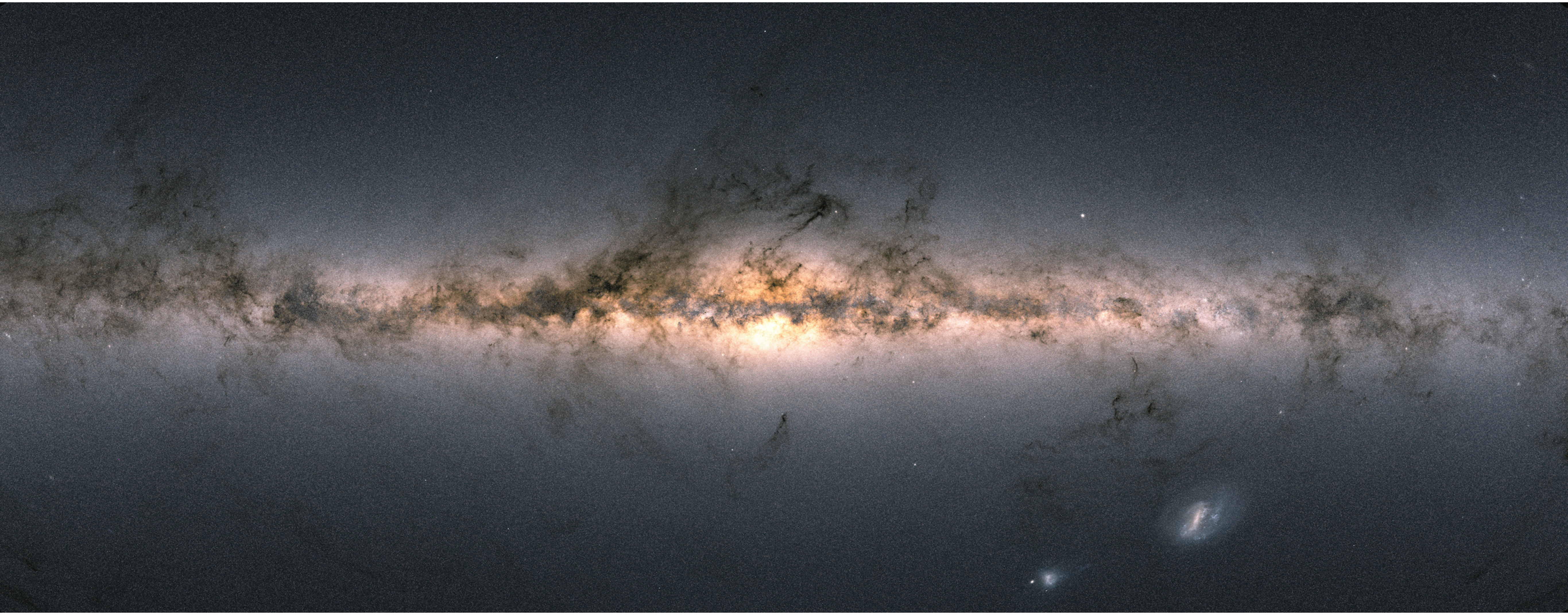


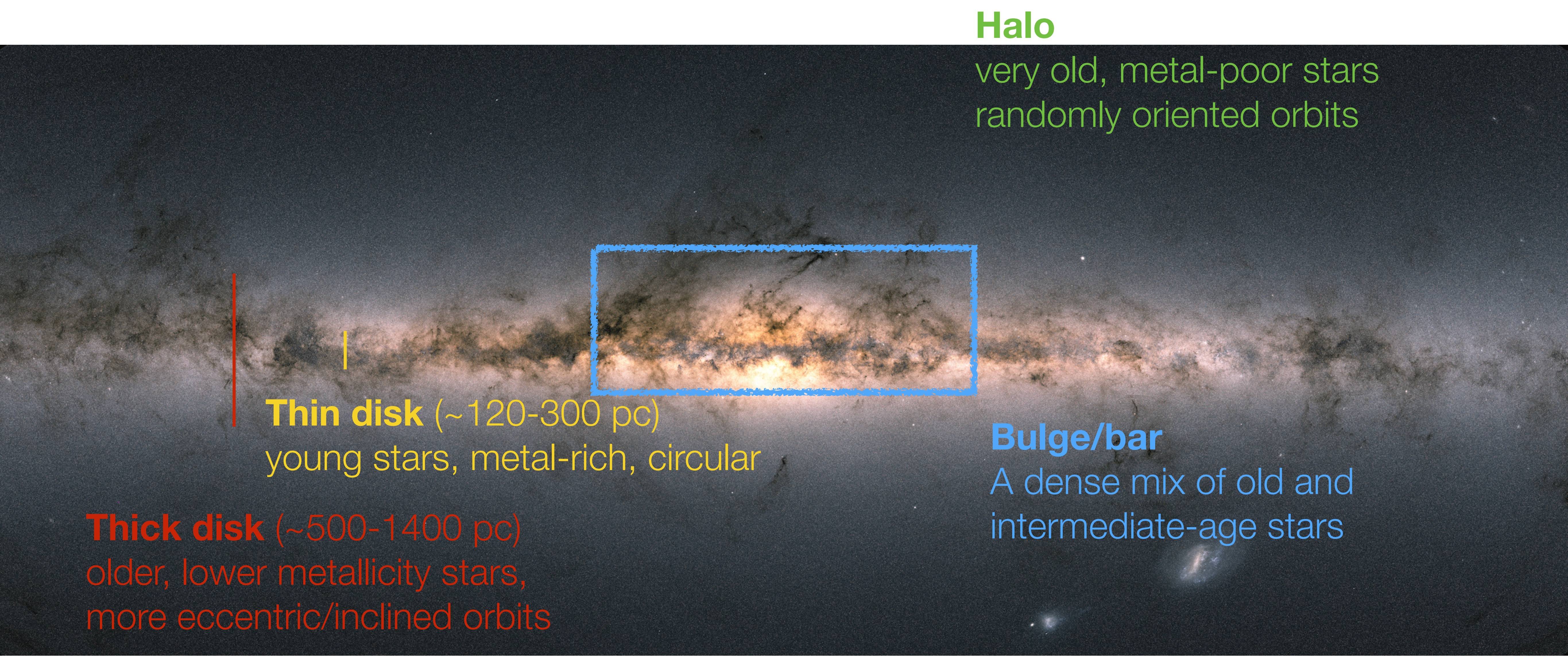
Maser Investigation toward Off-Plane Stars (MIOPS): detection of SiO masers in the Galactic thick disk and halo

