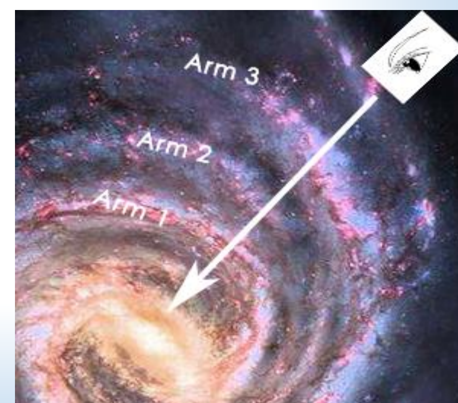

银河系旋臂结构
徐 烨
2023.03 北京

银河系真正的图像？

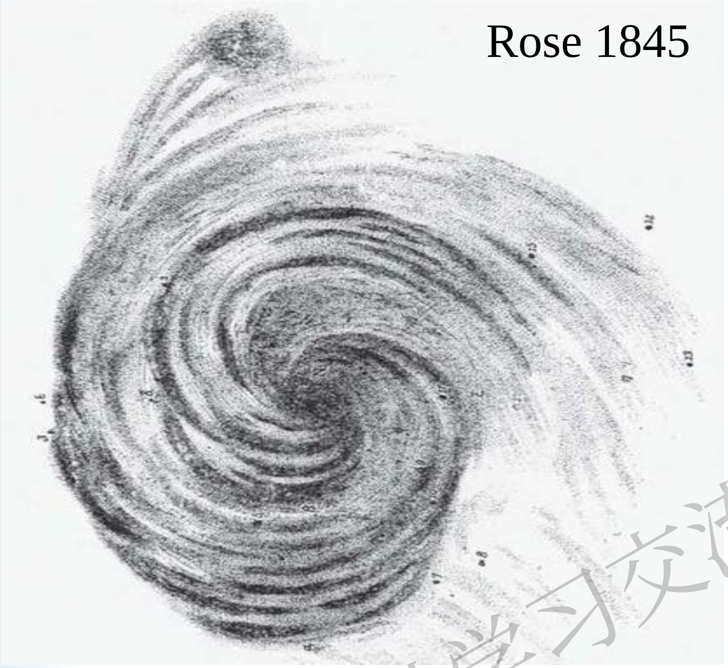
河外星系 NGC1300

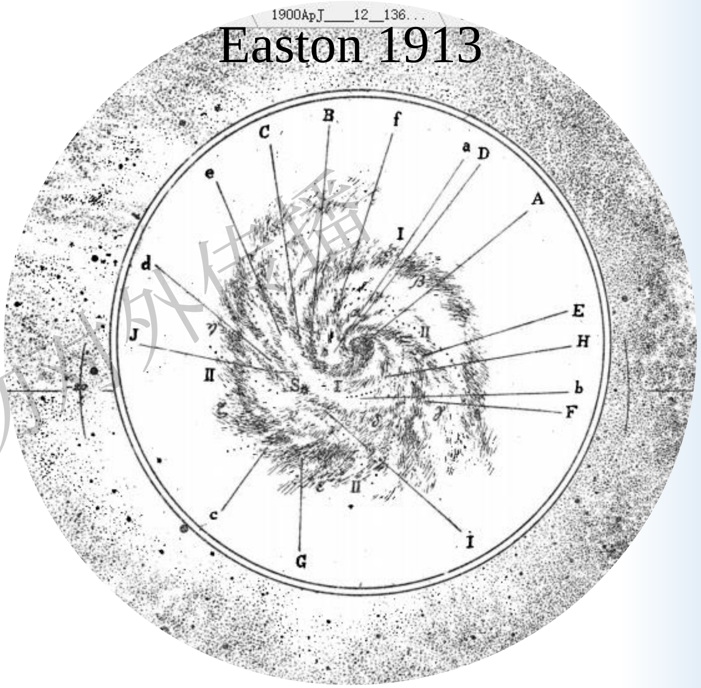
河外星系 NGC1312



银河系旋臂结构的研究历史

银河系旋臂结构的早期研究

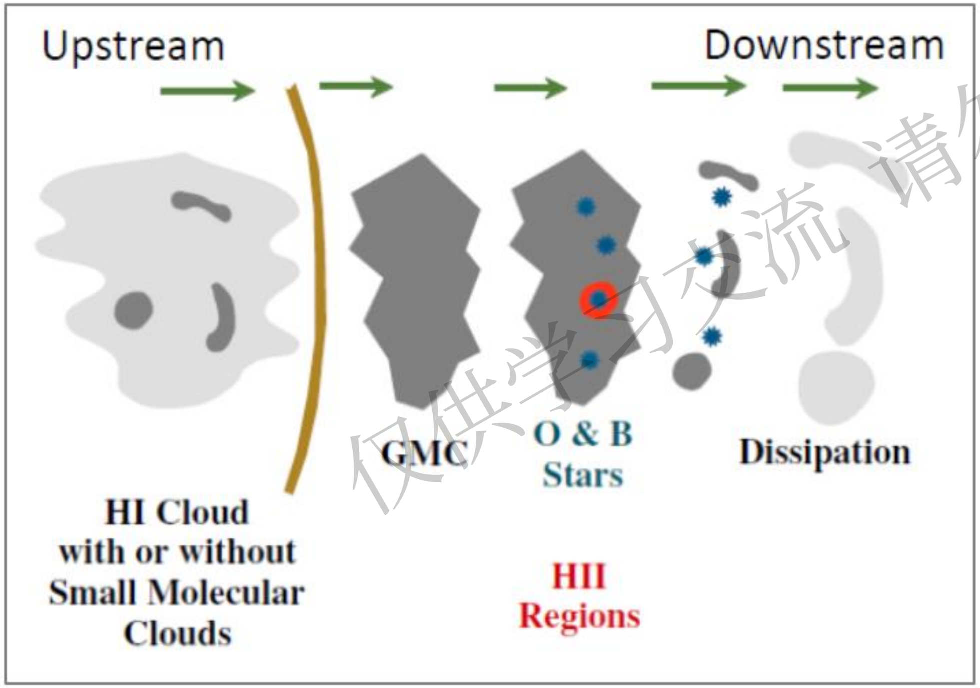




- 1845 年 Lord Rose 发现 M 51 的旋涡结构
- 1852 年 Alexander 推测银河系有旋臂结构
- 1900 年 Easton 给出较完整的模型
- 1927 年 Oort 证明银河系自转

揭示银河系结构的元素

银河系结构、运动与演化



- 多波段、多示踪天体相结合：

脉泽 (GMC & HI)：示踪旋臂结构

OB 星：示踪旋臂结构

疏散星团：研究旋臂演化

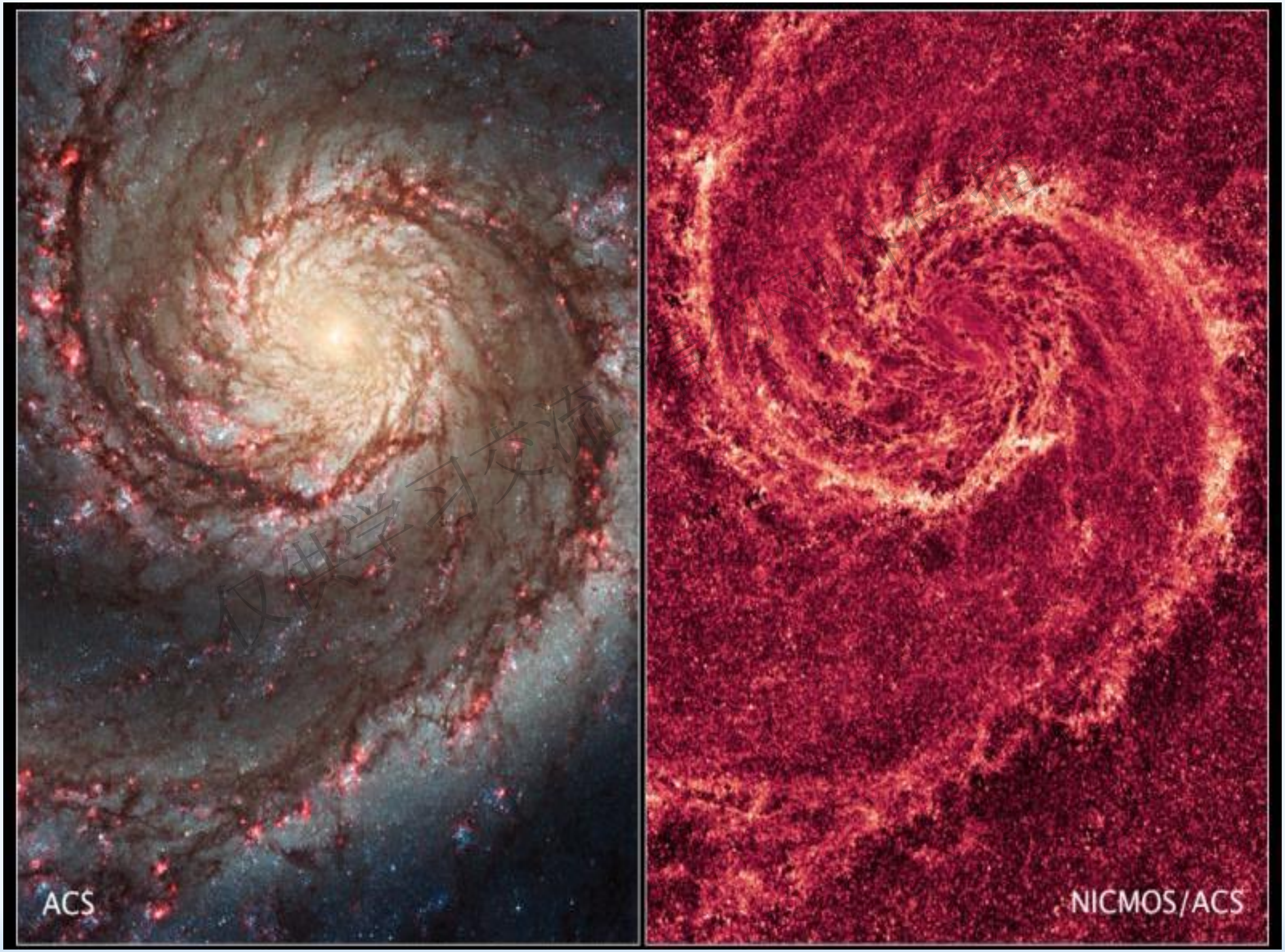
晚型星：示踪盘形态

造父变星：盘边缘翘曲

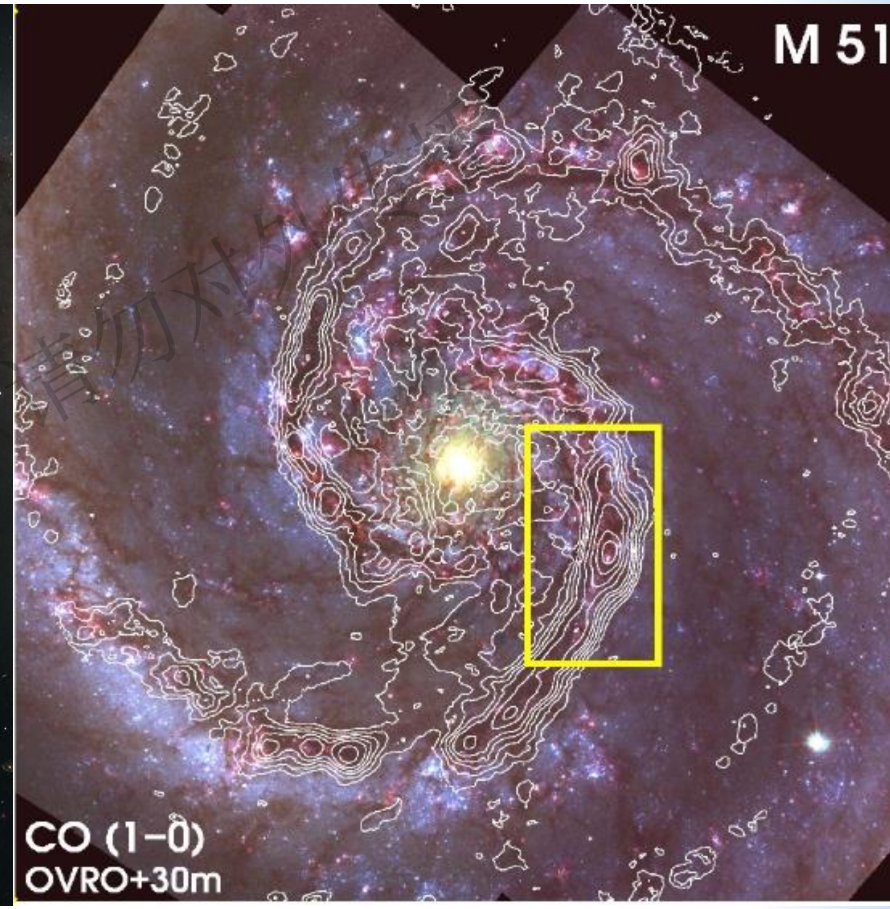
- 探索旋臂形成理论！

密度波理论？ or 动态旋臂理论？

M 51: 光学和红外



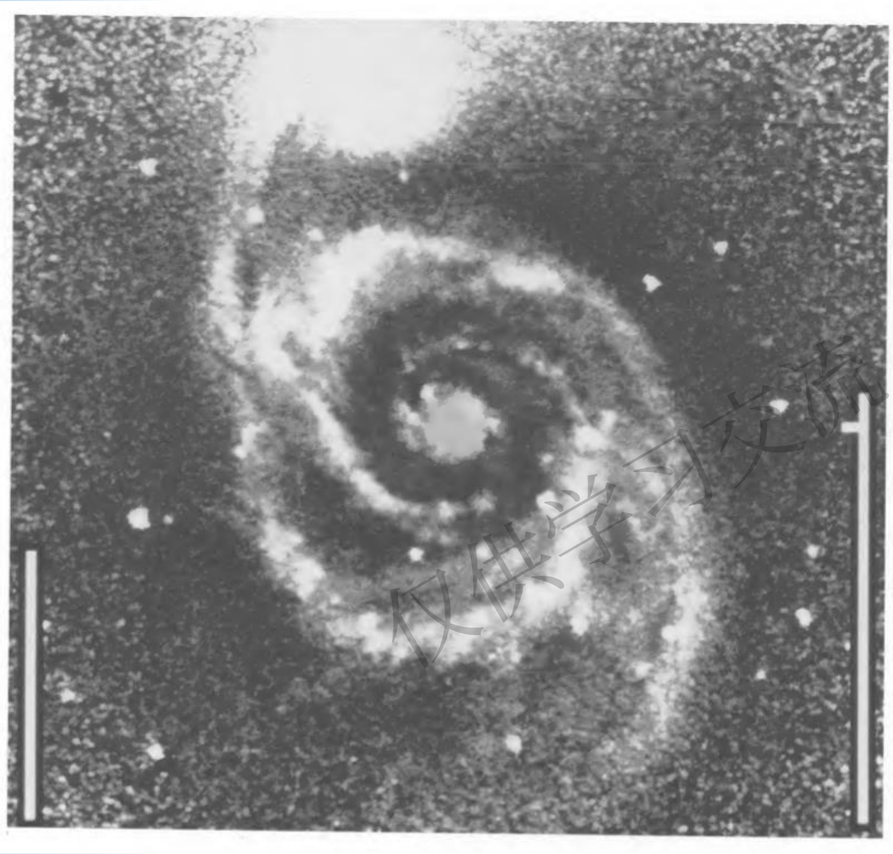
M 51: 光学和毫米波



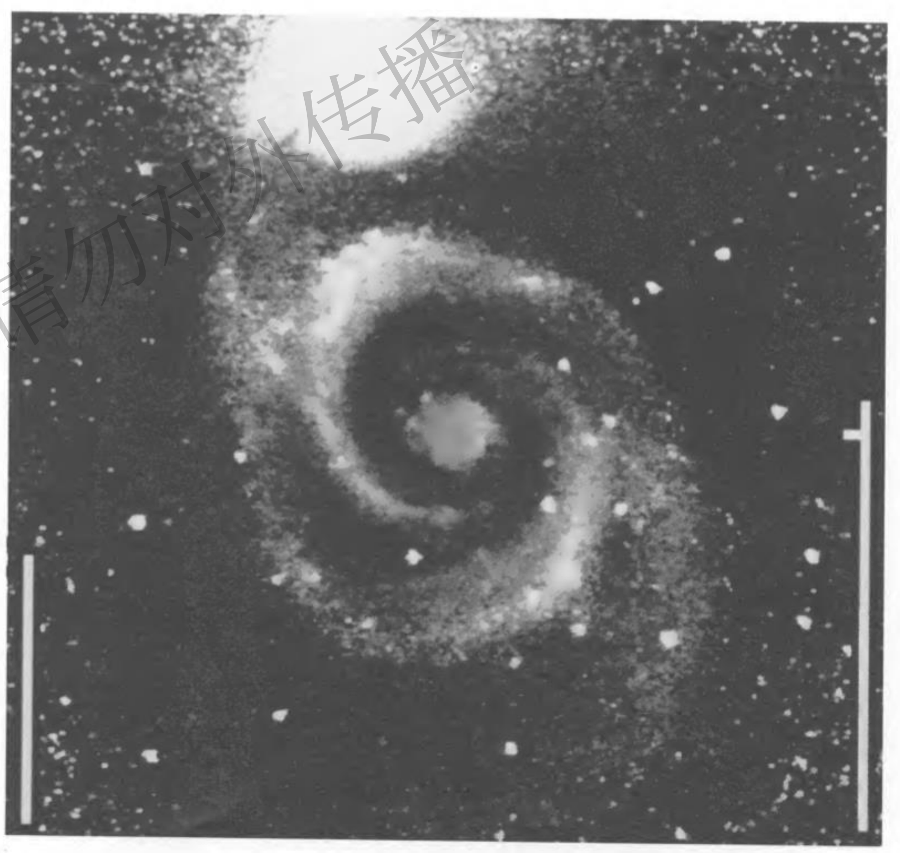
Aalto et. al 1999

M51: 年轻 & 年老-恒星

1. 河外星系 M51 的蓝色图像 (年轻恒星)

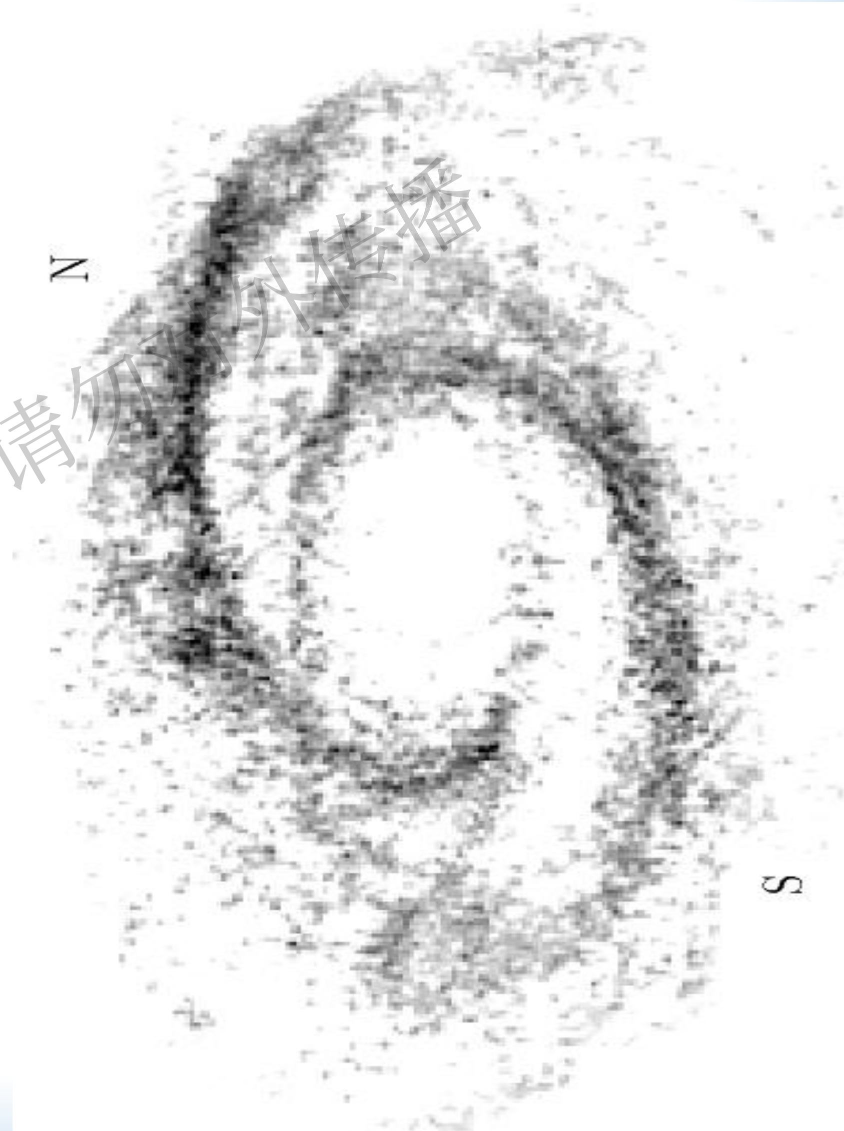


2. 河外星系 M51 的近红外图像 (年老恒星)

