Dynamical Origin for the Collinder 132-Gulliver 21 Stream:
A Mixture of three Co-Moving Populations with an Age Difference of 250 Myr

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(Received July 23, 2022; Revised August 27, 2022; Accepted August 30, 2022)

Submitted to ApJL

arXiv:2208.14456

ABSTRACT

We use Gaia DR 3 data to study the Collinder 132-Gulliver 21 region via the machine learning algorithm StarGO, and find eight subgroups of stars (ASCC 32, Collinder 132 gp 1–6, Gulliver 21) located in close proximity. Three co-moving populations were identified among these eight subgroups: (i) a coeval 25 Myr-old moving group (Collinder 132); (ii) an intermediate-age (50–100 Myr) group; and (iii) the 275 Myr-old dissolving cluster Gulliver 21. These three populations form parallel diagonal stripe-shape over-densities in the U–V distribution, which differ from open clusters and stellar groups in the solar neighborhood. We name this kinematic structure the *Collinder 132-Gulliver 21 stream*, as it extends over 270 pc in the 3D space. The oldest population Gulliver 21 is spatially surrounded by the Collinder 132 moving group and the intermediate-age group. Stars in the Collinder 132-Gulliver 21 stream have an age difference up to 250 Myr. Metallicity information shows a variation of 0.3 dex between the youngest and oldest populations. The formation of the Collinder 132-Gulliver 21 stream involves both star formation and dynamical heating. The youngest population (Collinder 132 moving group) with homogeneous metallicity is probably formed through filamentary star formation. The intermediate-age and the oldest population were then scatted by the Galactic bar or spiral structure resonance to intercept Collinder 132's orbit. Without mutual interaction between each population, the three populations are flying by each other currently and will become distinct three groups again in approximately ~50 Myr.

arXiv:2208.14456

Introdution

Formation mechanism

1. stochastic transient spiral waves： heat up the disk and generate moving groups.
   - produces horizontal velocity components along the Galactic disk
2. resonances：
   - horizontal branch/arch of constant V in the U –V space,
3. external perturbation： triggered by a minor merger event。
   - produces vertical phase mixing

- Collinder 132 host two populations （Clari´a (1977); Eggen (1983).
- Collinder 132 to be a coeval moving group extending 197 pc with an age of 25 Myr. Kounkel & Covey (2019)）
- in the same sky region, Gulliver 21 with age of 275 Myr.

> As no investigation has been made for Collinder 132 and Gulliver 21 yet, whether or not this older cluster, Gulliver 21, is associated with Collinder 132 moving group is still unknown. If an association exists, the origin of this moving group can be further constrained by the dynamical formation mechanism.

- 利用Gaia DR 3的运动学数据来研究Ccollider 132 moving group与Gulliver 21之间可能的联系
- 二者的运动学关系将为moving group的形成和演化提供强有力的观测约束。

Data

Table 1. General properties of eight subgroups in the Collinder 132-Gulliver 21 stream

Cluster	R.A. (deg)	Decl. (deg)	Dist. (pc)	X_c (pc)	Y_c (pc)	Z_c (pc)	RV (km s^{-1})	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	Age (Myr)	M_{cl} ($M_\odot$)	r_h (pc)	r_t (pc)	N
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
ASCC 32	105.730278	−26.449193	795.2	−416.7	−664.6	−130.3	32.4	−3.228	3.475	25	577.6	17.4	11.7	519
Collinder 132 gp 1	108.870127	−31.069356	655.1	−287.8	−579.4	−103.2	21.7	−4.227	3.756	25	144.4	28.7	7.3	142
Collinder 132 gp 2	107.042730	−25.625351	689.6	−364.9	−576.7	−98.7	28.0	−3.916	3.617	25	362.7	28.2	10.0	385
Collinder 132 gp 3	107.437642	−25.401309	602.2	−316.9	−506.1	−78.4	26.1	−4.949	3.749	25	121.1	15.2	6.9	123
Collinder 132 gp 4	107.181518	−30.328868	789.1	−365.5	−686.4	−133.9	30.3	−3.417	3.407	25	68.4	14.6	5.7	58
Collinder 132 gp 5	107.638309	−27.792975	599.4	−297.3	−513.2	−87.3	37.9	−3.231	6.356	50	53.1	9.0	5.3	56
Collinder 132 gp 6	111.643982	−30.322059	615.6	−270.2	−548.8	−69.8	34.1	−4.354	6.113	100	39.5	15.5	4.8	40
Gulliver 21	106.972407	−25.450964	648.7	−345.0	−542.1	−89.4	39.8	−1.907	4.214	275	176.5	9.3	7.9	173

