基于LAMOST巡天的银河系并合研究

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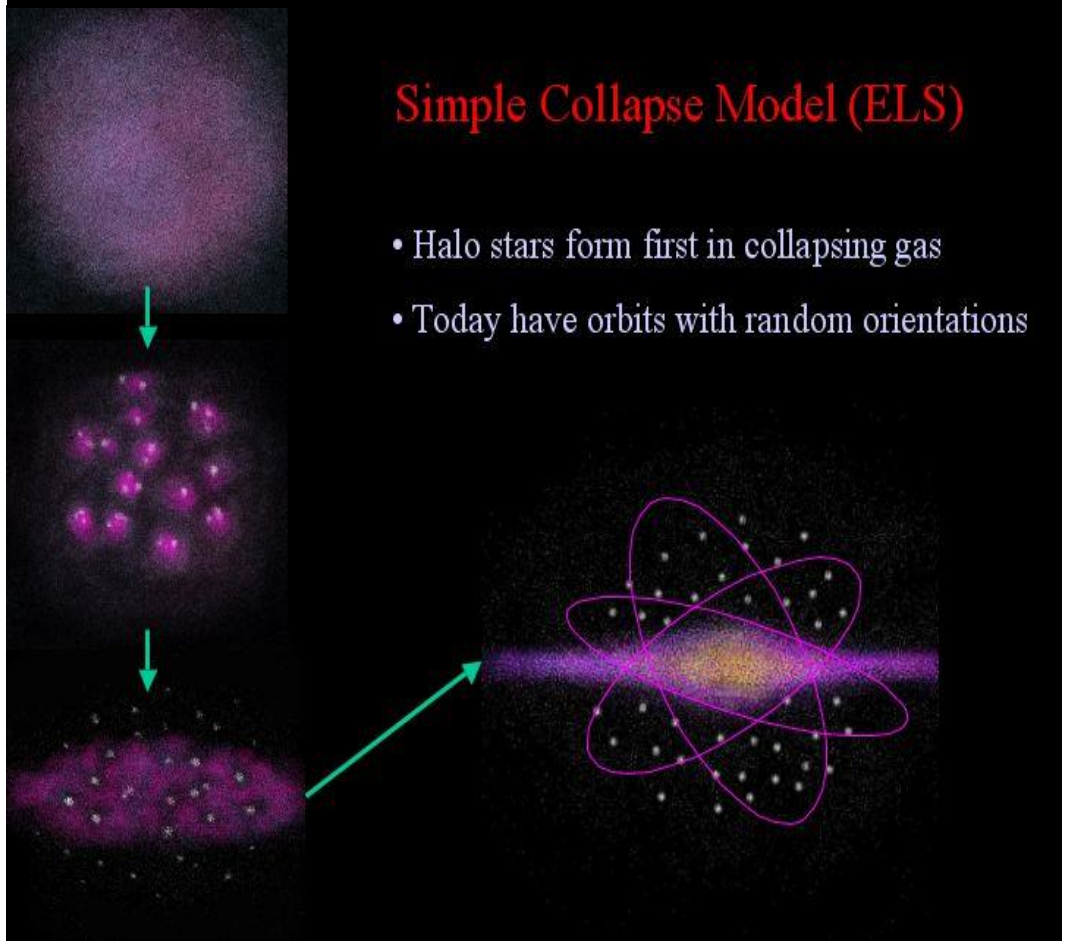
提 纲

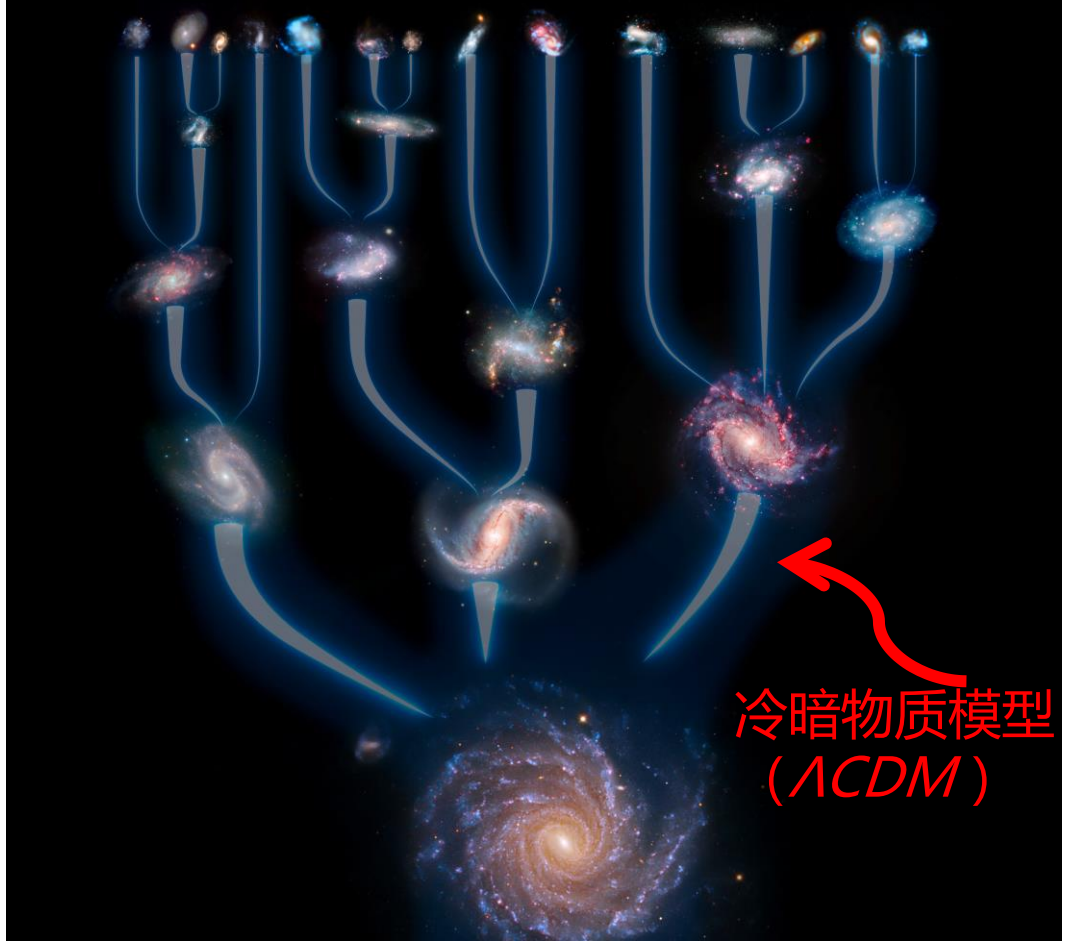
- 研究背景
- 研究现状
- 基于LAMOST取得的进展
- 小结和展望

星系形成机制

坍缩形成机制（ELS）



层级并合形成机制(SZ)



层级并合星系形成理论

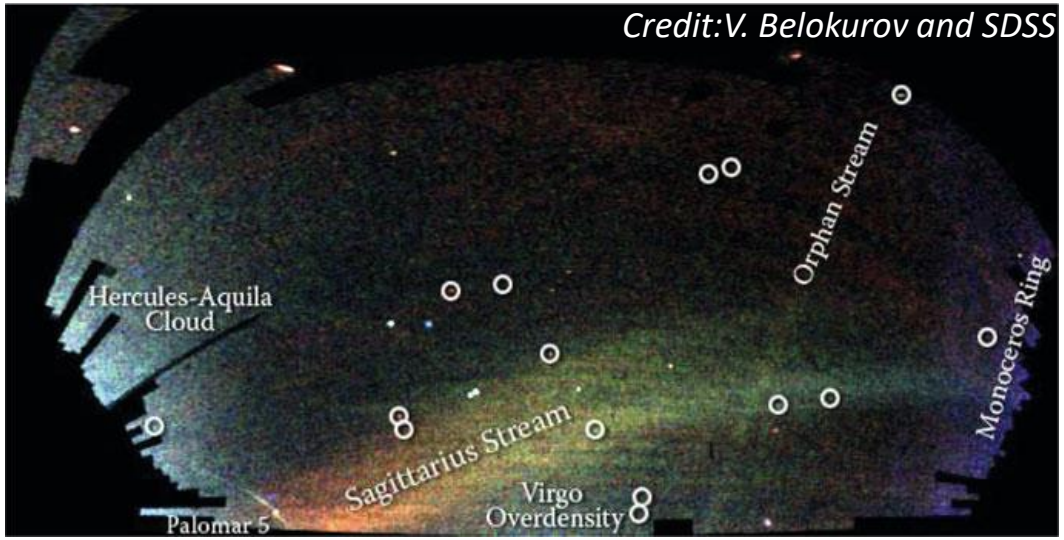
- 冷暗物质宇宙学模型(*ΛCDM*)预言银河系形成过程中发生过上百起并合事件。
- 人马座星流等的观测发现支持了层级并合理论。
- 但是，理论和观测依然存在不符。
  - *卫星星系丢失问题*

并合遗迹的演化形态

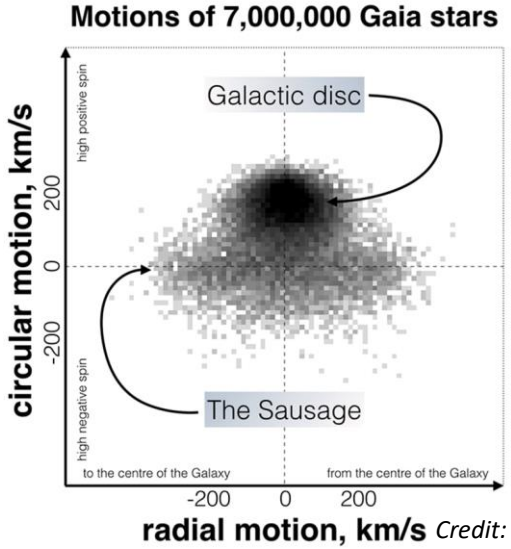
- 早期形态 ==> 位置空间
  - *来自矮星系的恒星在银河系潮汐力的拖拽牵引下在空间上保持着很好的形态--星流。*

- 中期形态 ==> 速度空间
  - *随着时间的演化，空间上的形态逐渐被潮汐力瓦解，但在速度空间依然还保留着成团性。*

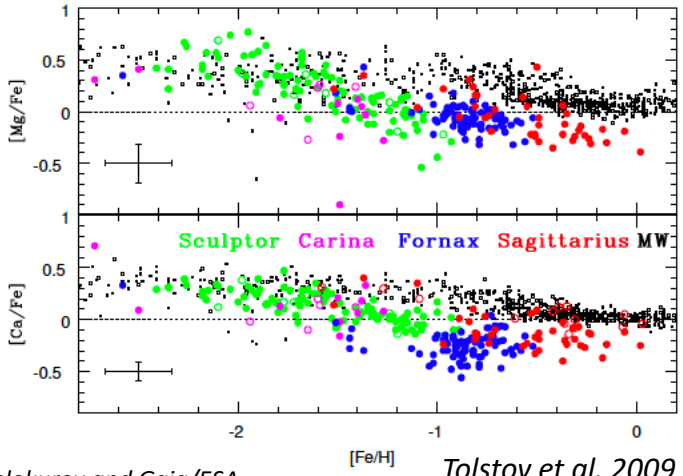
- 晚期形态 ==> 化学空间
  - *最终这些外来的恒星被充分混合，分布非常弥散，仅留化学DNA记录着它们的起源。*



Credit:V. Belokurov and SDSS

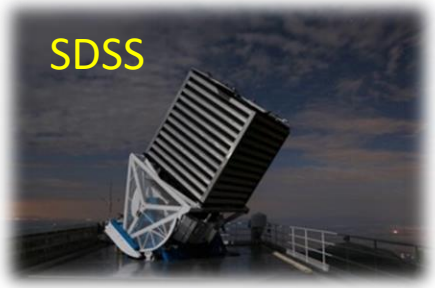


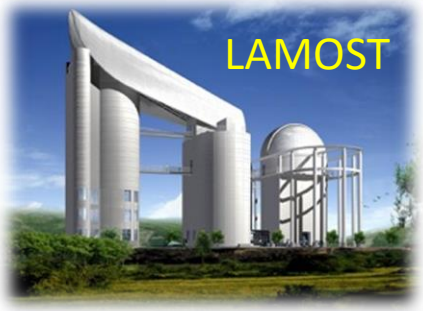
Credit: V. Belokurov and Gaia/ESA

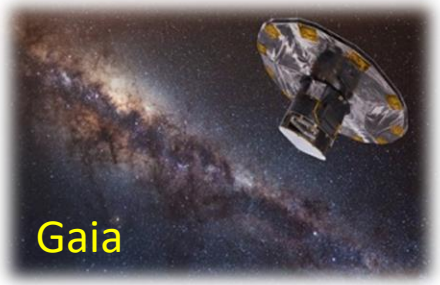


Tolstoy et al. 2009

近三十年来银河系研究的重大进展







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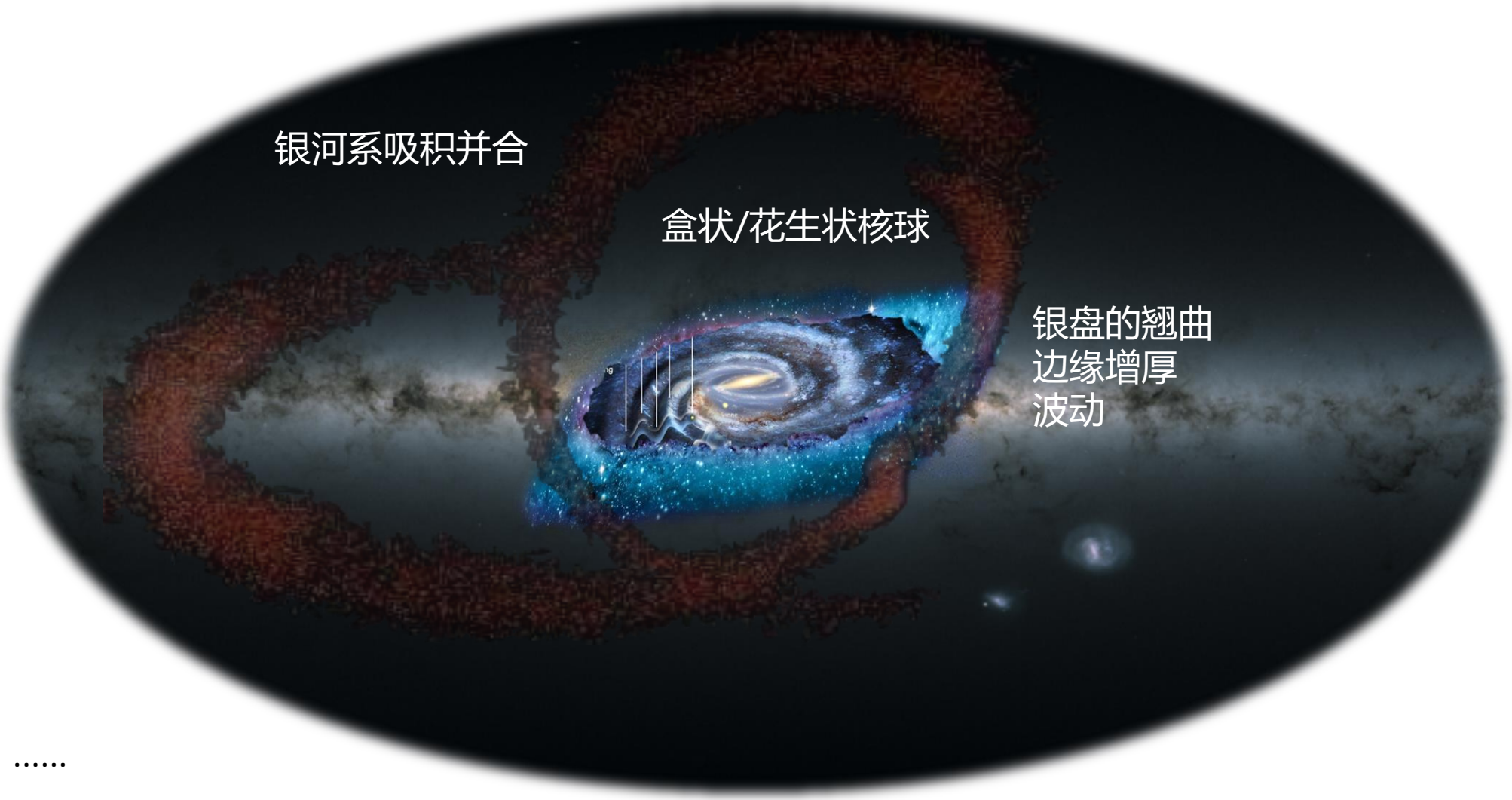
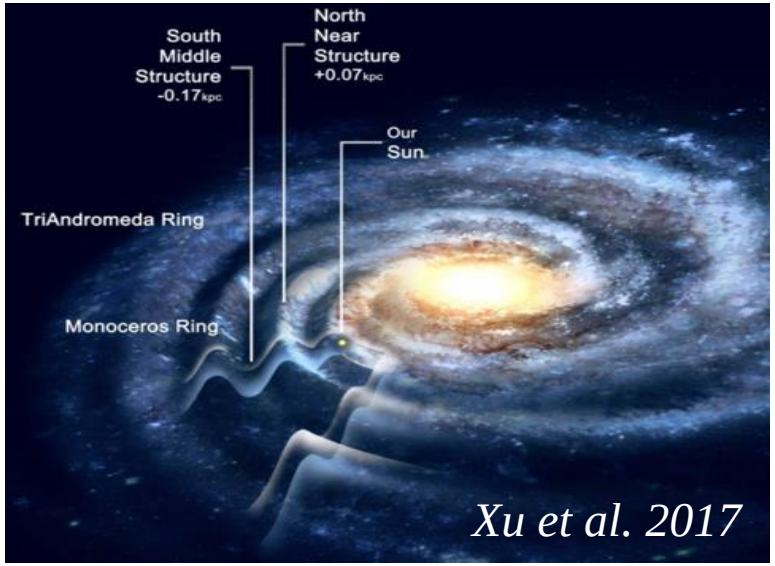


大规模巡天项目驱动银河系研究

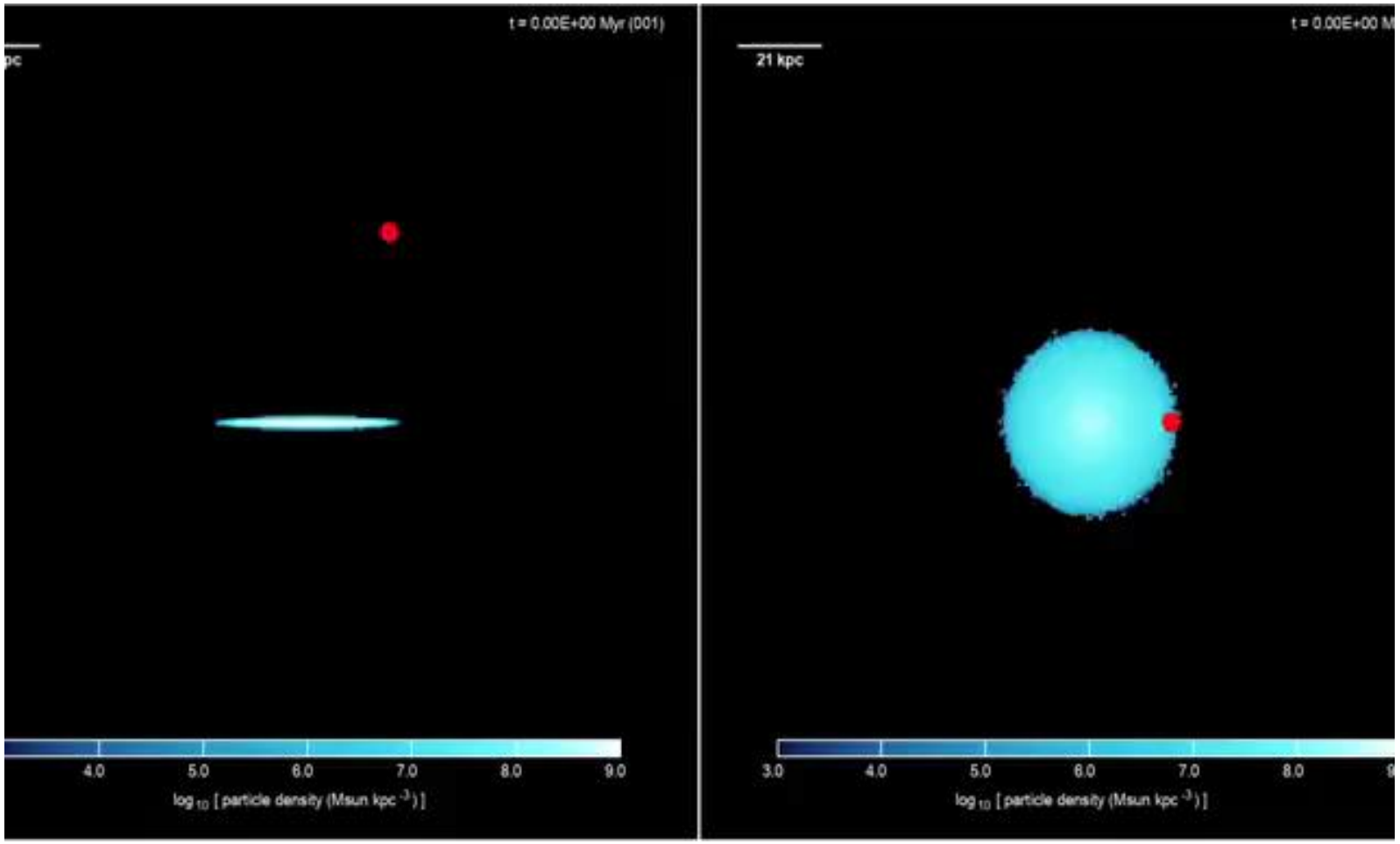
- 目前人们已经在多波段开展了大规模巡天，覆盖全天，如2MASS，GALEX，Gaia等；
- 在光学和红外波段，已经获得了数十亿颗恒星的测光星等和颜色，如SDSS，2MASS，PS1，SkyMapper等测光巡天；
- 这些恒星中只有一小部分具有高质量的光谱分类、视向速度、金属丰度和距离，如SDSS，LAMOST等光谱巡天；
- 更小的一部分恒星有高精度多种元素丰度测量，如GALAH，Gaia-ESO等高分辨率光谱巡天；
- 年龄的测量非常困难。

