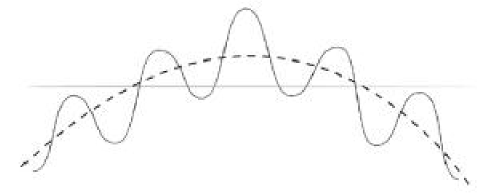
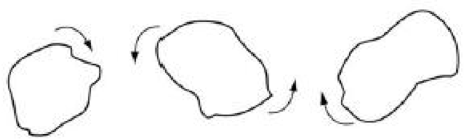
4.3 本群星系的形成

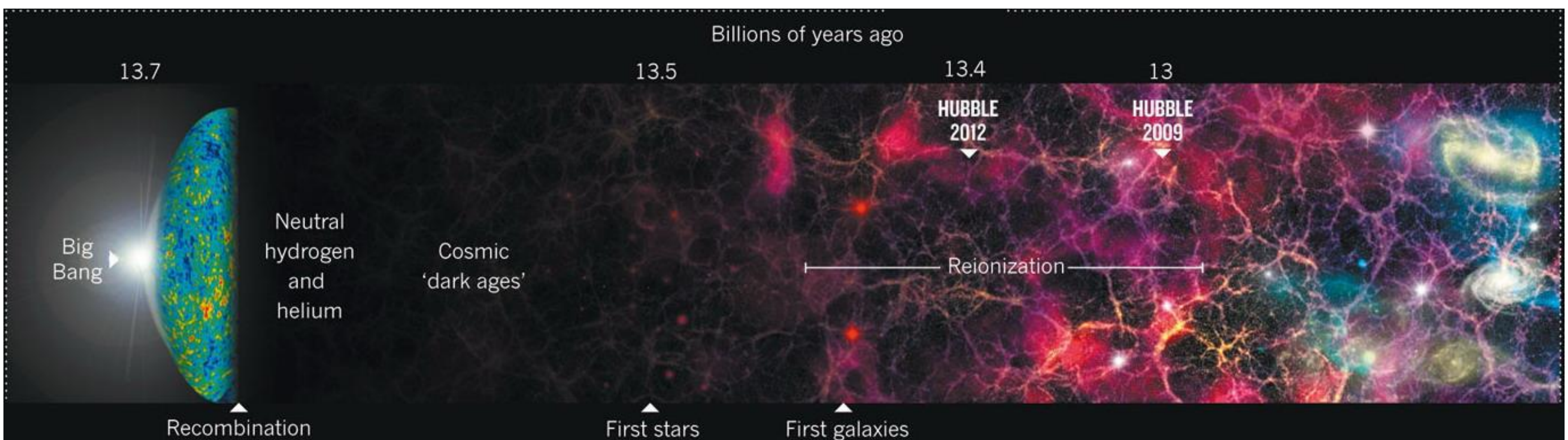


物质密度涨落，引力导致星云塌缩形成原初星系

- 宇宙膨胀温度降低，T ~ 350000 yrs，光子能量不能电离氢和氦：质子和电子结合成中性原子，光子可自由传播：宇宙透明
- 气体不再受到光子压支持：高密区引力大，导致向内塌缩：中心附近的团块相互吸引，并合成大星系；靠外团块则可能变成较小的伴星系（原初星系）
- 早期宇宙小，原初星系彼此靠近，原星系的引力相互拉拽：潮汐矩会拉着原星系慢慢转动起来
- 原星系内气体云彼此碰撞，它们会失去其部分能量而内落；因角动量守恒，原星系的旋转逐渐增加。

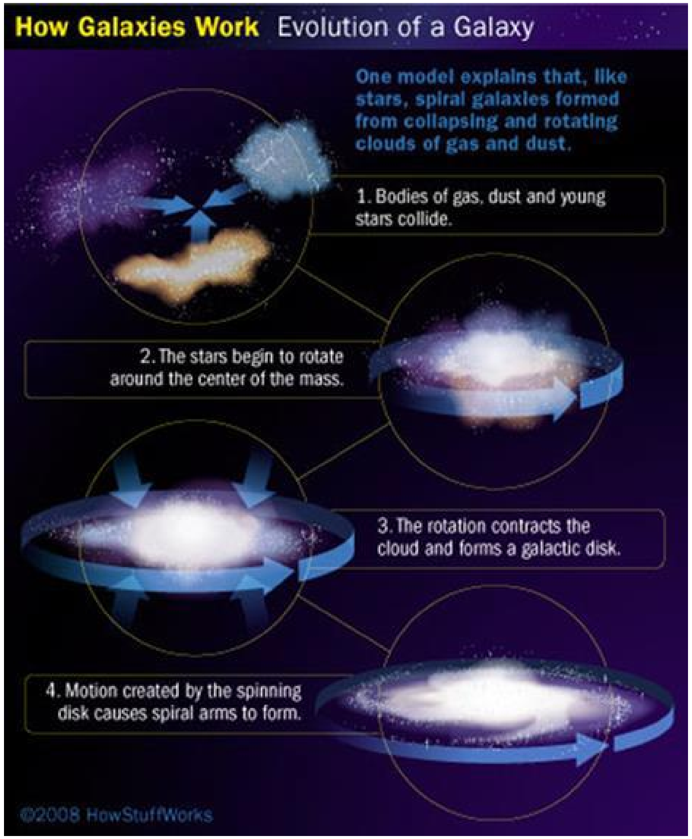


潮汐矩：不规则团块彼此吸引，并开始旋转

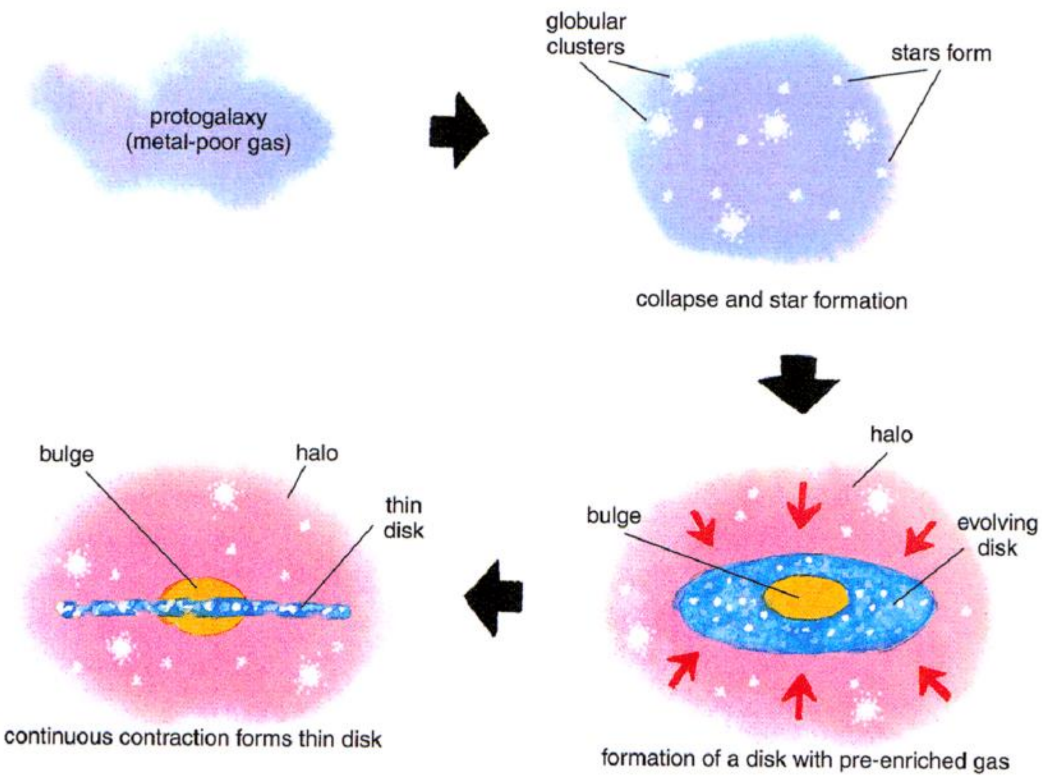


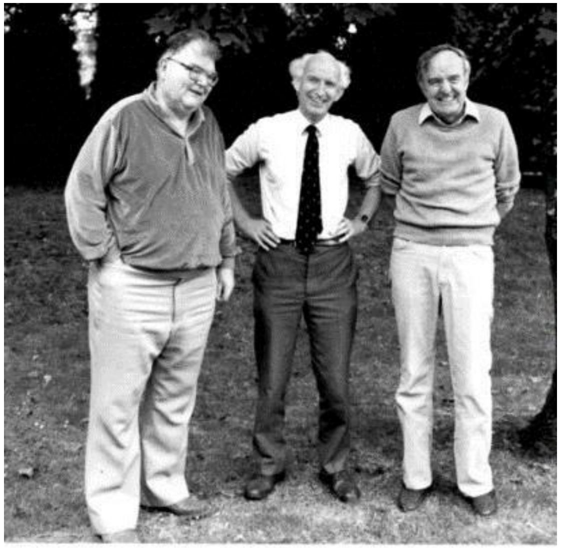
4.3.1 银河系形成-塌缩模型

- 宇宙早期引力扰动导致星云塌缩，形成第一代恒星：超新星爆炸使得元素增丰，但金属丰度很低
- 贫金属气体云相互运动碰撞，压缩气体，形成球状星团、晕星：年老（宇宙早期）、贫金属
- 气体云在形成恒星前，还没有向中心下落太远：球状星团和晕星的轨道取向随机；有序转动少
- 气体云坍缩时角动量损失缓慢(垂直轴方向)，沿着旋转轴方向下落：形成有序运动扁平盘结构
- 气体塌缩时标$t \sim 1/\mathrm{sqrt}(\rho)$：密度较高云快速形成恒星，超新星爆炸使得气体进一步增丰，厚盘星
- 厚盘超新星爆发，增丰气体。气体进一步下落，星系逐渐变为扁平状，形成由离心力支撑的薄盘
- 薄盘星开始诞生：较早代恒星产生的重元素已使气体增丰，薄盘星年轻、金属丰度高、有序运动



银河系形成-塌缩模型





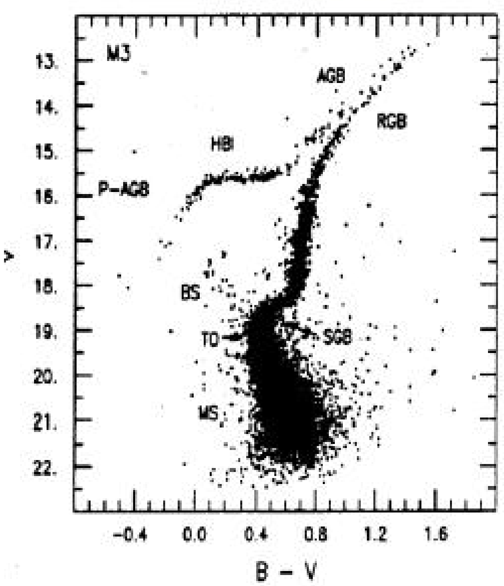
Eggen、Lynden-Bell & Sandage(ELS，1962)

核球恒星

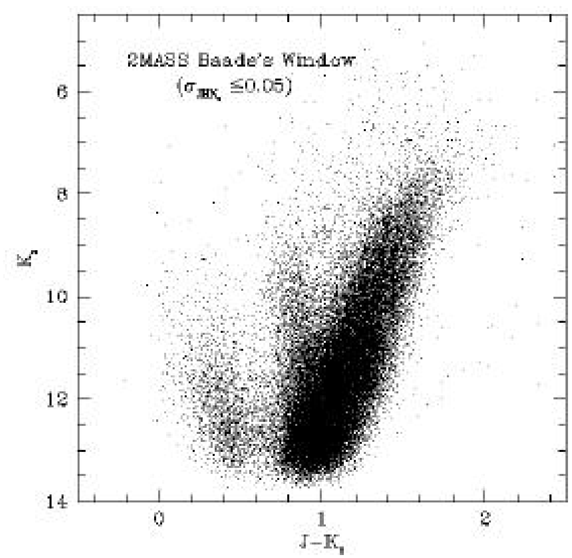
- 银河系核球区域的颜色—星等图（HRD）显示，其没有水平支星
  - 极少有核球的恒星能够像球状星团中的恒星那么老T~ 13 Gyr
  - 绝大多数核球恒星的年龄T <8-10 Gyr，有些可能更年轻

致密的中央核球一旦形成，整个银河系的引力束缚其气体：
俘获超新星增丰的气体，不断形成大量富金属恒星。

球状星团M3



银河系核球区CMD



不清楚核球中恒星是如何形成的?

