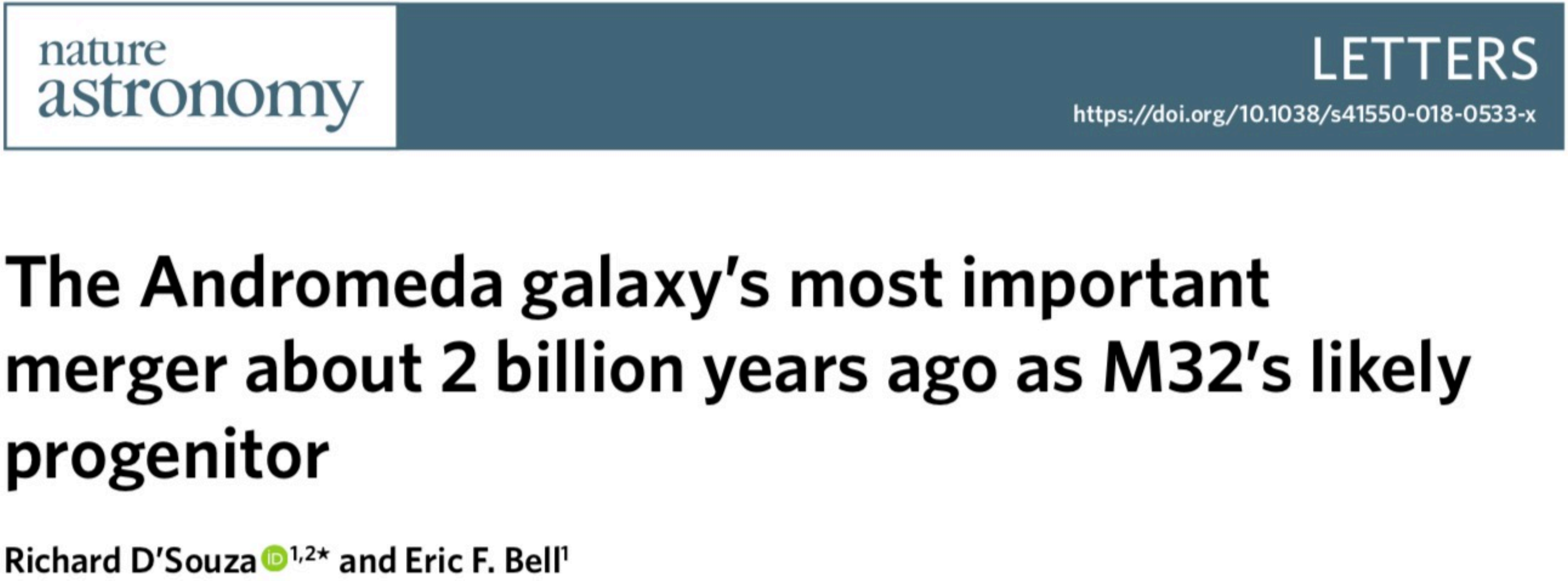

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The Andromeda galaxy’s most important merger about 2 billion years ago as M32’s likely progenitor

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0. Background

- M31 & M32
  - M32, classified as a compact elliptical galaxy. This class of galaxies are quite rare, with only 200 objects presently known. They are small, compact (100 pc < Reff < 500pc), high stellar density, non-star-forming galaxies with low stellar masses (10^8 < M*/ M$\odot$ < 10^10).
- Galactic Interaction & Merger, satellite
- Simulation
  - Progenitor, Dominant (M_dom, f_dom)
  - M_acc: accreted masses
  - Debris
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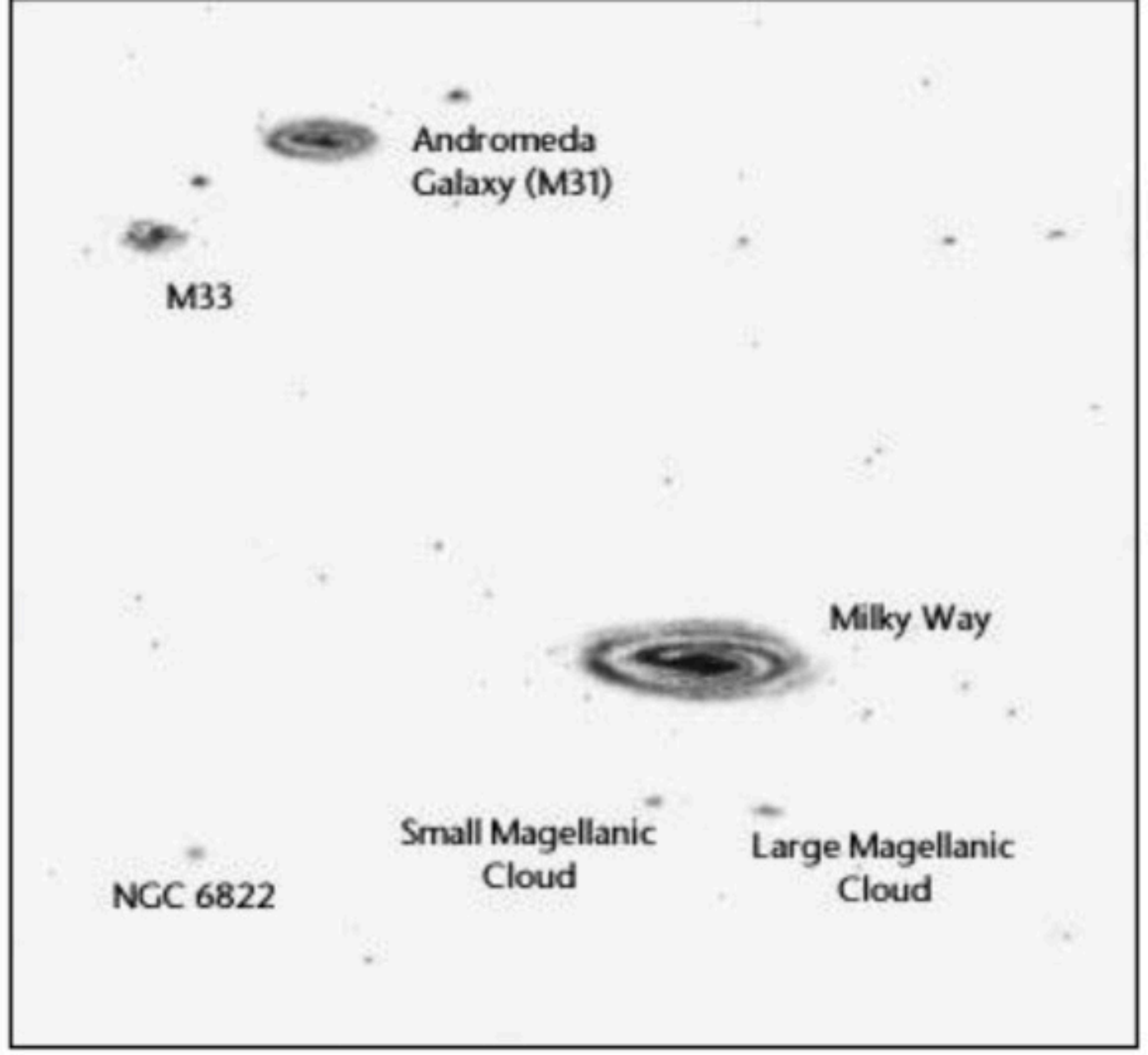
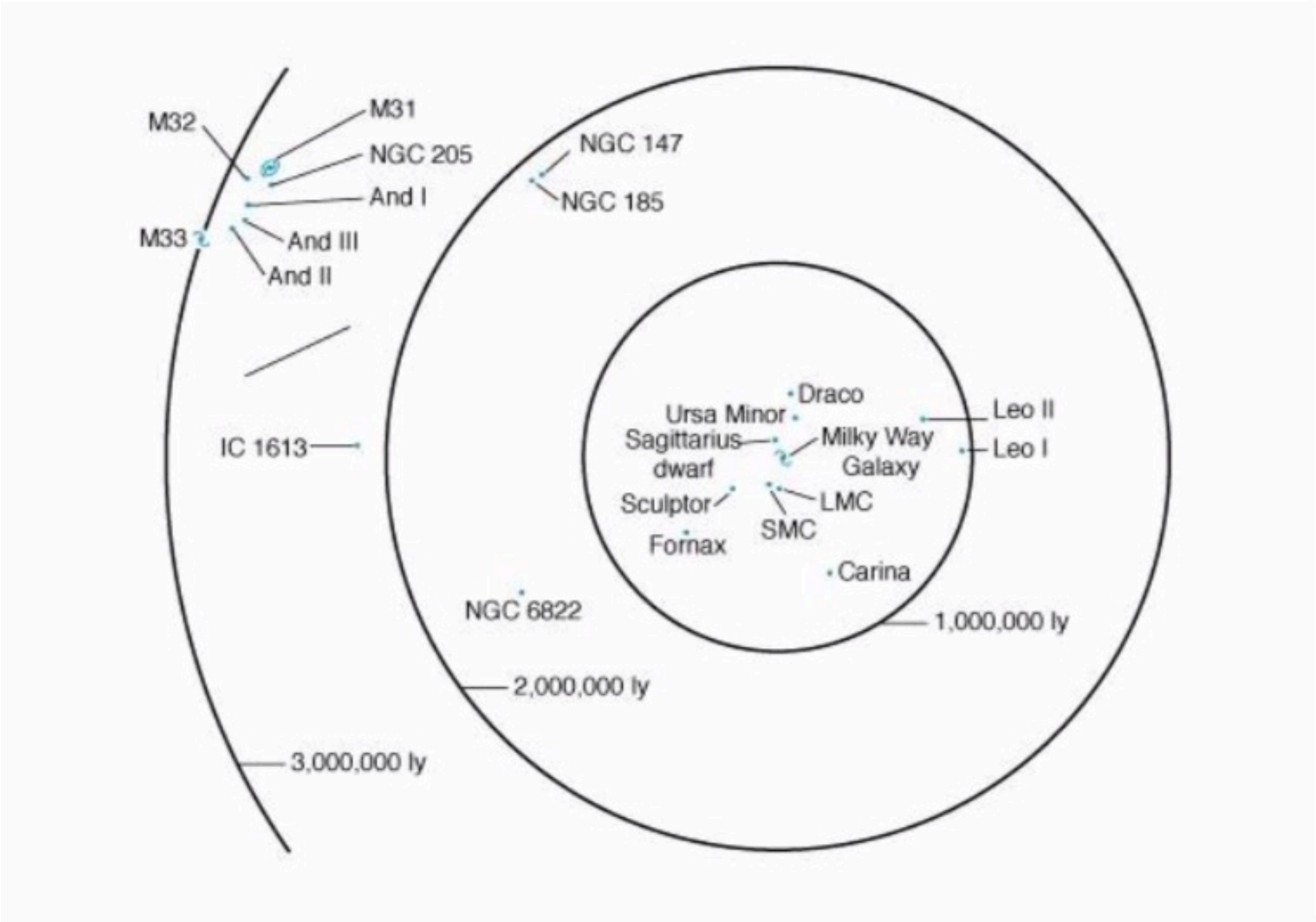
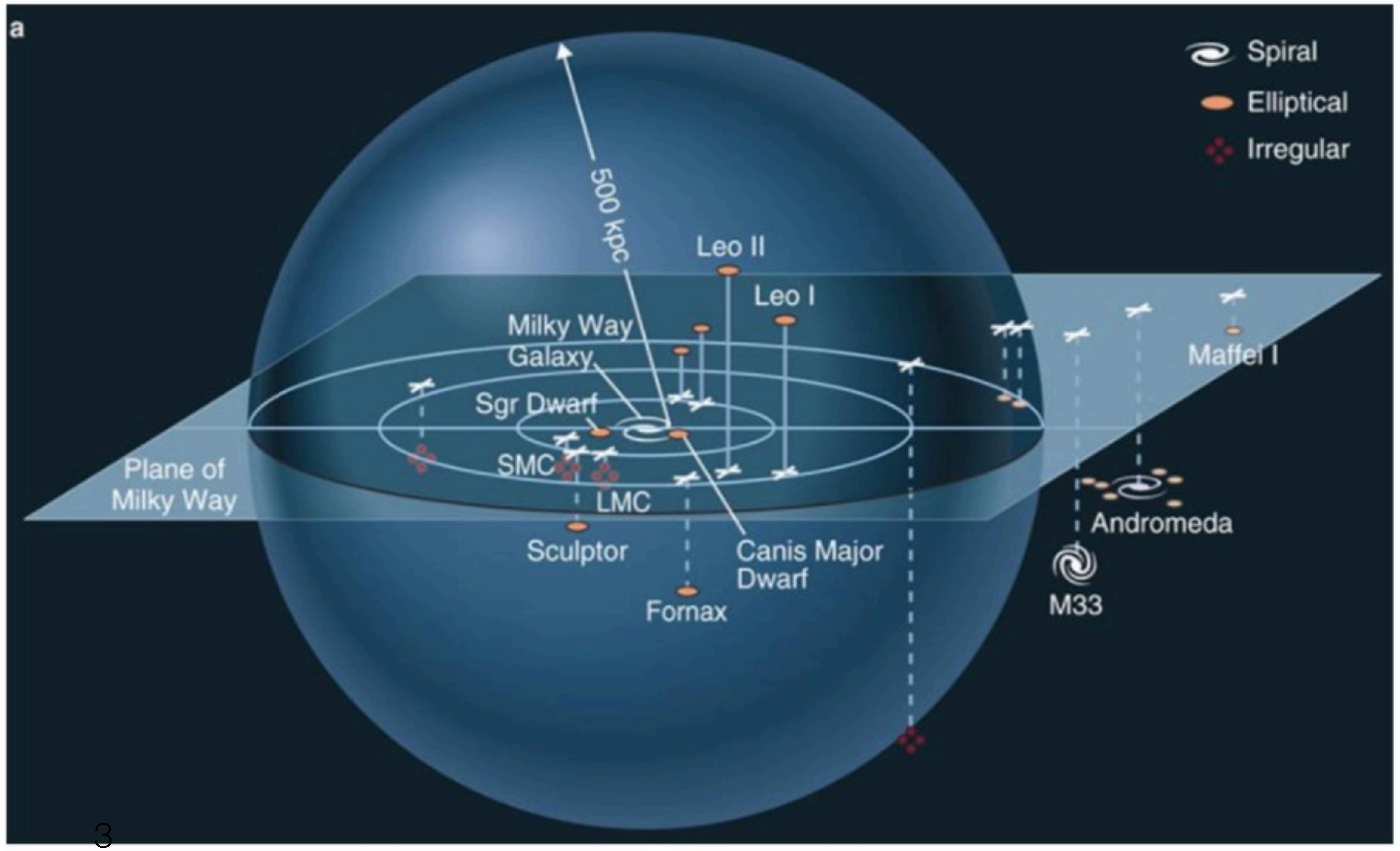
- 本星系群：以银河系和M31的公共重心为中心，半径约为1.2 Mpc 的空间内的星系总称。
- 两个质量最大的成员星系：银河系与M31；M31比银河系亮约50%。
- 第三亮星系为M33，L(M33)～0.2L(MW)；M31/MW/M33辐射了本星系群可见光～90%



