地質学的試料に残る超新星起源の60Feと
銀河化学進化シミュレーションで探る
太陽系の周囲環境

特に、銀河渦状腕との関係に着目

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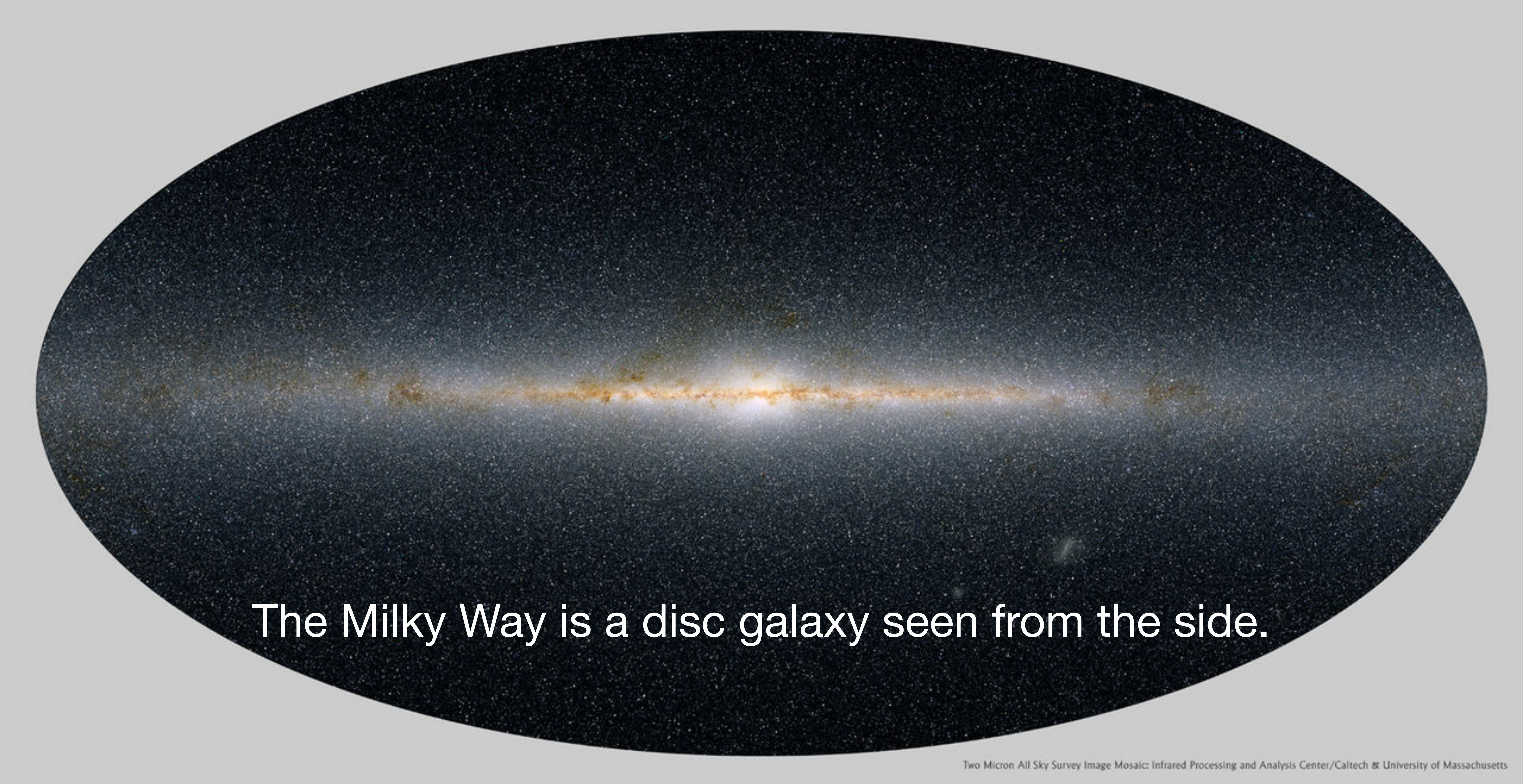
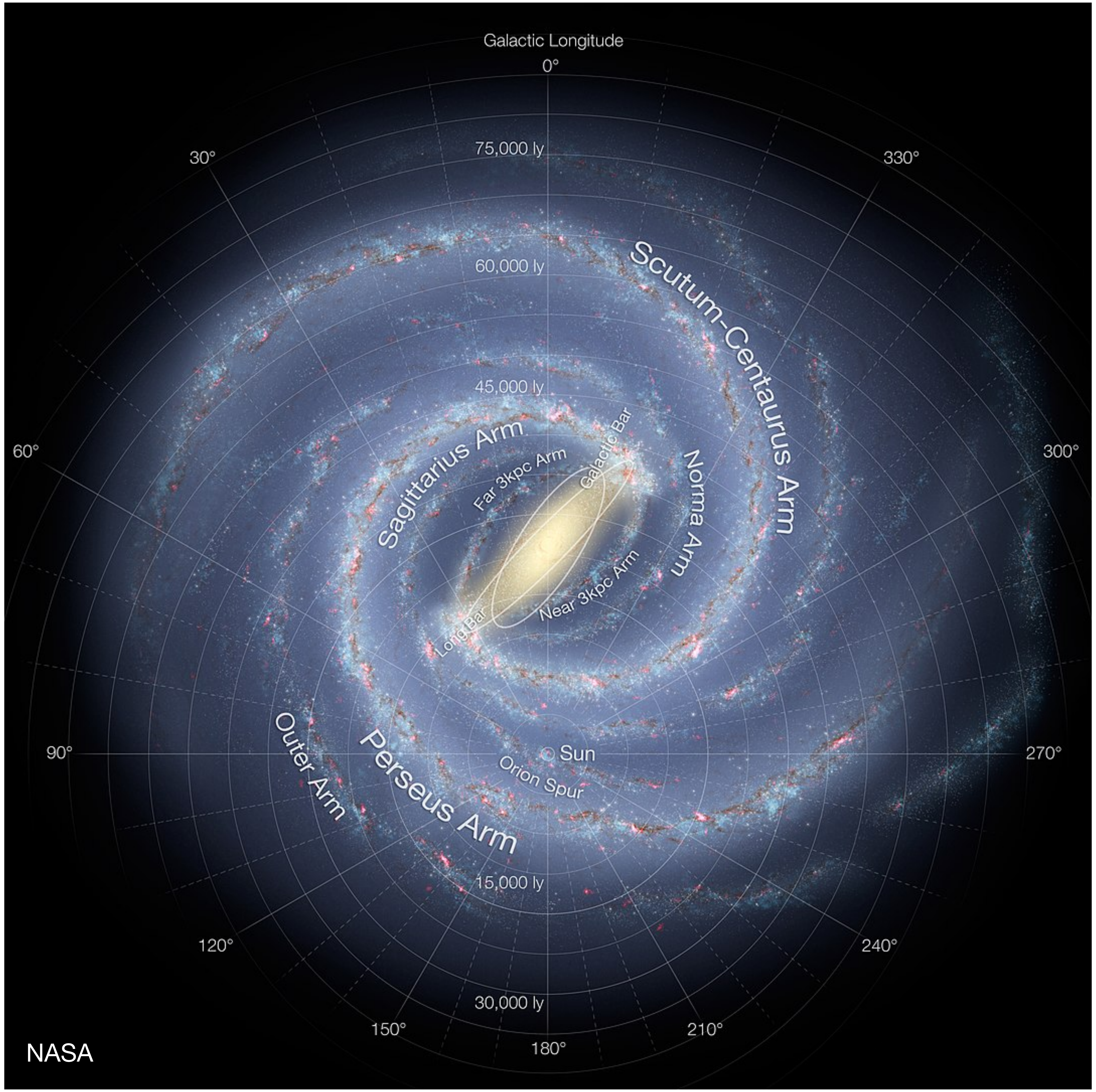
Overall picture of the Milky Way Galaxy



Imaginary view of the Milky Way Galaxy seen from directly above.



Because we are located in the Milky Way Galaxy, it is difficult to know what it looks like and the structure we reside.

Astronomers have inferred the Milky Way’s shape and Sun’s location from many kinds of observations

Short-lived radioactive nuclide (SLR) can be the key

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

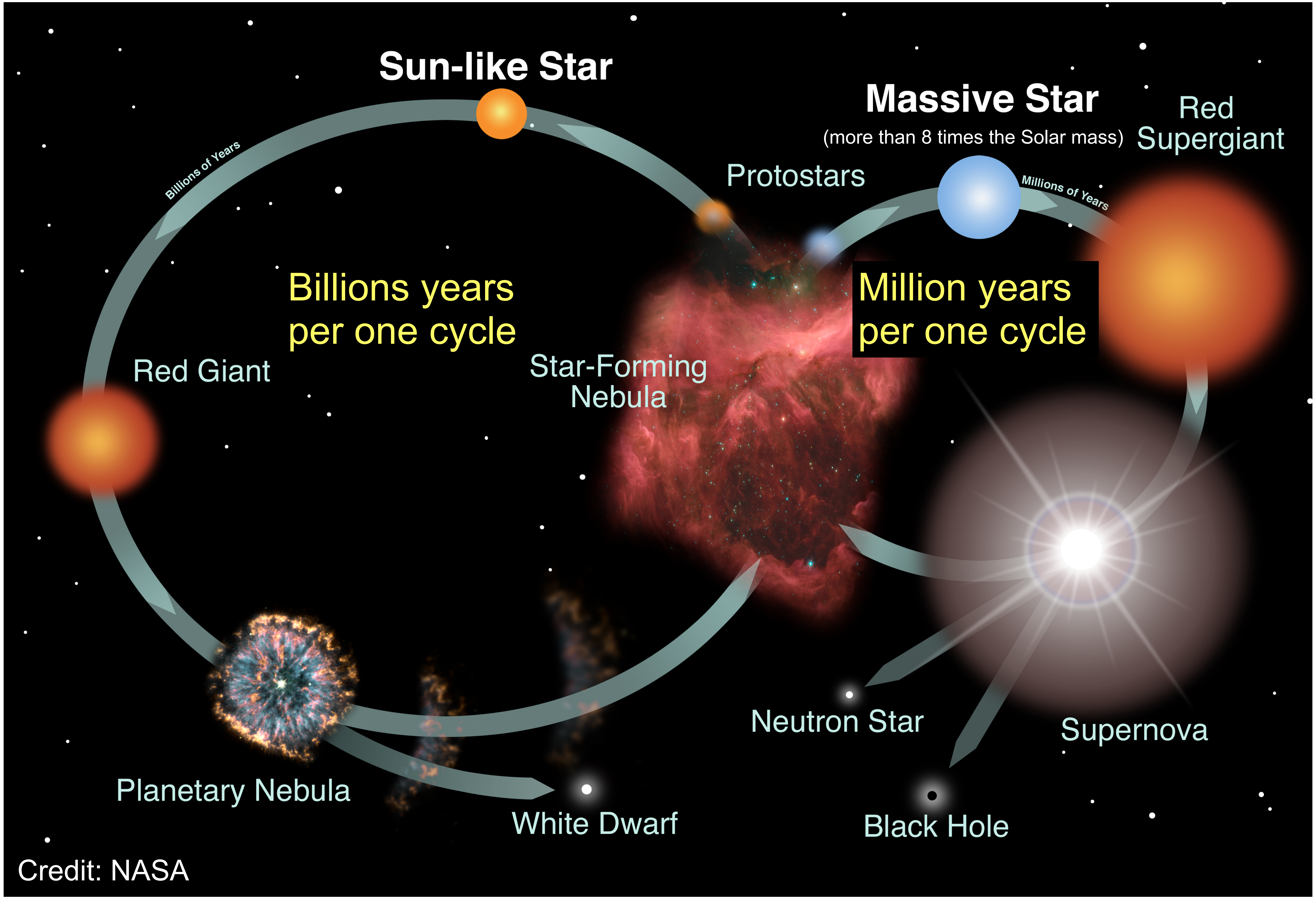
What is the <u>origin sites</u> of the SLR?