并合对银盘的扰动

并合不仅对银晕的形成很重要，对银盘结构的塑造也有影响



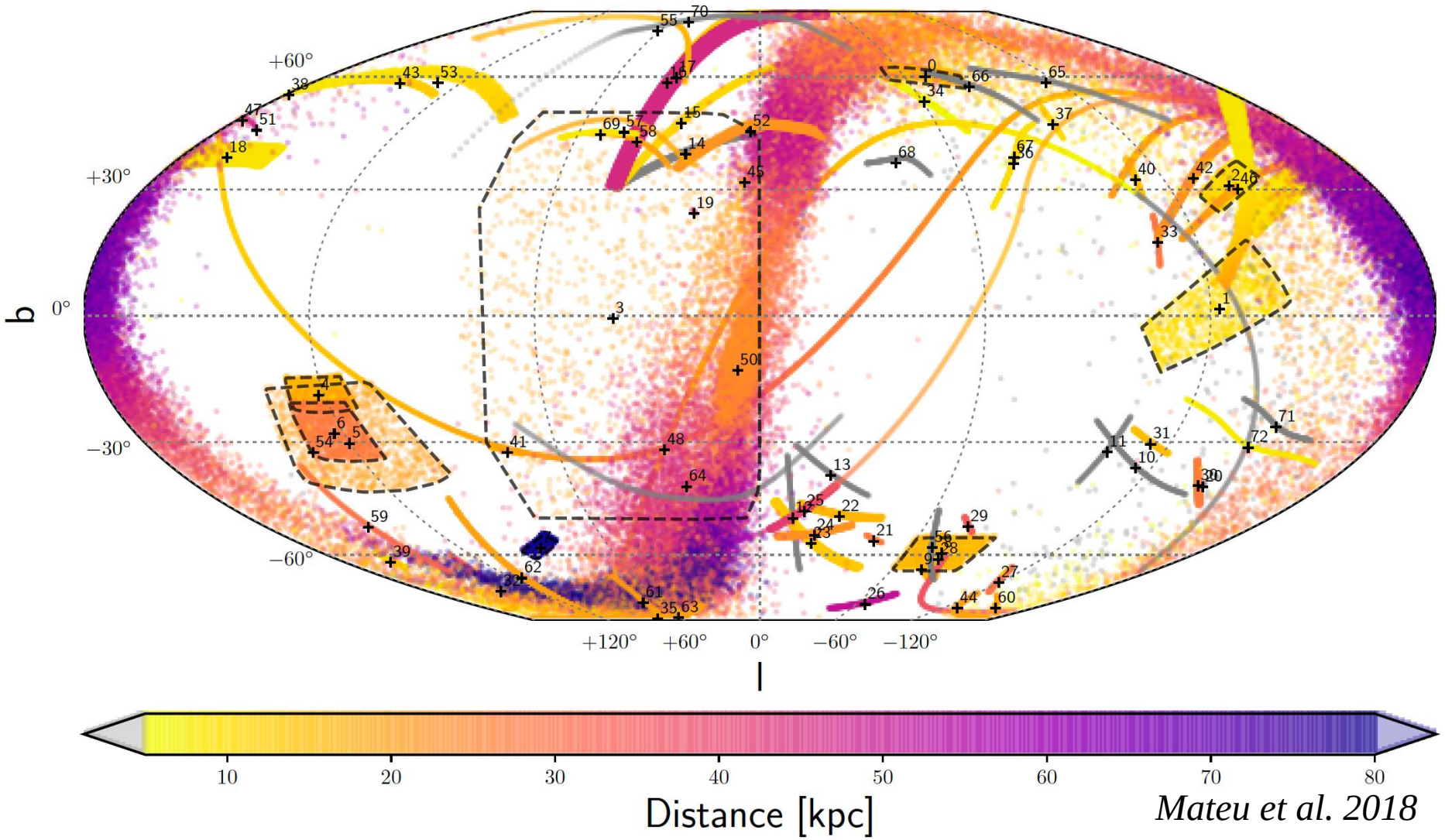
Xu et al. 2017



研究现状

0: **VOD/VSS**	1: **Monoceros**	2: **EBS**	3: **Her – Aq**	4: **PAndAS**	5: **Tri – And**	6: **Tri – And2**	7: **PiscesOv**	8: **EriPhe**
9: Phoenix	10: WG1	11: WG2	12: WG3	13: WG4	14: Acheron	15: Cocytos	16: Lethe	17: Styx
18: ACS	19: Pal15	20: Eridanus	21: TucanaIII	22: Indus	23: Jhelum	24: Ravi	25: Chenab	26: Elqui
27: Aliqa Uma	28: Turbio	29: Willka Yaku	30: Turranburra	31: Wambelong	32: Palca	33: Jet	34: Gaia-1	35: Gaia-2
36: Gaia-3	37: Gaia-4	38: Gaia-5	39: PS1-A	40: PS1-B	41: PS1-C	42: PS1-D	43: PS1-E	44: ATLAS
45: Ophiucus	46: Sangarius	47: Scamander	48: Corvus	50: Sgr-L10	51: Orphan	52: Pal5	53: GD-1	54: Tri/Pis
55: NGC5466	56: Alpheus	57: Hermus	58: Hyllus	59: Cetus	60: Kwando	61: Molonglo	62: Murrumbidgee	63: Orinoco
64: Phlegethon	65: Slidr	66: Sylgr	67: Ylgr	68: Fimbulthul	69: Svol	70: Fjorm	71: Gjoll	72: Leiptr

基于SDSS，PS1，Gaia等测光巡天，发现了73个星流。

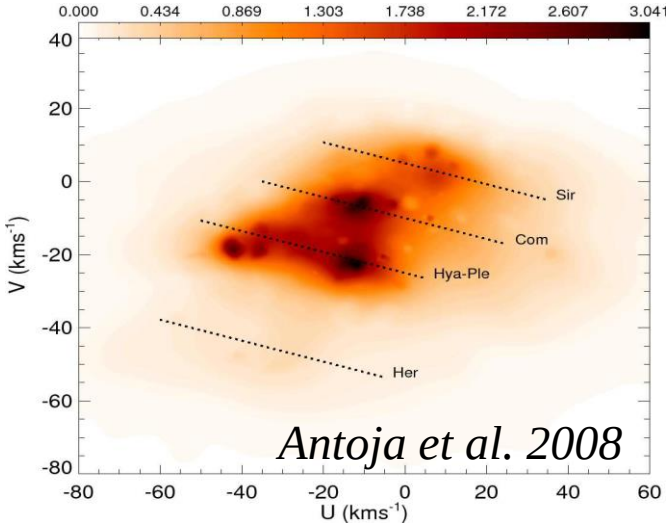


Mateu et al. 2018

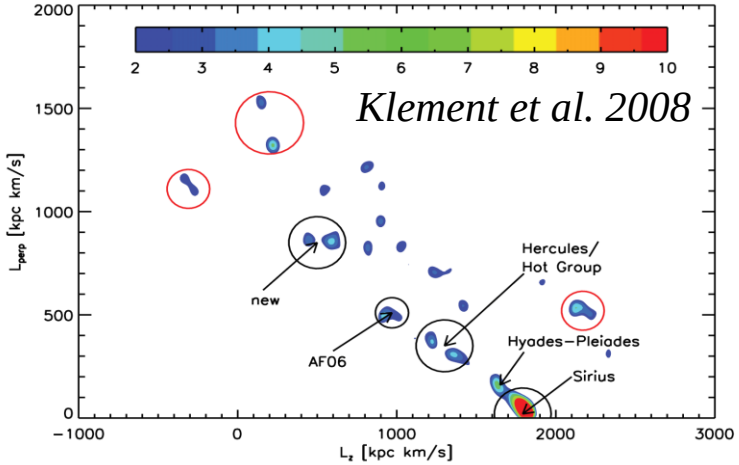
Name	Reference	Name	Reference
Alpheus	Grillmair 2013	PAndAS	Grillmair & Carlin 2016
Acheron	Grillmair 2009	Phoenix	Balbinot 2016
ACS	Grillmair 2006	PiscesOv	Grillmair & Carlin 2016
ATLAS	Koposov 2014	PS1-A	Bernard 2016
Cetus	Newberg 2009	PS1-B	Bernard 2016
Cocytos	Grillmair 2009	PS1-C	Bernard 2016
GD-1	Price-Whelan & Bonaca 2018	PS1-D	Bernard 2016
EBS	Grillmair & Carlin 2016	PS1-E	Bernard 2016
Eridanus	Myeong2017	Sagitarius	Law & Majewski 2010 (model)
Eri/Phe	Li2016	Sangarius	Grillmair 2017
Hermus	Grillmair 2014	Scamander	Grillmair 2017
Her-Aq	Grillmair & Carlin 2016	Styx	Grillmair 2009
Hyllus	Grillmair 2014	Tri-And	Grillmair & Carlin 2016
Kwando	Grillmair 2017b	Tri-And2	Grillmair & Carlin 2016
Lethe	Grillmair 2009	Tri/Pis	Bonaca 2012
Molonglo	Grillmair 2017b	VOD/VSS	Vivas et al. 2001
Monoceros	Grillmair & Carlin 2016	WG1	Agnello 2017
Murrumbidgee	Grillmair 2017b	WG2	Agnello 2017
NGC5466	Grillmair & Johnson2006	WG3	Agnello 2017
Ophiucus	Bernard 2014	WG4	Agnello 2017
Orphan	Newberg 2010	Jet	Jethwa et al. 2017

Name	Reference	Name	Reference
Orinoco	Grillmair 2017b	Indus	Shipp et al. 2018
Pal5	Grillmair 2006	Jhelum	Shipp et al. 2018
Pal15	Myeong2017	Ravi	Shipp et al. 2018
Chenab	Shipp et al. 2018	Elqui	Shipp et al. 2018
Aliqa Uma	Shipp et al. 2018	Turbio	Shipp et al. 2018
Willka Yaku	Shipp et al. 2018	Turranburra	Shipp et al. 2018
Wambelong	Shipp et al. 2018	Palca	Shipp et al. 2018
Corvus	Mateu et al. 2018	Tucana III	Shipp et al. 2018
20.0-1	Mateu et al. 2018	Gaia-[1,5]	Malhan et al. 2018
Phlegethon	Ibata et al. 2018	Slidr	Ibata et al. 2019
Sylgr	Ibata et al. 2019	Fjorm	Ibata et al. 2019
Ylgr	Ibata et al. 2019	Gjoll	Ibata et al. 2019
Fimbulthul	Ibata et al. 2019	Leiptr	Ibata et al. 2019
Svol	Ibata et al. 2019		