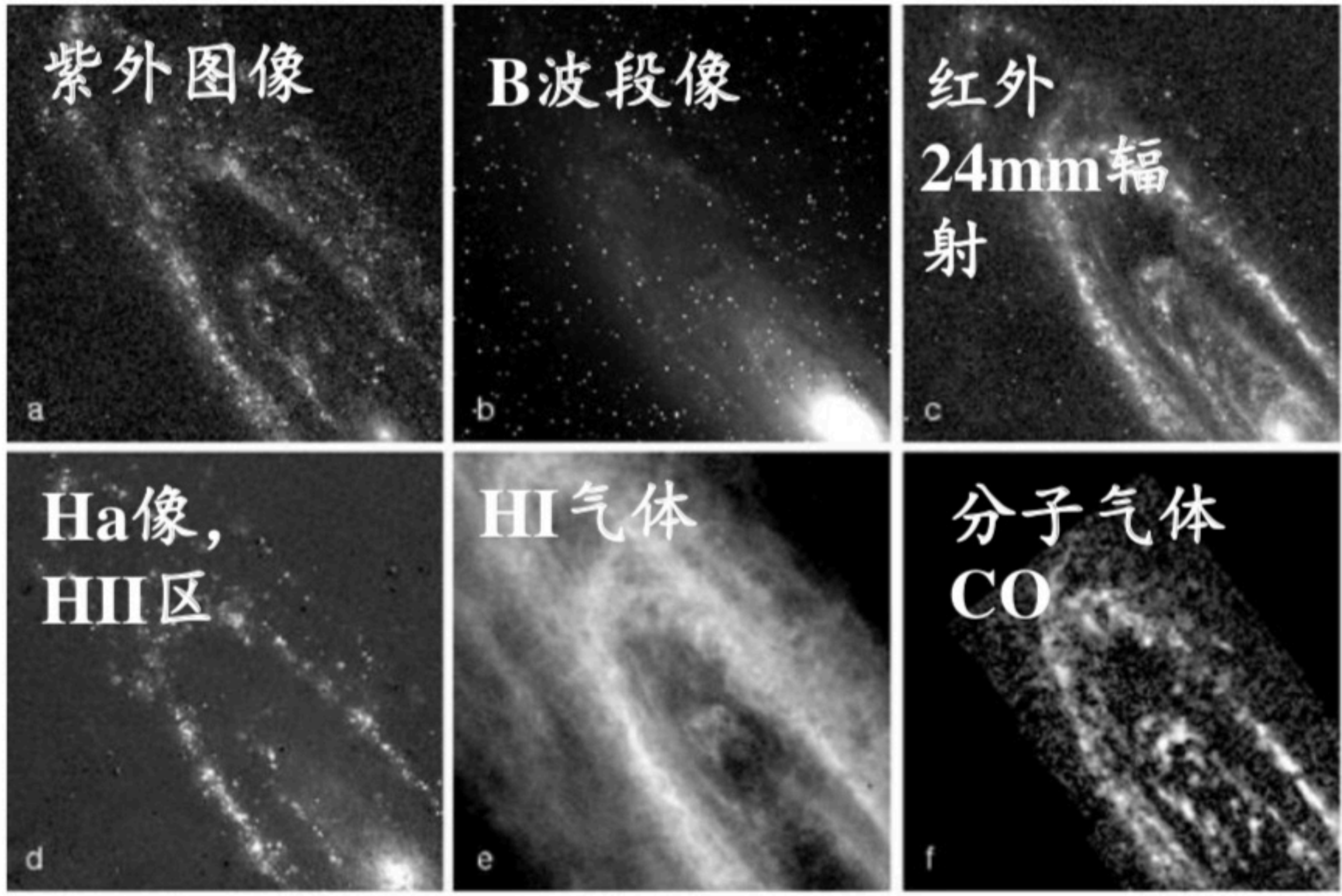


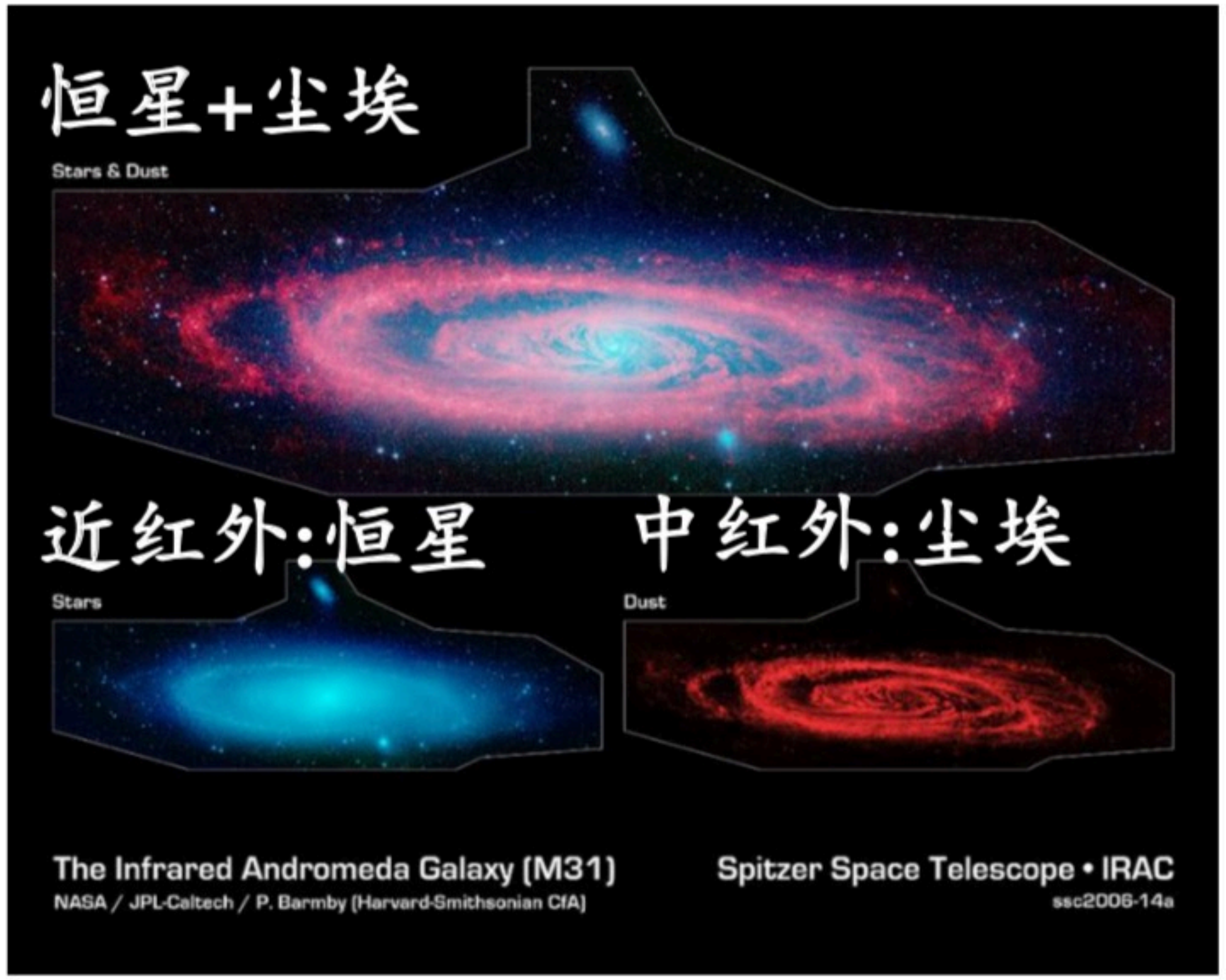


From Kong Galactic Astronomy Chapter 4

- M31在很多方面，都是一个比银河系大的星系
  - 质量M = 1.5×10^{12} $M_\odot$，M(MW) = 8.5×10^{11} $M_\odot$
  - M31中有10^{12}个恒星，银河系有2–4 ×10^{11}个恒星
  - M_V =−21.52，L_V = 3.64×$10^{10}L_\odot$ (MW M_V =−20.9)
  - 盘中恒星旋转快，V~260 km/s (MW V~220 km/s)
  - 已知的球状星团约 460 个（超过银河系中的2倍）
- 伴星系包括椭圆星系M32，3个dE，~10个dSph

- M31中央核球占其总光度的比例大于银河系的相应值，~30%−40%
- 核球在紫外波段很暗，几乎不含年轻恒星
- 核球含有稀薄的电离气体，以及少量较密的 HI 气体尘埃云。





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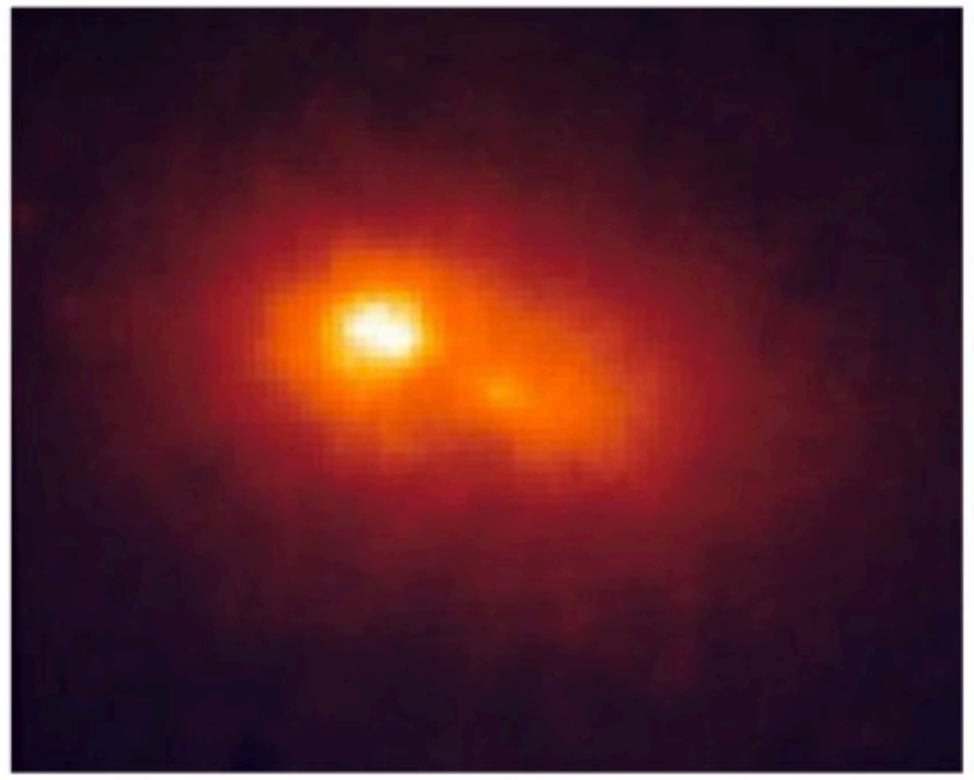
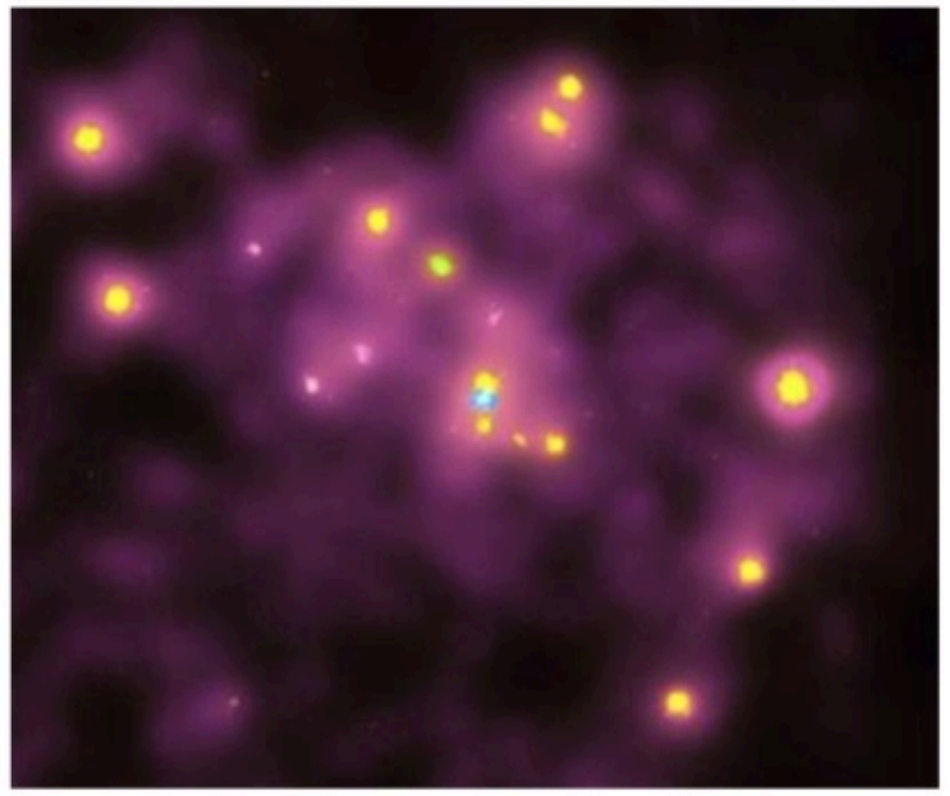
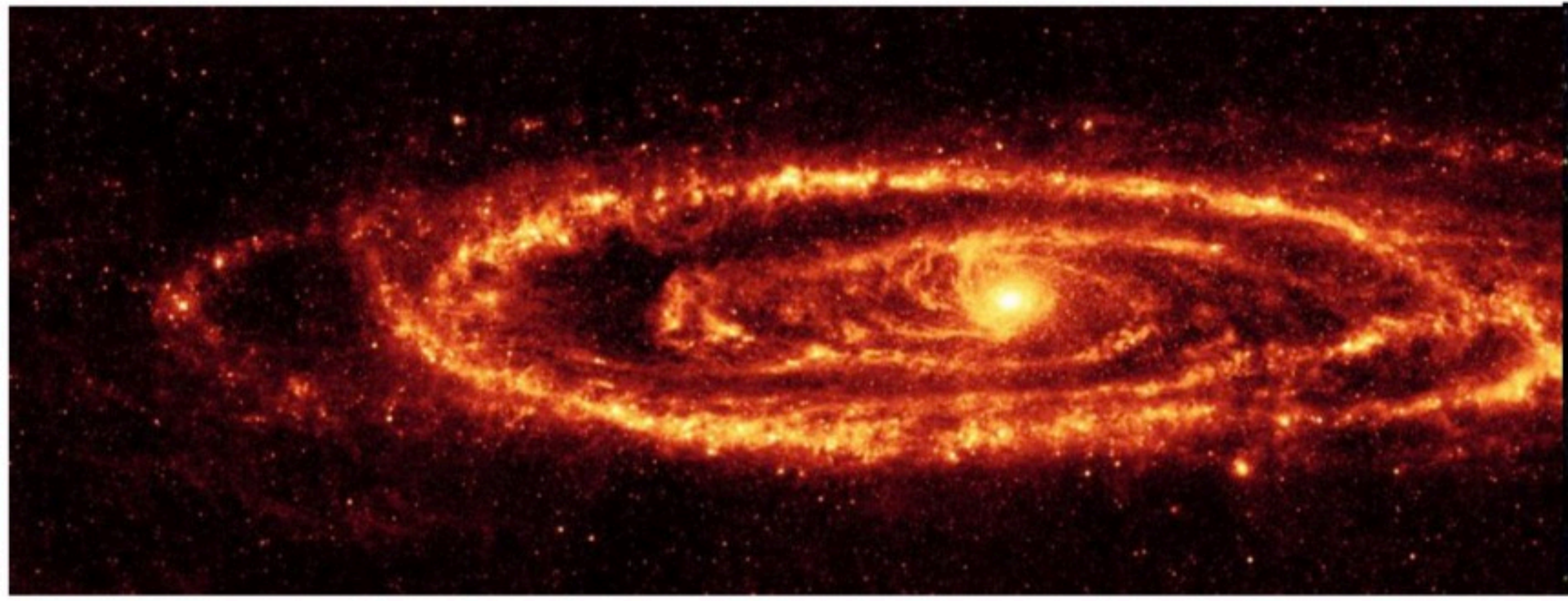
M31的结构

- 星系核
  - HST观测发现，M31核有两个相隔约 0.5″ 或 2pc光斑
  - 一个是致密的中心天体，质量$M_{BH}\backsim 2\times10^8\ M_\odot$黑洞
  - 另一个可能是在动力学摩擦影响下已旋入中心的星团
  - 与银河系不同，M31 核没有气体和尘埃（或含量少）
- 球状星团
  - M31 的贫金属球状星团遵循随机运动轨道；星团系统很少或几乎没有显示出有序转动。
  - 与银河系不同，M31中球状星团的年龄分布很广，除了年老球状星团，也有较年轻球状星团：吞食其他星系？
- 气体：HI质量约 $4 - 6\times10^9\ M_\odot$， 集中于 r ~ 10 kpc 处的环形恒星形成区。SFR ~ 1 $M_\odot$/yr （MW SFR ~ 3-5 $M_\odot$/yr ）







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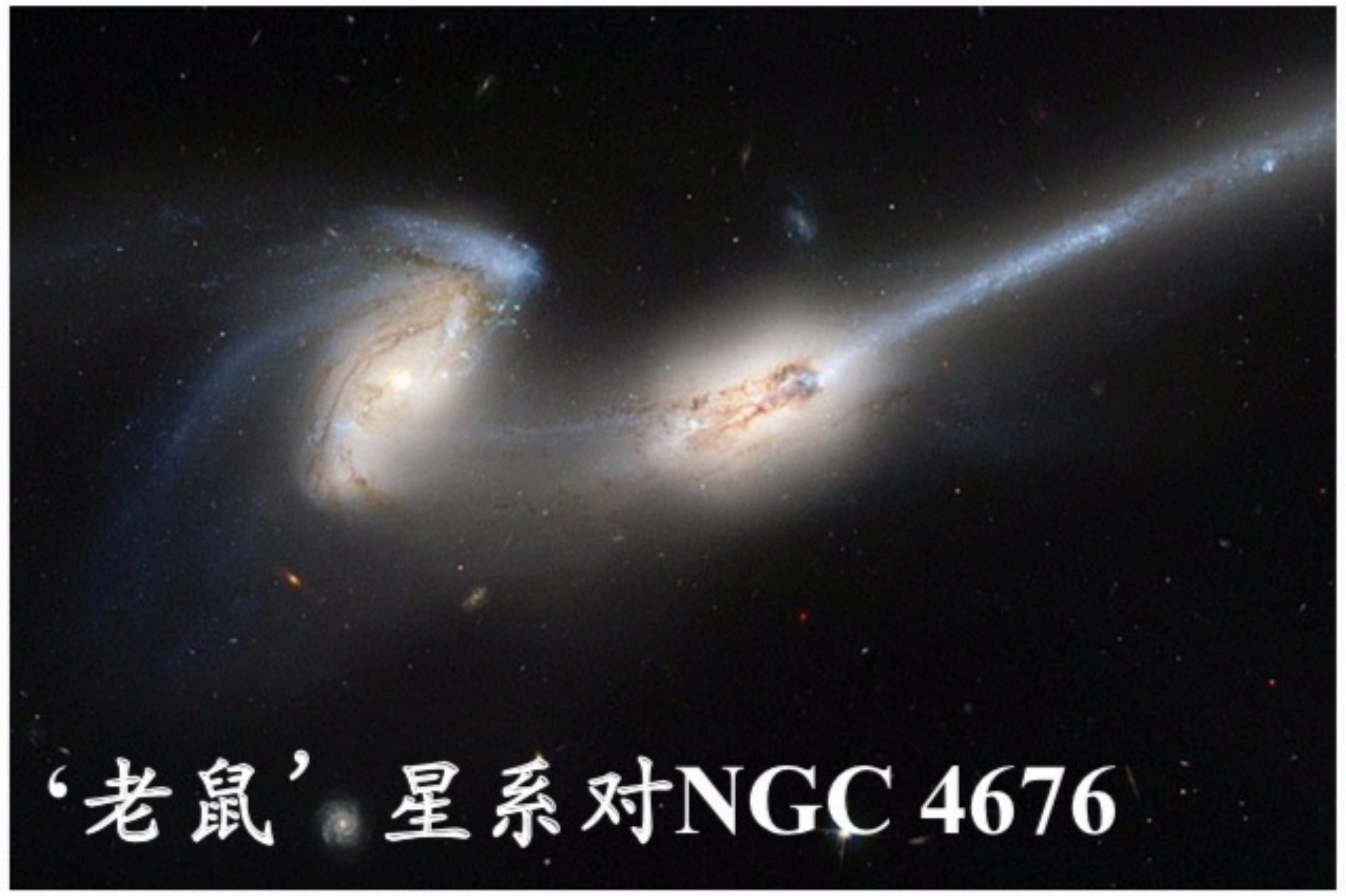
7.1.3 星系相互作用 • Interaction

- 恒星随机运动增加→星系内能增加→系统的束缚减弱，星系开始进入膨胀状态
- 获得很大能量的恒星逃离星系；获得能量较少者仍保持松散束缚，成为一个膨胀的外包层
- 富星系团中星系运动快，不大可能彼此减慢到足以变为一个束缚对：会分开，但两者都会留下一些扰动遗迹
- 星系群中，星系运动较慢，近交会产生的扰乱大得多：处于并合过程中的几乎所有星系都在星系群中
    - 近掠交会能够使星系产生棒或旋臂结构
    - 并合和近掠也促使盘气体流向星系中心
- 星系碰撞 → 压缩气体 → 触发恒星形成


‘老鼠’星系对NGC 4676

From Kong Galactic Astronomy Chapter 7

星系次并合 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，质量比大于 3:1 – 4:1.
- 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

From Kong Galactic Astronomy Chapter 7

星系主并合 Major Mergers

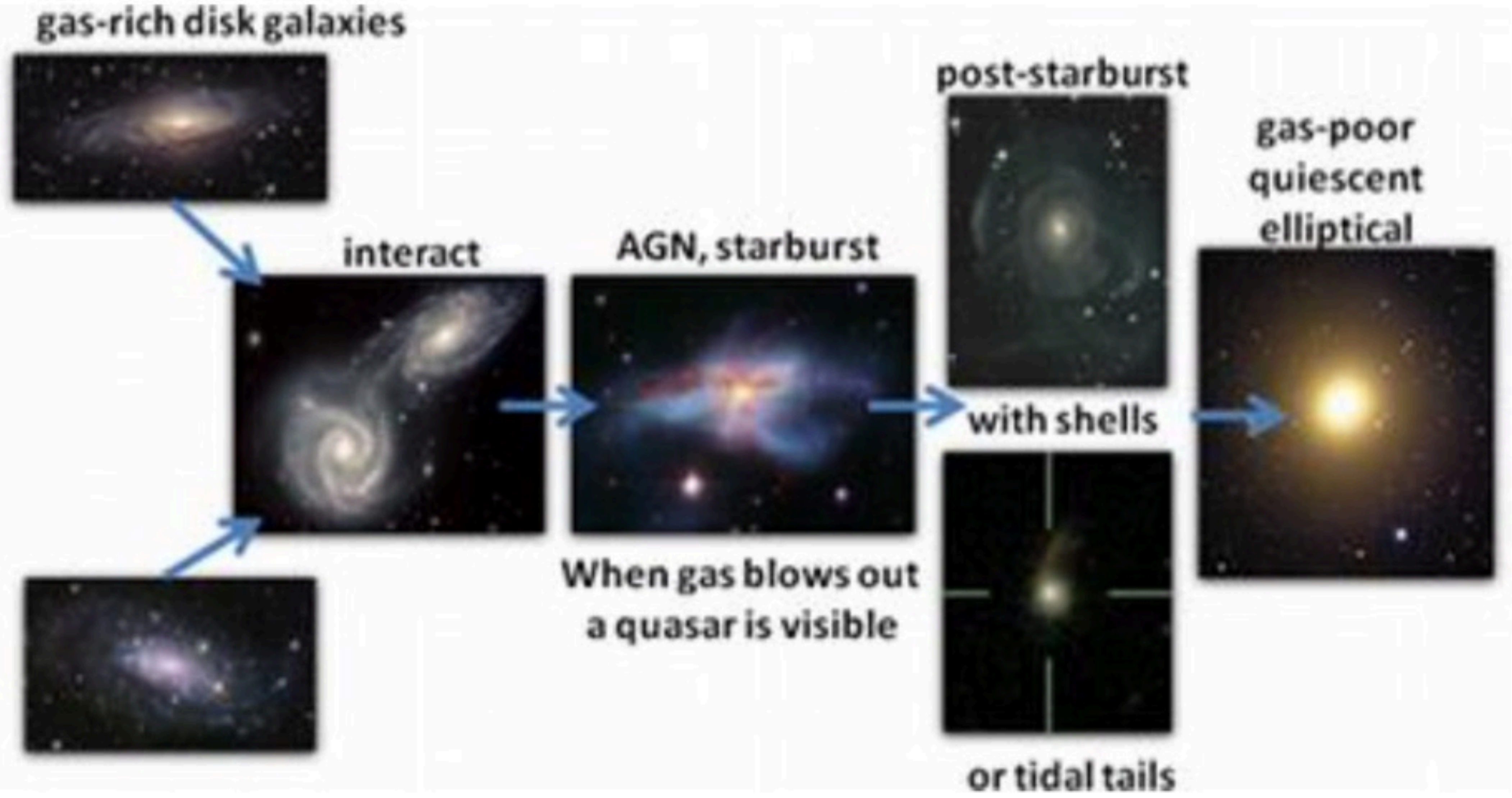
- **Major Mergers: mergers of two large, roughly equal mass disk galaxies**

- **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

两个等质量星系相互作用：随时间变化

2 spiral galaxies → Major merge → ULIRGs → AGN/QSOs → E+A → Es: many astronomers hypothesize that this is the primary mechanism that creates Es.