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

Lugaro et al. 2018

Therefore, SLRs can be tracers for astronomical events, such as supernovae.

Massive stars are important for galaxy evolution

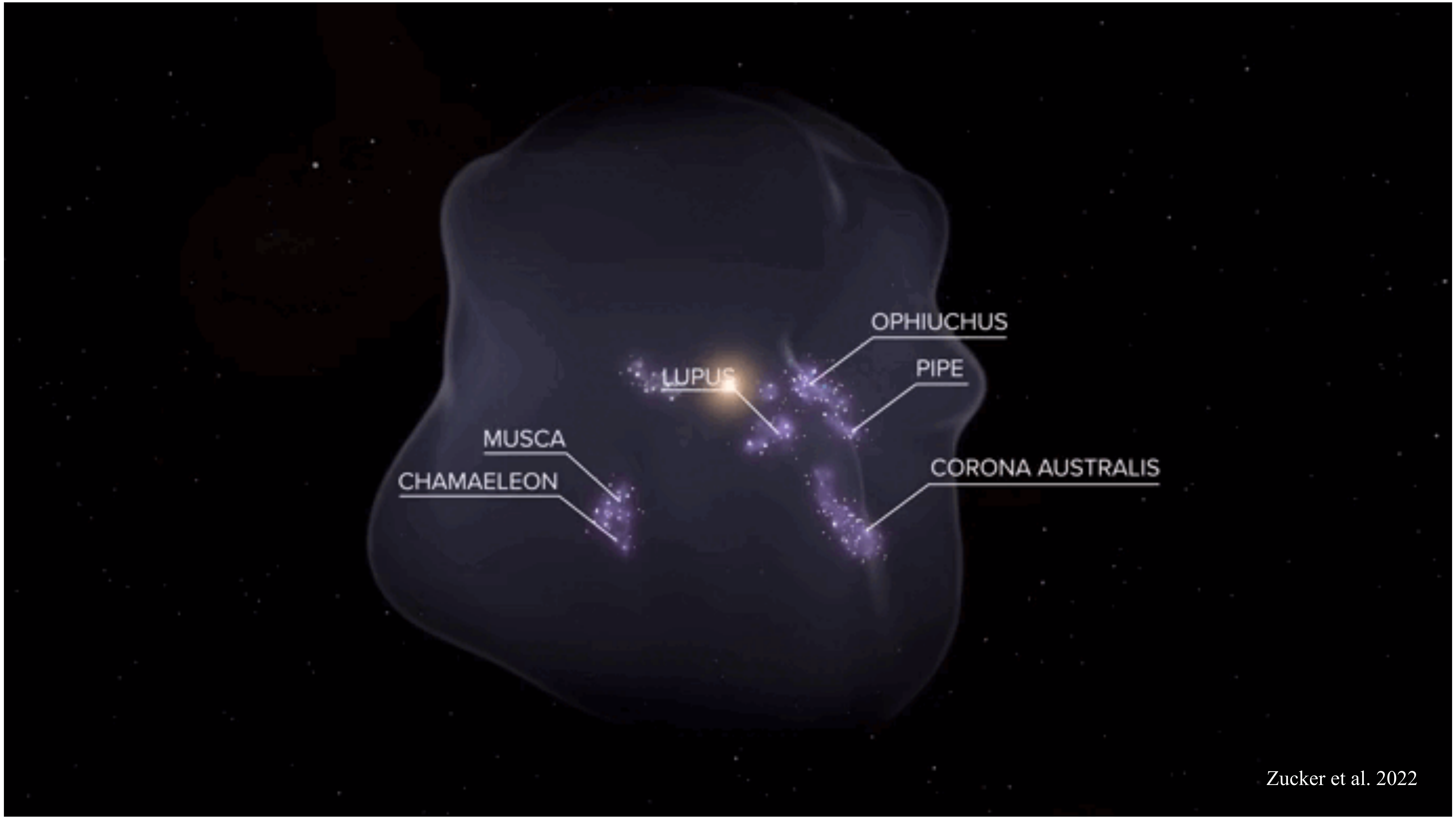


1. Very luminous
   (heat and ionize surrounding gas)
2. Explode as supernova
   (disperse surroundings gas & cloud)
3. Distribute heavy elements
4. Much shorter life cycle

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

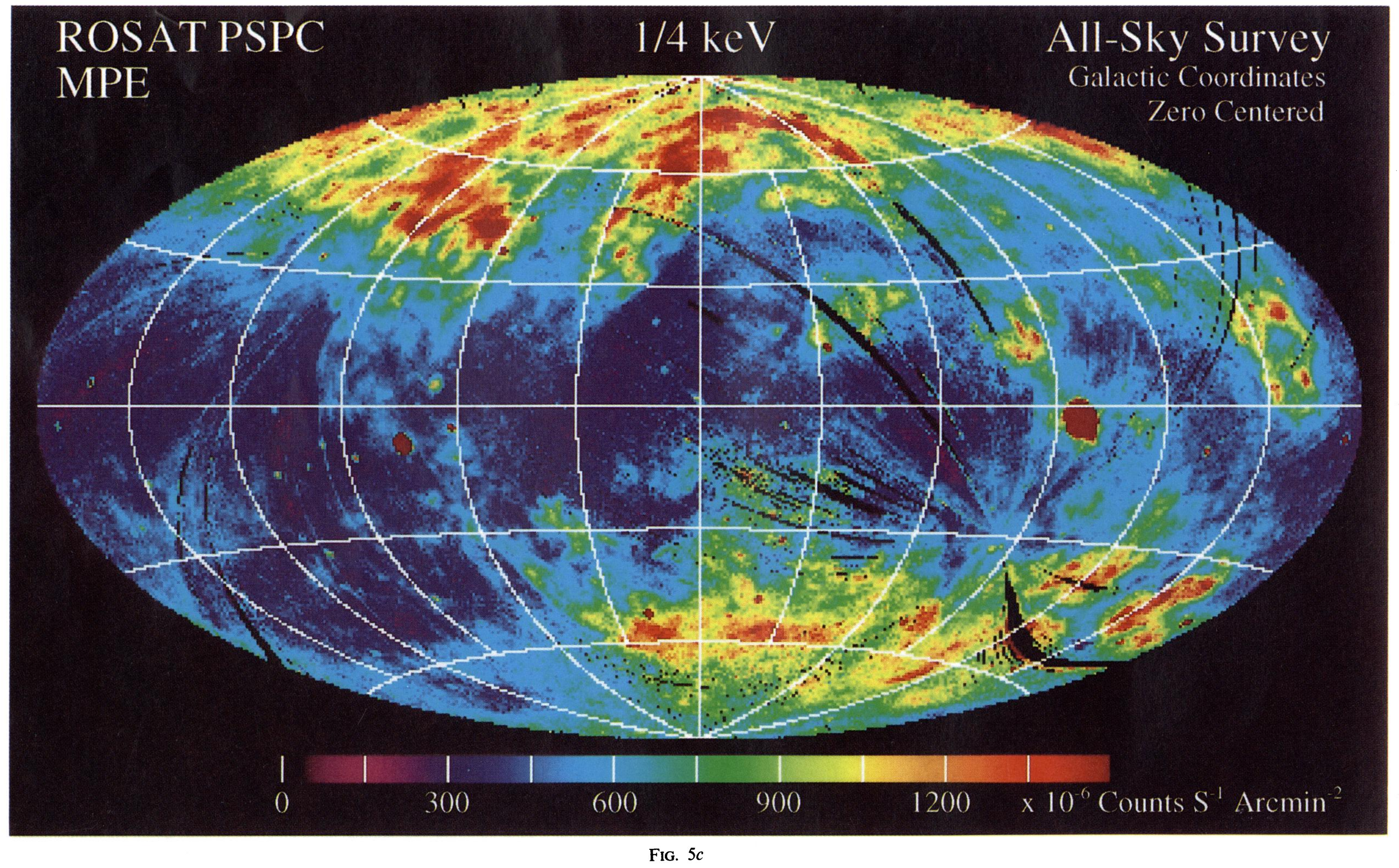
The Solar system has been affected by nearby massive stars for recent ~ 10 Myr

Local Bubble



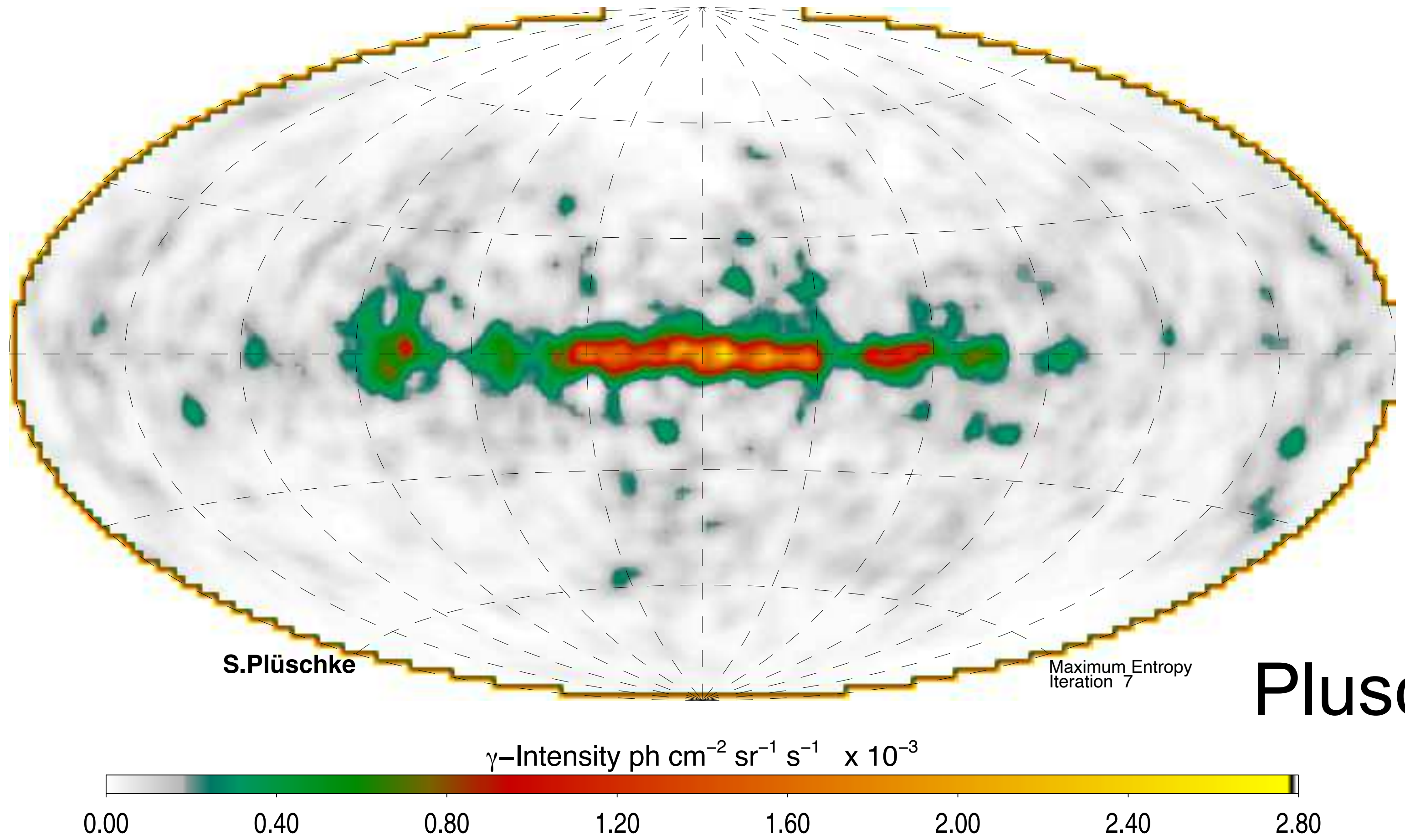
Three independent pieces of observational evidence