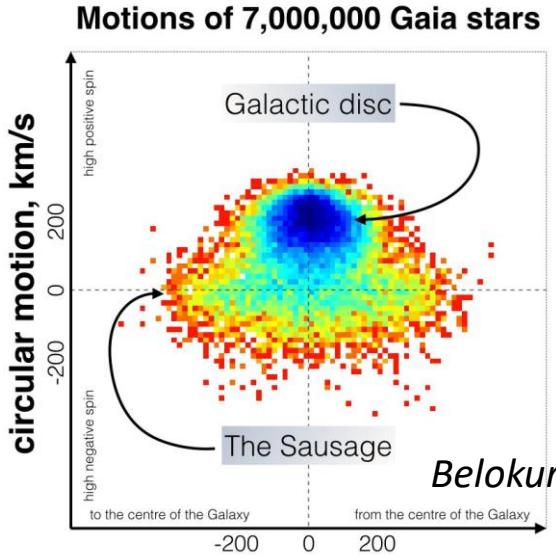
太阳邻域：6D相空间参数，可以计算能量和角动量（IoM）



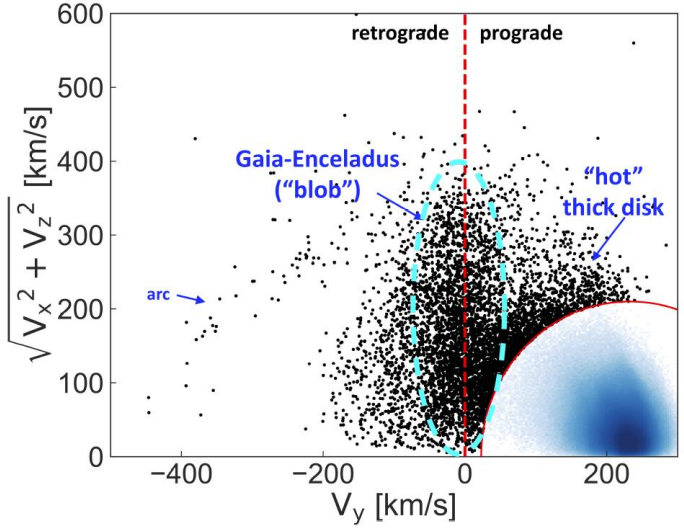
Antoja et al. 2008

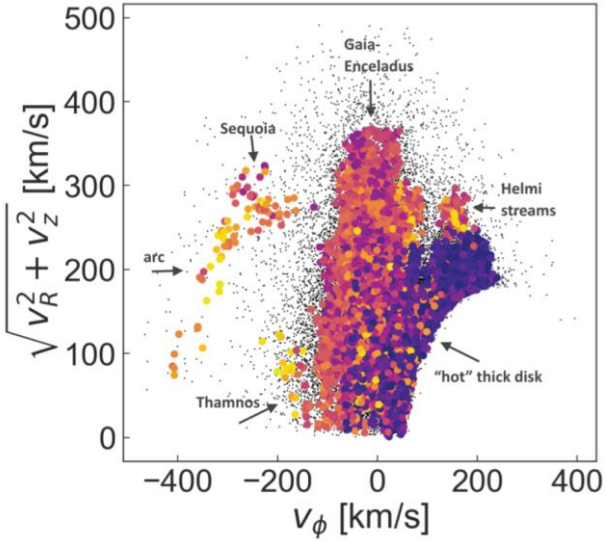


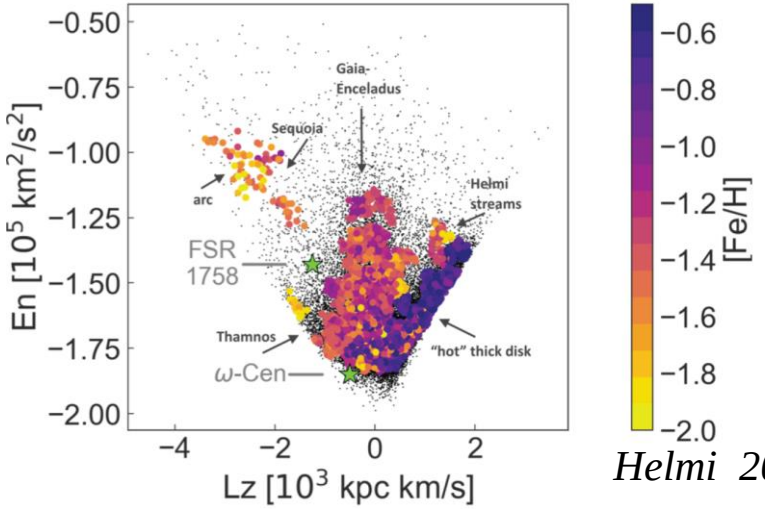
Klement et al. 2008



Belokurov et al. 2018

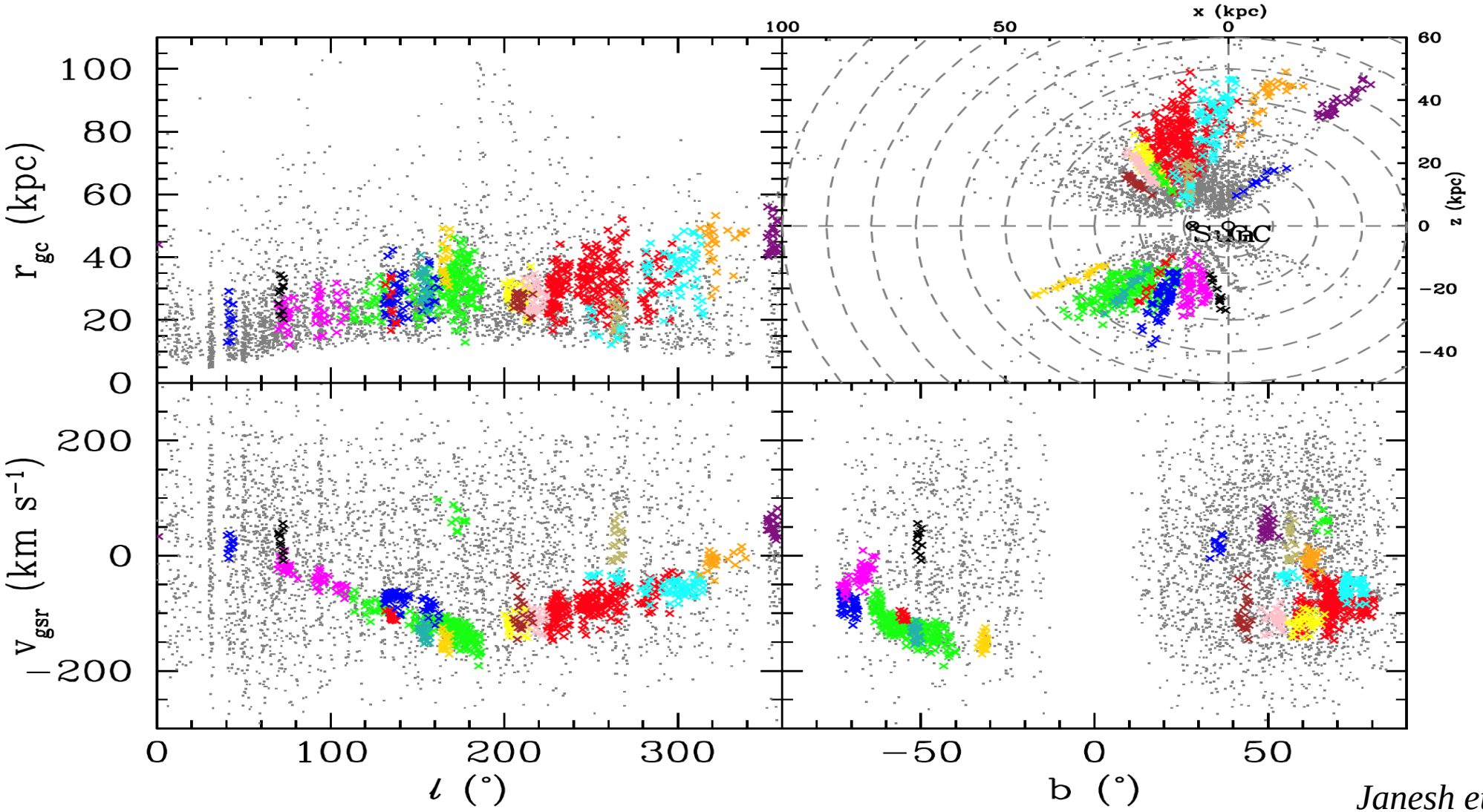






Helmi 2020

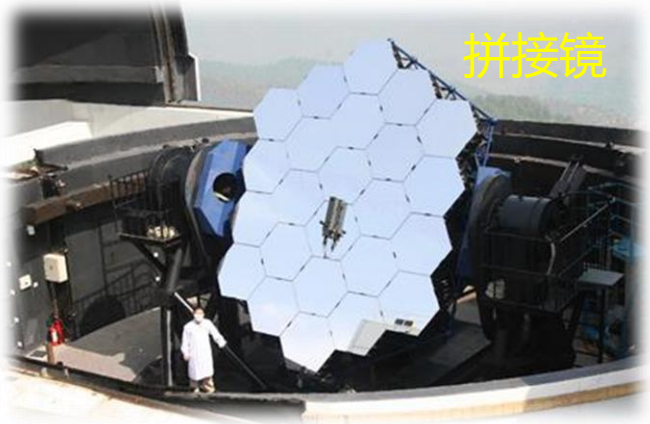
遥远银晕：Gaia DR2之前没有可用的自行

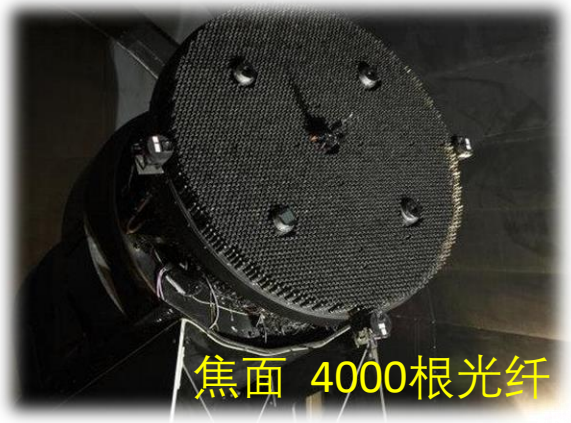


Janesh et al. 2016

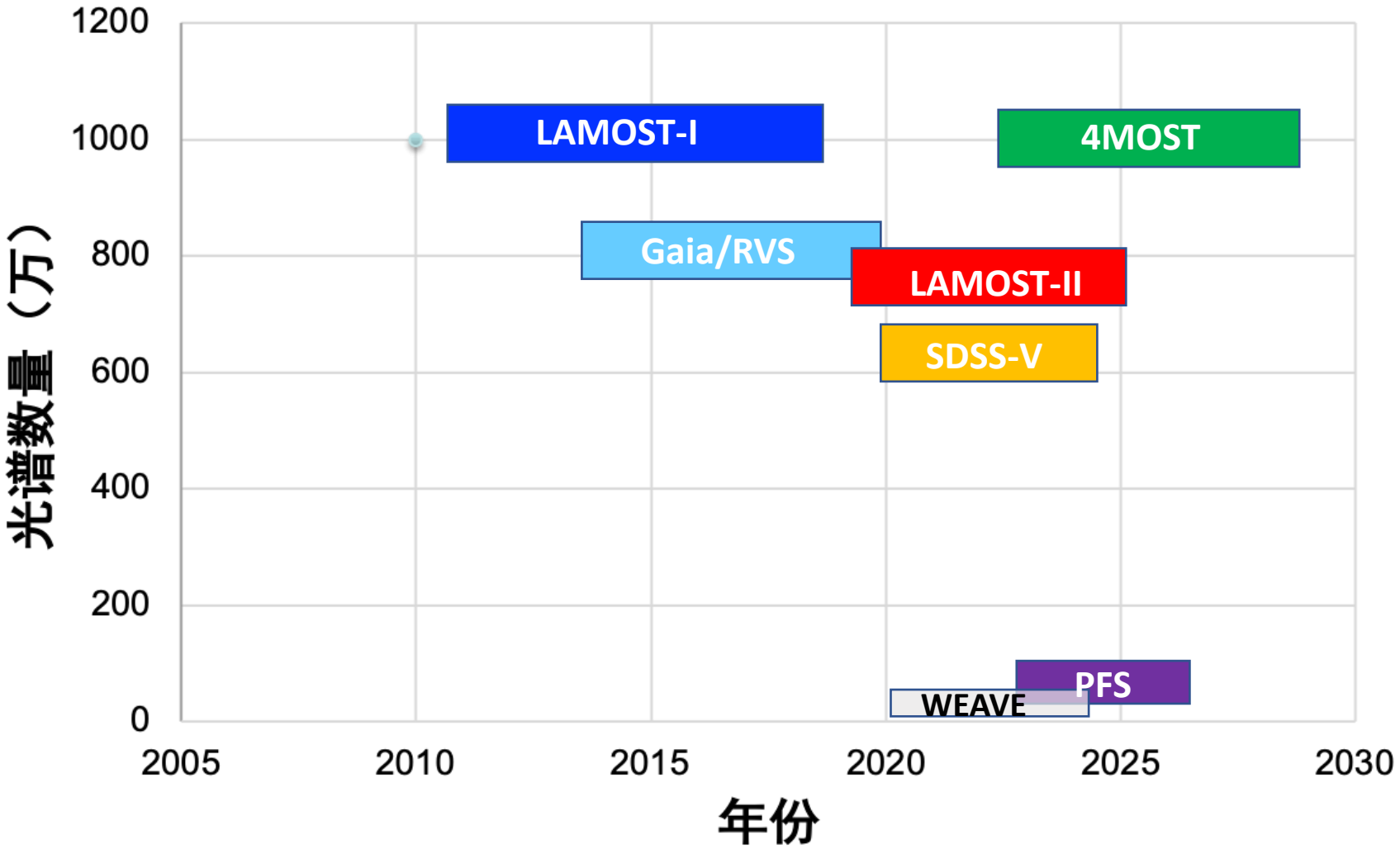
我国大科学装置LAMOST简介

- LAMOST拥有创新性设计
  - 大口径（4米）+大视场（5度）
    ➔ “独一无二”
  - 4000根光纤
    ➔ “史无前例”
- 性能表现
  - 最高的光谱获取率
  - 突破了天文研究中的光谱观测的瓶颈，成为最具效率的光谱巡天望远镜





LAMOST持续为研究银河系吸积并合提供绝佳机遇

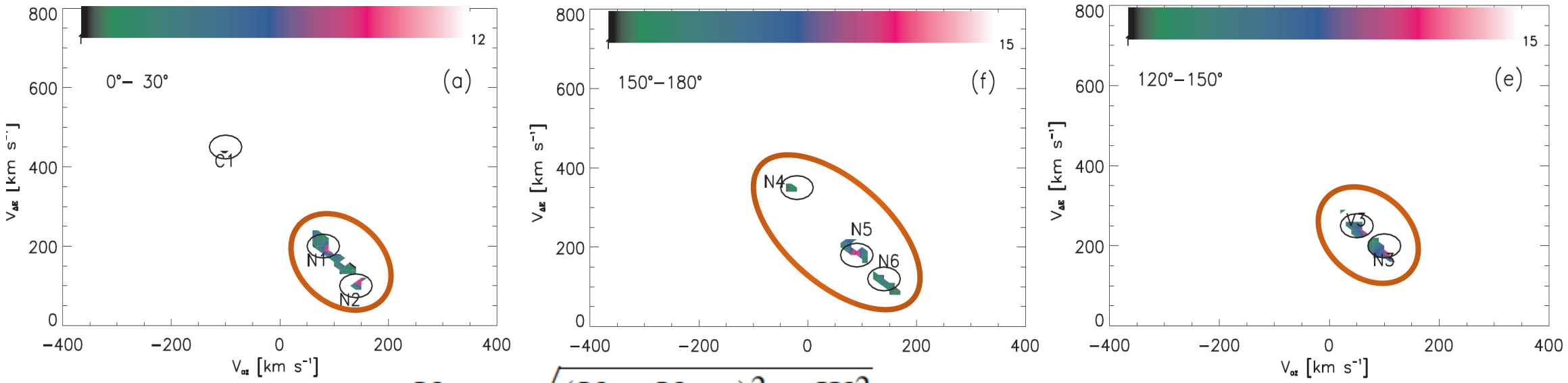


- 目前LAMOST光谱是世界上其他**所有光谱总和的2倍**！
- 中分辨率光谱观测**领先欧洲WEAVE项目至少2年**
- 时域光谱巡天**领先美国SDSS-V项目至少3年**

在太阳邻域发现了7个新的银晕移动星群（Moving Group）

- LAMOST DR1光谱+SDSS测光+USNO自行 ➔ ~8千主序星（d<2kpc）
- LAMOST DR2光谱+2MASS/WISE测光+PPMXL自行 ➔ ~7万贫金属主序星 ([Fe/H]<-0.7,d<2kpc)
- 基于拥有6D相空间参数的样本，利用小波变换，在速度空间发现了7个新的银晕移动星群 V3、N1-6，占国际同类发现的一半

$$V_{\Delta E} = \sqrt{U^2 + 2(V_{LSR} - V_{az})^2}.$$

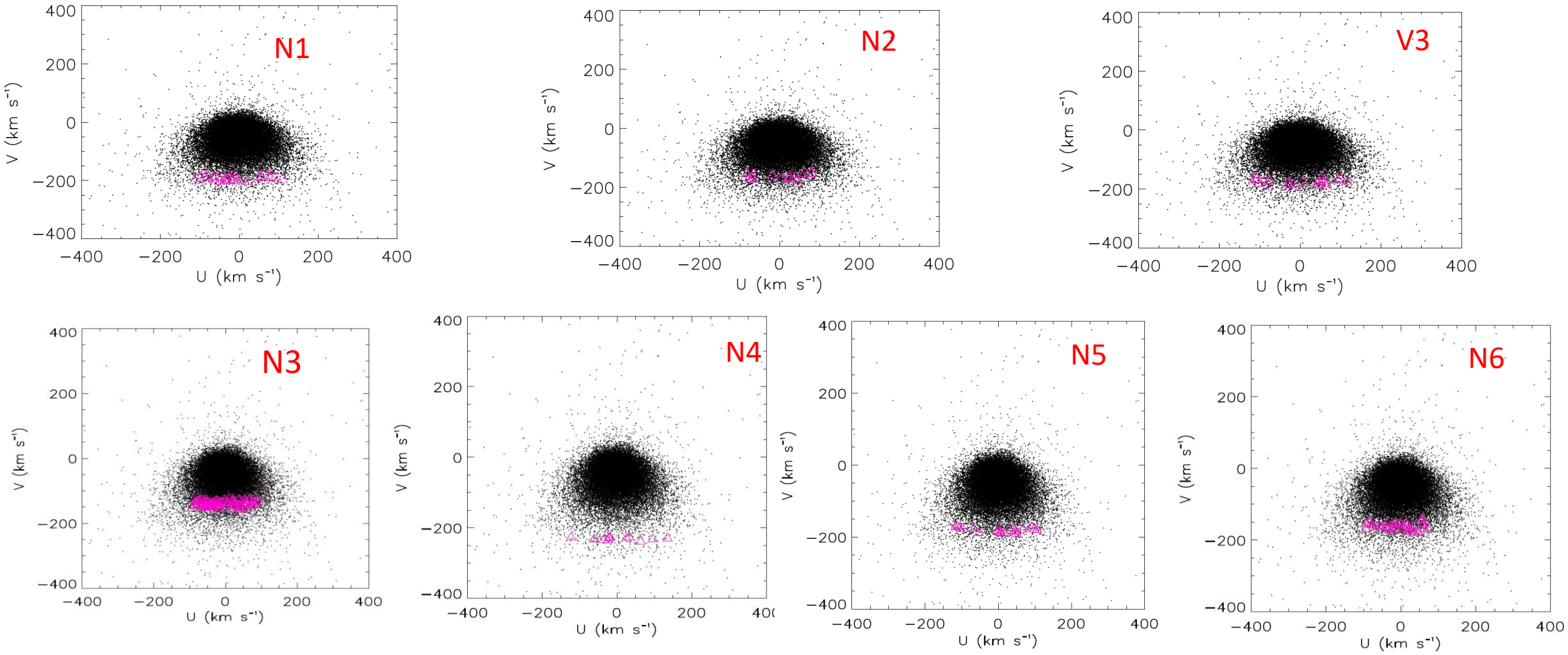


$$V_{az} = \sqrt{(V + V_{LSR})^2 + W^2},$$

Zhao J.K. et al. 2014 ApJ, 2015 RAA

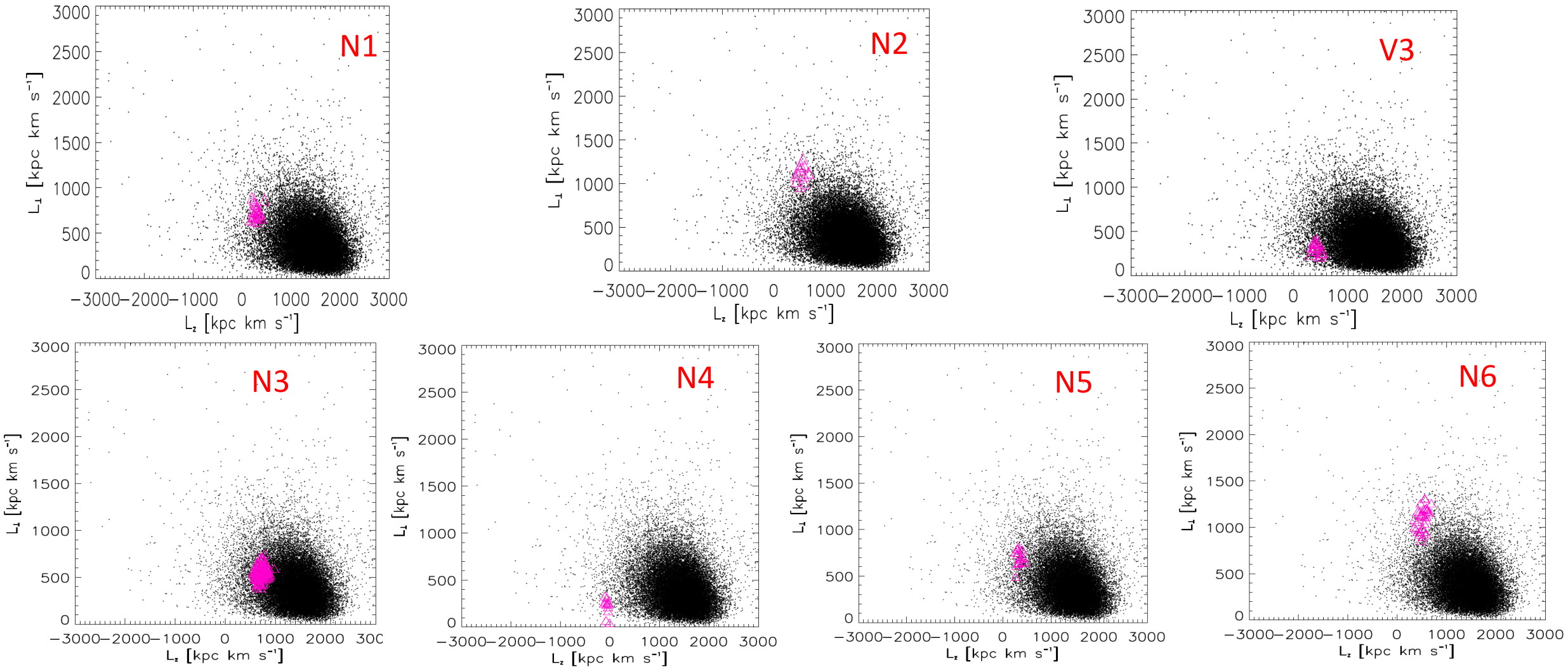
7个新的银晕移动星群的速度分布

Zhao J.K. et al. 2014 ApJ, 2015 RAA



7个新的银晕移动星群的角动量分布

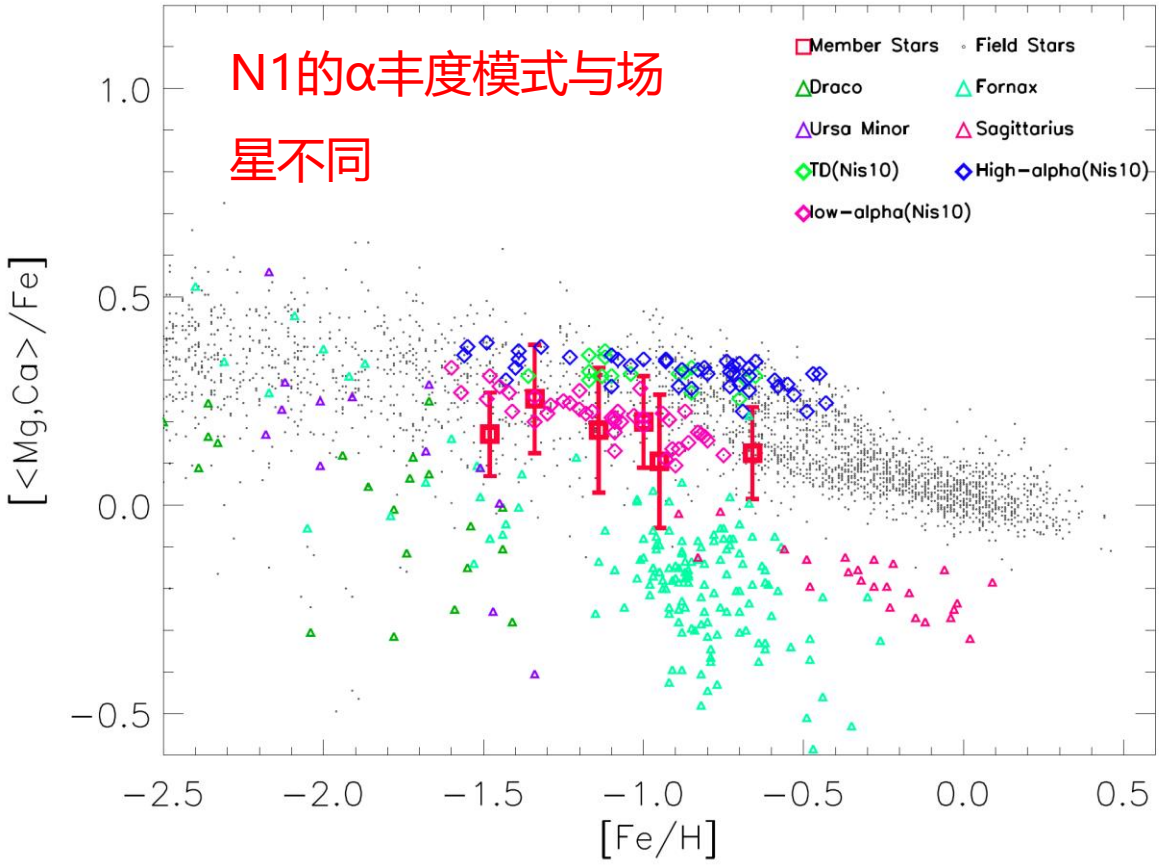
Zhao J.K. et al. 2014 ApJ, 2015 RAA

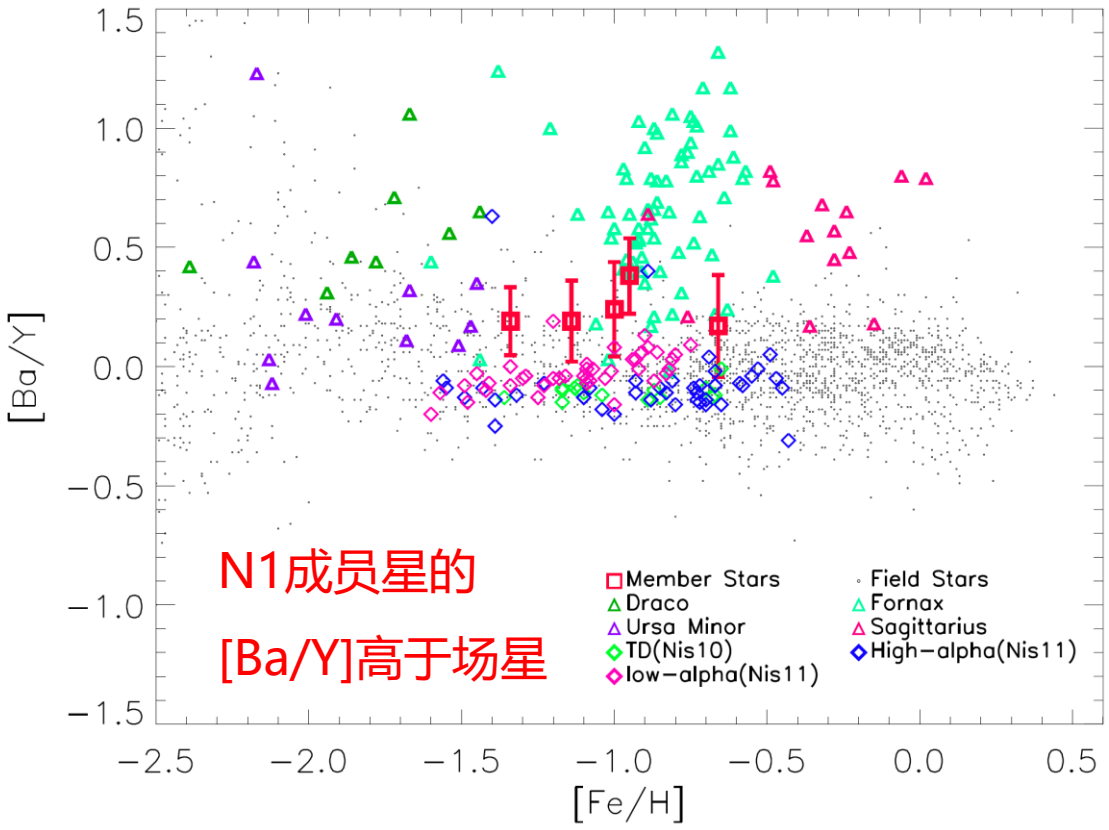


Follow-up观测证实N1起源于矮星系

Zhao J.K. et al. 2018 ApJ

- 通过Subaru对N1 中的6颗成员星进行了高分辨率光谱观测，得到了11种元素的丰度
- 与银河系场星以及河外矮星系成员星比较推断N1的前身可能是一个化学演化比银河系慢的矮星系