Wenjin Yang

Main Collaborators: Yuanwei Wu (PI), Yan Gong, Nicolas Mauron, Bo Zhang, Karl M. Menten

MPIFR Group Talk @ 2023-Oct-31

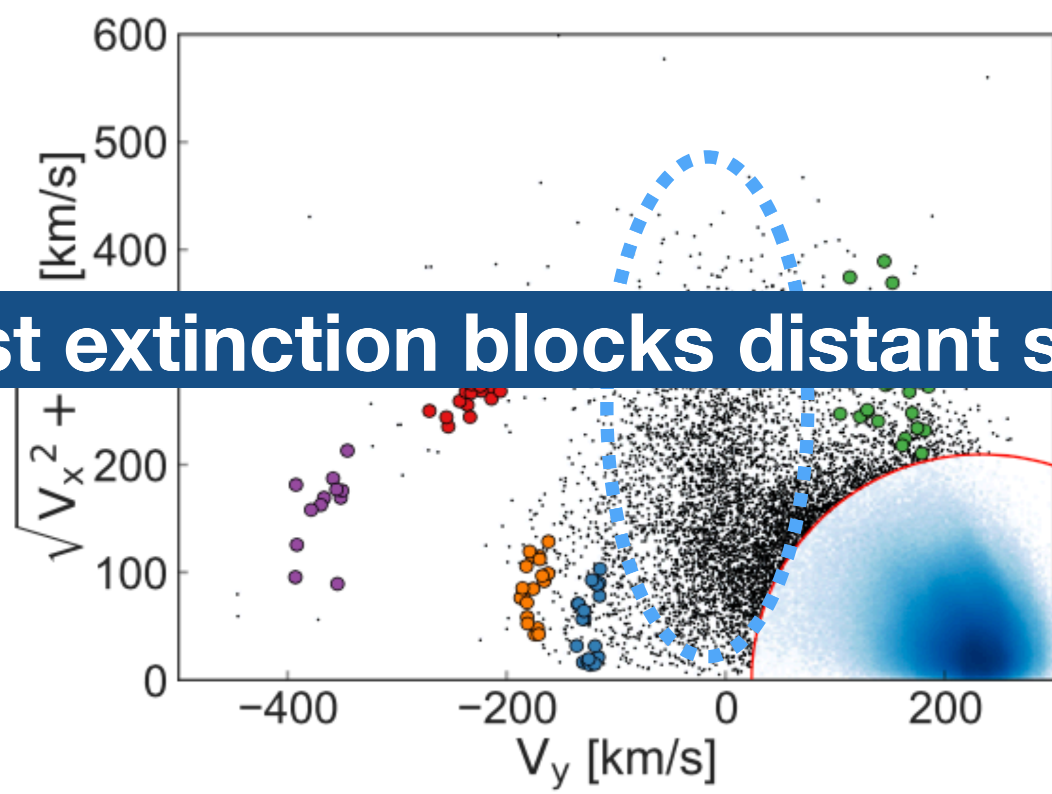
Galactic structures



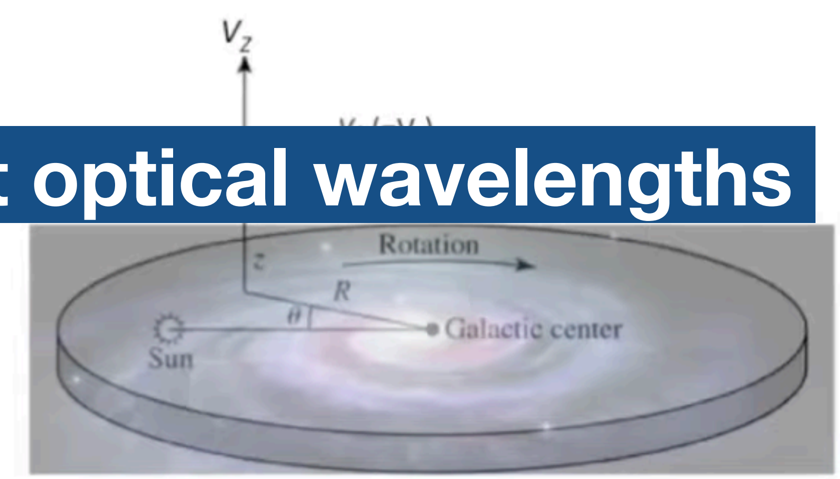
Galactic Archaeology

- **Stars are "fossils"**
  Motions ➜ where they came from
  Age ➜ when they were born
  Chemical ➜ reflect chemical compositions of ISM which they formed

  Substructures in halo ➜ debris from accretion events
- **Accurate 6D information ➜formation history of the milky Way**



