Formation and migration history of the Solar system in the Galaxy using **short-lived radioactive nuclides**

Yusuke Fujimoto
University of Aizu

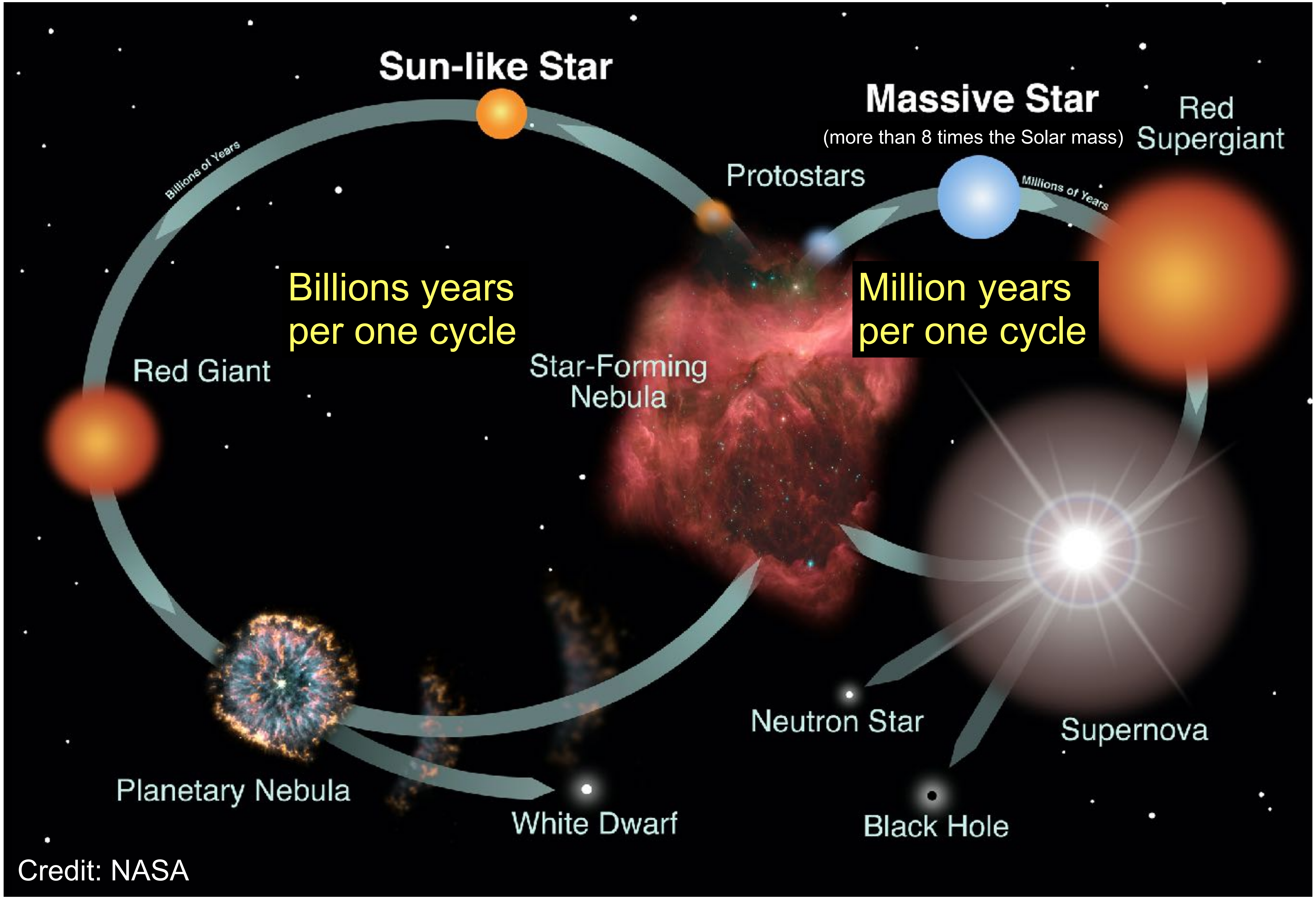
What is the short-lived radioactive nuclide (SLR)?

SLR	Daughter	$T_{1/2}$(Myr)
^{26}Al	^{26}Mg	0.717(24)
^{10}Be	^{10}B	1.388(18)[a]
^{53}Mn	^{53}Cr	3.74(4)
^{107}Pd	^{107}Ag	6.5(3)
^{182}Hf	^{182}W	8.90(9)
^{247}Cm	^{235}U	15.6(5)
^{129}I	^{129}Xe	15.7(4)
^{92}Nb	^{92}Zr	34.7(2.4)
^{146}Sm	^{142}Nd	68[e]/103[f]
^{36}Cl	^{36}S, ^{36}Ar	0.301(2)
^{60}Fe	^{60}Ni	2.62(4)
^{244}Pu	[i]	80.0(9)
^{7}Be	^{7}Li	53.22(6) days
^{41}Ca	^{41}K	0.0994(15)
^{205}Pb	^{205}Tl	17.3(7)
^{126}Sn	^{126}Te	0.230(14)
^{135}Cs	^{135}Ba	2.3(3)
^{97}Tc	^{97}Mo	4.21(16)
^{98}Tc	^{98}Ru	4.2(3)

Lugaro et al. 2018

Origin sites	**SLRs**
Low-mass AGBs (= Asymptotic Giant Branch star)	^{107}Pd, ^{108}Pd ^{135}Cs, ^{133}Cs ^{182}Hf, ^{180}Hf ^{205}Pb, ^{204}Pb
Massive and Super-AGBs	^{26}Al ^{41}Ca, ^{36}Cl, ^{60}Fe ^{107}Pd, ^{135}Cs, ^{182}Hf
WR stars (= Wolf–Rayet stars)	^{26}Al ^{41}Ca, ^{36}Cl ^{97}Tc, ^{107}Pd, ^{135}Cs, ^{205}Pb
CCSNe (= Core Collapse Supernovae)	^{26}Al, ^{27}Al ^{60}Fe ^{36}Cl, ^{41}Ca ^{35}Cl, ^{40}Ca ^{53}Mn, ^{55}Mn, ^{56}Fe ^{107}Pd, ^{126}Sn, ^{135}Cs ^{129}I, ^{182}Hf, ^{205}Pb ^{92}Nb, ^{92}Mo, ^{97}Tc, ^{98}Tc ^{144}Sm, ^{146}Sm ^{10}Be, ^{92}Nb
SNIa (= Type Ia Supernovae)	^{53}Mn, ^{55}Mn, ^{56}Fe ^{92}Nb, ^{93}Nb, ^{146}Sm, ^{144}Sm ^{97}Tc, ^{98}Tc, ^{98}Ru
NSMs/special CCSNe (= Neutron Star Merger)	^{107}Pd, ^{108}Pd, ^{126}Sn, ^{124}Sn ^{135}Cs, ^{133}Cs, ^{129}I, ^{127}I ^{182}Hf, ^{180}Hf ^{247}Cm, ^{235}U, ^{244}Pu, ^{238}U
novae	^{26}Al
CRs (= Cosmic rays)	^{7}Be, ^{10}Be, ^{9}Be ^{26}Al, ^{41}Ca, ^{36}Cl, ^{53}Mn

Why is massive star important?



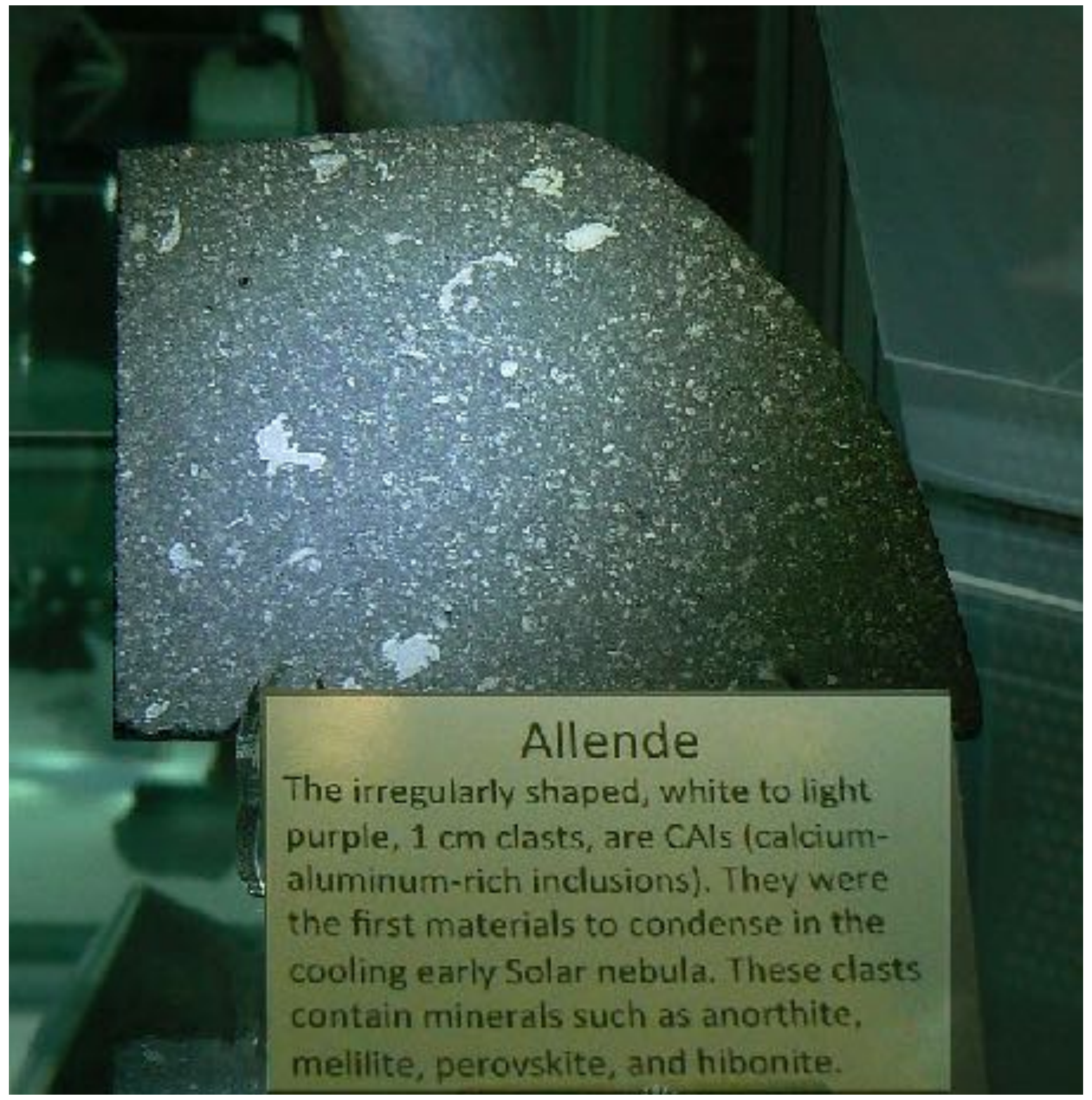
1. Very luminous
   (heat and ionize surrounding gas)
2. Explode as supernova
   (disperse surroundings gas & cloud)
3. Distribute heavy elements
4. Much shorter life cycle

➡ Influential in galactic-scale star formation and Milky Way evolution

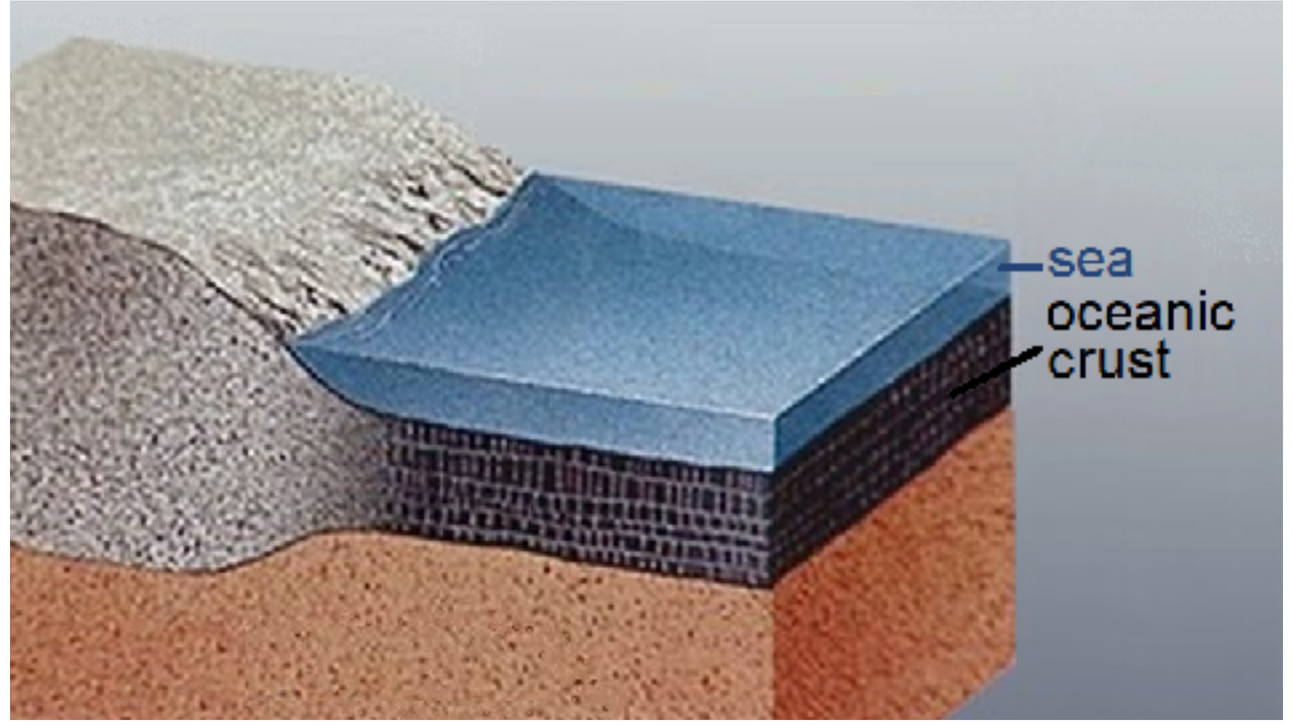
This is why we focus on 26Al and 60Fe.

Where can we find SLRs?

