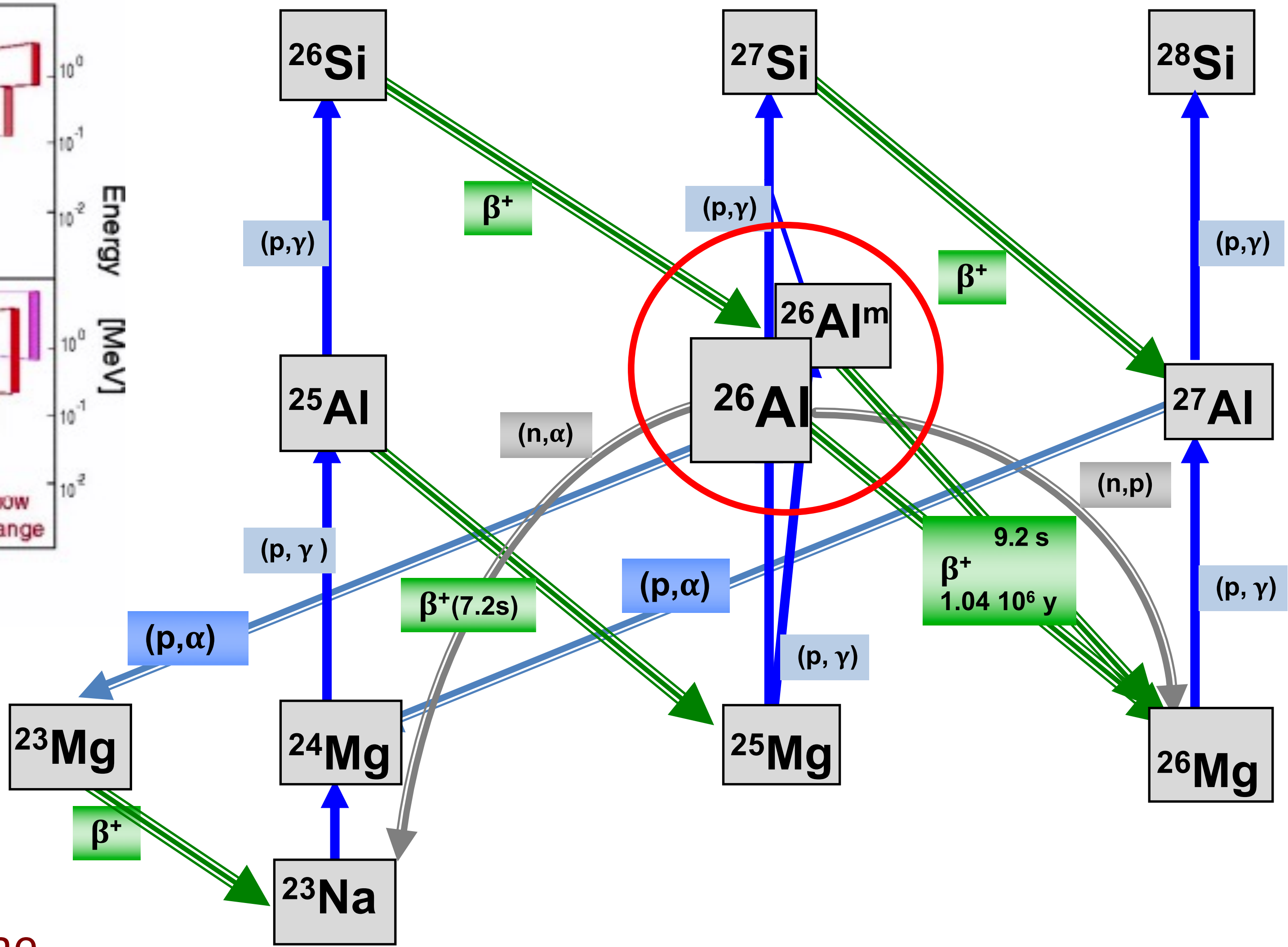
Figure: ChETEC 2021

Nuclear reactions to produce ^{26}Al

p capture during H burning in stellar core, + H shell in AGB stars,...novae...)

☆ The Na-Al-Mg cycle: production versus destruction reactions...



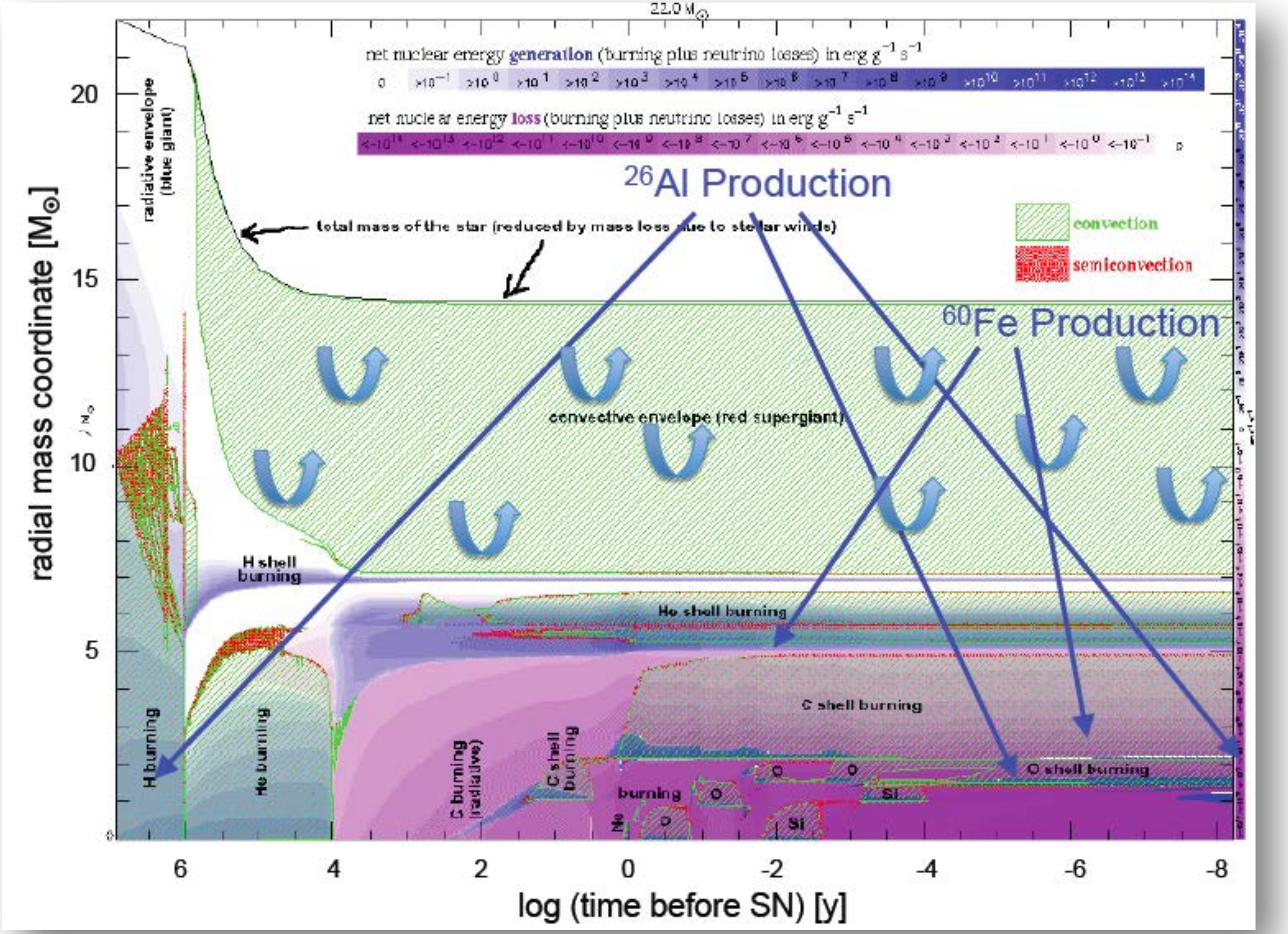


☞ stellar interiors, supernovae

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

→ Messengers from Massive-Star Interiors!

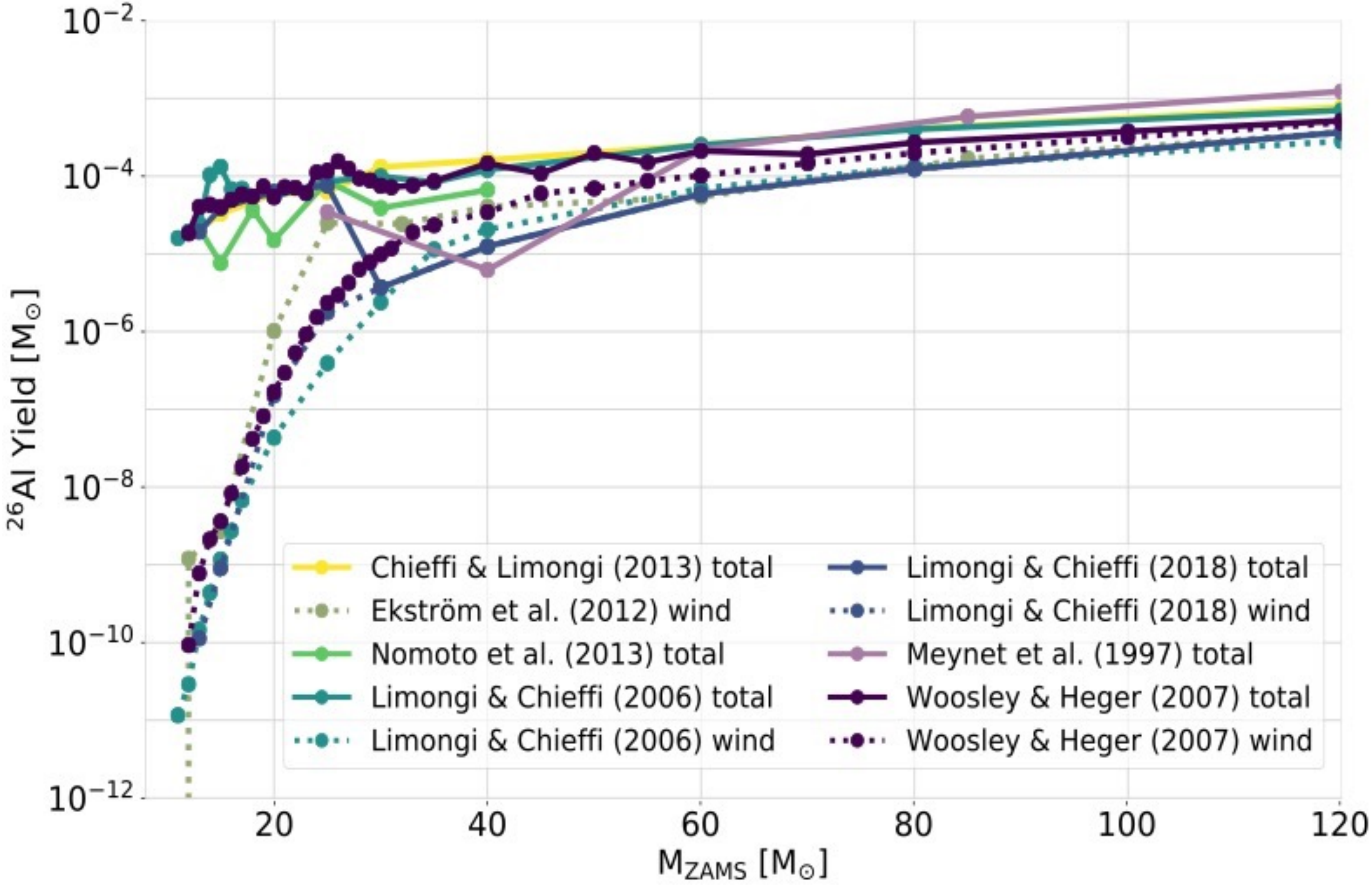
…complementing neutrinos and asteroseismology!



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

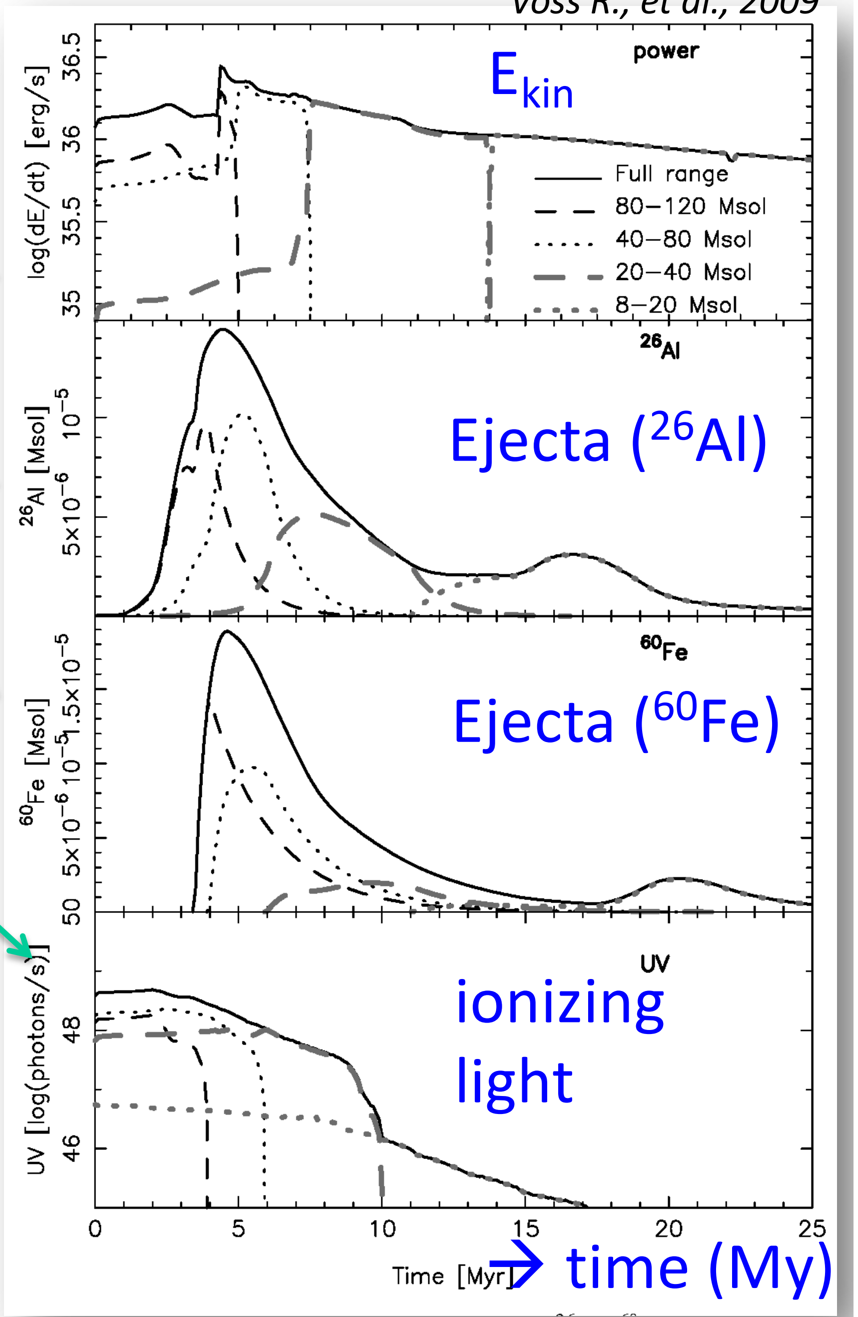
Studying Massive-Star Groups (including nucleosynthesis)

- We model the "outputs" of a massive star ensemble 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

➔ obtain cluster / model validation

with adjusted parameters to match observational constraints

Voss R., et al., 2009



Nuclear ^{26}Al Gamma-Ray Line Telescopes

INTEGRAL

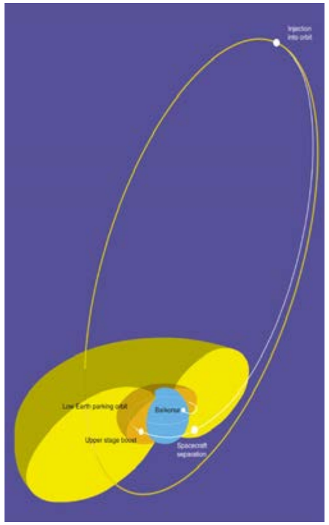
2002-2025 (..2029)

