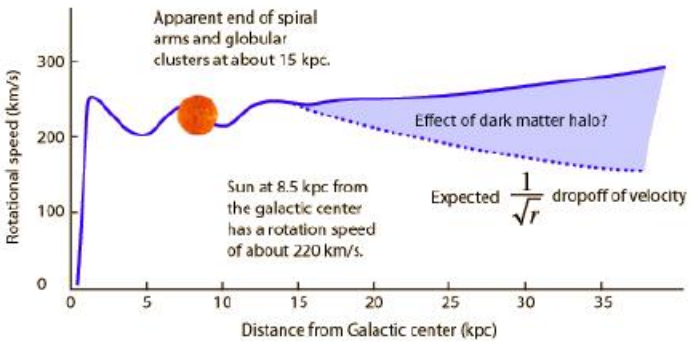
6.4 暗物质和黑洞

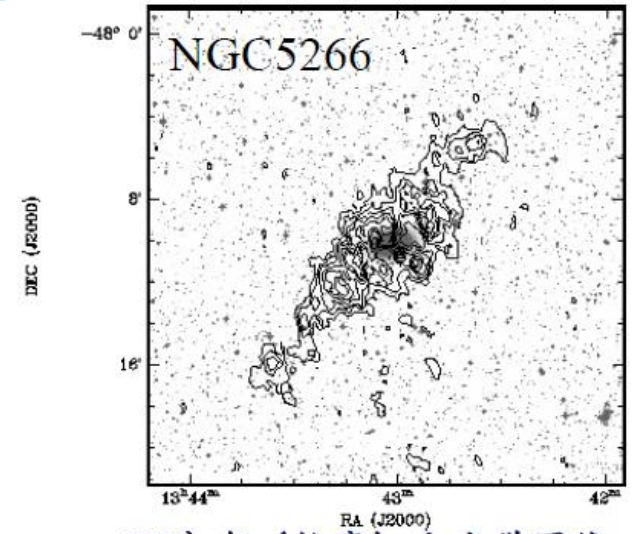
- 旋涡星系:
  - 测量旋转速度，估计中心半径R 以内质量
  - 星系质量分布的区域远大于星光辐射区域
  - 测量离中心越远时，测得质光比M/L



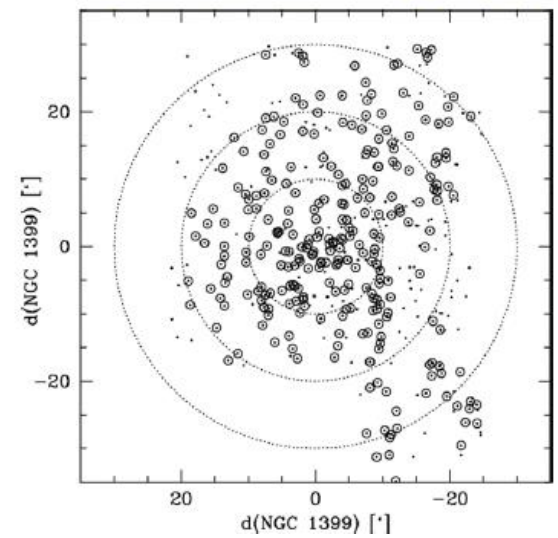
- 椭圆星系：是否也含有暗物质？
  - elliptical galaxies should reside in similar dark halos. However, finding direct, dynamical evidence for dark halos around elliptical galaxies has proven difficult
  - Techniques that have been used to probe the gravitational potentials of elliptical galaxies at large radii:
    - stellar kinematics, obtained from absorption line spectroscopy of the integrated stellar light.
    - use discrete dynamical tracers, such as globular clusters, planetary nebulae or satellite galaxies.
    - X-ray mapping
    - gravitational lensing.

暗物质晕测量方法 I

- 冷气体：对于极少数有冷气体的椭圆星系，可以利用与盘星系相似的方法求质量
- NGC 5266
  - 利用中性氢21cm线观测：近圆轨道V(R) ~ 250 km/s，$M_{HI}(R < 4') \sim 10^{11}\ M_\odot$
  - $R < 50$ kpc：$M/L \approx 10 - 20\ (M_\odot/L_\odot)$
  - 大于星系中心的$(M/L_V) \sim 7\ (M_\odot/L_\odot)$
  - 含有冷气体的椭圆星系外部存在大量暗物质
- 球状星团：利用近邻椭圆星系中的球状星团的运动，可以检验椭圆星系外区物质分布
- NGC 1399：
  - 对$r < 9'$的468个球状星团进行速度测量
  - 球状星团随机运动，没有整体旋转运动
  - $\sigma_r \sim 275$ km/s：$r < 50$ kpc，质光比$M/L_V \sim 50$
  - 有球状星团的椭圆星系外部存在大量暗物质

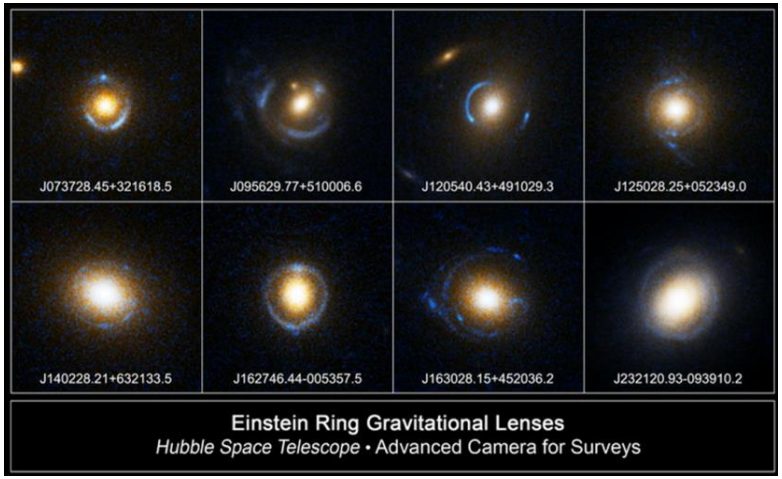


HI分布（轮廓）和光学图像



暗物质晕测量方法 II

- **引力透镜效应**：根据广义相对论，由背景光源发出的光在引力场附近经过时，光线会像通过**透镜**一样发生**弯折**
  - 一个遥远的星系发出的光在经过另一个较近的**椭圆星系**后被扭曲了，形成了“**爱因斯坦环**”：由环的大小（θ_E）可求星系质量（M），$\theta_E \sim \sqrt{M}$

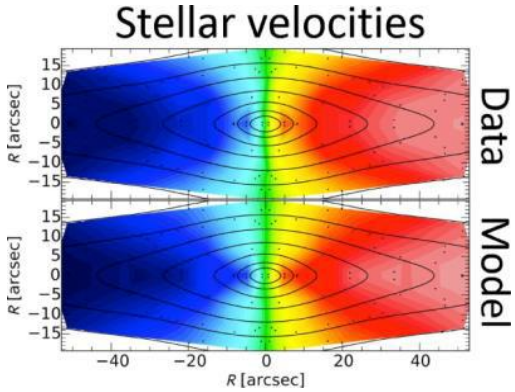


- **X射线晕**：研究椭圆星系暗物质**最有效**的方法是利用其X射线晕
  - 椭圆星系存在一个延展的X射线晕，典型尺寸大于50 kpc
  - 假定热气体是流体静力学平衡，有：

$$M(<r) = \frac{r k_B T_g}{G \mu m_p}\left[-\frac{d\ln\rho_g}{d\ln r} - \frac{d\ln T_g}{d\ln r}\right]$$

ρ是气体密度；T是气体温度，~10^7K，m 是热气体质量，~$10^{10}M_\odot$，M为星系总质量

- **恒星旋转速度**：少量椭圆星系，恒星绕星系中心旋转运动，可利用旋转速度测量星系质量



暗物质晕

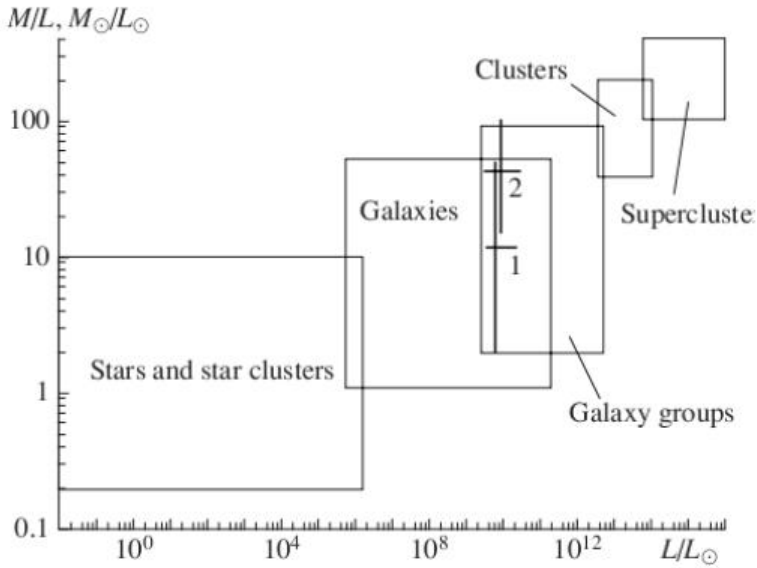
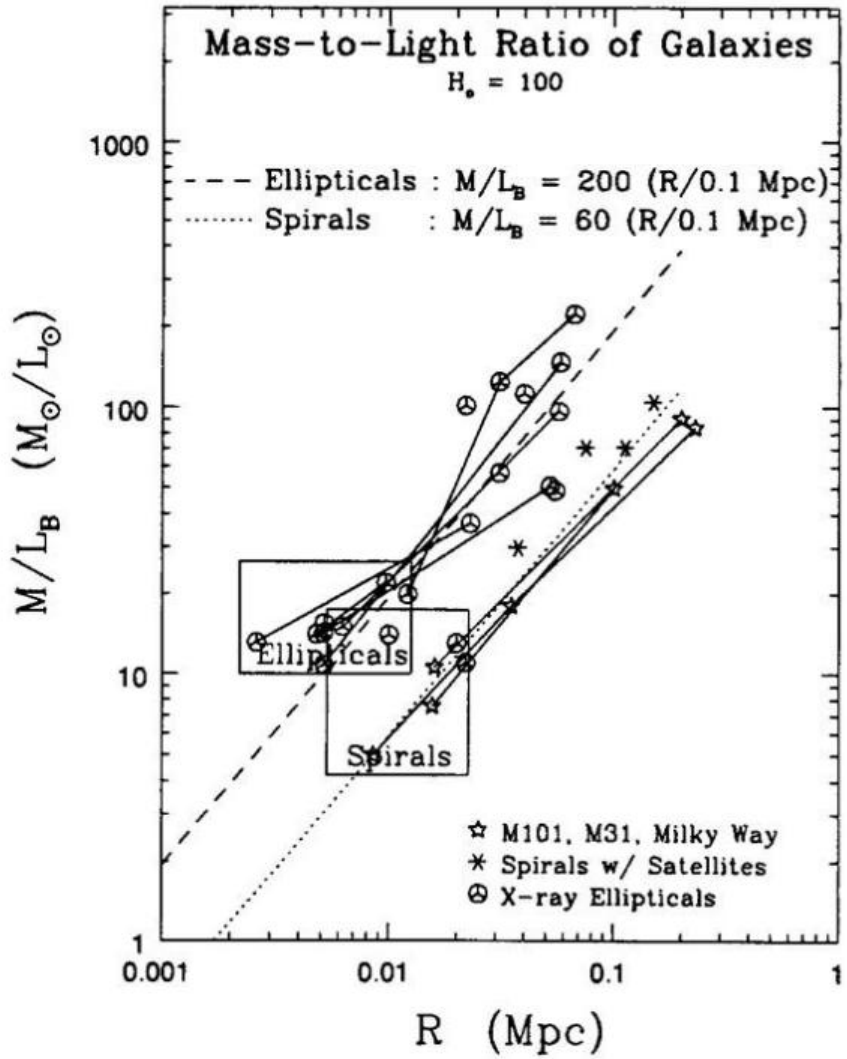


Fig. 5. Mass-to-light ratios in a wide luminosity range for various objects in the universe, from stars to superclusters. Crosses 1 and 2 correspond to the medians and quartiles for pairs and triplets, respectively.