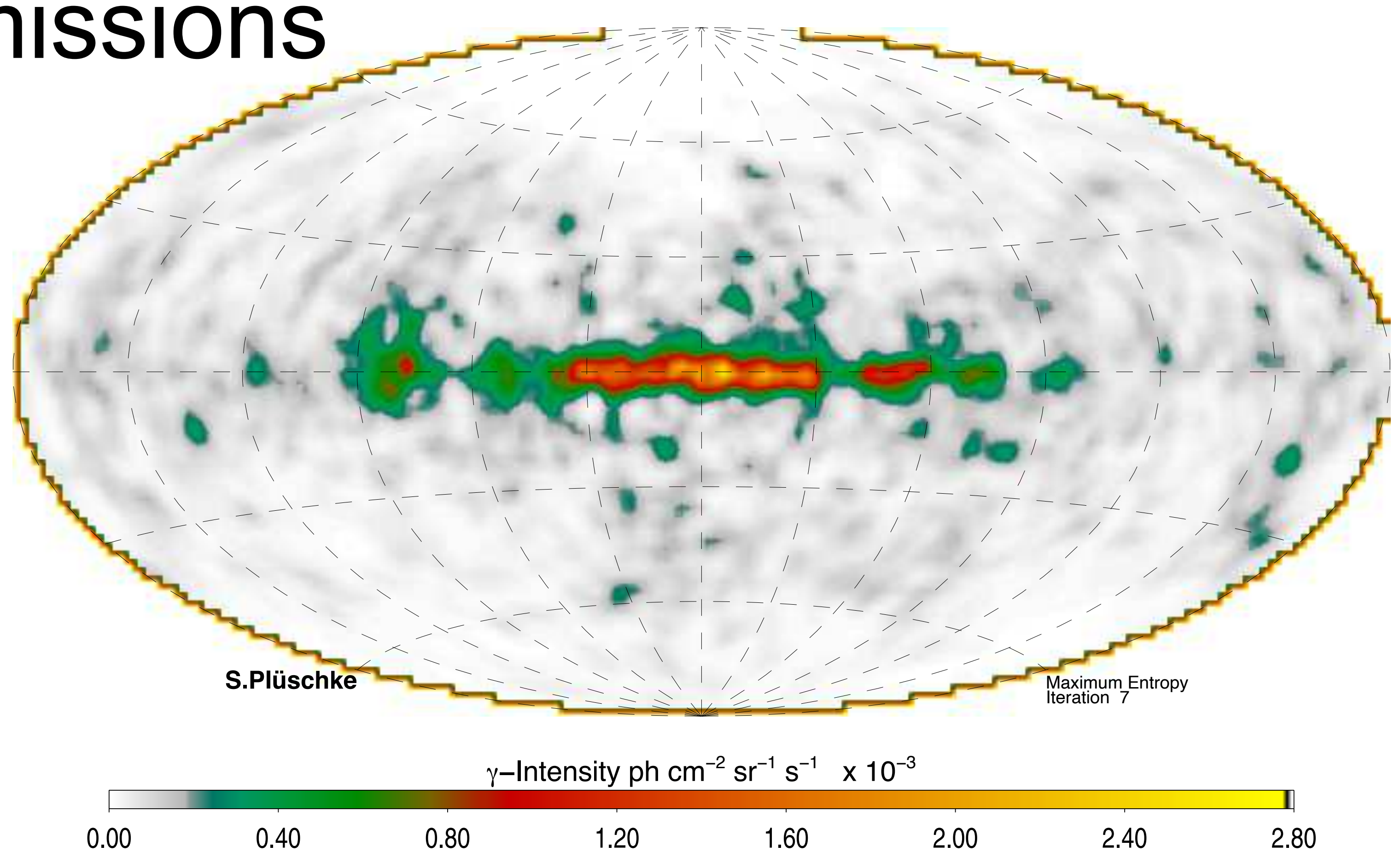
1. Meteorite



2. Deep-sea and Antarctica



3. Galactic γ-ray emissions



Outline

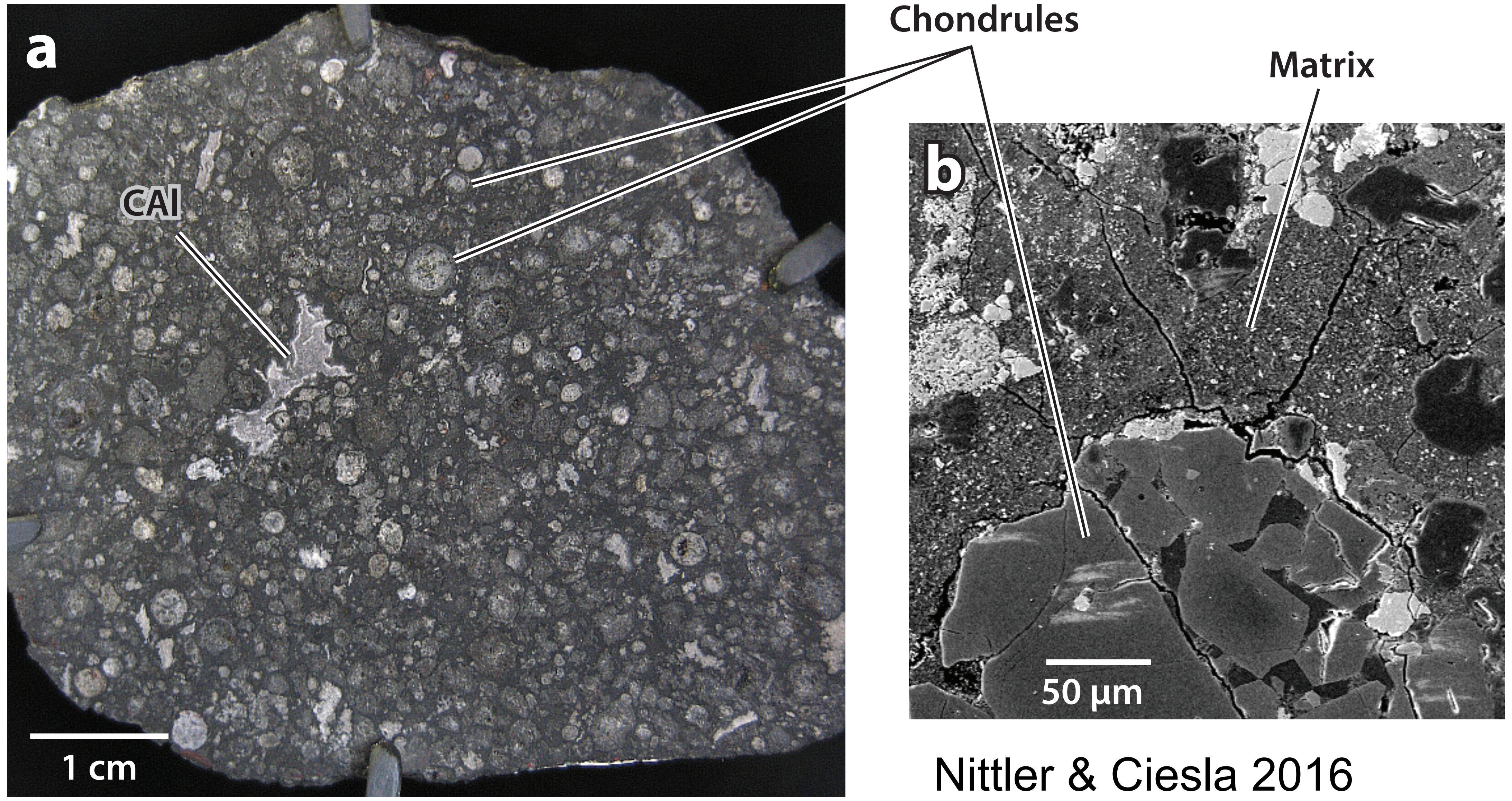
1. The birth environment of the early Solar system 4.6 Gyr ago

2. The local interstellar environment of the current Solar system

3. The formation mechanism of the Milky Way’s spiral arms

Significant quantities of SLRs in early Solar system

- The daughter products of SLRs are found in primordial materials in meteorites, ex. CAI and chondrules



Nittler & Ciesla 2016

- Isotopic abundance ratios are measured

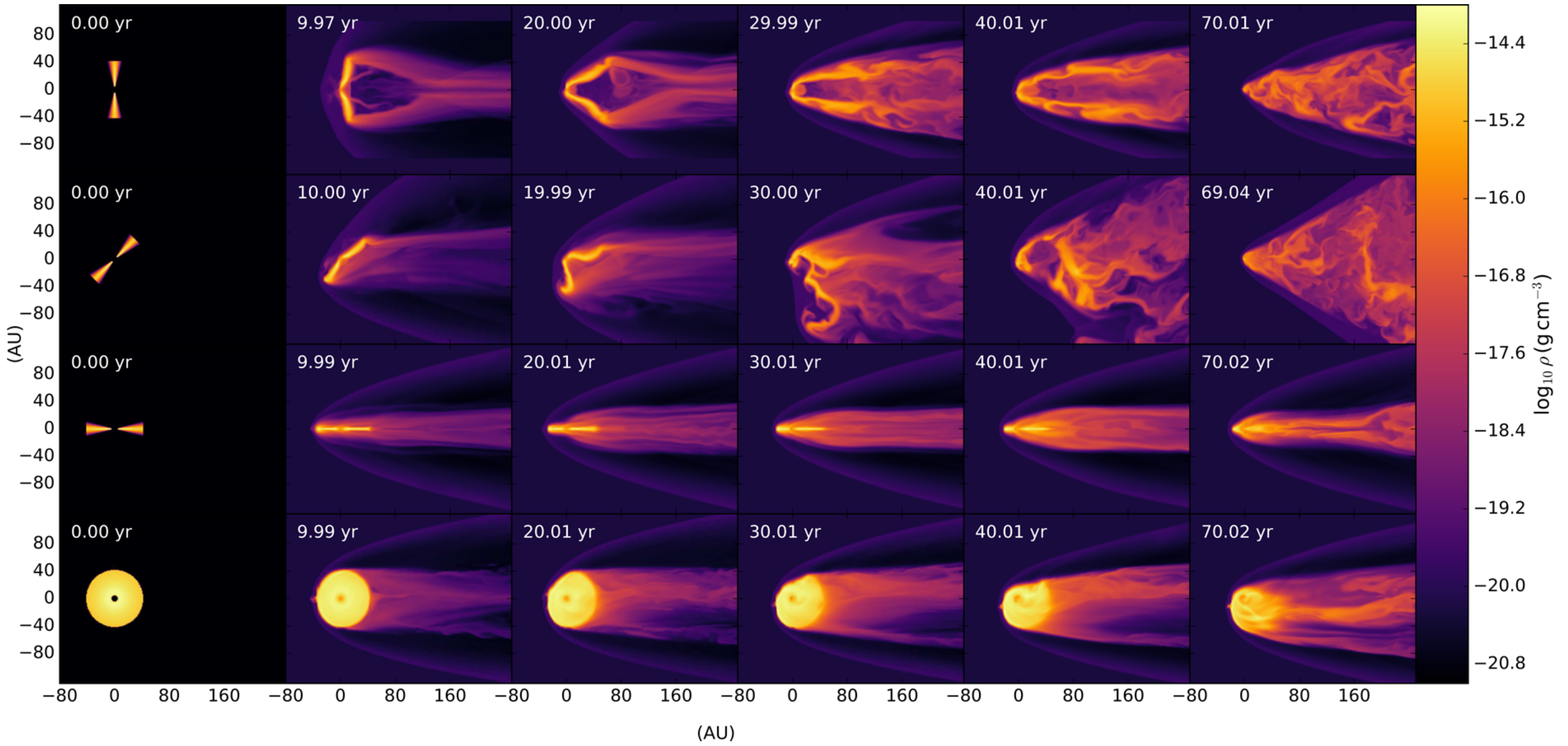
SLR	Daughter	Half-life (Myr)	Main source	Early Solar system ratio
26Al	26Mg	0.717	WR winds & CCSNe	5.23E-05
60Fe	60Ni	2.62	CCSNe	1.01E-08

How did the Solar birth environment get SLRs?

Topic 1: Solar birth environment

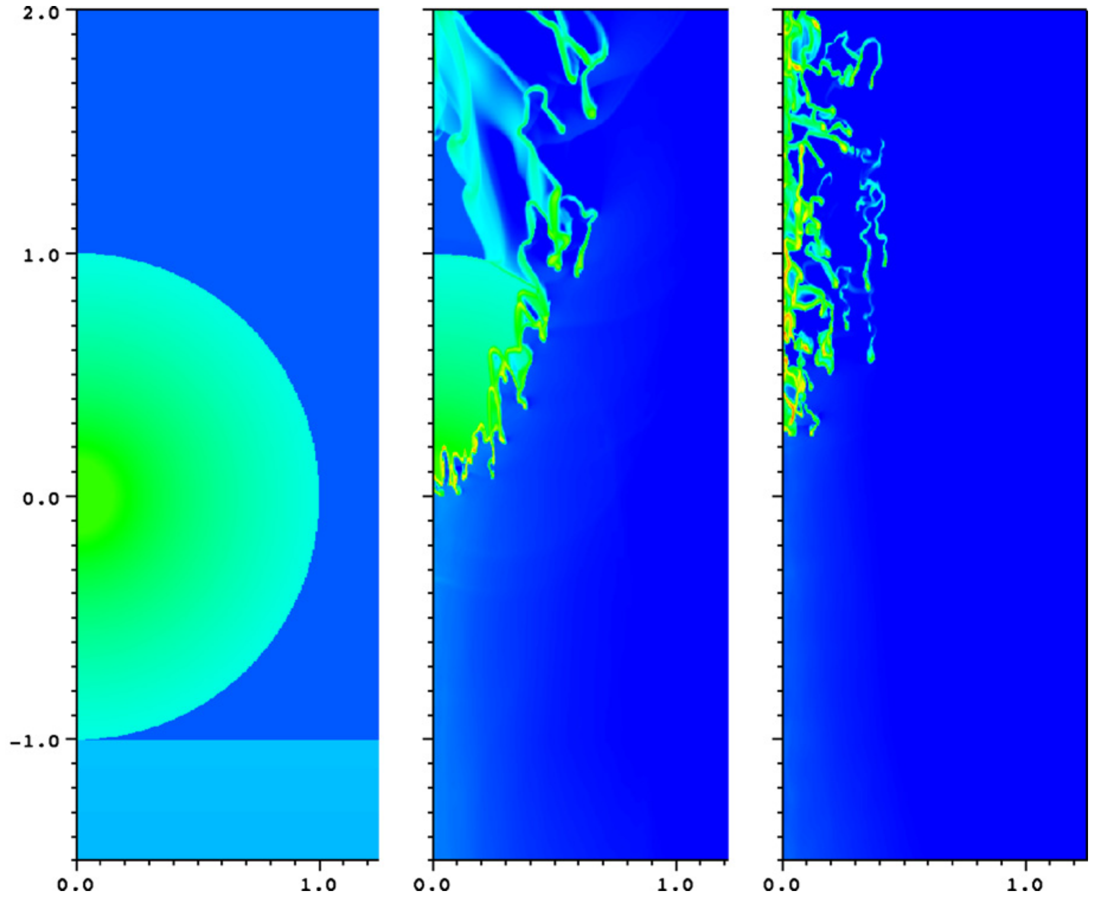
Proposed enrichment scenarios

1. Direct pollution of a protoplanetary disc by SN ejecta



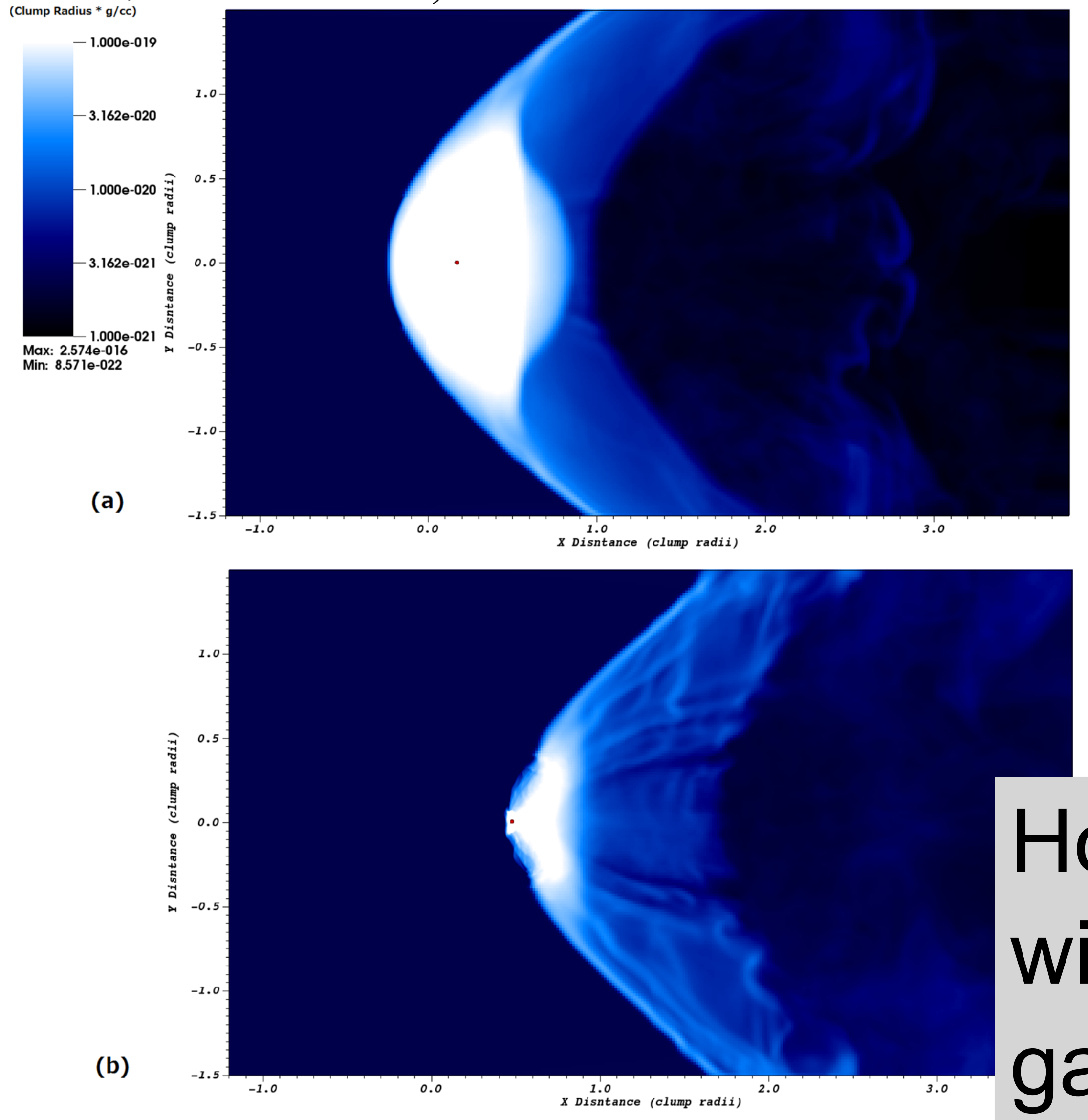
Close & Pittard 2017
See also Ouellette et al.

2. Supernova triggered collapse of pre-solar dense cloud core

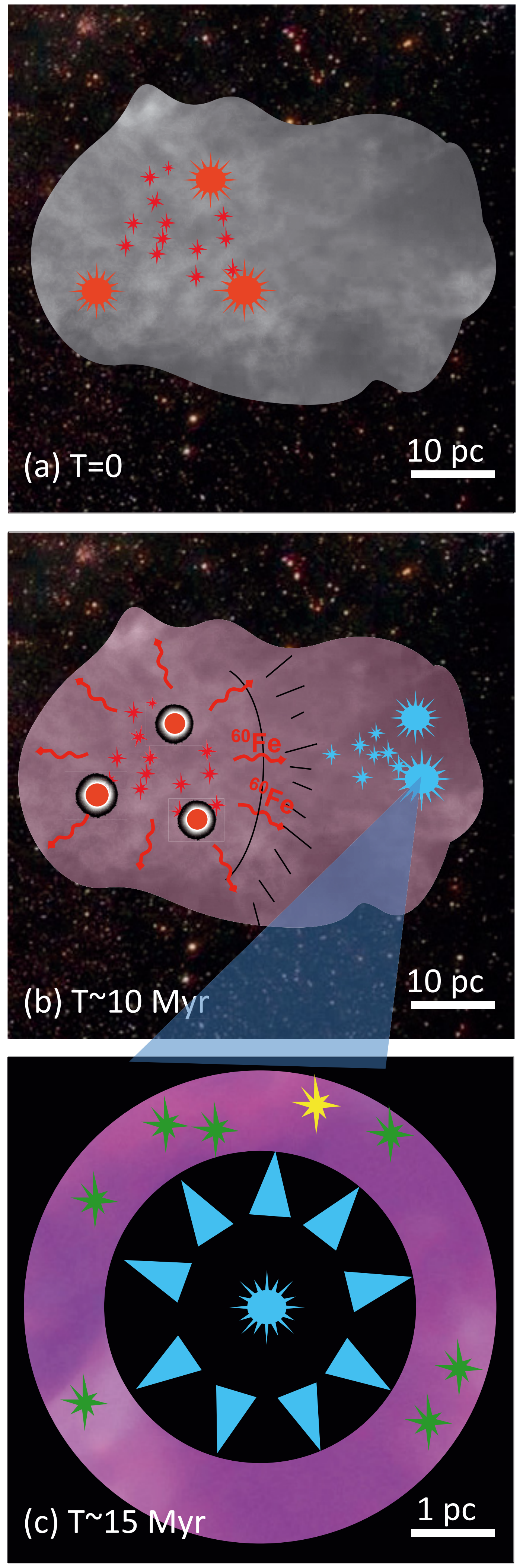


Gritschneder et al. 2012
See also Cameron & Truran 1977, Boss 2017, etc.