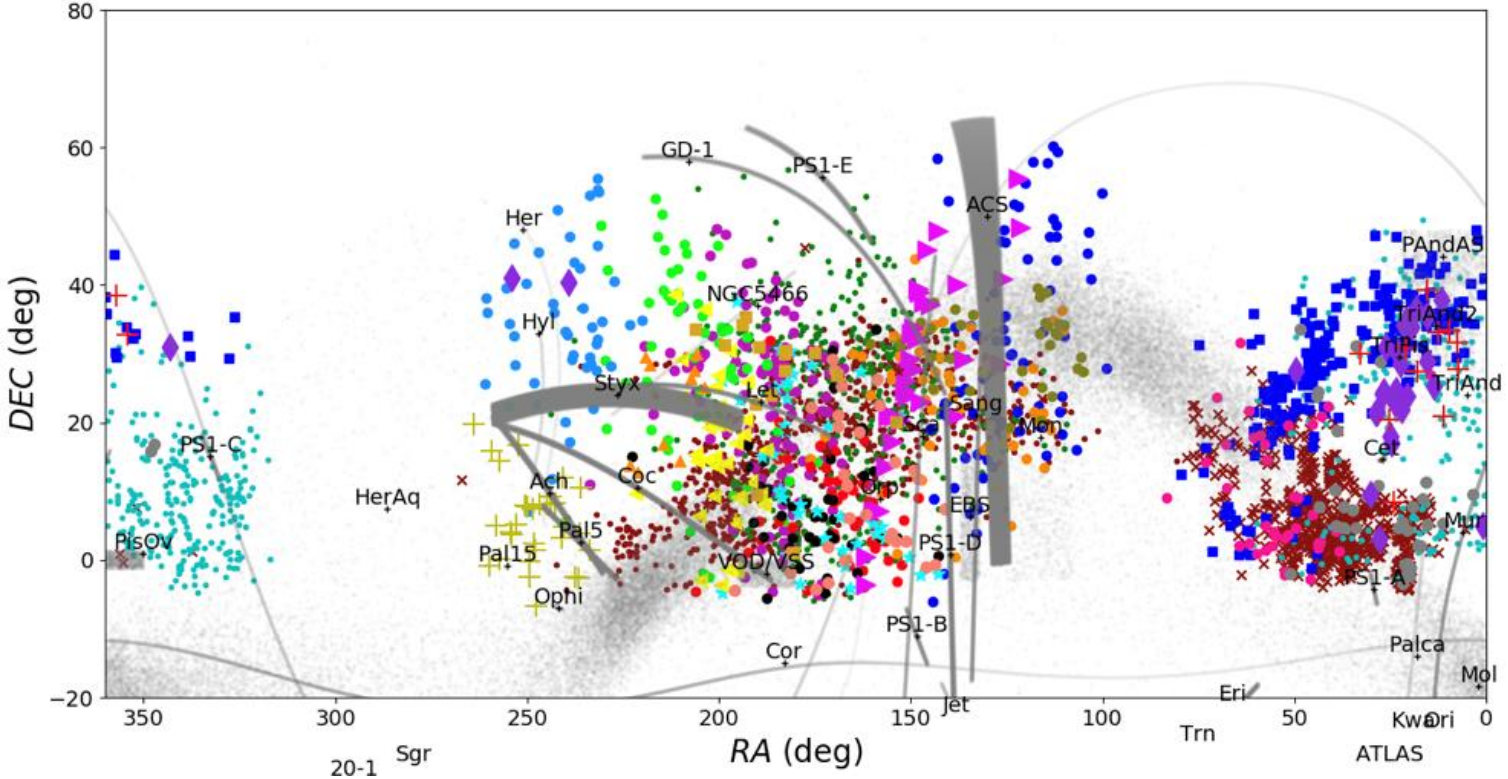




在遥远银晕中证认出大量并合遗迹的成员星

Yang et al. 2019a ApJ, Xue et al. to submit

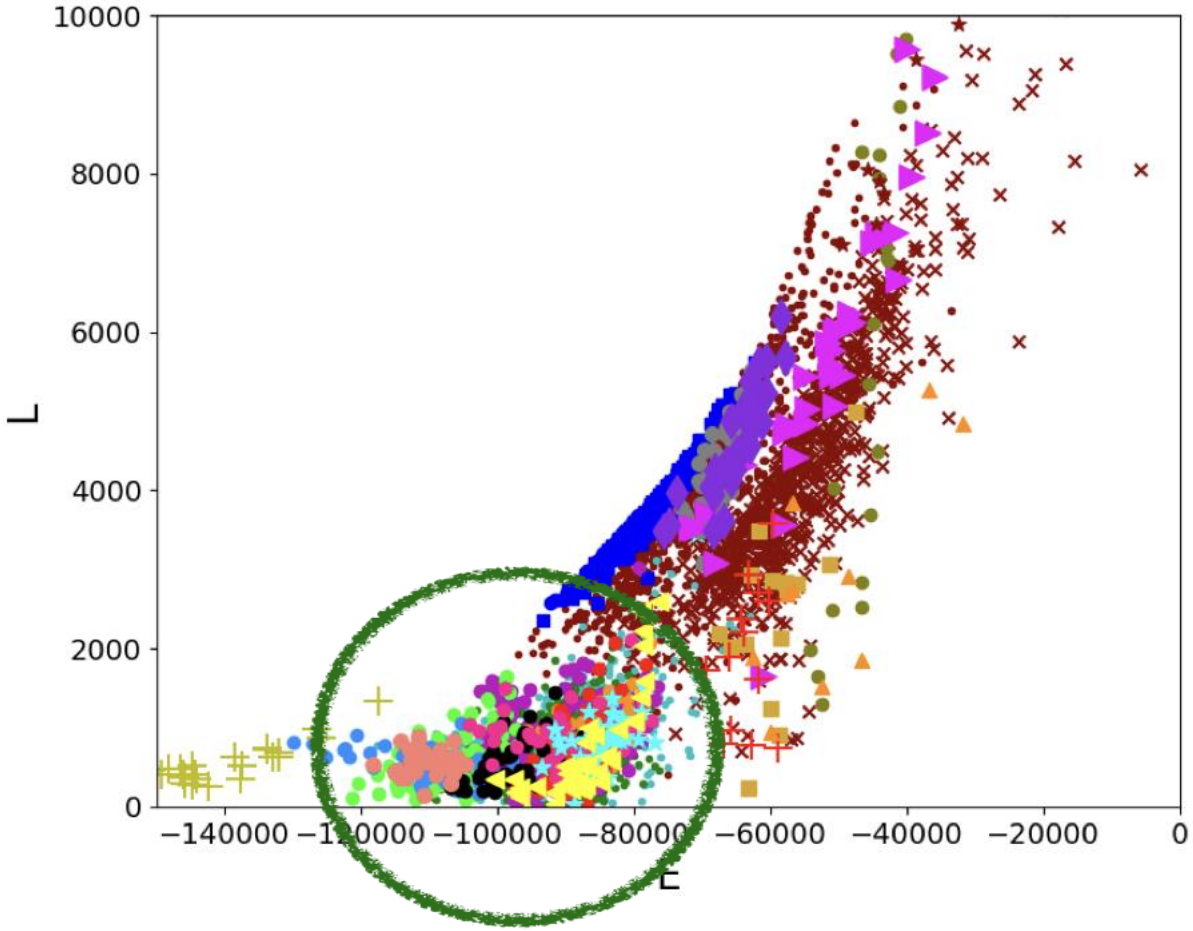
- LAMOST DR5光谱+Gaia DR2测光和自行 ➔ ~1.8万晕星（2kpc<d<120kpc）
- 利用Fiends-of-friends算法，在IoM空间证认出21个group（成员星≥30颗），近5000颗星，包含人马座星流、麒麟环、孤儿星流和鲸鱼座星流等已知星流，还有一些未知星流。

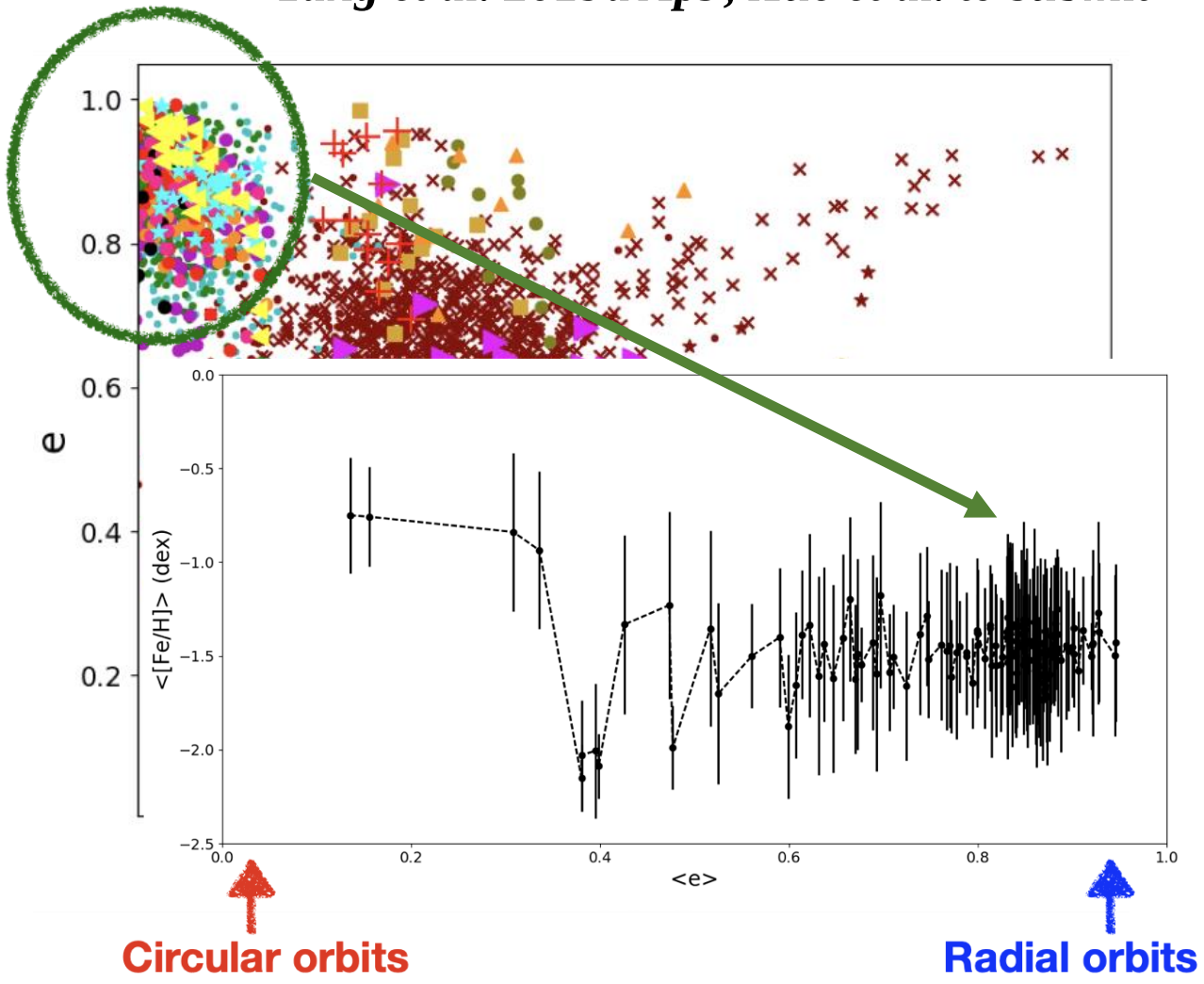


- **Monoceros Ring麒麟环（跨越南天和北天）**
- **Sagittarius streams人马座星流**
- **Orphan stream孤儿星流**
- **Cetus stream鲸鱼座星流**
- **Gaia-Sausage**

并合遗迹成员星的能量角动量分布

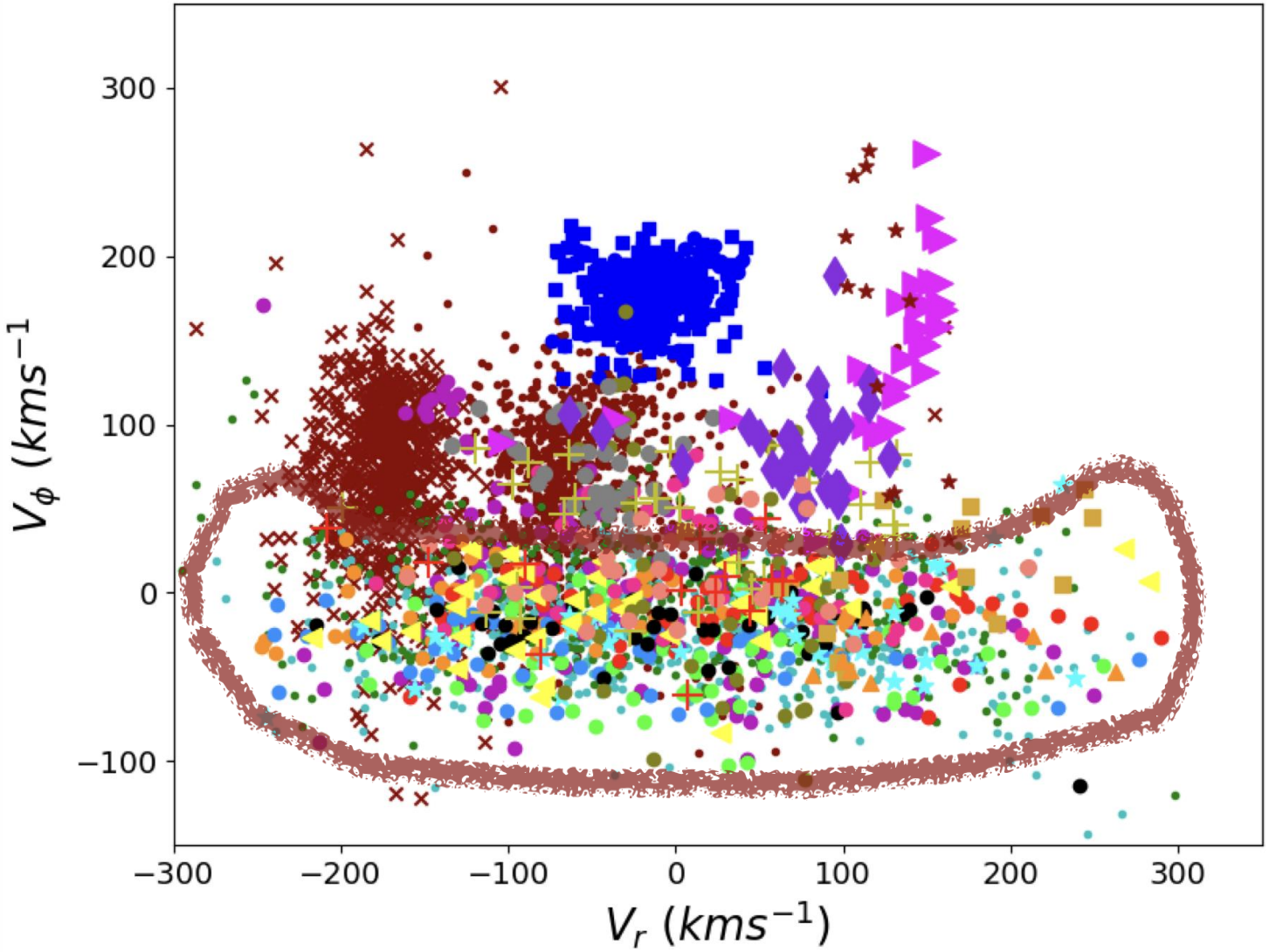
Yang et al. 2019a ApJ, Xue et al. to submit

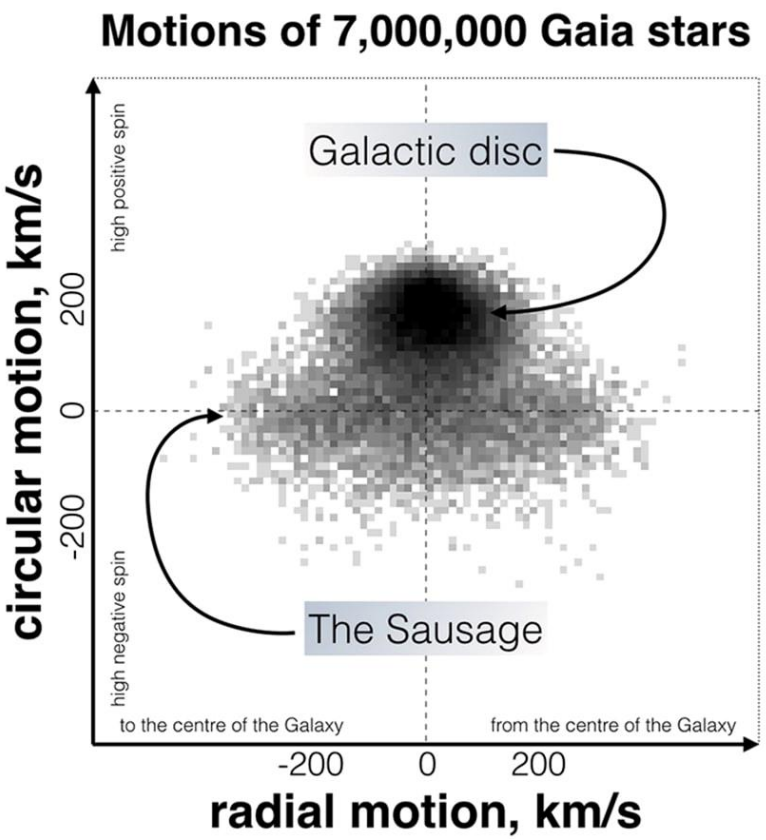




并合遗迹成员星的速度分布

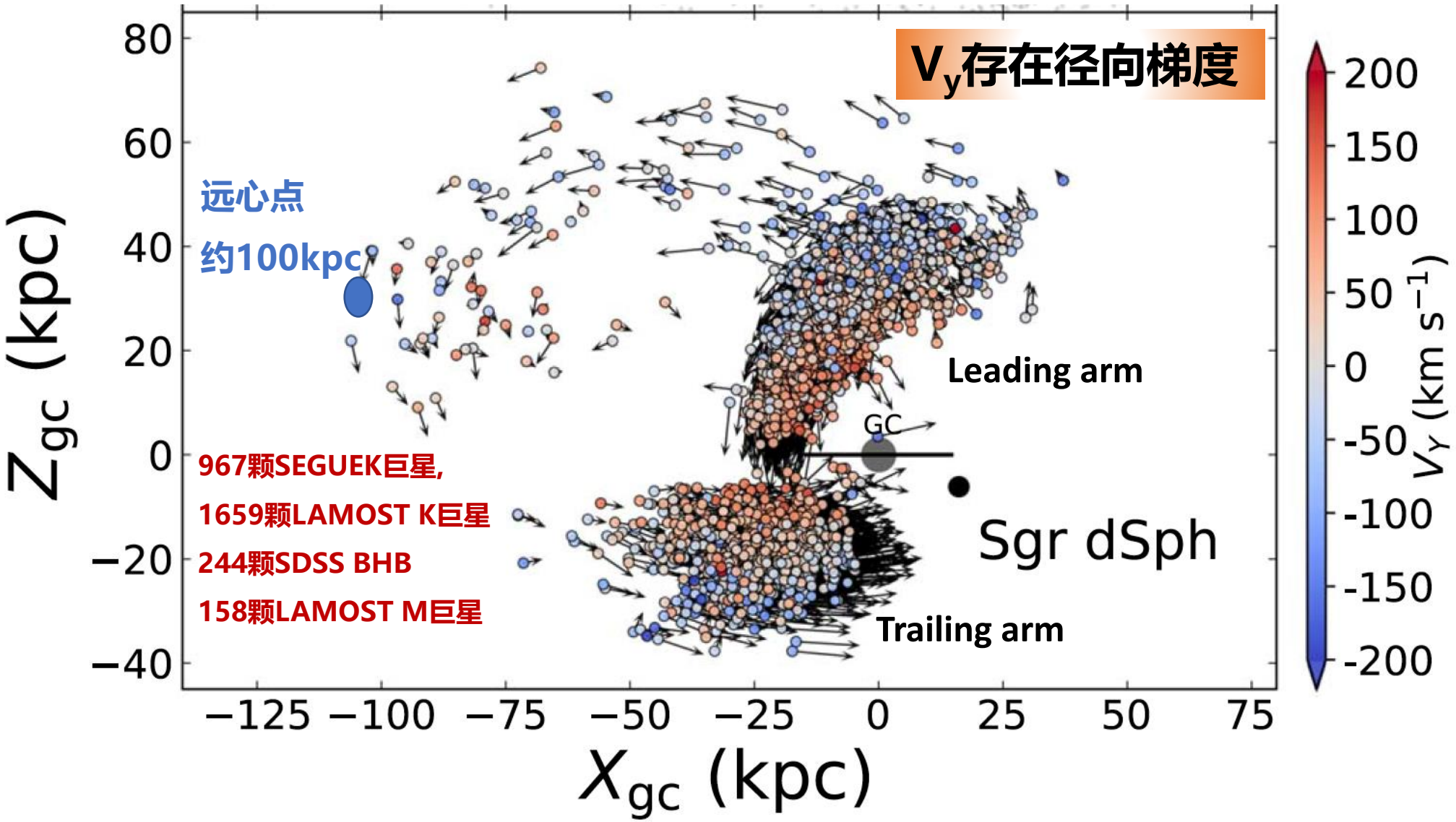
Yang et al. 2019a ApJ, Xue et al. to submit