椭圆星系发光区域的$3 \le M/L_V \le 5$（利用星族合成方法）；在较大半径处则有$M/L \ge 20$：椭圆星系外部的质量大部分是暗物质。

星系中心黑洞

- 星系核区黑洞搜寻方法
  - 需要示踪天体：用于测量近核区的速度场
  - 示踪天体包括气体或者恒星，利用多普勒效应或者自行方法，测量运动速度
  - 需要更多的信息：速度各向同性/各向异性；旋转/无旋转

- 旋涡星系：单个恒星运动、恒星平均运动、电离气体谱线、脉泽(水)天体、AGN宽线区谱线等

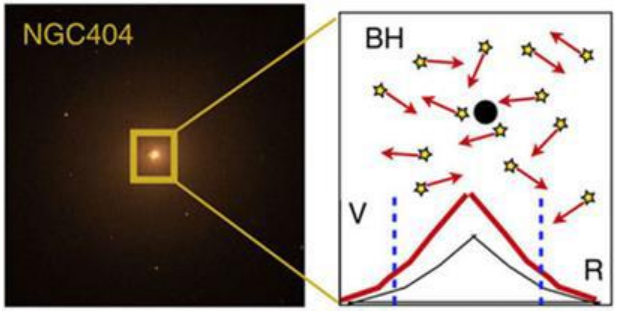
- 椭圆星系：测量困难
  - 非旋转体系，速度有无各向异性不清楚
  - 黑洞影响区域很小：高空间分辨观测+ 星系中心光度集中（$R^{1/4}$律）
  - 投影效应等可能影响结果的因素，需扣除

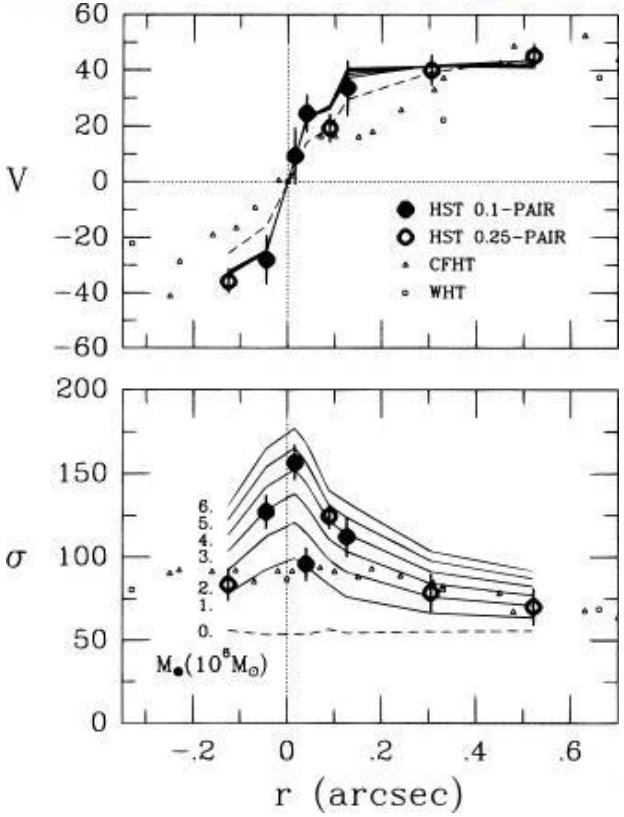
黑洞质量测量

- 质量为M_{BH}黑洞将剧烈影响$r_{BH} \sim GM_{BH}/\sigma^2$（$\sigma = c$时，$r_{BH} = 2R_{Sch}$）内的恒星运动(速度弥散)：$r_{BH} < R_e/100$，需要高分辨观测

$$r_{BH} \approx 45\,\mathrm{pc} \times \left(\frac{\mathcal{M}_{BH}}{10^8 \mathcal{M}_\odot}\right) \times \left(\frac{\sigma_c^2}{100\,\mathrm{km\,s^{-1}}}\right)^{-2}$$

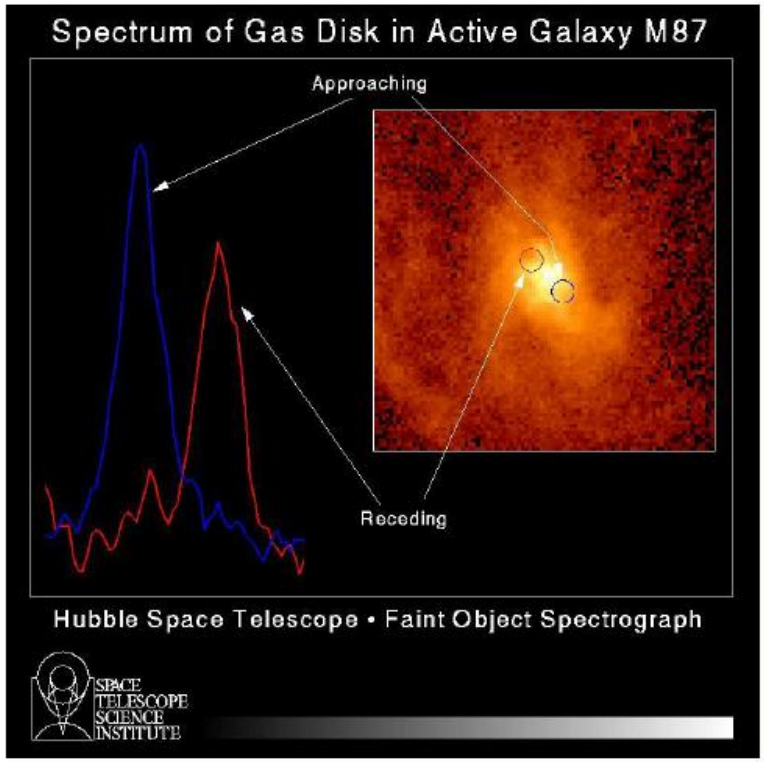
- 黑洞附近的恒星比外围的恒星运动得快。如果它们旋转的方向是随机的，将在由星系光谱吸收线测得的速度弥散中看到一个中央升起。

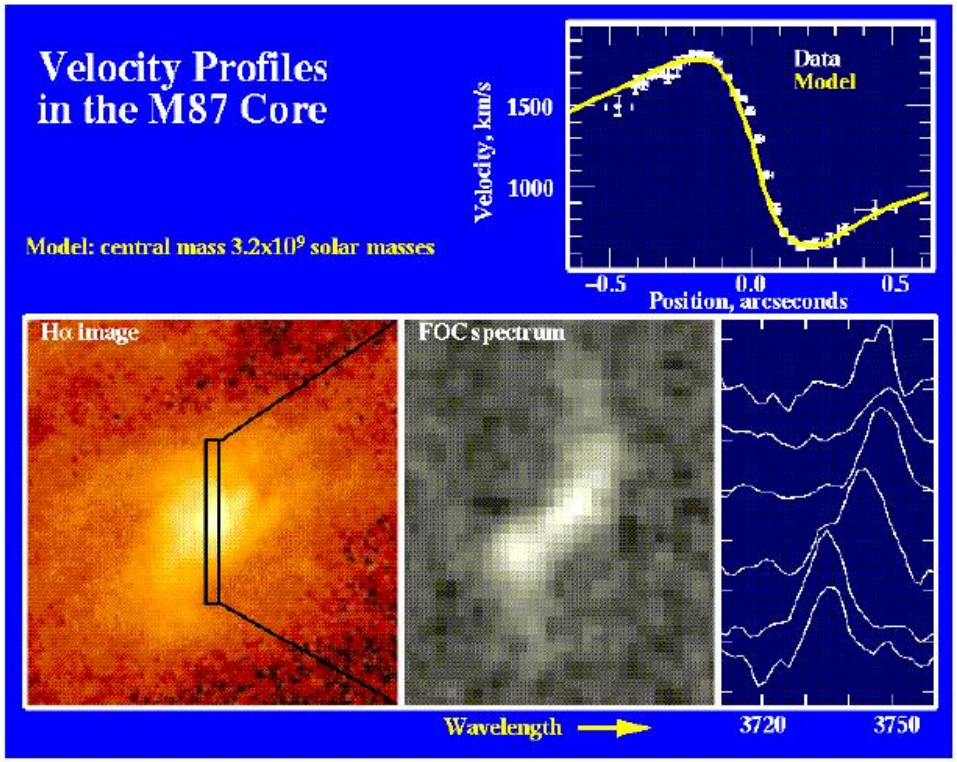




- M32中心黑洞质量测量
  - van der Marel(1997) 利用HST/FOS观测M32中心区域的光谱
  - 中心区域r < 0.15arcsec(0.5pc)：速度弥散快速上升: $\sigma \sim 70 \rightarrow 150$ km/s
  - 利用不同的黑洞质量（$M_{BH} = 0, 1, \ldots 6 \times 10^6 M_\odot$）拟合观测数据：$M_{BH} \sim 3.0 \times 10^6 M_\odot$

M87-Giant Elliptical

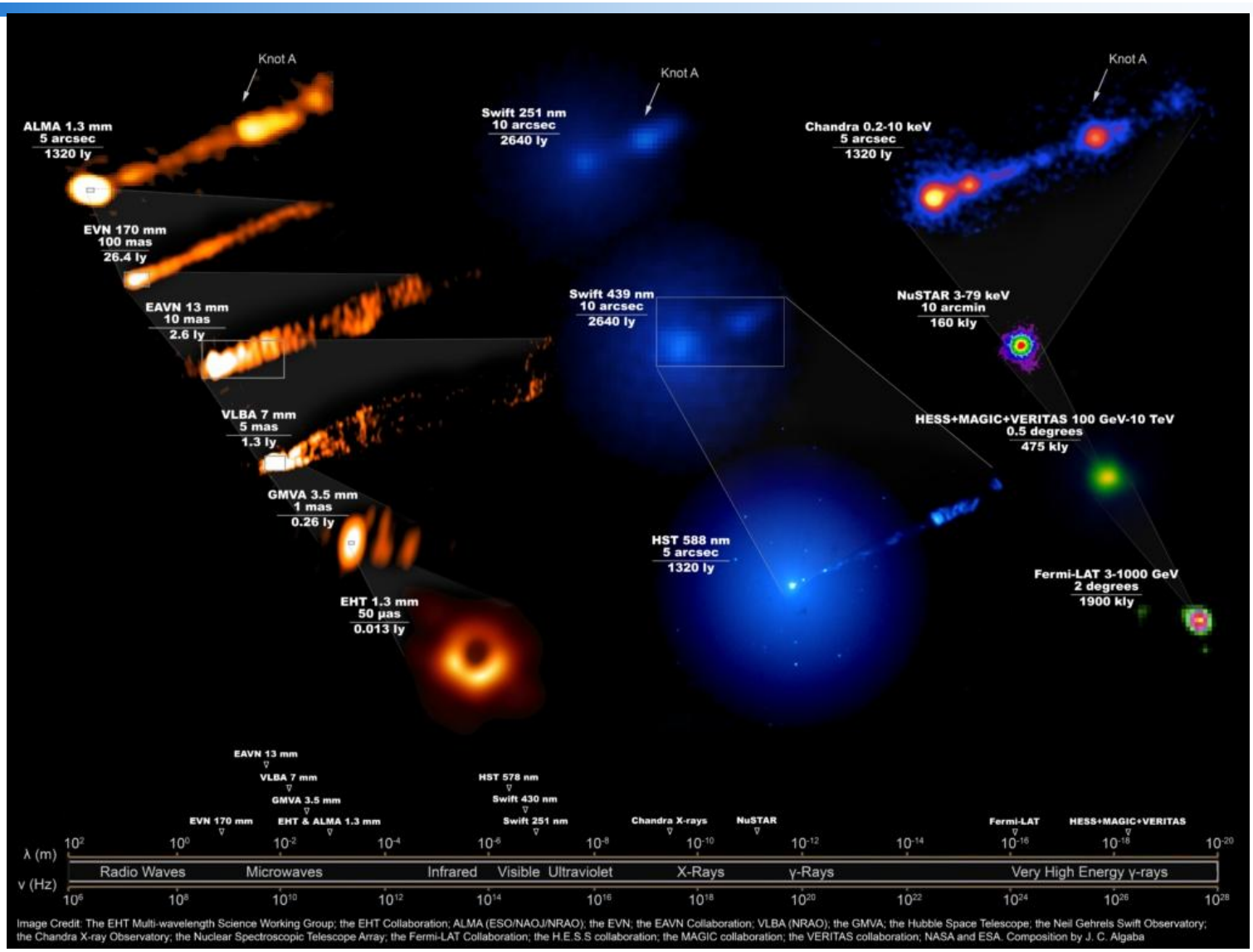




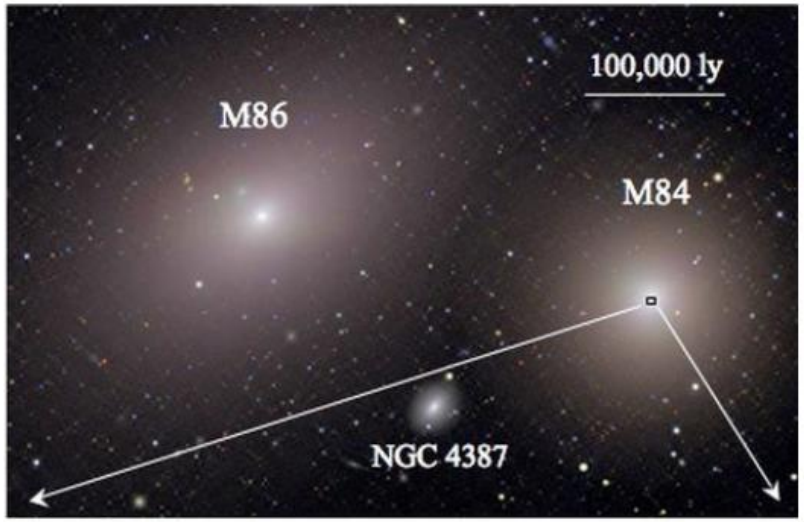
Ionized gas velocities were measured on either side of the nucleus using HST (Harms et al 1994)

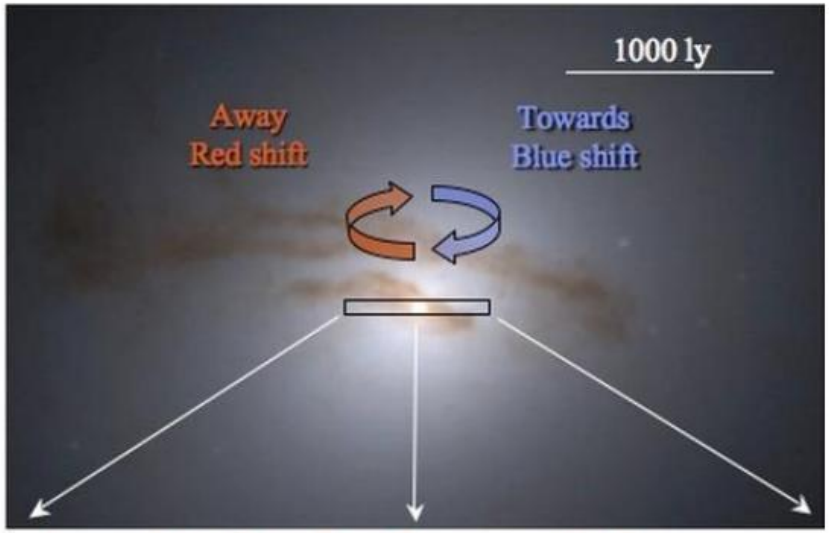
Since the HST Hα image indicates a gas disk, rotation is assumed: a (simple) estimate yields : $M_{BH} \sim 3 \times 10^9\ M_\odot$, which is now fairly robust.

