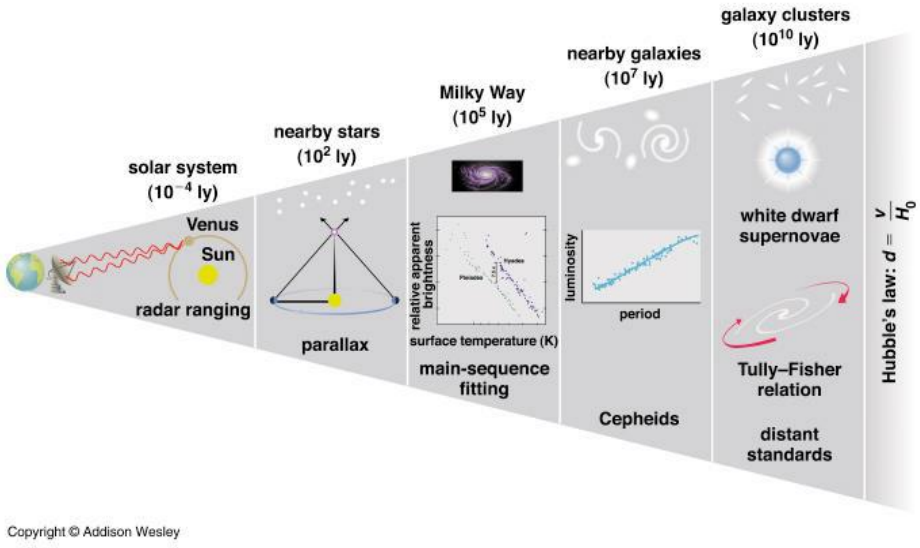
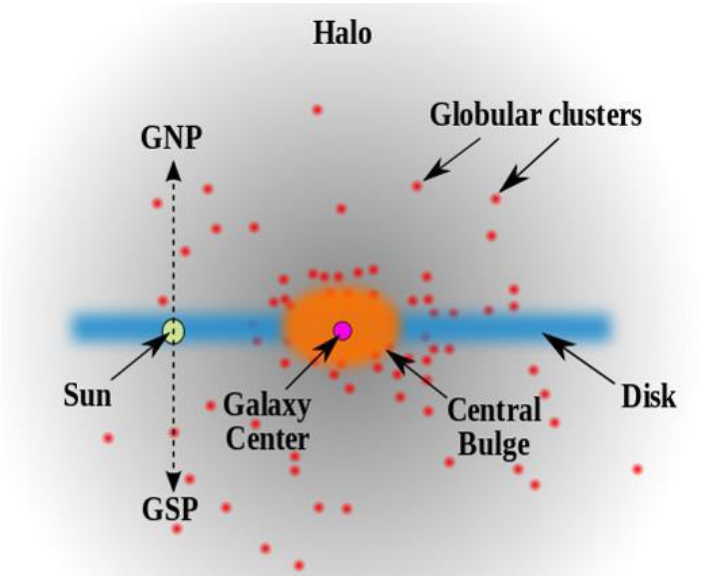
2.2 The Stars in the Galaxy

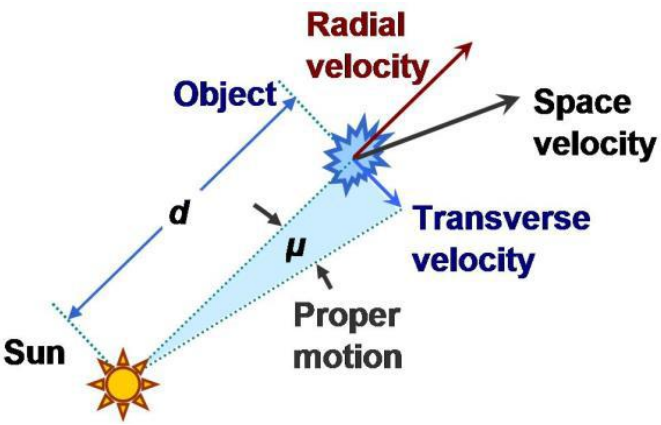
- 恒星和星团在银河系中的分布 → 揭示银河系的基本结构
- 银河系比500pc要大得多 → 三角视差方法不能估计更远恒星的距离
- 新的距离测量方法：
  - 运动学距离
  - 星团测距等





2.2.1 运动学距离

- 恒星相对于太阳系（LSR）的运动速度可分解成两个分速度
  - 视向速度V_r：朝向或远离观测者的速度分量
  - 可利用恒星或气体光谱中的发射线或吸收线的Doppler移动测量
  - 切向速度V_t：恒星在天空横向视运动角速率
- 自行μ：恒星相对于太阳系的质量中心，单位时间其位置在角度上的变化，单位是“角秒/年”
- 自行μ非常小，常以每年毫角秒(mas)测量；切向速度V_t是距离d和自行μ的乘积



如果知道V_r和V_t关系，则可通过测量V_r(计算V_t)和自行μ，求出天体距离d

2.2.2 分光视差：盘的垂直结构

- 分光视差方法：知道恒星光谱型和视星等，测量恒星距离的一种方法
- 不需测量视差：只是因为和三角视差一样，可以测恒星距离，故称做视差
- 基础：假设“具有相同光谱型的恒星，光度相同”。只适用于主序星。

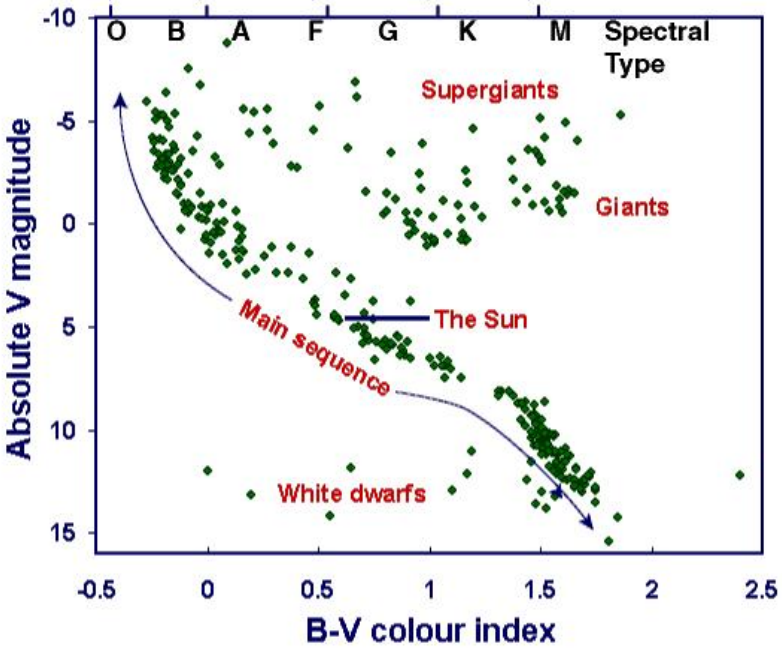
- 测量方法

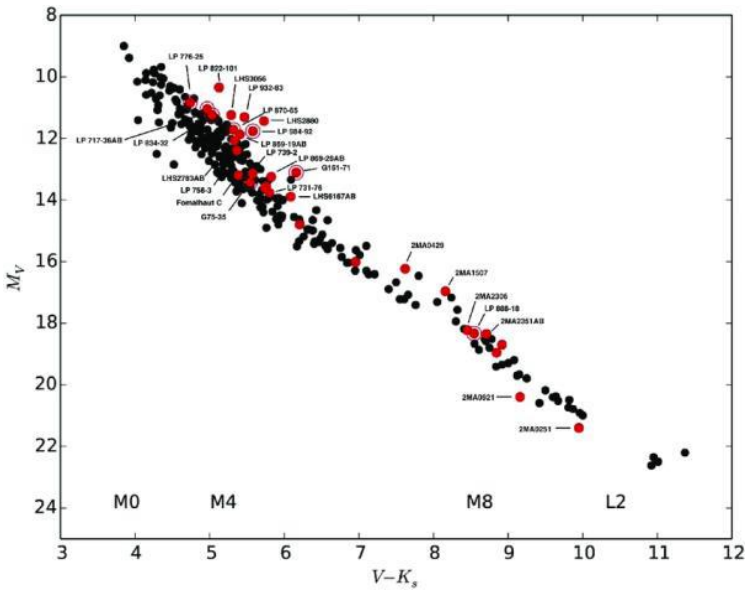
$$m_V - M_V = 5\log d - 5$$

  - 利用三角视差方法，测得近距离某一光谱型恒星距离和视星等：光度
  - 假定更远的同光谱型恒星光度与近距恒星一样：测得远距离恒星视星等，即可求出远距恒星的距离d
  - 光谱观测只能对比较亮的恒星 → 距离极限大约在10,000 pc范围

测光视差

- 对许多暗星拍摄高质量的光谱，需要在大望远镜上进行长时间观测
- 变通办法：由恒星的颜色估计其光谱型，并用其他指标来认定它是巨星还是矮星
- 测光视差：利用恒星颜色等观测信息，确定恒星光谱类型，计算恒星距离的一种方法

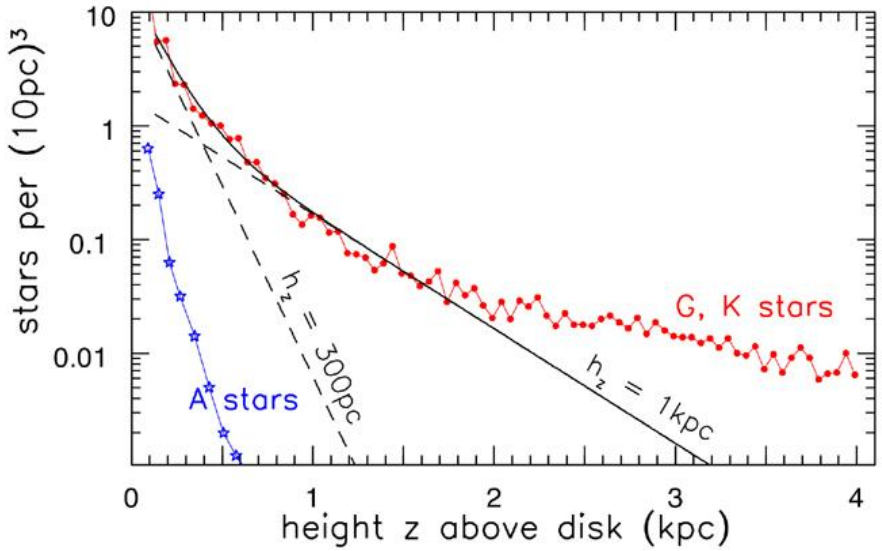




银盘的垂直结构——南银极方向

$$n(R, z, S) = n(0, 0, S)\exp[-R/h_R(S)]\exp[-|z|/h_z(S)],$$

- 测量南银极方向视星等$m_V < 19$的12500颗恒星的V－I颜色
- 利用颜色确定光谱型 + 测光 → 距离
- 利用距离和光谱型信息 → 垂直银盘方向的恒星分布



实圈显示G、K型矮星的密度：在z ≥ 2 kpc，大多数恒星属于贫金属晕星
A型矮星（主序星）处于非常薄的层内

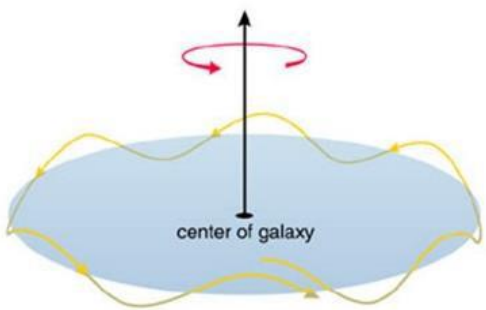
盘和晕中气体和恒星的标高和速度

Table 2.1 Scale heights and velocities of gas and stars in the disk and halo

Galactic component	h_z *or shape*	$\sigma_x = \sigma_R$ (km s^{-1})	$\sigma_y = \sigma_\phi$ (km s^{-1})	σ_z (km s^{-1})	$\langle v_y \rangle$ (km s^{-1})	*Fraction of local stars*
HI gas near the Sun	130 pc		≈ 5	≈ 7	Tiny	
Local CO, H_2 gas	65 pc		4		Tiny	
Thin disk: $Z > Z_\odot/4$	(Figure 2.9)					90%
$\tau < 3$ Gyr	≈ 280 pc	27	17	13	-10	
$3 < \tau < 6$ Gyr	≈ 300 pc	32	23	19	-12	
$6 < \tau < 10$ Gyr	≈ 350 pc	42	24	21	-19	
$\tau > 10$ Gyr		45	28	23	-30	
Thick disk	0.75–1 kpc					5%–15%
$\tau > 7$ Gyr, $Z < Z_\odot/4$	(Figure 2.9)	68	40	32	-32	
$0.2 \lesssim Z/Z_\odot \lesssim 0.6$		63	39	39	-51	
Halo stars near Sun	$b/a \approx 0.5$–0.8					$\sim 0.1\%$
$Z \lesssim Z_\odot/50$		140	105	95	-190	
Halo at $R \sim 25$ kpc	Round	100	100	100	-215	