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



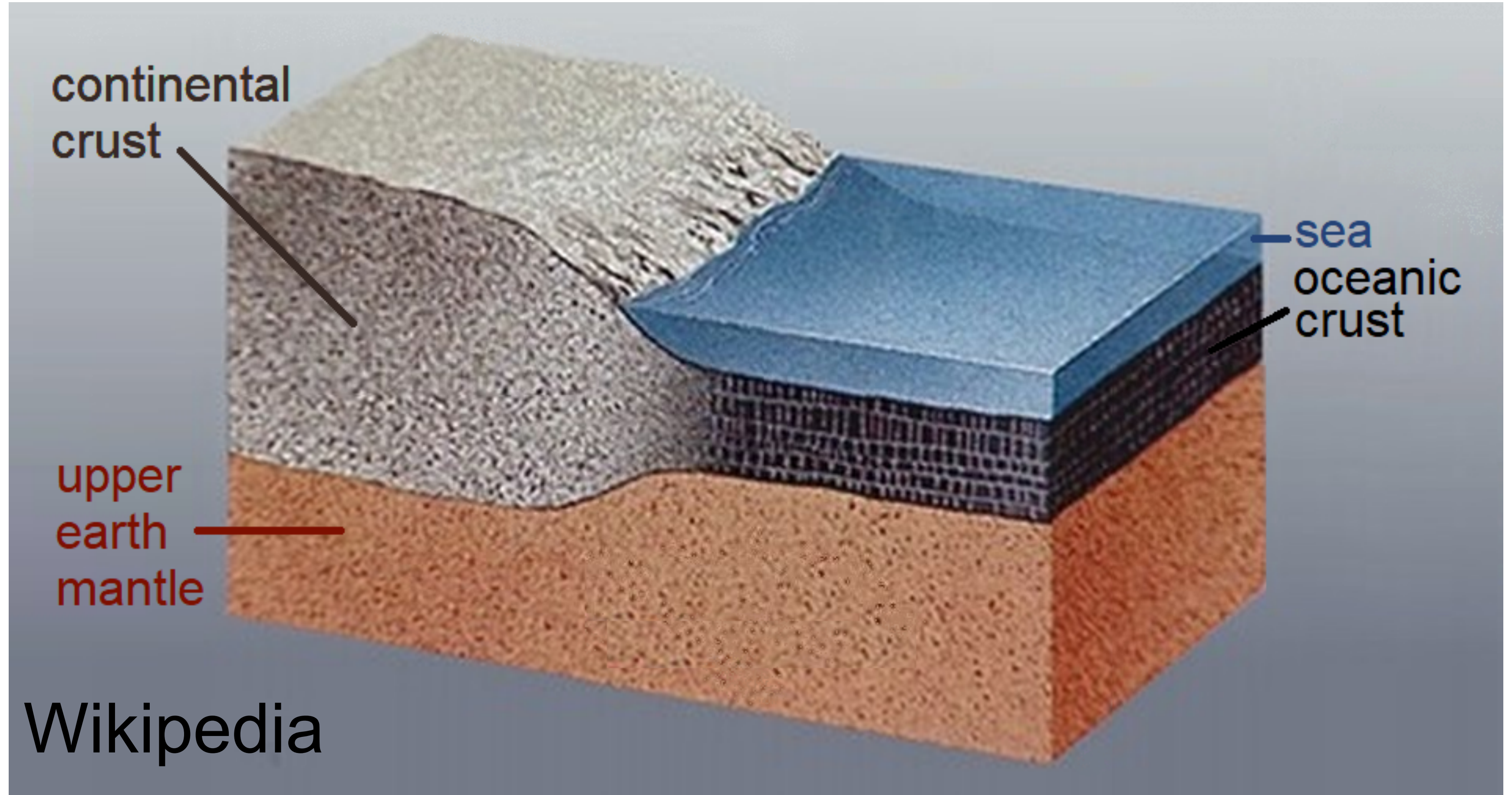
Snowden et al. 1995

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)