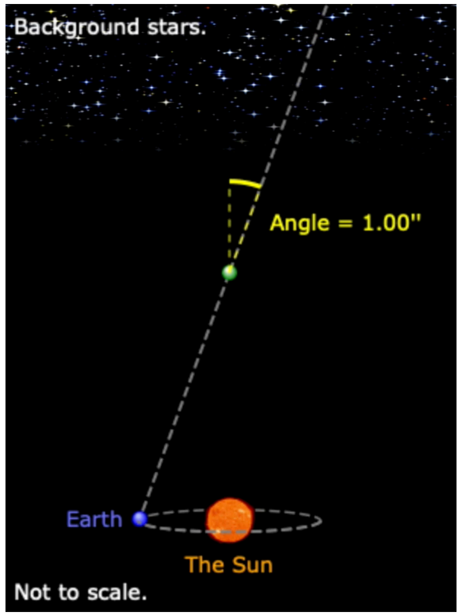
Dust extinction blocks distant stars at optical wavelengths



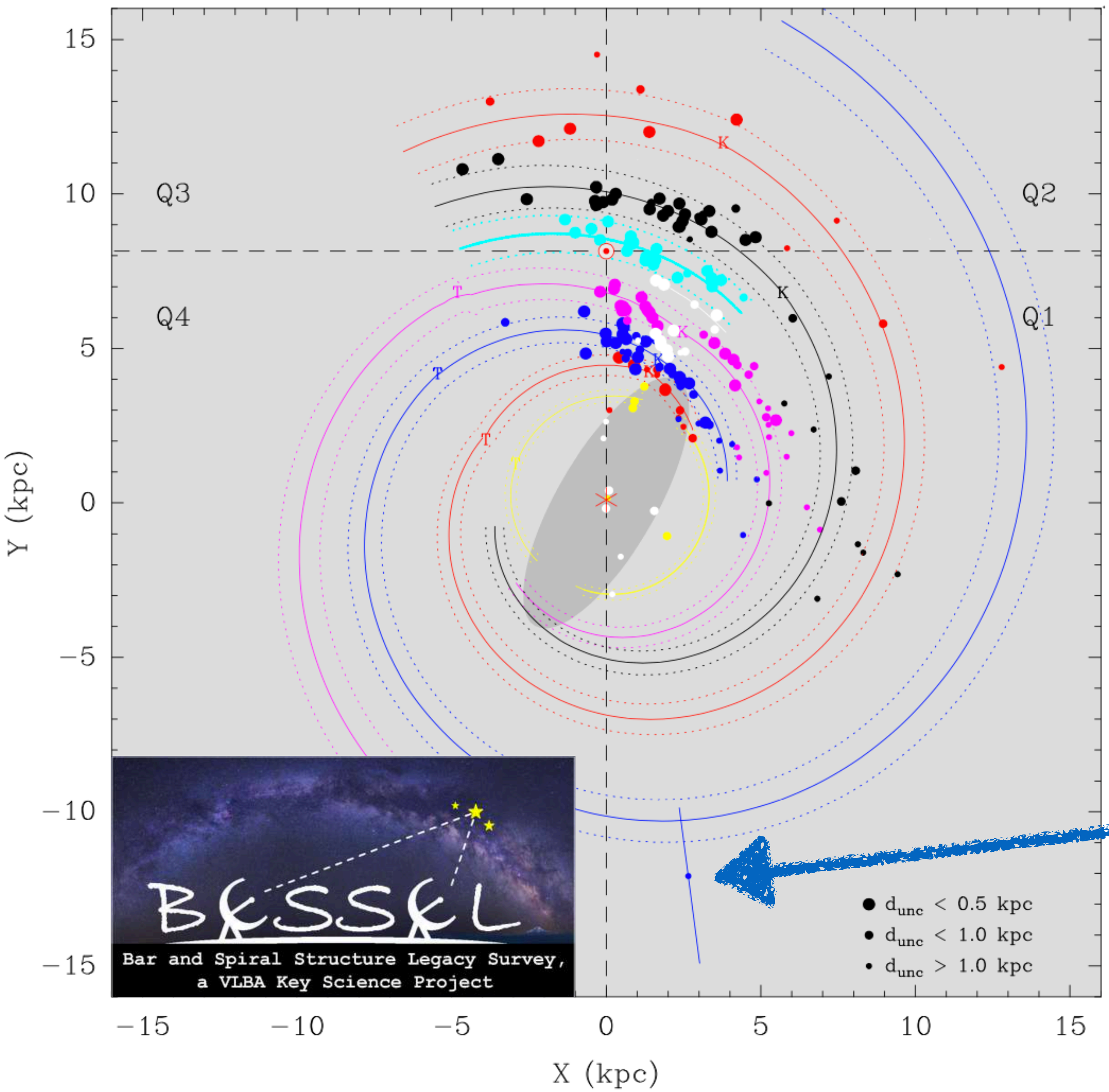
Koppelman et al. (2018)

All Gaia DR2 stars within 1 kpc from the Sun
Relatively accurate parallaxes (uncertainty < 20%)

VLBI astrometry pinpoint spiral arms



The BeSSeL Survey + VERA project
Aim: study the spiral structure and kinematics of the Milky Way



~ 200 High-mass SFRs
(6.7 GHz CH_3OH masers
22 GHz H_2O masers)
Typical parallax accuracy ~0.02 mas