盘和晕中气体和恒星的标高和速度

- 恒星标高
  - 晚型F、K型矮星:hz≈ 300 －350 pc；早型A型矮星: hz≤ 200 pc
  - 盘内的气体，以及与之混合的尘埃，被约束在甚至更薄的层内
- 为何较老的恒星有较大的标高?
  - 恒星在绕转时会受到银盘内和旋臂内的恒星和气体团块的引力作用
  - 引力作用，使得恒星在径向运动和垂直方向运动速度会随时间累加
  - 年龄较老的恒星，运动得更快，标高较大：较老恒星一般运动较快



Stars in the disk all orbit in the same direction with a little up-and-down motion

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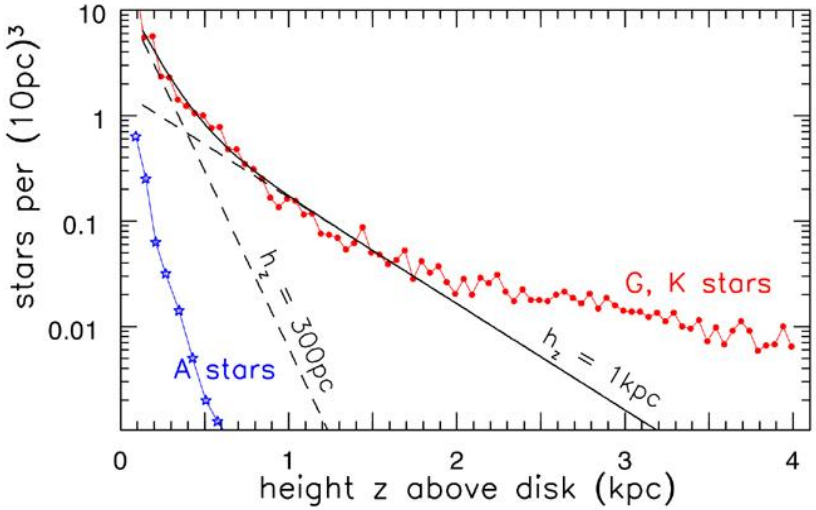
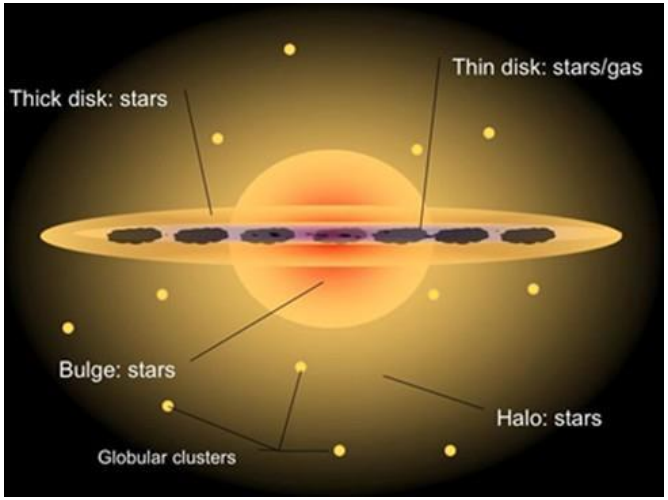
盘的垂直结构



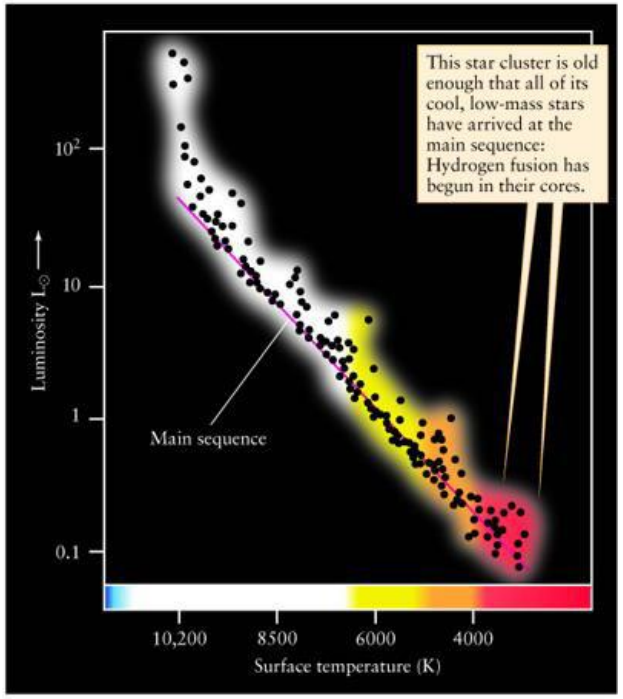


- 距银盘面d < 400pc区域，为薄盘；外面为厚盘，$h_z \approx 1kpc$，厚盘的恒星数密度较小
- 薄盘：有不同年龄的星族，金属丰度高：$0.5Z_\odot \leq Z \leq Z_\odot$
- 厚盘：年老的星族；金属丰度低：$0.1Z_\odot \leq Z \leq 0.5Z_\odot$

- 厚盘可能是银河系早期薄盘的遗迹：
  - 与伴星系相互作用，盘会受到震动，将大部分能量转换为恒星随机运动
  - 气体会落入盘的中平面；后来从中形成的恒星，构成我们今天观察到的薄盘

2.2.3 星团测距

(a) The Pleiades star cluster



(b) An H-R diagram of the stars in the Pleiades

- 星团：由十几颗至上百万颗恒星组成的有共同起源、相互之间有较强的力学联系的天体系统.
- 星团有很多颗恒星组成，亮度大 → 可以更大范围的测距；从同一气态原始物质中几乎同时形成，金属丰度一样 → 可以更加精确测量距离

疏散星团 Open Clusters

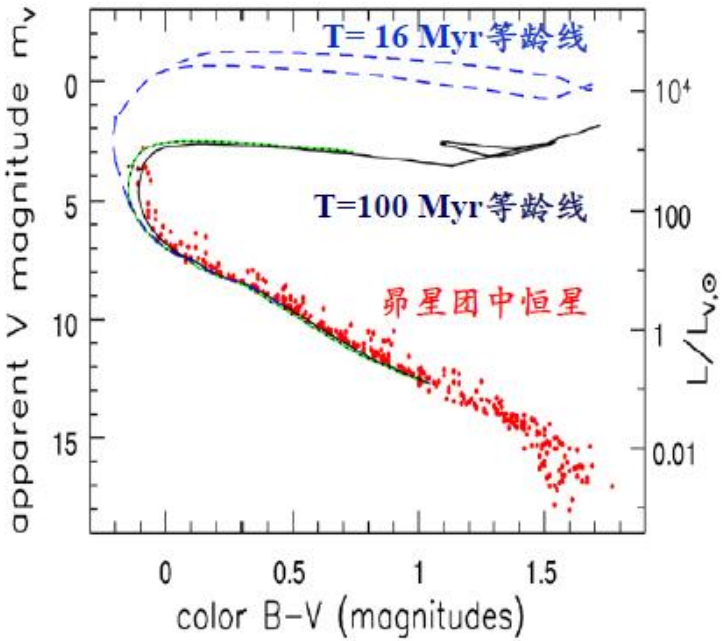
Table 2.2 Some open clusters in the Milky Way

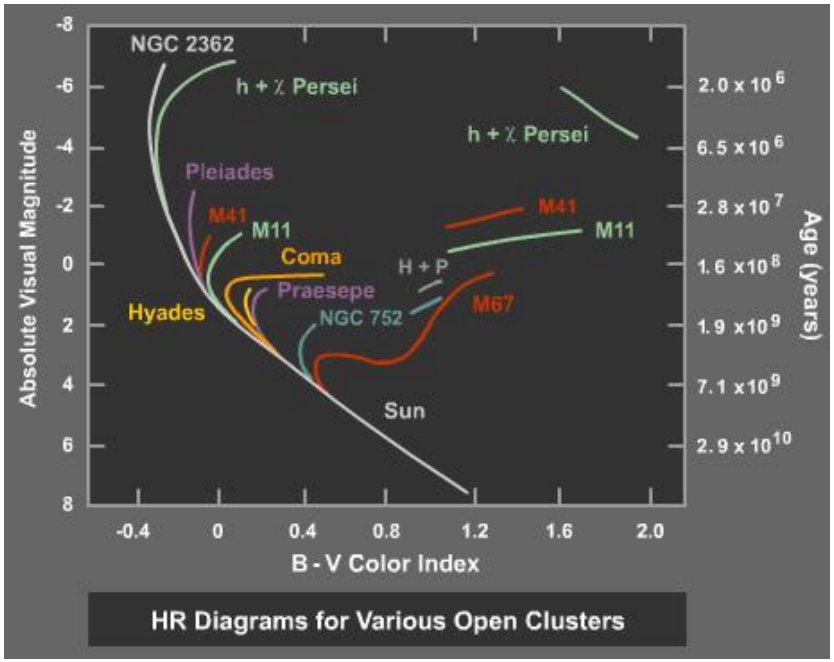
Cluster	d (pc)	[Fe/H]	M_V (*mag*)	L_V ($10^3 L_\odot$)	*Color* ($B-V$)	r_c (pc)	σ_r (km s^{-1})	*Age*	*Mass* ($\mathcal{M}_\odot$)	$\mathcal{M}/L$ ($\mathcal{M}_\odot/L_\odot$)
NGC 3603	6500	–	–	20 000	−0.3	0.5	–	<5 Myr	7000	0.001
Pleiades (M45)	132	0.0	−4.3	4.5	−0.05	3	0.5	0.125 Gyr	800	0.2
NGC 6705 (M11)	1900	0.14	−6.0	22	0.18	1	–	0.25 Gyr	–	–
Hyades	46	0.14	−2.7	1.0	0.40	3	0.3	0.625 Gyr	460	0.4
NGC 7789	2000	−0.26	−5.7	17	0.98	5	0.8	1.5 Gyr	–	–
NGC 2682 (M67)	860	−0.05	−3.3	1.8	0.78	1	0.8	4 Gyr	2000	1
NGC 6791	4000	0.3	−3.5	2.1	1.02	3	–	8–10 Gyr	–	–

Note: d is distance from the Sun; [Fe/H] $= \log_{10}(Z/Z_\odot)$; M_V and $B-V$ are corrected for the obscuring effect of dust; r_c is the core radius measured for stars of roughly the Sun's luminosity; σ_r is the dispersion in the radial velocity V_r of stars in the cluster's central region. Masses are found from the stellar luminosity function, using infrared observations to find faint or obscured stars.

- 光度范围较大；中心密度可达~100$L_\odot$ pc^{-3}
- 核半径大小rc一般为数秒差距
- 内部恒星具有小的随机速度，σ<1km/s
- 质光比M/L<1：随年龄增大，M/L会增加
- 疏散星团多处于靠近银河系盘平面、旋臂
- ~ 1200个已知OC，~ 5% T>1Gyr，多数T<300Myr

等年龄线拟合





- 等龄线：年龄相同的各种质量的恒星在赫罗图上的位置线
- 星团中所有恒星具有相同的年龄和相同的重元素丰度，主序很窄
- 将理论的等龄线进行移动，拟合星团中恒星在HRD上的分布　获得星团的距离模数$(m-M)_0 = 5\log10(d/10pc)$ → 昴星团的距离d = 132pc

球状星团

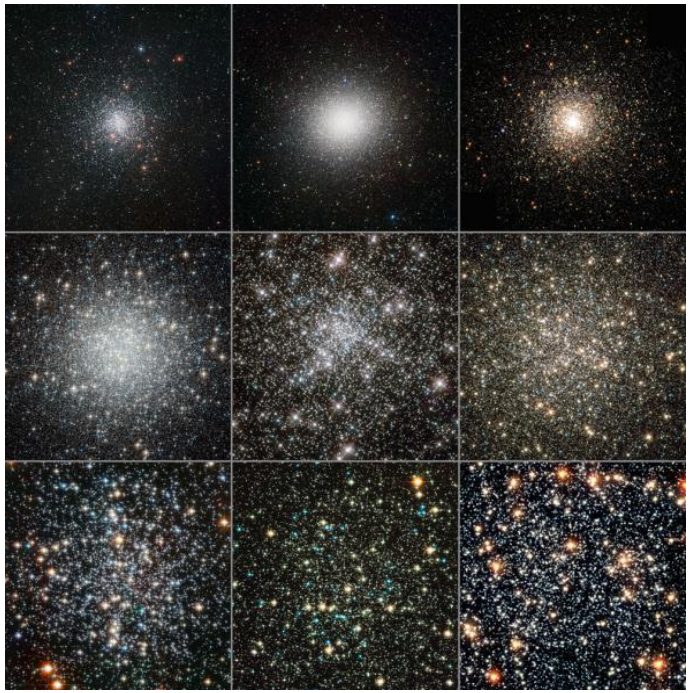
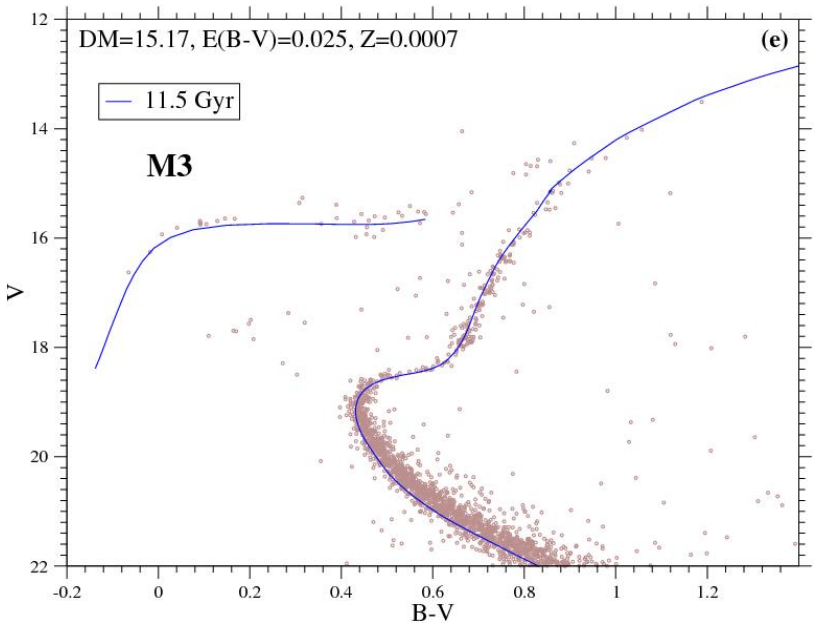