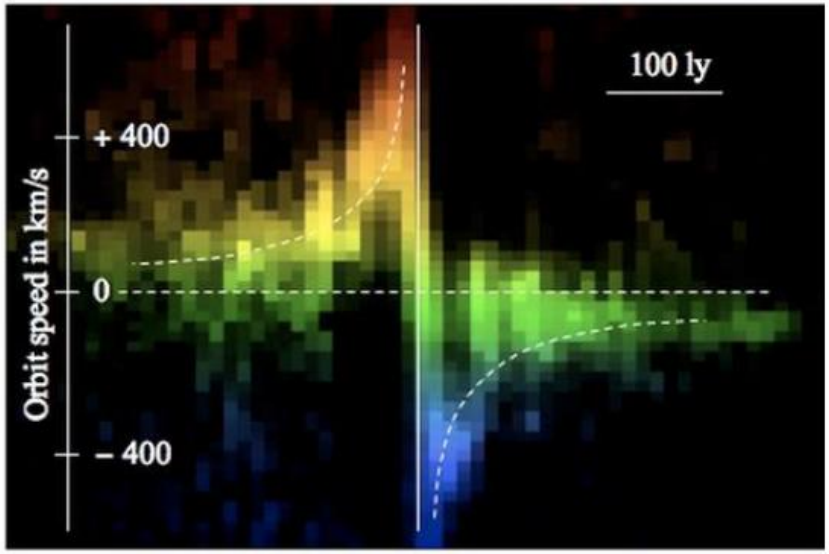
M87-Giant Elliptical



M84——Another Giant Elliptical







Giant elliptical M84 has an approximately edge on gas disk: STIS observations of the nuclear gas disk in M84.

The approximately Keplerian velocity suggests a black hole mass of $\sim 3 \times 10^8\ M_\odot$.

M – σ relation

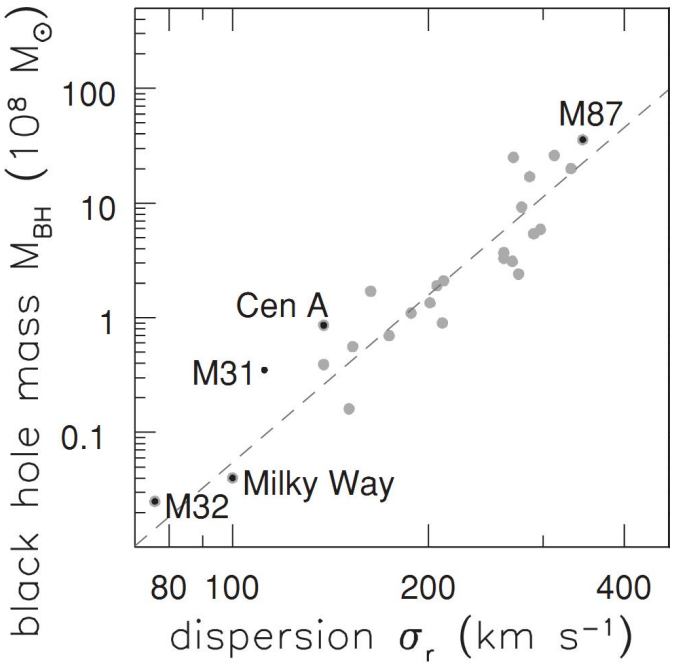
- M – σ关系：星系核球区域恒星速度弥散σ和星系中心黑洞质量经验关系
- 由Ferrarese &Merritt(2000，ApJL)最早提出：Faber – Jackson law for black holes

$$\frac{M}{10^8 M_\odot} \approx 3.1 \left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right)^4 .$$

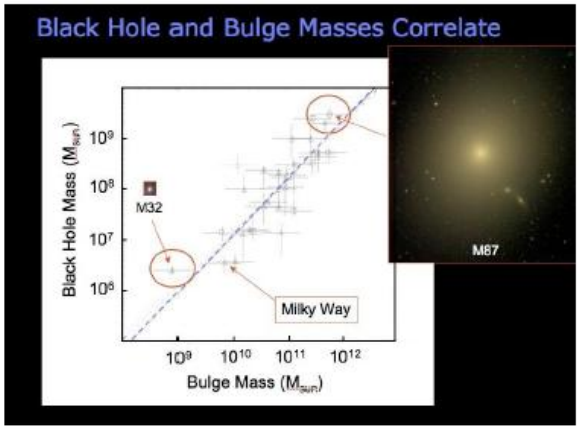
- 利用更大的样本，得到：

$$\mathcal{M}_{\mathrm{BH}} \approx 2 \times 10^8 \mathcal{M}_\odot \times \left(\frac{\sigma_c}{200\,\mathrm{km\,s^{-1}}}\right)^{4.86} .$$

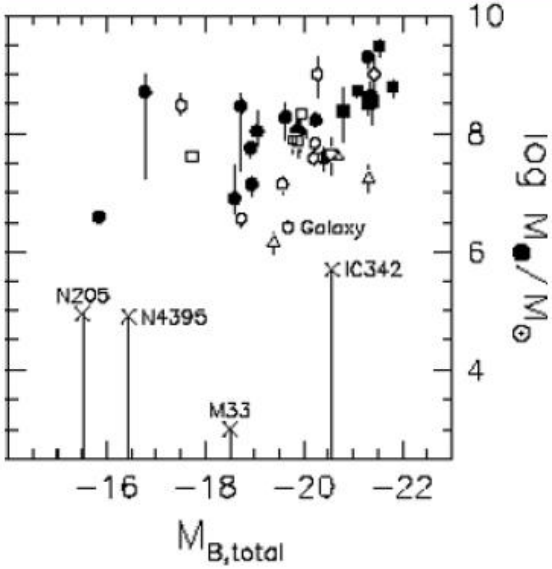
- 中心MBH大的星系，速度弥散最高：位力定理表明其引力势阱最深；与Faber-Jackson关系和椭圆星系基本面预期一致，速度弥散高，光度越高



黑洞的其他标度关系



M_{BH}与星系核球质量相关



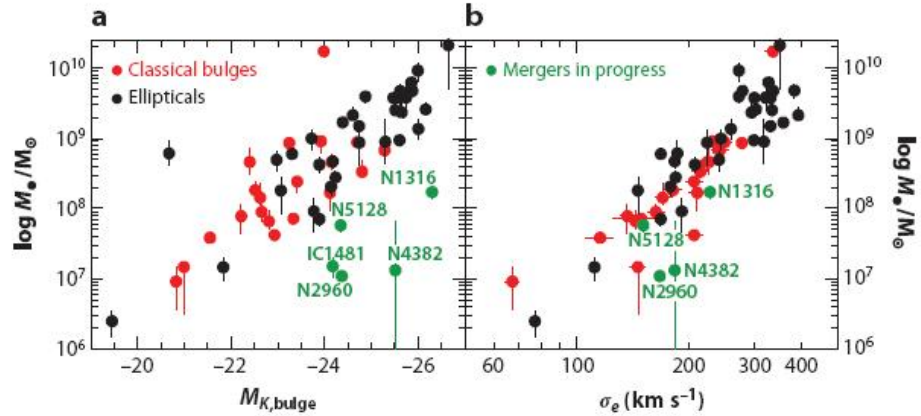
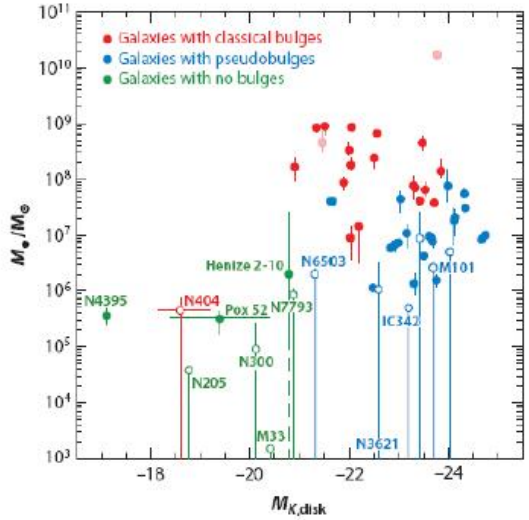


Figure 14

Correlations between $M_\bullet$ and (*a*) the *K*-band absolute magnitude of the bulge or elliptical and (*b*) its effective velocity dispersion for classical bulges, ellipticals, and mergers in progress.



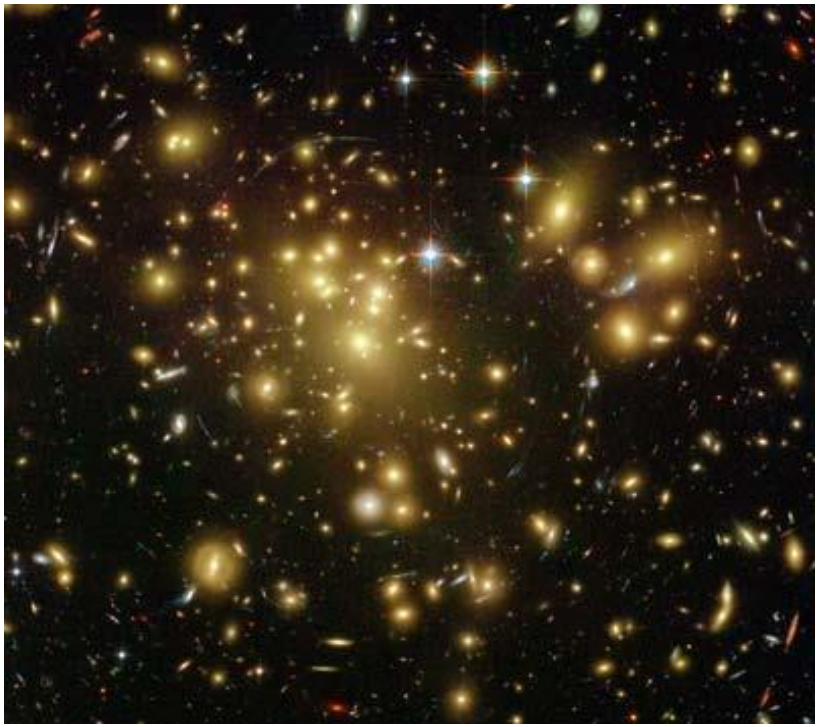
M_{BH}与星系中心速度弥散相关性更强

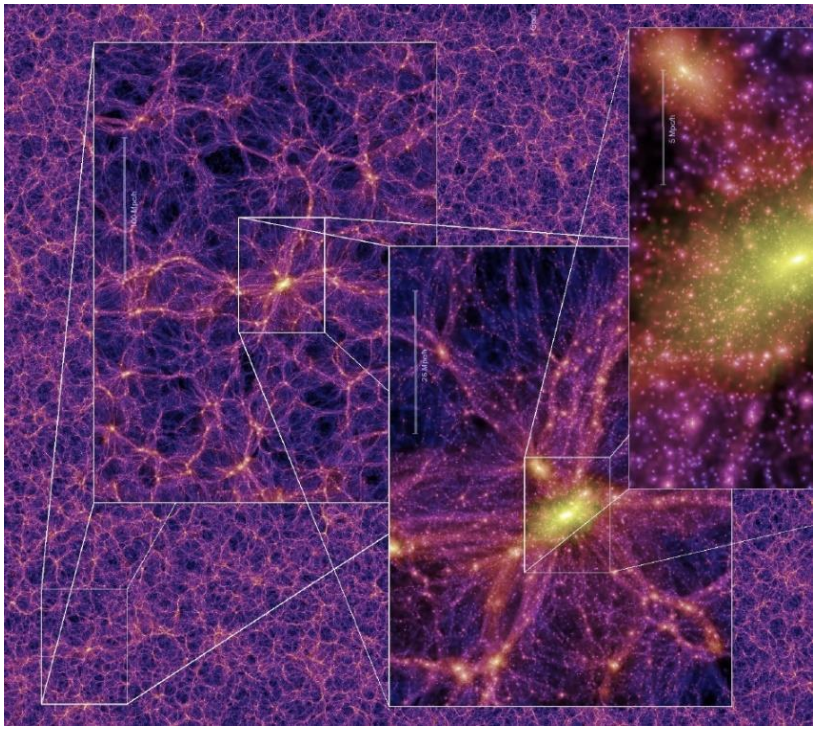
M_{BH}与星系总光度相关性较弱；与星系盘光度不相关：核球存在时，盘对黑洞的形成和增长几乎没有影响。