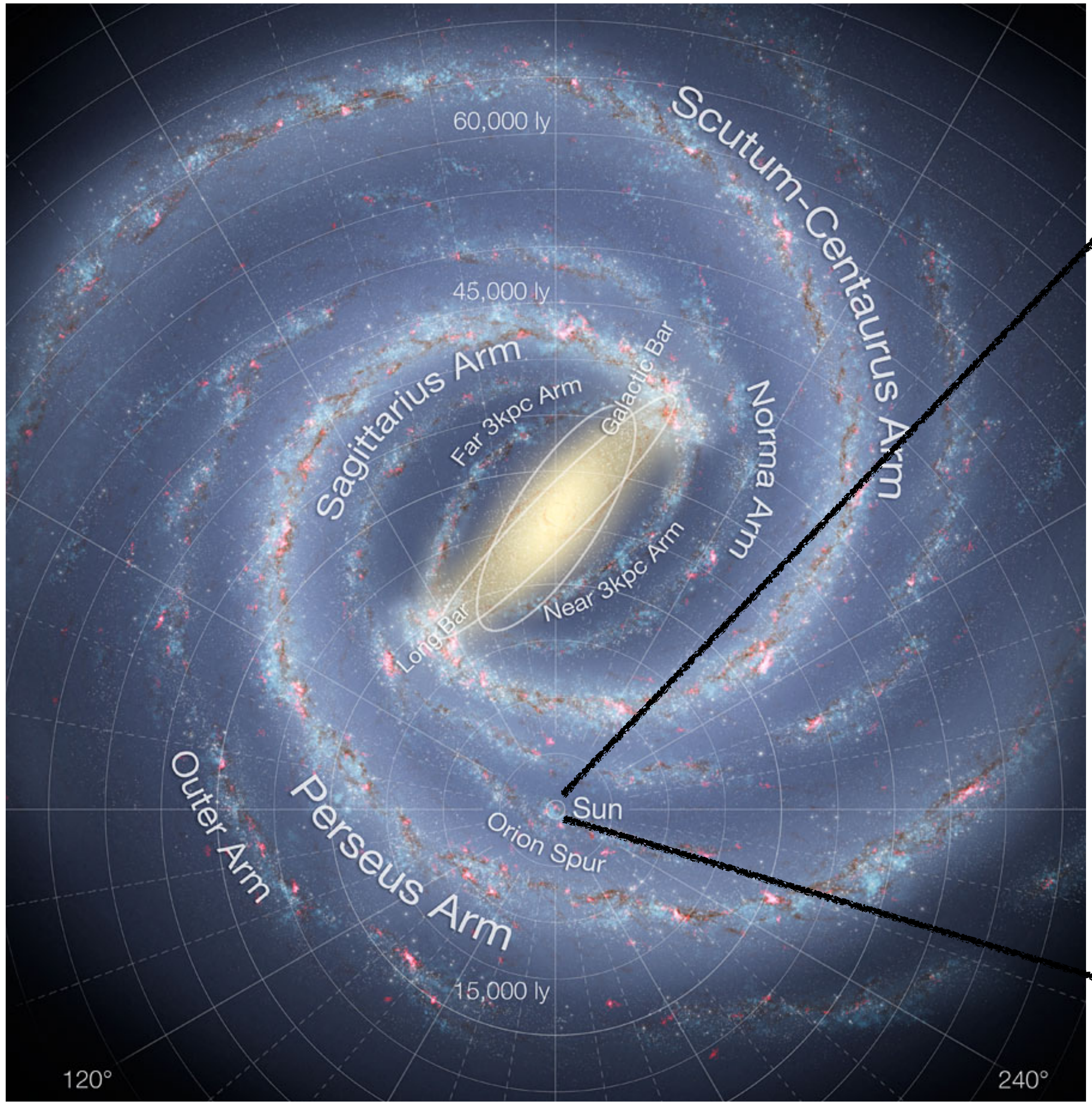


Wikipedia

	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	$1.2^{+0.6}_{-0.5}$

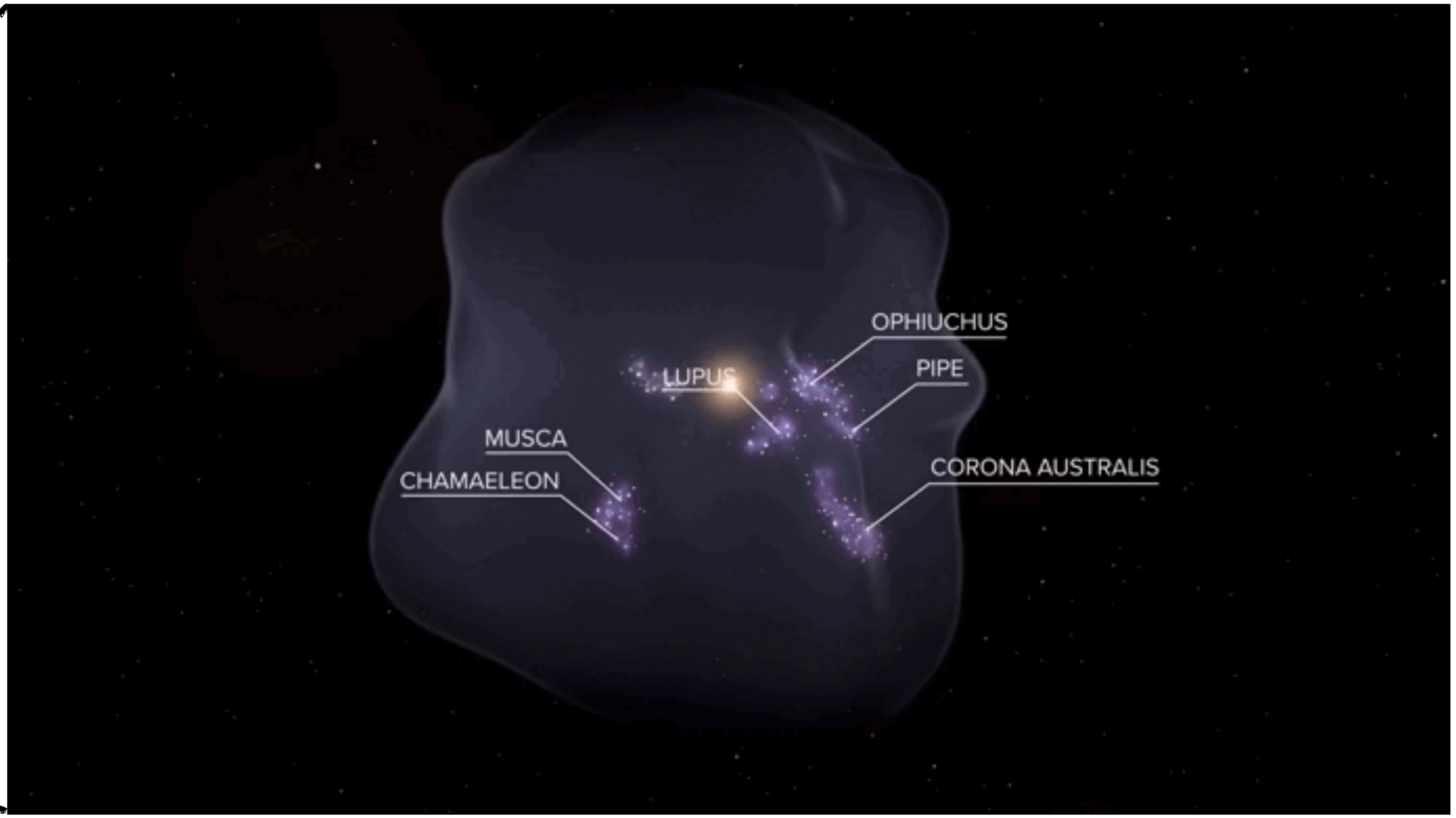
Table from Koll et al. 2019

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



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

Local Bubble



Zucker et al. 2022

N-body + Hydro+ Chemo dynamic simulation of the entire Milky Way

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

- Include almost all necessary physics

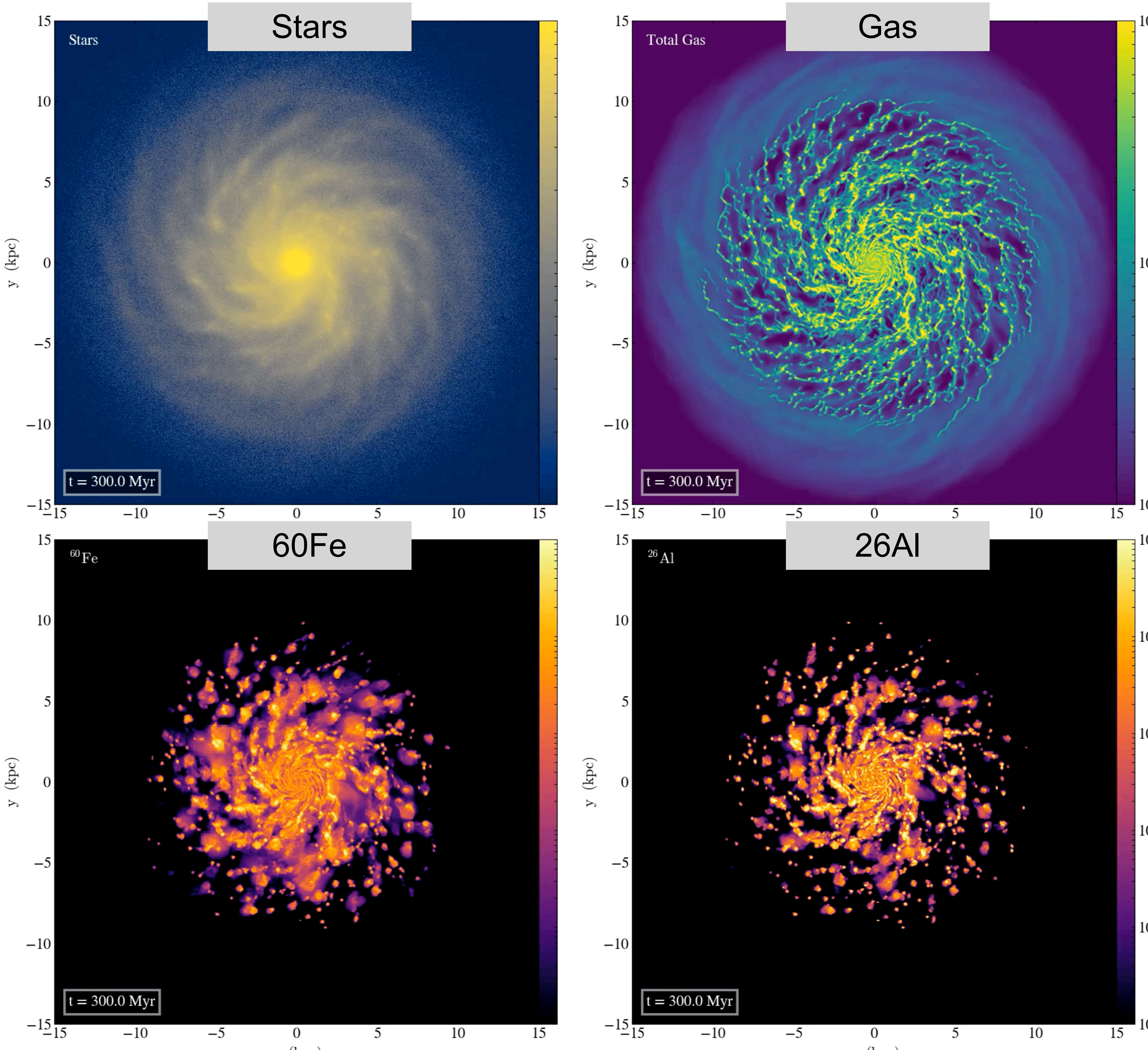
  (radiative cooling and heating, self-gravity, star formation and massive stellar feedback)

- **SLR injection from massive stars, and time decay**

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

0.72 Myr for ^{26}Al

The originality of this research

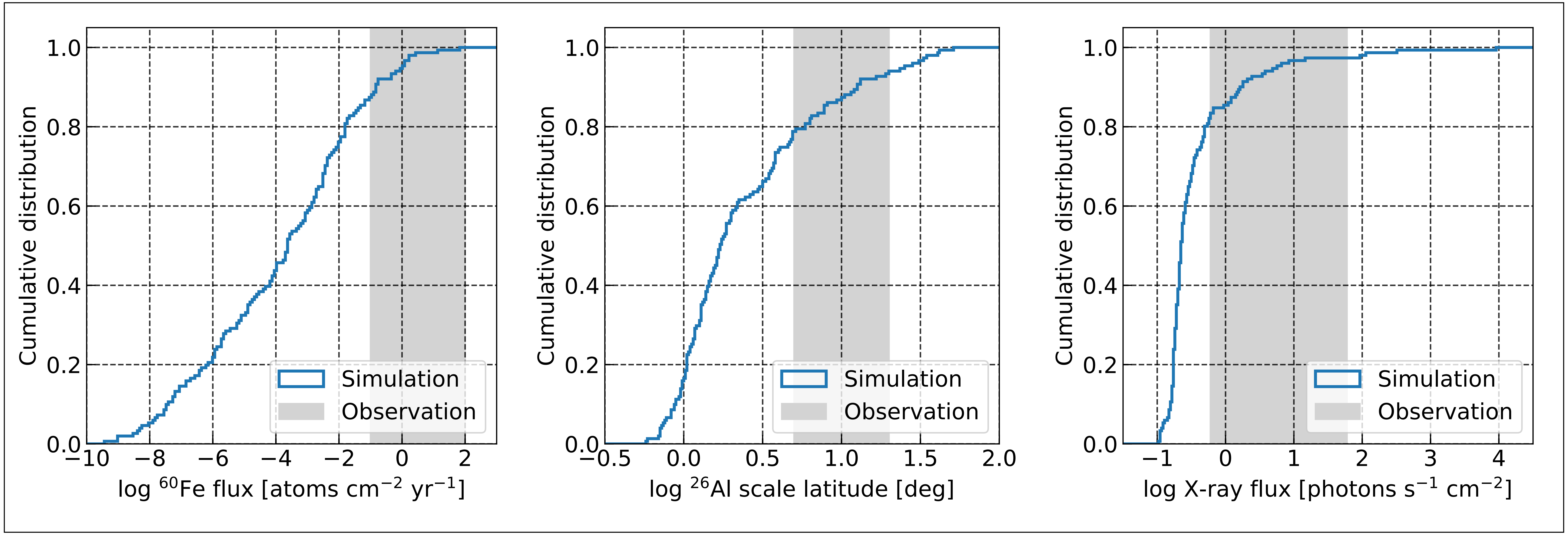


Investigated the location of stars whose environments are consistent with the observations:

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

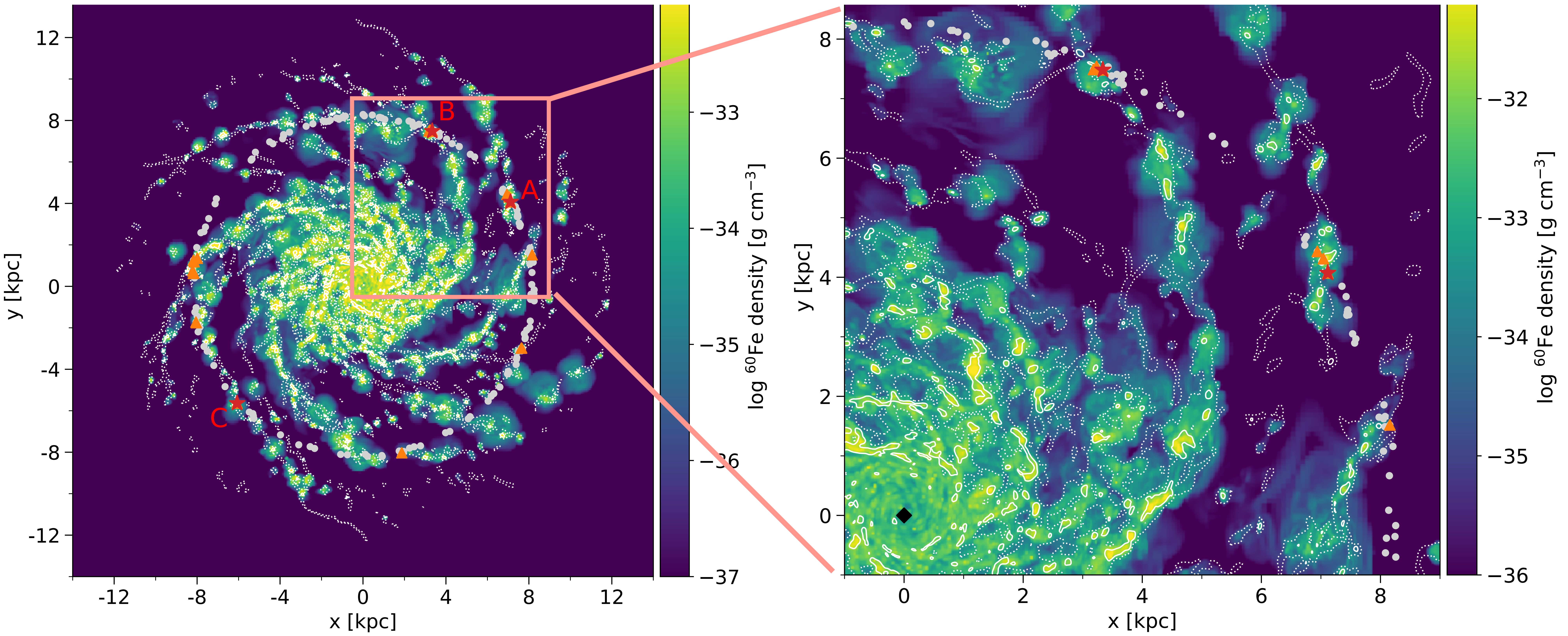
(2) A broad distribution of ^{26}Al observed in the γ-ray sky-maps