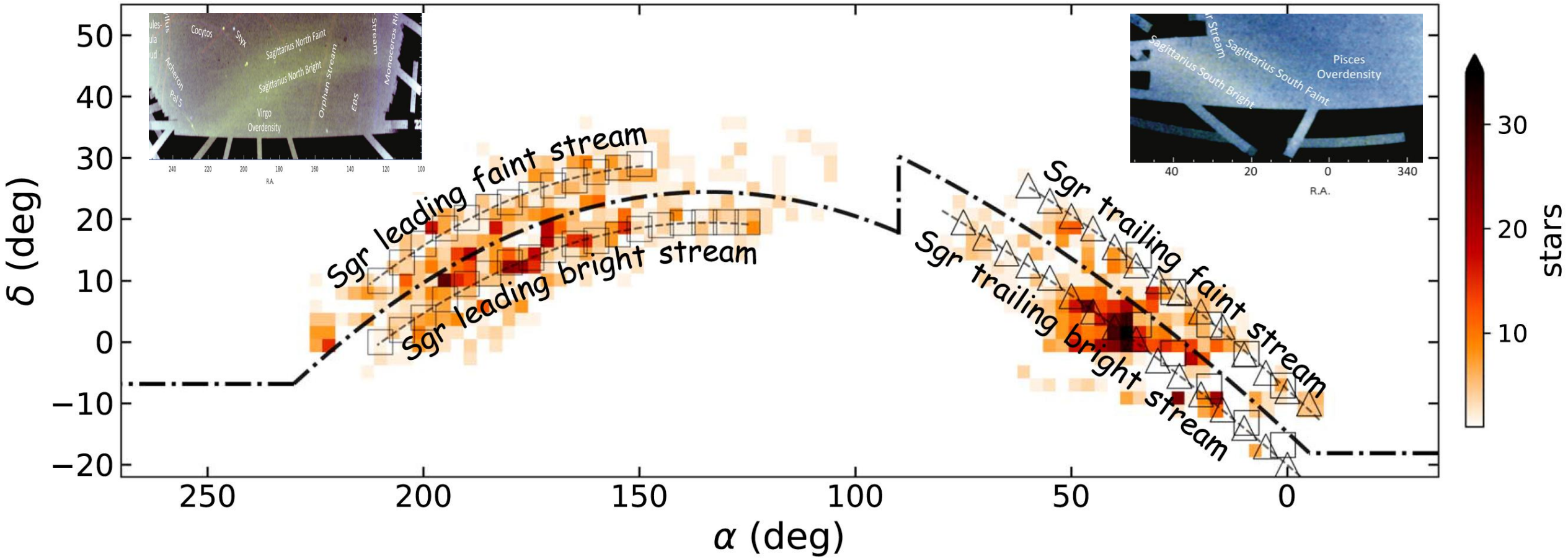
3千颗人马座星流成员星的3D运动

Yang et al. 2019b ApJ



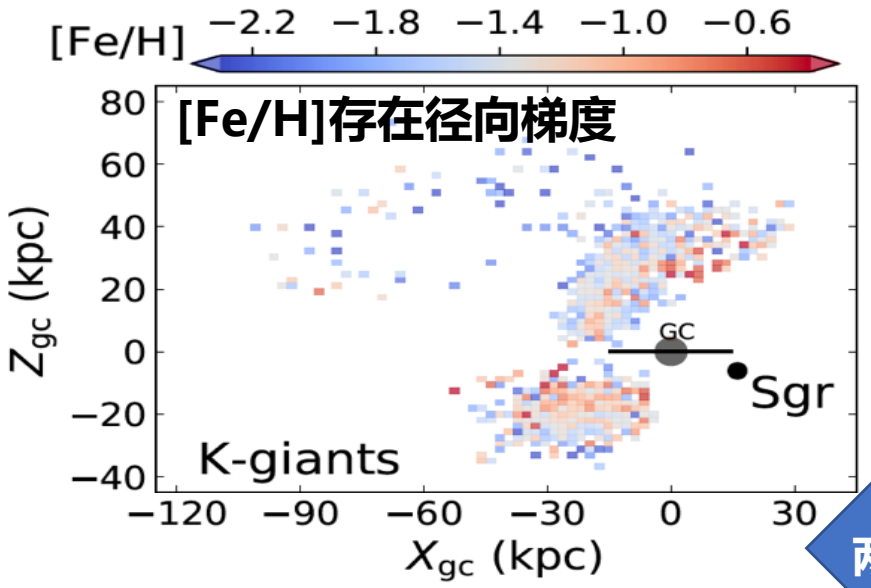
首次光谱呈现人马座星流的分叉结构

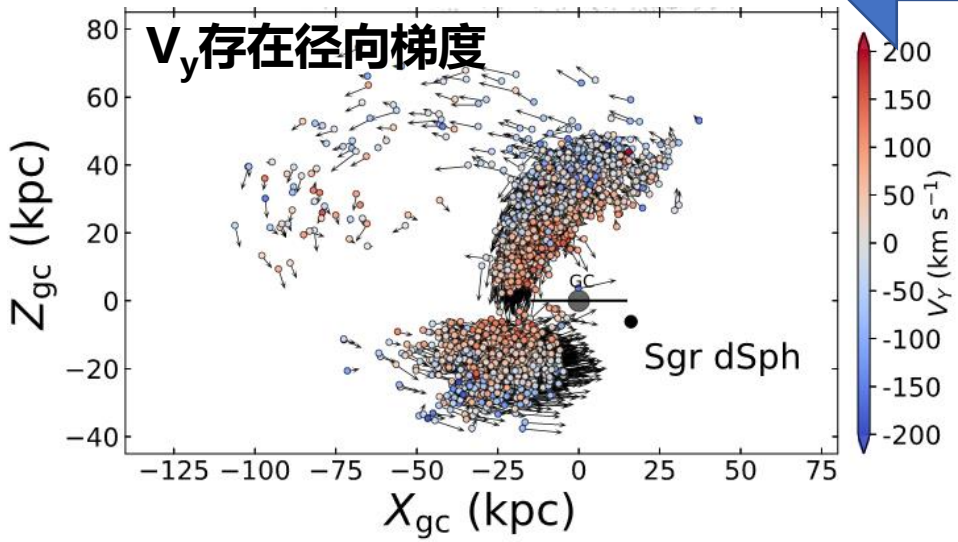
Yang et al. 2019b ApJ



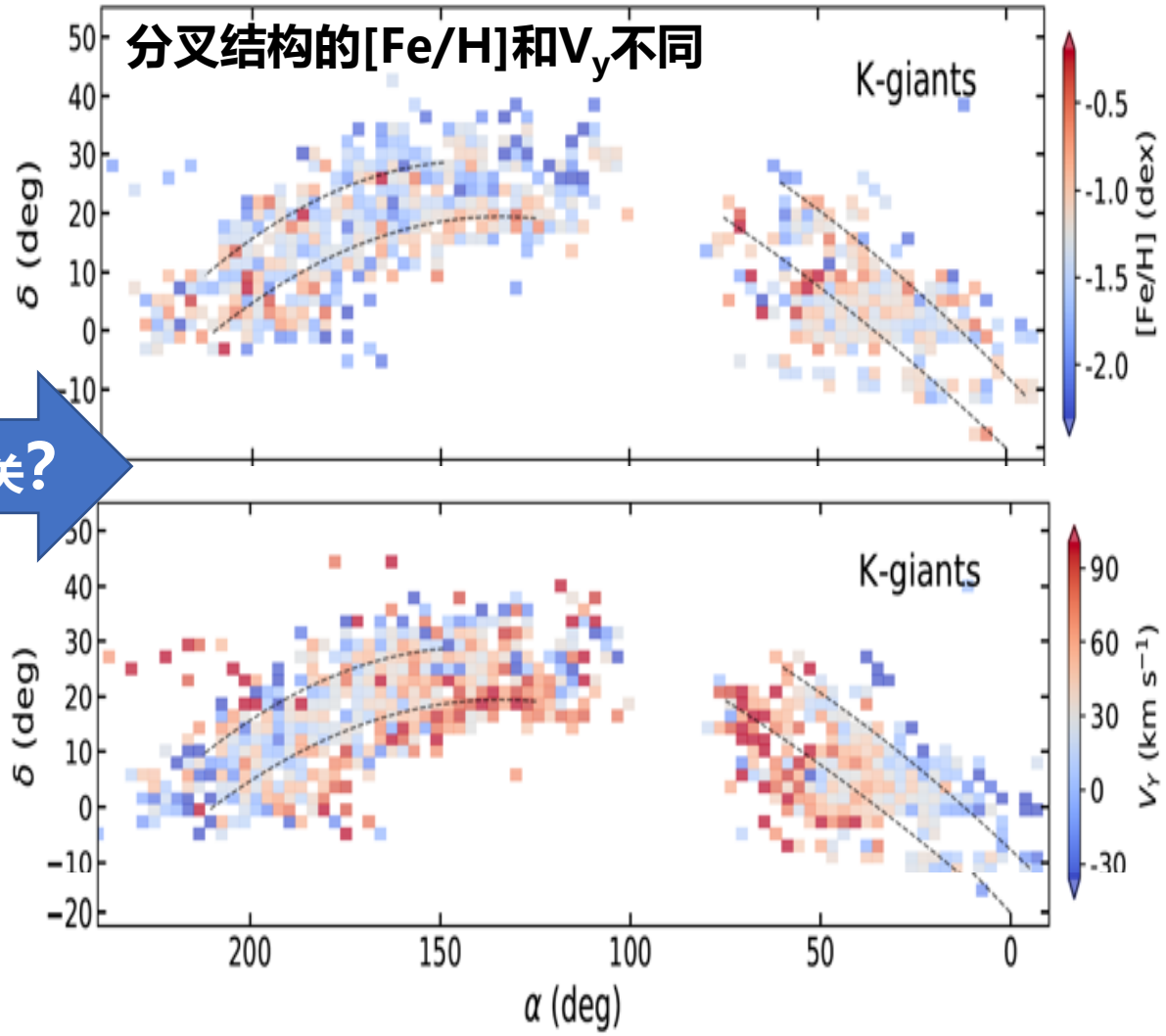
人马座星流的速度和金属丰度分布

Yang et al. 2019b ApJ



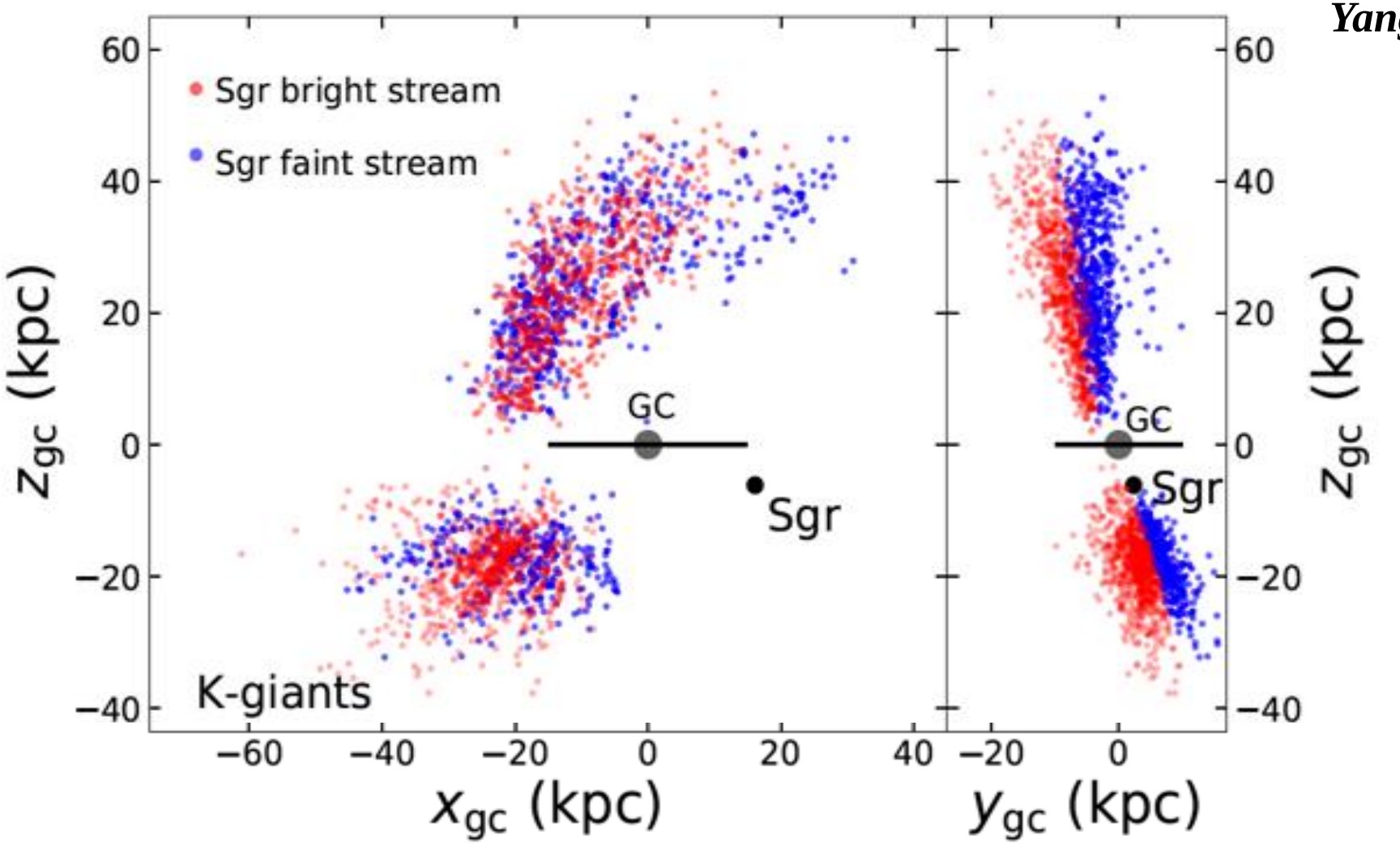


两者是否有关?