Li, Frank & Blackman 2014



3. Sequential star-formation events in a molecular cloud



Gounelle & Meynet 2012
See also Young 2014, Kuffmeier et al. 2016

However, the massive stellar feedback is a widespread contamination mechanism, BUT, galaxy-scale dynamics have not been considered

Topic 1: Solar birth environment

Chemo-hydrodynamical simulation of the entire Milky Way

- *Enzo*: 3D adaptive mesh refinement (AMR) hydrodynamics code

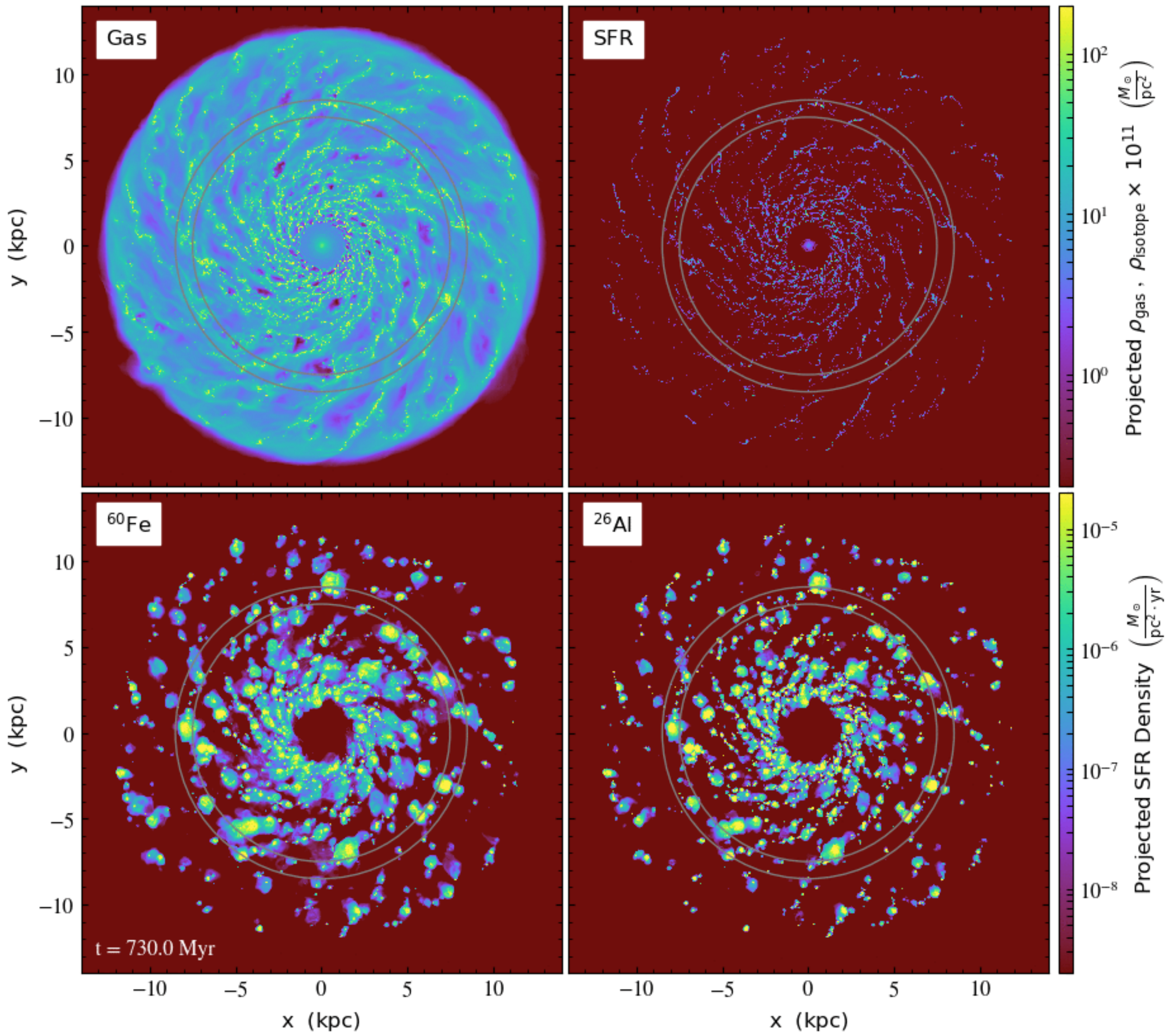
- Include almost all necessary physics

  (radiative cooling and heating, self-gravity, star formation and massive stellar feedback)

- **<u>SLR injection from massive stars, and time decay</u>**

  $T_{1/2}$ = 2.62 Myr for ^{60}Fe

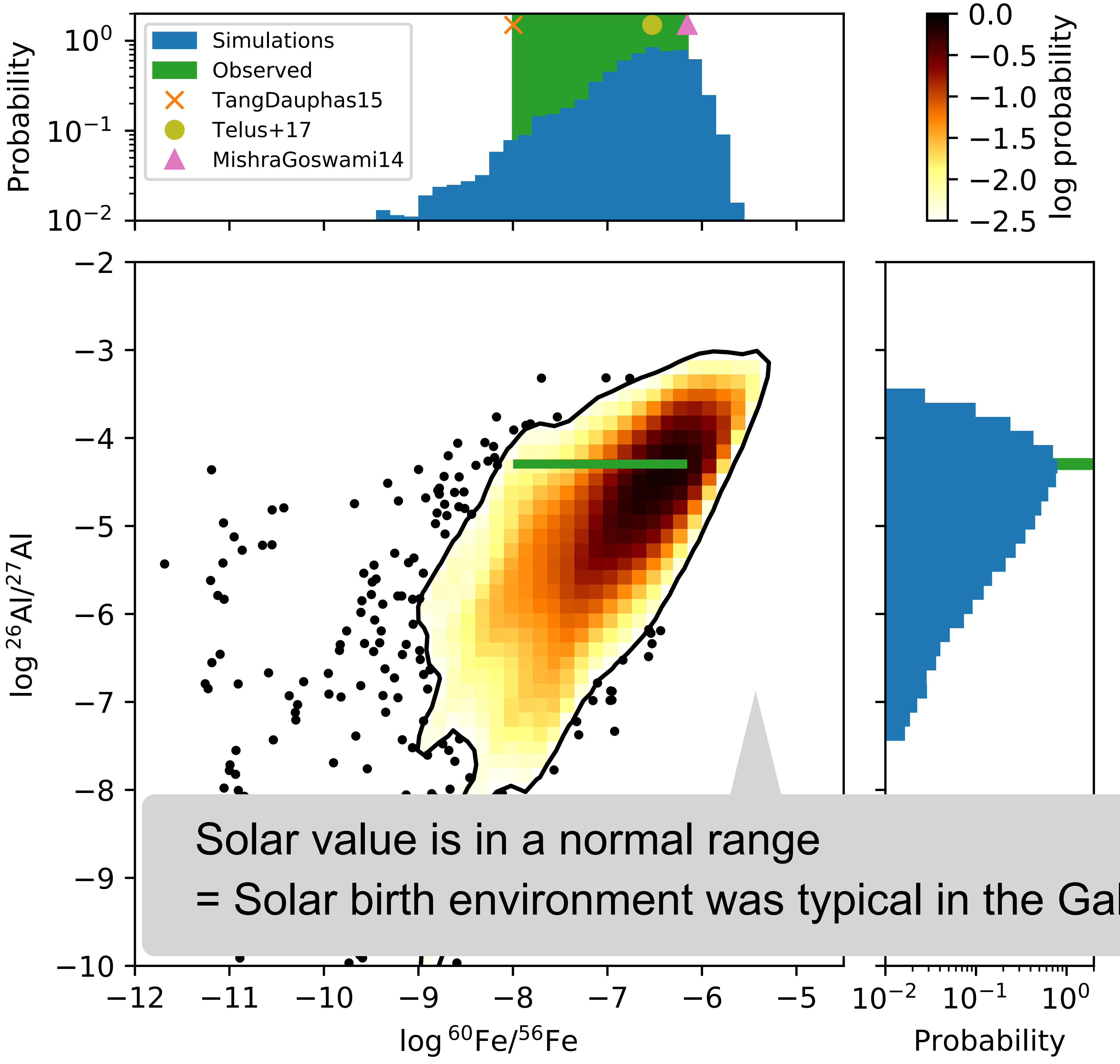
  0.72 Myr for ^{26}Al



Topic 1: Solar birth environment

Results: SLR abundances in newborn stars

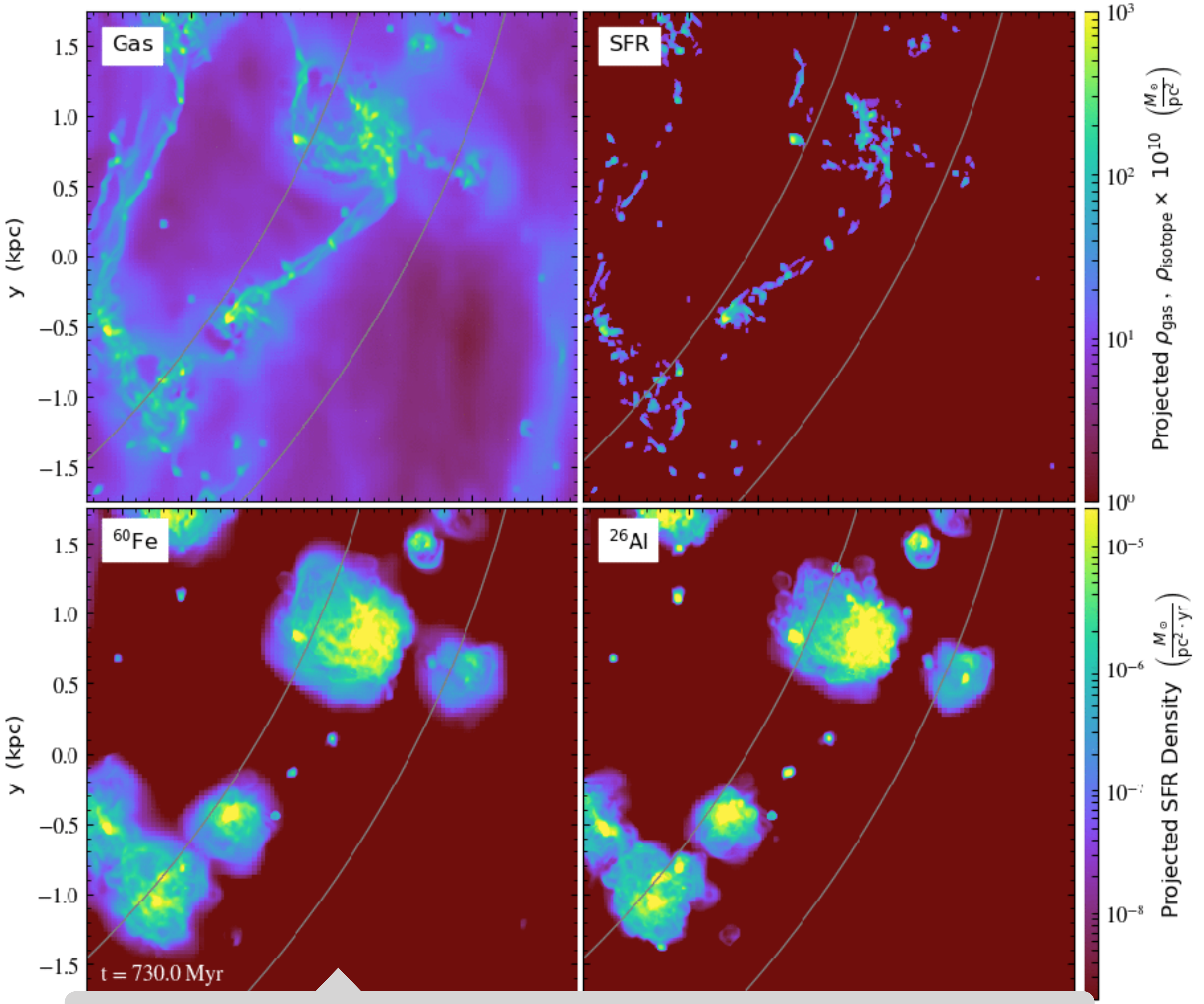
Compare with meteoritic Solar abundance



Solar value is in a normal range
= Solar birth environment was typical in the Galaxy

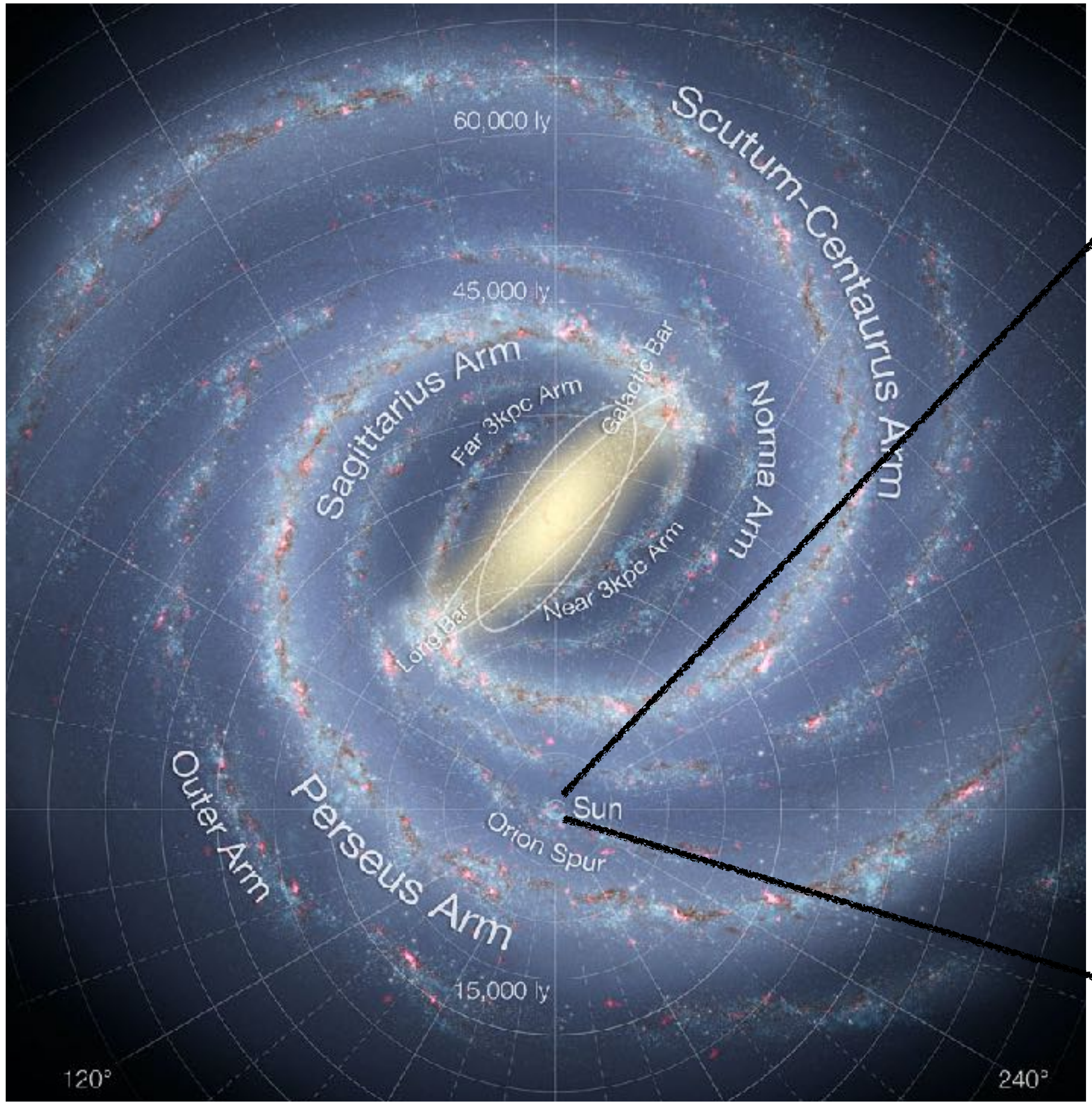
Fujimoto, Krumholz & Tachibana 2018, MNRAS

Zoom-in movies near the Solar circle



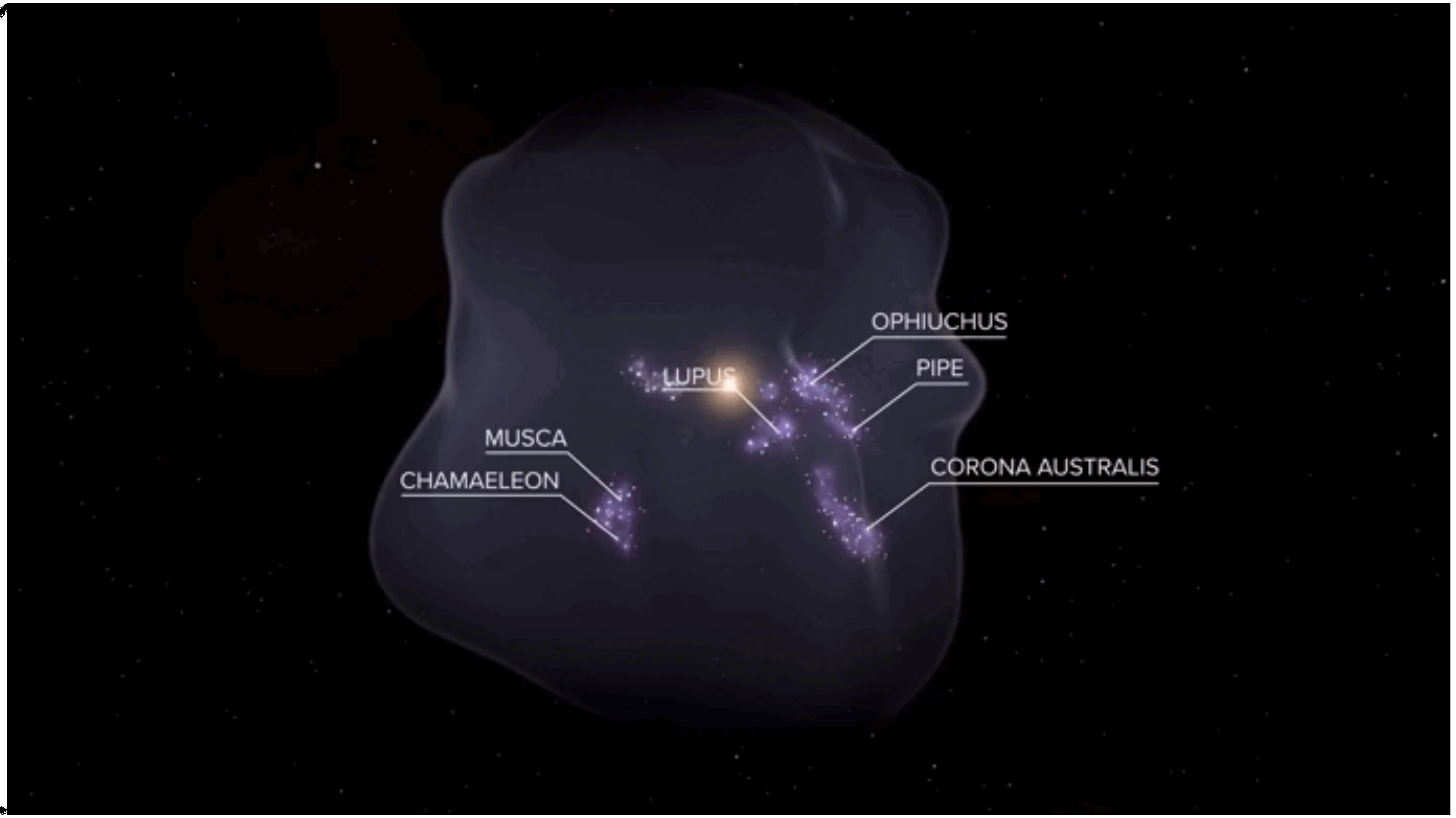
Stars form in an already-enriched SLR bubble
contaminated by previous generations of massive stars

