Decoding Galaxy Assembly with Andromeda

II. The Last Significant Merger: N-body and Cosmological Models and the Disk's Response

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XII LAPIS 2026: Local Volume Cosmology
Universidad Nacional de La Plata
October 21, 2026



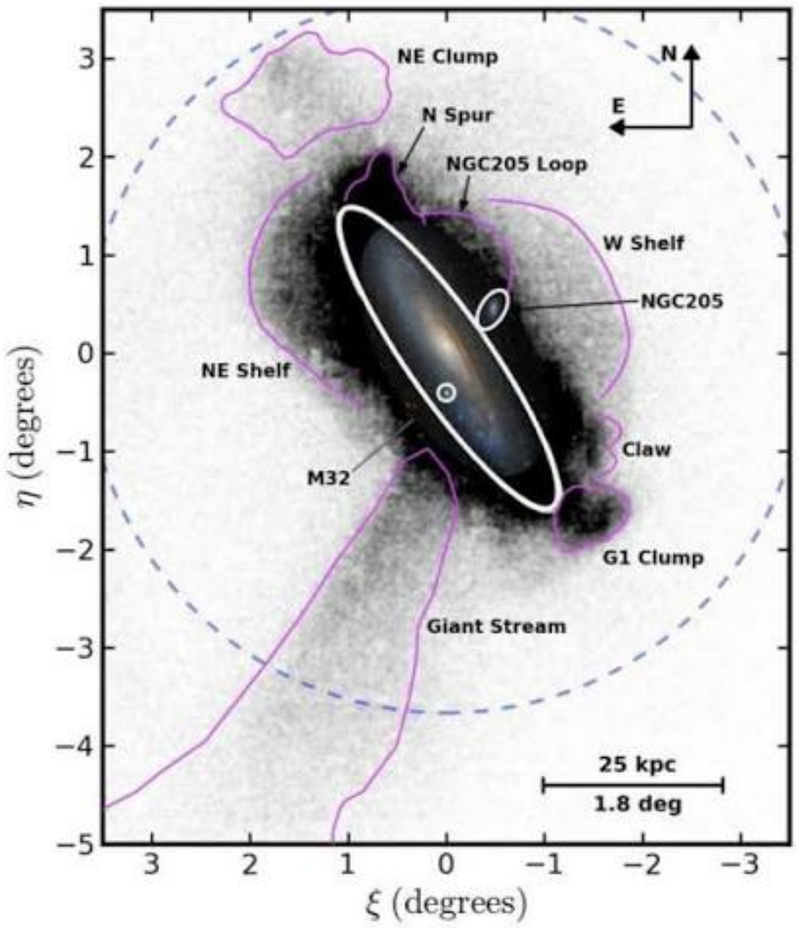
Image credit: Francois Hammer

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Outline

- Tidal-system recap
- The minor-merger paradigm
  - N-body models
  - Tidal shells
- Observed properties of the disk
  - Star formation history
  - Kinematics and spatial structure
- Major-merger scenarios
  - Cosmological models
  - The role of M32
  - Observational constraints
- Synthesis and summary

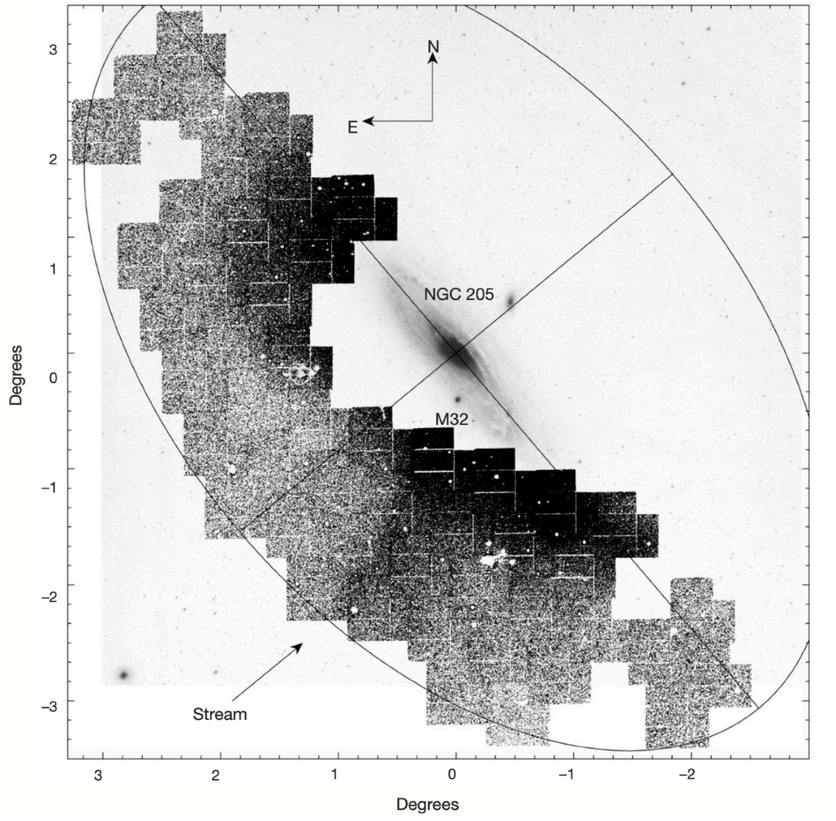
The Giant Stellar Stream and tidal shell system of M31 suggest it experienced a recently active merger history

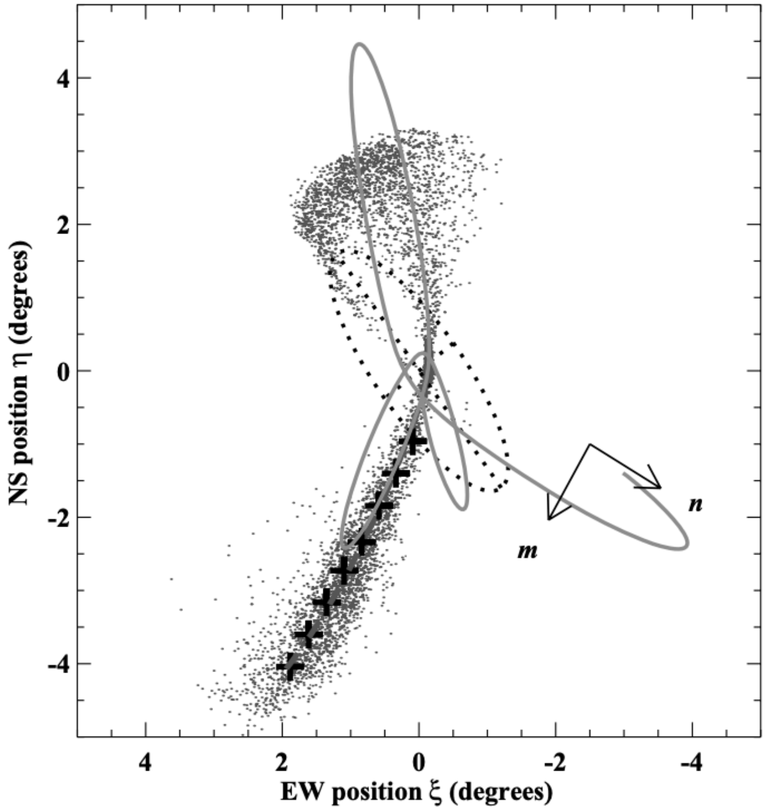


- Models of the last significant merger attempt to reproduce these features (GSS, NE shelf, SE shelf, W shelf)
- *What was the mass of the progenitor, and the timing of the merger event?*
- Halo debris provides a clock for dynamical age

Image credit: D. Mackey & A. Ferguson
e.g., Ibata+01,07,14; Ferguson+02,05; Gilbert+07; Fardal+07; Richardson+08; McConnachie+03,09,18

The discovery of the Giant Stellar Stream served as the first indication of a recent massive merger event

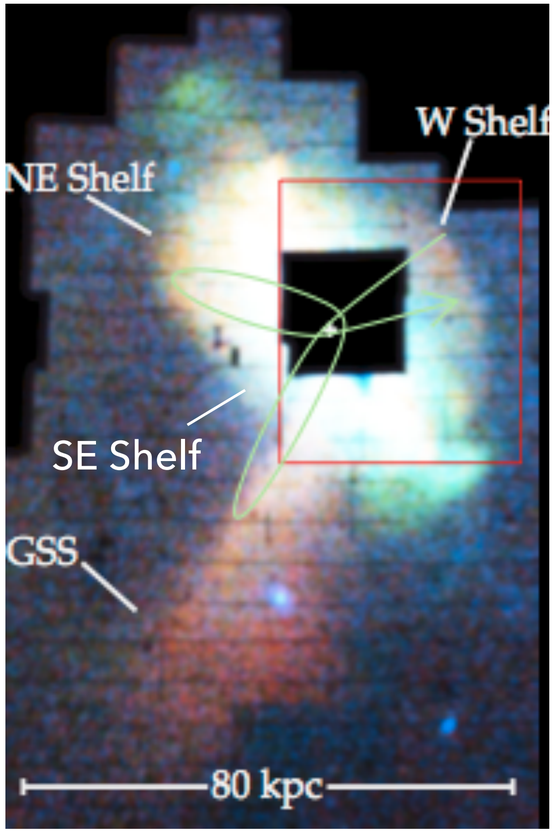


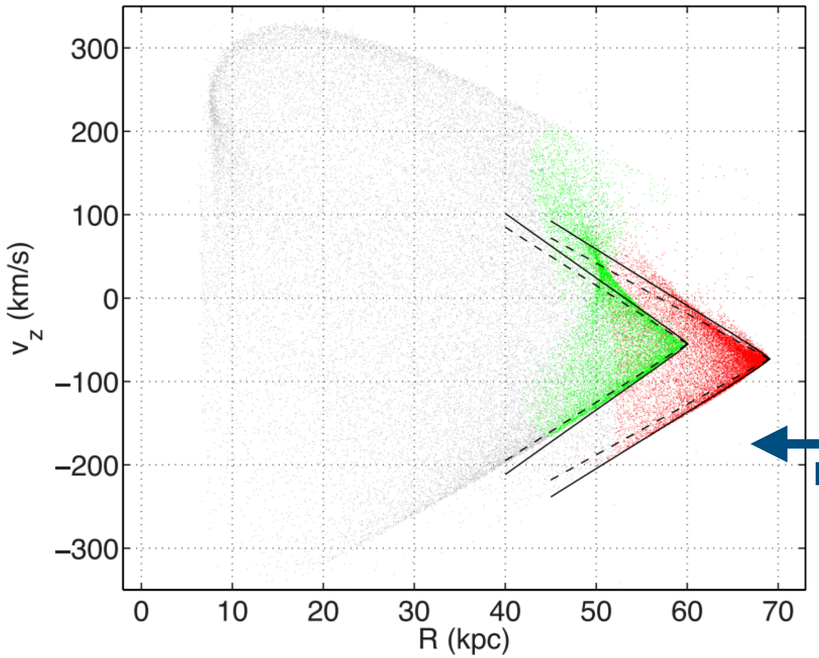


- M32 (and NGC 205) initially proposed as the progenitor
- Spans >100 kpc in LOS distance and >6 deg on the sky
- Highly radial orbit, <1 Gyr disruption, lower stellar mass limit of 10^8 Msun (likely 10^9 Msun)

Image credit: R. Ibata (01) & M. Fardal (06)
e.g., McConnachie+03; Ibata+04; Font+06; Fardal+06; Conn+16

The presence of stellar shelves in M31 suggests young tidal shells formed from successive orbital wraps in a radial merger