  - 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



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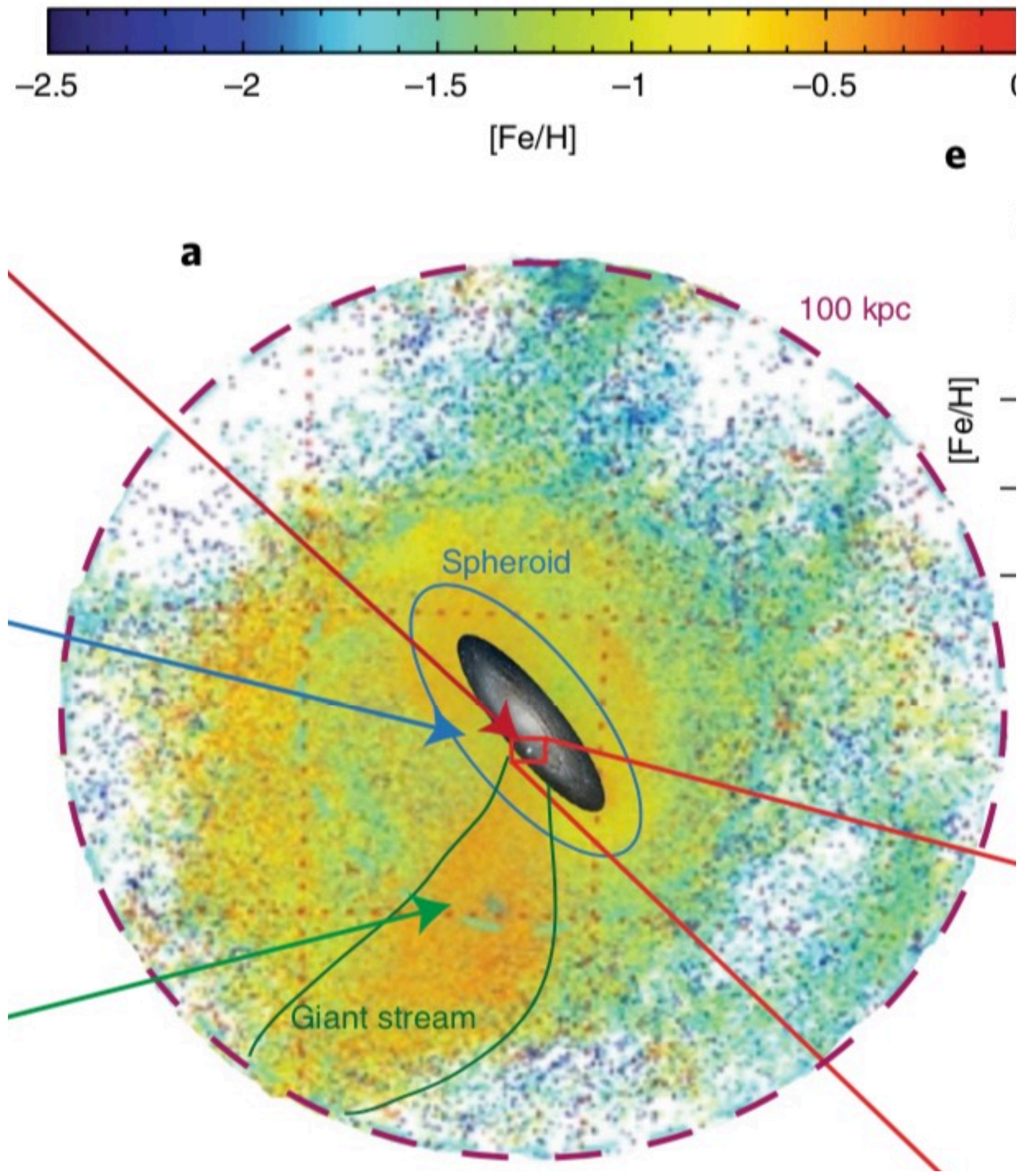
1. Introduction

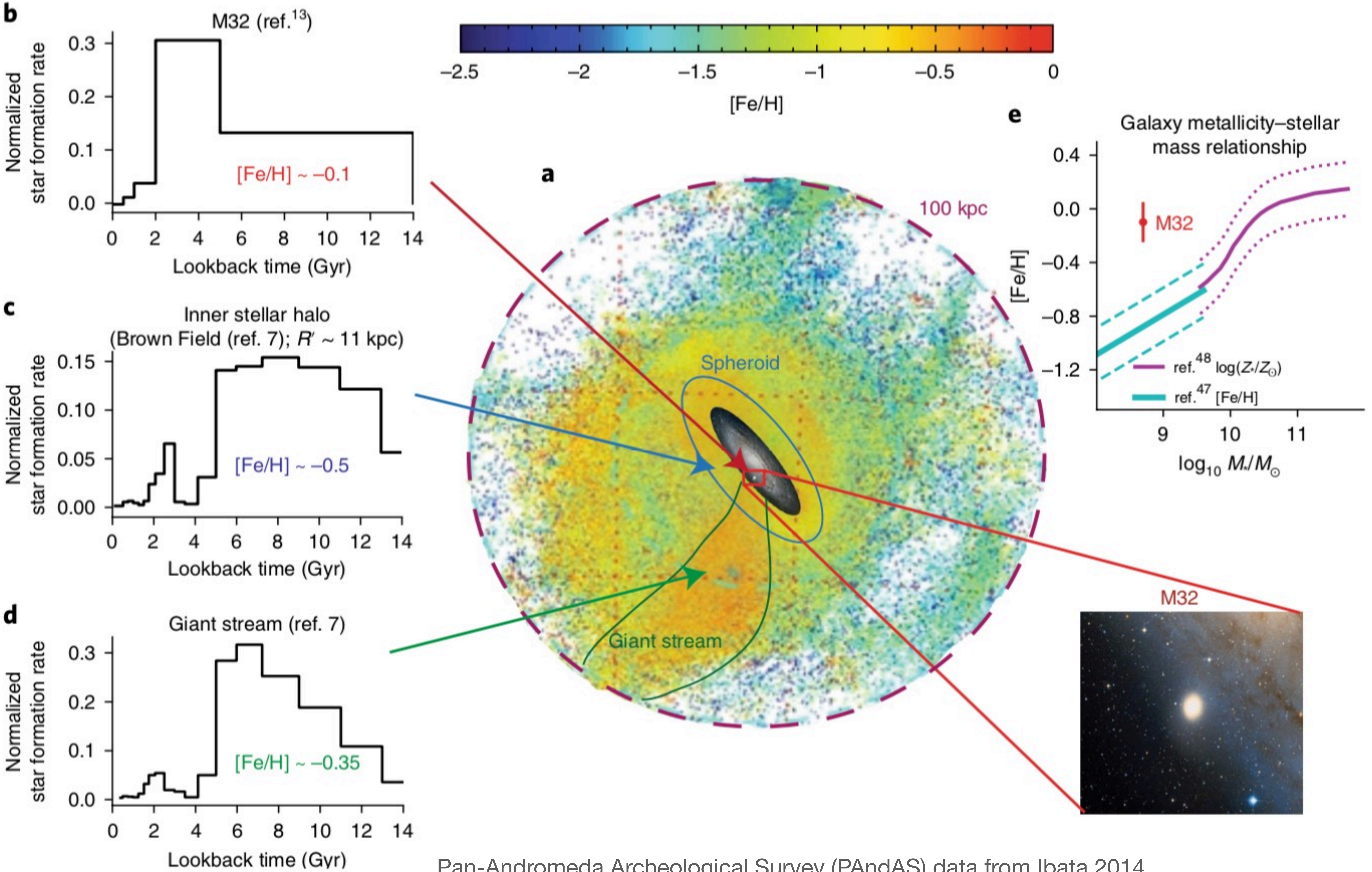


- Although the proximity of the Andromeda galaxy (M31) offers an opportunity to understand how **mergers** affect galaxies, **uncertainty** remains about M31's **most important mergers.** Previous studies focused **individually** on the **giant stellar stream** or the impact of **M32** on **M31's disk**, suggesting **many substantial satellite interactions.**

- Yet models of **M31's disk heating**[6] and the **similarity** between the **stellar populations** of **different tidal substructures** in **M31's outskirts**[7] both suggested **a single large merger.** M31's stellar halo (its outer low-surface-brightness regions) is built up from the tidal debris of satellites and provides information about its important mergers.

- Here we use cosmological models of galaxy formation
  - M31-mass galaxies/analogues — total accreted component (Ms & [M/H]) — Dominate progenitor

SFH



Pan-Andromeda Archeological Survey (PAndAS) data from Ibata 2014

Fig. 1 | The massive and extensive metal-rich stellar halo of M31 contains a substantial population of young and intermediate-aged stars. a, The

2. Method & 2.1 Simulation

- Use 2 independent cosmological large-scale galaxy formation models, the **Illustris** hydrodynamical simulations and **particle-tagging** simulations C13 based on the Munich semi-analytic model.
  - **only the accreted stellar component of central galaxies** (accreted stellar particles are formed in **subhalos** that are not part of the main progenitor branch of the galaxy).
  - **‘Dominant’ progenitor** is the **satellite** that contributed the **most stellar material** to the **accreted stellar mass** of the galaxy.
  - The **mass** of the **satellite** is its **maximum mass** before it is accreted by the main galaxy.
  - Median value of the **stellar metallicity** (all elements above He).
  - **The time of accretion** of a **satellite** is **when it merges with the main progenitor branch of the galaxy**. Accreted satellites at this stage are usually stripped of most of their stellar material and are within **100 kpc** of the host galaxy.
- Demonstrate that the **mass** and **metallicity** of **M31’s total accreted stellar component** constrains the **mass** of its **most dominant merger**.

2.1.1 Advantages of the models

- Interested only in the **mass** and **metallicity** of **M31’s stellar halo**. This choice of metrics is less subject to systematic error, since they are **independent** of the exact positions, orbits and motion of the accreted stars.

- The two simulations are particularly suitable to study the bulk properties of the accreted stellar component of M31-mass galaxies for the following reasons.

  - a) Due to their **large volume,** they encode **a diversity of accretion histories.**

  - b) They represent the accretion histories of M31-mass galaxies reasonably well: both simulations have approximately the right halo occupation of accreted satellites of M31-galaxies enforced through the galaxy stellar mass function ($9 < \log M^* < 10$) and the cosmic star formation history.

  - c) They reproduce the **stellar-mass metallicity relationship** of galaxies fairly well.

  - d) They have **enough resolution** to resolve the **general properties** of the most significant progenitors of **M31-mass galaxies.**

2.1.2 Limitations of the models

- Interested only in the **mass** and **metallicity** of **M31's stellar halo**. Consequently, while we are less concerned with our simulations reproducing the exact phase-space information of M31's stellar halo, we **cannot constrain the exact orbit of M31's most massive merger event.**

- The radial profile of the accreted stellar component depends upon the tidal disruption of satellites and is still highly **model dependent**:

  - a) The disruption of accreted satellites depends upon the satellite galaxies having the right **sizes** and **shapes** (correct **binding energies**).

  - b) The distribution of the debris depends upon the model getting the **right potential of the galaxy**.

- The physical extent of galaxies in the Illustris simulations can be a factor of a few larger than observed for $M^* < 10^{10.7} M_\odot$, affecting the spatial distribution of the accreted stellar debris. The C13 simulation is **limited** in its ability to reproduce the 3D distribution of the accreted stellar debris, as its galaxies assume the shape of the inner part of their dark matter halos and do not account for the potential of galactic disks.

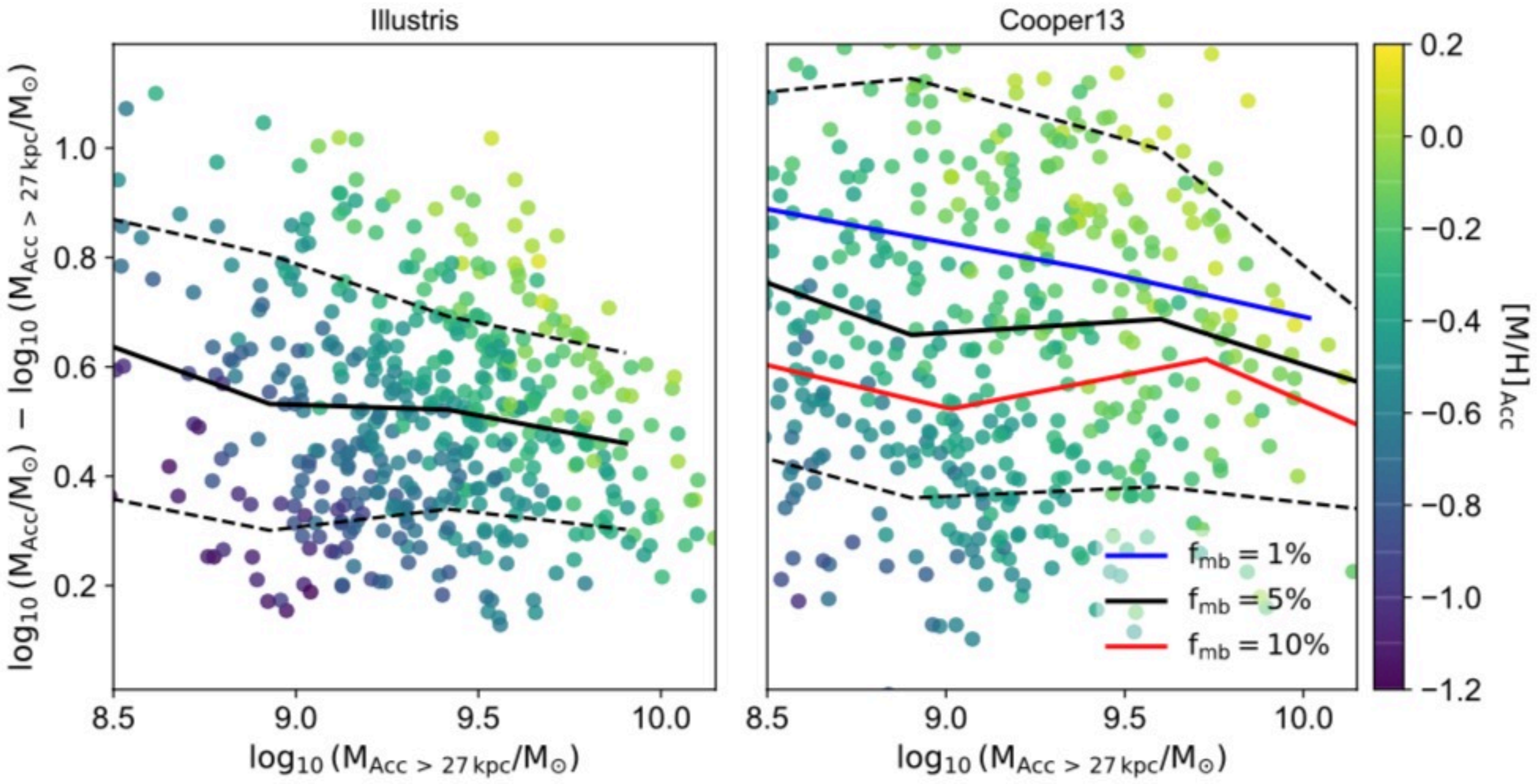
- Furthermore, the **mass resolution** of the simulations ($\sim 10^6 M_\odot$) becomes a **limiting factor** in studying the phase-space distribution of the debris of the most massive progenitor. These simulations also cannot resolve M32-like compact cores in the progenitors, or their remnants in the final stellar halos.

- Since the radial profiles of the accreted stellar component are subject to substantially larger systematic errors than the total accreted stellar mass and metallicity, **the use of the outer stellar halo mass alone to choose M31 analogues** would **yield a sample more subject to systematic** differences from model to model than a set **selected on the more robust total accreted stellar mass alone**.

2.2.1 M31-mass galaxies/analogues selection

  - The constraints on the **virial mass** of M31 come from the systematic effect from the LMC: **1.33 × 10^12 M⊙**.
  - Constraints from SDSS ugriz and Spitzer 3.6 μm imaging suggest that **M31's stellar mass** is **10-15 × 10^10 M⊙**
  - **M31's total accreted stellar mass** from measurements of **M31's outer stellar halo** estimated by the PAndAS survey over a radial range of **27.2 kpc** out to 150 kpc, assuming an age of 13 Gyr, to be **10.5 × 10^9 M⊙**.
- **M31-mass galaxies** from the Illustris and the C13 simulations such that **10.7 < logM* < 11.3**, **11.86 < logM_DM < 12.34** and **(M_acc/M*) < 0.5**. The last condition on the total accreted stellar fraction ensures that we select only **disk-like galaxies**. A total of **548** and **680** galaxies satisfy these constraints in Illustris and C13 simulations, respectively.
- We chose **M31 analogues** from our **M31-mass galaxies** by imposing a lower limit on **total accreted stellar mass: log(Macc,*) > 10.3**. We found a total of **39** and **57** galaxies in the Illustris and C13 simulations, respectively. Of these, **35** and **37** galaxies **accreted a large satellite** (median mass: logMsat ~10.3, median metallicity: [M/H] ~0.0) in the last 5 Gyr.
  - We conclude that it is possible for M31 to have both a large satellite like M33 as well as have accreted a large progenitor (log M*~10.3) in the last 5 Gyr. Furthermore, it does not change any of the findings of this work, but only decreases our number statistics.

2.2.2 Constraining M31's total accreted component



- We constrained M31's total accreted stellar mass by placing **lower** and **upper limits** from measurements of **M31's outer stellar halo.**
  - We adopted this radial range estimated from PAndAS, **a radial range of 27.2 kpc** out to 150 kpc, to define the **outer stellar halo** as it both avoids the inner stellar halo and the associated concerns about contributions from an in situ stellar component and is dominated by the debris of the most dominant accreted progenitor.
  - A **lower limit** on the M31's total accreted stellar mass is based on the ratio of total accreted stellar mass to the accreted stellar mass **beyond a projected galactocentric radius of 27 kpc**.
    - For Illustris, we find that the total accreted stellar mass is **~0.5 dex** larger than that beyond 27 kpc.
    - For C13, assuming a fiducial tagging fraction of 5%, we found that the total accreted stellar mass is **~0.65 dex** larger than external to 27 kpc.
  - In both models, the total accreted stellar mass of a galaxy exceeds the accreted stellar mass outside 27 kpc by **at least 0.4 dex**. Assuming that the mass of the M31's stellar halo beyond 27 kpc is 8.8 × 10^9 M⊙, we conclude that **the total accreted stellar mass of M31** is larger than **2.0 × 10^10 M⊙**.