第七章 星系群和星系团

主要内容

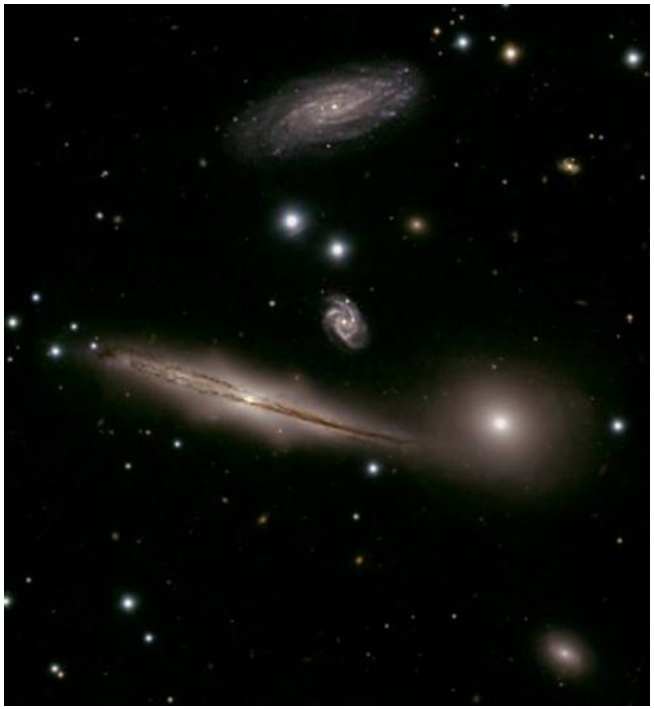
- 近邻宇宙中多数星系位于星系群或星系团中：星系群/团不随宇宙膨胀
- 群和团中，星系数密度是宇宙平均星系数密度10~100倍
- 星系群中旋涡星系和不规则星系多；星系团中椭圆星系和S0星系占主导地位：研究星系形成演化与星系环境关系
- 宇宙中最大的引力束缚体系：可用于研究宇宙的大尺度结构，约束宇宙学参数

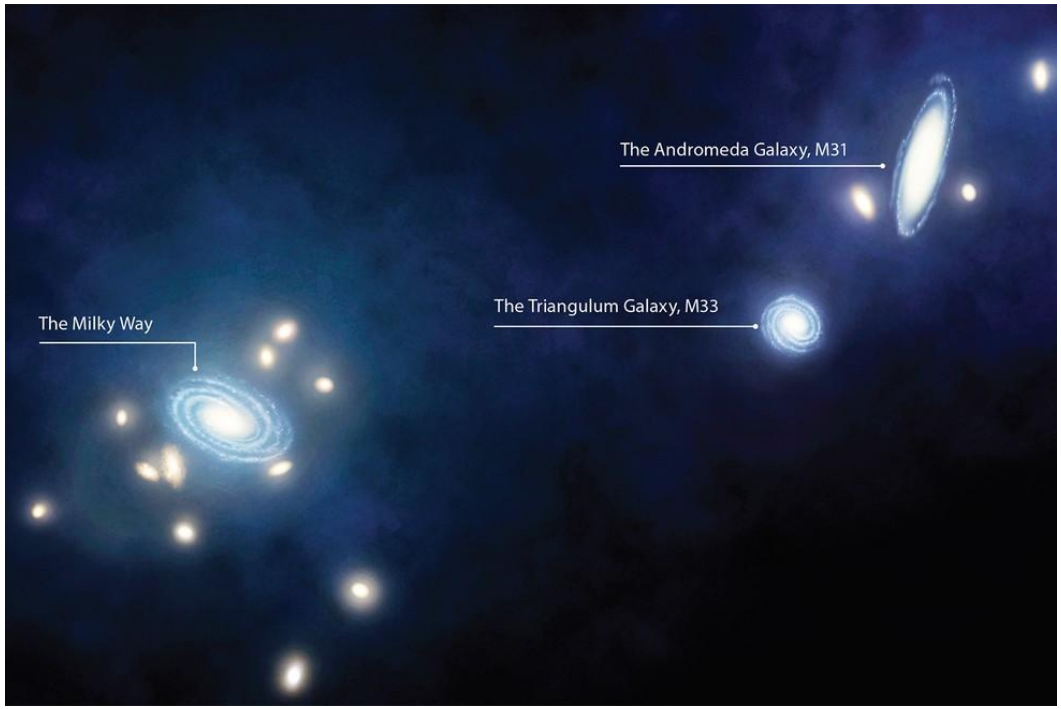




7.1 星系群：盘星系的家园

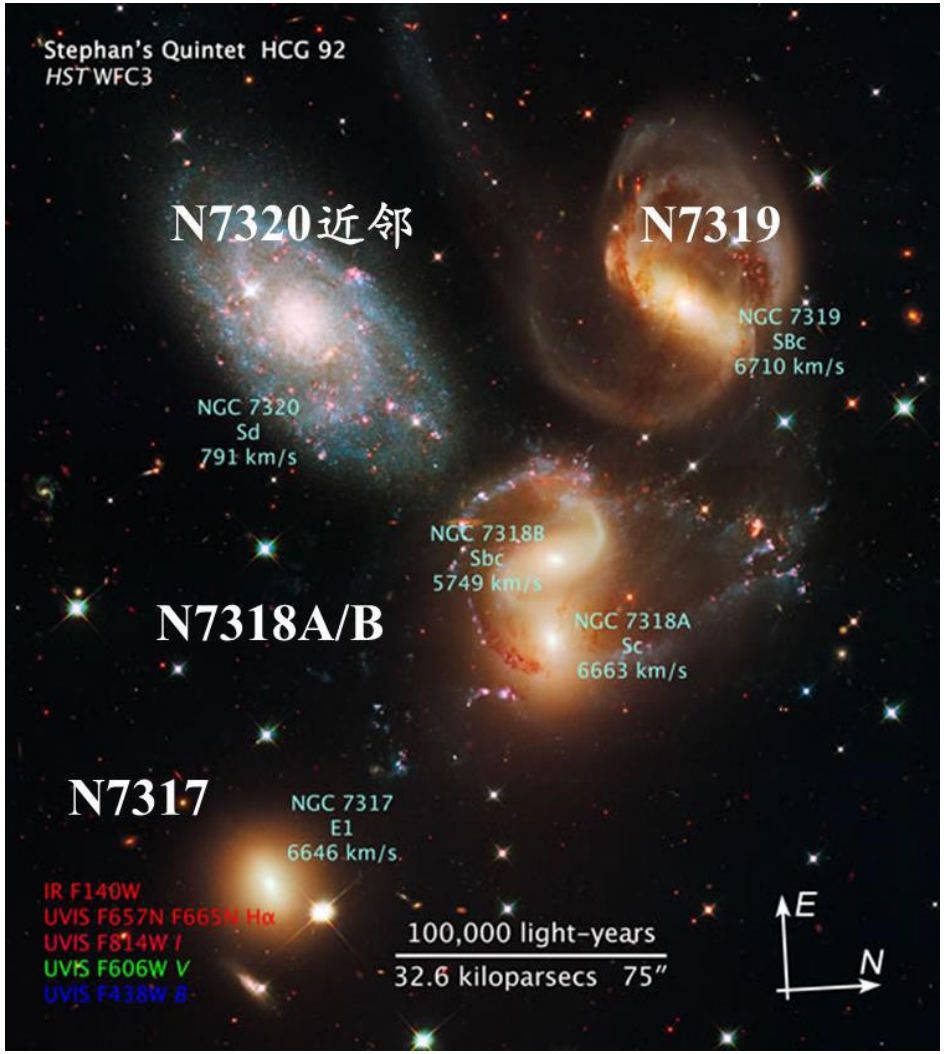
- 星系群：星系数目少于星系团的星系聚集区
  - 包括3 – 30个~ $10^{10}L_{\odot}$星系，$L_B \sim 10^{10.5} - 10^{12}L_{\odot}$
  - 群中星系数密度是宇宙平均星系数密度~ 20倍
  - 半径~ 0.1 – 1Mpc；星系速度$\sigma \sim 300$ km/s
  - $M_{dyn} \sim 10^{12.5} - 10^{14}M_{\odot}$；$(M/L_B) \sim 100(M_{\odot}/L_{\odot})$





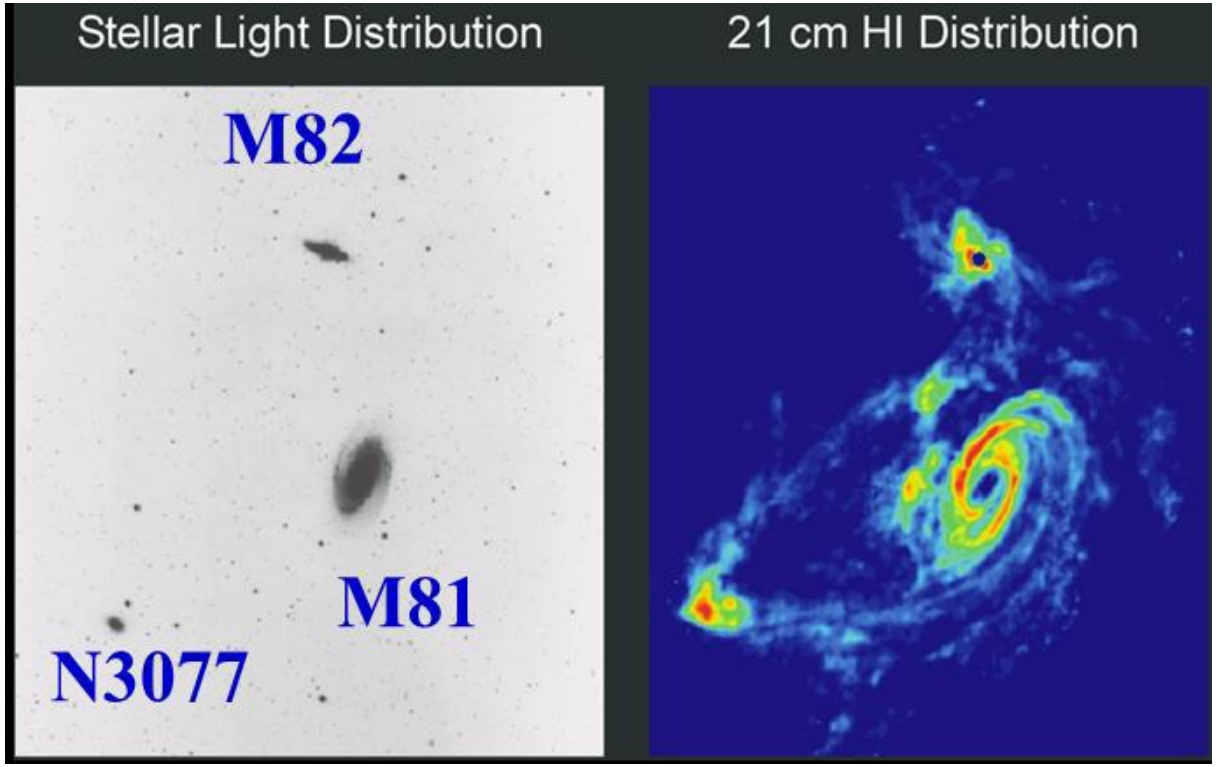
星系群

- 致密星系群：包括几个星系，星系数密度很高；星系之间正在并合或强烈的相互作用
- Hickson致密星系群(HCGs)
  - Hickson (1982)利用照相底片构建
  - 包括约100个致密的星系群
  - 每个群包括4 -5个星系，投影半径50 – 100 kpc.
  - ~ 40%星系存在相互作用特征
  - 致密群中有大量高温热气体，X射线辐射强
  - 致密群中有丰富的冷气体，星系中冷气体少
  - 冷HI气体可能是从星系盘剥下来；某些气体云被加热到温度很高，辐射X射线



星系群

- **松散星系群**：如本星系群；M81群等
  - 星系之间的**恒星**数目很少，但存在大量的**中性氢气体**
  - 盘星系中HI的分布比恒星盘**范围大**：星系交会时，气体盘更易受损
  - 松散群中的气体是从星系中撕下来的，大部分仍是**冷的，无X辐射**



星系群

- **化石星系群：如**
  - **正常星系群完成星系并合（动力学摩擦）后，形成了一个大质量的椭圆星系**
  - **前身星系群X射线晕保留：弥散X射线辐射，辐射强**
  - **化石群中存在矮星系，但大的星系已经并合成为中心星系：$\Delta M_{1,2} \geq 2.0$mag**