Projection

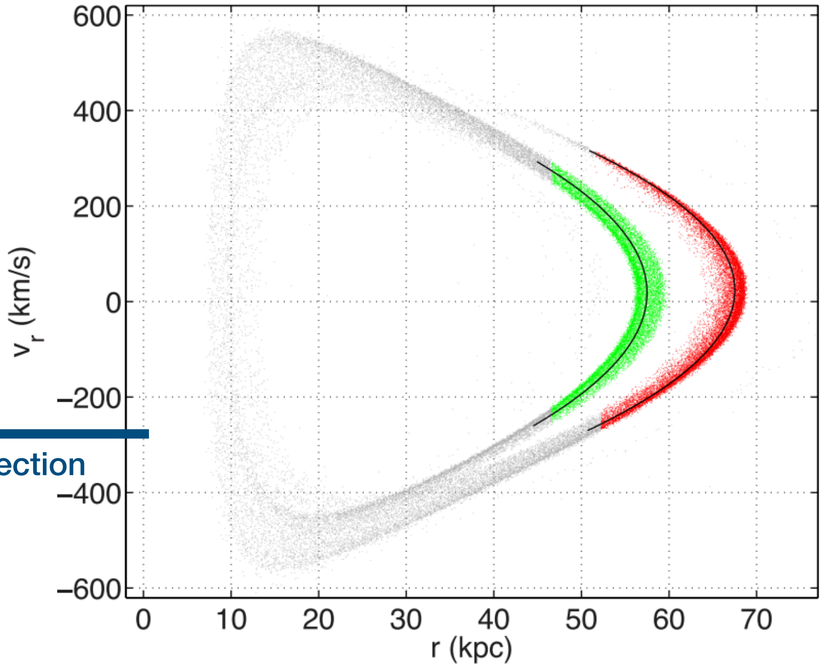
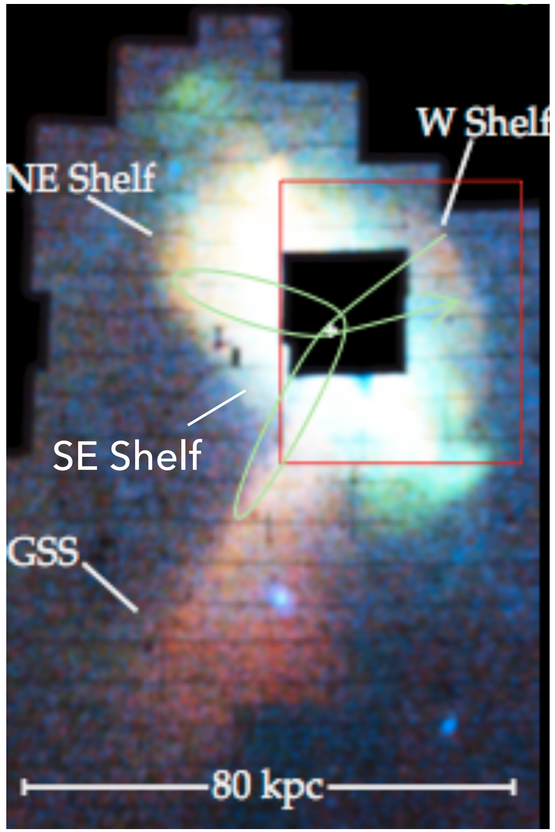


Image credit: Fardal+12, Sanderson & Helmi 2013

e.g., Quinn 1984; Merrifield & Kuijken 1998; Hernquist & Quinn 1998, 1999: Sanderson & Bertschinger+10; Ebrova+12; Hendel & Johnston 2015

Matching kinematics (and metal-rich stars) across the shells and streams point to a single massive accretion event



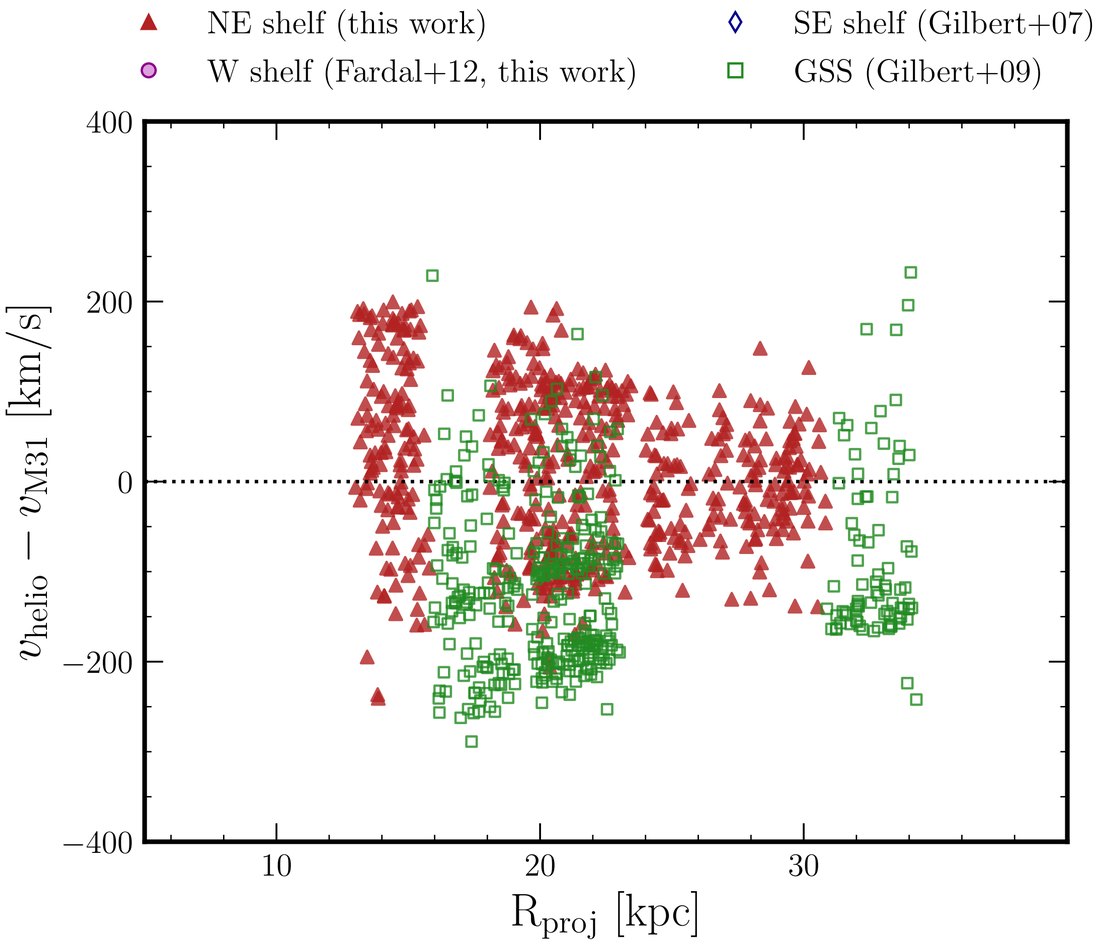
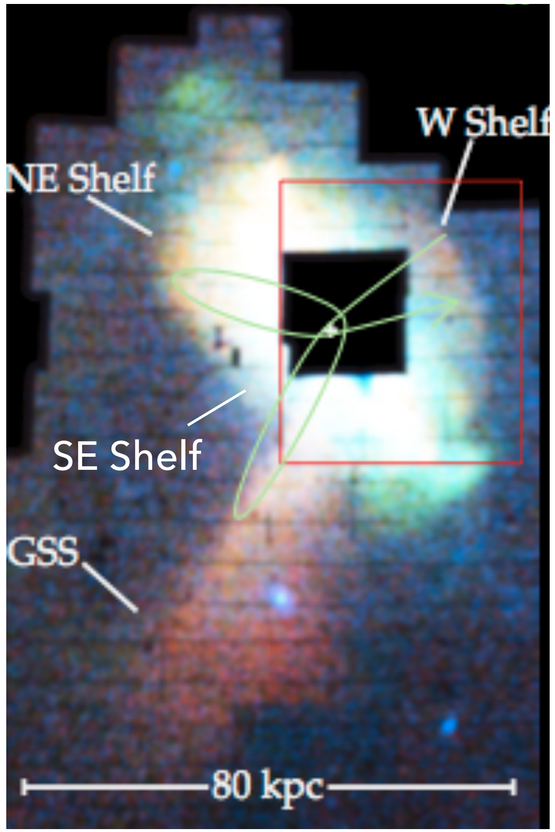


Image credit: Fardal+12 (left), Escala+22 (right)
See also Gilbert+07,09; Fardal+07

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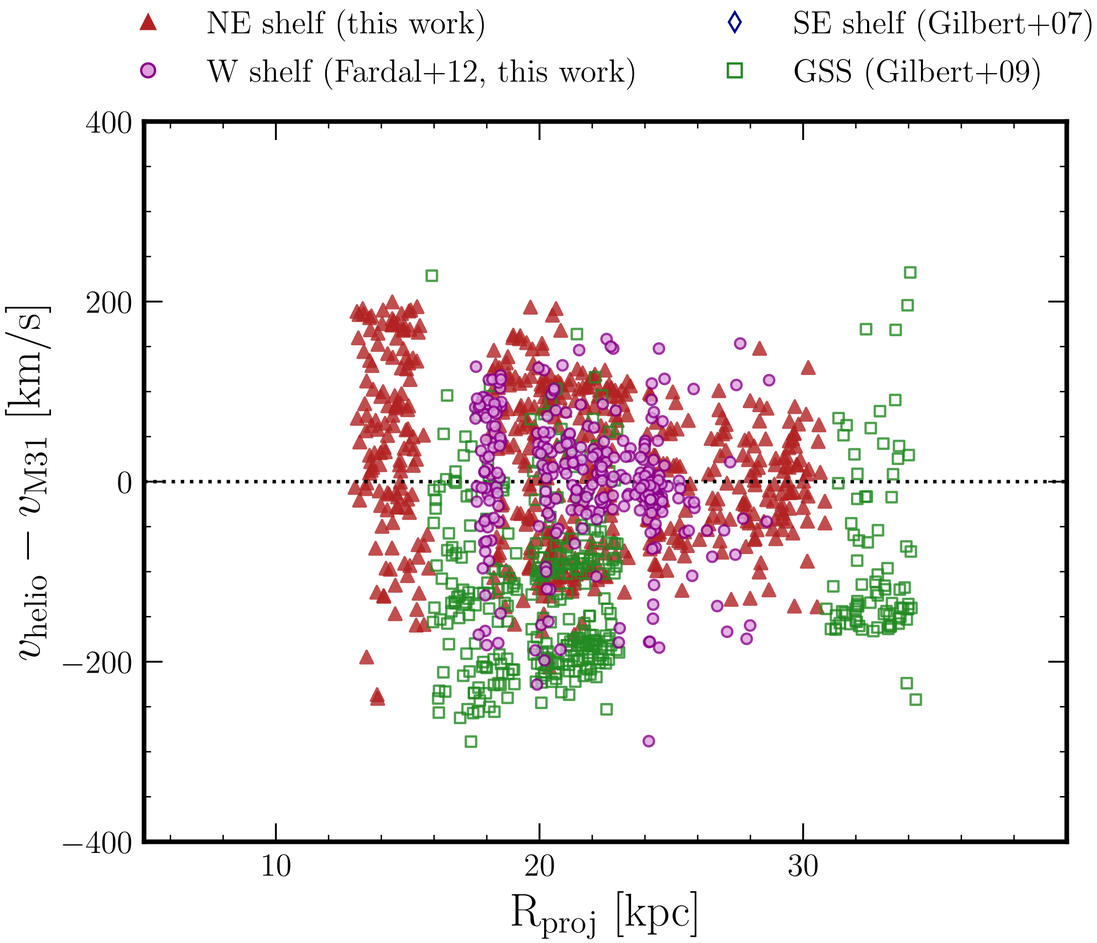
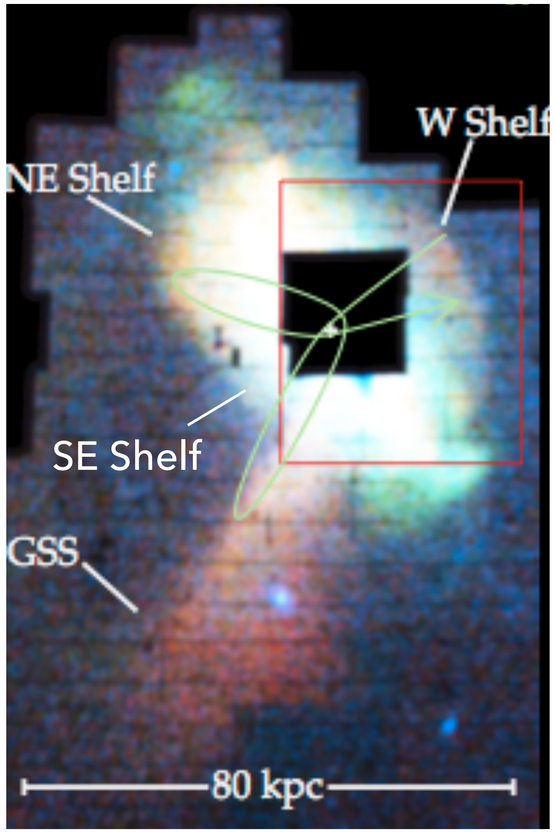