NOTE— Columns 2–10 list the median values of the subgroup member properties. R.A. and Decl. are the right ascension and declination. Dist. is the corrected distance. X_c, Y_c, and Z_c are the positions of each subgroup in heliocentric Cartesian coordinates after distance correction. RV is the radial velocity. $\mu_\alpha \cos\delta$ and μ_δ are the components of the proper motion. The age of each subgroup is derived from PARSEC isochrone fitting (Figure 1). $M_{\rm cl}$ is the total mass of each subgroup. $r_{\rm h}$ and $r_{\rm t}$ are the half-mass radius and the tidal radius of each subgroup, respectively. The tidal radius is computed using Equation (12) in Pinfield et al. (1998). N is the total number of members in each subgroup.

Age and Metallicity Difference

在8个subgroups中根据明显的年龄差异分成3个group

1. Collinder 132 moving group：包含5个subgroup为ASCC 32, Collinder 132 gp 1–4, 年龄为25Mry。
   - [M/H]~ –0.32
2. Collinder 132 gp 5–6：年龄50-100Myr。
   - [M/H]~ –0.24
3. Gulliver 21：275Myr。
   - [M/H]~ –0.09

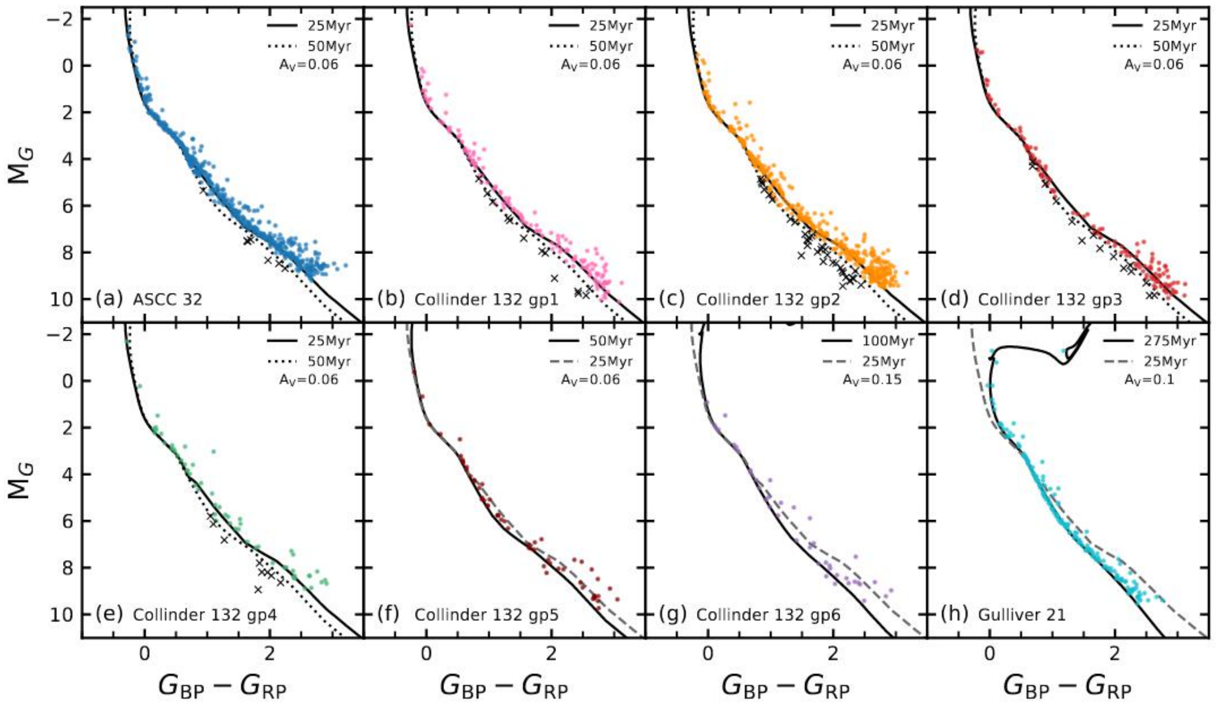


Figure 1. Absolute magnitude CMDs (with M_G adopting Gaia DR 3 parallaxes) for member stars obtained from Gaia DR 3. The colored dots in each panel represent the corresponding member candidates in each subgroup. Black crossed symbols are field stars that are excluded from further investigation (see Section 3.1). The PARSEC isochrones of the best fitted age are indicated with the black solid curves, with solar metallicity and estimated A_V. The black dotted curve is isochrone of 50 Myr, with solar metallicity and A_V=0.06. The grey dashed curves in (f)–(h) are 25 Myr isochrones for comparison.