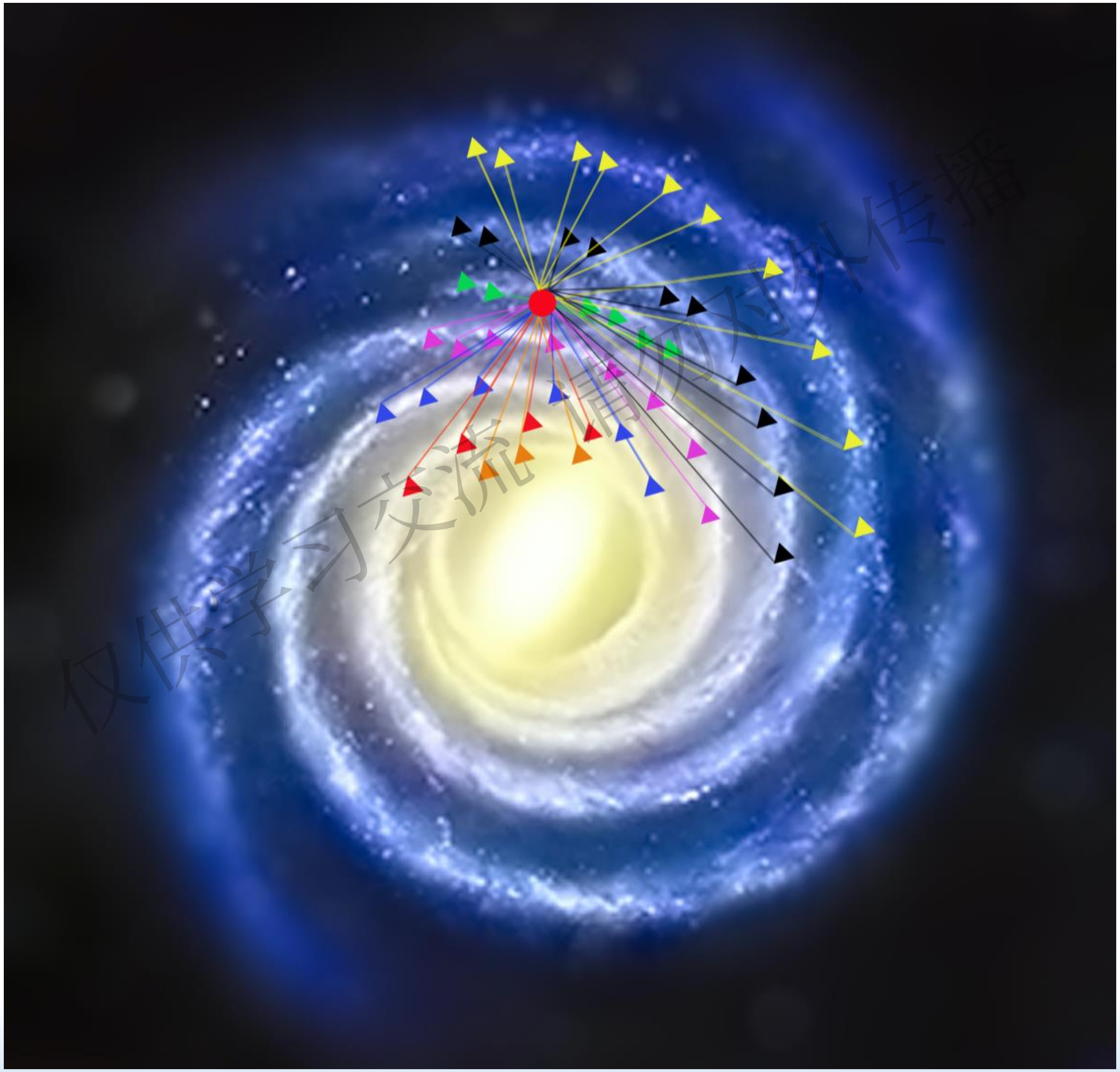


Elmegreen, Elmegreen & Seiden 1989, ApJ

M 81: 光学和中性氢

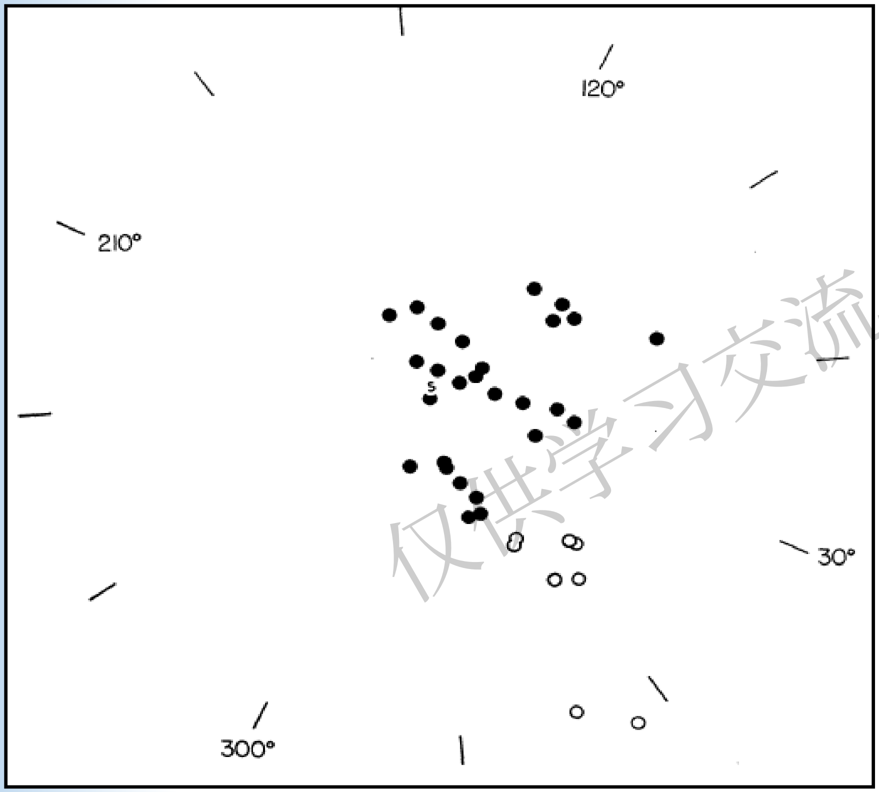


如何构建旋臂



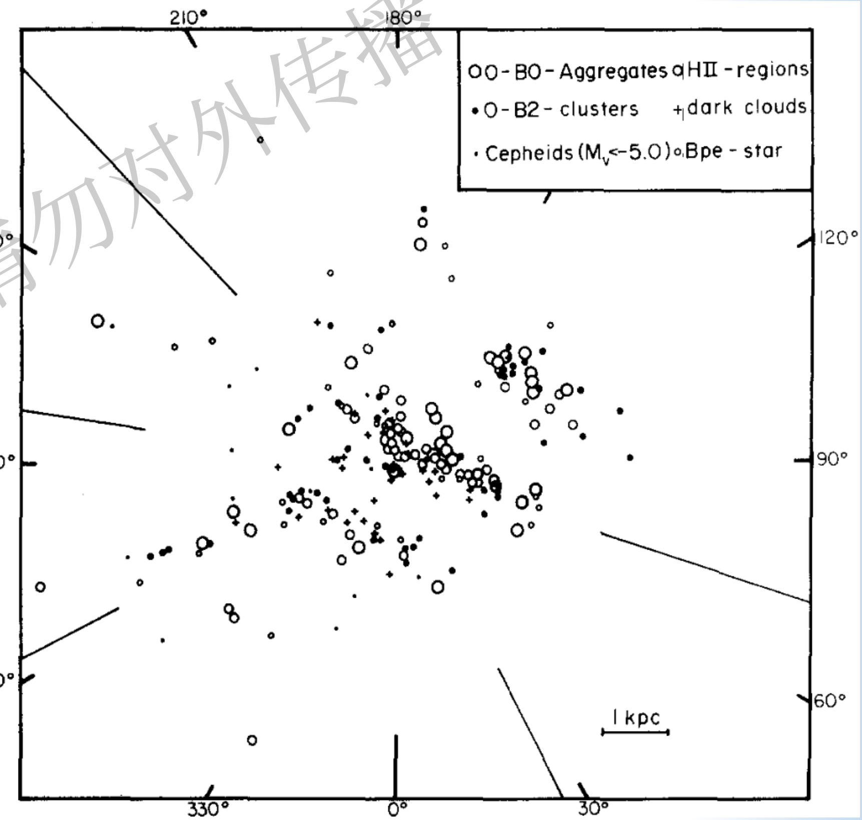
银河系旋臂结构的发现

1. 太阳附近大质量 OB-型恒星的分布



Morgan et al. 1952, 1953

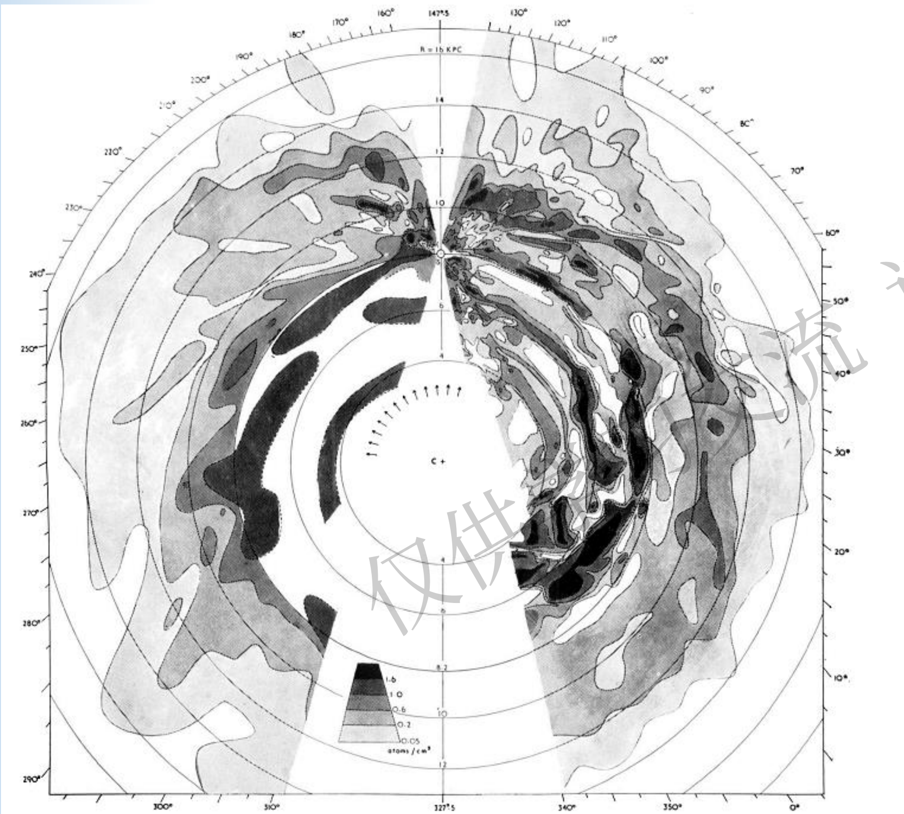
2. 太阳附近 OB-星集、OB-星团、造父变星、HII 区的分布



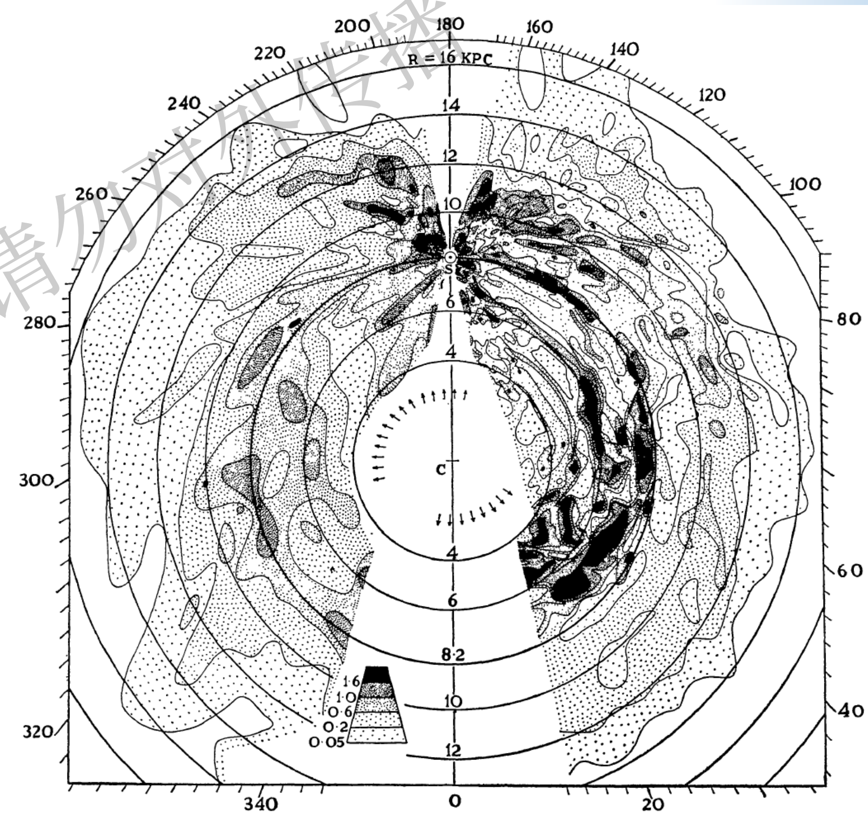
Schmidt-Kaler, 1966

中性氢绘制银河系旋臂结构

基于运动学距离的银河系中性氢 (HI) 的分布



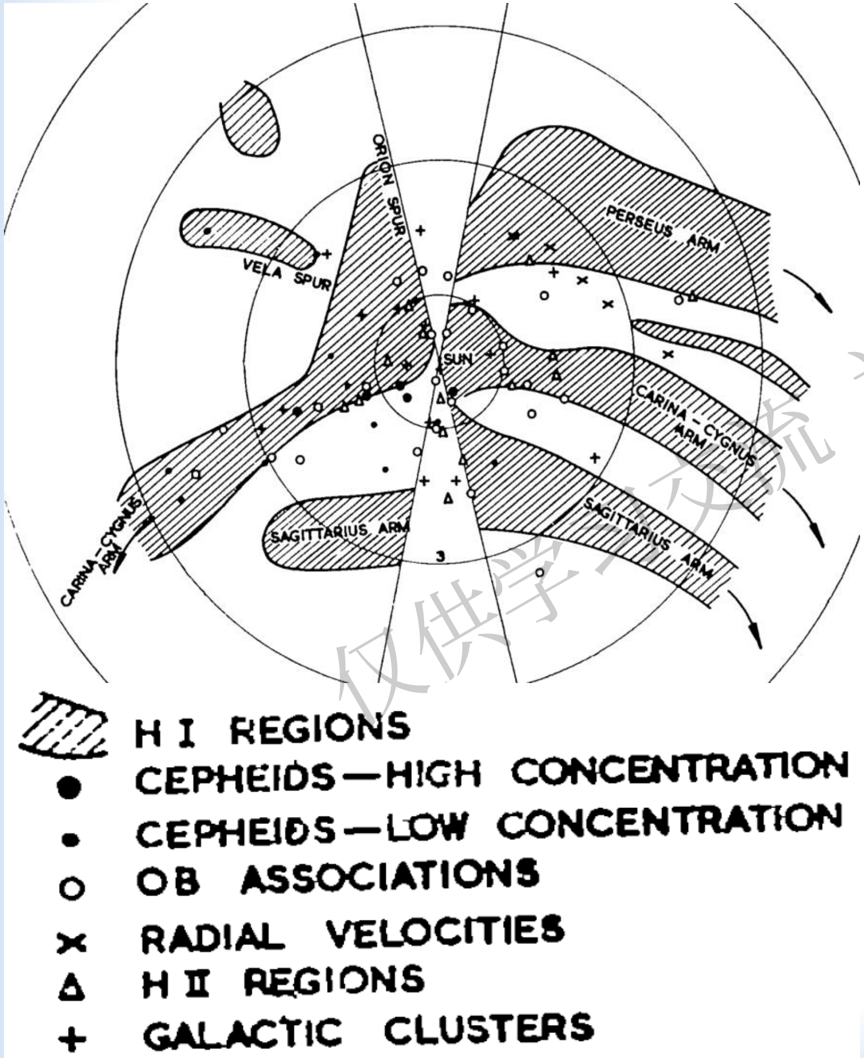
Oort et al. 1958



Kerr 1962

本地臂的提出

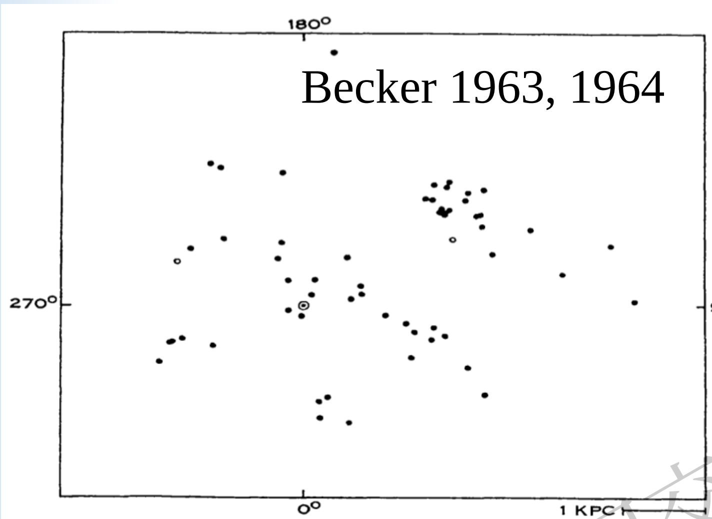
Bok 1959



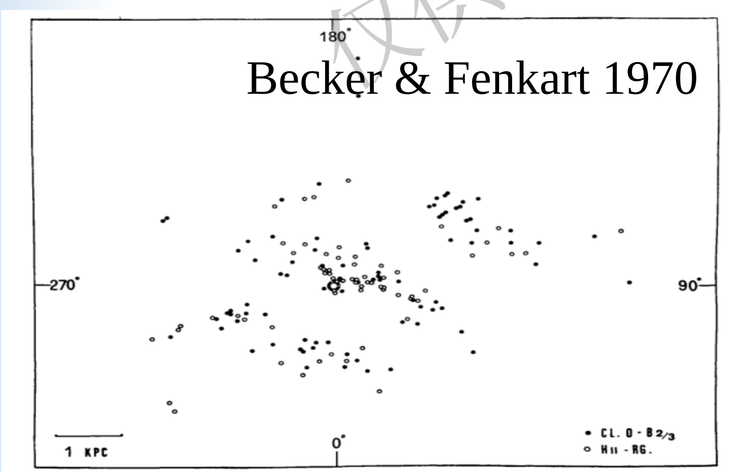
- 使用 HI、造父变星、OB星协、HII区、星团等确定旋臂结构；
- Bok 认为 Local 可能是一条主臂，即 Carina-Cygnus 臂；
- Carina-臂是从 Sagittarius-臂中分离出来的旋臂的一部分，该旋臂可能穿过太阳与Cygnus-旋臂相连。

疏散星团描绘的旋臂结构

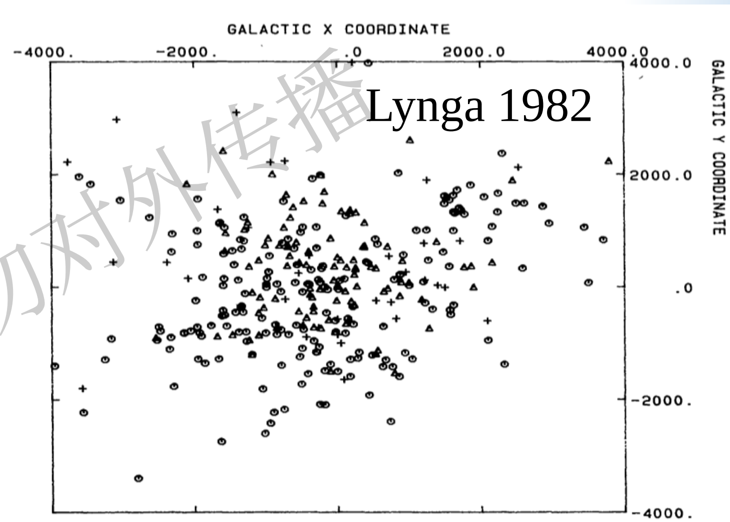
1. 年轻疏散星团示踪的旋臂结构

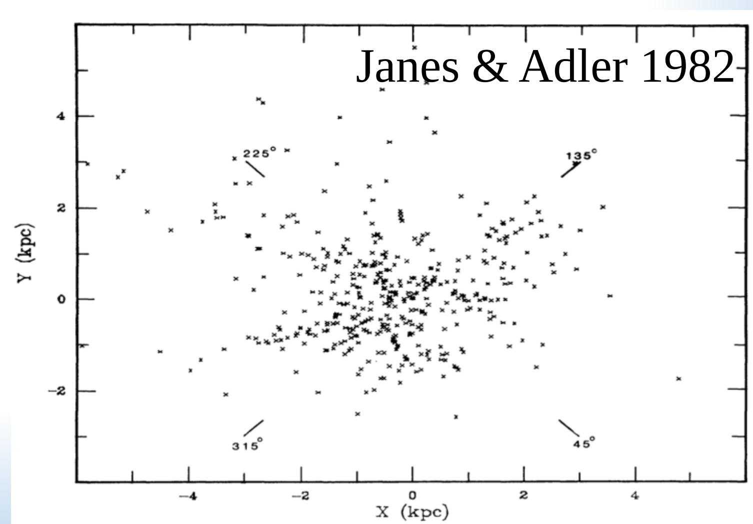


2. 年轻疏散星团与HII区示踪的旋臂结构



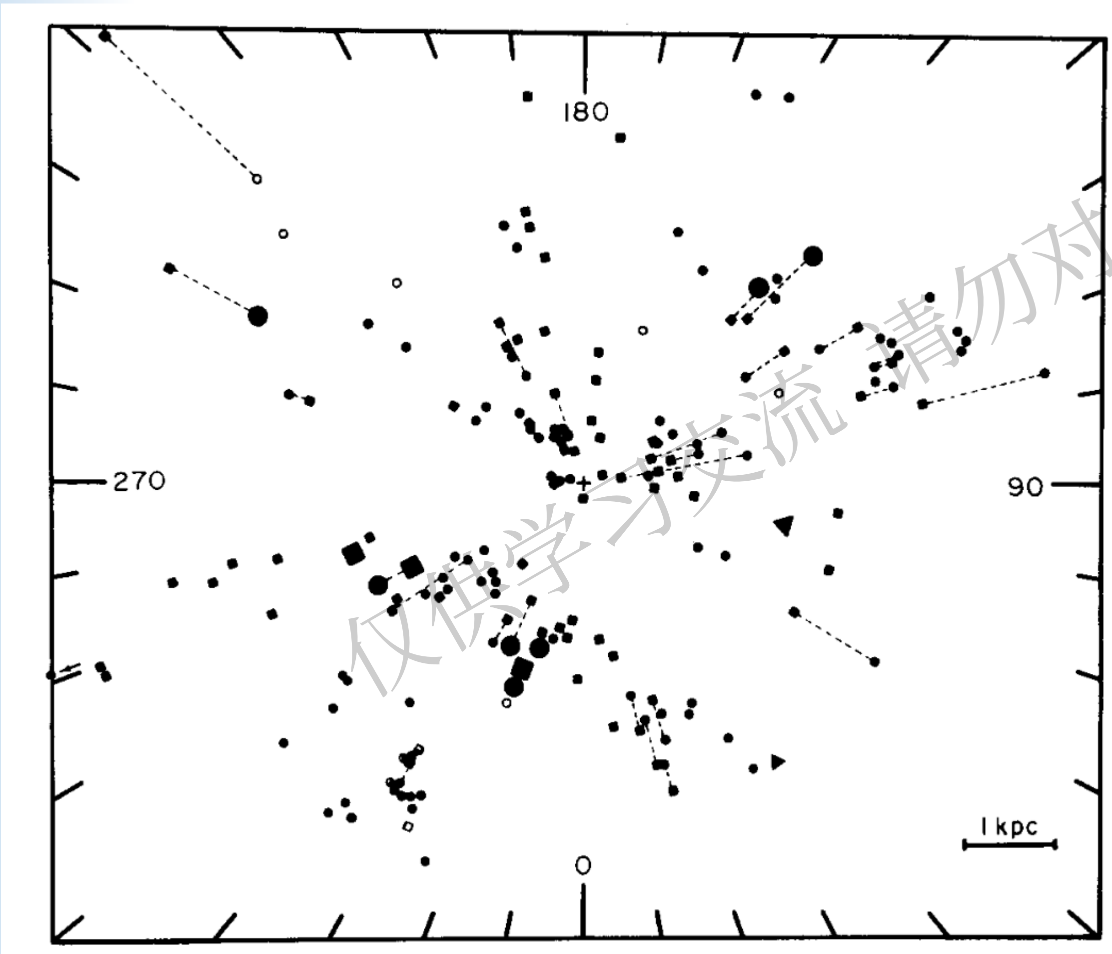
3. 疏散星团不能示踪旋臂





HII 区描绘的旋臂结构

Courtès 1972



- 大约 200 个 HII 区示踪的旋臂结构。
- 圆点表示运动学距离，方块表示测光距离。
- 四旋臂：

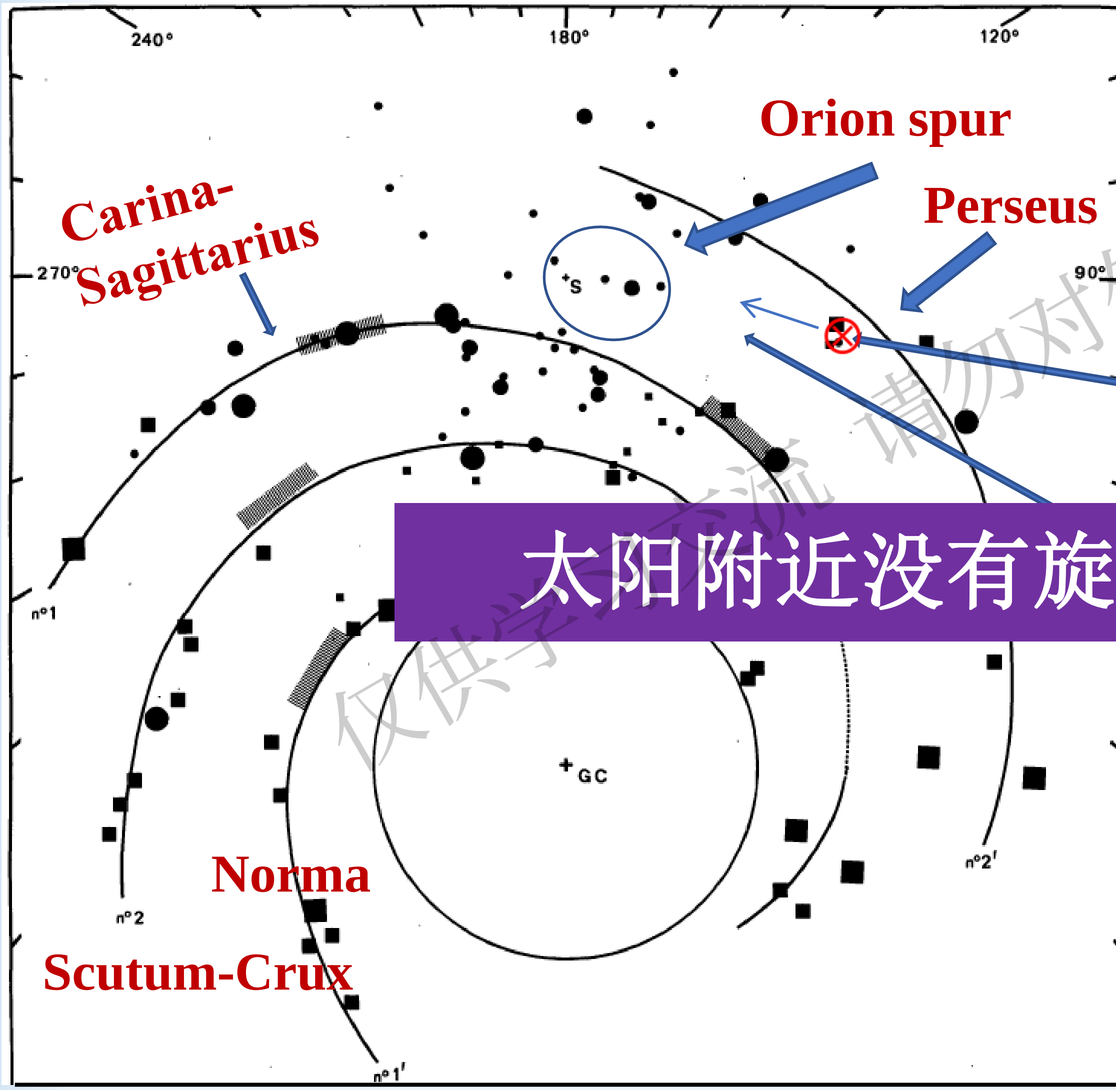
  Perseus arm，

  Orion arm，

  Sagittarius-Carina arm,

  Norma-Centaurus arm

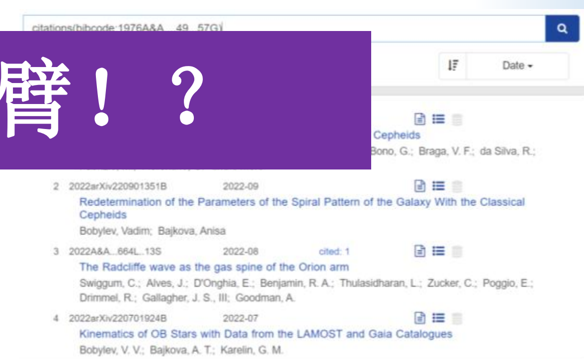
银河系旋臂结构“标准模型”