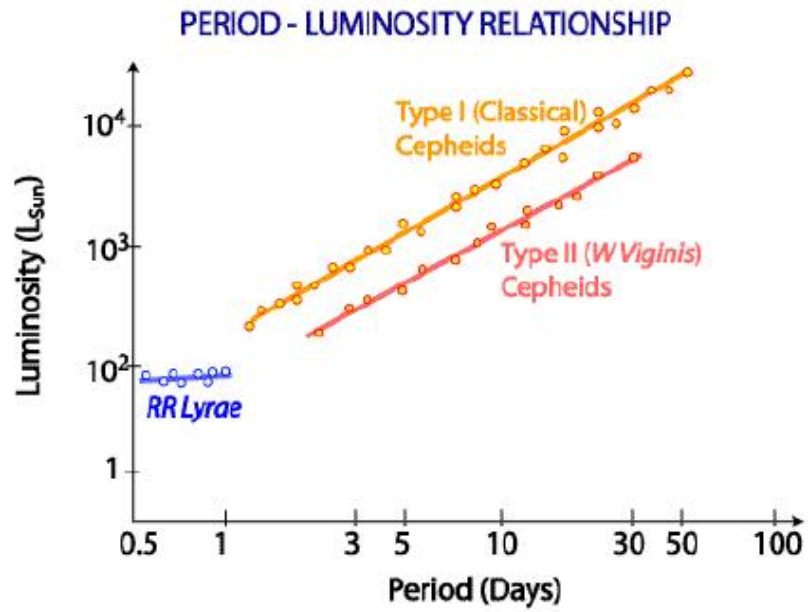
Table 2.3 Some globular clusters in the Milky Way, and one belonging to the Fornax dwarf spheroidal galaxy

Cluster		d (kpc)	[Fe/H]	M_V (*mag*)	L_V ($10^3 L_\odot$)	r_c (pc)	r_t (pc)	σ_r (km s^{-1})
NGC 5139	ω Cen	5.2	-1.6^a	−10.2	1100	4	70	20
NGC 104	47 Tuc	4.5	−0.71	−9.5	500	0.5	50	11
NGC 7078	M15	10.8	−2.15	−9.3	440	$<0.01^b$	85	12
NGC 6341	M92	8.5	−2.15	−8.3	180	0.5	35	5
NGC 7099	M30	9.1	−2.13	−7.6	95	$<0.1^b$	45	5
NGC 6121	M4	1.73	−1.2	−7.2	60	0.5	25	4
	Pal 13	24.3	−1.9	−3.8	3	0.5	>50	0.6–0.9
NGC 1049	Fornax 3	140	−2.0	−7.8	100	1.6	>50	9

- 球状星团包含的恒星数目多，结构更紧密。光度$L \approx 10^6 \sim 10^4 L_\odot$
- 内部恒星具有较高随机速度sr；星族的金属丰度低，星族年老
- 在核半径rc以内，恒星的数密度大致为常数
- 在潮汐半径或截断半径rt处，恒星数密度锐降至零

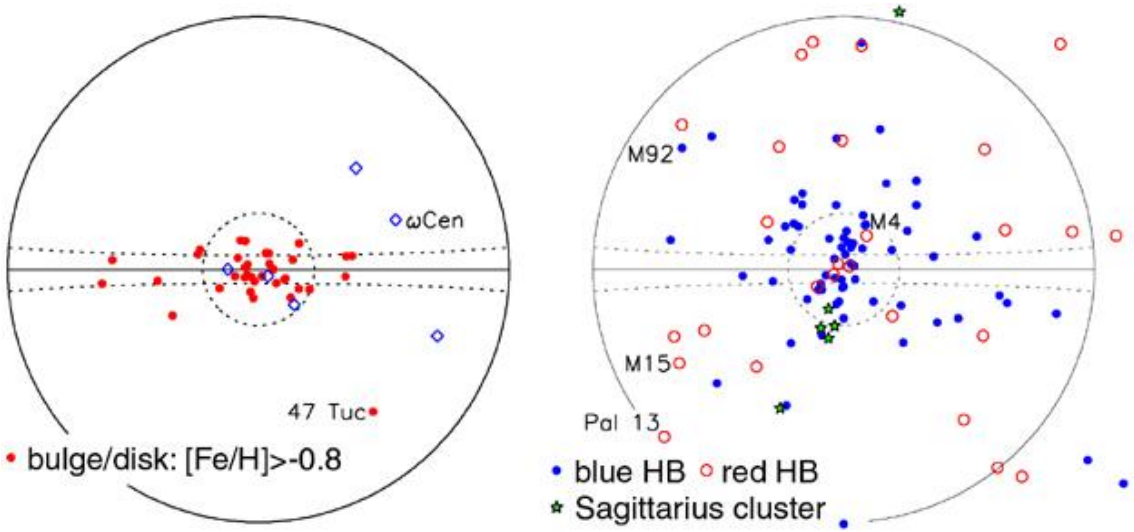
球状星团测距





- **两种方法**
  - **CMD方法：将观测到的星团CMD（HRD）同恒星演化模型进行比较；调整假设的距离、年龄和元素丰度，获得最佳拟合**
  - **变星方法：天琴座RR型变星(L ≈ 50 L⊙)或者造父变星周期-光度关系**

银河系球状星团分布

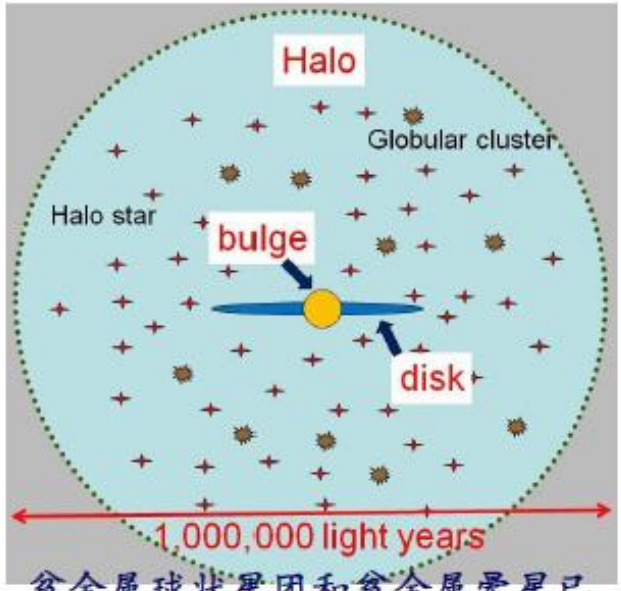


- 富金属球状星团在银河系内区为数较多，而且离中平面较近；可能是同核球和厚盘一起形成的。
- 贫金属球状星团围绕银河系中心形成一个大致球形：
  - 有红水平支的球状星团(相对年轻)，分布区域更加弥散
  - 有蓝水平支的球状星团(相对年老)，向银河系中心聚集
- 多数贫金属球状星团不遵循圆轨道：晕星团的轨道几乎是随机取向的，富金属球状星团像盘中的恒星一样旋转

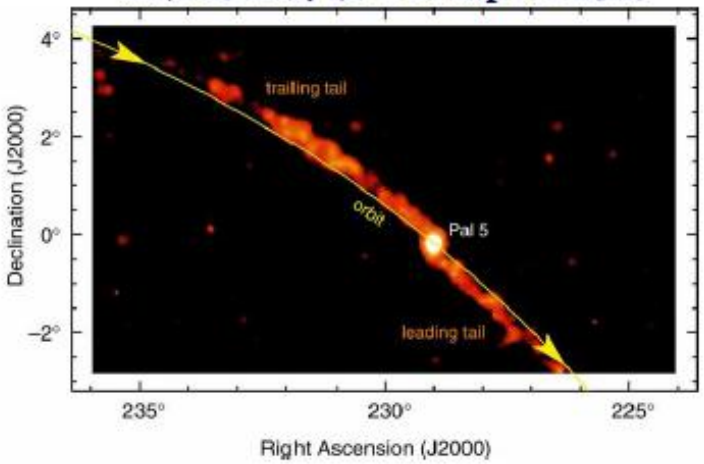
GLOBULAR STAR CLUSTER
Group of tens of thousands to hundreds of thousands of stars
Highly symmetrical ball of stars
Frequently contains bright red giant stars
Located in the halo or bulge of a galaxy
Composed of old stars that formed when the universe was younger
No longer forming in our galaxy, the Milky Way
Group of stars held together by mutual gravitational attraction
All of its stars are the same age, having formed from the same cloud of gas and dust.
Stars in the cluster are at the same distance from Earth.
The star colors in a cluster indicate the age of the cluster.
Orbits the center of a galaxy
OPEN STAR CLUSTER
Group of hundreds of stars
Irregularly shaped grouping of stars
Contains bright blue stars
Located in the arms of the Milky Way and other spiral galaxies
Composed of young stars that recently formed in the disks of galaxies
Continues to form in the arms of spiral galaxies, including the Milky Way

晕区恒星：球状星团和晕星

- 银河系晕中包括贫金属的**球状星团**和**贫金属、年老的晕星**(不属于星团)
- 晕星**数目**比球状星团多~ 100倍，某些晕星金属丰度为太阳金属丰度的10-5
- 太阳周围（银盘附近）的贫金属晕星极少，晕星轨道类似于**贫金属球状星团**
- 晕星相对于太阳运动非常快，可以通过**高自行速度**发现近邻的晕星
- 有些晕星是被银河系引力瓦解或撕碎的**球状星团的遗迹**：如球状星团帕洛马5可能已失去90%的恒星；从它伸出的两条长的恒星尾跨天空大于10°
- 有些贫金属晕星遵循共同的轨道，可能是被**俘获**的伴星系的遗迹

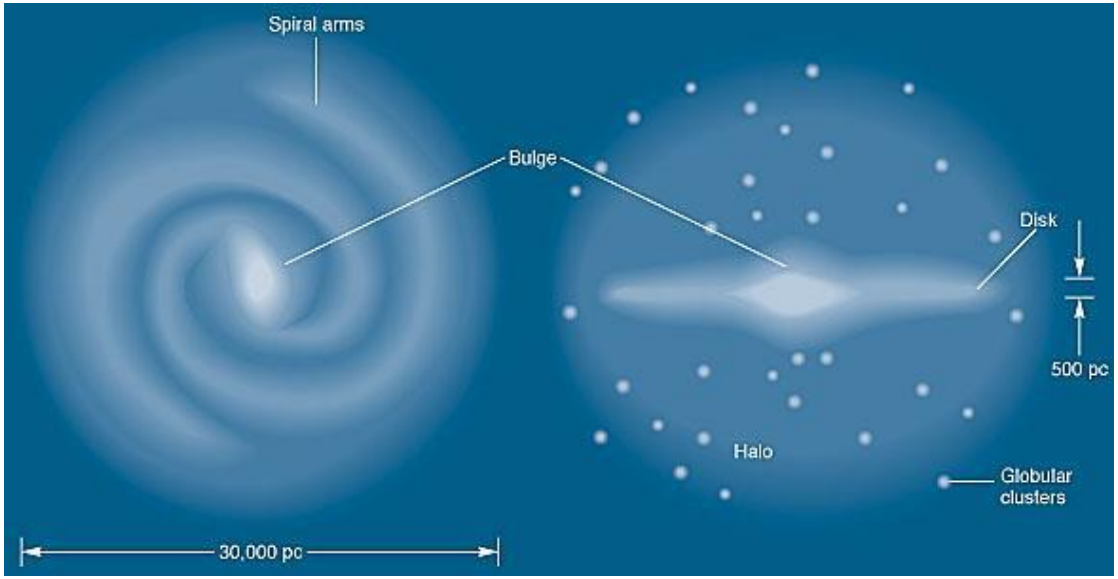


贫金属球状星团和贫金属晕星已经在远至离银心100kpc处发现



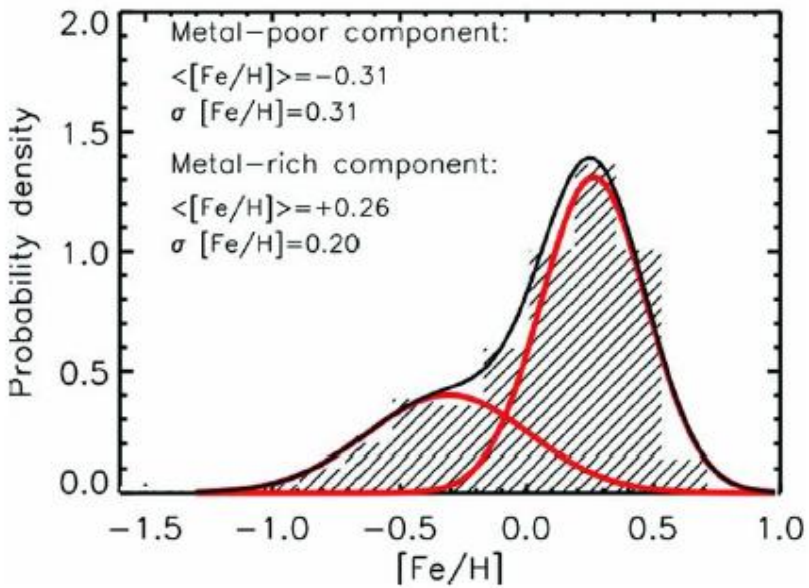
2.2.4 红外观测：核球

- The central regions of our Galaxy are dominated by the bar/bulge.
- The boxy appearance of the bulge is typical of galactic bars seen edge-on.
- 太阳在银盘附近，银盘中存在大量尘埃：观测研究银河系核球和核心的最佳方法是使用红外（IR）观测
- 近红外图像显示银河系有一个扁平的中央核球：它贡献了银河系总光~ 20%；恒星金属丰度和年龄范围大