- 形成于星系气体致密中心？
- 从星系盘较密的内区长出？
- 致密星团遗迹：动力学摩擦进入星系中心？

星族：Pop I and Pop II

- 星族指年龄、化学组成、空间分布与运动特性较接近的恒星集合。星族可分为三类：
  - 星族I：年轻恒星，形成较晚，金属丰度高，圆轨道。位于银盘、旋臂等区域
  - 星族II：年老恒星，形成较早，金属丰度低，随机运动。位于星系晕、核球等区域
  - 星族III：诞生于宇宙极早期，零金属、大质量的恒星。没有被发现，理论预言。

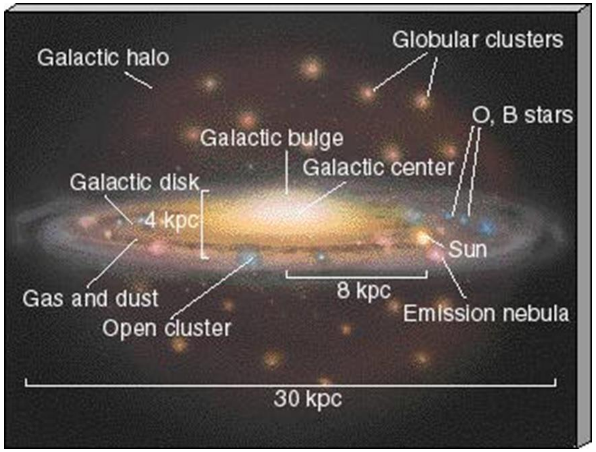
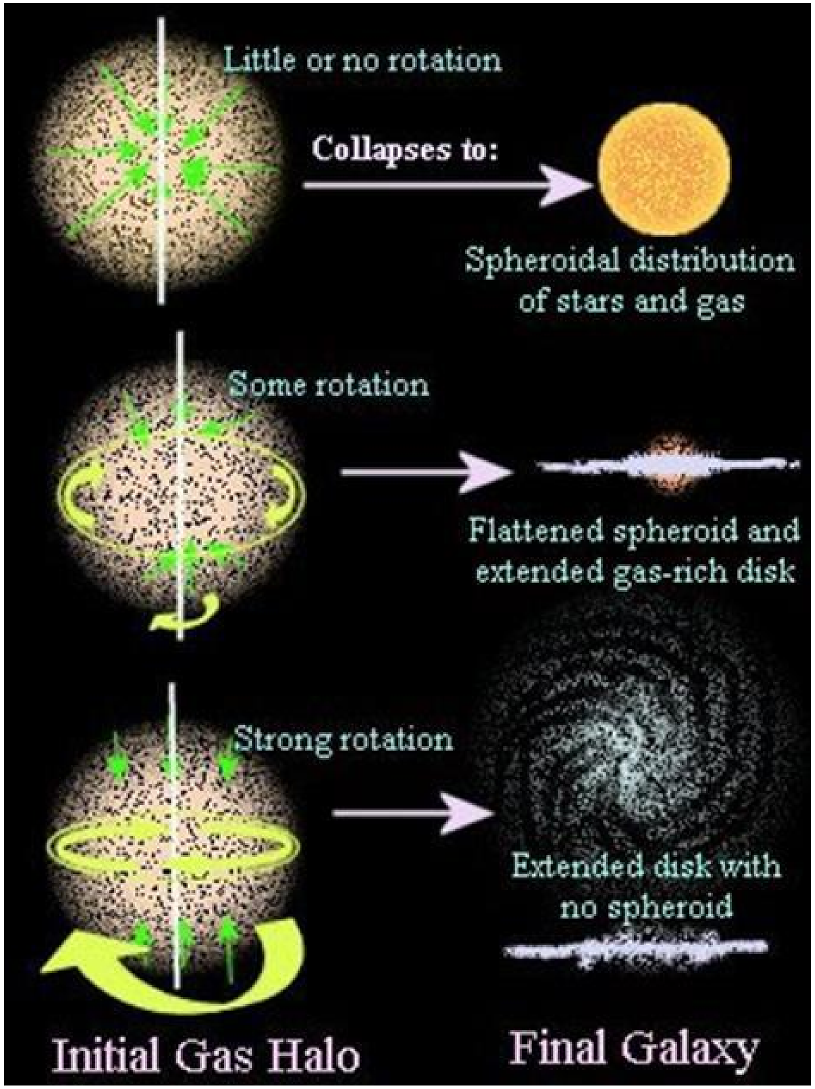


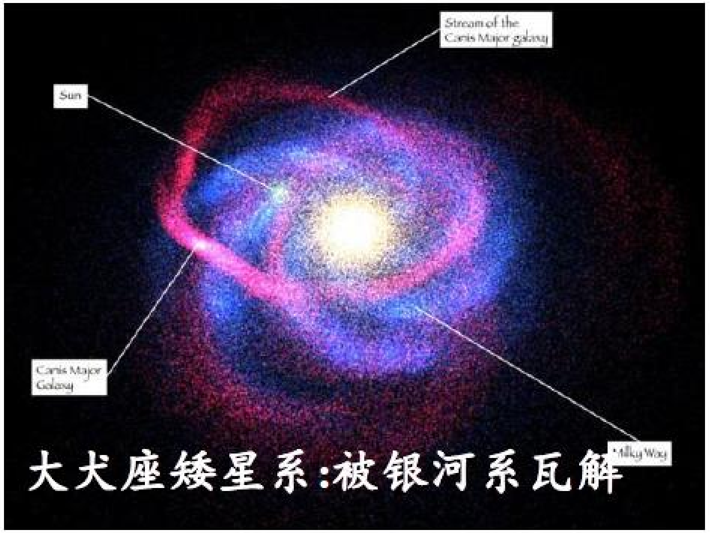
TABLE 15-1
Stellar Populations

	Population I		Population II	
	Extreme	*Intermediate*	*Intermediate*	*Extreme*
Location	Spiral arms	Disk	Nuclear bulge	Halo
Metals (%)	3	1.6	0.8	Less than 0.8
Shape of orbit	Circular	Slightly elliptical	Moderately elliptical	Highly elliptical
Average age (yr)	100 million and younger	0.2–10 billion	2–10 billion	10–13 billion

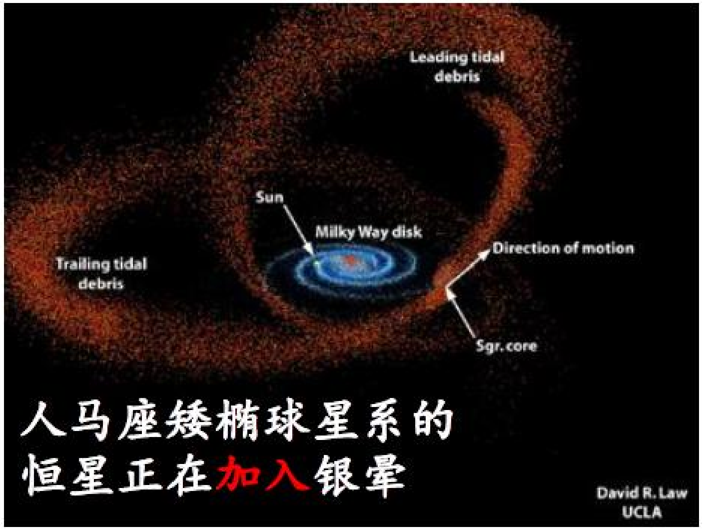
银河系-继续构建



Little or no rotation
Collapses to:
Spheroidal distribution of stars and gas
Some rotation
Flattened spheroid and extended gas-rich disk
Strong rotation
Extended disk with no spheroid
Initial Gas Halo
Final Galaxy

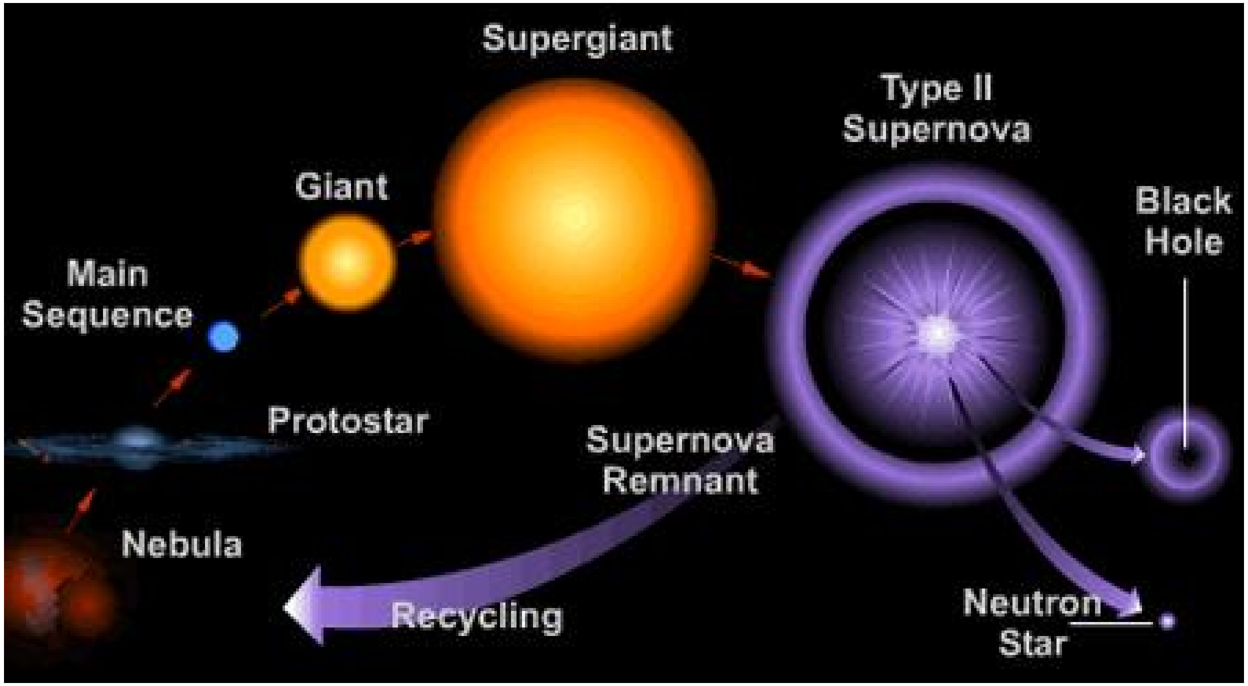


Stream of the Canis Major galaxy
Sun
Canis Major Galaxy
Milky Way
大犬座矮星系:被银河系瓦解



Leading tidal debris
Sun
Milky Way disk
Direction of motion
Trailing tidal debris
Sgr. core
人马座矮椭球星系的
恒星正在加入银晕
David R. Law
UCLA