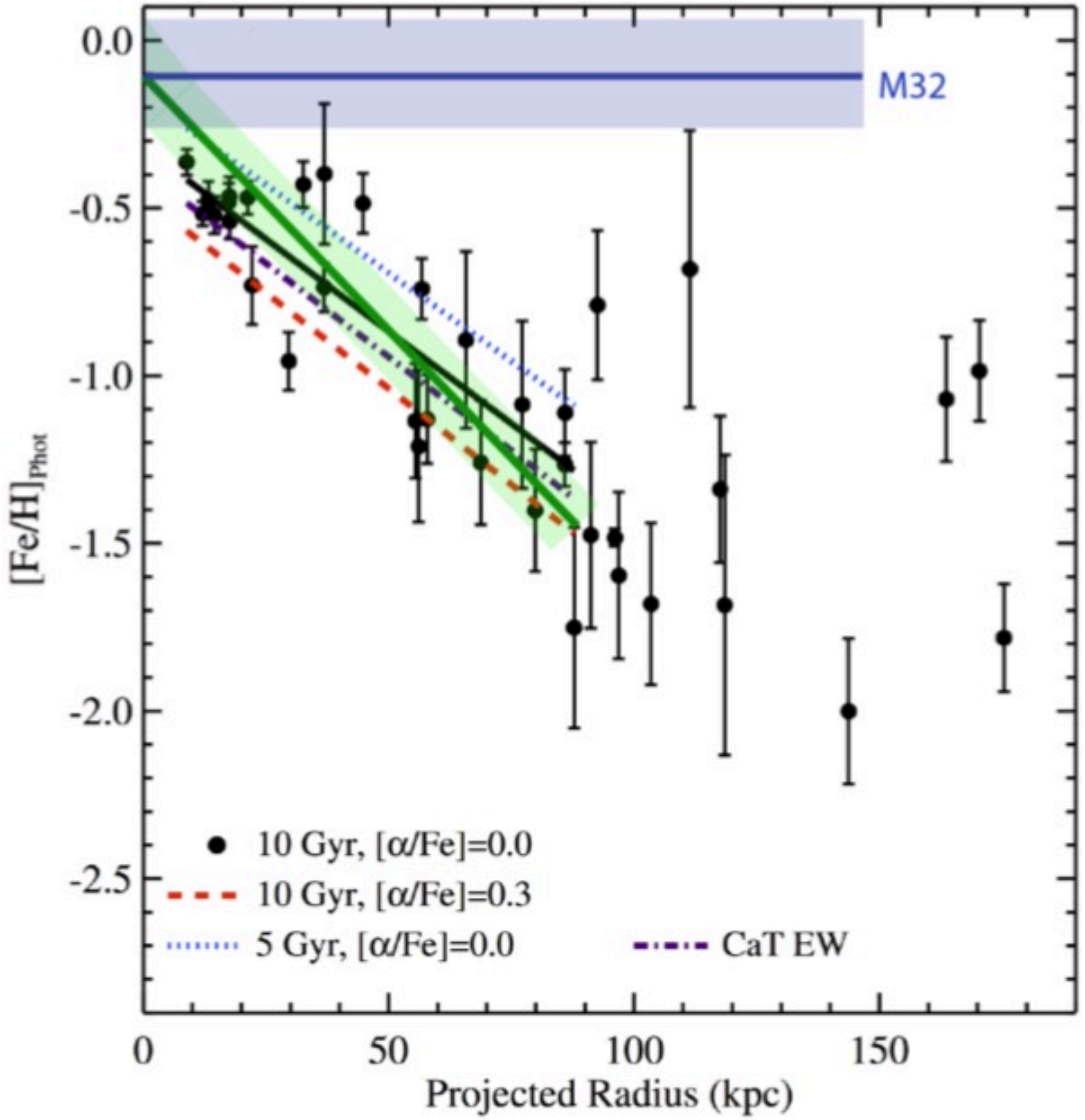


Fig. The black line is the **photometric metallicity** assuming a stellar population with an age of 10 Gyr and [α/Fe]=0.0. The red and blue lines represent variations in the photometric metallicity gradient by allowing for a higher [α/Fe] (~0.3) and a younger stellar population (age ~ 5 Gyr) respectively. The dotted-dashed line represents the spectroscopic metallicity gradient derived from the CaT lines. Assuming that the outer stellar halo contains older populations, while the inner stellar halo is made up of intermediate-age populations, **the green line and the accompanying shaded region represents our best-estimate along with the confidence limits (statistical errors) of the metallicity** of M31's outer stellar halo. The intercept of the green line at R=0 gives the estimated metallicity of M31's total accreted stellar component.

- The metallicity of the total accreted stellar component **is dominated by the metallicity of the most massive accreted progenitor.** Galaxies with a large and massive stellar halo have accreted a massive progenitor (for M31, logMDom,* ~10.3) with a strong metallicity gradient. As this progenitor gets accreted, the metal-rich core of the disrupted satellite sinks to the centre, leading to strong metallicity gradients in the accreted stellar component of the host galaxy. In such cases, the metallicity of the total accreted stellar component is higher than the metallicity of the outer stellar halo.

- Estimating the metallicity of the total accreted stellar component of M31 using **the minor axis metallicity gradient of its stellar halo**.

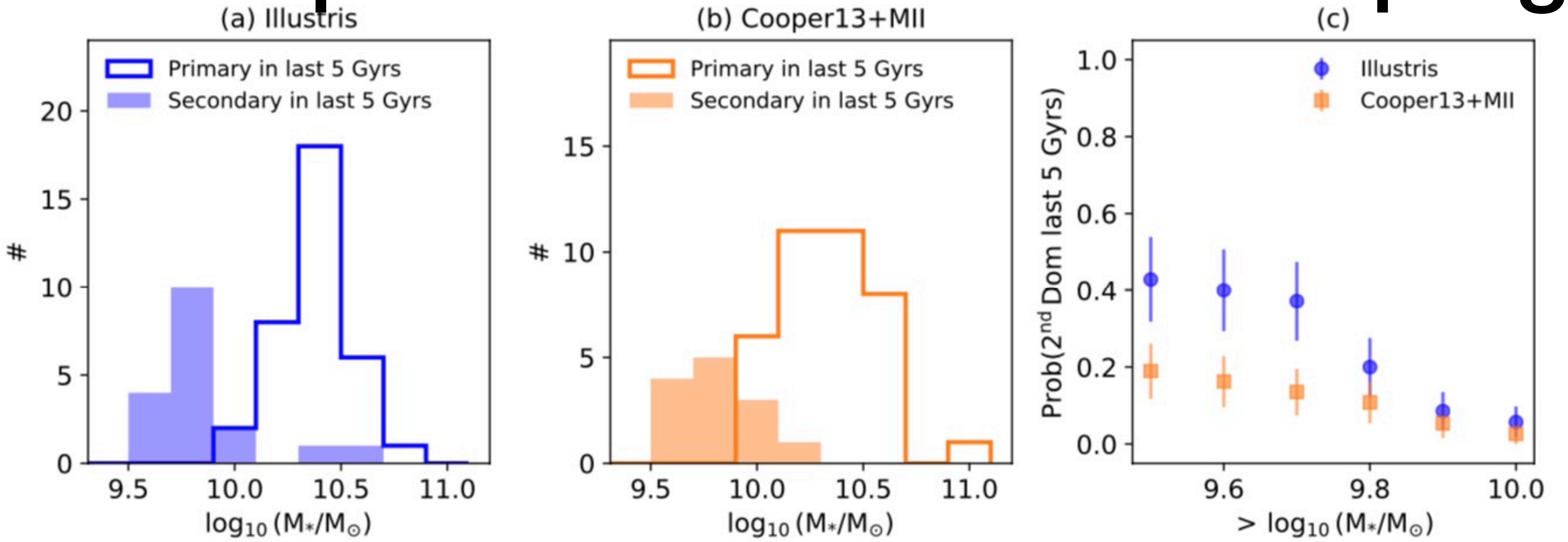
    - The metallicity of the stellar halo of M31 along the minor axis in the **SPLASH12 survey** was derived assuming an age of 10 Gyr and an [α/Fe] = 0.0.

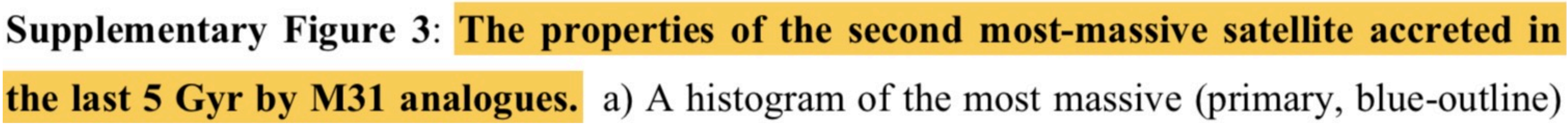
    - The outer stellar halo (>60 kpc) is older in age ~10 Gyr, while the inner stellar halo is built up from stars that are considerably younger including intermediate-age stars, likely from large satellites accreted fairly recently ([α/Fe] ~0.0, age ~5 Gyr). This would make the **metallicity gradient steeper** than previously estimated.

- A robust lower limit for the metallicity of M31's total accreted stellar component is **[Fe/H]_acc > –0.3** (**highest** metallicity in the outer stellar halo).

- Extrapolating the metallicity gradient towards the centre of the galaxy suggests that **M31's total accreted stellar component has a median metallicity of [Fe/H]_acc ~– 0.1+/–0.15 dex**.

2.2.3 Uniqueness of the dominant progenitor

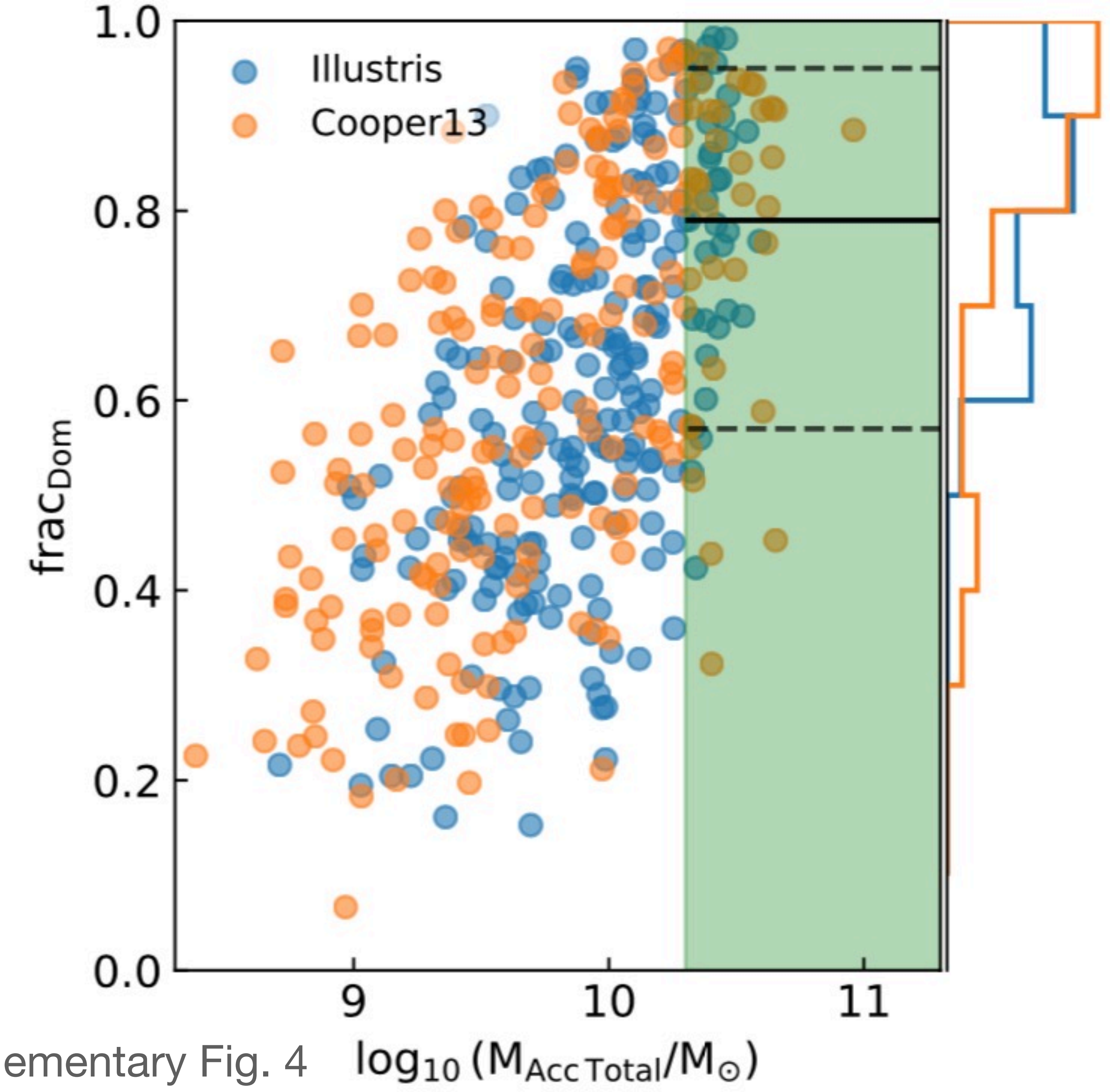




Supplementary Figure 3: **The properties of the second most-massive satellite accreted in the last 5 Gyr by M31 analogues.** a) A histogram of the most massive (primary, blue-outline)

- Although the dominant progenitor contributes most of the mass to the accreted stellar component of M31 analogues, in a few cases, the second most massive progenitor can be comparable. We explore this **issue** by **quantifying the fraction of M31 analogues that have had a second massive accretion** in the last 5 Gyr above a given mass threshold
  - We considered only those 'recent' M31 analogues whose dominant accretion was within the last 5 Gyr (90% of M31 analogues). This probability is **10%(7%)** for satellites with **log(M*) > 10**.

- Two pieces of evidence suggest that M31 **is dominated by a single large progenitor.**



Supplementary Fig. 4

    - M31's **large accreted stellar mass.** We demonstrate this by calculating **the fraction of accreted stellar material contributed by the dominant progenitor (fracDom)** as a function of accreted stellar mass for M31-mass galaxies in the Illustris and C13 models. For M31 analogues, fracDom spans between 0.4 and 1.0 with the mean of the distribution being around **0.8**, implying that their stellar halos are built up through the accretion of single large progenitors.

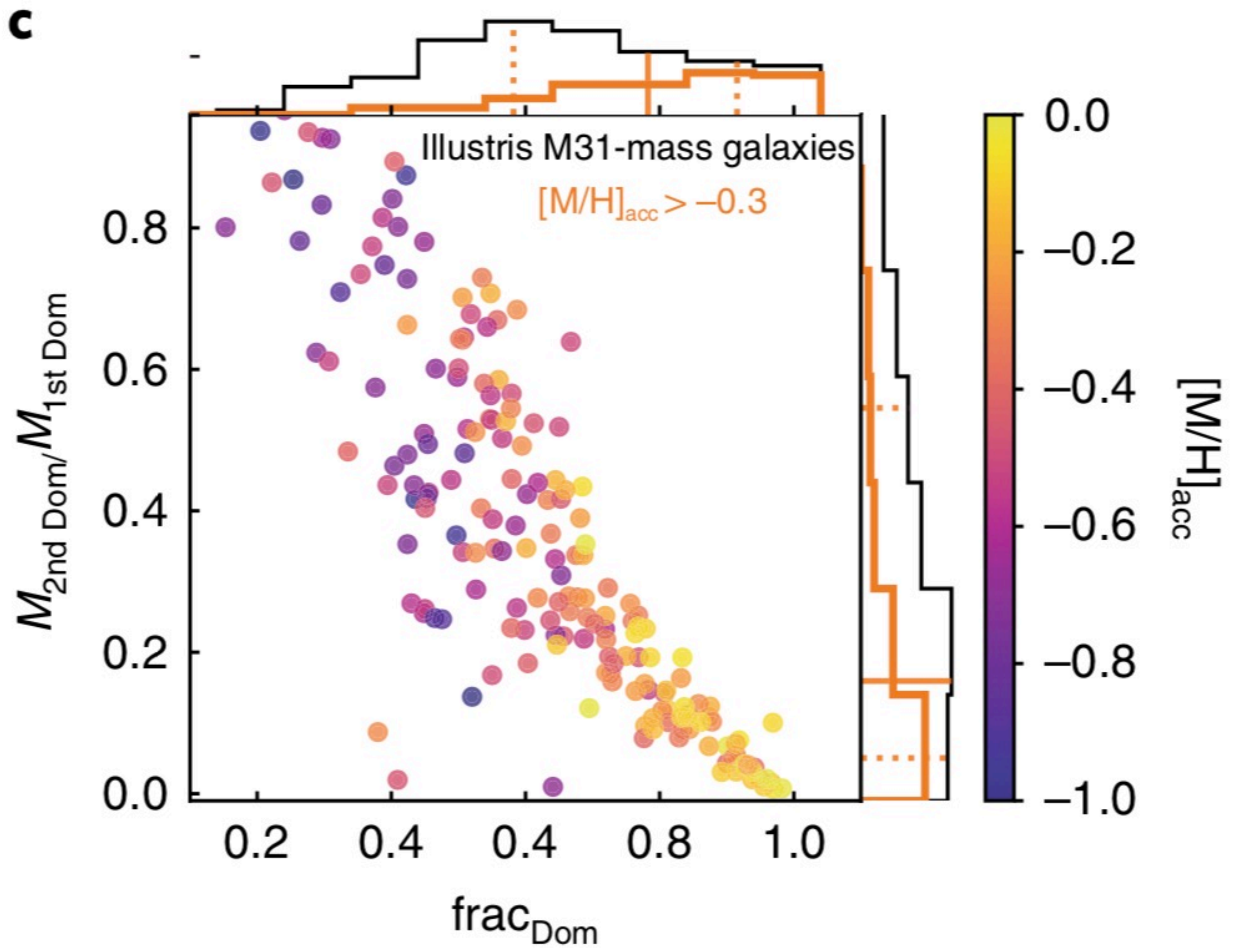


Fig. 2c

    - The **high metallicity of M31's accreted stellar component**. M31-mass galaxies have a **high accreted stellar metallicity component ([M/H]acc > –0.3)** are dominated by a single large accretion event (high fracDom) and have an average ratio of the stellar mass of the most massive progenitor to the dominant progenitor less than **0.2**.