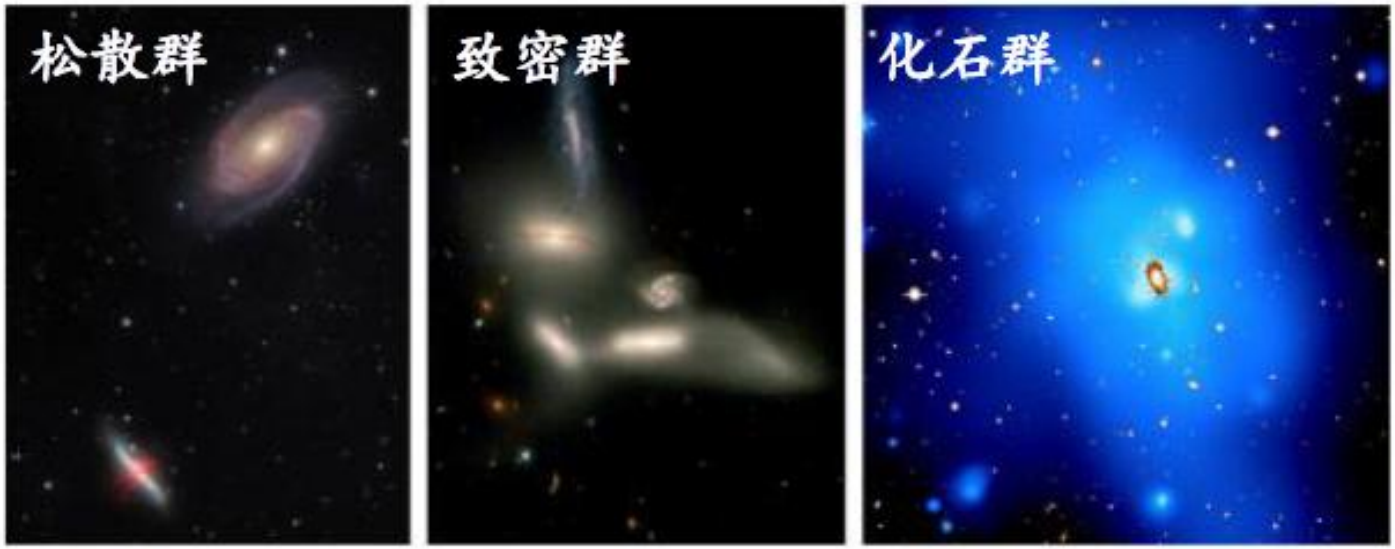
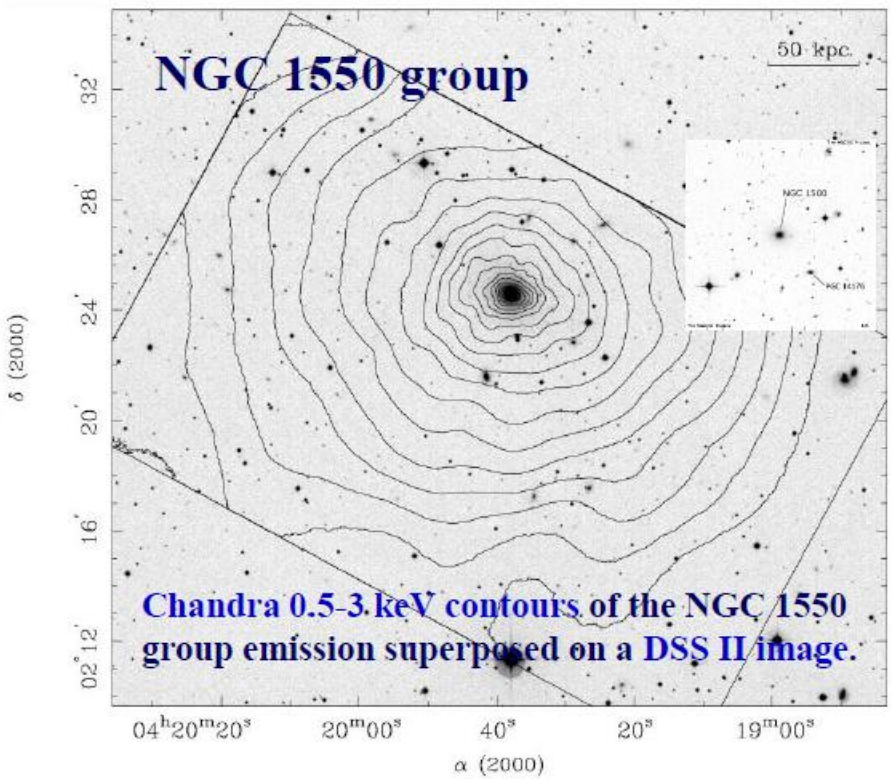
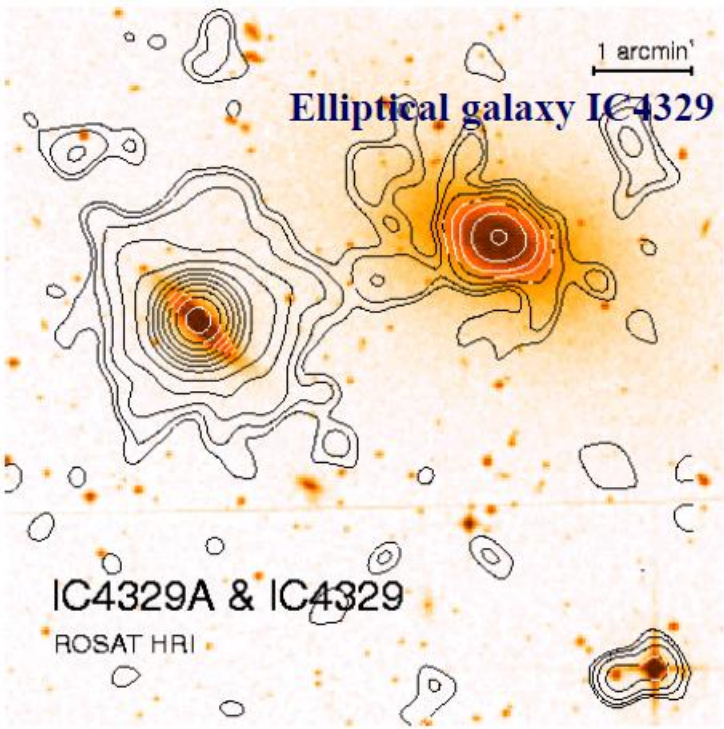


Figure 1.1: Poor, compact and fossil groups of galaxies. The examples shown are the M81 group, Seyfert's Sextet, and the fossil RX J1416.4+2315. The fossil is shown in false colours where orange reveals the central elliptical in the optical while blue displays the surrounding X-ray halo. Credits: R. Zmaritsch & A. Gross; J. English; Khosroshahi et al. (2006a).

7.1.1 星系群中的气体

- NGC1550群（D ~ 1Mpc范围）包含15个星系，其中2个Es；$L_X \sim 4 \times 10^9 L_\odot$，比Stephan五重星系群X辐射强100多倍
- 星系群中心区金属丰度高，外围丰度低只有约一半星系群中有X射线辐射：热气体（$T \geq 3 \times 10^6$ K）存在与星系群特性有关
- 有热气体的星系群，群的成员星系较多，并且至少有一个是椭圆星系：化石群



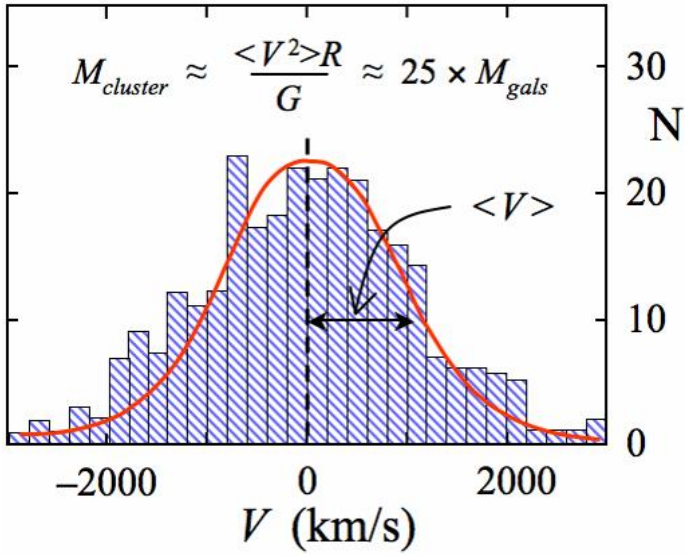


星系群质量估计

- 运动学方法
  - 如果星系群是孤立、引力平衡，则可以利用位力定律，求星系群质量：

$$\frac{3\mathcal{M}\sigma_r^2}{2} = \mathcal{K}\mathcal{E} = -\frac{\mathcal{P}\mathcal{E}}{2} = \frac{3\pi}{64}\frac{G\mathcal{M}^2}{a_P}$$

  - NGC 1550群：成员星系的速度弥散是$\sigma_r = 310\ \mathrm{km\ s^{-1}}$
  - 星系群密度分布可用$a_P = 100$ kpc的Plummer球描述
  - 则星系群的质量$M \sim 2 \times 10^{13} M_\odot$

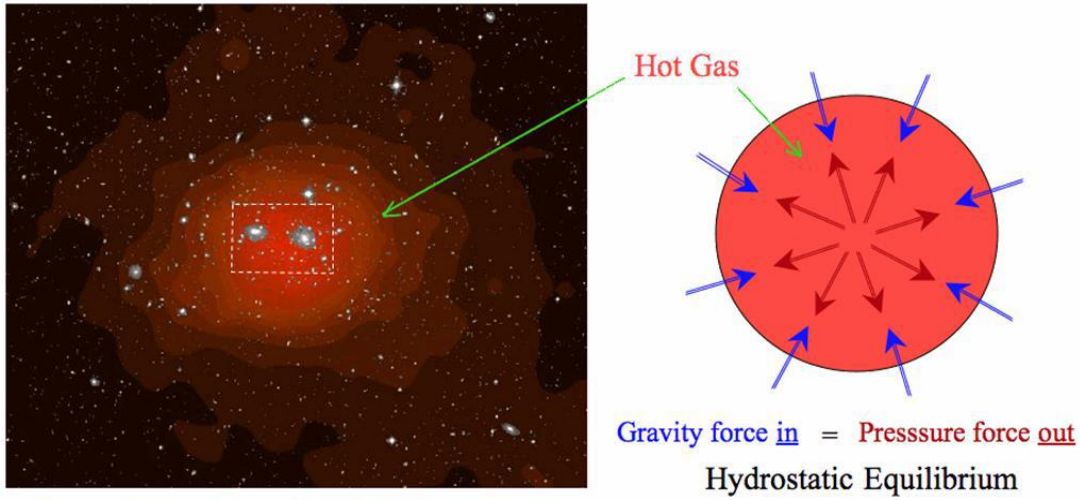


星系群质量估计

- 热气体方法
  - 当星系群含有热气体时，根据流体静力学平衡方程，估计需要多大的引力才能阻止热气体外流，可求引力质量

$$\mathcal{M}(<r) = \frac{k_{\mathrm{B}}}{\mu m_{\mathrm{p}}} \frac{r^2}{G\rho(r)} \frac{\mathrm{d}}{\mathrm{d}r}(-\rho T)$$

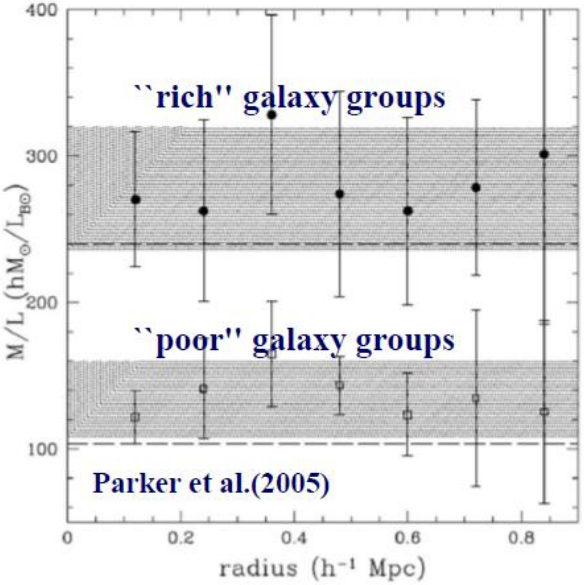
  - 完全电离的氢：μ = 0.5；太阳丰度的气体：μ ≈ 0.6
  - 利用X射线光谱谱线，估计X射线发射区域温度TX
  - 测量X射线面亮度分布，计算星系群气体密度分布ρ(r)