4.3.2 重元素的合成



- 原初气体 → 第一代恒星 → 合成重元素 → SN爆炸 → 星际介质丰度增加 → 第二代恒星 → …
- 恒星燃烧H、He气体，形成重元素：恒星年龄与金属丰度相关；较老恒星几乎不含金属，年轻恒星则有较高金属丰度 → 化学演化

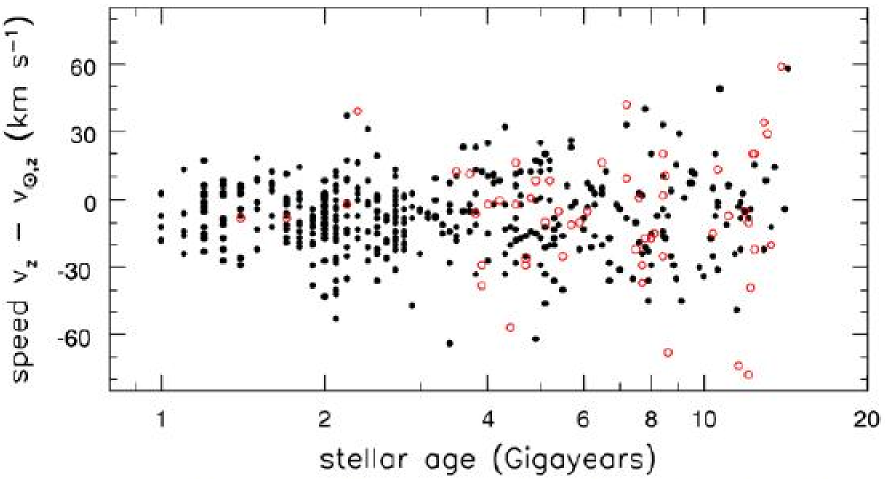


Fig.2.9 太阳附近F、G型主序星垂直于盘方向运动：年老恒星运动速度大

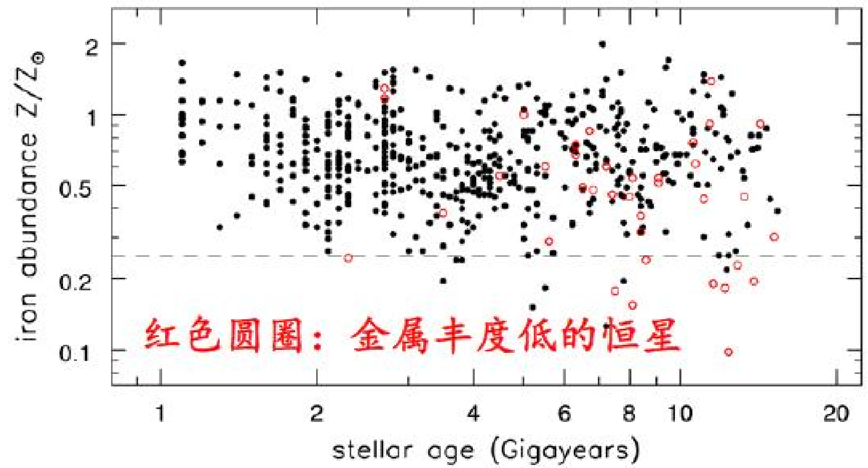
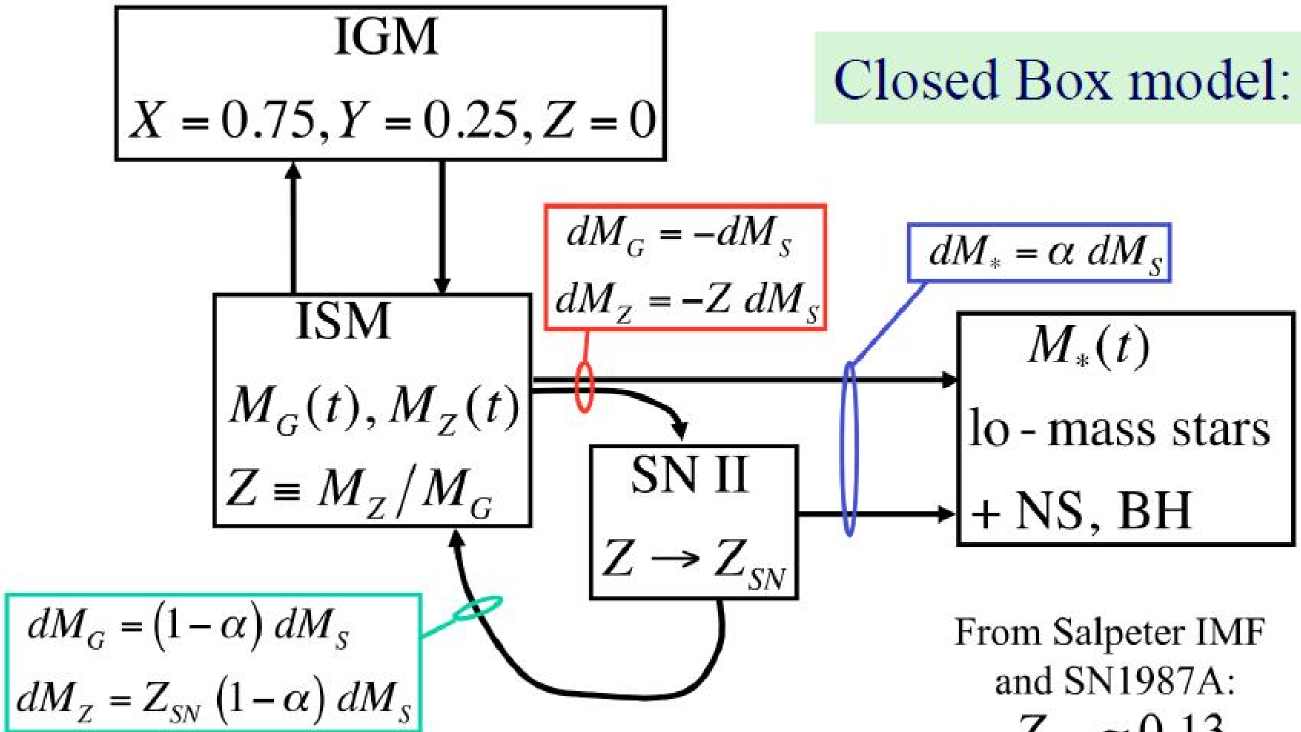


Fig.4.14 太阳附近F、G型主序星金属丰度与年龄关系：年老恒星的金属丰度低

The Closed Box Model

Closed Box model: 1 and 2 only.



Intergalactic medium (IGM)

Interstellar medium (ISM)

From Salpeter IMF and SN1987A:

$Z_{SN} \approx 0.13$

$\alpha \approx 0.93$

Processes that alter the metalicity:

1. Type-II SNe enrich the ISM. 2. Low-mass stars form from enriched ISM and "lock-up" metals. 3. Primordial gas falls in from IGM. 4. ISM ejected into IGM. (e.g. SN explosions, galaxy collisions)

单区瞬时循环模型——化学演化

- 假设：
  - 星系的气体充分混合，处处具有相同化学组成
  - 恒星将它们核聚变的产物瞬时返回到星际气体
  - 无气体从星系逃离，也无气体流入：闭区模型
  - 所有比氦重的元素，彼此保持完全相同的比例

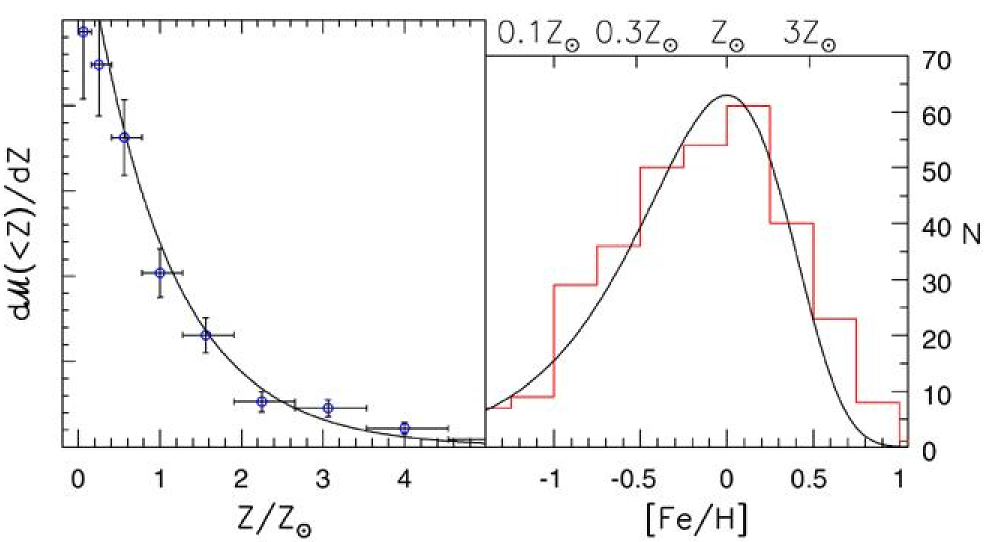
- $M_g(t)$：t时刻，星系(ISM)中气体的质量；
- $M_*(t)$：t时刻，小质量恒星和恒星遗迹质量（被锁定在这些天体中的物质质量)；
- $M_h(t)$：t时刻，星系气体(ISM)中比氦重的元素总质量；
- $Z(t) = M_h(t) / M_g(t)$，气体的金属丰度

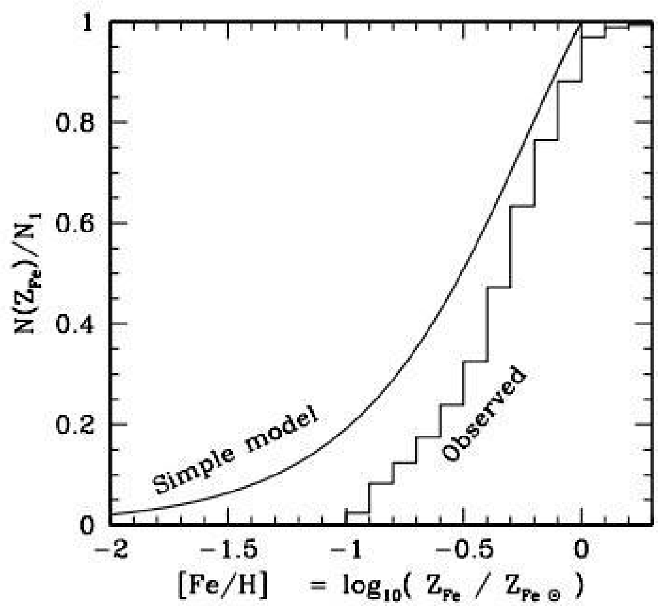
$$\Delta Z \equiv \Delta\left(\frac{\mathcal{M}_{\rm h}}{\mathcal{M}_{\rm g}}\right) = \frac{p\,\Delta\mathcal{M}_\star - Z[\Delta\mathcal{M}_\star + \Delta\mathcal{M}_{\rm g}]}{\mathcal{M}_{\rm g}}$$