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



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

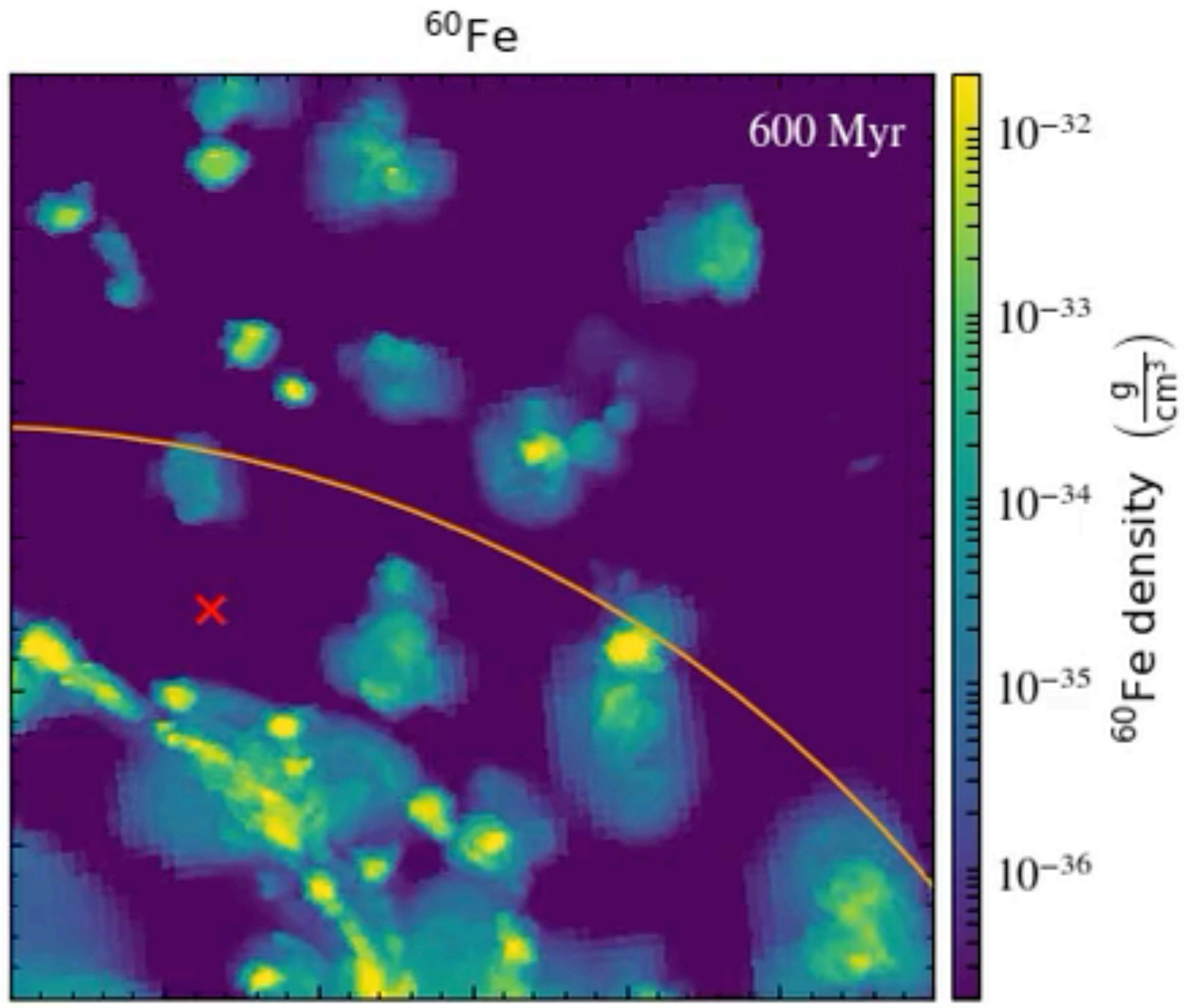
Where are such Sun-like stars located in the galactic disc?



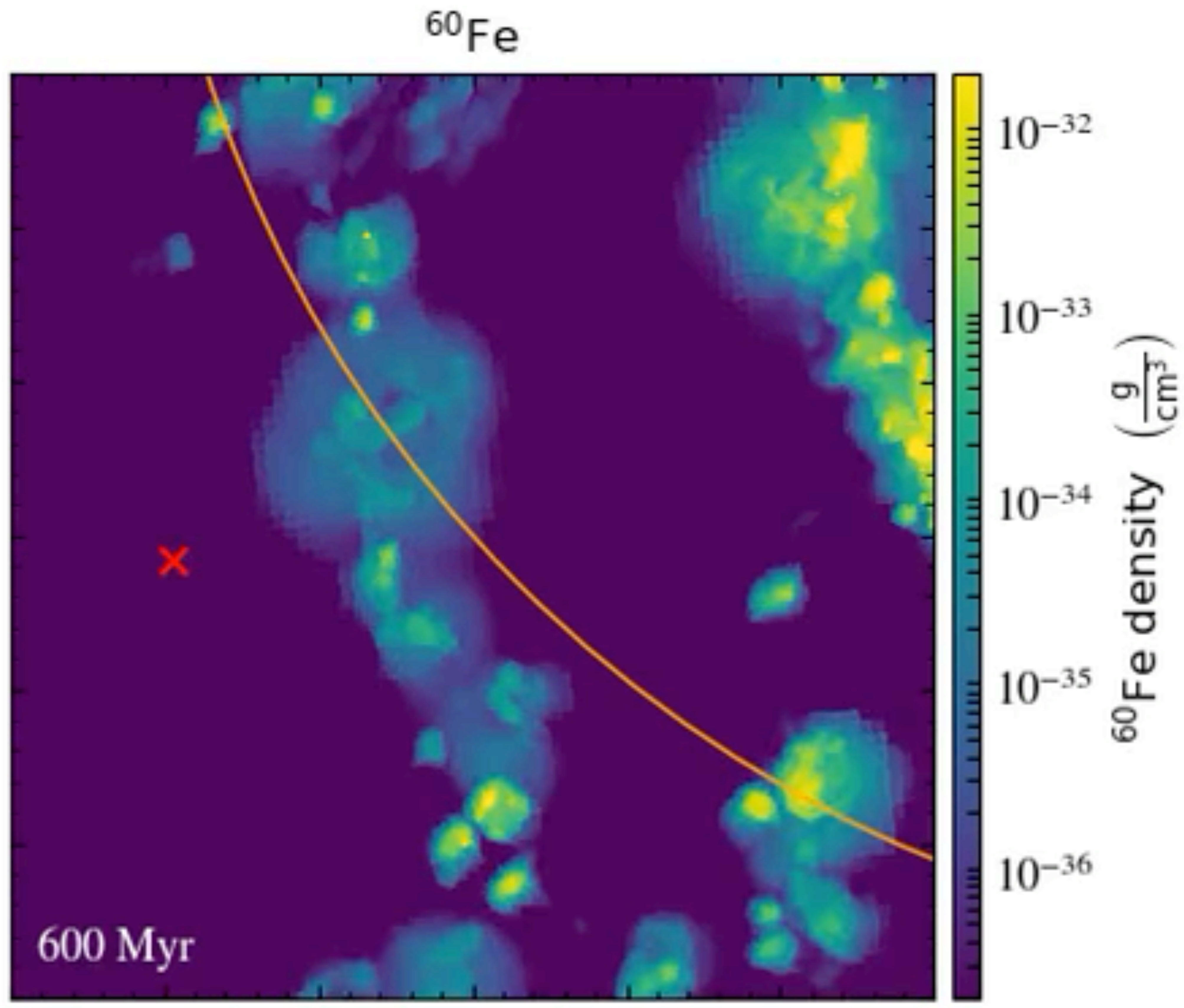
They are located inside or close to big SLR bubbles created by massive stars on the galactic spiral arms.