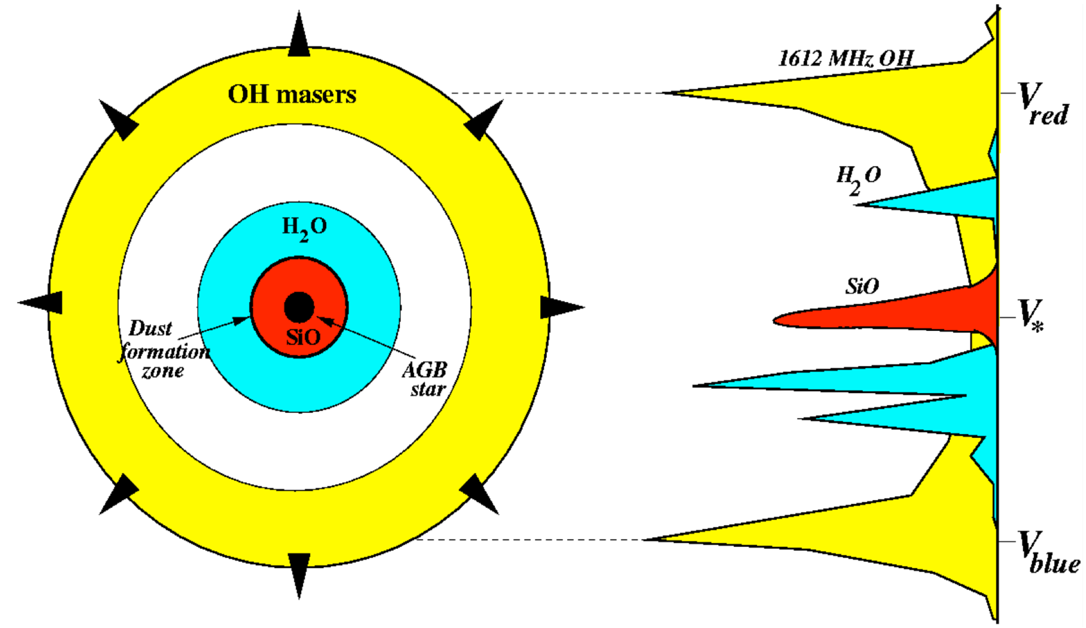
A flat Galactic rotation curve
$R_0 = 8.15 \pm 0.15$ kpc
$\Theta_0 = 236 \pm 7$ km/s
Reid et al. (2019)

0.049 ± 0.006 mas
distance: 20.4 (+2.8, -2.2) kpc
(Sanna et al. 2017)

Very high accuracy

AGBs + SiO masers

- **Asymptotic giant branch (AGB) stars:**
  a few Gyr & widely distributed & host maser
  > 2000 O-rich AGBs host SiO masers
  OH & SiO masers trace **stellar velocity**
  (e.g., Reid & Dickinson et al. 1976, Jiang et al. 1995, Sevenster 1999, Wu et al. 2018, Iwanek et al. 2023)



- **Bulge Asymmetries and Dynamical Evolution - BAaDE**
  survey ~28000 AGB/RGBs in the Galactic bulge and inner Galaxy for SiO maser emission at 7 & 3mm ➜ **Dynamics of the Milky Way bar and bulge**
  (Trapp et al. 2018; Stroh et al. 2018, 2019; Lewis et al. 2020)

- No masers in streams were detected (Deguchi et al. 2010, Wu et al. 2018, 2022).

- **An off-plane O-rich AGBs catalog**:
  417 stars belong to the thick disk, the halo, and the Sgr stream (Mauron et al. 2019)