Velocity Distribution Features

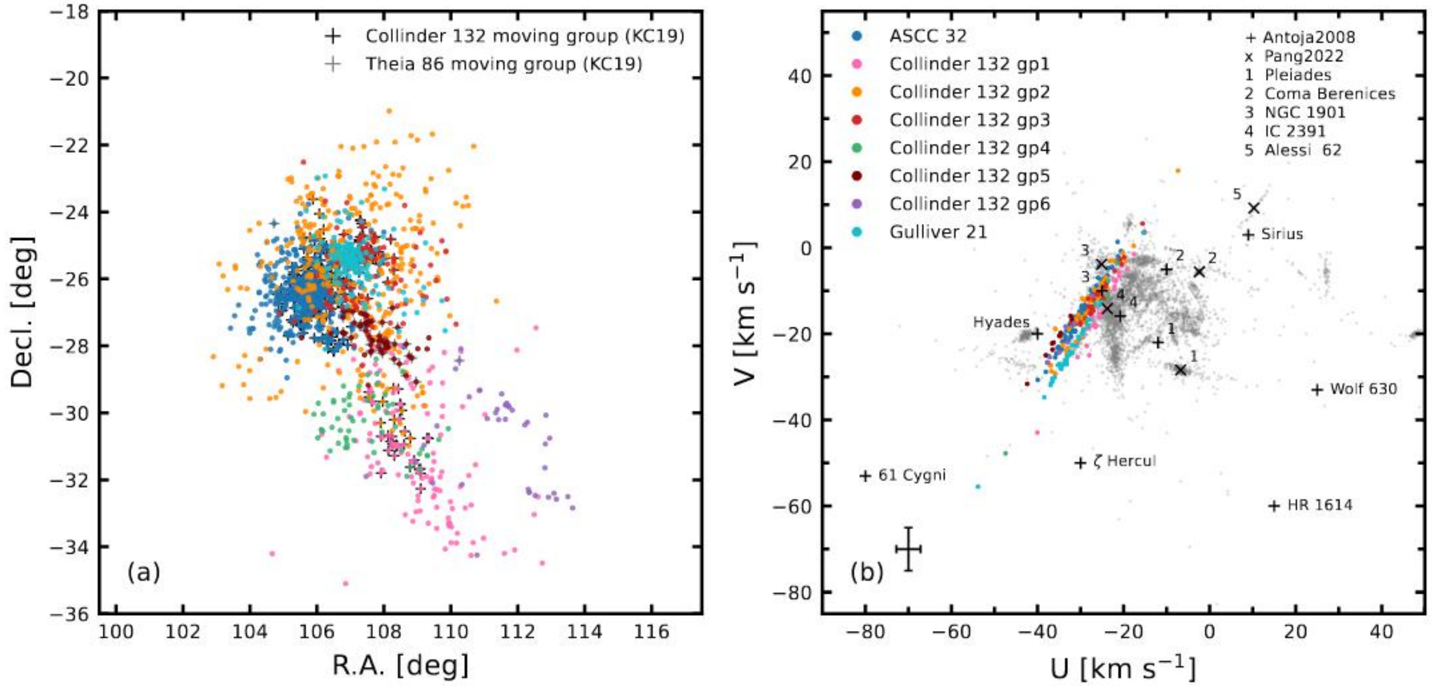


Figure 2. (a) Projected spatial distribution of member candidates. Cross-matched members with the Collinder 132 moving group in Kounkel & Covey (2019, KC19) are indicated by the black plus symbols. Matched stars with Theia 86 moving group in KC19 are shown as grey plus symbols. (b) The U–V velocity distribution for eight subgroups in the Collinder 132-Gulliver 21 region obtained from this study. Members of these eight subgroups are shown as colored dots. The mean errors of U and V are indicated in the bottom-left corner.

- tight correlation _x000F_between U-V
- form parallel diagonal stripes with identical slopes in the U –V plane
- kinematic structure is similar to the 692 Myr-old dissolving cluster Alessi 62