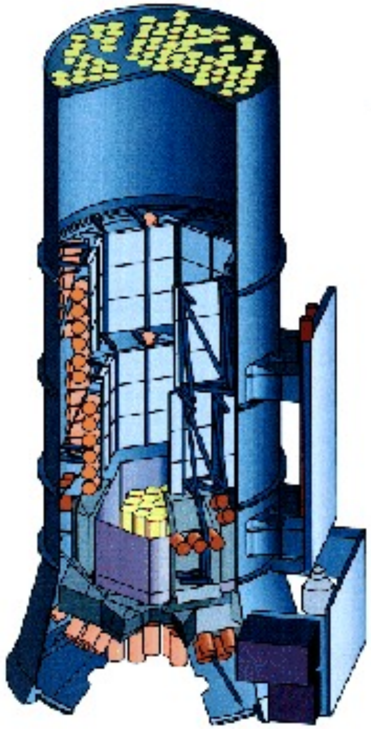
ESA

high E resolution

Ge detectors

15-8000 keV





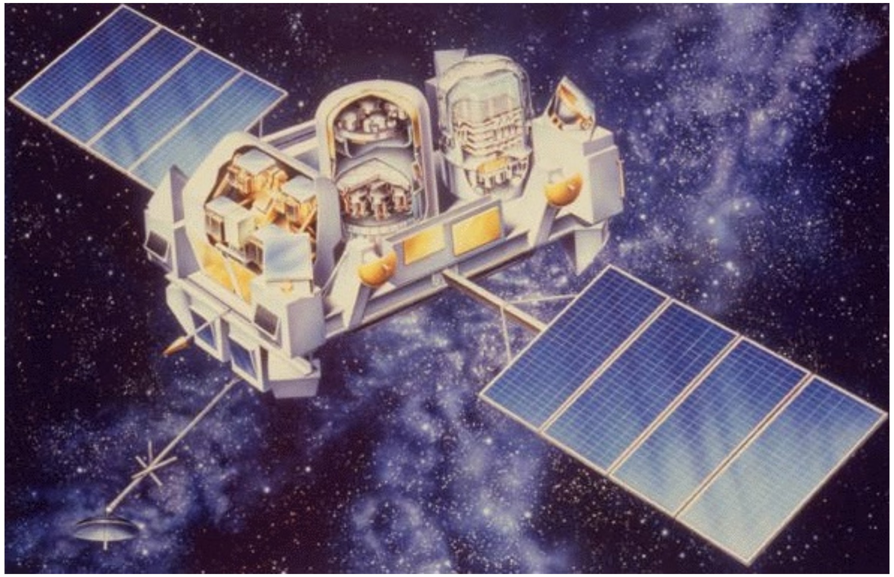
CGRO-COMPTEL

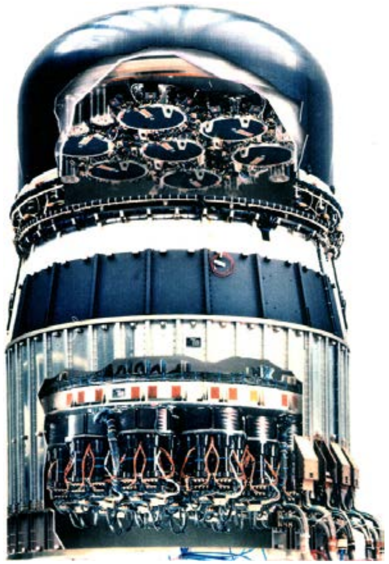
1991-2000

NASA

Compton Telescope

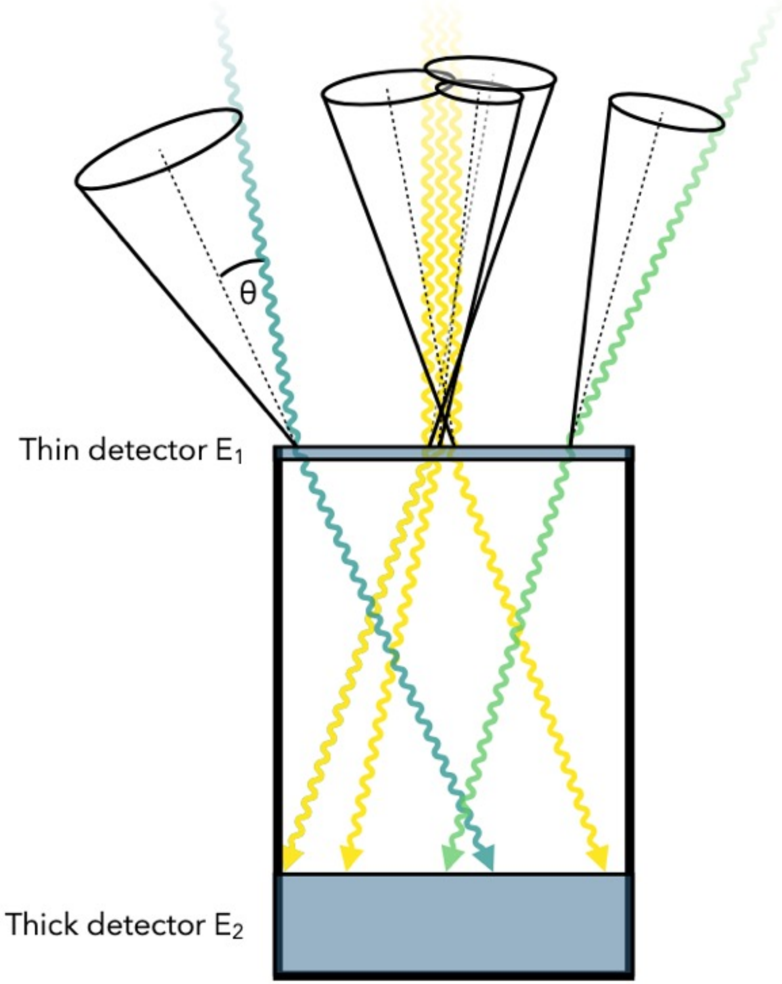
800-30000 keV

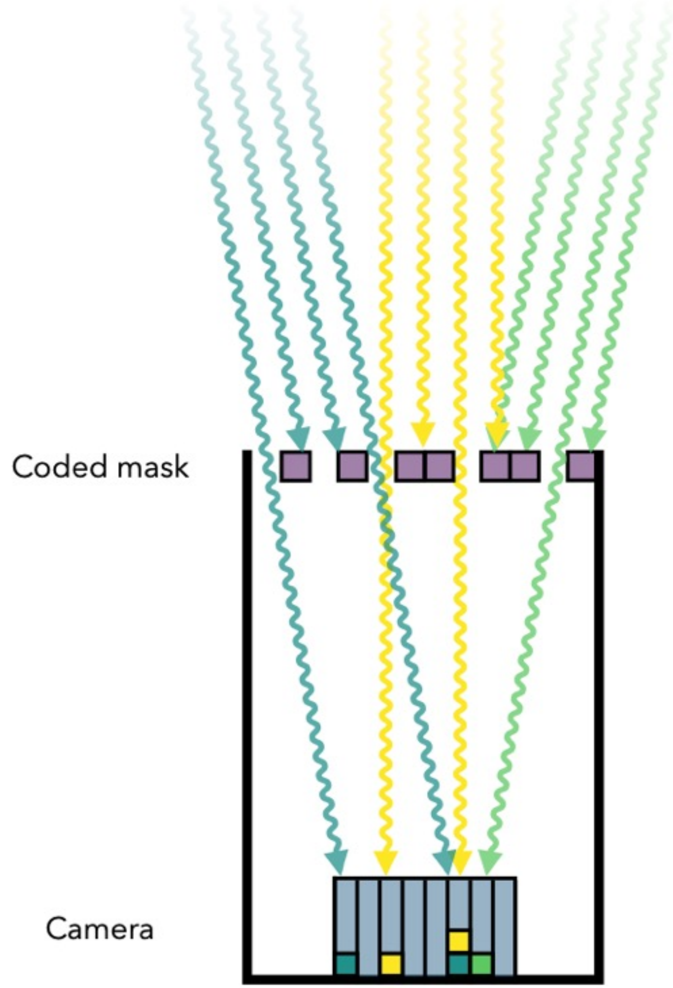




Imaging principles for a MeV-range γ-ray telescope

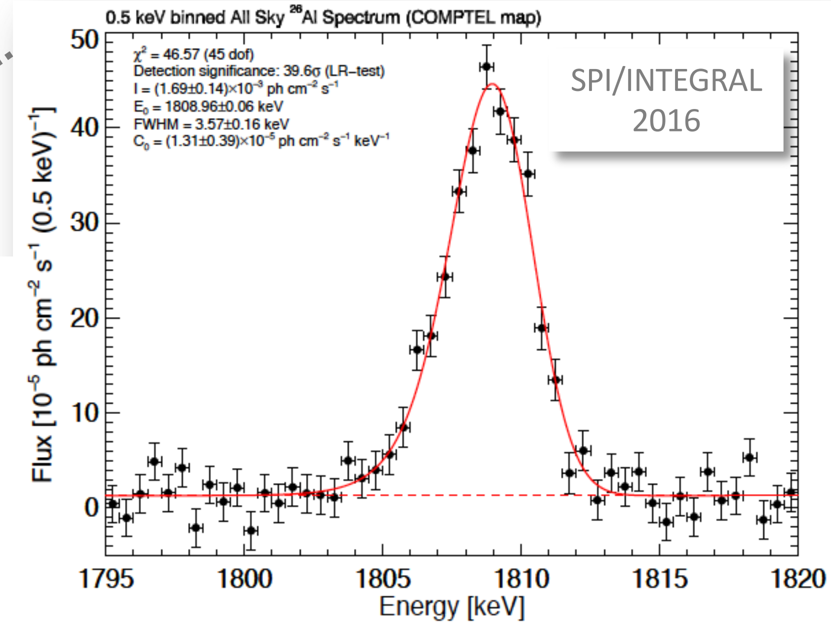
- **Compton Telescopes and Coded-Mask Telescopes**

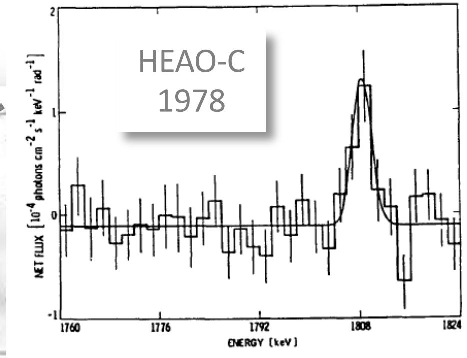


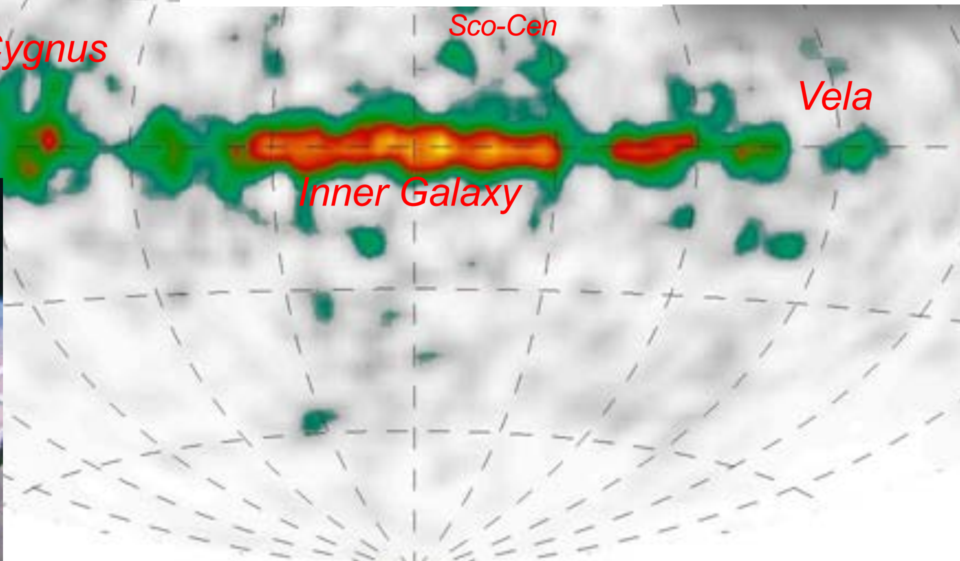


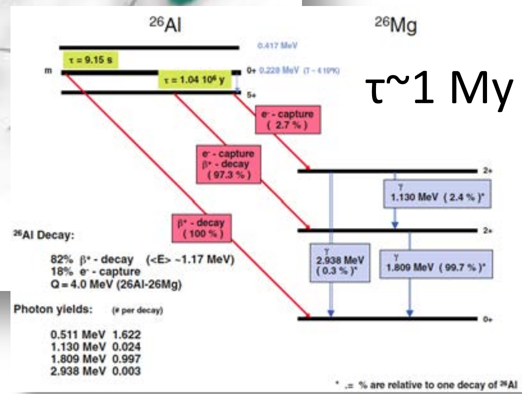
Achievable Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

^{26}Al γ-rays from the Galaxy

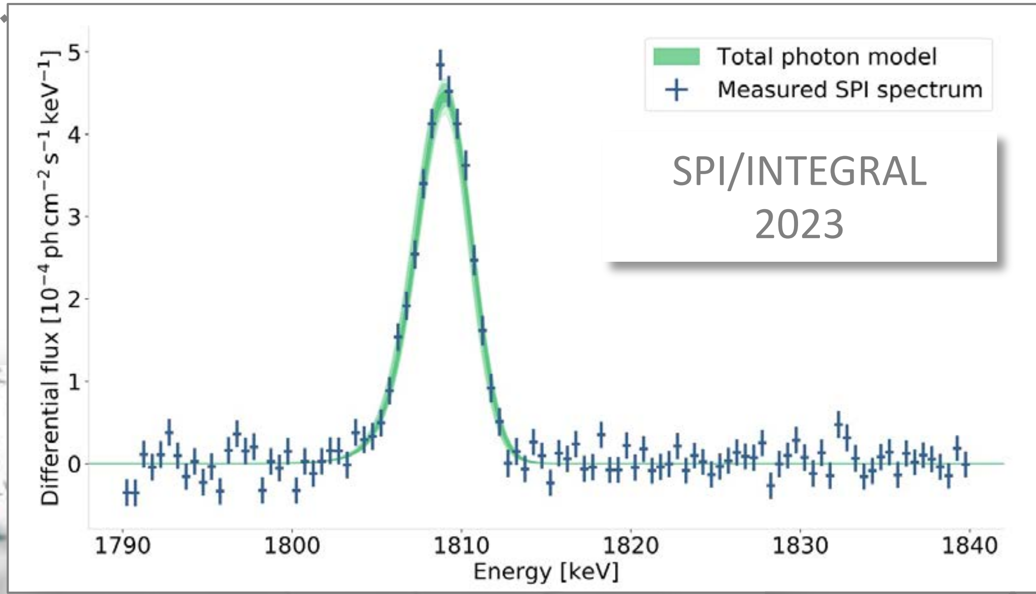


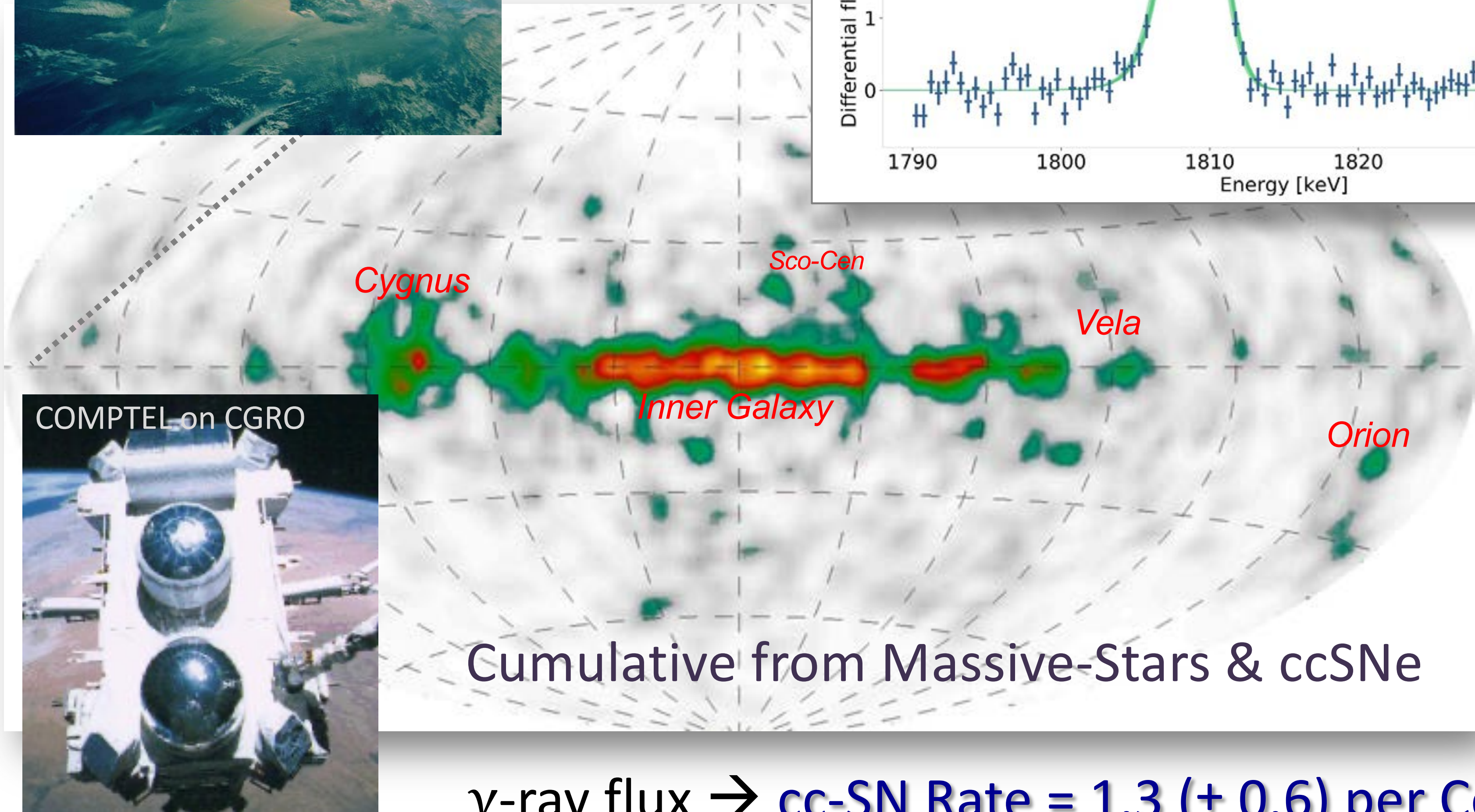






^{26}Al γ-rays and the galaxy-wide massive star census





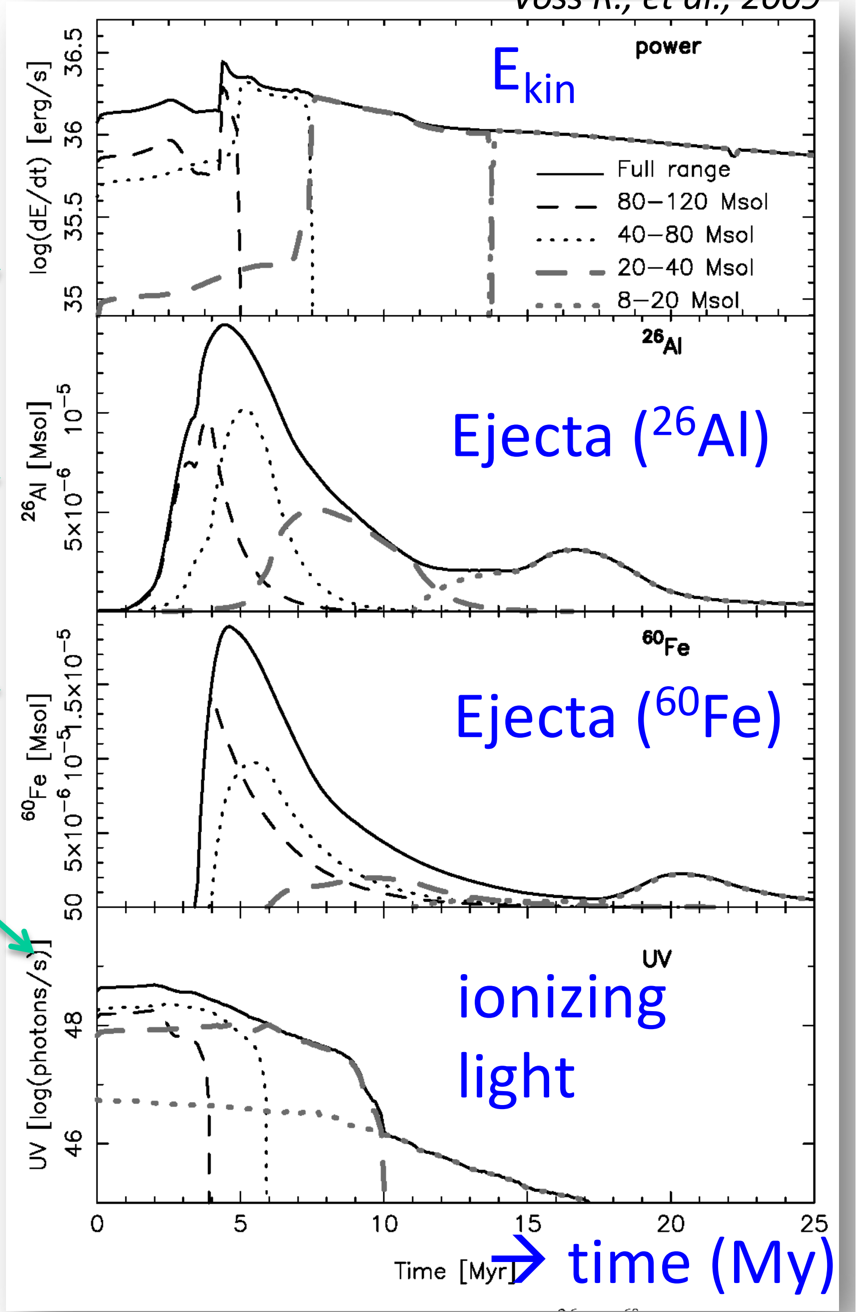
γ-ray flux → **cc-SN Rate = 1.3 (± 0.6) per Century**