模型检验

- 在旋涡星系外盘等富气区域，恒星和气体是相对贫金属的：与恒星形成相关的气体密度高的地方，重元素的平均丰度低预言一致
- 银河系核球中G和K型巨星的金属丰度：核球可能成功地留住了所有气体，并完全将其变成了恒星 → 所以观测结果能够与单区瞬时循环模型预言复合较好
- 观测太阳邻域132 颗G 型矮星样本，发现只有33 颗小于太阳铁丰度的25%，并且只有1颗小于太阳氧丰度的25%。

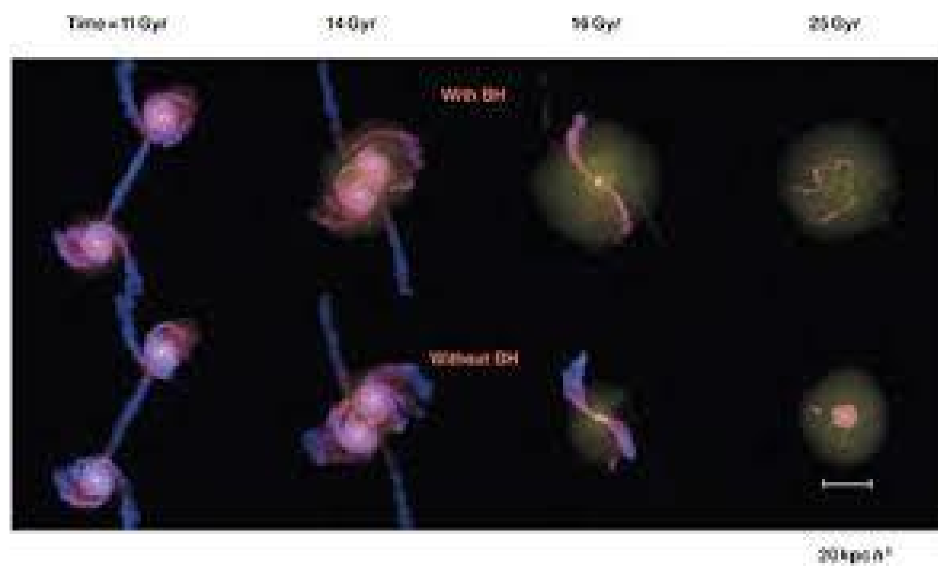
对于太阳邻域，闭区模型给出太阳附近局域盘星几乎一半有$Z < Z_\odot/4$。





G-dwarf Problem——解决办法

- 形成恒星的气体金属丰度Z(t=0)不等于0：
  - 以前恒星产生的重元素已同形成盘的气体混合，使其‘预增丰’
  - 令Z(t=0) ≈ 0.15 $Z_\odot$，可以近似给出局域金属丰度的观测分布
- 气体外流、内落存在：闭合假定不成立
  - 外部贫金属气体的内流，阻止丰度上升得像闭区模型预言的那样快
  - 矮星系或者星团等引力势不足于束缚其中气体，发生外流，带走重元素
  - 外流和内落，导致形成恒星的气体金属丰度不均匀：瞬时混合假定不成立



Models with Inflow and Outflow

In the presence of gas flow, the total mass of the system changes with time according to

$$\frac{dM_{\rm tot}}{dt} = \mathscr{A}(t) - \mathscr{W}(t), \tag{10.127}$$

where $\mathscr{A}(t)$ and $\mathscr{W}(t)$ are the inflow and outflow rates of gas mass, respectively. The equation for the gas mass now becomes

where $\Psi(t)$ is the star-formation rate of the system, and $\mathscr{E}(t)$ is the rate at which the stars return mass to the gas phase by stellar winds and supernovae (hereafter called the return rate). If we

$$\frac{dM_{\rm gas}}{dt} = -\Psi(t) + \mathscr{E}(t) + \mathscr{A}(t) - \mathscr{W}(t). \tag{10.128}$$

Under the assumption of uniform mixing of the gas in the system, the equation for the metallicity is

$$\frac{d(ZM_{\rm gas})}{dt} = -Z\Psi(t) + \mathscr{E}_Z(t) + Z_A\mathscr{A}(t) - Z(t)\mathscr{W}(t), \tag{10.129}$$

where Z_A is the metallicity of the inflowing gas. These equations can be solved once $\mathscr{A}(t)$ and $\mathscr{W}(t)$ are known.

metal yield, y_Z.

$$\mathscr{E}(t) = \Psi(t)\mathscr{R},$$

假定：$\mathscr{A}(t) = 0$ and $\mathscr{W}(t) = \alpha(1-\mathscr{R})\Psi(t)$

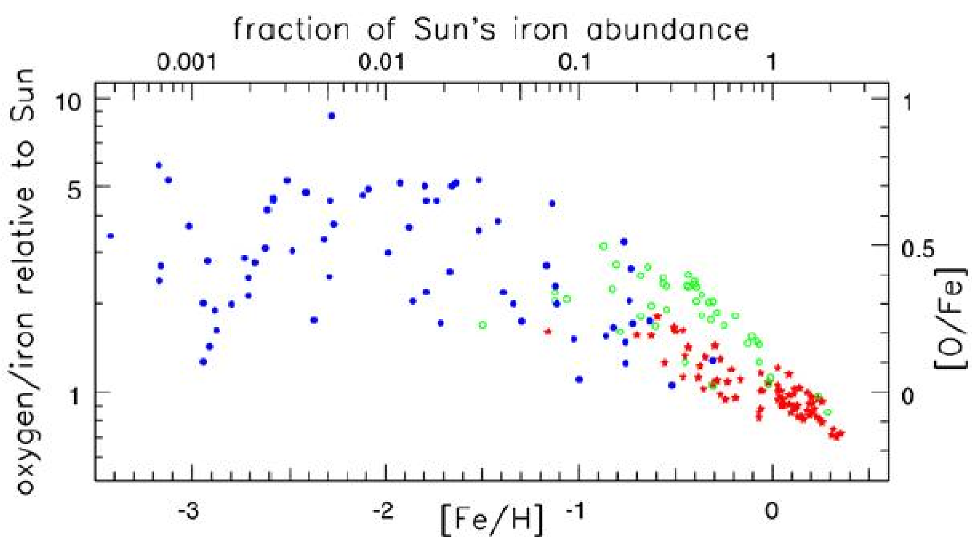
$y_Z/(1+\alpha)$ is called the effective yield,

$$Z(t) = Z(0) + \frac{y_Z}{1+\alpha}\ln\left[\frac{M_{\rm gas}(0)}{M_{\rm gas}(t)}\right]$$

$$\begin{aligned} M_\star(<Z) &= M_{\rm tot}(t) - M_{\rm gas}(t) \\ &= \frac{M_{\rm tot}(0)}{1+\alpha}\left\{1 - \exp\left[-\frac{Z - Z(0)}{y_Z/(1+\alpha)}\right]\right\} \end{aligned}$$

贫金属星α元素增丰

- α元素和Fe元素产生机制不同
  - 星际气体中的铁元素主要是由Ia型超新星爆炸释放到ISM中，发生SN Ia爆炸的恒星为小质量恒星，年龄在1 Gyr或以上
  - 星际气体中α元素主要II型超新星爆发时抛到ISM中，II型超新星为大质量恒星产物（T < 100Myr）：SN II 的Fe 保留在中子星、黑洞中
  - 贫金属晕星形成的早（t < 1Gyr），Ia型超新星还没有开始把铁加入星际气体中：α元素同铁的比[a/Fe]要高于在太阳中的值



不同金属丰度恒星的氧元素与铁元素丰度比[O/Fe]：贫金属星中氧相对于铁更丰富

蓝色点：银晕中的恒星
绿色点：厚盘星
红色点：薄盘星

Time delay of at least ~ 10^8 yr between the onset of Type Ia supernova explosions and that of Type II for a coeval population of stars.