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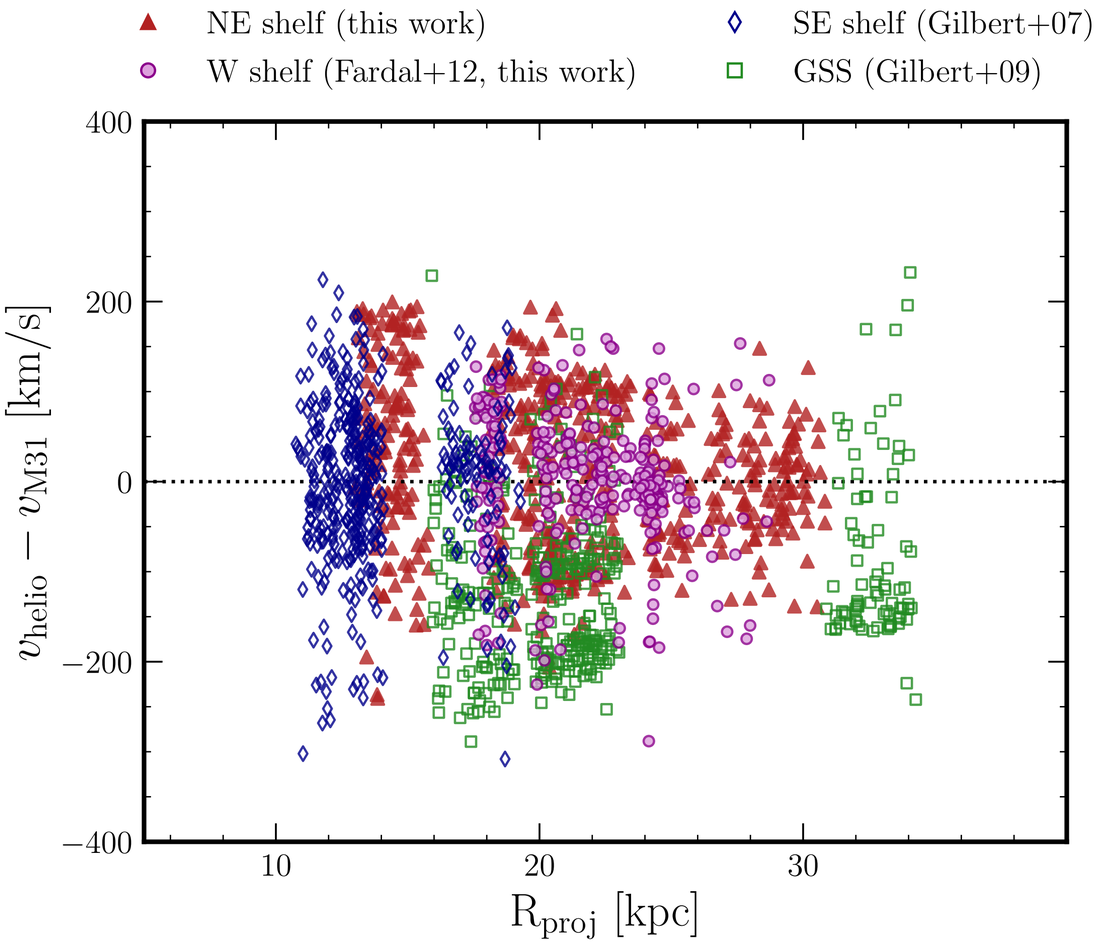
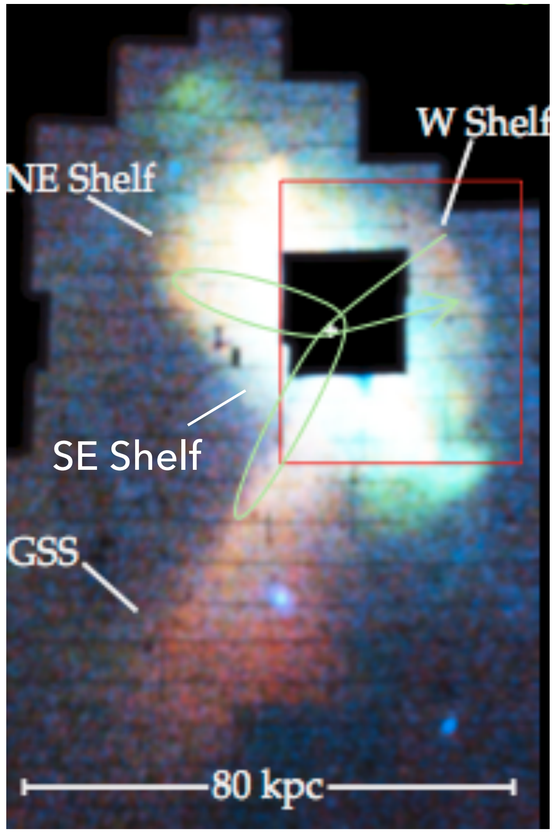


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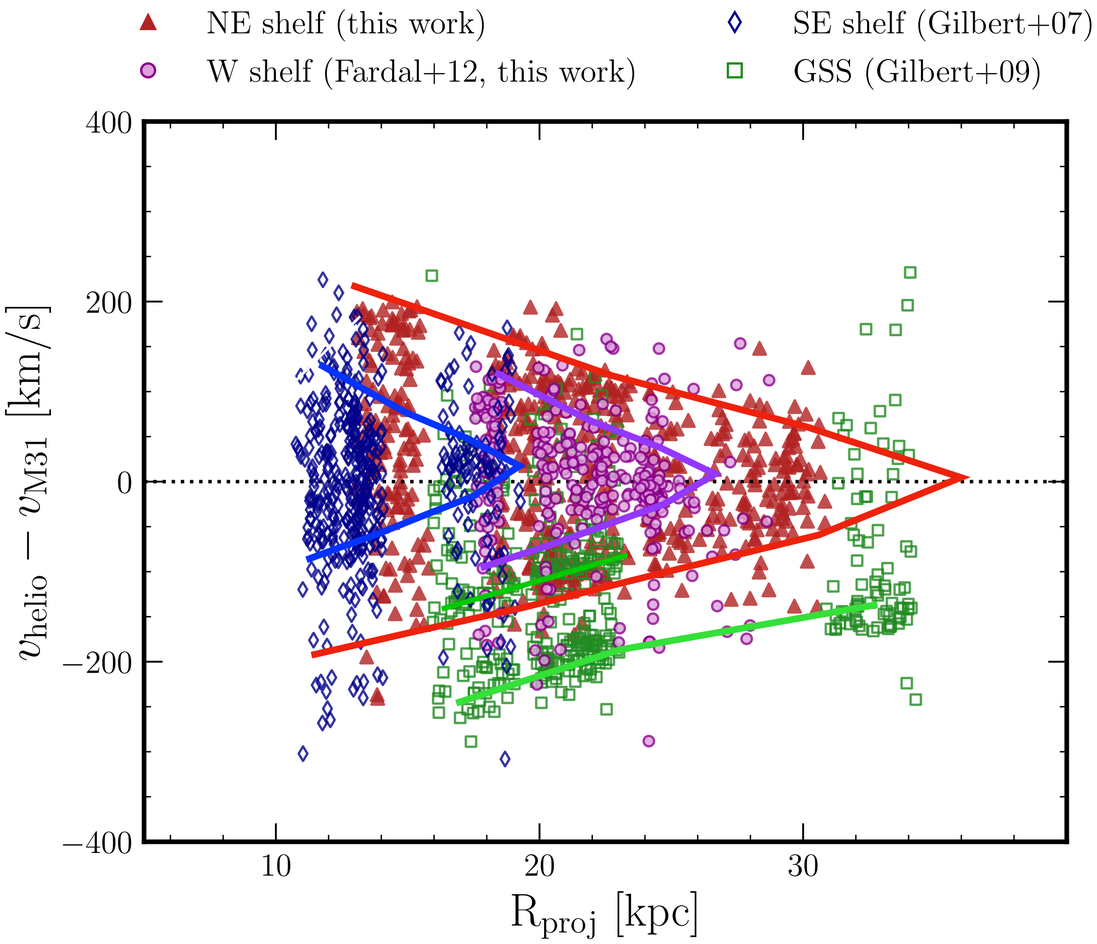
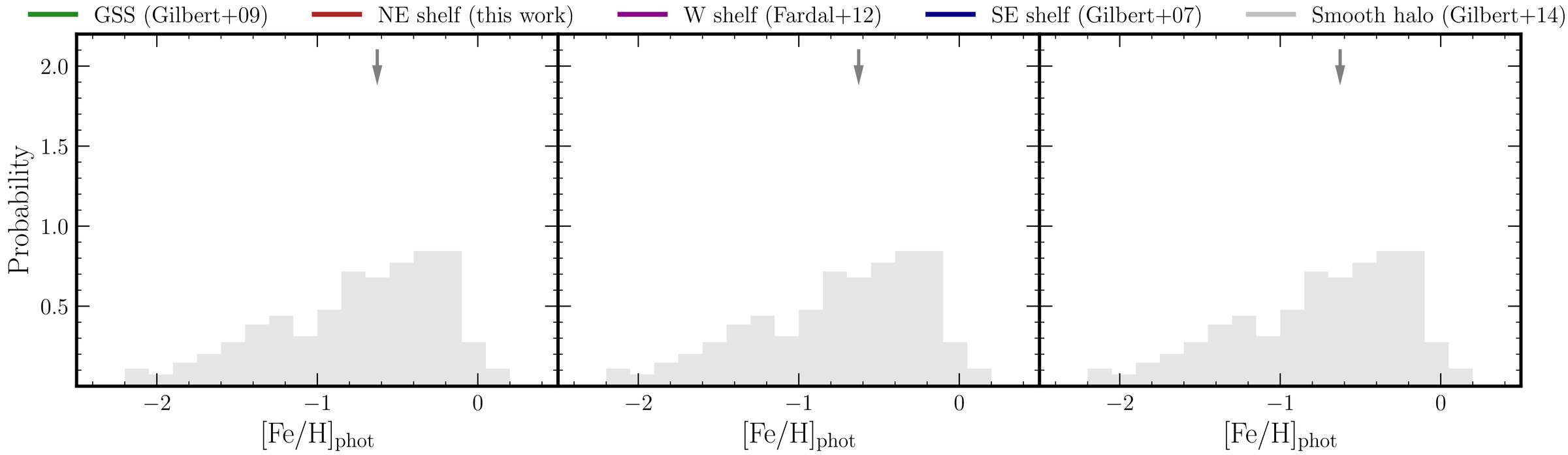