3 Result: a Single Merger Event

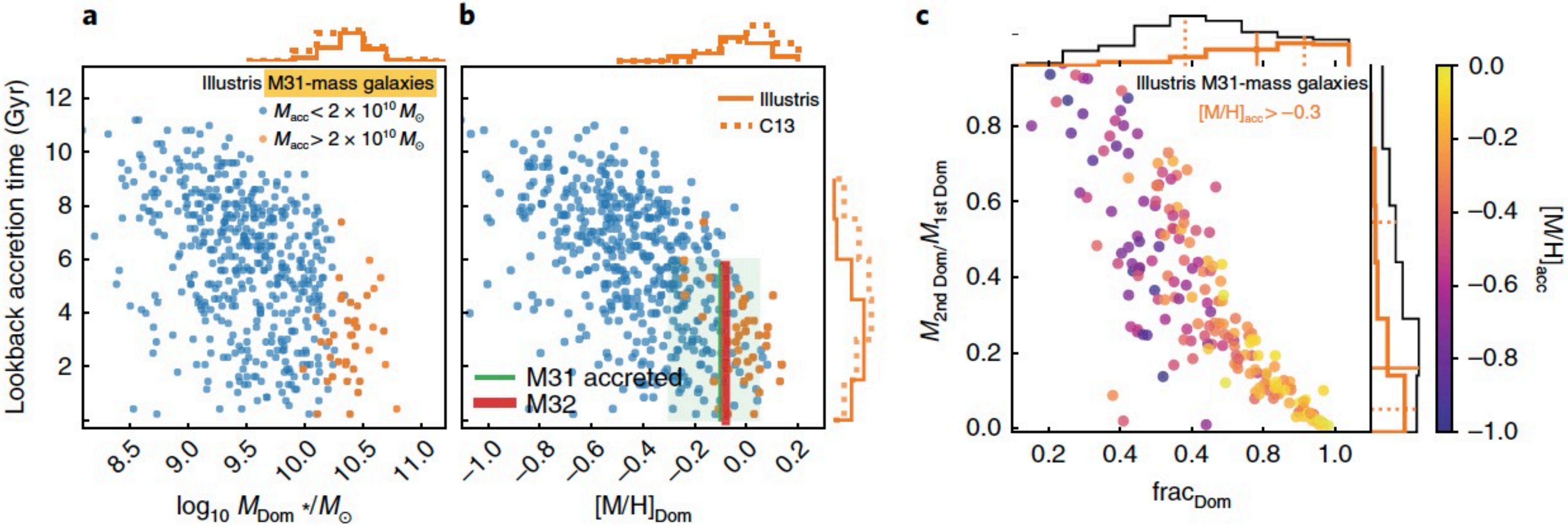
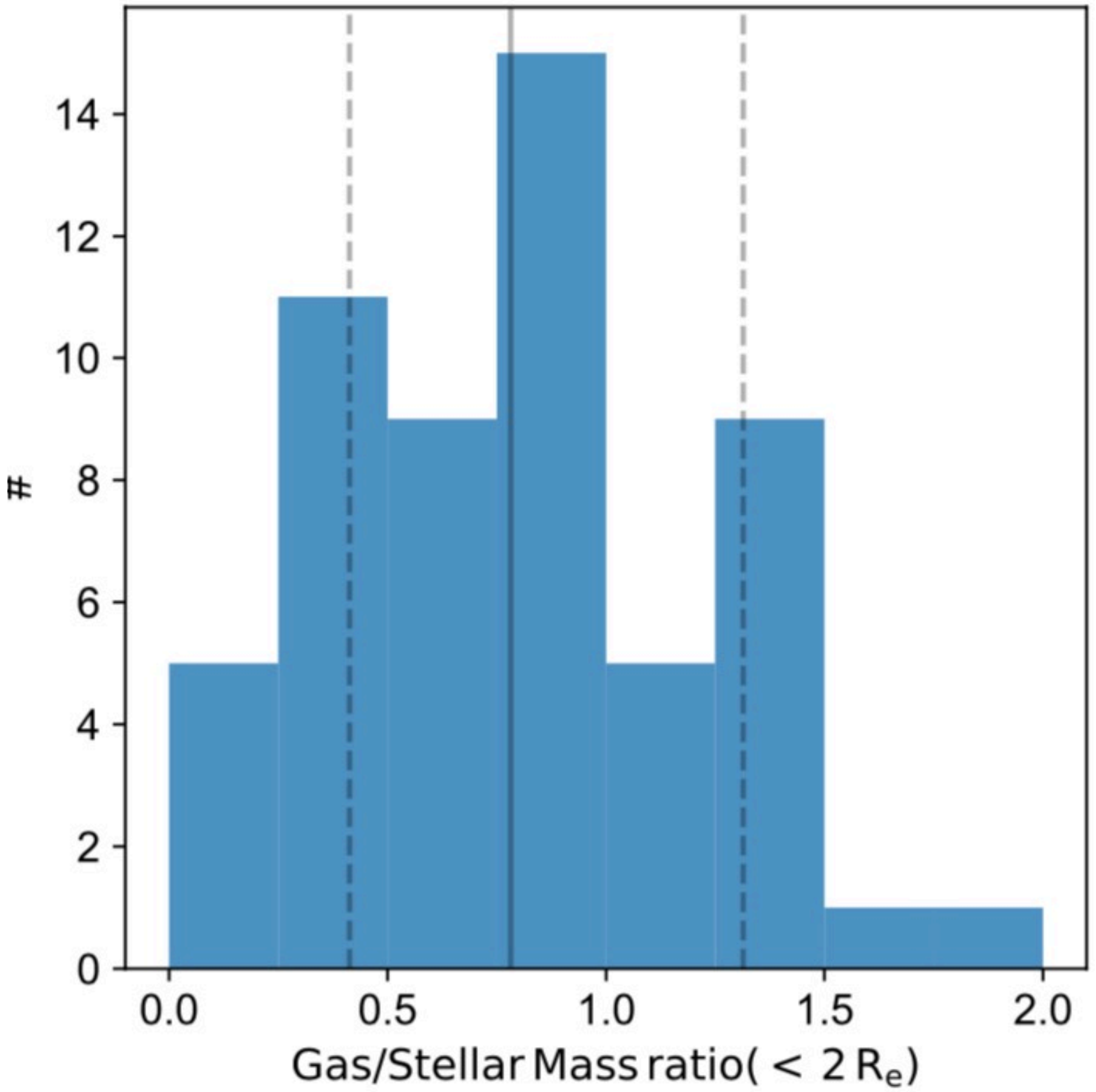



Fig. 2 | M31's large accreted component and high metallicity constrains its dominant merger to have been a single massive, metal-rich galaxy ($10^{10} < M_{Dom}/M_\odot < 5 \times 10^{10}$, $-0.2 < [M/H]_{Dom} < 0.2$) accreted in the last ~5 Gyr. a, **b**, The most massive accreted progenitors of M31 analogues

- We conclude that it is highly likely that M31 suffered **a single large metal-rich accretion event** (**larger than 10^10 M⊙, [M/H] ~–0.1**) in the last 5 Gyr, which contributed the bulk of the material to its accreted stellar component.

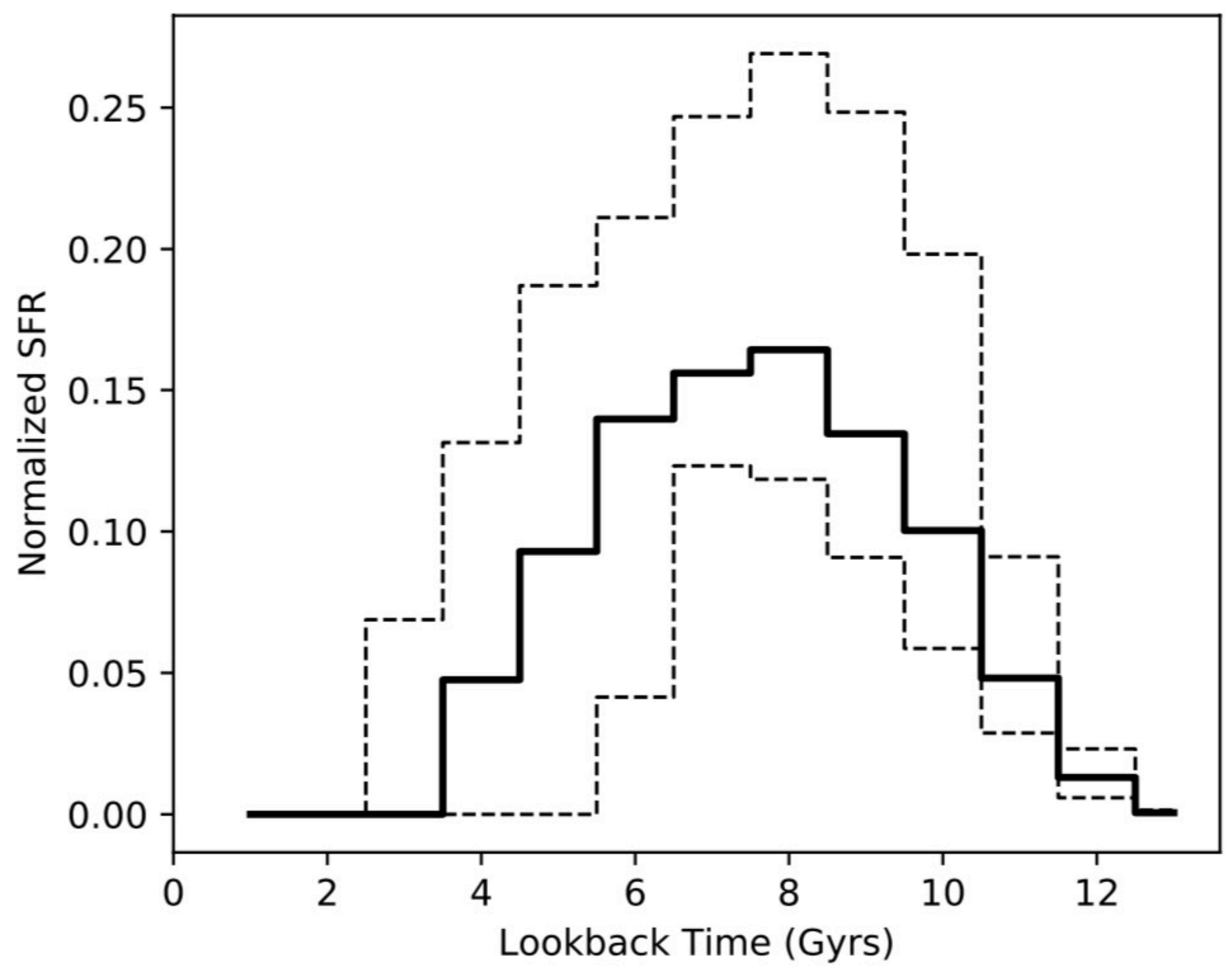
3.1 Properties of the dominant progenitor



Supplementary Fig. 5: The gas-to-stellar mass ratios of the dominant accreted progenitor of Illustris M31 analogues. The gas-to-stellar mass ratios were estimated within a sphere enclosing twice the effective radius when the galaxy had its maximum stellar mass. The solid vertical line indicates the median of the distribution, while the dashed vertical lines indicates the 16 and 84 percentiles of the distribution.

- In the Illustris simulations, the majority of the dominant accreted progenitors of M31 analogues are gas-rich (between 0.4 and 1.3), star-forming, rotating galaxies with pronounced metallicity gradients.
- These galaxies were star-forming when they were accreted and experienced a peak of star formation at z = 1.
- The star formation shuts down gradually from the outskirts to the inner parts of the galaxy around 4 to 6 Gyr ago as the galaxy is being accreted.
- The centre of the galaxy tends to be more metal-rich. The centrally concentrated star formation in these accreted satellites leads to strong star formation history and metallicity gradients.

Properties of the dominant progenitor



Supplementary Fig. 6 The star-formation history of the dominant progenitors of Illustris M31 analogues. The solid black line shows the median star-formation rate of the dominant progenitors of M31 analogues as a function of lookback time, while the dashed lines show the 10 and the 90% percentile of the distribution of star-formation rates.

- In the Illustris simulations, the majority of the dominant accreted progenitors of M31 analogues are gas-rich (between 0.4 and 1.3), star-forming, rotating galaxies with pronounced metallicity gradients.
- These galaxies were star-forming when they were accreted and experienced a peak of star formation at z = 1.
- The star formation shuts down gradually from the outskirts to the inner parts of the galaxy around 4 to 6 Gyr ago as the galaxy is being accreted.
- The centre of the galaxy tends to be younger and more metal-rich. The centrally concentrated star formation in these accreted satellites leads to strong star formation history and metallicity gradients (Supplementary Fig. 7).

he dominant progenitor

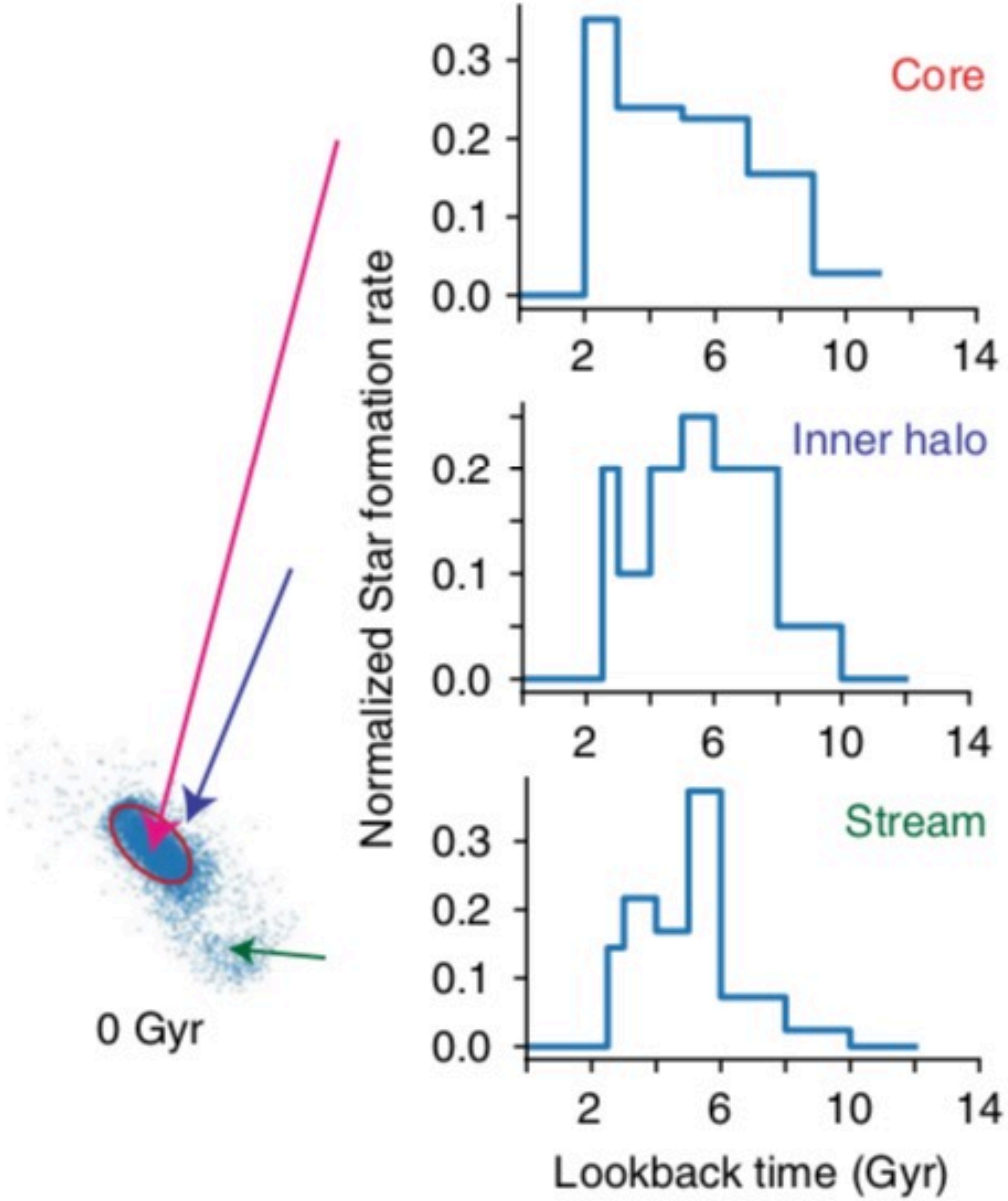


Fig 3.a An example of the tidal disruption of a massive dominant satellite (accompanied by a burst of centrally concentrated star formation) by an M31 analogue in the Illustris simulation. Blue signifies all the stellar particles of the dominant progenitor and orange signifies those particles that experienced star formation in the last 0.5 Gyr. The red ellipse signifies the extent of the present-day inner stellar halo (40 kpc semi-major axis length).

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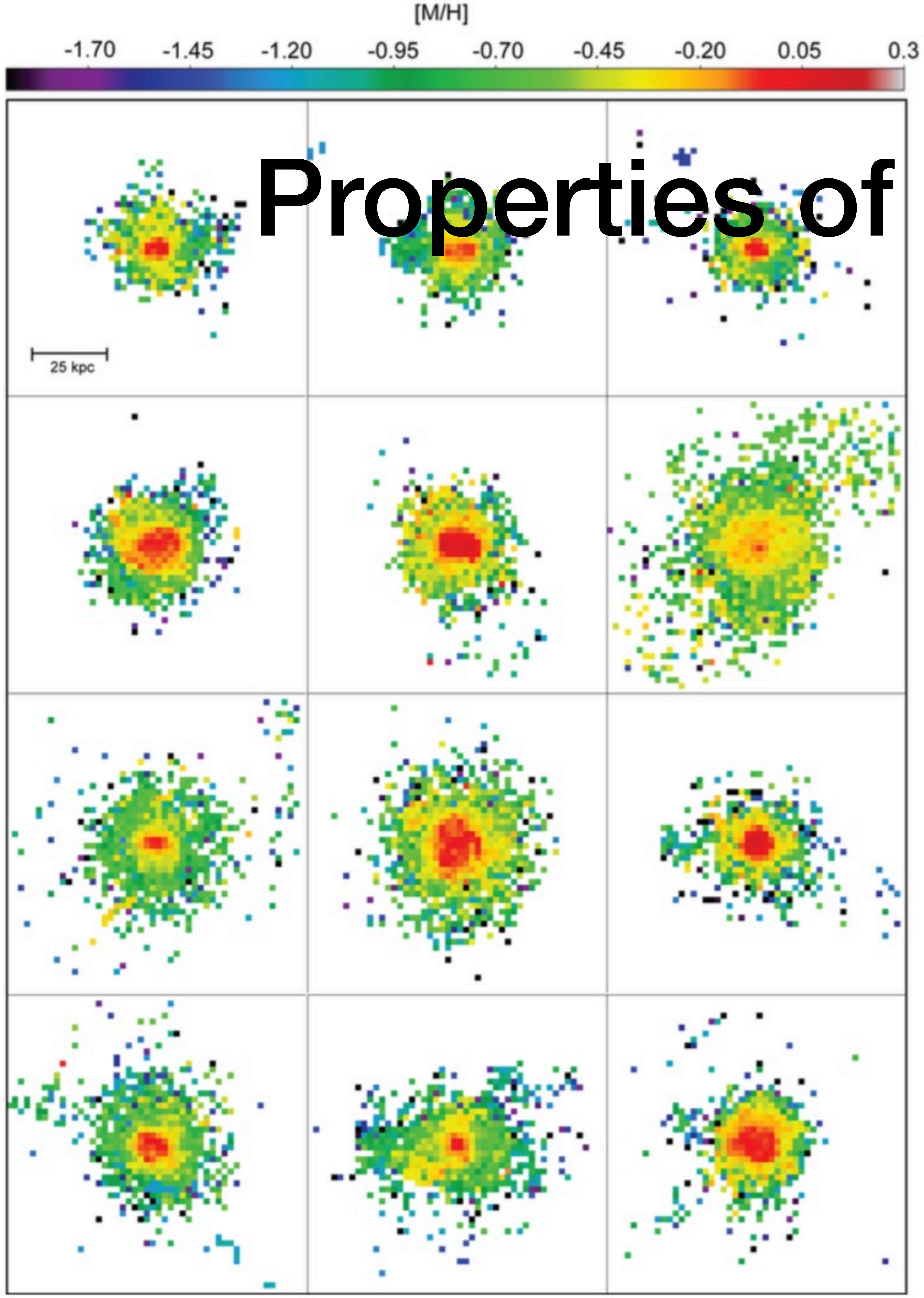
Properties of the dominant progenitor



Supplementary Figure 7: **Metallicity gradients in the dominant accreted progenitors of M31 analogues.** Face-on median metallicity maps of selected dominant accreted satellites which are later accreted by the Illustris M31 analogues.