Diehl+2006;2018

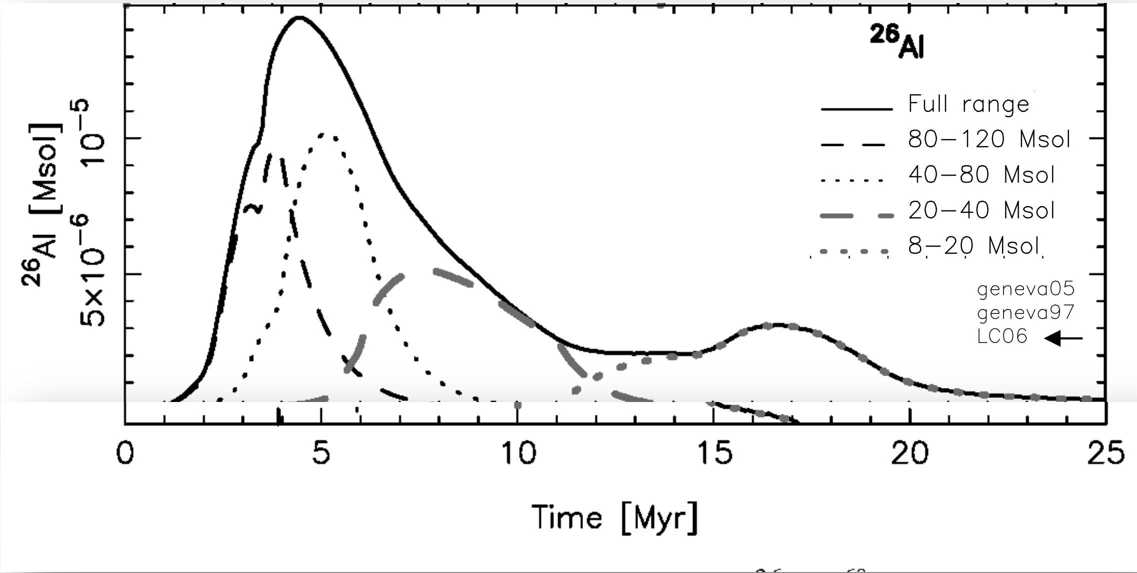
Massive-Star Groups: Population Synthesis

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

Voss R., et al., 2009

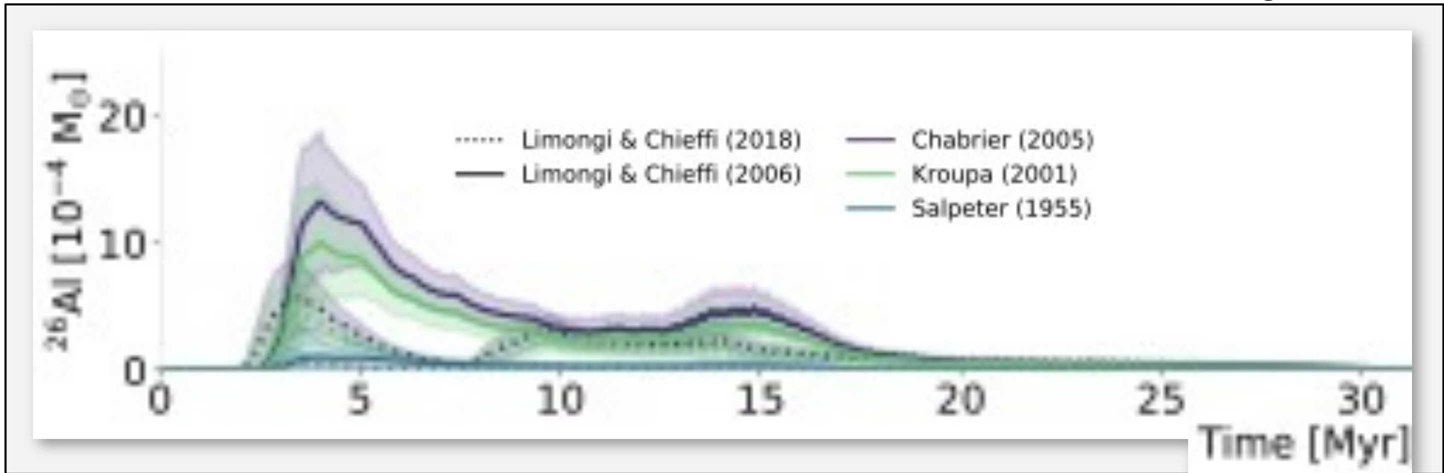


Massive-Star Groups: Population Synthesis



Voss R. et al. 2009

Pleintinger M. 2020

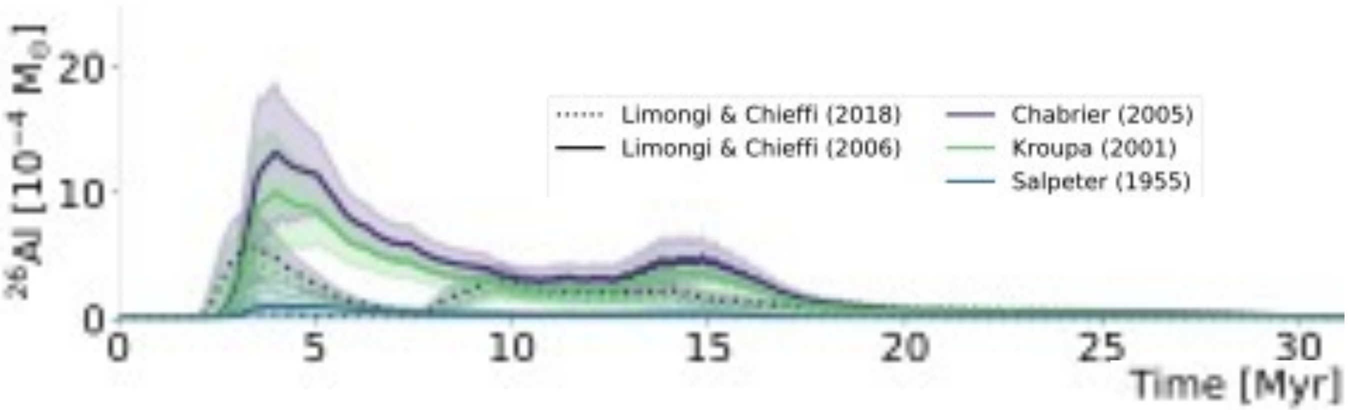


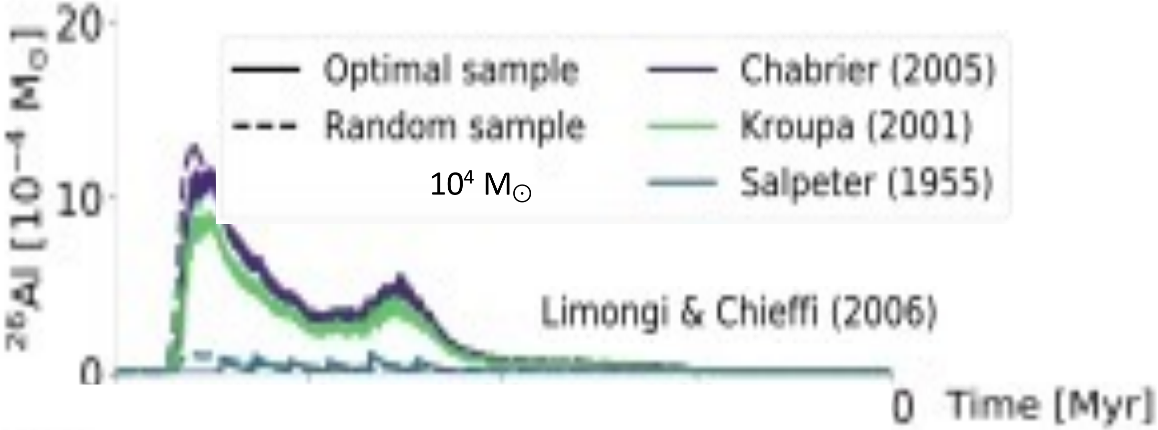
- Re-written PopSyn code
  (Voss+2009 → Python)
  - IMF variants & sampling
  - Nucleosynthesis yield alternatives
  - Explodability variants

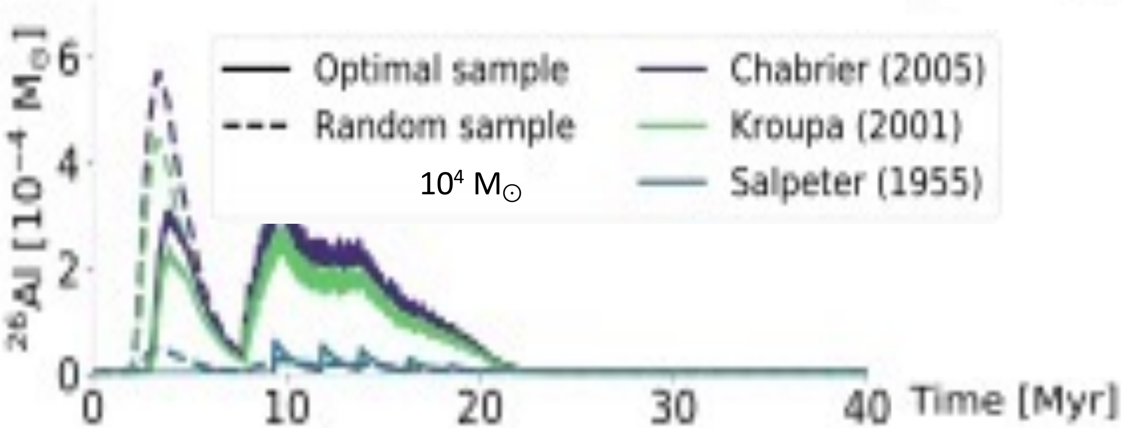
Massive-Star Groups: Population Synthesis

Pleintinger M. 2020

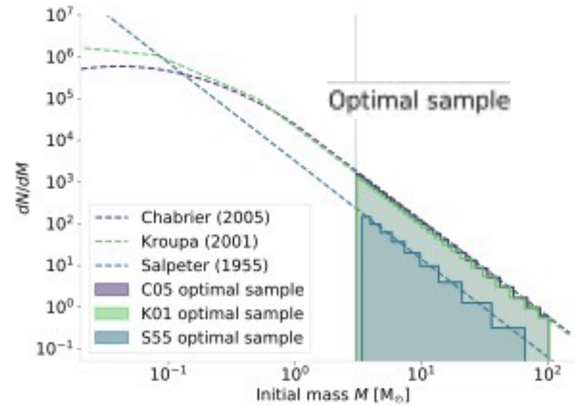
Re-written PopSyn code

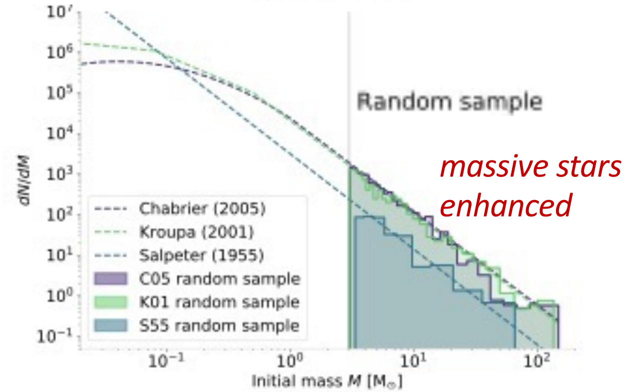






– IMF variants & sampling





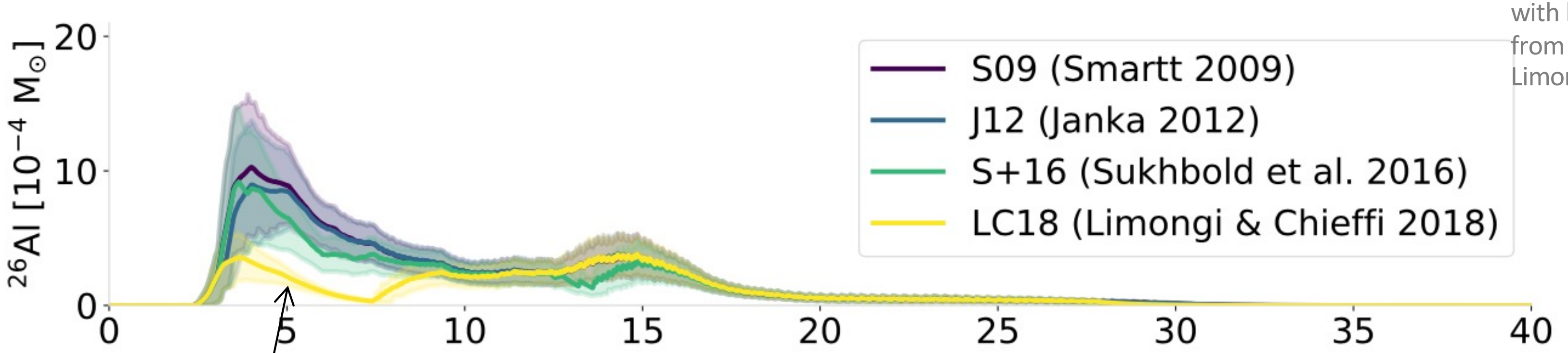
Population synthesis: impact of different inputs