Collinder 132-Gulliver 21 stream

Characteristics

Spatial Distribution

- extend 270pc
- 接近Local Arm center
- 年老的group被其余两个group环绕
- ASCC 32, Collinder 132 gp 1–4)：filamentary-type (Pang 2022a)

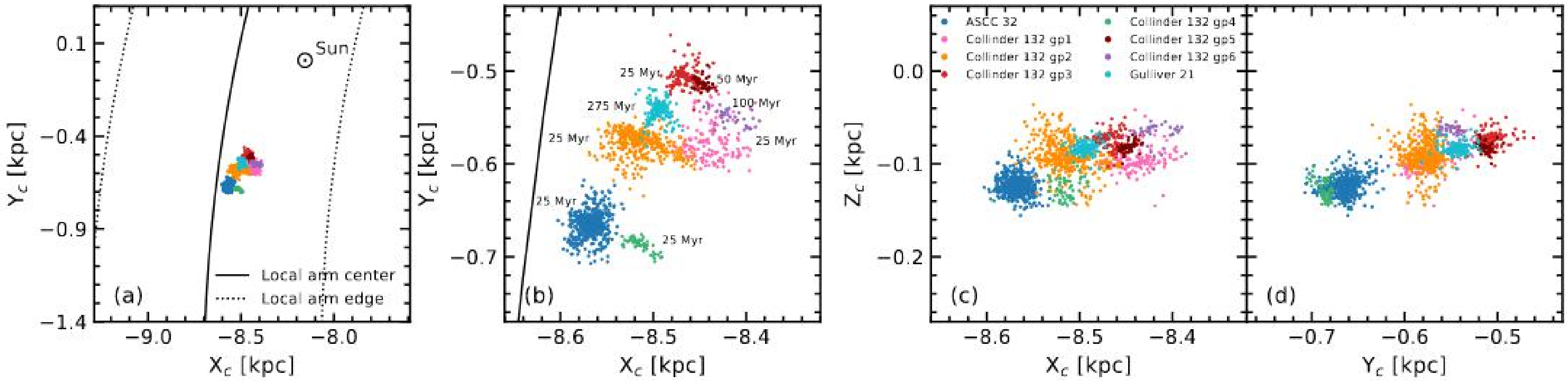


Figure 3. 3D morphology of the Collinder 132-Gulliver 21 stream in Galactocentric Cartesian coordinates after distance correction via a Bayesian approach (Pang et al. 2021a). The black solid curve represents the Local Arm center, and the Local Arm edge is denoted as the black dotted curve. The position of the Sun is taken at $(X, Y, Z) = (\mathbf{-8150,\ 0,\ 5.5})$ **pc** (Reid et al. 2019). The age of each subgroup is indicated in panel (b) to show that the oldest population is surrounded by young populations.