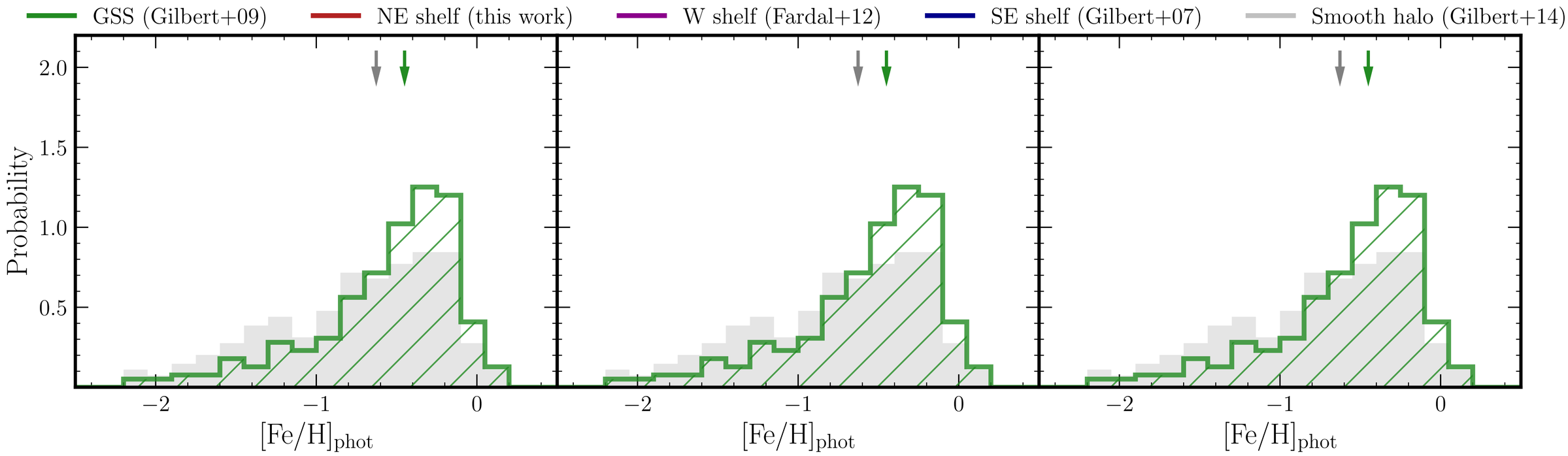
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Matching kinematics (and metal-rich stars) across the shells and streams point to a single massive accretion event



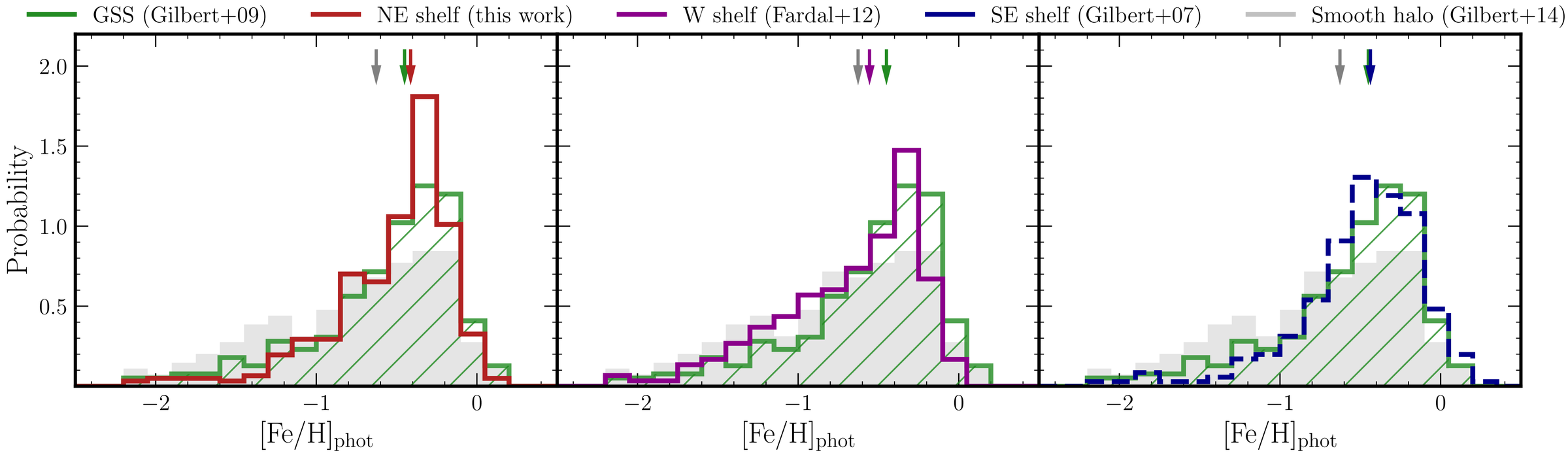
Escala+22

Matching kinematics (and metal-rich stars) across the shells and streams point to a single massive accretion event



Escala+22

Matching kinematics (and metal-rich stars) across the shells and streams point to a single massive accretion event



Escala+22

Contiguous coverage of the streams and shells from DESI confirms their kinematics, and reveals chevrons in the GSS

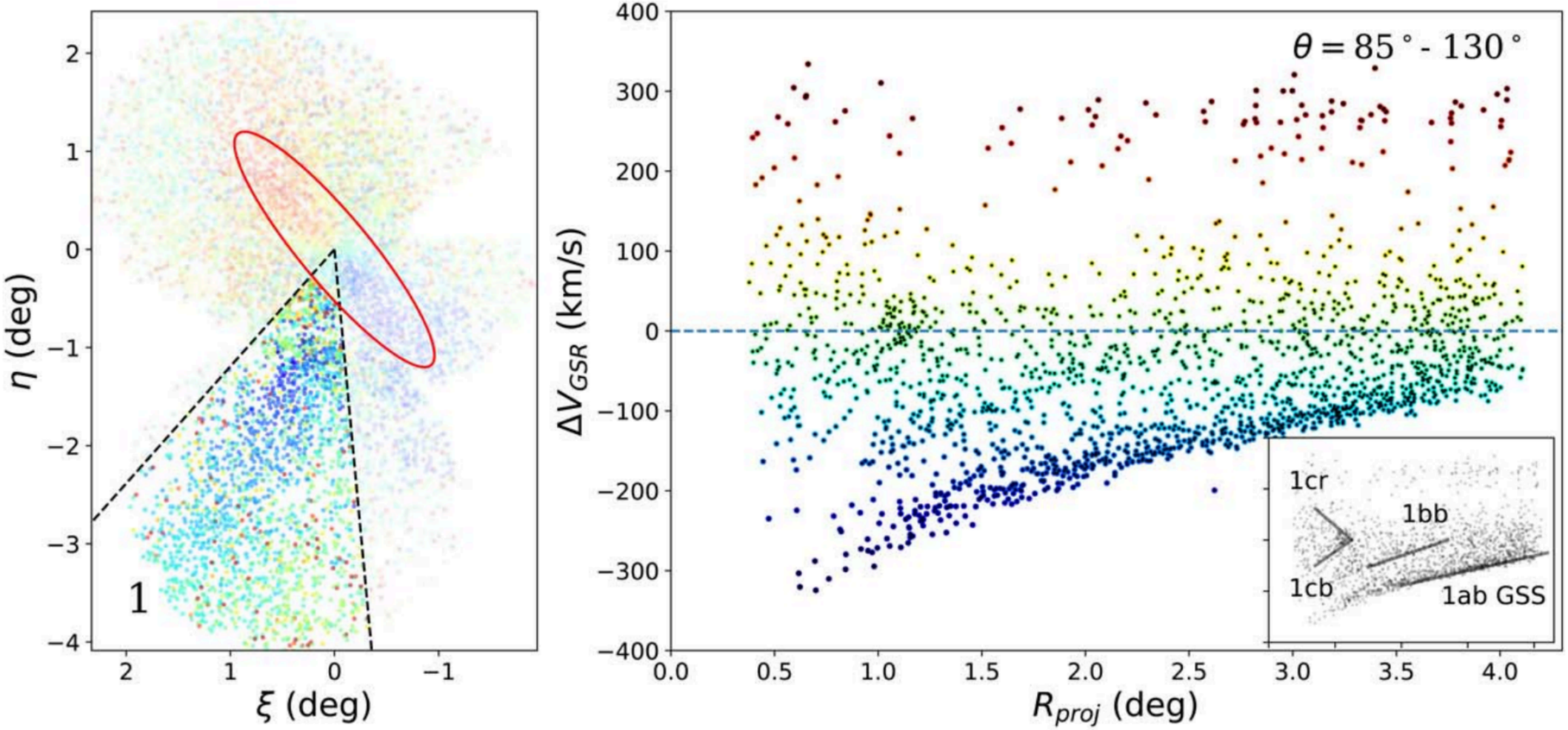
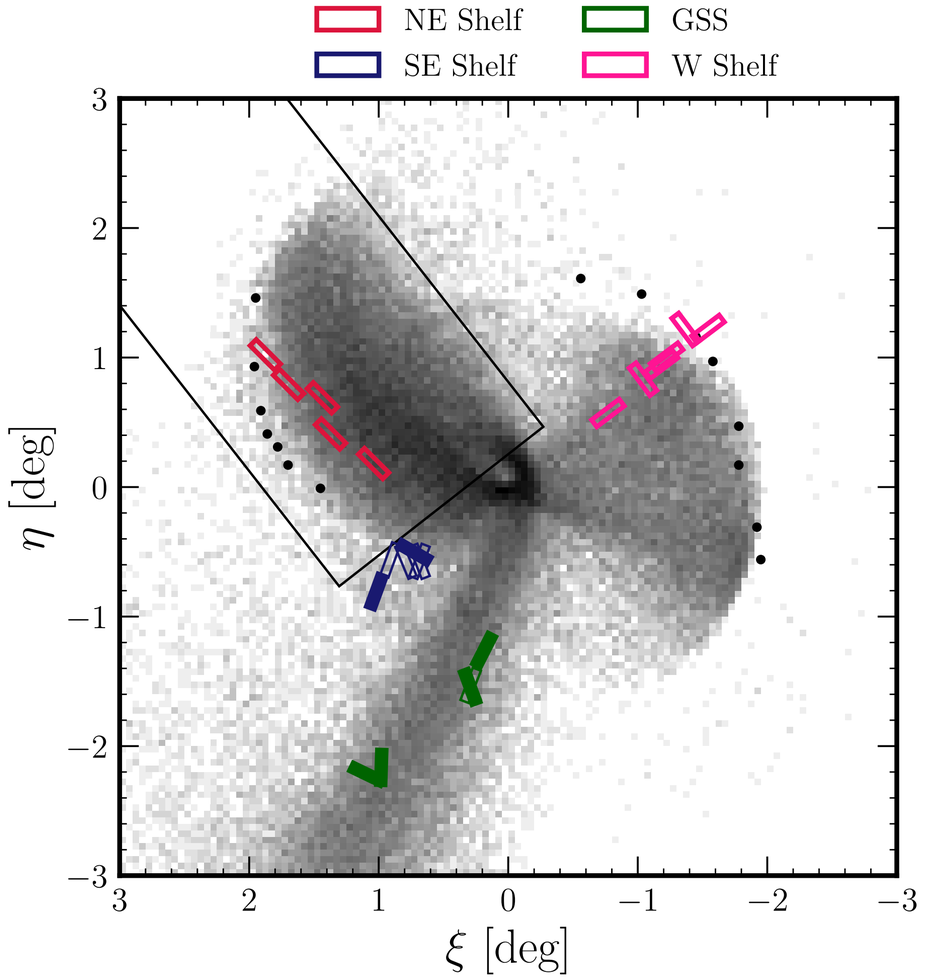


Image credit: Dey+23

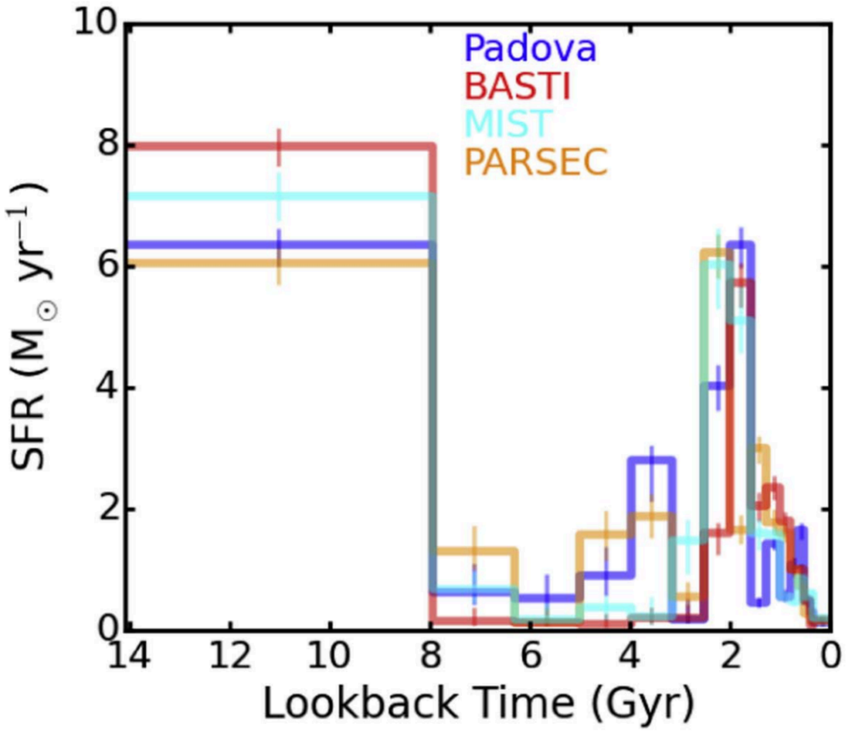
N-body models in a minor-merger framework reproduce the stream (and shells) in detail, but predict the disk is undisturbed