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	$8 \leq M_* \leq 25$

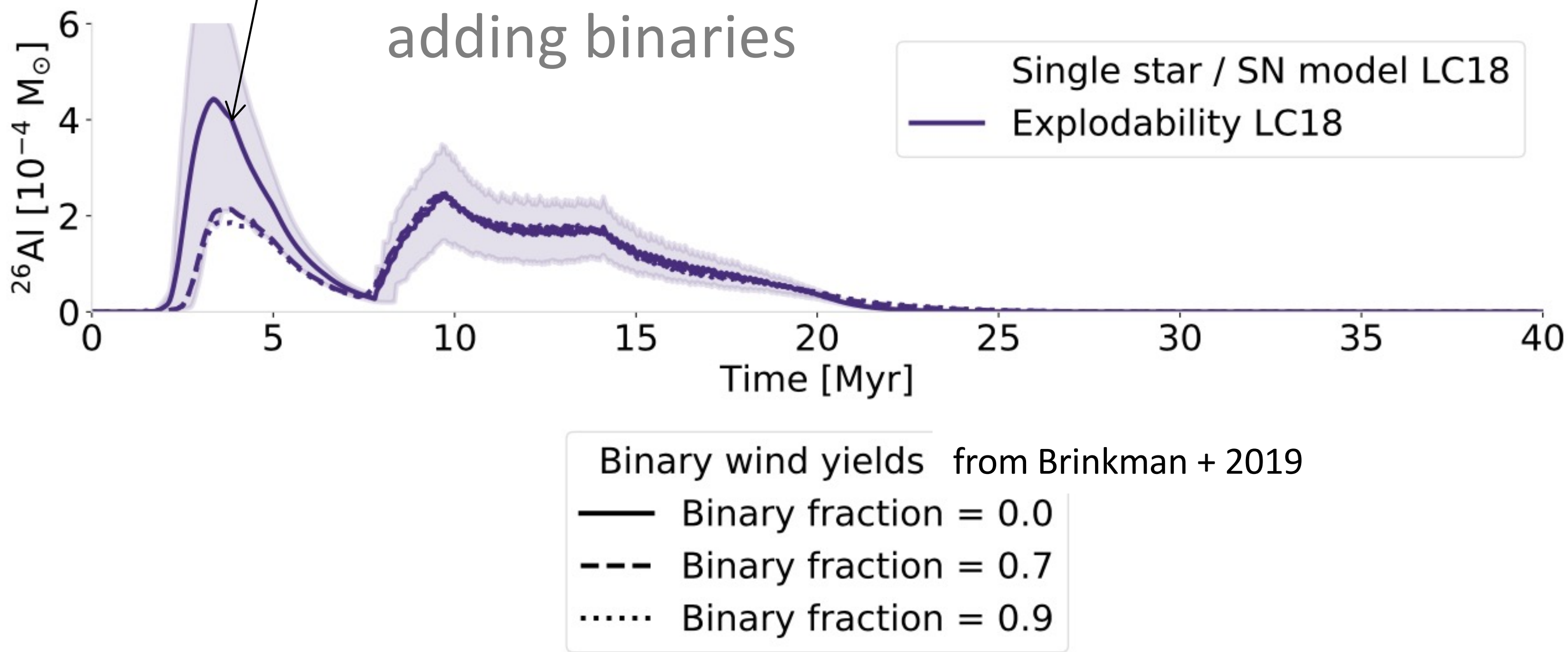
Pleintinger 2020

variation of explodability

with basic yields from Limongi & Chieffi 2006



adding binaries

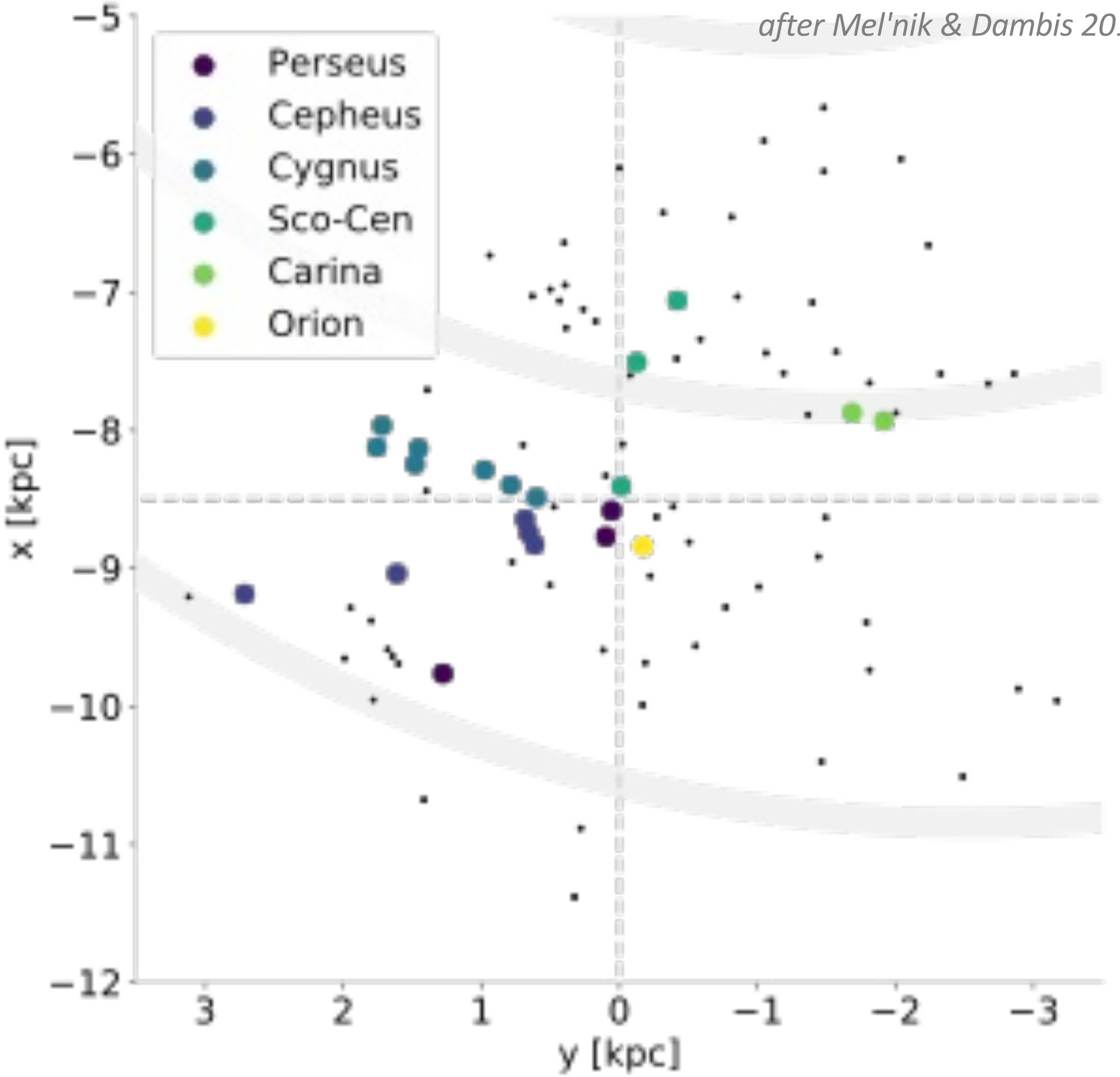


from Brinkman + 2019

Our use of star clusters throughout the Galaxy

Gaia-supported nearby clusters expected to be ^{26}Al sources

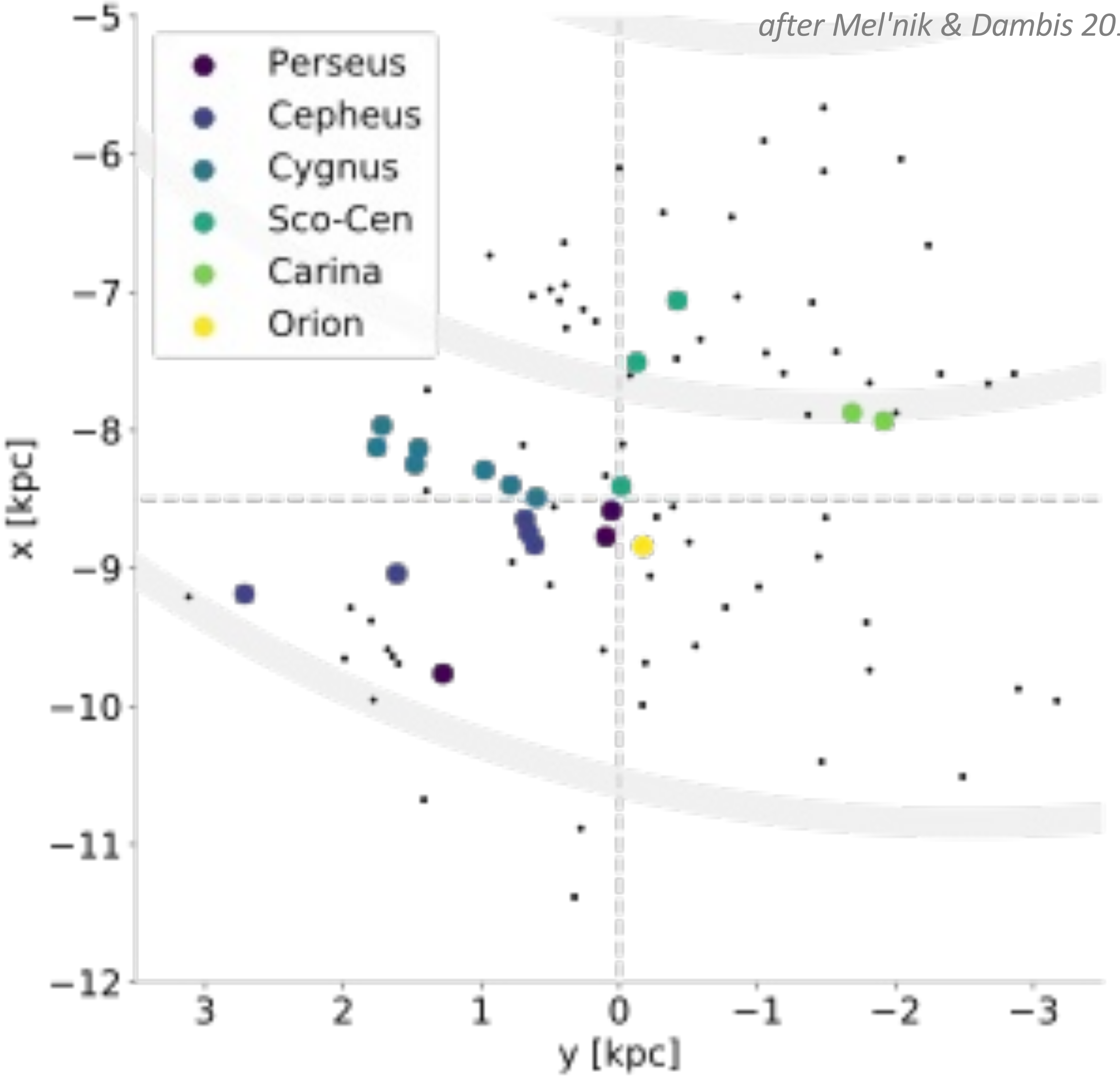
Pleintinger 2020
after Mel'nik & Dambis 2017



Our use of star clusters throughout the Galaxy

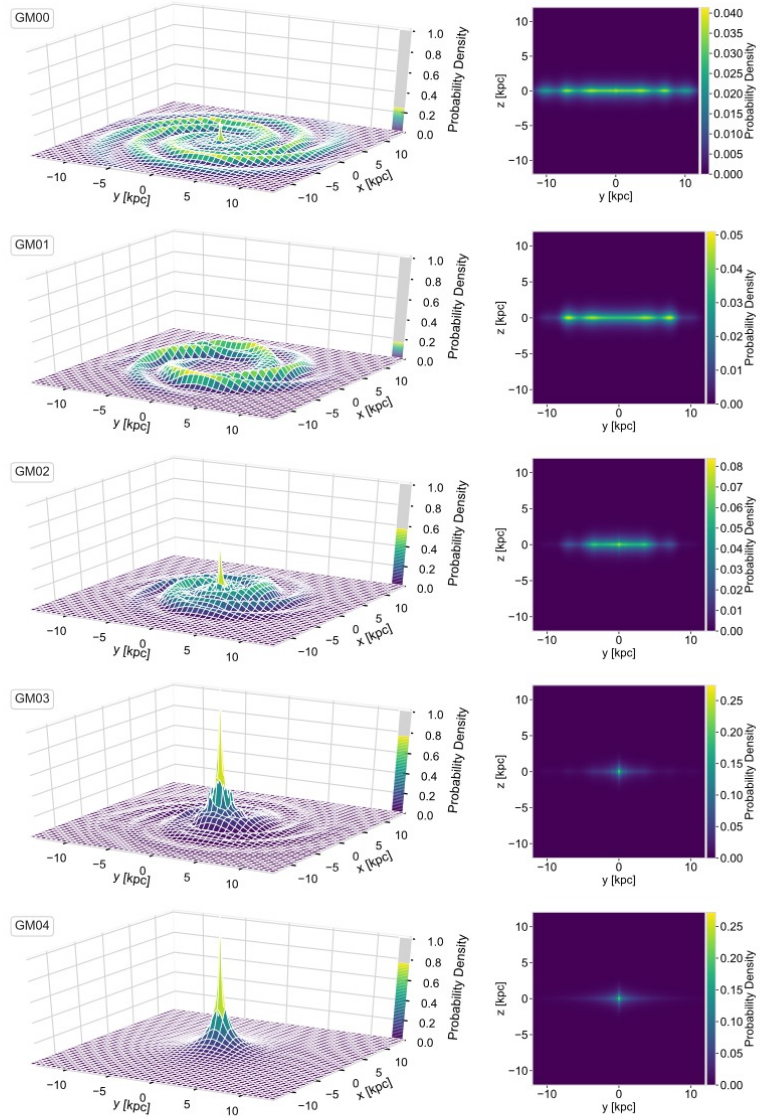
Gaia-supported nearby clusters expected to be ^{26}Al sources

after Mel'nik & Dambis 2017



Pleintinger 2020

sampling distant clusters from a large scale model



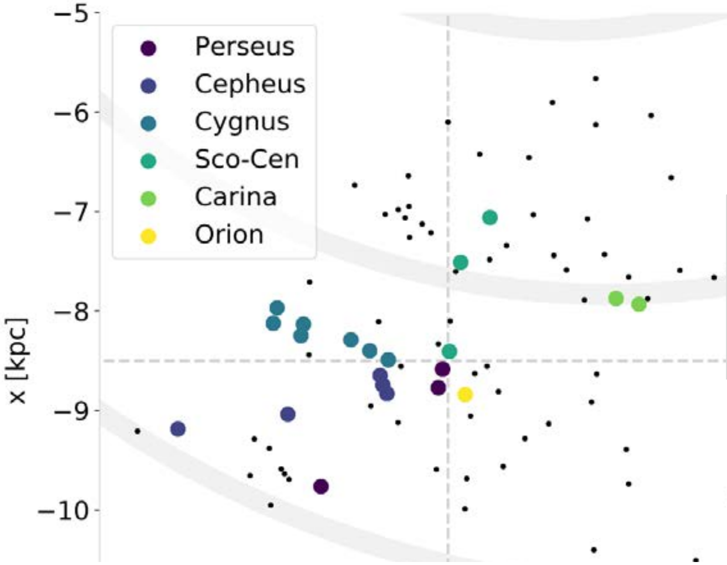
Diffuse radioactivity throughout the Galaxy

Galactic Population Synthesis Modelling

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

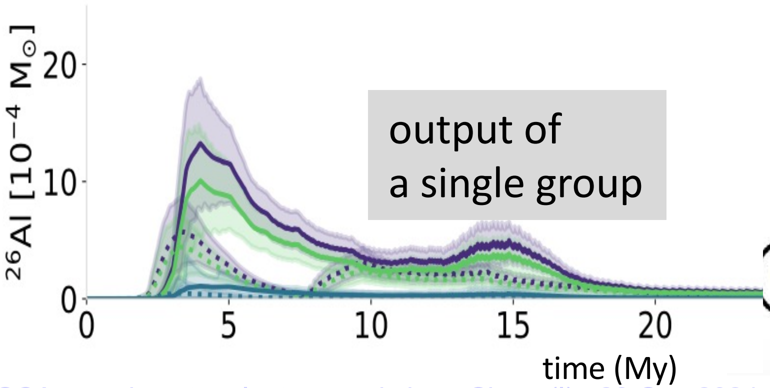
→ bottom-up model for the ^{26}Al observations