太阳附近没有旋臂！？

G75.8+0.4
~ 5.7 kpc
⇒英仙臂

3.5 kpc
⇒本地臂

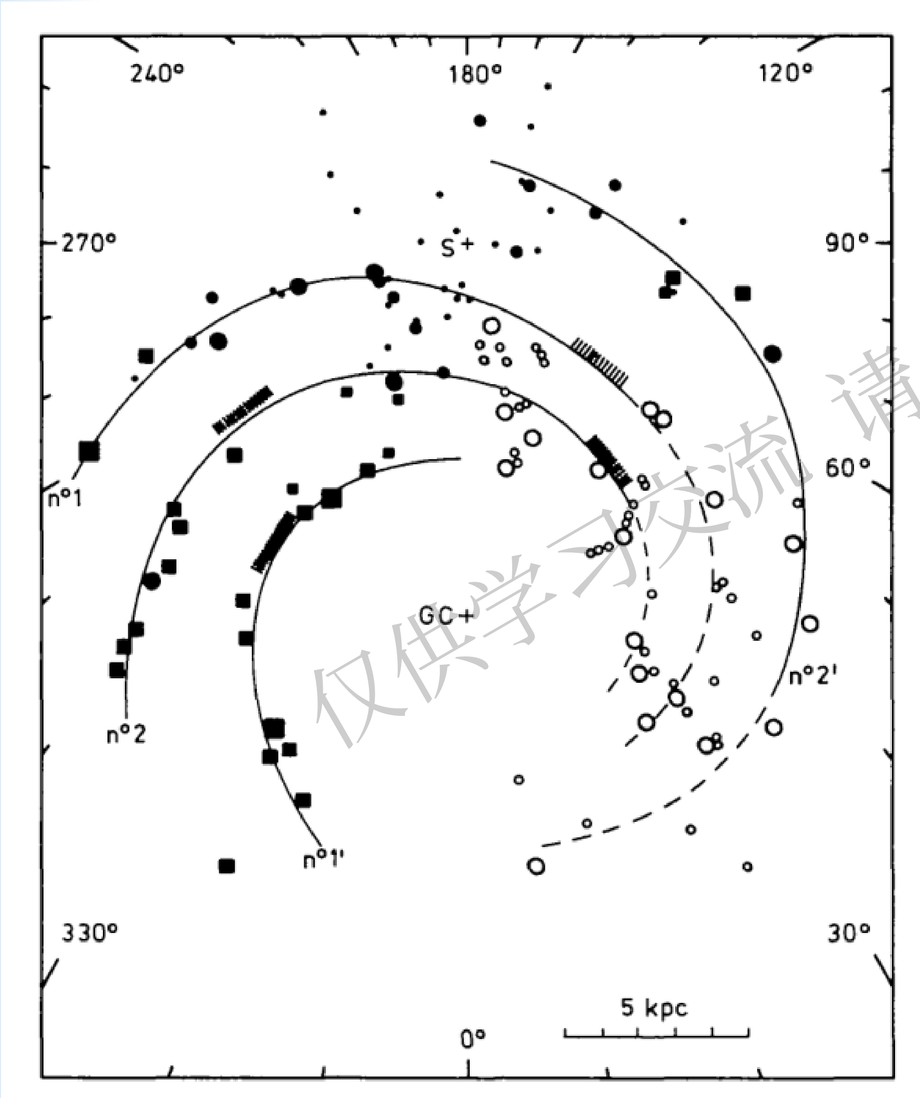


Georgelin & Georgelin 1976

引用720次

GG76 模型的调整-1

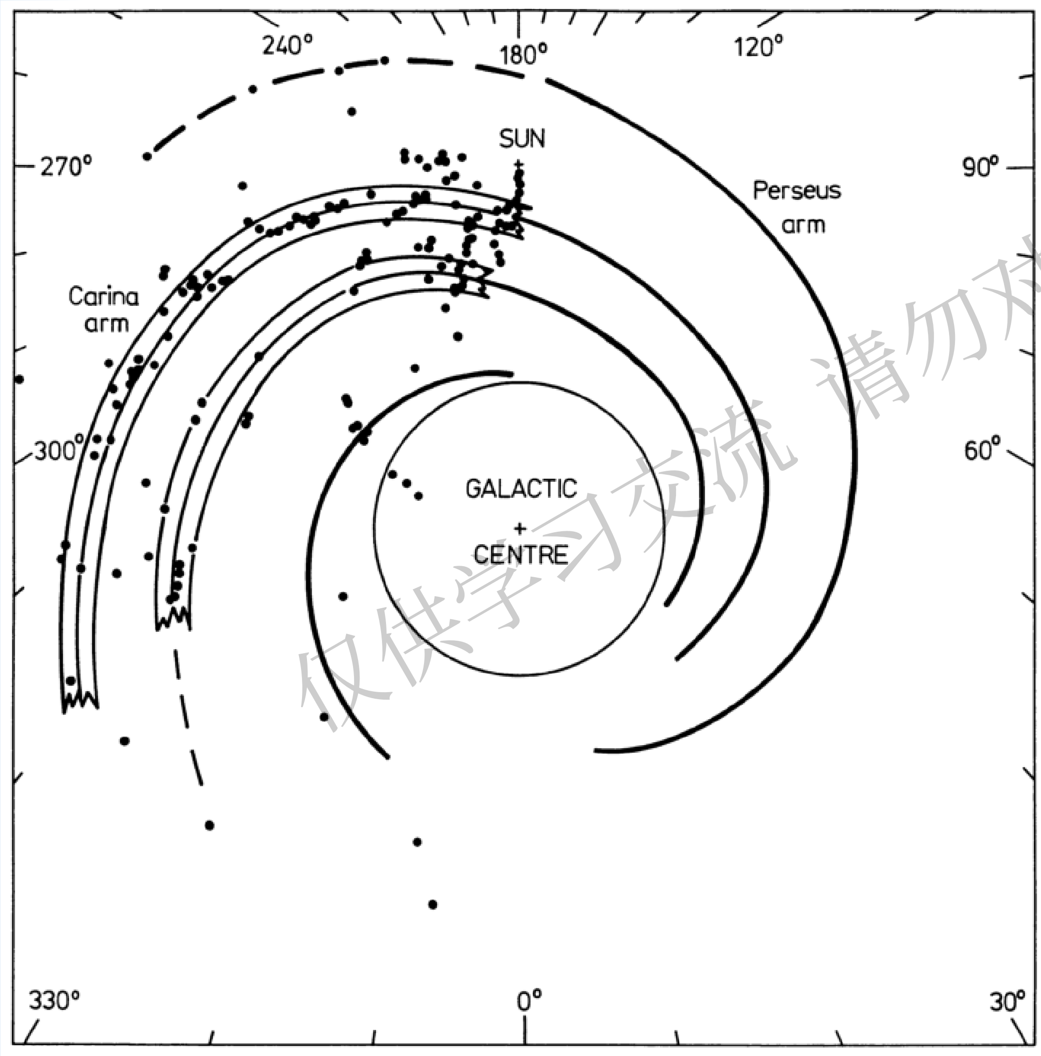
Downes et al. 1980



- Effelsberg 100-m 望远镜巡天确定了银经 l = 0 – 60 度范围内的大约 70 个（没有运动学距离模糊的）HII 区的运动学距离。
- 根据这些结果对 GG76 模型进行了调整。

GG76 模型的调整-2

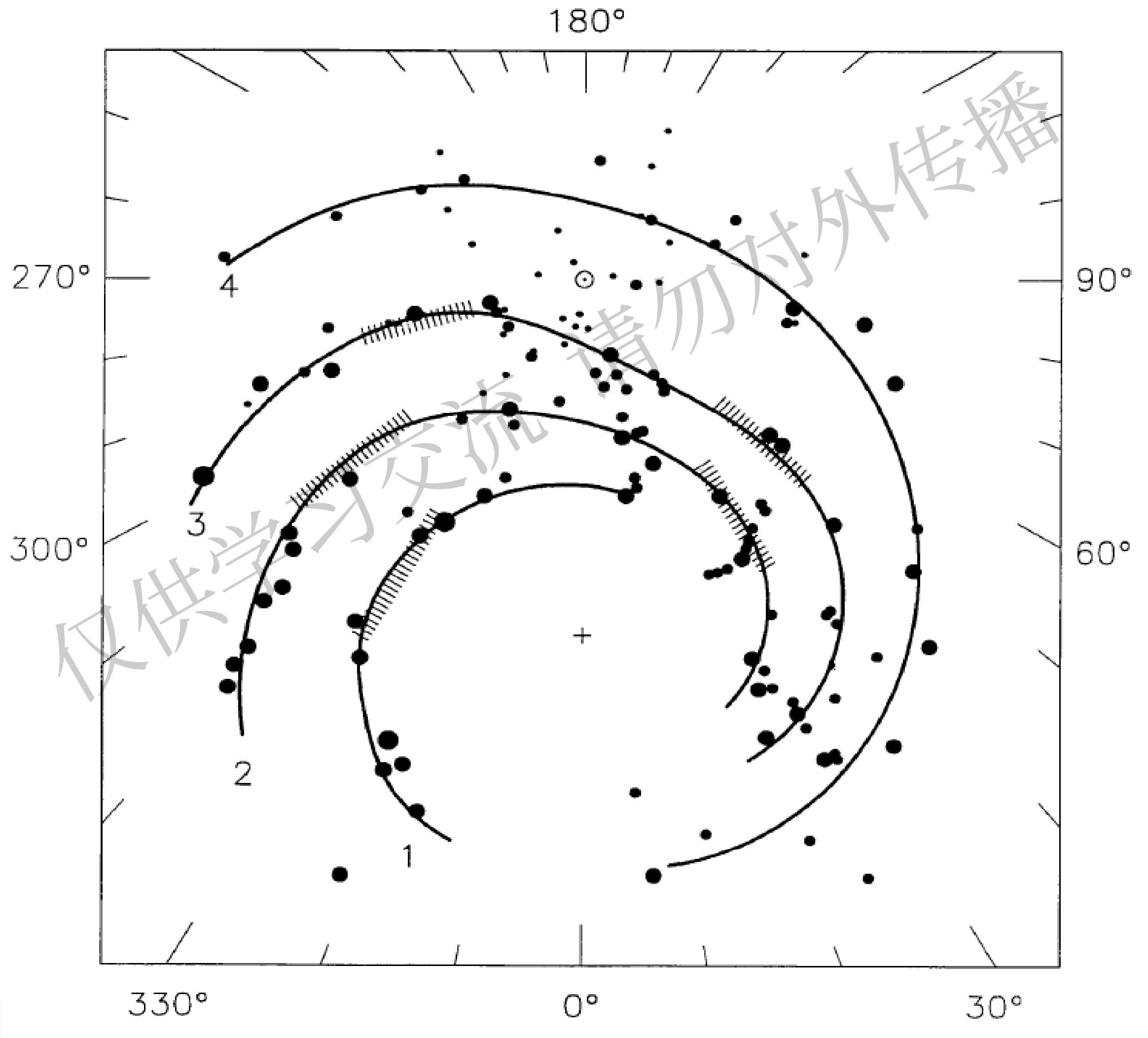
Caswell et al. 1987



- Parkes 64-m 测定了南天 HII 区的运动学距离。
- 根据这些结果在 Downes et al. (1980) 的基础上，对 GG76 模型进行了调整。

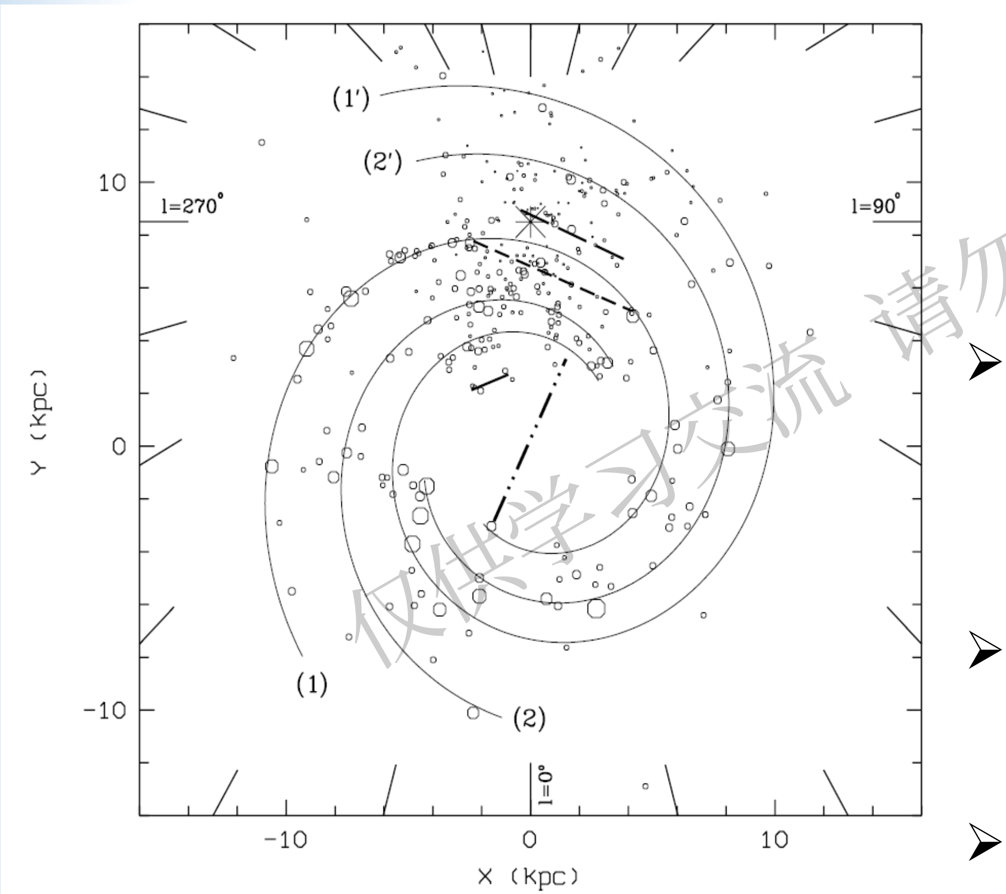
GG76 模型的调整-3

Taylor et al. 1993: 利用电子密度确定切点



GG76 模型的调整-4

Russeil 2003

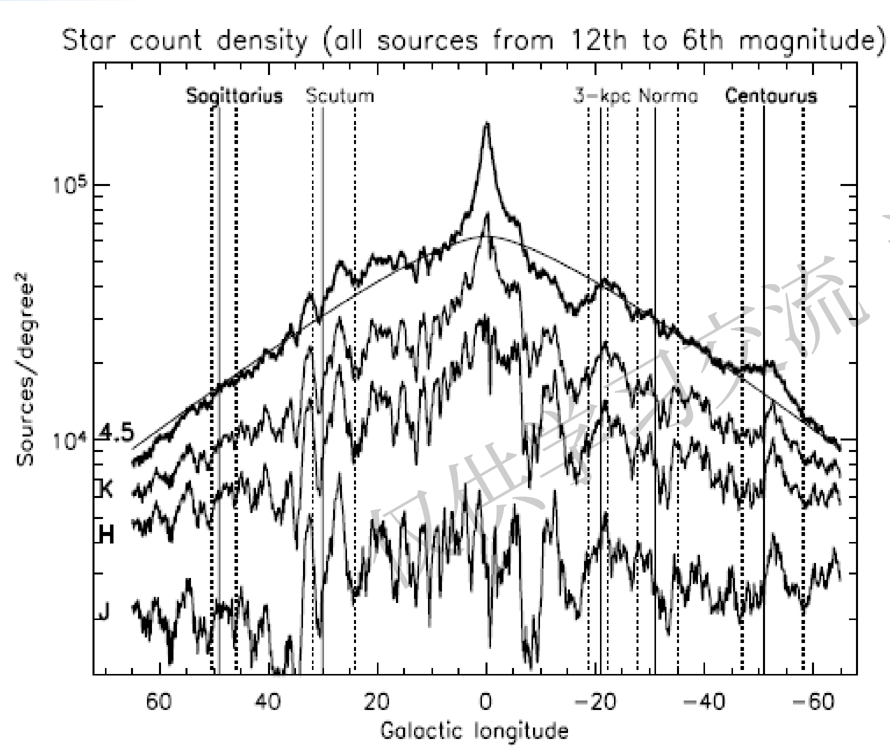


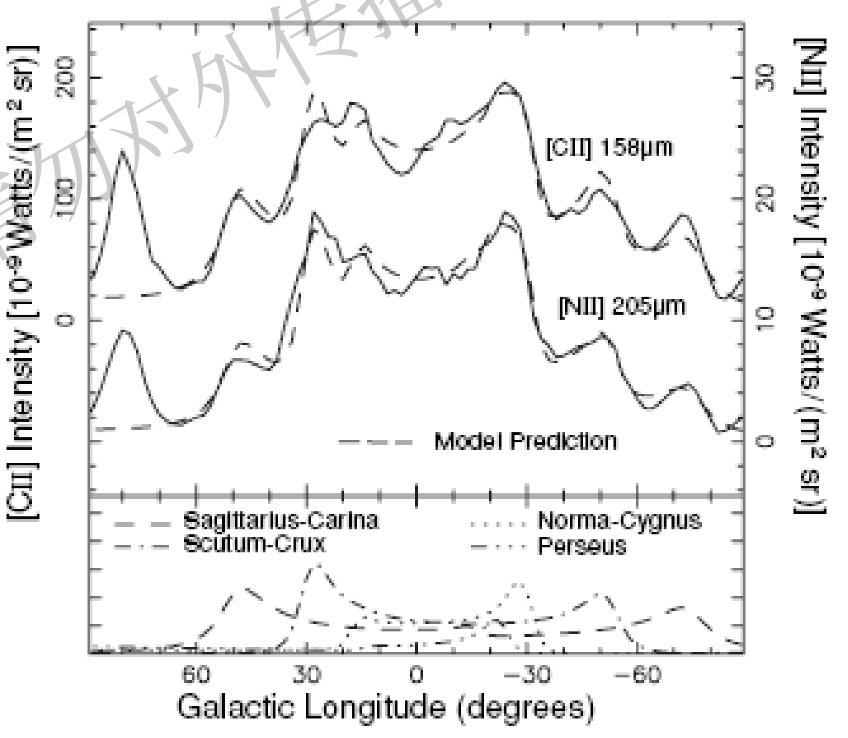
- 观测天体包括 Hα、H109α、CO、射电连续谱和吸收谱，并确定了它们的位置，系统速度，运动学距离；
- 拟合的旋臂模型证实 GG76 的四旋臂模型，并将旋臂的已知长度增加了一倍；
- 根据银河系和河外星系的特征，两臂模型可以明确排除；
- 三臂和四臂模型仍然处于激烈的争论中，然而后者略为优先。

测量切点描绘的旋臂结构

1. Spitzer 巡天中晚型星在银经方向的统计计数分布

2. [NII] 受消光影响小，提供了 HII 区的一个完全不同的电离结构和气体密度的探针





Churchwell et al. 2009

Steman-Cameron et al. 2010

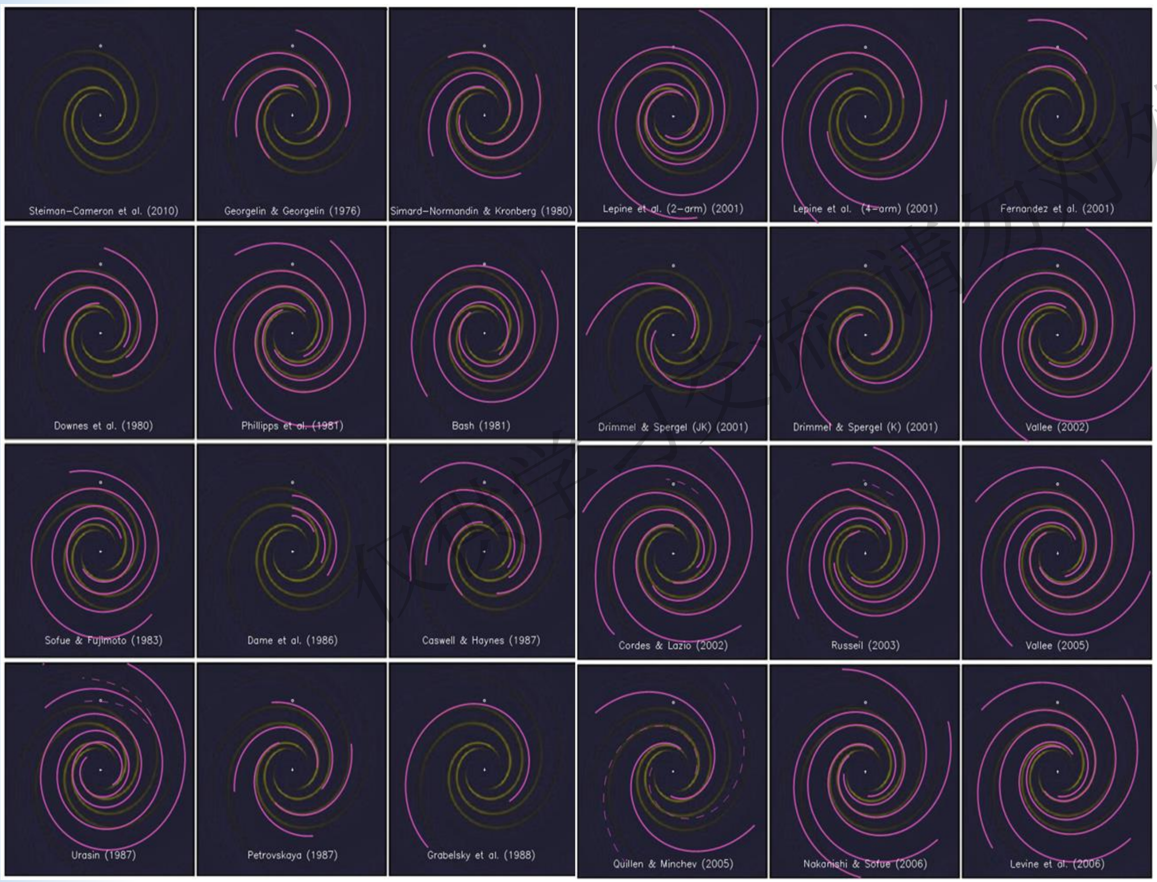
银河系旋臂结构的研究瓶颈

- 早期对银河系的研究集中在可见光波段，由于天文学家并不了解星际介质的存在及其消光作用，因而得到关于银河系结构的错误的结论。

- 尽管后来认识到星际介质的分布及其对观测的重要影响，并发展了射电与红外的手段来研究银河系的结构，但由于距离不准确，使得对银河系旋臂结构仍不清楚。

银河系旋臂模型

纷繁复杂的银河系旋臂模型



- 旋臂的数量 2 3 4 5？

仍不确定

- 银河系的类型

仍不确定

- 棒的位置，长度，角度？

仍不确定

- 银河系基本参数

不够准确

- 旋转曲线、暗物质分布

不够准确，不清楚

构建银河系结构的基础 → 运动学距离

- 很难精确测定旋转曲线
- 非圆运动
- 运动学距离模糊

G9.62+0.20

运动学距离，远：15 kpc

近：0.5 kpc

视差距离：5.7 kpc

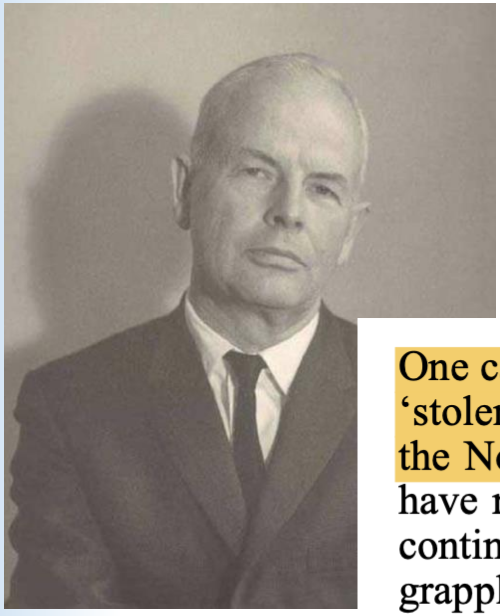
- 运动学距离反常

W3OH：

运动学距离：～4.3 kpc

视差距离：～2.0 kpc

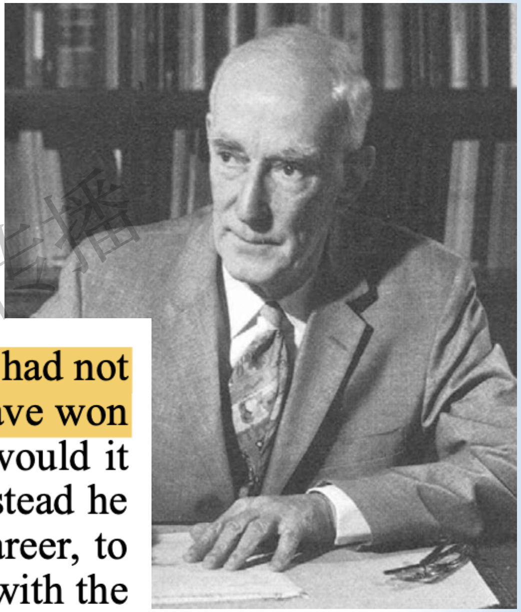
OB-型星 vs 中性氢



摩根

“劣币驱逐良币”