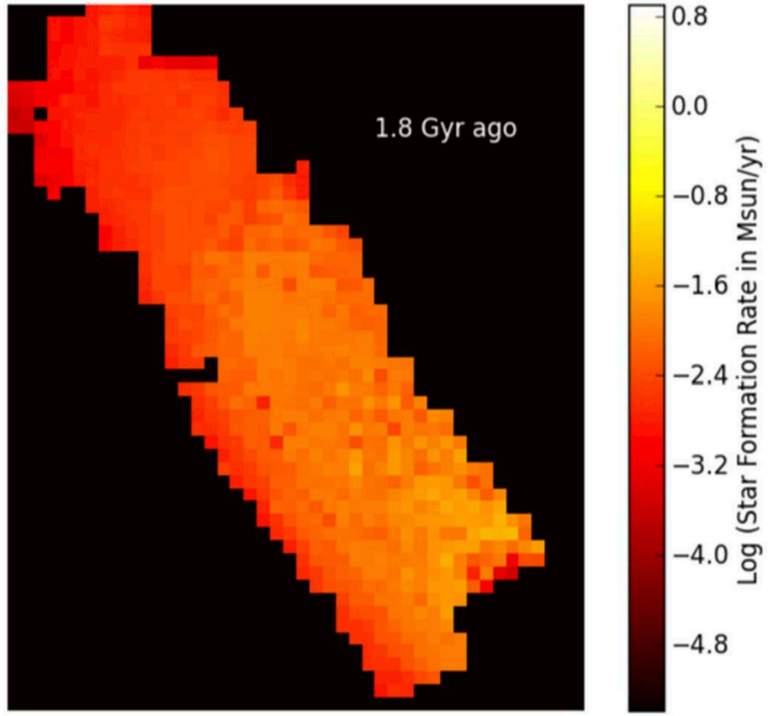


- Likely a rotating, disky progenitor with an initial metallicity gradient
- LMC or M33 mass (~10^9 Msun), 0.8 Gyr ago disruption
- Key observables: asymmetric stream profile, metal-rich core vs. metal-poor envelope (Ibata+07), shelf edges
- No intact remnant in the East has been found (e.g., Escala+22)

Image credit: Fardal+07, 12 (simulation), Escala+22 (figure)
e.g., Fardal+08; Mori & Rich 2008; Fardal+13; Sadoun+14; Miki+16: Kirihara+17; Mislosevic+22,24; Yamaguchi+25

Evidence of a widespread starburst 2-4 Gyr ago in M31's disk challenges the minor-merger picture

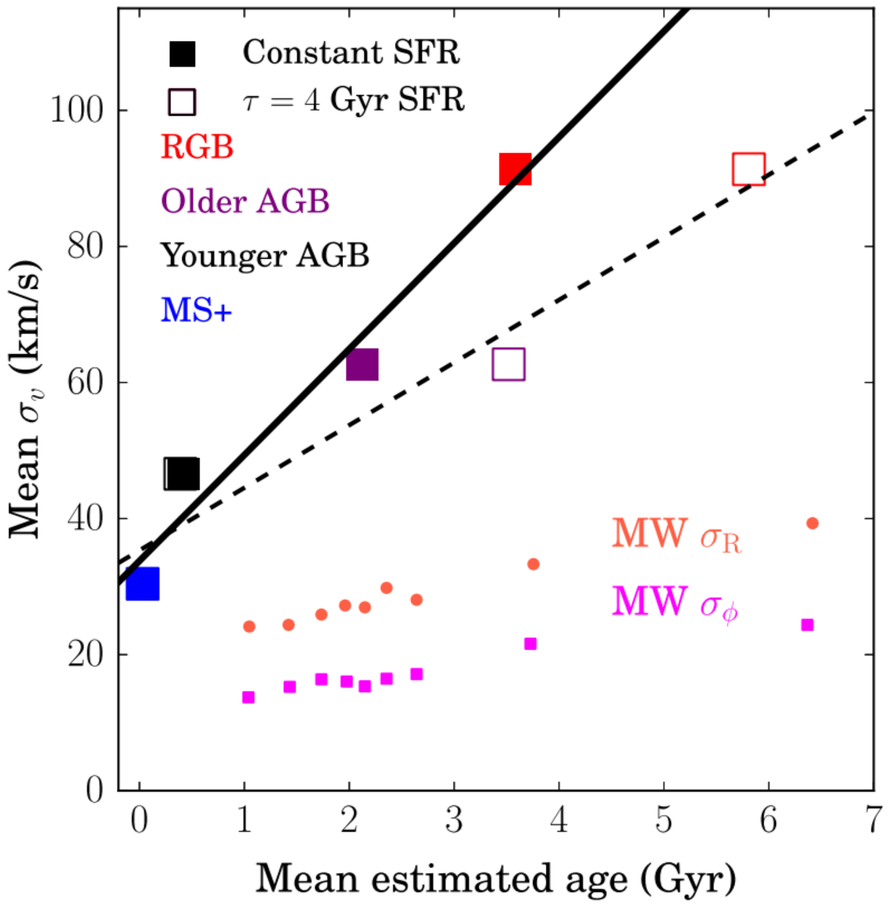




- Merger with galaxy >20% of pre-merger mass of M31 (>1:5) occurring 2 Gyr ago?
- M33 flyby? M32? Or GSS progenitor?
- *Mass budget argument assuming gas originates from progenitor, not M31*

Williams+17
See also Williams+15; Bernard+15; Lewis+15; Wainer+26

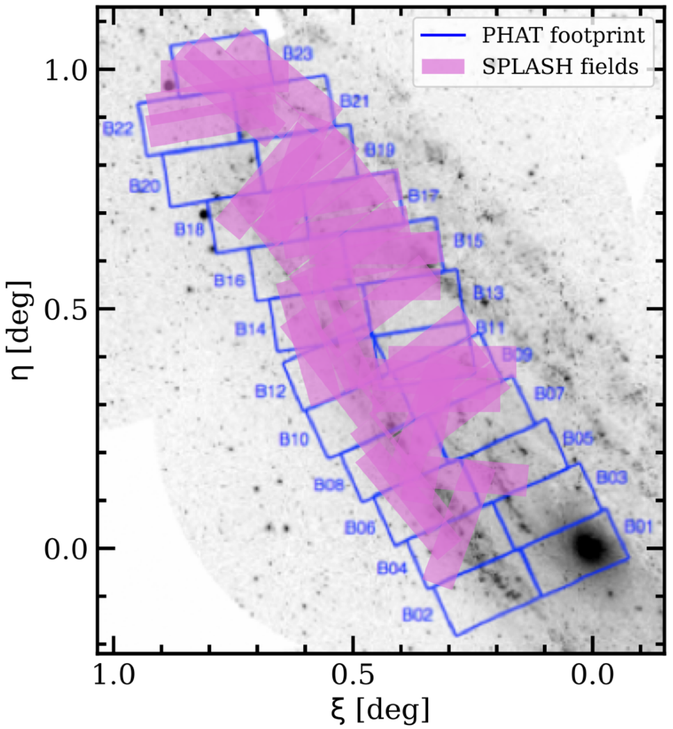
The steep age-velocity dispersion relation the disk, and the degree of asymmetric drift, argues for substantial disk heating

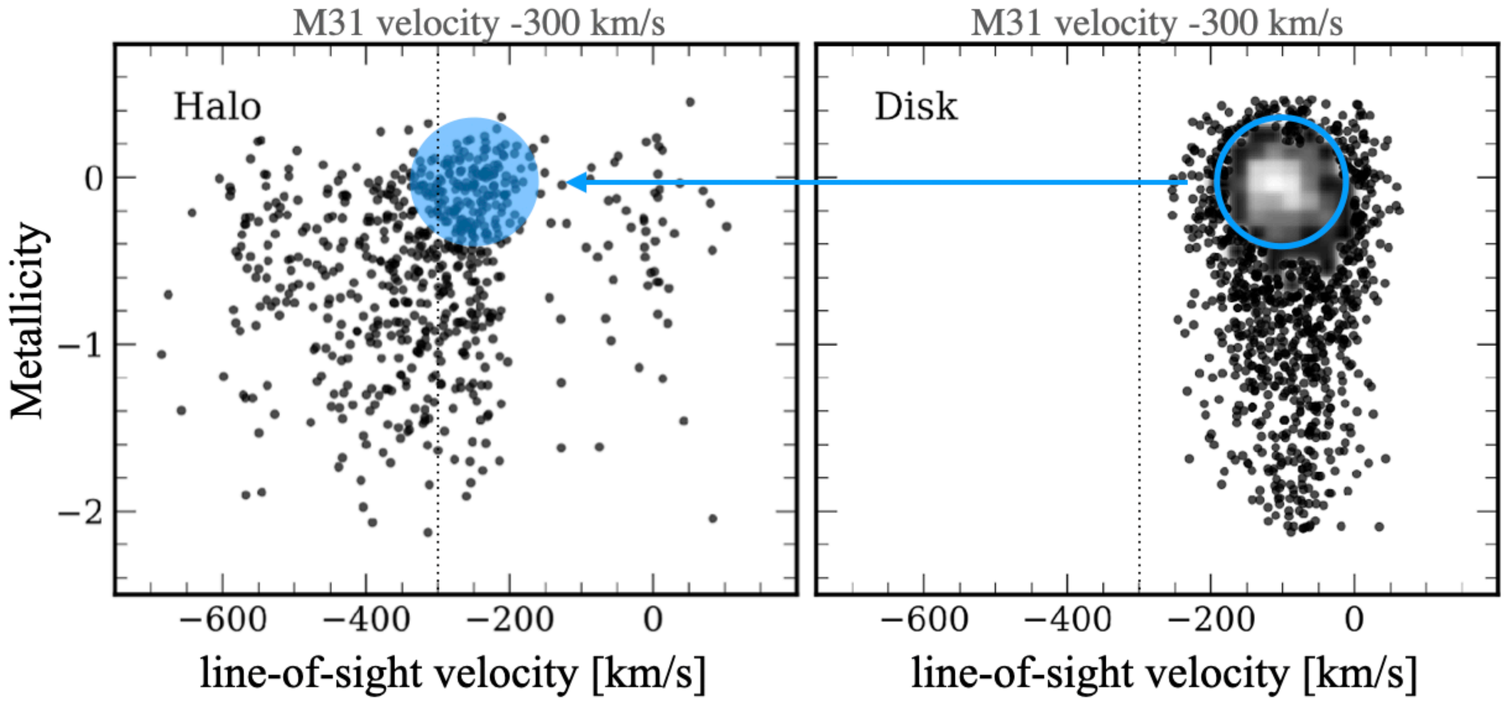


- ~2-3x more disk heating in M31 than the MW (Dorman+15)
- Old stars lag the gas more than young stars (~60 km/s), consistent with 1:4 merger (Quirk+19, Quirk & Patel 20)
- PNe age-dispersion relation suggest a 1:5 satellite-to-disk mass merger 2-4 Gyr ago (Bhattacharya+19)
- *Caution: RGB disk velocity dispersion is significantly inflated by halo star contamination (Escala+23; Grion-Filho+26)*

Dorman+15
e.g., Quirk+19, Quirk & Patel 20, Bhattacharya+19; Grion Filho+ (submitted)