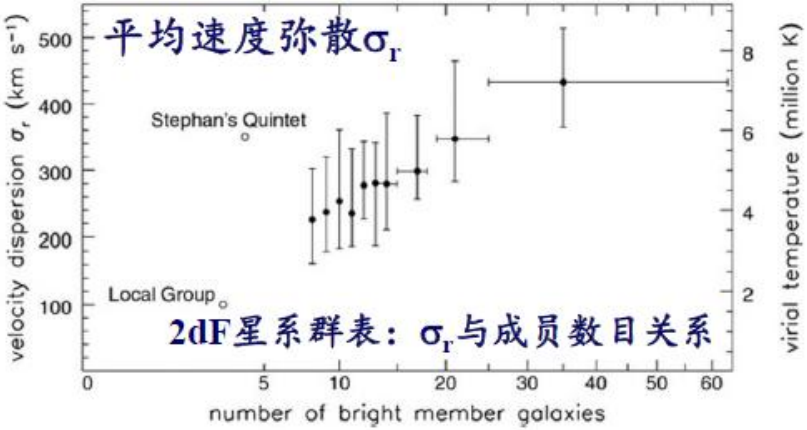


Coma cluster: X-ray (red), Optical (white)

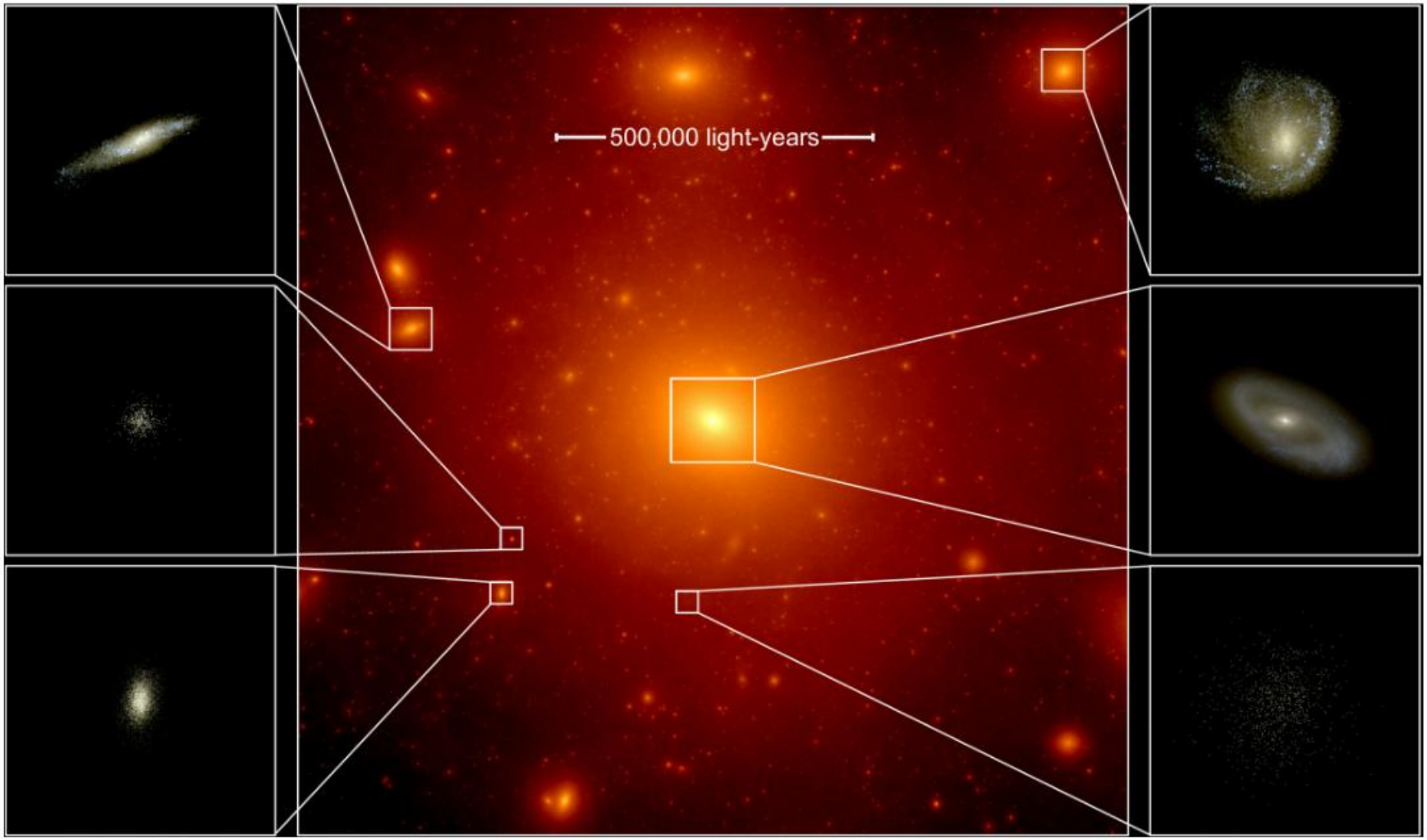
星系群的质光比M/L

- 利用星系群中星系运动、热气体或者引力透镜，测得星系群的总质量
- 观测星系群中每个星系中恒星光度，根据恒星的质光比，求得星系群中恒星质量
- 恒星和热气体的质量比例，小于星系群总质量的10%
  - 每个星系的暗物质晕，比HI盘分布更为延伸
  - 大量物质作为’群晕’，位于群成员星系之间
  - 星系群质光比：$80 \leq M/L \leq 300$
- 星系群中星系运动速度σ_r~100 – 500 km/s，与星系内的恒星运动速度相近
- 由于群星系的相对运动速度低，引力有较长时间强烈拉拽从其周围经过的其他星系中的气体和恒星：星系相互作用





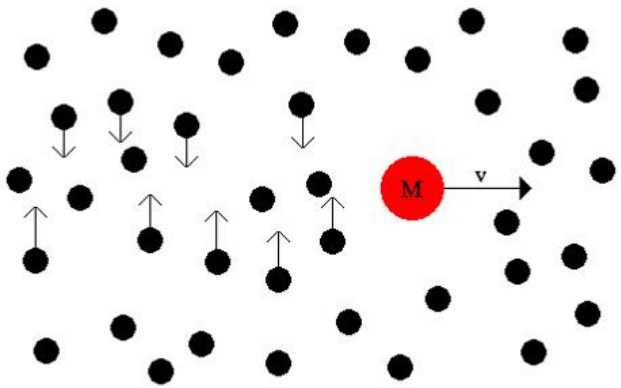
星系群的暗物质晕



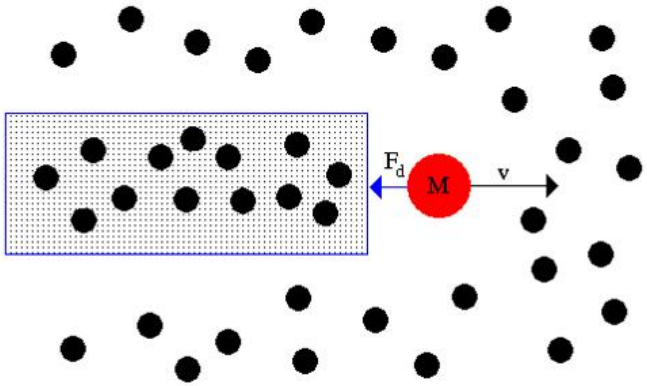
7.1.2 动力学摩擦

- 一个星系（I）通过另外一个星系（II）附近（星系发光区域或延展暗物质区域）
- 星系II的恒星和暗物质的“sea” 的物质分布会发生变化，星系I受到星系II物质的引力作用，将导致星系I速度变慢：动力学摩擦(dynamical friction)
- 两个星系彼此近交会时，它们向前运动能量的一部分转化为其内部恒星的运动：
  - 当这两个星系分开时，两个星系运动速度将会比它们趋近时慢
  - 如果这两个星系随后的运动太慢，以至不能彼此逃离，两个星系会彼此再度交会，最终并合
- 星系II的恒星和暗物质的引力使得星系I速度减慢：星系I在运动中损失能量和角动量，效应等同于摩擦力或粘滞力

consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.



this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction



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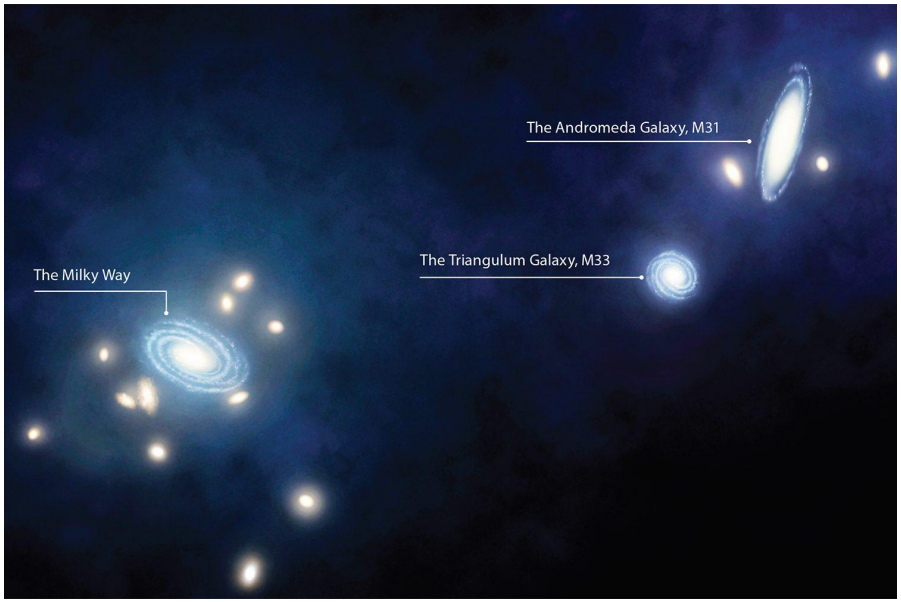
$$T_{\rm mg}^{\rm proj}(<r_{\rm p}) = \frac{10^{-0.23}}{0.66}\frac{m_{1,\rm v}}{m_{2,\rm v}}[m_{1,\rm v}GH_0E(z)]^{-1/3}r_{\rm p}.$$

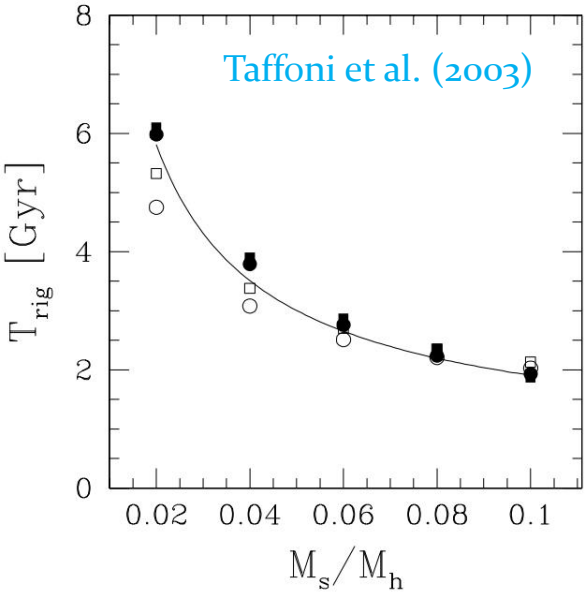
Jiang et al. (2012)

$$T_{\rm m}(L_{\rm A}, L_{\rm B}) \sim T_{\rm m}(L_1, L_2) \sim \left(\frac{L_1}{L_2}\right)^a (L_1 + L_2)^b$$

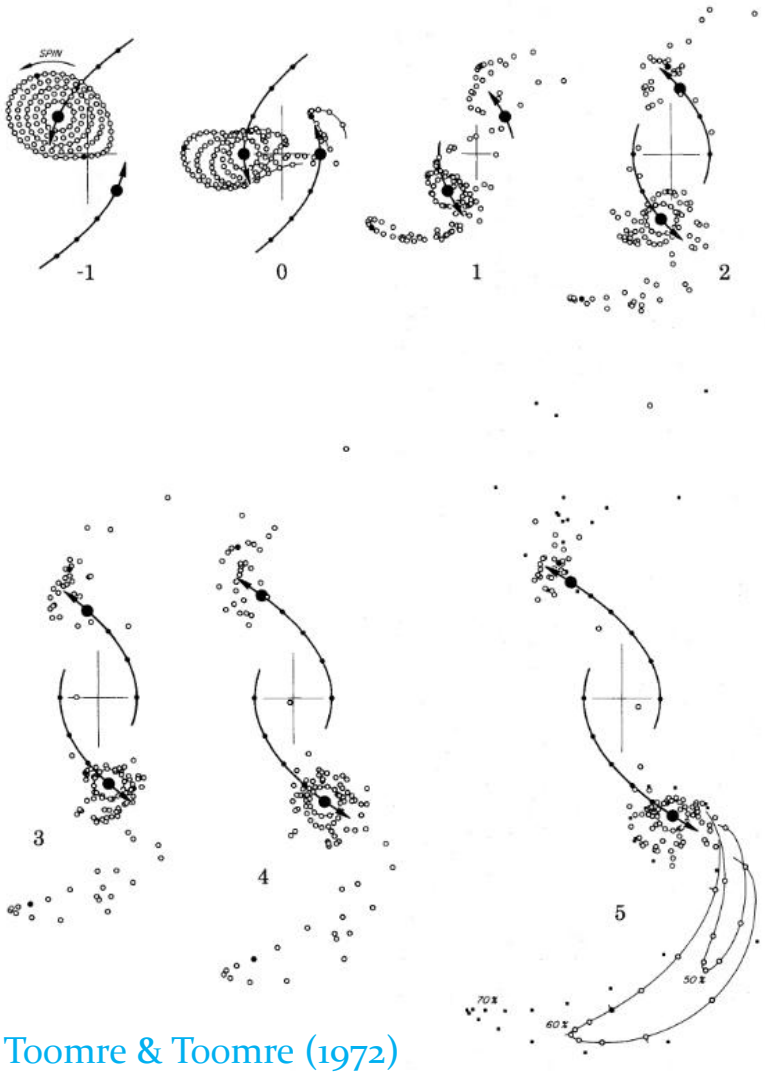
Feng et al. (2019)