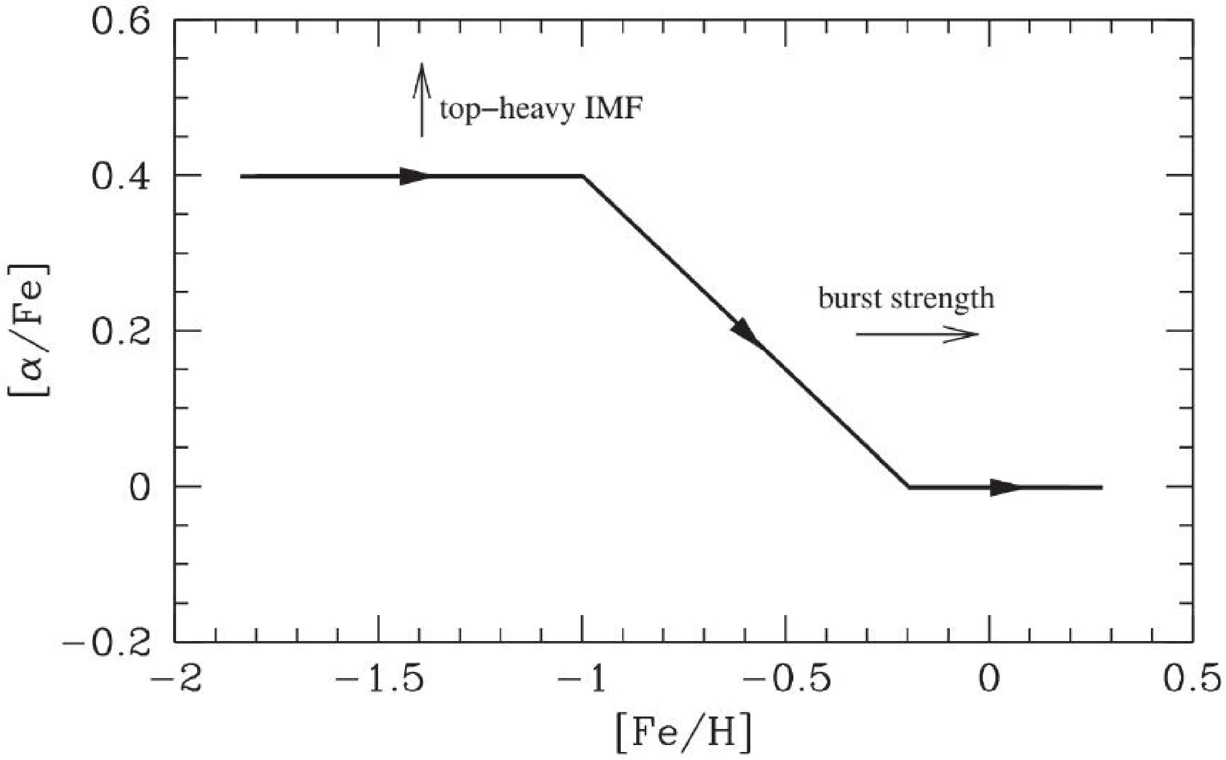
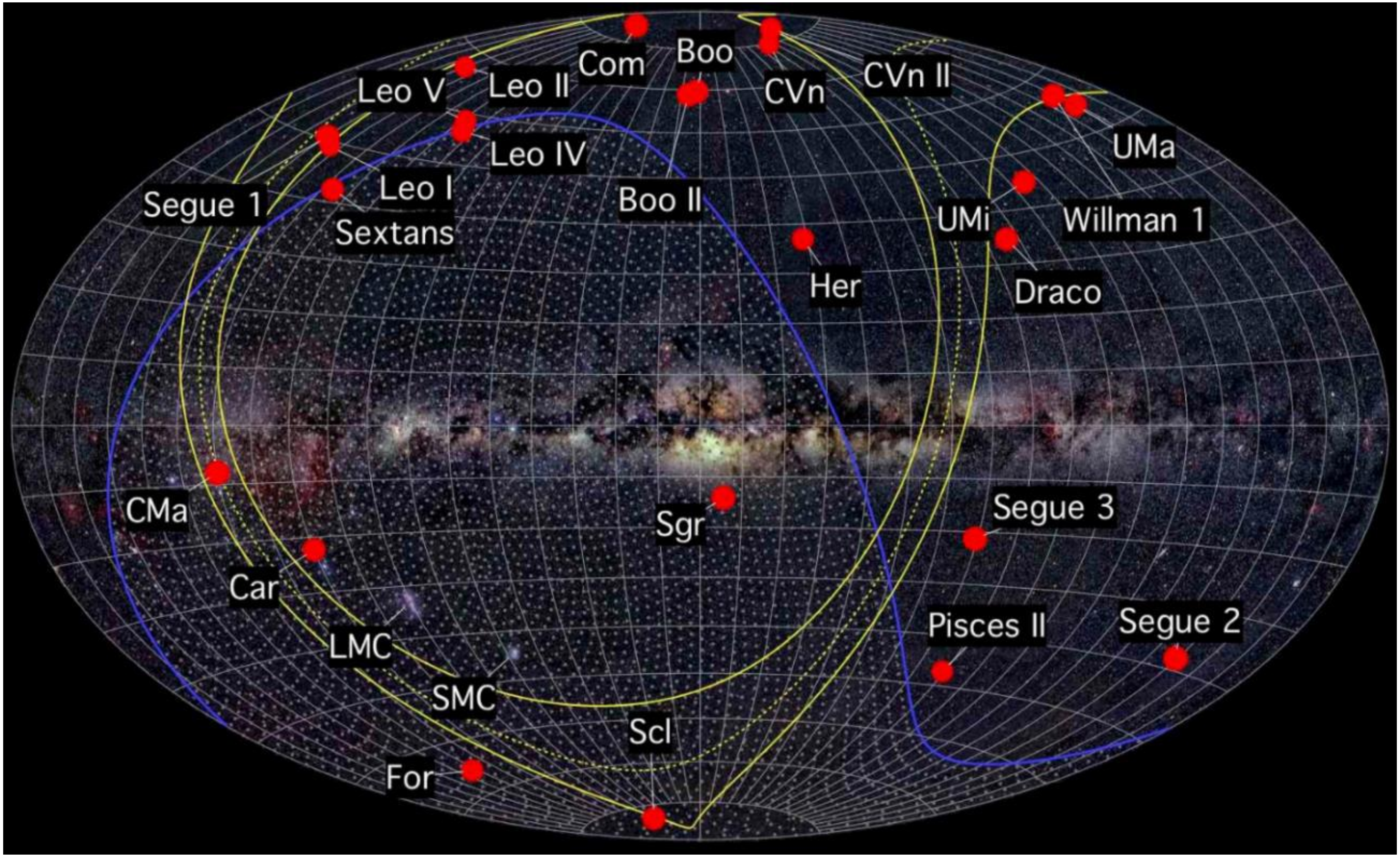


Fig. 10.10. A schematic of the chemical enrichment pattern of the ISM for a single coeval burst of star formation. Time advances along the thick curve as indicated by the arrows. The thin arrows indicate the impact of making the IMF more top-heavy and of increasing the strength of the burst.

4.4 本星系群中的矮星系

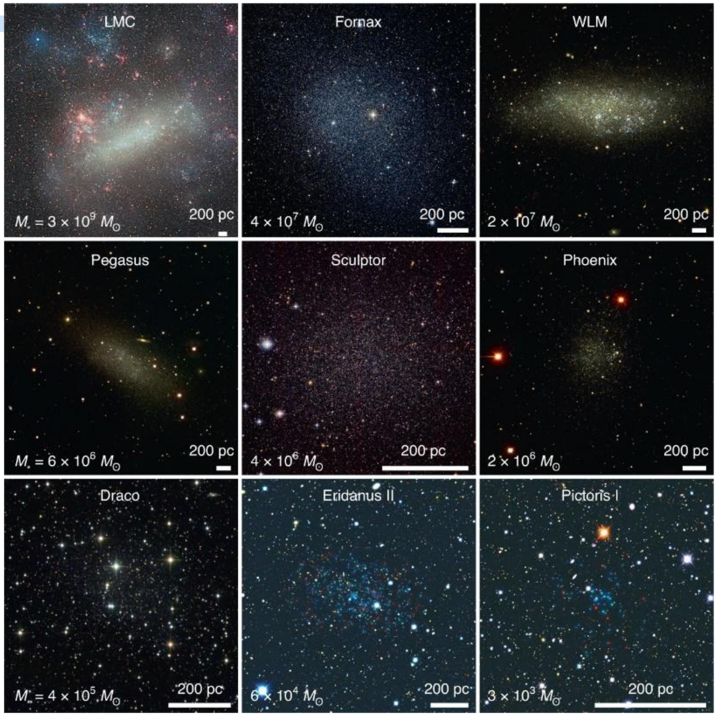


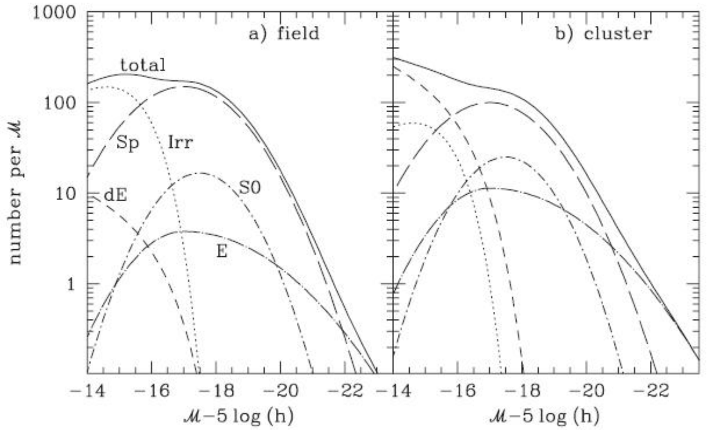
Distribution of Dwarfs in the LG

- Dwarf Ellipticals (dEs)
  - concentrated around M31
  - M32, N147, N205, N185
  - Little gas, old stellar pops
  - N147, N185, N205 rotationally supported
- Dwarf Irregulars (dIrr, Sdm)
  - All over, even at outskirts
  - Lots of gas (HI), mixed stellar pops
  - Rotationally supported
- Intermediate/Transition
  - Some gas, some SF, some with very few old stars
  - Probably not rotationally supported
- Dwarf Spheroidal (dSphs)
  - Satellites of MWG, M31
  - Complex SFH
  - gas?
  - Glorified globular clusters, but with dark matter
  - High σ/Vrot

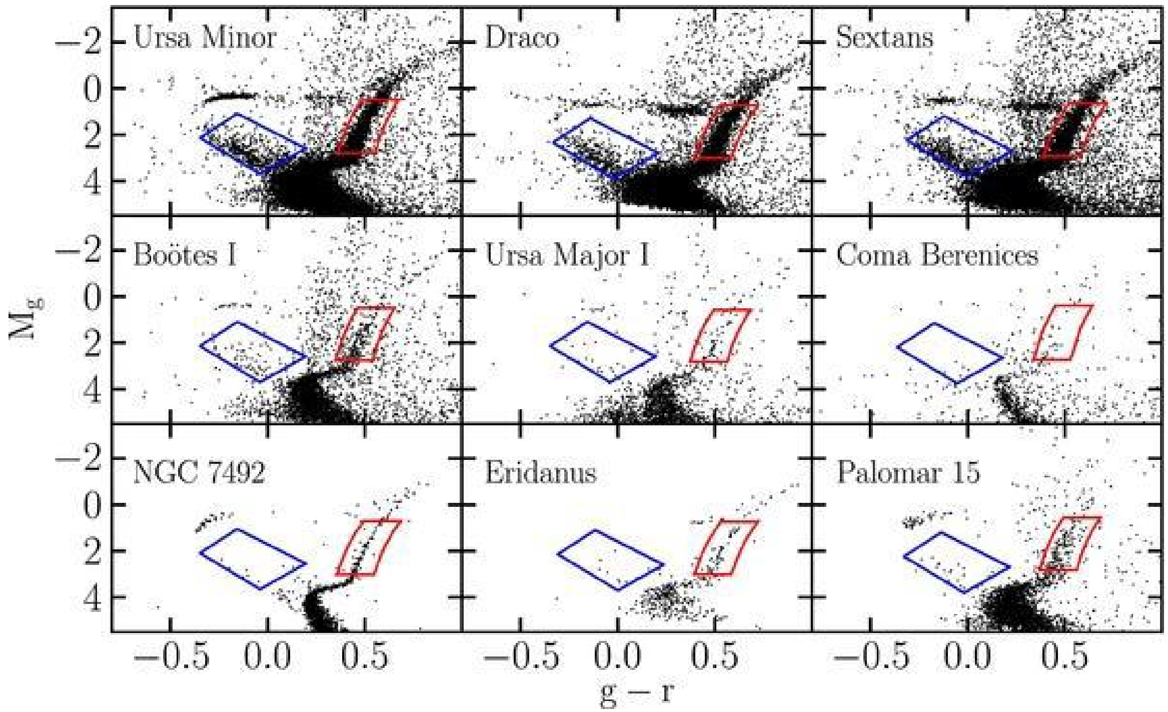
Why Dwarf Galaxies are so important

- Dwarfs
  - are 1st to form and the most numerous objects in the early Universe;
  - dominate faint galaxy counts in any deep survey;
  - should dominate local galaxy luminosity function;
  - are the building blocks of larger galaxies.
- But…
  - They do not contain most of the stars and baryonic matter
- Cold Dark matter halo
  - 1st structures are low mass halos
  - Larger structures form via hierarchical merging