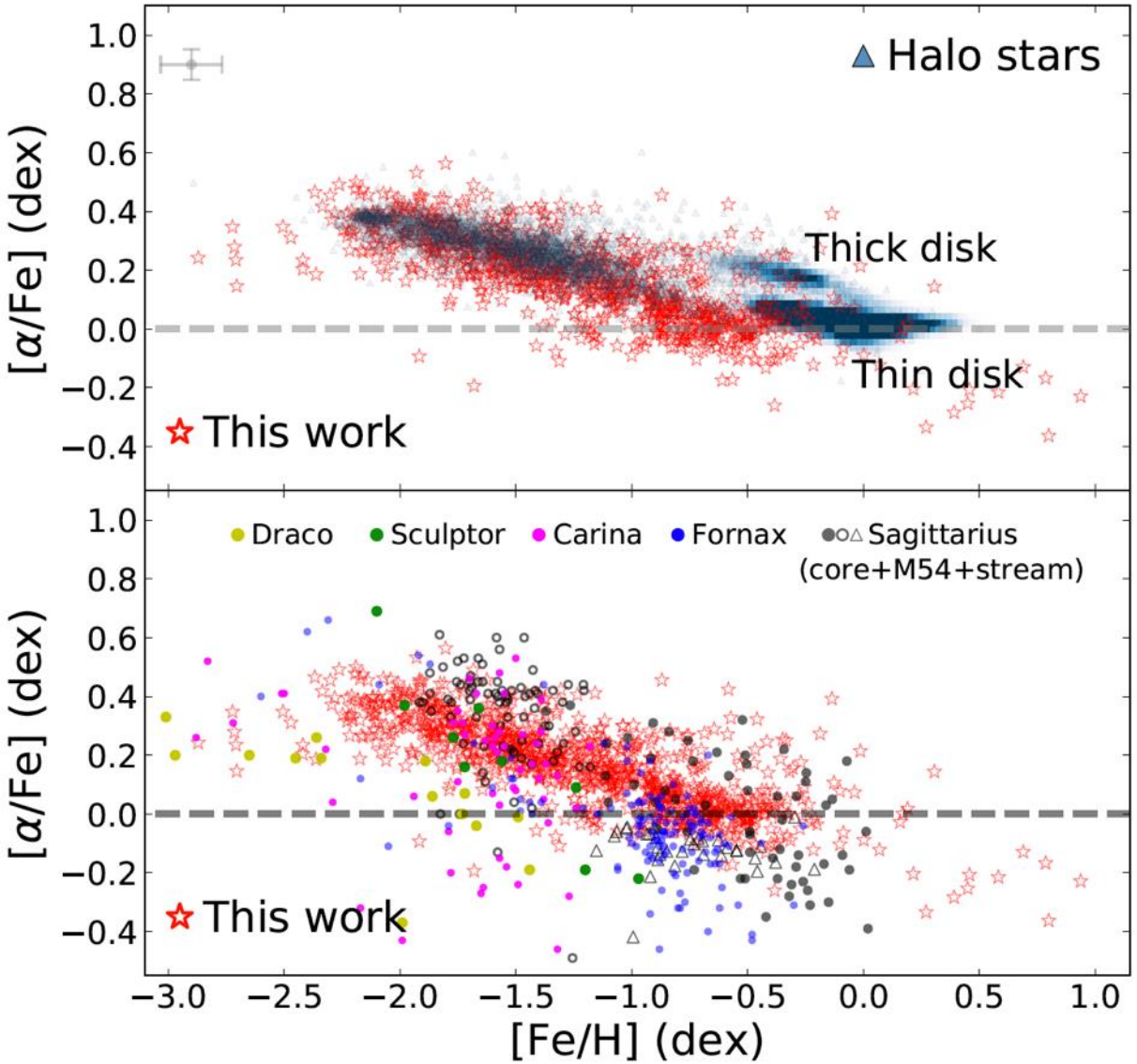


人马座星流的分叉结构与V_γ和金属丰度的径向梯度无关

Yang et al. 2019b ApJ



人马座星流的丰度模式



Yang et al. 2019b ApJ

贫金属区域与银河系晕星一致

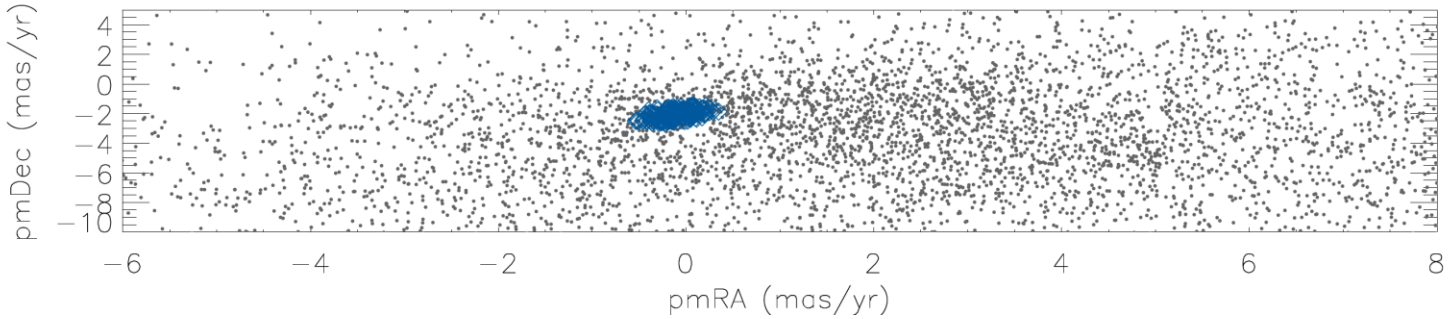
富金属区域继续向下演化到盘星的丰度以下

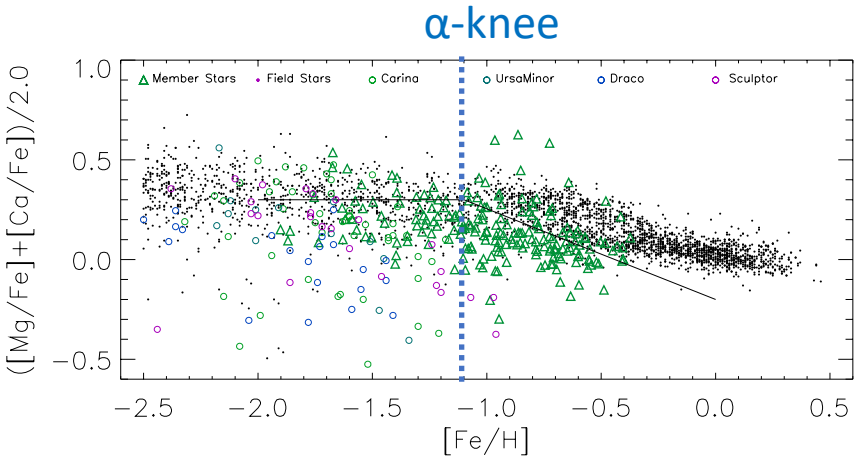
人马座星流的 α 元素演化模式与银河系矮星系相似

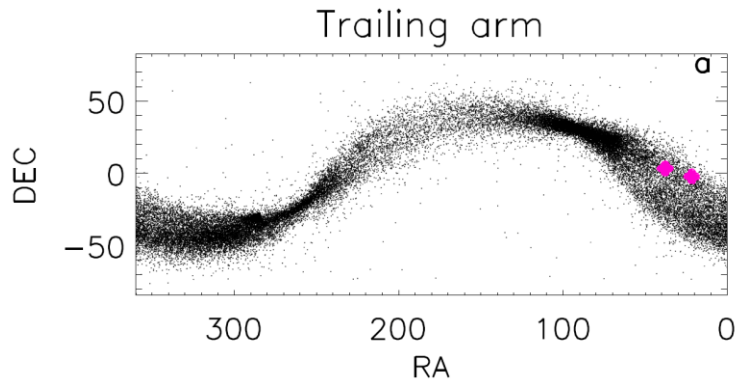
银盘附近的人马座星流

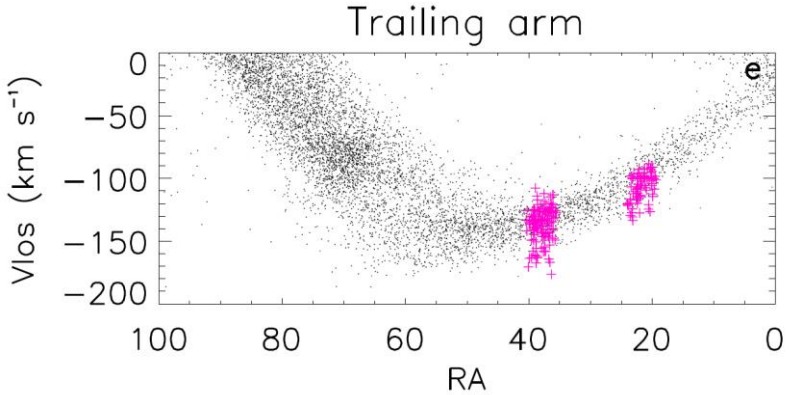
Zhao J. K. et al. 2020 ApJ

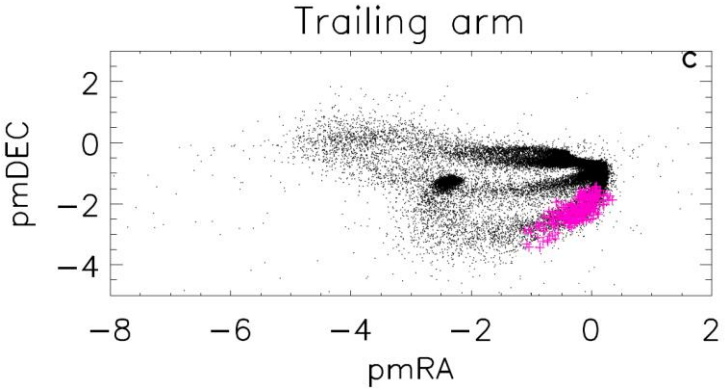
- LAMOST 南银冠40平方度完备天区+Gaia DR2测光和自行 ➔ ~1.4万恒星（2kpc<d<120kpc）
- 利用DBSCAN算法，在自行空间结合视向速度证认出106颗人马座星流成员星





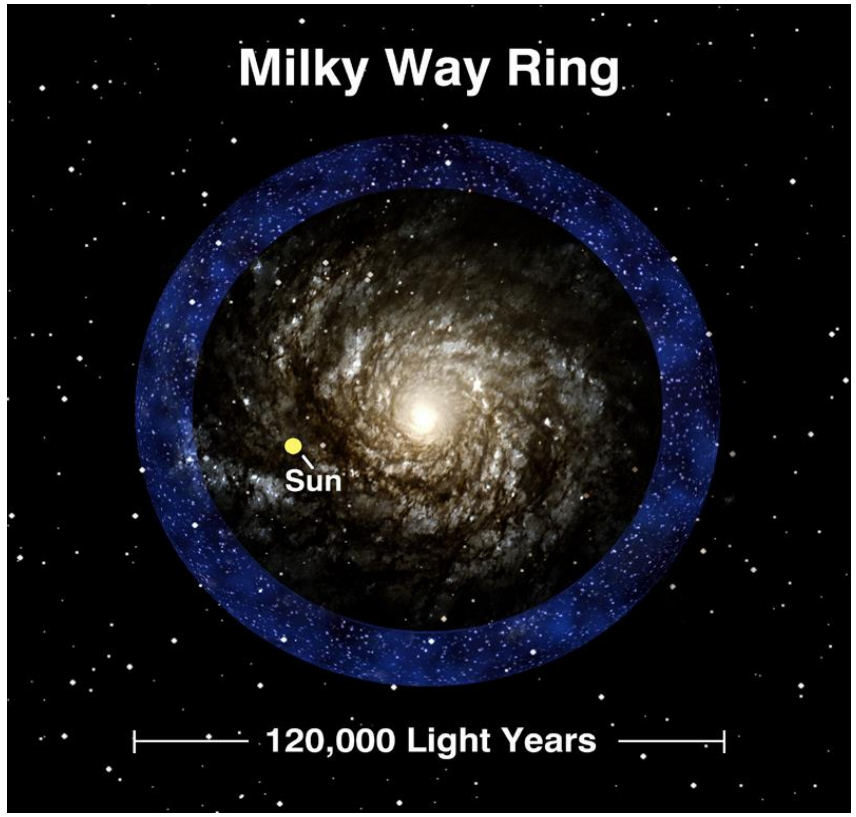


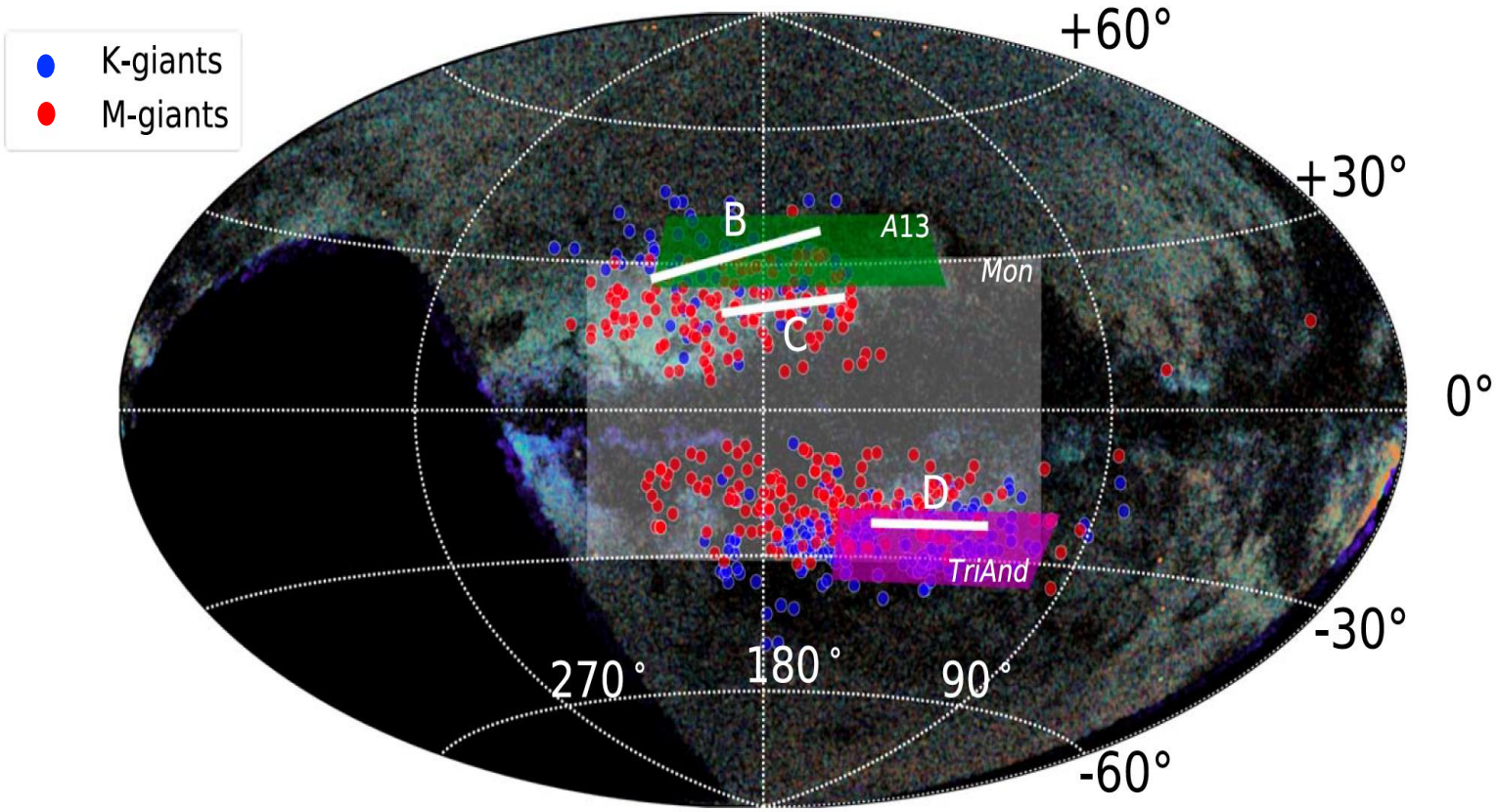




Li et al. 2021 ApJ

麒麟环的天区分布

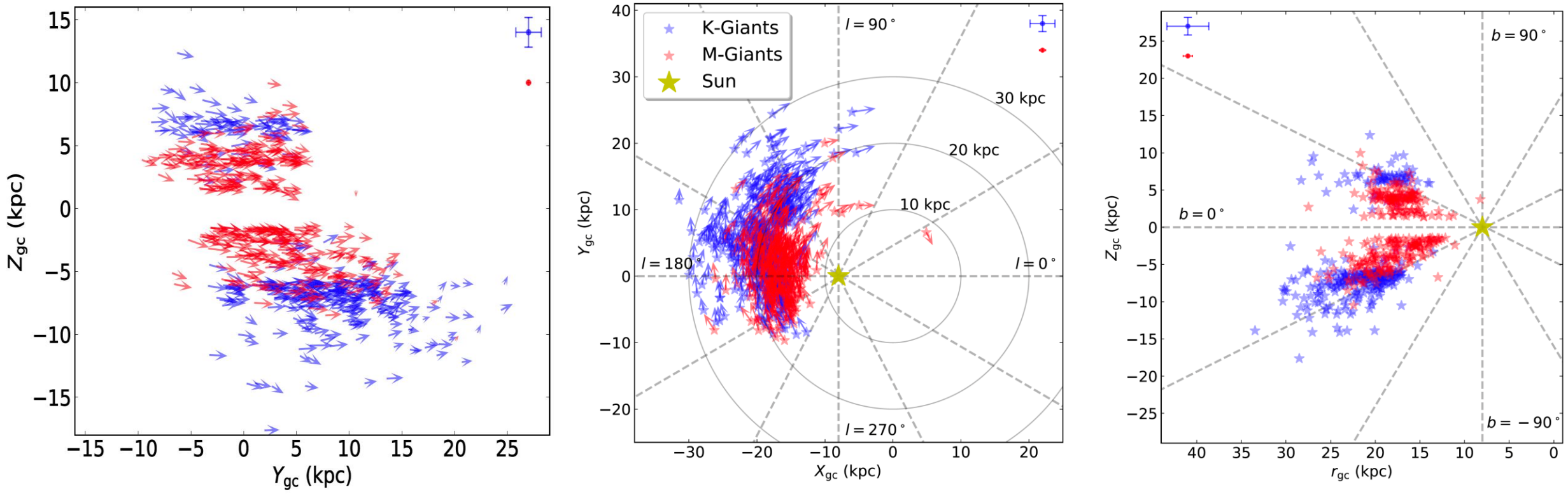




- LAMOST DR5 K巨星和M巨星+IoM空间证认 ➔ ~600颗麒麟环成员星（*Xue et al. to submit*）
- 天区背景图是Pan-STARRS主序拐点星的密度分布

麒麟环的3D运动和空间分布

Li et al. 2021 ApJ

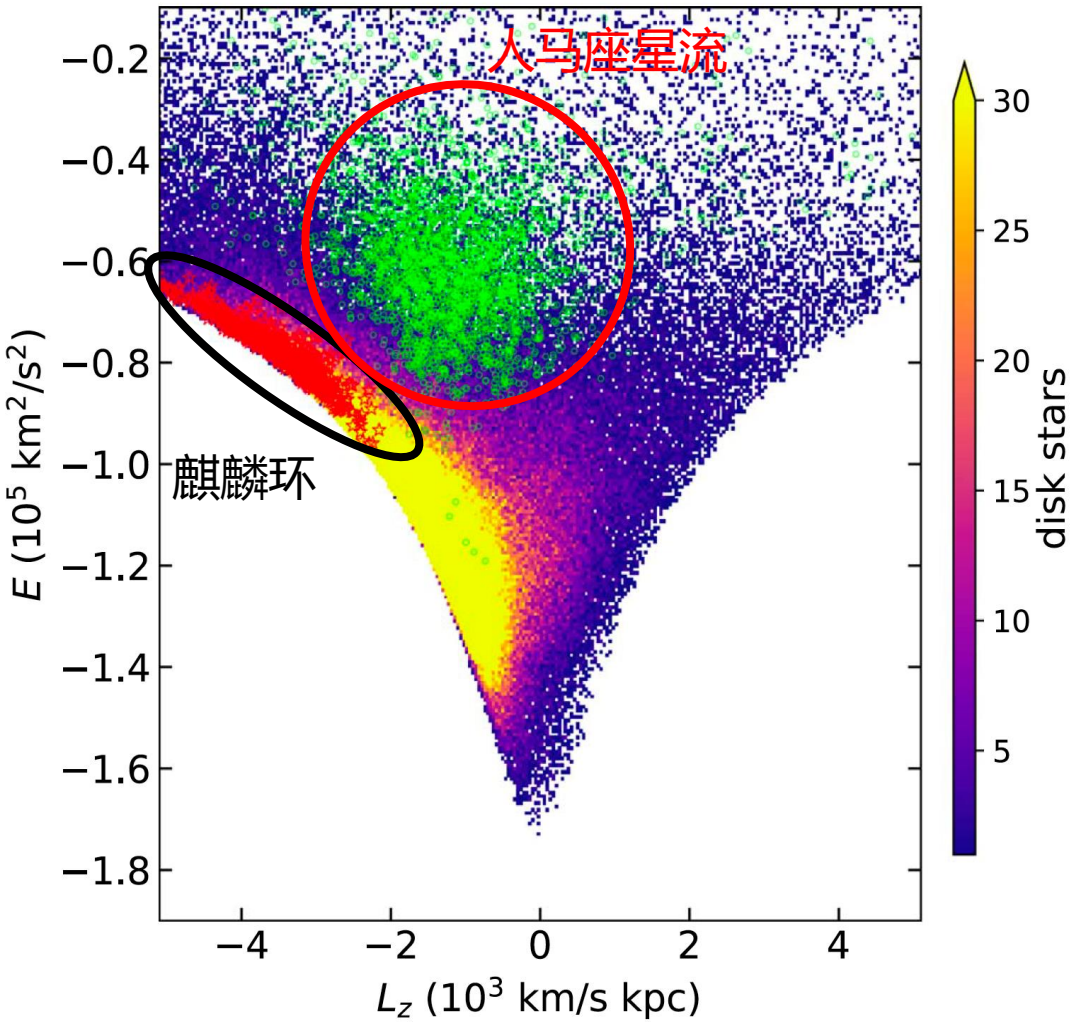


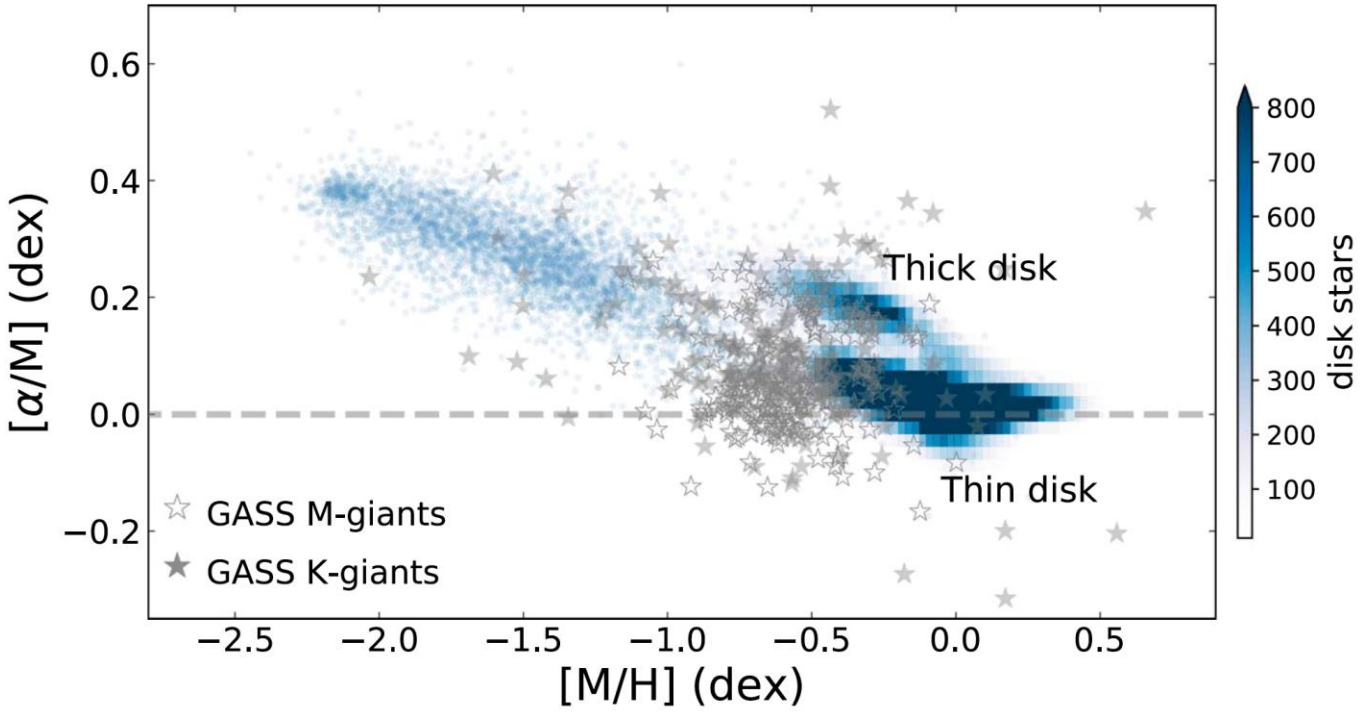
- 麒麟环在一个近圆轨道运动，Z方向高度可达15kpc，延银盘可至30kpc，呈现出南北不对称。