The Solar system has been affected by nearby massive stars for recent several Myr



Credit: NASA/JPL-Caltech/ESO/R. Hurt

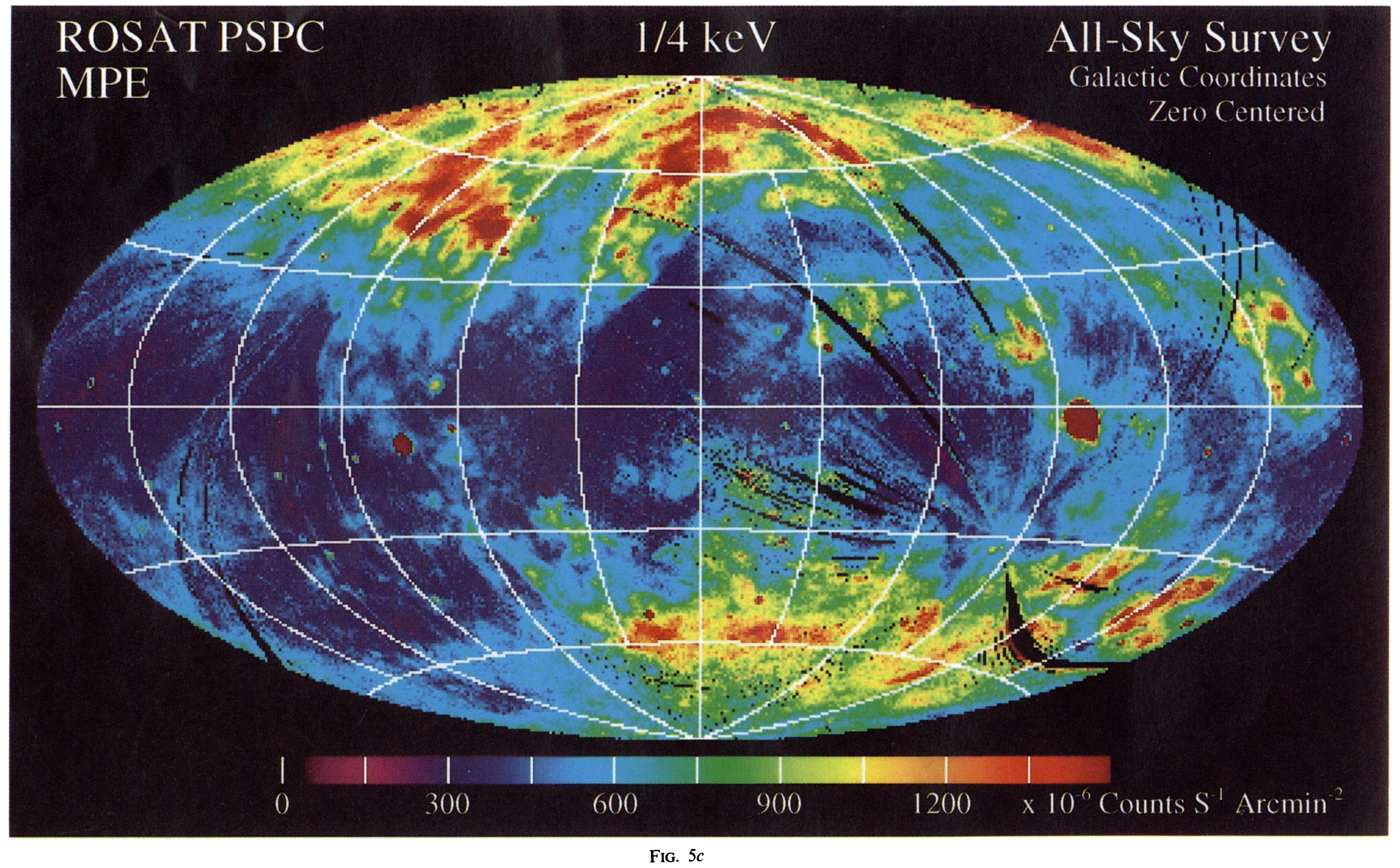
Local Bubble



Zucker et al. 2022

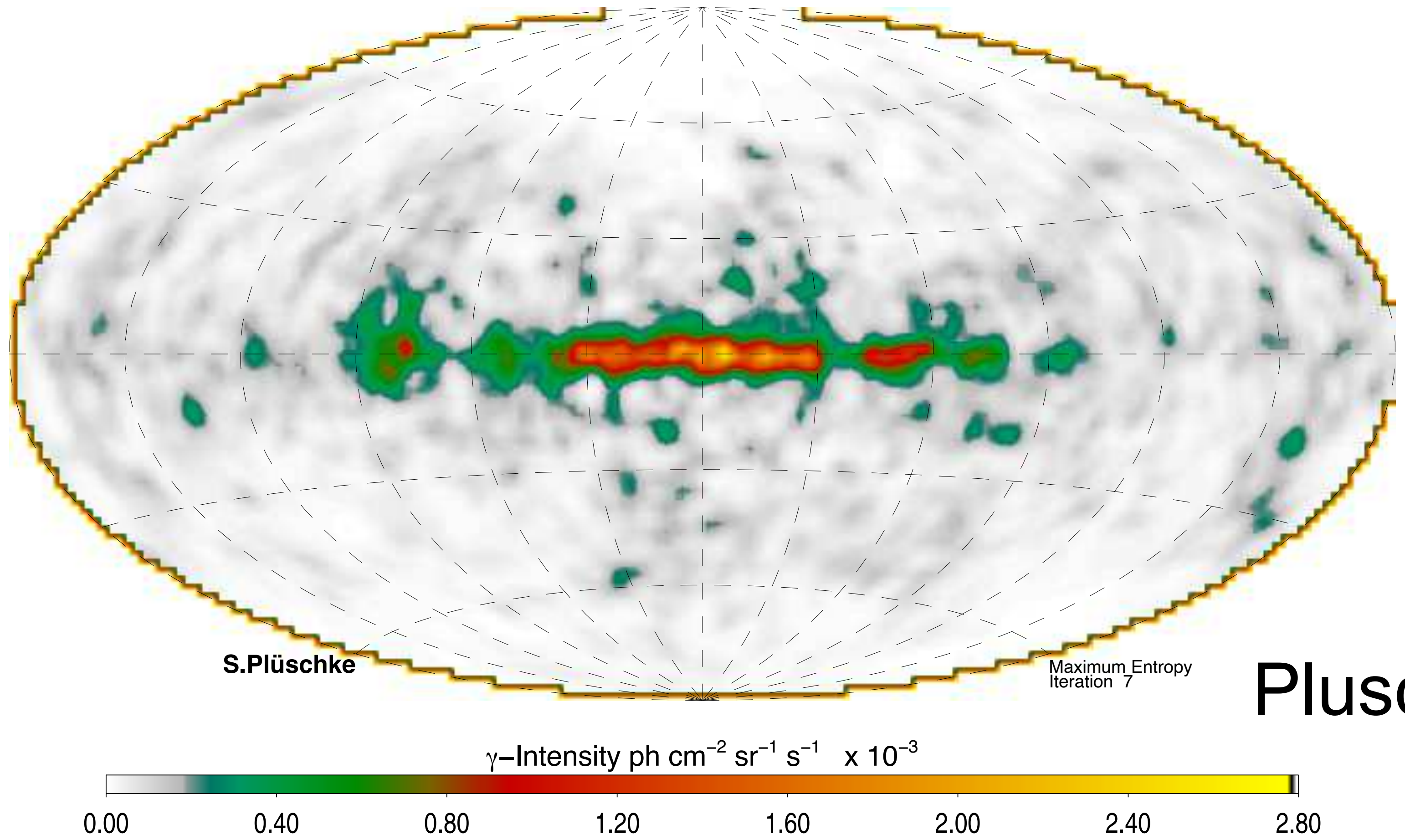
Three independent pieces of observational evidence

1. Soft X-ray (~ 1/4 keV) emission map of all-sky



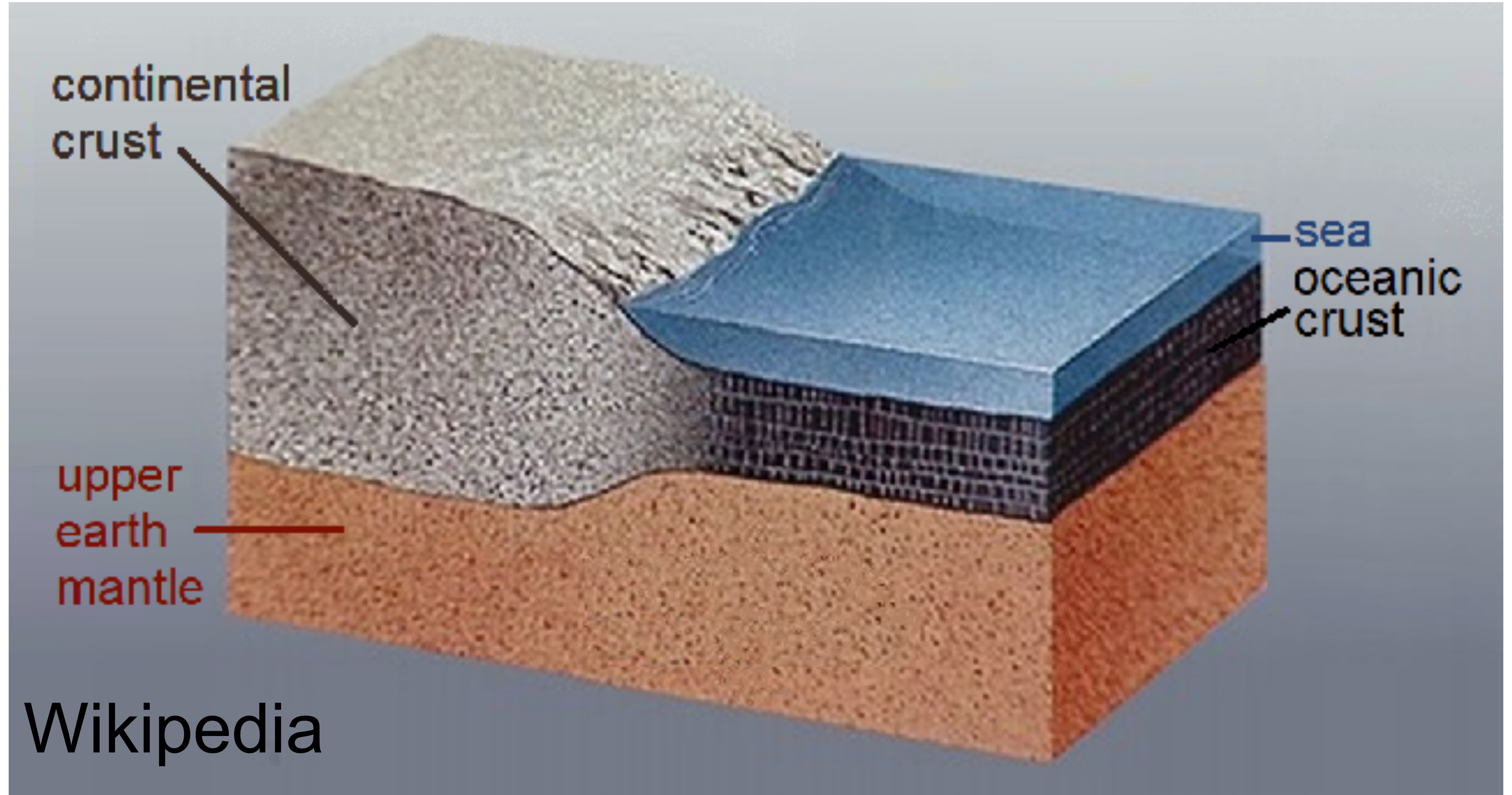
Snowden et al. 1995

2. ^{26}Al-line gamma-ray emission map of all-sky



Pluschke et al. 2001

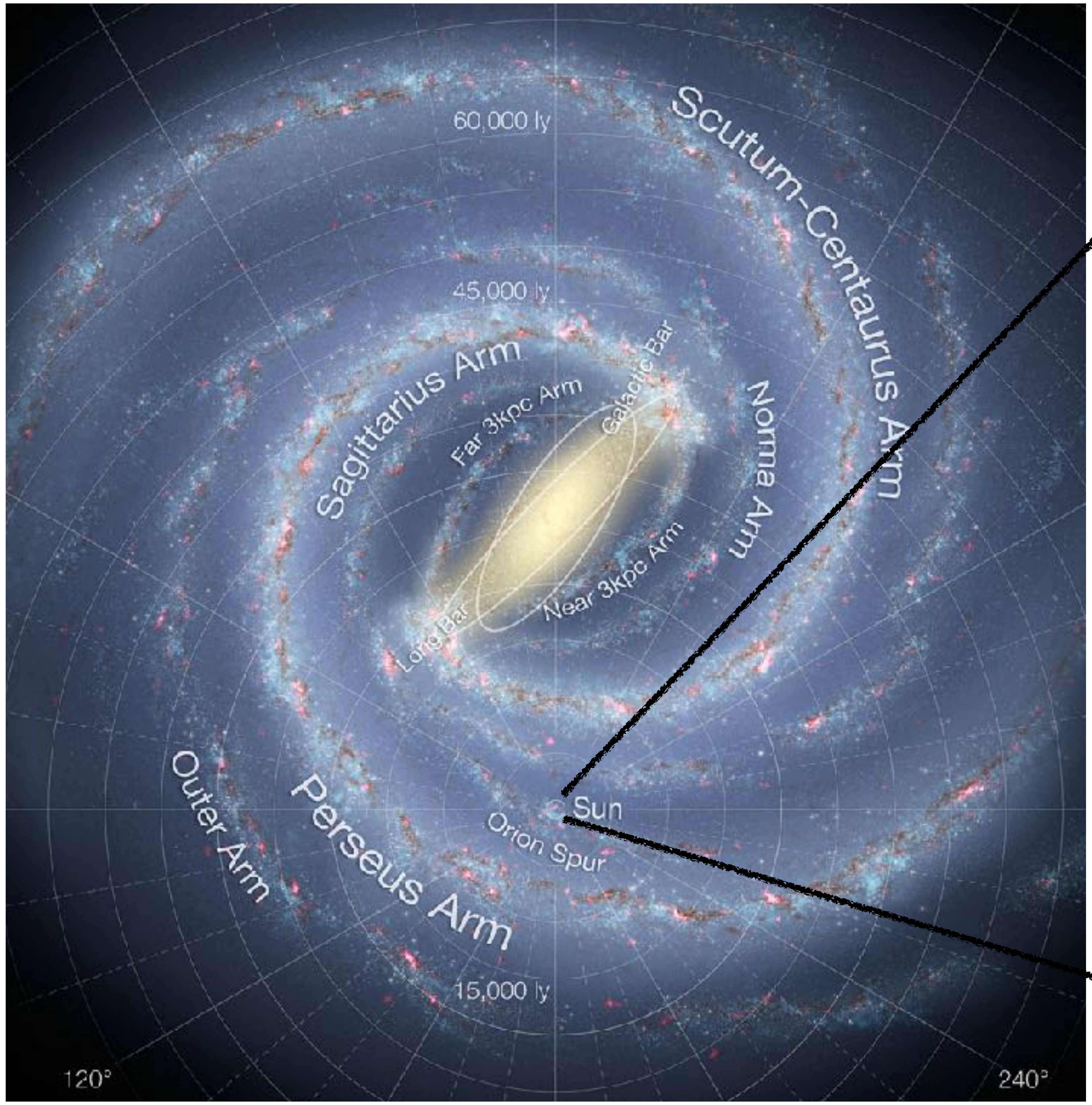
3. Live ^{60}Fe found in deep-sea crusts, Antarctic snow, and lunar surface (geological evidence)



	Sample	Origin	^{60}Fe flux [atoms cm^{-2} yr^{-1}]
Knie *et al.* [12]	Ferromanganese crust	South Pacific	0.5–5
Knie *et al.* [13]	Ferromanganese crust	Equatorial Pacific	1–5
Wallner *et al.* [14]	Sediments	Indian Ocean	20–40
	Ferromanganese crusts	Equatorial Pacific	1–3
	Ferromanganese nodules	South Atlantic	0.2–0.5
Ludwig *et al.* [15]	Sediments	Equatorial Pacific	0.4–1.2
Fimiani *et al.* [16]	Lunar regolith	Moon	20–100
This work	Surface snow	Antarctica	$1.2^{+0.6}_{-0.5}$