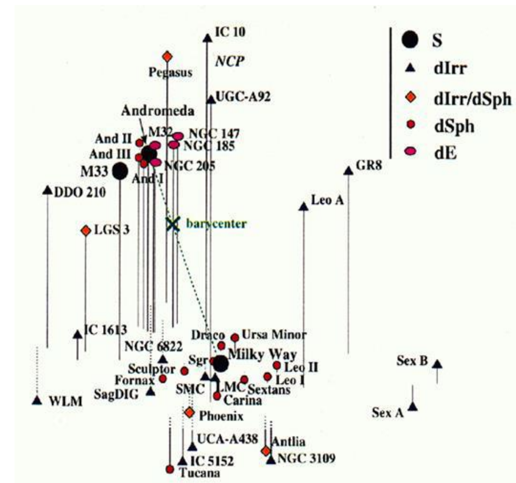




矮星系特征



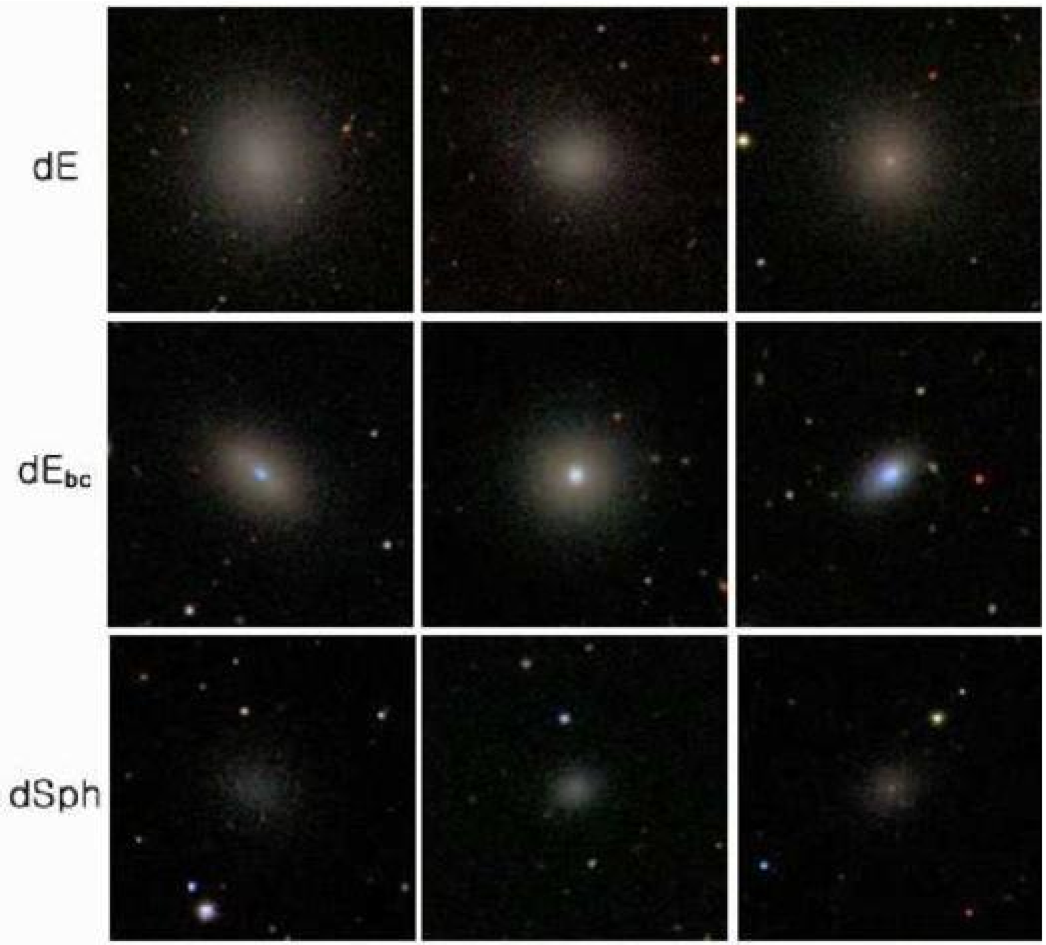
上：经典矮星系；
中：极暗矮星系；
下：球状星团



- 本群中所有的矮星系都含有一些水平支恒星：水平支恒星的年龄至少有10 Gyr，所以矮星系形成其首批恒星是在宇宙历史开始的2 – 3 Gyr
- 矮椭圆星系(dE)和矮椭球星系(dSph)基本都是银河系或者M31的伴星系；而矮不规则星系(dIrr)大多都不是较大系统的伴星系 → 自由飞行者

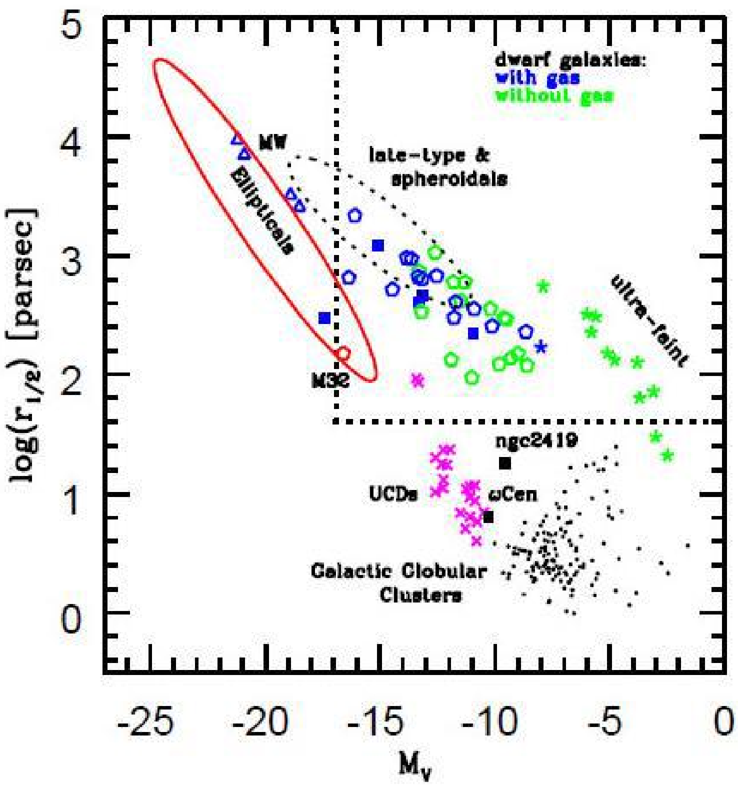
4.4.1 矮椭圆星系

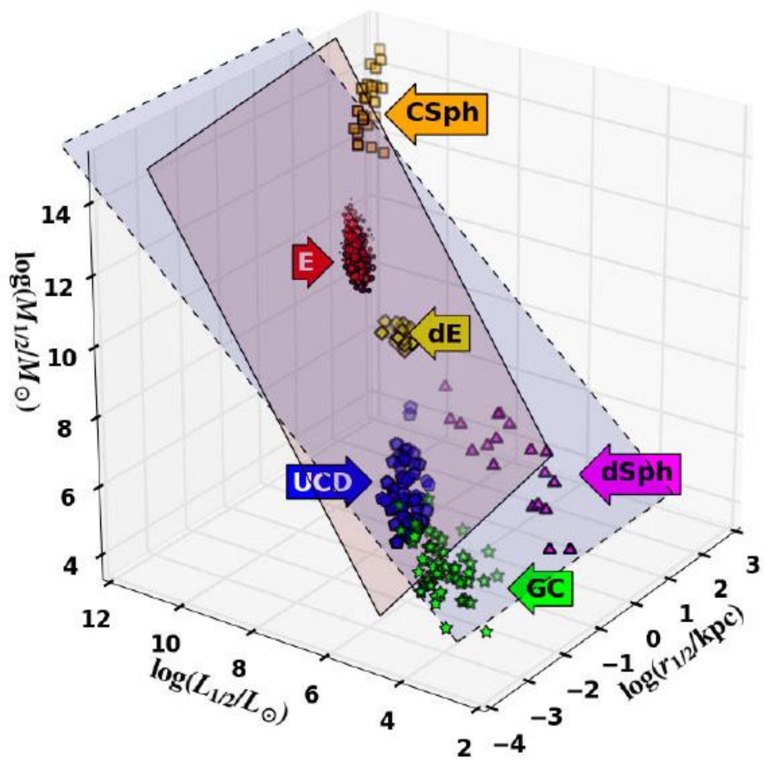
- 相同特性
  - 年老星族、冷气体少、SFR较低
- dE比dSph亮，其光度$L \geq 3 \times 10^7 L_\odot$
- dE尺度类似于dSph，但更亮，恒星密度高
- dE呈现为椭圆形，内部恒星没有显示出有序运动



Dwarf Ellipticals

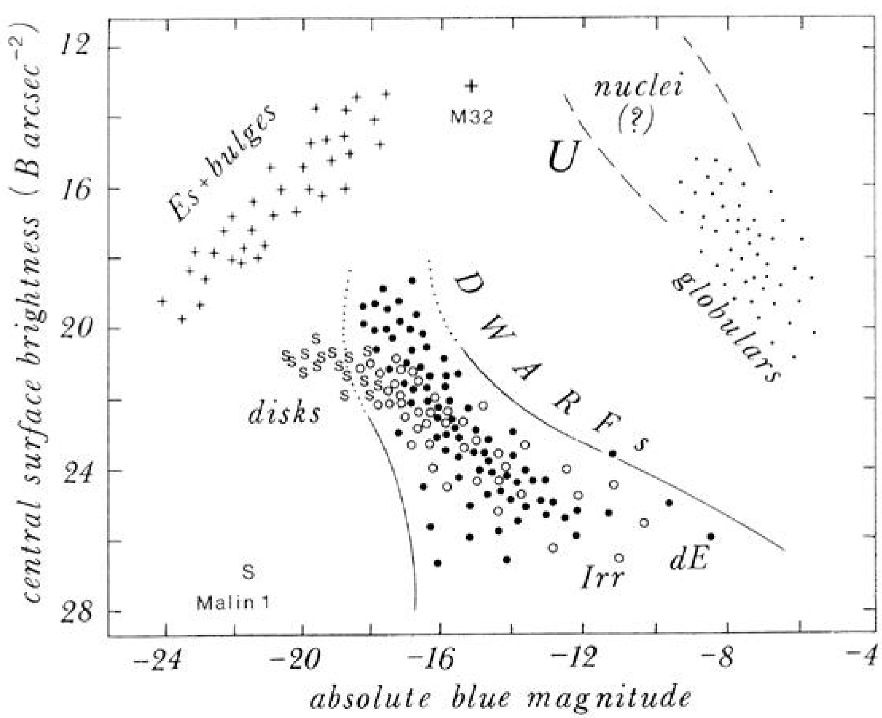
- Are they just scaled down versions of giant ellipticals?
  - Most are dominated by velocity dispersion
  - A few are rotating
  - Most lie on the fundamental plane