One can speculate that if the radio astronomers had not ‘stolen his thunder’ then Morgan might even have won the Nobel Prize for his discovery. If he had, would it have resolved his struggle for self-esteem? Instead he continued, through a long and accomplished career, to grapple with the classification of galaxies and with the alternating creative phases of elation and let-down. His was the condition of many of those with creative temperaments, “… the greatness and misery of man …” as Pascal put it. Near the end of his life, Morgan (1983) wrote:



奥尔特

1、1970 年，人们意识到奥尔特确定的中性氢云的距离不精确；摩根工作再次得到人们的充分赞赏；

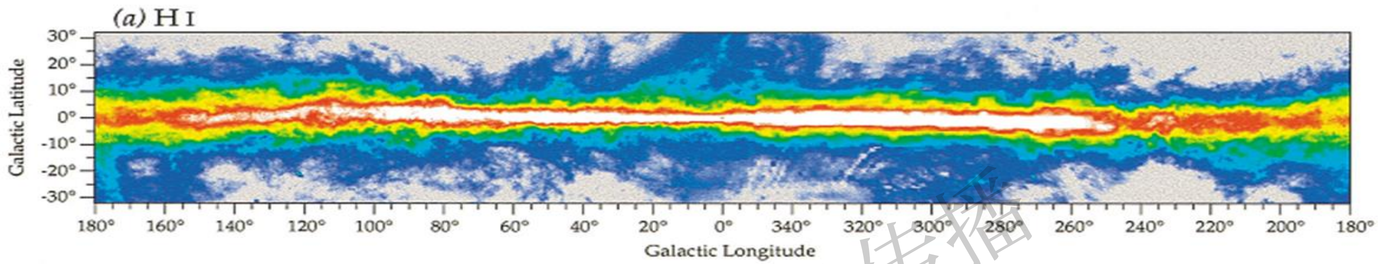
2、随后，各种各样的示踪剂继续被用来描绘银河系旋臂结构。

21世纪银河系旋臂结构的研究突破

银河系内大尺度结构

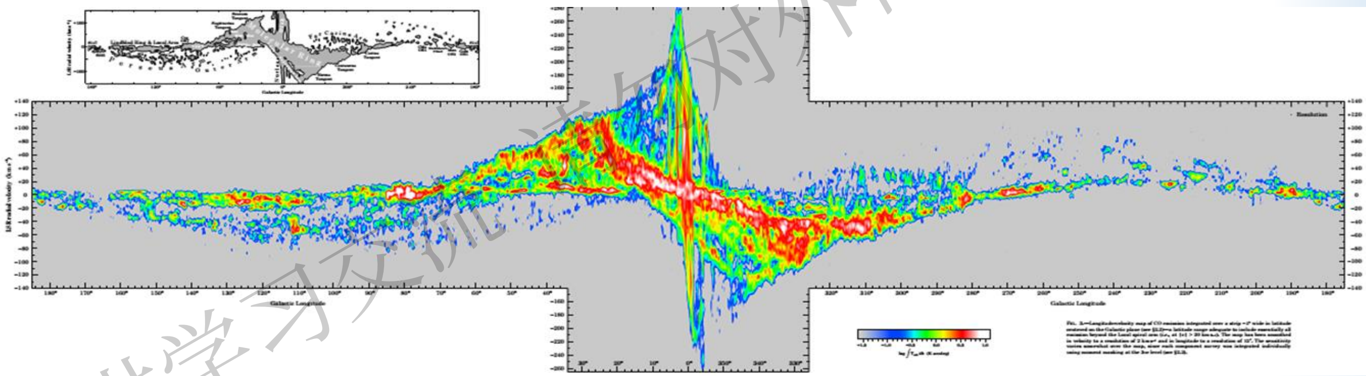
HI

原子气体



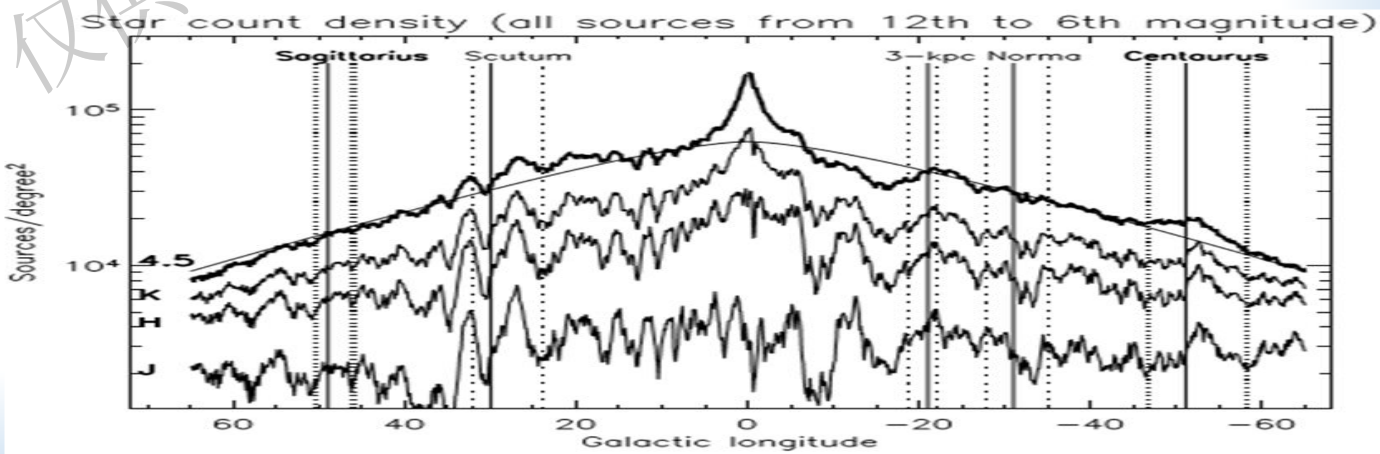
CO

分子气体



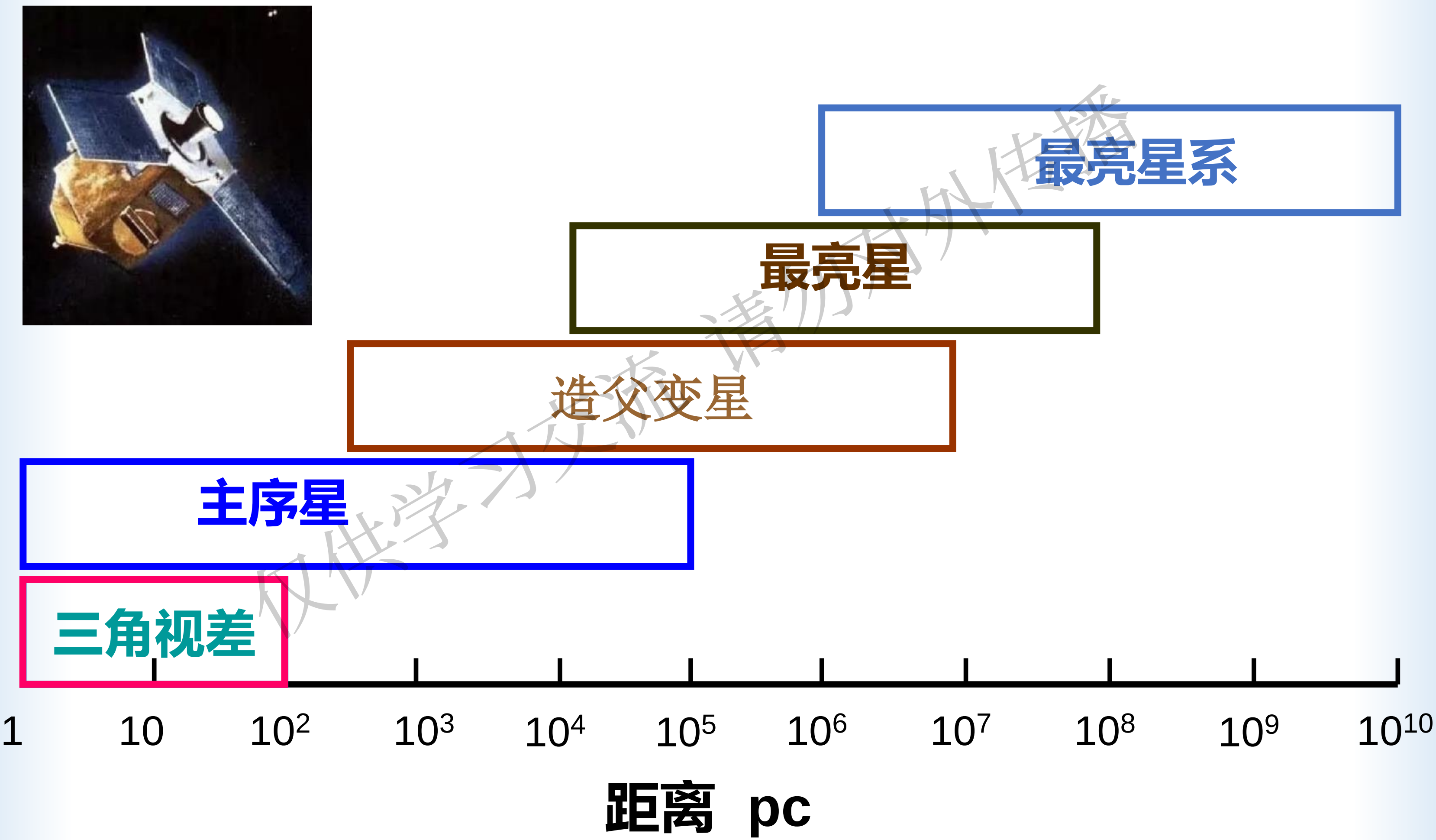
Giants

年老恒星



三角视差

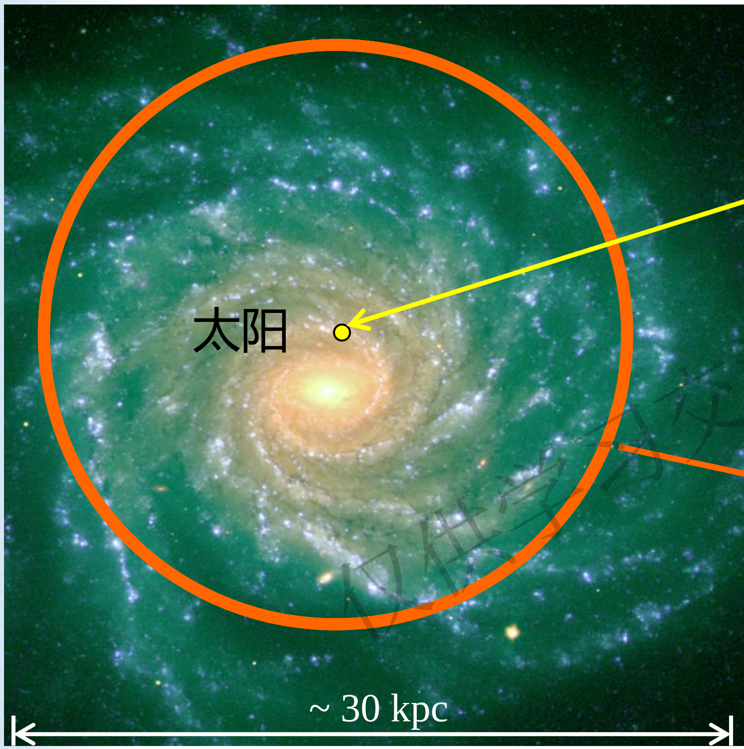
依巴谷卫星

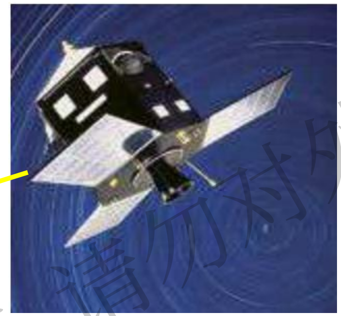


依巴谷 0.1 kpc → > 10 kpc

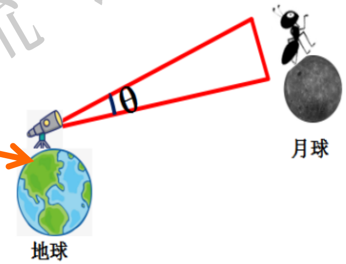
测距技术有极大挑战

相当于在地球上看月球上的一只蚂蚁！





光学：
依巴谷卫星
视差精度： 1 毫角秒
可测距离： 100 pc

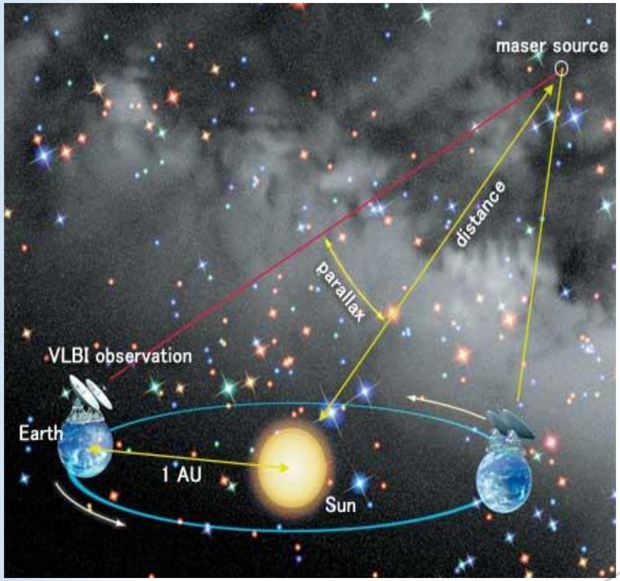


测量银河系尺度的
视差精度要求

射电：
世界最大的望远镜(VLBA)
等效口径：8611 km

为测量银河系提供了可能！

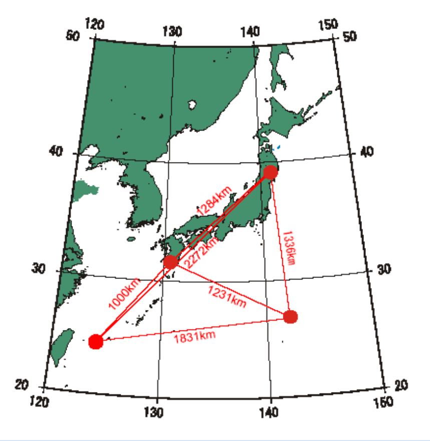
射电观测技术的突破



- 三角视差
- 甚长基线干涉测量 + 相位参考
- 射电波能够“看穿” 银河系
- 综合孔径望远镜大小能够比拟地球

VLBA

VERA

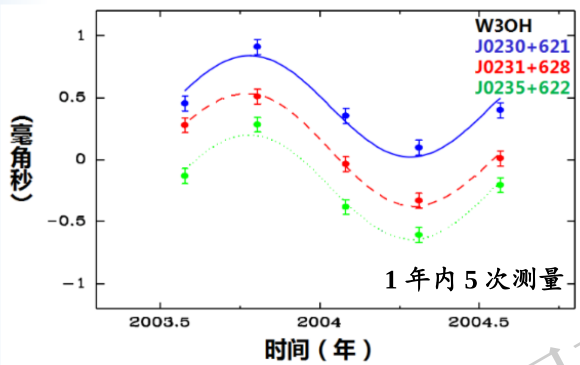


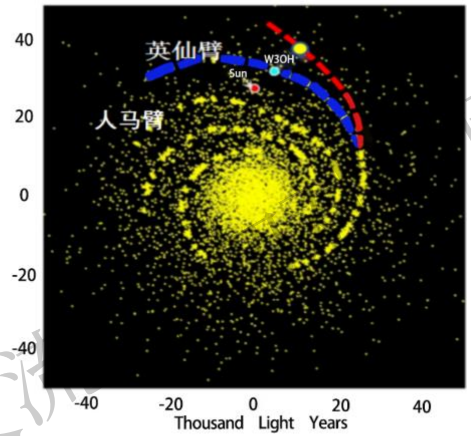
EVN

精确测量银河系英仙臂的距离

实现视差测量 10 微角秒精度——天体测量技术划时代突破

W3OH 视差曲线



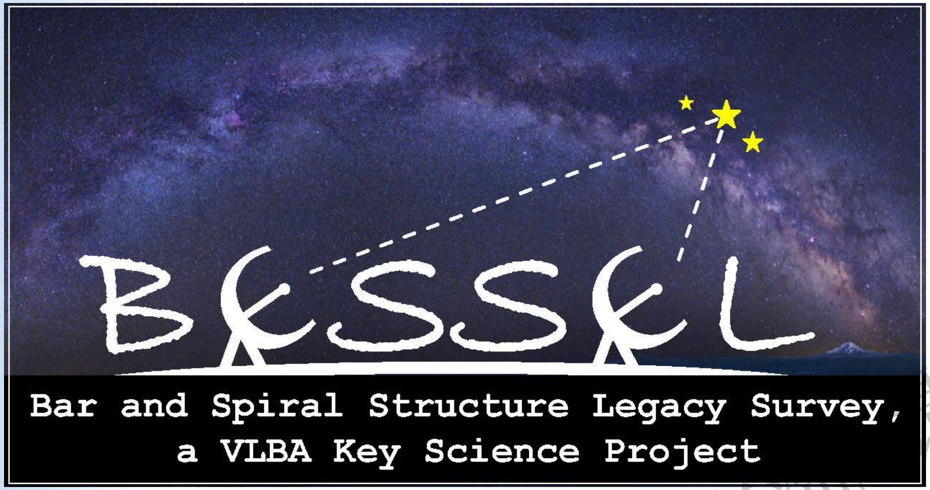


距离：1.95 ± 0.04 kpc　(视差精度：10 微角秒；相对精度：2%)

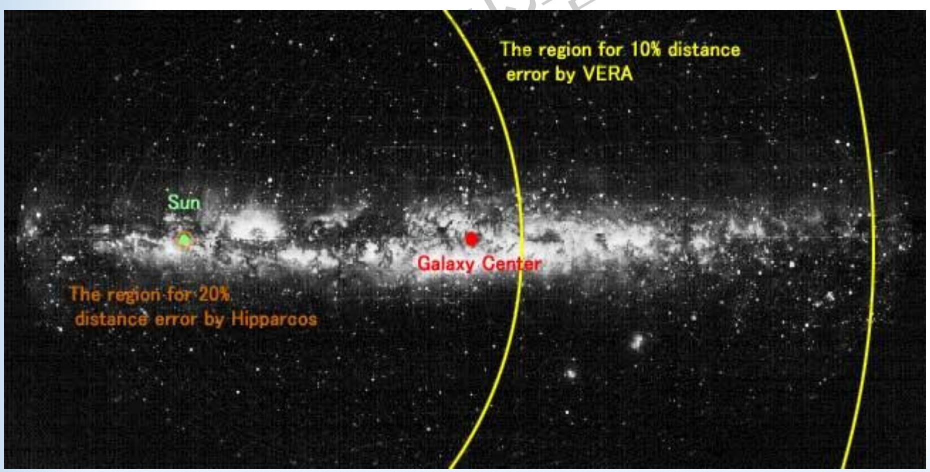
视差：0.512 ± 0.010 毫角秒　(比依巴谷卫星提高两个数量级！！！)

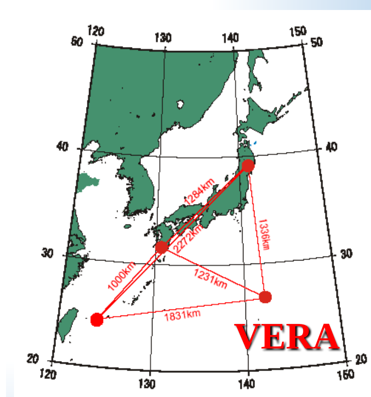
- 标志着直接测量银河系旋臂结构成为可能 ！
- 彻底解决了关于英仙臂距离的长期争论！

推动 BeSSeL 项目成立



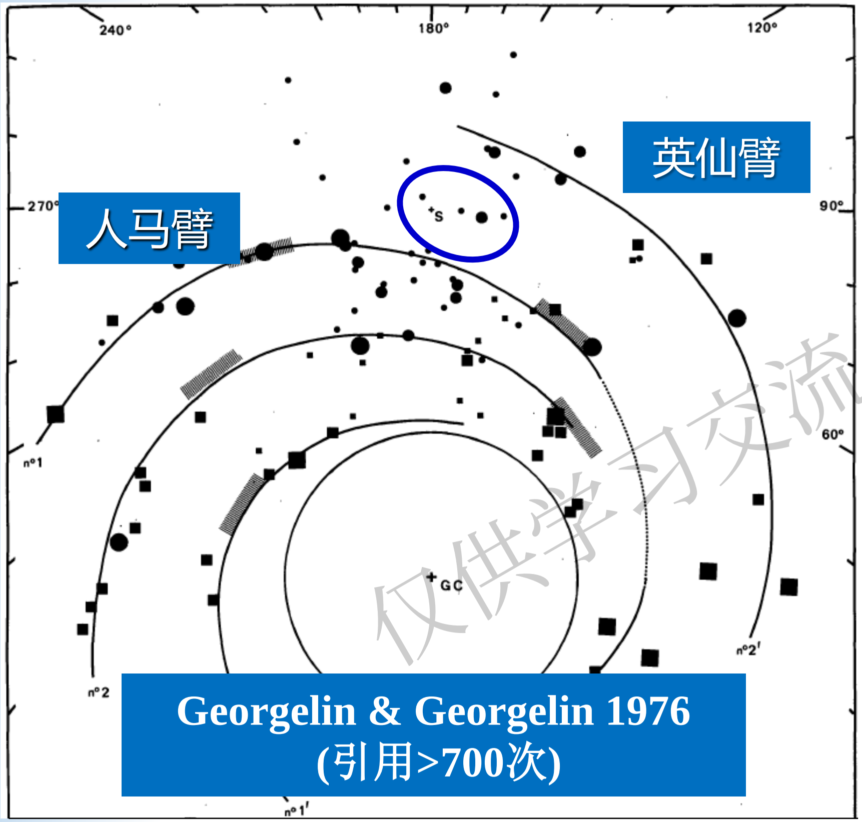
- 推动了美国国立射电天文台史上最大的项目—BeSSeL，**开启了银河系研究的新时代**。
- 1000 个脉泽源
- 5000 hs
- 视差 & 三维运动