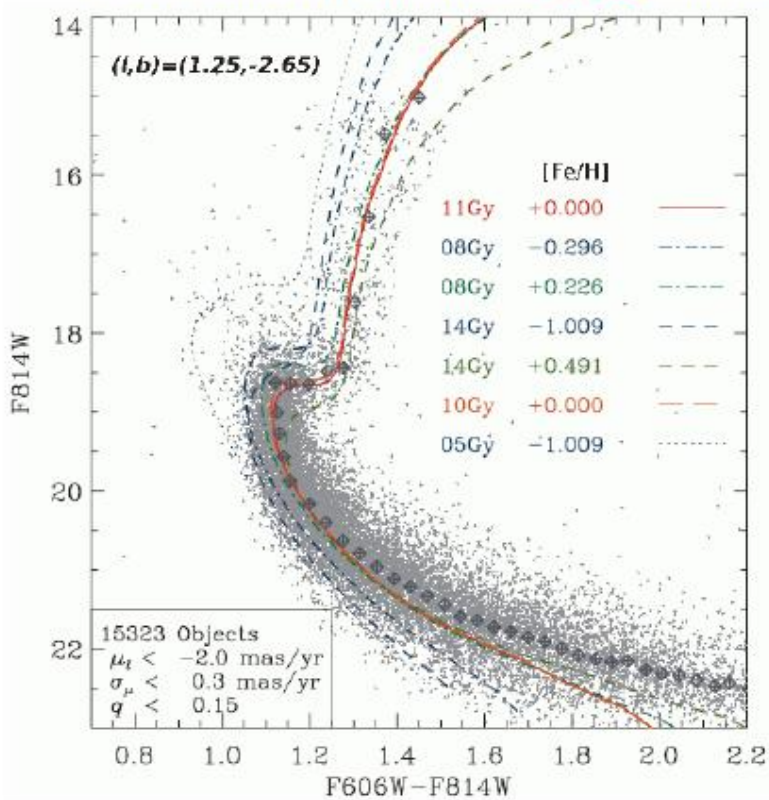


核球星族

- The stellar population of the bulge is as old as the stars in the globular cluster 47 Tucanae.
- Bulge stars follow the old isochrones, with the precise age depending on the adopted metallicity.



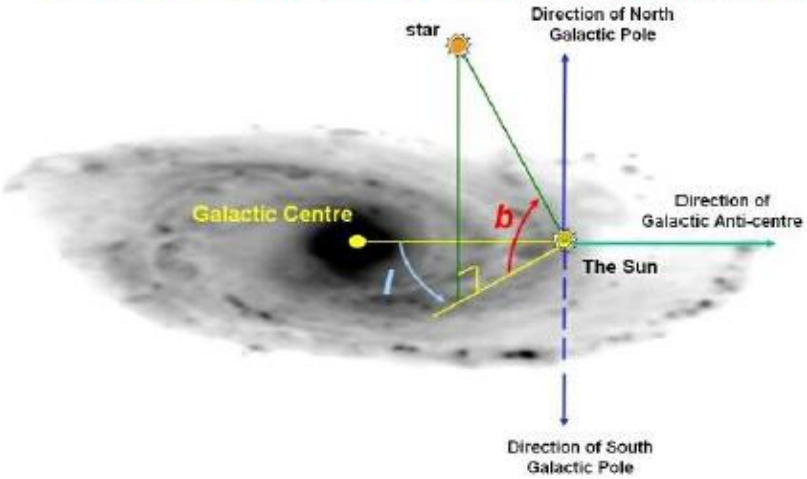
CMD of a clean sample of bulge stars



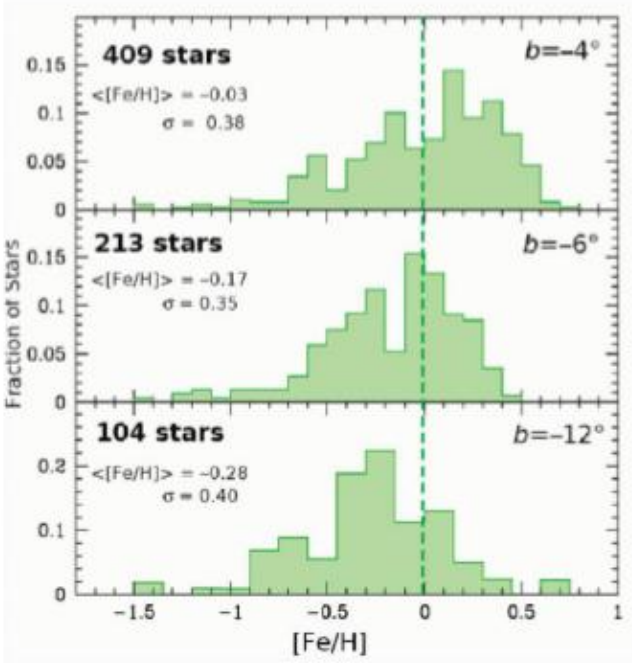
The Galactic bulge of the Milky Way is made up of stars with a broad range of metallicity, -3.0 < [Fe/H] < 1 dex.

The bulge metallicity

- The mean metallicity is higher in the innermost field, and decreases towards the outer one.
- The presence of a radial metallicity gradient along the bulge minor axis favors a bulge formation through dissipational collapse：气体耗散了其主要的能量，形成一个稳定的旋转盘，星系恒星形成由内而外，导致星系中心金属丰度高，外面金属丰度低

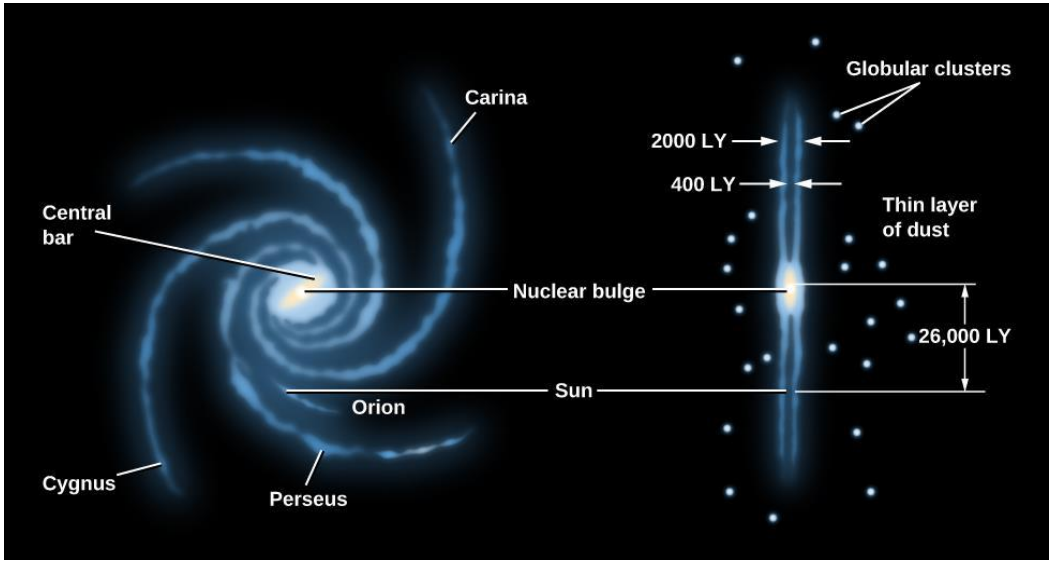


The bulge MDF in three fields along the minor axis, at latitudes listed on the top right corners. Mean metallicities and dispersions are labeled.



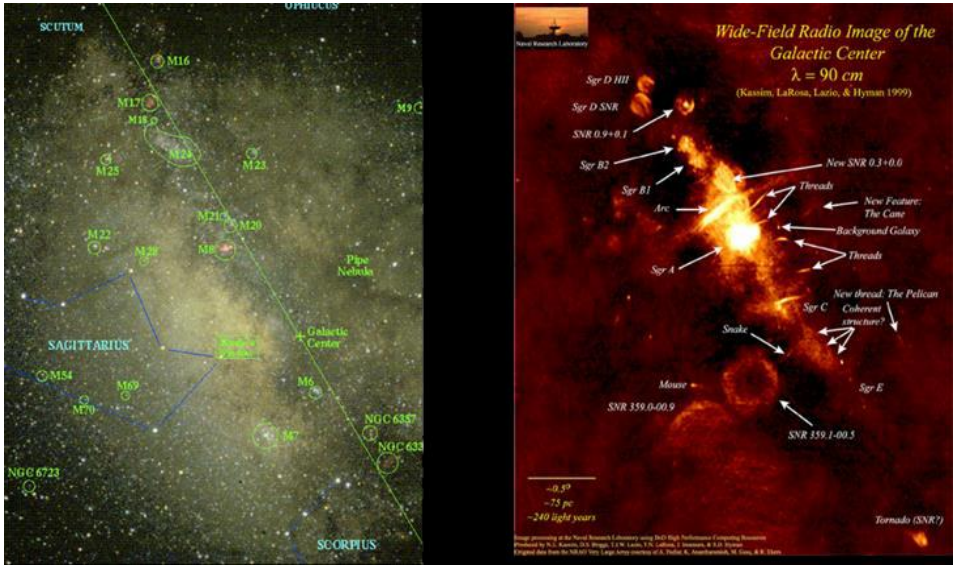
Where do these bulges/bars come from?

- About 2/3 of spiral galaxies show some kind of central bar structure in the infrared.
- Bar-driven?
  - The bars come naturally from instabilities of the disk. A rotating disk is often unstable to forming a flat bar structure at its center.
  - This flat bar in turn is often unstable to vertical buckling which generates the boxy appearance (bulge).