➔ 不对称结构与银盘的震荡结构有关，外盘可达30kpc

麒麟环的化学和动力学特征

Li et al. 2021 ApJ

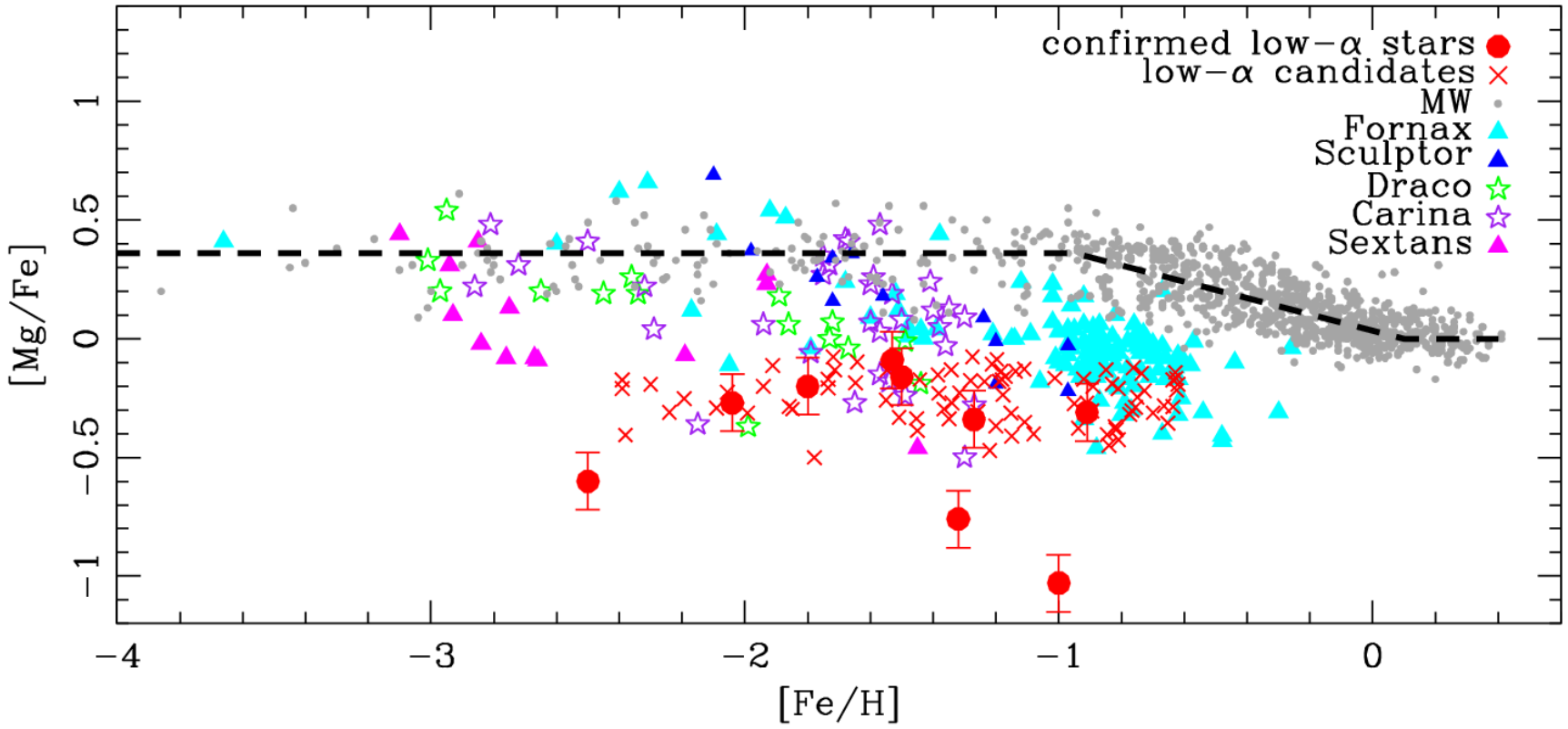




麒麟环的能量角动量分布类似薄盘，金属丰度比薄盘低，α丰度比厚盘低，是盘到晕的延伸。

化学空间搜寻“星系际移民”

Xing et al. 2015 ApJ, 2018 MN



利用LAMOST搜寻了92颗来自矮星系的低α晕星，是国际同类发现的2倍。

低α晕星占比：估计矮星系对银晕形成作出的物质贡献

低α晕星丰度模式：矮星系的化学演化

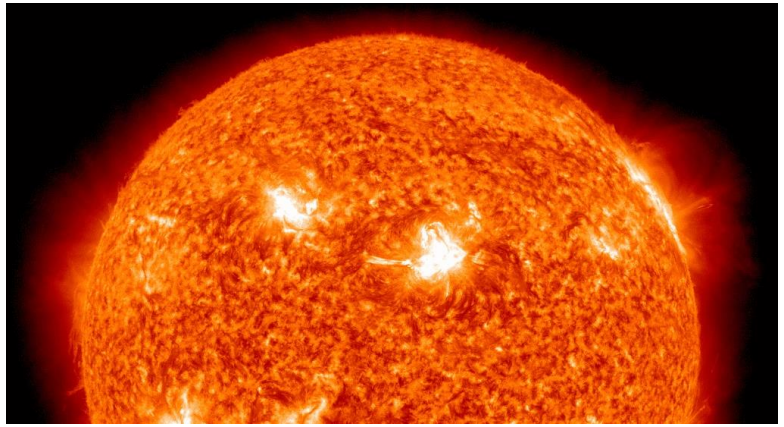
银河系内[Mg/Fe]最低的场星([Mg/Fe]=-1.1)：第一代超大质量恒星存在的化学证据

化学成分识别“星系际移民”

Xing et al. 2019 Nature Astronomy

它的化学成分与矮星系成员星高度吻合：源自被银河系瓦解的近邻矮星系！该矮星系经历了中子星并合！

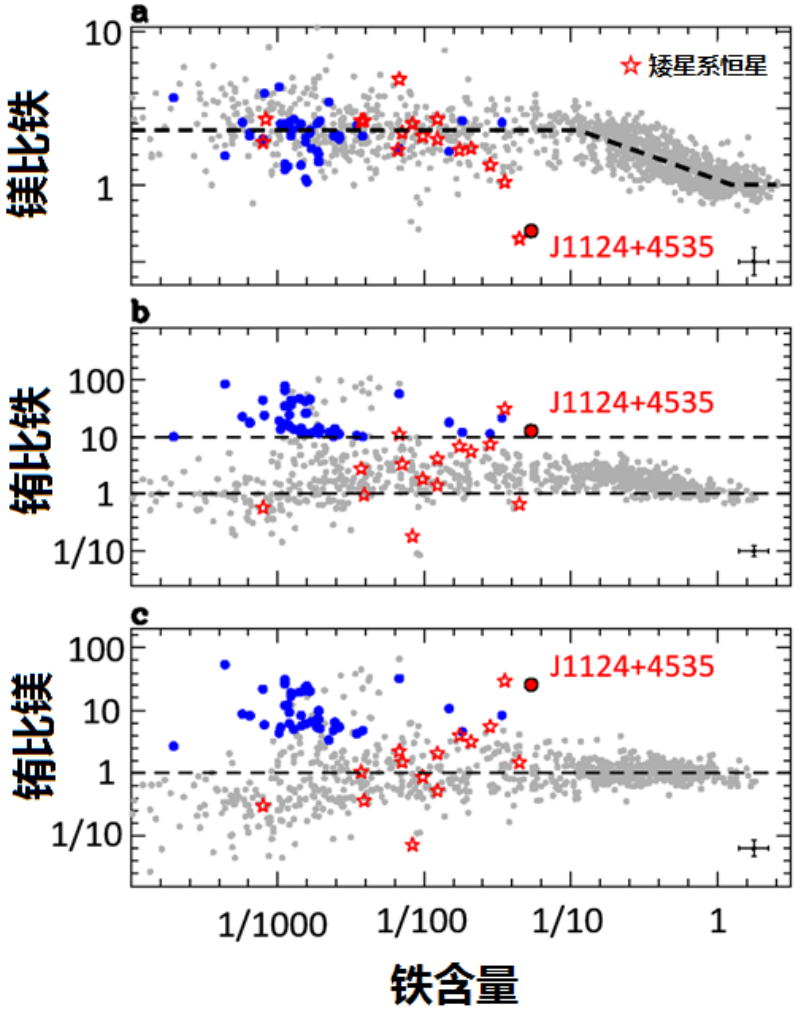
富有的“星系际移民”



快中子俘获过程元素相对于铁的比率是太阳的10余倍

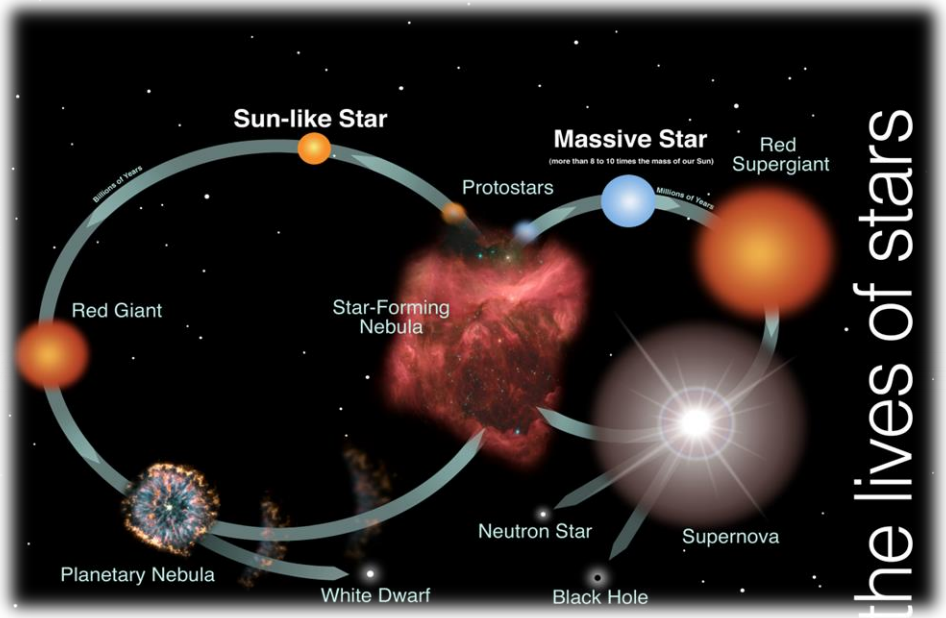
快中子俘获过程元素：铕(Eu), 金(Au),和铀(U)等重元素

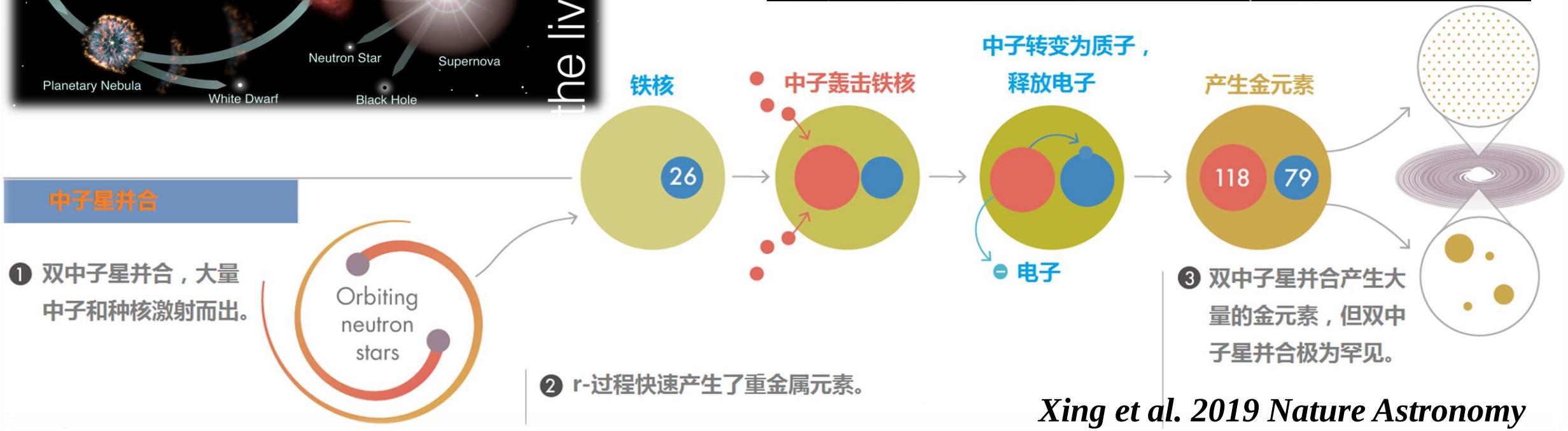
Xing et al. 2019 Nature Astronomy



基于LAMOST取得的进展

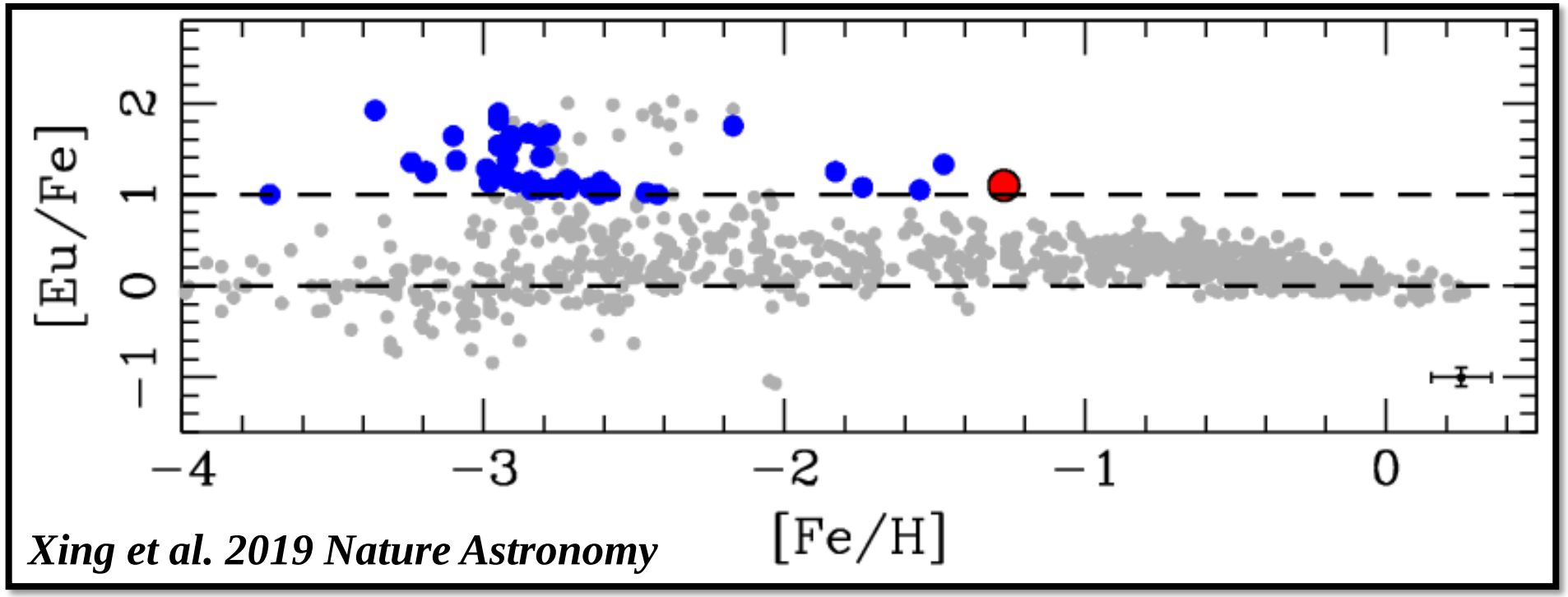
黄金的产生





Xing et al. 2019 Nature Astronomy

快中子俘获过程元素超丰与中子星并合的时间延迟



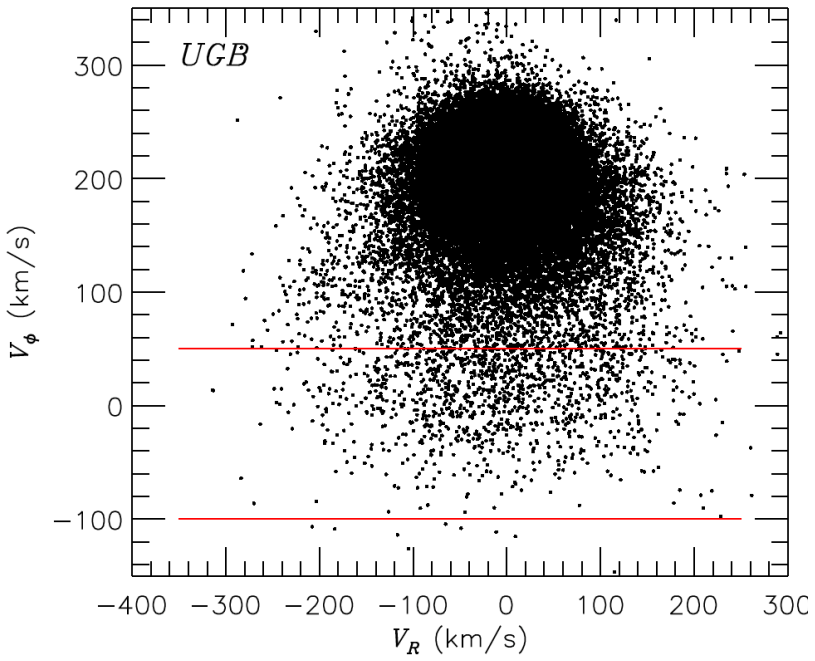
Xing et al. 2019 Nature Astronomy

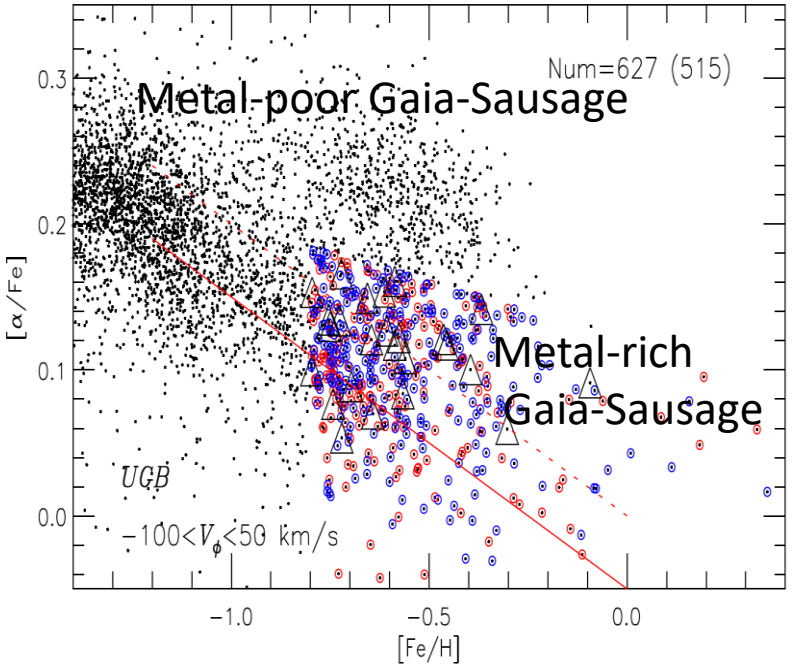
- 双中子星系统形成后，1亿-10亿年发生并合
- 极低的金属丰度与中子星并合的时间延迟间的矛盾！
- 快中子俘获过程元素超丰恒星有特殊的起源？ 来自矮星系！