$$a = 0.40, b = -0.33$$

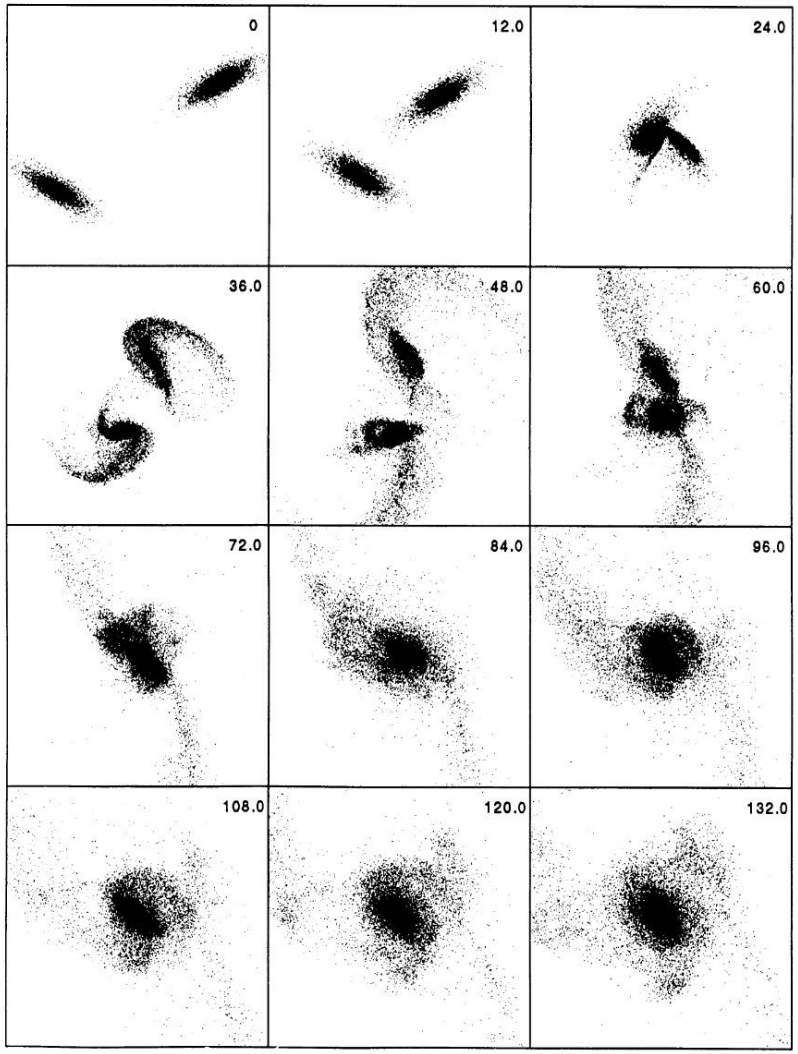




近交会

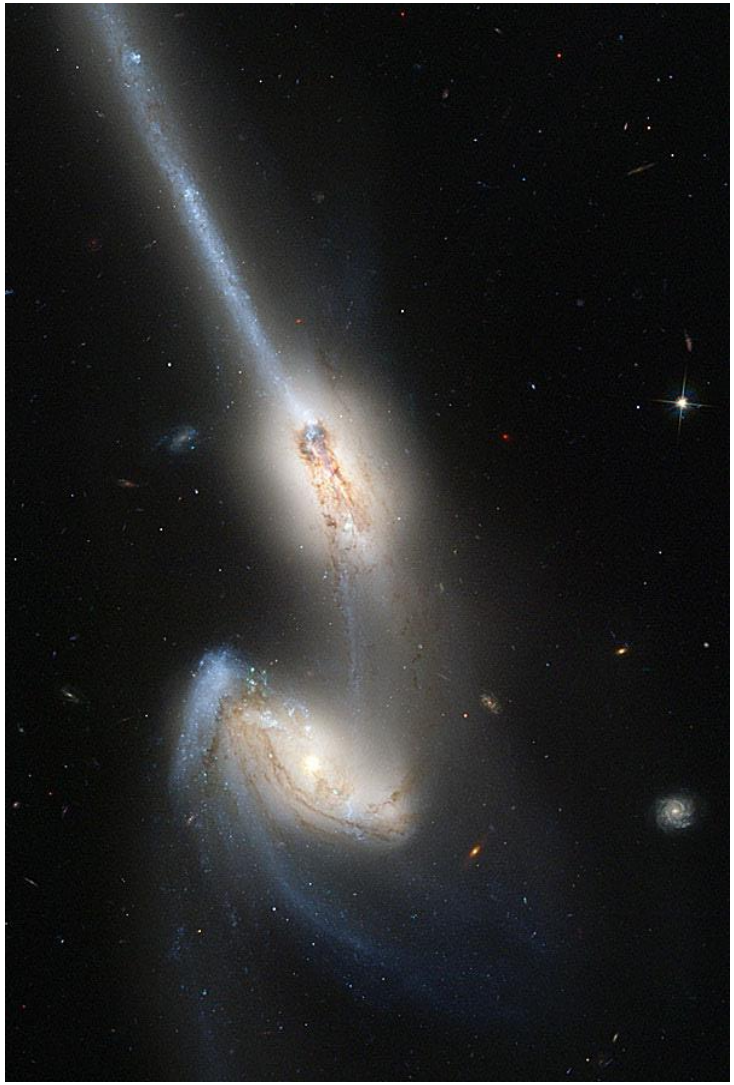


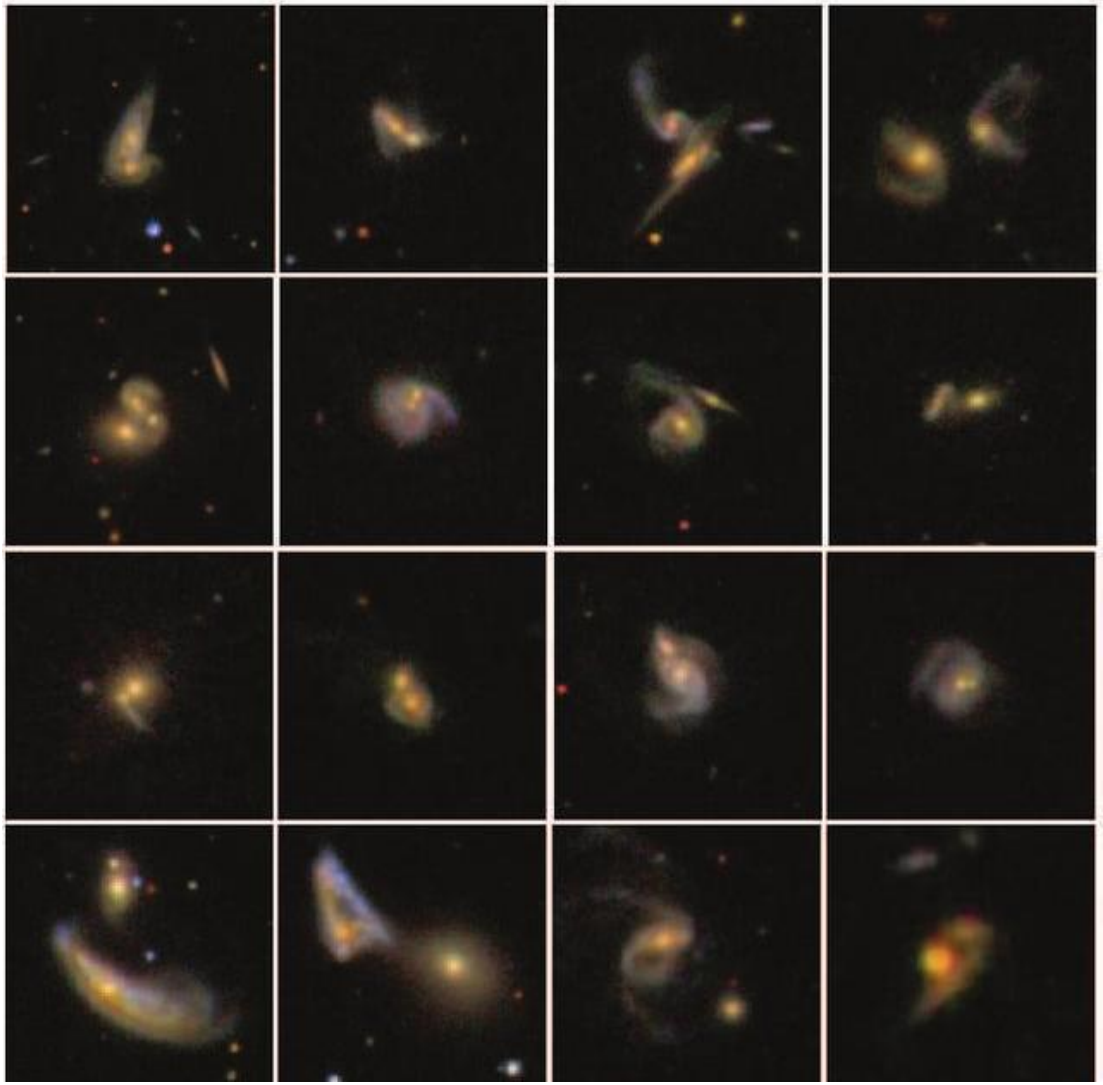
Toomre & Toomre (1972)



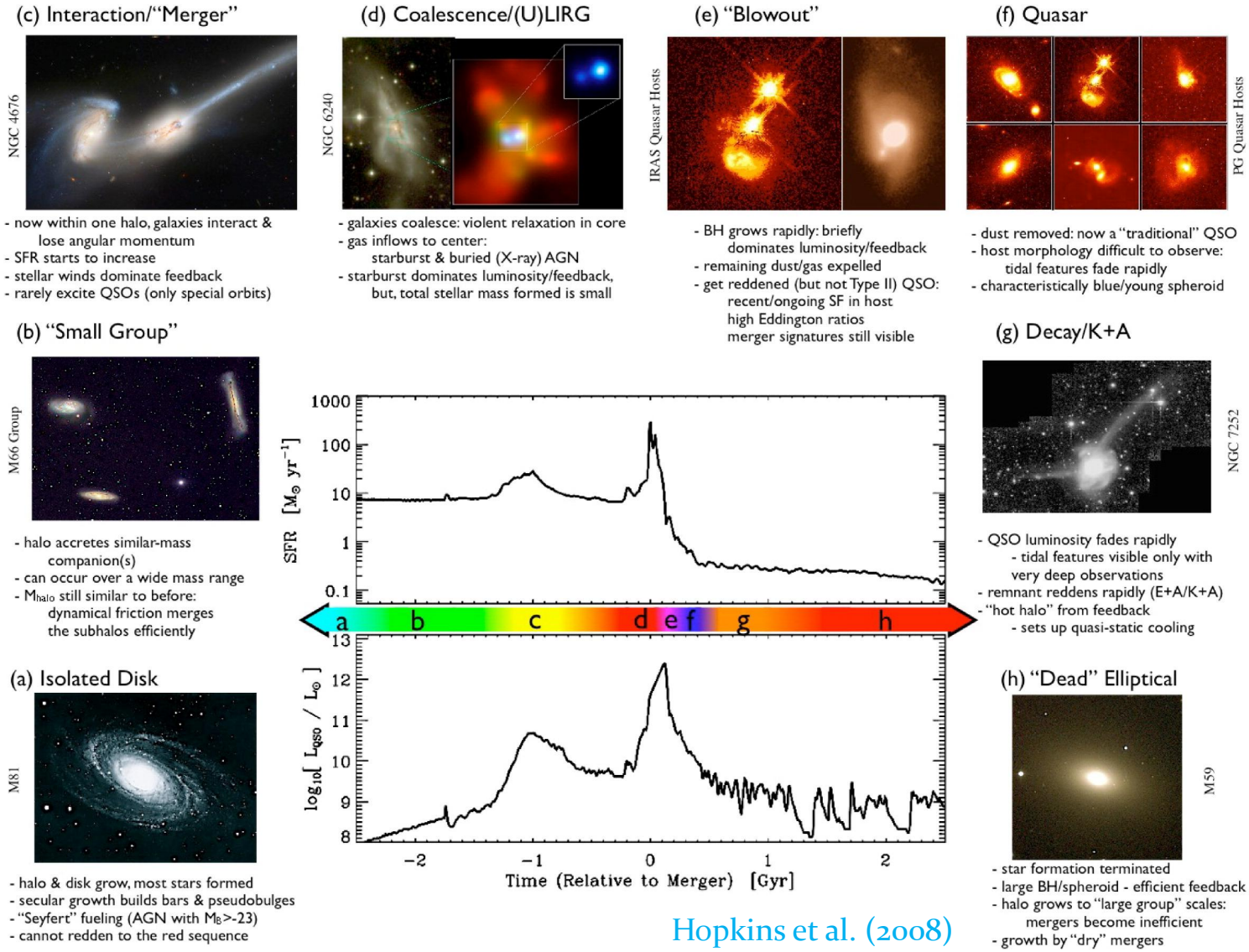
Hernquist (1993)