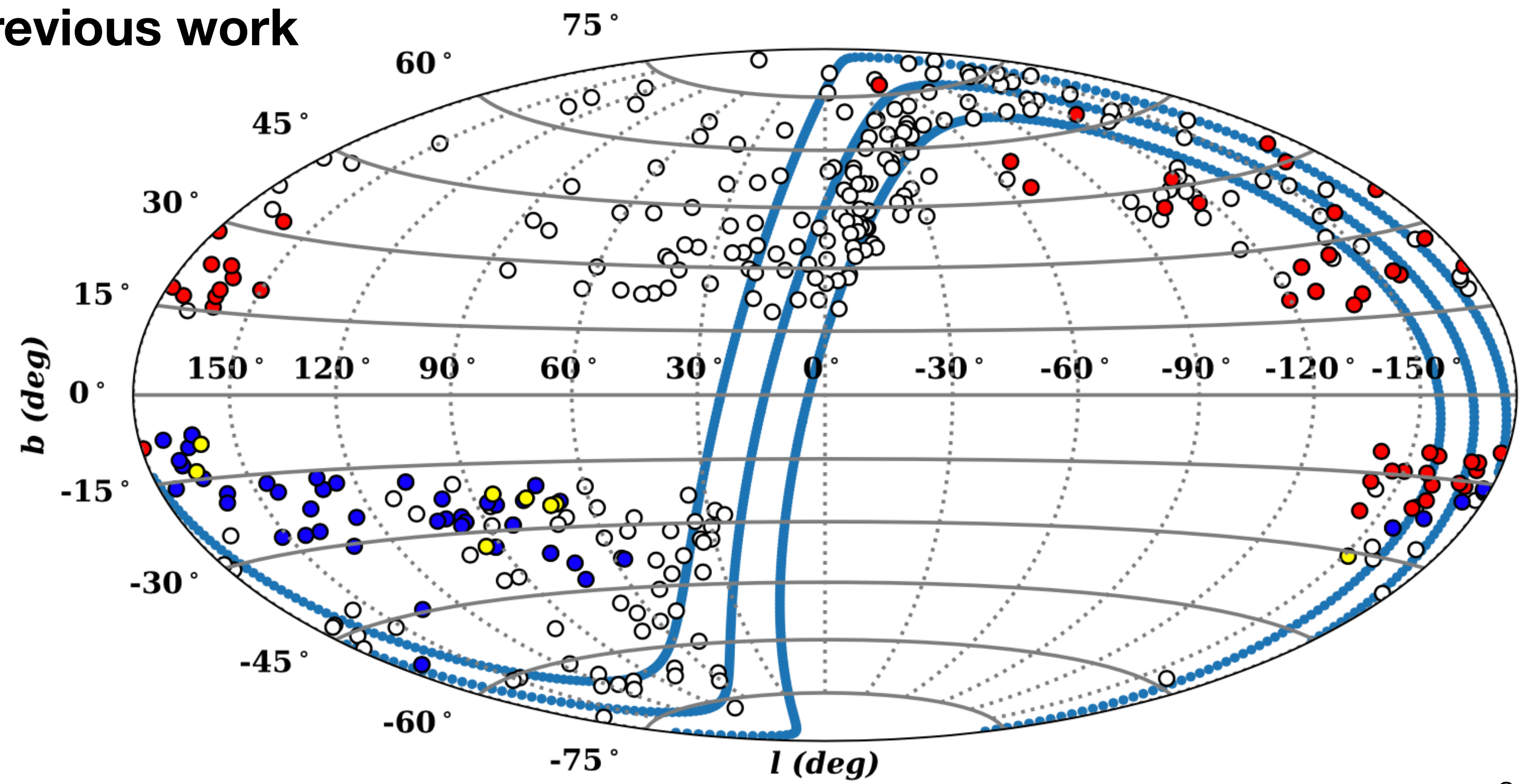
As a first step

Find off-plane SiO masers ➜ SiO maser VLBI measurements
➜ accurate distance, proper motions (6D)
➜ dynamics of the thick disk, halo (even streams)
➜ formation/merge history of the Milky Way

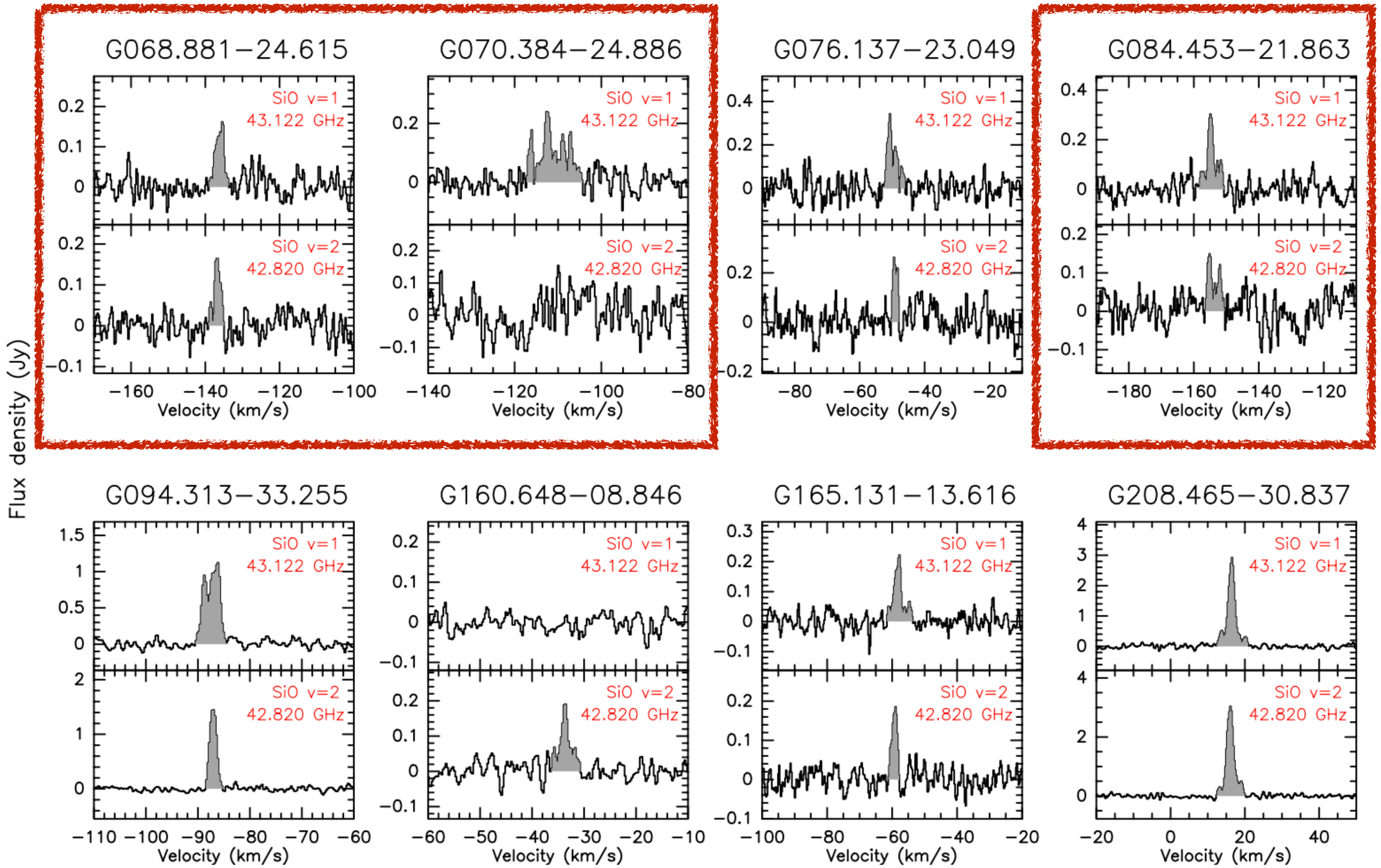
Motivation

Observations

- **Targets:** 102 AGBs from Mauron et al. (2019)
  5< corrected Ks < 11 ➜ **Faint stars**
- **Targeted lines**: SiO J=1–0, v=1 (43.122030 GHz)
  v=2 (42.820480 GHz)
- **Obs. dates**: 2022 Sep — 2023 Feb
- **rms:**
  52 stars, ~0.04 Jy @ 0.27 km/s (Effelsberg-100 m)
  50 stars, ~0.03 Jy @ 0.21 km/s (Tianma-65 m)
  more sensitive than previous work