Pleintinger PhD thesis 2020 and Siegert+ A&A 2023

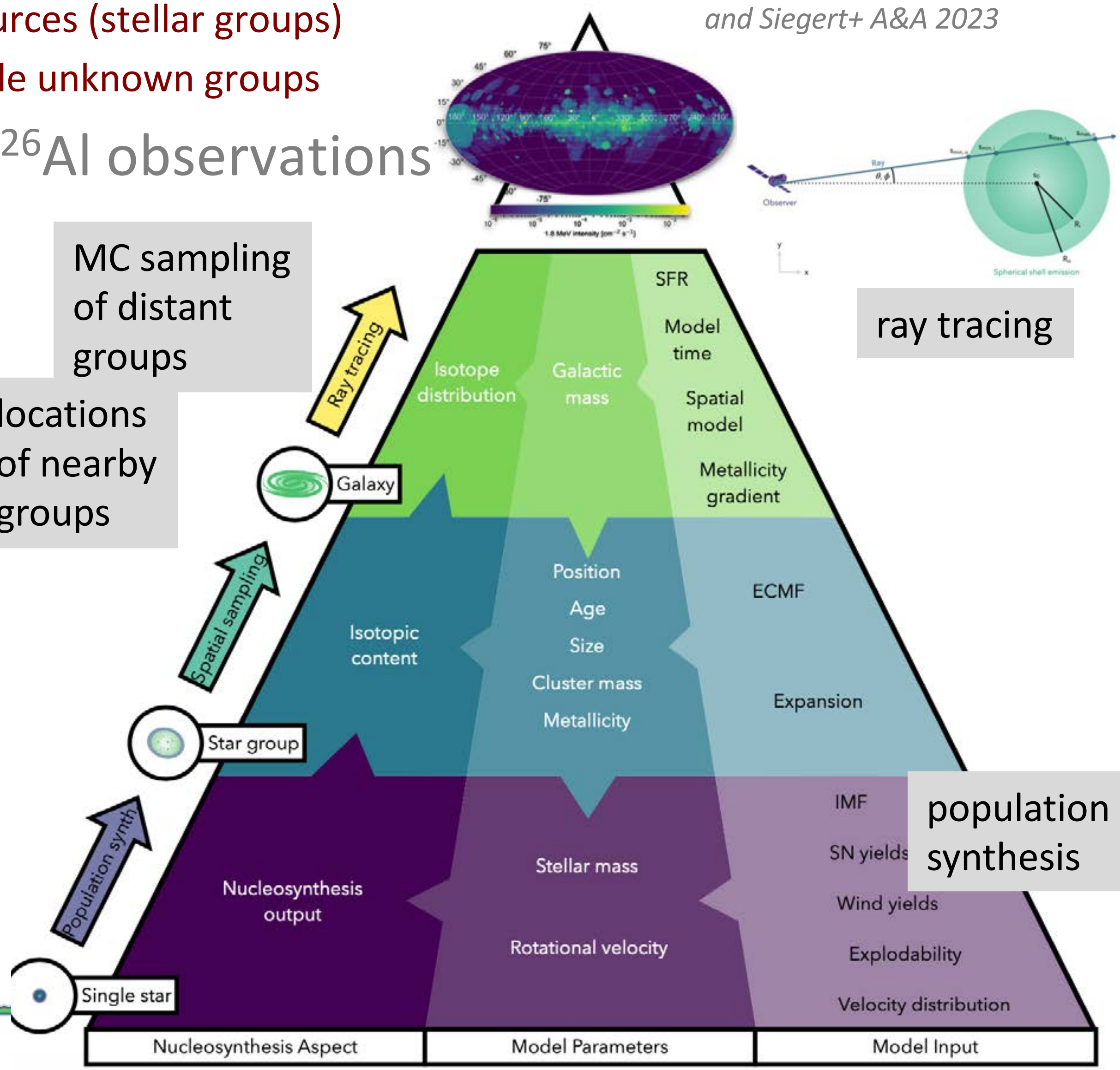


MC sampling of distant groups

locations of nearby groups



output of a single group

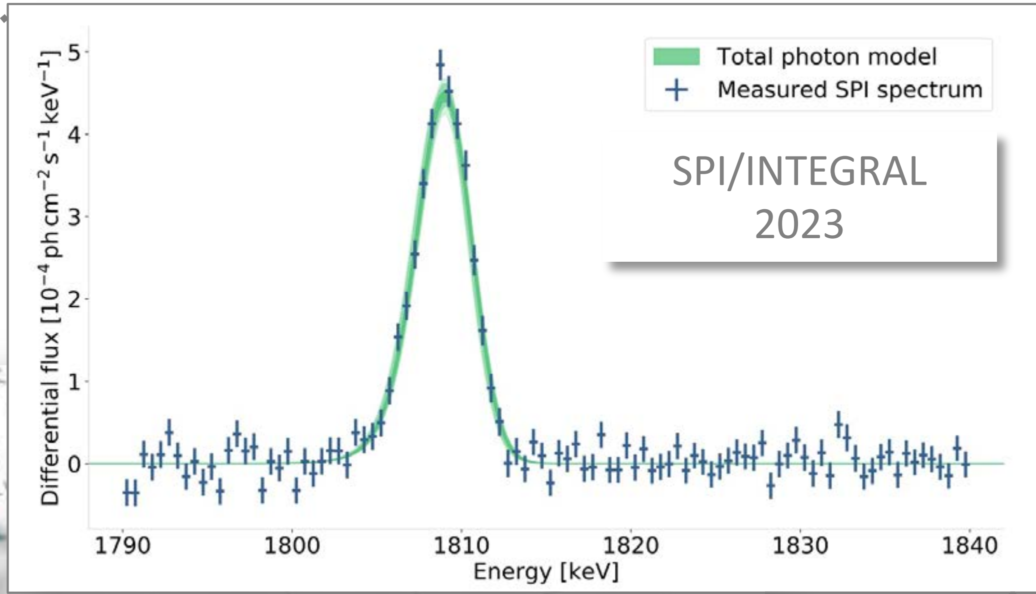


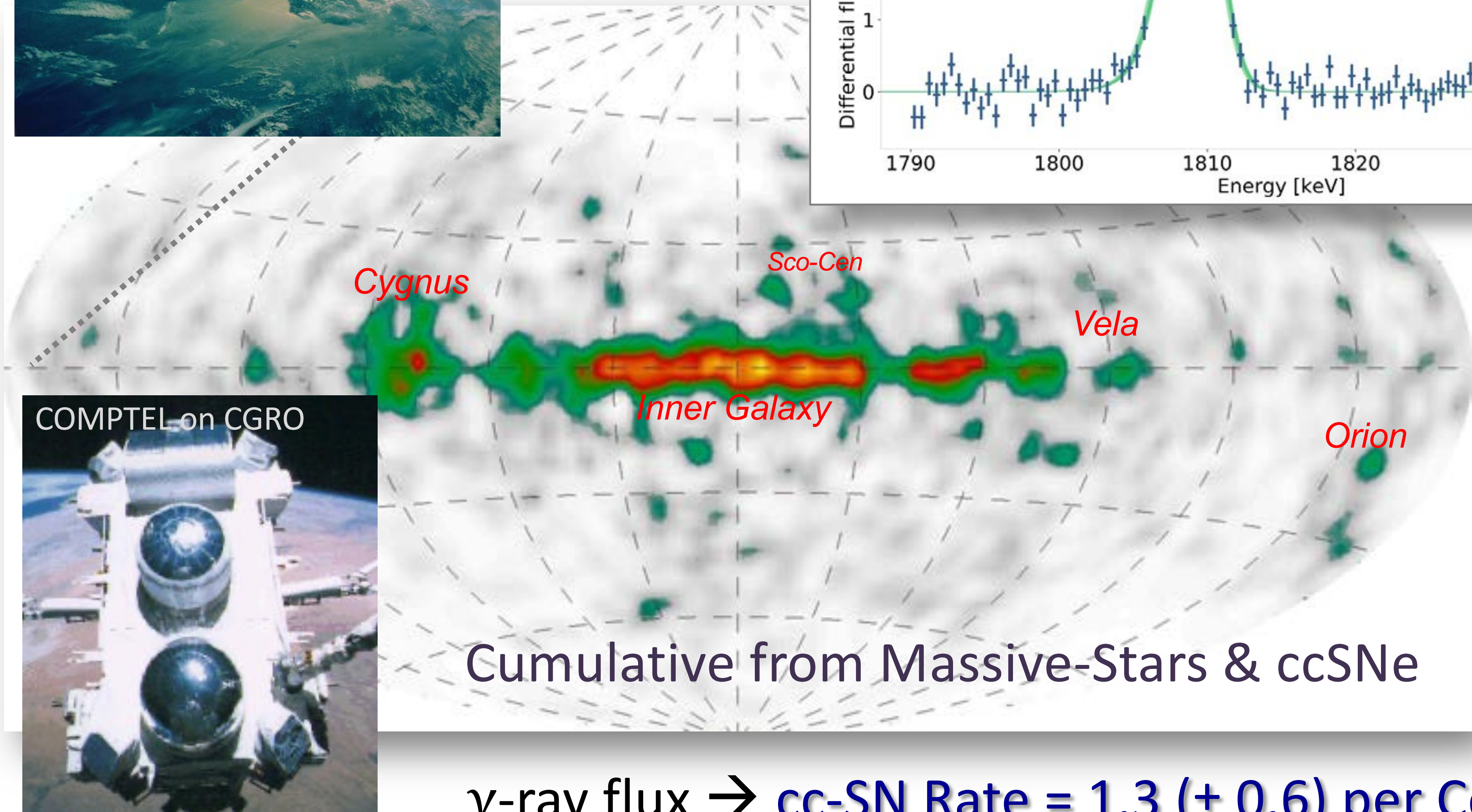
ray tracing

population synthesis

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

Pleintinger+2023





Cumulative from Massive-Stars & ccSNe

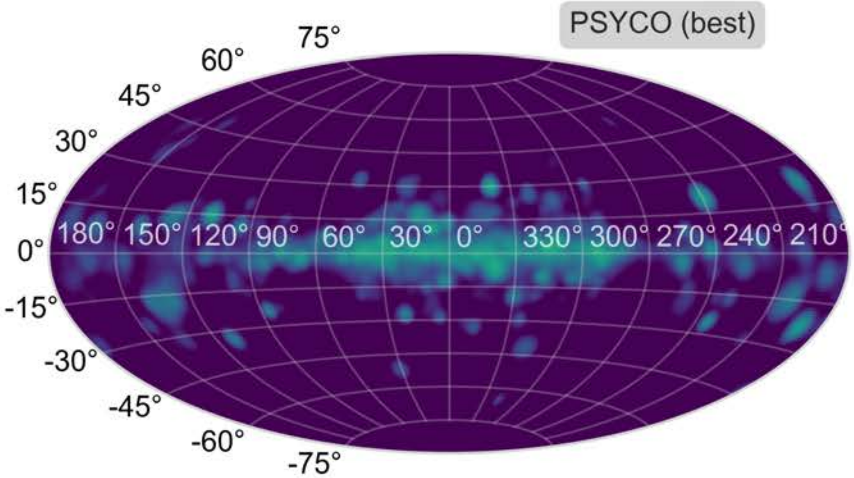
γ-ray flux → cc-SN Rate = 1.3 (± 0.6) per Century

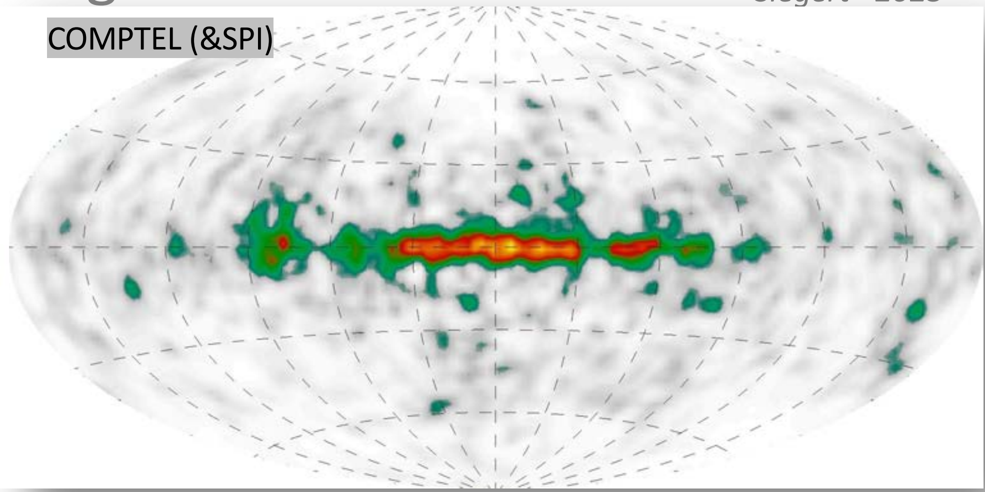
Diehl+2006;2018

Diffuse radioactivity throughout the Galaxy

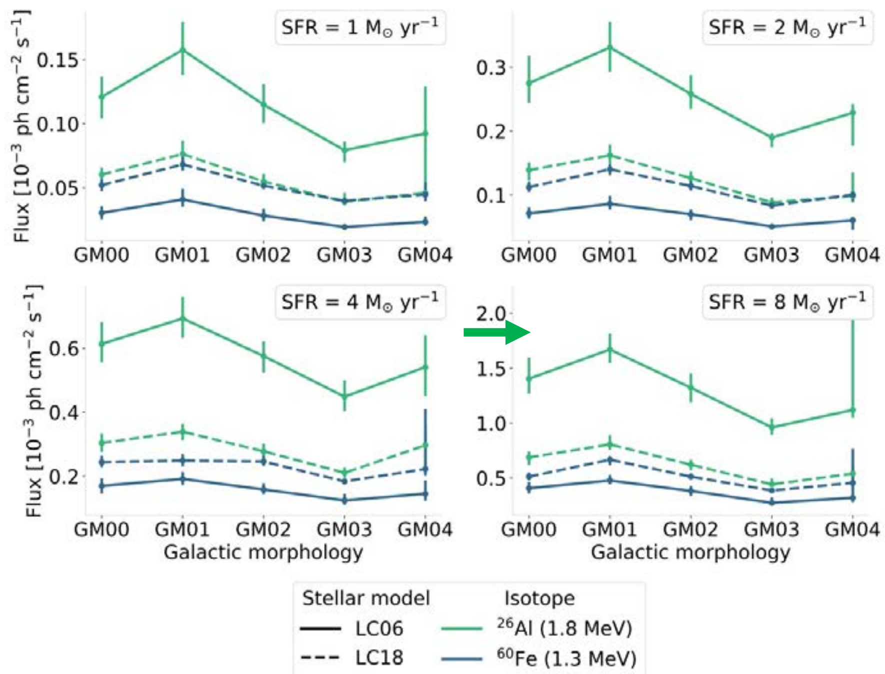
Galactic Population Synthesis Modelling versus observations

(Pleintinger 2020)
Siegert+ 2023





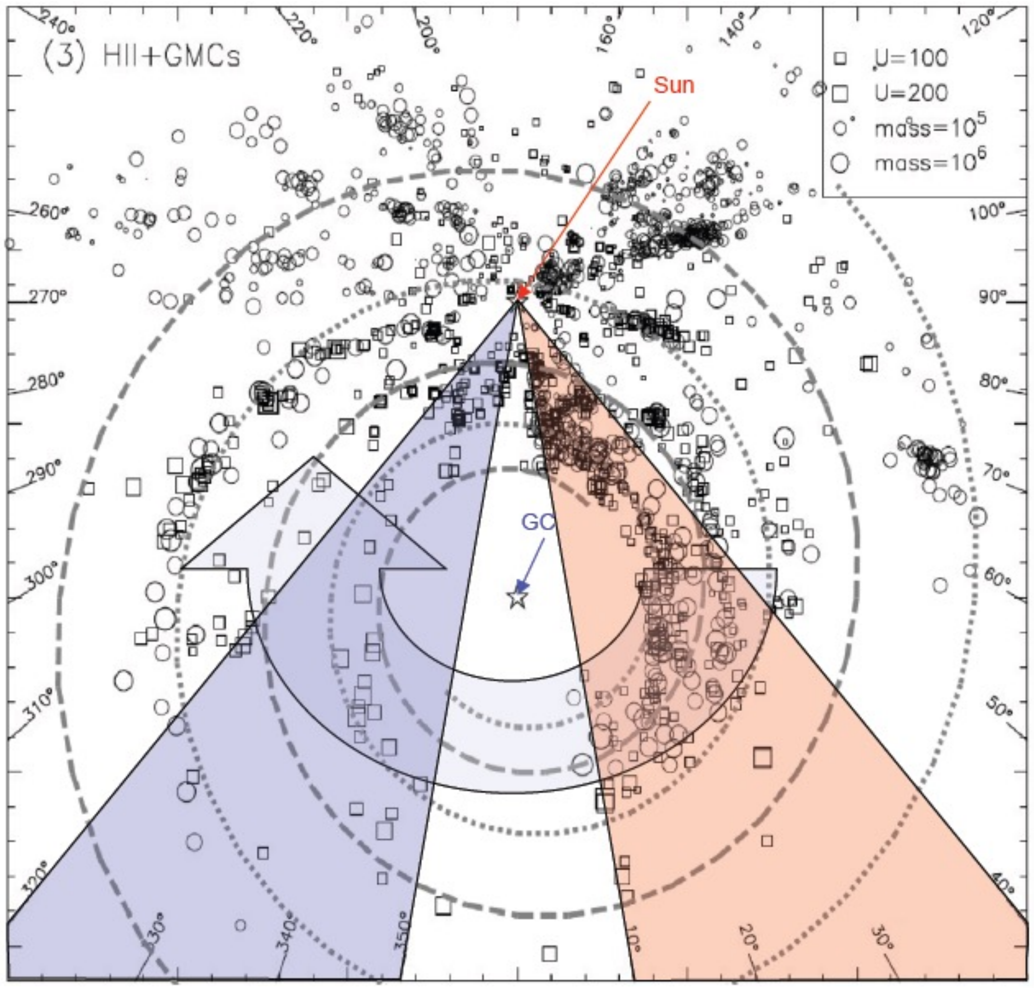
- PSYCO modeling: (30000 sample optimisation)
  → best: 4-arm spiral 700 pc, LC06 yields, SN explosions up to 25 $M_\odot$
- SPI observation: → full sky flux
  $(1.84 \pm 0.03)\ 10^{-3}$ ph cm^{-2} s^{-1}
- flux from model-predicted ^{26}Al:
  → $(0.5..13)\ 10^{-4}$ ph cm^{-2} s^{-1} → too low
- Best-fit details (yield, explodability) depend on superbubble modelling
  (here: sphere only)

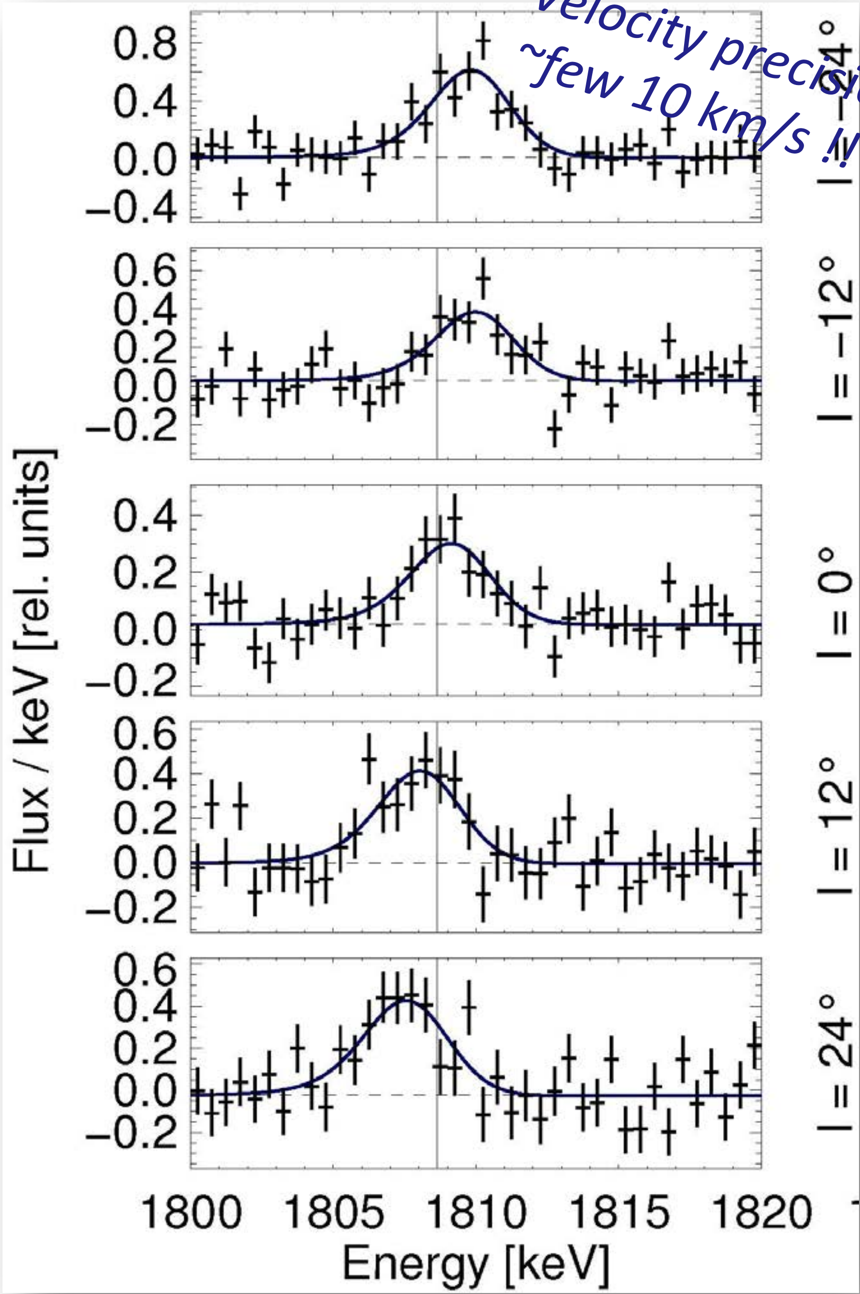


cmp. Gaia/2MASS: ~3.3 $M_\odot$ y^{-1} *(Zari+2022)*

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

☞ Large-scale Galactic rotation



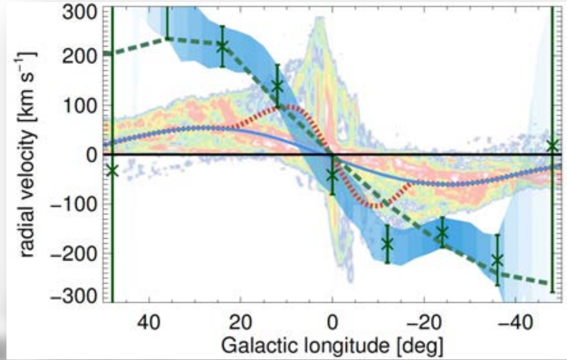


Velocity precision ~few 10 km/s !!