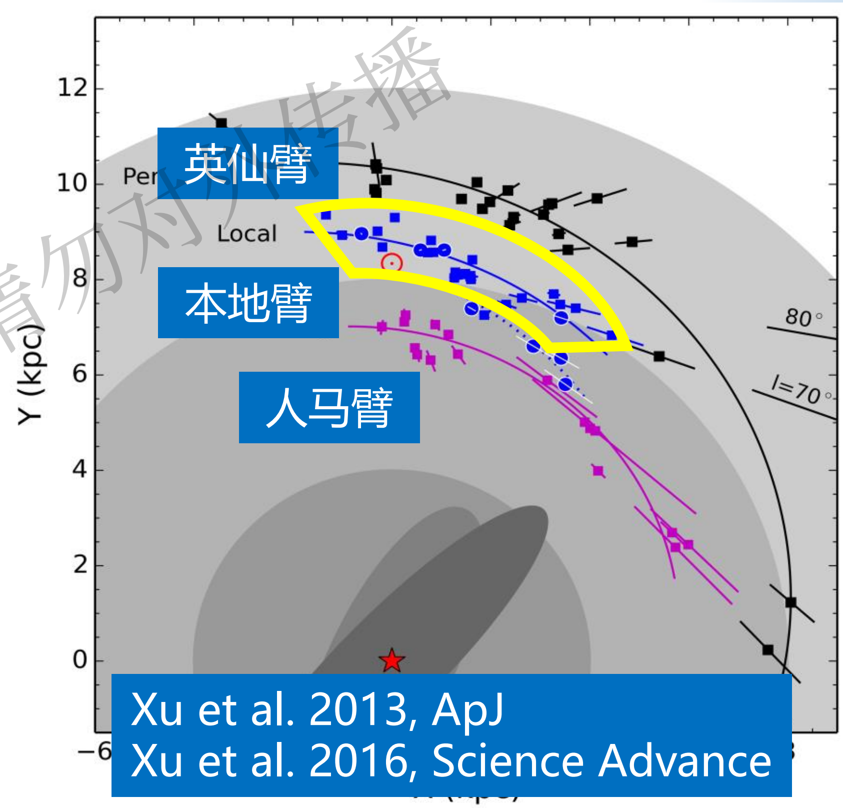


发现银河系新旋臂——本地臂

1. 银河系旋臂标准模型

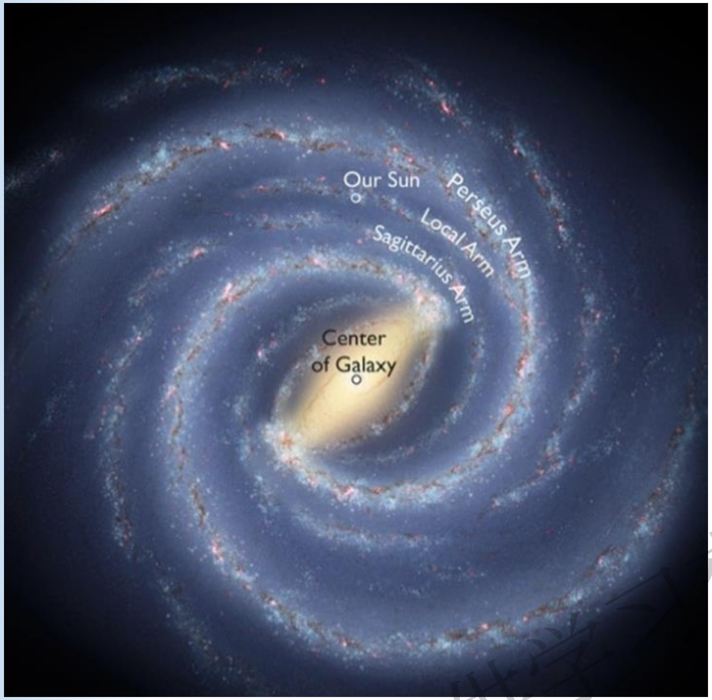


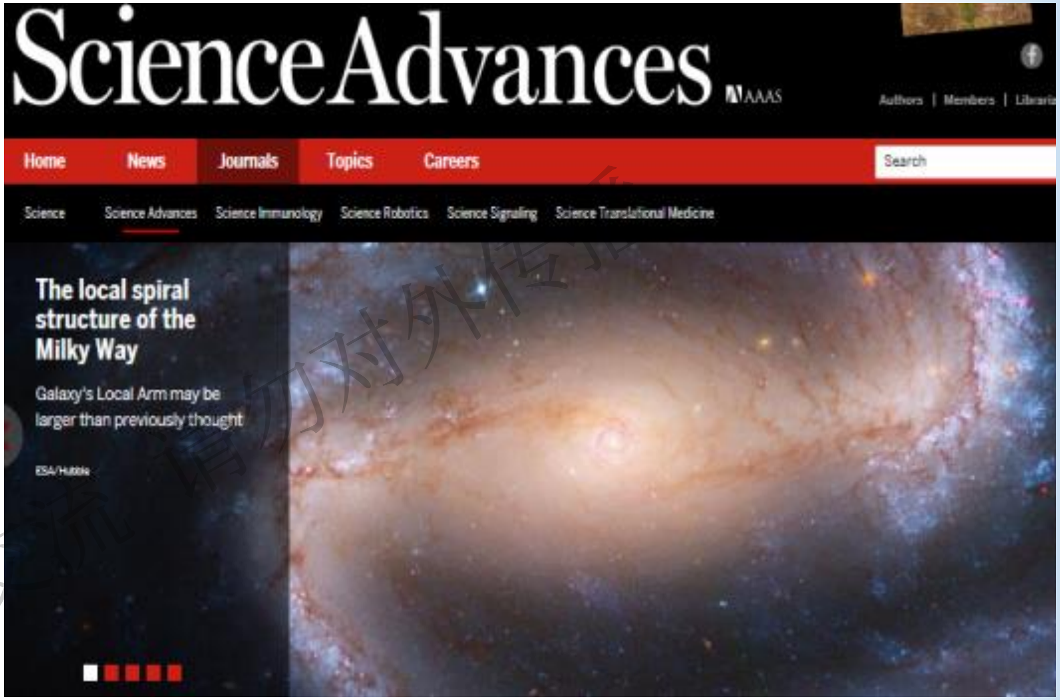
2. 脉泽示踪本地臂



颠覆银河系旋臂结构认知

直接测量银河系旋臂结构变为现实



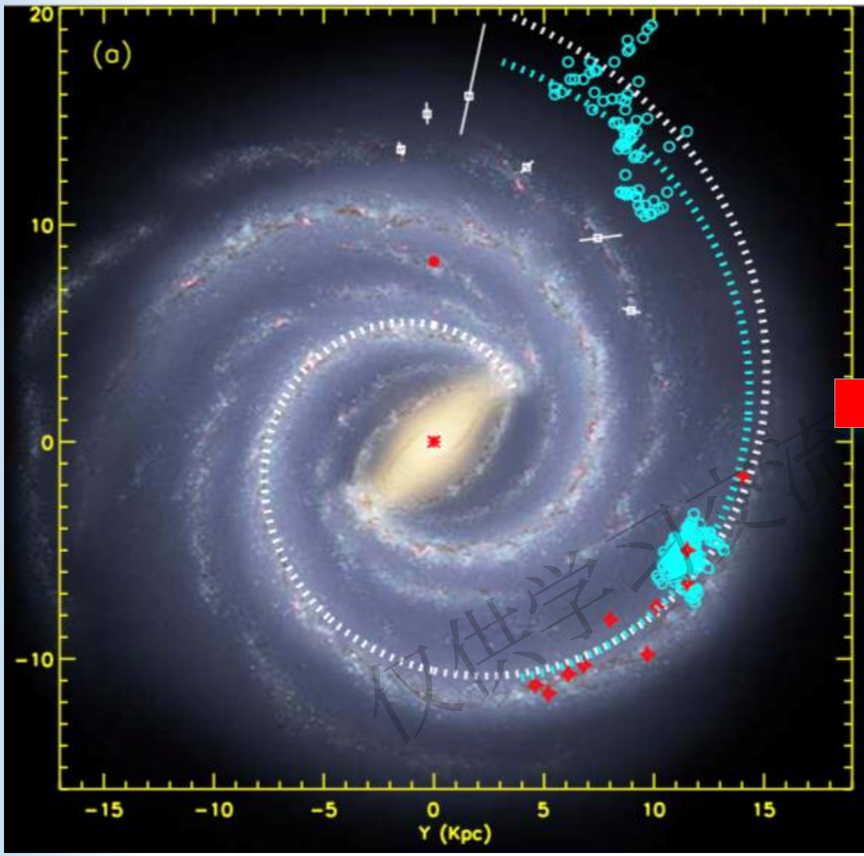


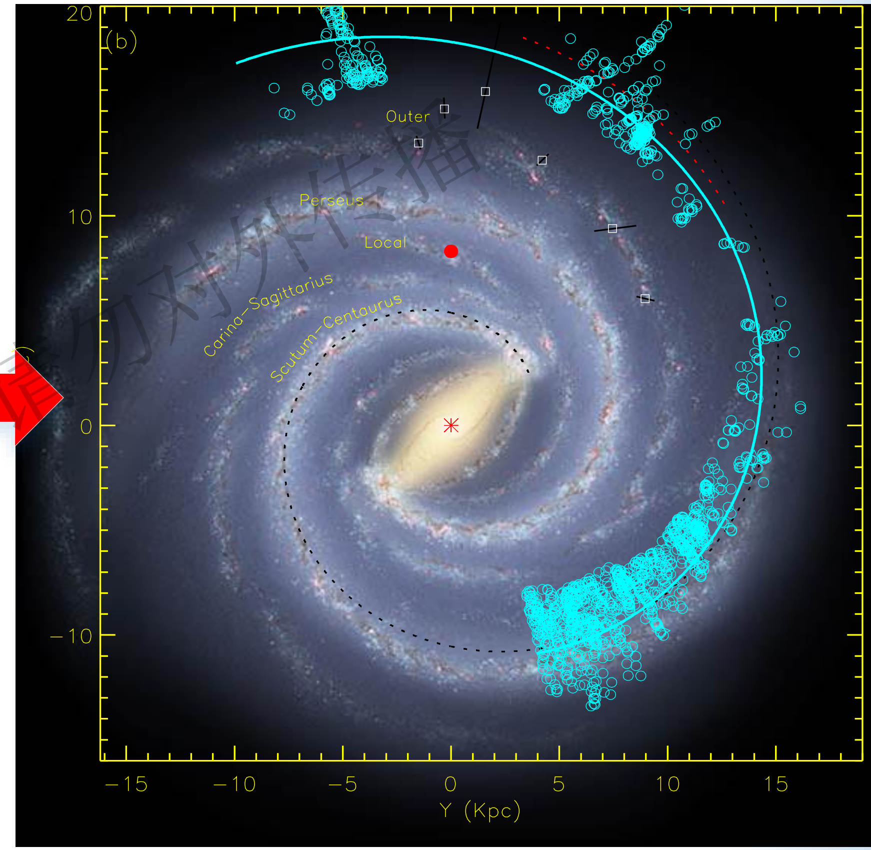
1. 该成果为 2013 年第 222 届美国天文学会上的亮点

2. 2016 年 9 月被《Science Advances》作为亮点工作发表

- 彻底排除了长期以来认为本地臂只是微弱次结构的观点！
- 标志着直接测量银河系旋臂结构变为现实 ！

发现离银心最远的分子气体旋臂





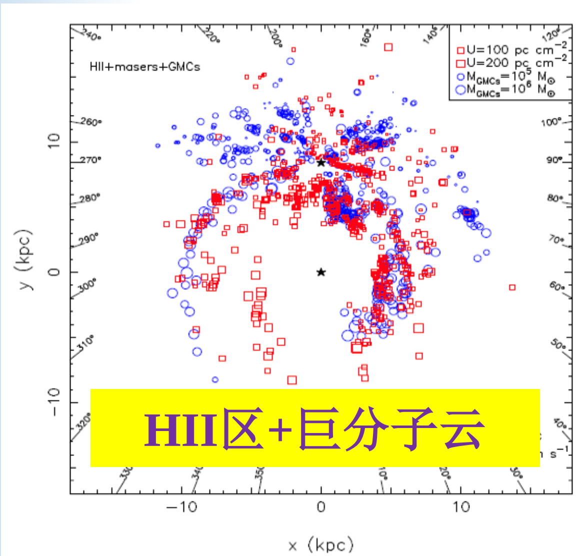
Y. Sun, Y. Xu, J. Yang, et al. 2015, ApJL

Y. Sun, Y. Su, S. Zhang, et al. 2017, ApJS

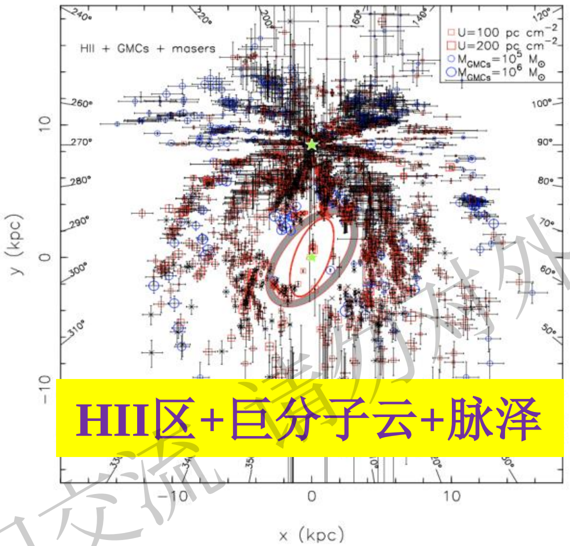
Y. Sun, et al. 2023, in prep.

多波段天体探索银河系整体旋臂结构

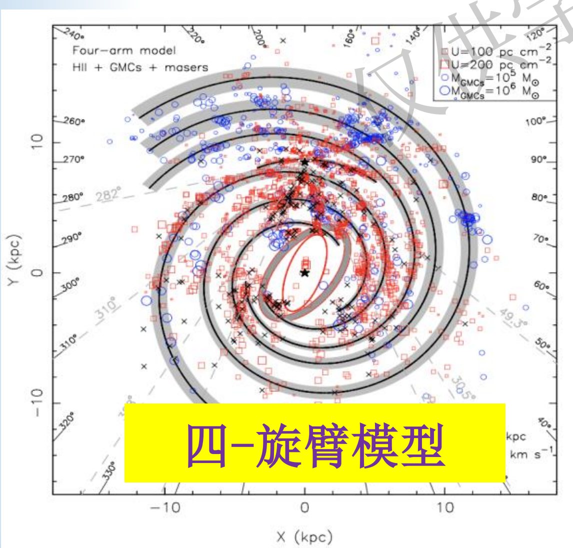
Hou, Han & Shi, 2009, A&A, 499, 473



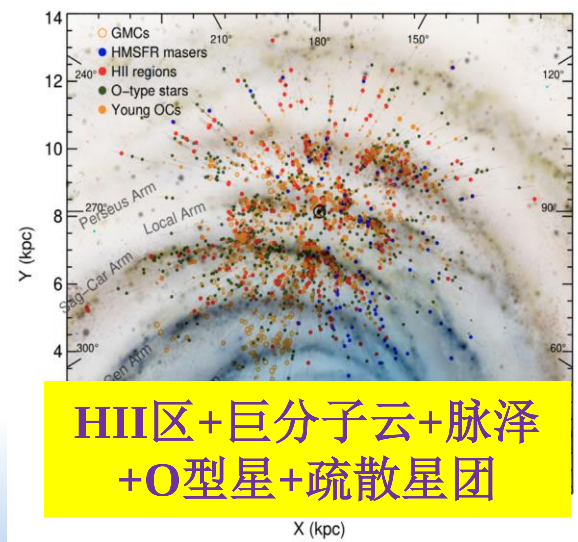
Hou & Han, 2014, A&A, 569, 125



Hou & Han, 2014, A&A, 569, 125



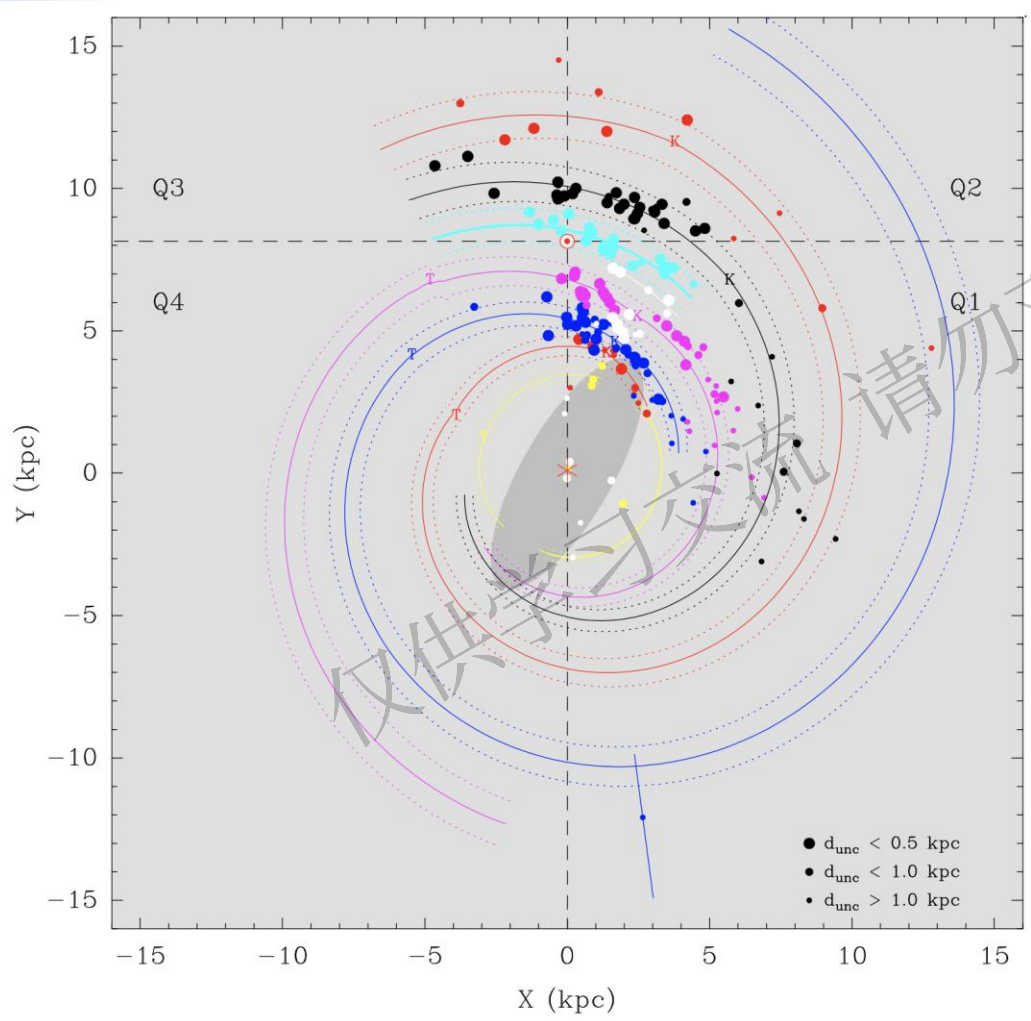
Hou 2021, FrASS, 8, 193 (邀请综述)



国家天文台团队(侯立刚等)：利用多波段、多种示踪天体、多样距离测量，对银河系的旋臂图样、可能的旋臂模型进行了详细研究。

银河系旋臂结构的研究现状

VLBI 天体脉泽示踪的银河系旋臂结构



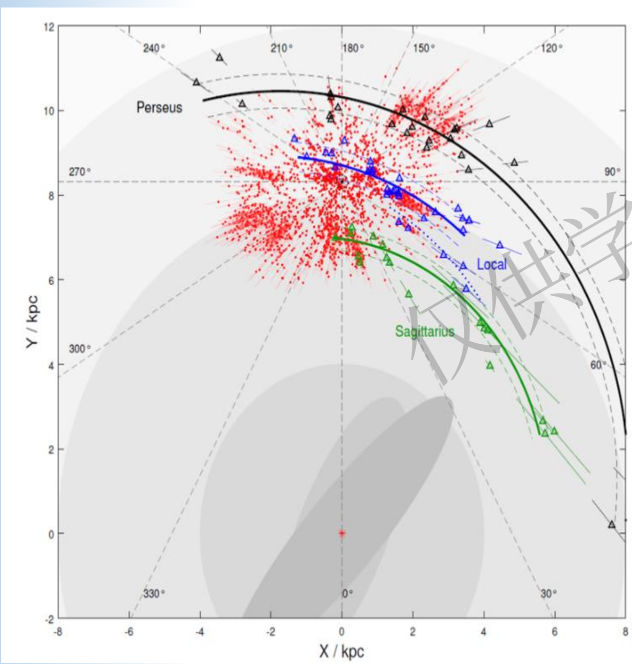
Reid, Menten, Brunthaler et al. 2019, ApJ

- VLBA, VERA & EVN 获得超过 200 个的脉泽；
- 脉泽示踪了银河系的多条旋臂；
- 银河系是一个 four-arm 旋涡星系，旋臂间存在臂段和刺结构；
- 少量脉泽位于旋臂间或银心区域。

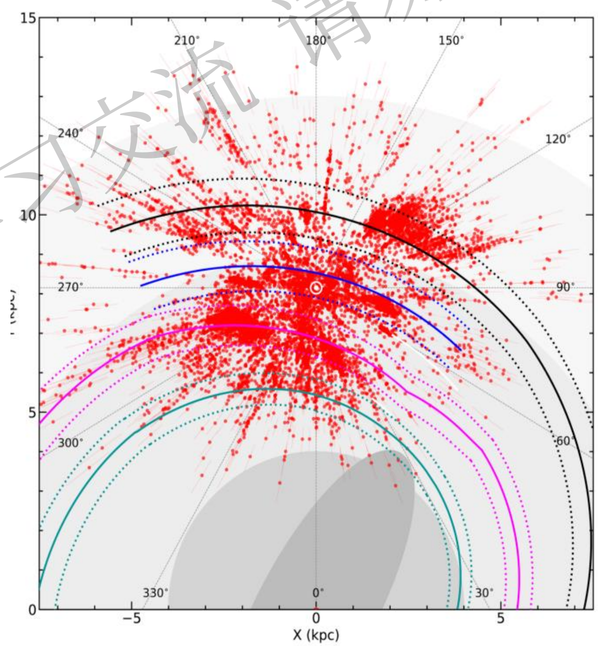
Gaia OB–型星揭示银河系结构

- *Gaia* EDR3 OB 星：太阳 ～5 kpc 内，部分至 ～7 kpc；
- 旋臂延伸到第四象限，证实 2016 年提出的银河系复杂结构的观点；
- 提出银河系旋臂结构不均匀的学术观点；

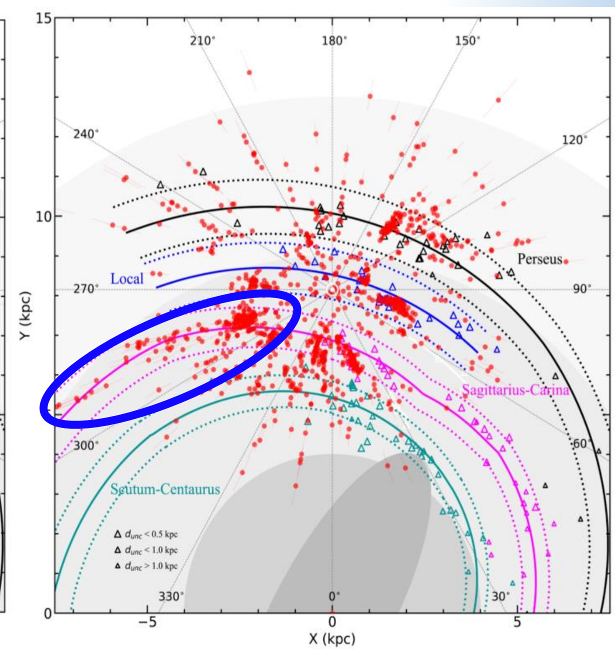
1. *Gaia* DR2: O-B2 型星



2. *Gaia* EDR3: O-B2 型星 (9750)