Detection

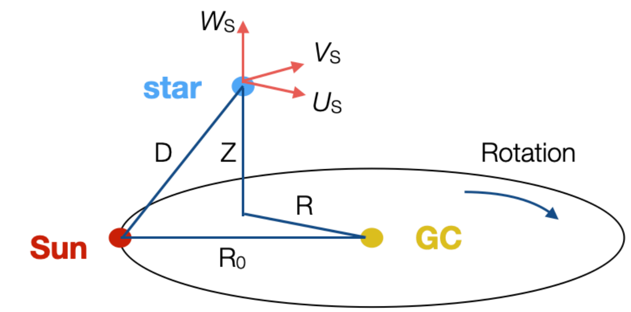


- **Narrow line profile ➜ maser**
  All new maser detections

- No stellar radial velocity given in the APOGEE DR17, RAVE DR6, Gaia DR3
  ➜ **Firstly provide the stellar velocity for the faint stars**

- **Three SiO masers with velocities < -100 km/s**
  clearly offset circular motions

Revisit distances ➜ Locations



WISE Period-Luminosity Relations dist. (Iwanek et al. 2023)

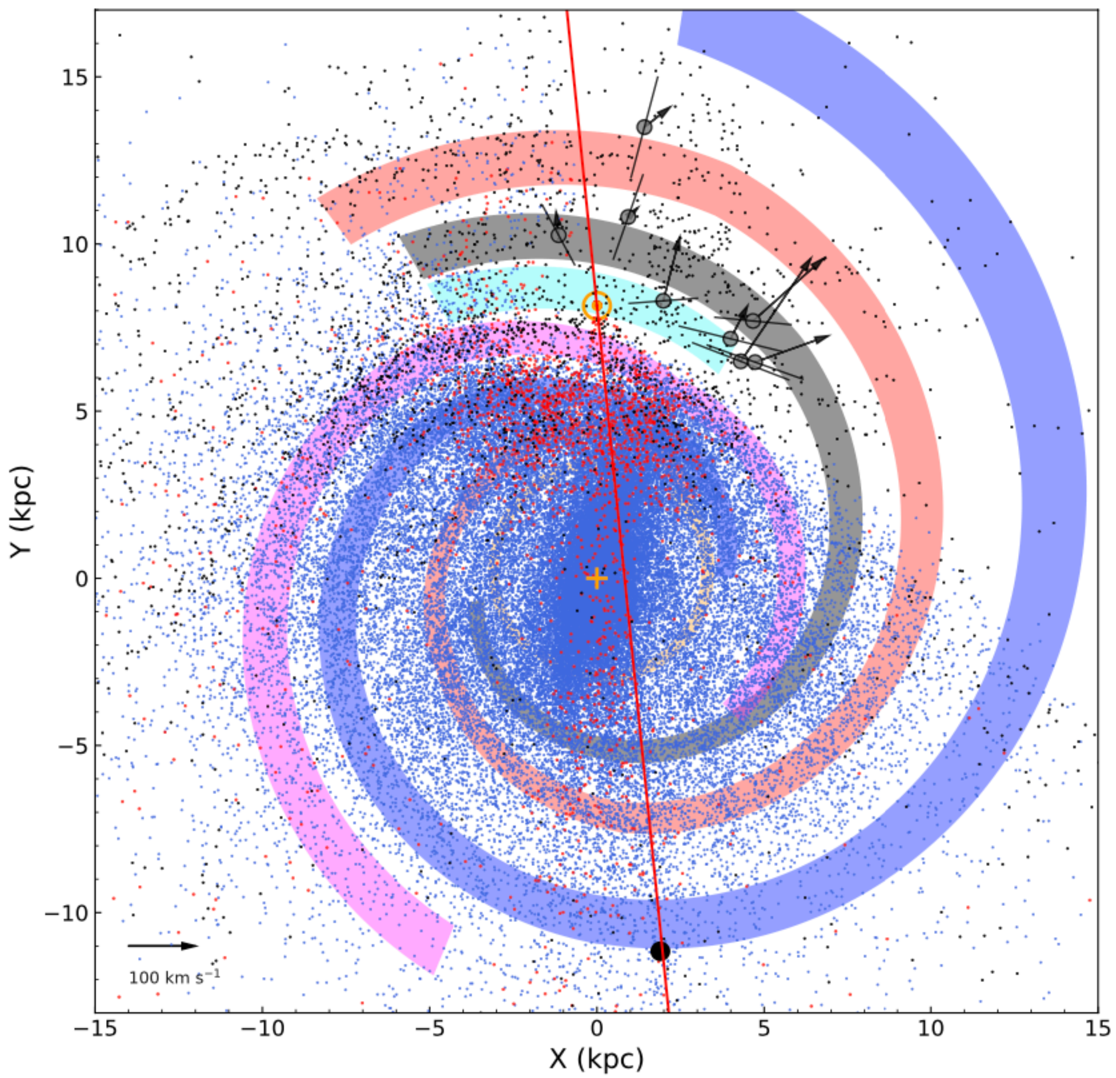
Gaia DR3 corrected parallax **GC dist.** **Gaia DR3 proper motions** **Peculiar motions**