Dynamical origin

Fig （a）
- 紫红色指向西：young Collinder 132 moving subgroups
- 蓝色：50Myr的group。
- 粗箭头：Gulliver 20 的成员星。

Fig （b）：
- Gulliver 21 is passing through the Collinder 132 moving groups
- intermediate-age group move toward Gulliver 21's orbit

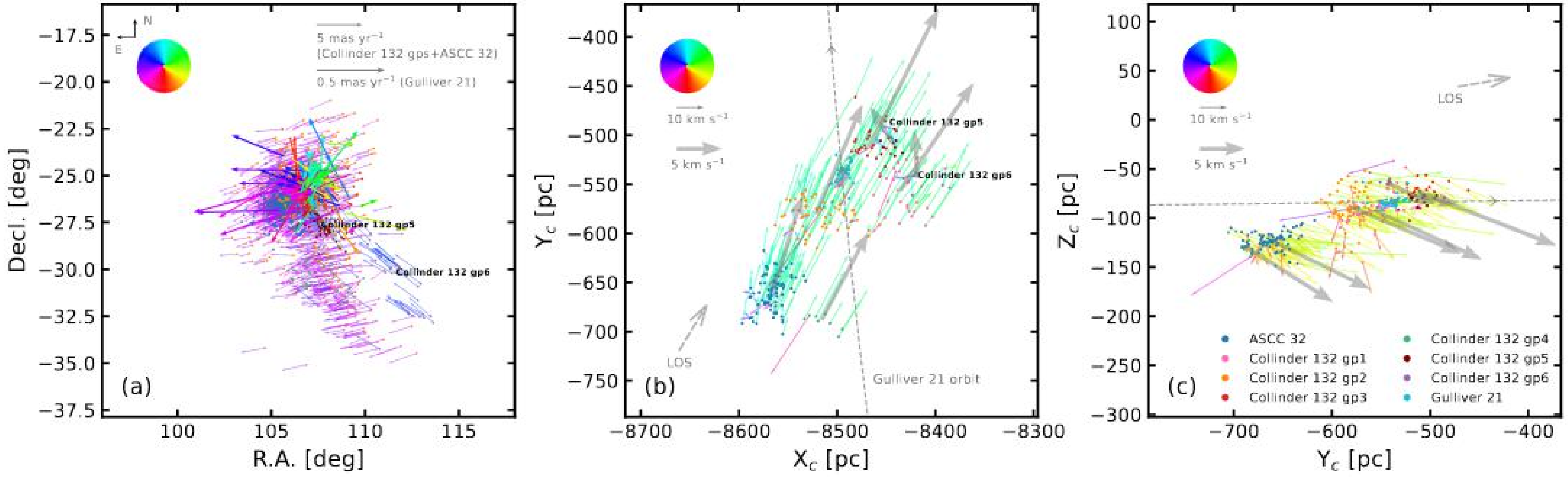


Figure 5. (a) The relative PMs of member candidates. All PM vectors are relative to the median PM of Gulliver 21. The vectors of Gulliver 21 members are thicker and are using different scaling than those for other groups (upper-right corner). (b)–(c) The relative 3D velocity vectors for members, projected onto the X–Y and Y–Z planes. The median motion of Gulliver 21 is taken as the reference. We only show velocity vectors for stars with S/N>20 in RV, of which the mean error is 5.8 $\mathrm{km\,s^{-1}}$. The large thick grey arrows represent the mean velocity of each subgroup relative to that of Gulliver 21, whose scaling is indicated in the upper-left corner (grey arrow)

- 现在余下7 subgroups离Gulliver 21最近的时候
- Collinder 132-Gulliver 21 stream是轨道重叠形成的
- 50Myr后Collinder 132 gp 5-6 以及Collinder 132将远离Guliver20