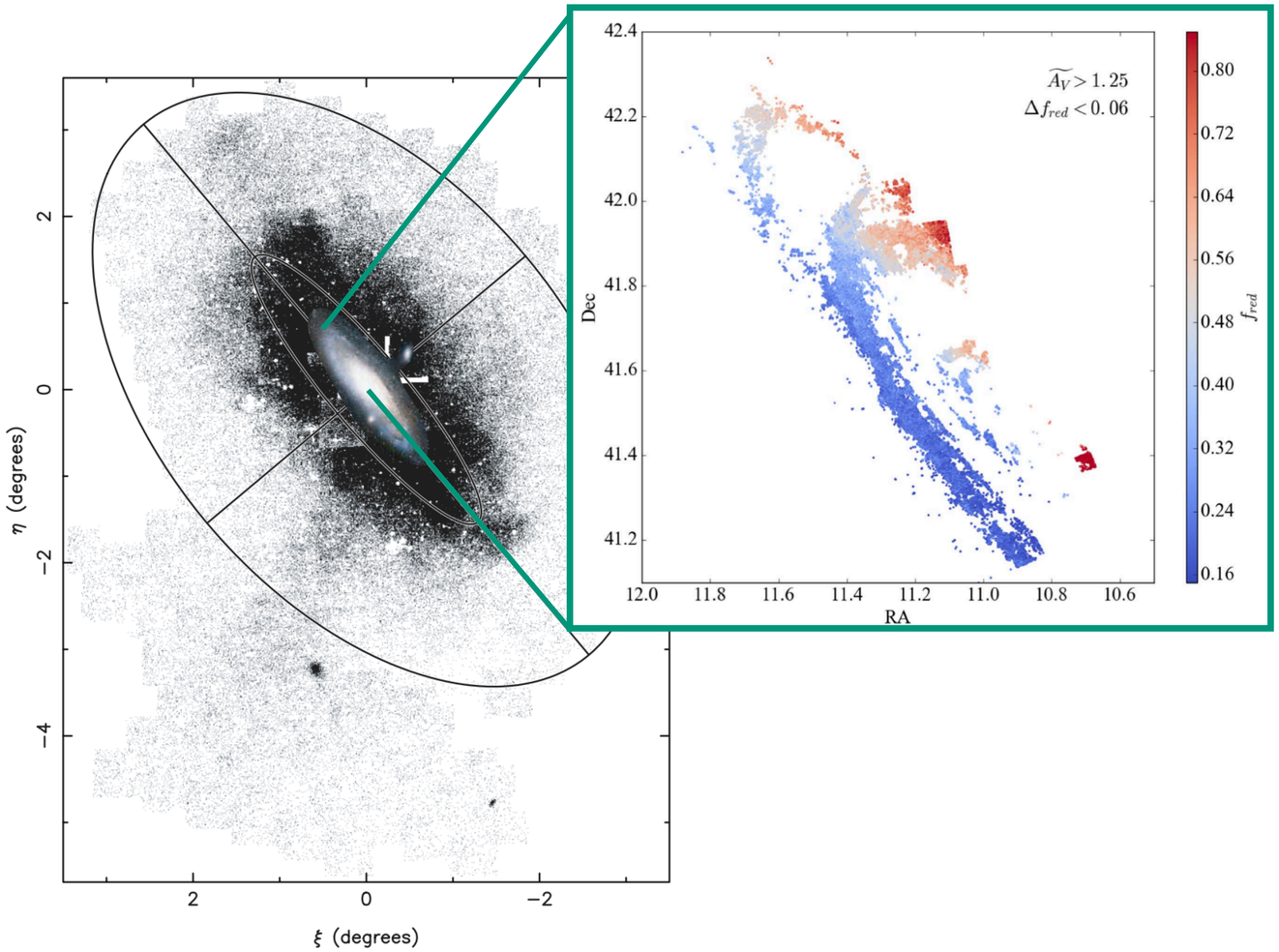
Metal-rich disk stars with halo-like kinematics show that M31's disk was heated and kicked-up into the halo





Escala+23
e.g. Dorman+13; Grion Filho+ (submitted)
See also Di Matteo+19, Belokurov+20, Grand+20, Amarante+20 for the MW

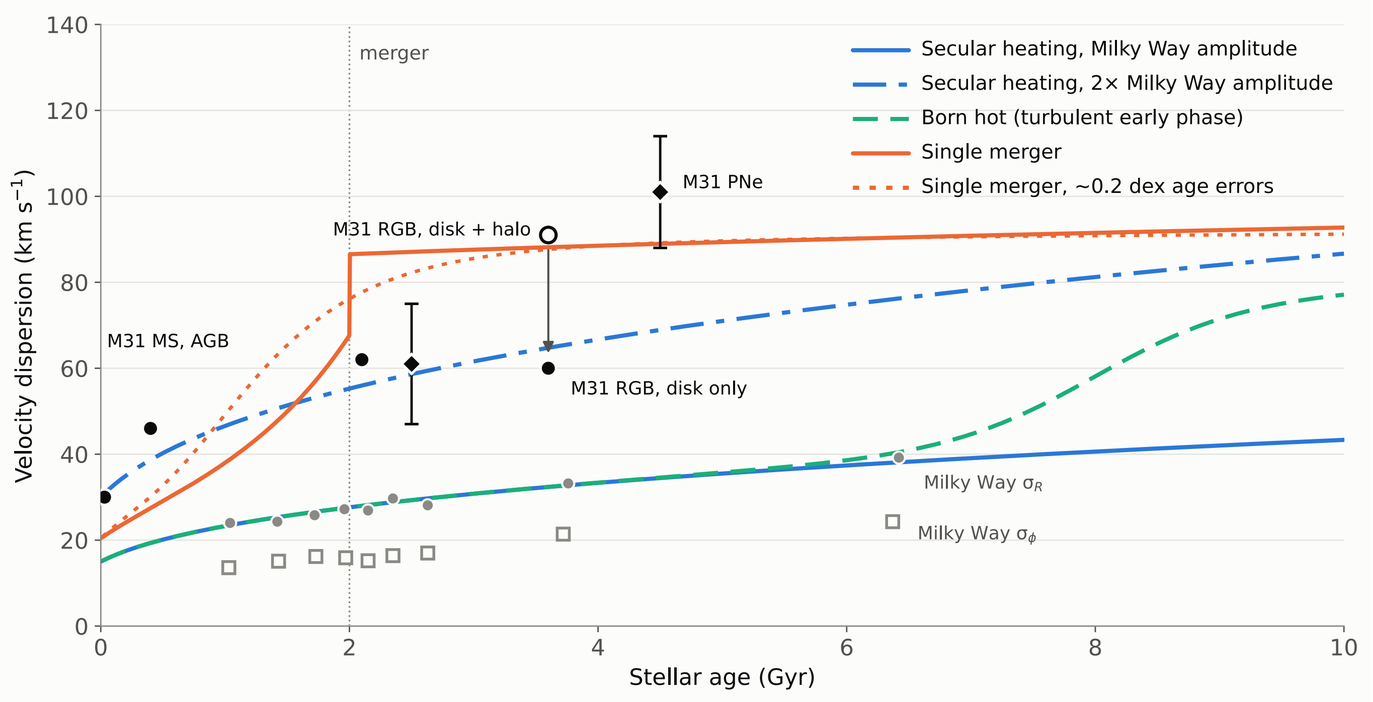
A globally thick, vast disk also records strong heating, but not necessarily the cause



- Uniformly thick RGB disk in the north (0.8 kpc scale height; Dalcanton+15, 23)
- Extended cold, rotating disk between ~15-40 kpc, with detections out to 70 kpc (Ibata+05)
- Asymmetries in structure of northern and southern disk? (Collins+11; Gibson+25; Grion-Filho+26)

Image credit: Ibata+05 (left), Dalcanton+23 (right)
See also Tsakonas+26 for discussion of extended disk

Though disk heating can result from internal processes, the bursty, hot, thick disk argues for merger contributions

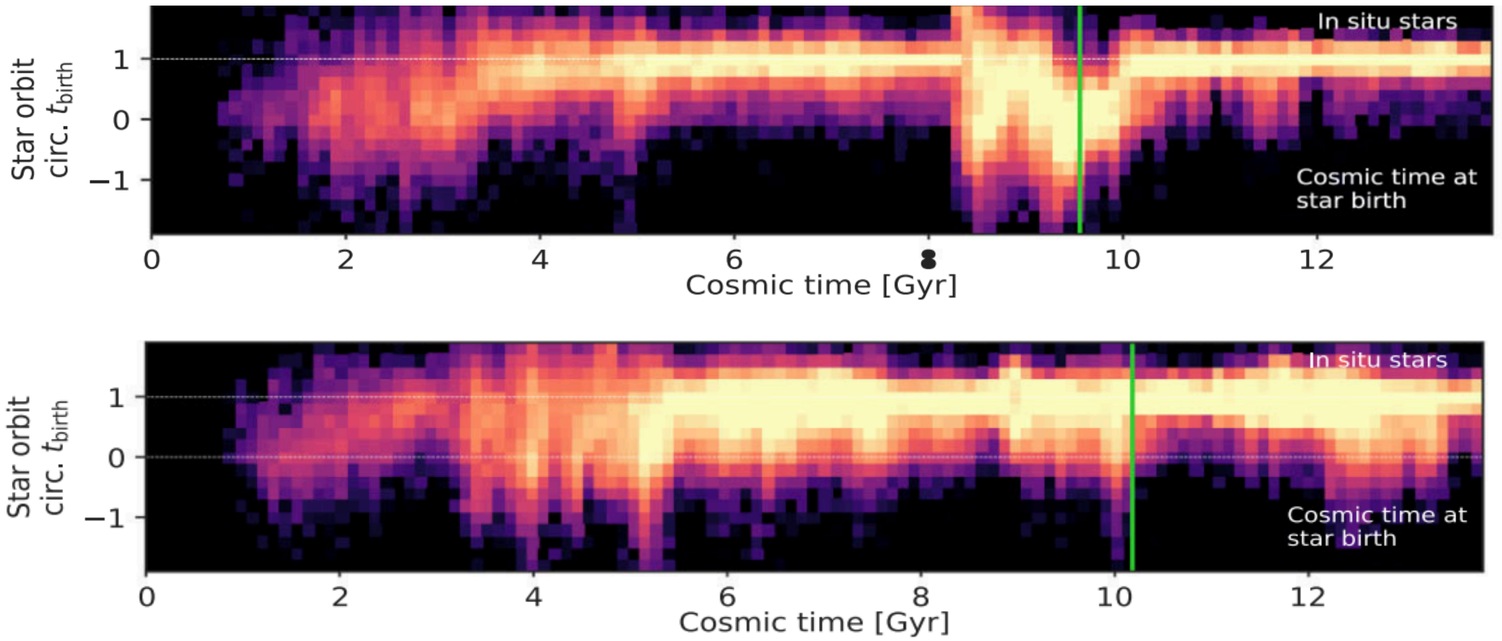


- A single merger produces a jump in velocity dispersion for stars born after the event, and heats existing stars
- Alternatives: upside-down formation and secular disk heating in a massive disk

Image credit: I. Escala (using Claude Opus 5.5)

e.g., Purcell+10; McCarthy+12; Bird+13; Martig+14; Grand+16; Aumer+16,17; Yu+21

Disks can survive disruption in gas-rich major mergers, or re-form following complete disruption



- The stability of the disk previously prohibited major-merger scenarios in M31
- Requires high gas fractions for merger
- Major mergers are common (85%) in MW and M31-mass galaxies, with 16% experiencing one within last 5 Gyr

Sotillo-Ramos+22
e.g. Springel & Hernquist 05; Hopkins+09; Peschken+20

Tailored hydrodynamical simulations show that a *major merger* could reproduce M31's hot, bursty, thick disk