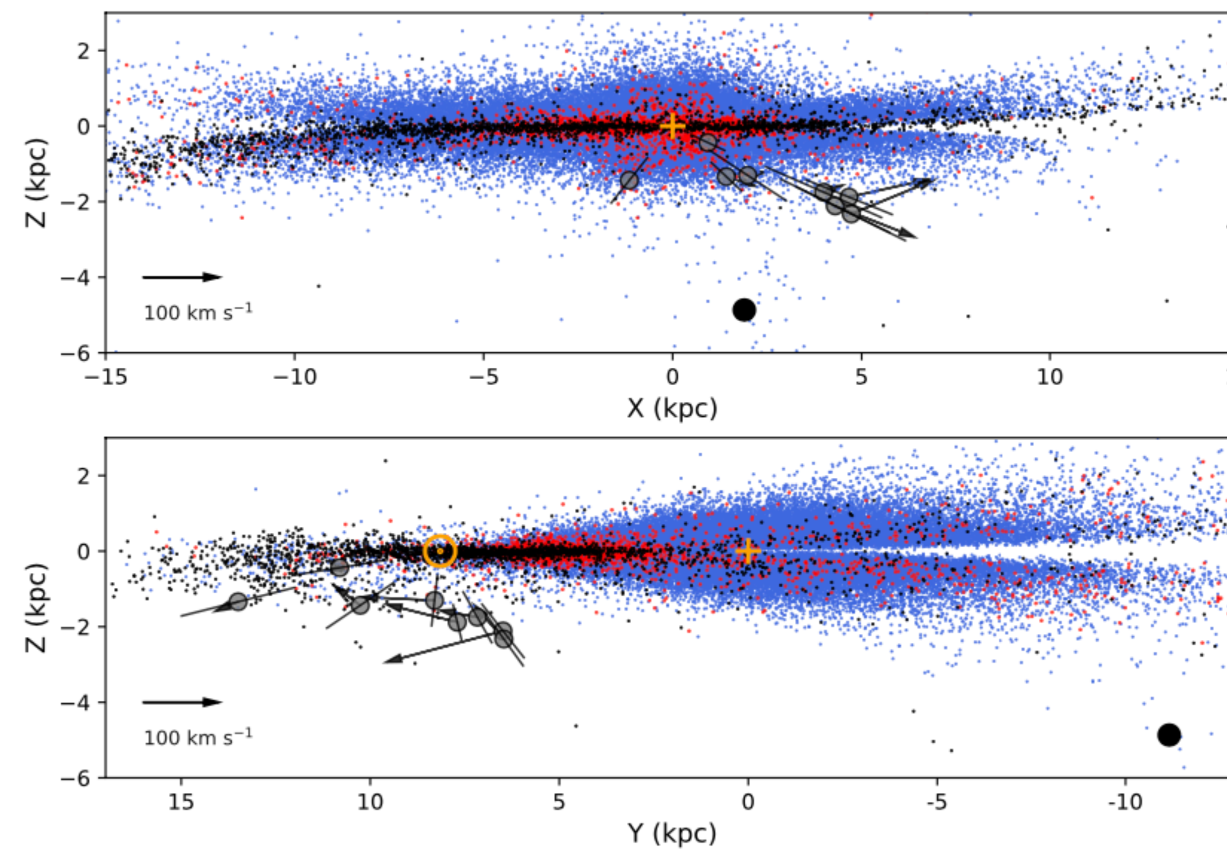
Name	Parallax (mas)	$D_{\mathrm{m-PLR}}$ (kpc)	D_{adopt} (kpc)	R (kpc)	Z (kpc)	μ_x (mas yr^{-1})	μ_y (mas yr^{-1})	V_{LSR} (km s^{-1})	U_s (km s^{-1})	V_s (km s^{-1})	W_s (km s^{-1})
G068.881−24.615	0.0792±0.1530	4.79±1.07	5.1±1.7	8.1±0.7	−2.1±0.7	1.301±0.076	−6.217±0.066	−136.0	−184.61± 7.50	−2.73±18.22	−33.52±27.03
G070.384−24.886	0.2647±0.1521	6.42±1.63	5.5±1.7	8.3±0.7	−2.3±0.7	−4.021±0.086	−5.380±0.082	−112.6	−92.18±31.43	69.83±20.85	44.46± 5.30
G076.137−23.049	0.3277±0.3549	4.93±1.13	4.5±1.7	8.4±0.7	−1.8±0.7	−2.345±0.108	−3.974±0.098	−50.0	−56.83± 7.42	−2.36± 3.14	11.07± 6.20
G084.453−21.863	0.2581±0.0869	5.96±1.33	5.1±1.2	9.2±0.6	−1.9±0.5	−1.759±0.064	−4.104±0.056	−154.9	−128.78±14.34	47.61±10.26	17.56±11.18
G094.313−33.255	0.3735±0.2583	2.27±0.66	2.4±1.2	8.6±0.5	−1.3±0.7	1.580±0.100	−5.730±0.098	−86.6	−102.64±12.92	1.02± 5.44	−2.80±27.72
G160.648−08.846	0.6016±0.1818	4.06±0.98	2.9±1.4	10.9±1.3	−0.4±0.2	0.185±0.150	−1.859±0.091	−33.5	−15.14± 7.35	13.79± 7.04	−3.91± 6.40
G165.131−13.616	0.1581±0.1387	6.07±1.31	5.7±1.6	13.6±1.6	−1.3±0.4	0.086±0.115	−1.818±0.072	−58.3	−36.11±13.97	34.92± 6.45	−14.36±13.05
G208.465−30.837	0.3344±0.2696	2.73±1.06	2.8±1.2	10.4±1.0	−1.4±0.6	3.736±0.115	−0.374±0.094	16.3	−35.35±12.20	0.20± 4.52	26.55±14.09

With large uncertainties!