M32

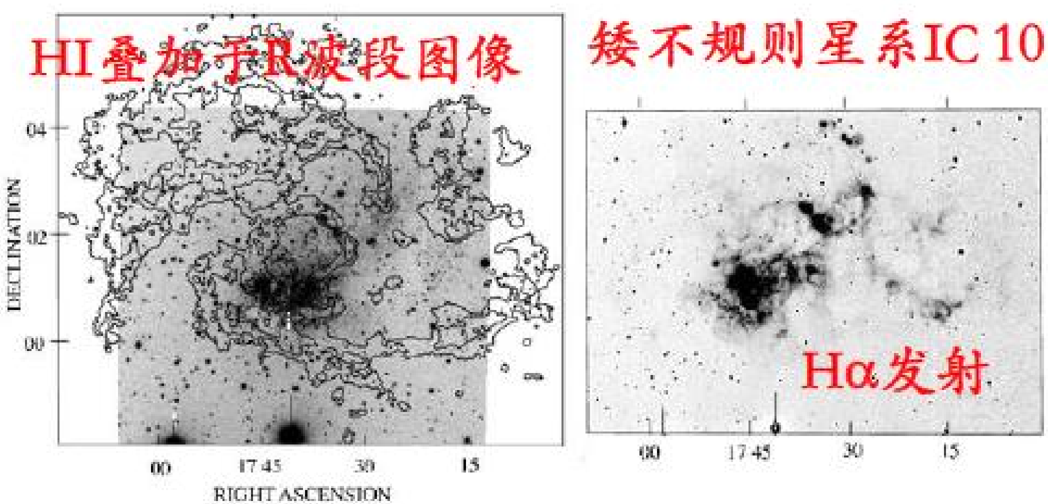
- M32是M31最亮的伴星系，星族年老、无冷气体
- 光度属于正常dE，但其密度非常高：M32是微型版正常或‘巨’椭圆星系
- M32 可能是一个大的旋涡星系的遗迹：外区被剥离，留下致密核球（? ）
- M32具有大质量星系的典型特征：中心恒星颜色红；重元素和太阳一样丰富
- M32 中恒星运动介于银盘(有序) 和银晕星(随机) 之间：V/s ~ 1 (银盘V/s ~ 7)

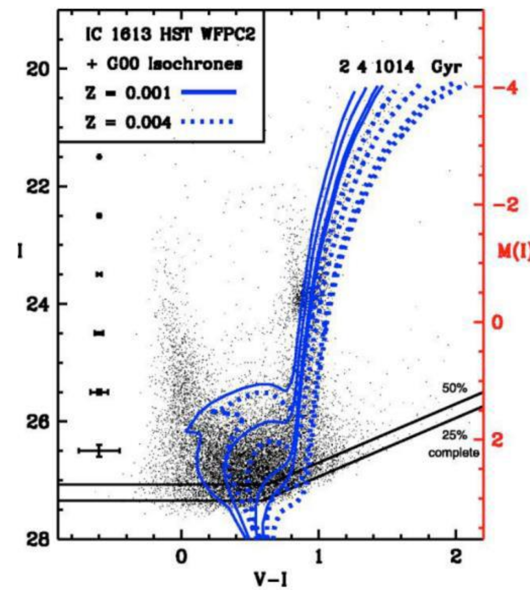


星系在绝对星等（V）与中心面亮度关系图上分布。+：亮椭圆星系和盘星系的核球；U：超致密矮椭圆星系；实圈：dE和dSph；空圈：不规则星系和矮不规则星系。S：旋涡星系的盘；Malin1 是低面亮度星系。

4.4.2 矮不规则星系

- 不规则星系和矮不规则星系光度分界：$L \sim 10^8 L_\odot$
- dIrr与dSph区别：
  - dIrr中存在大量年轻星族，年轻星族使得它们一般比矮椭球星系亮
  - dIrr含有气体和含有大量的中性氢气体，且气体层延伸超过主星盘
- dIrr与dSph相似：
  - 有序旋转运动不重要，V/σ ≤ 1
  - 金属丰度低，一般小于太阳丰度的10%。光度越小金属也越贫





Feedback in Dwarf Galaxies

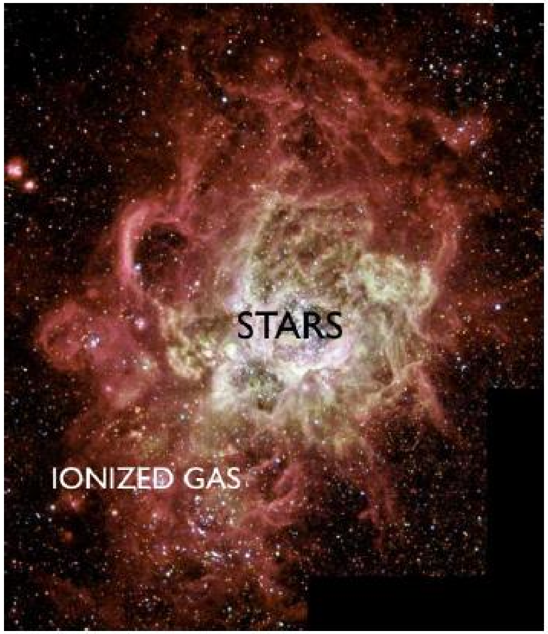
- **dIrr → dSph演化？恒星形成星风驱逐气体；恒星形成消耗气体；环境剥离气体（其它星系的引力作用）等**

- Massive stars deposit energy into ISM
  - $L_W \sim$ (mass loss rate) × (wind-velocity)^2
  - Create hot bubble (R ~ 60-200 pc)
  - SNe → 10^{38} erg s^{-1} → total E ~ 10^{50} erg
    - Shock heats gas to 10^6 K
    - Bubble expands at 10-100 km s^{-1}

- Dwarfs have "shallow" potentials
  - Low mass → low V_{esc} (~40 km s^{-1})

- Loss of ISM → effects Luminosity Function?
  - Enough to hamper future SF?
    - $M_{gal} = 10^6 M_\odot$ → should lose all their ISM
    - but dSphs have had multiple episodes of SF!

- Loss of metals
  - Enough to pollute the IGM?
  - Hot gas leaving NGC 1569 is metal rich

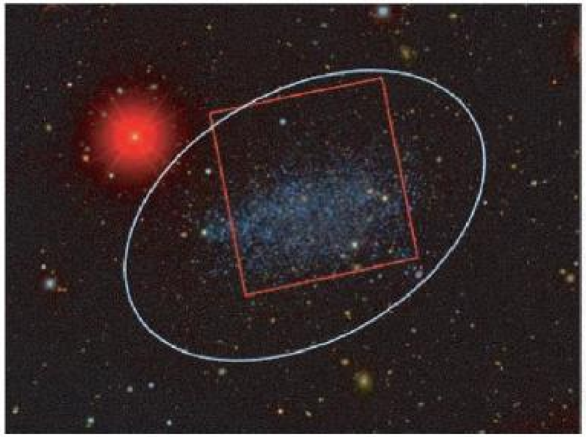


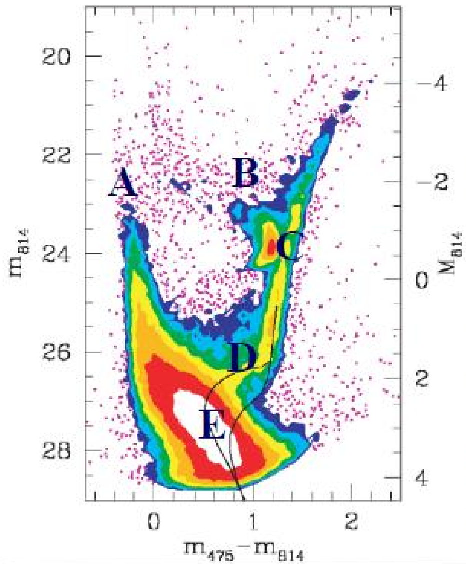
- Inferences on *feedback* in dwarfs:
  - Energy from star-formation preferentially blows out enriched gas local to the clumpy star-formation.
  - Inefficient for blowing out all gas, particularly cold gas.
  - → SF is on-going, but metal poor.

Resolving Galaxies with HST Imaging：LEO A

GLOBAL PROPERTIES OF LEO A

Quantity	Value	Refs.
Galactic coordinates (l, b) (deg)	196.9, +52.4	1
Distance modulus $(m - M)_0$	24.5 ± 0.1	2
Reddening $E(B - V)$	0.021	3
Absolute magnitude M_B^0	−11.7 ± 0.2	4
M(H I) (10^7 $M_\odot$)	1.1 ± 0.2	5
Total mass (10^7 $M_\odot$)	≲20	5
12 + log (O/H)	7.38 ± 0.1	6
Holmberg semiaxes, a_H, b_H (arcmin)	3.5, 2.2	7
Star formation rate ($M_\odot$ yr^{-1})	(1–2) × 10^{-4}	8, 9





Young Main Sequence (A) and Blue Loop (B), He-burning stars (t>15Myr)

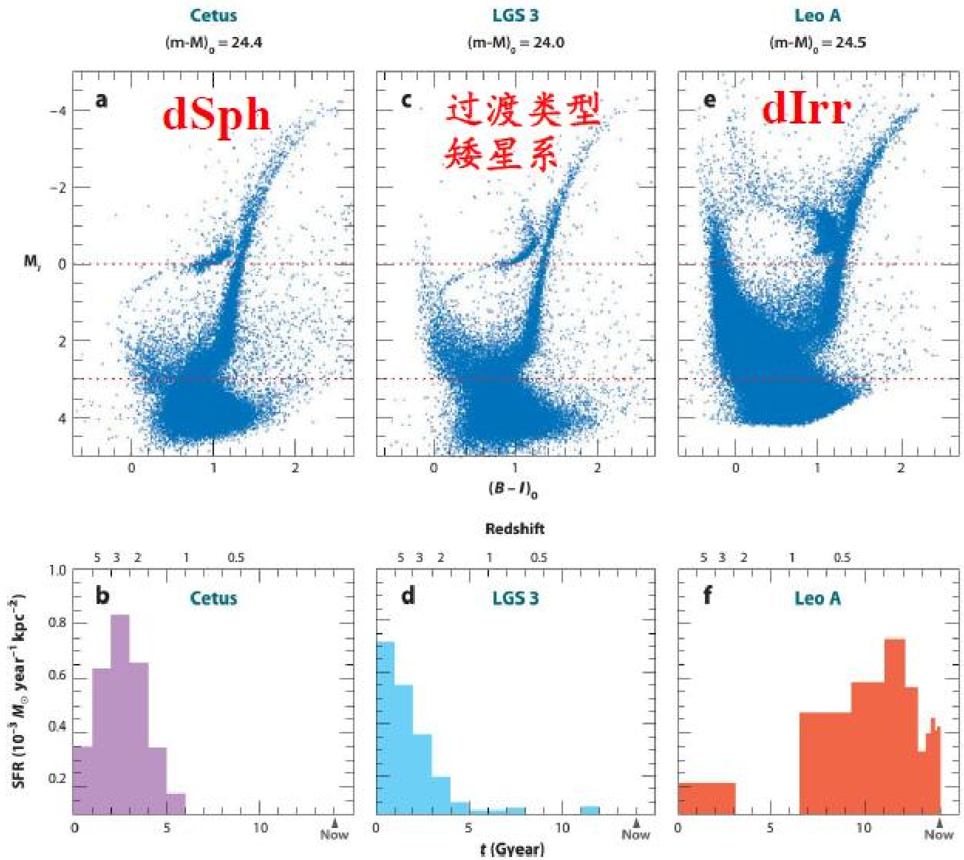
Strong red clump (C) - no serious horizontal branch