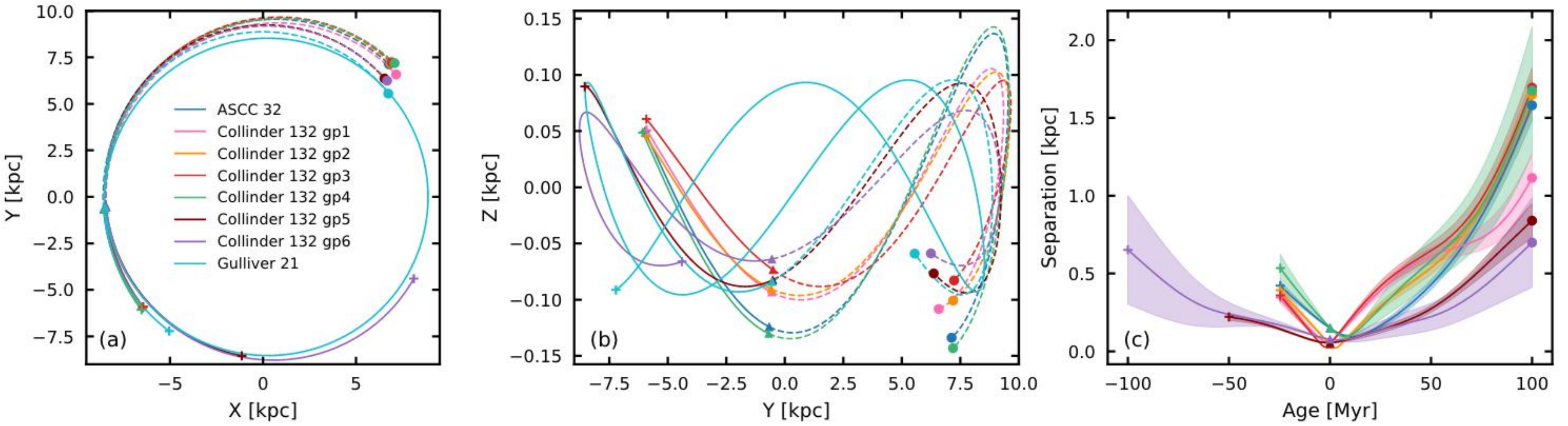


Figure 6. (a)–(b) Past and future 100 Myr integrated orbits of the eight subgroups in the Collinder 132-Gulliver 21 stream using Galpy. (c) Evolution of the separation between seven subgroups and the oldest population, Gulliver 21. The $\pm 1\sigma$ uncertainty interval computed from observational errors in the PM and RV is indicated with the shaded areas. An age of 0 Myr corresponds to the present day. The colored plus symbols in the three panels indicate the positions of the corresponding subgroups at the time of birth. The triangles represent the present-day positions, and the filled circles indicate the predicated positions at 100 Myr from the present.

- 加号表示形成时的位置
- 三角形表示现在的位置
- 圆：100Myr后的位置

Resonance Scenario

- Gulliver 21和Conllider 132 gp5、6 可能分散到Collider 132的位置。
- 随后fly-by，并在大约20Myr前形成了collider 132-Gulliver 21 stream。
- 50Myr后，轨道将再次分离。_x000F_

Phase-mixing Scenario

- the perturbation occurred 500～700 Myr ago,
- 但是先前的扰动激发了horizontal phase mixing，影响了盘上的恒星运动。
- 3个星团group的horizontal phase mixing导致了stream的形成

Summary

1. Eight subgroups are divided into three co-moving populations:
   - 25 Myr: Collinder 132 moving (ASCC 32, Collinder 132 gp 1–4)
   - 50–100 Myr: Collinder 132 gp 5–6
   - 275 Myr:Gulliver 21
2. In U –V velocity distribution, three populations stands out as parallel diagonal stripes, following a tight U –V correlation.
3. All three co-moving populations are gravitationally unbound, and are undergoing disruption.
4. The Collinder 132-Gulliver 21 stream has a dynamical origin。
   - Collinder 132 moving group was born in the spiral arm from filamentary star formation in its natal GMC
   - Galactic bar and spiral structure resonance may then have scattered Gulliver 21 and the Collinder 132 gp 5–6 towards the location of the Collinder 132 moving group.
   - After 50 Myr, the stream wil start separate

补充

transient spiral waves

- transient spiral waves
  - Sellwood & Binney (2002)首次提出由短暂的旋臂密度波会导致恒星的径向迁移。同样的机制也适用于星团，并且对它们没有破坏性，因为星团的内部cross time远比它们通过螺旋密度波所需的时间短(Gieles等人。2007年）。
  - 靠近旋臂的单个螺旋波可以在没有显著加热的情况下扰动角动量20%，使物体从一个圆形轨道移动到另一个圆形轨道
  - 多个旋臂的作用将导致随机运动。物体的角动量变化将持续几个Gyr。
  - 相反，长期的旋臂不会产生净效应，物体进入时与离开时的扰动抵消了。