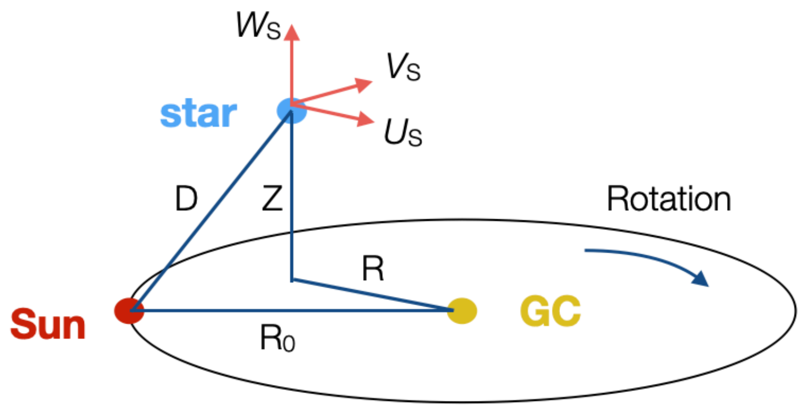
- **Thin disk scale: ~120 to 300 pc; Thick disk scale: ~500 to 1400 pc**
  (e.g., Gilmore & Reid 1983; Juri´c et al. 2008; de Jong et al. 2010)
  ➜ probably located in the thick disk (except for G160)
- $$\sqrt{U_s^2 + V_s^2 + W_s^2} > 180 \ \mathrm{km\,s^{-1}}$$
  (e.g., Venn et al. 1994, Nissen & Schuster 2010)
  ➜ G068 is likely to locate in the halo

Projections of 3D positions and 3D velocities





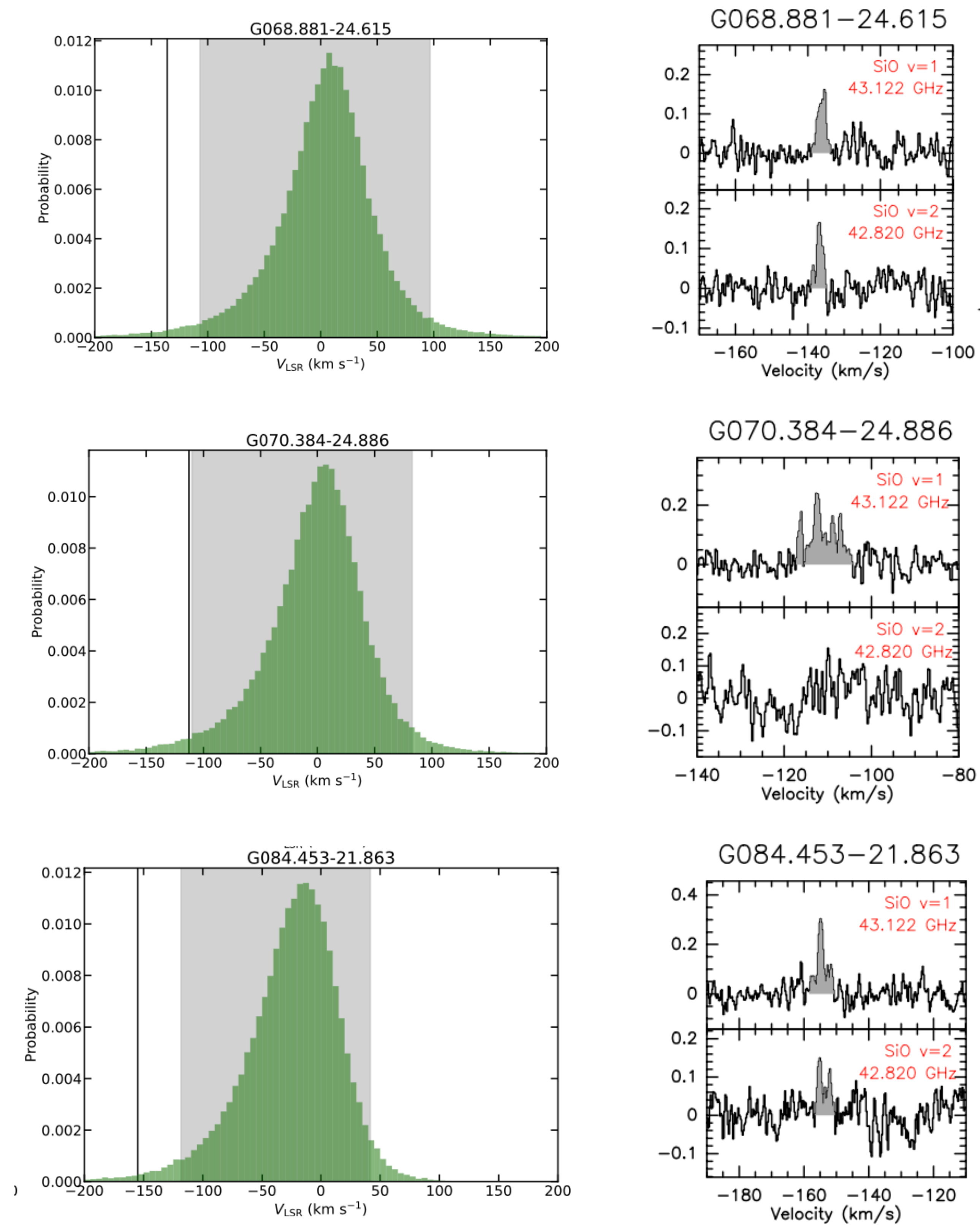
Sources that offset circular motions



- **A flat Galactic rotation curve**
  R_0 = 8.15 ± 0.15 kpc
  Θ_0 = 236 ± 7 km/s
  (Reid et al. 2019)

- **Assume a velocity dispersion of 30 km/s in U_S, V_S, W_S**

- **Monte Carlo analysis probability of LSR velocities if star follows circular motions**



Summary

- **SiO masers are newly detected toward 8 off-plane O- rich AGBs firstly provide the stellar radial velocities for these stars**
- Based on the current 6D information,
  G068.881–24.615 is likely in Galactic halo,
  G160.648–08.846 is probably in the thin disk,
  and the other six stars are probably in the thick disk.

- **Future work：**
  1. Single-dish observations to search for more off-plane masers
  (Effelsberg 100m proposal approved)
  2. VLBI measurements to determine the accurate distance
  (EAVN proposal submitted)