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- These galaxies were star-forming when they were accreted and experienced a peak of star formation at $z = 1$.
- The star formation shuts down gradually from the outskirts to the inner parts of the galaxy around 4 to 6 Gyr ago as the galaxy is being accreted.
- The centre of the galaxy tends to be more metal-rich. The centrally concentrated star formation in these accreted satellites leads to strong star formation history and metallicity gradients.

3.2 Merger Process

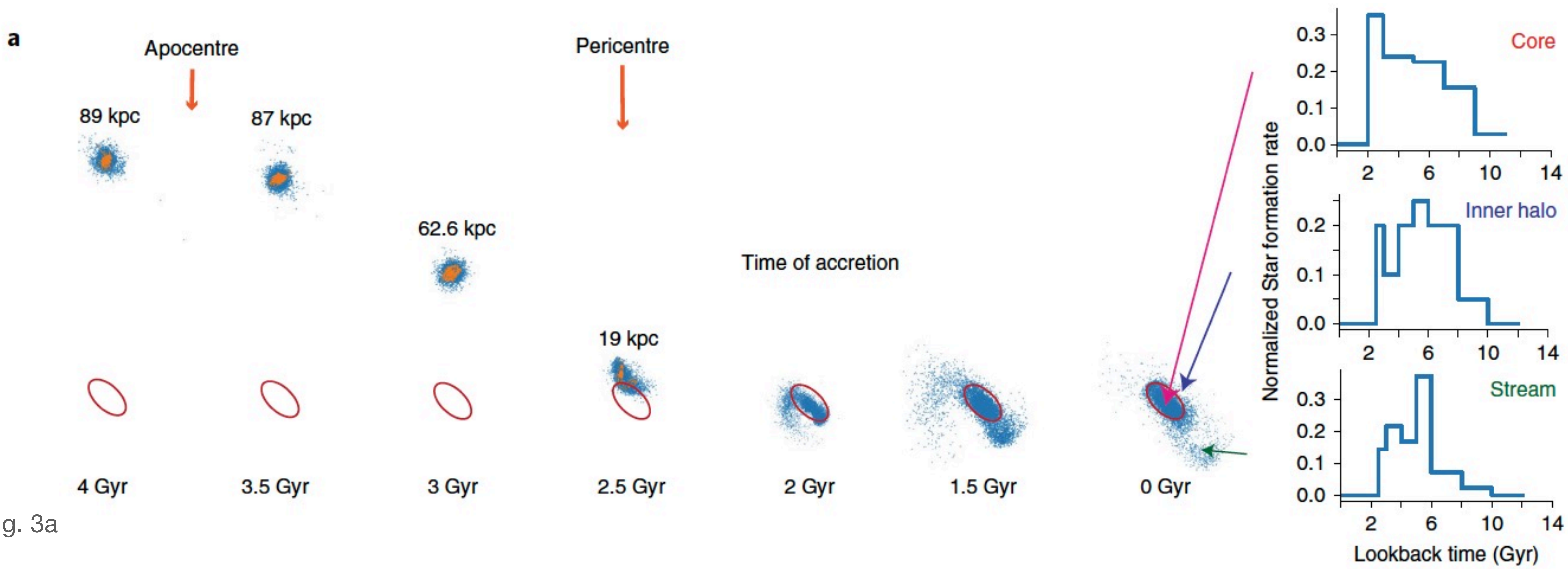


Fig. 3a

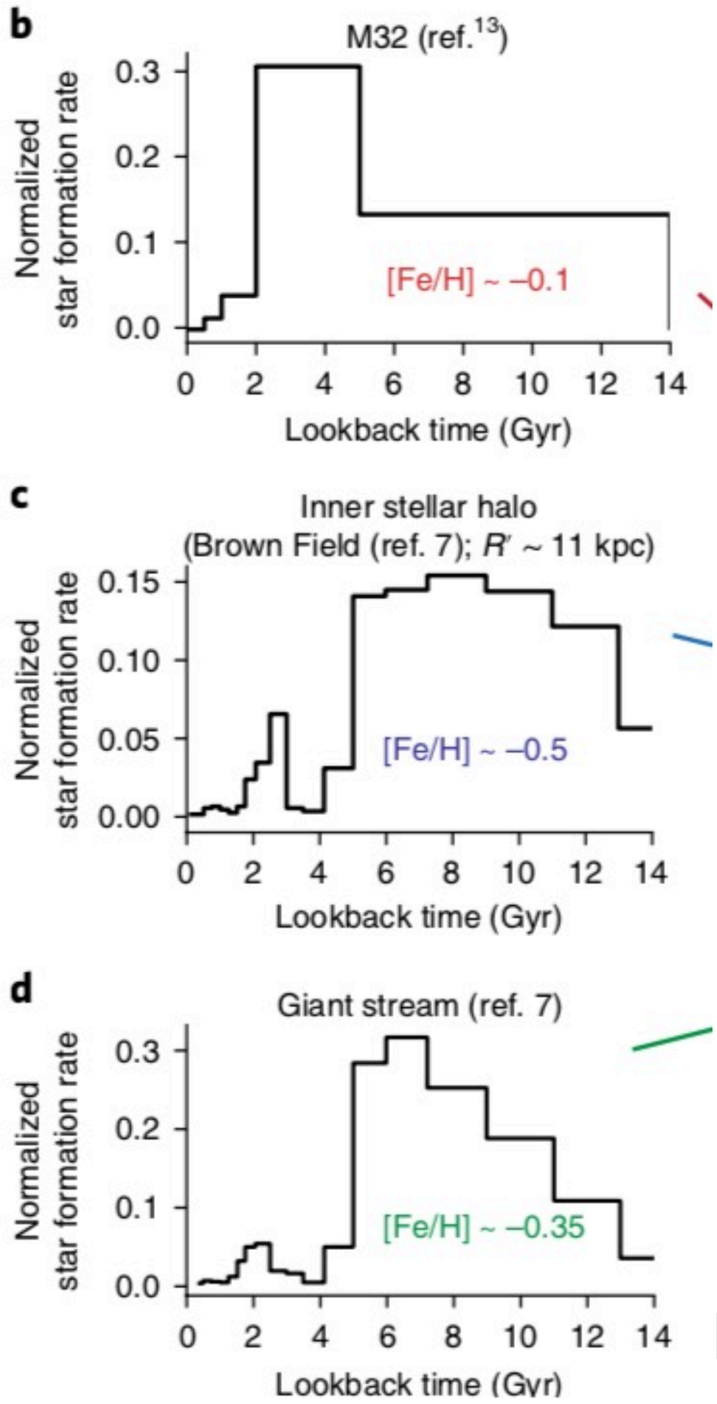
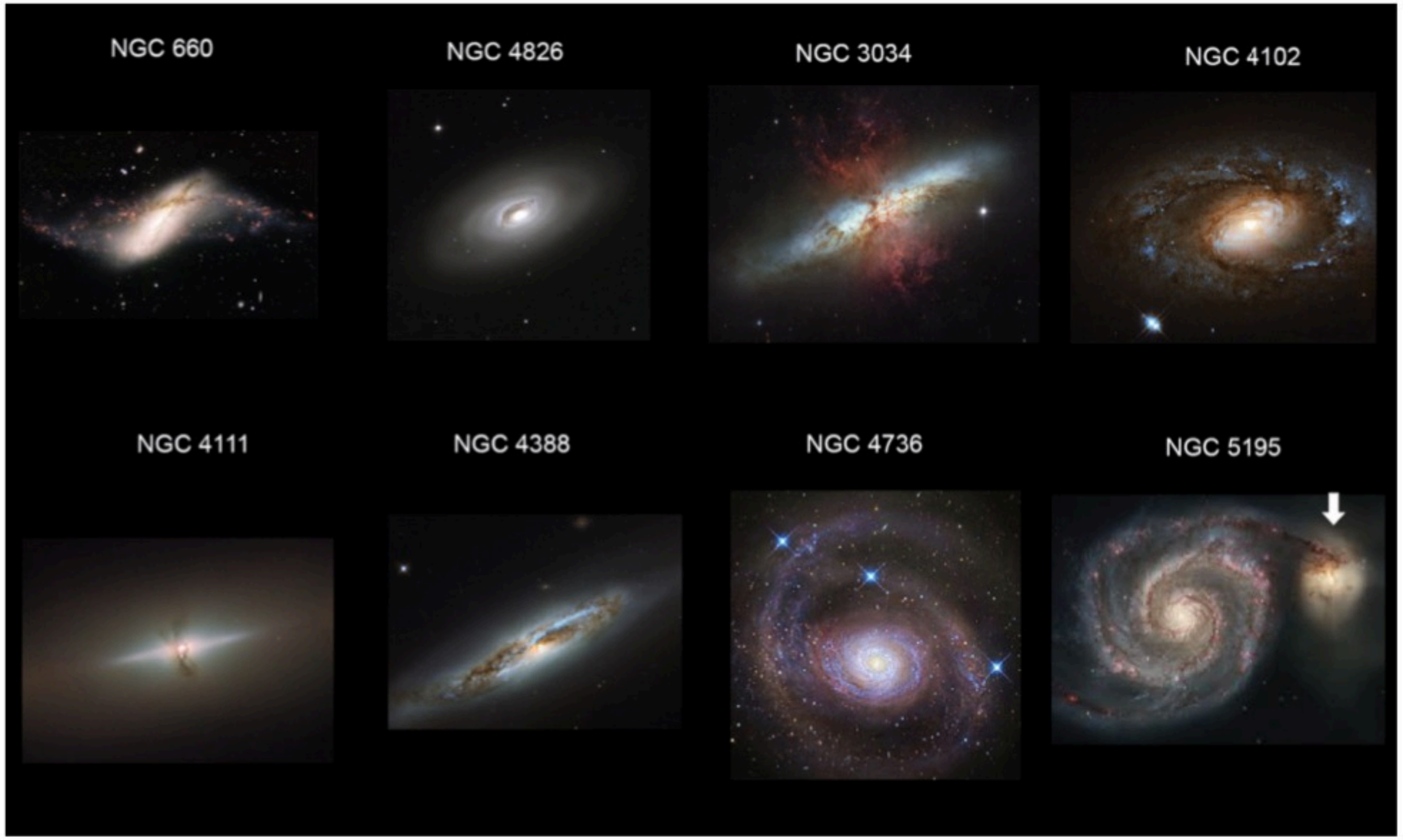


Fig. 1b-d

- We use M31 analogues to illustrate the merger process and identify likely debris, in the hope of further constraining the time of merger and the type of **progenitor**. As the merger progresses, the satellite galaxy is disrupted while experiencing a burst of star formation. The **cessation** in centrally concentrated star formation **occurs shortly before coalescence with the main galaxy**. Most of the satellite is **disrupted** into a structured, but **highly flattened rotating** inner stellar halo with an exponential density profile along the major axis, a R1/4 profile along the minor axis. The debris field is metal-rich. Gradients in the progenitor result in the stellar halo having variations in metallicity by a factor of 10 and time of star formation shut off by>2 Gyr, with the most metal-rich and youngest parts concentrated towards the centre. In most cases, a prominent metal- rich tidal stream is produced.

- The observational features most consistent with the metal-rich debris of M31’s massive accreted progenitor are **M32**, the **inner stellar halo** and **the giant stellar stream**, while excluding the other metal-poor satellites and streams that are expected to be from numerous smaller accretion events. **We hypothesize that all these three metal-rich features stem from M31’s massive accreted progenitor**.

Searching for M32p analogues



Supplementary Figure 13: **M32p analogues selected from the S4G survey**. The images are taken from the public domain. Credits: NGC 660 (Gemini Observatory), NGC 4826 (NOAO/AURA/NSF), NGC 3034, NGC 4012, NGC 4111, NGC 4388 & NGC 5195 (ESA/Hubble & NASA), NGC 4736 (Jay Gabany).

- We selected a M32p analogue from S4G survey
  - Stellar mass, **10.2 < log*M* < 10.6**, and a central surface brightness comparable to M32, surface brightness is **greater than 16** mag arcsec–2 in [3.6] band for R < 100 pc.
  - **8** such M32p analogues (of 115 S4G galaxies), exhibits considerable rotation (Vrot ~150-200 kms–1). Two are currently interacting with larger primary galaxies (NGC 3034/M82 and NGC 5195/M51b), showing that interactions of **M32p-like galaxies** with larger primaries at recent times are **reasonably common**.

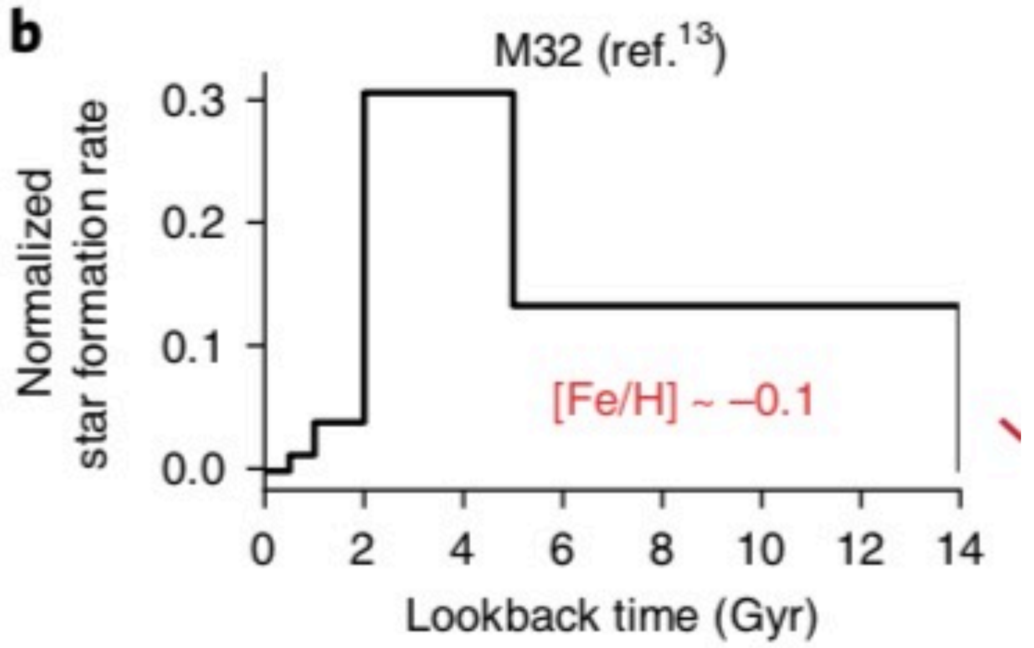


Fig. 1b

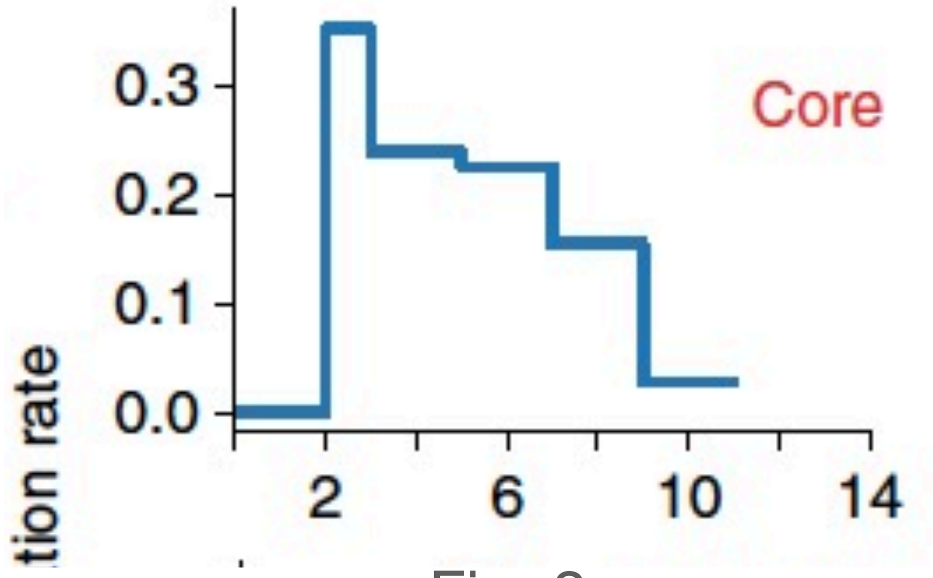


Fig. 3a

- M32 are easily explained if it is the compact core of M31’s massive (~2.5 × 10^10 M⊙) gas- and metal-rich accreted progenitor (**M32p**). M32p is likely to have experienced **a burst of late star formation triggered by gas inflow to the centre of the galaxy as it was being accreted**, similar to the observed star formation experienced by **M32 ~2–5 Gyr** ago (Fig. 1).

- M32’s relatively low-mass central black hole implies that M32p originally likely had **a low-mass bulge.** Such a small bulge would have experienced **little dynamical friction**, consistent with M32 not sinking to the centre of M31.