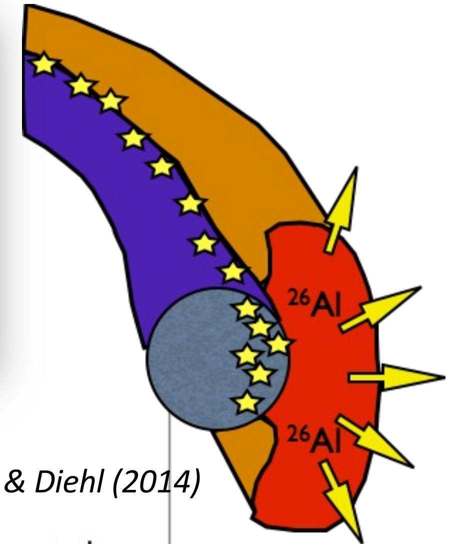
Kretschmer et al., A&A (2013)

How massive-star ejecta are spread out…

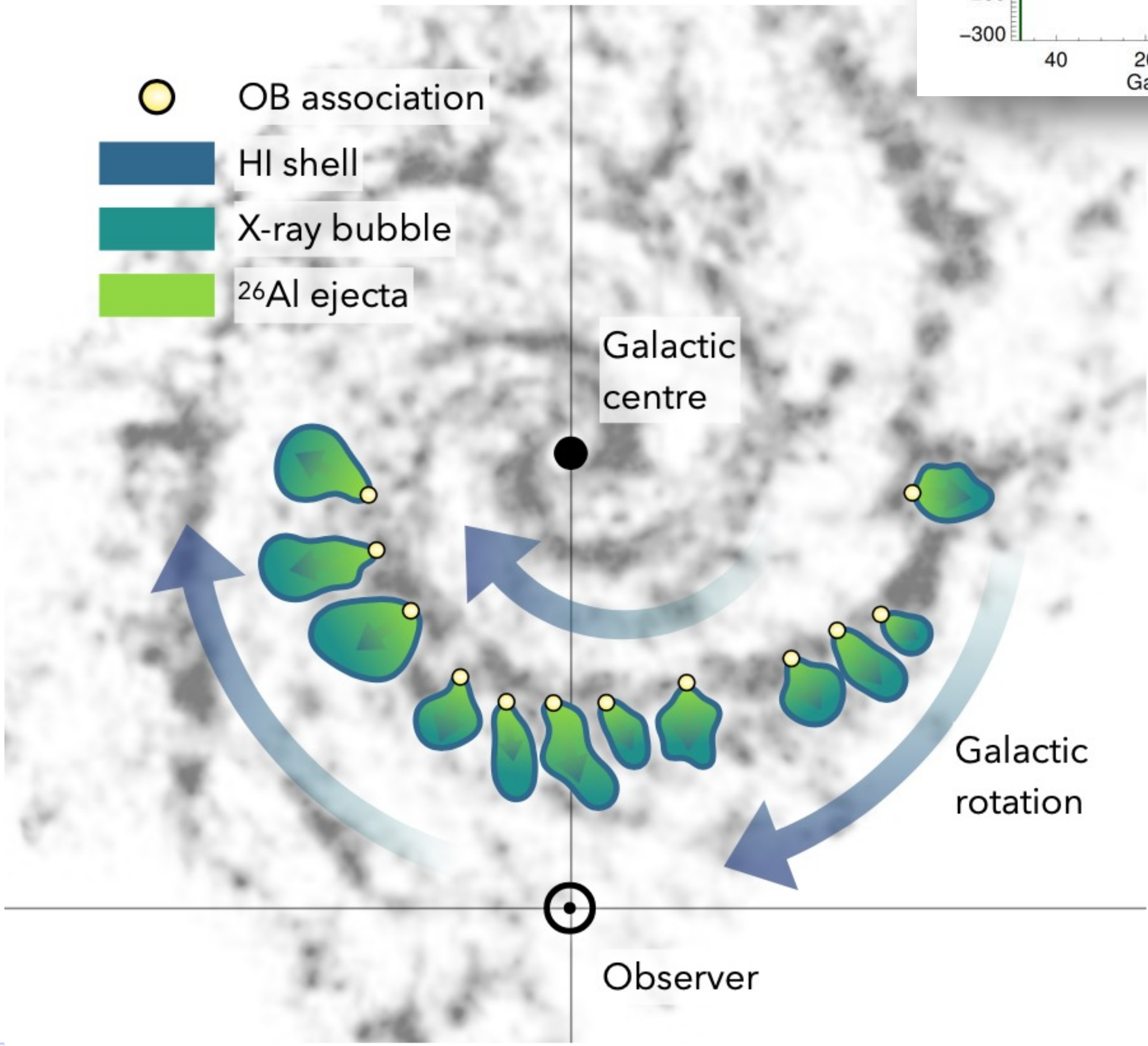
Superbubbles extended away from massive-star groups



Kretschmer+(2013)



Krause & Diehl (2014)



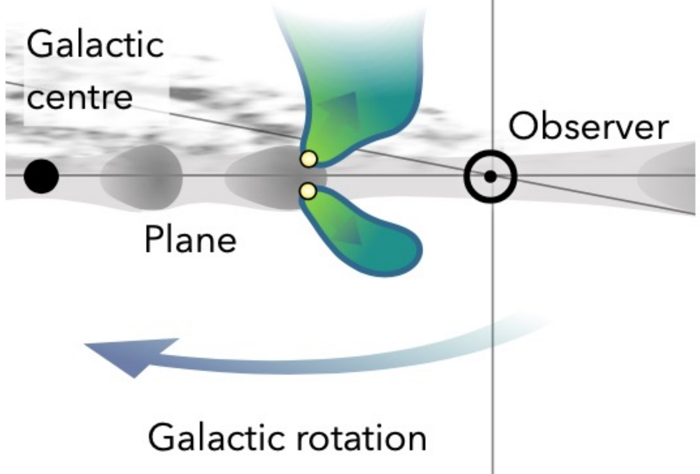


Illustration by M. Pleintinger (2020)

Simulations of (inhomogeneous) galactic evolution

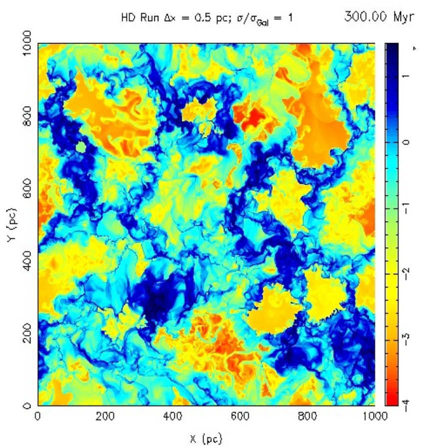
→ ejecta with excess velocities appear naturally within a spiral galaxy

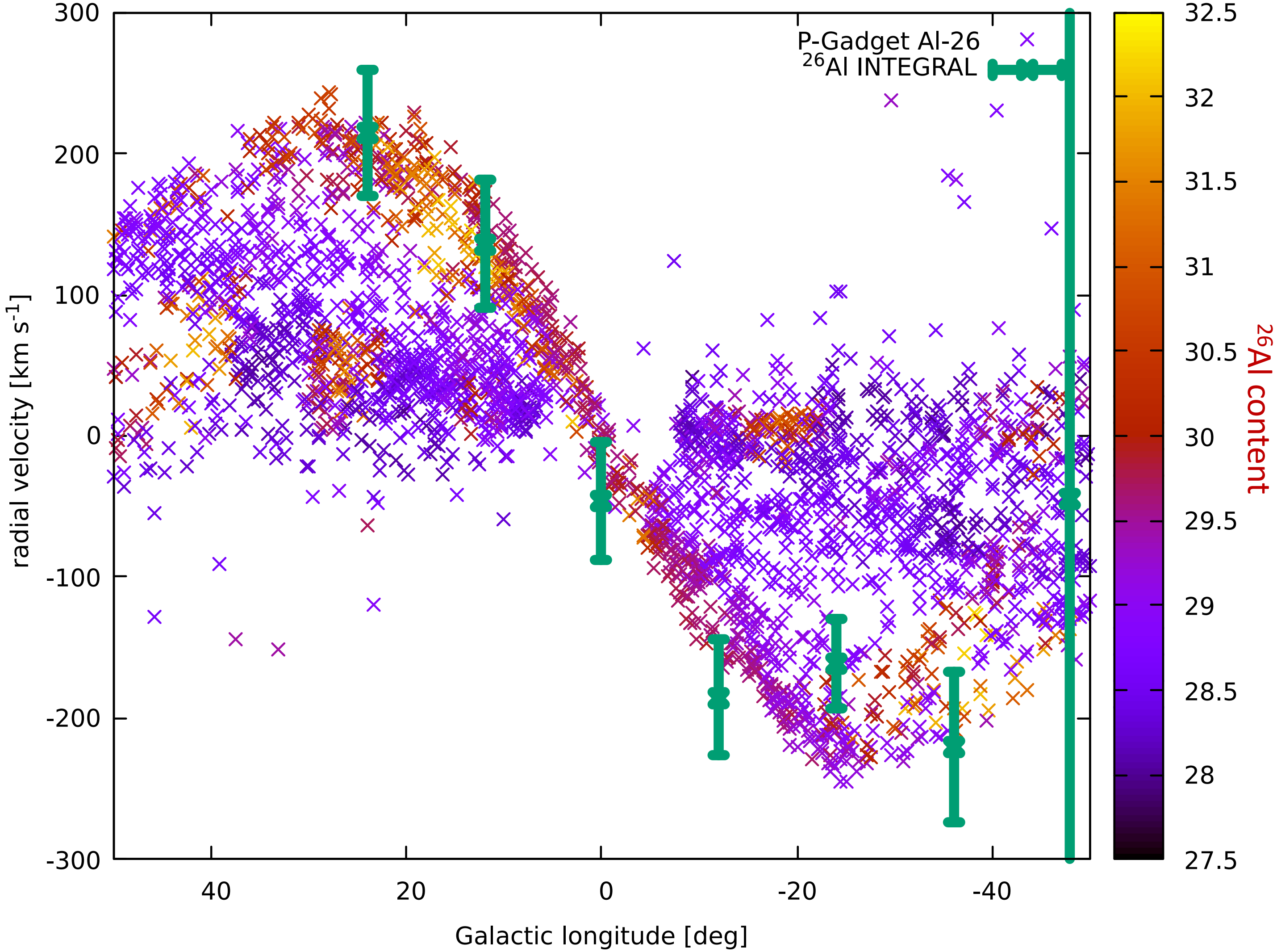
3D SPH simulation: analyze velocities of ^{26}Al-enriched matter from star formation activity

Wehmeyer & Kobayashi 2022

The dynamic ISM (3D MHD)

Breitschwerdt & de Avillez 2003



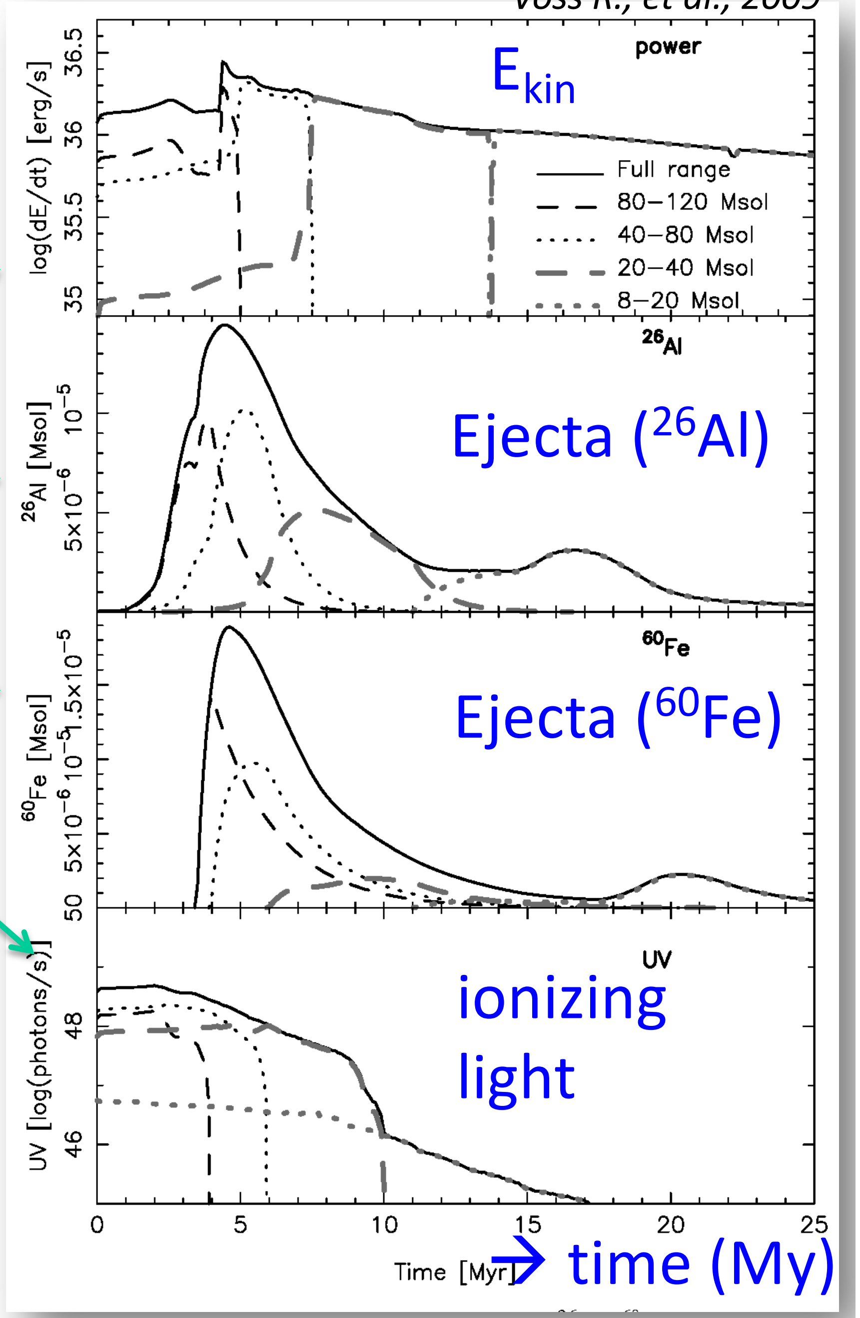


Studying Massive-Star Groups: Models versus Observations

- 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

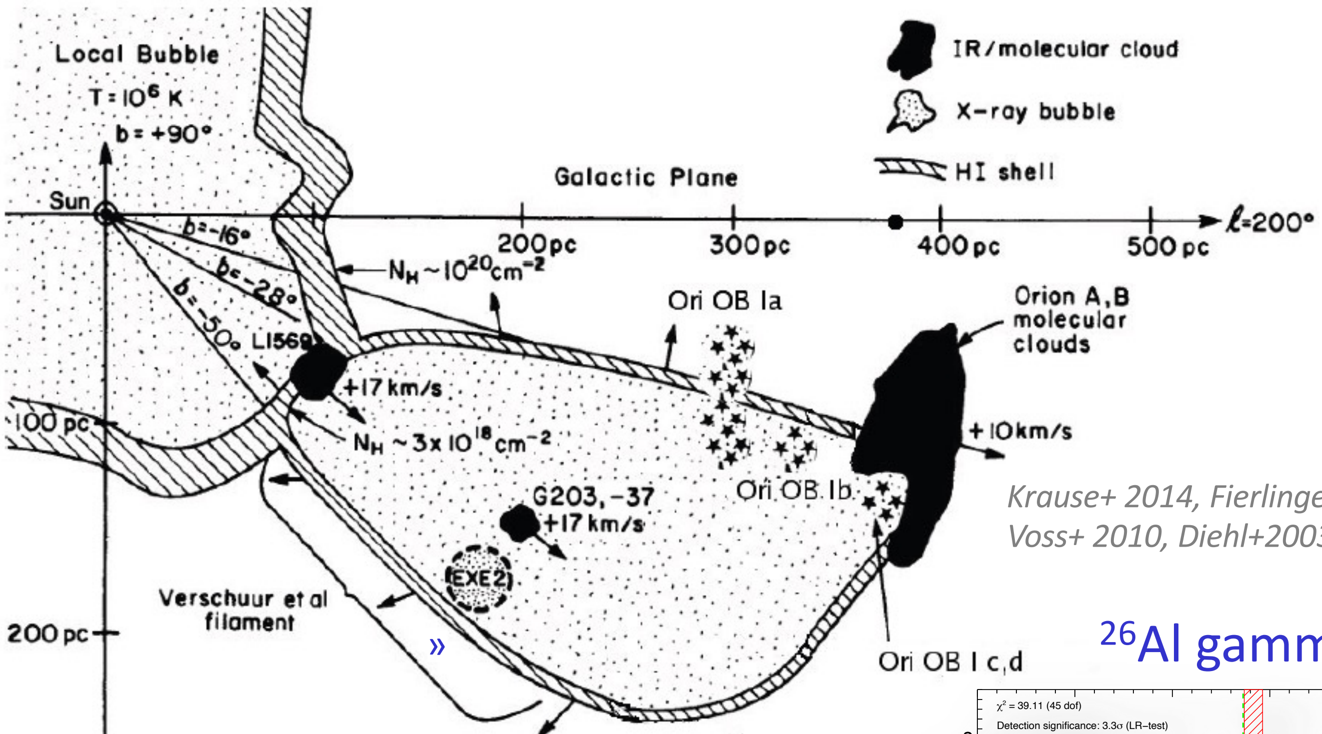
Cygnus: Martin P., et al., 2010
Orion: Voss R., et al., 2010
Carina: Voss R., et al., 2012
Sco-Cen: Diehl R., et al., 2010