化学-动力学空间寻找百手巨人失落的孩子

Zhao G. et al. 2021

- 利用LAMOST数据找到Gaia-Sausage-Enceladus的富金属成分（[Fe/H]>-0.8 dex），与已知的贫金属成分形成自然延续

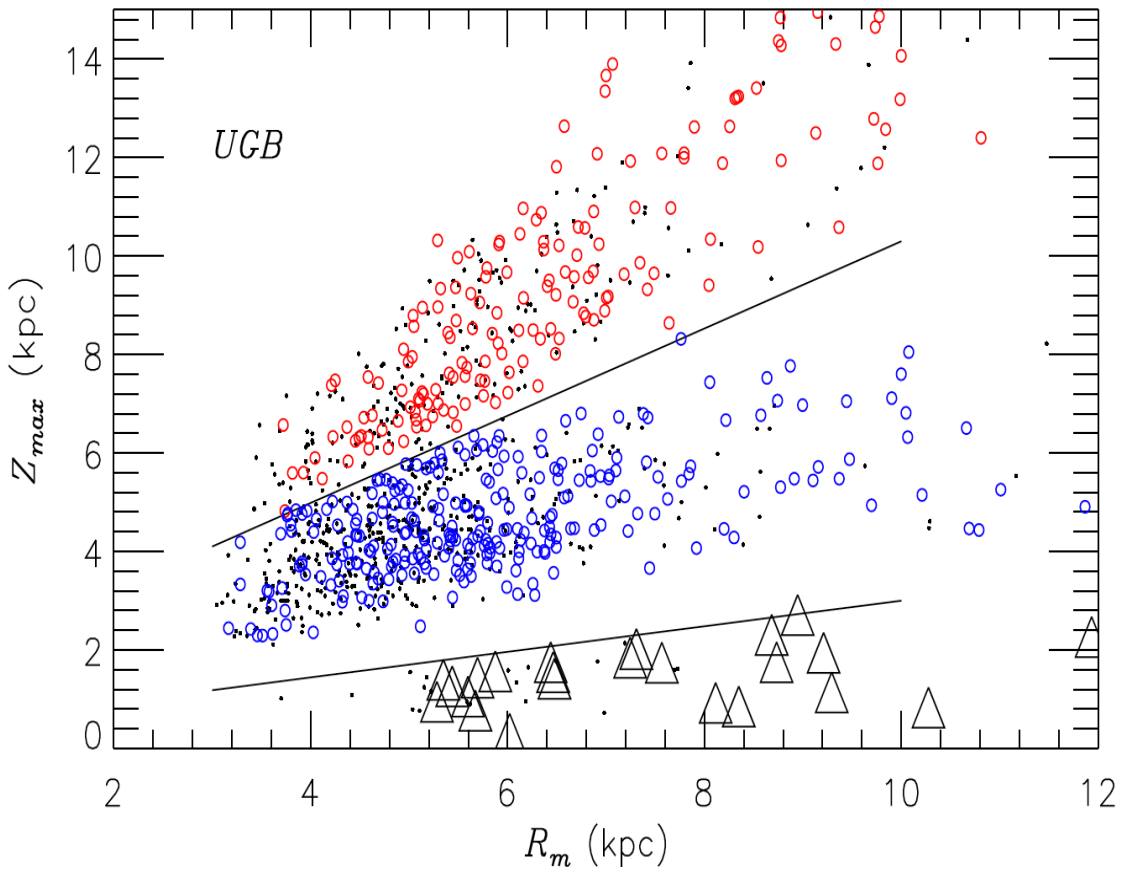


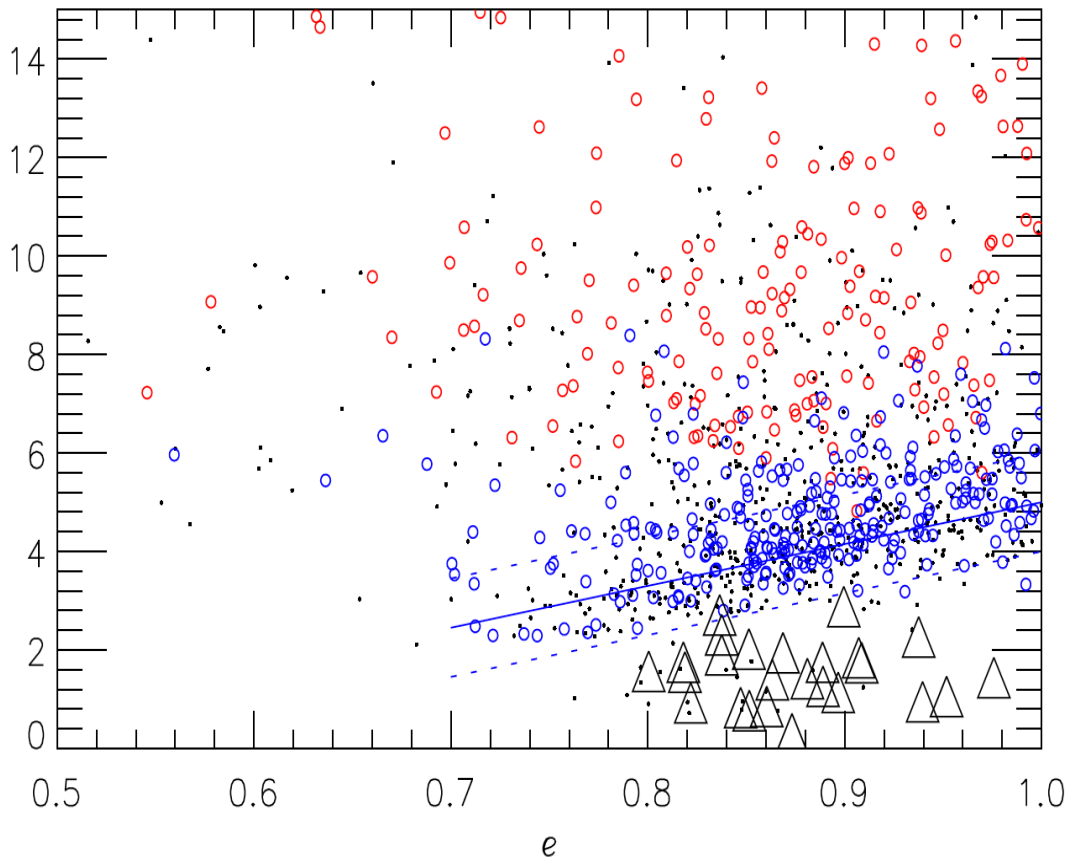


百手巨人失落的孩子造成晕盘分界

Zhao et al. 2021 SCPMA

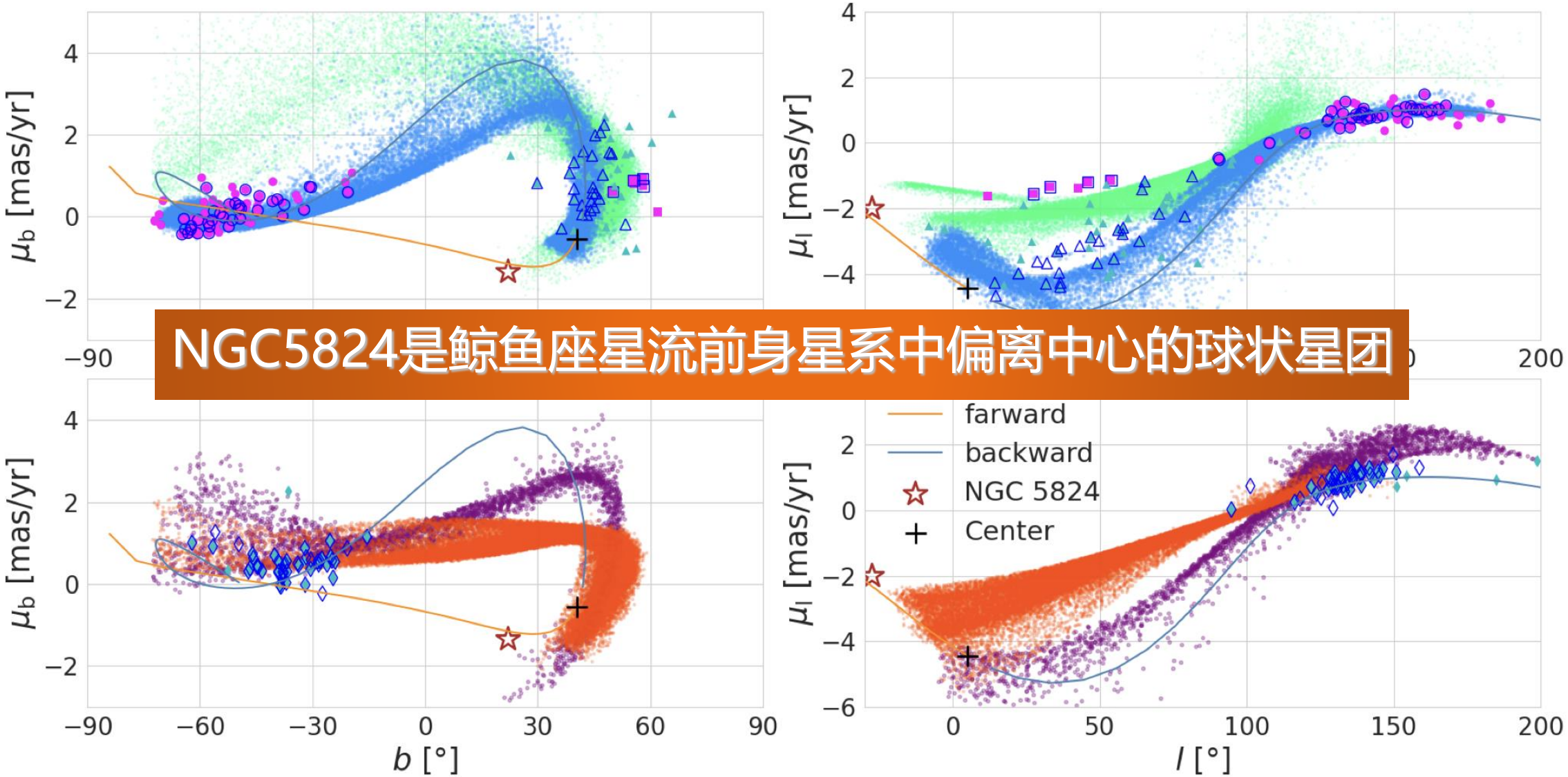
- 这些富金属成员星聚集在距离银盘4kpc处，形成银盘和银晕的分界





动力学追溯鲸鱼座星流的起源

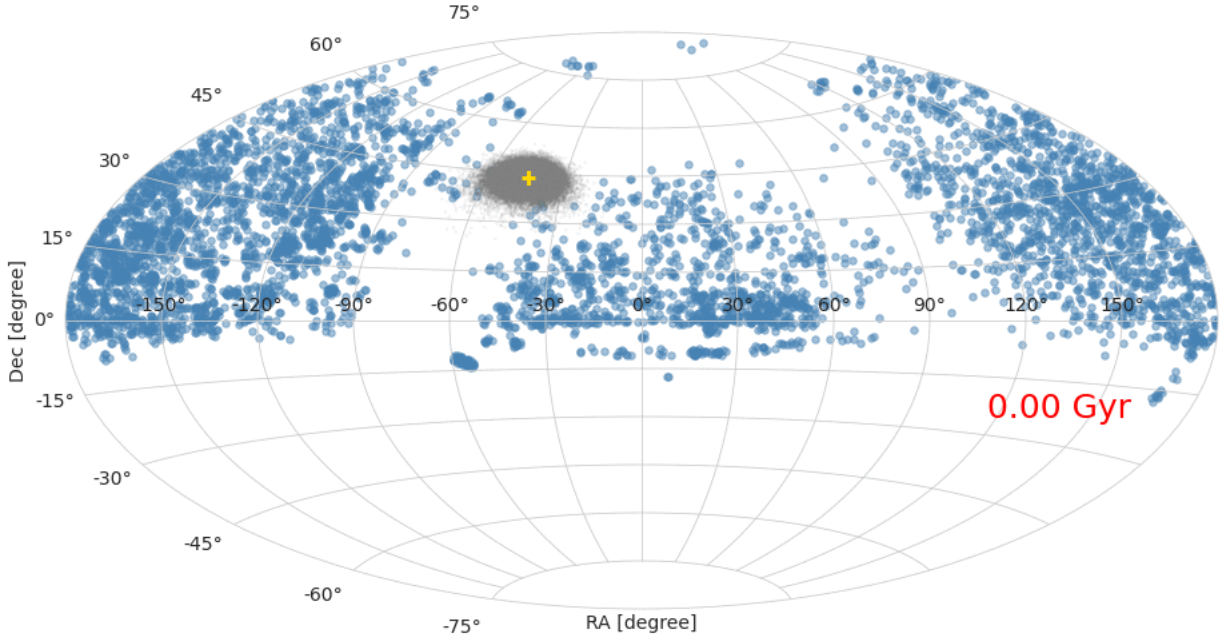
Chang et al. 2020 ApJ

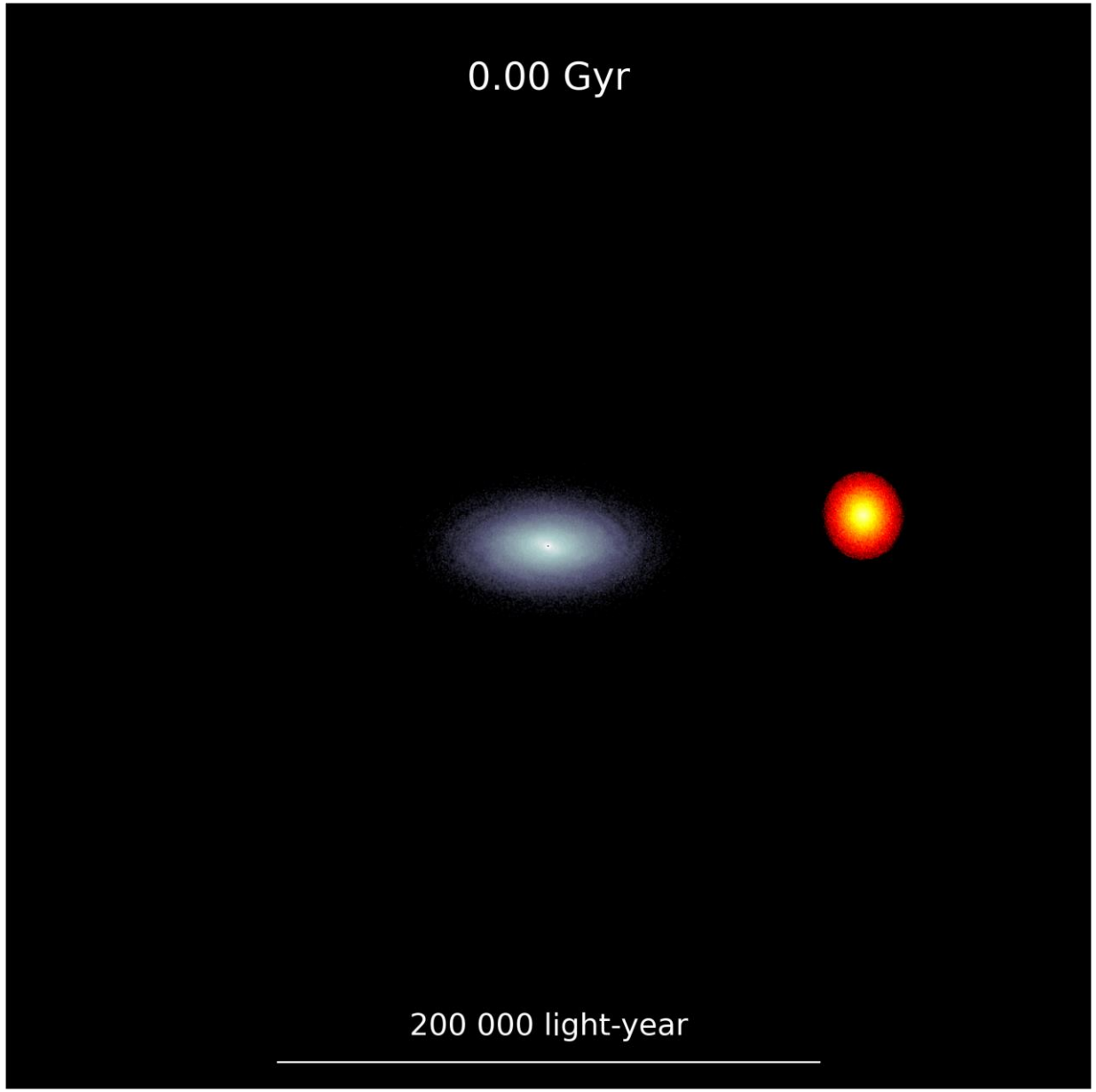


NGC5824是鲸鱼座星流前身星系中偏离中心的球状星团

基于LAMOST取得的进展

鲸鱼座星流形成过程数值模拟





Chang et al. 2020

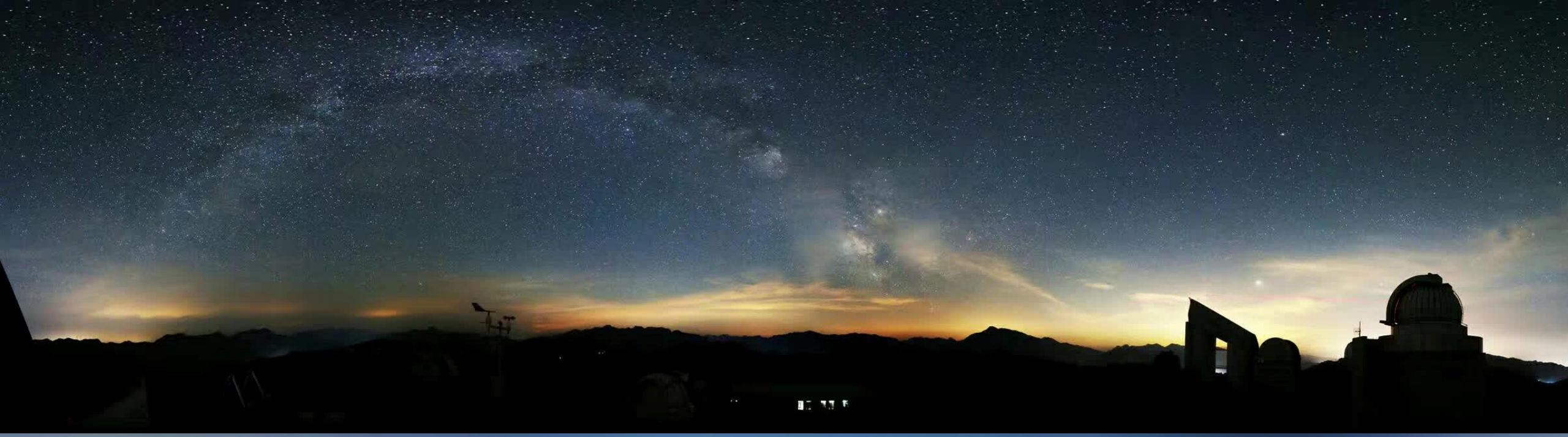
小结

利用LAMOST数据研究了处于不同演化阶段的吸积并合遗迹

1. 在太阳邻域发现7个新的移动星群，并利用大望远镜进行后随观测，证实银晕中的移动星群N1起源于矮星系。
2. 在遥远银晕中证认出7千多颗吸积并合遗迹成员星，并对其中的人马座星流、麒麟环等进行了细致的化学运动学分析，推断麒麟环属于盘的一部分。
3. 搜寻低alpha恒星，发现一颗重元素超丰的，揭示其起源于矮星系的双中子星并合过程。
4. 发现Gaia-Sausage-Enceladus是造成晕盘分界（4kpc）的物理原因。
5. 利用数值模拟重现了鲸鱼座星流，确定NGC5824是其前身星系中偏离中心的球状星团。

展望

- 正在开展的SDSS-V是第一个全天均匀的光谱巡天（H<13, i<20）。
- Subaru主焦点深度巡天PFS（i~22.3）计划于2023年开始巡天，将对银河系、M31和近邻矮星系中约1百万恒星进行光谱观测。
- 我国巡天空间望远镜 CSST计划于2024年开始巡天，将对近场宇宙开展多波段深度测光巡天（r~26）和无缝光谱巡天（r~23）。
- 以上大规模巡天项目将观测更深更广的海量恒星，提供史无前例的精确的化学-运动学参数，我们将能够对全天分布的并合遗迹开展研究，探测更暗的银河系星流，研究M31的并合等。



谢谢！

gzhao@nao.cas.cn