3. *Gaia* EDR3: O 型星 (1089)



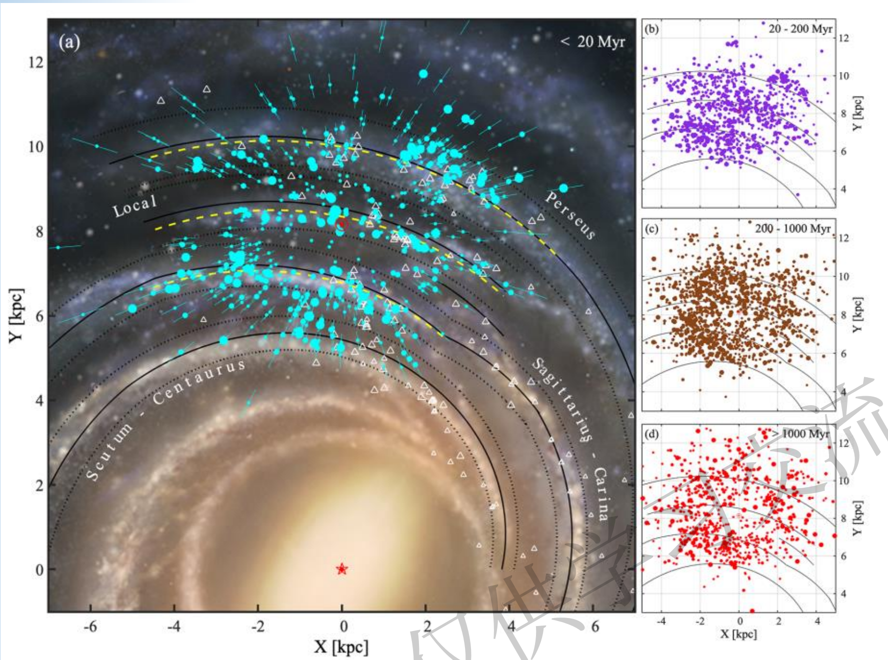
Xu, Bian, Reid et al. 2018, A&A

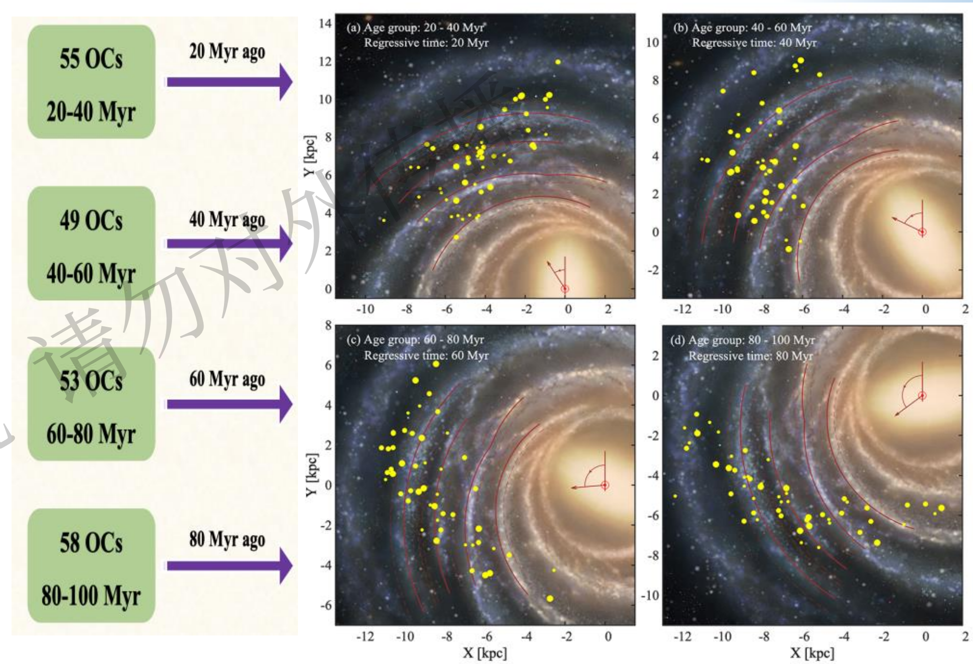
Xu, Hou, Bian et al. 2021, A&A

Gaia 疏散星团研究银河系旋臂的演化

1. 不同年龄疏散星团的分布

2. 疏散星团回归至年轻时的分布



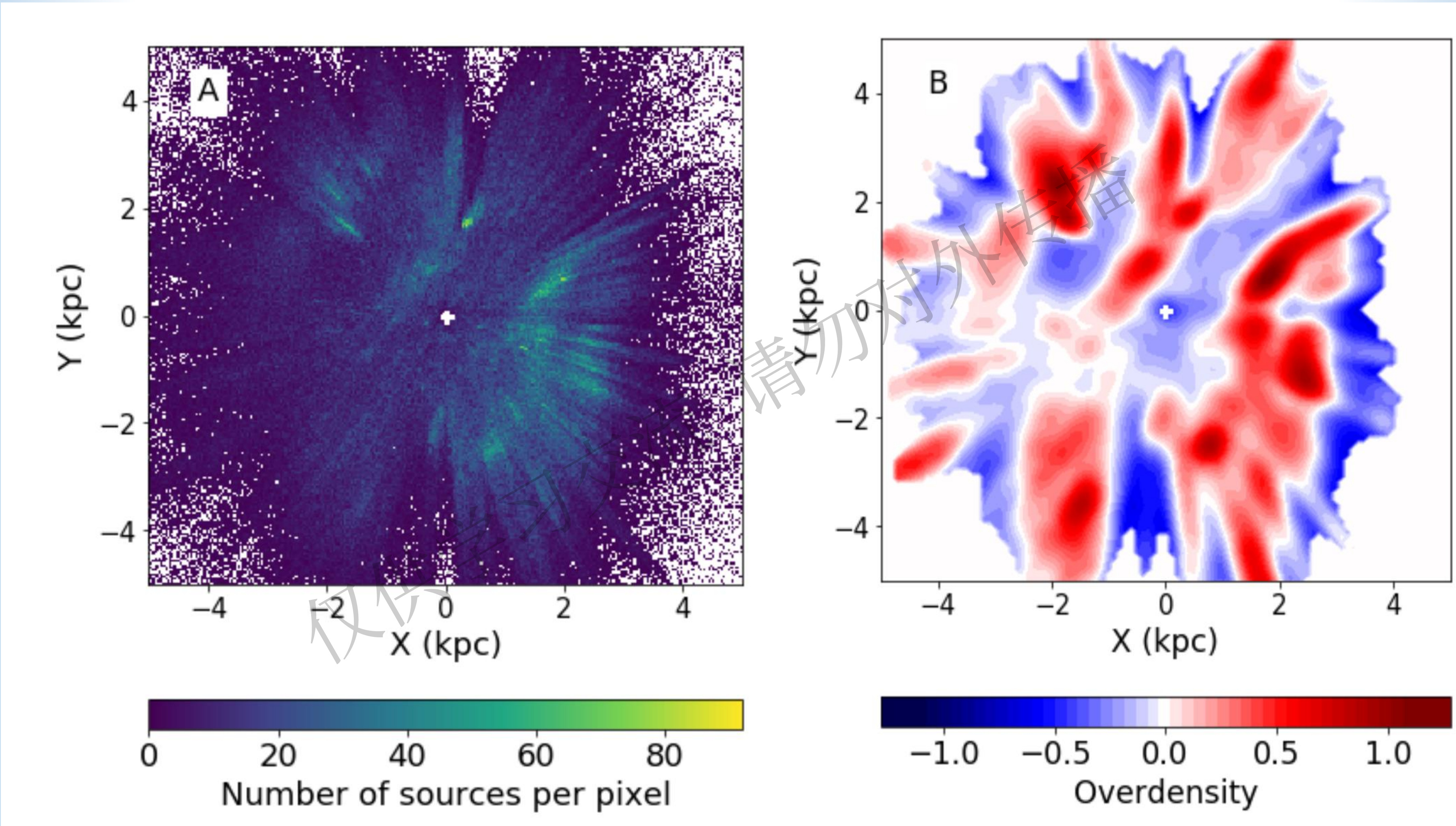


Hao, Xu, Hou et al. 2021, A&A

- 太阳附近旋臂结构符合长期存在的旋涡图案特性；
- 经典密度波理论更适合我们的银河系。

- 动态旋臂机制
- 密度波理论 ✓

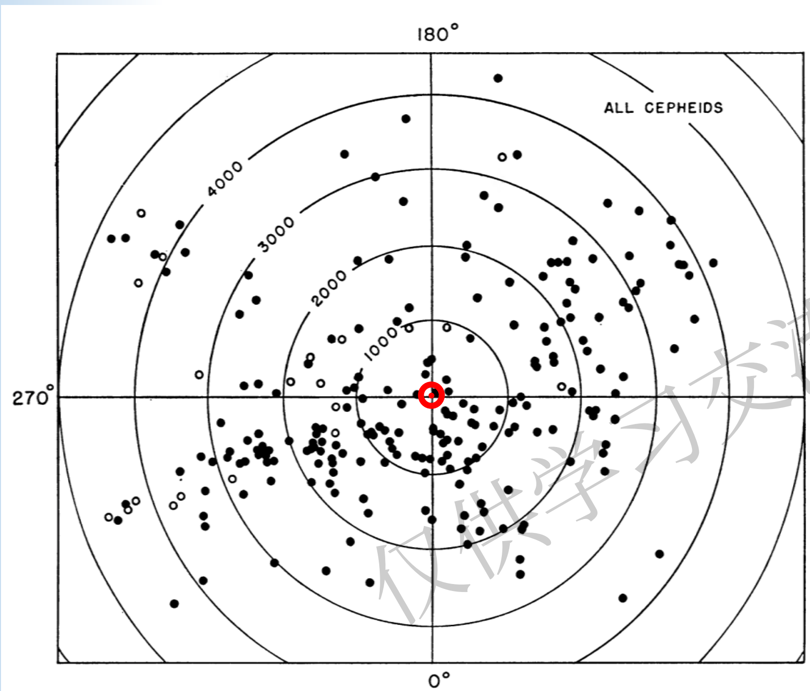
Gaia 上主序星示踪银河系旋臂结构



Poggio, Drimmel, Cantat-Gaudin, et al. 2021, A&A

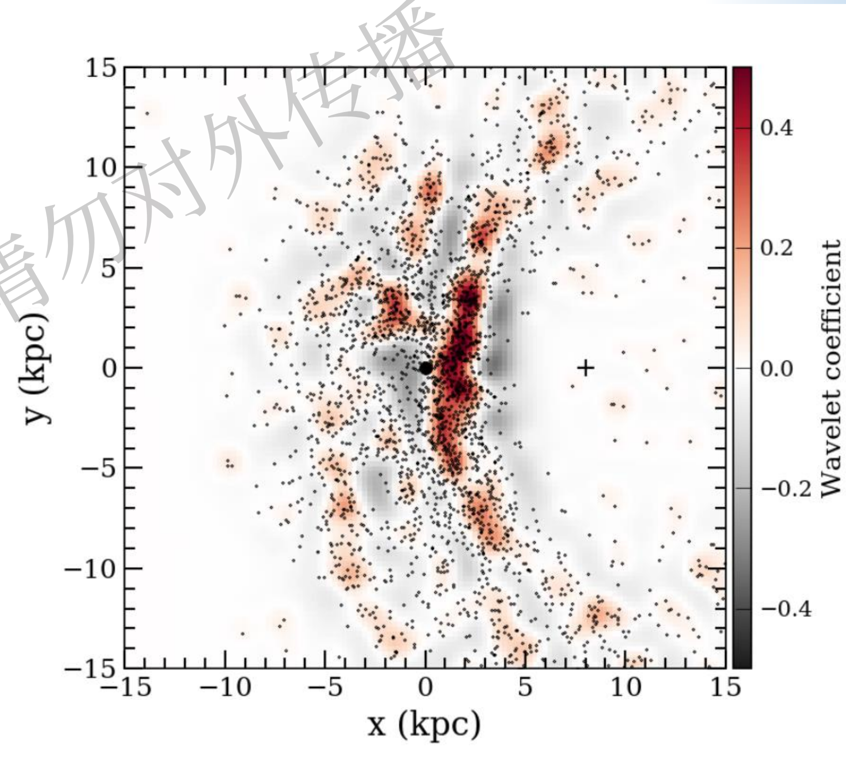
Gaia 造父变星示踪银河系旋臂结构

1. 早期研究中造父变星的分布



Kraft 1963

2. *Gaia* 卫星中造父变星示踪的旋臂

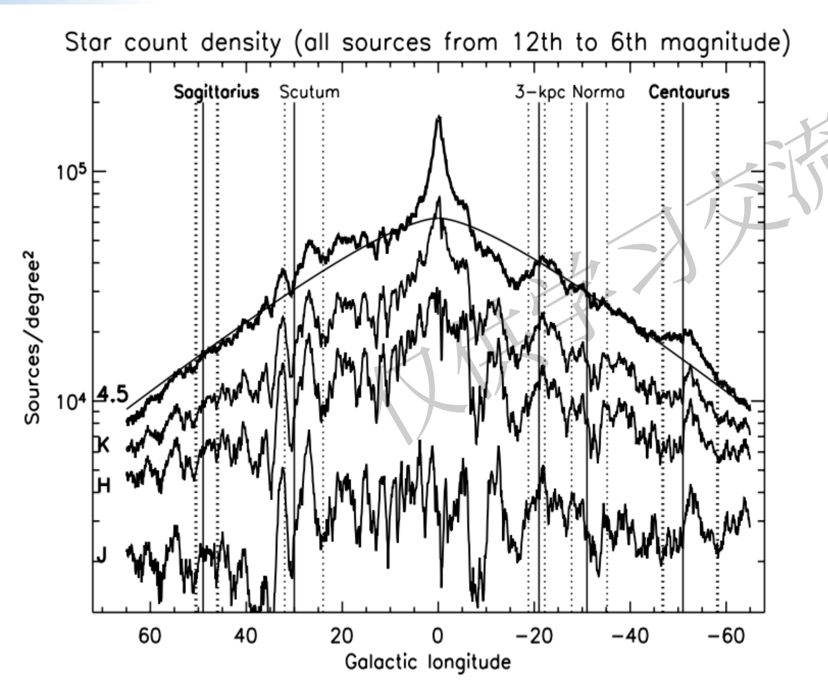


Gaia Collaboration: R. Drimmel, et al. 2022

Gaia 红团簇星示踪银河系旋臂结构

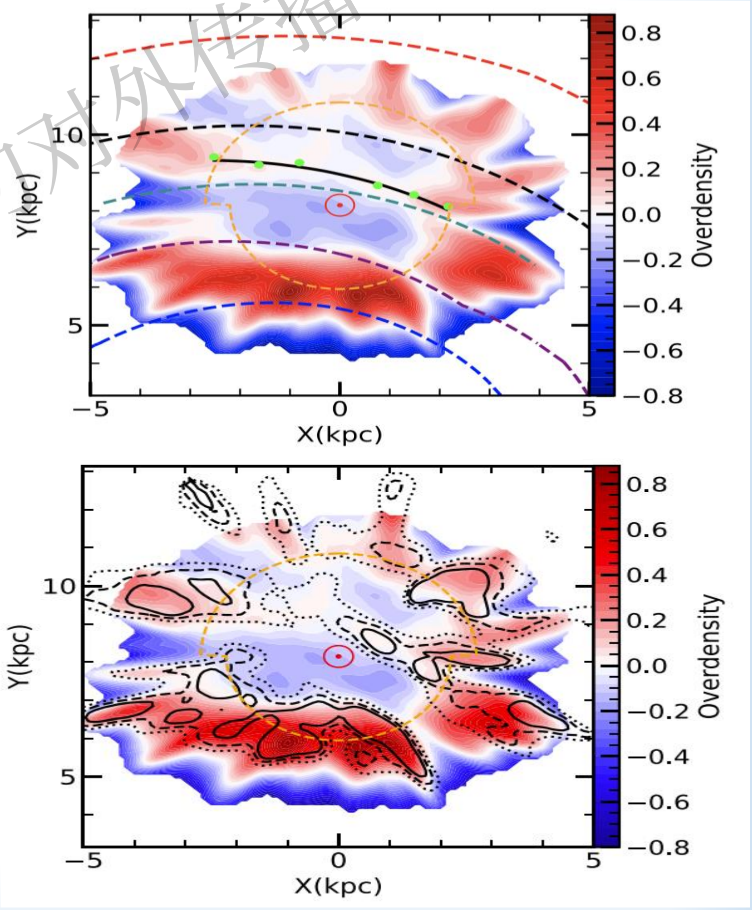
- 首次精确描绘晚型星所示踪的太阳附近的银河系旋臂结构；
- 年老的红团簇星与年轻天体示踪的旋臂之间存在偏移，而且旋臂缠绕的更松散。