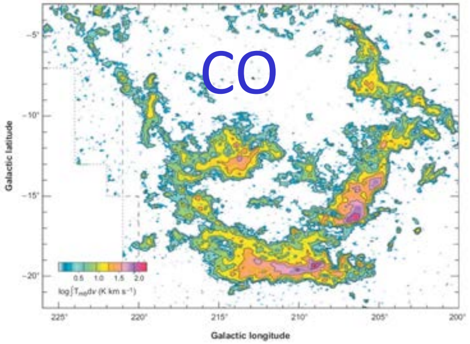
Voss R., et al., 2009

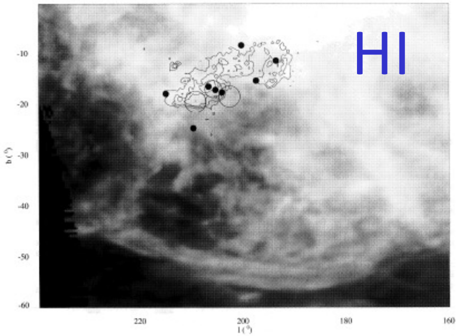


Orion-Eridanus: A superbubble blown by stars & supernovae

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

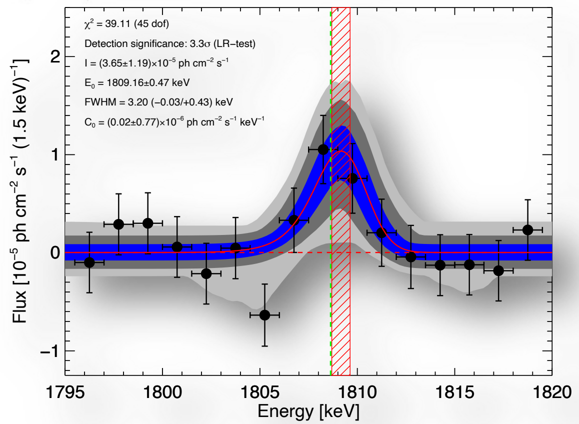


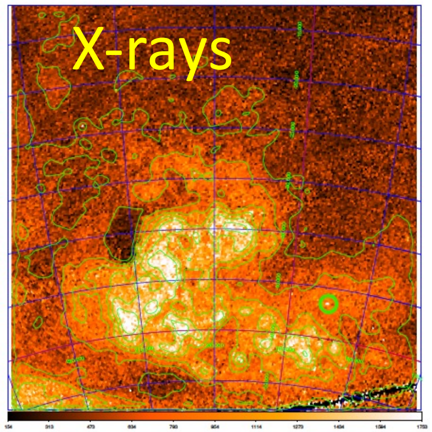


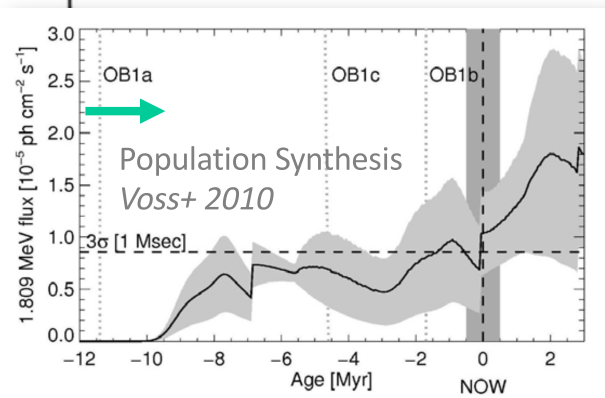


Krause+ 2014, Fierlinger+ 2016, Voss+ 2010, Diehl+2003

^{26}Al gamma-rays





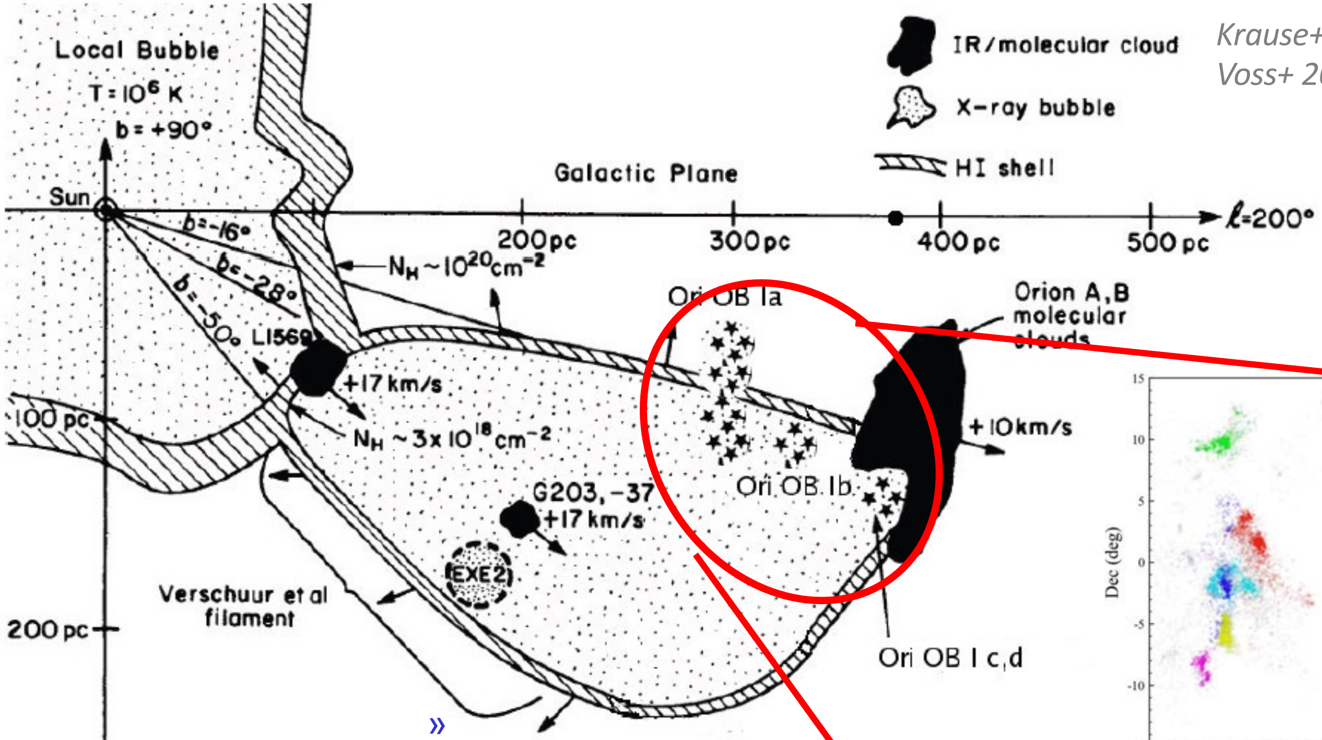


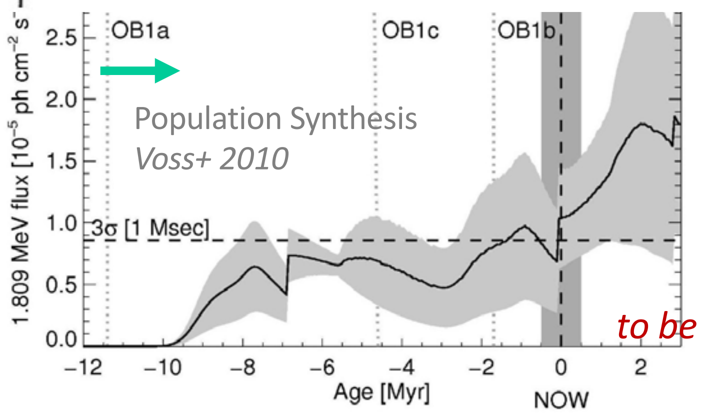
Star and stellar clusters in Orion and the Eridanus shell

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

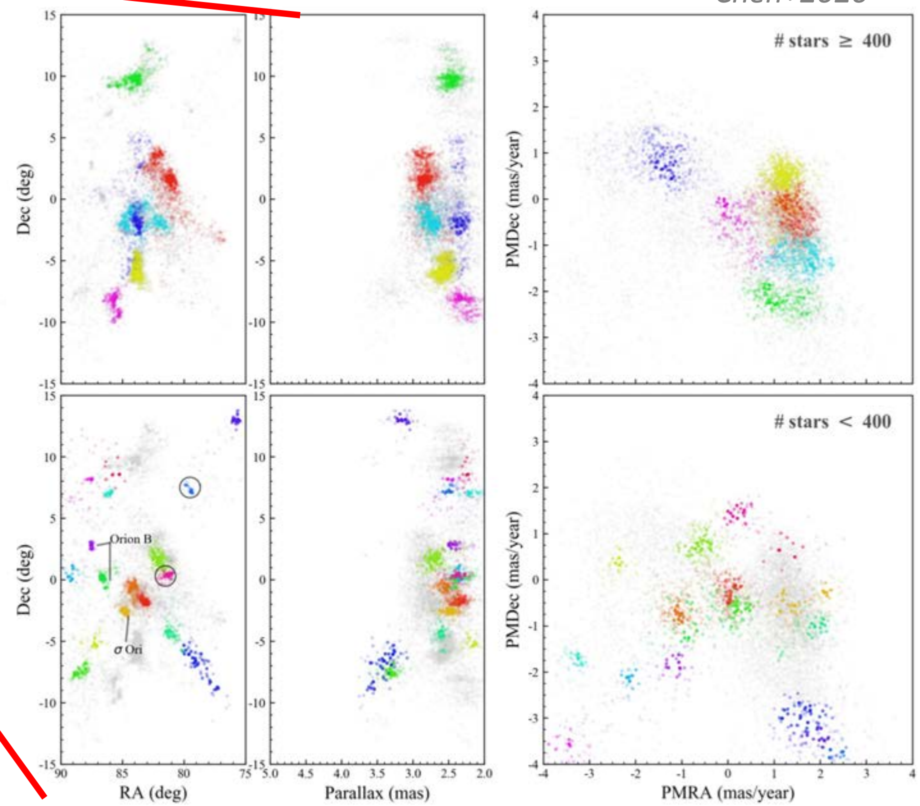




to be renewed...

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

Chen+2020

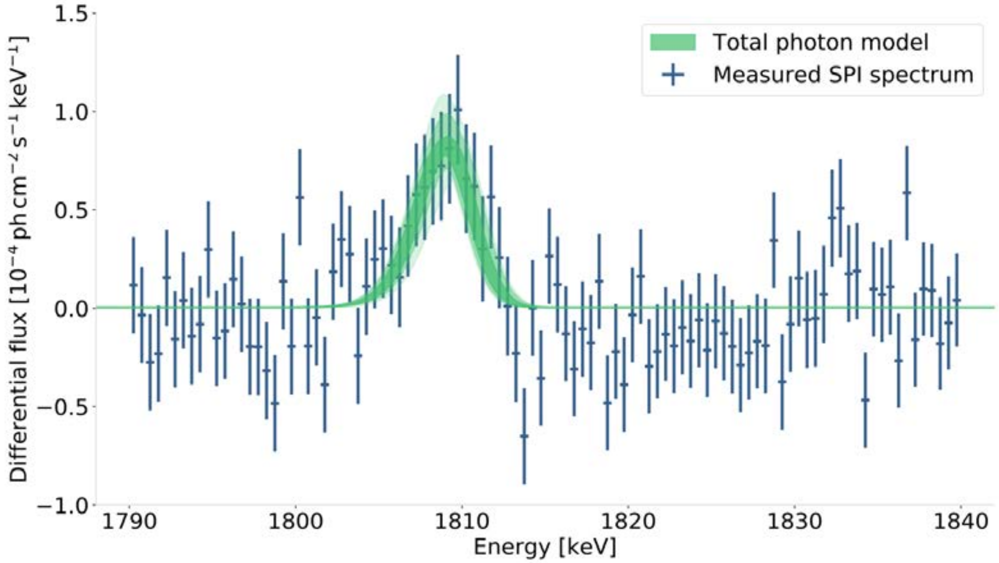


The Perseus OB Association

Pleintinger 2020

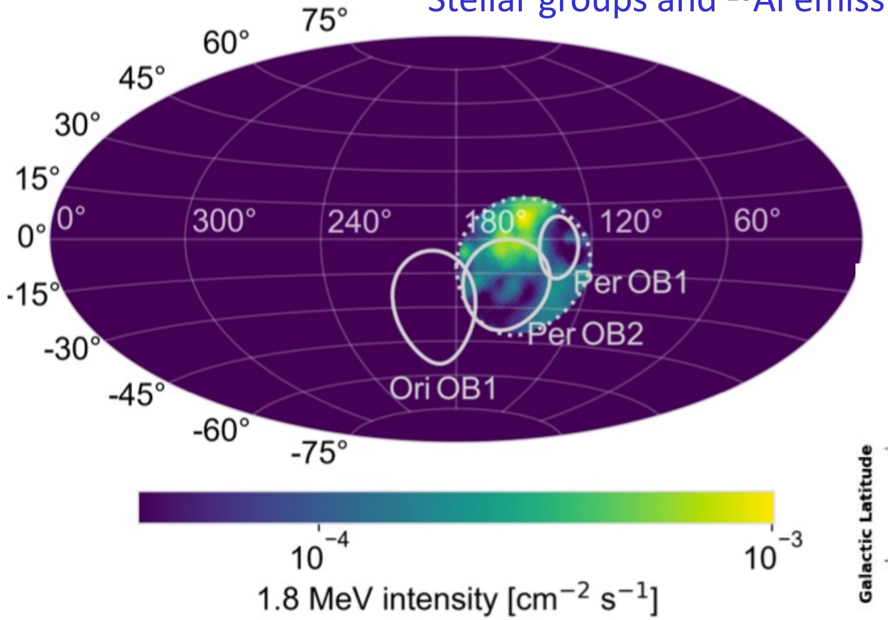
Distance ~300 pc (Per OB2);
location (l,b)= 165°,-15°); age ~6 My

^{26}Al signal 3.6 10^{-4} ph cm^{-2} s^{-1} (>8σ),
~3 10^{-3} $M_{\odot}$



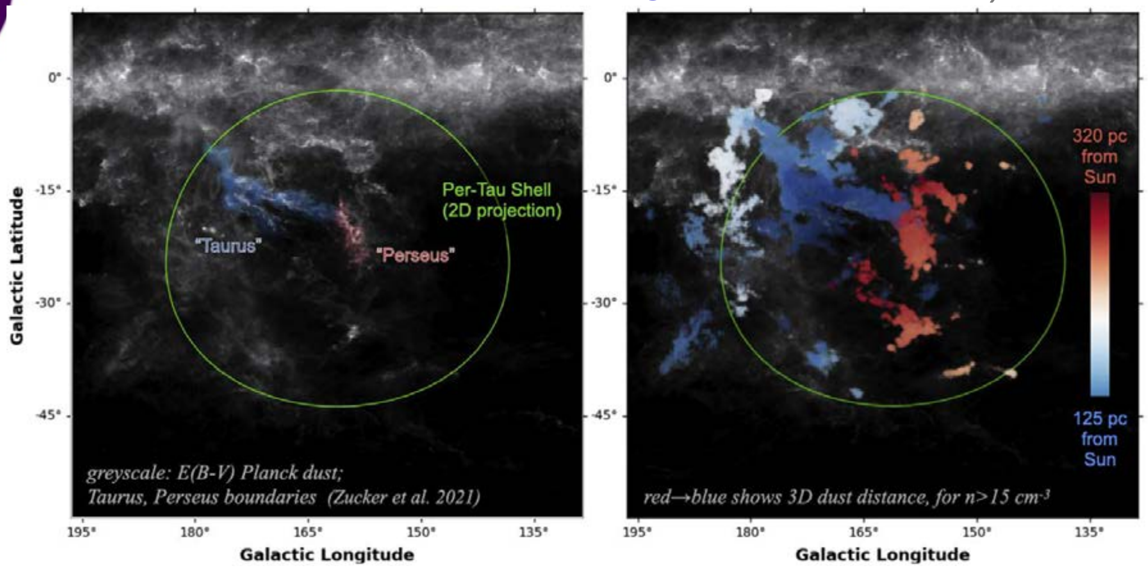
^{26}Al flux offset
from OB groups (l,b)= 149°,-8°