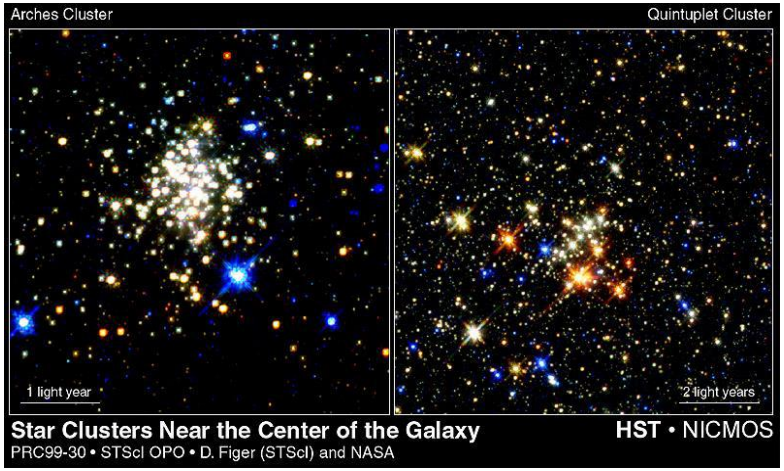
2.2.4 银河系：核心

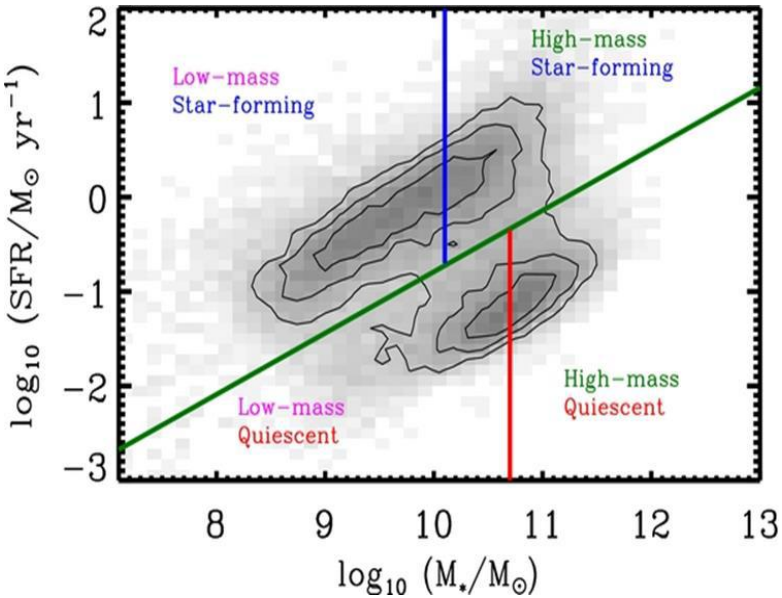
- Inner 500pc of Galaxy, extinction makes optical studies impossible -use radio or IR
- Observe ionized gas, line emission, dust, star clusters：stellar density is 10^7 stars / pc^3 (~ 0.1 in the solar neighborhood)
- If the Sun were near the GC
  - Nearest star would be 1000AU away
  - 106stars brighter than Sirius in the night sky
  - Total starlight more than 200 times brightness of the full Moon



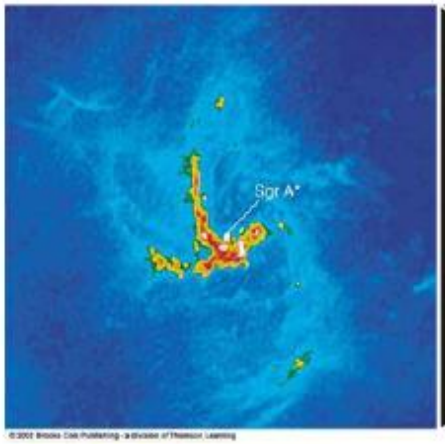
Star Formation in the Galactic Center

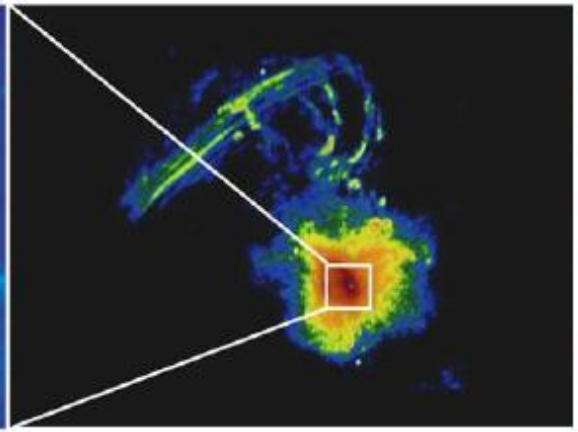
- Molecular material in inner 200 pc relatively hot and dense
  - 10^4per cm^3 and 70 K
  - High velocity dispersion (s~ 50 km/s) of molecules
  - Mass: $10^8 M_\odot$
- High density helps star formation but high temps don’t
- Star formation rate (SFR) ~ 1 M⊙/yr
- 银河系SFR估算
  - 取质光比$M/L_V \approx 2$ （星系的M/L_V介于2 -10)
  - 银盘光度$L_V \sim 1.5 \times 10^{10} L_\odot$；由质光比→ 银盘恒星质量$M_\star \sim 3 \times 10^{10} M_\odot$
  - 为了在10Gyr内把盘建构起来，必须每年产生$(3-5) M_\odot$的恒星，即为SFR





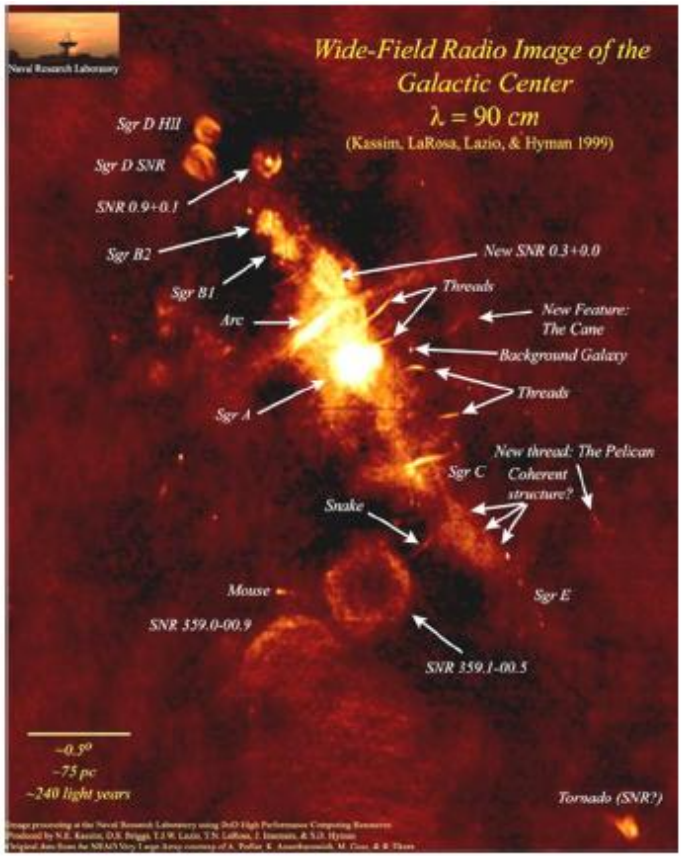
银河系中心—超大质量黑洞

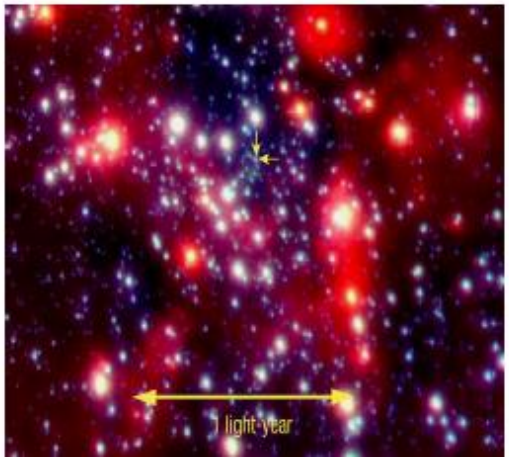




射电图像 (10 pc)：Sgr A West – center of this is Sgr A*

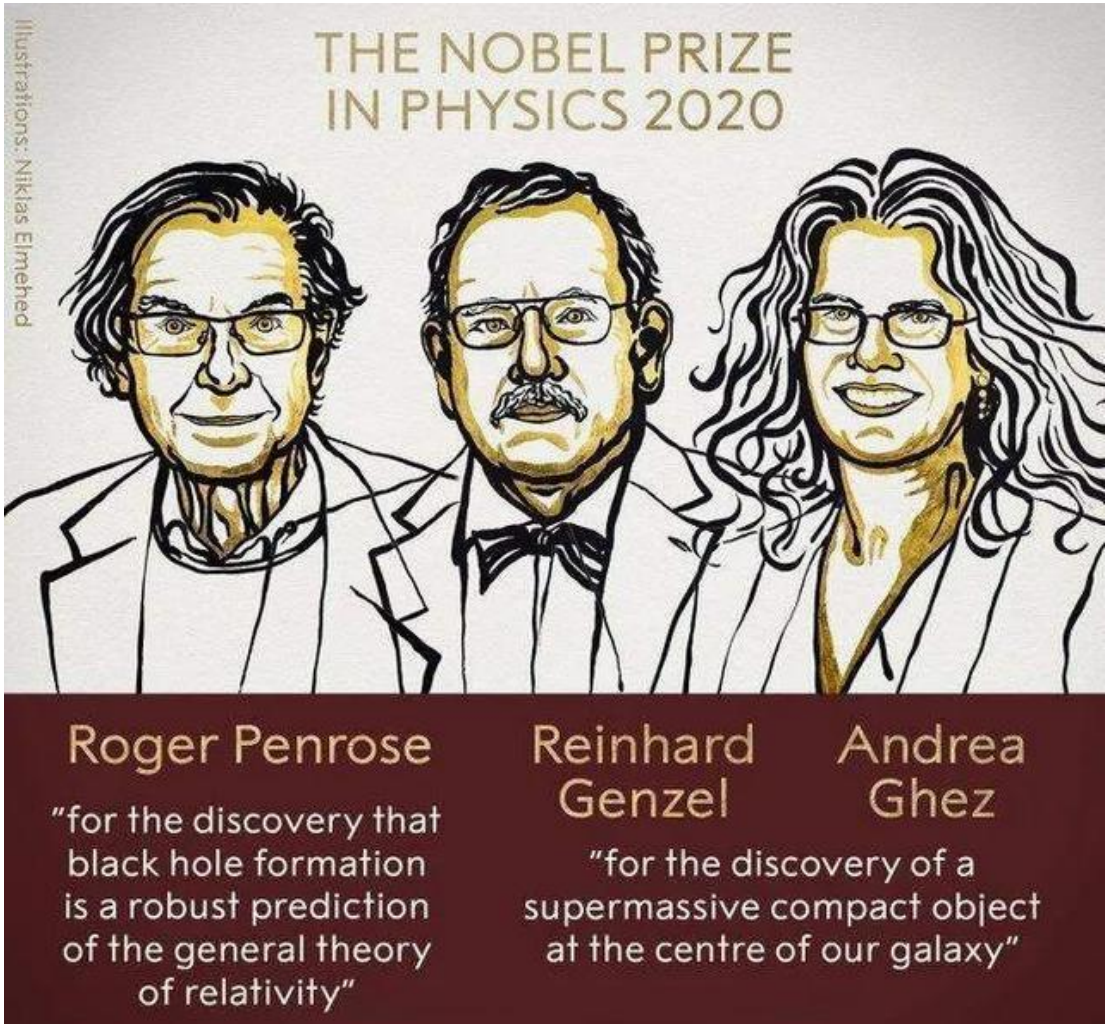
星系中心射电图像 (80 pc)：Sgr A and radio filaments

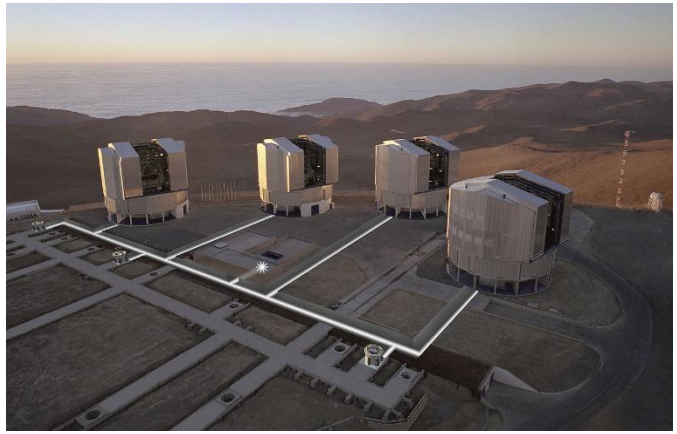




红外图像 (~ few ly)：观测恒星运动，估计BH质量

银河系中心区域，有很多超新星遗迹、壳状和纤维状结构；黑洞位于中央点状源人马座A * (Sgr A *)

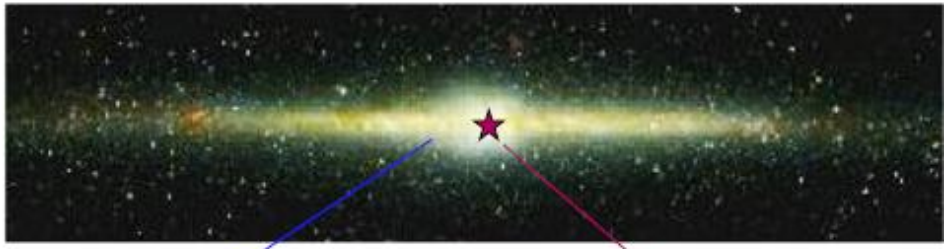

THE NOBEL PRIZE
IN PHYSICS 2020
Illustrations: Niklas Elmehed
Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"for the discovery of a supermassive compact object at the centre of our galaxy"



Black Hole

At the center of the bulge lies a supermassive black hole.

Central BHs are common in galaxies: their mass is usually a small fraction of the bulge mass.



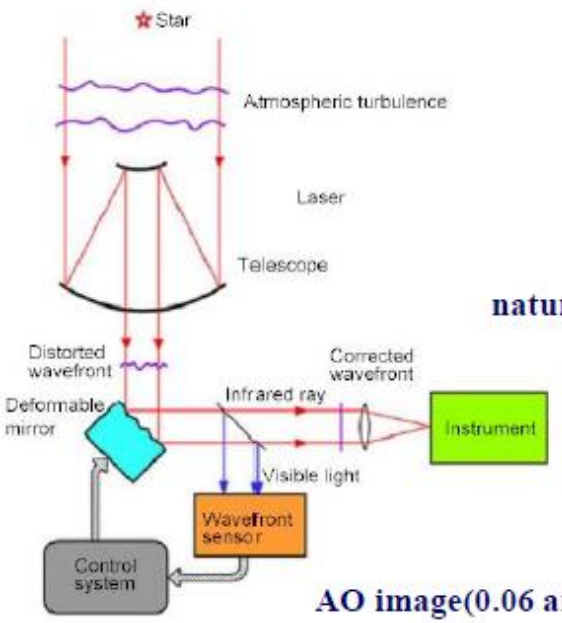
The Galactic bulge: mass = $2*10^{10}$ $M_\odot$

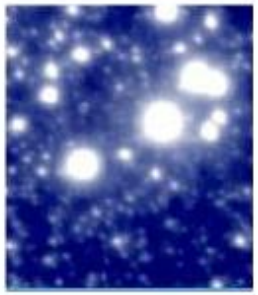
The central black hole: mass = $4*10^{6}$ $M_\odot$

The black hole itself is invisible, but we can measure its gravitational effect on nearby stars.