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

Case 1: The duration is ~ 100 Myr



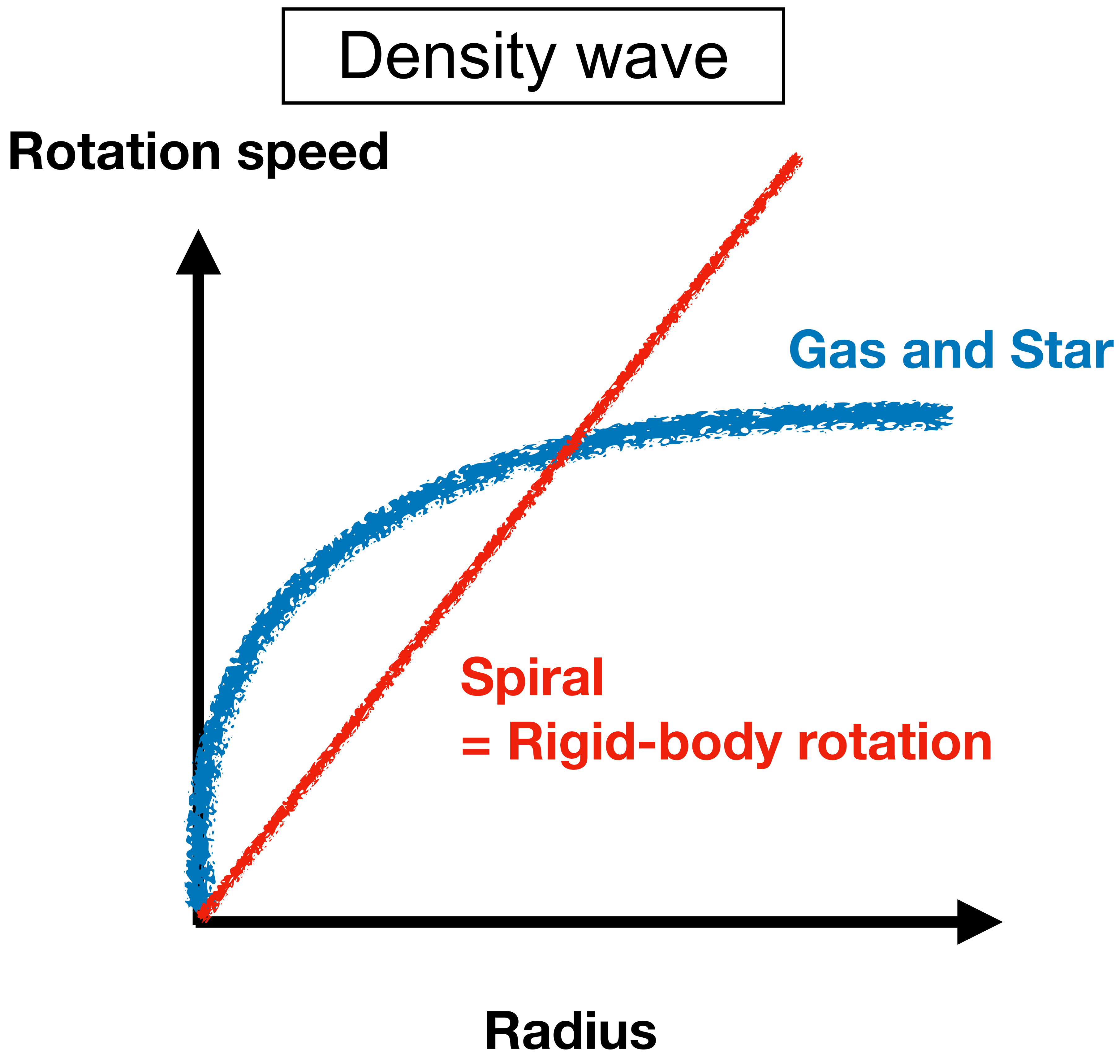
Case 2: The duration is ~ 20 Myr



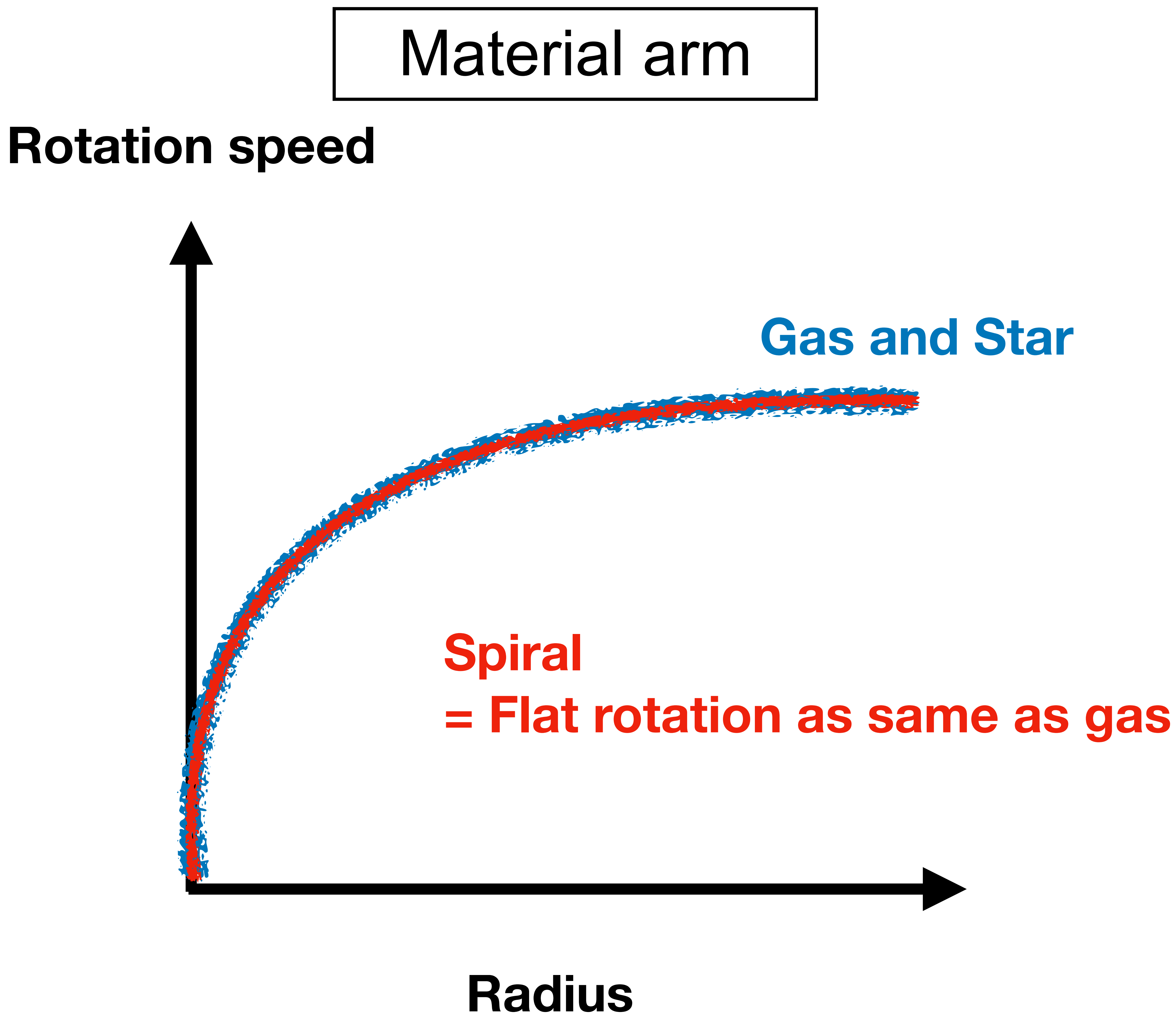
It depends. The duration is governed by the crossing time of stars across the spiral arm

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

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



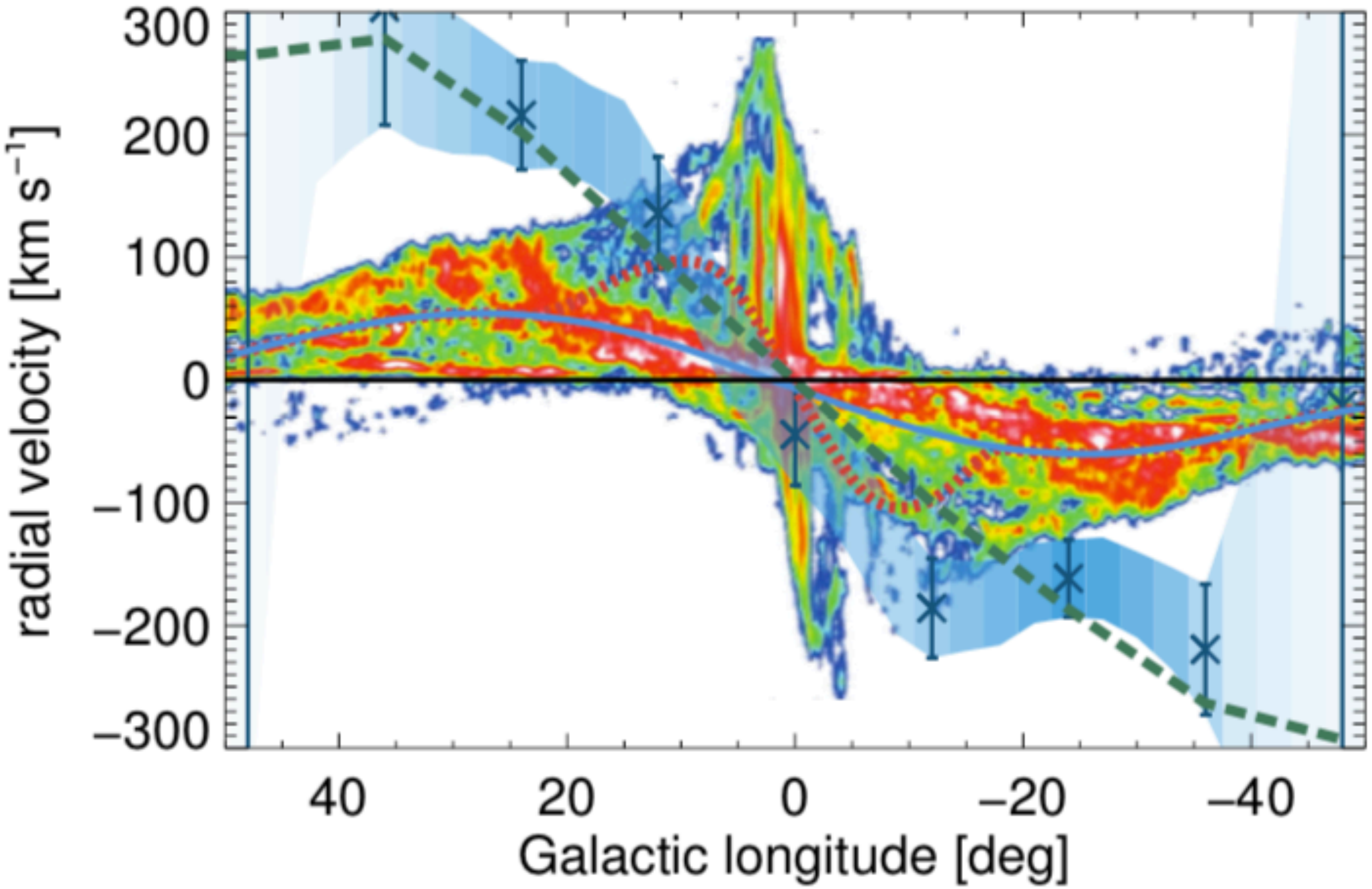
Gas compression and star formation occur on the leading edge of the arms where the gas shocks upon entry.



Gas slowly falls into spiral arms from both leading and trailing sides as a colliding flow, and then stars form in the middle 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