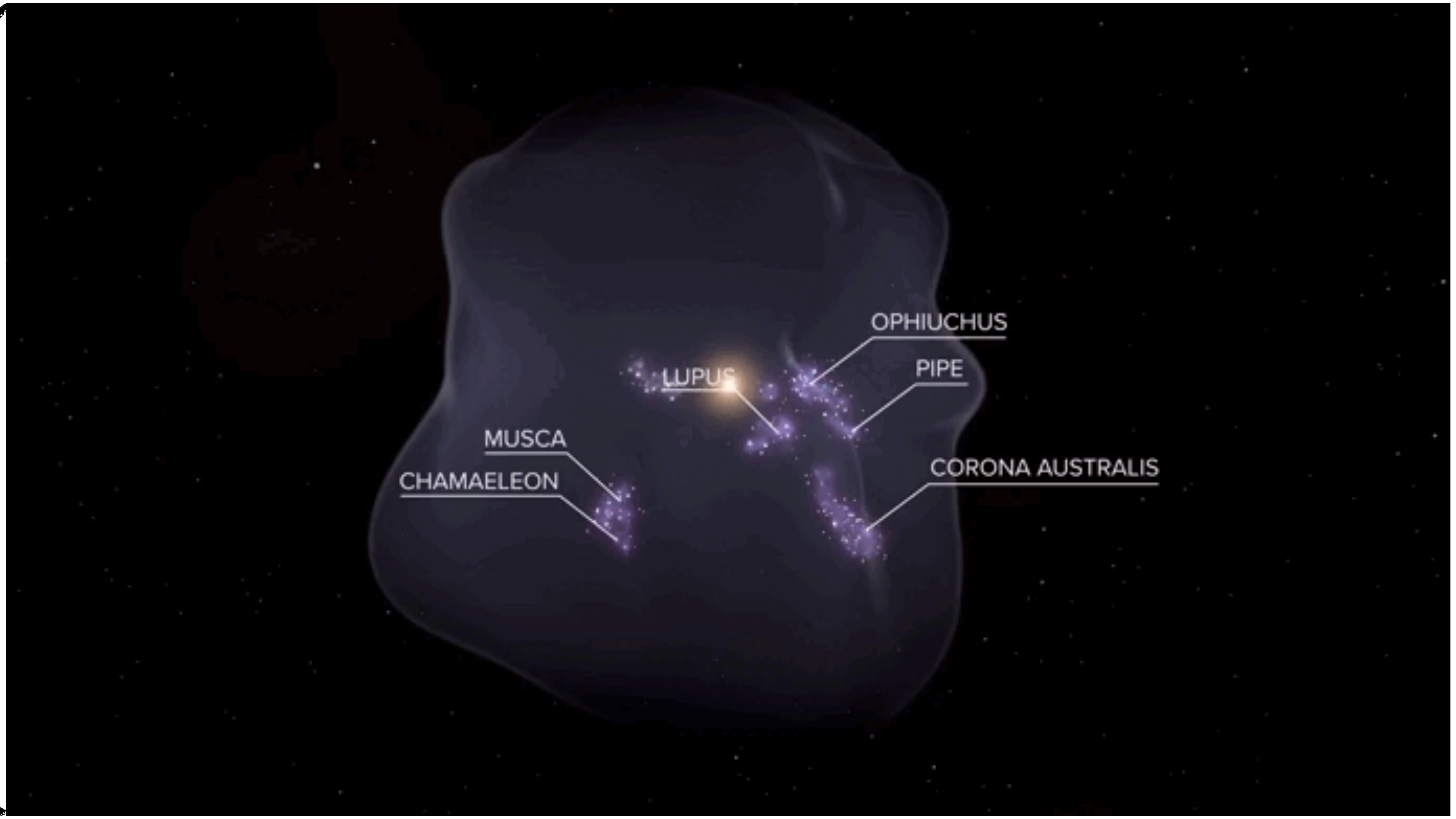
Table from Koll et al. 2019

The Solar system has been affected by nearby massive stars for recent several Myr



Credit: NASA/JPL-Caltech/ESO/R. Hurt

Local Bubble

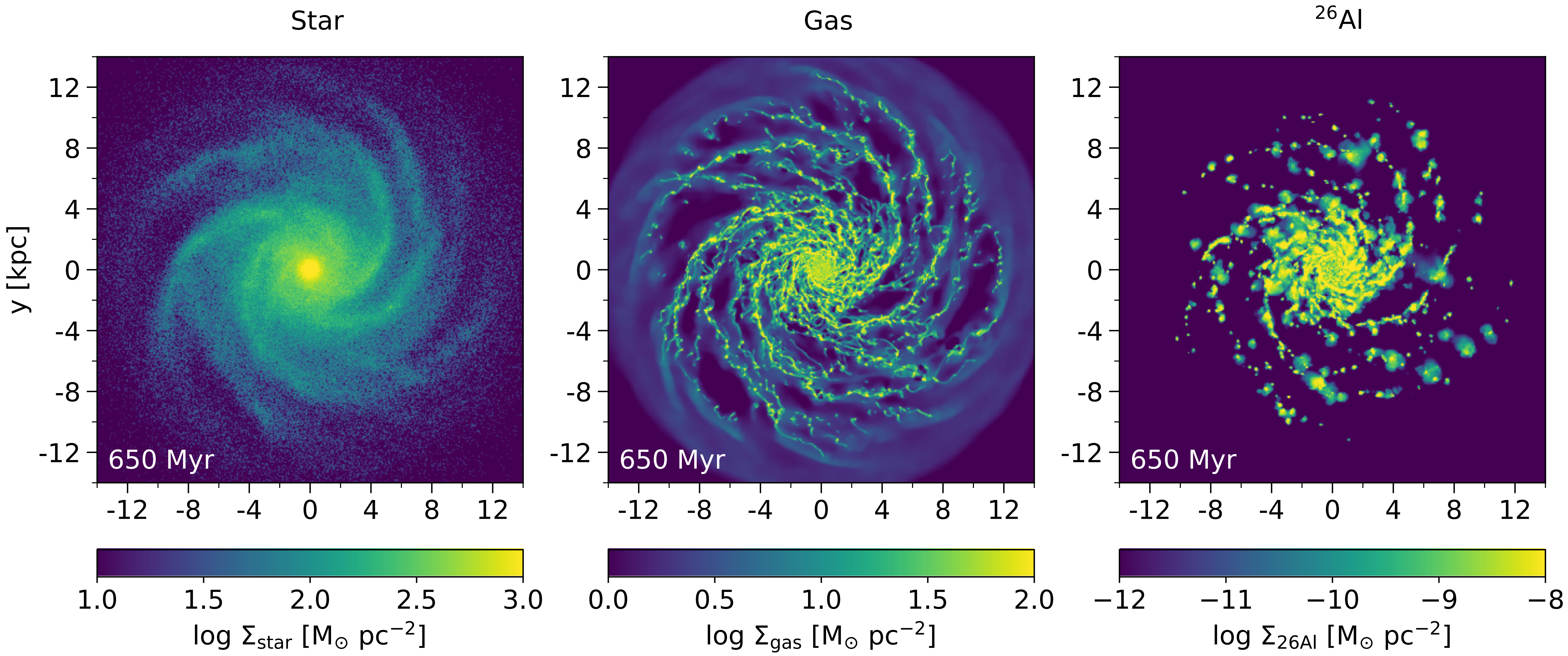


Zucker et al. 2022

How did such an environment form in a relation to the global galactic dynamics?

N-body + hydrodynamics simulation of the Milky Way

- Self-consistent galactic spiral arms: dark matter and old stellar populations using N-body particles

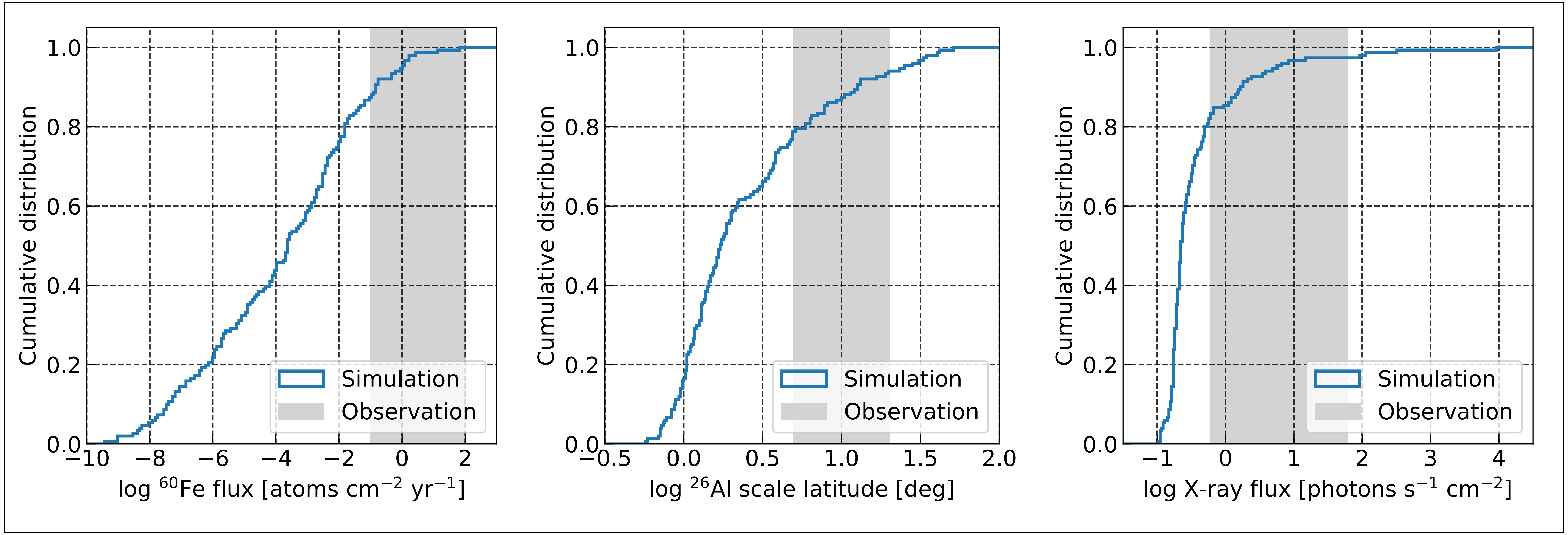


Investigated the location of stars whose environments are consistent with the observations:

(1) The ^{60}Fe influx onto the Earth detected in deep-sea archives and Antarctic snow

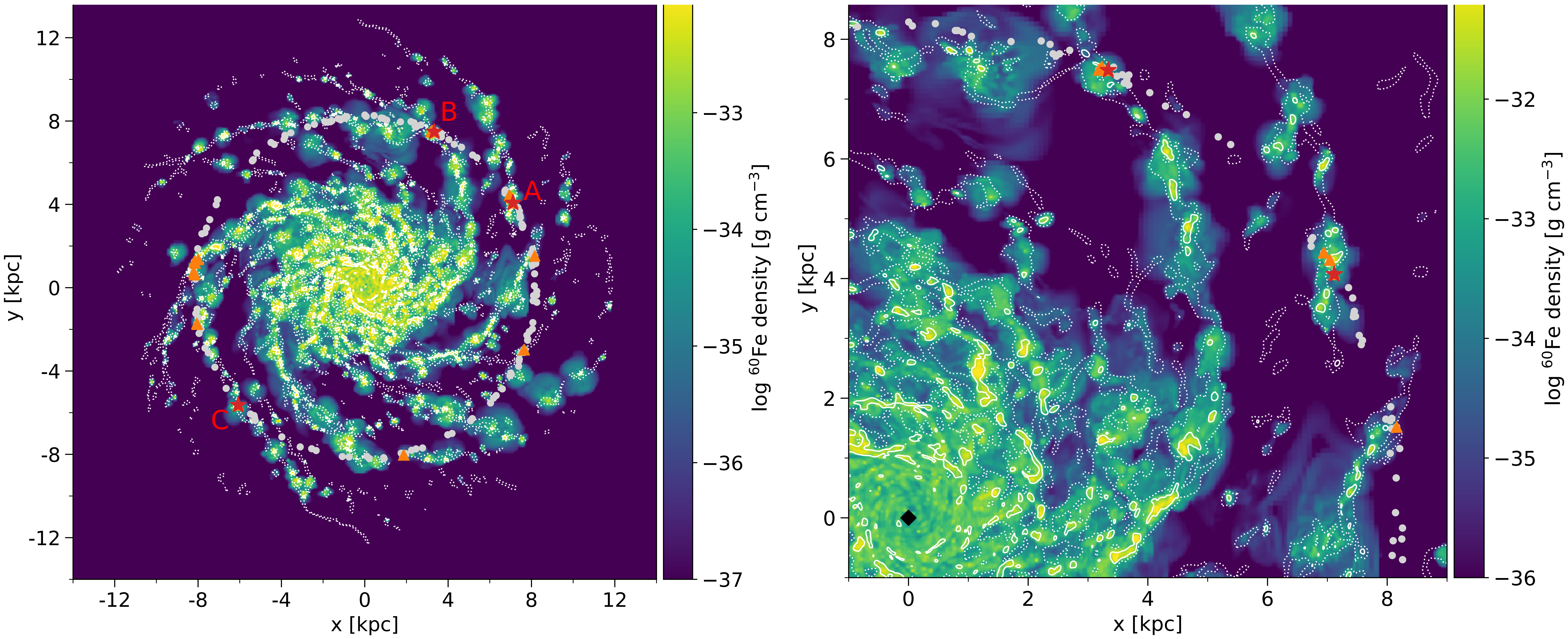
(2) A broad distribution of ^{26}Al observed in the γ-ray sky-maps

(3) The mean flux of diffuse soft X-ray emission.



Stars who meet all three conditions are uncommon (~2%), but not exceptionally rare

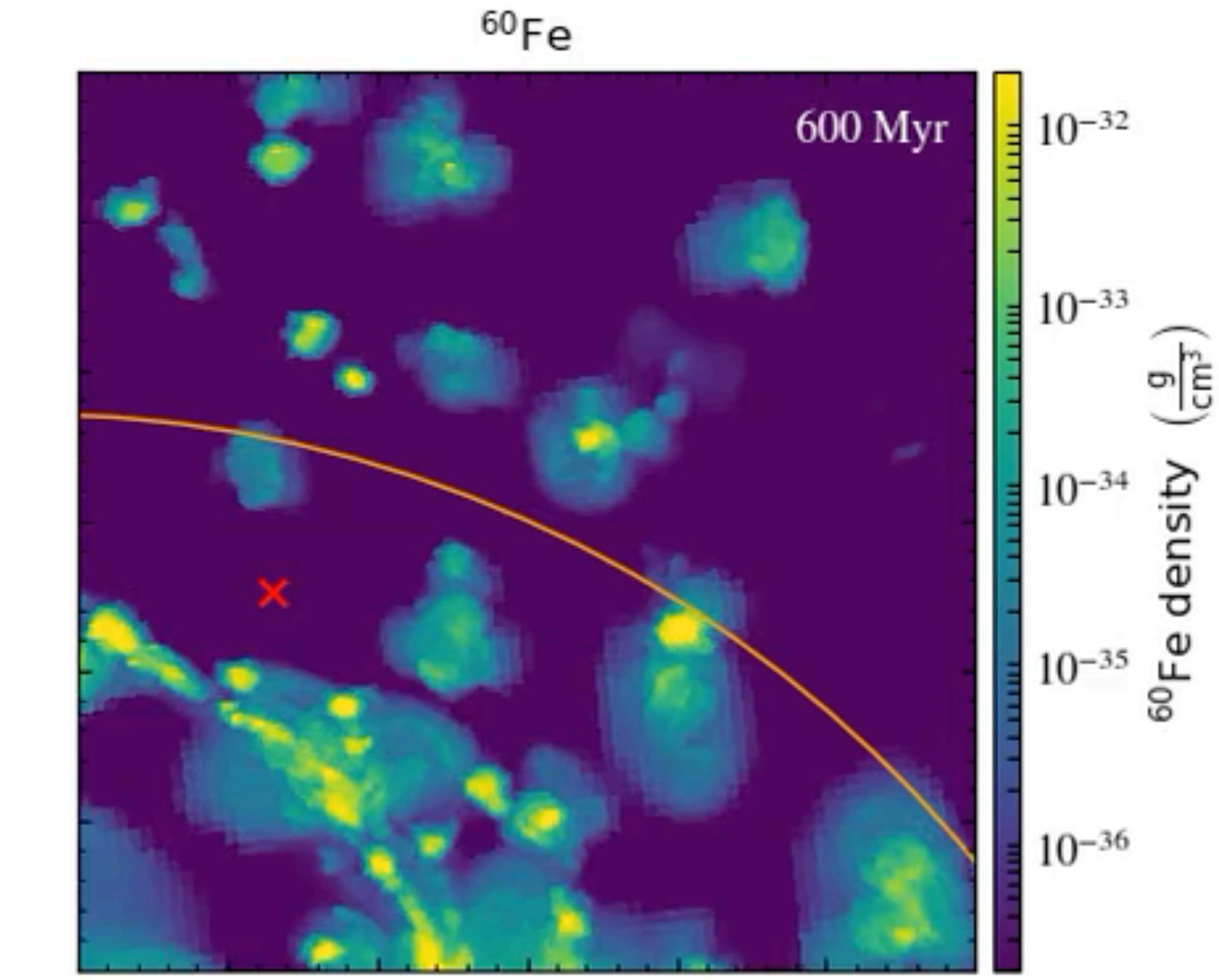
Where are such Sun-like stars located in the galactic disc?