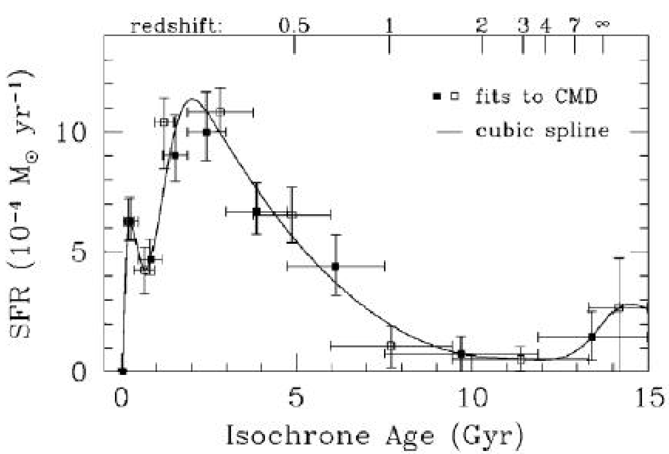
Peak density of subgiants (D), 2-6 Gyr old

Oldest Main Sequence, Turnoffs (E), 6-13 Gyr

SFHs Local Group Dwarfs

- With HST can observe CMD for **individual stars** in local group galaxies
- Using the techniques discussed earlier can invert this to get the **star formation history**
- Note 2 extremes: **very old** systems Cetus, **wide range** of SF histories (Leo A)

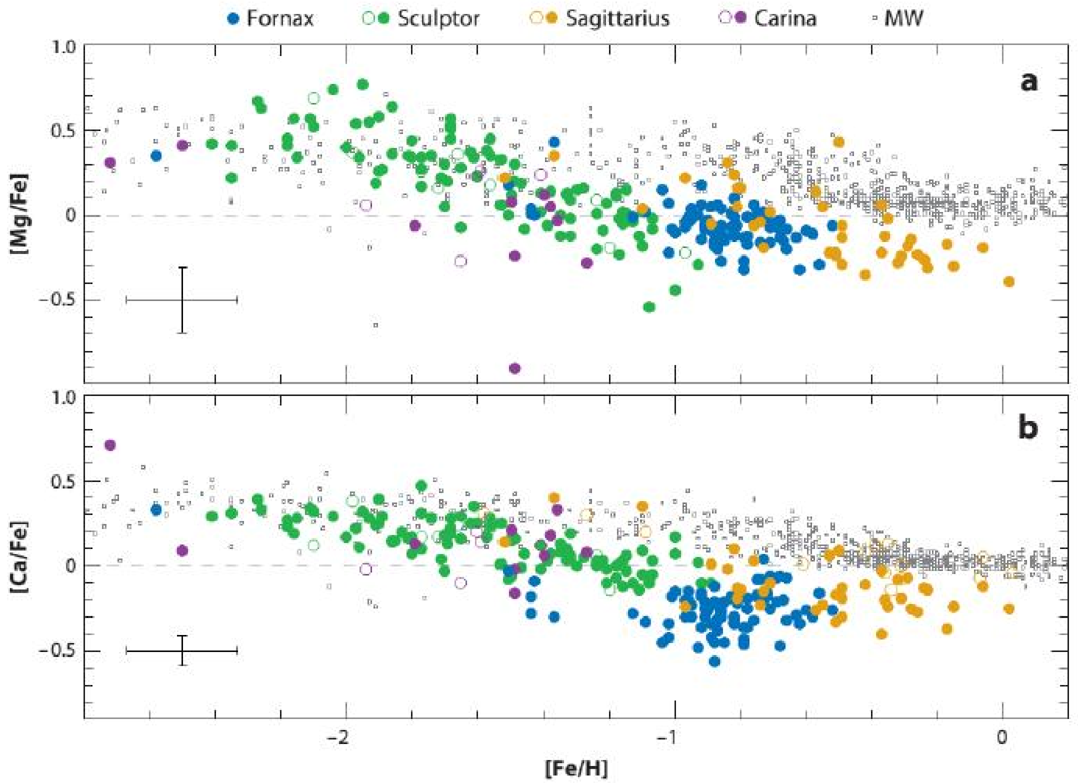




Derived SFH of central Leo A.

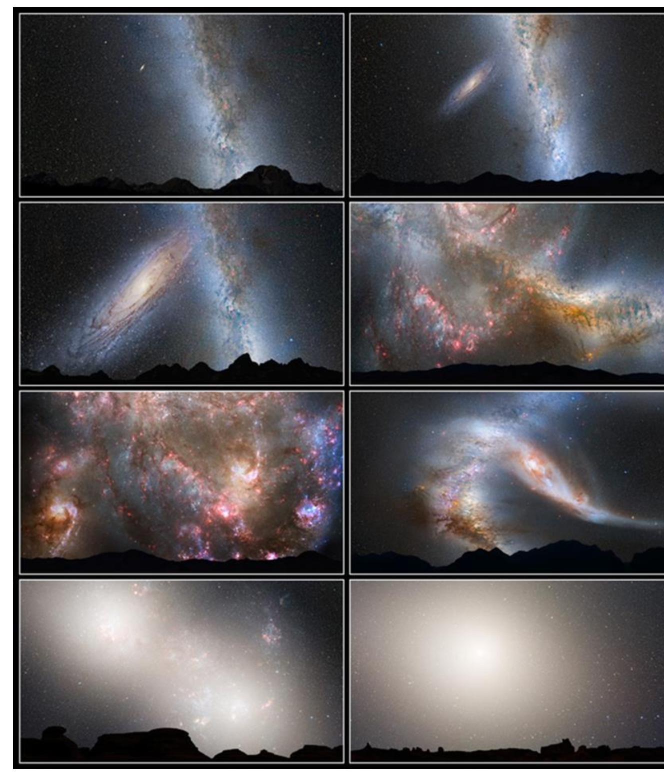
Metallicities In LG Dwarfs vs. MW

- Overall metallicity of LG dwarfs is low but some patterns:
  - some similar;
  - others different to stars in MW (black)
- How to reconcile their low observed metallicity with the fairly high SFR of the most metal-poor systems many of which are actively star-forming?



- Best answer metal-rich gas outflows, e.g. galactic winds, triggered by supernova explosions in systems with shallow potential wells, efficiently remove the metal-enriched gas from the system.
- In LG can wind models be well constrained by chemical abundance observations.

4.5 本星系群的未来



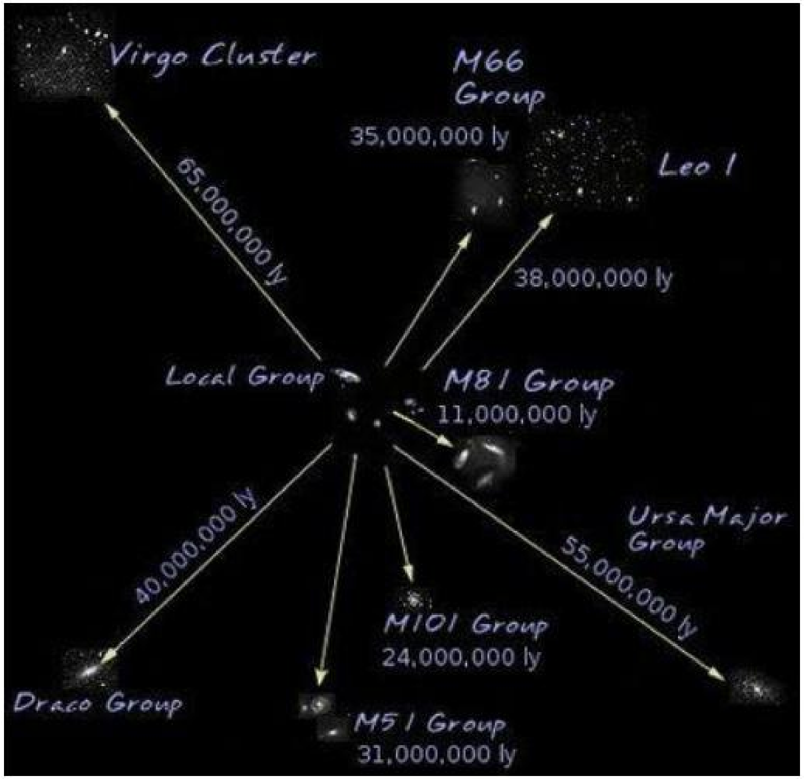
本星系群中的星系不再按照哈勃定律，随着宇宙膨胀而相互远离：引力已强到足以将星系群的成员朝向彼此拉回

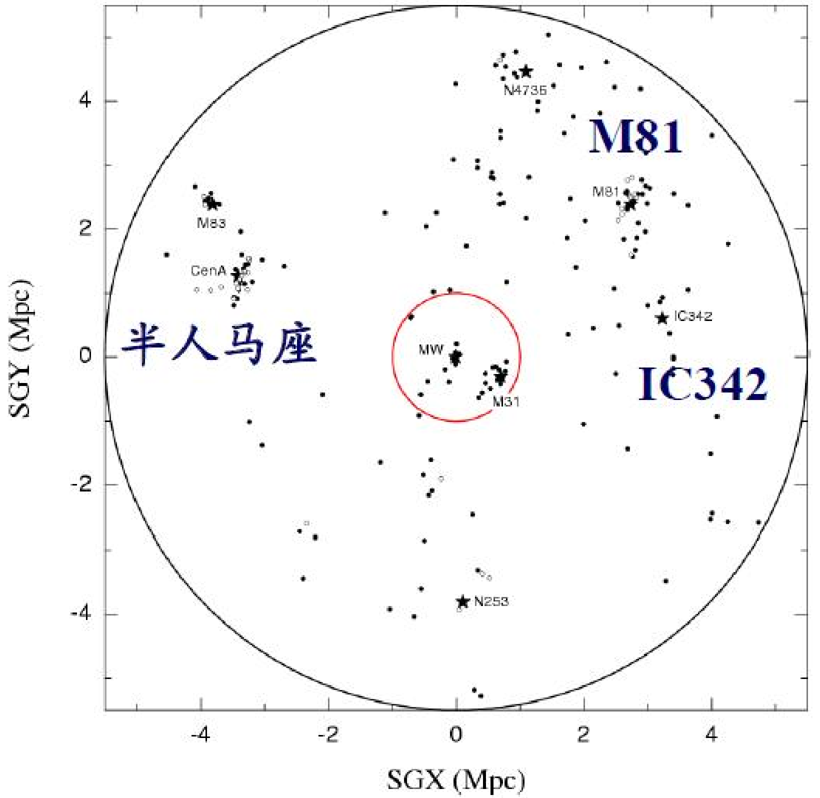
除了银河系、M31、M33和矮星系等可见物质，本星系群中还存在着大量的暗物质

银河系和M31目前正在彼此趋近，可能将在几十亿年内接近、并合，形成椭圆星系：

- 现在：MW和M31以v =110km/s相互接近
- 20亿年：M31星系接近MW，盘显著变大
- 39亿年：引力压缩气体，恒星形成已开始
- 40亿年：M31被拉伸，MW被显著的扭曲
- 51亿年：两个星的系核心区域显示为一对
- 70亿年：两个星系并合完成，巨椭圆星系
- 最后可能留下一个红星系，几乎没有了气体和年轻恒星

本星系群周围





- NGC5128（半人马座 A）位于半人马座星系群，是离我们最近的一个巨椭圆星系 D = 3.8 Mpc
- NGC1569 位于鹿豹座，IC342星系群，是一个离我们最近的星暴星系 D = 3.4 Mpc
- UGC 4483 (M81 group)：最近的贫金属星系，D = 3.4 Mpc
- Virgo Cluster