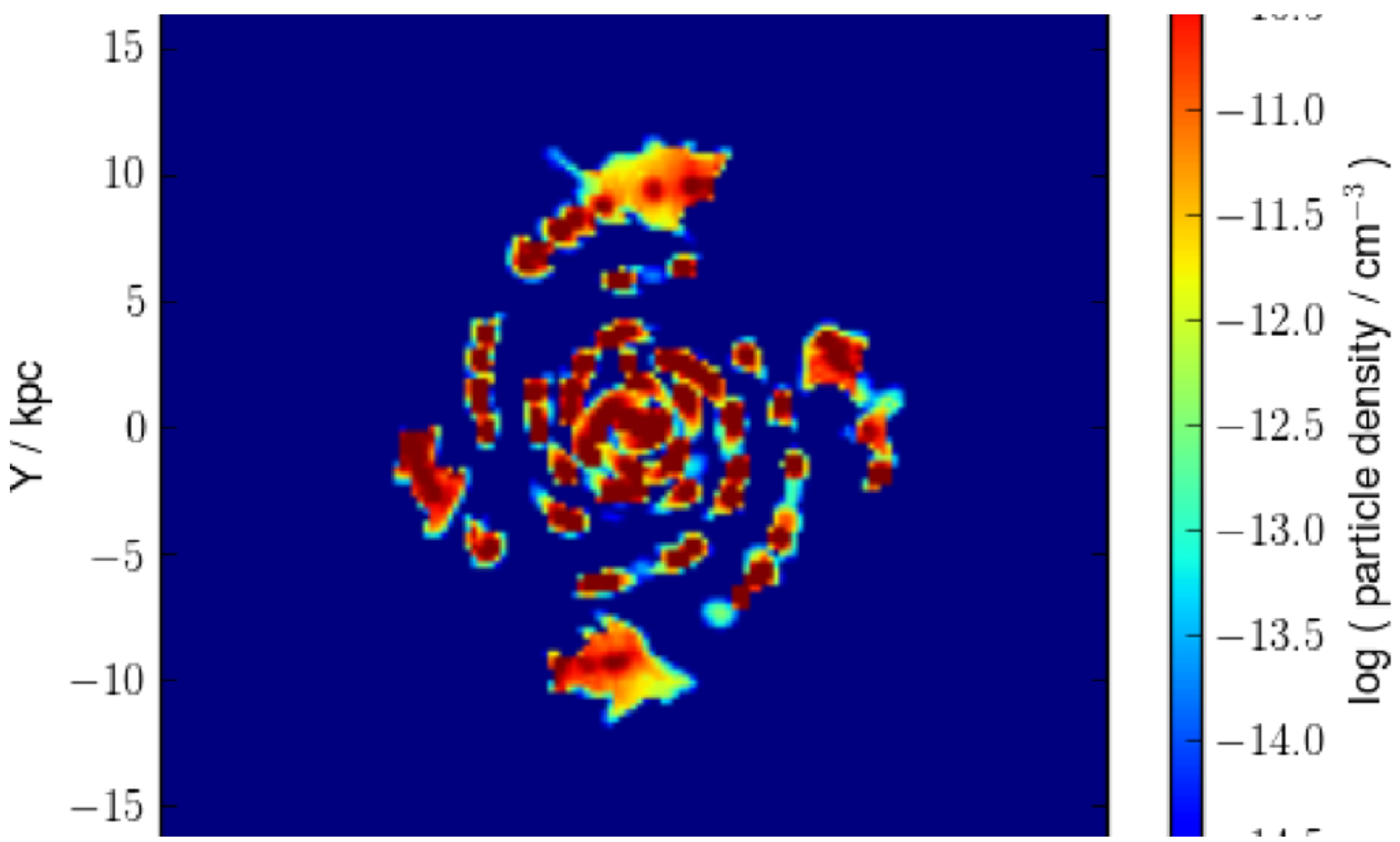
Blue shaded region: 26Al

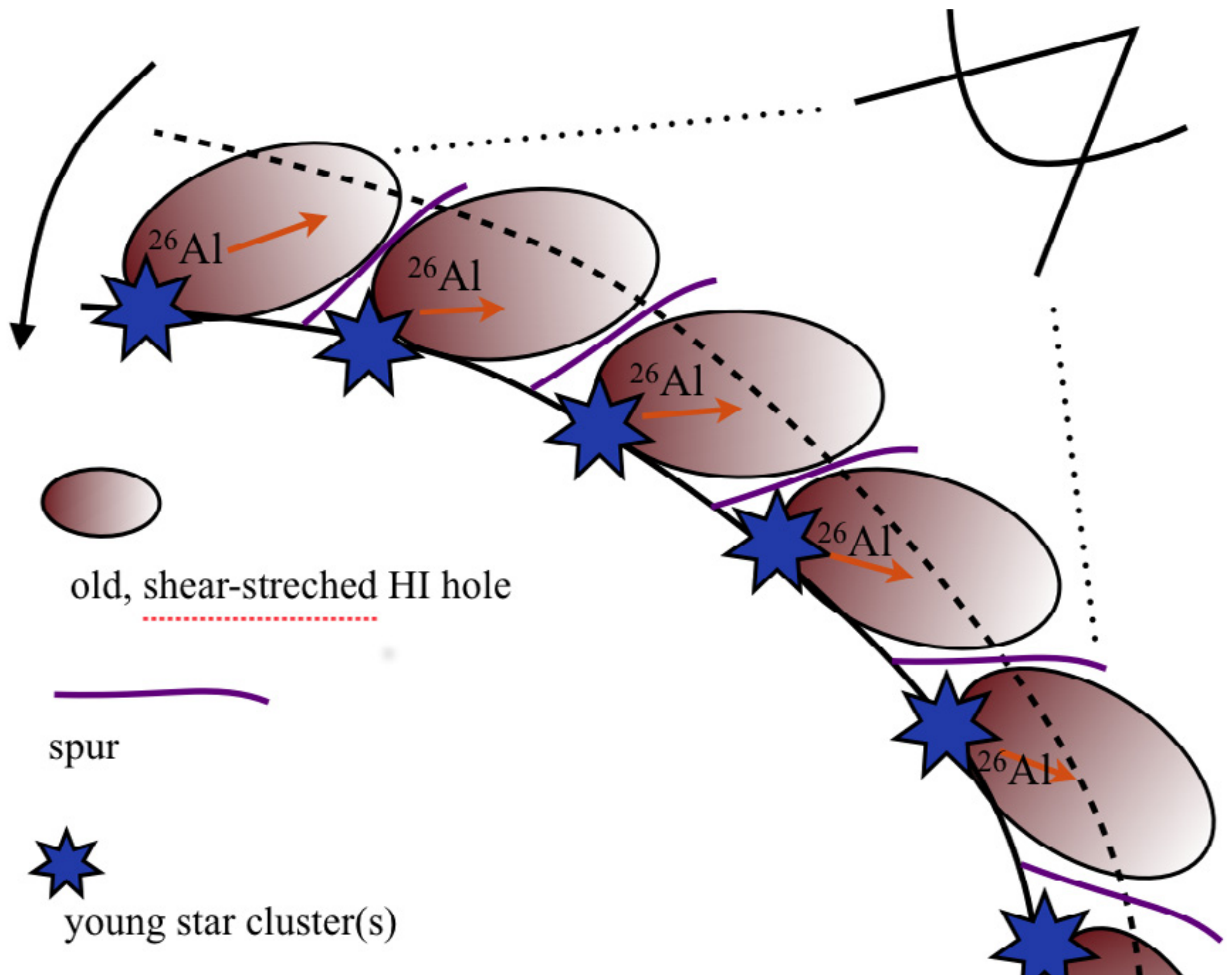
Colored region: CO (1-0)