  - If M32 is indeed the core of the massive accreted progenitor of M31, then the timing of the starburst allows us to approximately date the interaction: **M32p possibly started interacting with M31 approximately 5 Gyr ago and its disruption continued until around 2 Gyr ago.**

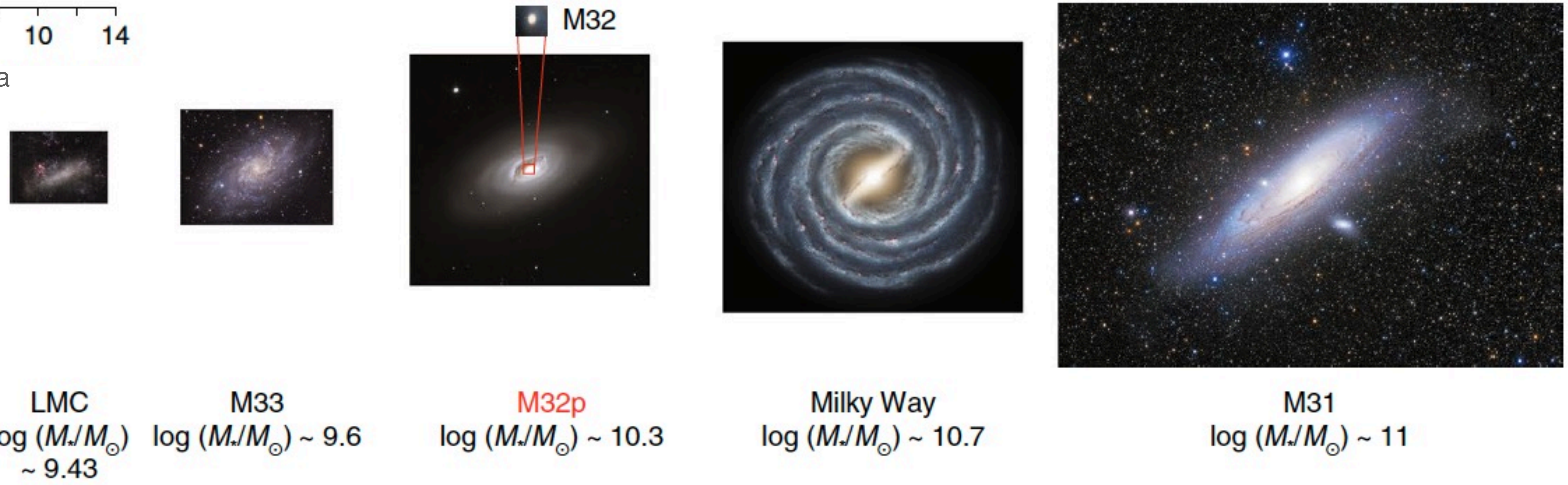


Fig. 4 | M32p, the most massive progenitor accreted by M31, was the third largest member of the Local Group. We compare M32p with the largest present-day members of the Local Group: LMC, M33, Milky Way and M31. We represent M32p using an analogue in the local universe M64. We find a total of eight M32p analogues out to a volume of ~24 Mpc (Supplementary Fig. 13). The Milky Way is shown using an artist’s representation. Credit: LMC,

4.1 Discussion on M32

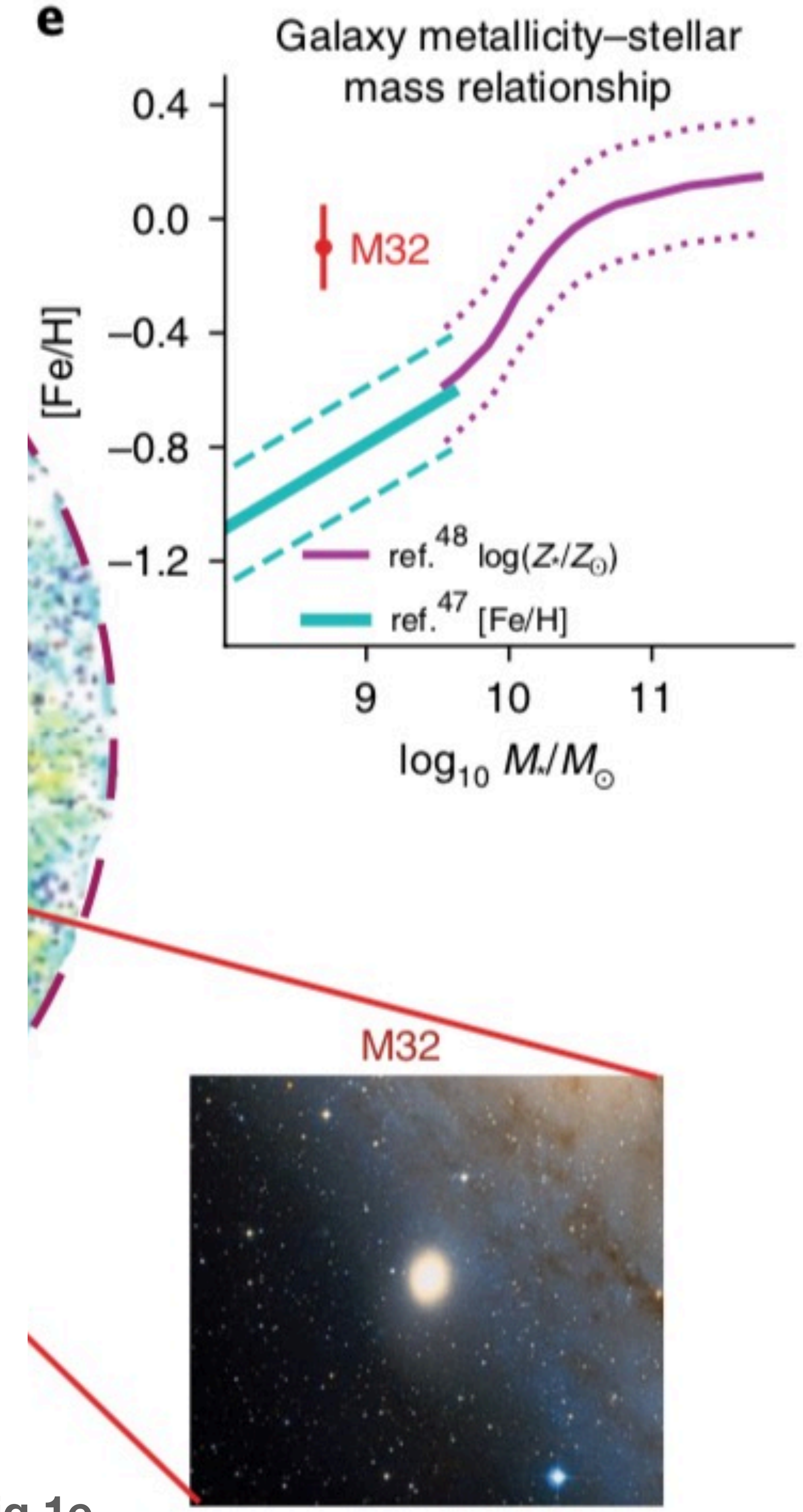


Fig 1e

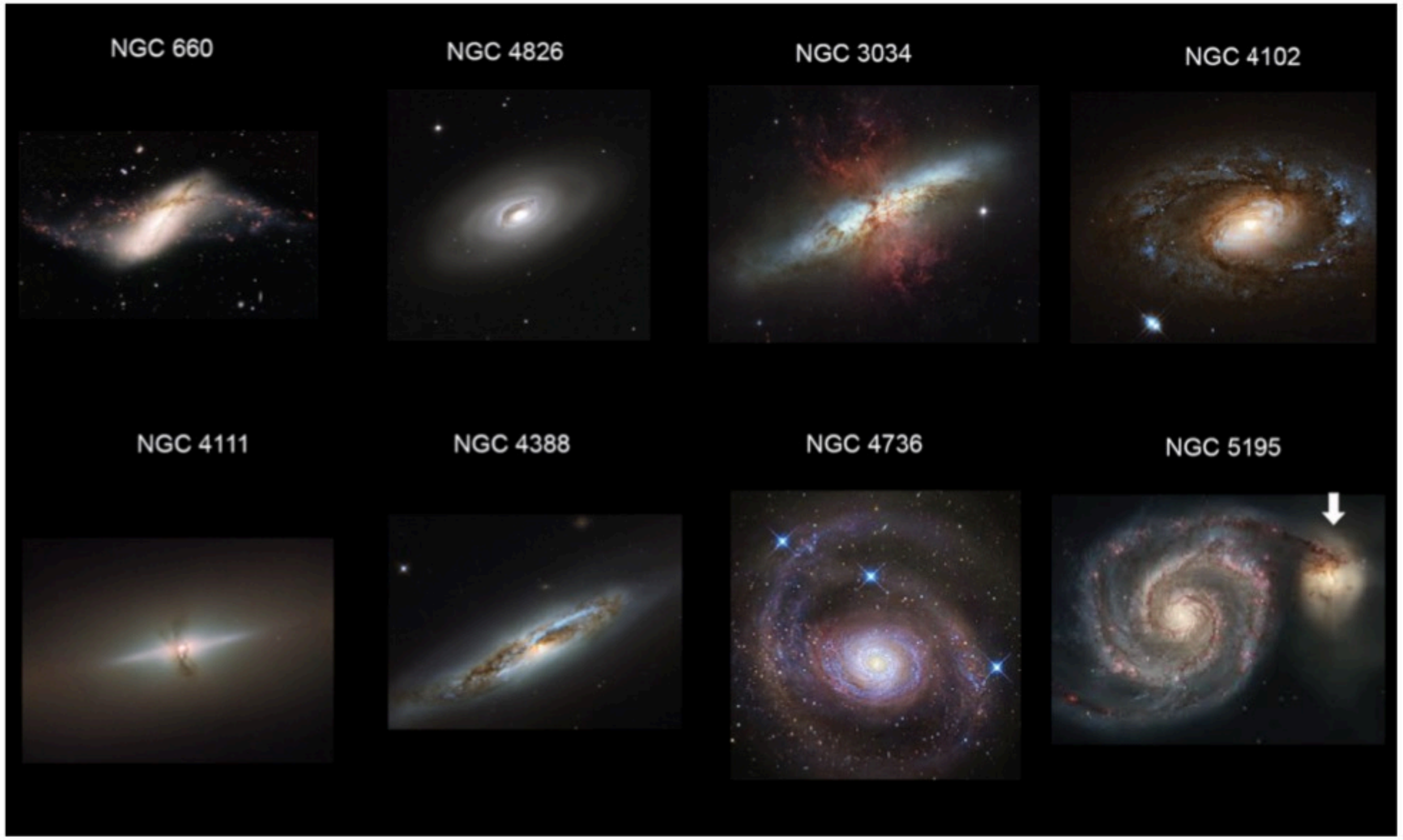
- Our formation scenario for M32 impacts the debate about its origin. Compact elliptical galaxies (~10^9 M⊙) are believed to be the **stripped cores of previously more massive galaxies**. Yet, it has also been suggested that compact ellipticals might have formed in **a starburst followed by a violent collapse, with no stripping involved**. We suggest that the evidence proposed for an intrinsic origin of M32 is ambiguous. M32's absence of tidal features can be easily explained if it is **the compact dense core of M32p** allowing it to resist further stripping. Built up from the small bulge of its progenitor, M32 naturally obeys the structural scaling relations of classical bulges and ellipticals. Evidence of tangential anisotropy in M32's outer velocity dispersion is consistent with the preferential tidal stripping of its stars. While M31–M32 interaction models designed to reproduce M31's long-lived 10kpc star-forming ring have been used to support M32's intrinsic origins, major-merger simulations can also reproduce M31's star-forming ring.

- In contrast, **M32's unique properties make it stand out among other compact ellipticals and strongly suggest a stripped origin for at least M32.** M32 has the smallest size among all known compact ellipticals. Not only does its extended star formation history and starburst 2–4 Gyr ago rule out an intrinsic formation at a higher redshift, but these properties are also predicted by models that tidally strip gas-rich progenitors with compact cores21. M32 has a very high metallicity for its stellar mass, suggesting it was once much more massive. Our work advances this debate in two primary ways.

  - First, we suggest that **M31's stellar halo is the reservoir of much of M32's stripped material** and provides decisive guidance to constrainits formation history.

  - Second, we find that the rarity of **M32-like objects** in the local Universe is set by the **number density** of M32p analogues convolved with their merger rate since redshift z ~2.

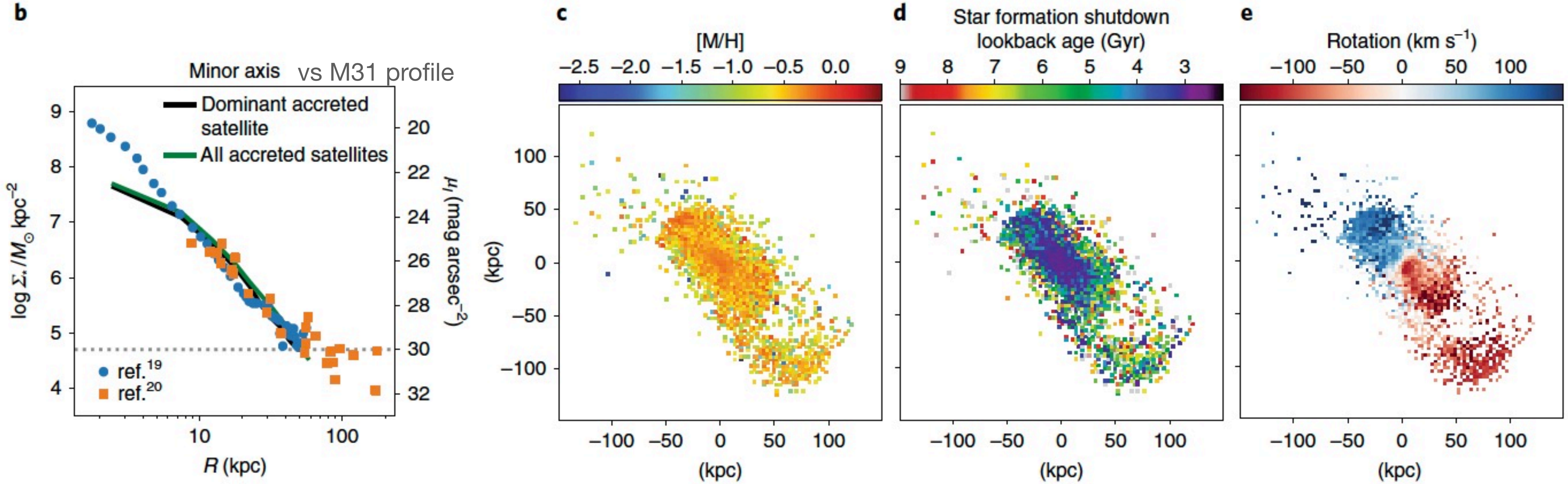
Number density of M32p analogues/M32



Supplementary Figure 13: M32p analogues selected from the S4G survey. The images are taken from the public domain. Credits: NGC 660 (Gemini Observatory), NGC 4826 (NOAO/AURA/NSF), NGC 3034, NGC 4012, NGC 4111, NGC 4388 & NGC 5195 (ESA/Hubble & NASA), NGC 4736 (Jay Gabany).

- We selected a M32p analogue from S4G survey
    - Stellar mass, $10.2 < \log M < 10.6$, and a central surface brightness comparable to M32, surface brightness is greater than 16 mag arcsec–2 in [3.6] band for R < 100 pc.
    - 8 such M32p analogues (of 115 S4G galaxies), exhibits considerable rotation (Vrot ~150-200 kms–1). Two are currently interacting with larger primary galaxies (NGC 3034/M82 and NGC 5195/M51b), showing that **interactions** of **M32p-like galaxies** with larger primaries at recent times are **reasonably common**.
- Number density of M32p analogues in this volume
    - Two known M32-like galaxies out to ~24 Mpc: M32 and NGC4486B, in the volume out to ~24 Mpc was 10.
    - M32p analogues in this volume is **$\log_{10}[N_{M32p}\,(\mathrm{Mpc}^{3})] = -3.5+/-0.316$**
    - M32-like galaxies in the same volume is **$\log_{10}[N_{M32p}\,(\mathrm{Mpc}^{3})] = -4.2+/-0.7$**
    - The **major-merger rate of galaxies of mass log(M*) > 10.0** is ~ **0.1** since z ~2. Hence, the number of M32-like galaxies in the local Universe (~24 Mpc) is consistent with number density of M32p analogues, suggesting that **number density of M32p analogues** (mid-mass galaxies with a high central surface density) **dictates the rarity of M32-like objects** in the local Universe.