PAndAS observations



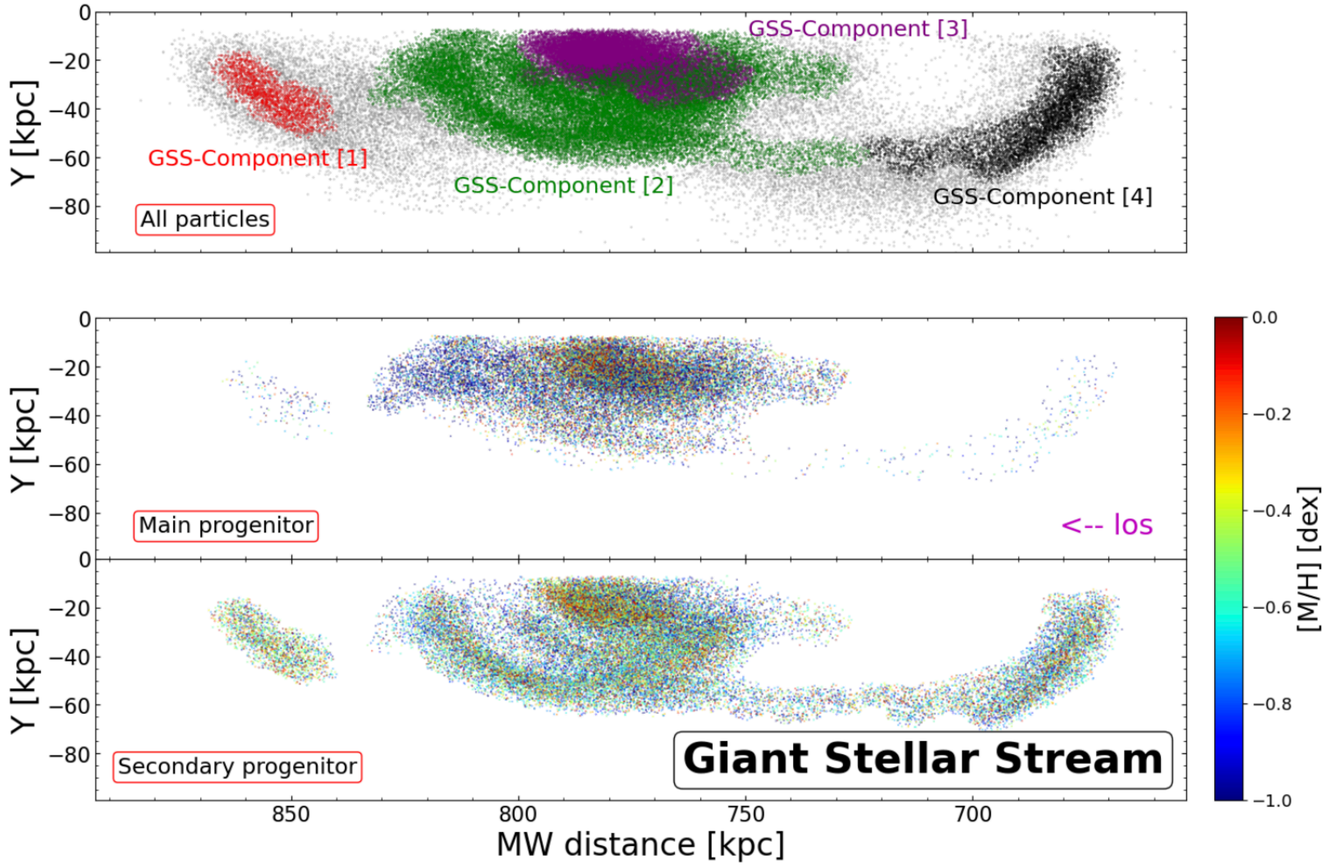
Simulation



- 300 simulations, with 4:1 merger (~10^{10} Msun), first passage 7-10 Gyr ago at 32 kpc, coalescence 2-3 Gyr ago (no remnant)
- Tuned to reproduce age-dispersion relation from Dorman+15, also reproduces starburst and extended disk
- Produce GSS-like and NE shelf-like tidal features
- *The GSS can be formed with mass ratios from 2:1 to 300:1, but the disk breaks the degeneracy*

Hammer+18
See also Hammer+10

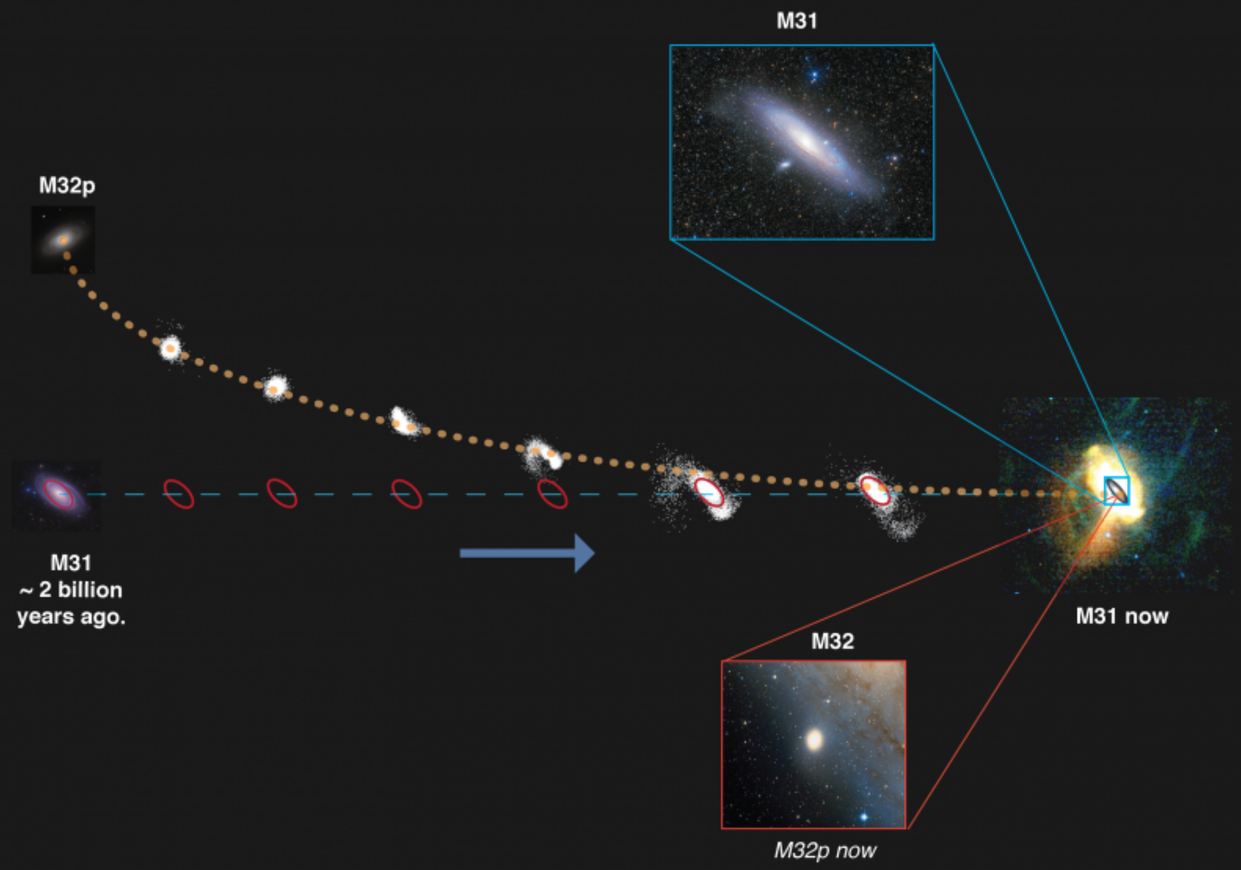
This major merger qualitatively reproduces multiple loops in the GSS and other observed features



- Broad agreement with NE shelf, W shelf, and GSS (Escala+22, Dey+23)
- Predict GSS is a composite of loops at different energies from successive pericentric passages (Tsakonas+25)

Image credit: Tsakonas+25
See also Bhattacharya+23; Tsakonas+26

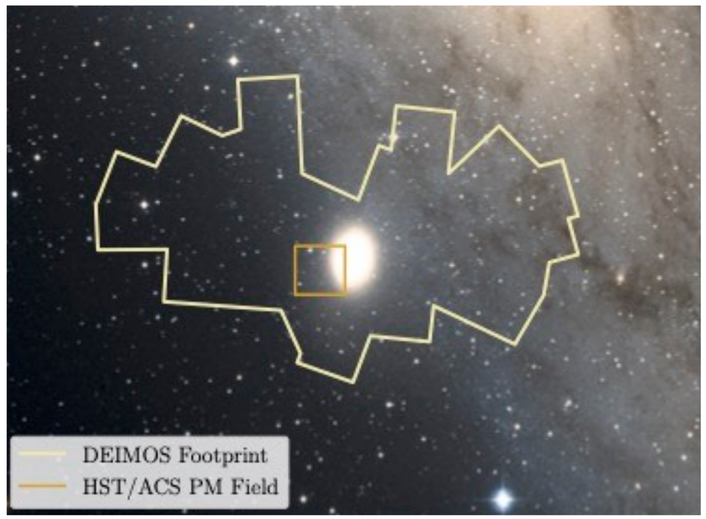
M31's massive, metal-rich halo also points to a single dominant, accreted progenitor in a cosmological context

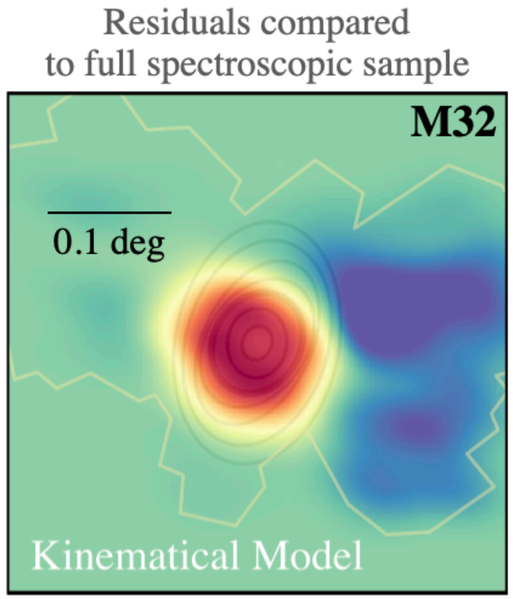


- Unifies halo properties, disk properties, tidal system, and M32 in a single cosmological framework
- Comparison to M31 analogs in Illustris
- In this scenario, third most massive member of Local Group, ~10^{10} Msun, occurring 2 Gyr ago
- *Caveat: High photometric metallicity assumed for halo, no simulations run for M31/M32*

D'Souza & Bell 2018a,b
Artist model of a possible formation pathway for M32

M32 may be the stripped core of a massive progenitor, or have formed from a similar-mass dwarf galaxy