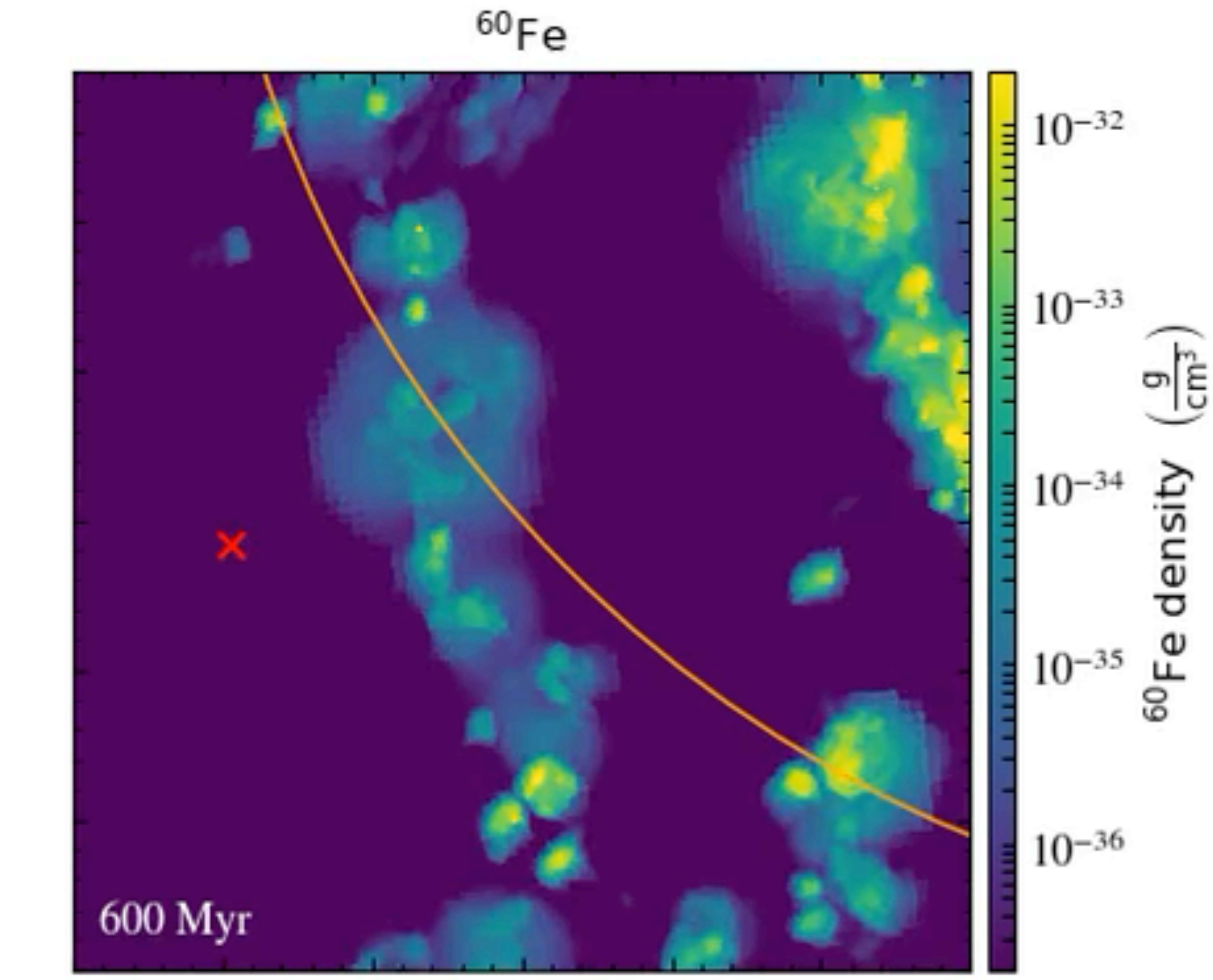
They are located inside or close to big SLR bubbles created by massive stars on the galactic spiral arms.

How long do such Sun-like stars stay in the bubble?

Case 1: The duration is ~ 100 Myr



Case 2: The duration is ~ 20 Myr

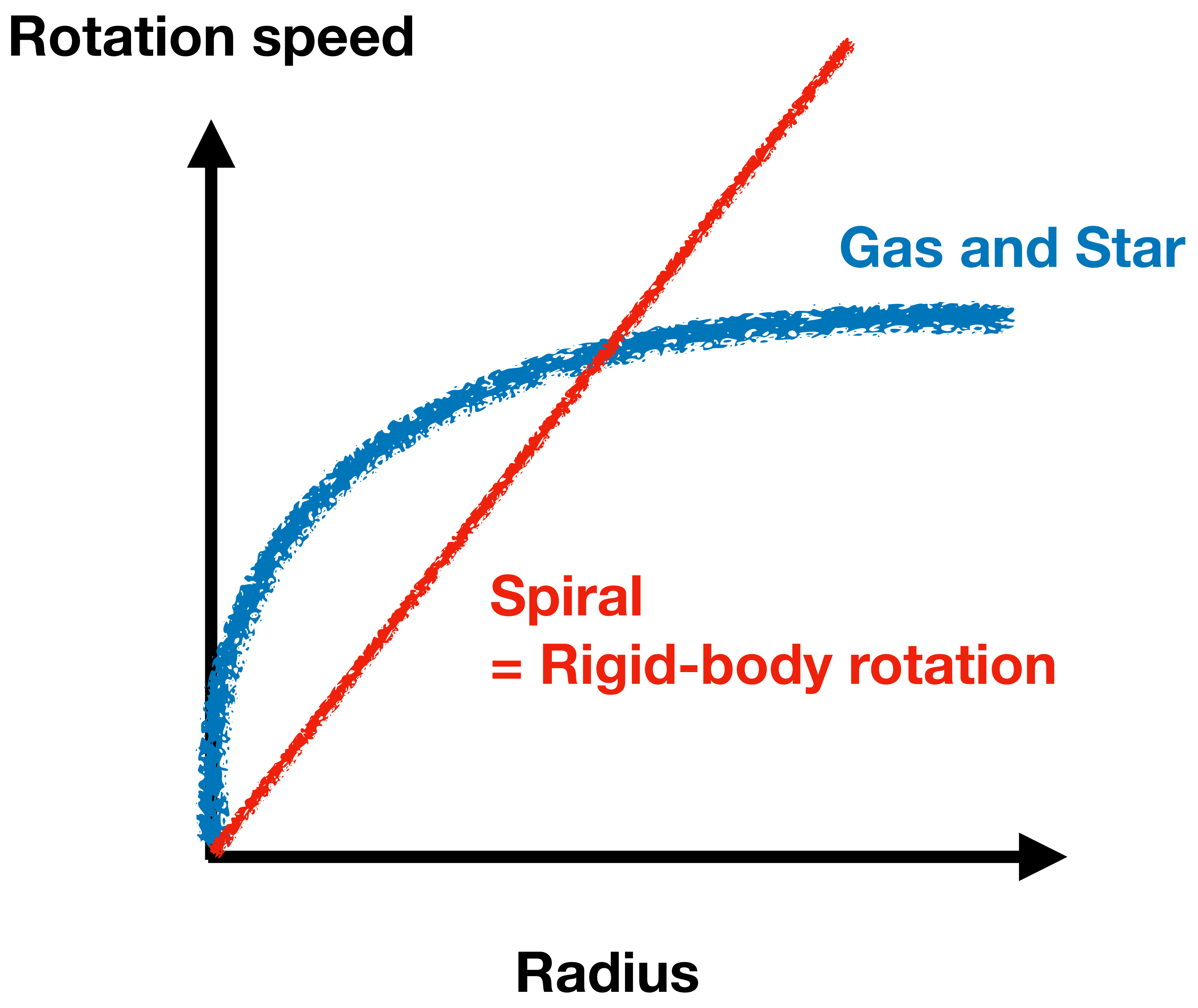


It depends. The duration is governed by the crossing time of stars across the spiral arm

Fujimoto, Krumholz, Inutsuka, Boss, & Nitter 2020, MNRAS

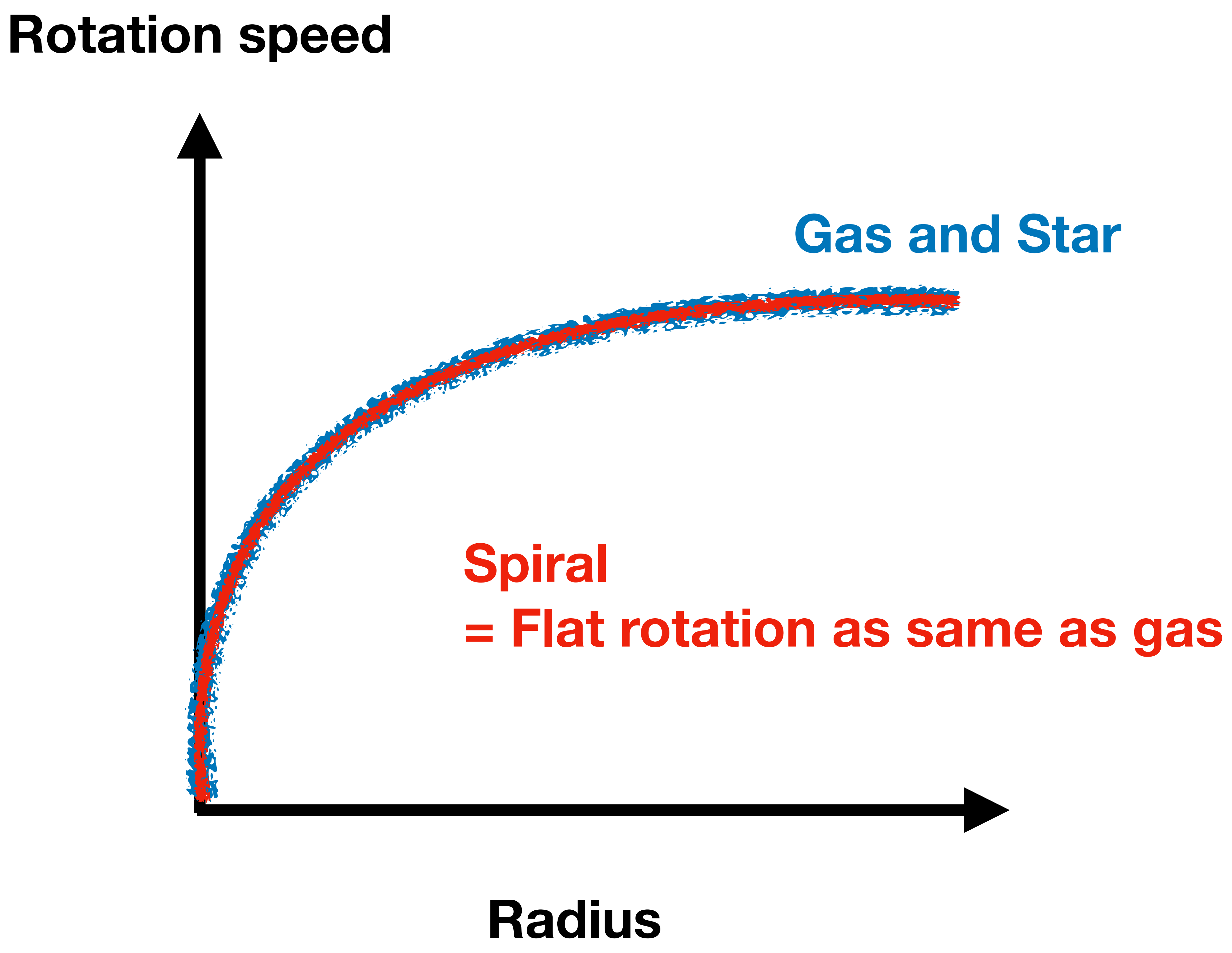
Is the Milky Way’s spiral arm a **density wave**? Or a **material arm**?

Density wave



Gas compression and star formation occur on the <u>leading edge</u> of the arms where the gas shocks upon entry.

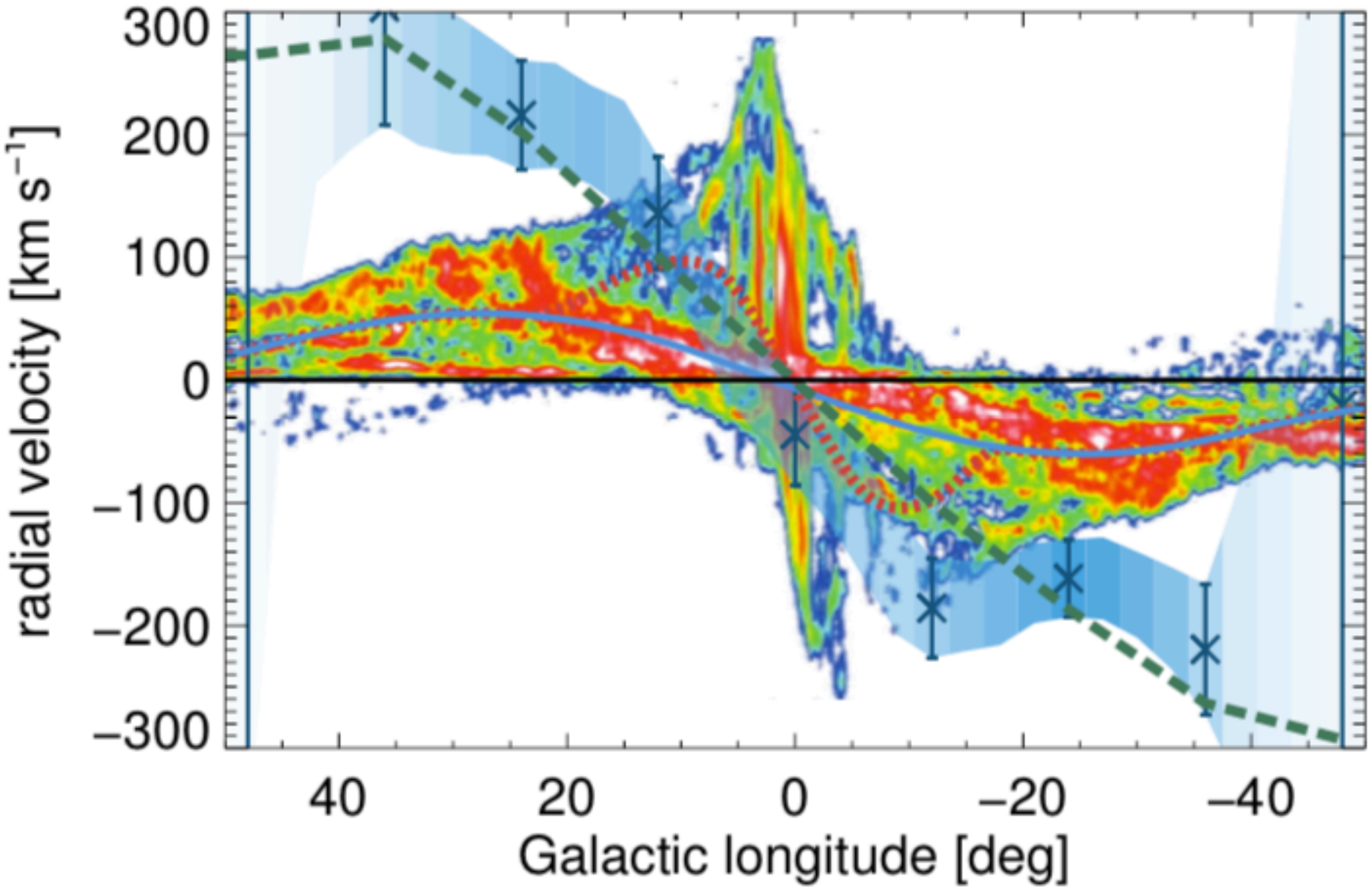
Material arm



Gas slowly falls into spiral arms from both leading and trailing sides as a colliding flow, and then stars form in the <u>middle</u> of the spiral arm.

This is still under debate

The key: galactic gamma-ray observation shows systematic excess of rotation velocity of 26Al, ~ 200km/s