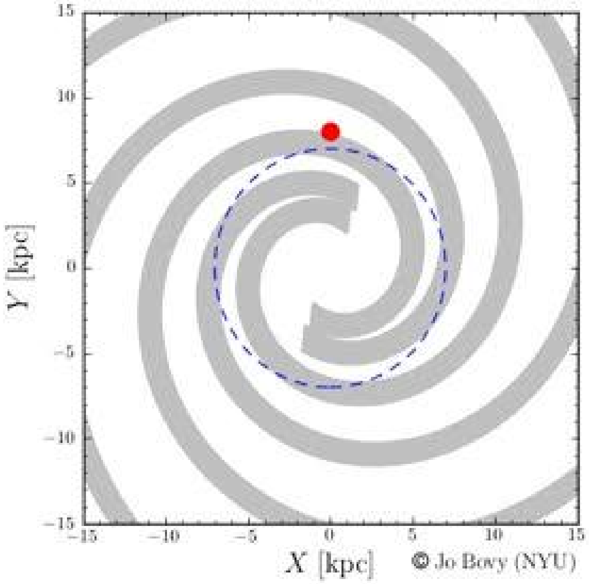
Lindblad resonance

- 在距离星系中心一定距离的星系盘中，能影响到恒星的共振。
- 当恒星在其轨道上运动的径向分量(即中心方向的内外分量)的固有频率与恒星通过passage时的与spiral pattern相关的引力势最大值的频率相同时，就会发生这种现象。
- 如果恒星绕中心运动的速度快于并超过spiral pattern的速度，那么就会发生inner Lindblad resonance。反之则为outter Lindblad resonance

Lindblad resonance

QUICK REFERENCE

A resonance that can affect stars in a galaxy's disk at certain distances from the galaxy's centre. It occurs when the natural frequency of the radial (i.e. in and out in the direction of the centre) component of motion of a star in its orbit is the same as the frequency of passage of the star through the maxima of the gravitational potential associated with the spiral pattern. If the star is moving around the centre faster than, and overtakes, the spiral pattern, then an inner Lindblad resonance occurs; if the pattern is moving faster than the star around the centre, then an outer Lindblad resonance occurs. At an inner resonance, energy is fed into the orbits of the stars from the spiral pattern, and vice versa at an outer resonance. The effect is named after B. Lindblad.



space type（Pang2022）

1. **Filamentary (f1-type)**: young clusters (groups) <100 Myr with uni-directional filaments that is mostly elongated along one direction.
2. **Fractal (f2-type)**: young clusters (groups) <100 Myr with multi-directional fractal substructures.
3. **Halo (h-type)**: clusters with age >100 Myr having a compact core but show some low-density stars spread out in the outskirt.
4. **Tidal-tail (t-type)**: clusters older than 100 Myr show uni-directional tidal tails.