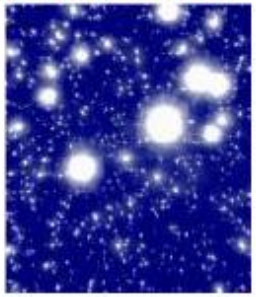
Turbulence in the earth's atmosphere blurs out any details smaller than about 0.5 arcsec.

To see stars close enough to the black hole (0.1 arcsec), adaptive optics are needed to correct for the effects of the atmospheric turbulence.

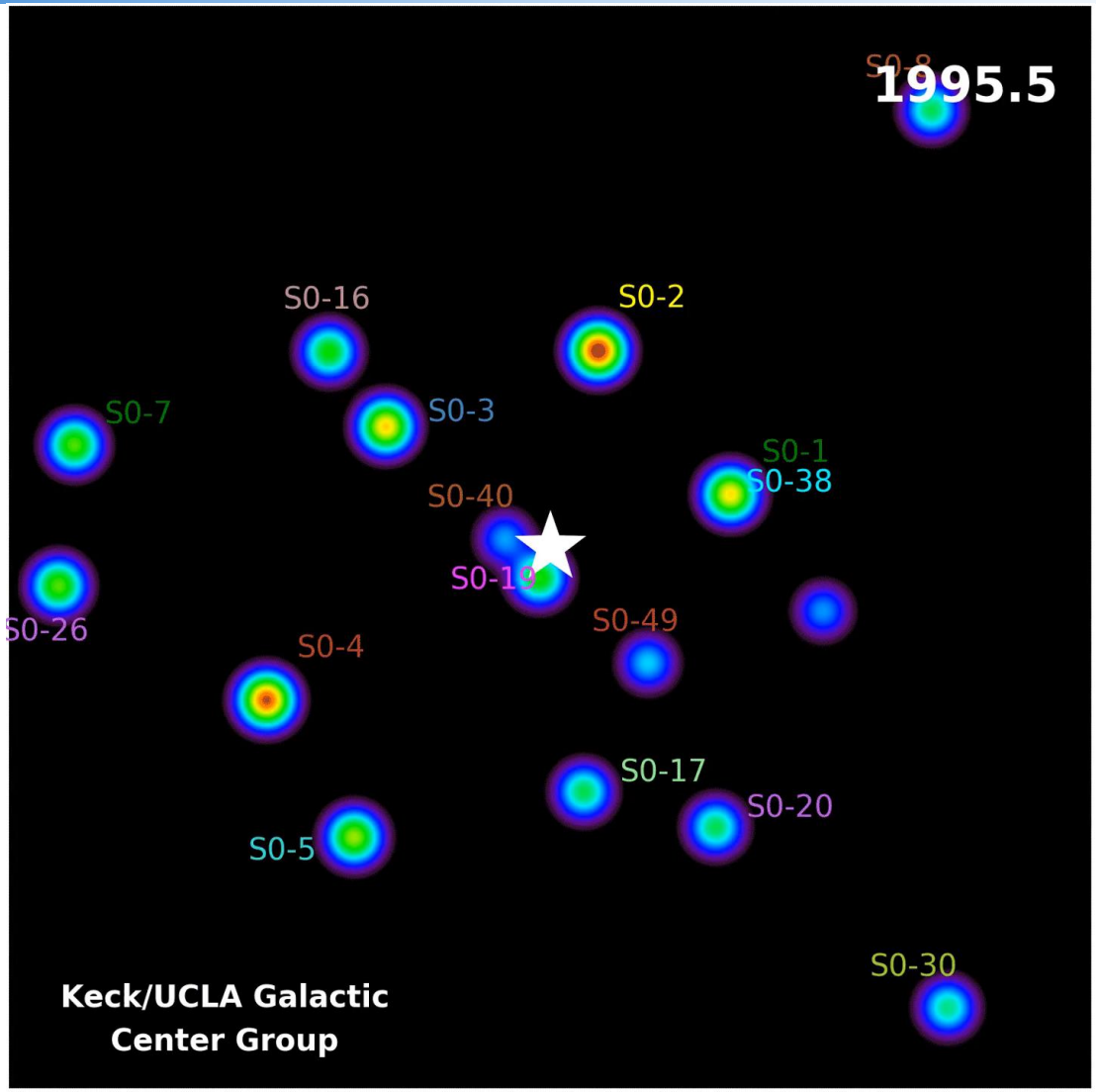




natural seeing image (0.26")



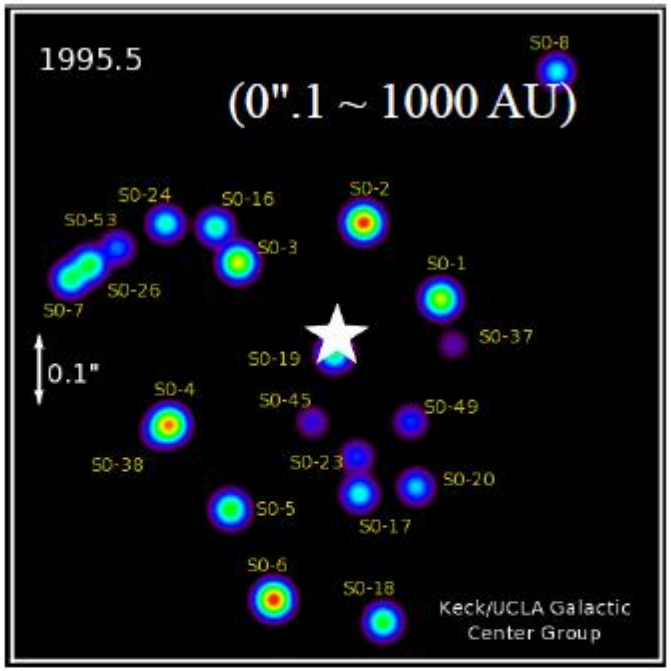
AO image(0.06 arcsec)


1995.5
S0-8
S0-16
S0-2
S0-7
S0-3
S0-1
S0-38
S0-40
S0-19
S0-26
S0-49
S0-4
S0-17
S0-20
S0-5
S0-30
Keck/UCLA Galactic
Center Group

Black Hole

The best estimate of the mass of the black hole at the galactic center was made using:

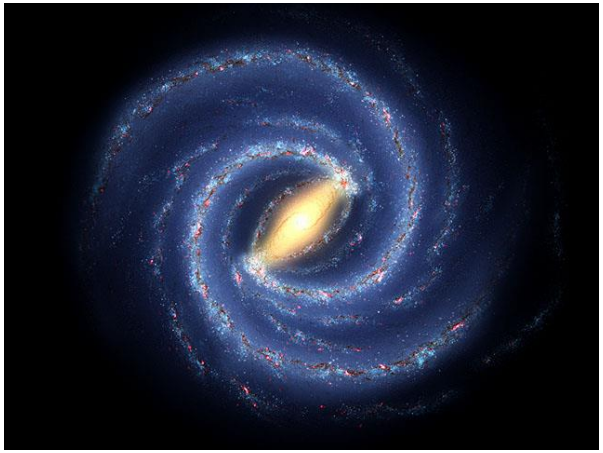
- Observations of nearby star orbits in IR
- Radio observations of accretion disk
- Orbit of stars in spiral arms [Kepler's 3rd law]
- X-ray observations of coronal gas
- Dark matter studies using rotation curves

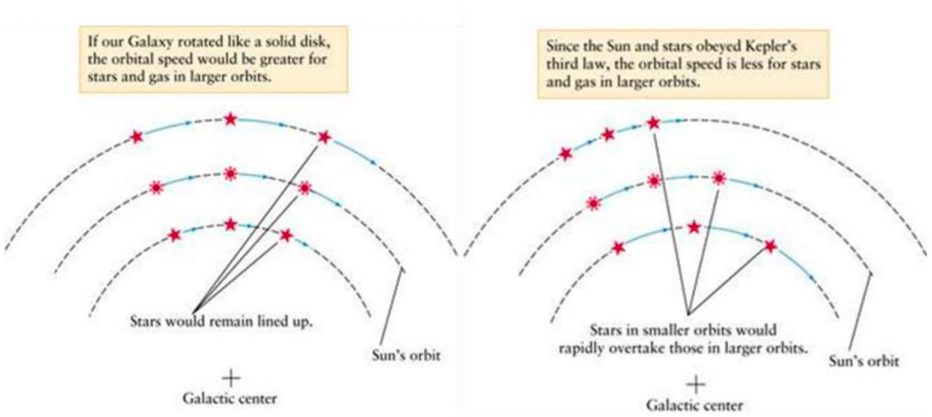


- Fastest moving star moves at 2% of the speed of light, 5000 km/s
- Mass is about 3 million solar masses
- Emits radio and X-rays
- Almost certainly a black hole

2.3 Galactic Rotation

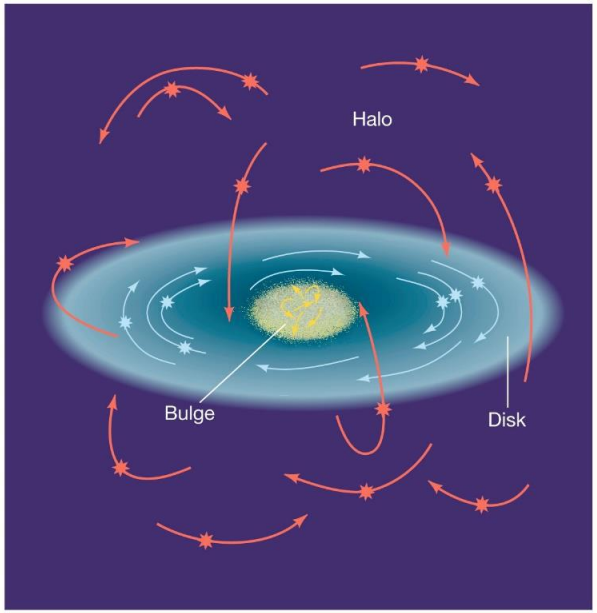
- 银盘中的恒星和气体在绕银心的近圆轨道上运动（V、ω如何随半径R变化？）
- 利用恒星、气体的运动，研究银河系气体分布、物质种类、物质分布
  - 气体运动 → 引力 → 质量
  - 质量 → 有无暗物质存在?





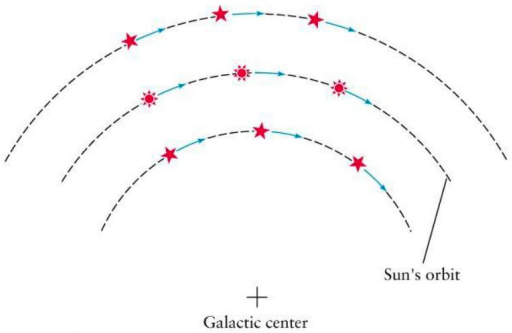
恒星角速度ω=V/R =常数（如刚体盘）→ V随R变化，恒星间距离不变？

恒星速度V~常数→ ω = V/R 随半径变化 (R小，ω大；R大，ω小）？



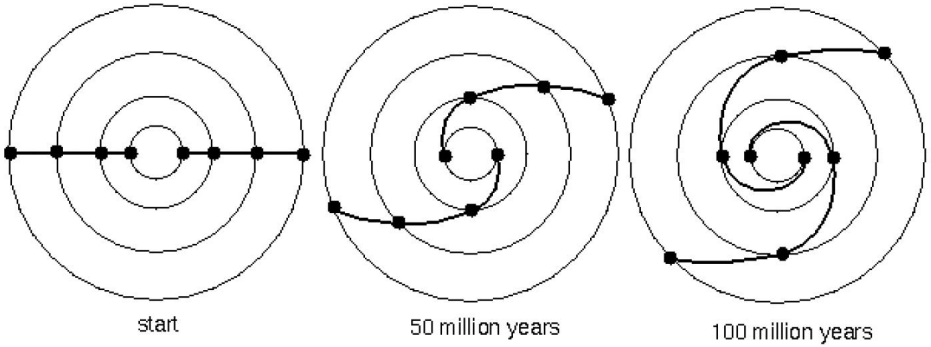
较差自转

- 较差自转：是指一个天体在自转时，不同部位的角速度（ω）互不相同的现象
  - 较差自转在大多数非固体的天体中存在，比如星系、巨型气体行星等等
- 银河系：离银心较近的恒星（ω大）转一圈所用的时间（$T=2\pi r/V=2\pi/\omega$），短于较远的恒星