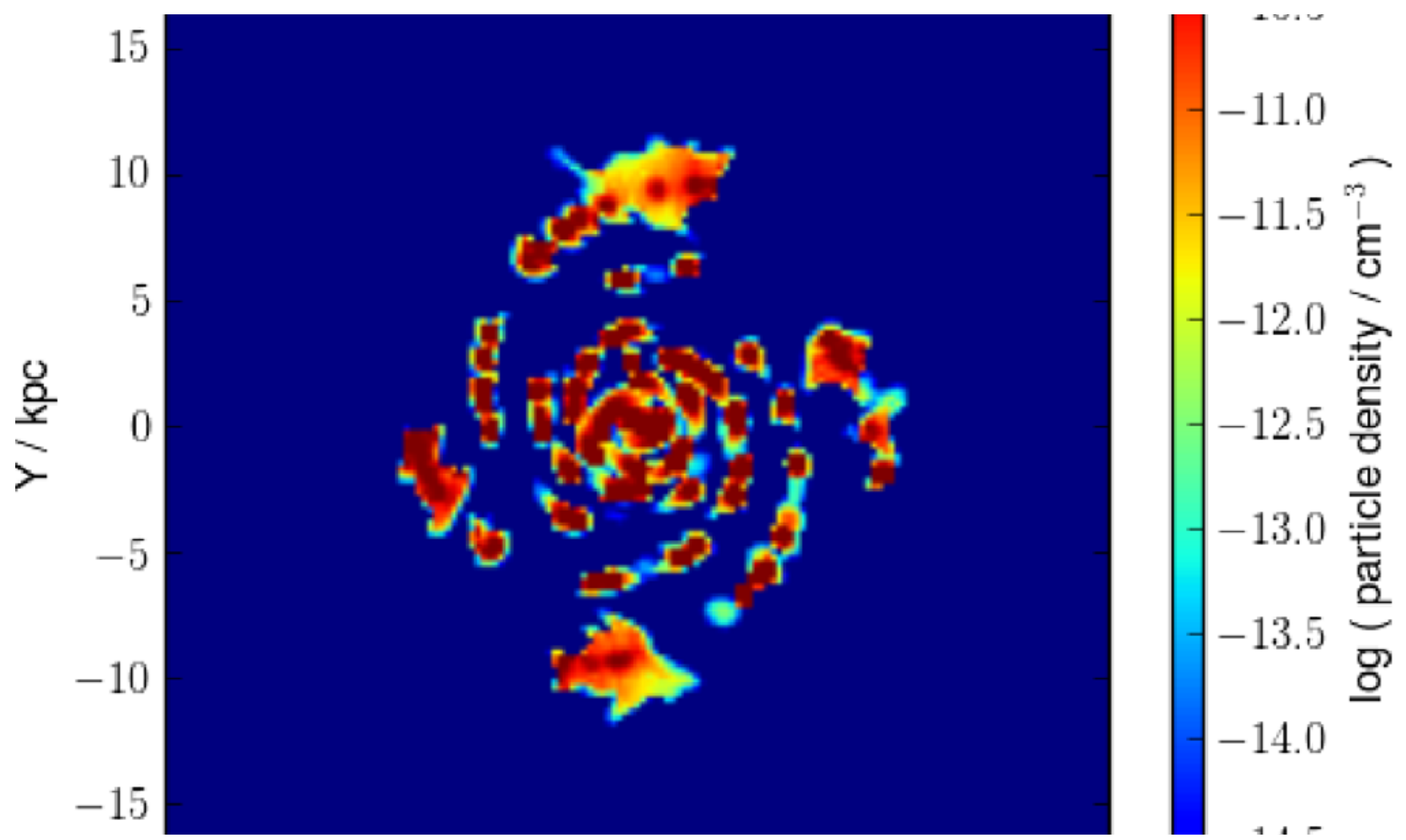
Blue shaded region: 26Al

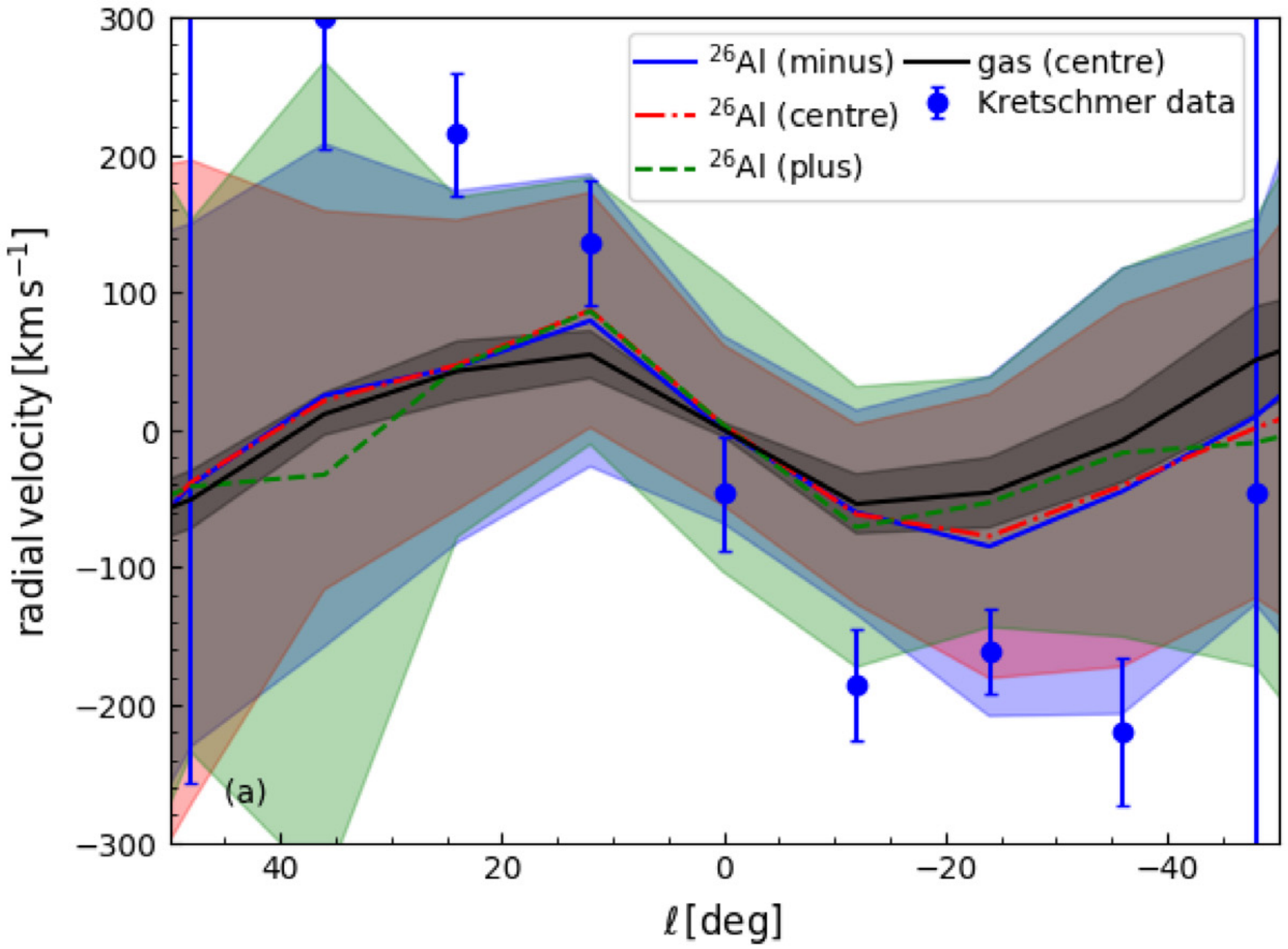
Colored region: CO (1-0)

Kretschmer+ 2013

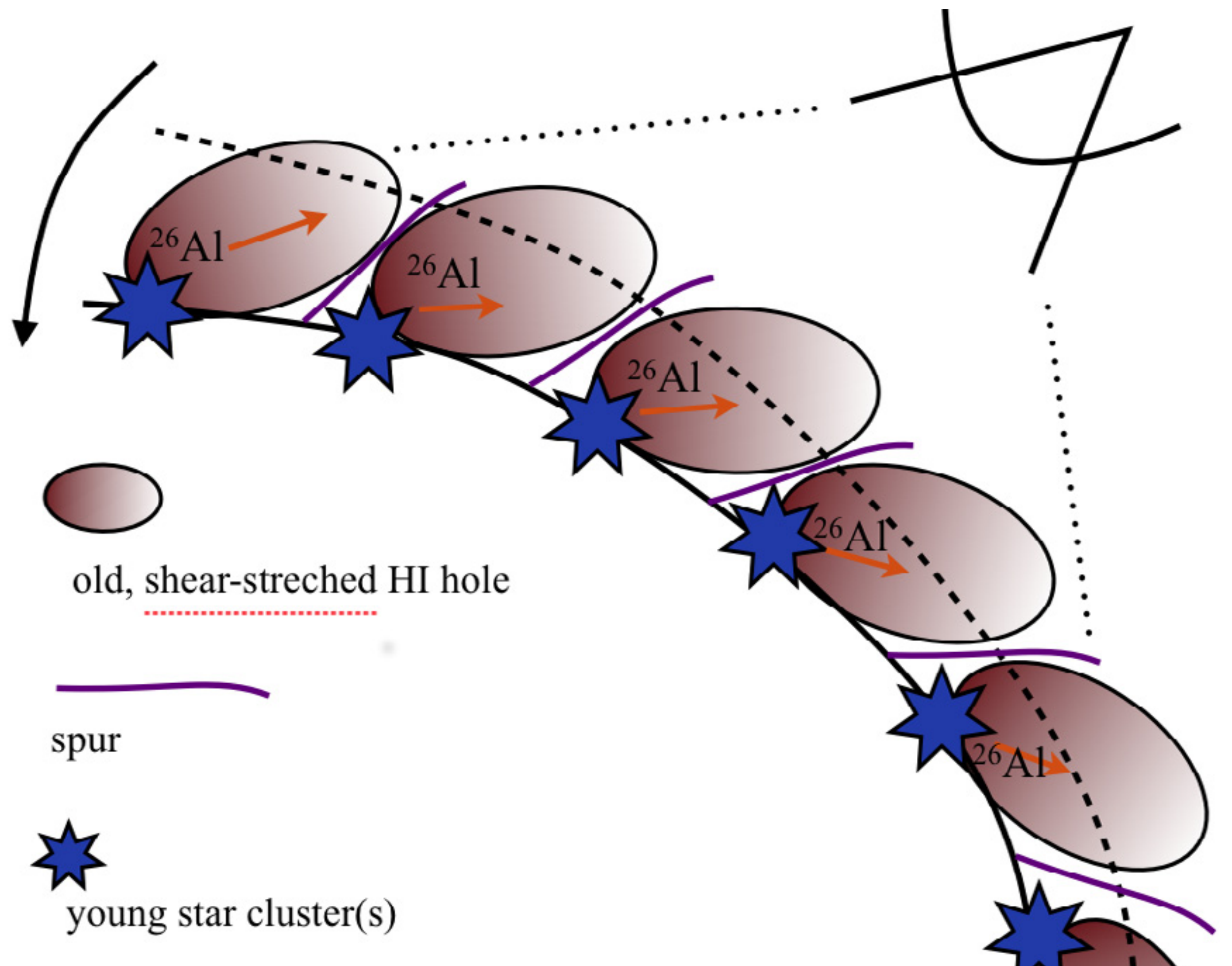
Some previous works support the density wave

Hydro simulation with 26Al, using rigid rotation spiral arm potential





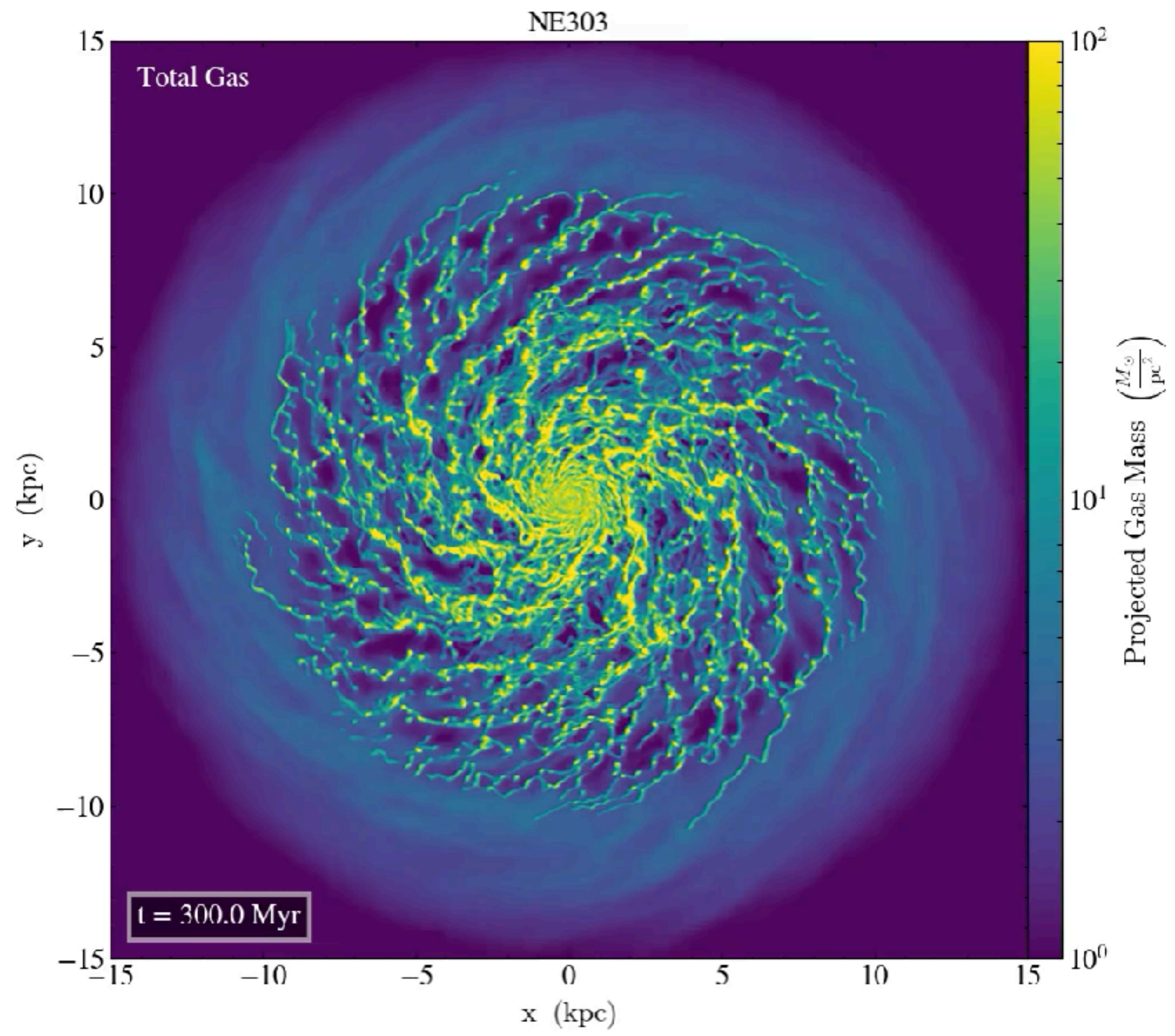
Rodgers-Lee+ 2019

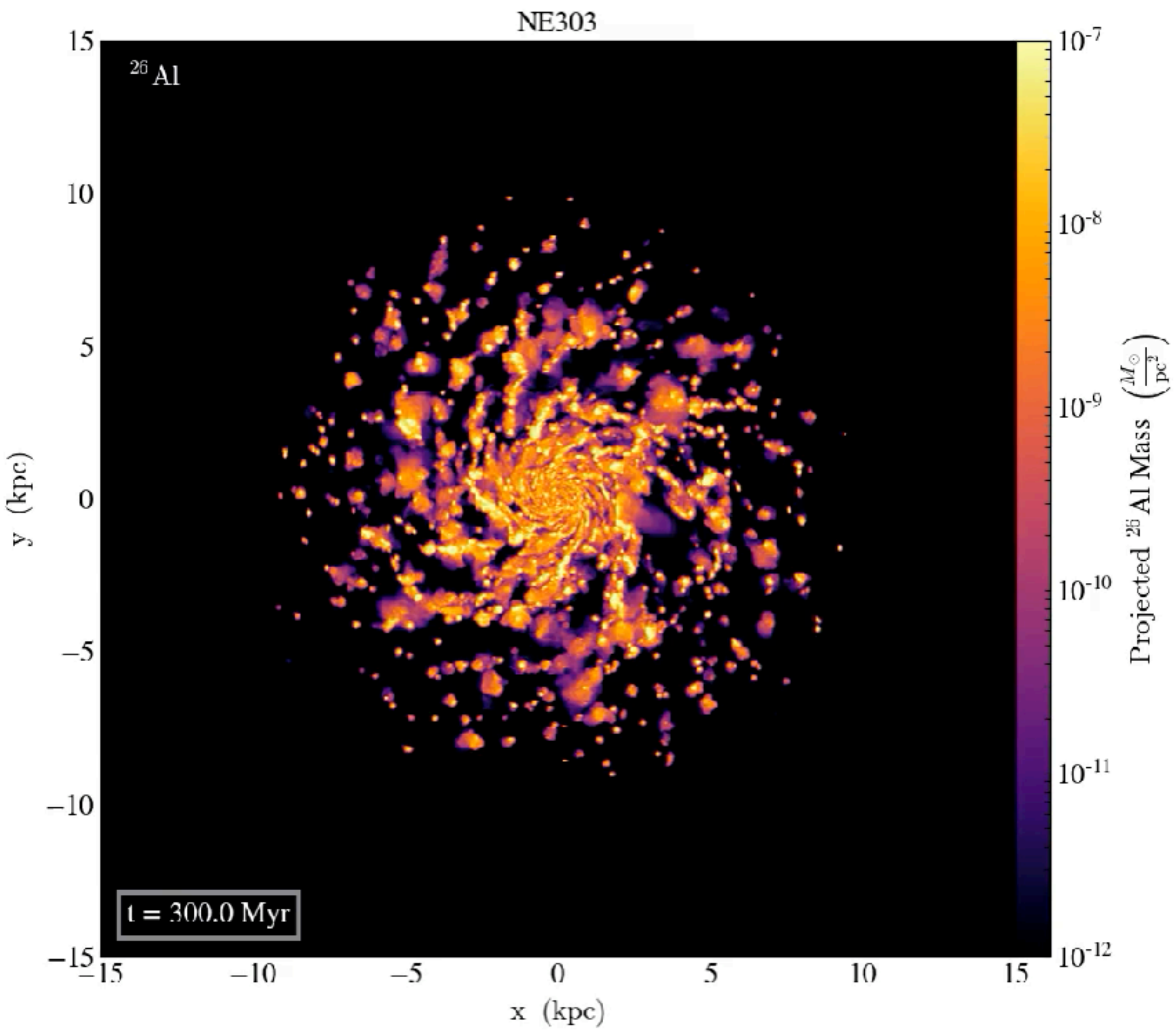


Massive stars form at the leading edges of the arm,
and 26Al blow out into the low-density regions forward of the arm