星系并合





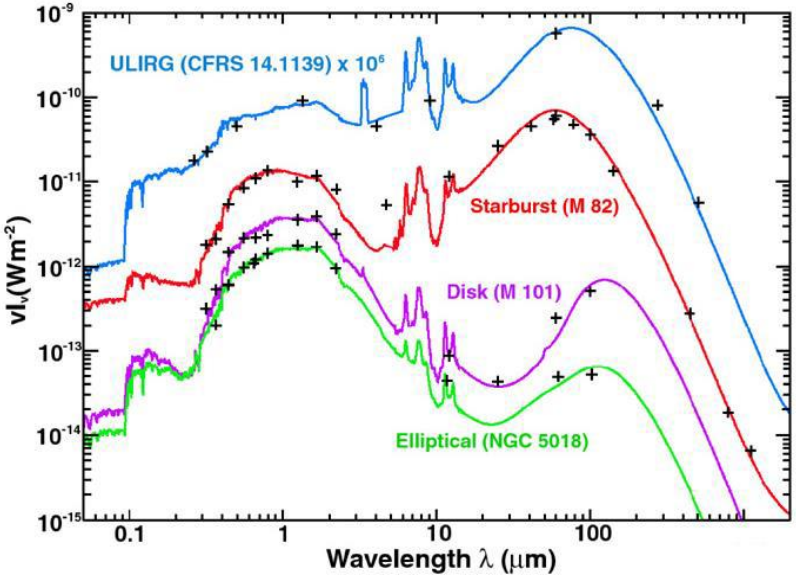
星系并合

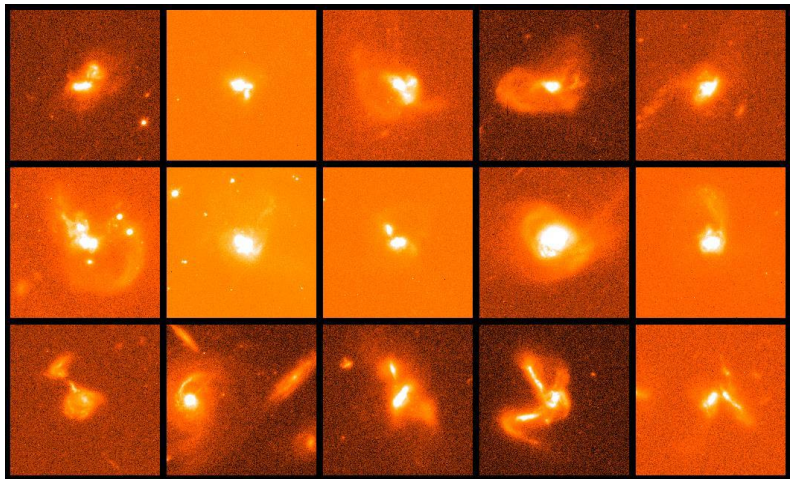


Hopkins et al. (2008)

ULIRG

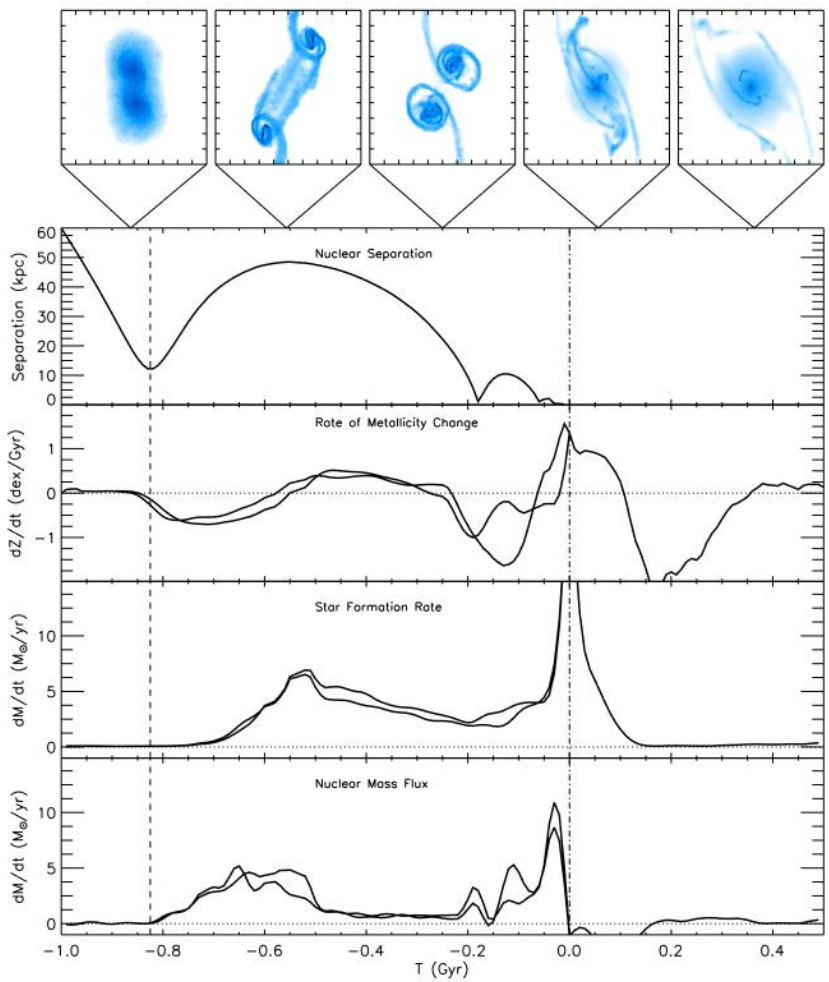
- 星暴星系(Starburst Galaxies)：正在发生剧烈恒星形成的星系。
  - 如星暴能够保持稳定，星系将在短时间内消耗完其内部的气体，恒星形成只能是爆发式
- 亮红外星系（Luminous Infrared Galaxies LIRGs）：$L_{IR} > 10^{11} L_{\odot}$，亮红星系辐射主要在红外波段。
- 极亮红外星系（Ultra-Luminous Infrared Galaxies，ULIRGs）：$L_{IR} \geq 10^{12} L_{\odot}$
  - 星暴如发生在富尘埃气体里，尘埃吸收大部分星光，并在红外波段再辐射
  - 几乎所有的ULIRG都处于并合的晚期阶段：SFR极高，SF时标短
- 星暴星系和极亮红外星系中，尘埃拦截了绝大部分紫外、可见光 → 红外再辐射强





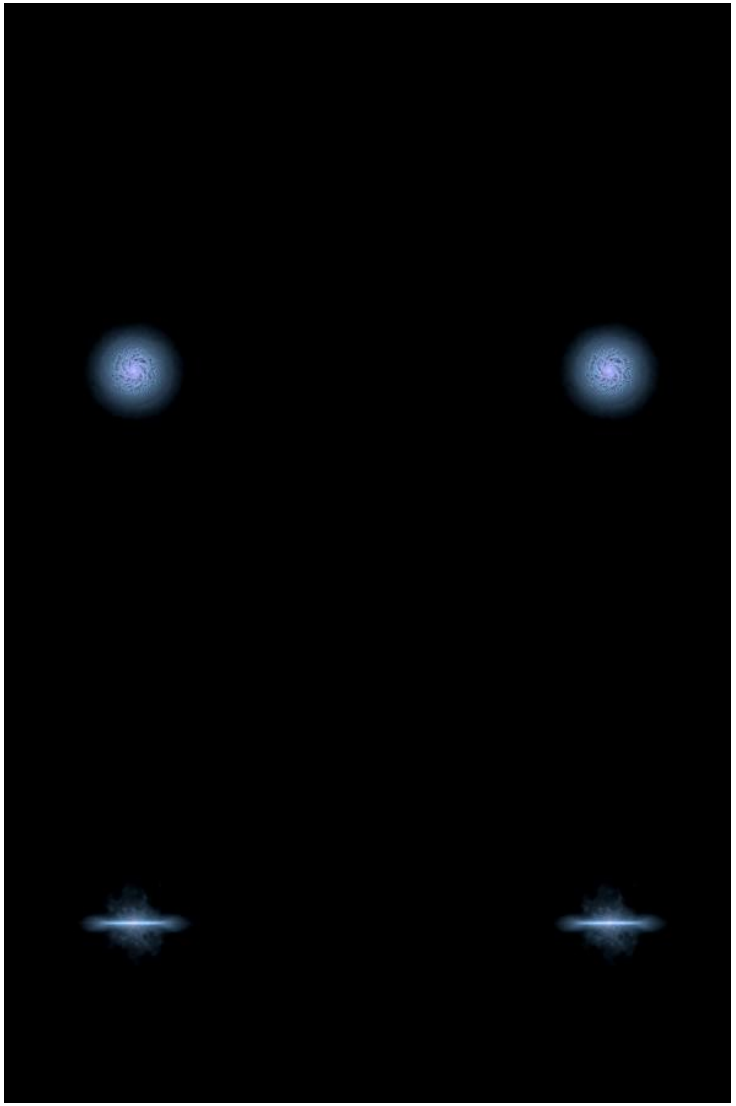
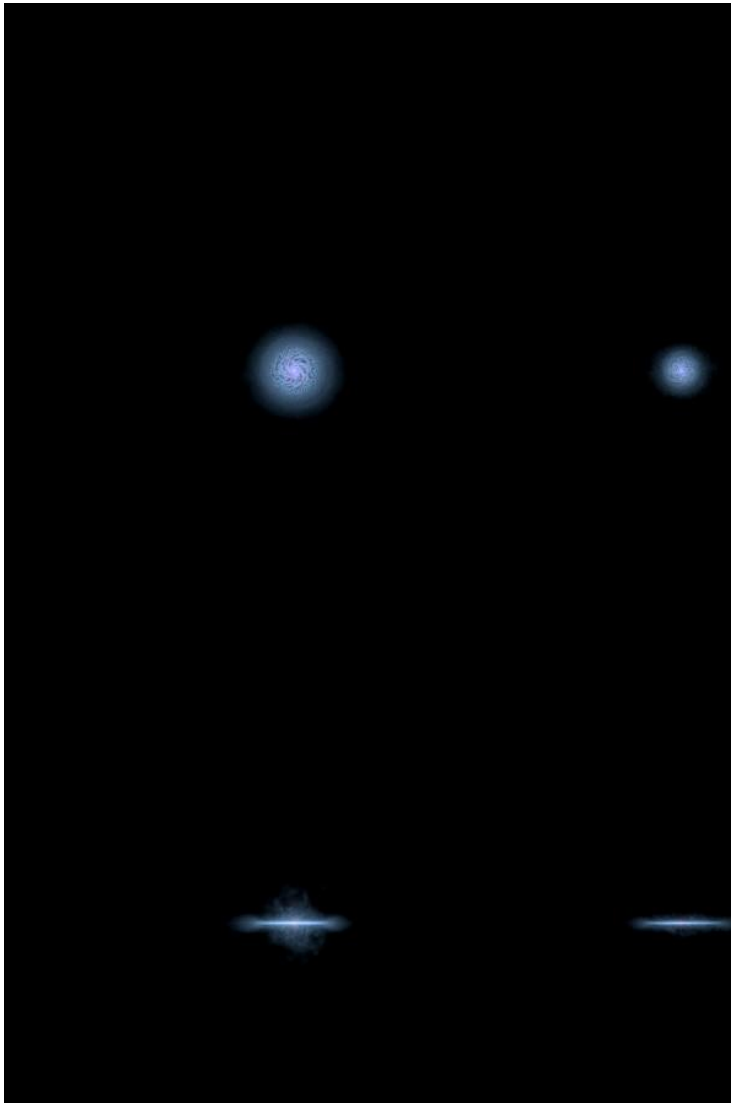
Major Mergers

- Major Mergers: mergers of two large, roughly equal mass disk galaxies
- A number of general results:
  - Global behaviour
    - a) Mergers are surprisingly rapid;
    - b) Galaxy encounters are very sticky;
    - c) Dark Matter halos play a crucial role in the merger
  - Disks are fragile, they are destroyed during the merger
    - Some gas is heated and leaves the system; some gas can cool and goes to the center.
  - As gas goes to the center, we expect high nuclear star formation rates → Starburst



Torrey et al. (2012)

Minor Mergers

- 次并合：并合的两个星系，其中一个星系质量明显大于另一个
- The larger galaxy will often "eat" the smaller. A minor merger is less disruptive
  - dynamical friction operates more slowly, over several (~10) orbits
  - accretion occurs more slowly, possibly along with tidal stripping
- Some general results from simulations of satellite accretion:
  - heats and thickens the disk; ultimately, enters the disk plane
  - induces spirals and bar → gas inflow → (SFR increases; AGN turns on)
- 大星系有很多伴星系，次并合发生的频率高，对星系形成演化重要

数值模拟