a Actual rotation of our Galaxy

- 从太阳向内看，恒星在其轨道上超过我们；方向和太阳轨道速度V_0相同
- 从太阳向外看，恒星落在我们后面，它们有相反方向的自行

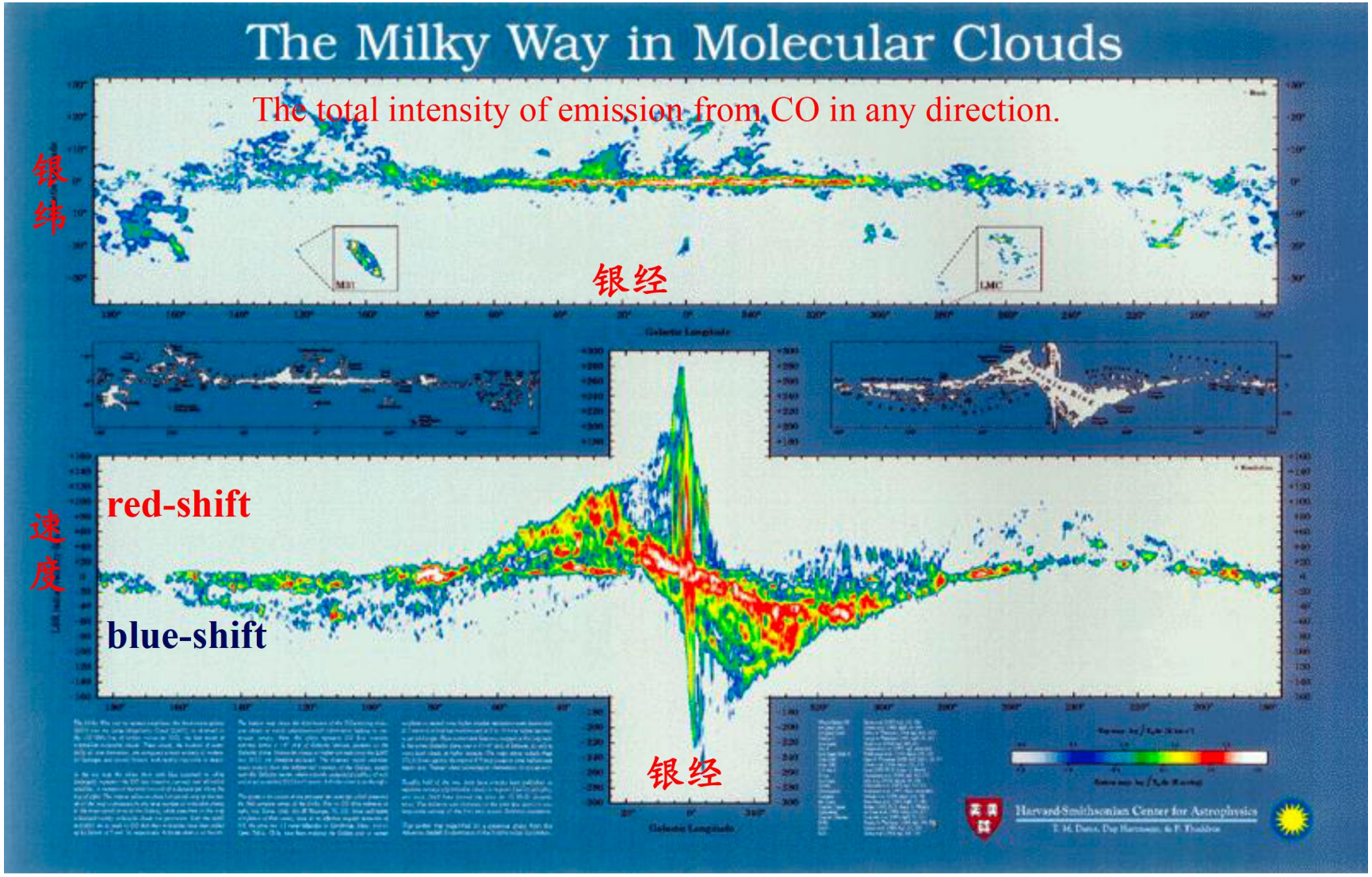


Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

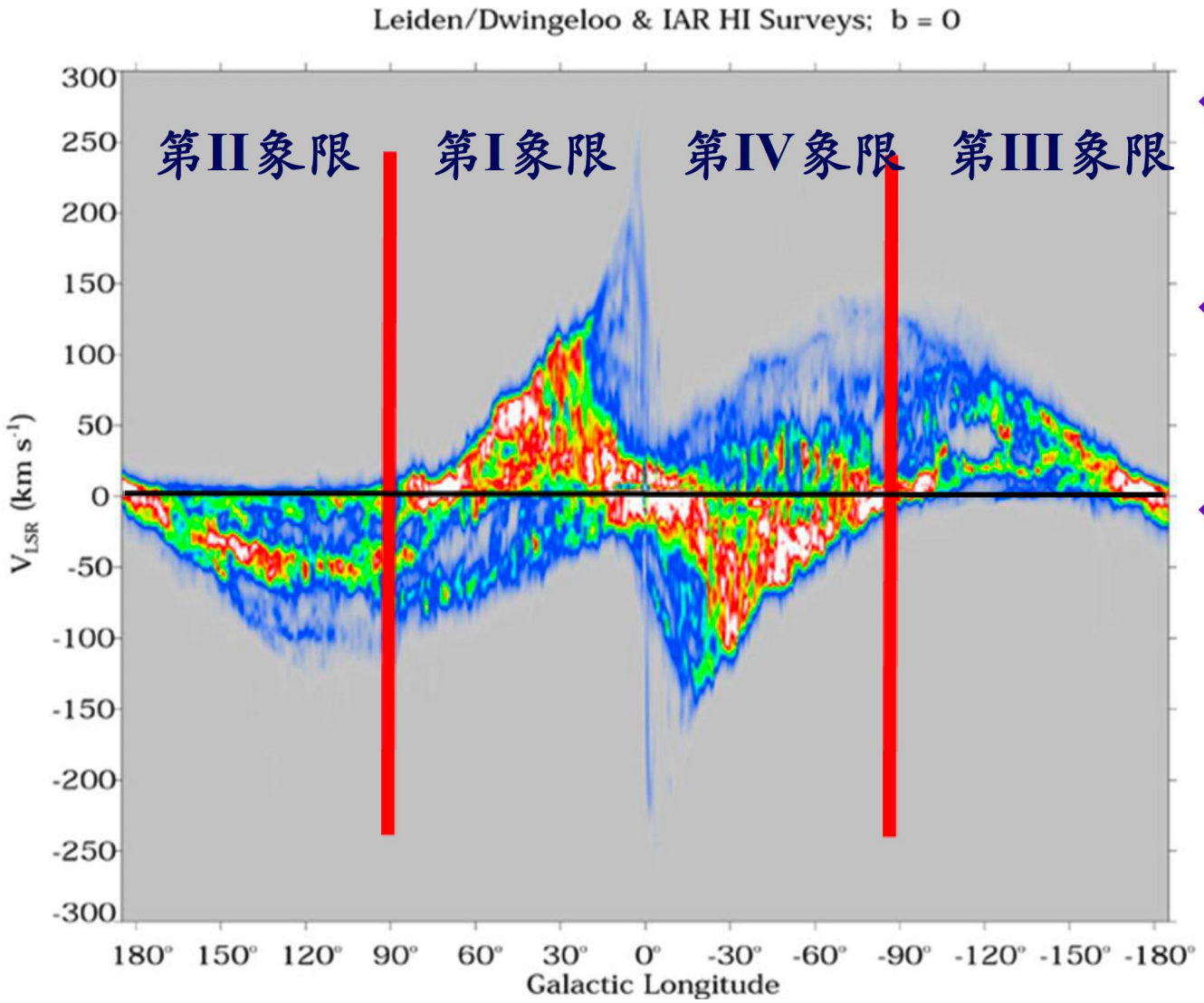
Our Galaxy rotates, and the center rotates faster than the outer parts do !

由于旋涡星系的自转是较差自转，内部的自转角速度大于外部的角速度，旋臂会越缠越紧，最终完全缠绕在一起：旋臂缠绕问题 → 密度波理论

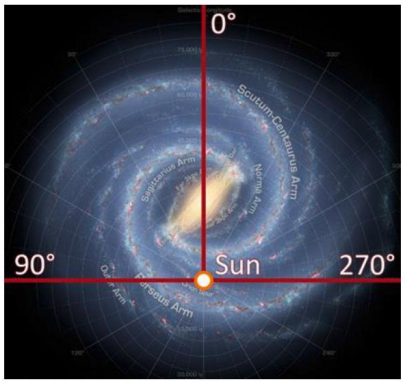
2.3.1 测量银河系转动曲线



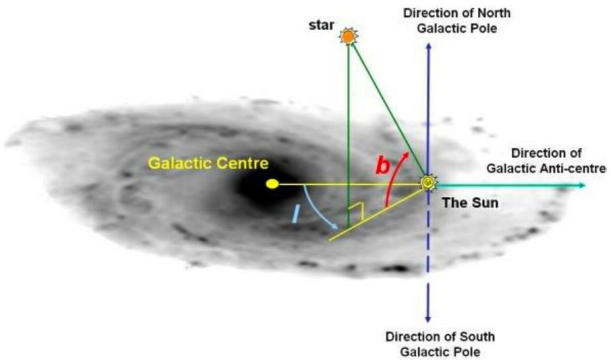
HI

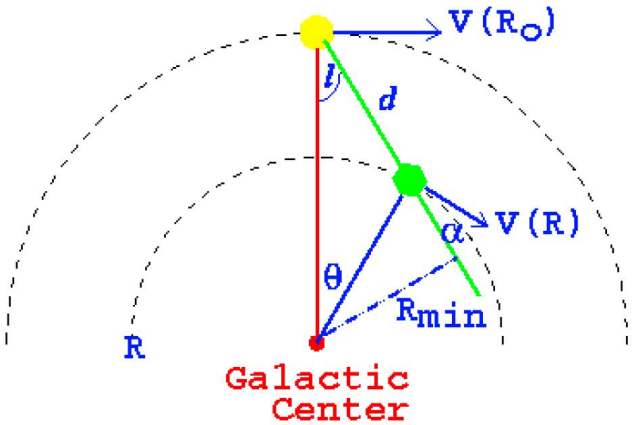


- 没有在第二象限(90<l<180)速度为正气体
- 没有在第三象限速度为负气体
- 第I、IV象限速度刚好相反



Vr 与银经 l 关系



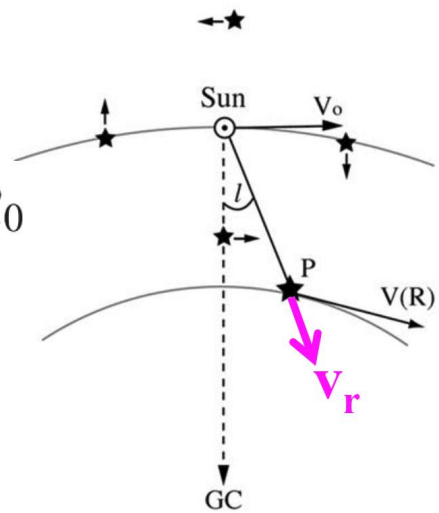


- 在半径R_0处，太阳以速度 $V(R_0) = V_0$ 运转（假定轨道为圆轨道）
- 半径R处的一颗恒星P，轨道速度为V(R)；视向速度为Vr（离开我们的速度）：