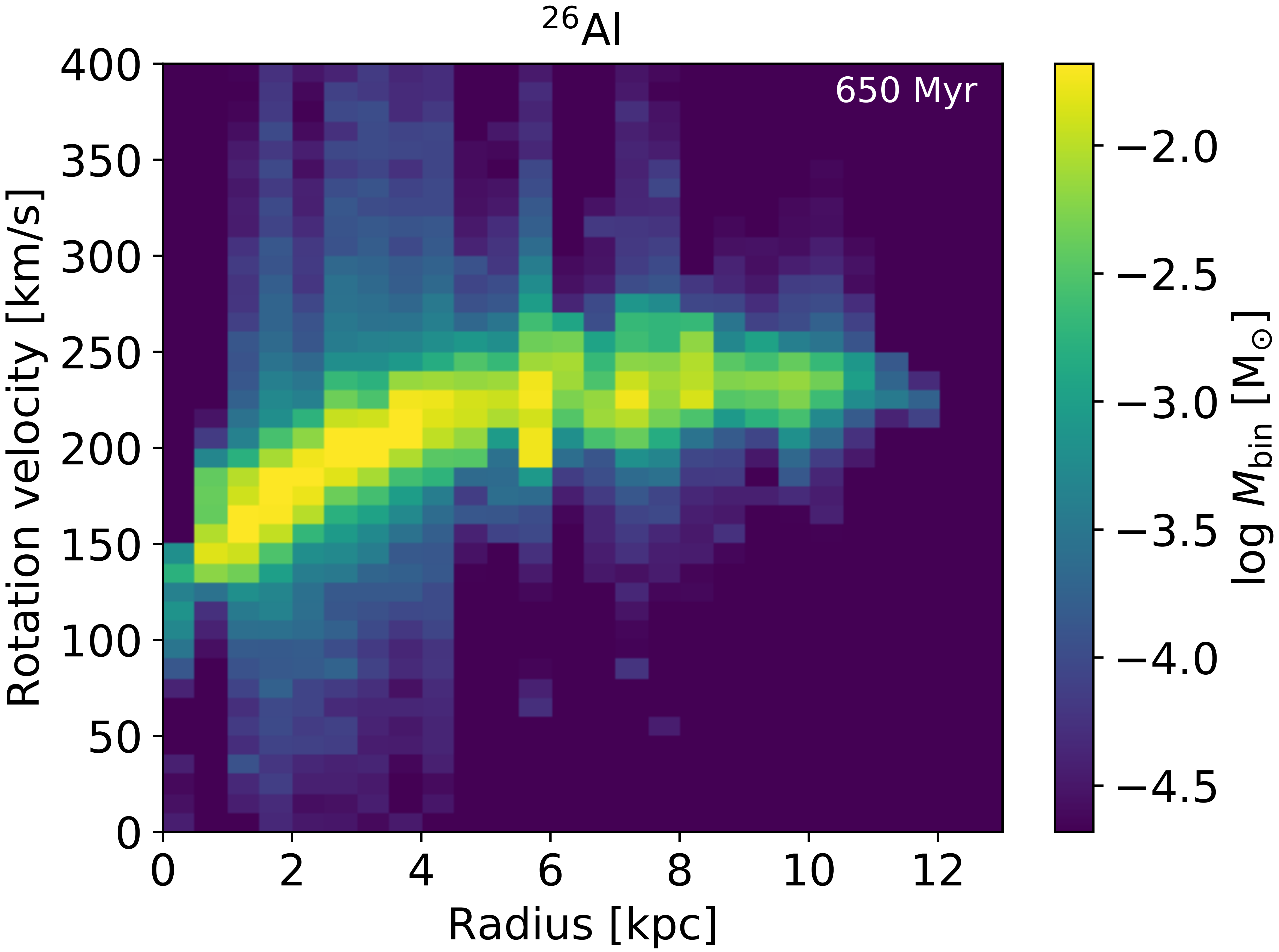
Krause+ 2015

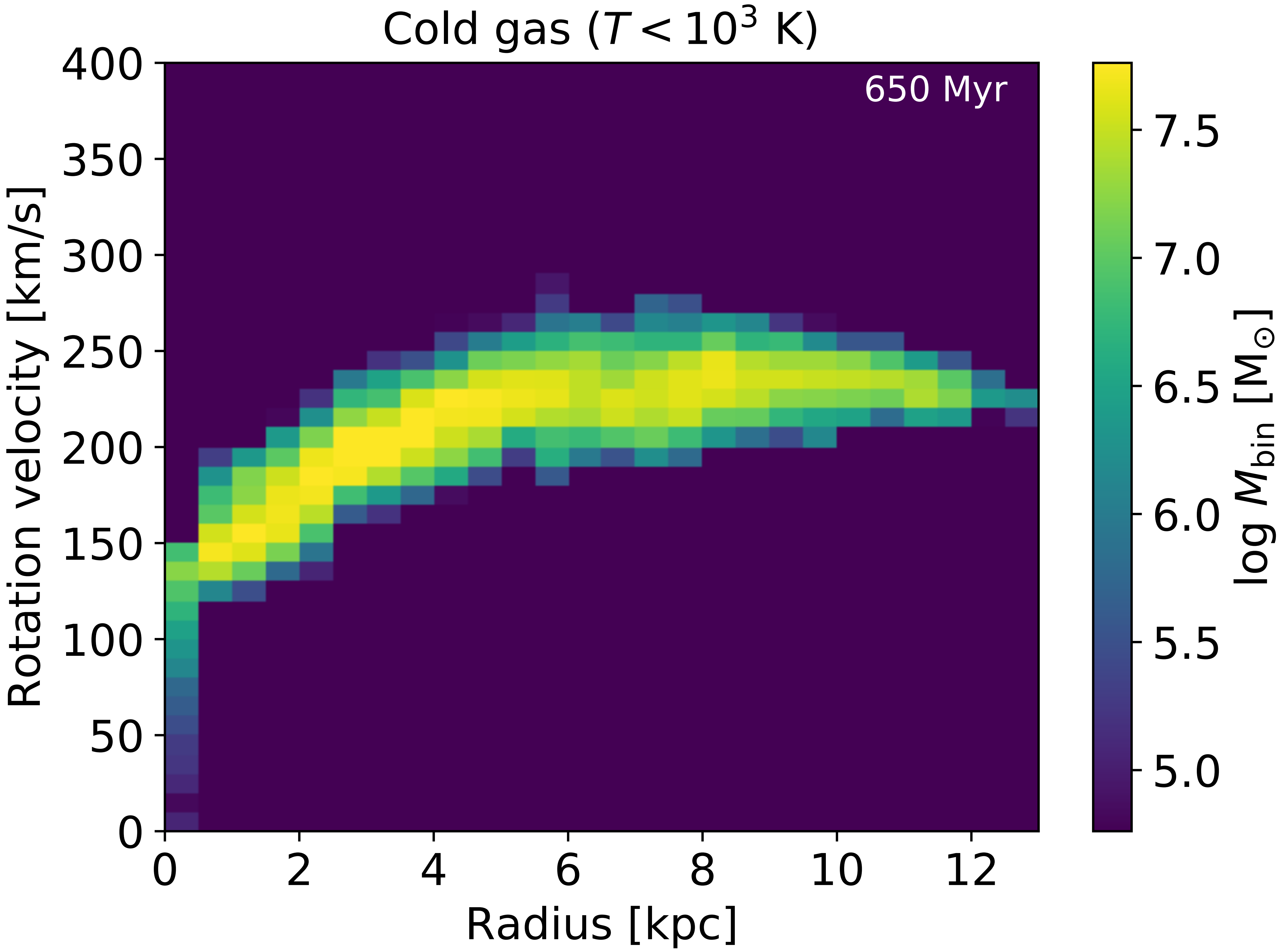
What about my simulation in which spiral arms are material arms?



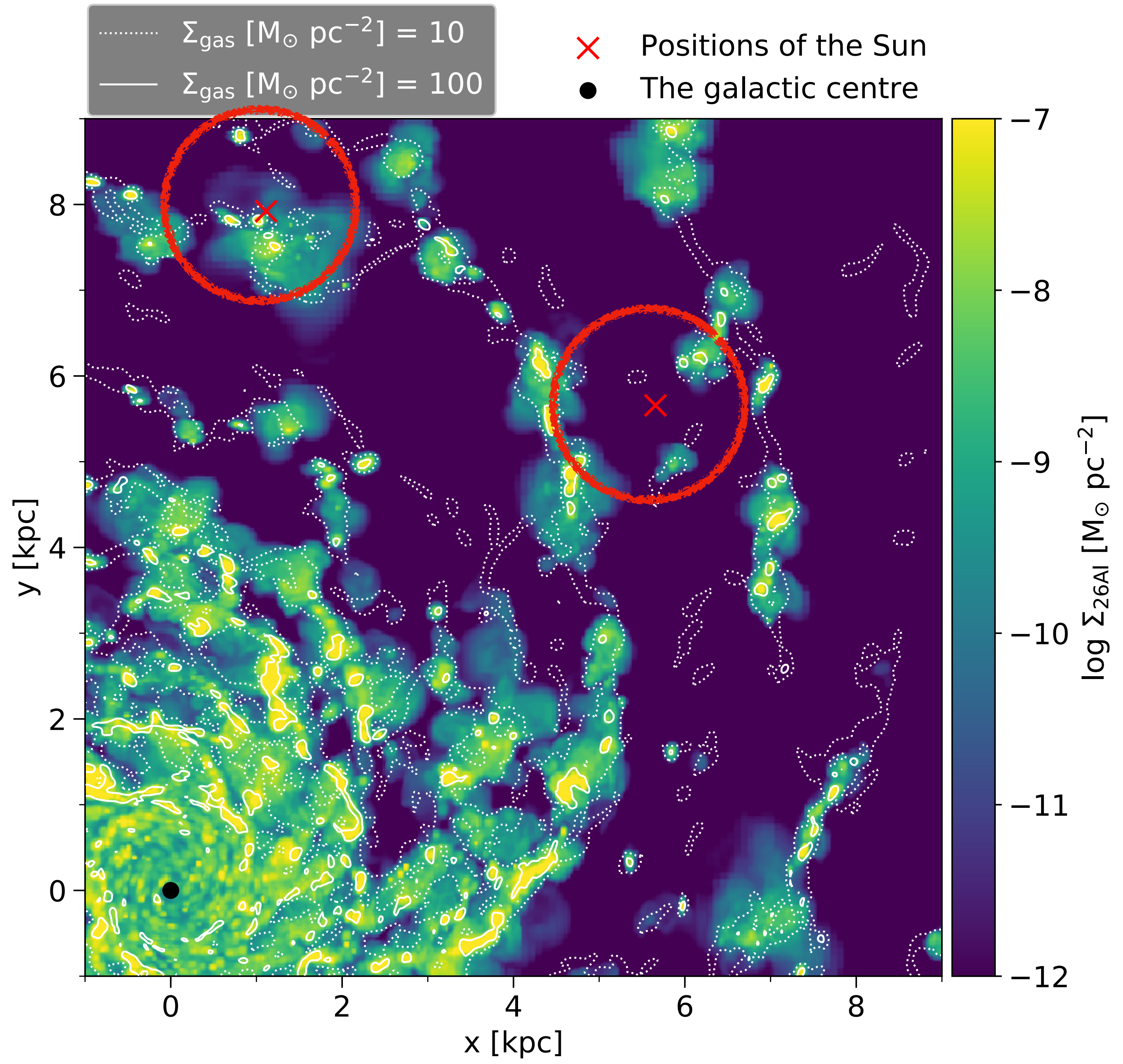


No systematic excess of 26Al in the rotation curve

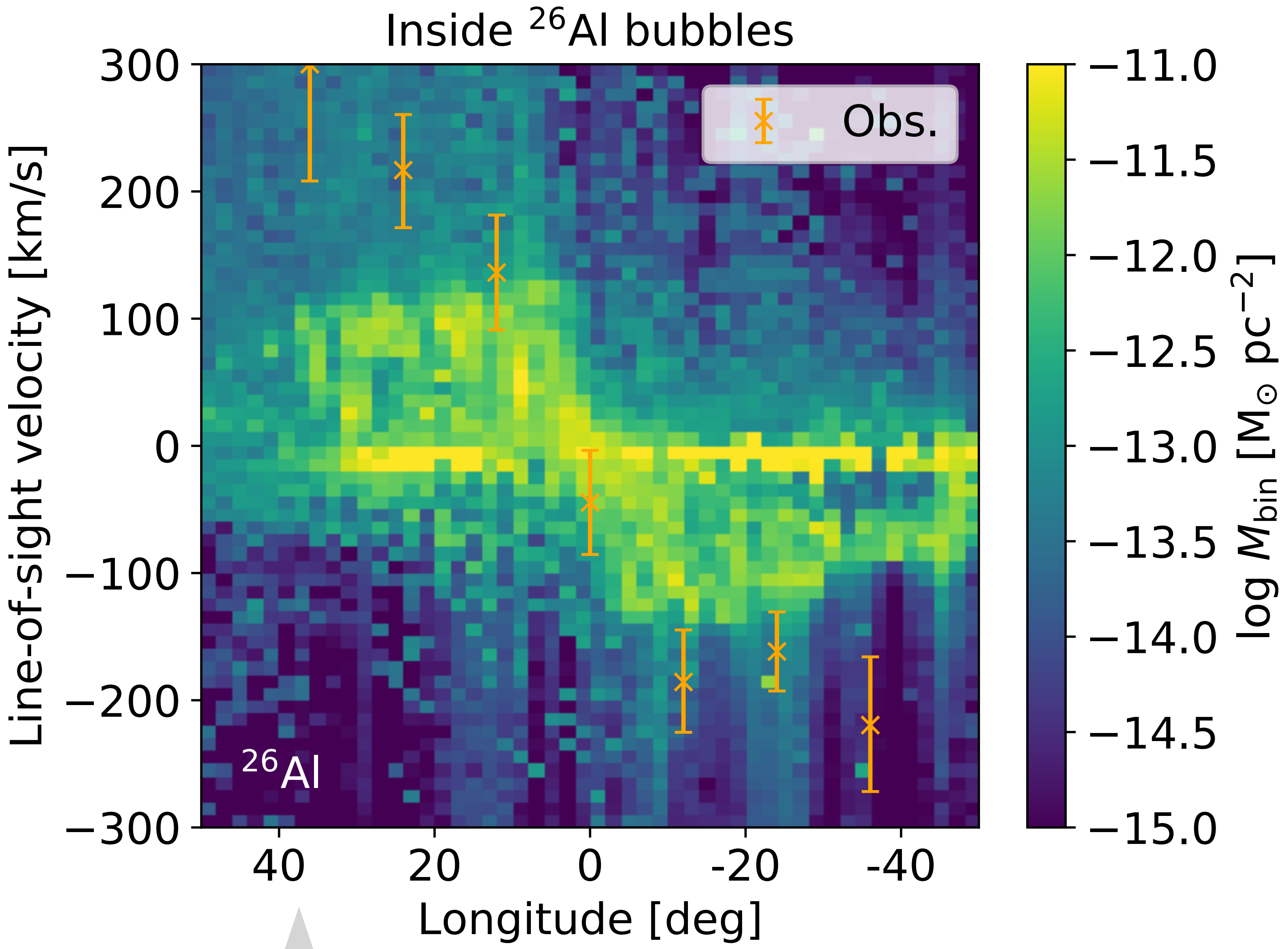




Synthetic 26Al emission maps for two different positions

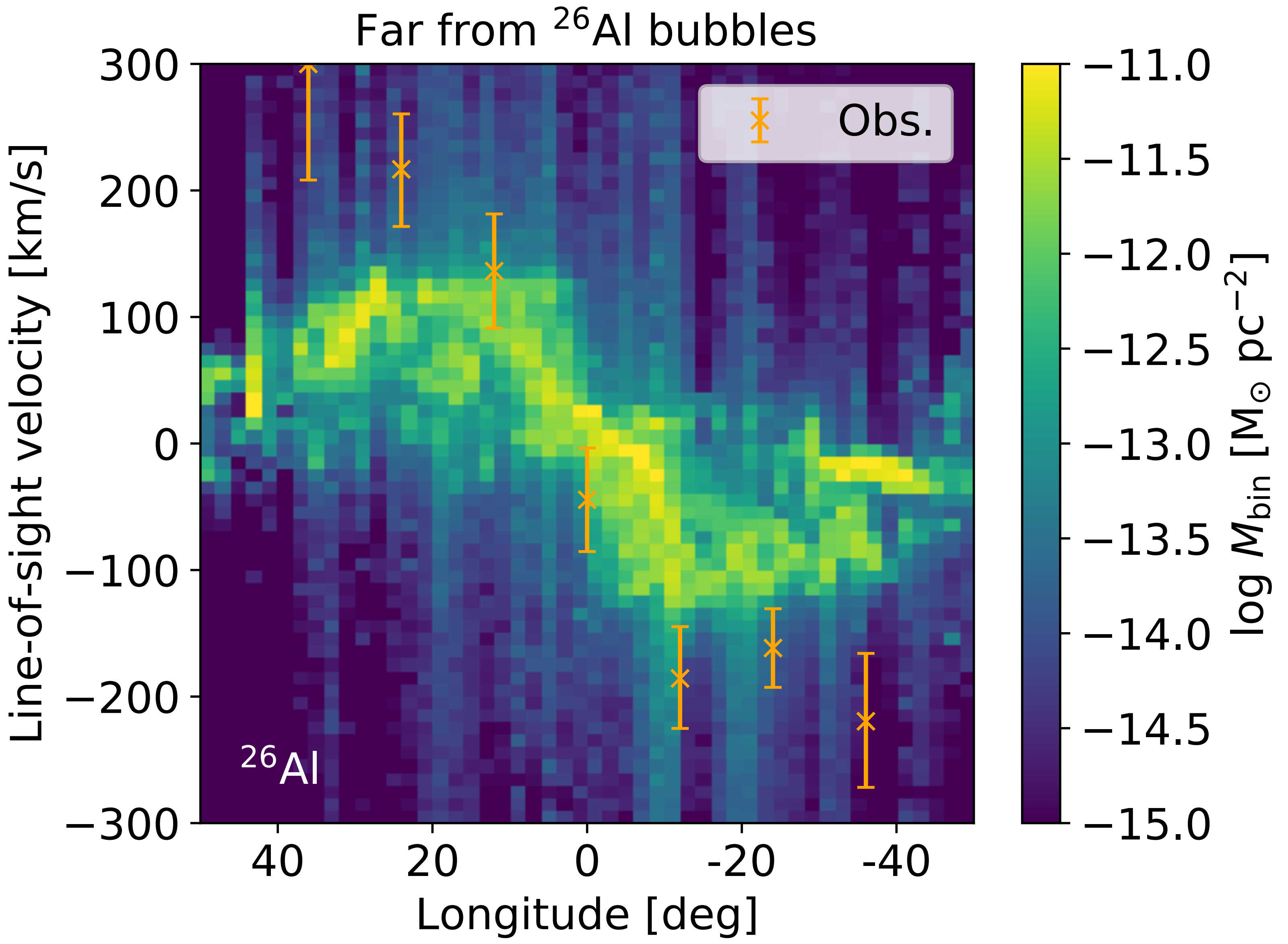


Inside 26Al bubble



We see some excess

Outside 26Al bubble



The observed excess of 26Al velocity may be the product of foreground emission from nearby massive stars, like Local Bubble

The material arm scenario is still alive

Fujimoto, Krumholz & Inutsuka 2020, MNRAS

Summary

1. The birth environment of the early Solar system 4.6 Gyr ago

2. The local interstellar environment of the current Solar system

3. The formation mechanics of the Milky-Way's spiral arms

Using SLRs, we can discuss such broad topics. How useful they are!