过 去



Churchwell, Babler, Meade et al. 2009, PASP

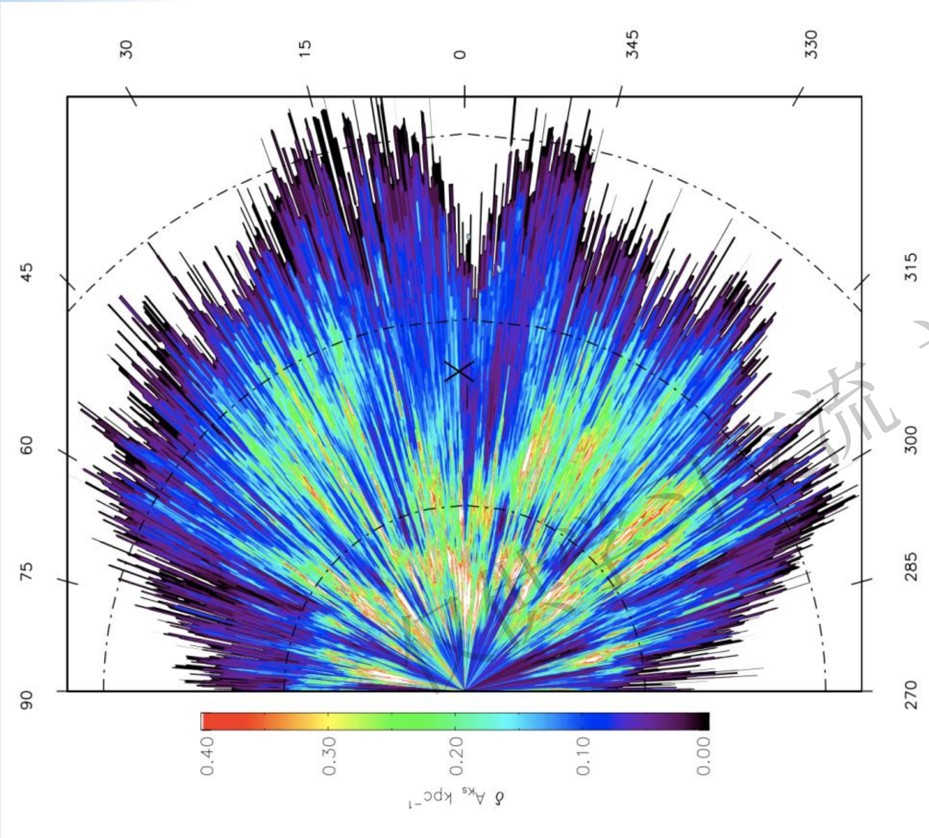
现 在



Lin, Xu, Hou et al. 2022, ApJ

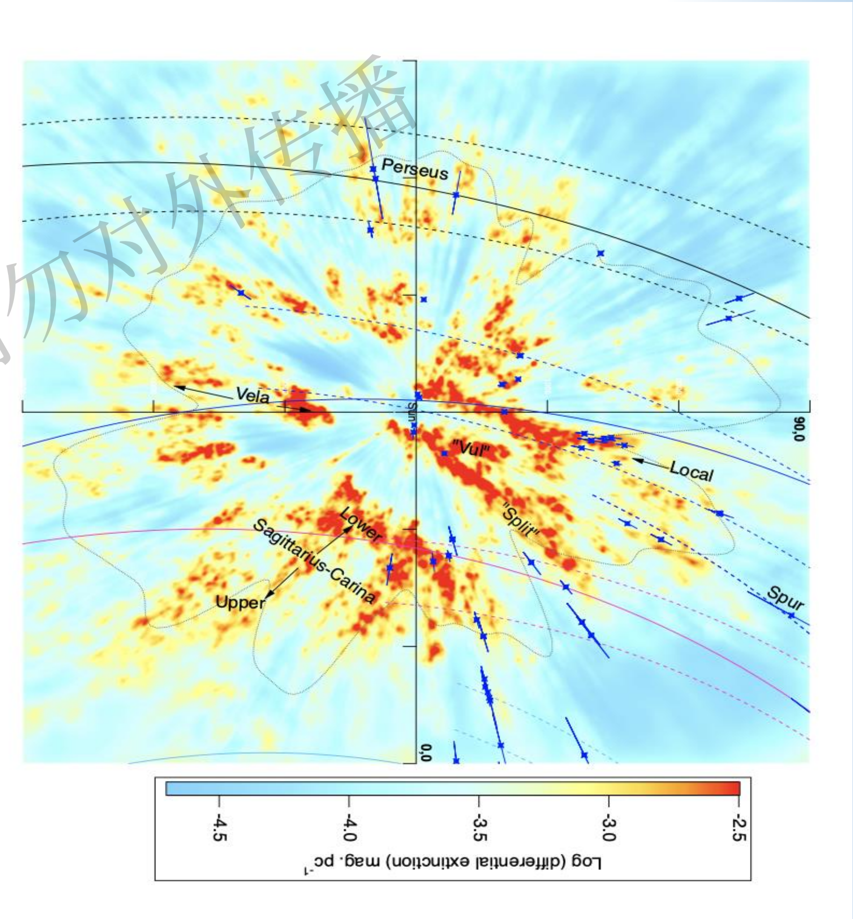
Gaia 获得的尘埃分布示踪的银河系旋臂结构

1. 2MASS 获得的尘埃分布



Marshall1, Robin, Reyle et al. 2006

2. *Gaia* 获得的尘埃分布所描绘的旋臂

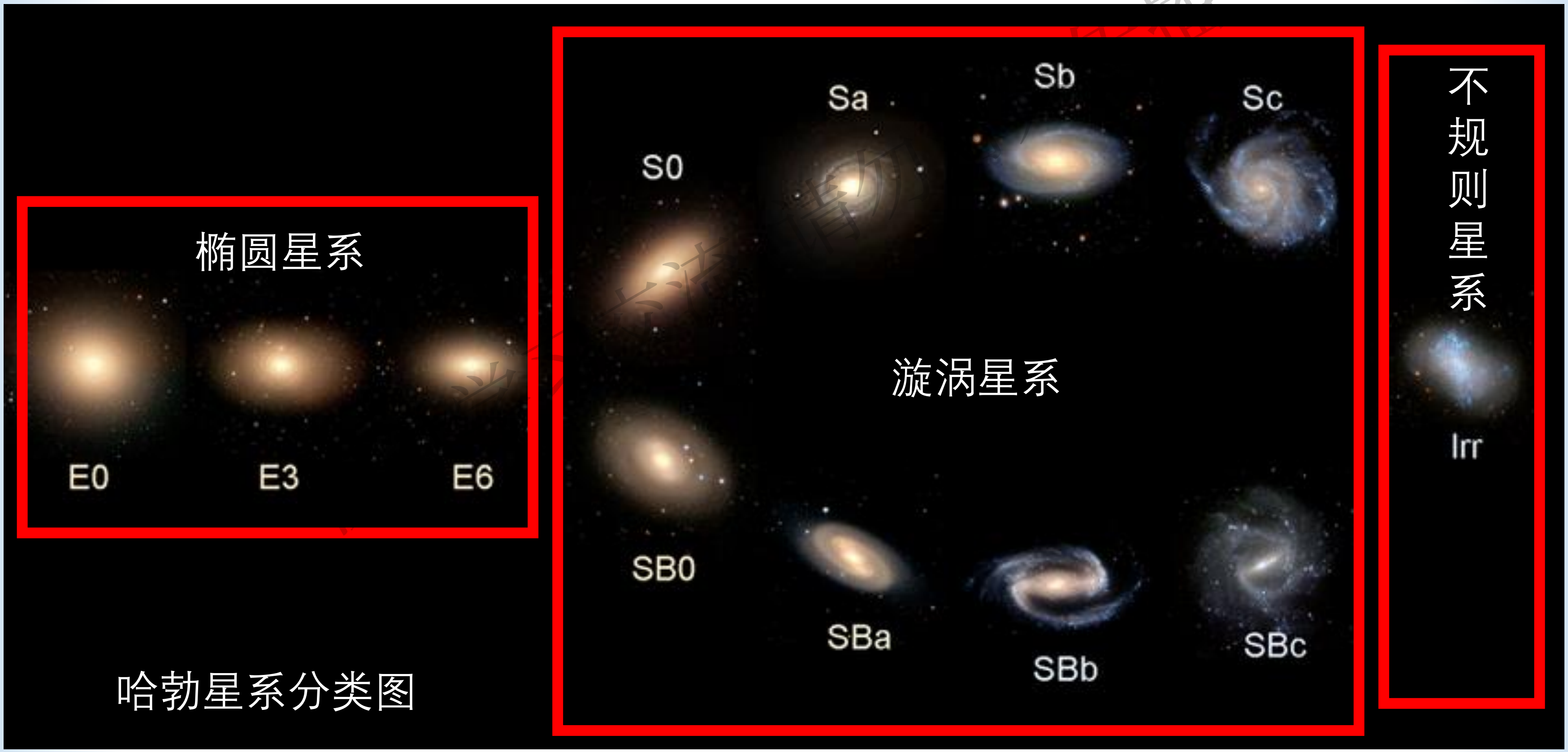


Lallement, Babusiaux, Vergely et al. 2022

银河系旋臂结构的研究挑战

河外星系形态

绝大多数星系都是漩涡星系！

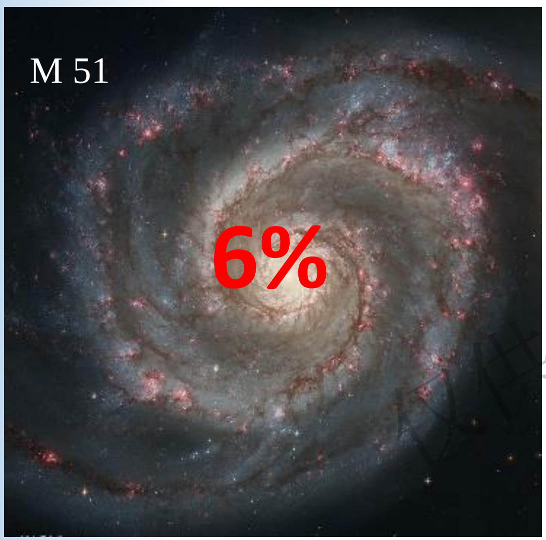


河外星系形态

大量河外旋涡星系统计表明旋涡星系存在

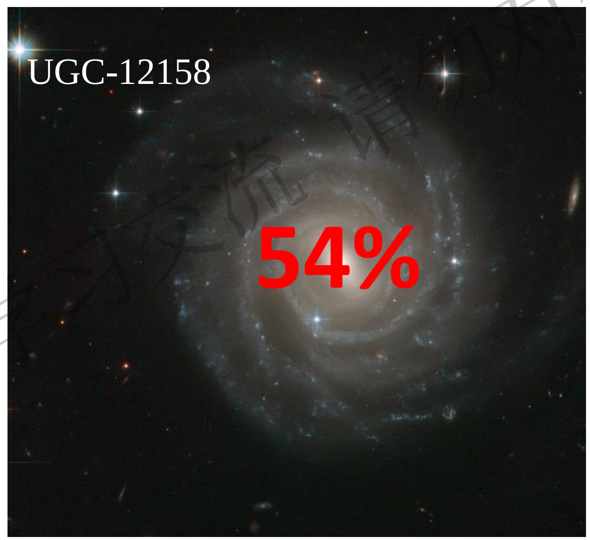
三种星系形态

1. grand-design



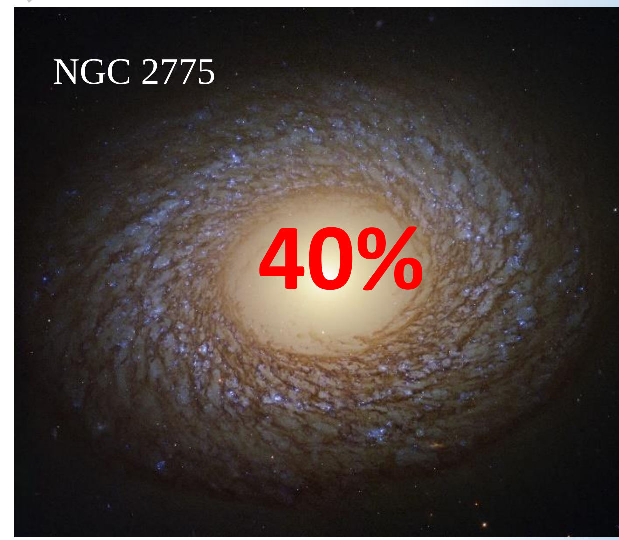
两旋臂从内到外高度对称

2. multiple-arm



内部两旋臂外部多旋臂

3. flocculent

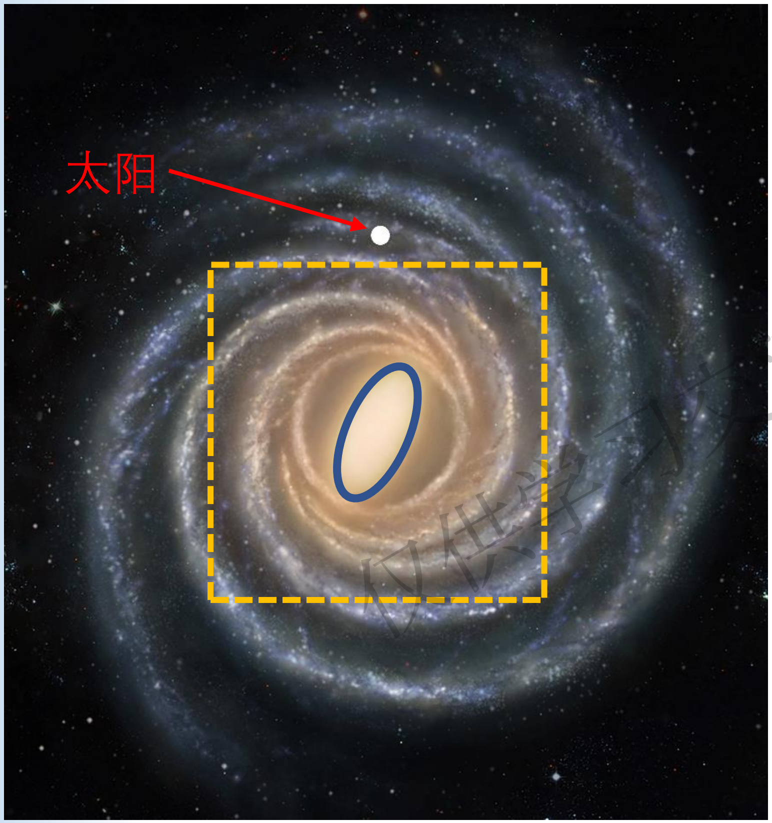


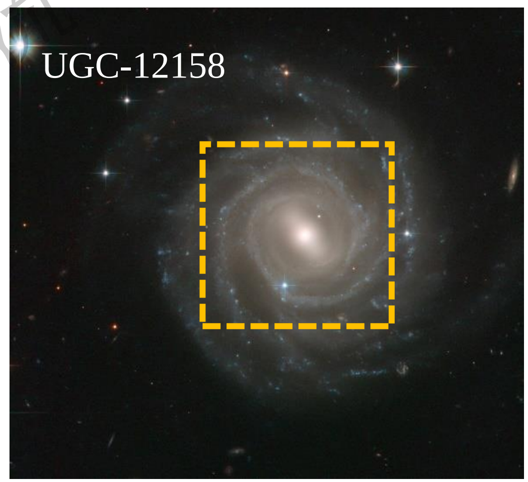
短、不规则、零碎的臂段

银河系形态（想象）

特征：
多旋臂
中心有棒

推测 → 多旋臂星系



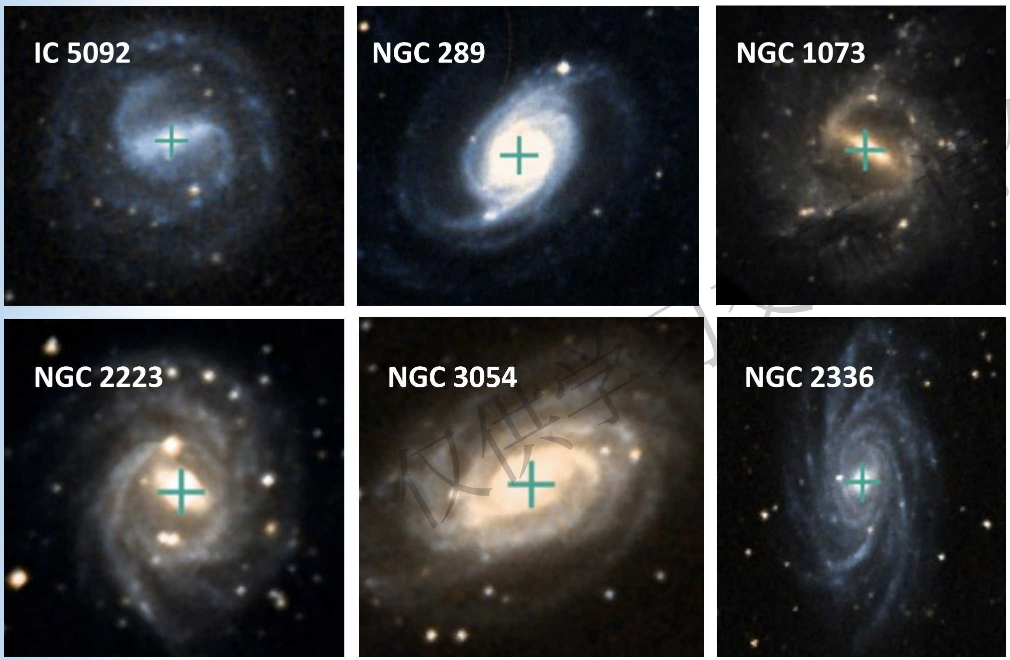


银河系想象图中内部多旋臂

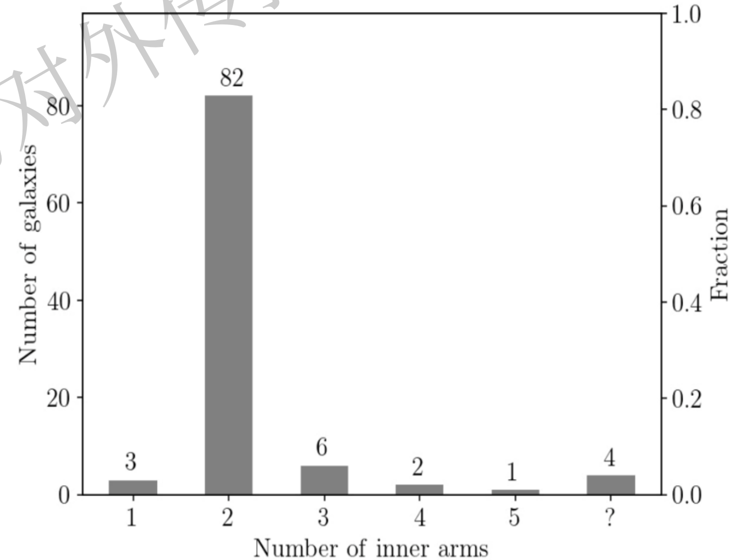
多旋臂星系内部只有两条旋臂

类银河系的河外星系统计

99 个类银河系星系（SBbc or SBc）



类银河系星系内部旋臂数目



Xu Y., et al. 2023, revised version submitted

83% 是内部两旋臂

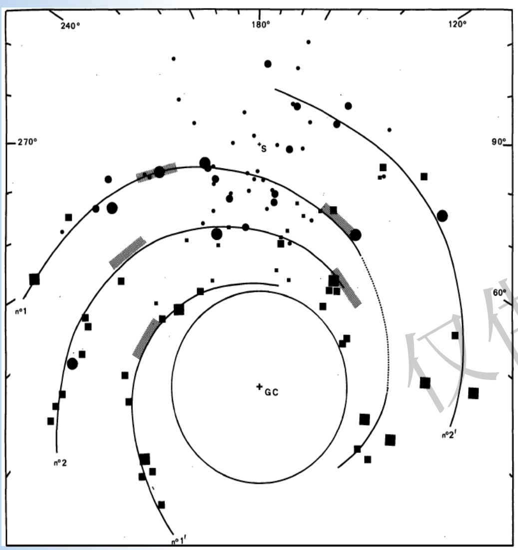
只有 2% 是内部四旋臂

银河系旋臂结构模型的争论

当前广泛认识的模型：
银河系是从内到外的四旋臂结构

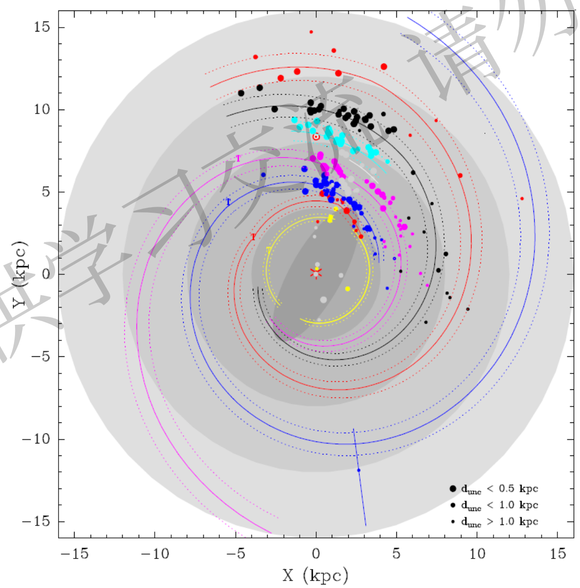
基于 VLBI 脉泽和*Gaia*年轻天体
银河系是 multiple-arm 的形态

银河系旋臂标准模型

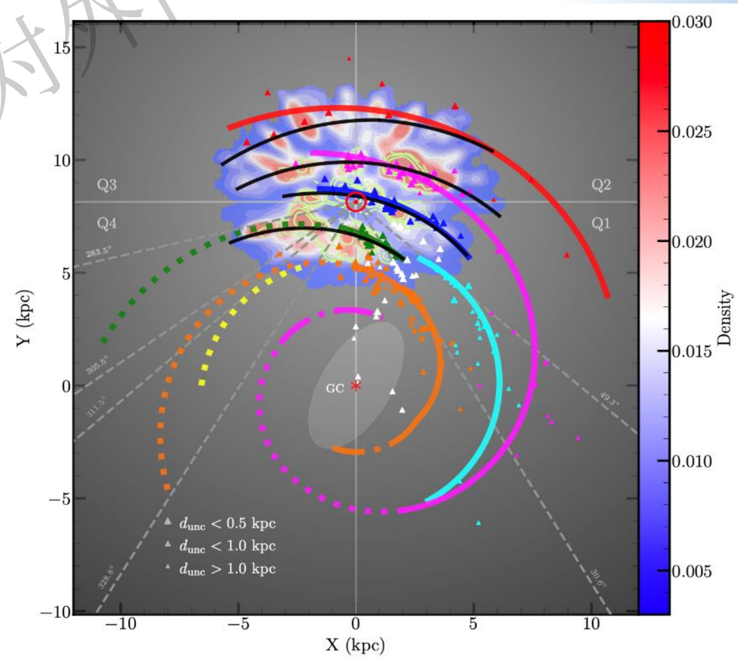


Georgelin & Georgelin 1976
(引用**700+**次)

VLBI 三角视差四旋臂模型



Reid M. J., et al. 2019
(引用**301**次)



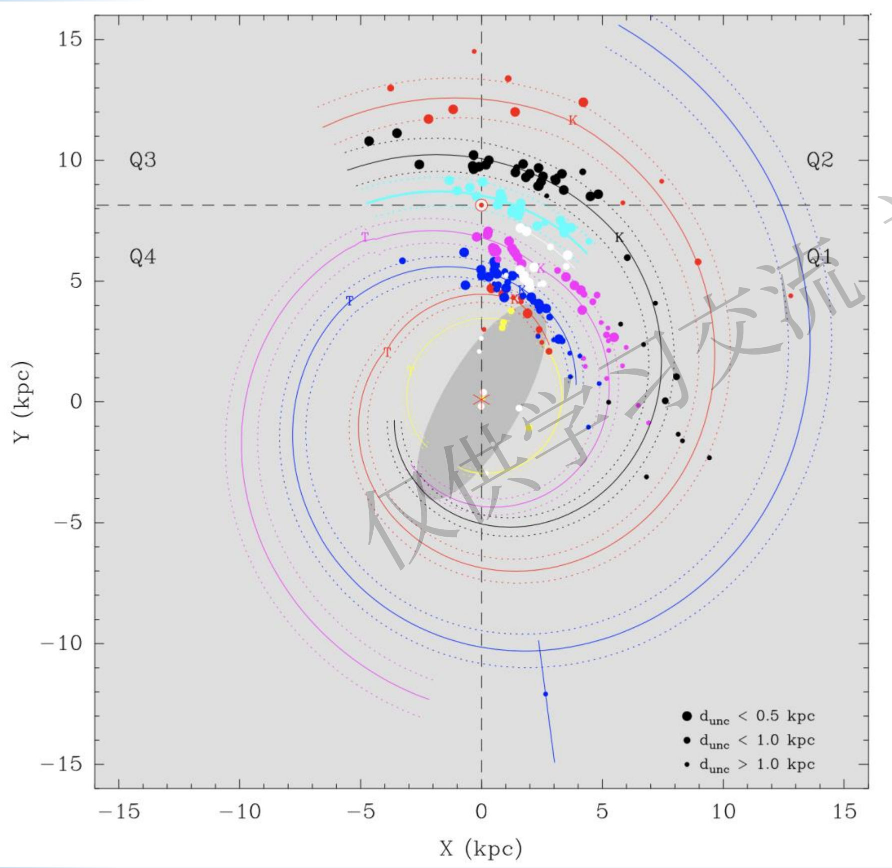
Xu Y., et al. 2023, revised version submitted

内部两臂 + 外部多臂的结构

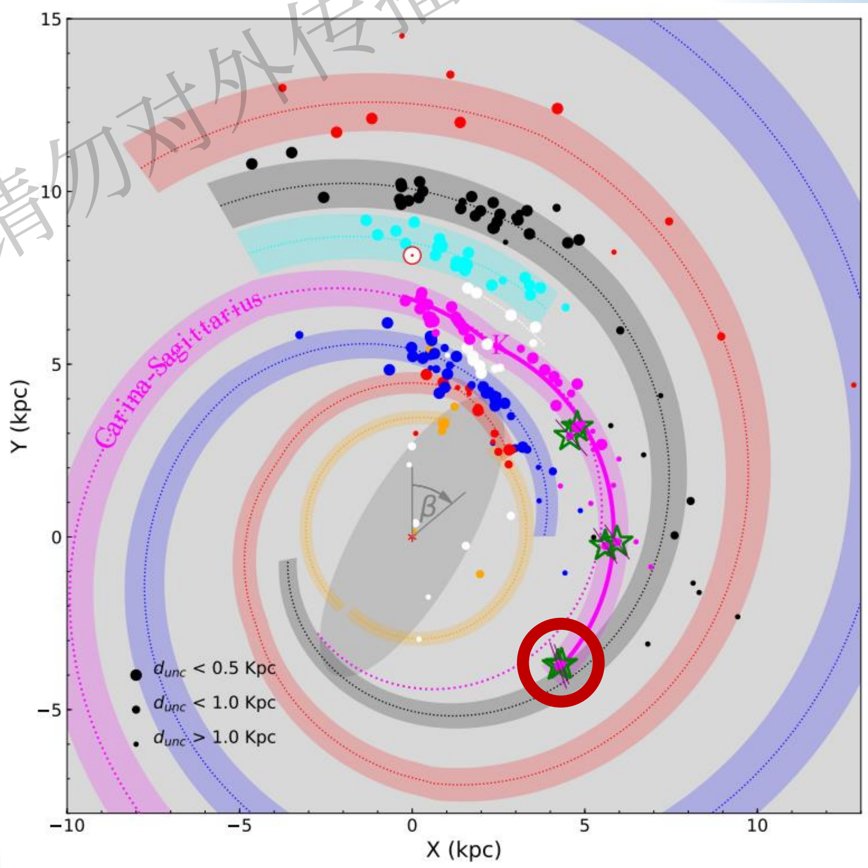
银河系旋臂结构形态的新构想

1. Reid19 模型：人马臂与英仙臂不相交 **“基于猜想”**

2. 本项目：人马臂与英仙臂相交 **“基于实测，远至 13 kpc的高精度天体测量”**



Reid, Menten, Brunthaler et al. 2019, ApJ



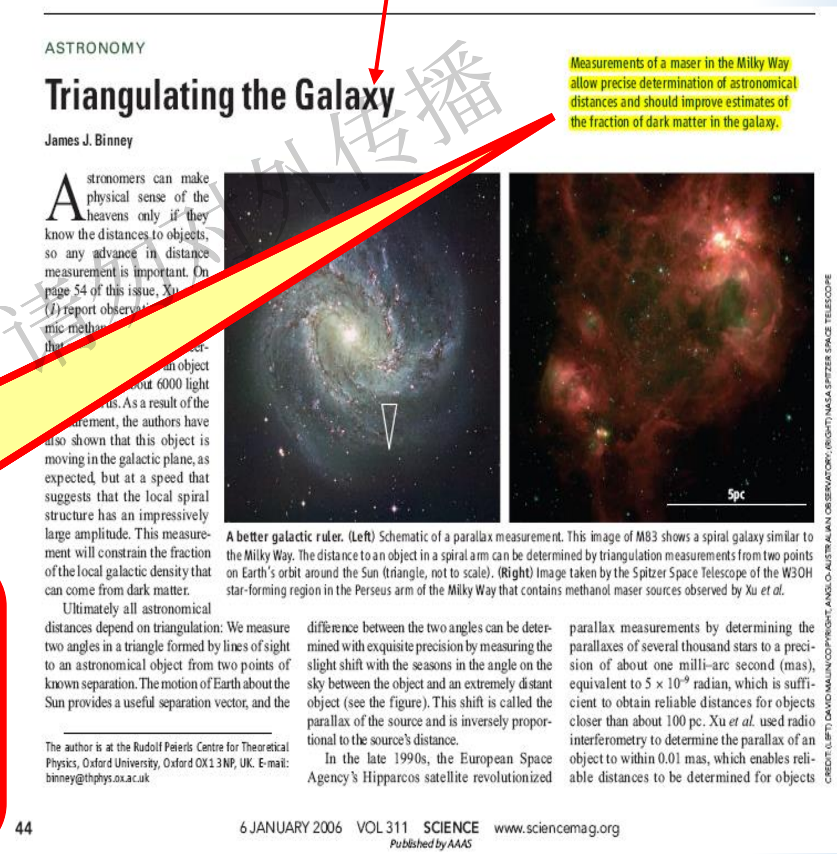
Bian, Wu, Xu et al. 2023, in preparation

国际影响与评价

有利于正确估计银河系中暗物质比重

《Science》同期发表专题评论文章“三角视差测量银河系”

英国皇家学会院士、银河系结构和动力学方面的权威James J. Binney发表专刊评论，全面评价了项目的科学意义。


ASTRONOMY

Triangulating the Galaxy

James J. Binney

Measurements of a maser in the Milky Way allow precise determination of astronomical distances and should improve estimates of the fraction of dark matter in the galaxy.

Astronomers can make physical sense of the heavens only if they know the distances to objects, so any advance in distance measurement is important. On page 54 of this issue, Xu (1) report observ… mic methan… that … cer- … an object … out 6000 light … us. As a result of the …rement, the authors have also shown that this object is moving in the galactic plane, as expected, but at a speed that suggests that the local spiral structure has an impressively large amplitude. This measurement will constrain the fraction of the local galactic density that can come from dark matter.