4.2 Discussion on the stellar halo



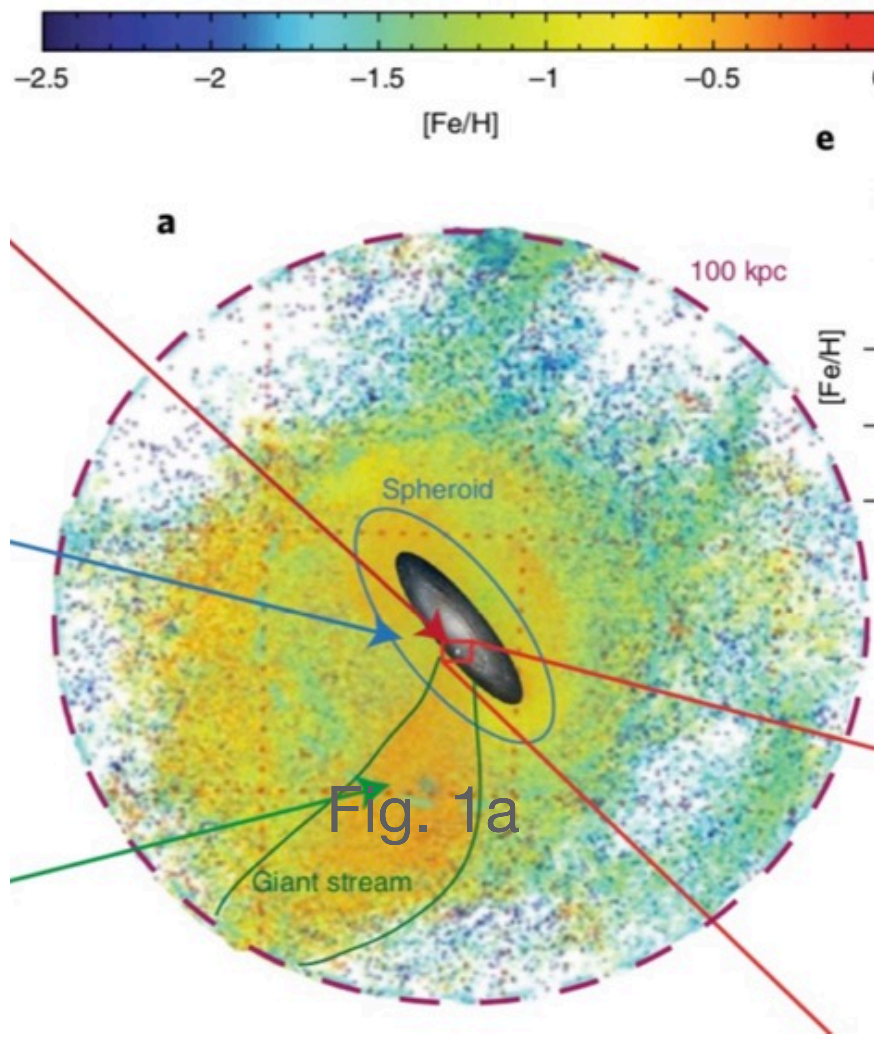


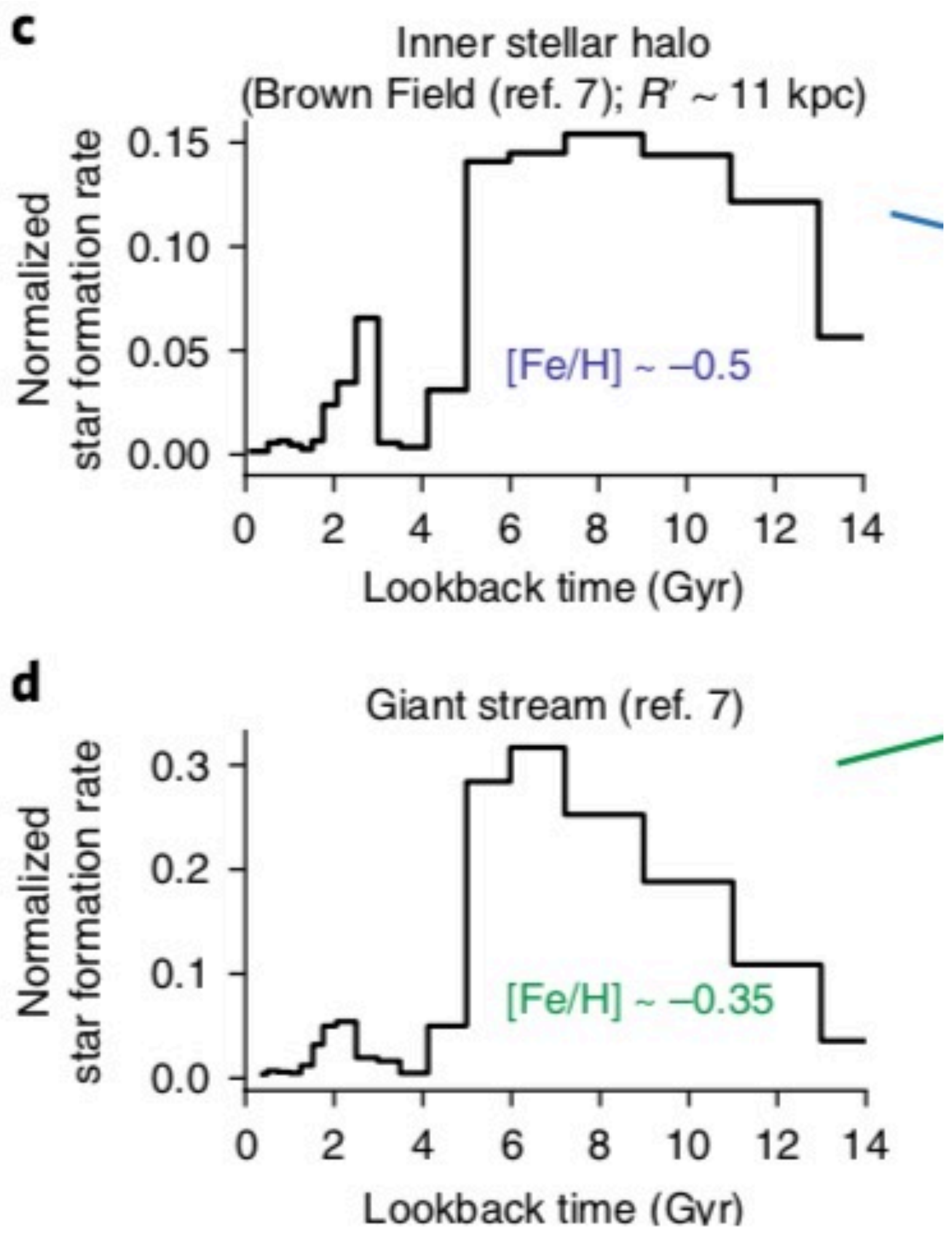
Fig. 1a

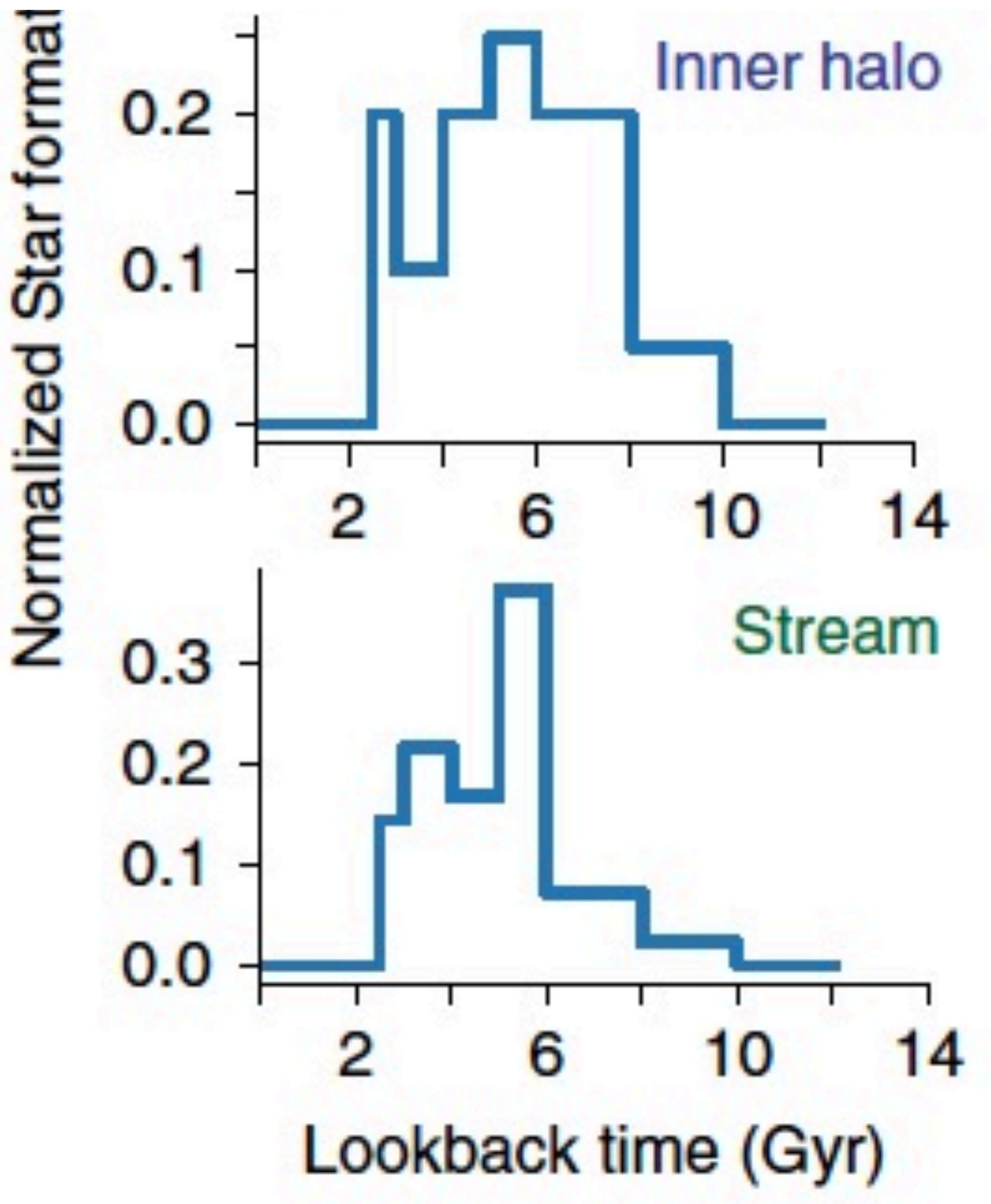
Fig. 3 | The disruption of the most massive progenitor results in a debris field similar to the stellar halo of M31. a, We show an example of the tidal

- M32p’s tidally stripped, centrally concentrated debris shares many of the properties of M31’s metal-rich inner stellar halo, including its flattened spheroidal nature, its disk-like rotation, the presence of intermediate-age stars and some of its stellar population variations.

- While stellar population studies suggest that the **inner halo** is a **mixture** of **disk** and **accreted material**, **M32p’s debris** dominates the minor axis density profile of M31 from a projected distance of **~8 kpc out to 25 kpc**, suggesting that the inner stellar halo in this radial range is built up primarily by the debris of M32p.

4.3 Discussion on the Giant Stream





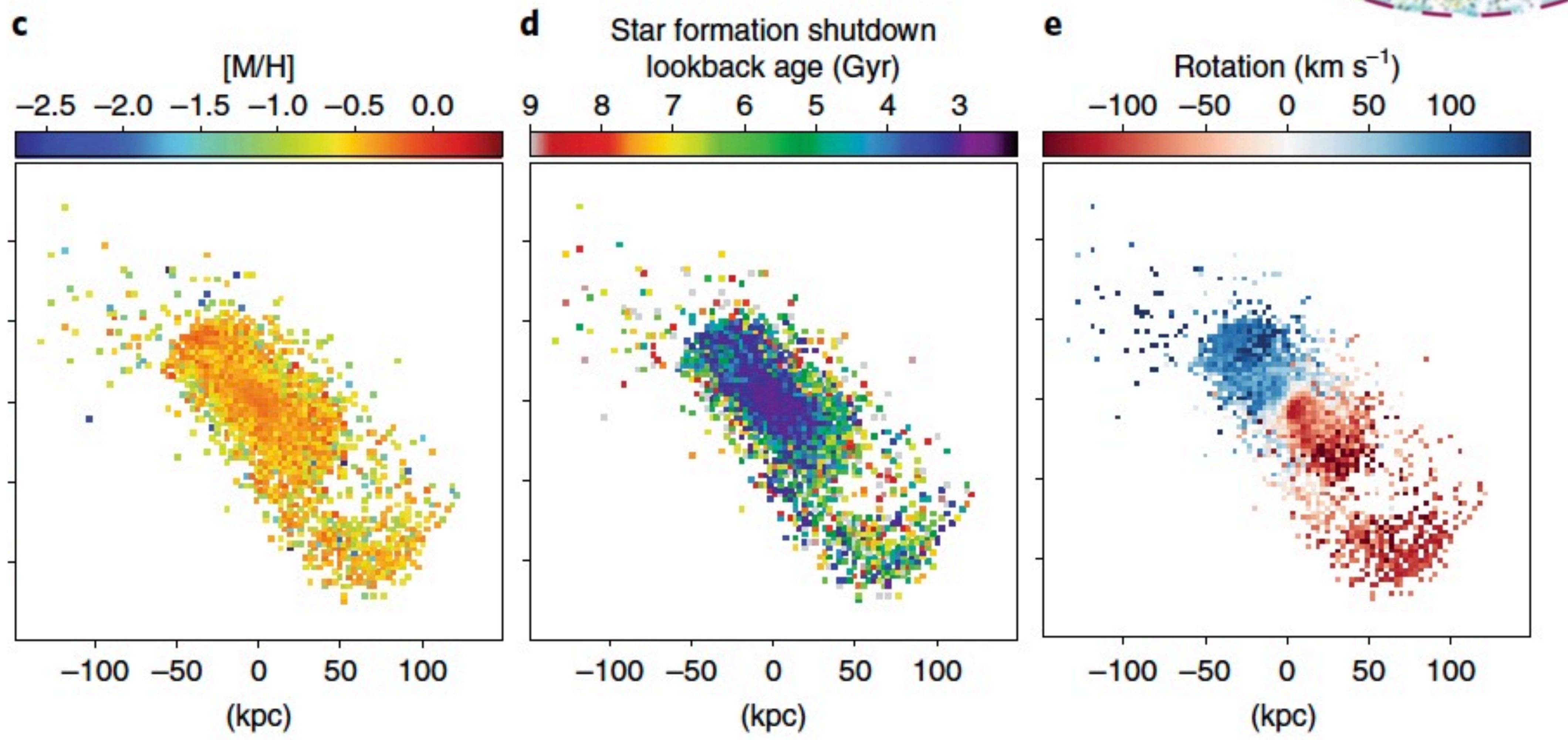
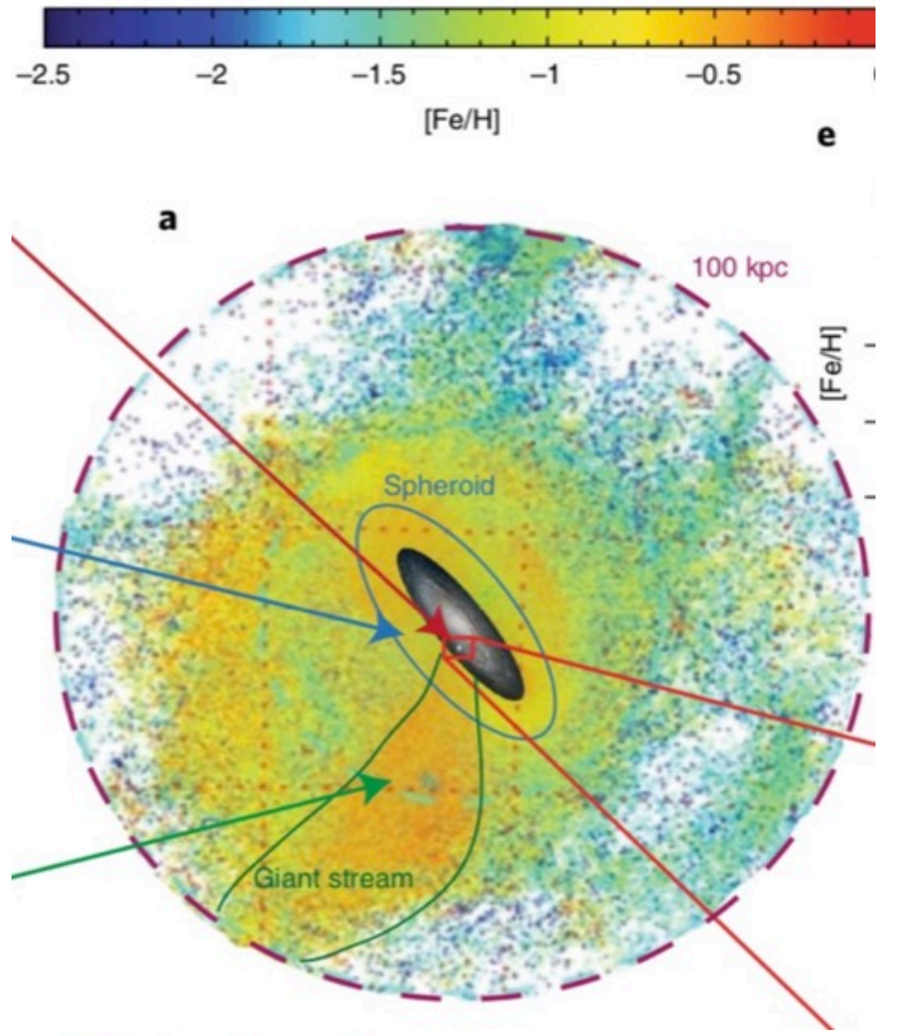
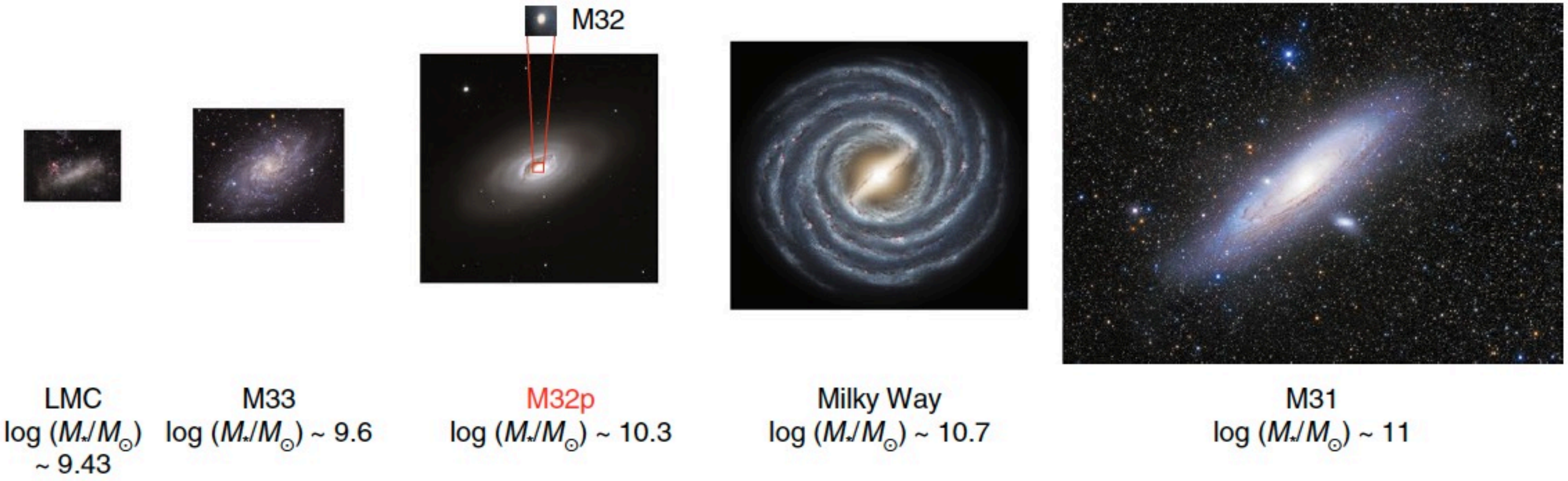


Fig. 1a



- Since large metal-rich tidal streams are frequently produced by the most-massive satellite, we suggest that it is likely that the giant stream is from **M32p's tidal disruption**. The **similarity** in **stellar populations** between the giant stream and the inner stellar halo as well as the **synchronous star formation burst ~2 Gyr ago evident** in the high-metallicity accreted populations of the giant stream, the inner stellar halo and M32, dramatically increase the probability of this association. If so, then the giant stream offers the potential to constrain the orbit of M32p.

- If the giant stream stems from M32p, then M32's position and line-of-sight velocity should be consistent with the forward orbit of the stream's progenitor. **Uncertainties** in distances and the nature of the stream's progenitor make it **challenging to model the progenitor's orbit**, and a progenitor has not been found. Despite these uncertainties, there is strong evidence that the northeastern and western shelves trace out the stream's for- ward orbit. **M32** is consistent with the positional and radial velocity constraints of these shelves, and thus could be **the core of the giant stream's progenitor.** This proposition can be tested using future measures of M32's proper motion, coupled with future models of the stream that incorporate suitable priors on the progenitor's mass, rotation and central density.



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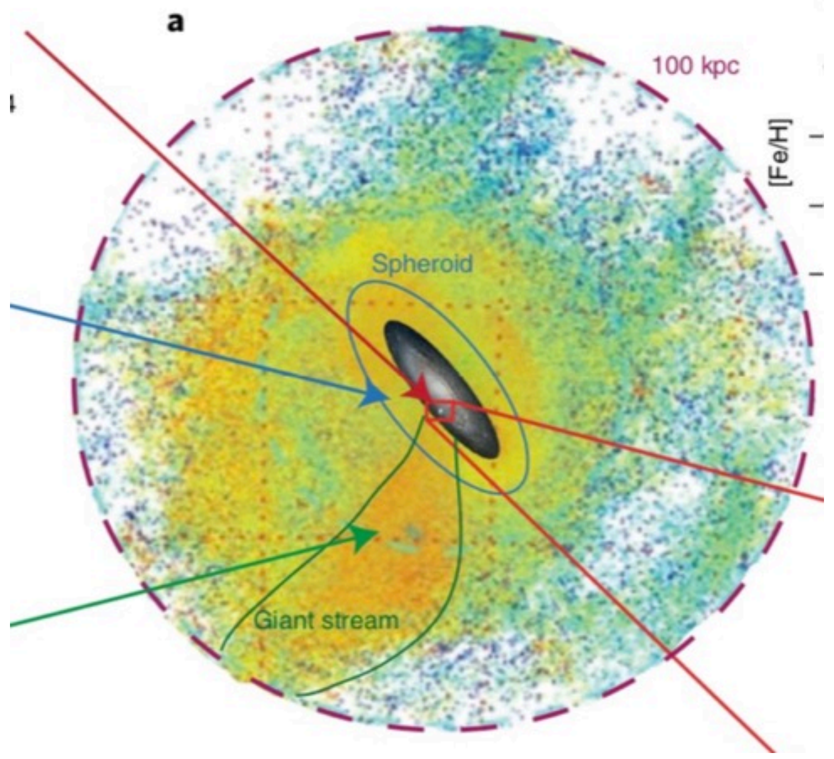
- Our inferences about M32p, the third largest member of the Local Group, give further weight to recent attempts to use the steep age–velocity dispersion relationship of M31's disk to constrain the accretion of a recent (1.8–3 Gyr) massive progenitor (1:4). These major-merger simulations also reproduce the general properties of the giant stream.

- However, these simulations assume that M31's bulge and bar were also created by this merger, and consequently the nuclei of the two galaxies are forced to coalesce. Not only have we enriched this picture by suggesting that the core of that massive accreted progenitor survived to the present day as the metal-rich compact M32, and consequently did not form M31's bulge and bar, but we have also provided direct unambiguous evi- dence of this recent major merger from M31's stellar halo.



5. Summary

- Here we use cosmological models of galaxy formation to show that M31’s massive and metal-rich **stellar halo**, containing intermediate-age stars, dramatically **narrows the range of allowed interactions**, requiring **a single dominant merger** with **a large galaxy** (~ 2.5 × 10^10 M☉ ~ 3rd largest member of the Local Group) about 2 Gyrs ago.

- M31’s compact and metal-rich satellite **M32** is likely to be **the stripped core of the disrupted galaxy,** its rotating inner stellar halo contains most of the merger debris, and the **giant stellar stream** is likely to have been thrown out during the merger.

- M31’s global burst of **star formation** about **2 Gyr ago** in which approximately **1/5 of its stars were formed**. Moreover, M31’s disk and bulge were already in place, suggesting that **mergers of this magnitude need not dramatically affect galaxy structure.**
  - First, because M31’s disk pre-dates the interaction with M32p, M31’s disk survived a merger with mass ratio between ~0.1 and ~0.3.
  - Second, as demonstrated by recent simulations, this major merger may be responsible for the thickening of M31’s disk to its present scale height of ~1 kpc as well as the steepness of its stellar age–velocity dispersion relationship.
  - Third, If indeed this episode is associated with M32p's merger with M31, this provides the first empirical measurement of the lifecycle effects of such a merger.
  - Finally, large bulges such as M31’s have been suggested to have been made in galaxy mergers. Yet, M31 had already formed its bulge stars >6 Gyr ago, long before M31’s merger with M32p.