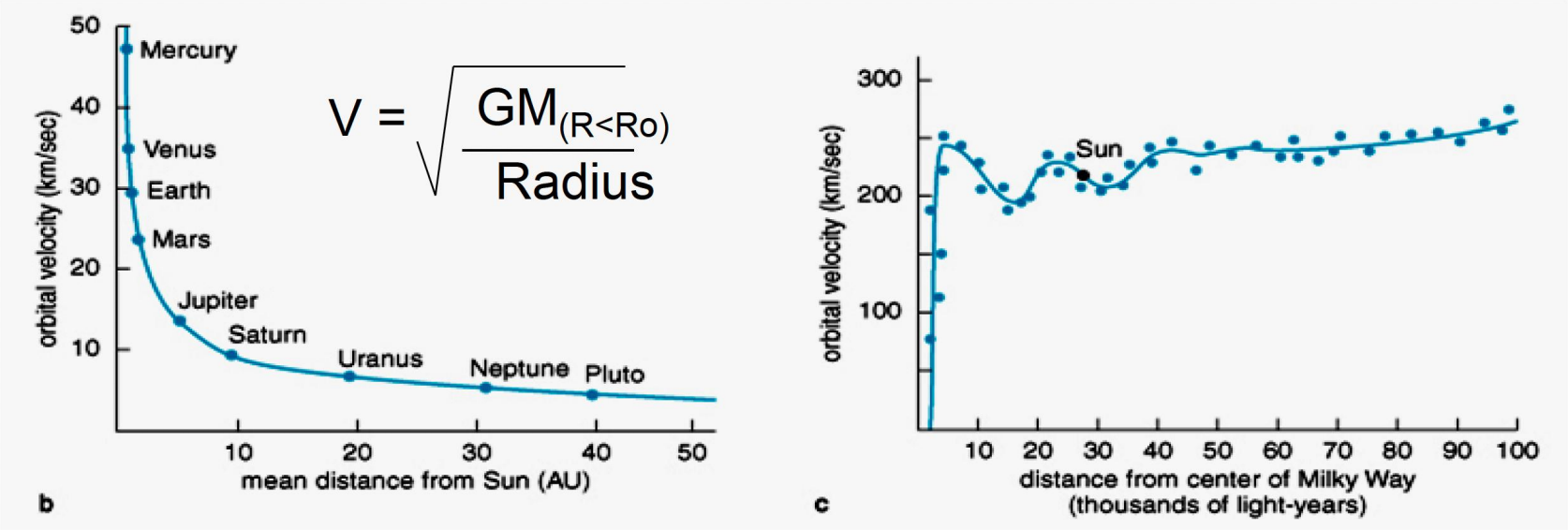
$$V_r = V\cos\alpha - V_0 \sin l. \qquad \sin l/R = \sin(90^\circ + \alpha)/R_0$$

$$V_r = R_0 \sin l\left(\frac{V}{R} - \frac{V_0}{R_0}\right)$$

$$V_r = R_0 \sin l\,(\omega - \omega_0)$$

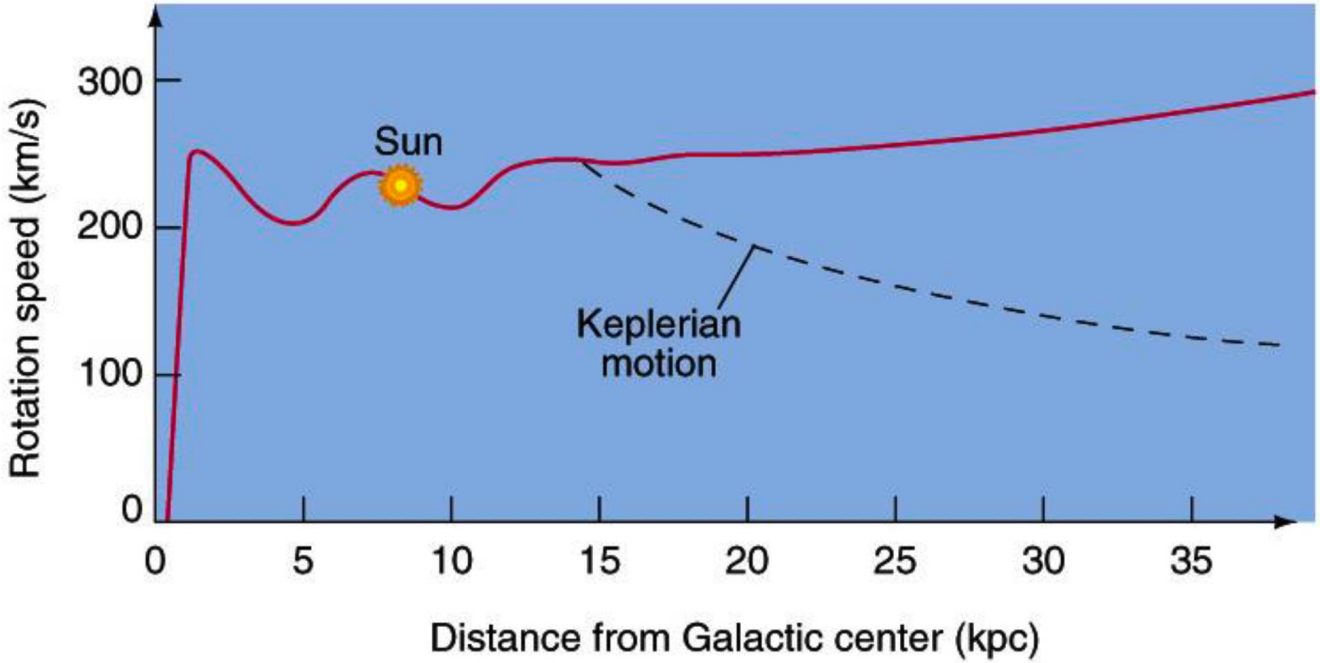


Understanding rotation curves



- For planets in the Solar System, M is dominated by Msun, so M does not change much with R - Keplarian rotation curve
- Inside the Galaxy, M increases with radius, so velocity may stay constant or even increase with radius.
- Outside the Galaxy, as in the Solar System, M remains constant with increasing R (if most mass ends at visible edge): we would expect the rotation curve to slope downward in Keplarian-like motion.

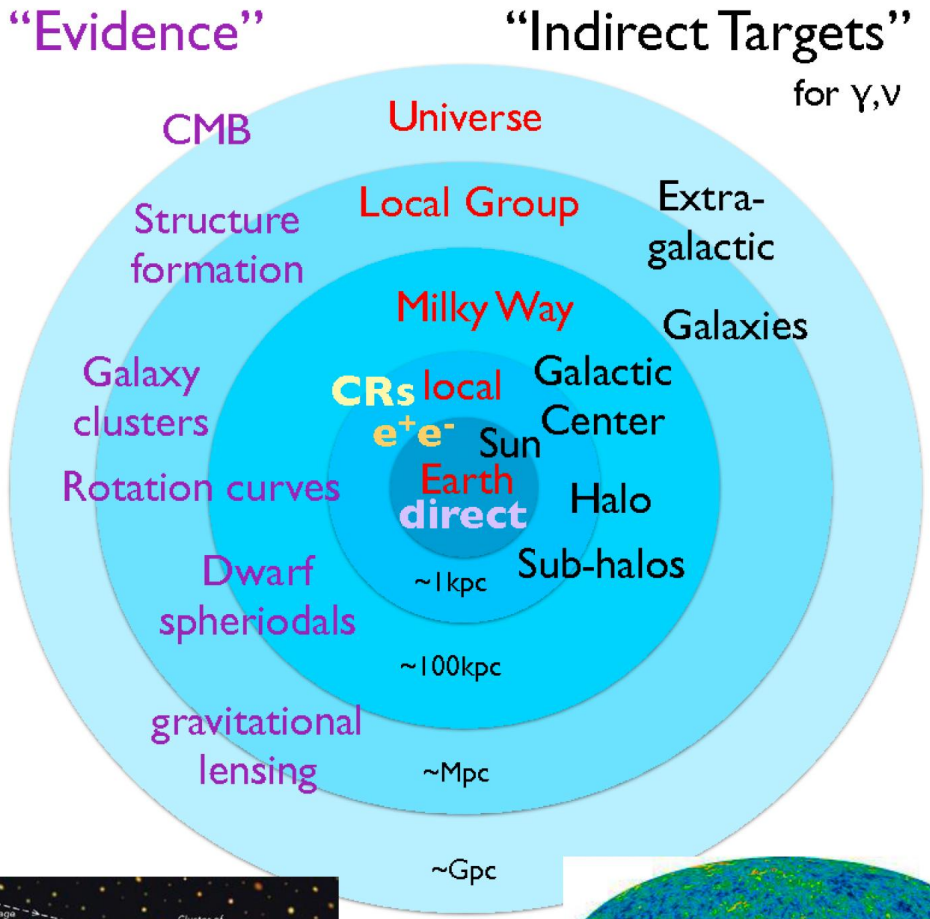
2.3.2 银河系中的暗物质

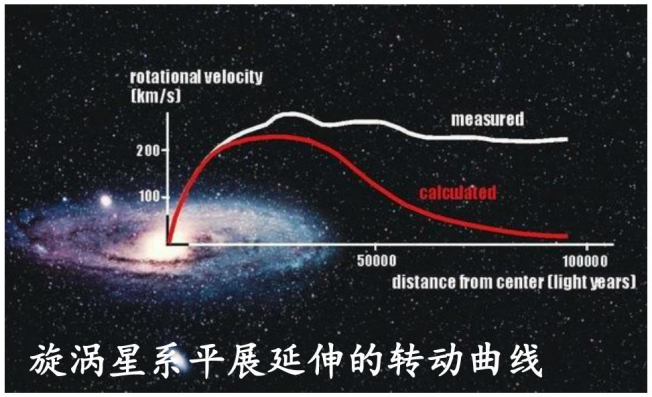


What does the MW rotation curve tell us?

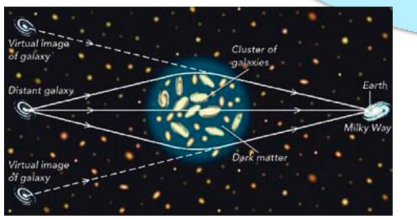
- **Since the MW rotation curve shows no drop in velocities beyond the visible edge of the disk (around R=15 kpc): indicates that some additional non-luminous material must be present → Dark Matter (matter too dim to be detected by current technology)**

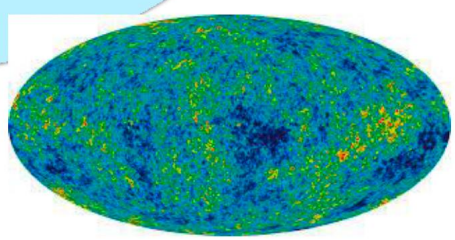
暗物质存在的证据

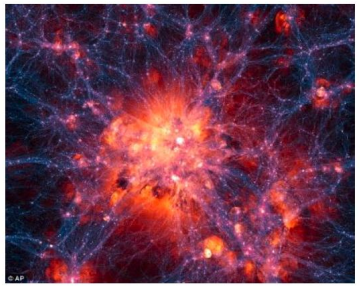




旋涡星系平展延伸的转动曲线

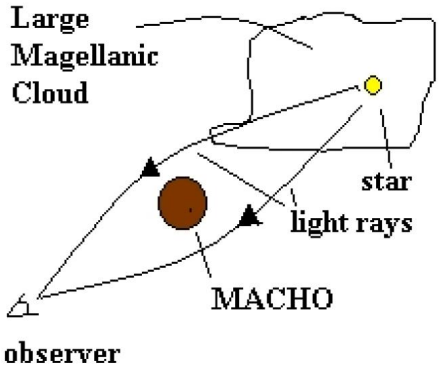






What is the Dark Matter?

- 暗物质：可分为重子暗物质和非重子暗物质两类



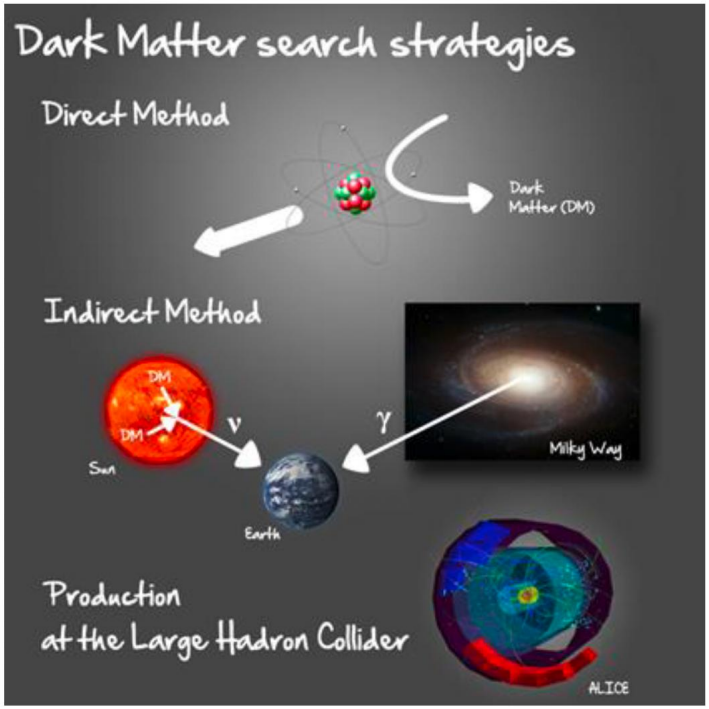
- 重子暗物质
  - 参与电磁相互作用，但缺乏发光条件（不发光）
  - 晕族大质量致密天体（MAssive Compact Halo Objects，MACHOs）：如黑洞、中子星、衰老白矮星、褐矮星（M < 0.08 Msun）、行星
  - 观测表明，MACHO占宇宙中暗物质的比例很小。

- 非重子暗物质
  - 不参与电磁相互作用，因而不会发光。只能通过引力产生的效应得知宇宙中有大量暗物质的存在。
  - 统称为大质量、弱相互作用粒子 (Weakly Interacting Massive Particles，WIMP)
  - 热暗物质：静质量不为零的中微子 ($mc^2 < kT_d$)
  - 冷暗物质：质量大、速度慢的粒子 ($mc^2 > kT_d$)
  - 温暗物质：温度介于两者之间，$T_d = 10^{11}$K

WIMP ?

Dark Matter Detection

- 加速器上模拟宇宙大爆炸
  - 通过高能粒子碰撞，模拟宇宙大爆炸，将暗物质粒子打出来，然后去探测
- 地下直接探测
  - 通过探测暗物质粒子与普通原子核碰撞产生微弱信号来探测暗物质粒子
  - 放在地底下：把宇宙射线本底屏蔽掉
- 空间间接探测
  - 间接探测暗物质粒子在与暗物质粒子碰撞以后，会产生看得见的粒子
  - 通过探测这些看得见的粒子去探测看不见的暗物质粒子



暗物质粒子探测卫星：悟空，DAMPE

锦屏山引水隧洞：极深地下暗物质探测实验室