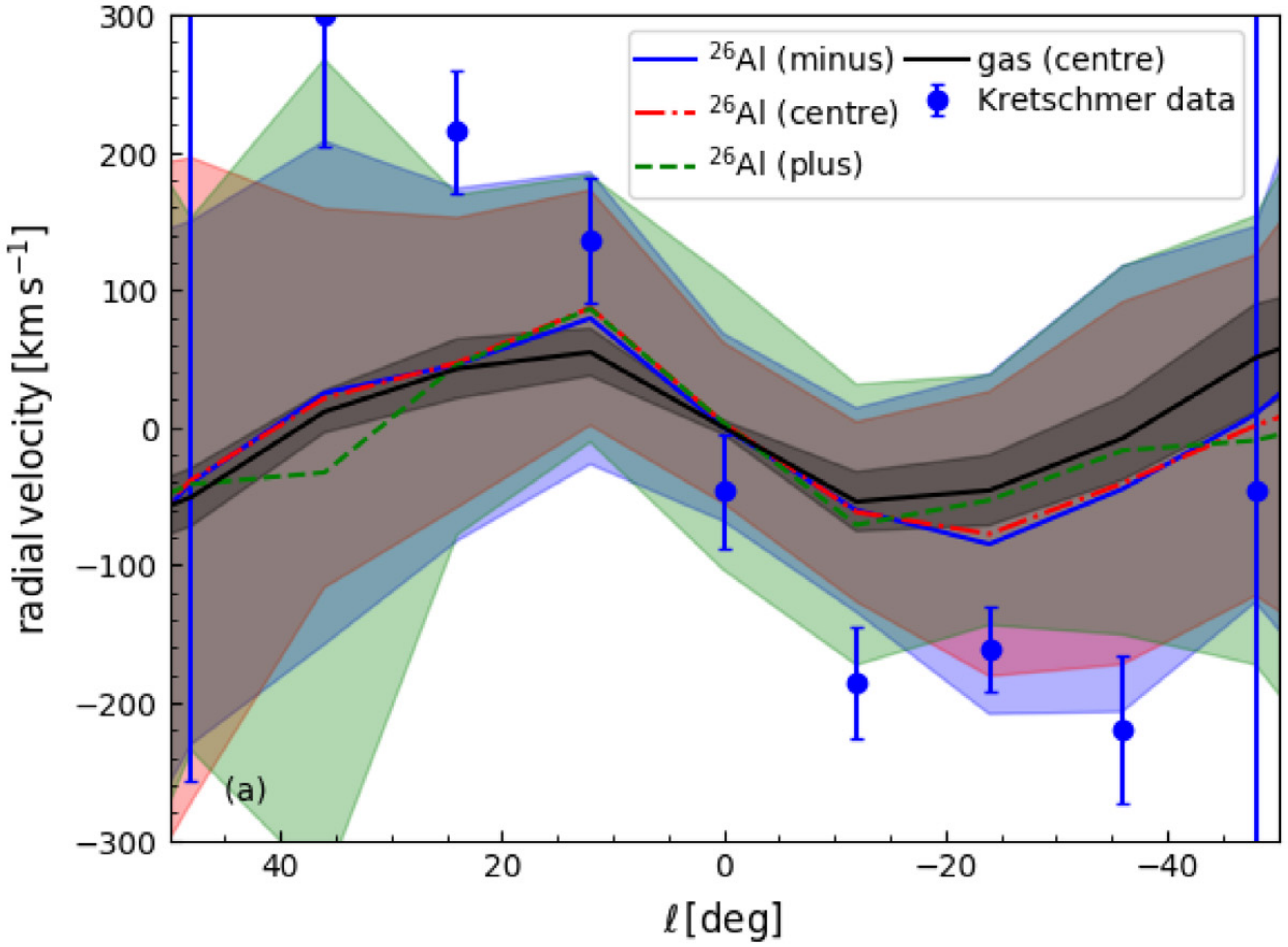
Kretschmer+ 2013

Some previous works support the density wave

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





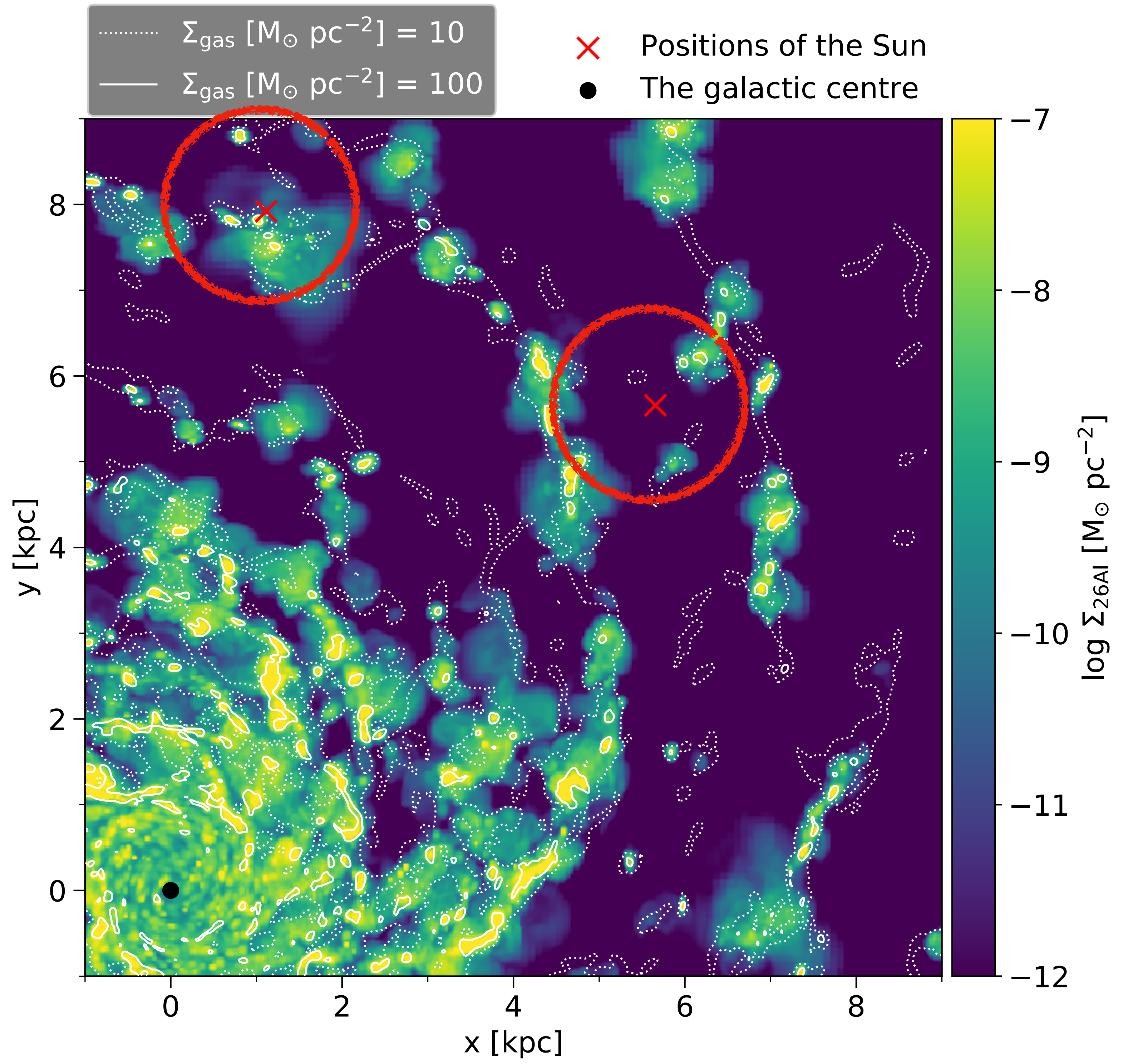


Rodgers-Lee+ 2019

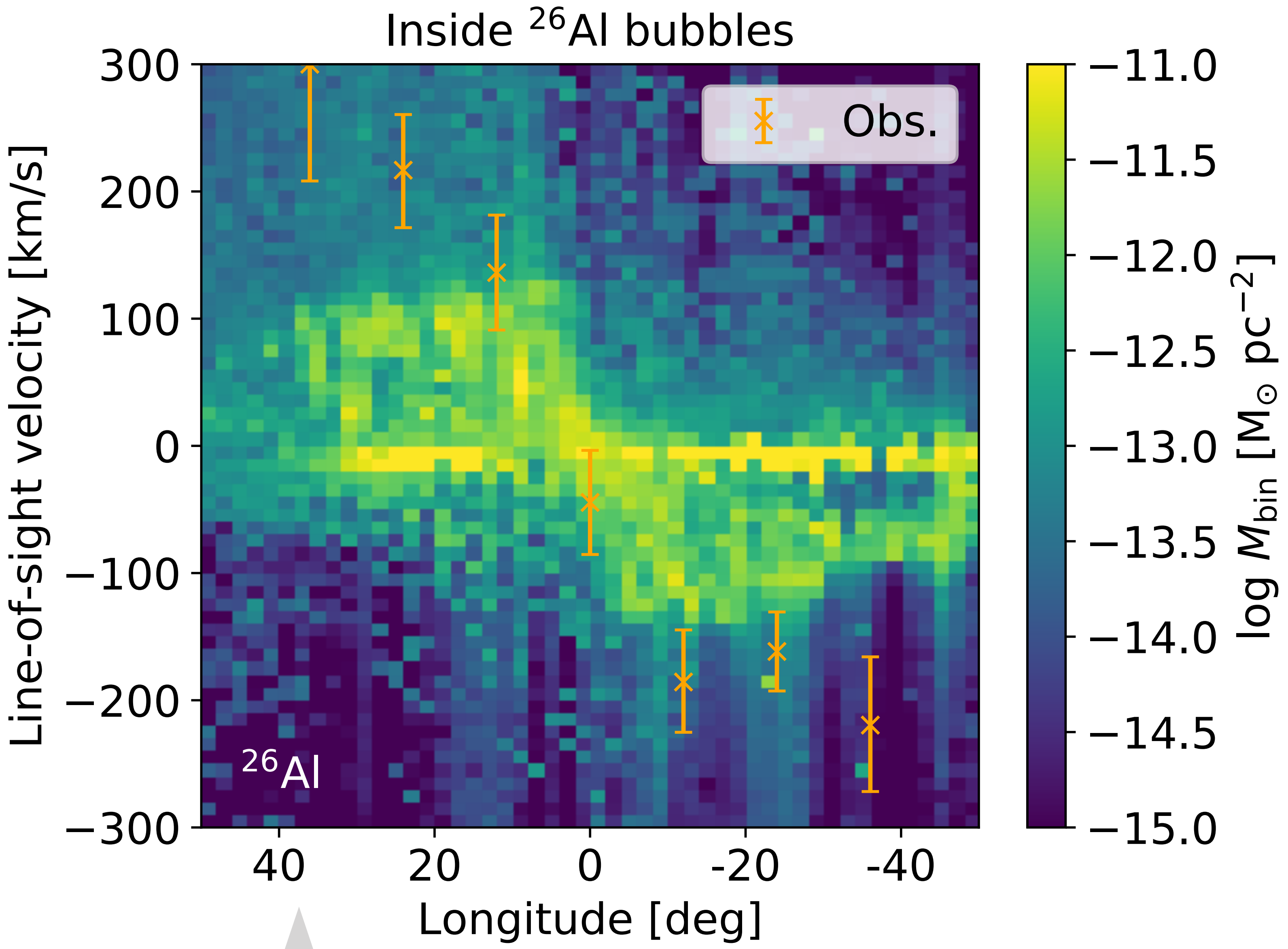
Massive stars form at the leading edges of the arm,
and 26Al blow out into the low-density regions forward of the arm

Krause+ 2015

Synthetic 26Al emission maps for two different positions

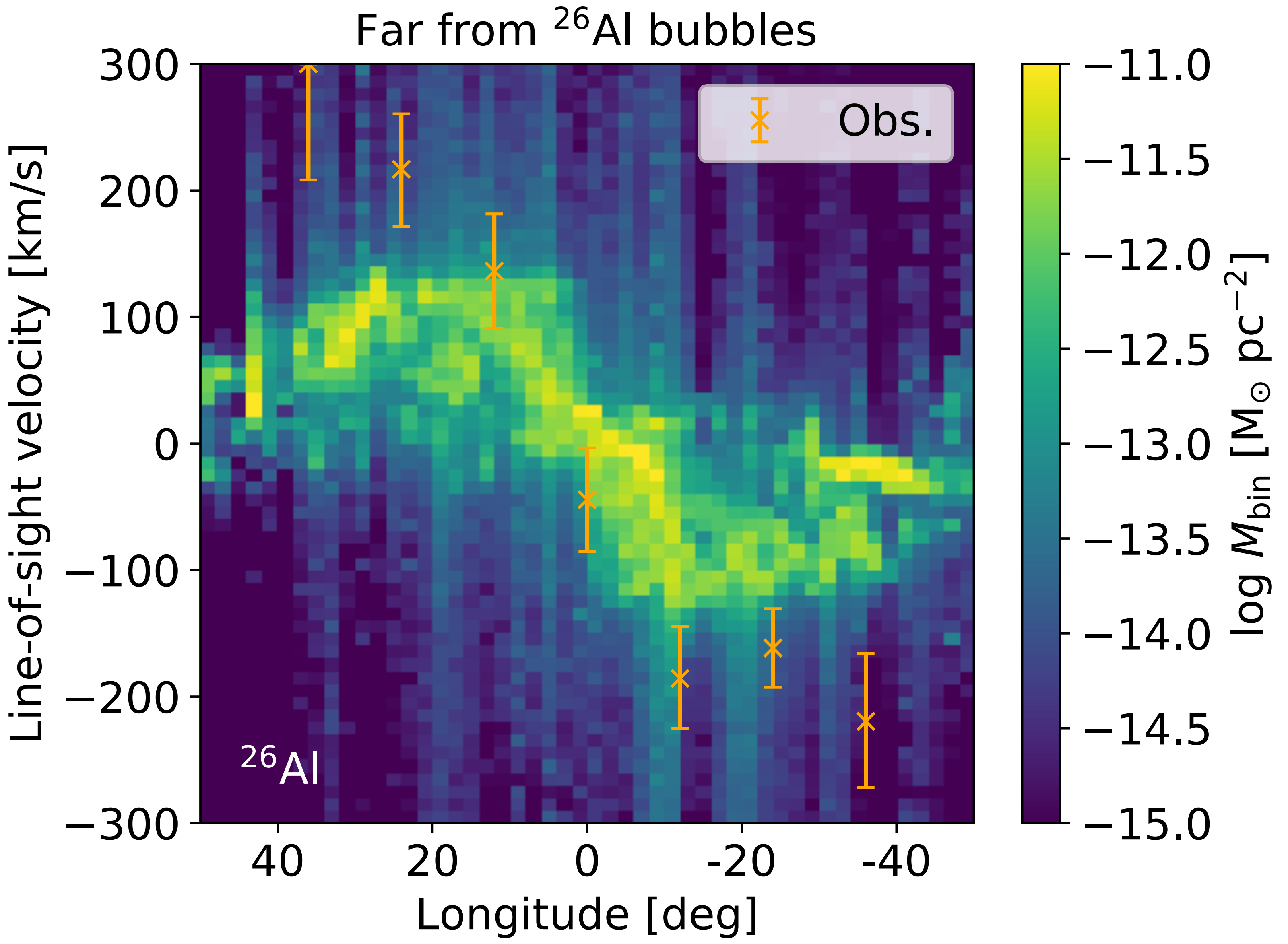


Inside 26Al bubble



We see some excess

Outside 26Al bubble



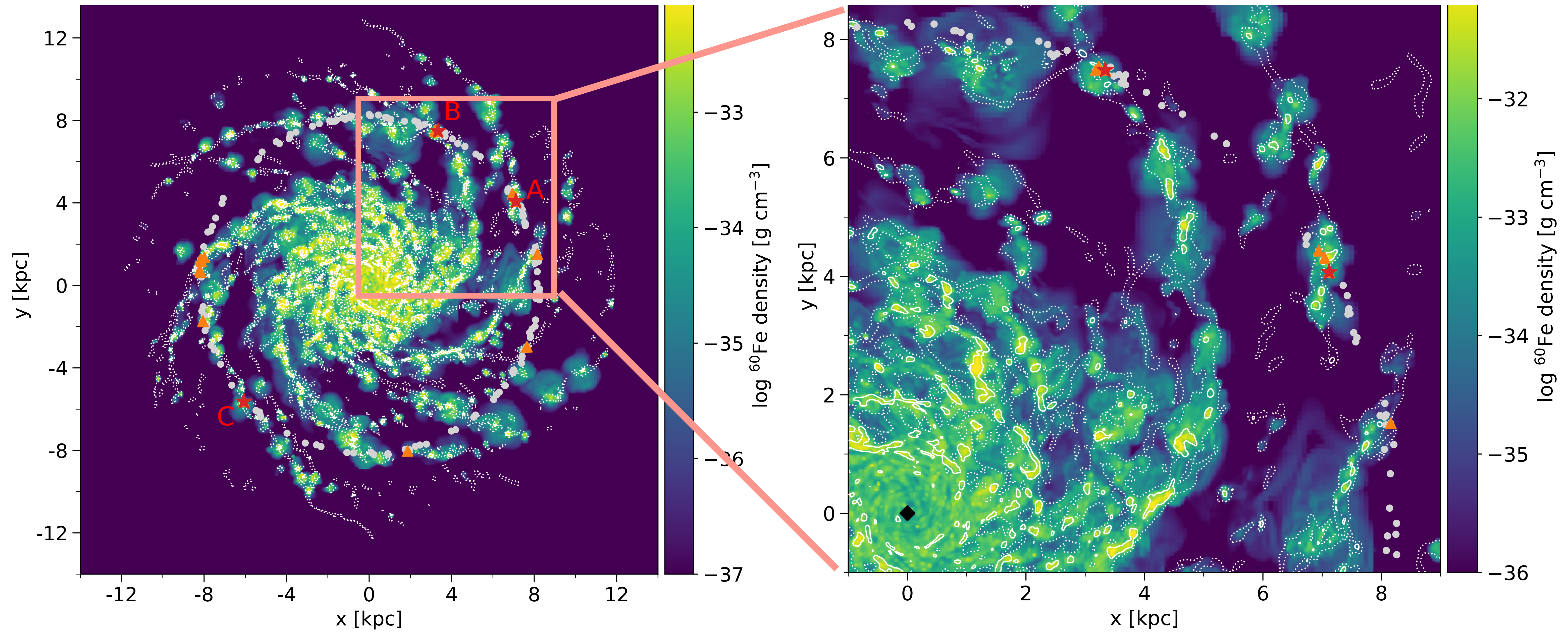
The observed excess of 26Al velocity may be the product of foreground emission from nearby massive stars, like Local Bubble

The material arm scenario can explain the observed excess

<u>Fujimoto</u>, Krumholz & Inutsuka 2020, MNRAS

Summary

- N-body + Hydro+ Chemo dynamic simulation of the entire Milky Way
- Compare with the following observations:
  - (1) ^{60}Fe influx onto the Earth detected in deep-sea archives and Antarctic snow
  - (2) ^{26}Al observed in the γ-ray sky-maps
  - (3) Diffuse ionized gas observed in soft X-ray emission.



The Sun is located inside big SLR bubbles created by massive stars on the galactic spiral arms.