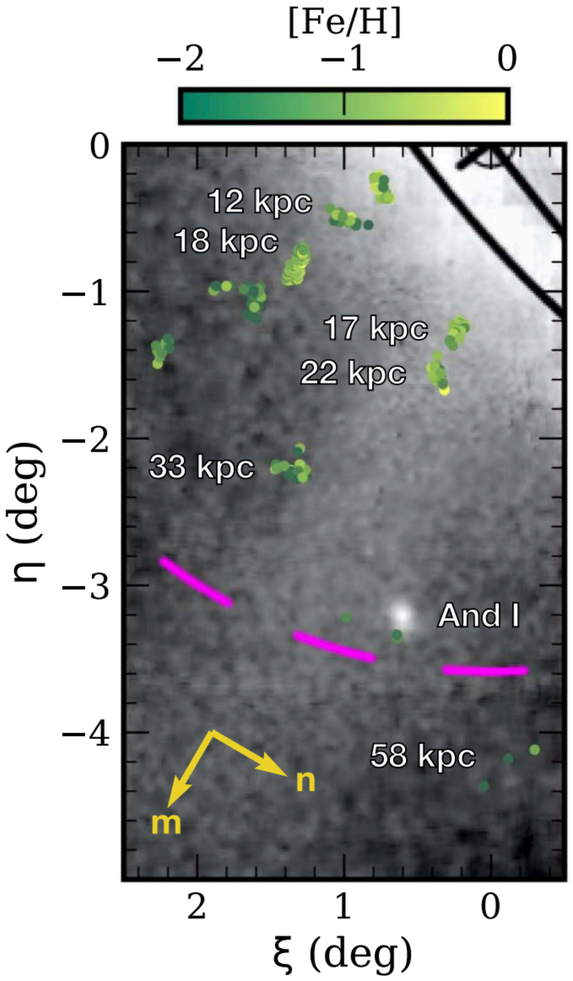


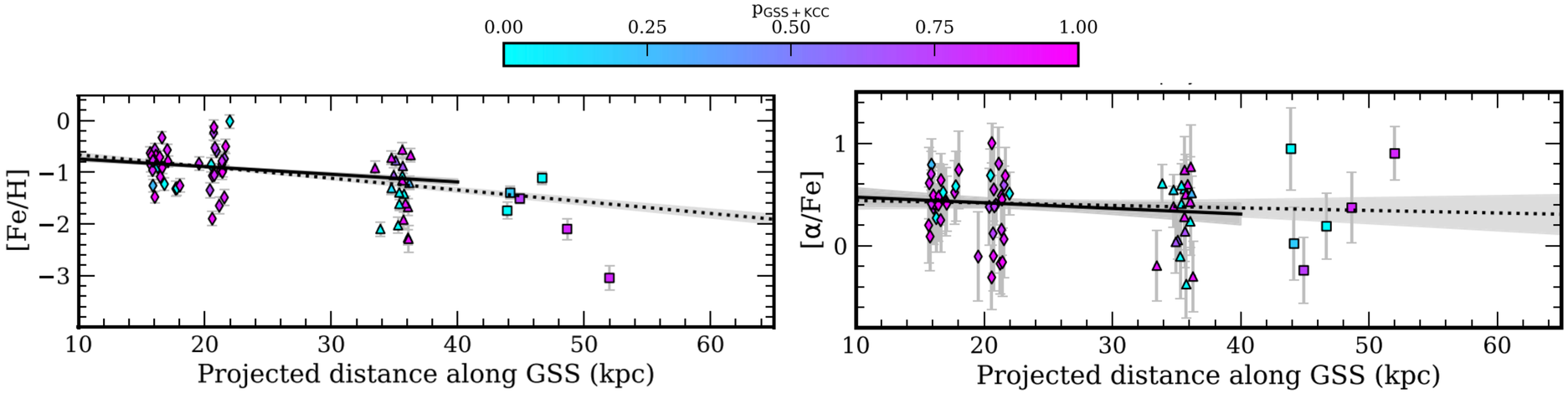


- 2-5 Gyr starburst, metal-rich (Monachesi+11, 12), central black hole (~10^6 Msun), and compact (100 pc, Choi+02)
- Evidence for M32 as core of GSS progenitor is structural and chemical, not dynamical (e.g., Fardal+06,13; Escala+22)
- Kinematical evidence that M32 has interacted with M31 (Escala+25)
- *HST-based PMs and modern orbits for M32 will provide a decisive piece of evidence (Fardal+ in prep, Patel+ in prep)*

Escala+25
e.g., Bekki+01; Choi+02; Block+06; Gordon+06; Howley+13; Dierickx+14; Du+19; Deeley+23, Bian+24, Jang+24

Chemistry of resolved stars provides a path forward for distinguishing between various scenarios for M31's last significant merger

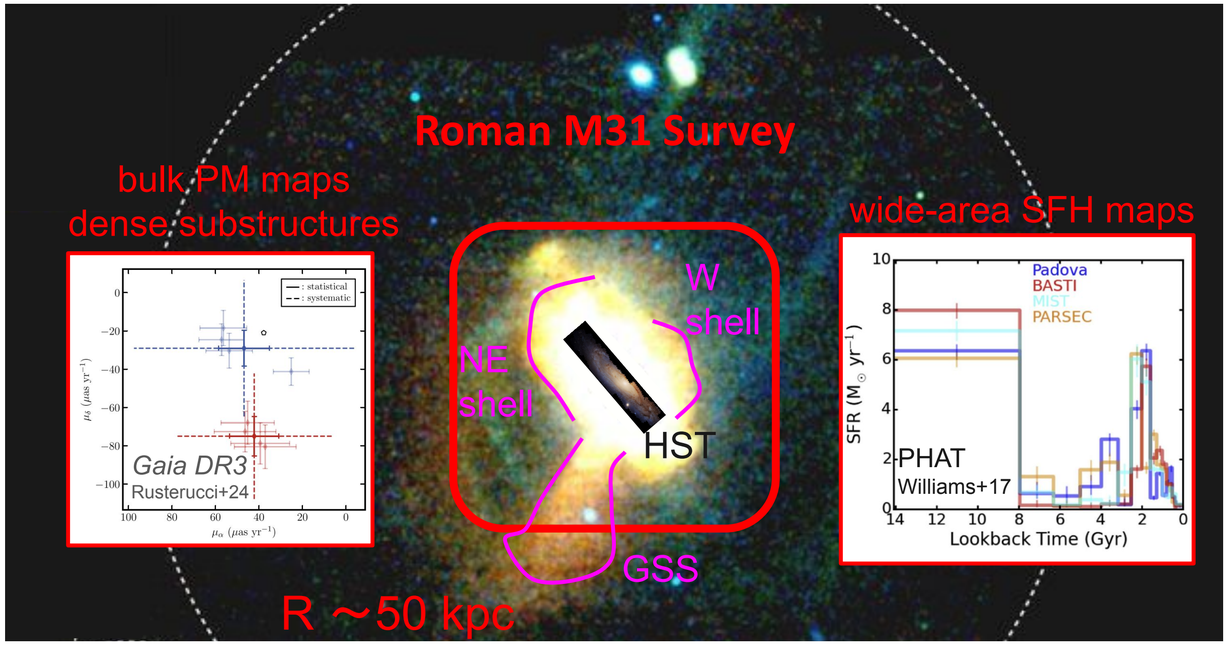




- Lower limit on GSS stellar mass of 1-5 x 10^9 Msun (Gilbert+19)
- GSS components chemically indistinguishable, shells chemically consistent (Escala+21, 22)
- Most conservative limit with normal dark matter halo implies progenitor with ~10^{11} $M_\odot$ at infall, or ~1:10–1:30 merger mass ratio

Escala+21
e.g., Gilbert+19; Escala+20a,20b; Bhattacharya+22; Arnaboldi+22; Wojno+23

The *Cycle 1* Roman Legacy Survey of Andromeda will enable proper motions throughout M31's halo, breaking existing model degeneracies



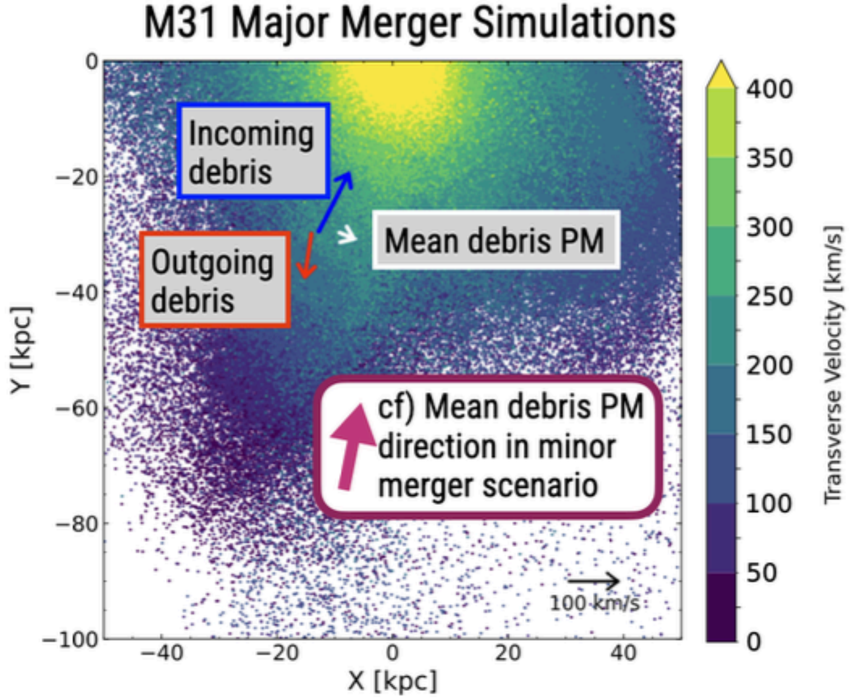


Image credits: K. Gilbert, I. Escala, C. Tsakonas, T. Sohn, M. Fardal, and the Andromeda with Roman team

Summary: Discriminating between modeled scenarios for M31's last significant merger

Discriminant	Minor merger (Fardal-type, M★ ~10^9 M ⊙)	Major merger, no M32 (H18, 4:1)	Major merger, M32 as core (D'Souza & Bell)	Observations to date
Progenitor remnant	Core disrupted, or near the disk	Fully coalesced	M32 is the surviving core	No core in the NE shelf; M32's outskirts tidally distorted, but its position doesn't match model core locations
GSS phase-space structure	One stream (one-sided shell), with nested shells at successive wraps	Superposition of loops from successive pericenters	Not modeled in detail	DESI maps the GSS, a second cold component and compact chevrons continuously; H18 reproduces these qualitatively
GSS second cold component	Same event; leading debris or a W-shelf extension; not clearly reproduced in Fardal-type models	Debris from several wraps of the progenitor, plus M31 stars displaced along its orbit	Not modeled in detail	~100 km/s offset from the GSS, parallel velocity gradient, spatially offset and shorter; chemistry consistent with the GSS
Debris age	≤1 Gyr since first pericenter	Coalescence 1.8–3 Gyr ago	~2 Gyr ago	Set by the models, not measured independently
Disk star formation	No disk-wide burst predicted	Disk-wide burst	Burst concentrated toward the center	Disk-wide episode 2–4 Gyr ago
Disk kinematics and structure	Little heating expected (not modeled)	Hot, thick disk; steep age–dispersion relation; kicked-up stars; extended warped disk	Hot, thick disk	Older stars hotter than in the MW (RGB σ ~60 km/s disk only; PNe ~100 km/s at 4.5 Gyr); whole disk thick; kicked-up population
Progenitor chemistry	Set by a ~10^9 M ⊙ progenitor with a gradient	Metal-rich, efficiently star-forming progenitor with gradient	Metal-rich progenitor, third most massive member of LG	Metal-rich GSS with high [α/Fe] and a gradient; same metal-rich distribution in the shelves and GSS core
Open predictions	Debris where the GSS and W shelf cross the southern disk; location of any core remnant; 3D motions of stream and shell stars	Quantitative fit to the velocities and distances of the GSS loops, shells; 3D motions; outer-disk structure	M32's proper motion consistent with the GSS progenitor's orbit	Southern disk being mapped (PHAST imaging and Keck/DEIMOS spectroscopy); HST proper motions of M32; Roman halo proper motions

Summary: Models for the last significant merger of M31 and the response of its disk

- **The GSS and shelves trace one recent, massive accretion event.** The positions, velocities, and chemistry of the system of tidal features strongly support a common origin scenario. Both major- and minor- merger models produce qualitative agreement, though the multiple-loop structure of the GSS points to a major merger.

- **The progenitor was massive, though its stellar mass is debated within an order of magnitude.** Minor merger models favor an M33 or LMC mass progenitor, which the chemistry of the GSS agrees with at face value. Major merger models favor a galaxy that may have been the third most massive member of the Local Group.

- **The disk is hot, thick, and bursty, where these properties point to a major merger.** Gas-rich major mergers can leave a disk intact, or enable them to rebuild, but leave disk properties altered. Minor merger scenarios do not model any impacts on M31's disk, whereas a major merger could explain its observed properties.

- **The compact satellite M32 likely has a tidal origin, but its role in M31's merger history remains unclear.** M32's extreme properties suggest it may be the remnant core of a formerly more massive galaxy also responsible for M31's tidal system, but this scenario is not dynamically consistent with M32's observed position and velocity.

- **Independent clocks of the merger are the bottleneck.** The age of the merger debris is inferred from models, not directly from the data. Disk chemical abundances, proper motions of M32, and 3D motions throughout the halo from Roman will be able to discriminate between various scenarios for M31's last significant merger.

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