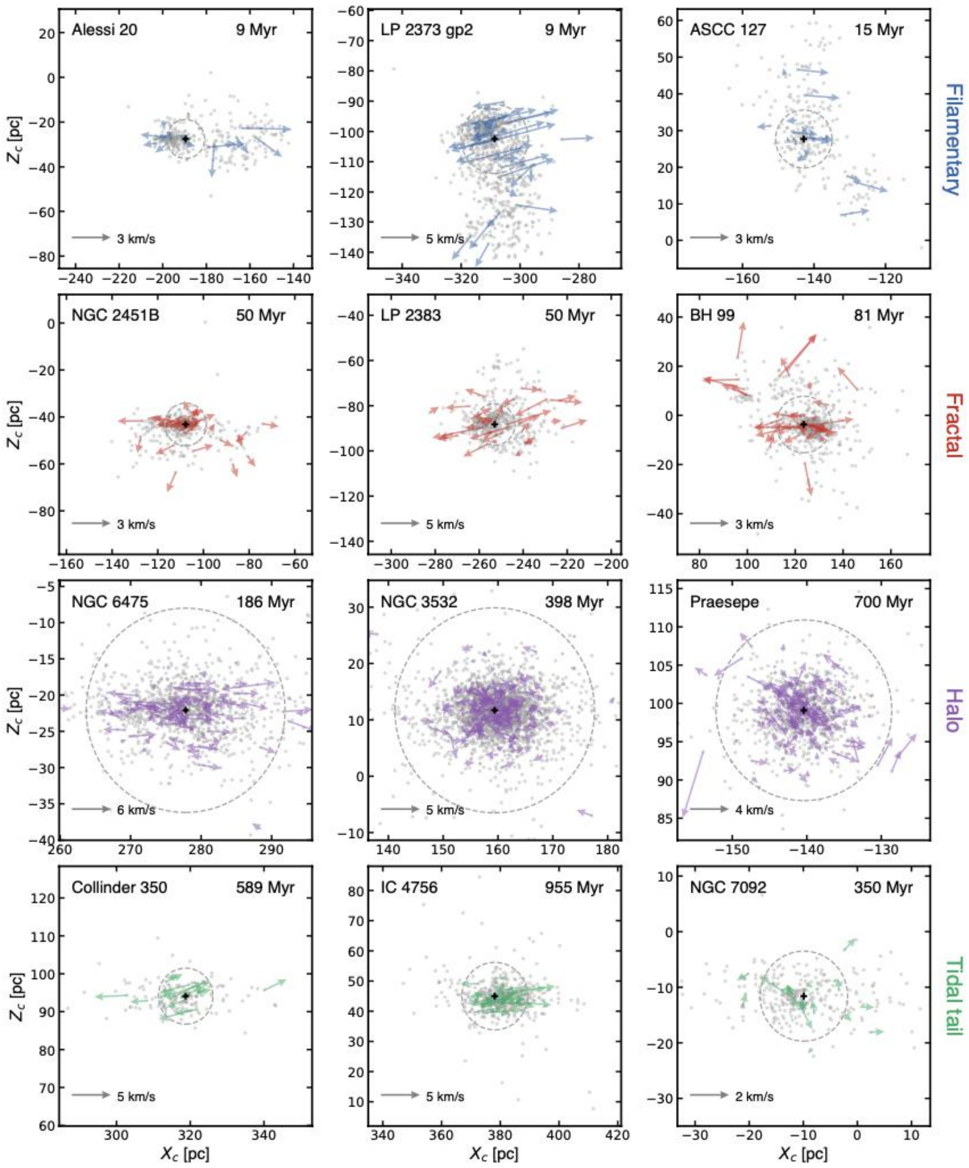


Figure 9. The relative 3D velocity vectors projected onto the X-Z plane, for members of the example clusters in Figure 5. The median value of each cluster is taken as the reference. The grey dashed circle represents the tidal radius of each cluster or group. Only 3D velocities within 3 median absolute deviation from the median value are shown. Colors are identical to those in Figure 5.

distance correction

Carrera 2019

- 后验分布
  $f(d|\varpi) = f(\varpi|d) * \Pi(d)$
  - $f(\varpi|d) = \frac{1}{\sqrt{2\pi}\sigma_\varpi} e^{-(\varpi - \frac{1}{d})^2/2\sigma_\varpi^2}$
    - 假设plx是Guassian分布，其中σ_ϖ:测量的plx误差
    - $\frac{1}{d}$:待测，撒点
  - $\Pi(d) = \alpha P(d) + (1-\alpha)\frac{1}{\sqrt{2}\sigma_d} e^{-(d-d_0)^2/2\sigma_d^2}$
  - $P(d) = \frac{1}{2L^3} d^2 e^{-d/L}$, for $d > 0$ L=8kpc
    - α:场星的概率
    - d_0:星团中心
    - σ_d:成员星到星团中心的距离的弥散
      - 视差倒数做为距离
      - 所有成员星用相同的距离
      - （视差倒数做为距离+相同的距离）/2

- Moving groups ： co-moving stars that typically extend from a few hundred parsecs to a few kiloparsec in space.
- Formation：
  - originate from disolving cluster
  - form simultaneously in the same (GMC)
- formation mechanism of non-coeval moving groups
  - stochastic transient spiral waves： heat up the disk and generate moving groups. produces horizontal velocity components along the Galactic disk
  - resonances：
  - external perturbation： triggered by a minor merger event。
    - produces vertical phase mixing