Stellar groups and ^{26}Al emission



Molecular clouds in the Per-Tau region

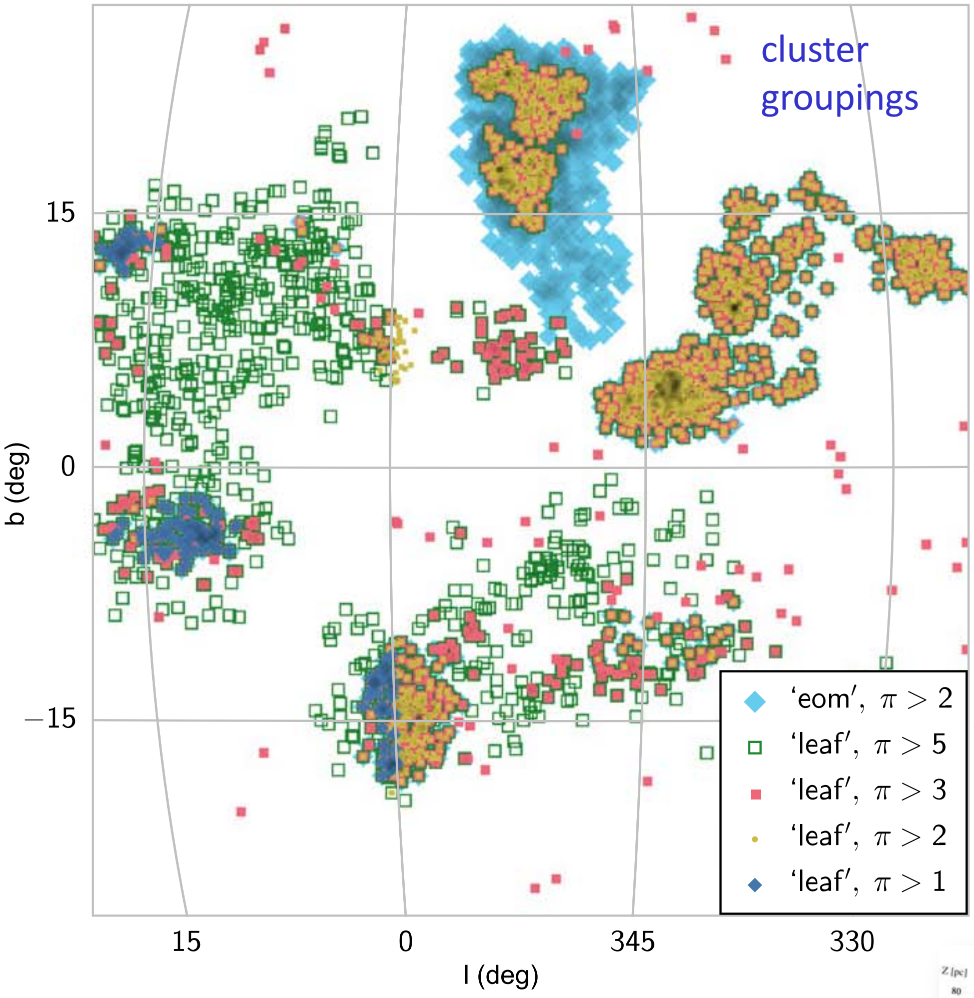
Bialy+ 2021

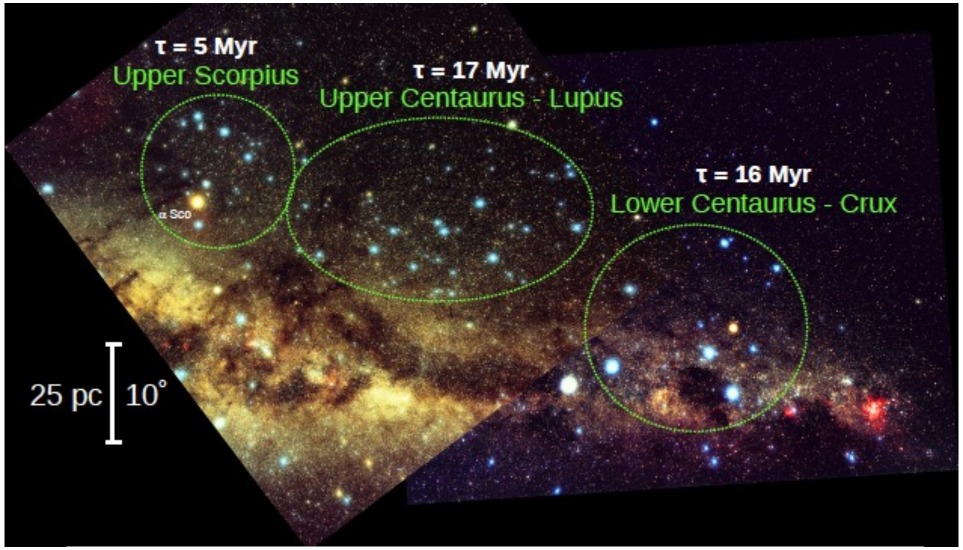


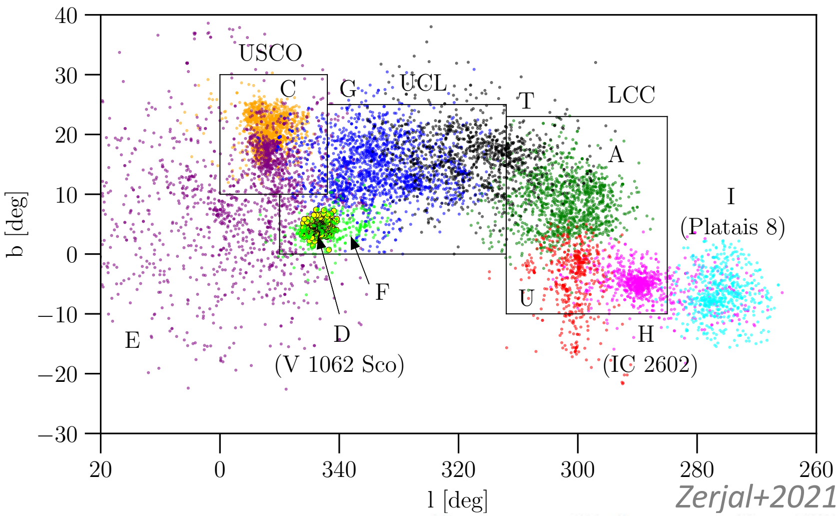
The Sco-Cen Association: Identifying the entire stellar population

- Nearest OB Association (~120pc)

Kounkel&Covey+2019



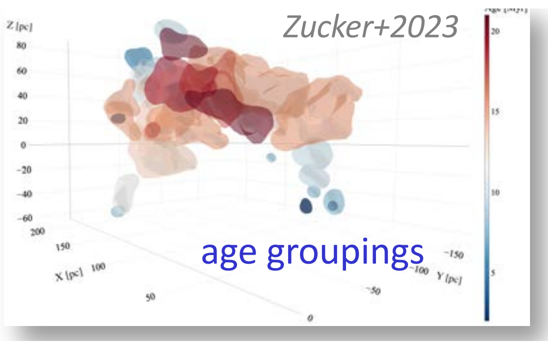




Zerjal+2021

ID	Members			T_{age}	ΔT_{birth}
	p>0.5	p>0.8	p>0.9	Myr	Myr
UCL Components					
● T	1056	755	586	15	3
● G	1713	1037	649	13	8
● D	512	422	360		
● F	298	219	187	15	2
LCC Components					
● A	1264	883	639	7	5
● U	490	410	374	9	4
USCO Components					
● C^a	1444	1253	1119	4	4
● E^a	1926	1233	887	11	4

Zucker+2023



- ~ 15000 member stars now identified

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

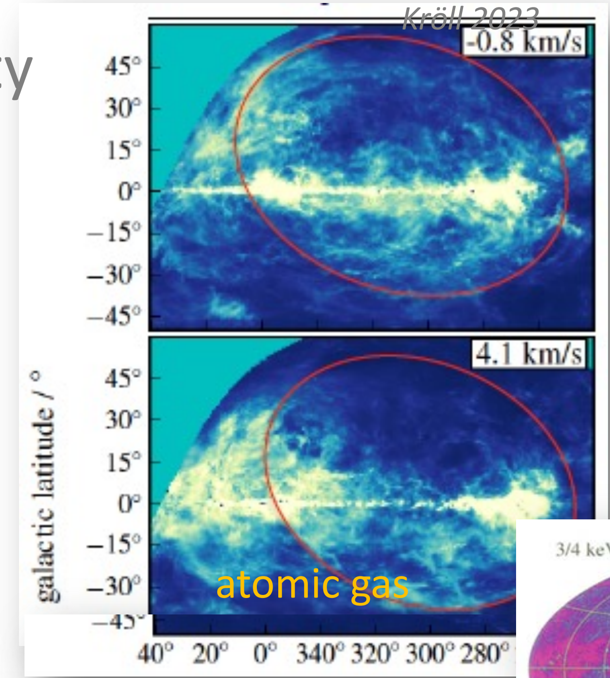
The nearby ISM holds a variety of cavities and shells

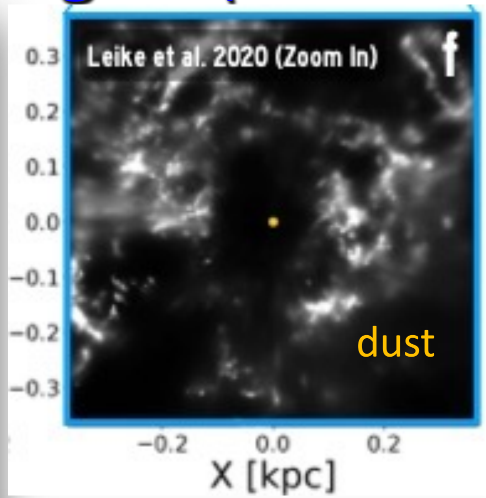
SF in Sco-Cen has been ongoing for ~15+ My; distance~140pc

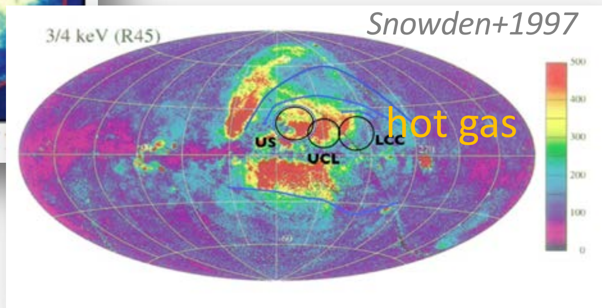
Hot gas and ^{26}Al seen from SF

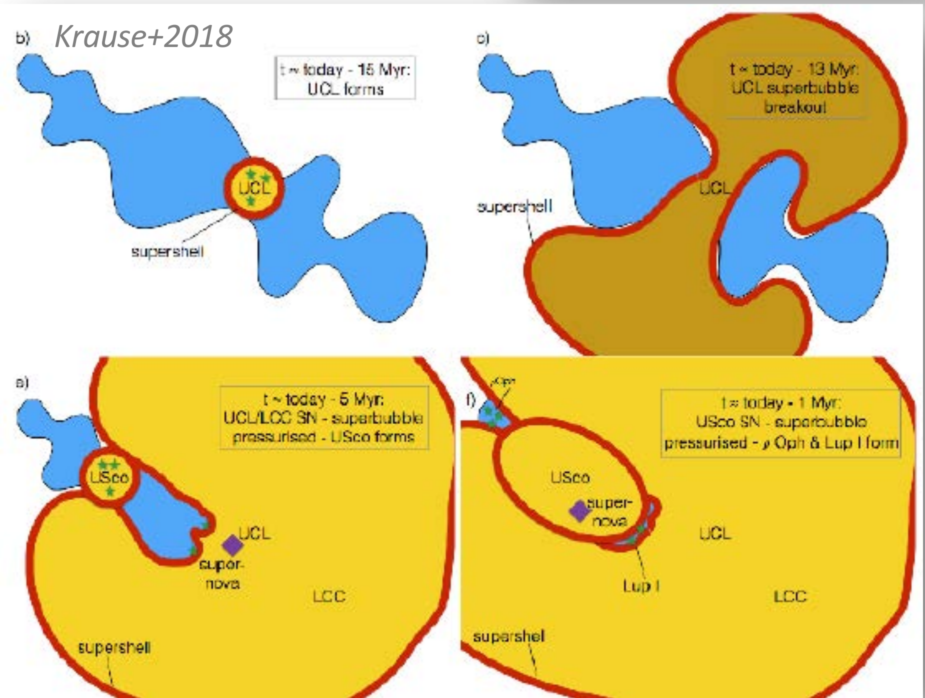
→ *"surround & squish"*

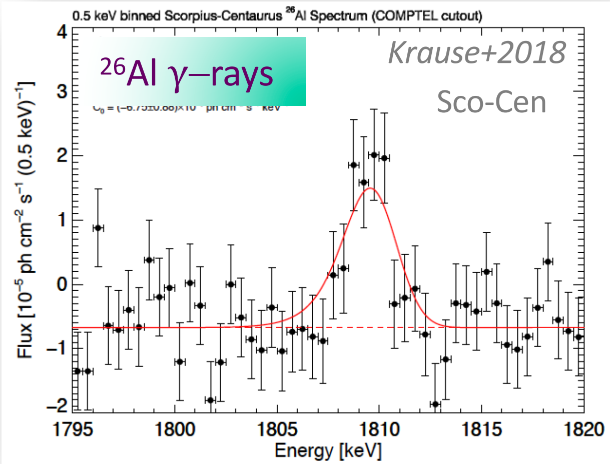
rather than "triggered" star formation









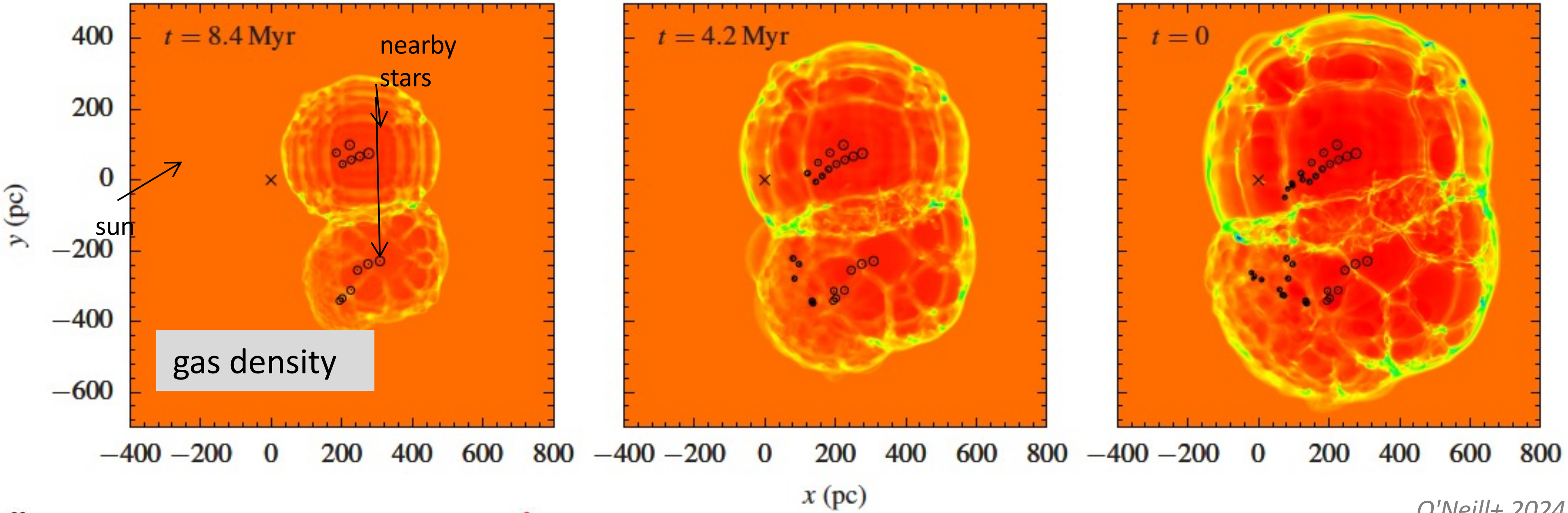


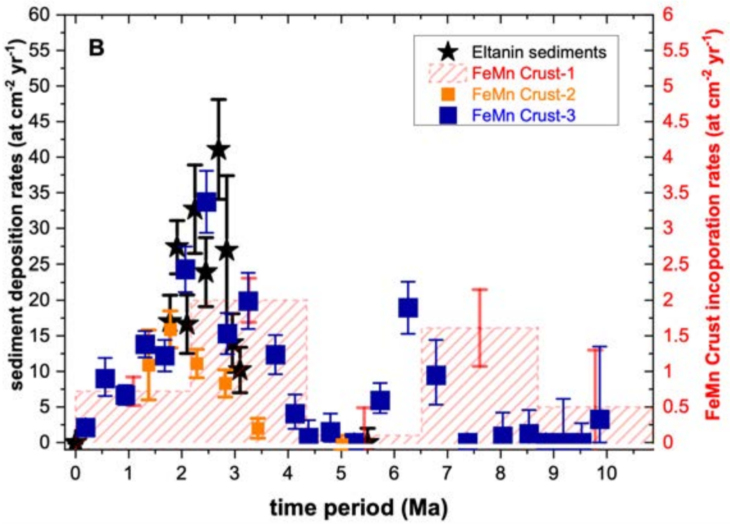
^{60}Fe on Earth from recent nearby massive-star activity?

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

created by massive-star winds and SN explosions, recent SNe adding ejecta flows

Schulreich+ 2017

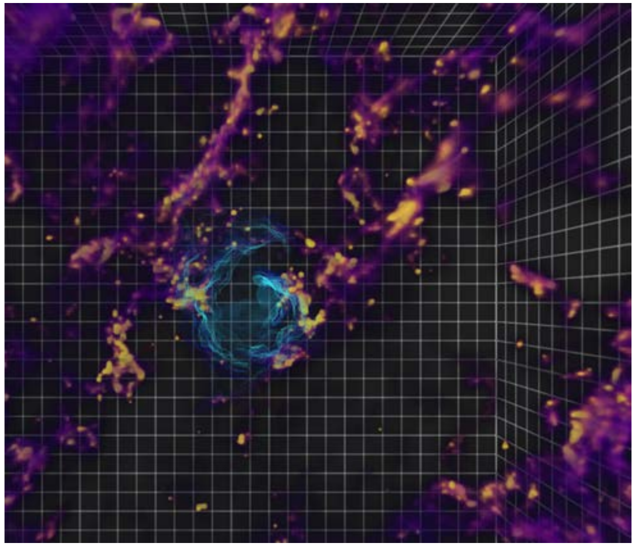




← Ocean crusts show ^{60}Fe deposition history

(Wallner+ 2015,2016,2021)

O'Neill+ 2024

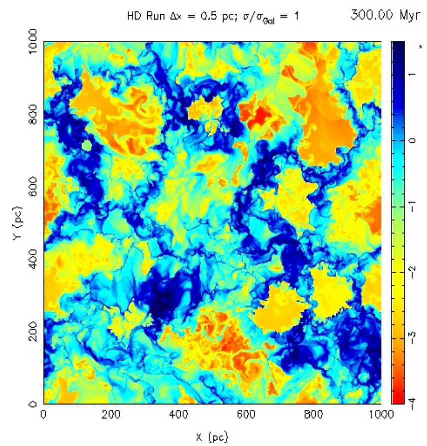


recent updates on
the solar vicinity
with superbubbles, clusters,
molecular gas...
(*Zucker+ 2022, O'Neill+2024*)

^{26}Al from massive-star clusters - Summary

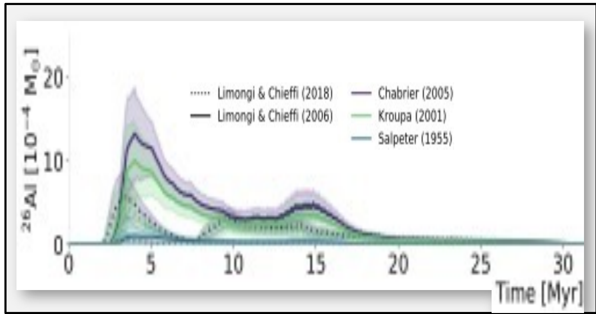
☆ Cycling of cosmic gas through sources and ISM is a challenge

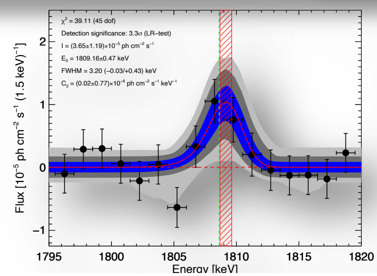
- ^{26}Al preferentially appears in superbubbles
  → massive-star ingestions rarely due to single WR stars or SNe
- Superbubbles around clusters change ISM dynamics (mixing)
- Different clusters allow testing stellar/supernova yields
- Kinematics of ^{26}Al supports superbubble model

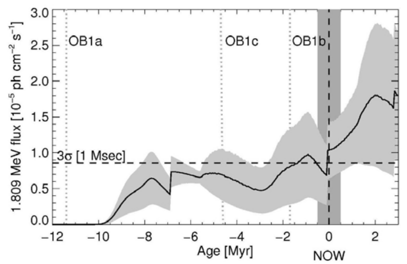


☆ Massive-star clusters are dominant sources of ^{26}Al

- The large-scale galactic bottom-up model provides
  a convincing model (morphology parameters)
- Source yields insufficient to explain observations
- Nearby cluster contributions need a realistic (?!) model
  for the diffuse extent from their superbubble morphology
- ^{26}Al observations constrain cluster ages / magnitudes
  for nearby clusters
- New (Gaia DR3) results suggest re-analysis of nearby clusters







Thank you!