Ultimately all astronomical distances depend on triangulation: We measure two angles in a triangle formed by lines of sight to an astronomical object from two points of known separation. The motion of Earth about the Sun provides a useful separation vector, and the difference between the two angles can be determined with exquisite precision by measuring the slight shift with the seasons in the angle on the sky between the object and an extremely distant object (see the figure). This shift is called the parallax of the source and is inversely proportional to the source's distance.

In the late 1990s, the European Space Agency's Hipparcos satellite revolutionized parallax measurements by determining the parallaxes of several thousand stars to a precision of about one milli–arc second (mas), equivalent to 5×10^{-9} radian, which is sufficient to obtain reliable distances for objects closer than about 100 pc. Xu *et al.* used radio interferometry to determine the parallax of an object to within 0.01 mas, which enables reliable distances to be determined for objects

5pc

A better galactic ruler. (Left) Schematic of a parallax measurement. This image of M83 shows a spiral galaxy similar to the Milky Way. The distance to an object in a spiral arm can be determined by triangulation measurements from two points on Earth's orbit around the Sun (triangle, not to scale). **(Right)** Image taken by the Spitzer Space Telescope of the W3OH star-forming region in the Perseus arm of the Milky Way that contains methanol maser sources observed by Xu *et al.*

CREDIT: (LEFT) DAVID MALIN/COPYRIGHT, ANGLO-AUSTRALIAN OBSERVATORY; (RIGHT) NASA SPITZER SPACE TELESCOPE

The author is at the Rudolf Peierls Centre for Theoretical Physics, Oxford University, Oxford OX1 3NP, UK. E-mail: binney@thphys.ox.ac.uk

副标题：“脉泽测量有利于精确测定天文学距离，正确估计暗物质在银河系中所占的比重 ”

Science (2006), 311, 44

开创了三角视差测量的新纪元

closer than 10 kpc, slightly in excess of the dis-
tance to the galactic ce
precision because t
ferometer are on di
turn is made possib
brightness of many

The successor to
uled to be launched
it will be yielding
precision for tens
fortunately, Gaia
wavelengths, with t
of the galactic plan
from it by dust. Ra
of masers are not h
decade from now t
by Xu *et al.* will be

The masers obs
star-forming region
Perseus spiral arm
measurements of th
this region, together
is on a circular orbit
yield a distance of 4.2
great as the distance estimated from the brightness of some of the region's stars (2.2 kpc). Xu *et al.* find the distance to be 1.95 kpc and thus demonstrate that the region is not on a circular orbit. The results of Xu *et al.* complement the known line-of-sight velocity with the velocity
of the sky, and they show that
ing in the galactic plane at about
h respect to the circular orbit
tion. This velocity differential is
dispersion of star-form-
W3OH proba-
by
substantial fraction
mass would have to be concen-
sk rather than the dark halo, and
n density contrast of the Galaxy's
ould have to be at the upper end
ed range.
irst clear near-infrared images of
were made about a decade ago,
ere surprised by the large ampli-
rals seen in them (3). Given that
uminosity is dominated by stars
ntain most of the disk's mass, this
that spiral structure is associated
ctuations. The results of Xu *et al.*
with this picture. Modeling of gravitational microlensing and noncircular motions inside the solar circle has demonstrated that at most a small fraction of the matter in the inner several kiloparsecs of the Galaxy can be in exotic dark matter rather than stars (4, 5). The distance from the galactic center to W3OH is 1.2 times the distance to the Sun, so if the Xu *et al.* datum could be complemented by similar measurements of noncircular motions outside the solar circle, the same argument could be used to constrain dark matter's contribution to the mass budget outside the solar circle, where it is thought to be dominant.

Xu *et al.* have opened up a new era of trigonometric parallaxes by exploiting the enormous surface brightnesses of maser sources. They show that distances can now be determined geometrically to sources that lie within a sphere that extends to beyond the galactic center. The next decade will see a trickle of such measurements that will become a flood around 2015 after Gaia has flown. These measurements will have a big impact on our understanding of what galaxies are and how they work.

James J. Binney
院士在《Science》
文章里高度评价：
“通过观测极高表
面亮度的微波激射
源，徐等人开创了
三角视差测量的新
纪元(new era)。”

References

1. Y. Xu *et al.*, *Science* **311**, 54 (2006); published online 8 December 2005 (10.1126/science.1120914).
2. R. M. Humphreys, *Astrophys. J. Suppl.* **38**, 309 (1978).
3. H.-W. Rix, D. Zaritsky, *Astrophys. J.* **447**, 82 (1995).
4. N. Bissantz, V. Debattista, O. Gerhard, *Astrophys. J.* **601**, L155 (2004).
5. B. Famaey, J. Binney, *Mon. Not. R. Astron. Soc.* **363**, 603 (2005).

10.1126/science.1122245

Science (2006), 311, 44

银河系结构领域的里程碑(2011)

Proceedings "Science with Parkes @ 50 Years Young

UNDERSTANDING OUR GALAXY - KEY CONTRIBUTIONS FROM THE PARKES TELESCOPE.

J. L. Caswell
CSIRO Astronomy and Space Science, ATNF

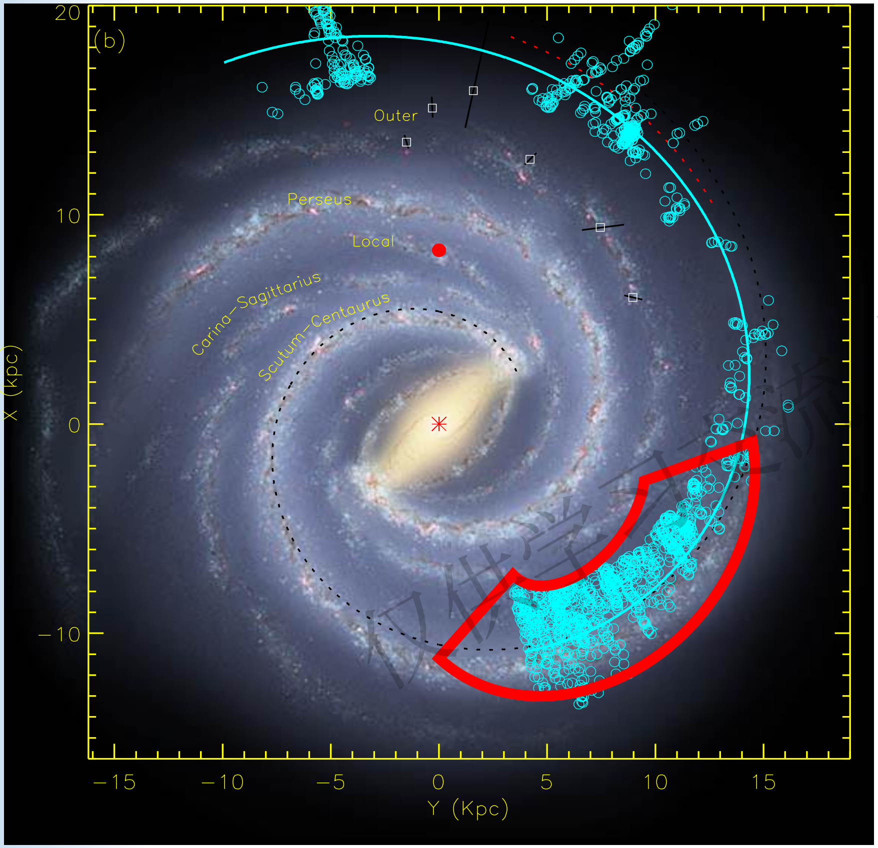
Science with Parkes @ 50 Years Young, 31 Oct. – 4 Nov., 2011

A landmark was achieved in 2006, with a demonstration that VLBI had matured to permit accuracies of better than 0.01 mas (Xu et al. 2006), allowing astrometric parallaxes and precise distance measurements to masers at the Galactic Centre and beyond, extending to the outer edge of the Galaxy (Reid et al. 2009). This achievement with the US VLBA at 12 GHz was shortly matched by similar measurements for 22-GHz water masers (which often accompany methanol masers) using the Japanese array VERA (Honma et al. 2007), and measurements of 6.6-GHz methanol masers using the EVN (Rygl et al. 2010).

So astrometry of masers can now provide a remarkable opportunity to map our Galaxy in detail, to reveal for the first time its precise geometry and velocity field. These are the parameters that must be replicated by a valid dynamical model of the Galaxy. Southern and northern hemisphere telescopes will be needed to acquire the necessary observations and, in these endeavours, Parkes will be a key high sensitivity element in the southern LBA.

银河系领域的权威、澳大利亚Caswell教授在关于银河系结构的综述文章中指出:(银河系结构)的一个里程碑由徐等(2006)实现。测量精度好于 0.01 mas, 能够精确测定超过银心并远至银河系边缘地方。为详细描绘银河系，首次揭示银河系精确的几何结构和速度场提供一个绝佳的机会。

发现离银心最远的分子气体旋臂(2015)



部分专业评论和报导 (关于孙燕等人的工作)

- 《科学美国人》(2015)：

"中国天文学家发现银河系的一条旋臂可能环绕整个银河系，这使得银河系跻身漩涡星系的名流之中"

"出乎我意料的是2011年我们发现了Scutum-Centaurus的新的一段延伸，当时我们认为这已经是旋臂的终点了，所以看到这个发现时我非常震惊"

- Phys.org 亮点报导（2015）

以前所未有的细节描绘旋臂结构(2016)

Detailed imaging of the local Milky Way suggests that it may resemble far-away spiral galaxies.

GALACTIC STRUCTURE

Mapping the local Milky Way

The spiral structures of far-away galaxies are among the most familiar celestial features. Viewed from within, the structure of our own Milky Way galaxy is harder to appreciate. Interstellar dust also makes it difficult to measure distances between stars in our galaxy with optical astronomy. Using radio astronomy, Xu *et al.* mapped the nearest spiral arm of the Milky Way in unprecedented detail. This approach helps constrain its size and orientation, as well as the rate of star formation within our galaxy. —KVH

Sci. Adv. 10.1126.sciadv.1600878 (2016).

Science (2016), 353, 1509

"徐等以前所未有的细节（in unprecedented detail）描绘了银河系内离我们最近的旋臂。他们所使用的方法有助于确定银河系的大小和运动，以及银河系内的恒星形成率。"

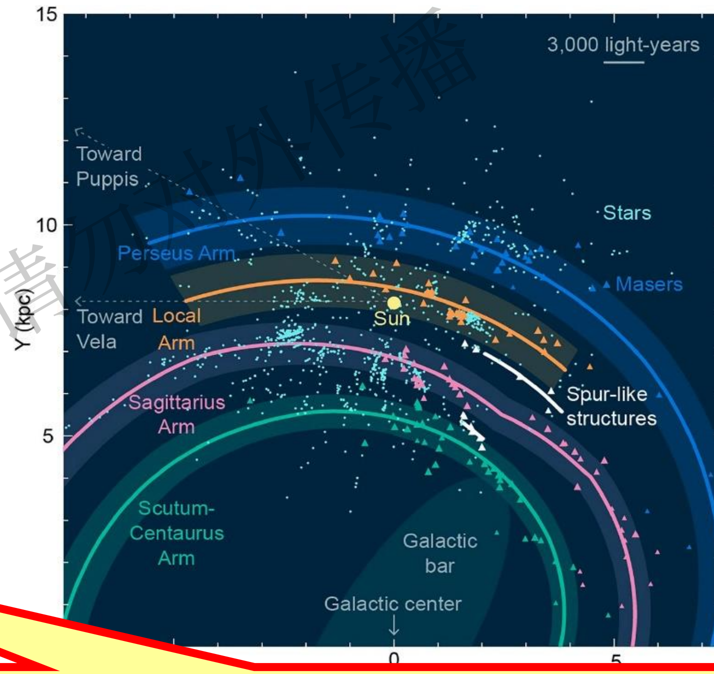
银河系最新图像(2021)

PNAS 直接引用为银河系最新结构图

PNAS Proceedings of the National Academy of Sciences of the United States of America

Ken Croswell, 2021, PNAS

"Remarkably, the Local Arm traced by the distribution of O-type stars is distinct, it extends much longer than previously expected, and it seems more similar to a major spiral arm feature," writes a team led by Ye Xu at the Purple Mountain Observatory in Nanjing, China (6). Xu thinks that the Milky Way's arms resemble those of the beautiful spiral galaxy M101. From the new Gaia data, he estimates the Local Arm to be at least 25,000 light-years long, agreeing with Reid's assessment from the maser parallaxes.



由紫金山天文台徐烨领导的团队认为银河系类似美丽的旋涡星系M101.

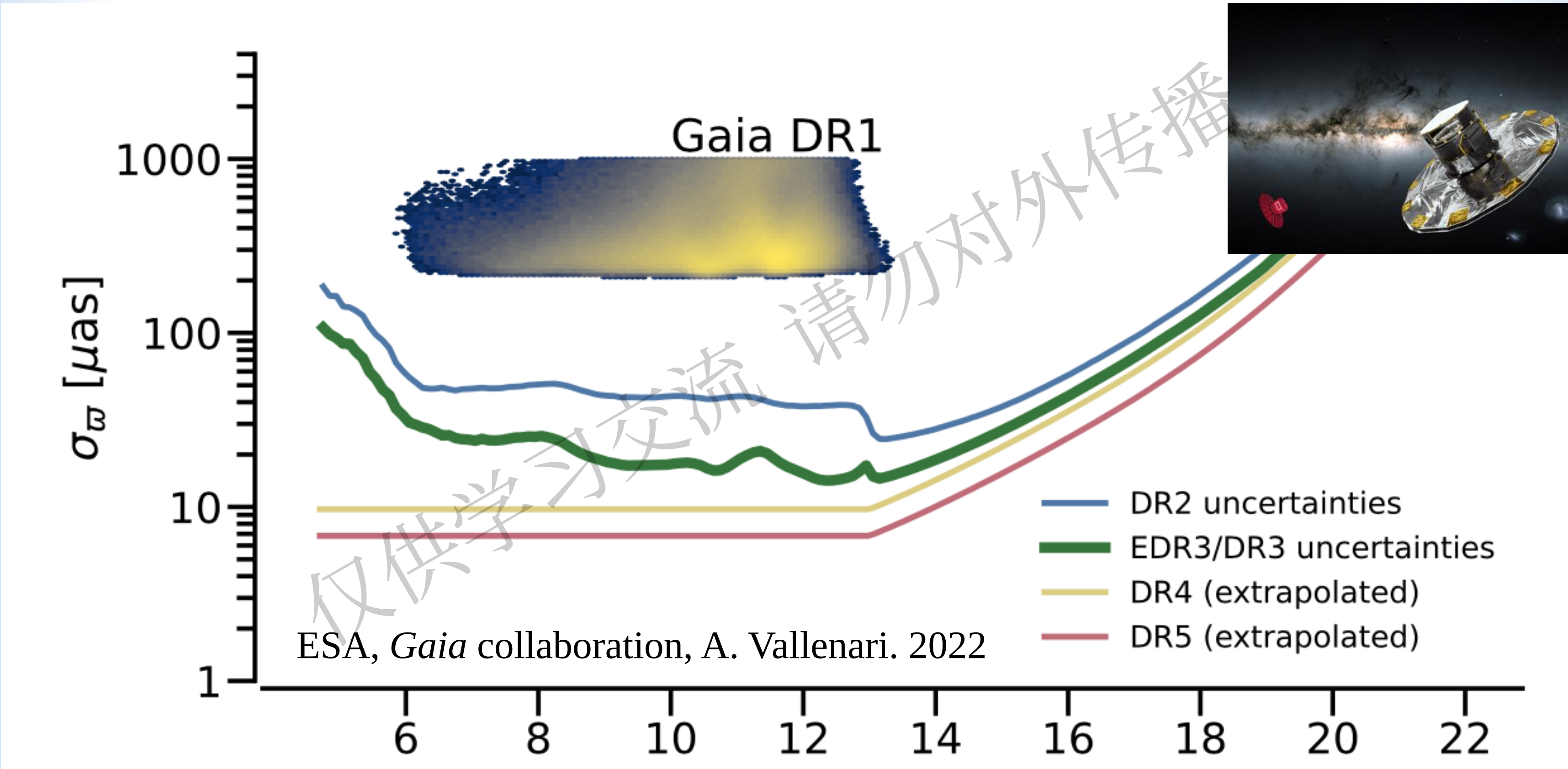
1 W. W. Morgan, S. Sharpless, D. Osterbrock, Some features of
2 W. W. Morgan, A. E. Whitford, A. D. Code, Studies in Galacti
blue giants. *Astrophys. J.* **118**, 318–322 (1953).
3 Y. M. Georgelin, Y. P. Georgelin, The spiral structure of our G
4 Y. Xu *et al.*, On the nature of the local spiral arm of the Milky
5 M. J. Reid *et al.*, Trigonometric parallaxes of high-mass star-for
6 Y. Xu *et al.*, Local spiral structure based on the Gaia EDR3 parallaxes. *Astron. Astrophys.* **645**, L8 (2021).
7 E. Poggio *et al.*, Galactic spiral structure revealed by Gaia EDR3. *Astron. Astrophys.* **651**, A104 (2021).

文中列出的 7 篇文章中，两篇是项目组 PI 为第一作者

银河系旋臂结构的研究未来

Gaia 天体测量

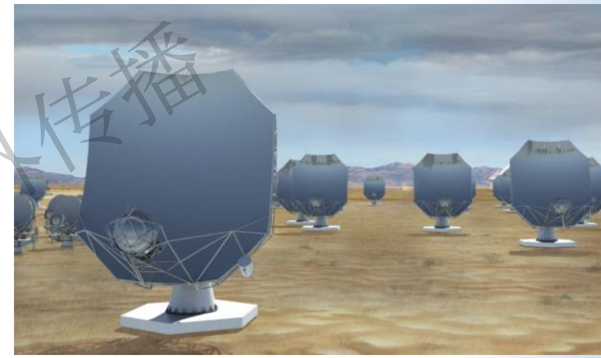
Gaia 卫星数据的预期精度



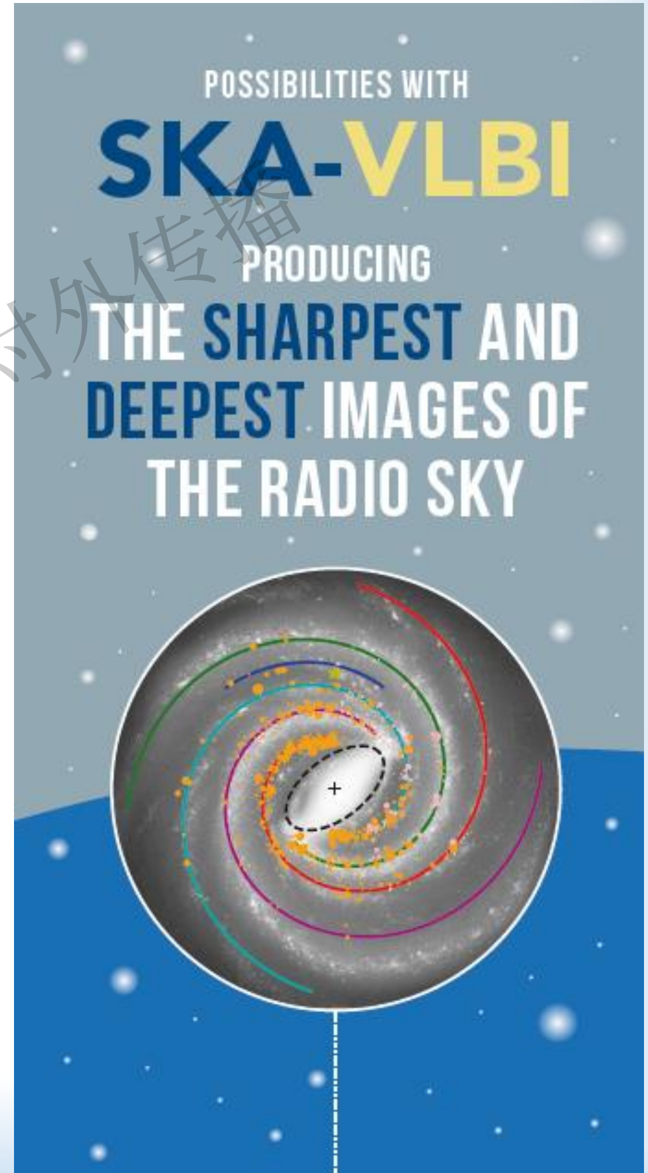
ESA, *Gaia* collaboration, A. Vallenari. 2022

Gaia DR4 (2025): 精度 10 微角秒； *Gaia* DR5 (2030): 精度 7 微角秒。

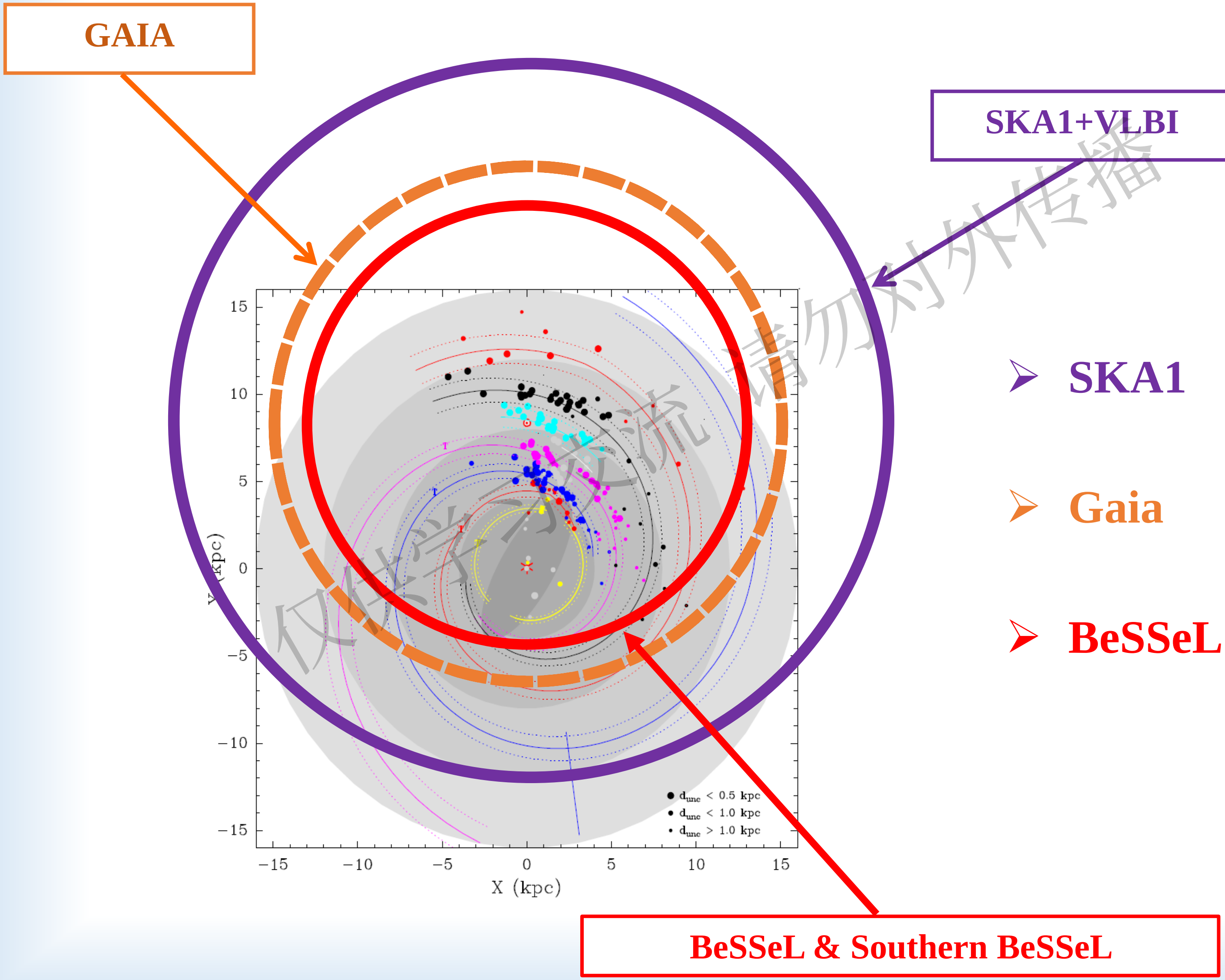
下一代甚长基线干涉阵（ngVLA）



SKA 天体测量：**mJy → μJy**



未来展望



- SKA1 ~ 5 μas
  ~ 20 kpc
- Gaia ~ 7 μas
  ~ 14 kpc
- BeSSeL ~ 8 μas
  ~ 12 kpc

谢 谢 大 家